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ELECTROWEAK AND TOP PHYSICS AT CDF IN RUN II

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Abstract

The CDF experiment at the Tevatron has used $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV to measure the production cross sections of W and Z bosons using several leptonic final states. An indirect measurement of the W width and the ratio of tau and electron electroweak couplings have been extracted. The forward-backward charge asymmetry, $\mathrm{A_{FB}}$, in Drell-Yan dilectron production has been measured up to an invariant mass of 600 GeV/c^2. CDF has also started looking for WW production in the dilepton channel, $WW' \rightarrow ll'\nu\nu$, with the aim of measuring its cross section and derive limits on on the anomalous WWZ and WWγ couplings. The presence of a top quark signal in the Tevatron data has been reestablished by measuring the top quark pair production cross section in the *dilepton* channel, $t\overline{t} \rightarrow WbW\overline{b} \rightarrow \overline{l}\nu_l bl'\overline{\nu}_{l'}\overline{b}$ and in the *lepton plus jets* channel, $t\overline{t} \rightarrow WbW\overline{b} \rightarrow q\overline{q}'bl\overline{\nu}_l\overline{b} + \overline{l}\nu_l bq\overline{q}'\overline{b}$. A pre-tagged *lepton plus jets* sample has also been used to reconstruct the top quark mass.

1 Introduction

The Collider Detector at Fermilab (CDF) has started recording $p\overline{p}$ interactions with its full functionality during 2002. CDF has used the physics-quality data collected until January 2003, corresponding to an integrated luminosity of 72 pb^{-1}, to re-established W, Z and top signals. With those first Run II signals, CDF has measured their production rate in different decay channels, and has extracted measurement of the W width, forward-backward asymmetry, ratio of tau and electron electroweak couplings, and has made a first attempt in reconstructing the top quark mass.

2 W and Z Cross Sections

W and Z bosons are produced at the Tevatron through $q\overline{q}$ annihilation. W boson appears in the detector as a high-momentum lepton and large missing energy due to the undetected neutrino. As the z component of p^{ν} is not measured, all quantities are measured in the transverse plane. A Z boson appears as two high-momentum opposite-signed leptons with an invariant mass around 90 GeV/c^2.

The cross section can be expressed as:

$$\sigma \cdot B = \frac{N_{obs} - N_{bkg}}{A\varepsilon \int \mathcal{L}dt} \tag{1}$$

where N_{obs} is the number of observed candidates, N_{bkg} is the estimated number of background events, A is the kinematic and geometrical acceptance, ε is the total efficiency and $\int \mathcal{L}dt$ is the integrated luminosity.

2.1 W Cross Section Measurements

At CDF, $\mathrm{W} \rightarrow \mathrm{e}\overline{\nu}_{\mathrm{e}}$ candidates are collected with a trigger selecting high-$\mathrm{E_T}$ central electron candidates; after requiring one tight electron candidate with $\mathrm{E_T} > 25$ GeV matched to a track of $\mathrm{p_T} > 10$ GeV/c and missing transverse energy $\not{E}_T > 25$ GeV, 38628 events remain in the data. The main background source comes from QCD dijet events, where a jet mimics the electron signal and large $\not{E}_T$ is due to a poorly measured jet. This background is evaluated by assuming that its distribution is flat in the electron isolation plane versus $\not{E}_T$. By extrapolating from the low isolation and small $\not{E}_T$ region (non-W) to the high isolation and large $\not{E}_T$ region (W dominated), $1344 \pm 82 \pm 672$ events are estimated from that process. Additional backgrounds from $\mathrm{W} \rightarrow \tau\overline{\nu}_{\tau}$ decays (768 ± 22 events) or misidentified $\mathrm{Z}^0/\gamma^* \rightarrow \mathrm{e}^+\mathrm{e}^-$ decays (344 ± 17 events) are estimated from Monte Carlo simulations. The transverse mass spectrum of the candidate events and the estimated background is shown in fig.1 (left).

