University of Rome 'Tor Vergata'

FACULTY OF MATHEMATICAL PHYSICAL AND NATURAL SCIENCES

MASTER OF SCIENCE

**A Multivariate Tool to Reject Background in a
WZ Diboson Search with the Full CDF Run II
Data Set**

Master Thesis in Physics

Advisors

Prof. Giorgio Bellettini

Prof. Anna Di Ciaccio

Co-advisor

Doct. Marco Trovato

Candidate

Matteo Cremonesi

ACADEMIC YEAR 2010-2011

Università degli Studi di Roma 'Tor Vergata'

FACOLTÁ DI SCIENZE MATEMATICHE FISICHE E NATURALI

CORSO DI LAUREA MAGISTRALE IN FISICA

**Uno Strumento Multivariato per la Riduzione del
Fondo in un'Analisi sulla Produzione Associata di
Bosoni WZ con Tutto il Campione del RUN II di
CDF**

Tesi di Laurea Magistrale in Fisica

Relatori

Prof. Giorgio Bellettini

Prof.ssa Anna Di Ciaccio

Correlatore

Dott. Marco Trovato

Candidato

Matteo Cremonesi

ANNO ACCADEMICO 2010-2011

Abstract

In the frame of the strong on-going data analysis effort of the CDF collaboration at Fermilab, a method was developed by the candidate to improve the background rejection efficiency in the search for associated pair production of electroweak W, Z bosons. The performances of the method for vetoing the $t\bar{t}$ background in a $WZ/ZZ \rightarrow \ell\nu q\bar{q}$ diboson search are reported. The method was developed in the inclusive 2-jets sample and applied to the “tag-2 jets” region, the subsample defined by the request that the two jets carry beauty flavor. In this region the $t\bar{t}$ production is one of the largest backgrounds. The $t\bar{t}$ veto proceeds in two steps: first, a set of pre-selection cuts are applied in a candidate sample where up to two leptons are accepted in addition to a jet pair, and the ZZ component of the signal is thus preserved; next, a Neural Network is trained to indicate the probability that the event be top-pair production. To validate the method as developed in the inclusive 2-jets sample, it is applied to veto $t\bar{t}$ events in the Tag 2 Jets region providing a significant rejection of this important background.

Sommario

Nel contesto dell'intenso sforzo attualmente in corso in analisi dati da parte della collaborazione CDF a Fermilab, é stato sviluppato dal candidato un metodo per migliorare l'efficienza di eliminazione del fondo nella ricerca di bosoni W e Z in produzione associata. Sono riportate le prestazioni del metodo per rigettare il fondo di coppie di quark top-antitop. Il metodo é stato sviluppato nel campione inclusivo con due getti nello stato finale e successivamente applicato alla nella cosiddetta "regione tag-2-getti", il sottocampione definito dalla richiesta che i due getti siano originati da un quark beauty. In questa regione la produzione di coppie $t\bar{t}$ é uno dei fondi principali. Il veto $t\bar{t}$ é sviluppato in due fasi: prima, una serie di tagli di pre-selezione sono stati applicati al campione nel quale vengono richiesti fino a due leptoni in aggiunta alla coppia di getti, accettando cosí la componente del segnale data dalla produzione di coppie di bosoni Z; la seconda, l'educazione di una Rete Neurale che indichi la probabilitá che un evento sia una coppia $t\bar{t}$. Per validare il metodo sviluppato nel campione inclusivo con 2 getti nello stato finale, il veto é stato poi applicato a eventi $t\bar{t}$ nella regione tag-2-getti, garantendo una significativa eliminazione di questo importante fondo.

Contents

Bibliography	1
Abstract	I
Sommario	III
List of Tables	VII
List of Figures	IX
1 The Electroweak Unification	1
1.1 The Standard Model	1
1.2 Electroweak Theory	3
1.2.1 QED	3
1.2.2 Electroweak Unification	4
1.3 Discovery of the W and Z Bosons	10
1.4 WZ Associated Production	13
1.4.1 Triple Gauge Couplings	13
1.4.2 Towards the Higgs	16
1.5 Diboson Production at Tevatron	16
2 The Experiment	19
2.1 The Tevatron Collider	19
2.1.1 The Proton Source	19
2.1.2 The Antiproton Source	19
2.1.3 The Tevatron Ring	21
2.1.4 Luminosity and Tevatron Performance	21
2.2 The CDF II detector	22
2.2.1 Coordinates System and Standard Definitions at CDF	22
2.3 The tracking system	24
2.3.1 The Silicon Tracker	25
2.3.2 Central Outer Tracker	26
2.3.3 Time Of Flight	27
2.4 Calorimeters	28
2.4.1 The Central Calorimeter	28
2.4.2 The Plug Calorimeter	30
2.5 The Muon Chambers	30
2.6 CLC detector	32

3	The CDF Trigger sistem	33
3.1	The CDF Trigger System	33
3.2	LEVEL 1	33
3.3	LEVEL 2	34
3.4	LEVEL 3	35
3.5	Trigger Paths	35
4	Physical Object Reconstruction	37
4.1	Track Reconstruction	37
4.1.1	Primary Vertex Reconstruction	38
4.2	Lepton Reconstruction and Identification	38
4.2.1	Electron Identification	38
4.2.2	Muon Identification	41
4.2.3	Neutrino Identification	45
4.2.4	Fake leptons	46
4.3	Jet Reconstruction	46
4.3.1	JETCLU algorithm	47
4.3.2	Jet Energy Corrections	47
4.4	Reconstruction of the Secondary Vertex: Bottom Jets Identification	52
4.4.1	Jet- <i>b</i> ness	52
5	Composition and Modeling of the Selected Data Sample	57
5.1	Event selection	57
5.2	Trigger Paths Accepted	61
5.3	Modeling of the Triggers in High- E_T Data Stream	62
5.3.1	Variable for Trigger Parameterization	62
5.3.2	Trigger-based Jet Selection Cuts	63
5.3.3	Trigger Parameterization	63
5.4	Sample Composition	63
5.5	Signal and Background Content Estimate	67
5.5.1	Electroweak and Top Content	67
5.5.2	QCD and $W + jets$ Content	68
5.6	Tag 2 Jets Modeling	70
6	The $t\bar{t}$ Veto	79
6.1	Motivation	79
6.2	The Preselection Cuts	79
6.3	The Neural Network Training	80
6.3.1	The $t\bar{t}$ Veto's NN	80
6.4	The NN Output Modeling	83
6.4.1	Pretag 2 Jets Region	83
6.4.2	Tag 2 Jets Region	84
6.4.3	Distributions of a Number of Observables	84
6.5	The Sensitivity Estimate	84
6.5.1	The Test Statistic	86
6.5.2	Sensitivity and Optimization	94
6.5.3	Check on the Sensitivity Improvement	95

7	The Final Fit	97
7.1	Fitting Procedure to the Z-Mass Distribution in the Tag 2 Jets Region	97
7.2	Systematic Uncertainties	98
7.2.1	Signal Extraction	98
7.2.2	Cross Section Evaluation	99
7.3	Fit Results on Data	99
8	Conclusion and Future Plans	101
	Bibliography	103
A	The Higgs Mechanism	107
A.1	Spontaneous Symmetry Breaking	107
A.2	The Goldstone Model	108
A.3	The Higgs Mechanism	110
A.4	Higgs Mechanism and Standard Model	111
B	Instantaneous Luminosity Measurement	113
C	Trigger Paths Description	115
D	Tracking Algorithm	117
E	NN inputs	119
F	Studies on the development of a $t\bar{t}$ veto in the 3 jets sample using a χ^2 fitter	121
F.1	Motivation	121
F.2	χ^2 fitter	122
F.3	Conclusions	123

List of Tables

1.1	Next-to-leading order (NLO) predicted the cross sections for the diboson production at $\sqrt{s} = 1.96\text{TeV}$ [26].	13
1.2	Branching ratios for WW, WZ and ZZ processes [25].	14
1.3	BR and expected cross sections for WZ/WH. At the Tevatron, the $WH \rightarrow \nu b \bar{b}$ process has an $\sigma \times \text{BR}$ expected about five times lower than $WZ \rightarrow \nu b \bar{b}$ for $m_H = 120\text{GeV}/c^2$	17
2.1	Accelerator nominal parameters for Run II configuration.	21
2.2	Summary of the main characteristics of the CDF II calorimeter system.	30
2.3	Design parameters of the muon detectors. Assembled from Ref. [10], [11]	30
4.1	Definition of fully identified Tight Central Electron (TCE).	40
4.2	Definition of Forward Electrons (PHX)	40
4.3	Definition of central electron probe.	41
4.4	Definition of central electron fakeable object.	41
4.5	Definition of CMUP central muons.	42
4.6	Definition of CMU central muons.	43
4.7	Definition of CMP central muons.	43
4.8	Definition of CMX central muons. The exit radius, ρ_{cot} is defined as $\rho_{\text{cot}} = (z_{\text{cot}} - z_0) \cdot \tan \theta$	44
4.9	Definition of CMIOCES central muons.	44
4.10	Definition of CMIOCES central muons.	45
4.11	Definition of CrkTrk central muons.	45
5.1	Summary of the cuts defining the candidate events samples.	59
5.2	Trigger path(s) for each lepton category. Data-taking CDF periods are listed with increasing order numbers. In black trigger paths used over the whole datasets, in red trigger paths used for periods up to 14, in blue trigger paths used from period 15 to 38.	62
5.6	Predicted and observed number of events of the notag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the E_T -fit in data (Sec. 5.5.2). The expected rates are separated according to the triggered lepton type. We also require the invariant mass of the two E_T -leading jets to be within $[30,310] \text{ GeV}/c^2$. By construction the overall expected rates are the same as the observed ones in each region.	70
5.7	Predicted and observed number of events of the tag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the E_T -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310] \text{ GeV}/c^2$. By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type.	70

5.8	Predicted and observed number of events of the notag 3jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are etimated from the $\cancel{E}_T$ -fit in data (Sec. 5.5.2). The expected rates are separated according to the triggered lepton type. We also require the invariant mass of the two E_T -leading jets to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region.	71
5.9	Predicted and observed number of events of the tag 3jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are etimated from the $\cancel{E}_T$ -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type.	71
6.1	List of input variables with their separation power between signal(WZ) and background ($t\bar{t}$) reported by TMVA.	82
6.2	List of input variables with their “importance“ reported by TMVA.	82
6.3	Predicted and observed number of events of the tag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are etimated from the $\cancel{E}_T$ -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type. The $t\bar{t}$ veto is applied.	85
6.4	$Signal/\sqrt{Background}$ ratio calculated when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied.	85
6.5	P-value estimate when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied.	95

List of Figures

1.1	Feynman diagram of a Z decaying in ee	8
1.2	Compilation of the PETRA measurements for the angular distribution of $e^+e^- \rightarrow \mu^+\mu^-$ at 34.5 GeV center of mass energy. The full curve is a fit to the data allowing for an asymmetry. The dashed curve is for the symmetric QED prediction after correcting for a small asymmetry from α^3 diagrams.	10
1.3	Schematic view of the UA1 detector	11
1.4	Schematic view of the UA2 detector	11
1.5	Two dimensional plot of the two azimuthal components of the missing transverse energy (neutrino momentum) relative to the electron direction (aligned along the positive y-axis in the plot) in UA1. This plot shows that the neutrino is emitted opposite to the charged lepton and with the same energy, as in the two-body decay of the W	12
1.6	Electron-neutrino transverse mass plots of UA1 (left) and UA2 (right)	13
1.7	Electron-positron invariant mass plots for UA1 (top) and UA2 (bottom) collected	14
1.8	Invariant mass of the highest p_T jet pair obtained with UA2: an excess of data over the decreasing background in the IVB mass region is evident	15
1.9	Tree level Feynman diagrams of WZ production. t-, u-, and s-channel diagrams are given in the left, center, and right, respectively. The s-channel diagram contains the trilinear WWZ gauge boson vector vertex.	15
1.10	SM Higgs boson production cross section (in pb) at the Tevatron Collider (left) and branching ratios (right) as functions of H mass: the WH associated production even if characterized by a lower cross section is the one leading to the the lowest background for a light Higgs boson.	17
2.1	The accelerator system operating at FNAL.	20
2.2	Integrated luminosity as a function of the Run II weeks (2.2a) and Tevatron peak luminosity as a function of the calendar date (2.2b). Empty periods correspond to Tevatron shut-down periods.	23
2.3	Isometric view of the CDF II Detector.	24
2.4	(a) The CDF II tracker layout showing the different subdetector systems. (b) Schematic drawing of the impact parameter d_0 . The sign of the impact parameter is defined as positive or negative with reference to the direction of the track momentum vector (in the X,Y quadrant in the drawing).	25
2.5	The SVX silicon detector: on the left, a three-dimensional view of the detector allows to see the barrel structure along the beam axes; on the right, the transverse plane section shows in detail the layer sequence.	26
2.6	A 1/6 section of the COT end-plate (2.6a): for each super-layer the total number of cells, the wire orientation (axial or stereo), and the average radius in cm are given. The enlargement shows in detail the slot where the wire planes (sense and field) are installed. Fig. 2.6 represents the cross-section of three axial cells in super-layer 2, the arrow indicates the radial direction.	27

2.7	One azimuthal electromagnetic calorimeter wedge 2.7a, the elevation view of one quarter of the plug calorimeter 2.7b. In 2.7c elevation view of the CDF detector showing the components of the CDF calorimeter: CEM, CHA, WHA, PEM and PHA.	29
2.8	Muon detectors coverage in the η - ϕ plane.	31
3.1	Functional block diagram of the CDF II trigger and data acquisition systems.	34
4.1	Top quark and anti top quark pair decaying into jets, visible as collimated collections of particle tracks, and other fermions in the CDF detector.	46
4.2	Jet reconstruction by the JETCLU algorithm.	47
4.3	η -dependent energy scale correction factor for JETCLU with radius 0.4; a sample of events with at least one trigger tower above 50 GeV is used.	48
4.4	(a) E_T in R=0.4 cone as a function of the number of reconstructed primary vertexes in minimum bias events. (b) Fractional systematic uncertainties due to multiple interactions for different cone sizes as a function of jet transverse momentum.	49
4.5	Absolute energy corrections for jets with cone size $\Delta R = 0.4$ as a function of jet p_T with uncertainty.	50
4.6	The fractional systematic uncertainty of the JES corrections as a function of the jet transverse momentum. The total uncertainty is taken as the sum in quadrature of all individual contributions.	51
4.7	Comparisons of track observables input into the track NN, for tracks from B-hadron decays vs. tracks not from B-hadron decays.	53
4.8	Comparisons of jet observables input into the jet NN, for jets including B-hadron decays (red) vs. jets without B-hadron decays (black).	54
4.9	Jet bness distribution from our electroweak MC, for jets matched to b quarks (red) vs. jets not matched to b quarks (black). This distribution represents the probability for a jet to be b-like depending on the bness value, that can be chosen in a range $[-1(\text{b-jets}), 1(\text{light flavour-jets})]$	55
5.1	M_T^W distributions for electrons.	60
5.2	M_T^W distributions for muons.	61
5.3	Turnon efficiency curve parameterizations for MET2J (up) and METDI (lower plot) triggers. Period<15 and Period $\geq$ 15 data were fitted by using $\frac{c}{1+e^{\frac{c}{(a-jetcorrmet)}b}}$, a , b , c being free parameters of the fit. WZ MC distributions are shown before (black histogram) and after the convolution with the trigger turnon parameterization (red histogram) to get of the effects due to the trigger requirements.	64
5.4	Feynman diagram for W+jets production	65
5.5	Feynman diagram for Z+jets production	65
5.6	Feynman diagram for top-antitop pair production	66
5.7	Feynman diagram for single top s-channel production	66
5.8	Feynman diagram for single top t-channel production	66
5.9	Feynman diagram for QCD multijet production	67
5.10	E_T^{lep1} in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).	72
5.11	E_T in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).	73
5.12	M_T^W in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).	74
5.13	E_T^{jet1} in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).	75
5.14	E_T^{jet2} in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).	76

5.15	$\Delta R(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right).	77
5.16	$M(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right).	78
6.1	$t\bar{t}$ composition in the tag 2 jets sample.	80
6.2	MLP with one hidden layer.	81
6.3	MJ1J2 distribution in the background sample before (upper left) and after (lower right) normalization. The same distribution in the signal sample before (upper right) and after (lower left) normalization.	83
6.4	The architecture choosen for the NN. The hidden layer with N+5 neurons is shown.	83
6.5	The Receiver Operating Characteristic (ROC) curve. It is a plot of the signal rate against the background rate for the different possible cutpoints. ROC curve gives an estimate of the NN background rejection effieciety.	84
6.6	The Kolmogorov-Smirnov test for the NN. No overtrainig.	84
6.7	NN output distribution for electrons and muons in the notag region. The lower distribution shows the difference data-simulation.	85
6.8	NN output distribution for electrons and muons in the tag region. The lower distribution shows the difference data-simulation. The empty histogram shows the expected WZ+ZZ signal multiplied by 40.	86
6.9	E_T^{lep1} in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	87
6.10	E_T in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation.	88
6.11	M_T^W in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	89
6.12	E_T^{jet1} in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	90
6.13	E_T^{jet2} in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	91
6.14	$\Delta R(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	92
6.15	$M(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1}=\text{TCE}$ (upper left), <i>CMUP, CMX</i> (upper right), <i>PHX</i> (lower left), <i>EMC</i> (lower right). The lower distributions show the difference data-simulation. . .	93
6.16	The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region , using MJ1J2 as the invariant mass, when no cuts are applied.	95
6.17	The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region , using MJ1J2 as the invariant mass, when preselection cuts are applied.	96
6.18	The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region , using MJ1J2 as the invariant mass, when the whole $t\bar{t}$ veto is applied.	96
7.1	Dijet invariant mass in the tag2j region. Templates used for the signal extraction are shown in solid colors. The templates have been normalized to the expected rates. The data points (dots) are superimposed and differences between predictions and data are plotted in the lower pads . .	98
7.2	Result of the fit to the data. Fitted Z-invariant mass distributions in the Tag2j are superimposed to the data. Both shapes and rates have been adjusted to the results obtained in data. The lower plot shows the difference data-simulation, after allowing for the best-fit signal contribution (highlighted in color)	100

A.1	For a fixed value of λ the potential is presented against the real and imaginary parts of Φ . The Mexican-hat or champagne-bottle profile at the ground should be noted	109
E.1	NN input variables.	119
E.2	NN input variables.	120
F.1	$t\bar{t}$ composition in the tag 2 jets sample.	121
F.2	$t\bar{t}$ lepton+jets decay mode.	123

Introduction

The study of associated WZ boson production with a lepton and a neutrino signaling the W , and a $b\bar{b}$ -pair in the final state is important since the event topology of this process is the same as expected for WH associated production of a W and the Standard Model light-Higgs boson ($M_H \lesssim 135$ GeV). Thus, the investigation of the process $W^\pm Z \rightarrow \ell \nu b\bar{b}$, whose rate can be accurately predicted, allows to calibrate and optimize many of the techniques used in the SM Higgs search and provides a “standard candle” for that crucially important search. In addition, WZ associated production generates a significant background for low mass Higgs Boson searches with H decaying into a $b\bar{b}$ pair.

At the Tevatron, the process $WH \rightarrow Wb\bar{b}$ has an expected $\sigma \cdot BR$ ¹ about five times lower than $WZ \rightarrow Wb\bar{b}$ for $m_H \simeq 120$ GeV/c². Therefore, observing that process would be a benchmark for the even more difficult search for the light Higgs in the $WH \rightarrow Wb\bar{b}$ process.

Observing associated WZ production at the Tevatron in the channel $WZ \rightarrow \ell \nu b\bar{b}$ is extremely difficult for two main reasons.

The event rate is extremely low. A WZ production cross section of ~ 3.22 pb [24] together with a $Z \rightarrow b\bar{b}$ branching ratio of $\sim 15\%$ [25] provides about 50 fb in the $WZ \rightarrow \ell \nu b\bar{b}$ channel. With a trigger and kinematical selection efficiency of the order of a few %, one expects a handful of events per fb⁻¹ of integrated luminosity.

An additional major difficulty is that the signal to background ratio is very poor, due to the contribution of associated production of W and incoherent jets and to a number of competing processes, primarily $t\bar{t}$ production, providing the same final state. This thesis reports on an effort to reconstruct and directly observe one of these background processes, for better separating it from the signal².

This statement remains valid even if the few ZZ events with leptonic decay of one Z , mimicking the W decay when one lepton is not observed, are included in the acceptance.

In the first chapter the theoretical context of this thesis is presented. A rather detailed description of the Electroweak Unification and the Higgs Mechanism is given (including Appendix A) in order to have a better picture of how important is observing diboson WZ production in the lepton plus jets channel. The historical process that led to the interest in such studies is also portrayed: from

¹BR being the Branching ratios of $Z/H \rightarrow b\bar{b}$

²A standard kinematical cut requests exactly two high energy jets in the candidate sample. Simulations show that if a third energetic jet is allowed the signal acceptance is increased by about 1/3. Therefore, it would be very important to be able to extract a $Z \rightarrow b\bar{b}$ signal also in events with more than two high energy jets. We report in Appendix F on an attempt to apply also in the 3 jets sample the $t\bar{t}$ veto algorithm described in this work

the discovery of the W and Z bosons by the UA1 and UA2 experiments to the observation of the diboson production in the leptonic channel by the CDF and DØ experiments.

In the second chapter the Fermilab Accelerator Complex and in particular the CDF detector are described in some details. Knowing how the detector is built and which triggers are used (chapter 3) is important to better understand the physical objects reconstruction, presented in the fourth chapter.

The work reported in this thesis is part of a very elaborate analysis being performed by the CDF diboson group. The framework of this analysis is described in chapter 5. My initial effort was spent in setting up this framework under the instructions of my supervisor, in order to learn how to work independently. In the course of the analysis the importance of developing a multivariate tool to improve the sensitivity of the measurement by rejecting one of the largest background became clear. My thesis work has been focused on this aim. The $t\bar{t}$ production is one of the main source of background when the two jets are originated by a b quark. Both the $t\bar{t}$ lepton plus jets and the dileptonic decay modes contribute as background when, respectively, either the information of the two light quark-jets or of one lepton is lost. In particular, considering also the ZZ as signal, the $t\bar{t}$ dileptonic decay mode can mimic the signal even when both leptons are detected. However, in these events we expect a larger missing transverse energy than in signal events. Based on these observations we applied first develop a set of preselection cuts in order to reject a large part of the $t\bar{t}$ background. To reject the remaining part of the $t\bar{t}$ background, a Neural Network was trained. To qualify the potential of the $t\bar{t}$ veto, we estimated the sensitivity of the measurement in the subsample of our interest and determined that an improvement of about 10% is reached. This quantifies the power of the method by increasing the capability of detecting a diboson signal.

Chapter 1

The Electroweak Unification

The Standard Model (SM) summarizes the current best understanding of elementary particle physics. Its picture of particles and interactions has been tested successfully in a variety of experiments in the last 50 years. In spite of this remarkable success the search for the fundamental laws governing the microscopic world is still far from being completed. There are still many open questions concerning primarily the long list of parameters of the model whose value has no dynamic justification. At the present time the activity of high energy physicists is in fact devoted to searching for new phenomena beyond the Standard Model. The best hint for new physics presently comes from the recent experimental evidence for neutrino oscillations [22], which implies that neutrinos have a very small mass, whose deeper origin is suspected to be related to new physics. In the Standard Model itself there is still a missing piece, since it predicts a particle, the Higgs boson, which plays a crucial role in assigning mass to the fundamental bosons and fermions, which has not yet been observed. It is hoped that this missing piece will soon be discovered and the model completed consistently. Looking much beyond the Standard Model, there is a very substantial reason for believing that we are still far from a true understanding of the fundamental laws of Nature. This is because gravity cannot be included in the model, since general relativity appears to be incompatible with quantum field theory [23].

1.1 The Standard Model

Most experimental data in Particle Physics can be explained to an impressively high precision by the so-called Standard Model (SM) of fundamental interactions[1]. All known matter is built, according to the SM, from spin $\frac{1}{2}$ fermions: six leptons and six quarks. Each fundamental fermion is associated to its antiparticle, which carries opposite quantum numbers.

The interactions that fundamental particles experience are of four kinds: gravitational, electromagnetic, weak and strong. The SM is a *gauge theory* including electromagnetic, weak and strong interactions (“gauge forces”), while incorporating gravity is still an open problem. Electromagnetic and weak interactions are described by a single interaction, named **Electroweak** (EW). The strong interaction is described by an additional **Quantum-Chromo-Dynamical interaction** (QCD). A scalar field, the *Higgs field*, permeates the physical vacuum breaking the symmetry of the theory and giving masses to fundamental bosons and fermions.

Leptons are sensitive only to gravitational and EW interactions. The six known leptons are the

electron $\mathbf{e}^-$, the muon μ^- , the tau-lepton τ^- and their associated neutrinos ν_e , ν_μ and ν_τ .

Quarks are sensitive to gravitational, EW and strong interactions. The six known quarks are distinguished by the so-called flavor: up $\mathbf{u}$, down $\mathbf{d}$, charm $\mathbf{c}$, strange $\mathbf{s}$, top $\mathbf{t}$ and bottom $\mathbf{b}$. Only up and down quarks are stable and build the ordinary matter. Except for the top quark, all quarks are bound to other quarks into composite hadrons, either baryons (three quarks or three antiquarks) or mesons (one quark and one antiquark). Since according to Fermi-Dirac statistics identical fermions cannot be bound in the same quantum state, this finding shows that quarks possess a new quantum number named “color”. Two quarks of the same flavor bound by strong interaction in a baryon are in a different color state.

The gauge interactions of fermions are described by the SM in terms of exchanges of spin 1 gauge bosons. The EW interaction is propagated by a massless **photon** γ and by three massive bosons $\mathbf{W}^+$, $\mathbf{W}^-$ and $\mathbf{Z}^0$. The strong interaction between quarks is carried by eight massless coloured **gluons** $\mathbf{g}$.

1.2 Electroweak Theory

We give a brief description of the Electroweak Theory [2][3][4]. Details on spontaneous symmetry breaking and on the Higgs mechanism for generating particle masses are given in Appendix A.

1.2.1 QED

In a gauge theory as the SM, the fundamental particles are described by quantized fields ψ and their interactions are expressed by the Lagrangian density L . Considering the Noether's theorem, each transformation of the fields that leaves unchanged the action $S = \int L d^4x$ (the Lagrangian density is invariant under this transformation) can be associated to a conserved quantity (current, charge).

The Lagrangian density for a free fermion described by a Dirac spinor ψ in SM is:

$$L_{free} = \bar{\psi} (i\gamma^\mu \delta_\mu - m) \psi \quad (1.1)$$

Where γ^μ are the Dirac matrices. The minimal substitution is applied:

$$\delta_\mu \rightarrow D_\mu = \delta_\mu + iQeA_\mu \quad (1.2)$$

where A^μ is the relativistic expression for the EM scalar and vector potentials associated to the photon field, and it is required the Lagrangian density to be invariant under the transformation:

$$A_\mu \rightarrow A'_\mu = A_\mu + \delta_\mu \Lambda(x) \quad (1.3)$$

with $\Lambda(x)$ a scalar function of the coordinates. This invariance is true if the $U(1)$ local phase transformation $U = e^{i\Lambda(x)}$ is true. The two transformations are known as *gauge transformations*. If a local phase transformation is applied to the Lagrangian density or a free fermion, we obtain:

$$L'_{free} = L_{free} + eQ\bar{\psi}\gamma^\mu\psi\delta_\mu\Lambda(x) \quad (1.4)$$

So the Lagrangian density for a free fermion is not invariant. In order to have a Lagrangian density that is invariant under a local phase transformation it is necessary to add an interaction term:

$$L_{int} = QeA_\mu\bar{\psi}\gamma^\mu\psi \quad (1.5)$$

where the expression $Qe\bar{\psi}\gamma^\mu\psi$ is the current associated to the interacting particle of charge Q times the electron charge e .

