TOP QUARK PAIR CROSS SECTION MEASUREMENTS AT THE TEVATRON

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for the D0 and CDF Collaborations

Outline

- Motivation
- Top quark pair production cross section in lepton + jets channel
  - Using kinematical information of events
  - Using b-jet identification algorithms
- Top quark pair production cross section in dilepton channel
- Top quark pair production cross section in all jets channel
- Combined ttbar cross sections
- Conclusions

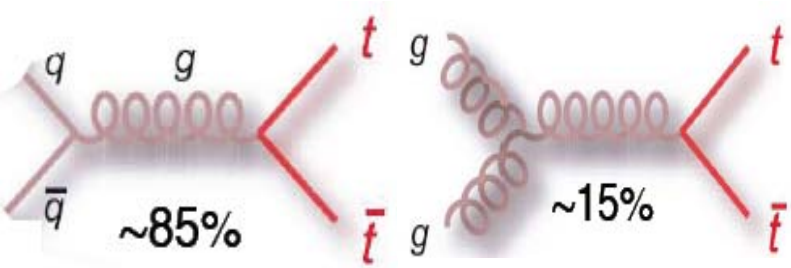
Motivation for accurate measurements of ttbar production cross section

- Top quark, the heaviest known quark, was discovered in 1995 at the Tevatron by CDF and D0 experiments
- Test of perturbative QCD at high Q^2
- Sensitive to new physics
  - Measure in different channels
    - Non-SM top decays ($t \rightarrow H^+$ or stop) modify contributions to different channels
    - di-lepton/l+jets ratio probes non-W top decays
  - Measure with different techniques
    - b-tagging method
    - Kinematic fit methods
- Gives input for searches for which top quark pair production is a dominant background.

Top quark production and decay

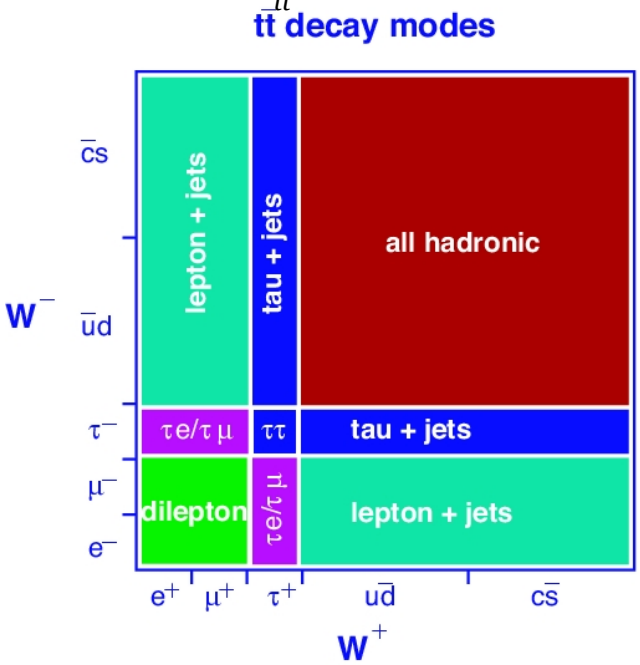
- Top quark pair production via strong interaction. For m_t=172.5 GeV,

$$\sigma_{t\bar{t}} = 7.46^{+0.66}_{-0.80}\ \text{pb}\ \ (\text{S.Moch and P.Uwer})$$
$$\sigma_{t\bar{t}} = 7.27^{+0.76}_{-0.85}\ \text{pb}\ \ (\text{N.Kidonakis and R.Vogt})$$
$$\sigma_{t\bar{t}} = 7.14^{+0.76}_{-0.87}\ \text{pb}\ \ (\text{Cacciari } et\ al.)$$



Theoretical $\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} \sim 9\%$

- Assuming unitarity of 3-generation CKM matrix $\Rightarrow$ B(t$\rightarrow$Wb) ~ 100%
- Distinguish top quark pair events by the consequent decays of the W bosons:
  - Both W$\rightarrow\ell\nu$ - dilepton channels
  - One W$\rightarrow\ell\nu$ and other W$\rightarrow$qq' – lepton+jets channels
  - Both W $\rightarrow$qq' – all jets events



ttbar cross section in lepton + jets channel

- Cross section:

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_B}{\varepsilon \int dtL}$$

Number of observed events in selected sample

Number of background events in selected sample

Ttbar selection efficiency

Integrated luminosity

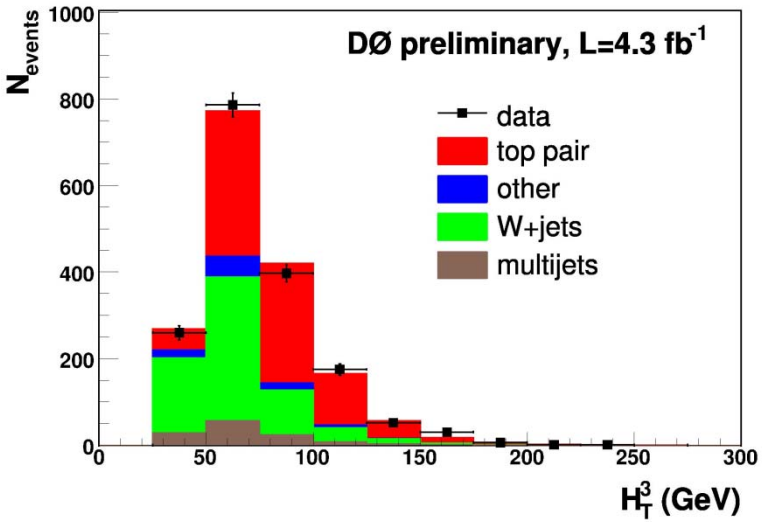
- Two methods, kinematic and using b-tagging, to separate signal (ttbar) from backgrounds
- Backgrounds:
  - W+jets production (data driven estimation)
  - QCD multijet production (data driven estimation)
  - Single top production (estimated using theoretical cross section)
  - Small physics backgrounds like VV production, Z+jets,… (estimated using theoretical cross sections)