The total acceptance is $A_{e\nu} = 23.4 \pm 0.05$ (stat.) $\pm$ 0.70 (sys.)%, where the systematic error is dominated by the uncertainty on the parton distribution function (PDF) and the knowledge of the material in the tracking volume. The result is:

$$\sigma_W \cdot B(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}) = 2.64 \pm 0.01 \text{ (stat.)} \pm 0.09 \text{ (sys.)} \pm 0.16 \text{ (lum.) n}b \quad (2)$$

in good agreement with the NNLO calculations [1], 2.731 ± 0.002 nb.

$\mathrm{W} \to \mu\overline{\nu}_\mu$ candidates are collected from high-$\mathrm{p_T}$ muon triggers. After requiring an isolated muon with $\mathrm{p_T} > 20$ GeV/c and $\not{E}_T > 20$ GeV, 21599 W candidates remain. Backgrounds in this channel include misidentified boson decays ($\mathrm{Z}^0/\gamma^* \to \mu^+\mu^-$, $\mathrm{W} \to \tau\overline{\nu}_\tau$), cosmic rays and QCD processes; their sum is estimated to 10.82 ± 0.18 (stat.) $\pm$ 0.96 (sys.)%. The total acceptance is $A_{\mu\nu} = 14.8 \pm 0.5$ (stat.)%, where the systematic error is dominated by the uncertainty on the PDF and the measurement of the W recoil. The result is:

$$\sigma_W \cdot B(\mathrm{W} \to \mu\overline{\nu}_\mu) = 2.64 \pm 0.02 \text{ (stat.)} \pm 0.12 \text{ (sys.)} \pm 0.16 \text{ (lum.) n}b \quad (3)$$

again in good agreement with the NNLO calculations.

$\mathrm{W} \to \tau\overline{\nu}_\tau$ candidates can also be selected at CDF by collecting events with a $\not{E}_T > 25$ GeV at the level 1 hardware trigger complemented by a subsequent τ identification at the level 3 software trigger. Monojet candidates are kept if they have a single jet with $E_T > 25$ GeV containing one charge leading track with $\mathrm{p_T} > 4.5$ GeV in a 10^o cone and no other track in a $10^o - 30^o$ cone around the leading track. Tight electron events from $\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}$ decay are explicitly removed. 2345 events pass the selection, with an estimated background of 612$\pm$61 events mainly due to QCD processes. The cross section times branching ratio is measured to be:

$$\sigma_W \cdot B(\mathrm{W} \to \tau\overline{\nu}_\tau) = 2.62 \pm 0.07 \text{ (stat.)} \pm 0.21 \text{ (sys.)} \pm 0.16 \text{ (lum.) n}b \quad (4)$$

Additionally, by using the previously excluded $\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}$ candidates in the same data sample, the ratio of the electroweak coupling constants is extracted to be:

$$\frac{g_\tau}{g_e} = 0.99 \pm 0.04 \text{ (stat.)} \pm 0.07 \text{ (sys.)} \quad (5)$$

2.2 Z Cross Section Measurements

The selection of $\mathrm{Z}^0/\gamma^* \to \mathrm{e}^+\mathrm{e}^-$ candidates is done by requiring two central electrons with opposite charge, $\mathrm{E_T} > 25$ GeV and $\mathrm{p_T} > 10$ GeV/c with and invariant mass between 66 and 116 GeV/c^2. 1830 candidate events are obtained with an estimated background of 10 ± 5 events. The total acceptance is $A_{ee} = 11.49 \pm 0.07$ (stat.) $\pm$ 0.64 (sys.)%, where the systematic error is dominated by