It is possible to write the full **Quantum-Electro-Dynamics (QED) Lagrangian** density for a fermion as:

$$L_{QED} = \bar{\psi} (i\gamma^\mu \delta_\mu - m) \psi + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + QeA_\mu\bar{\psi}\gamma^\mu\psi \quad (1.6)$$

Where the element:

$$L_\gamma = \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad (1.7)$$

express the Lagrangian density yielding the Maxwell equations. The term $F^{\mu\nu} F_{\mu\nu}$ is the kinetic energy of the vector field, with $F^{\mu\nu} = \delta^\mu A^\nu - \delta^\nu A^\mu$. Since no mass term $m^2 A^\mu A_\mu$ appears, the photon must be a massless gauge boson.

QED processes can be perturbatively calculated according to the Feynman's rules, often shown in graphic representations of the processes called Feynman diagrams. The strength of the interaction depends on the constant associated to each fermion-fermion-boson vertex in Feynman diagrams, called coupling constant.

1.2.2 Electroweak Unification

The observed weak interaction phenomena are consistent with the fermions being organized into doublets of weak isospin $\chi = (\psi_u, \psi_d)$. To account for this nature of the weak interaction and to include QED into this description, during 1960s, S.L. Glashow, A. Salam and S. Weinberg unified weak and electromagnetic forces creating a $SU(2) \otimes U(1)$ gauge theory that describes the two interactions, known as the electroweak theory. The theory predicted the existence of neutral currents and W and Z gauge bosons.

Starting from the invariance of the QED Lagrangian density under a global phase transformation $U = e^{i\alpha}$ (a transformation where the phase is the same for every x), one can obtain a conserved current:

$$J^\mu = q\bar{\psi}\gamma^\mu\psi \quad (1.8)$$

and a conserved charge:

$$Q = \int d^3x J^0 \quad (1.9)$$

that in the case of QED is the *electric charge*.

Analogously to QED, one can build a gauge theory for the weak interactions finding a global phase transformations that leaves invariant the free Lagrangian density for a lepton and leads to the conservation of the weak charged current known from the Intermediate Vector Boson (IVB) theory:

$$J^\mu(x) = \bar{\psi}_l(x)\gamma^\mu(1 - \gamma^5)\psi_{\nu_l}(x) \quad (1.10)$$

where l stands for e, μ or τ . Since the weak current couples only to left handed (LH) fermions, it is possible to decompose spinors ψ_l in their left handed and right handed components and define the isospin doublet χ_L as:

$$\chi_L = \begin{pmatrix} \psi_{\nu_l} \\ \psi_l \end{pmatrix}_L \quad (1.11)$$

the right handed (RH) fields are weak isospin singlets l_R . Assuming that all the leptons are massless, one can write the free Lagrangian density for leptons as:

$$L_0 = \sum_l \bar{\chi}_L(x)\gamma^\mu\delta_\mu\chi_L(x) + \bar{\psi}_l^R(x)\gamma^\mu\delta_\mu\psi_l^R(x) + \bar{\psi}_{\nu_l}^R(x)\gamma^\mu\delta_\mu\psi_{\nu_l}^R(x) \quad (1.12)$$

Under a $SU(2)$ global phase transformation $U = e^{i\alpha_j \frac{\tau_j}{2}}$, where τ_j is Pauli matrix, the Lagrangian density as defined so far is invariant. The conserved currents that comes from this invariance are:

$$J_\mu^j(x) = \bar{\chi}_L\gamma_\mu\frac{\tau^j}{2}\chi_L \quad (1.13)$$

We obtain three EW currents (one for each SU(2) generator), that can be linked to the positive and negative charged current interactions and to the neutral current interaction: J^1_μ and J^2_μ are linear combinations of the charged ones (J_μ and J^+_μ); J^3_μ is the neutral current:

$$J^3_\mu = \frac{1}{2} \left(\bar{\psi}_{\nu_l}^L \gamma_\mu \psi_{\nu_l}^L - \bar{\psi}_l^L \gamma_\mu \psi_l^L \right) \quad (1.14)$$

Also the weak isospin charge is conserved:

$$I_j^W = \int d^3x J_j^0 \quad (1.15)$$

Noticing that the second term of the neutral current as defined so far is a part of the electromagnetic current, one can define the *ipercharge current* as:

$$J_\mu^Y = \frac{J_\mu^{EM}}{e} - J_\mu^3 \quad (1.16)$$

and the ipercharge Y as the related conserved quantum number:

$$Y = Q - I_3^W \quad (1.17)$$

Alternatively one can use a second approach: starts from the invariance of the free Lagrangian density requiring the conservation of the weak ipercharge when a $U(1)$ global phase transformation $U = e^{i\beta Y}$ is applied simultaneously to the leptonic fields. The conservation of the Q_e electric charge is obtained.

In order to build a local gauge theory, $SU(2)$ local phase transformations $U = e^{ig\Lambda_j(x)\frac{\tau_j}{2}}$ for the left handed doublet are applied. Λ is real function of x and g is a constant. The right handed components of the Lagrangian density are invariant, but the left handed are not. In order to obtain an invariant Lagrangian density, the covariant derivatives are introduced:

$$\delta_\mu \rightarrow D_\mu = \delta_\mu + i\frac{g}{2}\tau_j W_\mu^j(x) \quad (1.18)$$

$W_\mu^j(x)$ are the three real gauge field that transforms as:

$$W_\mu(x) \rightarrow W_\mu'(x) = W_\mu(x) + \delta_\mu \Lambda(x) + i\Lambda(x) \times W_\mu(x) \quad (1.19)$$

Using the second approach, a local $U(1)$ local phase transformation $U = e^{i\beta(x)Y}$ is applied to the Lagrangian density leptonic fields. In order to keep the Lagrangian density invariant, the covariant derivatives are introduced:

$$D_\mu = \delta_\mu + ig' Y B_\mu(x) \quad (1.20)$$

$B_\mu(x)$ is a new gauge field that transforms as:

$$B_\mu \rightarrow B_\mu' = B_\mu + \delta_\mu \Lambda(x) \quad (1.21)$$

Using both substitutions simultaneously, we obtain the full **Electro-Weak (EW) Lagrangian** density:

$$L_0 = \sum_l \bar{\chi}_L(x) \gamma^\mu D_\mu \chi_L(x) + \bar{\psi}_l^R(x) \gamma^\mu D_\mu \psi_l^R(x) + \bar{\psi}_{\nu_l}^R(x) \gamma^\mu D_\mu \psi_{\nu_l}^R(x) \quad (1.22)$$

$$D_\mu \chi_L(x) = \left(\delta_\mu + i\frac{g}{2}\tau_j W_\mu^j + ig' Y B_\mu \right) \chi_L(x) \quad (1.23)$$

$$D_\mu \psi_l^R(x) = \left(\delta_\mu + ig' Y B_\mu \right) \psi_l^R(x) \quad (1.24)$$

$$D_\mu \psi_{\nu_l}^R(x) = \delta_\mu \psi_{\nu_l}^R(x) \quad (1.25)$$

The LH quark field expression must take into account the observation of flavour changing charged currents coupled to it:

$$\chi_L = \begin{pmatrix} u_i \\ d'_i \end{pmatrix}_L \quad (1.26)$$

where the index i runs on the quark families with $u_1 = u$, $u_2 = c$ etc. The d'_i are the fields expressed in terms of the Cabibbo-Kobayashi-Maskawa quark mixing matrix:

$$d' = dV_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad (1.27)$$

which is requested to be unitary.

The interaction Lagrangian density is thus written in terms of the weak fields B_μ and $\mathbf{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$ as:

$$L_{int} = g\mathbf{J}_\mu \mathbf{W}^\mu + \frac{g'}{2} J_\mu^Y B^\mu \quad (1.28)$$

In order to express the weak isospin currents J_μ^1 and J_μ^2 in terms of the charged ones J_μ and J_μ^+ the non hermitian gauge fields are introduced:

$$W^\pm = \frac{1}{\sqrt{2}}(W^1 \pm iW^2) \quad (1.29)$$

These are the physical carriers of the weak charged current interaction. Using this definitions it is possible to write the interaction Lagrangian density for the $W^\pm$ bosons:

$$L_{W^\pm} = \frac{g}{2\sqrt{2}} (J^{+\mu} W_\mu^- + J^\mu W_\mu^+) \quad (1.30)$$

where the charged currents appear. This is the Lagrangian density term of weak charged current predicted by the IVB theory. The remaining terms of the interaction Lagrangian density can be interpreted as an arbitrary linear combination of two hermitian fields:

$$A_\mu = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}} = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (1.31)$$

$$Z_\mu^0 = \frac{g' W_\mu^3 - g B_\mu}{\sqrt{g^2 + g'^2}} = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (1.32)$$

The angle θ_W is called weak mixing angle, that is a fundamental parameter of the theory also known as the *Weinberg angle*. Requiring A to be the photon field, the EM current is decoupled from the weak neutral current by mixing W_μ^3 and B_μ . The Lagrangian density of the EM interaction can be rewritten in terms of the couplings to the W_μ^3 and B_μ fields as:

$$L_{EM} = e A^\mu J_\mu^{EM} = A_\mu \left(g \sin \theta_W J_\mu^3 + g' \cos \theta_W \frac{J_\mu^Y}{2} \right) \quad (1.33)$$

And for consistency:

$$g \sin \theta_W = g' \cos \theta_W = e \quad (1.34)$$

Also the Lagrangian density of the neutral current can be written in terms of the couplings to the W and B bosons:

$$L_{NC} = Z_\mu^0 \left(g \cos \theta_W J_\mu^3 - g' \sin \theta_W \frac{J_\mu^Y}{2} \right) \quad (1.35)$$

$$L_{NC} = Z_\mu^0 g \frac{1}{\cos \theta_W} (J_\mu^3 - \sin^2 \theta_W J_\mu^{EM}) \quad (1.36)$$

Z^0 is the neutral carrier of the weak interaction. The coupling between EM and weak interactions (electroweak unification) is guaranteed by the presence of the *Weinberg angle*: if θ_W was zero, the two interactions would be decoupled. Experimental measurements of θ_W verified the electroweak unification:

$$\sin \theta_W = 0,2326 \pm 0,0008 \quad (1.37)$$

Although the Z^0 boson couples to both fields, it discriminates axial and axial-vector couplings, known as the *V-A theory*:

Figure 1.1: Feynman diagram of a Z decaying in $e\bar{e}$

The vertex of the decay shown in Figure 1.1 can be expressed by:

$$ig \frac{1}{\cos \theta_W} \gamma^\mu \left(\frac{1 - \gamma^5}{2} \tau^3 - \sin^2 \theta_W Q \right) \quad (1.38)$$

where $Q = Y/2 + \tau^3$. The vertex can be rewritten as:

$$ig \frac{1}{\cos \theta_W} \gamma^\mu \left(\frac{C_V - C_A \gamma^5}{2} \right) \quad (1.39)$$

Finally the free field Lagrangian density for the physical γ , $W^\pm$ and Z^0 bosons can be written:

$$L_{\gamma,w,z} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} W^{+\nu\mu} W_{\nu\mu}^- - \frac{1}{4} Z^{\nu\mu} Z_{\nu\mu} \quad (1.40)$$

Where the $W_{\nu\mu}^+$, $W_{\nu\mu}^-$ and $Z_{\nu\mu}$ tensors are defined in the same way as $F_{\nu\mu}$. The Lagrangian density for the gauge boson can be completed introducing the interactions among the EW gauge bosons:

$$L_B = L_{\gamma,w,z} + g\varepsilon_{ijk}W_{i\mu}W_{j\nu}\delta^\mu W_k^\nu - \frac{1}{4}g^2\varepsilon_{ijk}\varepsilon_{ilm}W_j^\mu W_k^\nu W_{l\mu}W_{m\nu} \quad (1.41)$$

The full EW Lagrangian density is:

$$L_{EW} = L_B + L_{int} \quad (1.42)$$

1.3 Discovery of the W and Z Bosons

The evidence of massive carriers of weak interactions was clear after the $e^+e^- \rightarrow \mu^+\mu^-$ cross section measurements at PETRA (DESY), which showed a remarkable forward/backward asymmetry due to the γ/Z interference:

Figure 1.2: Compilation of the PETRA measurements for the angular distribution of $e^+e^- \rightarrow \mu^+\mu^-$ at 34.5 GeV center of mass energy. The full curve is a fit to the data allowing for an asymmetry. The dashed curve is for the symmetric QED prediction after correcting for a small asymmetry from α^3 diagrams.

The direct search for W and Z bosons started with the construction of the CERN SppS, a $\bar{p}p$ collider. Two experiments housed at the SppS, UA1 and UA2, were dedicated mainly to this search. They were named accordingly to their “Underground Area” (UA), i.e. were located underground at an interaction point on the SPS accelerator which was modified to convert it into a collider. The UA1 was a huge and complex detector for its day. The detector was a 6 drift chamber assembly 5.8 m long and 2.3 m across, the largest imaging drift chambers of its day. It recorded the tracks of charged particles curving in a 0.7 Tesla magnetic field, measuring their momentum, the sign of their electric charge and their rate of energy loss (dE/dx). The geometrical arrangement of the 17000 field wires and 6125 sense wires allowed a 3-D of reconstructed physics events to be produced. Iron absorbers and tracking chambers for muon identification completed the apparatus:

UA2 was a compact calorimetric detector designed to search for W and Z decaying into electrons and tuned to high p_T jets studies. In its first generation version, at the time of W and Z discovery, it consisted of a small vertex tracking chamber, two toroidal spectrometer magnets in the forward region and highly segmented calorimeters covering the central region:

The search for W was carried on looking for W decaying to any lepton-neutrino pair of the first two generations $W \rightarrow e\nu_e$, $W \rightarrow \mu\nu_\mu$. Lepton identification in UA1 and UA2 relied on calorimetric energy deposition and charged particle tracking (electrons) or high penetration power and charged particle tracking (muons, UA1 only), while the presence of neutrinos was inferred by the unbalance of the total transverse momentum. In the W^+ rest frame the differential cross section behaviour is:

$$\frac{d\sigma}{d\cos\theta^*} \propto (1 + \cos\theta^*)^2 \quad (1.43)$$

Figure 1.3: Schematic view of the UA1 detector

Figure 1.4: Schematic view of the UA2 detector

where θ^* is the center of mass angle between the charged lepton momentum and the proton beam direction. Since θ^* is not measurable, one must make use of the p_T of the lepton to get an expression of the cross section in terms of measurable quantities in the laboratory frame. The lepton transverse momentum is invariant between the two frames if the W transverse momentum is neglected such that the W frame is boosted in the beam direction. Then, by expressing the

transverse momentum in terms of laboratory variables one finally gets:
one finally gets:

$$\frac{d\sigma}{dp_T} = \frac{d\sigma}{d\cos\theta^*} \frac{d\cos\theta^*}{dp_T} \propto \left(1 + \frac{m_W^2 - 2p_T^2}{m_W} \frac{1}{\sqrt{m_W^2 - 4p_T^2}} \right) \cdot \frac{4p_T}{m_W^2}$$

This cross section is hence peaked at $p_T = m_W/2$ (Jacobean peak), but can be sensitive to the W transverse momentum if this is not null. This sensitivity is strongly reduced by using the transverse mass m_T instead of p_T :

$$m_T^2 = (E_{Tl} + E_{T\nu})^2 - (\mathbf{p}_{Tl} + \mathbf{p}_{T\nu})^2 \quad (1.44)$$

Figure 1.5: Two dimensional plot of the two azimuthal components of the missing transverse energy (neutrino momentum) relative to the electron direction (aligned along the positive y-axis in the plot) in UA1. This plot shows that the neutrino is emitted opposite to the charged lepton and with the same energy, as in the two-body decay of the W

Fig. 1.4 shows the transverse mass plots for the electron-neutrino pairs in UA1 and UA2 data obtained after imposing kinematical constraints such as the relative back-to-back azimuthal directions of the electron and neutrino momenta (Fig. 1.5). The search for Z as performed by looking for a peak in the invariant mass of opposite sign charged leptons (Fig. 1.7):

The discovery of the W boson which was announced in 1982, followed next year by the Z one, is one of the most important results in experimental particle physics ever. It led to the Nobel Prize for Physics being awarded to Carlo Rubbia and Simon van der Meer in 1984, just a year after the discovery. UA1 could observe decays of W and Z both in the e and μ channels. The UA2 experiment was not equipped with a muon detector but its calorimeters were capable of observing a weak signal of vector bosons decaying to hadrons, consisting of an excess of events with dijet invariant mass in W and Z mass region (Fig. 1.8).

Figure 1.6: Electron-neutrino transverse mass plots of UA1 (left) and UA2 (right)

1.4 WZ Associated Production

The work reported in this thesis is related to the measurement of the production of events containing a W boson that decays leptonically ($W \rightarrow l\nu$, $l = e$ or μ) in association with a Z boson that decays hadronically ($Z \rightarrow q\bar{q}$). The leading order (LO) Feynman diagrams for these processes are shown in Fig.1.9.

Cross section	Predicted value
$\sigma(p\bar{p} \rightarrow WW)$	$11.34^{+0.56}_{-0.49} pb$
$\sigma(p\bar{p} \rightarrow WZ)$	$3.22^{+0.20}_{-0.17} pb$
$\sigma(p\bar{p} \rightarrow ZZ)$	$1.20^{+0.05}_{-0.04} pb$

Table 1.1: Next-to-leading order (NLO) predicted the cross sections for the diboson production at $\sqrt{s} = 1.96 TeV$ [26].

1.4.1 Triple Gauge Couplings

A primary motivation for studying diboson physics is that their interactions provide a test of the electroweak sector of the SM. Diboson production can be studied by measuring their interactions and their production cross sections via trilinear gauge-boson couplings (TGC). The WWZ and WW γ couplings can be measured by studying the diboson (WW, WZ and W γ) production. The virtual W propagator diagram in WZ production in particular is sensitive to the WWZ coupling. To account for non-SM physics, an effective theory can be built to describe the WWZ coupling [6], parametrizing the TGC in terms of 7 Anomalous Triple Gauge Couplings (ATGC), in the

Figure 1.7: Electron-positron invariant mass plots for UA1 (top) and UA2 (bottom) collected

Process	Decay Mode	BR
WZ	$l\nu ll$	3.3
	$l\nu\nu\nu$	6.5
	$l\nu q\bar{q}$	22.6
	$q\bar{q}' ll$	6.8
	$q\bar{q}'\nu\nu$	13.5
	all hadronic	47.2
ZZ	$llll$	1.2
	$ll\nu\nu$	4.0
	$\nu\nu\nu\nu$	4.0
	$llq\bar{q}$	14.1
	$\nu\nu q\bar{q}$	27.9
	all hadronic	48.8
WW	$l\nu l'\nu'$	10.5
	$l\nu q\bar{q}'$	43.8
	all hadronic	45.7

Table 1.2: Branching ratios for WW, WZ and ZZ processes [25].

Figure 1.8: Invariant mass of the highest p_T jet pair obtained with UA2: an excess of data over the decreasing background in the IVB mass region is evident

Figure 1.9: Tree level Feynman diagrams of WZ production. t-, u-, and s-channel diagrams are given in the left, center, and right, respectively. The s-channel diagram contains the trilinear WWZ gauge boson vector vertex.

hypothesis of vector bosons coupled to massless fermions ($m_W \gg m_q$):

$$\begin{aligned}
 L_{WWZ/(-g\cos\theta_W)} = & ig_1^Z (W_{\mu\nu}^+ W^{-\mu} Z^\nu - W_\mu^+ Z_\mu W^{-\mu\nu}) \\
 & + i\kappa_Z W_\mu^+ W_\nu^- Z^{\mu\nu} - g_4^Z W_\mu^+ W_\nu^- (\partial^{\mu\nu} Z^\nu + \partial^\nu Z^\mu) \\
 & + g_5^Z \epsilon^{\mu\rho\sigma} [W_\mu^+ (\partial^\rho W^{-\nu}) - (\partial^\rho W_\mu^+) W^{-\nu}] Z^\sigma \\
 & + i\tilde{\kappa}_Z W_\mu^+ W_\nu^- \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} Z_{\rho\sigma} \\
 & + i\frac{\tilde{\lambda}_Z}{m_W^2} W_{\lambda\mu}^+ W_\nu^{-\mu} \frac{1}{2} \epsilon^{\nu\lambda\rho\sigma} Z_{\rho\sigma}
 \end{aligned} \tag{1.45}$$

L_{WWZ} can be reduced to the SM appearance at tree level if $g_1^Z = k_Z = 1$ and $\lambda_Z = g_4^Z =$

$g_5^Z = \tilde{k}_Z = \tilde{\lambda}_Z = 0$. If $WW\gamma$ coupling is considered instead of the WWZ one, the corresponding Lagrangian density remains unchanged in form, while by exploiting the relations between g , e , θ_W , A^μ , Z^μ one gets $\lambda_Z = \lambda_\gamma = \lambda$ and $\tilde{\lambda}_Z = \tilde{\lambda}_\gamma = \tilde{\lambda}$. If CP and gauge invariances are assumed, only four out of the 12 remaining couplings are independent and potentially different from zero: g_1^Z , $k_{Z,\gamma}$, and λ . Under the further assumption of equal ATGC for the WWZ and $WW\gamma$ vertices the set of parameters is finally reduced to two:

$$\lambda(\hat{s}) = \frac{\lambda}{(1 + \hat{s}/\Lambda^2)^2}, \quad \Delta\kappa(\hat{s}) = \frac{1 - \kappa}{(1 + \hat{s}/\Lambda^2)^2} \quad (1.46)$$

It became customary to quantify the consistency of the TGC's with the SM values by quoting the observed deviations from $\lambda = 1$ and of $\Delta\kappa = 0$. At the time being no significant such deviations have been found.

1.4.2 Towards the Higgs

The SM Higgs search is often performed in the diboson channel. One of the most promising channels for discovering a low mass Higgs ($M_H \leq 130 \text{ GeV}/c^2$) is in associated production with a W that decays leptonically. The Feynman diagrams for $W^\pm H_0 \rightarrow l\nu b\bar{b}$ are similar to those for $W^+W^-/W^\pm Z_0 \rightarrow l\nu q\bar{q}$. In both cases, the final state particles are a lepton and neutrino from the decay of a W boson and a quark-antiquark pair from the decay of either the Higgs or a weak gauge boson (W or Z). One consequence of this similarity is that $W^+W^-/W^\pm Z_0 \rightarrow l\nu q\bar{q}$ is an important background for these Higgs searches. Making this direct measurement of diboson production supplies an in situ measurement of the size of this background. An even more important consequence, however, is that detecting WZ in this channel represent a benchmark for Higgs searches with similar final states. The Higgs boson searches and this analysis share the same challenge of separating a small signal from a large background. Of course, this analysis has the advantage that the signal is in several times larger and that the Z mass is known. Additionally, the ability to discover the Higgs boson (and to measure $W^+W^-/W^\pm Z_0 \rightarrow l\nu q\bar{q}$) depends largely on how precisely a resonance in the dijet invariant mass is reconstructed. A measurement of $W^+W^-/W^\pm Z_0 \rightarrow l\nu q\bar{q}$ would determine the actual resolution of the measurement of a dijet resonance. The event selection for this search shares most of the trigger, Monte Carlo (MC) simulation, and normalization methods of the $H \rightarrow b\bar{b}$ search. The multivariate event classification schemes¹ that are becoming increasingly popular in Higgs boson searches can also be checked using a known signal. Finally, the statistical techniques used for the entire SM Higgs mass range can be tested on this known signal, providing opportunities for optimization.

1.5 Diboson Production at Tevatron

WZ associated production was observed by both the CDF and DØ experiments [7][8] in the $l^+l^-l^\pm\nu$ final state.

The DØ observation was made on $\int L dt \simeq 300 \text{ pb}^{-1}$, searching for final states with three high p_T ($> 15 \text{ GeV}$) charged leptons and large p_T unbalance ($> 20 \text{ GeV}$), compatible with the presence

¹The use of Neural Networks is crucial in the search for small signals. Recent Higgs boson analysis results are based on multivariate discriminants that separate the Higgs signal from the background. Different approaches are used depending on the specific channel. An example can be found in the $Z_0 H \rightarrow l^+l^-b\bar{b}$, where a final multilayer discriminant is built up unifying the output of three different Neural Networks trained against the three larger backgrounds ($t\bar{t}, W + jets, diboson$)[9]

Figure 1.10: SM Higgs boson production cross section (in pb) at the Tevatron Collider (left) and branching ratios (right) as functions of H mass: the WH associated production even if characterized by a lower cross section is the one leading to the the lowest background for a light Higgs boson.

	BR
$W \rightarrow l\nu(l = e, \mu)$	21.6%
$Z \rightarrow b\bar{b}$	15.1%
$H \rightarrow b\bar{b}$	64.9%
	$\sigma \times \text{BR} [\text{pb}]$
$p\bar{p} \rightarrow WZ$	3.22%
$p\bar{p} \rightarrow WH$	0.15%
$WZ \rightarrow l\nu b\bar{b}(l = e, \mu)$	0.105%
$WH \rightarrow l\nu b\bar{b}(l = e, \mu)$	0.021%

Table 1.3: BR and expected cross sections for WZ/WH. At the Tevatron, the $WH \rightarrow l\nu b\bar{b}$ process has an $\sigma \times \text{BR}$ expected about five times lower than $WZ \rightarrow l\nu b\bar{b}$ for $m_H = 120 \text{ GeV}/c^2$.

of a neutrino from W decay). The Z boson is selected from oppositely charged electron (muon) pairs with invariant mass differing no more than 20 GeV from the Z mass. The total number of observed events is three, one in the $e\bar{e}e$ channel and two in the $\mu\nu\mu\mu$ one. Since the total background is expected to be of 0.71 ± 0.08 events, the observation is claimed and a cross section is measured $\sigma_{WZ} = 4.5^{+3.8}_{-2.6} \text{ pb}$, where the quoted error includes systematic uncertainties. This value is in agreement with the NLO prediction of SM: $\sigma_{WZ} = 3.96 \pm 0.06 \text{ pb}$. Some limits on anomalous WWZ couplings could be extracted.

The CDF Collaboration observed WZ production in the same final state as $D\bar{O}$ using 1.1 fb^{-1} of integrated luminosity. The event selection requires 3 high p_T ($> 20 \text{ GeV}$) charged leptons and large p_T unbalance ($> 25 \text{ GeV}$). In order to limit the background due to detector malfunctioning, the angle between the direction of the candidate neutrino and any candidate lepton or reconstructed hadron jet is required to be greater than 9° . The flavor-like opposite-charge lepton pair is required to have invariant mass different from Z mass no more than 15 GeV . Further vetoes are applied to reject ZZ production. The total number of observed events is 16: six of $e\bar{e}e$ type, one of $e\nu\mu\mu$ type, one of $\mu\nu\mu\mu$ type, 8 with two well-identified leptons and one high p_T isolated track with unknown flavor. The total background is expected to be of 2.7 ± 0.4 events. The measured cross

section is still in agreement with the SM prediction: $\sigma_{WZ} = 5.0^{+1.8}_{-1.4}(stat) \pm 0.4(syst)pb$.

WZ associated production in a final state involving hadrons has not been observed yet. It is natural to pursue this goal by looking for $Z \rightarrow hadrons$ in a sample of inclusive $W \rightarrow l\nu$, which has a relatively large statistics. However, this search is particularly challenging because it is affected by a large background, whose cross section is orders of magnitude greater.

Chapter 2

The Experiment

The work described in this thesis uses the full data sample collected by the CDF II detector during the Run II of Fermilab's Tevatron collider. This chapter provides a general description of the experiment, both collider and detector.

2.1 The Tevatron Collider

The Tevatron is a proton-antiproton accelerator located at the “Fermi National Accelerator Laboratory” (FNAL) and producing $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$. Proton and antiprotons collide at two interaction points, where the “Collider Detector at Fermilab” (CDF) and DØ detectors are installed. The Tevatron proton and antiproton beams are the result of a complex apparatus, which involves proton and antiproton production, antiproton storage, an intermediate acceleration chain up to the injection into the Tevatron ring. The Tevatron acceleration complex is shown in Fig. 2.1.

2.1.1 The Proton Source

The acceleration cycle of the proton beam begins with the production of negatively ionized hydrogen atoms, H^- , which are initially accelerated to a kinetic energy of 750 KeV by a Cockroft-Walton electrostatic accelerator. Preaccelerated H^- ions are then injected into the LINAC, where they reach an energy of 400 MeV by traveling through a 150 m long chain of radio-frequency (RF) accelerating cavities. Prior to being injected into the *Booster*, the H^- ions pass through a carbon foil which strips their electrons off. In the booster the protons are accelerated to 8 GeV by a number of RF cavities and then they are transferred to another synchrotron, called *Main Injector* ¹, which brings their energy up to 150 GeV . This is the final step before protons are injected into the Tevatron.