Kinematic methods for ttbar cross section measurements

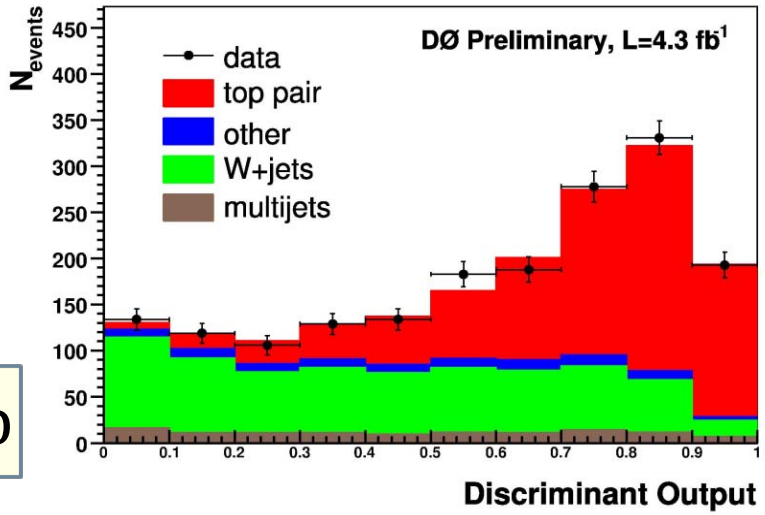
- Event selection at D0:
  - One high p_T (>20 GeV) e or μ
  - Large missing E_T (>20 GeV)
  - At least two high p_T jets (>20GeV)
  - Leading jet p_T >40 GeV
- Event selection at CDF:
  - One high p_T (>20 GeV) e or μ
  - Large missing E_T (>35 GeV)
  - At least three high p_T jets (>20GeV)
  - Leading jet p_T >35 GeV
- Use difference in kinematics of signal events (ttbar) and major background (W+jets)
  - Use variables that provide the maximal separation between signal and background and are well described by Monte Carlo simulation
  - D0 uses Boosted Decision Trees (BDT) technique to distinguish between signal and background
  - CDF uses Artificial Neural Network for the same purpose

D0 results obtained with kinematic fit

- Used 7 variables as input for BDT
- Performed analysis in three jet multiplicity bins, 2 jets, 3 jets and ≥4 jets
- Data set 4.3 fb^{-1}; used σ_{tt} = 7.7 pb to draw the expected signal
- Largest sources of the final uncertainly



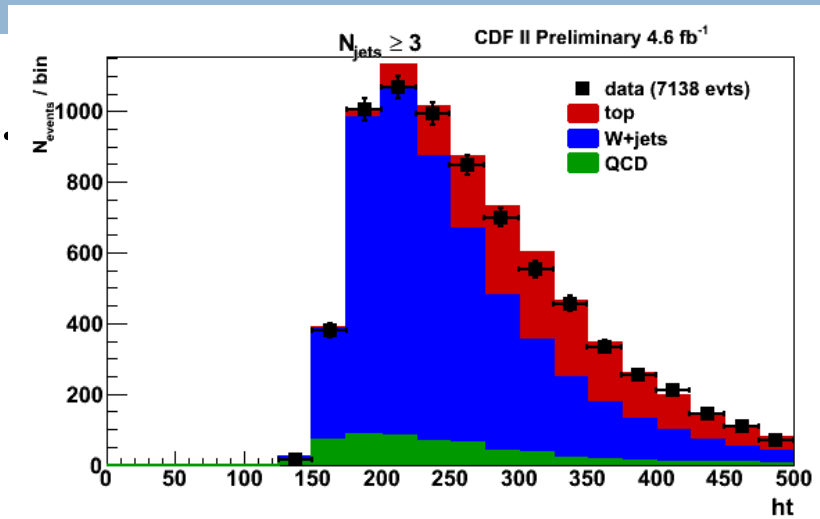
Source	$+\Delta\sigma$, pb	$-\Delta\sigma$, pb
Statistical	+0.13	–0.12
Electron ID	+0.18	–0.16
Signal modeling	+0.14	–0.13
Luminosity	+0.50	–0.43



$$\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70} \ (\text{stat.} + \text{syst.} + \text{lumi}) \ \text{pb}$$

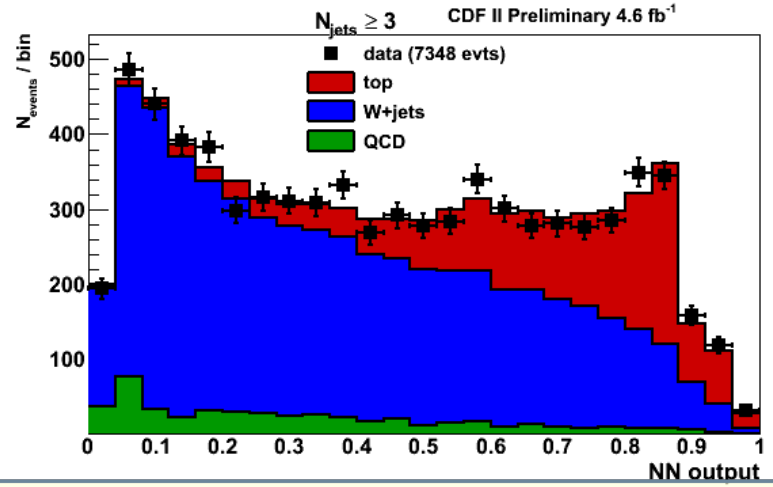
CDF results with ANN

- Used NN technique with 7 variables.
- To reduce the luminosity error, replace it with variation of σ_Z^{theor} using relation: $\frac{\sigma_{t\bar{t}}^{meas}}{\sigma_Z^{meas}}\sigma_Z^{theor}$



- Leading sources of syst. uncertainties

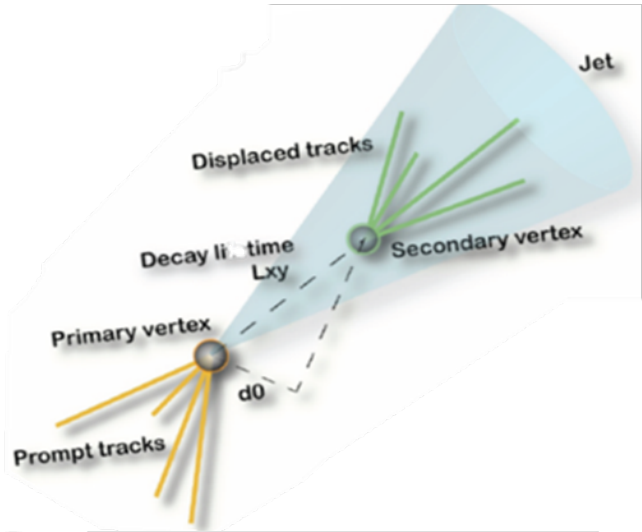
Source	+Δσ, %	–Δσ, %
Jet ET scale	+2.93	–2.9
W+jets Q^2 scale	+1.33	–1.33
Signal modeling	+2.50	–2.50
Z theory	+1.99	–1.99