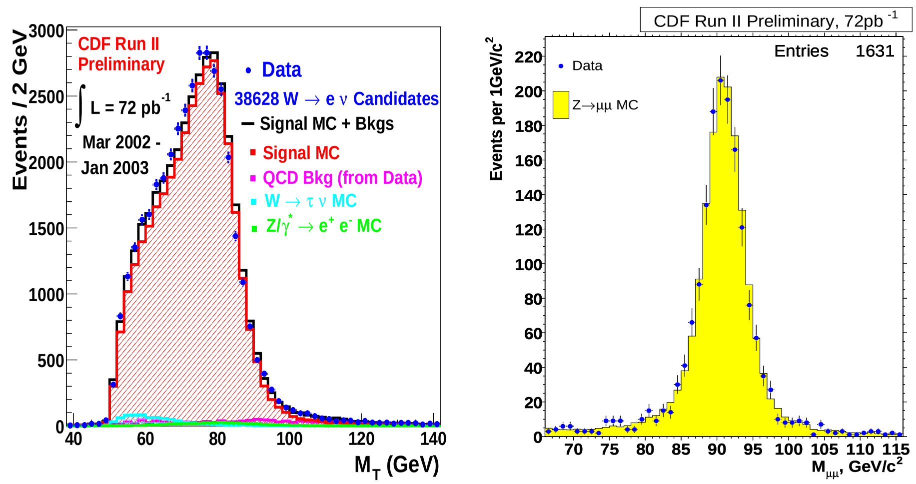

Figure 1: *Transverse mass distribution of* $\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e}$ *candidates (left) and invariant mass of* $\mathrm{Z}^0/\gamma^* \to \mu^+\mu^-$ *candidates (right) collected by the CDF experiment in 72* pb^{-1}.

the uncertainty on the PDF and the modeling of the material budget in the tracking volume. The cross section times branching ratio is measured to be:

$$\sigma_Z \cdot B(\mathrm{Z}^0 \to \mathrm{e}^+\mathrm{e}^-) = 267.0 \pm 6.3 \text{ (stat.)} \pm 15.2 \text{ (sys.)} \pm 16.0 \text{ (lum.) p}b \quad (6)$$

higher but consistent that the NNLO calculation [1)] of 250.5 ± 3.8pb.

$\mathrm{Z}^0/\gamma^* \to \mu^+\mu^-$ candidates are selected by requiring one isolated central muon with $\mathrm{p_T} > 20$ GeV/c and an second isolated high-$\mathrm{p_T}$ track passing minimum ionizing energy requirements. The same invariant mass window as in the electron channel is considered. From the 1631 candidates (see fig.1, right), CDF measures:

$$\sigma_Z \cdot B(\mathrm{Z}^0 \to \mu^+\mu^-) = 246 \pm 6 \text{ (stat.)} \pm 15 \text{ (sys.)} \pm 15 \text{ (lum.) p}b \quad (7)$$

in good agreement with the NNLO calculations.

3 W/Z ratio and W width

Using the cross section measurements in the electron channel presented in sections 2.1 and 2.2, the ratio of the cross sections times branching ratios is computed to be:

$$\mathrm{R_e} = \frac{\sigma_W \cdot B(\mathrm{W} \to \mathrm{e}\overline{\nu}_\mathrm{e})}{\sigma_Z \cdot B(\mathrm{Z}^0 \to \mathrm{e}^+\mathrm{e}^-)} = 9.88 \pm 0.24 \text{ (stat.)} \pm 0.47 \text{ (sys.)} \quad (8)$$

and is found lower but consistent with the NNLO prediction ($R = 10.66 \pm 0.05$ [1]). Similarly, using the muon results, CDF computes:

$$\mathrm{R}_\mu = 10.69 \pm 0.27 \text{ (stat.)} \pm 0.33 \text{ (sys.)} \tag{9}$$

The indirect measurement of $\Gamma(W)$ can be extracted using equation 10, where $\sigma(p\overline{p} \to W)/\sigma(p\overline{p} \to Z)$ is taken from theoretical predictions [1], $\Gamma(W \to l\nu)$ is taken from the P.D.G. [2] and $\Gamma(Z \to ee)/\Gamma(Z)$ from the LEP measurements [2].

$$\Gamma(W) = \frac{\sigma(p\overline{p} \to W)}{\sigma(p\overline{p} \to Z)} \frac{\Gamma(W \to e\nu)}{\Gamma(Z \to ee)} \frac{\Gamma(Z)}{R} \tag{10}$$

Using $\mathrm{R_e}$, CDF extractes:

$$\Gamma(W) = 2.29 \pm 0.06 \text{ (stat.)} \pm 0.10 \text{ (sys.) GeV} \tag{11}$$

while using R_μ, CDF obtains:

$$\Gamma(W) = 2.11 \pm 0.05 \text{ (stat.)} \pm 0.07 \text{ (sys.) GeV} \tag{12}$$

Both results are found in relatively good agreement with the most recent average of 2.118 ± 0.042 GeV [3] and the theoretical prediction of 2.067 ± 0.021 GeV. Fig.2 (right) shows those results with previous measurements of the W boson width.