2.1.2 The Antiproton Source

The production of the antiproton beam is significantly more complicated. The cycle starts with the extraction from the *Main Injector* of a 120 GeV proton beam, which is directed onto a Nickel alloy

¹Completed in 1999 for Run II, it is located in a 3 km circumference tunnel, which houses also the antiproton *Recycler* and is approximately tangent to the Tevatron.

Figure 2.1: The accelerator system operating at FNAL.

target. The collisions create a variety of different particles, among which are $\bar{p}$, that are produced with an efficiency of about $18 \bar{p}/10^6 p$. The particles, coming off the target at different angles, are focused into a beam line by means of a magnetic lithium collection lens. In order to select only the antiprotons, the beam is sent through a pulsed magnet which acts as a charge-mass spectrometer. The emerging antiprotons, which have a bunch structure similar to that of the incident protons and a large momentum spread, are stored in the *Debuncher*, a storage ring where the $\bar{p}$ momentum spread is reduced via stochastic cooling² [12].

At the end of the debunching process, the bunch structure is destroyed resulting in a continuous beam of 8 GeV antiprotons which are successively transferred to the *Accumulator*. The accumulator is a triangle-shaped storage ring, housed in the same tunnel as the debuncher, where the antiprotons are further cooled down and stored until all the debuncher cycles are completed. When the collected antiprotons saturate the accumulator acceptance ($\sim 6 \times 10^{11}$ antiprotons), they are transferred to the *Recycler*³, a 8 GeV fixed energy storage ring with a larger acceptance, made of permanent magnets and placed in the main injector enclosure. In the recycler the size and spread of the

²Stochastic cooling is a technique used to reduce the transverse momentum and energy spread of a particle beam without any accompanying beam-loss. This is achieved by applying iteratively a feedback mechanism that senses the beam deviation from the ideal orbit with a set of electrostatic plates, processes and amplifies the signal, and transmits an adequately-sized synchronized correction pulse to another set of plates downstream.

³Antiproton availability is the most limiting factor at the Tevatron for attaining high luminosities: keeping a large antiproton beam inside the recycler has been one of the most significant engineering challenges and the excellent performance of the recycler has been an achievement of prime importance for the good operation of the accelerator.

antiproton beam is further shrunk by the electron cooling process: in one of the sections of the recycler a beam of electrons travels close to the antiprotons at the same velocity, absorbing energy from the antiprotons. When a current sufficient to create 36 bunches with the required density is available, the $\bar{p}$ are injected into the main injector where they are accelerated to 150 GeV . At this point also the antiprotons are ready to be injected into the Tevatron, in opposite direction to the proton beam.

2.1.3 The Tevatron Ring

The Tevatron is 1 km -radius superconducting synchrotron, that accelerates particles from 150 GeV to 980 GeV . The proton and antiproton beams circulate in opposite directions in the same beam pipe. Electrostatic separators produce a strong electric field that keeps the two beams away from each other except at the collision points. The beam is steered by 774 super-conducting dipole magnets and focused by 240 quadrupole magnets with a maximum magnetic field of 4.2 Tesla. A cryogenic system based on a liquid nitrogen followed by a liquid helium state cools down the Tevatron magnets to 4.2 K, at which temperature the niobium-titanium alloy of the magnet coils becomes superconducting. The process of injecting particles into the machine, accelerating them, and initiating collisions is referred to as a “shot”. It starts with the injection from the main injector of 150 GeV protons, two bunches at a time. Once the proton beam is in the machine, groups of four antiprotons bunches are mined from the recycler, accelerated to 150 GeV in the main injector and injected into the Tevatron. The RF cavities accelerate the beams to 980 GeV , and then some electrostatic separators switch polarity to cause the beams to collide at two points. Each interaction point lies at the center of a particle detector: DØ named after its location in the Tevatron optics, and CDF located at BØ. Successively, beams are scraped with remotely-operated collimators to remove the beam halo and, as soon as the beam conditions are stable, the experiments begin to take data. A continuous period of collider operation with the same protons and antiprotons beams is called a “store”.

Parameter	Run II value
number of bunches (N_b)	36
revolution frequency [MHz] (f_{bc})	1.7
bunch rms [m] σ_l	0.37
bunch spacing [ns]	396
protons/bunch (N_p)	2.7×10^{11}
antiprotons/bunch ($N_{\bar{p}}$)	3.0×10^{10}
total antiprotons	1.1×10^{12}
β^* [cm]	35

Table 2.1: Accelerator nominal parameters for Run II configuration.

2.1.4 Luminosity and Tevatron Performance

The performance of a collider is evaluated in terms of two key parameters: the available center-of-mass energy, $\sqrt{s}$, and the instantaneous luminosity, $\mathcal{L}$. The former defines the accessible phase-space for the production of final state particles. The latter is defined as the interaction rate per unit cross section of the colliding beams (collisions/(cm^2s)). In the absence of a crossing angle or

position offset of the beams, the luminosity at CDF or DØ is given by the expression:

$$\mathcal{L} = \frac{f_{bc} N_b N_p N_{\bar{p}}}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} F \left(\frac{\sigma_l}{\beta^*} \right), \quad (2.1)$$

where f_{bc} is the revolution frequency, N_b is the number of bunches, $N_{p(\bar{p})}$ is the number of protons (antiprotons) per bunch, and $\sigma_{p(\bar{p})}$ is the transverse proton (antiproton) beam size at the interaction point. F is a form factor with a complicated dependence on the beta function (β^*) value at the interaction point ⁴, β^* , and the bunch length, σ_l . Tab. 2.1 shows the design Run II accelerator parameters while Fig. 2.2 shows the evolution of the integrated luminosity, defined as $L = \int \mathcal{L} dt$, and the instantaneous luminosity at the start of Tevatron stores during the Run II. The steady increase of the integrated luminosity and the continuous improvement of the instantaneous luminosity prove the outstanding performance of the accelerator. The Tevatron program was terminated on September 30, 2011. During the Run II the Tevatron delivered 12 fb^{-1} of data per experiment, ~ 10 of which were collected by the CDF and DØ detectors.

2.2 The CDF II detector

The CDF II detector, in operation from 2001 to 2011, is an azimuthally and forward-backward symmetric apparatus designed to study the $p\bar{p}$ collisions at the BØ interaction point of the Tevatron. It is a general purpose, cylindrical-shaped detector (Fig. 2.3), which consists of:

- a **tracking system**, which comprises three silicon microstrip trackers (Layer 00, SVXII and ISL) and an open-cell drift chamber (COT) inside a superconducting solenoid, that provides a constant 1.4T magnetic field parallel to the beam direction, with the purpose of bending into helices the trajectories of charge particles to allow determining their momentum and charge;
- a **Time of Flight** system (TOF), located outside the COT, for measuring the mass of charged particles with momenta up to 2 GeV/c;
- a **calorimeter system**, with the purpose of measuring the energy of charged and neutral particles;
- **muon chambers and scintillators**, used to track and identify muons, that pass through the calorimeters interacting as minimum-ionizing-particles (m.i.p.);
- **luminosity monitors**, for the instantaneous luminosity measurement, necessary to derive cross section from event yields.

2.2.1 Coordinates System and Standard Definitions at CDF

CDF adopts a left handed Cartesian coordinate system with origin at the nominal BØ interaction point, coincident with the center of the drift chamber. The positive z-axis lies along the nominal beam-line and has the direction of the proton beam (eastwards). The x-y plane is therefore perpendicular to the beam-line, with the y-axis pointing upwards and the x-axis in the horizontal plane, pointing radially outward with respect the center of the accelerator ring. Since the colliding

⁴The suitable normalized beta function (β^*) represents a measure of the transverse beam size along the accelerator ring.

Figure 2.2: Integrated luminosity as a function of the Run II weeks (2.2a) and Tevatron peak luminosity as a function of the calendar date (2.2b). Empty periods correspond to Tevatron shut-down periods.

beams of the Tevatron are unpolarized, the resulting physical observations are invariant under rotations around the beam line axis. Thus, a cylindrical (r, ϕ, z) coordinate system is particularly

Figure 2.3: Isometric view of the CDF II Detector.

convenient to describe the detector geometry, where

$$r = \sqrt{x^2 + y^2} \quad \text{and} \quad \phi = \tan^{-1} \frac{y}{x} . \quad (2.2)$$

A momentum-dependent particle coordinate, named *rapidity*, is also commonly used in particle physics for its transformation properties under Lorentz boosts. The rapidity is defined as

$$Y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} , \quad (2.3)$$

where E is the energy and p_z is the z component of the particle momentum. Rapidity intervals turn out to be Lorentz invariant. In the relativistic limit, or when the mass of the particle is negligible, rapidity depends only upon the production angle of the particle with respect to the beam axis, $\theta = \tan^{-1} \frac{\sqrt{x^2 + y^2}}{z}$. This approximation is called *pseudorapidity* η and is defined as

$$Y \xrightarrow{p \gg m} \eta = -\ln \left(\tan \frac{\theta}{2} \right) . \quad (2.4)$$

A value of $\theta = 90^\circ$, perpendicular to the beam axis, corresponds to $\eta = 0$. Since the event-by-event longitudinal position of the interaction is distributed around the nominal interaction point with a 30 cm rms width, sometimes a distinction between the detector pseudorapidity (usually indicated with η_{det}), measured with respect to the (0,0,0) nominal interaction point, and the event pseudorapidity (η), which is measured with respect to the z position of the actual event vertex, is considered. The spatial separation between particles in the detector is commonly given in terms of a Lorentz invariant variable defined as:

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} . \quad (2.5)$$

Other quantities, useful to describe the kinematics of $p\bar{p}$ interactions, are the transverse momentum and the transverse energy, defined as $p_T = p \sin \theta$ and $E_T = E \sin \theta$, respectively.

2.3 The tracking system

A three-dimensional tracking of charged particles is achieved through an integrated system consisting of three inner silicon subdetectors and a large outer drift-chamber, all immersed in the magnetic

field of a superconducting solenoid. The silicon detectors provide a precise determination of the track impact parameter, the azimuthal angle and the z coordinate at production, whereas the drift chamber has excellent resolution on the transverse momentum, ϕ and η . The combined information of the tracking detectors provides very accurate measurements of the helical paths of charged particles inside the detector. We will describe this system starting from the devices closest to the beam and moving outwards (see Fig. 2.6a).

Figure 2.4: (a) The CDF II tracker layout showing the different subdetector systems. (b) Schematic drawing of the impact parameter d_0 . The sign of the impact parameter is defined as positive or negative with reference to the direction of the track momentum vector (in the X,Y quadrant in the drawing).

2.3.1 The Silicon Tracker

The full CDF silicon detector is composed of three approximately cylindrical coaxial subsystems: the Layer 00 (L00), the *Silicon Vertex* detector (SVX) and the Intermediate *Silicon Layers* (ISL). Silicon sensors operate as reverse-biased p - n junctions. By segmenting the p or n side of the junctions into “strips” and reading out the charge deposition separately on every strip the point of trasversal of a charged particle is measured. At CDF the typical distance between two strips is about $60 \mu\text{m}$. There are two types of microstrip detectors: single- and double-sided. In single-sided detectors only one side (p) of the junction is segmented into strips, double-sided detectors have both sides of the junction segmented into strips. In general single-sided sensors have strips parallel to the z direction and provide only r - ϕ position measurements, while double-sided detectors have strips at an angle (stereo angle) with respect to the z direction on one side and, therefore, provide also information on the particle position along z .

L00 is a 90 cm -long, radiation hard, assembly of single-sided silicon detectors, structured in longitudinal strips. It is mounted directly on the beam pipe at $1.35 - 1.62 \text{ cm}$ from the beam axis. The detector support structure is in carbon fiber with integrated cooling system. Being so close to the beam, L00 allows to reach a resolution of $\sim 25 - 30 \mu\text{m}$ on the impact parameter of tracks of moderate p_T , providing a powerful handle to identify long-lived hadrons containing a b quark.

SVX is composed of three 29 cm -long cylindrical barrels, radially organized in five layers of double-sided silicon wafers extending from 2.5 cm to 10.7 cm (see Fig. 2.5a). Each barrel is segmented

into 12 wedges, each covering $\sim 30^\circ$ in ϕ . The double-side structure of the wafers allows a three dimensional position measurement: one side of the wafer has axial strips (parallel to the beam), the other one has either 90° strips (perpendicular to the beam) or 1.2° stereo strips (at small angle with respect to the beam). This detector provides position information with a $12\ \mu\text{m}$ resolution on the single hit and some dE/dx ionization information.

Figure 2.5: The **SVX** silicon detector: on the left, a three-dimensional view of the detector allows to see the barrel structure along the beam axes; on the right, the transverse plane section shows in detail the layer sequence.

ISL consists of two layers of double sided silicon wafers, similar to those of **SVX**, one of which is assembled in a twofold telescopes with planes at a radial distance of 22cm and 29cm from the beam-line and covering $1 < |\eta| < 2$. One single central layer is located at $r = 22\text{cm}$, covering $|\eta| < 1$. The two **ISL** layers are important to increase the tracking coverage in the forward region, where the **COT** coverage is limited, and to improve the matching between **SVX** and **COT** tracks.

The combined resolution of the CDF inner trackers for high momentum tracks is $\sim 40\ \mu\text{m}$ in impact parameter and $\sim 70\ \mu\text{m}$ along the z direction. All silicon detectors are used in the off-line track reconstruction algorithms, while **SVX** plays a crucial role also in the on-line track reconstruction of the trigger system. The CDF trigger employs an innovative processor, the Silicon Vertex Trigger (SVT) [13, 14], which uses the **SVX** information to measure the track impact parameter on-line with a precision that allows to resolve the secondary vertices, displaced from the primary interaction point, such as those produced in B hadron decays.

2.3.2 Central Outer Tracker

Surrounding the silicon detector is the Central Outer Tracker (**COT**) [15]. It is a 3.1m -long cylindrical drift chamber, coaxial with the beam, which covers the radial range from 40 to 137cm for $|\eta| < 1$. The **COT** contains 96 sense wire layers, which are radially grouped into 8 superlayers, as inferred from the end plate slot structure shown in Fig. 2.6. Each superlayer is divided in ϕ into supercells, and each supercell has 12 alternated sense and field shaping wires. So within the supercell width the trajectory of a particle is sampled 12 times. The maximum drift distance is approximately the same for all superlayers. Therefore, the number of supercells in a given superlayer scales approximately with the radius of the superlayer. The entire **COT** contains 30240 sense wires.

Figure 2.6: A 1/6 section of the COT end-plate (2.6a): for each super-layer the total number of cells, the wire orientation (axial or stereo), and the average radius in cm are given. The enlargement shows in detail the slot where the wire planes (sense and field) are installed. Fig. 2.6 represents the cross-section of three axial cells in super-layer 2, the arrow indicates the radial direction.

Approximately half the wires run along the z direction (*axial* wires), the other half are strung at a small stereo angles (2°) with respect to the z direction (*stereo* wires). The combination of the axial and stereo information allows to measure the z positions and a three-dimensional reconstruction of tracks. Particles originated from the interaction point, which have $|\eta| < 1$, pass through all the 8 COT superlayers. The COT is filled with an Argon-Ethane gas mixture and isopropyl alcohol (49.5:49.5:1). The mixture is chosen in order to have a constant drift velocity, approximately $50 \mu\text{m}/\text{ns}$, across the cell width. The maximum electron drift time is approximately 100 ns . Due to the magnetic field that the COT is immersed in, electrons drift at a Lorentz angle of 35° . The supercells are tilted by 35° with respect to the radial direction to compensate for this effect and make the drift path perpendicular to the radial direction.

The hit position resolution in the r - ϕ plane is about $140 \mu\text{m}$. Tracking algorithms are utilized to reconstruct particle trajectories (helices) that best fit to the observed hits. The reconstructed trajectories are referred to as “tracks”. Particle momentum and charge are determined from the bending of tracks in the magnetic field. The COT hits are also processed on-line by the XFT, which reconstructs the tracks used in the trigger system, (Sec. 3.5). The transverse momentum resolution of off-line tracks, estimated using cosmic ray events, is:

$$\frac{\sigma_{p_T}}{p_T^2} = [0.017][\text{GeV}/c]^{-1} \quad (2.6)$$

for tracks with $p_T > 2 \text{ GeV}/c$ [17].

2.3.3 Time Of Flight

Just outside the tracking system, supported on the inside of the solenoid, see Fig. 2.4, CDF II has a Time of Flight (TOF) detector [16]. It is a barrel of scintillator bars almost 3 m long located at 140 cm from the beam line with a total of 216 bars, each covering 1.7° in φ and the pseudorapidity range $|\eta| < 1$. Light is collected by photomultipliers at both ends of each scintillator bar. Single hit

position in the TOF is determined by the comparison of the signal times of the photomultipliers. Particle identification is achieved by measuring the time of arrival of a charged particle at the scintillators with respect to the collision time. Thus, combining the measured time-of-flight, the momentum and the path length the mass of the particle can be estimated.

$$m = \frac{p}{c} \sqrt{\frac{1}{\beta^2} - 1} = \frac{p}{c} \sqrt{\left(\frac{cT}{L}\right)^2 - 1} \quad (2.7)$$

where the momentum p and the path length L are precisely measured by the tracking system. For the TOF measurement the collision time must be known and this is found with a 50 ps uncertainty by a best-fit process over all tracks in the event. The resolution in the time-of-flight measurement is ≈ 120 ps and provides at least two standard deviation separation between $K^\pm$ and $\pi^\pm$ for momenta $p < 1.6 \text{ GeV}/c$.

2.4 Calorimeters

The calorimeter system, together with the muon and tracking systems, represents one of the main sub-detector of CDF II. A detailed description of this system can be found in the CDF II Technical Design Report [18]. The CDF II calorimetry system has been designed to measure energy and direction of neutral and charged particles leaving the tracking region. In particular, it is devoted to jet reconstruction and it is also used to measure the missing energy associated to neutrinos. Particles hitting the calorimeter can be divided in two classes, according to their main interaction with matter: electromagnetically interacting particles, such as electrons and photon, and hadronically interacting particles, such as mesons or barions produced in hadronization processes. To detect these two classes of particles, two different calorimetric parts have been developed: an inner electromagnetic and an outer hadronic section, providing coverage up to $|\eta| < 3.64$. In order to supply information on particle position, the calorimeter is also segmented in towers, projected toward the geometrical center of the detector. Each tower consists of alternating layers of passive material and scintillator tiles. The signal is read out via wavelength shifters (WLS) embedded in the scintillator and light from WLS is then carried by light guides to photomultiplier tubes. The central sector of the calorimeter, covering the region $|\eta| < 1.1$, was recycled from Run I, while brand new calorimeters (called plug calorimeters) were built up to cover the forward and backward regions. Fig. 2.7b shows the plug calorimeter system while Fig. 2.7c shows an elevation view of the components of the CDF calorimeter: CEM, CHA, WHA, PEM and PHA.

2.4.1 The Central Calorimeter

Excluding upgrades on the readout electronics, needed to cope with the increased collision rate, the central calorimeter is almost the same as in Run I⁵. The Central Electro-Magnetic calorimeter (CEM) is segmented in $\Delta\eta \times \Delta\phi = 0.11 \times 15^\circ$ projective towers consisting of 31 alternate layers of lead and scintillator, for a total material depth of $19 X_0$ ⁶. The Central and End-Wall Hadronic calorimeters

⁵CDF, from 1992 to 2004, used gas proportional chambers in the central calorimeter to improve the identification of electrons and photons (*Central Preshower* (CPR) and *Central Crack* (CCR) detectors). Late in 2004 the **CDF Central Preshower and Crack Detector Upgrade** was installed. The CDF Central Preshower and Crack Detector Upgrade consist of scintillator tiles with embedded wavelength-shifting fibers, clear-fiber optical cables, and multi-anode photomultiplier readout.

⁶The radiation length X_0 describes the characteristic amount of matter transversed by high energy electrons to lose by bremsstrahlung all but $1/e$ of their energy, which is equivalent to $7/9$ of the length of the mean free path

Figure 2.7: One azimuthal electromagnetic calorimeter wedge 2.7a, the elevation view of one quarter of the plug calorimeter 2.7b. In 2.7c elevation view of the CDF detector showing the components of the CDF calorimeter: CEM, CHA, WHA, PEM and PHA.

(CHA and WHA respectively), whose geometry tower segmentation matches the CEM one, use 32 steel layers sampled each 2.5 cm (5 cm in the wall) by 1 cm thick acrylic scintillator. The total thickness of the hadronic section is approximately constant and corresponds to 4.5 interaction lengths (λ_0)⁷. A perspective view of a central electromagnetic calorimeter module (*wedge*) is shown in Fig. 2.7a, where both the arrangement in projective towers and the light-collecting system are visible. The projective geometry has been used in order to take advantage of the momentum conservation in the transverse plane: before the $p\bar{p}$ collision, the projection in the transverse plane w.r.t. the beam direction of the beam energy is zero, therefore this quantity must be the same after the collision. Thus, for each tower the transverse energy E_T is defined as $E_T = E \sin \theta$, where E is the energy detected by the tower and θ is the angle between the beam axis and the projective tower direction. Two position detectors are embedded in each wedge of CEM:

- The Central Electromagnetic Strip chamber (CES) is a two-dimensional stripwire chamber arranged in correspondence to maximum shower development ($\sim 5.9X_0$). It measures the charge deposit of the electromagnetic showers, providing information on their pulse-height and position with a finer azimuthal segmentation than calorimeter towers. This results in an increased purity on electromagnetic object reconstruction. The CES purpose is to measure the position and the shape of electromagnetic showers in both transverse plane and longitudinal direction, which is used to distinguish electrons and photons from hadrons.

for e^+e^- pair production of high energy photons. The average energy loss due to bremsstrahlung for an electron of energy E is related to the radiation length by $\left(\frac{dE}{dx}\right)_{brem} = -\frac{E}{X_0}$

⁷An interaction length is the average distance that a particle will travel before interacting with a nucleus: $\lambda = \frac{A}{\rho\sigma N_A}$, where A is the atomic weight, ρ is the material density, σ the cross section and N_A the Avogadro number.

- The Central Pre-Radiator (CPR) consists of two wire camber modules placed immediately in front of the calorimeter. It acts as pre-shower detector by using the tracker and the solenoid coil material as radiators, resulting to be a very useful tool in rejection of electron and photon background.

Tab. 2.2 summarizes the basic quantities of calorimeter detectors. The energy resolution for each calorimeter section was measured in the test beam and, for a perpendicularly incident beam, can be parametrized as:

$$\frac{\sigma}{E} = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2 \quad (2.8)$$

where the first term comes from the sampling fluctuations and the photostatistics of the PMTs, (stochastic term) and the second term comes from the non-uniform response of the calorimeter (constant term), and the symbol $\oplus$ indicates addition in quadrature.

2.4.2 The Plug Calorimeter

The plug calorimeter covers the η region from 1.1 to 3.64. Both electromagnetic and hadronic sectors are divided in 12 concentric η regions, with $\Delta\eta$ ranging from 0.10 to 0.64, according to increasing pseudorapidity. Each of them is segmented in 48 or 24 (for $|\eta| < 2.11$ or $|\eta| > 2.11$ respectively) projective towers. The actual size of these towers was chosen so that identification of electron in the narrow forward jets would be optimized. Projective towers consist of alternating layers of absorbing material (lead and iron for electromagnetic and hadronic sectors, respectively) and scintillator tiles. The first layer of the electromagnetic tiles is thicker (10 mm instead of 6 mm) and made of material with higher photon yield. It acts as a pre-shower detector.

Calorimeter	CEM	CHA	WHA	PEM	PHA
Absorber	Lead	Steel	Steel	Lead	Iron
Segmentation ($\eta \times \phi$)	0.1×15	0.1×15	0.1×15	$(0.1 \div 0.6) \times (7.5 \div 15)$	$(0.1 \div 0.6) \times (7.5 \div 15)$
Num. Towers ($\eta \times \phi$)	20×24	9×24	6×24	$12 \times 24(48)$	$11 \times 24(48)$
Thickness	$[19]X_0, 1\lambda_0$	$4.7\lambda_0$	$4.7\lambda_0$	$[23]X_0, 1\lambda_0$	$6.8\lambda_0$
Resolution (%)	$14/\sqrt{E_T} \oplus 2$	$50/\sqrt{E_T} \oplus 3$	$75/\sqrt{E_T} \oplus 4$	$16/\sqrt{E} \oplus 1$	$80/\sqrt{E} \oplus 5$

Table 2.2: Summary of the main characteristics of the CDF II calorimeter system.

2.5 The Muon Chambers

Parameter	CMU	CMP	CMX	IMU
Pseudorapidity range	$ \eta < 0.6$	$ \eta < 0.6$	$0.6 < \eta < 1.0$	$1.0 < \eta < 1.5$
Azimuthal coverage $[\circ]$	360	360	360	270
Maximum drift time [ns]	800	1400	1400	800
Drift tube cross section [cm]	2.68×6.35	2.5×15	2.5×15	2.5×8.4
Pion interaction length	5.5	7.8	6.2	62 - 20.0
Minimum $p_T(\mu)$ [GeV/c]	1.4	2.2	1.4	1.4-2.0

Table 2.3: Design parameters of the muon detectors. Assembled from Ref. [10], [11]

Most particles produced in the primary interaction or in subsequent decays have a very high probability of being absorbed in the calorimeter system. Muons represent an exception. Muons do

Figure 2.8: Muon detectors coverage in the η - ϕ plane.

not interact via strong interaction with nuclei in matter either. Therefore, a muon with enough energy will pass through the calorimeter systems releasing only a small amount of its energy⁸. The minimum muon energy required to reach the muon detectors, placed radially outside of the calorimeters, is 1.4 GeV . The muon system is the outermost layer of the CDF II detector and consists of four layers of drift cells and one layer of scintillation counters which are used to reconstruct track segments (“stubs”) of minimum ionizing particles and to provide accurate timing. Stubs are matched with the COT information in order to reconstruct the full trajectory of the muons. Some additional steel shielding layers, in between the chambers and the calorimeters, reduce the probability for other particles to escape the calorimetric system. Four independent systems detect muons in the $|\eta| \lesssim 1.5$ pseudo-rapidity range reconstructing a small segment of their path (stub) sampled by the chambers, employing similar combinations of drift tubes, scintillation counters, and absorbers [10], [11]. The track momentum is found by pointing back the stub to the corresponding track bent in the COT. Scintillators serve as trigger and vetoes while the drift chambers measure the ϕ coordinate using the absolute difference of drift electrons arrival time between two cells, and the z coordinate by charge division. All types of muon detectors use single wire, rectangular drift chambers, arranged in arrays with fine azimuthal segmentation and coupled with scintillator counters. The chambers use a 50:50 gas admixture of Argon and Ethane, and operates in proportional regime. The four sub-detector systems are (see Fig. 2.8):

CMU: the CMU detector is located around the central hadronic calorimeter at a radius of 347 cm from the beam-line with coverage $0.03 \lesssim |\eta| \lesssim 0.63$. It is segmented into 24 wedges of 15° . However, because of wedge effects only 12.6° of each wedge is active, resulting in an overall azimuthal acceptance of 84%. Each wedge is further segmented into three 4.2° modules each containing four layers of four drift cells.

CMP: the CMP is a second set of muon drift chambers outside of CMU behind an additional 60 cm -thick steel absorber. The material further reduces the probability of hadronic punch-through to the CMP. Muons need a transverse momentum of about 2.2 GeV to reach the CMP. The CMP system is arranged in a box shape of similar acceptance as the CMU and serves as a confirmation of CMU for higher momentum muons. A layer of scintillation counters (CSP) is

⁸Muons are over 200 times more massive than electrons, so bremsstrahlung radiation, inversely proportional to the mass squared of the incident particle, is suppressed by a factor of $4 \cdot 10^4$ with respect to electrons.

mounted on the outer surfaces of the **CMP**. The **CMP** and **CMU** have a large overlap in coverage and are often used together in indicating a muon track. **CMP** helps to cover **CMU** ϕ gaps and the **CMU** covers the **CMP** η gaps. Muon candidates which have both **CMU** and **CMP** stubs are the least contaminated by fake muons.