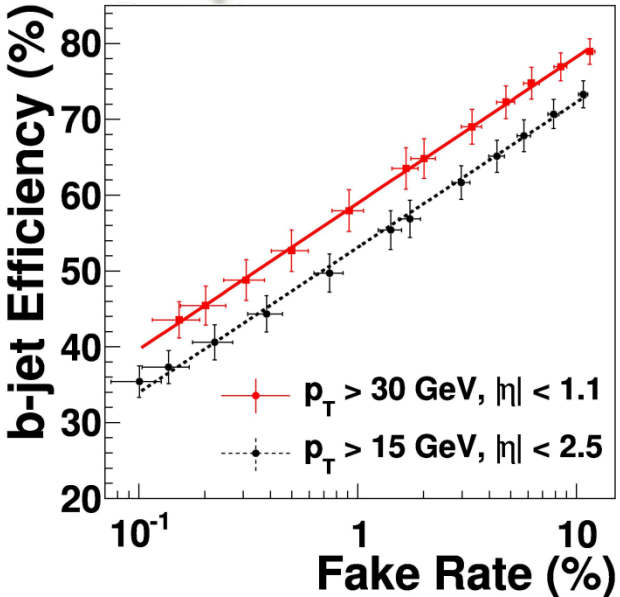


$$\sigma_{t\bar{t}} = 7.63 \pm 0.37\,(\text{stat.}) \pm 0.35\,(\text{syst.}) \pm 0.15\,(\text{theor.})\ \text{pb}; \quad \frac{\Delta\sigma}{\sigma} = 7\%$$

B-tagging for ttbar cross section measurements

- Dominant backgrounds have small *b*-jet fractions
- Requirement of b-jets presence significantly improves signal-to-background ratio
- Assume that Br(t→bW) = 1
- Both experiments employ NN b-tagging algorithms, incorporating information from track impact parameters, a possible secondary vertex, semileptonic decays and others.
- Typical efficiency per b-jet is 50-60% at 1% mistag rate





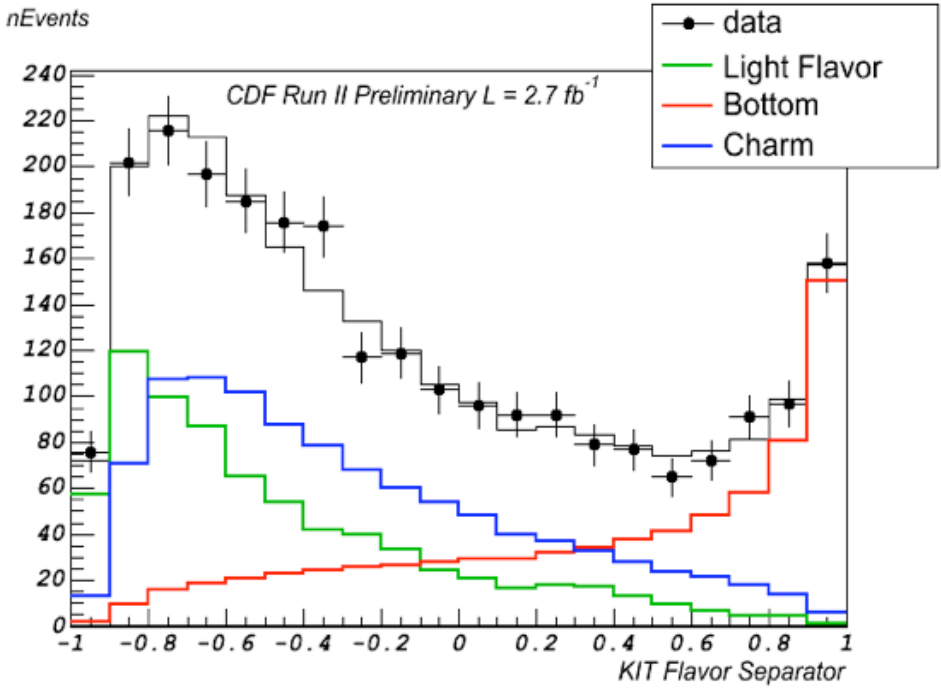
Heavy flavor background

- W+heavy flavor jets (W+bb, W+cc) production becomes most important BG
- Normalize ALPGEN W+jets to data before tagging
- Determine heavy flavor fraction in ALPGEN W+jets
- Measure correction factor K to heavy flavor fraction:

$$N_{W+HF}^{data\ fit} = N_{W+jets}^{data} \cdot K \cdot f_{W+HF}^{Alpgen}$$

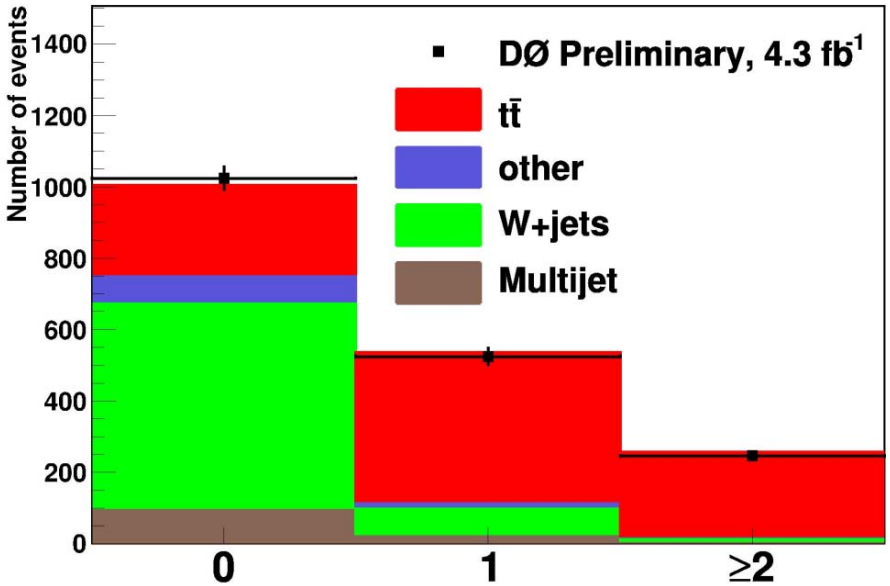
- K factors

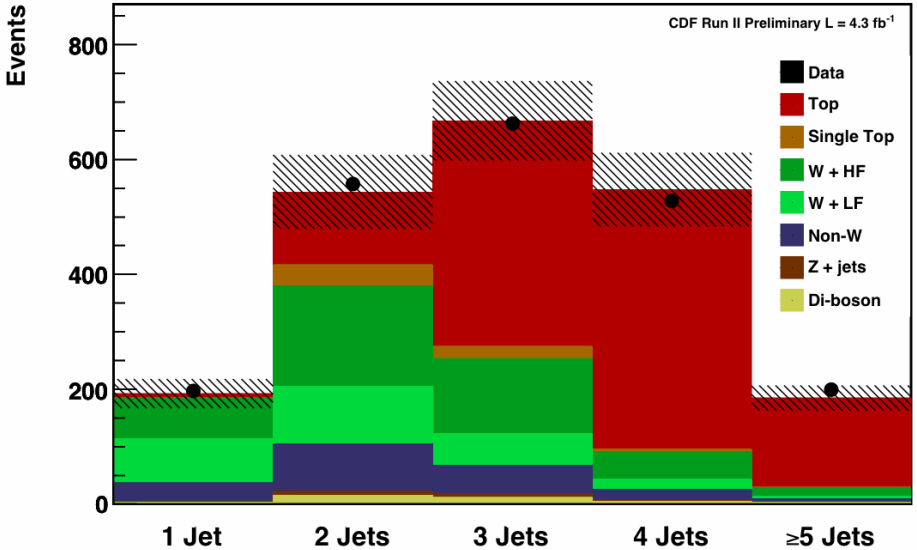
$K_{CDF} = 1.5 \pm 0.3$
$K_{D0} = 1.5 \pm 0.45$



ttbar cross section measurement in l+jets channel using b-tagging

- D0: Split sample into 0-tags, 1-tag and 2 or more tags
- CDF: additional selection cut on H_T>230 GeV



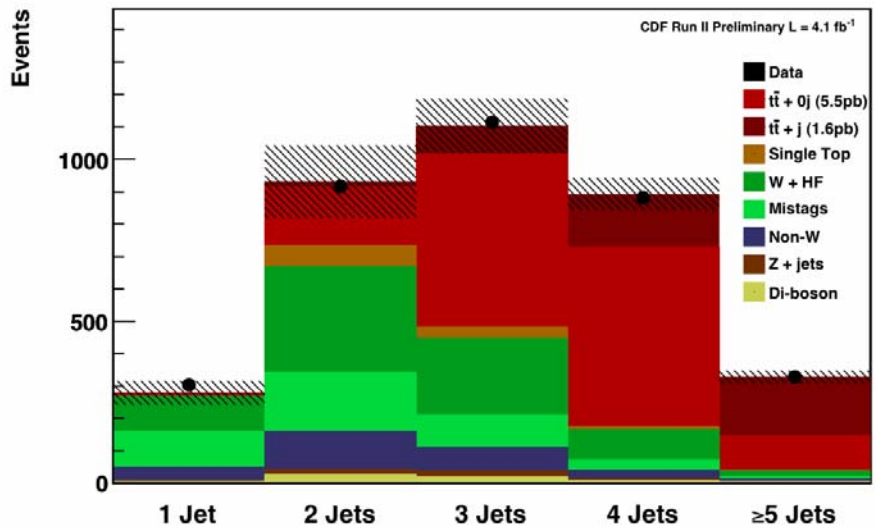


$$\sigma_{t\bar{t}}^{\mathrm{D0}} = 7.93^{+1.04}_{-0.91}\ \left(\mathrm{stat.} + \mathrm{syst.} + \mathrm{lumi}\right)\ \mathrm{pb}$$

$$\sigma_{t\bar{t}}^{\mathrm{CDF}} = 7.32 \pm 0.36\,(\mathrm{stat.}) \pm 0.59\,(\mathrm{syst.}) \pm 0.14\,(\mathrm{Z\ theor.})\ \mathrm{pb}$$

ttbar+1 jets cross section measurement

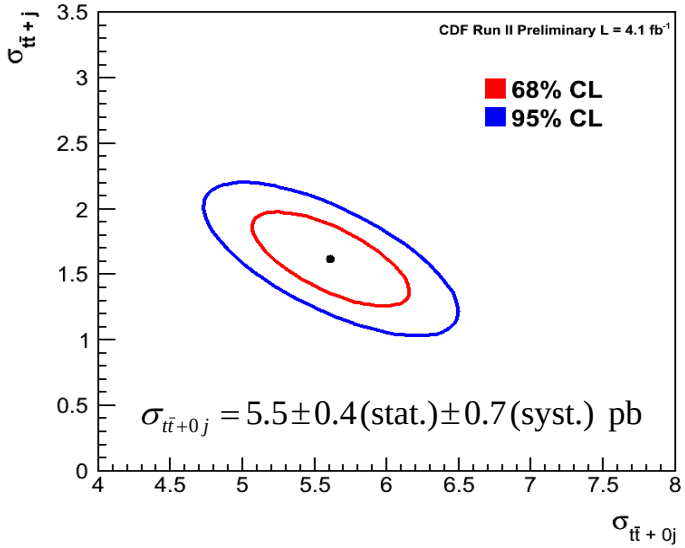
- Important test of pQCD
- Substantial BG for new physics searches at the LHC
- Measured by CDF using b-tagging method
- Performed simultaneous fit of ttbar+0 jets and ttbar+1 jet cross sections



$$\sigma^{\text{meas}}_{t\bar{t}+1j} = 1.6 \pm 0.2(\text{stat.}) \pm 0.5(\text{syst.})\ \text{pb}$$

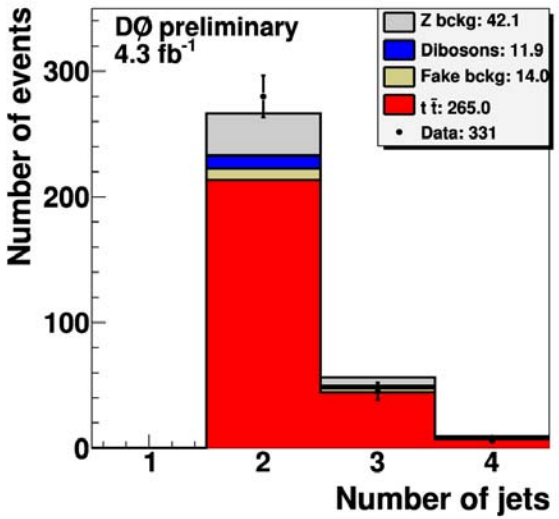
$$\sigma^{\text{theor}}_{t\bar{t}+1j} = 1.79^{+0.16}_{-0.31}\ \text{pb}$$