4 Forward-Backward Dilectron Asymmetry

The reaction $p\overline{p} \to ll'$, where l stands for and isolated high-$\mathrm{p_T}$ electron or muon, is mediated by virtual photon at low invariant mass ($M_{l^+l^-}$) values, by the $\mathrm{Z^0}$ for $M_{l^+l^-}$ around the Z pole and by photon-Z interference everywhere else. The presence of both vector and axial-vector couplings of electroweak bosons to fermions in the process $q\overline{q} \to \mathrm{Z^0}/\gamma^* \to \mathrm{l^+l^-}$ gives rise to an asymmetry in the polar angle (θ) of the electron momentum in the center of mass frame of the lepton pair. The forward-backward asymmetry is defined as:

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} \tag{13}$$

where N_F is the number of forward events with positive $\cos\theta$ and N_B is the number of backward events with negative $\cos\theta$.

A_{FB} is a direct probe of the relative strength of the vector and axial-vector couplings over the Q^2 range considered. Additionally, A_{FB} allows to constrains the properties of any additional heavy neutral gauge boson not included in the

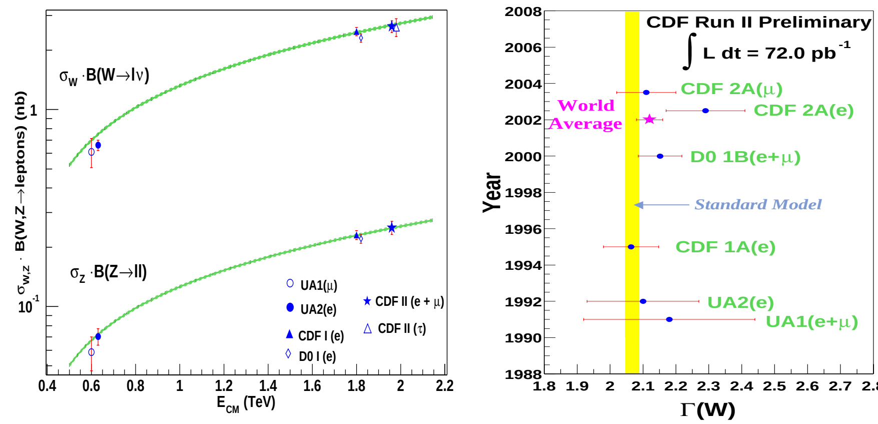

Figure 2: *Left: Comparison of the cross section measurements for W and Z boson with NNLO calculations (line). Right: Comparison of CDF Run II results on the W boson width with the previous measurements and SM predictions.*

Standard Model, and is complementary to a direct search for them via excesses in the total cross section.

CDF uses 5438 events with $40 < M_{e^+e^-} < 600$ GeV/c^2 from $p\overline{p} \to Z^0/\gamma^* + X \to e^+e^- + X$ process to measure the forward-backward asymmetry over a wide Q^2 range. The results are showed in fig.3 and agree well with the theoretical predictions.

5 WW production in dilepton channel

The study of WW production in the dilepton channel, $WW' \to ll'\nu\nu$ (l = e *or* μ) with Run II data will improve the measurement of the WW cross section and the limits on the anomalous WWZ and WWγ couplings. CDF has started looking for WW decay to dilepton in the 72 pb^{-1} of data collected so far, by selecting two high-p_T isolated electron(s) or muon(s) with opposite charge and $\not{E}_T > 25$ GeV. Vetos to reject $t\bar{t}$ and Z events are applied. Table 1 summaries the number of data candidates, estimated background events and expected signal. The results are found consistent with the SM WW production and background, but a cross section measurement has not been derived at this time due to the lack of statistics.