CMX: the **CMX** consists of drift tubes and scintillation counters (CSX) assembled in conically arranged sections. The **CMX** extends the pseudo-rapidity coverage to $0.6 \lesssim |\eta| \lesssim 1$. There are 8 layers of drift chambers in total with a small stereo angle between layers.

IMU: the **IMU** extends the pseudo-rapidity coverage even further to $1.0 \lesssim |\eta| \lesssim 1.5$. The **IMU** is mounted on the toroid magnets which provide shielding.

Tab. 2.3 summarizes a few of the relevant design parameters of there detectors.

2.6 CLC detector

Absolute measurements of the instantaneous luminosity by the machine, based on beam parameters measurements, have uncertainties of the order of 15-20%. For this reason in CDF the collider luminosity is determined using gas Cherenkov counters (CLC)[?] located in the pseudorapidity region $3.7 < |\eta| < 4.7$, which measure the average number of inelastic interactions per bunch crossing. Each module consists of 48 thin, gas-filled, Cherenkov counters. The counters are arranged around the beam pipe in three concentric layers, with 16 counters each pointing to the center of the interaction region. The cones in the two outer layers are about 180 cm long and the inner layer counters, closer to the beam pipe, have a length of 110 cm. This geometry allows detecting only particles produced at the collision point. The total signal of the counters allows separating forward inelastic interactions from background and deriving the collider luminosity from their observed rate (see Appendix B)

Chapter 3

The CDF Trigger system

This chapter is focused on the CDF trigger system, which is one of the most relevant element for this analysis . In particular, a list of the trigger paths used and a short description is given.

3.1 The CDF Trigger System

The collisions at Tevatron happen with a frequency of 2.5 MHz (i.e every 396 ns). The bunch-bunch luminosity and the interaction cross section are such that in average one or a few interactions take place at each bunch crossing. With an average event size of $\sim 250\text{ Kb}$ this represents a huge amount of data which would flow through the CDF data acquisition system (DAQ). The CDF DAQ can sustain only a small fraction of this data flow, since the maximum rate for storing data to disk is $\sim 200\text{ Hz}$. The trigger is the system devoted to perform a quick online selection and keep only the events interesting for physics. A rejection factor of 10000 is needed to match the DAQ capabilities. As shown in Fig. 3.1, the CDF trigger is implemented in three levels of successively tighter and more sophisticated event selections.

The first level is hardware based, while the second is a mixture of hardware and software and the third is purely software, implemented in an on-line computer cluster.

3.2 LEVEL 1

At LEVEL 1 the decision logic is implemented in hardware, that is the selection algorithms are hard-coded into the electronic circuits of the trigger boards. In a synchronous pipeline up to 42 subsequent events can be stored for $\sim 5.5\mu\text{s}$ while the hardware is taking a decision. If no acceptance decision is made within that time the event is lost. L1 decision are made on average in about $4\mu\text{s}$: no dead time is expected from this level. Level 1 rejects 97% of the events, by reducing the event rates from 2.53 MHz to less than 40 kHz . The L1 decision is generated using

- XFT (extremely fast tracker), which reconstructs approximate tracks ($p_T > 1.5\text{ GeV}$) in the transverse plane by exploiting information from COT superlayers. These tracks are extrapolated to the calorimeters and muon chambers parts to contribute to all trigger levels.
- the calorimeter towers, which carry information on the electromagnetic and hadronic energy deposits (these can be seed for electrons or jets identification).

Figure 3.1: Functional block diagram of the CDF II trigger and data acquisition systems.

- the muon “stubs” (segment of tracks reconstructed in the muon chambers), which are matched to the XFT tracks.

The XFT is a custom processor used to reconstruct two-dimensional tracks in the (r, ϕ) plane in the COT. The XFT is capable of reconstructing tracks with $p_T \gtrsim 1.5 \text{ GeV}$ with an efficiency of about 95% and a fake rate of a few percent. The XFT has an angular segmentation of 1.25° , and an angular resolution of 0.3° . The momentum resolution is $\sigma_{p_T}/p_T^2 \approx 0.017 [\text{GeV}/c]^{-1}$. XFT sends the tracks to an extrapolation unit (XTRP) feeding three L1 elements: L1 CAL, L1 TRACK, and L1 MUON. L1 CAL and L1 MUON use extrapolated tracks and information from the calorimetry and muon systems respectively to search for possible electron, photon, jets and muon candidates. A decision stage combines the information from these low-resolution physic objects, called “primitives”, into more sophisticated objects.

3.3 LEVEL 2

LEVEL 2 is an asynchronous system which processes events that have received a L1 accept in a FIFO (First In, First Out) manner. It is structured as a two stage pipeline with data buffering at the input of each stage. The first stage is based on dedicated hardware processor which assemble information from a particular section of the detector. The second stage consists of a computer which uses the list of objects generated by the first stage and implements in software the event selection. Each of the L2 stages is expected to take approximately $10 \mu\text{s}$ with a latency of approximately $20 \mu\text{s}$. The input buffers can store up to four events. After the Level 2, the event rate is reduced to about 1 KHz (rejection factor ~ 40). L2 purposes are:

- to cluster the enery deposited in the towers around L1 seeds, as an approximate measure of an electron photon or jet energy.
- to use calorimeter and CES chamber information to improve separation of $e^\pm$ from γ .

- to improve the matching between **XFT** tracks and muon stubs in order to have a better muon signature.
- to provide a measurement of the track impact parameters by means of the Silicon Vertex Trigger element (**SVT**), which allow to select events with secondary vertexes from decay of long-lived heavy flavour hadrons.

The **SVT** uses **SVX** $r - \phi$ hits to extend **XFT** track primitives inside the **SVX** volume, closer to beam-line. The **SVT** improves the **XFT** ϕ_0 and p_T resolutions and allows to measurement of the impact parameter d_0 (original **XFT** track primitives are beam-line constrained).

3.4 LEVEL 3

LEVEL 3 is a software trigger. It is operated on a cluster of ~ 300 processors which reconstruct the entire event with the same accuracy as in the off-line analysis. The final decision to accept an event is made on the basis of a list of observables indicating candidate events of physical interest (top quark production events, W/Z events, Drell-Yan events, etc.). Events that satisfy the Level 3 trigger requirements are transferred onward to the Consumer Server/Data Logger (**CSL**) system for storage first on disk and later on tape. The average processing time per event in Level 3 is on the order of one second. The Level 3 leads to a further reduction in the output rate, with an accepted maximum of about 200 Hz .

3.5 Trigger Paths

A set of requirements that an event has to fulfill at Level 1, Level 2 and Level 3 constitutes a trigger path. The CDF II trigger system implements about 150 trigger paths, which are periodically adjusted depending on machine luminosity and physics needs. An event will be accepted if it passes the requirements of any one of these paths. The trigger system described above exploits the information of all detector subsystems. Combining the measurements of the various subsystems it is possible to efficiently record, at the same time, events characterized by different signatures. Triggers which use a bandwidth fraction larger than the assigned one are prescaled. A trigger path is said to be prescaled by a factor N if it is configured to accept only one event out of N recorded events. Prescaling is dynamically implemented by luminosity-dependent factors during data taking. This is important in order to ensure that no trigger path reaches rates so high as to create unacceptable dead time to triggers on rare events of primary importance. During data taking the luminosity decreases with time, and consequently a number of prescale factors can be relaxed. The prescale factors decrease proportionally to the rate of triggered events, so as the number of recorded events is constant. Using dynamic prescaling ensures that optimal use for physics is made of the available luminosity.

The accepted events are recorded to tape and organized in “data sets” according to the trigger path which satisfy.

Chapter 4

Physical Object Reconstruction

Outgoing particles from $p\bar{p}$ interactions are identified using the information provided by the CDF sub-detectors described in the previous chapter. The raw outputs from the CDF detector are electronic signals recorded by the hardware components which must be converted into physical information. From the raw data, high level objects (such as tracks, vertices, calorimeter clusters) are reconstructed and combined to identify physical objects (electrons, muons, neutrinos and jets) of interest for the analysis. The ability to detect and reconstruct charged particle trajectories is essential for particle identification and momentum measurement.

4.1 Track Reconstruction

Charged particles traveling through a homogeneous solenoidal magnetic field along the z direction follow helical trajectories. Knowing that the projection of the helix on the x - y plane is a circle, to uniquely parameterise a helix in three dimensions, five parameters are needed:

- C – signed helix (half)-curvature, defined as $C = q/2R$, where R is the radius of the helix and q is the particle charge. This is directly related to the transverse momentum. When the magnetic field (B) is measured in Tesla, C in m^{-1} and p_T in GeV/c : $p_T = 0.15 qB/|C|$.
- ϕ_0 – ϕ azimuthal angle of the particle trajectory at the point of closest approach to the z -axis.
- d_0 – signed impact parameter, i.e. the radial distance of closest approach to the z -axis. defined as $d_0 = q(\sqrt{x_0^2 + y_0^2} - R)$, where (x_0, y_0) are the coordinates of the center. This is schematically drawn in Fig. ??.
- λ – helix pitch, i.e. $\cot(\theta)$, where θ is the polar angle of the particle at the point of its closest approach to the z -axis. This is directly related to the longitudinal component of the momentum: $p_z = p_T \cot \theta$.
- z_0 – the z coordinate of the point of closest approach.

Another useful quantity is the displacement of the secondary vertices of decaying particles in the transverse plane, L_{xy} :

$$L_{xy} = \frac{\hat{x}_V \cdot \vec{p}_T}{|p_T|} \quad (4.1)$$

where $\hat{x}_V$ is the decay vertex position in the transverse plane.

The trajectory of a charged particle satisfies the following equations

$$\begin{aligned}x &= r \sin \phi - (r - d_0) \sin \phi_0 \\y &= -r \cos \phi + (r + d_0) \cos \phi_0 \\z &= z_0 + s\lambda\end{aligned}\tag{4.2}$$

where s is the projected length along the track, $r = 1/2C$ and $\phi = 2Cs + \phi_0$. The reconstruction of a charged particle trajectory consists in determining the above parameters through an helical fit of a set of spatial measurements (“hits”) reconstructed in the tracking detectors by clustering and pattern-recognition algorithms. The helical fit takes into account field non-uniformities and scattering by the detector material. All tracks are first fit in the COT and then extrapolated inward the silicon. This approach guarantees fast and efficient tracking with high tracks purities. The greater radial distance of the COT with respect to the silicon tracker results in a lower track density and consequent fewer accidental combination of hits in the track reconstruction. A brief overview of the tracking algorithms is given in Appendix D. For more details see Ref. [19], [20].

4.1.1 Primary Vertex Reconstruction

The primary vertex position for a given event is found by fitting high quality tracks to a common point of origin. At high luminosities, multiple collisions occur on a given bunch crossing. For a luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, there is an average of 2.3 interactions per bunch crossing. Typically, since the luminous region is sufficiently long (with $\sigma_z = 29 \text{ cm}$), the primary vertices associated to the collisions are well separated in z . An iterative algorithm is used to find the vertex associated to the hardest collision: the first estimate of its position (x_V, y_V, z_V) is binned in the z coordinate, then the z position of each vertex is calculated from the weighted average of the z coordinates of all tracks within 1 cm of the first iteration vertex, with a typical resolution of $100 \mu\text{m}$; finally the vertex associated with the highest sum of the tracks p_T is defined as primary vertex of the event.

The locus of all primary vertices defines the beam-line, the position of the luminous region of the beam-beam collisions through the detector. The beam-line is used as a constraint to refine the knowledge of the primary vertex in a given event. Typically the beam transverse section is circular with a width of $\sim 30 \mu\text{m}$ at $z = 0$, rising to $\sim 50 - 60 \mu\text{m}$ at $|z| = 40 \text{ cm}$. The beam at the interaction point is not necessarily parallel to the detector axis nor centered in the detector and moves up to fractions of millimeter as a function of time.

4.2 Lepton Reconstruction and Identification

Lepton reconstruction depends on the type of lepton and its direction inside the detector. In this analysis we are interested in the identification of electrons and muons. In the following we will present a brief overview of the identification criteria we used in this work.

4.2.1 Electron Identification

Electrons are identified by requiring a track matched to an energy cluster in the calorimeter with an appropriate shower profile. The cluster reconstruction starts with an energetic tower in the electromagnetic calorimeter, the *seed tower*. Electrons are assumed to be massless end, in order to reconstruct the four momentum, $(E, \vec{p})$, track information is used to determine the three dimensional direction, $\vec{p}/|\vec{p}|$, while the calorimetric energy measurement gives the magnitude $E \equiv |\vec{p}|$. We used the following electron categories

Tight Central Electrons (TCE) Central electrons ($|\eta| < 1.0$) with high p_T are expected to traverse the silicon and COT detectors, leaving behind a track. Then they enter the EM calorimeter where they will produce an electromagnetic shower and deposit most of their energy. The selection criteria applied to identify the *tight central electrons* are reported in Tab. 4.1. The observable used are

- Track p_T is the transverse momentum of the track associated to the EM cluster.
- Track z_0 is the position along the longitudinal direction at the point of closest approach to the beam-line.
- *Axial and Stereo Superlayers*, (SL) are the numbers of axial and stereo superlayers in the COT having at least 5 hits associated to the track in question.
- $Q \times \Delta x_{CES}$ is the distance in the $r - \phi$ plane between the extrapolated track and the nearest cluster reconstructed in the CES detector multiplied by the charge of the track (to account for asymmetric tails originated from bremsstrahlung).
- E_{had}/E_{EM} is the ratio between the energy deposited in the hadronic calorimeter and the energy deposit in the electromagnetic one.
- E/P is the ratio of the EM cluster transverse energy to the track transverse momentum as measured by the tracking system; expected to be ~ 1 for the electrons, it can be up twice as much of radiated energy along the trajectory.
- *CalIso* is the calorimetric isolation, defined as

$$CalIso \equiv \frac{E_T^{\Delta R=0.4} - E_T^e}{E_T^e} \quad (4.3)$$

where $E_T^{\Delta R=0.4}$ is the transverse energy in a cone of radius $\Delta R \leq 0.4$, with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, around the electron cluster and E_T^e is the energy in the electron cluster.

- L_{shr} , the lateral shower profile, compares the energy distributions of the EM towers adjacent to the seed tower to the distribution derived from electron test-beam data.
- Δz_{CES} is the distance in the $r - z$ plane between the extrapolated track and the best matching CES cluster.

Forward Electrons Electron candidate clusters in the plug calorimeter are made starting from a seed tower and adding neighboring towers within two towers in η_{det} and ϕ from the seed. The hadronic energy of the cluster is required to be less than 0.05 times the electromagnetic energy. Plug electrons have to be reconstructed in a well-instrumented region of the detector, defined as $1.2 \leq |\eta| \leq 2.0$ as measured by the PES sub-system (η_{det}^{PES}). To improve the quality of the track-cluster matching, we require a track with hits in at least 3 layers of the silicon detector, given the COT limited coverage in the forward region. The track is further required to have $|z_0| < 60 \text{ cm}$. Additional requirements are summarized in Table 4.2. Some of the observable used to define the forward electrons are

- $PEM 3 \times 3 \chi^2$ is the χ^2 of a fit to the signal shape in electron test beam data.
- $PES 5 \times 9 \text{ U/V}$ are the ratios of the charge collected in the central 5 over a set of 9 PES strips in the horizontal and vertical planes.
- $\Delta R(PES, PEM)$ is the angular distance between the PEM and the PES clusters.

	TCE
Region	central ($ \eta < 1.0$)
Fiducial	track fiducial to CEM
Track p_T	≥ 10 (5 if $E_T < 20 \text{ GeV}$)
Track $ z_0 $	$\leq 60 \text{ cm}$
# Ax SL (5hits)	≥ 3
# St SL (5hits)	≥ 2
Conversion	false
E_{had}/E_{EM}	$\leq 0.055 + 0.00045 \cdot E [\text{GeV}]$
$CalIso$	≤ 0.1
L_{shr}	$\leq$
E/P	$< 2.5 + 0.015 \cdot E_T [\text{GeV}]$
$\Delta x \cdot Q$	$-3 \leq q \cdot \Delta x \leq 1.5 \text{ cm}$
Δz_{CES}	$< 3 \text{ cm}$
Track	Beam constrained

Table 4.1: Definition of fully identified Tight Central Electron (TCE).

	PHX
Region	Plug
$ \eta_{det}^{PES} $	$1.2 \leq \eta_{det}^{PES} \leq 2.0$
E_{had}/E_{EM}	≤ 0.05
PEM $3 \times 3 \chi^2$	≤ 10
PES5 $\times$ 9U	≥ 0.65
PES5 $\times$ 9V	≥ 0.65
$CalIso$	≤ 0.1
$\Delta R(\text{PES}, \text{PEM})$	≤ 3.0
$NSiHits$	≥ 3
Track z_0	$\leq 60 \text{ cm}$

Table 4.2: Definition of Forward Electrons (PHX)

Likelihood-Based Electrons (LBE) In order to maintain an high efficiency in rejecting fake electrons one defines a set of variables to be combined in a single discriminant to be allied in a likelihood method. The quantities considered are

- $TrkIso$ is similar to the $CalIso$ variable defined by Eq. A.25 but measured using tracks instead of calorimeter towers.
- $NCotHitsAx$ is the number of Axial COT super-layers hits belonging to the track associated to the candidate electron.
- $NCotHitsSt$ is the number of Stereo COT super-layers hits belonging to the track associated to the candidate electron.
- χ_{COT}^2 is the χ^2 of the track fit computed using only the COT hits belonging to the track.
- $NSvxHits$ is the number of SVX hits belonging to the track associated to the candidate electron.

These variables, together with those defined in Sec. 4.2.1, are used to form the likelihood

$$\mathcal{L} = \frac{L_{sig}}{L_{sig} + L_{bkg}} = \frac{\prod_{i=1}^N P_i^{sig}(x_i)}{\prod_{i=1}^N P_i^{sig}(x_i) + \prod_{i=1}^N P_i^{bkg}(x_i)} \quad (4.4)$$

where x_i is one of the variable listed above; N is the number of ID variables, in this case, 11; P_i^{sig} and P_i^{bkg} are the probability function of getting the x_i value off the i -th ID variable given a *real* or a *fake* electron (*template* in the following).

Data is used to build signal (from real electrons) and background (from fake electrons) templates selecting sample dominated by real or by fake electrons. Real electrons are obtained selecting two events in the *Z-mass region* (i.e. with an invariant mass in the $76 < m_{\ell\ell} < 106 \text{ GeV}/c^2$ window), a *fully* identified electron and a *probe* one with opposite charge. A fully identified electron is selected through the previous variables and the cuts defined in Tab. 4.1. *Probe* electrons are required to have an identified electron-like cluster associated with a track with looser selection as listed in Tab. 4.3. The ID variables of probe objects are used to make the signal templates.

Fake electrons are obtained from a jets data sample (jets are defined in Sec. 4.3). This sample is selected by requiring at least one jet with energy greater than 20 GeV . One reconstructed jet with $E_T > 20 \text{ GeV}$ and a loose electron, a *fakeable* one (the definition is in Tab. 4.4), per event is required, with an invariant mass out the *Z*-peak region (i.e. $m_{\ell\ell} < 76 \text{ GeV}$ or $m_{\ell\ell} > 106 \text{ GeV}$). The ID variables of fakeable objects are used to build the background template.

	Central Electron Probe
Region	Central
Track p_T	$\geq 5 \text{ GeV}/c$
Track z_0	$\leq 60 \text{ cm}$
Conversion	false

Table 4.3: Definition of central electron probe.

	Fakeable Central Electron
Region	Central
E_{had}/E_{EM}	$\leq 0.125 + 0.00045 E[\text{GeV}]$
$CalIso$	< 0.3
Conversion	false

Table 4.4: Definition of central electron fakeable object.

4.2.2 Muon Identification

Muons traverse the entire CDF detector, depositing a minimum ionization energy in the calorimeters, and leave hits in the outer muon chambers, in cases where they point to a region which is covered by them. A muon is reconstructed starting from a track and adding track segments (stubs) formed with hits in the muon drift chambers. The track origin in the $x - y$ plane is constrained to the beam position. The muon four momentum $(E, \vec{p})$ is determined by measuring the track p and assuming a massless particle: $E \equiv |\vec{p}|$. Muons are reconstructed in eight non-overlapping categories. Six of them require the muons to have hits in one muon detector subsystem, and we call them stubbed muons. The other two are designed to recover muons that do not have a stub

and are referred as stubbless muons. To further increase acceptance we also define an extra lepton category in which both electrons and muons can fall. This category accepts leptons which fall in regions of the detector not fully instrumented (cracks) and fail electron and muon selections.

Stubbed Muon Stubbed muon candidates are required to have a reconstructed track with a fit $\chi^2/n.d.f. < 3$. The track is required to have at least three Axial and two Stereo COT super-layers with at least 5 hits. The track $|z_0|$ has to be less than 60 cm. For all muons, the impact parameter (d_0), has to be less than 0.2 cm, and it is tightened to be less than 0.02 cm if the track has also hits in the Silicon detectors, giving a much precise measurement of the impact parameter. To reject background we also require the track to be isolated: $TrkIso < 0.1$, where $TrkIso$ is defined as

$$TrkIso \equiv \frac{\sum_i p_T^{i, \Delta R=0.4} - p_T}{p_T} < 0.1 \quad (4.5)$$

The reconstructed track is then required to be compatible with a minimum ionizing particle (*m.i.p.*) by cutting on the energy deposited in the EM and HAD towers hit by the extrapolated track. We also require calorimetric isolation

$$CalIso = \frac{E_T^{\Delta R=0.4}}{p_T^\mu} < 0.1 \quad (4.6)$$

where $E_T^{\Delta R=0.4}$ has been defined above and p_T^μ is the track transverse momentum. Stubbed muons are divided in four categories, depending on the region of the detector that the extrapolated track is pointing to, CMUP, CMU, CMP and CMX. We measure the location of an extrapolated muon track candidate with respect to the drift direction (local x) and wire axis (local z) of a given chamber. We do not take into account possible multiple scattering in the extrapolation. We refer to these requirements as fiduciality of the track to the given muon detector. The fiduciality requirements ensure that all the categories are non-overlapping: a given muon cannot be classified into two different categories. The cuts applied to each category are summarized in Tables 4.6 - 4.8.

	CMUP
Region	Central
Track $\chi^2/n.d.f.$	≤ 3
N_{AxL} (5 hits)	≥ 3
N_{StL} (5 hits)	≥ 2
Track z_0	$\leq 60 \text{ cm}$
Track d_0	$\leq 0.2 \text{ cm} (\leq 0.02 \text{ cm if } N_{SiHits} > 0)$
$TrkIso$	≤ 0.1
$CalIso$	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115) \text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028) \text{ GeV}$
Δx_{CMU}	$\leq 7 \text{ cm}$
Δx_{CMP}	$\leq \max(6.0, 150/p_T [\text{GeV}/c^2]) \text{ cm}$
Fiduciality	$x\text{-fid}_{CMU} < 0 \text{ cm } z\text{-fid}_{CMU} < 0 \text{ cm}$ $x\text{-fid}_{CMP} < 0 \text{ cm } z\text{-fid}_{CMP} < -3 \text{ cm}$

Table 4.5: Definition of CMUP central muons.

	CMU
Region	Central
Track $\chi^2/n.d.f.$	≤ 3
N_{AxL} (5 hits)	≥ 3
N_{StL} (5 hits)	≥ 2
Track z_0	$\leq 60\text{ cm}$
Track d_0	$\leq 0.2\text{ cm} (\leq 0.02\text{ cm if } N_{SiHits} > 0)$
$TrkIso$	≤ 0.1
$CalIso$	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115)\text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028)\text{ GeV}$
Fiduciality	$x\text{-fid}_{CMU} < 0\text{ cm } z\text{-fid}_{CMU} < 0\text{ cm}$ Not CMP Fiducial Not CMX Fiducial
Δx_{CMU}	$\leq 7\text{ cm}$
Good Trigger	Run > 270062

 Table 4.6: Definition of **CMU** central muons.

	CMP
Region	Central
Track $\chi^2/n.d.f.$	≤ 3
N_{AxL} (5 hits)	≥ 3
N_{StL} (5 hits)	≥ 2
Track z_0	$\leq 60\text{ cm}$
Track d_0	$\leq 0.2\text{ cm} (\leq 0.02\text{ cm if } N_{SiHits} > 0)$
$TrkIso$	≤ 0.1
$CalIso$	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115)\text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028)\text{ GeV}$
Fiduciality	$x\text{-fid}_{CMP} < 0\text{ cm } z\text{-fid}_{CMP} < -3\text{ cm}$ Not CMU Fiducial
Δx_{CMU}	$\leq 7\text{ cm}$
Δx_{CMP}	$\leq \max(6.0, 150/p_T [\text{GeV}/c])\text{ cm}$
ϕ - gaps	$\phi \bmod 15^\circ \leq 2 \text{ OR } \geq 13$
Good Trigger	Run > 229764

 Table 4.7: Definition of **CMP** central muons.

Stubless Muon Stubless muons are recovered by selecting an isolated high-pT track which deposited in the calorimeter an amount of energy consistent with a minimum ionizing track. Two categories are defined

- **CMIOCES** are the central stubless muons fiducial to the central calorimeter.
- **CMIOPES** are the forward stubless muons fiducial to the plug calorimeter.

The requirements of these two categories are reported in Table 4.9 and 4.10.

	CMX
Region	Central
Track $\chi^2/n.d.f.$	≤ 3
N_{AxL} (5 hits)	≥ 3
N_{StL} (5 hits)	≥ 2
Track z_0	$\leq 60\text{ cm}$
Track d_0	$\leq 0.2\text{ cm} (\leq 0.02\text{ cm if } N_{SiHits} > 0)$
$TrkIso$	≤ 0.1
$CalIso$	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115)\text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028)\text{ GeV}$
Fiduciality	$x\text{-fid}_{CMX} < 0\text{ cm}$ $z\text{-fid}_{CMX} < -3\text{ cm}$ $-0^\circ < \phi < 75^\circ$ OR $105^\circ < \phi < 225^\circ$ OR $315^\circ < \phi < 360^\circ$
Δx_{CMX}	$\rho_{cot} > 140\text{ cm}$
ϕ - gaps	$\leq \max(6.0, 125/p_T [\text{GeV}/c])\text{ cm}$
Good Trigger	$\phi \bmod 15^\circ \leq 2$ OR ≥ 13 Run ≥ 227704

Table 4.8: Definition of CMX central muons. The exit radius, ρ_{cot} is defined as $\rho_{cot} = (z_{cot} - z_0) \cdot \tan \theta$

	CMIOCES
Region	Central
N_{AxL} (5 hits)	≥ 3
N_{StL} (5 hits)	≥ 3
Track $\chi^2/n.d.f.$	≤ 3
Track z_0	$\leq 60\text{ cm}$
Track d_0	$\leq 0.02\text{ cm}$
$TrkIso$	≤ 0.1
$CalIso$	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115)\text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028)\text{ GeV}$
$E_{EM} + E_{had}$	$> 0.1\text{ GeV}$
Fiduciality	CES Fiducial
Uniqueness	Not a CMUP, CMU, CMP, CMX, CMXMsKs

Table 4.9: Definition of CMIOCES central muons.

CrkTrk To further increase the acceptance the leptons that fall in a crack of the sub-detectors are recovered. To specifically select these leptons and to preserve the uniqueness of the categories the track has not to be fiducial to the central or plug calorimeter and we explicitly veto overlaps with stubbed muon categories. The selection criteria are similar to CMIOCES muons, but we do not require any deposit in the calorimeter, since these tracks point to or near the cracks in the calorimeter. However we still require a low calorimeter and tracking activity near the track ($CalIso$ and $TrkIso$) which is fundamental in order to reduce fake lepton identification. We further require the track not to be consistent with a conversion electron. Table 4.11 lists the detailed selection criteria applied.

	CMIOPES
Region	Plug
COT hit fraction	≥ 0.6
<i>NSiHits</i>	≥ 3
Track z_0	$\leq 60 \text{ cm}$
Track d_0	$\leq 0.02 \text{ cm}$
$C/\sigma(C)$	> 12
<i>TrkIso</i>	≤ 0.1
<i>CalIso</i>	≤ 0.1
E_{EM}	$\leq 2 + \max(0, (p - 100) \cdot 0.0115) \text{ GeV}$
E_{had}	$\leq 6 + \max(0, (p - 100) \cdot 0.028) \text{ GeV}$
$E_{EM} + E_{had}$	$> 0.1 \text{ GeV}$
Fiduciality	PES Fiducial
Uniqueness	Not a BMU

Table 4.10: Definition of CMIOPES central muons.