S. Dittmaier, P.Uwer, and S.Weinzierl, arXiv:0810.0452v2 [hep-ph]



ttbar cross section in dilepton channels (1)

- D0 selection of events
  - Two opposite charge leptons with p_T >15 GeV
  - Missing E_T >20 GeV in ee, μμ; no MET cut in eμ
  - At least two high p_T jets (>20GeV)
  - eμ channel: HT>110 GeV; ee and μμ channels: use BDT to discriminate signal from BG
- Backgrounds:
  - Physics: $Z/\gamma^* \to \ell^+\ell^-$
  - Instrumental: fake electrons (which are actually jets), fake isolated muons (which are not isolated)

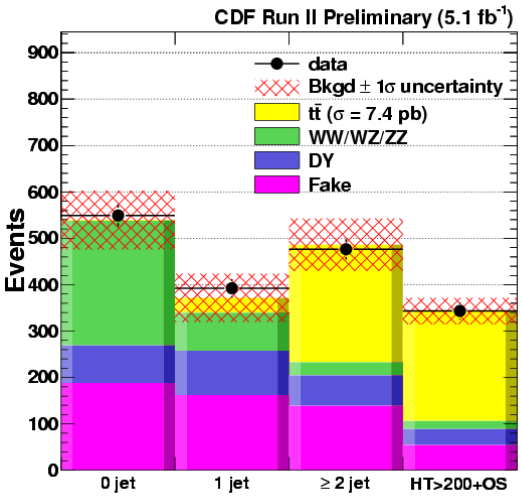


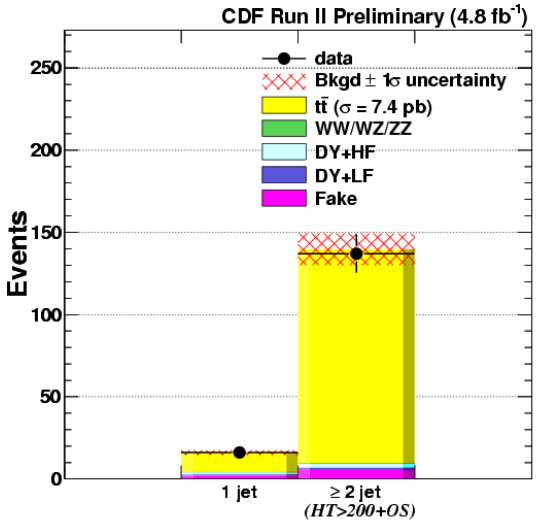
	ee	eμ	μμ
$Z \to \ell\ell$	$8.5^{+3.4}_{-3.4}$	$11.9^{+2.7}_{-2.5}$	$21.7^{+5.6}_{-6.2}$
Dibosons	$2.1^{+0.8}_{-0.8}$	$6.5^{+2.1}_{-2.0}$	$3.3^{+1.1}_{-1.2}$
Instrumental background	$0.1^{+0.2}_{-0.1}$	$10.7^{+4.1}_{-3.9}$	$3.2^{+0.8}_{-0.7}$
$t\bar{t} \to \ell\ell jj$ ($\sigma = 7.45$ pb)	$36.9^{+3.8}_{-3.8}$	143.4 ± 14.3	$45.1^{+4.4}_{-4.3}$
Total expected events	47.6 ± 6.2	$172.6^{+16.5}_{-16.4}$	$73.3^{+8.1}_{-8.8}$
Data	55	204	72

$$\sigma_{t\bar{t}} = 8.4 \pm 0.5\,(\text{stat.})\,^{+0.9}_{-0.8}\,(\text{syst.})\,^{+0.7}_{-0.6}(\text{lumi.})\ \text{pb}$$

ttbar cross section in dilepton channels (2)

- CDF selection:
  - At least two jets with pT>15 GeV
  - Missing ET >25 GeV (>50 GeV if angle between lepton and MET directions is small)
  - Two opposite charged leptons
  - H_T > 200 GeV
  - At least 1 jets is identified as a b-jet
- Results:



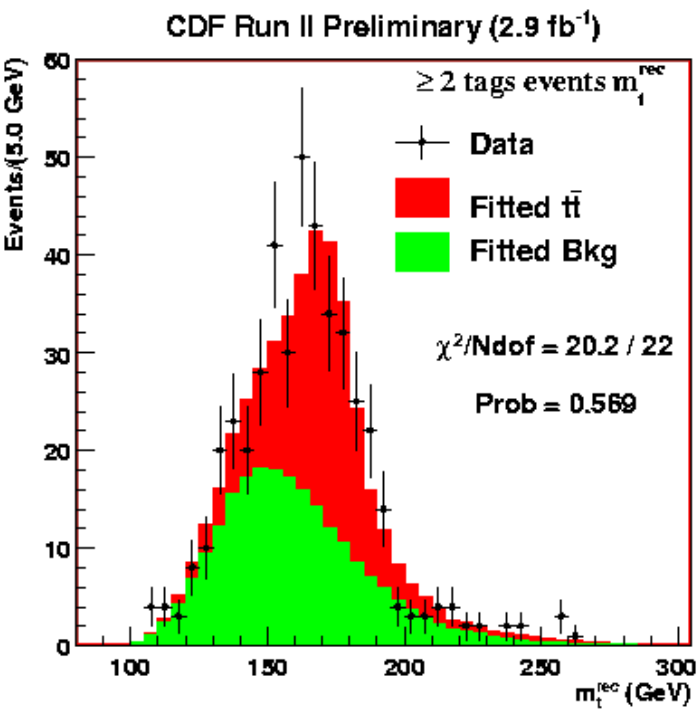


$$\sigma_{t\bar{t}}^{no-btag} = 7.4 \pm 0.6(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.5(\text{lumi.}) \ \text{pb}$$

$$\sigma_{t\bar{t}}^{btag} = 7.3 \pm 0.7(\text{stat.}) \pm 0.5(\text{syst.}) \pm 0.4(\text{lumi.}) \ \text{pb}$$

ttbar cross section measurement in all jets channel

- CDF: The measurement is performed using the signal yields derived from a top quark mass measurement with in situ measurement of the (JES) using 2-D Template Method (TMT2D)
- Split sample into 1-tag and 2-tags events samples