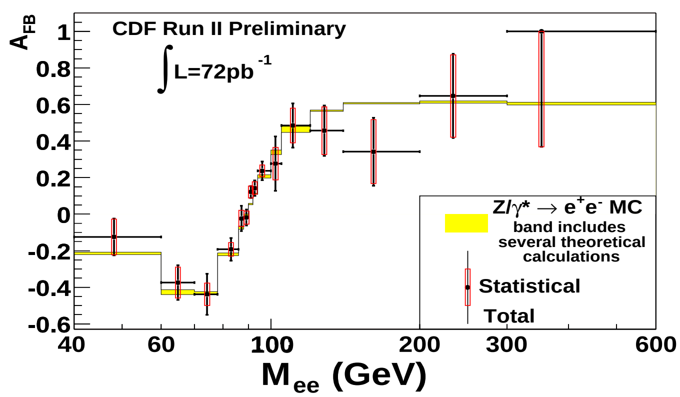

Figure 3: *CDF measurement of the forward-backward asymmetry, A_{FB}, of electron-positron pairs compared with theoretical predictions.*

Table 1: *WW to dilepton results in 72 pb^{-1}.*

Source	ee	$\mu\mu$	eμ	ll
Backgrounds	0.29 ± 0.13	0.46 ± 0.18	0.77 ± 0.60	1.52 ± 0.64
$WW \rightarrow ll\nu\nu$	0.54 ± 0.12	0.65 ± 0.14	1.55 ± 0.34	2.74 ± 0.59
Data	1	0	1	2

6 Top Quark Production Cross Section

To this date, all direct measurements of top quark have been performed at the Tevatron, where top quarks are pair produced via $q\overline{q}$ annihilation (90%) and gg fusion (10%). Within the SM, top quark decay almost exclusively to Wb. The $t\bar{t}$ *dilepton* channel, where both W's decay leptonically, to e or μ ($t\bar{t} \rightarrow WbW\overline{b} \rightarrow l\nu_l bl'\nu_{l'}\overline{b}$), has the smallest branching ratio of 5%. In the so-called *lepton plus jets* channel, where one W decays leptonically and the other hadronically ($t\bar{t} \rightarrow WbW\overline{b} \rightarrow q\overline{q}'bl\overline{\nu}_l\overline{b} + \overline{l}\nu_l bq\overline{q}'\overline{b}$), the branching ratio is in the order of 30%. Due to the increase in the center of mass energy to from 1.8 TeV in Run I to 1.96 TeV in Run II, the $t\bar{t}$ cross section will increase by about 30%.

6.1 $\sigma_{t\bar{t}}$ in the *dilepton* channel

Dilepton $t\bar{t}$ events are selected by requiring two central isolated high-p_T electron or muon of opposite charge, $\not{E}_T > 25$ GeV and at least 2 jets within $|\eta| < 2.0$

Table 2: $t\bar{t}$ *dilepton results for 72 pb^{-1}.*

Source	ee	$\mu\mu$	eμ	ll
All Backgrounds	0.103 ± 0.056	0.093 ± 0.054	0.100 ± 0.037	0.30 ± 0.12
SM $t\bar{t} \rightarrow l\nu_l b l'\overline{\nu}_{l'}\overline{b}$	0.47 ± 0.05	0.059 ± 0.07	1.44 ± 0.16	2.5 ± 0.3
Data	1	1	3	5

and $E_T > 10$ GeV. Drell-Yan ($Z^0/\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$), are rejected by requiring that the the dilepton invariant mass, M_{ee} or $M_{\mu\mu}$ to be outside the range of 76 to 106 GeV/c^2. In order to eliminate instrumental contributions to the $\not{E}_T$ due to mismeasured energies of lepton or jets, CDF requires $\not{E}_T > 50$ GeV if $\Delta\phi(\not{E}_T, l \text{ or } j) < 20^o$ [1]. Finally, to enhance the signal to background ratio, $H_T > 200$ GeV[2] is required. The main background processes that remain after this selection are dibosons (WW, WZ), Drell-Yan ($Z^0/\gamma^* \rightarrow e^+e^-, \mu^+\mu^-$), $Z^0/\gamma^* \rightarrow \tau^+\tau^-$ and *fake lepton*. Table 2 summaries the total background estimate, the expected $t\bar{t}$ *dilepton* signal and the number of data candidates. Figure 4 (left) shows the dilepton candidates and the expected $t\bar{t}$ MC with $M_{top} = 175$ GeV/c^2. The cross section is measured to be:

$$\sigma_{t\bar{t}} = 13.2 \pm 5.9 \text{ (stat.)} \pm 1.5 \text{ (sys.)} \pm 0.8 \text{ (lum.) p}b \tag{14}$$

and is found to be higher but consistent with the NLO prediction of $6.70^{+0.71}_{-0.88}$pb [4].