	CrkTrk
<i>NAxL</i> (5 hits)	≥ 3
<i>NStL</i> (5 hits)	≥ 3
Track $\chi^2/n.d.f.$	≤ 3
Track z_0	$\leq 60 \text{ cm}$
Track d_0	$\leq 0.02 \text{ cm}$
$C/\sigma(C)$	> 12
<i>TrkIso</i>	≤ 0.1
<i>CalIso</i>	≤ 0.1
	OR
	≤ 0.1 using nearest EM cluster with $\Delta R = 0.05$
$E_{EM} + E_{had}$	$> 0.1 \text{ GeV}$
Fiduciality	Not PES Fiducial Not CES Fiducial
Uniqueness	Not a CMUP, CMU, CMP, CMX, CMXMsKs

Table 4.11: Definition of CrkTrk central muons.

4.2.3 Neutrino Identification

Neutrinos cannot be detected directly with the CDF detector. However, an indirect way to account for the escaping neutrinos is to measure the momentum unbalance in the detector.

The momentum umbalance can only be measured in the transverse plane. The total event vector momentum in the transverse plane is initially taken to be zero. The energy measured in the calorimeter cells is taken as a measure of the momentum carried by the interacting particles. We can thus define the transverse “missing energy” as

$$\vec{E}_T = - \sum_i E_T^i \hat{n}_i, \quad (4.7)$$

where E_T^i is the transverse energy measured in the i -th tower of the calorimeter and $\hat{n}_i$ is the projection of the versor pointing from the event vertex to the i -th calorimeter tower onto the plane

perpendicular to the beam axis.

4.2.4 Fake leptons

The probability for jets to fake a lepton, the *fake rate*, is measured from tracks in the jet samples of our electroweak data set, corrected for small contribution of real leptons. The jet-like objects that pass a very loose selection of lepton cuts, the *denominator objects*, are counted. Different lepton categories have different denominator objects and all of these objects may pass a full lepton definition. The master formula for the fake rate is given by

$$f_i = \frac{N_i(\text{Identified Leptons}) - \sum_{j \in \text{EWK}} N_i(\text{Identified Leptons})}{N_i(\text{Denominator Objects}) - \sum_{j \in \text{EWK}} N_i(\text{Denominator Objects})} \quad (4.8)$$

where the number real leptons have been subtracted from the numerator and denominator. More than one jet sample is used to estimate the fake rate and the average of these estimation is used as the fake probability.

4.3 Jet Reconstruction

The color-carrying quarks and gluons, created in the scattering process, undergo the hadronization process which produces collimated bunches of colorless hadrons (jets) which keep track of the energy and the direction of the originating parton. From the experimental point of view, the resulting shower of particles appears as a large energy deposit in a localized area of the detector (Fig. 4.1). The challenge is to recover from the detector information the initial energy, the momentum and, possibly, the nature of the particle produced in the original interaction. To reconstruct jets, CDF

Figure 4.1: Top quark and anti top quark pair decaying into jets, visible as collimated collections of particle tracks, and other fermions in the CDF detector.

developed several different jet reconstruction algorithms [28].

4.3.1 JETCLU algorithm

The most common et reconstruction algorithm used at CDF is a “cone algorithm” named JETCLU [29], which consists of three steps. In the first step preclusters are built from adjacent “seed towers”

Figure 4.2: Jet reconstruction by the JETCLU algorithm.

(calorimeter towers with $E_T > 1 \text{ GeV}$). The size of these preclusters is limited to $2R_{\text{cone}} \times 2R_{\text{cone}}$ in the η - ϕ plane, where R_{cone} is the parameter of the jet algorithm which controls the size of the jets.

After that, for each precluster a cone is defined by all seed towers inside the precluster and all towers with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < R_{\text{cone}}$ with respect to the highest E_T tower. The centroids of the cones are calculated. The identification of the members of the cones and the calculation of their centroids is repeated until the old centroids (the cone axes) agree with the new ones.

In the last step overlapping stable cones have to be reconsidered because each calorimeter tower may only belong to one jet. A pair of overlapping cones is merged if more than 75% of the transverse energy of one of the cones is shared by the other one. Otherwise they are separated using an iterative algorithm. The towers are redistributed to the cone whose centroid is closer and the centroids are recalculated until a stable configuration is reached.

The transverse energy and the position of the reconstructed jet are then given by:

$$E_T^{\text{jet}} = \sum_i E_T^i \quad (4.9)$$

$$\eta = \frac{1}{E_T^{\text{jet}}} \sum_i E_T^i \eta^i \quad (4.10)$$

$$\phi = \frac{1}{E_T^{\text{jet}}} \sum_i E_T^i \phi^i \quad (4.11)$$

where E_T^i , η_i and ϕ_i are the energy and the position of the i -th tower.

4.3.2 Jet Energy Corrections

The four-momentum assigned to a jet must be corrected to account for detector defects and reconstruction algorithm imperfections. In order to convert the measured transverse jet energy into the transverse energy of the partons, a set of corrections to the measured jet energy (“raw energy”) have been developed.

The corrections, developed using data and simulation of the CDF detector, address the response inhomogeneity in η , the contributions from multiple interactions, the non-linearity of the calorimeter response, the contribution by the underlying event (particles emitted in the event but not belonging to the hard interaction) and the jet energy flow out of the jet cone.

Figure 4.3: η -dependent energy scale correction factor for JETCLU with radius 0.4; a sample of events with at least one trigger tower above 50 GeV is used.

Each of those corrections has a fractional uncertainty, $\sigma_{JES}(p_T)$ which can be parameterized as a function of the corrected transverse momentum of the jet p_T .

They are applied in a sequence of levels (of “L-levels”) in order to correct for each bias independently [30].

The correction can be parameterized as follows

$$p_T^{\text{parton}} = (p_T^{\text{jet}} \cdot C_\eta - C_{MI}) \cdot C_{Abs} - C_{UE} + C_{OOC} = p_T^{\text{particle}} - C_{UE} + C_{OOC},$$

where the terms are described below.

C_η : pseudorapidity-dependent correction (L1)

The L1 corrects for non-uniformities in calorimeter response along η . It is obtained by studying the p_T balancing in dijet events, which are selected in order to have one jet (“trigger jet”) in the $0.2 < |\eta| < 0.6$ region (far away from detector cracks). The other jet, called “probe jet”, is free to span over the entire $|\eta| < 3$ region.

Since in a perfect detector the two jets must be balanced in p_T , a balancing fraction is formed

$$f_b = \frac{\Delta p_T}{p_T^{\text{ave}}} = 2 \cdot \frac{p_T^{\text{probe}} - p_T^{\text{trigger}}}{p_T^{\text{probe}} + p_T^{\text{trigger}}}$$

The average of f_b in the analyzed η bin is used to define the β_{f_b} factor¹ (see Fig. 4.3)

$$\beta_{f_b} = \frac{2 + \langle f_b \rangle}{2 - \langle f_b \rangle} \quad (4.12)$$

The final L1 correction is defined as $f_{L1}(\eta, E_T^{\text{raw}}, R) = 1/\beta_{f_b}$ and the uncertainty associated with this correction is estimated to be of the order of 1% for central jets and 7.5% for forward jets.

¹The definition of 4.12 is in average equal to $p_T^{\text{probe}}/p_T^{\text{trigger}}$ but it reduces the sensitivity to the presence of non-Gaussian tails which affect the $p_T^{\text{probe}}/p_T^{\text{trigger}}$ ratio.

Figure 4.4: (a) E_T in $R=0.4$ cone as a function of the number of reconstructed primary vertexes in minimum bias events. (b) Fractional systematic uncertainties due to multiple interactions for different cone sizes as a function of jet transverse momentum.

C_{MI} : multiple interactions correction (L4)

The number of interactions occurring during beam bunch crossings follows a Poisson distribution whose mean increases with instantaneous luminosity.

These additional interactions, dominantly soft *minimum bias* events, cause extra unwanted energy to be deposited in the calorimeter.

L4² correction takes into account the number of reconstructed vertices to estimate the effect. The average energy flow in minimum bias events, which are triggered by the luminosity monitor CLC, is measured in the best-performing region ($0.2 < |\eta| < 0.6$) of the calorimeter as a function of the number of reconstructed vertices. The resulting plot is fit to a straight line (see Fig. 4.4). This is used to correct in average the energy of the jets. Because of the finite reconstruction efficiency of the vertices, this linear approximation works well for events with less than seven vertices.

This is not a serious limitation because in practice events with so many vertices are very rare.

The uncertainty on this correction is estimated to be of the order of 15%.

Figure 4.5: Absolute energy corrections for jets with cone size $\Delta R = 0.4$ as a function of jet p_T with uncertainty.

C_{Abs} : absolute energy scale corrections (L5)

While L1 and L4 are corrections at calorimeter level, L5 steps back to particle level. The procedure used to estimate the L5 correction factor is described accurately in [30]. It uses a MC sample of inclusive dijet events simulated with PYTHIA [32].

The correction is derived comparing particle jets at generator level (before they are passed through the detector simulation), with calorimeter jets, as obtained from the detector simulation. These are required to be within 0.1 of each other in the $\eta - \phi$ plane to ensure that they are the same object. The probability at the distribution maximum of measuring a value of p_T^{jet} given $p_T^{particle}$ is taken as a correction factor (see Fig. 4.5). The uncertainty on this corrections is estimated to be of the order of 3.5% (15% near the edge of the calorimeter).

²L2 and L3 have survived in the CDF jargon but are not used anymore.

C_{UE} and C_{OOC} : underlying event (L6) and out-of-cone (L7) corrections

Reconstructed jet energies in hard $p\bar{p}$ interactions may contain contributions by particles created by interactions involving other partons in the colliding hadrons (spectator interactions) or by gluons from initial state radiation in the hard interaction. These contributions are called *underlying event*. On the other hand a fraction of the parton energy may be lost outside the jet cone because of final state gluon radiation, fragmentation at large angles relative to the jet axis or low p_T particles bending in the magnet field. This energy is modeled imperfectly in MC events, so a systematic uncertainty is assigned by examining photon + jets events in data and MC. A ring around the jet with a radius between 0.4 and 1.3 in the $\eta - \phi$ plane is examined, and the energy in this region is compared between data and MC simulation. The largest difference between MC events and data is taken as a systematic uncertainty.

Figure 4.6: The fractional systematic uncertainty of the JES corrections as a function of the jet transverse momentum. The total uncertainty is taken as the sum in quadrature of all individual contributions.

Fig. 4.6 shows the individual fractional systematic uncertainties as a function of jet p_T in the central region, $0.2 < |\eta| < 0.6$, of the calorimeter. They are independent of each other and thus are added in quadrature to derive the total uncertainty.

C_{qg} : quarks and gluons corrections (L9)

L9 jet energies corrections are based on the initial parton type originating the jet. The procedure used to estimate the L9 corrections is fully described in [31]. Differences between quark and gluon jet energy scales are not well modeled in ALPGEN + PYTHIA Monte Carlo simulations. It is possible to derive separate corrections for quark jets and gluon jets in data and MC given two independent samples of jets, with different quark fractions, balanced against objects of known energy. To derive a correction for Monte Carlo, Z-jet (rich in gluons) and γ -jet (rich in quarks) samples are used. Rather than derive full and separate jet energy corrections for data and MC, the balance in data and MC in Z-jet and γ -jet is compared:

$$K_{Z/\gamma} = (E_T^{jet}/p_T^{Z/\gamma}) - 1 \quad (4.13)$$

From this comparison, an additional correction to be applied to MC jets (on top of the L5 or L7 corrections) based upon whether they are quarks or gluons, in order to better match the data, is found. Quark jet energies, at L5 or L7, should be corrected upwards by $\sim 1\%$, while gluon jet

energies should be corrected downwards by $\sim 7\%$. These corrections are independent of the jet energy for energies $\gtrsim 15$ GeV.

4.4 Reconstruction of the Secondary Vertex: Bottom Jets Identification

The identification of B-hadrons in jets was fundamental for the discovery of the top quark in 1995 and is one of the crucial features of the searches for SM light Higgs boson at the Tevatron collider. Jets carrying b-flavour (b-jets) are produced from b-quark hadronization in top or Higgs decays, while mostly light-quark jets are produced from the main background processes (e.g. W +jets), which contaminate the candidate event data sample. Several methods to identify b-jets exist at CDF. They take advantage of the long proper lifetime of the B-hadrons³, which, together with a large relativistic boost, can fly several millimeters before decaying. Therefore, the vertex where the decay products originate may be displaced enough to be distinguishable from the primary one. We will describe the b-tagger used in this analysis, the *bness*.

4.4.1 Jet-*bness*

In the analysis described in this thesis the *b*-tagger employed is the *bness*, which is a multivariate, neural network (NN) based tagger. It provides an output value which serves as a figure of merit to indicate how *b*-like a jet appears to be.

What distinguishes this tagger from other multivariate taggers used at CDF is its emphasis on studying individual tracks for characteristics indicating they may have come from a *B*-hadron decay. This is done by implementing a *track-by-track* NN, whose output is fed into the final *jet-by-jet* NN.

track-by-track NN

A NN output is assigned to each track within a jet as a figure of merit to indicate how likely the track appears to be associated to a *B*-hadron decay product. Only tracks with $p_T > 0.4$ GeV are considered. Within a pool of investigated variables in simulations, those with the largest discrimination power were selected.

The track observables used to train this NN are

- p_T
- P_{perp} , momentum perpendicular to the jet axis
- rapidity with respect to the jet axis
- d_0 and σ_{d_0}
- z_0 and σ_{z_0}
- parent jet E_T

³The B^0 has a proper life time of 1.5 ps ($c\tau = 476\mu\text{m}$). The average transverse momentum of a B-hadron coming from a WZ event is about 40 GeV/c. A B^0 meson has typically $\beta\gamma = 7.6$ and the average decay length is 3.5 mm

Note that the choice of the observables in the track NN reflect the fact that tracks from B -hadron decay products will tend to have higher momentum and be more collinear with the jet than other tracks, and also have a larger impact parameter relative to the primary vertex.

The parent jet E_T is used as an input as distributions of B vs. non- B track observables may change depending on the jet's E_T . However, when the training was performed a weighting was applied such that the parent jet E_T distributions were the same both for B and non- B tracks: this was to ensure that application of the tagger wouldn't introduce a kinematic bias. The same weighting is applied to the jet-by-jet NN. In Fig. 4.7 the input observables for the track NN are shown.

Figure 4.7: Comparisons of track observables input into the track NN, for tracks from B -hadron decays vs. tracks not from B -hadron decays.

jet-by-jet NN

The NN trained to identify b -jets uses as input the following variables:

- top five highest track's $bness$
- number of tracks with $bness > 0$
- invariant mass of tracks with $bness > 0$
- $\sigma_{L_{xy}}$
- number of K_S candidate in the jet cone
- muon likelihood

Here, not only individual track $bness$, but also the multiplicity and invariant mass of high- $bness$ tracks are used as inputs into the NN to evaluate the jet $bness$.

Furthermore L_{xy} , the displaced vertex significance, is calculated by taking all tracks with a $bness > -0.5$, and removing the lowest- $bness$ tracks in the set until the fit for a secondary vertex is returned with a $\chi^2 < 50$.

Two other input variables are: the number of candidate K_S or Λ particles in the jet and the highest-likelihood muon candidate in the jet [33].

In Fig. 4.8 the input variables of the jet b ness for jets matched to b -hadrons⁴ and the other jets are compared.

Finally, in Fig. 4.9 we see the jet b ness output for jets matched to b quarks versus the other jets. The difference between the two distributions is evident.

Figure 4.8: Comparisons of jet observables input into the jet NN, for jets including B -hadron decays (red) vs. jets without B -hadron decays (black).

b ness-Tagger Validation

In order to verify that jet- b ness response is similar in data (collected with high- p_T lepton triggers) and MC, $t\bar{t} \rightarrow \text{leptons} + \text{jets}$ and $Z \rightarrow \ell\ell + 1 \text{ jet}$ selections are compared. The former offers a comparison of jets in a b -enhanced region (b -jets are about 50% of the total), while the latter compares jets that largely do not originate from bottom quarks. These studies are described in [36].

⁴a $dR < 0.4$ is required in order to consider a B -hadron matched to a jet.

Figure 4.9: Jet $bness$ distribution from our electroweak MC, for jets matched to b quarks (red) vs. jets not matched to b quarks (black). This distribution represents the probability for a jet to be b -like depending on the $bness$ value, that can be chosen in a range $[-1(b\text{-jets}), 1(\text{light flavour-jets})]$

Chapter 5

Composition and Modeling of the Selected Data Sample

5.1 Event selection

Our final goal will be to observe the associated production of W and Z bosons in the $WZ \rightarrow l\nu jj$ final state. We use the whole collected dataset up to period 38¹. The selected range of data, from run 150145 to 312510, has an integrated luminosity of about $8.9/fb$. In order to improve the sensitivity of the measurement, the whole data sample (**pretag** sample²) is divided in four subsamples that are studied separately. The division is based on the following characteristics:

- **jet flavour**: using the jet bness as b -flavor jet tagger, we isolate a sample with two b -jets in the final state (the **tag** region) from the one highly dominated by light flavor jets (the **notag** region)³. The **tag** region is the golden channel for the light SM Higgs boson search at Tevatron $WH \rightarrow l\nu b\bar{b}$.
- **number of jets**: we accept events with 2 or 3 jets in the final state.

The definition of the four regions depending on the jet flavor and the number of jets is given below.

- **2 jets**: exclusively 2 jets with $E_T > 25$ GeV, $|\eta| < 2$
- if additional jets exist, they must have $E_T < 15$ GeV or $|\eta| > 2$
 1. **2 jets - tag**: $jet1\ bness > 0.75$, $jet2\ bness > -0.2$, jet1,2 being respectively the highest and second highest-bness jets
 2. **2 jets - notag**: in order to ensure the orthogonality of the regions, we remove region 1 from the 2 jets selected sample.

¹Note for CDF internal use: We use reprocessed periods 18-38 with silicon clustering scheme 6.1.6.p+

²Pretag sample is the one where no constraints on jets flavor are applied

³in the notag regions jets are ordered in decreasing E_T , while in the tag regions where heavy flavor jets (HF) dominate, jets are ordered in decreasing bness.

- **3 jets:** exclusively 3 jets. Two jets with $E_T > 25, 15$ GeV, $|\eta| < 2$, the third jet with $E_T > 15$ GeV, $|\eta| < 3.6$
- if additional jets exist, they must have $E_T < 10$ GeV or $|\eta| > 3.6$
 1. **3 jets - tag:** $jet1 \text{ bness} > 0.75$, $jet2 \text{ bness} > -0.2^3$, jet1,2 being respectively the highest and second highest bness jets
 2. **3jets - notag:** we remove the above region from the sample.

Moreover, we further divide the sample depending on the used triggered or triggered lepton ⁴. The following lepton types are investigated separately:

- TCE, CMUP, CMX
- PHX
- EMC

Depending on the highest- E_T lepton type, the following QCD vetoes are applied:

- CMUP, CMX: $M_T^W > 10$ GeV
- TCE: $M_T^W > 30$ GeV, $\text{metsig}^5 > 1.8$
- PHX: $M_T^W > 30$ GeV, $\text{metsig} > 2.2$, $\cancel{E}_T > 25$ GeV
- CMU, CMP, CMIOPEs: $M_T^W > 10$ GeV
- CMIOCES: $M_T^W > 10$ GeV, $\delta\phi(jet2, \cancel{E}_T) > 0.3$
- CRKTRK: $M_T^W > 20$ GeV, $\delta\phi(jet2, \cancel{E}_T) > 0.3$

For EMC leptons we further require the trigger-based selection cuts described in Sec. 5.3.2. The invariant mass distributions in the notag and tag samples will be fitted separately and the results will be combined in order to extract the signal.

Leptons First, high p_T electrons and muons are identified. The trigger requires an electron or a muon with $E_T > 18$ GeV. The basic lepton selection cuts applied at trigger level still accept a large number of fake leptons. Offline *good* leptons satisfying some quality criteria are identified in order to purify the sample, making it easier to be modeled and to estimate the background contribution. We require the presence of at least one of the lepton categories listed in Sec. 5.2. Such a lepton must have $E_T > 20$ GeV (electron) or $P_T > 20$ GeV/c (muons). These selection cuts were optimized to enhance the WZ signal over the overwhelming background processes. However, as mentioned before, a ZZ event can be accepted in our sample since a lepton can be missed by the detector (in that case the leptonically decaying Z is equivalent to a W). To consider also ZZ as our signal, we allow for more than one good lepton per event. This increases the number of events by about 5% for the electron sample and by 18% for the muon sample, albeit at the expense

⁴the high- $\cancel{E}_T$ triggered data is characterized by an hadronic invariant mass which differ from the high- P_T triggered data. This is due to the trigger requirements. On the other side, the sample with a PHX lepton is characterized by a larger QCD contamination

⁵See Eq. 5.2 [37]

Variable	Requirement
E_T (TCE, CMUP, CMX, PHX, EMC)	≥ 20 GeV
$\cancel{E}_T$	≥ 20 GeV
M_T^W (CMUP, CMX, CMU, CMP, CMIOPEs, CMIOCES)	≥ 10 GeV
M_T^W (CRKTRK)	≥ 20 GeV
M_T^W (TCE, PHX)	≥ 30 GeV
metsig (TCE, PHX)	≥ 1.8
number of jets	$= 2$
E_T J1	≥ 25 GeV
E_T J2	≥ 25 GeV
$ \eta $ J1	≤ 2
$ \eta $ J2	≤ 2
b -ness J1 if tag	≥ 0.75
b -ness J2 if tag	≥ -0.2
b -ness J1 if notag	< 0.75
b -ness J2 if notag	< -0.2
number of jets	$= 3$
E_T J1	≥ 25 GeV
E_T J2	≥ 15 GeV
E_T J3	≥ 15 GeV
$ \eta $ J1	≤ 2
$ \eta $ J2	≤ 2
$ \eta $ J3	≤ 3.6
b -ness J1 if tag	≥ 0.75
b -ness J2 if tag	≥ -0.2
b -ness J1 if notag	< 0.75
b -ness J2 if notag	< -0.2

Table 5.1: Summary of the cuts defining the candidate events samples.

of some degradation in resolution. This is due to the fact that, requiring two leptons, $\cancel{E}_T$ comes completely from a jet energy mis-measurement. Since we have required $\cancel{E}_T > 20$ GeV, we accept only events in which the mis-measurement is large. The dijet mass resolution is more degraded in the electron sample than in the muon one, because of the more restrictive requirement on the transverse energy for electrons.

Missing Transverse Energy In order to compute the transverse mass of the W we need also the missing transverse energy to account for the non interacting neutrino. $\cancel{E}_T$, corrected for the presence of muons and with jet corrections up to L5 ⁶, is required to be larger than 20 GeV. With this cut the multijet background is reduced by 75% while the signal only by 15%.

⁶All jets stored in the Stntuples are used. However, it should be noticed that jet energy corrections are not applied to jets with raw $E_T < 8$ GeV

Transverse Mass From the $\cancel{E}_T$ and the lepton we reconstruct the transverse mass of the W candidate ⁷.

$$M_T^W = \sqrt{2 \cdot E_T^L \cdot \cancel{E}_T \cdot (1 - \cos \Delta\phi_{l\nu})} \quad (5.1)$$

In Fig. 5.1 5.2 are shown M_T^W distributions for electrons and muons, after the offline lepton selection. We observe that while the distributions peak approximately at the W mass as expected for W events, there is a large tail at low mass due mainly to QCD background where the $\cancel{E}_T$ is a fake. The tail at low M_T^W values is more enhanced for electrons, corresponding to a larger fraction of QCD events since it is easier for a jet to fake an electron than a muon. For these reasons, the transverse mass of the W is required to satisfy $M_T^W \geq 30 \text{ GeV}/c^2$ for electrons and $M_T^W \geq 10 \text{ GeV}/c^2$ for muons.

Figure 5.1: M_T^W distributions for electrons.

metsig We define **metsig** as:

$$\text{metsig} = (-\log_{10}(P(\cancel{E}_T^{fluc} \geq \cancel{E}_T))) \quad (5.2)$$

where P is the probability and $\cancel{E}_T^{fluc}$ is the expected missing transverse energy arisen from fluctuations in the energy measurements [37]. In order to reduce the QCD background in the electron data sample, a cut in **metsig** has been optimized in terms of the signal over background S/B ratio. Cutting on **metsig** allows us to reduce by about 50% the QCD fraction in the sample while the signal is reduced only by 7%⁸.

⁷The event is not longitudinally balanced, because the momenta of the partons inside the colliding protons are unknown.

⁸This estimation has been done after cuts on $\cancel{E}_T$ and M_T^W were applied.

Figure 5.2: M_T^W distributions for muons.

Jets The offline event selection identifies jets clustered by JETCLU, described in Sec. 4.3.1 with a cone radius of 0.4. Their energy is corrected for detector inefficiencies and physics effects (L9 jet corrections ?? are used). The final fit will use separately the two and three jets regions in both notag and tag samples. We look for two jets with $E_T > 15\text{GeV}$ and $|\eta| < 2$. In the two jets study we exclude events in which a third jet with $E_T > 15\text{GeV}$ is found in this rapidity range. For the three jets studies, we allow for a third jet with $E_T > 10\text{GeV}$ and $|\eta| < 3.6$, and we accept events in which only three jets are found. In order to select the tag sample we require the two leading jets to have $b_{\text{ness}} > 0.75, -0.2$ respectively. These cuts have been optimized against the sensitivity of the measurement, and are the same for the two jets region and three jets region studies [45]. Consequently we require in notag sample the two leading jets to not satisfy both the conditions for the tag sample, i.e. $b_{\text{ness}} > 0.75, -0.2$ respectively, in order to separate from each other tag and notag samples. Later in this thesis we will refer to the two leading jets as the

- E_T -highest jets in the notag sample
- b_{ness} -highest jets in the tag sample

5.2 Trigger Paths Accepted

The search WZ/ZZ exploits the leptonic decays of the weak vector bosons, which ensure a cleaner experimented signature. Therefore, the trigger paths which select events with a high p_T electron or muon are the most suitable to carry on the search. We select events with a signature of one or more charged leptons, large transverse missing E_T and exactly two or three jets. Considered leptons are listed in below. They are defined and fully described in Sec.4.2.2.

- TCE
- CMUP
- CMX

- PHX
- Extended muon coverage - "EMC" $\equiv$ {CMU, CMP, CMIOCES, CMIOPEs, CRKTRK}

We use the dedicated *high- p_T* lepton triggered data streams (*bhel, bhmu*), the high- $\cancel{E}_T$ data stream (*emet*), and *high- p_T* plug trigger. For each lepton category we further accept the trigger paths presented in Table 5.2. Some of them will be fully described in Appendix C.

Lepton	Trigger
TCE	ELECTRON_CENTRAL_18
CMUP	MUON_CMUP, MUON_CMUP_L2_PT15,
CMX	MUON_CMX18, MUON_CMX18_L2_PT15, MUON_CMX18_L2_PT15_LUMI_200, MUON_CMX18_LUMI_250, MUON_CMX18_DPS
PHX	METPEM
EMC	MET35_&_TWO_JETS, MET35_&_CJET_&_JET, MET35_&_CJET_&_JET_LUMI_190, MET35_&_CJET_&_JET_DPS, MET35_&_CJET25_&_JET10, MET35_&_CJET25_&_JET10_LUMI_265, MET35_&_CJET_&_JET10_DPS MET_DIJET

Table 5.2: Trigger path(s) for each lepton category. Data-taking CDF periods are listed with increasing order numbers. In black trigger paths used over the whole datasets, in red trigger paths used for periods up to 14, in blue trigger paths used from period 15 to 38.

5.3 Modeling of the Triggers in High- E_T Data Stream

In this section we describe the trigger paths required while analyzing the *emet* data stream (Table 5.2): we call MET2J triggers highlighted in red and METDI the one highlighted in blue for simplicity.

As the name suggests, MET2J fires if there is a large missing transverse energy in the event as well as two jets. Except for the first version of this trigger (MET35_&_TWO_JETS), at least one jet is required to be central

Also METDI requires large missing transverse energy and two jets. This trigger was designed for Higgs boson searches and is therefore more efficient than MET2J. It was implemented during period 15 and it was never prescaled.