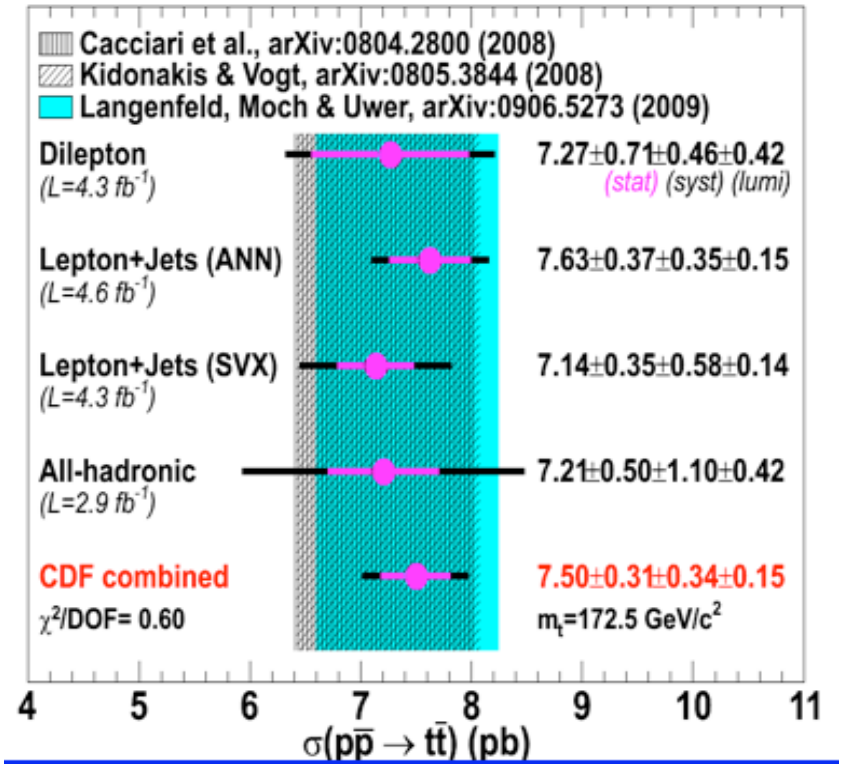


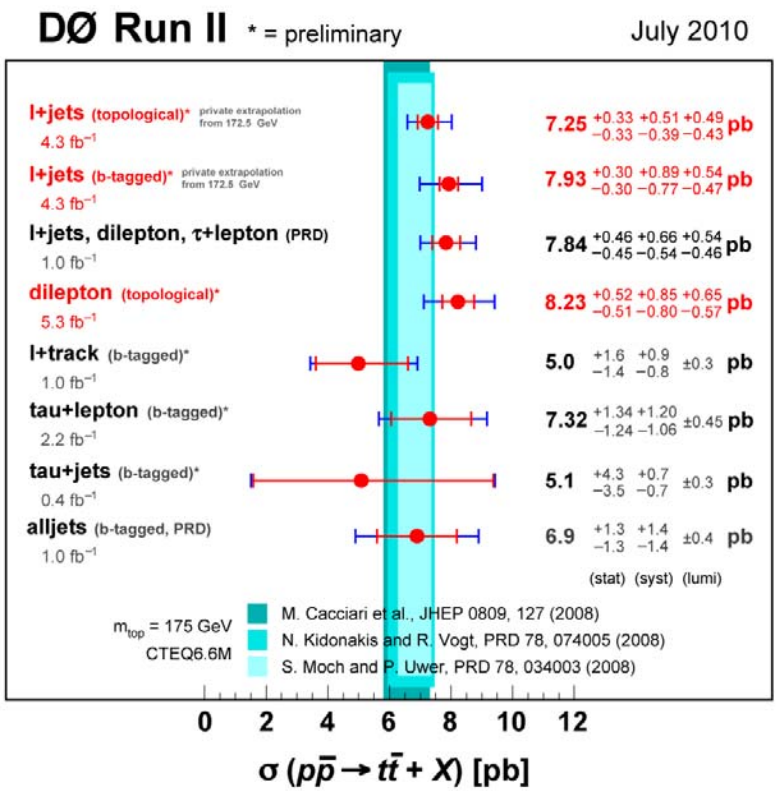
CDF preliminary, L = 2.9 fb^{-1}			
	Symbol	1 tag	$\geq$ 2 tags
Top mass (GeV/c^2)	M_{top}	$174.8 \pm 2.4^{+1.2}_{-1.0}$	
JES displacement	ΔJES	$-0.3 \pm 0.47^{+0.34}_{-0.37}$	
Observed candidates	n_{obs}	3452	441
Expected background	$n_{(b,exp)}$	2785 ± 83	201 ± 29
Fitted background	$n_{(b,fit)}$	2802 ± 70	220 ± 21
Signal from fit	$n_{(s,fit)}$	643 ± 80	216 ± 25

$$\sigma_{t\bar{t}} = 7.2 \pm 0.5(\text{stat.}) \pm 1.1(\text{syst.}) \pm 0.4(\text{lumi.}) \ \text{pb}$$

CDF and D0 combined results on ttbar cross section measurements

Results of several analyses performed on 2.9-4.6 fb^{-1}





$$\sigma_{t\bar{t}}^{\mathrm{CDF}} = 7.5 \pm 0.31(\mathrm{stat.}) \pm 0.34(\mathrm{syst.}) \pm 0.15(\mathrm{lumi.})\ \ \mathrm{pb} \qquad \frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = 6.5\%$$

Conclusions

- Updated ttbar production cross section measurements from D0 and CDF are in agreement with the SM.
- Tevatron experiments have measured the ttbar production cross section with an accuracy of 6.5% which exceeds the theoretical uncertainty.
- Presented results are based on the ~4.6 fb^{-1} of data; have ~8 fb^{-1} on tape
  - Expect results with higher precision, probing further the SM
- CDF and D0 are working on the combination of Tevatron results on ttbar production cross section measurement

Background slides

ttbar x-section calculations

Data/MC agreement for variables used in NN, BDT

Systematic errors

Ttbar x-section calculation in BDT analysis

- D0 kinematic Fit: Perform a maximum likelihood fit to the BDT discriminants distributions to get a number of ttbar pairs in the sample $L\left(N_t^{t\bar{t}}, N_t^W, N_t^{MC}, N_t^{QCD}\right) = \left[\prod_i p\left(n_i^o, \mu_i\right)\right] p\left(N_{l-t}^o, N_{l-t}\right)$

(here p is Poisson pdf for n observed events in i-th bin of the discriminant, m is expected n of events in this bin, and N^W, N^{MC}(diboson, single top, Z+jets), N^{QCD} are numbers of corresponding types of events.