6.2 $\sigma_{t\bar{t}}$ in the *lepton+jets* channel

The *letpton plus jets* event selection consists of requiring one central isolated high-p_T electron or muon, $\not{E}_T > 20$ GeV, at least 1 jet within $|\eta| < 2.0$ and $E_T > 15$ GeV and Z boson veto. The 1 and 2 jets bins are used as a control sample and only ≥ 3 jets are used to compute $\sigma_{t\bar{t}}$. To increase the signal to background ratio, the Silicon Vertex Detector is used to identify the b-quark displaced vertices. A jet is b-tagged if it contains a secondary vertex with at least two charged tracks and $L_{xy}/\sigma_{xy} > 3$ [3]. The efficiency for identifying at least one b quarks in $t\bar{t}$ decays is about 45% and is measured from $t\bar{t}$ MC and corrected with a data to MC scale factor. The mistags from

[1] $\Delta\phi(\not{E}_T, l \text{ or } j)$ is the azimutal separation between the vector $\not{E}_T$ and the nearest lepton or jet.

[2] H_T is the scalar sum of the transverse energy of the leptons, jets and neutrino in the event.

[3] L_{xy} is the distance in the transverse plane to the beam direction between the secondary and primary vertices. σ_{xy} is the error on L_{xy}.

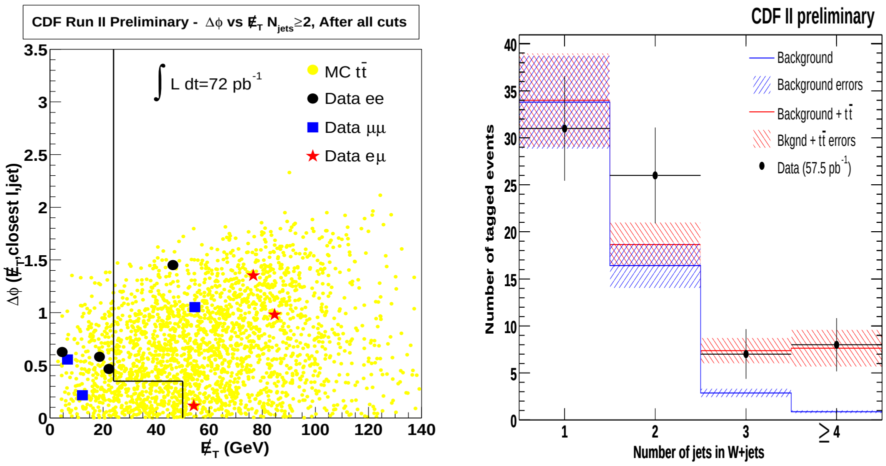

Figure 4: *Left: $t\bar{t}$ dilepton candidates found in 72 pb^{-1} in the plane $\Delta\phi(\not\!\!E_T, l$ or $j)$ versus $\not\!\!E_T$. The yellow dotes are MC Herwig $t\bar{t}$. Right: Number of events in the W+jets sample with at least one b-tag. The* 3$^{\rm rd}$ *and* 4$^{\rm th}$ *bins are used to extract $\sigma_{t\bar{t}}$.*

light quarks and gluon jets are evaluated using the negative tag rate of L_{xy} extracted from inclusive jet samples and applied to the W+jets data. $Wb\bar{b}$ and $Wc\bar{c}$ backgrounds are estimated from W+jets data using the Run I heavy flavor composition in W+jets and the b-tagging efficiency. The non-W background is estimated from W+jets data using the isolation versus $\not\!\!E_T$ method used in the W cross section analyses (see sec.2.1). Other small contribution from WW/WZ, Drell-Yan and single top production are evaluated from the MC. Table 3 summarizes the background estimate, with and without $t\bar{t}$ contribution, and the number of data candidates before and after requiring at least 1 jet with a b-tag. From the 15 candidates in ≥ 3 jets events (see fig.4 right), the cross section is measured to be:

$$\sigma_{t\bar{t}} = 5.3 \pm 1.9 \text{ (stat.)} \pm 0.8 \text{ (sys.)} \pm 0.3 \text{ (lum.) p}b \qquad (15)$$

lower but consistent with the NLO prediction 4).