In order to keep things simple we require the MET2J trigger paths for data periods up to 14 and the METDI trigger paths from period 15 to 38.

5.3.1 Variable for Trigger Parameterization

We parameterize the trigger efficiency turnon curves as a function of the missing transverse energy. We need the offline $\cancel{E}_T$ to be as close as possible to the trigger $\cancel{E}_T$. The natural choice would be the uncorrected $\cancel{E}_T$, but such a variable is not well modelled in our MC. A better modeling is observed when the $\cancel{E}_T$ is recalculated by using the z position of the primary interaction vertex and jet corrections are applied. This variable, which we call "jetcorrmet", can be thought as the transverse energy of the W -boson candidate.

5.3.2 Trigger-based Jet Selection Cuts

Since we want to model the trigger efficiency curves with only `jetcorrmet`, we have to make sure that the curve parameterization doesn't depend on any other quantities (e.g jet energy). This is needed in order to prove that we use specific offline jet requirements which ensure to be away from any trigger biases. Those cuts are reported below

- MET2J: Both jets with $E_T > 25 \text{ GeV}$, $\Delta R(\text{jet1}, \text{jet2}) > 0.9$, at least one jet with $|\eta^{\text{det}}| < 0.9$.
- METDI: Both jets with $E_T > 25 \text{ GeV}$ and at least one jet with $E_T > 40 \text{ GeV}$

These cuts are imposed since

- MET2J requires at level 2 to have exclusively 1 jet with $E_T^{\text{jet}} > 20 \text{ GeV}$ and $|\eta| < 1.1$, and at least 2 jets with $E_T^{\text{jet}} > 15 \text{ GeV}$ and $|\eta| < 3.6$
- METDI requires at level 1 one tower with transverse energy more than 10 GeV

5.3.3 Trigger Parameterization

Since we will be using the trigger parameterization for lepton categories which are mostly muons, we use the `bhmu` to decide such a parameterization. Events are selected as follows:

- at least a muon (CMU, CMP, CMUP, CMX) with $P_T > 20 \text{ GeV}$
- exclusively 2 jets
- $M_T^W > 10 \text{ GeV}$
- Trigger-based jet cuts described in Sec. 5.3.2

Turnon efficiency curves and their parameterization is shown in Fig. 5.3.

5.4 Sample Composition

The study presented in this thesis is a contribution to a search for the associated production of W(Z) and Z bosons, where the primary W(Z) boson decays leptonically and the associated Z boson decays into two quarks that hadronize into jets. Also the ZZ contribution is included in our signal, since even if Z boson decays into two charged leptons, a lepton can escape detection and fake large $\cancel{E}_T$ as in W decay.

Several other processes can simulate the same signature, primarily W(Z) events with associated hadron jets, or jet-only events where a jet fakes a lepton and jet mismeasurements fake large $\cancel{E}_T$. Our data sample has a large contamination of different backgrounds. Online and offline selections are tuned in order to improve the signal over background ratio. **W+jets**, i.e. the production of a W boson in association with multiple high p_T jets, is the main background in the notag sample. The production of multiple jets in association with a Z boson (**Z+jets**) is second in importance. In Fig. 5.4 5.5 are shown some lowest order Feynman diagrams for these processes. **Top** quarks are produced mostly in pairs at the Tevatron (Fig. 5.6), though single top quark production is also possible with a factor of ~ 3 lower cross section. Single top quarks are produced through two electroweak processes: a charged current interaction generates a top quark and a bottom quark (s-channel Fig. 5.7) or a virtual W interacts with a b-quark in the proton sea to produce a top quark (t-channel Fig. 5.8). Top production processes may have final states very similar to the

Figure 5.3: Turnon efficiency curve parameterizations for MET2J (up) and METDI (lower plot) triggers. Period<15 and Period $\geq$ 15 data were fitted by using $\frac{c}{1+e^{\frac{a-jetcorrected}{b}}}$, a , b , c being free parameters of the fit.

WZ MC distributions are shown before (black histogram) and after the convolution with the trigger turnon parameterization (red histogram) to get of the effects due to the trigger requirements.

diboson signal, with a leptonically decaying W and two detected jets. Since top production is characterized by b -jets in the final state we expect it to give a more significant background in the tag sample. Because of the extremely large cross section of **QCD** multijet events even rare mismeasured events can contaminate the sample significantly (Fig. 5.9). Signal signature can be faked by a jet passing all lepton cuts and simultaneously the energies are so poorly measured that a large missing transverse energy is found.

The low probability for a jet to fake a lepton would require to generate a huge MC sample in order to simulate the effect. Moreover, one would have to be very confident in details of the detector simulation. Since it would be highly unreliable to simulate this background with MC studies, a data driven technique has been used to compute it.

Figure 5.4: Feynman diagram for W +jets production

Figure 5.5: Feynman diagram for Z +jets production

Figure 5.6: Feynman diagram for top-antitop pair production

Figure 5.7: Feynman diagram for single top s-channel production

Figure 5.8: Feynman diagram for single top t-channel production

Figure 5.9: Feynman diagram for QCD multijet production

5.5 Signal and Background Content Estimate

To model the selected sample we use both Pythia and Alpgen+Pythia MC. The dominant W +jets background is modeled by using Alpgen+Pythia samples. We estimate the expected composition of the selected sample in a sequence of steps by using a method which is similar (at least in the first steps) to Method2, which is used in many physics analyses at CDF looking at a signature of $W + 2jets$ with heavy flavour tagging [38]. One of the differences with Method2 is that rather than apply a simple renormalization of b and non- b jets in the Monte Carlo based on the calculated scale factors for the efficiency and mistag rate, we locate the equivalent cut in the Monte Carlo that matches the measured efficiency (for processes that have real b jets, like top backgrounds and our signal) and mistag rates (for processes without real b jets, like WW) in the data. In the same manner, we determine equivalent cuts on b ness in the Monte Carlo that match the $\pm 1\sigma$ uncertainty values on the mistag rate and efficiency. These values are summarized in Table 5.3. The method assumes that the following processes contribute to the selected data sample:

- **Electroweak and Top:** processes characterized by accurately predicted cross sections (see Sec. 5.5.1)
- **QCD:** multi-jet production associated to a hadron faking the lepton and $\cancel{E}_T$ ("fakes", see Sec. 5.5.2)
- **W +jets:** production of a W -boson associated to hadron jets (see Sec. 5.5.2)

The steps implemented by the method are the following:

1. The contribution of processes whose cross sections are well known is computed.
2. The contribution of QCD fakes and of W +jets is estimated with a data-based method.

In this way we avoid using the imprecise theoretical predictions for the production cross section of W -boson with associated jets [39].

5.5.1 Electroweak and Top Content

The electroweak (EW) and top processes contributing to the selected data sample are WW , WZ , ZZ , Z +jets, $t\bar{t}$, single- top . Each of these processes can produce signatures consistent with one or

Sample	bness cut in Data	Equivalent MC cut		
		-1σ	Central Value	1σ
Non b -jets	-0.2	-0.425	-0.33	-0.35
Non b -jets	0.75	0.65	0.68	0.72
b -jets	-0.2	-0.06	0.07	0.18
b -jets	0.75	0.79	0.825	0.86

Table 5.3: Equivalent bness cuts applied to MonteCarlo samples. These cuts are chosen to match the measured mistag rates and b -tag efficiency in data. The uncertainties on these cuts are determined using the calculated uncertainties on the mistag rates and tagging efficiencies ([35]).

more leptons, large $\cancel{E}_T$, and two jets, arising from correctly identified or mis-identified objects in the CDF detector. The contamination of each of the EW processes to the notag and tag samples is estimated as:

$$N_X^{pretag} = \sigma_{p\bar{p} \rightarrow X} \cdot A \cdot \int L dt \quad (5.3)$$

$$N_X^{tag} = \sigma_{p\bar{p} \rightarrow X} \cdot A \cdot \epsilon \cdot \int L dt \quad (5.4)$$

where

- $X = WW, WZ, ZZ, Z + jets, t\bar{t}, single - top$;
- $\sigma_{p\bar{p} \rightarrow X}$ is the theoretical cross-section for $p\bar{p} \rightarrow X$ (see Table 5.4);
- A is the MC-derived acceptance in the pretag sample;
- ϵ is the tagged selection efficiency estimated as the number of events in the tag sample divided by the number of events in the notag sample.

In Table 5.6 we report the number of expected EW and top events in the notag and tag selected data samples.

Process	Cross-Section (pb)
WZ	3.96 ± 0.06
WW	12.4 ± 0.25
ZZ	1.58 ± 0.05
$t\bar{t}$	7.04 ± 0.8
$single - top$	
t -channel	1.98 ± 0.08
s -channel	0.88 ± 0.05
$Z + jets$	787.4 ± 50

Table 5.4: Theoretical cross sections for Electroweak and Top processes ($M_t = 172.5 \text{ GeV}/c^2$) [46].

5.5.2 QCD and $W + jets$ Content

In this section we present a method to estimate the contamination of the QCD and $W + jets$ in the selected pretag and tag samples.

QCD

The background from QCD multi-jet production arises when a jet is mis-identified as a lepton, and jet energy mis-measurements fake a large missing transverse energy. A particular problem is the multi-jet production where some of the jets are originated by b -quarks. In this case the semileptonic decays of b -hadrons produce electrons or muons, and neutrinos, altogether faking the signature of W 's.

To model the QCD background in the selected samples we use data samples selected as described in Sec. 5.1, except for the identification cuts on the primary lepton. Some of these identification cuts are inverted to ensure that the QCD samples are orthogonal and at the same time kinematically close to the samples that we want to model. In Table 5.5 we list the lepton types used for modeling the QCD contamination in the sample. For brevity we will often assign the names of these leptons to the QCD templates/models themselves.

lep1 type	QCD model
TCE	Anti-TCE
CMUP,CMX	Non-isolated CMUP,CMX
PHX	Anti-PHX
EMC	Non-isolated EMC

Table 5.5: QCD models used per each lep1 type. Non-isolated means that $Isolation > 0.1$. Further info can be found in [38]

W+jets

Due to the presence of real leptons and neutrinos, the $W + jets$ background is the hardest to be reduced.

Estimation of QCD and $W + jets$ Content - $\cancel{E}_T$ Fit

Depending on lep1 type we perform a fit of the $\cancel{E}_T/M_T^W$ distributions in the notag and tag data samples in order to obtain the expected rates of QCD and $W + jets$ events in those samples. We allow for events with $metsig < 1.8$ for lep1=TCE, $M_T^W < 10$ for lep1=CMUP,CMX,EMC, and $\cancel{E}_T < 25$ for lep1=PHX in order to perform the fit. Three templates are used for the fit:

1. EW: MC-based template built by using EW selected events. The normalization of this template is constrained to the content reported in table 5.6 (notag sample) or 5.7 (tag sample)
2. $W + jets$: MC-based template built by using $W + jets$ selected events. The normalization of this template is a free parameter of the fit.
3. QCD:
 - > **Notag samples**: data-based template built by using the models described in Sec. 5.5.2.
 - > **Tag samples**: we measure in data the tag rate in bins of $\cancel{E}_T$ (lep1=TCE,PHX) or M_T^W (CMUP,CMX,EMC), and we use this rate to weight the pretag QCD template. The resulting distribution is used as the QCD template in the tag sample⁹.

⁹The requirements on the b -flavour content of the jets (b -ness cuts) drastically reduce the number of events of

The expected number of QCD and W +jets events in the pretag and tag samples (2/3 jets) along with rates for other backgrounds and signal are reported in table 5.6 - 5.8.

Process	Rate (TCE)	Rate (CMUP,CMX)	Rate (PHX)	Rate (EMC)	Rate (All)
Signal	133.6 ± 1.3	132.8 ± 1.3	59.7 ± 0.8	64.9 ± 0.6	390.9 ± 2.2
WW	814.8 ± 4.9	617.4 ± 3.9	300.6 ± 3	380 ± 8.7	2112.8 ± 7.5
tt	262.9 ± 1.5	213.1 ± 1.3	55.7 ± 0.7	150.6 ± 1	682.2 ± 2.3
single-top	124.2 ± 0.6	102.4 ± 0.5	29.6 ± 0.3	75 ± 0.1	331.3 ± 0.9
Zjets	541.4 ± 5.2	1707.1 ± 6.9	108.1 ± 2.7	685.2 ± 14.8	3041.8 ± 9.8
Wjets	17461.2 ± 73.9	13291 ± 56.9	9208.7 ± 58.5	6865.2 ± 1538.3	46826.1 ± 116.845
QCD	1606.9 ± 65.4	137.3 ± 3.1	1758.6 ± 89.4	129.2 ± 8.7	3632.0 ± 110.9
Data	20945 ± 144.7	16201 ± 127.3	11521 ± 107.3	8350 ± 8350	57017 ± 238.782

Table 5.6: Predicted and observed number of events of the notag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the $\cancel{E}_T$ -fit in data (Sec. 5.5.2). The expected rates are separated according to the triggered lepton type. We also require the invariant mass of the two E_T -leading jets to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region.

Process	Rate (TCE)	Rate (CMUP,CMX)	Rate (PHX)	Rate (EMC)	Rate (All)
Signal	9.3 ± 0.4	8 ± 0.3	4.2 ± 0.2	3.2 ± 0.2	24.7 ± 0.6
WW	6.4 ± 0.5	4.2 ± 0.3	2.2 ± 0.3	1.6 ± 0.2	14.4 ± 0.6
tt	132.8 ± 1.1	108.2 ± 0.9	27.8 ± 0.5	50.7 ± 0.7	319.5 ± 0.9
single-top	30.6 ± 0.2	25.1 ± 0.2	6.1 ± 0.1	12.6 ± 0.2	74.4 ± 0.3
Zjets	10.2 ± 0.8	31.6 ± 1.1	1.9 ± 0.5	9.4 ± 0.8	53.1 ± 1.4
Wjets	221.7 ± 6.5	178.7 ± 5.3	62 ± 3.3	88.1 ± 6	550.5 ± 9.0
QCD	32.2 ± 0.5	5.2 ± 0	15.8 ± 0.6	8.4 ± 0.3	61.6 ± 0.3
Data	443 ± 21	361 ± 19	120 ± 11	174 ± 18.1	1098 ± 24.9

Table 5.7: Predicted and observed number of events of the tag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the $\cancel{E}_T$ -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type.

5.6 Tag 2 Jets Modeling

Once the background levels are predicted, we want to investigate the agreement between data and MC of various kinematic distributions. Before doing that, we need to apply another correction to the MC to take into account the different luminosity profiles with respect to the data. A quantity directly related to the instantaneous luminosity is the number of reconstructed vertices. We deal with the observed different luminosity profile between data and MC by reweighting the MC events. We then compare a number of observables (see Figs. 6.9 - 6.15) in data and simulated events in

the data-based QCD template, thus making it impossible to build a reasonable QCD template directly in the tag sample. It is demonstrated that the b -ness cuts do not change the shape of the templates, making our procedure applicable.

Process	Rate (TCE)	Rate (CMUP,CMX)	Rate (PHX)	Rate (EMC)	Rate (All)
Signal	79.3 ± 1.1	80.7 ± 1	34 ± 0.7	35.8 ± 0.3	229.8 ± 1.7
WW	465.5 ± 3.7	360.9 ± 3	169.3 ± 2.3	204.3 ± 4.6	1200.0 ± 5.7
tt	348.3 ± 1.7	292.1 ± 1.4	72 ± 0.8	212.8 ± 1.3	925.1 ± 2.6
single-top	79.6 ± 0.5	64.3 ± 0.4	18.9 ± 0.2	40.9 ± 0.1	203.7 ± 0.7
Zjets	416.8 ± 4	1375.6 ± 5.7	94.9 ± 2.3	479.7 ± 7.7	2366.9 ± 7.8
Wjets	13857.4 ± 48.1	10456.6 ± 35.4	7275.8 ± 38.7	4510.7 ± 445.7	36100.5 ± 74.2
QCD	1657.2 ± 62.7	162.8 ± 3.5	2355.2 ± 96.8	72.3 ± 3.3	4247.4 ± 115.4
Data	16904 ± 130	12793 ± 113.1	10020 ± 100.1	5436 ± 5436	45153.0 ± 212.5

Table 5.8: Predicted and observed number of events of the notag 3jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the E_T -fit in data (Sec. 5.5.2). The expected rates are separated according to the triggered lepton type. We also require the invariant mass of the two E_T -leading jets to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region.

Process	Rate (TCE)	Rate (CMUP,CMX)	Rate (PHX)	Rate (EMC)	Rate (All)
Signal	4.8 ± 0.3	4.7 ± 0.3	2 ± 0.2	0.9 ± 0	12.5 ± 0.4
WW	7.5 ± 0.5	4.9 ± 0.4	2.7 ± 0.3	1.1 ± 0	16.5 ± 0.7
tt	168.9 ± 1.3	142.7 ± 1.1	32.2 ± 0.6	44.4 ± 0.3	388.2 ± 1.8
single-top	28.2 ± 0.3	22.9 ± 0.2	5.8 ± 0.1	6.3 ± 0	63.2 ± 0.4
Zjets	9.7 ± 0.6	26.6 ± 0.9	1.4 ± 0.3	5.5 ± 0.1	43.1 ± 1.2
Wjets	167 ± 4.2	190.9 ± 4.4	82.6 ± 4.1	29.2 ± 1.5	469.7 ± 7.4
QCD	35 ± 0.3	0.3 ± 0	34.4 ± 0.6	2.5 ± 0	72.2 ± 0.7
Data	421 ± 20.5	393 ± 19.8	161 ± 12.7	90 ± 90	1065 ± 32.6

Table 5.9: Predicted and observed number of events of the tag 3jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the E_T -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type.

order to validate the MC, the QCD templates, and the expected rates. Since the aim of this thesis is to improve the sensitivity of the **tag 2 jets sample** developing a $t\bar{t}$ veto, we present plots of variables only in this subsample. in order to compare them before and after the application of the $t\bar{t}$ veto (see Sec. 6.4.3).

Figure 5.10: E_T^{lep1} in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right).

Figure 5.11: F_T in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right).

Figure 5.12: M_T^W in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP,CMX$ (upper right), PHX (lower left), EMC (lower right).

Figure 5.13: E_T^{jet1} in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right).

Figure 5.14: E_T^{jet2} in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right).

Figure 5.15: $\Delta R(jet1, jet2)$ in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right).

Figure 5.16: $M(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1} = \text{TCE}$ (upper left), CMUP, CMX (upper right), PHX (lower left), EMC (lower right).

Chapter 6

The $t\bar{t}$ Veto

In this chapter the development of a $t\bar{t}$ veto is described. The tool is developed in the tag 2 jets region presented in the previous chapter, where the $t\bar{t}$ production is one of the largest source of background. Background rejection is fundamental in the improving of the sensitivity of the measurement. The development of this and the study of other possible vetoes has been the core of my original thesis work

6.1 Motivation

As mentioned before, observing associated WZ(ZZ) production at the Tevatron in the channel $WZ(ZZ) \rightarrow l\nu b\bar{b}$ is extremely difficult. For such a measurement, the signal to background ratio is very poor. This is due primarily to the contribution of associated production of W and incoherent jets, but also to the contributions of other background sources. Since the sensitivity of a measurement improves with increasing the $Signal/\sqrt{Background}$ ratio, reducing the number of background events is important in order to maximize the sensitivity. In particular, for the search of WZ/ZZ production in events with lepton(s) plus jets plus missing transverse energy, the $t\bar{t}$ background is one of the largest background, when the two jets are required to be b-like (see Table 5.7).

6.2 The Preselection Cuts

First of all we analyze the composition of $t\bar{t}$ background. Since in the candidate sample one or more leptons were required, we expect a contribute mostly from the dileptonic and the lepton+jets $t\bar{t}$ decaying modes. Looking at the Fig. 6.1 it is clear that the largest part of the $t\bar{t}$ background comes from its dileptonic decay mode. We choosed a set of preselection cuts which would reject a significant number of $t\bar{t}$ background events by preserving the ZZ signal (with a Z decaying in two leptons). For the development of such a $t\bar{t}$ veto we require a central lepton (TCE, CMUP, CMX) as the first lepton. We then require a second lepton to be a central or a forward lepton (considering also PHX and EMC) with the same flavor of the first one and opposite charge.

We also require for the two leptons to have an invariant mass in the Z window. The Z window we choose is $[60,120]\text{GeV}/c^2$, optimized against sensitivity.

After the preselection we keep the 97% of the signal events rejecting the 36% of the $t\bar{t}$ background.

Figure 6.1: $t\bar{t}$ composition in the tag 2 jets sample.

6.3 The Neural Network Training

Neural Networks are more and more used in various fields for data analysis and classification, both by research and by commercial institutions. In particle physics they are used mainly for classification tasks, i.e. signal over background discrimination. NNs are non-linear statistical data modeling tools, used to model complex relationships between inputs and outputs or to find patterns in data [44]. A Neural Network is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information, using a connectionist approach to computation. The key element is the structure of the information processing system, which consists of an interconnected group of artificial neurons (this is why they are named networks), working in unison to solve specific problems. NNs learn to distinguish between two different samples by example. The examples must be selected carefully otherwise time may be wasted or even worse the network might be functioning incorrectly. The disadvantage is that finding the network how to solve the problem by itself, its operation can be unpredictable. Choosing the most representative data and performing an accurate training is fundamental to help the NN learning the structure of the data itself.

The MLP More than 50% of neural networks are *MultiLayer Perceptrons* (MLP). The MLP is a simple feed-forward network: signals flow forward from input through any hidden units, eventually reaching the output units. Such a structure has stable behavior. An example system has three layers, see Fig. 6.2 The first layer has input neurons, which send data via synapses to the second layer of neurons, and then via more synapses to the third layer of output neurons. The synapses store parameters called weights that manipulate the data in the calculations. Each neuron in any subsequent layer first computes a linear combination of the outputs of the previous layer. The output of the neuron is then function of that combination. More details about activation function and MLP methods are given in [34]

6.3.1 The $t\bar{t}$ Veto's NN

We trained a Neural Network (NN)[34] on the events that pass the preselection cuts. The NN has been trained using the MLP method choosing 10 variables that, apart for the jet dimass, give the best separation (Table 6.1) between signal and background. The NN combines kinematical information about the processes: we consider variables connected to the angles (dR , $d\Phi$, $d\eta$) between the reconstructed objects, and to the transverse energy and transverse momentum. Below

Figure 6.2: MLP with one hidden layer.

is the list of the variables used:

- jet_dimass: the invariant mass of the system of the two jets.
- Ht: the sum of the transverse energy of all the reconstructed object.
- dEta_lep1jet12: the difference in η between the reconstructed lepton and the system of the two jets.
- dijet_Pt: the transverse momentum of the system of the two jets.
- met: the missing transverse energy.
- lep1met_Pt: the transverse momentum of the system of the reconstructed lepton and the missing transverse energy.
- pt_imbalance_12: the sum of the two jets' transverse momenta minus the lepton transverse momentum and the missing transverse energy.
- lep1met_Mt: the transverse mass of the system of the reconstructed lepton and the missing transverse energy.
- Pt_lep1jet12: the transverse momentum of the system of the reconstructed lepton and the two jets.
- Pt_allLV: the transverse momentum of the system of all the reconstructed objects.

The variable's separation power¹ is summarized in Table 6.1. In Table 6.2 is shown the list of the input variables along with the “importance”² reported by the Toolkit for MultiVariate Data Analysis (TMVA), the ROOT package used in the training of the NN. In order to avoid background (W+jets, $t\bar{t}$, etc...) being sculpted later, the input variables are weighted. Weights applied are calculated such that the jet_dimass distribution in the signal sample and $t\bar{t}$ background sample

¹Separation s is defined as: $\langle s^2 \rangle = \int_{-\infty}^{+\infty} (S^2(x) - B^2(x)) / (S(x) + B(x)) dx$, where S stands for signal distribution, B stands for background distribution and x is a specific observable.

²Importance ranking is computed by counting the number of cuts made in each dimension. The variable with which the maximum number of cuts was performed is ranked highest.

Rank	Variable	Separation
1	Ht	$2.064e - 01$
2	lep1met_Mt	$1.998e - 01$
3	Pt_lep1jet12	$1.659e - 01$
4	Pt_allLV	$1.499e - 01$
5	met	$1.436e - 01$
6	pt_imbalance_12	$1.258e - 01$
7	dEta_lep1jet12	$1.236e - 01$
8	lep1met_Pt	$1.062e - 01$
9	dijet_Pt	$1.042e - 01$
10	jet_dimass	$2.033e - 02$

Table 6.1: List of input variables with their separation power between signal(WZ) and background ($t\bar{t}$) reported by TMVA.

Rank	Variable	Importance
1	lep1met_Mt	$1.131e + 02$
2	Ht	$5.634e + 01$
3	jet_dimass	$5.265e + 01$
4	Pt_allLV	$4.088e + 01$
5	lep1met_Pt	$1.806e + 01$
6	dijet_Pt	$1.717e + 01$
7	met	$6.452e + 00$
8	Pt_lep1jet12	$6.018e + 00$
9	dEta_lep1jet12	$3.911e + 00$
10	pt_imbalance_12	$1.820e + 00$

Table 6.2: List of input variables with their “importance” reported by TMVA.

become approximately the same. With this procedure we modify the rate of the background events, giving a higher weight to the events that with a two jets invariant mass comparable to the Z boson one. By doing this we will decorrelate the NN output from the numerical value of jet_dimass and make it sensitive only to the difference in kinematical distributions of the involved variables. After reweighting, we still use the jet_dimass to train our NN: even if there is no separation in this variable by construction, it is useful to make the NN create correlations between the other variables and the one that will be our final discriminant during the training process. In Fig. 6.3 the jet_dimass distributions before and after normalization in both subsamples are shown. The variables listed above are weighted accordingly and are used for training the Neural Network, using the MLP method. For the distributions of the variables after the reweighting in the signal and background samples see Appendix E. We choose for the NN an architecture with a sigmoid transfer function and one hidden layer with N+5 neurons. The test and the training sample are forced to have the same number of events (10000) for the signal and for the background.

We cut on the NN output (NNttbar_rej) at a value of 0.15 (NNttbar_rej > 0.15), optimized against sensitivity. After this cut we keep the 97% of the signal events that passed the preselection cuts rejecting the 47% of the $t\bar{t}$ background that passed the preselection cuts. The whole $t\bar{t}$ veto (preselection+NN) allows us to keep the 94% of the signal events rejecting the 60% of the $t\bar{t}$ background.

Figure 6.3: MJ1J2 distribution in the background sample before (upper left) and after (lower right) normalization. The same distribution in the signal sample before (upper right) and after (lower left) normalization.

Figure 6.4: The architecture chosen for the NN. The hidden layer with $N+5$ neurons is shown.

6.4 The NN Output Modeling

In order to investigate the agreement between data and MC of the NN output, we look at the distribution of this variable in both the pretag and tag regions. We use the pretag as a control region: due to the larger statistics, we can see better if the NN output is well modeled.

6.4.1 Pretag 2 Jets Region

In this section we compare the NN output distribution in data and simulation events in order to validate the MC, the QCD templates, and the expected rates in the notag sample. The agreement is satisfactory (Fig. 6.7).

Figure 6.5: The Receiver Operating Characteristic (ROC) curve. It is a plot of the signal rate against the background rate for the different possible cutpoints. ROC curve gives an estimate of the NN background rejection efficiency.

Figure 6.6: The Kolmogorov-Smirnov test for the NN. No overtraining.

6.4.2 Tag 2 Jets Region

In this section we plot the NN output in order to validate the MC, the QCD templates and the expected rate in the tag sample. $t\bar{t}$ background and signal are well separated (Fig. 6.8).

6.4.3 Distributions of a Number of Observables

We present the expected rates of a number of observables (see Figs. 6.9 - 6.15) in data and simulated events after the application of the whole $t\bar{t}$ veto.