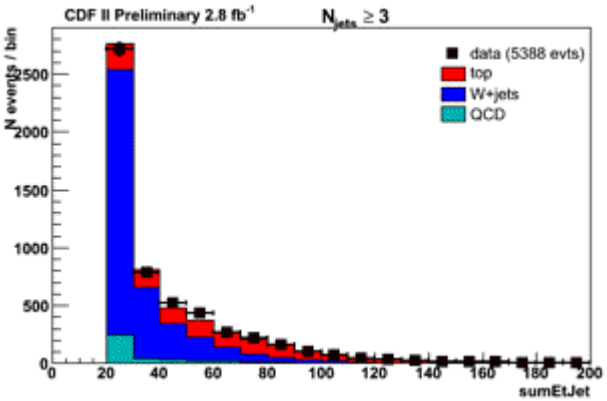
- The negative of the log-likelihood function is minimized

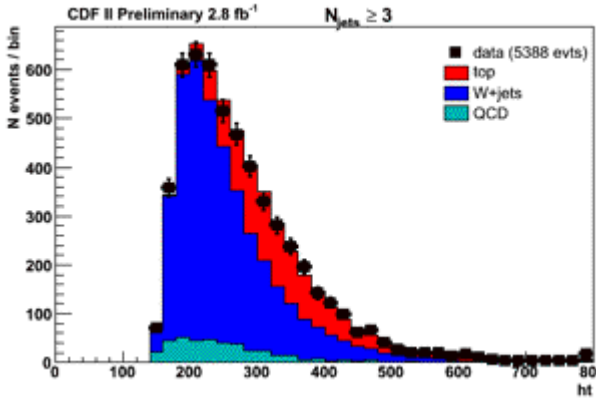
$$-\log L(N_t^{t\bar{t}}, N_t^W, N_t^{MC}, N_t^{QCD}) \cong \sum_i \left(-n_i^o \log \mu_i + \mu_i\right) - N_{l-t}^o \log N_{l-t} + N_{l-t}$$

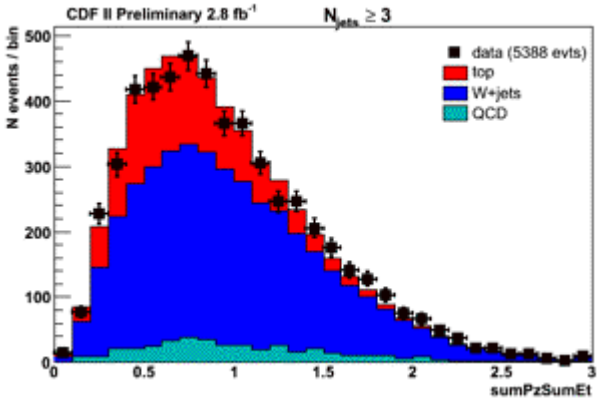
- The extraction of is performed using nuisance parameter method
  - Each individual source of systematic uncertainty is allowed to float
  - All results are provided for m_t=172.5 GeV