7 Top Quark Mass Measurement

The most precise determination of the top mass can be obtained by using the *lepton plus jets* sample. The 24 combinations, 12 corresponding to the jet-parton match where every combination has two solutions for the neutrino

Table 3: $t\bar{t}$ *lepton+jets results for* 57.5 pb^{-1}.

Source	W+1jet	W+2jets	W+3jets	W≥4jets
SM Backgrounds	33.8 ± 5.0	16.4 ± 2.4	2.88 ± 0.05	0.87 ± 0.2
SM backgrounds + $t\bar{t}$	34.0 ± 5.0	18.65 ± 2.4	7.35 ± 1.4	7.62 ± 2.0
Events before b-tagging	4913	768	99	26
Events (≥1 b-tag)	31	26	7	8

p_z, can be reduce down to 12 by requiring 1 b-tagged jet and to 4 with 2 b-tagged jets. The method used to reconstruct the top mass consists of using a constraint-fitting technique ($M_{l\nu} = M_W; M_{jj} = M_W; M_t = M_{\bar{t}}$) and choosing the combination with the lowest χ^2. The reconstructed top mass distribution from the data is then compared to the parametrized templates of top plus background Monte Carlo. The top mass is then extracted by fitting the observed and expected distributions using a maximum likelihood method.

CDF first attempt in reconstructing the top mass with Run II data, has used events with one lepton and 4 jets, but without any b-tagging requirement. The top mass obtained (see fig. 5) is:

$$171^{+14.4}_{-12.5}\ \text{(stat.)} \pm 9.9\ \text{(sys.) GeV}/c^2 \tag{16}$$

The systematic error is dominated by the uncertainty on the jet energy measurement, which is currently of 9.3 GeV/c^2 compared to 4.4 GeV/c^2 achieved in Run I. CDF aims to reduce this error to ≈ 2 GeV/c^2.

8 Summary

The W, Z and $t\bar{t}$ production cross sections have been measured in several decay channels by CDF using the first Run II physics quality data. All measurements obtained are in agreement with the theoretical predicition at 1.96 TeV. CDF has calculated the ratio of the W and Z cross section, R, and used it to extract an indirect measurement of the W width. $Z^0/\gamma^* \to e^+e^-$ events have been use to measure the forward-backward asymmetry up to 600 GeV/c^2. CDF has also started selecting $WW' \to ll'\nu\nu$, in order to measure the WW cross section and derive limits on the anomalous WWZ and WWγ couplings. Finally, the first attempt in measuring the top quark mass using Run II data has been made.

9 Acknowledgments

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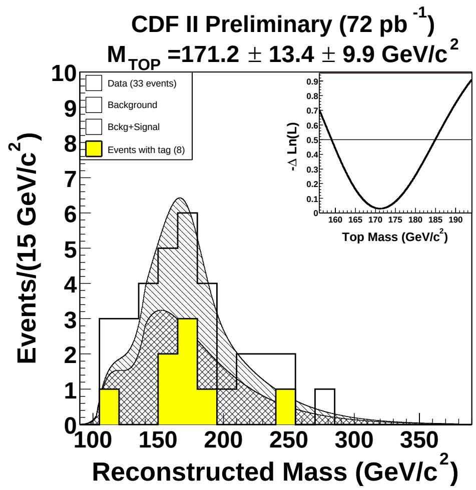

Figure 5: *Reconstructed top mass distribution of pre-tagged l+4jets events. The yellow histogram represents events with a b-tag jet, but the information is not used in the top mass reconstruction.*

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