6.5 The Sensitivity Estimate

In order to test the possible improvements introduced by the use of the $t\bar{t}$ veto, we estimate the $Signal/\sqrt{Background}$ ratio in the tag 2 jets region when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied. We repeat the same procedure

Process	Rate (TCE)	Rate (CMUP,CMX)	Rate (PHX)	Rate (EMC)	Rate (All)
Signal	8.5 ± 0.4	7.7 ± 0.3	4.1 ± 0.2	3.1 ± 0.2	23.4 ± 0.6
WW	5.5 ± 0.4	3.5 ± 0.3	2.1 ± 0.3	1.4 ± 0.2	12.5 ± 0.6
tt	34.8 ± 0.6	30.4 ± 0.5	9.3 ± 0.3	16.5 ± 0.3	91 ± 0.9
single-top	22.3 ± 0.2	18 ± 0.2	4.7 ± 0.1	8.5 ± 0.1	53.5 ± 0.3
Zjets	4.4 ± 0.6	22.6 ± 1	1.5 ± 0.7	7.1 ± 0.5	35.6 ± 1.4
Wjets	175.5 ± 6.3	134.5 ± 5	53.9 ± 3.4	59.1 ± 3.7	423 ± 9.0
QCD	25 ± 0.2	4.3 ± 0	8.4 ± 0.2	3.3 ± 0.1	41 ± 0.4
Data	276 ± 16.6	221 ± 14.9	84 ± 9.2	99 ± 9.9	680.0 ± 25.4

Table 6.3: Predicted and observed number of events of the tag 2jets sample selected according to the requirements described in Sec. 5.1. W +jets and QCD rates are estimated from the $\hat{F}_T$ -fit in data (Sec. 5.5.2). We also require the invariant mass of the two jets with the highest b -ness to be within $[30,310]$ GeV/ c^2 . By construction the overall expected rates are the same as the observed ones in each region. The expected rates are separated for different triggered lepton type. The $t\bar{t}$ veto is applied.

Figure 6.7: NN output distribution for electrons and muons in the notag region. The lower distribution shows the difference data-simulation.

Step	$Signal/\sqrt{Background}$ ratio
No $t\bar{t}$ veto	0.62
Preselection cuts	0.65
NN cut	0.70

Table 6.4: $Signal/\sqrt{Background}$ ratio calculated when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied.

giving a sensitivity estimate for each step.

Figure 6.8: NN output distribution for electrons and muons in the tag region. The lower distribution shows the difference data-simulation. The empty histogram shows the expected WZ+ZZ signal multiplied by 40.

6.5.1 The Test Statistic

In order to separate signal from background, typical CDF analyses use histograms of a number of observables in data events (discriminants). Various signal hypotheses may be tested, parameterized by mass, cross section, BR. Signals and background depend on a variety of parameters which may not be of primary interest but which are of use in the discriminant. Their values are useful in order to extract measurements of, or limits on, the parameters of interest, and uncertainty in their values usually results in reduced sensitivity in the measurement of the parameters of interest. The systematic errors on observables are parameterized in terms of these “nuisance” parameters.

Data must be compared to a model. The predictions of the model are uncertain because of the lack of precise knowledge of the nuisance parameters. If two models are being compared, a null hypothesis (background only) and a test hypothesis (signal + background), the uncertainties in the nuisance parameters can reduce the ability of the analysis to reject one of the hypotheses [40]. In addition, if a background histogram is allowed to float freely in a fit to match data in which a signal is actually present, the sensitivity for detecting the signal may be greatly reduced. This problem is encountered in our case in particular when handling the $W + jets$ background, whose normalization cannot reliably be obtained from theory.

In order to evaluate the significance of an experimental result, the data must be compared to the expectations of the two hypothesis being tested, by means of a “test statistic”. A test statistic is a single real number which is a function of the experimental outcome, and is chosen to maximize the separation between experimental outcomes expected when a signal is present and those expected when only the background contributes [41]. The likelihood ratio Q is defined as a

Figure 6.9: E_T^{lep1} in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.10: E_T in the tag 2 jets sample when lep1=TCE (upper left), CMUP, CMX (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.11: M_T^W in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.12: E_T^{jet1} in the tag 2 jets sample when $lep1=TCE$ (upper left), $CMUP, CMX$ (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.13: E_T^{jet2} in the tag 2 jets sample when lep1=TCE (upper left), CMUP,CMX (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.14: $\Delta R(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1} = \text{TCE}$ (upper left), CMUP, CMX (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

Figure 6.15: $M(\text{jet1}, \text{jet2})$ in the tag 2 jets sample when $\text{lep1} = \text{TCE}$ (upper left), CMUP, CMX (upper right), PHX (lower left), EMC (lower right). The lower distributions show the difference data-simulation.

ratio of probabilities P in the fit of the data sample:

$$Q = \frac{P(s+b)}{P(b)} \quad (6.1)$$

where s and b are the number of signal and background events respectively. The goal is to compute Q , the ratio of $P(s+b)$, defined as the probability of observing the data in the test hypothesis, to $P(b)$, the probability of observing the data in the null hypothesis. The accuracy in predicting Q is reduced if the background estimates in each hypothesis are poorly known. A MINUIT [42] fit is usually applied to the observed spectrum, assuming either the signal + background hypothesis or the background-only hypothesis and the consistency of the data with the fits is compared to see how well the two hypothesis agree with the data.

A χ^2 function is useful in comparing Poisson distributed data with a sum of contributions, each of which may have correlated and uncorrelated systematic uncertainties on rate and shape. A general χ^2 function is computed, which includes all known uncertainties of the contributions. Once the number of degrees of freedom is known one can estimate the goodness of the fit using the χ^2 value [43]. We use the χ^2 function to select one of the two hypotheses by taking the χ^2 difference under the two hypotheses. Computing a difference of χ^2 values for the two hypotheses H_1 and H_0 is equivalent to taking the logarithm of the likelihood ratio:

$$\Delta\chi^2 = \chi^2(H_1) - \chi^2(H_0) = -2 \ln Q \quad (6.2)$$

6.5.2 Sensitivity and Optimization

The `mclimit_csm.C` [41] code provides a mean of obtaining an estimate for the p-value and the probability for an experiment to indicate a signal equivalent to a 2σ or to a 3σ fluctuation (a “ 2σ and 3σ measurement”) by generating pseudo-experiments and constructing $\Delta\chi^2$ distributions for test and null hypotheses. To obtain acceptable accuracy, we generate about 100,000 pseudo-experiments. P2 σ and P3 σ are the probability of a 2σ (3σ) evidence assuming test hypothesis is true. They are computed as follows:

- we generate 100,000 PEs in the null hypothesis and we compute the value of $\Delta\chi^2_{2\sigma}$ ($\Delta\chi^2_{3\sigma}$) such that the probability to have $\Delta\chi^2 > \Delta\chi^2_{2\sigma}$ ($\Delta\chi^2_{3\sigma}$) is 2.3%, (0.13%)
- we generate 100,000 PEs in the test hypothesis and we compute the integral from $-\infty$ to $\Delta\chi^2_{2\sigma}$ ($\Delta\chi^2_{3\sigma}$) corresponding to P2 σ (P3 σ).

In order to quantify the significance of the signal, i.e. the level of agreement between the data and the diboson hypothesis the corresponding *p-value* is computed. The *p-value* represents the probability that the background fluctuates to a number of events equal or greater than the number of expected signal events.

- we generate 100,000 PEs in the test hypothesis and we compute the median of $\Delta\chi^2$ distribution as an estimator of the most probable outcome in real data.
- we generate 100,000 PEs in the null hypothesis and we compute the integral from $-\infty$ to the median of $\Delta\chi^2$ distribution of test hypothesis.

The integral of the resulting distribution that exceeds the median is used to obtain the *p-value*. For this preliminary estimate no systematics are considered.

6.5.3 Check on the Sensitivity Improvement

In this section the improvement in sensitivity due to the application of the $t\bar{t}$ veto is checked. We estimate the sensitivity in the tag 2 jets region when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied.

Step	P-value
No $t\bar{t}$ veto	0.805 ± 0.004
Preselection cuts	0.832 ± 0.004
NN cut	0.876 ± 0.005

Table 6.5: P-value estimate when no cuts are applied, when only preselection cuts are applied and when the whole $t\bar{t}$ veto is applied.

Figure 6.16: The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region, using MJ1J2 as the invariant mass, when no cuts are applied.

Figure 6.17: The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region, using MJ1J2 as the invariant mass, when preselection cuts are applied.

Figure 6.18: The $\Delta\chi^2$ distributions for null and test hypotheses for the fit to the WZ/ZZ signal in the tag 2 jets region, using MJ1J2 as the invariant mass, when the whole $t\bar{t}$ veto is applied.

Chapter 7

The Final Fit

The technique used to extract the diboson contribution is a fit of the dijet mass distribution to a combination of signal and backgrounds. This chapter presents the results on data. The systematic uncertainties included in the fit are discussed.

7.1 Fitting Procedure to the Z-Mass Distribution in the Tag 2 Jets Region

The WZ/ZZ signal is extracted performing a χ^2 of the Z-invariant mass distribution. χ^2 minimizations is performed with MINUIT. The `mclimit_csm.C` code [41] is used for this purpose. We optimized the fit range and number of bins upon the sensitivity of the measurement. The fit is performed in the $[30,310]$ GeV/c^2 range with 28 bins of $10 \text{ GeV}/c^2$ width, in the region with two b-tags (double-tag), where TCE, CMUP, CMX, PHX, and EMC leptons are merged together. Histograms for background and signal are imputed, as well as various systematics like rate and/or shape uncertainties. The *templates* used are :

- W +jets, whose normalization is unconstrained in the fit.
- $t\bar{t}$, single top and Z+jets (EWK), Gaussian-constrained to the theoretical/measured cross section with uncertainties of 6%.
- QCD, data driven estimate, Gaussian-constrained with a systematic uncertainty of 50%¹ in the no-tag channel and its statistical uncertainty in the two-tag channel (Sec. 5.5.2).
- WW is scaled to the NLO cross section, Gaussian-constrained with an uncertainty of 6%.
- WZ/ZZ signal, with normalization allowed to float unconstrained in the fit, but unlike the W +jets background, with rates constrained to the expected ratio between the two channels.

The templates are stacked together and superimposed to the data in Fig. 7.1

¹ 50% was obtained by fitting the data (Sec. 5.5.2) in different configurations (different fit ranges, fitted distributions, and selection cuts)

Figure 7.1: Dijet invariant mass in the tag2j region. Templates used for the signal extraction are shown in solid colors. The templates have been normalized to the expected rates. The data points (dots) are superimposed and differences between predictions and data are plotted in the lower pads

7.2 Systematic Uncertainties

Since this analysis relies heavily on MC simulation, a large number of systematic uncertainties must be considered when checking if data and MC are consistent. Two classes of systematics are considered, those affecting the signal extraction (i.e. the number of signal events estimated in our data samples) and those affecting the acceptance and therefore the signal cross-section.

7.2.1 Signal Extraction

We estimate the systematics on the signal extraction by generating pseudo-experiments (PE) using additional models, corresponding to upward or downward fluctuations of the nuisance parameter for each systematic source. The pseudo-experiments are then fitted using the templates of the main fit on data. For each PE nuisance parameters are varied within their uncertainty to get the best agreement between pseudo-data and fitted model. The difference between the central value of the fit on data and the mean of the estimator of the signal content on the two corresponding pseudo-experiments is taken as systematic uncertainty on the corresponding source. For the signal extraction we consider the following sources of systematic uncertainty:

- **Jet Energy Scale (JES):** the effect of the JES uncertainty on the measurement is estimated by varying the energy of all jets in MC samples by $\pm 1\sigma$, where σ is the p_T -dependent uncertainty curve shown in Fig. 4.6. This procedure is applied at the same time to all the MC based processes.
- **b-tagger efficiency/mistag rate:** to speed-up the calculation, rather than applying scale factors to the tagging efficiency and mistag rate in order to make simulations to agree with data, we locate the cut in the MC computed efficiency parameter at the value that matches the measured efficiency and mistag rates in the data. In the same manner, we determine the cuts on bness in the MC that match the $\pm 1\sigma$ uncertainty values in the mistag rate and efficiency. This method produce the same effective rescaling as varying the scale factors [48].
- **Renormalization and Factorization Scales in the W +jets MC (Q^2):** the ALPGEN event generator used for W +jets events requires renormalization and factorization scales of the Q^2 parameter to be chosen appropriately to account for the finite order perturbative calculations of cross sections and for the factorization approximation of structure functions and cross sections. Since the Q^2 values are not known, and indeed not physically measurable since they are an artifact of the theoretical approximation, an uncertainty is assigned to cover

a variety of different possibilities. As a default, the renormalization and factorization scales are set to be the same at $Q^2 = M_W^2 + \Sigma p_T^2$, where M_W is the W boson mass and p_T^2 is the parton transverse momentum squared. The sum extends over all final state partons [50]. This parameter is doubled and halved to create two samples which are used to determine the shape uncertainty on the W +jets template².

7.2.2 Cross Section Evaluation

In the cross section estimation we assumed that the luminosity, the lepton trigger efficiency and the MC computed acceptance were exact. All of these assumptions are later considered as sources of systematics that contribute to the uncertainty of the cross section measurement, in addition to the signal fraction extraction systematics.

- **Jet Energy Resolution (JER):** the modeling of the jet energy resolution (JER) can be a source of systematic uncertainty. It can affect the signal acceptance: if the dijet resonance is wider, more signal events may fall below the jet E_T thresholds or outside the dijet mass window used in the fit. The uncertainty in the jet energy resolution is found to vary as $\Delta(\sigma/p_T) = (0.03 \pm 1.7)/p_T$ [GeV/c] [51]. Smearing the dijet mass due to energy resolution results in a 0.7% uncertainty in the measured cross section.
- **ISR/FSR:** this systematic affects the acceptance of the MC events. The PYTHIA showering algorithm is found to describe satisfactorily the spectrum of ISR/FSR, but the amount of ISR/FSR depends on input parameters, including the momentum scale of the interaction and the value of Λ_{QCD} , the energy scale at which perturbative quantum chromodynamics becomes not reliable. A systematic uncertainty is applied to predicted yields to account for an incomplete knowledge of these parameters. The impact of this uncertainty is evaluated by generating new simulated samples for WW/WZ signal varying the parameters within a plausible range of values. We determine a 2.5% systematic uncertainty due to more/less ISR and FSR.
- **PDF:** the parton distribution functions (PDFs) used in generating the MC models are determined by fitting a large number of experimental results which are subject to errors. We determine the change in the signal acceptance due to the PDF uncertainty to be 2%.
- **Luminosity and trigger efficiency:** A 6% uncertainty on the cross section is assigned due to uncertainty in acceptance and efficiency of the CDF luminosity counters. Uncertainties due to trigger efficiencies are calculated by varying the trigger scale factors³ within their uncertainties and applying the shifted scale factors in MC weight. A variation of 2.2% in the number of the expected events is found.

7.3 Fit Results on Data

The result of the fit to the data is shown in Table 7.2. We fit for signal. In Fig. 7.2 we plot the templates stacked together and adjusted for fitted shape and rate systematic variations. The

²This method addresses the shape uncertainty only. Since the theoretical cross section of W +jets is only known to the lowest order in QCD and suffers from large uncertainties, its normalization is derived from data

³Trigger scale factors are chosen run-by-run and during data-taking, and are used to weight MC events according to the corresponding efficiency.

Systematic	Region	Signal	EWK	W + jets	QCD	WW
JES shape/rate	1	yes/ $\pm 2\%$	yes/ $\mp 4\%$	yes	no	yes/ $\pm 3\%$
	2	yes/ $\pm 2\%$	yes/ $\pm 11\%$	yes	no	yes/ $\pm 4\%$
bness cuts rate	2	$\pm 5\%$	$\pm 0\%$	$\pm 0\%$	no	$\pm 1\%$
		$\pm 4\%$	$\pm 0\%$	$\pm 0\%$		$\pm 1\%$
Q^2	1	$\mp 8\%$	$\mp 11\%$	$\pm 11\%$	no	$\mp 6\%$
		$\mp 10\%$	$\mp 12\%$	$\pm 12\%$		$\mp 21\%$
	1	no	no	yes	no	no
	2	no	no	yes	no	no

Table 7.1: List of considered systematic uncertainties for the Tag2j region for each template used in the fit

data distribution is superimposed. The evidence for a signal is small but it corresponds to a 10% increase in sensitivity because of the application of the $t\bar{t}$ veto.

Parameter	Fit value (in units of σ)
QCD	0.47 ± 0.98
EWK	0.24 ± 0.98
BNESS	-0.44 ± 0.92
JES	0.37 ± 0.78
Q2	-0.16 ± 0.56
WW	-0.02 ± 0.99
Parameter	Fit value (in units of %)
WJETSUNCONSTRAINED	0.97 ± 0.10
SIGUNCONSTRAINED	0.98 ± 0.99

Table 7.2: The result of the fit from mclimit. The result of the fit for the unconstrained parameters related to the $W + jets$ (*WJETSUNCONSTRAINED*) and signal (*SIGUNCONSTRAINED*) templates are given in terms of % of their expected values. We fit for signal. The fitted signal rate is 0.98 ± 0.99 . The other parameters are given in units of σ .

Figure 7.2: Result of the fit to the data. Fitted Z -invariant mass distributions in the Tag2j are superimposed to the data. Both shapes and rates have been adjusted to the results obtained in data. The lower plot shows the difference data-simulation, after allowing for the best-fit signal contribution (highlighted in color)

Chapter 8

Conclusion and Future Plans

A method was developed to reject the $t\bar{t}$ background in the search for a WZ/ZZ signal with two jets in the final state originating from b-quarks. The search for the associated production of W(Z) and Z boson is extremely important, especially in the lepton, neutrino and two b-like jets channel, since this is also the final state with the largest branching ratio in the associated production of a light Higgs boson with a W boson. The WH production has a cross section lower than the inclusive H production, but requiring a lepton and a neutrino in the final state from an associated W, it has a better signal over background ratio. Indeed, the WH analysis in this channel is the most sensitive one at CDF.

After a detailed review of the diboson analysis, we described the $t\bar{t}$ veto to be applied to the candidate data sample in order to reduce this particular background. The $t\bar{t}$ veto consists of a number of preselection cuts and of a multivariate discriminant. The application of the veto gives a 10% improvement in sensitivity. After its application we are able to extract 0.9 σ evidence for the signal, as shown in Tab. 7.2 and Fig. 7.2.

At this point in time, a method as developed for the $t\bar{t}$ background is being explored to signal the $W + jets$ background. Since this is the largest background, its reduction could give a very important improvement in sensitivity.

Bibliography

- [1] M. Peskin and D. Schroeder *An Introduction to Quantum Field Theory* Westview Press 1995.
- [2] S. L. Glashow *Partial Symmetries of Weak Interactions* Nucl. Phys. A 22 (1961) 579.
- [3] S. Weinberg *A Model of Leptons* Phys. Rev. Lett. 19 (1967) 1264
- [4] A. Salam *Elementary Particle Theory* ed. by N. Svartholm (Almqvist and Wiksells, Stockholm, 1968).
- [5] P. W. Higgs *Broken Symmetries, Massless Particles And Gauge Fields* Phys. Rev. Lett. 12 (1964) 132; *Broken Symmetries And The Masses Of Gauge Bosons* Phys. Rev. Lett. 13 (1964) 508.
- [6] K. Hagiwara et al. *Measuring the WW Z coupling at the Fermilab Tevatron* Phys. Rev. D 41, 2113 (1990)
- [7] The DØ Collaboration: *Production of WZ Events in $p\bar{p}$ Collisions at $s = 1.96$ TeV and Limits on Anomalous WWZ Couplings* Phys. Rev. Lett. 95, 141802 (2005)
- [8] The CDF Collaboration: *Observation of WZ Production* Phys. Rev. Lett. 98, 161801 (2007)
- [9] ZHllbb Group – J. Pilot, S. Lockwitz, S. Shalhout, H. Wolfe, B. Jayatilaka, B. Kilminster, R. Hughes, B. Winer, P. Tipton, R. Erbacher, J. Conway, A. Kotwal, M. Stancari, R. Harr *Search for the Standard Model Higgs Boson Produced in Association with a Z boson* CDF/PUB/EXOTIC/CDFR/10817.
- [10] C. M. Ginsburg, “Cdf run 2 muon system,” *The European Physical Journal C - Particles and Fields*, vol. 33, pp. s1002–s1004, 2004. 10.1140/epjcd/s2004-03-1795-6.
- [11] G. Ascoli et al., “Central Muon Level-1 Trigger Electronics,” FERMILAB-PUB-87-188-E.
- [12] D. Mohl, “Physics and technique of stochastic cooling,” *Phys. Reports*, vol. 58, 1980.
- [13] I. Vila, “Performance and First Physics Results of the SVT Trigger at CDF II,” *ArXiv High Energy Physics - Phenomenology e-prints*, jul 2003.
- [14] B. Ashmanskas, A. Barchiesi, A. Bardi, M. Bari, M. Baumgart, S. Belforte, J. Berryhill, M. Bogdan, R. Carosi, A. Cerri, G. Chlachidze, R. Culbertson, M. dell’Orso, S. Donati, I. Fiori, H. Frisch, S. Galeotti, P. Giannetti, V. Glagolev, A. Leger, Y. Liu, T. Maruyama, E. Meschi, L. Moneta, F. Morsani, T. Nakaya, G. Punzi, M. Rescigno, L. Ristori, H. Sanders, S. Sarkar, A. Semenov, M. Shochet, T. Speer, F. Spinella, H. Vataga, X. Wu, U. K. Yang, L. Zanello, and A. M. Zanetti, “The CDF Silicon Vertex Trigger,” *Nuclear Instruments and Methods in Physics Research A*, vol. 518, pp. 532–536, Feb. 2004.
- [15] T. Affolder et al., “CDF central outer tracker,” *Nucl. Instrum. Meth.*, vol. A526, pp. 249–299, 2004.
- [16] D. Acosta et al. (CDF Collaboration) *A Time-Of-Flight Detector in CDF II* Nucl. Instrum. Meth. A518 (2004) 605.
- [17] <http://www-cdf.fnal.gov/cdfsim/validation/cot/cotVal.html>.
- [18] R. Blair et al., “The CDF-II detector: Technical design report,” FERMILAB-DESIGN-1996-01.

-
- [19] P. Gatto, “Performance of the new tracking system at CDF II,” Master’s thesis, University of Padova, 2001.
 - [20] S. Menzemer, “A tracking and alignment software package for the CDF II silicon detector,” Master’s thesis, University of Karlsruhe, 2002.
 - [21] F. D. Snider, “Tracking at CDF: Algorithms and experience from Run I and Run II,” *Nuclear Instruments and Methods in Physics Research A*, vol. 566, pp. 133–141, Oct. 2006.
 - [22] Y. Fukuda et al. *Evidence for oscillation of atmospheric neutrinos* Phys. Rev. Lett. 81 (1998) 1562 1567.
 - [23] M. Maggiore *A Modern Introduction to Quantum Field Theory* Oxford University Press 2005.
 - [24] J. M. Campbell and R. K. Ellis *Update on Vector Boson Pair Production at Hadron Colliders* Phys. Rev. D **65** (2002) 113007.
 - [25] K. Nakamura et al. (Particle Data Group) J. Phys. G **37** (2010) 075021.
 - [26] J. M. Campbell and R. K. Ellis, *Update on vector boson pair production at hadron colliders*, Phys. Rev. D 60, 113006 (1999).
 - [27] The DØ Collaboration: *Production of WZ Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV and Limits on Anomalous WWZ Couplings*, Phys. Rev. Lett. 95, 141802 (2005)
 - [28] G.C. Blazey et al. *Run II Jet Physics* CDF Note 5293
 - [29] F. Abe et al. (CDF Collaboration) *The Topology of Three Jet Events in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV* Phys. Rev. D 45 (1992) 1448.
 - [30] A. Bhatti et al. (CDF Collaboration) *Determination of the Jet Energy Scale at the Collider Detector at Fermilab* Nucl. Instrum. Meth.A566 (2006) 375.
 - [31] Wesley Ketchum Vadim Rusu Marco Trovato *New Jet Energy Scale Corrections for Quarks and Gluons* CDF/ANAL/JET/CDFR/10829
 - [32] T. Sjostrand et al. *High-Energy-Physics Event Generation with PYTHIA 6.1* Comput. Phys. Commun. 135 (2001) 238.
 - [33] L. Cerrito, A. Taffard *A Soft Muon Tagger for Run II* CDF Note 7122
 - [34] A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, and H. Voss *TMVA - Toolkit for Multivariate Data Analysis* (2007) arXiv:physics/0703039
 - [35] . Freeman, W. Ketchum, S. Poprocki, S. Pronko, V. Rusu, and P. Wittich *Search for WZ/ZZ in MET + $b\bar{b}$ channel*, CDF Note 10631.
 - [36] ketchum, lewis, poprocki, freeman, pronko, rusu, wittich CDF/ANAL/ELECTROWEAK/CDFR/10204 (2010).
 - [37] R. Culbertson et al., *Search for Anomalous Production of di-photon+MET Events in 2/fb of Data.*, CDF NOTE 9184
 - [38] J. Adelman et al., "Method II For You", CDF Internal Note 9185, 2008.
 - [39] Frankiln, et al., *Calibration of Heavy-Flavor Production in QCD Data*, CDF NOTE 8768
Frankiln, et al., *Heavy-Flavor Content of the W+Jets Sample*, CDF NOTE 8765
 - [40] Tom Junk *Frequentist Exclusion and Discovery of Signals in Combined Searches with Large Systematic Uncertainties on the Background* CDF Note 6525 (2003)
 - [41] Tom Junk, *Sensitivity, Exclusion and Discovery with Small Signals, Large Backgrounds, and Large Systematic Uncertainties*, CDF note CDF/DOC/STATISTICS/PUBLIC/8128 (2007)
 - [42] F. James and M. Roos *MINUIT: A system For Function Minimization And Analysis Of The Parameter Errors and Correlations* Comput. Phys. Commun. 10 (1975) 343
 - [43] Tom Junk *Building a More General χ^2* CDF Note 7904 (2006)
 - [44] G. Cowan *Statistical Data Analysis* Oxford Science Publications (1998)

- [45] G. Bellettini, G. Latino, V. Rusu, M. Trovato, G. Velev, C. Vernieri *Search for WZ/ZZ production in events with lepton(s) plus jets plus missing transverse energy* CDF Note 10630 (2011)
- [46] Tom Junk *et al.* Combined CDF and DZero Upper Limits on Standard Model Higgs Boson Production with up to 6.7 fb^{-1} CDF NOTE 10241
- [47] G. Bellettini, G. Latino, M. Trovato, V. Rusu, G. Velev, C. Vernieri, CDF Note 10642
- [48] J. Freeman, W. Ketchum, S. Poprocki, S. Pronko, V. Rusu, and P. Wittich *Search for Diboson Production in MET+bb channel* CDF Note 10204 [arXiv:1108:2060].
- [49] W. Ketchum, V. Rusu, Y.K. Kim *Search for WZ/ZZ Production in leptons+jets channel* CDF Note 10581 (2011)
- [50] M. L. Mangano *et al* *ALPGEN, a generator for hard multiparton processes in hadronic collisions* J. High Energy Phys. 0307 (2003) 001
- [51] F. Canelli *et al.* Jet Energy Resolution CDF Note 7856

Appendix A

The Higgs Mechanism

The symmetry of the Lagrangian density described so far must be broken in order to allow for non-zero physical masses of the particles. In fact, in order to have a theory that takes into account the mass of gauge bosons, it is necessary to add quadratical terms like $M_W W_{\mu\nu} W^{\mu\nu}$, which violate the invariance under gauge transformations. This violation introduces problems connected to the renormalization of the model. P. Higgs et al. [5] restored the invariance of the Lagrangian by introducing additional *scalar fields* that interact with both the fundamental fermions and the gauge bosons. The scalar field is then usually said to have a non vanishing vacuum expectation value (v.e.v.) that spontaneously breaks the given $SU(2) \otimes U(1)$ symmetry. Since the EW interactions are local and the masses of the particles are different from zero also when non interacting (during free propagation), the scalar field must be always locally present. This mechanism is called **Higgs mechanism**, after the name of the scientist who proposed it.

A.1 Spontaneous Symmetry Breaking

We can try to explain the spontaneous symmetry breaking using an example. We can consider a Lagrangian that is invariant under a generic symmetry (i.e. spatial rotations). If we have a non-degenerate energy level, it has only one eigenstate and it is invariant under the considered symmetry. If we have a degenerate energy level we can choose one of the different eigenstate as fundamental energy level, but it will not share the same symmetry of the Lagrangian. In this way the symmetry breaking is not due to the addition of asymmetrical terms in the Lagrangian, but it comes from the choice of one of its degenerate fundamental energy levels.

In fields theory, the lower energy level is the vacuum state. It is necessary to have a degenerate vacuum state in order to have a spontaneous symmetry breaking. This implies a quantity connect to the vacuum state that is not invariant under gauge transformations and that is useful to characterize the vacuum state itself. We can assume this quantity to be the *vacuum expectation value* (v.e.v.). Requiring the vacuum state to be invariant under Lorentz transformations and translations, we can consider a scalar field $\varphi(x)$ with:

$$\langle 0 | \varphi(x) | 0 \rangle = v \neq 0 \tag{A.1}$$

where v is the *vacuum constant*.

A.2 The Goldstone Model

We define the Lagrangian density:

$$L(x) = \delta^\mu \varphi^*(x) \delta_\mu \varphi(x) - \mu^2 \varphi^*(x) \varphi(x) - \lambda (\varphi^*(x) \varphi(x))^2 \quad (\text{A.2})$$

where $\mu^2 \varphi^*(x) \varphi(x)$ is the mass term and $\varphi(x)$ a complex classical scalar field:

$$\varphi(x) = \frac{1}{\sqrt{2}} [\varphi_1(x) + i\varphi_2(x)] \quad (\text{A.3})$$

We can derive the *Hamiltonian density*:

$$H(x) = \delta^0 \varphi^*(x) \delta_0 \varphi(x) + \nabla \varphi^*(x) \nabla \varphi(x) + V(\varphi) \quad (\text{A.4})$$

$$V(\varphi) = +\mu^2 \varphi^*(x) \varphi(x) + \lambda (\varphi^*(x) \varphi(x))^2 \quad (\text{A.5})$$

$V(\varphi)$ is the potential energy density. In order to have a classical theory with stable states for high values of $\varphi(x)$, where $(\varphi^*(x) \varphi(x))^2$ is dominant, we need to have $\lambda=0$. To study the stable states for the Hamiltonian density we can consider two cases:

1. $\mu^2=0$, in this situation we have only one non-degenerate fundamental state with $\varphi_1 = \varphi_2 = 0$. We can not have a spontaneous symmetry breaking.
2. $\mu^2 < 0$, in this case situation we can have two different condition of stationarity: $\varphi = 0$, $\varphi = \sqrt{\frac{-\mu^2}{2\lambda}} e^{i\vartheta}$.

The first condition is a maximum condition, the second condition is a minimum condition that correspond to a degenerate set of minima connected by the U(1) symmetry.

With the second condition, we will have a spontaneous symmetry breaking if we choose a specific value for φ as the vacuum state. Considering the U(1) invariance for the Lagrangian, we can choose $\theta=0$ to define the ground state:

$$\varphi_0 = \sqrt{\frac{-\mu^2}{2\lambda}} = \frac{v}{\sqrt{2}} \quad (\text{A.6})$$

Introducing two real field $\sigma(x)$ and $\eta(x)$, we can express the field $\varphi(x)$ as a perturbation of the ground state φ_0 :

$$\varphi(x) = \frac{1}{\sqrt{2}} (v + \sigma(x) + i\eta(x)) \quad (\text{A.7})$$

$$\varphi_1(x) = \frac{1}{\sqrt{2}} (v + \sigma(x)) \quad (\text{A.8})$$

$$\varphi_2(x) = \frac{\eta(x)}{\sqrt{2}} \quad (\text{A.9})$$

We can rewrite the Lagrangian density as:

$$L(x) = \frac{1}{2} \delta^\mu \sigma \delta_\mu \sigma - \frac{1}{2} (2\lambda v^2) \sigma^2 + \frac{1}{2} \delta^\mu \eta \delta_\mu \eta - \frac{\lambda}{4} (\sigma^2 + \eta^2) - \lambda v \sigma (\sigma^2 + \eta^2) \quad (\text{A.10})$$

Figure A.1: For a fixed value of λ the potential is presented against the real and imaginary parts of Φ . The Mexican-hat or champagne-bottle profile at the ground should be noted

and interpret:

$$L_0(x) = \frac{1}{2} \delta^\mu \sigma \delta_\mu \sigma - \frac{1}{2} (2\lambda v^2) \sigma^2 + \frac{1}{2} \delta^\mu \eta \delta_\mu \eta \quad (\text{A.11})$$

As the free Lagrangian density (without interactions between the fields). We can confront the last expression with the Klein-Gordon Lagrangian density and, by the quantization, connect the $\sigma(x)$ and $\eta(x)$ fields with neutral particles of spin 0: the σ boson with $m_\sigma = \sqrt{2\lambda v^2}$ and the massless η boson (*Goldstone boson*).

We can interpret $\sigma(x)$ as the potential radial excitation (variation) with the potential curvature due to the σ boson mass. We can also interpret $\eta(x)$, with its massless η boson, as the potential excitation along the circumference, where the potential is smooth.

For a particle in the vacuum state we have:

$$\langle 0 | \sigma(x) | 0 \rangle = \langle 0 | \eta(x) | 0 \rangle = 0 \quad (\text{A.12})$$

$$\varphi(x) = \frac{1}{\sqrt{2}} (v + \sigma(x) + i\eta(x)), v = \text{const} \quad (\text{A.13})$$

We can obtain a spontaneous symmetry breaking:

$$\langle 0|\varphi(x)|0\rangle = \frac{1}{\sqrt{2}} (\langle 0|v|0\rangle + \langle 0|\sigma(x)|0\rangle + i\langle 0|\eta(x)|0\rangle) = \frac{1}{\sqrt{2}} (\langle 0|v|0\rangle) = \frac{v}{\sqrt{2}} = \varphi_0 \neq 0 \quad (\text{A.14})$$

A.3 The Higgs Mechanism

The next step is introducing the gauge field A^μ . The Lagrangian density becomes:

$$L(x) = D^\mu \varphi^*(x) D_\mu \varphi(x) - \mu^2 \varphi^*(x) \varphi(x) - \lambda (\varphi^*(x) \varphi(x))^2 + \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \quad (\text{A.15})$$

$$D_\mu = \partial_\mu + iQeA_\mu \quad (\text{A.16})$$

The Lagrangian density introduced so far defines the **Higgs mechanism**. It is invariant under U(1) transformations and has 4 degrees of freedom (independent fields): $\varphi_1(x)$, $\varphi_2(x)$ and the two transverse polarization of the massless A^μ field.

As we did for the Goldstone model, we find a minimum condition for $\mu^2 < 0$, that is the same of the one found before and that correspond to a degenerate ground state with a non-zero expectation value. Introducing the $\sigma(x)$ and $\eta(x)$ fields as perturbations of the ground state, we obtain the Lagrangian density in term of these field. Looking at the free Lagrangian density:

$$\begin{aligned} L_0(x) = & \frac{1}{2} \delta^\mu \sigma(x) \delta_\mu \sigma(x) - \frac{1}{2} (2\lambda v^2) \sigma(x)^2 + \\ & + \frac{1}{2} \delta^\mu \eta(x) \delta_\mu \eta(x) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \\ & + \frac{1}{2} (eQv)^2 A^\mu(x) A_\mu(x) + qv A^\mu(x) \delta_\mu \eta(x) \end{aligned} \quad (\text{A.17})$$

we can notice that the gauge boson A^μ acquired mass. In this way the degrees of freedom connected to its polarization become three (longitudinal and transverse polarizations). Other two degrees of freedom come from the two real scalar fields $\sigma(x)$ and $\eta(x)$, for a total number of 5. The term $qv A^\mu(x) \delta_\mu \eta(x)$ shows that $A^\mu(x)$ and $\eta(x)$ are not independent. Applying a U(1) transformation to the complex field $\varphi(x)$ we can transform it in a real field:

$$\varphi'(x) = \frac{1}{\sqrt{2}} (v + \sigma(x)) \quad (\text{A.18})$$

eliminating $\eta(x)$ from the description and reinterpreting it as the longitudinal polarization of the gauge field $A^\mu(x)$:

$$\begin{aligned} L_0(x) = & \frac{1}{2} \delta^\mu \sigma(x) \delta_\mu \sigma(x) - \frac{1}{2} (2\lambda v^2) \sigma(x)^2 - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \\ & + \frac{1}{2} (eQv)^2 A^\mu(x) A_\mu(x) \end{aligned} \quad (\text{A.19})$$

The free Lagrangian density does not couple the $\sigma(x)$ and the $A^\mu(x)$ fields, so we can interpret it as the free Lagrangian density of a Klein-Gordon real field $\sigma(x)$ and a vectorial real massive field $A^\mu(x)$. After the quantization, we obtain scalar neutral bosons with mass $\sqrt{2\lambda v^2}$ from $\sigma(x)$ and vectorial neutral bosons with mass eQv from $A^\mu(x)$.

A.4 Higgs Mechanism and Standard Model

We can add the Higgs mechanism to the EW theory in order to obtain the mass of W and Z bosons. Since we need to break a SU(2) symmetry, it is necessary to introduce a scalar doublet for the Higgs field (weak isospin doublet):

$$\varphi(x) = \begin{pmatrix} \varphi_a(x) \\ \varphi_b(x) \end{pmatrix} \quad (\text{A.20})$$

where $\varphi_a(x)$ and $\varphi_b(x)$ are scalar fields under Lorentz transformations. We can include the Higgs field and its interactions with the gauge bosons field in the full EW Lagrangian density and keep the SU(2)⊗U(1) symmetry:

$$L = L_B + L_{int} + L_H \quad (\text{A.21})$$

$$L_H(x) = (D^\mu \varphi(x))^+ D_\mu \varphi(x) - \mu^2 \varphi^+(x) \varphi(x) - \lambda (\varphi^+(x) \varphi(x))^2 \quad (\text{A.22})$$

$$D_\mu = \delta_\mu + i \frac{g}{2} \tau_j W_\mu^j + i g' Y B_\mu \quad (\text{A.23})$$

For $\lambda=0$ and $\mu^2 < 0$ the classical energy density has a minimum for constant Higgs field:

$$\varphi_0 = \begin{pmatrix} \varphi_a^0 \\ \varphi_b^0 \end{pmatrix} \quad (\text{A.24})$$

with:

$$\varphi_0^+ \varphi_0 = \frac{-\mu^2}{2\lambda} = \frac{v^2}{2} \quad (\text{A.25})$$

we have a degenerate set of minima and spontaneous symmetry breaking. We can choose:

$$\varphi_0 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad (\text{A.26})$$

we can introduce real scalar fields as perturbations of the ground state and express the Higgs field in term of this parameters:

$$\varphi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta_1 + i\eta_2 \\ \frac{v^2}{2} + \sigma + i\eta_3 \end{pmatrix} \quad (\text{A.27})$$

Considering the SU(2)⊗U(1) symmetry of the Lagrangian density, we can apply a SU(2)⊗U(1) transformation and write the isospinor as:

$$\varphi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \frac{v^2}{2} + \sigma \end{pmatrix} \quad (\text{A.28})$$

The Lagrangian density L becomes:

$$\begin{aligned}
 L = & L_{int} - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4} W^{+\nu\mu} W_{\nu\mu}^- + \left(\frac{1}{2} v g \right)^2 W^{+\mu} W_{\mu}^- - \\
 & - \frac{1}{4} Z^{\nu\mu} Z_{\nu\mu} + \frac{1}{2} \left(\frac{v g}{2 \cos \theta_W} \right)^2 Z^{\mu} Z_{\mu} + \\
 & + \frac{1}{2} \delta^{\mu} \sigma \delta_{\mu} \sigma - \frac{1}{2} (-2\mu^2) \sigma^2 + L_{BB} + L_{HB} + L_{HH}
 \end{aligned}$$

where L_{BB} is the Lagrangian density for the interaction between gauge bosons; L_{HB} is the Lagrangian density for the interaction between the Higgs boson and gauge bosons; L_{HH} is the Lagrangian density for the interaction between the Higgs boson with itself.

We obtain W, Z and Higgs boson mass as:

$$m_W = \frac{1}{2} v g \quad (\text{A.29})$$

$$m_Z = \frac{v g}{2 \cos \theta_W} \quad (\text{A.30})$$

$$m_H = \sqrt{-2\mu^2} \quad (\text{A.31})$$

m_H can not be predicted because it depends on the arbitrary parameter μ .

In conclusion we can see that Z and W boson acquired mass from the spontaneous symmetry breaking. This process does not affect the photon that remains massless, as it has to be.

Appendix B

Instantaneous Luminosity Measurement

The Cherenkov light is detected with photomultiplier tubes and the momentum threshold for light emission is 9.3 MeV/ c for electrons and 2.6 GeV/ c for pions. The number of $p\bar{p}$ interactions in a bunch crossing follows a Poisson distribution with mean μ , where the probability of empty crossing is given by:

$$P_0(\mu) = e^{-\mu}$$

which is correct if the acceptance of the detector and its efficiency were 100%. In practice, there are some selection criteria, α , to define an “interaction.” An interaction is defined as a $p\bar{p}$ crossing with hits above a fixed threshold on both sides of the CLC detector. Therefore, an empty crossing is a $p\bar{p}$ crossing with no interactions. Given these selection criteria, the experimental quantity P_0 , called $P_0^{exp}\{\alpha\}$, is related to μ as:

$$P_0^{exp}\{\mu, \alpha\} = (e^{\epsilon_w \cdot \mu} + e^{-\epsilon_e \cdot \mu} - 1) \cdot e^{-(1-\epsilon_0) \cdot \mu}$$

where the acceptances ϵ_0 and $\epsilon_{w/e}$ are, respectively, the probability to have no hits in the combined east and west CLC modules and the probability to have at least one hit exclusively in west/east CLC module. The evaluation of these parameters is based on Monte Carlo simulations, and typical values are respectively 0.07 and 0.12. From the measurement of μ we can extract the luminosity. Since the CLC is not sensitive at all to the elastic component of the $p\bar{p}$ scattering, the rate of inelastic $p\bar{p}$ interactions is given by:

$$\mu \cdot f_{bc} = \sigma_{in} \cdot \mathcal{L}$$

where f_{bc} is the bunch-crossing frequency at the Tevatron and σ_{in} is the inelastic $p\bar{p}$ cross section. $\sigma_{in} = 60.7 \pm 2.0$ mb is obtained by extrapolating the combined results for the inelastic $p\bar{p}$ cross section of CDF at $\sqrt{s} = 1.8$ TeV and E811 measurements to $\sqrt{s} = 1.96$ TeV. Different sources of uncertainties are taken into account to evaluate the systematic uncertainties on the luminosity measurement. The dominant contributions are related to the detector simulation and the event generator used, and have been evaluated to be about 3%. The total uncertainty in the CLC luminosity measurements is 5.8%, which includes uncertainties on the measurement (4.2%) and on the inelastic cross section value (4%).

Appendix C

Trigger Paths Description

In the following we will briefly describe the online selection of the *high- p_T* and the high- $\cancel{E}_T$ electron and muon paths.

ELECTRON_CENTRAL_18 This trigger path selects electron candidates in the central region ($|\eta| < 1.1$) that satisfy

- At **LEVEL 1** this trigger requires a tower in the central calorimeter with at least 8 GeV and $E_{had}/E_{EM} < 0.125$ (to distinguish the electromagnetic energy from an energy deposit due to charged hadrons) which is associated to an **XFT** track with $p_T > 8\text{ GeV}/c$.
- At **LEVEL 2** is required an electromagnetic cluster of at least 18 GeV and $|\eta| < 1.317$.
- At **LEVEL 3** we require that $L_{shr} < 0.4$ (this is a variable that compares lateral shower profiles in towers next to the seed tower to some expected profile); Δz between the **COT** track and the **CEM** shower to be $< 8\text{ cm}$; a central track with $p_T \geq 9\text{ GeV}/c$ matched to an electromagnetic cluster with transverse energy, $E_T > 18\text{ GeV}$.

MET_PEM In this analysis we are also interested in the events that have an energy cluster in the plug electromagnetic calorimeter. The trigger requirements are the following

- At **LEVEL 1** a plug calorimeter tower with $E_T > 8\text{ GeV}$ and $E_{had}/E_{EM} < 0.0625$ is required; a $\cancel{E}_T$ ¹ $> 15\text{ GeV}$ is also required.
- At **LEVEL 2** we want a $\cancel{E}_T > 15\text{ GeV}$, a plug electromagnetic cluster object with $E_T > 20\text{ GeV}$ and $1.1 < |\eta| < 3.6$.
- **LEVEL 3** requires an “electromagnetic object” in the plug calorimeter with $E_T > 20\text{ GeV}$, $E_{had}/E_{EM} < 0.125$ and $\cancel{E}_T > 15\text{ GeV}$.

For the muons we use

¹ $\cancel{E}_T$ is the missing transverse energy

MUON_CMUP This trigger path selects muons with tracks in both the CMU and CMP detectors

- At LEVEL 1 we ask for an XFT track with $p_T > 4.09 \text{ GeV}/c$, associated to a CMU stub with $p_T > 6 \text{ GeV}/c$ and a CMP stub.
- At LEVEL 2 the requirement on the XFT is tightened by requiring a track with four COT superlayers having $p_T > 15 \text{ GeV}/c$.
- At LEVEL 3 the p_T cut is raised to $18 \text{ GeV}/c$.

MUON_CMX18 This trigger path identifies high- p_T muons that pass through the CMX muon detector

- At LEVEL 1 is required an XFT track with $p_T > 8 \text{ GeV}/c$ associated to a CMX stub with $p_T > 6 \text{ GeV}/c$ and a hit in the CSX scintillator.
- LEVEL 2 tightens the XFT criteria by requiring a four layer track with $p_T > 15 \text{ GeV}/c$.
- At LEVEL 3 the p_T cut is raised to $18 \text{ GeV}/c$.

MET35_&_CJET_&_JET

- At LEVEL 1 is required $\cancel{E}_T > 25 \text{ GeV}/c$.
- LEVEL 2 a central “electromagnetic cluster object” with $E_T > 10 \text{ GeV}$ and $0 < |\eta| < 1.1$
- At LEVEL 3 the $\cancel{E}_T$ cut is raised to $35 \text{ GeV}/c$.

MET35_&_TWO_JETS

- At LEVEL 1 is required $\cancel{E}_T > 25 \text{ GeV}/c$.
- LEVEL 2 two electromagnetic cluster objects with $E_T > 10 \text{ GeV}$ and $0 < |\eta| < 3.6$.
- At LEVEL 3 the $\cancel{E}_T$ cut is raised to $35 \text{ GeV}/c$.

MET_DIJET

- At LEVEL 1 is required an electromagnetic cluster objects with $E_T > 10 \text{ GeV}$ and $\cancel{E}_T > 28 \text{ GeV}/c$.
- LEVEL 2 two electromagnetic cluster objects with $E_T > 3 \text{ GeV}$ and $0 < |\eta| < 3.6$.
- At LEVEL 3 the $\cancel{E}_T$ cut is raised to $30 \text{ GeV}/c$.

Appendix D

Tracking Algorithm

Using the hit positions in the tracking system, pattern recognition algorithms reconstruct the particle original trajectory measuring the five parameters of the helix that best match to the observed hits.

CDF employs several algorithms for track reconstruction, depending on which component of the detector a particle travels through. The principal one is the Outside-In (OI) reconstruction. This algorithm, which exploits the information from both the central drift chamber and the silicon detectors, is used to track the particles in the central region ($|\eta| < 1$). It first reconstructs tracks in the COT and then extrapolates them inwards toward the beam.

The first step of pattern recognition in the COT looks for circular paths in the axial superlayers. Cells in the axial superlayers are searched for sets of 4 or more hits that can be fit to a straight line. These sets are called “segments”. Once segments are found, there are two approaches to track finding [21] (“segment linking” and “histogram linking” algorithms). One approach is to link together the segments which are consistent with lying tangent to a common circle. The other approach is to constrain its circular fit to the “beam-line” (see Sec. 4.1.1). Once a circular path is found in the r - ϕ plane, segments and hits in the stereo superlayers are added depending on their proximity to the circular fit. This results in a three-dimensional track fit. Typically, if one algorithm fails to reconstruct a track, the other algorithm will not. This results in high track reconstruction efficiency in the COT for tracks passing through all 8 superlayers (97% for tracks with $p_T > 10 \text{ GeV}/c$)¹.

Once a track is reconstructed in the COT, it is extrapolated inward to the silicon system. Based on the estimated errors on the track parameters, a three dimensional “road” is formed around the extrapolated track. Starting from the outermost layer, and working inwards, silicon hits found inside the road are added to the track. As hits are added, the road gets narrowed according to the knowledge of the updated track parameters and their covariance matrix. A reduction of the road width decreases the chance of adding wrong hits to the track, and also reduces the computation time. In the first pass of this algorithm, axial hits are added. In the second pass, hits with stereo information are added to the track. At the end, the track combination with the highest number of hits and lowest χ^2/ndf for the five parameters helix fit is kept.

¹The track reconstruction efficiency mostly depends on how many tracks are reconstructed in the event. If there are many tracks close to each other, hits from one track can shadow hits from the other track, resulting in efficiency losses.

Appendix E

NN inputs

Figure E.1: NN input variables.

Figure E.2: NN input variables.

Appendix F

Studies on the development of a $t\bar{t}$ veto in the 3 jets sample using a χ^2 fitter

In this section we explore the possibility to exploit the χ^2 fitter used in the measurement of the top quark mass in order to develop a the a $t\bar{t}$ veto in the 3 jets sample.

F.1 Motivation

In the 3 jets sample the situation is similar to the 2 jets sample one. Looking at Tables 5.8 5.9 we can notice that in the tag 3 jets sample $t\bar{t}$ background is one of the largest. The notag 3 jets region is mostly affected by W+jets. In the 3 jets sample the $t\bar{t}$ composition is slightly different. The largest contribute comes from the lepton+jets $t\bar{t}$ decay F.1: the requirement for the extra jet cut of a lрге part of the dileptonic contribute. For this reason a strategy based on a set of preselection cuts on lepton number and flavour will give will have a lower impact on sensitivity. To act directly against the lepton+jets $t\bar{t}$ decay mode we explore the possibility to include, in the preselection cuts, a cut on the χ^2 fitter used in the measurement of the top quark in the lepton+jets channel.

Figure F.1: $t\bar{t}$ composition in the tag 2 jets sample.

F.2 χ^2 fitter

In top mass analysis, the reconstructed mass is obtained with a χ^2 fit. The fitter applies energy and momentum conservation and gives constraints to the decay subsystems. The χ^2 minimization allows the fit quantities to vary within the errors of the measured quantities. For each variation, the χ^2 value is calculated. The minimum allowed χ^2 returns top mass. We can use a χ^2 fitter in the tag 3 jets sample in order to create a variable in which signal and $t\bar{t}$ background are well separated. We need to adapt the expression for the χ^2 fitter to our problem. The χ^2 fitter usually adopted in top mass analysis is presented in equation F.1.

$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} + p_T^{i,data})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} + p_j^{UE,data})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{top}^{reco})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{top}^{reco})^2}{\Gamma_t^2} \quad (F.1)$$

The first term accounts for the partons and the lepton transverse momenta to be fitted to the values of their observables. The second does the same with the unclustered energy transverse components. When forming the electron and muon primary four-vectors, their masses are set to zero and all the angles are assumed to have no errors. Uncertainties as in equations F.2 are assigned to the magnitudes of the electron and muon transverse momenta.

$$\begin{aligned} \frac{\sigma_{p_T^e}}{p_T^e} &= \sqrt{\left(\frac{0.135}{\sqrt{p_T^e} [GeV/c^2]}\right)^2 + (0.02)^2} \\ \frac{\sigma_{p_T^\mu}}{p_T^\mu} &= 0.0011 \cdot p_T^\mu [GeV/c^2] \end{aligned} \quad (F.2)$$

All energy deposits that are not assigned to the 4 leading jets or to the lepton are considered unclustered energy (UE) and corrections for calorimeter response to hadrons are applied. After corrections for calorimeter calibrations, the uncertainty of $0.4\sqrt{\Sigma E_T^{uncl}}$ is associated to the transverse components p_x^{UE} , p_y^{UE} , where E_T^{uncl} is the scalar sum of the transverse energies excluding the 4 jets and the lepton. The neutrino transverse momentum, that enters the χ^2 fit, is the quantity:

$$\vec{p}_T^\nu = -(\vec{p}_T^l + \Sigma \vec{p}_T^{jet} + \vec{p}_T^{UE}) \quad (F.3)$$

The neutrino longitudinal momentum p_T^ν is a free parameter. The conservation equation determines its absolute value but not its sign. The two following terms of the χ^2 fitter expression account for the difference between the invariant masses M_{jj} , $M_{l\nu}$ (the two light-jets system and the lepton-neutrino system) and the W mass $M_W = 80.42$ GeV. For M_W a gaussian distribution is assumed with width $\Gamma_W = 2.12$ GeV as in its natural Breit-Wigner shape. The last two terms compare the fitted masses of the systems $bl\nu$ (b-jet, lepton and neutrino) and bjj (b-jet and two light jets) to the free parameter M_{top}^{reco} . For M_{top} a gaussian distribution is also assumed with width $\Gamma_t = 1.5$ GeV as predicted by theory for a Top quark mass $M_{top} = 175$ GeV. To use an appropriate expression of the χ^2 fitter in the tag 3 jets sample, we have to take into account the fact that one of the for 4 jets produced in a lepton+jets $t\bar{t}$ decay is lost. In particular, when 2 of the 3 jets are required to be b-like, it is a light flavour jet the one the does not enters the final χ^2

fitter expression.

$$\begin{aligned} \chi^2 = & \sum_{i=l,3jets} \frac{(p_T^{i,fit} + p_T^{i,data})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} + p_j^{UE,data})^2}{\sigma_j^2} \\ & + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bl\nu} - M_{top}^{reco})^2}{\Gamma_t^2} \end{aligned} \quad (F.4)$$

Looking at the equation F.4 we can notice that the constraints on the Mjj and bjj (the two light-jets and b-jet and two light jets systems) are not present anymore.

F.3 Conclusions

By the minimization of the χ^2 fitter we would like to define a variable with a great separation power between signal and $t\bar{t}$ background. In particular, having built the χ^2 fitter considering the physics of the $t\bar{t}$ decay mode, we expect the χ^2 to be well minimized by background events. Considering the kinematics of a $t\bar{t}$ event, we can see if the system is constrained. The 4-momenta $p^\mu = (E/c, p_x, p_y, p_z)$ of the particles involved in such an event give 40 unknown quantities. CDF can measure, in the tag 3 jets region, the 4-momenta of the lepton l (electron or muon) and the three jets coming from the hadronized $b, \bar{b}, q$ (or $\bar{q}$) partons, for a total of 16 measured quantities. The $t\bar{t}$

Figure F.2: $t\bar{t}$ lepton+jets decay mode.

system decay has 5 vertexes (see Fig. F.2). For each vertex we can write the conservation relations as in equation F.5:

$$\begin{aligned} \vec{0} &= \vec{p}_T^{UE} + \Sigma \vec{p}_T^t + \vec{p}_T^{\bar{t}} \\ p_t^\mu &= p_b^\mu + p_{W^+}^\mu \\ p_{\bar{t}}^\mu &= p_{\bar{b}}^\mu + p_{W^-}^\mu \\ p_{W^\pm}^\mu &= p_{l^\pm}^\mu + p_\nu^\mu \\ p_{W^\mp}^\mu &= p_{q'}^\mu + p_{\bar{q}}^\mu \end{aligned} \quad (F.5)$$

For the first vertex, where a gluon g gives a $t\bar{t}$ system, we can only write the transverse momenta conservation because small angle particles are lost by the CDF detector around the beampipe. For

this reason, the total energy conservation cannot be enforced and the first expression gives 2 scalar equations. On the other hand, all the final products of the $t\bar{t}$ with the exception of the neutrino give signals from which we can reconstruct their full 4-momentum. We get from each of the other expressions four scalar equations. The total number of equation we can write is 18. We can assume that the measured missing transverse energy takes into account only the contribute due to the neutrino transverse energy¹. This gives other 2 scalar equations. Considering the constraints on the neutrino, W and top mass:

$$\begin{aligned} M_\nu &= 0 \\ M_{t(\bar{t})} &= 172.5 GeV/c^2 \\ M_{W^\pm} &= 80.4 GeV/c^2 \end{aligned} \tag{F.6}$$

we have 40 unknowns and 39 equations. The system is not constrained. This lead to the possibility to minimize the χ^2 fitter in both the signal and background hypothesis, having no separation between the two χ^2 distributions.

¹Actually, also the transverse momentum of the lost jet is taken into account