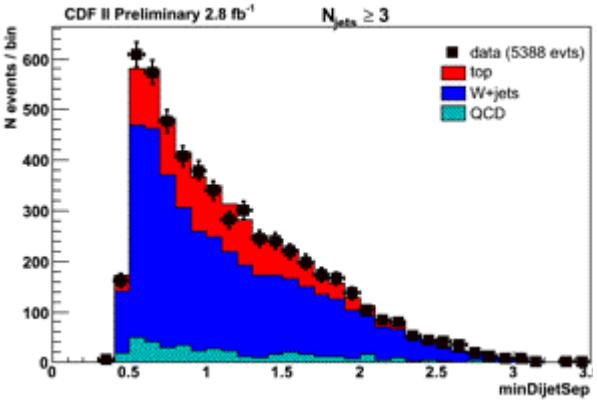
Data/MC agreement in CDF ANN analysis

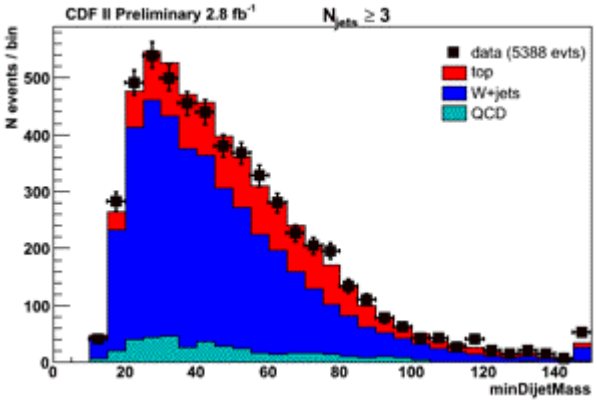
- CDF variables used in ANN analysis

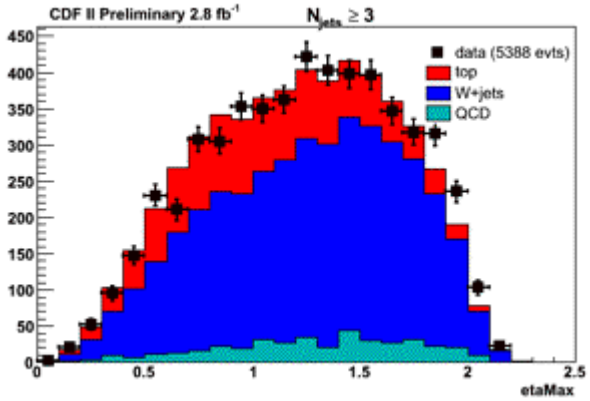






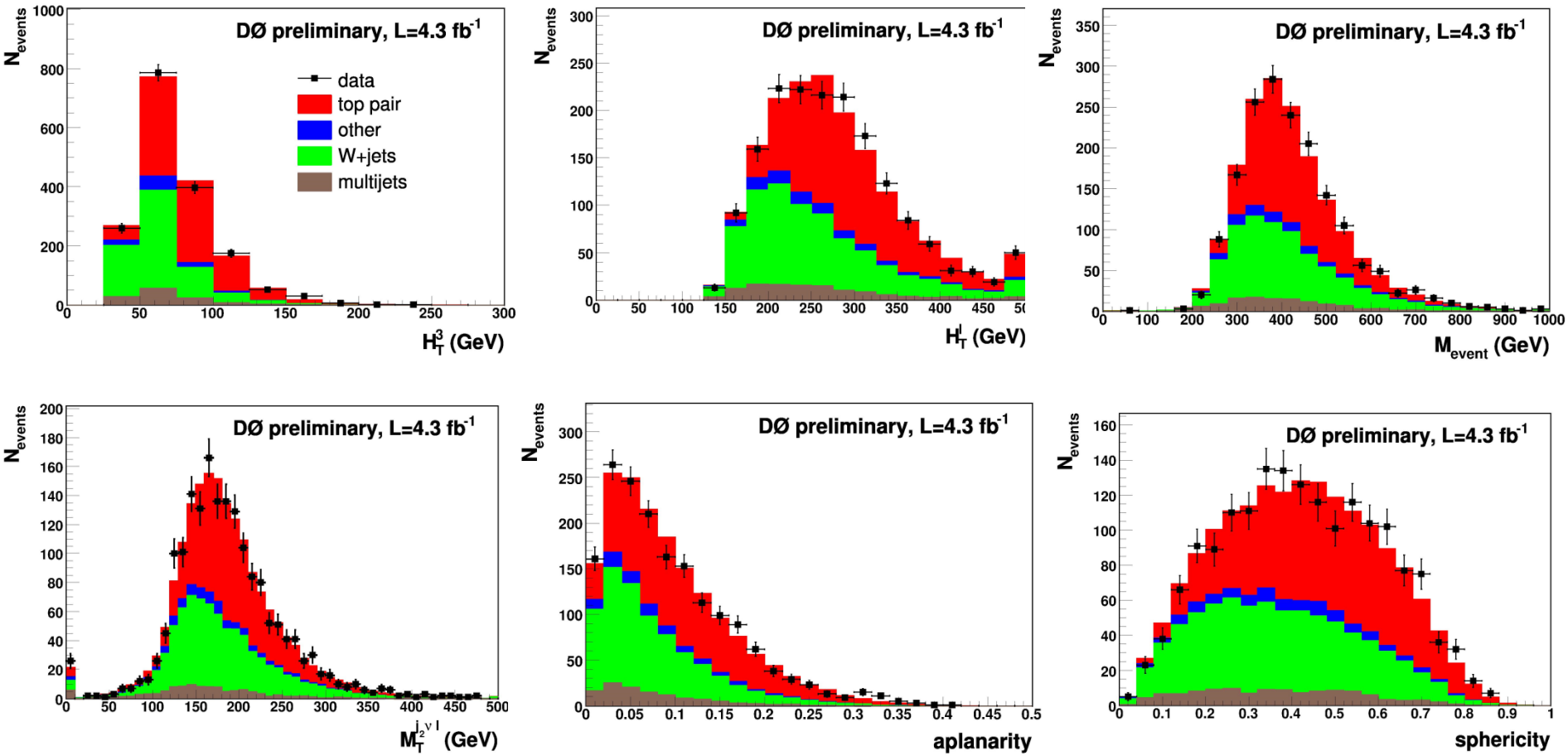






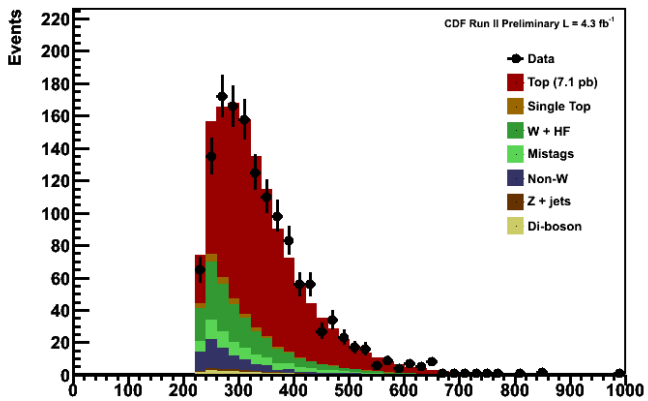
Data/MC agreement in D0 BDT analysis

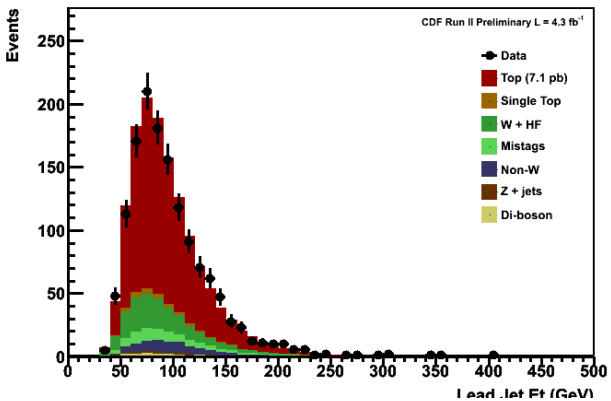
- D0 variables used in BDT analysis

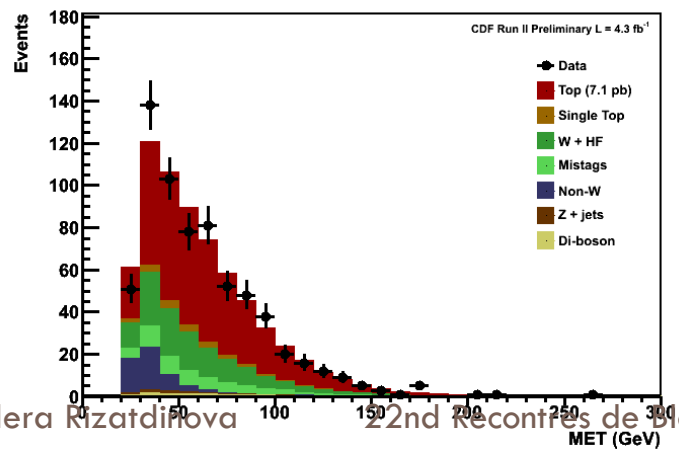


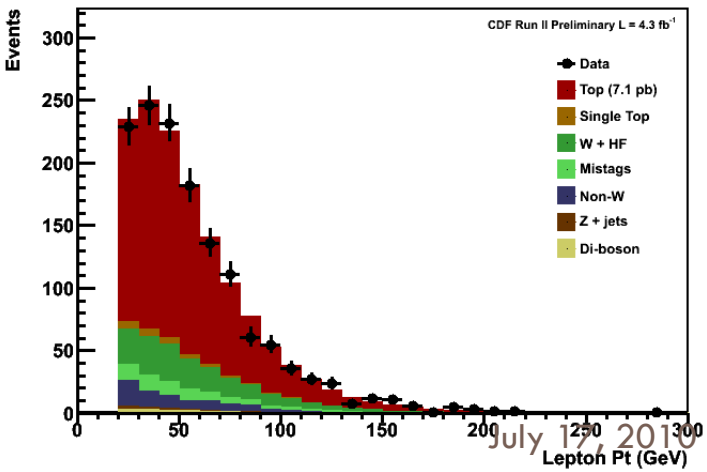
CDF b-tag analysis: data/MC comparison

- CDF analysis with secvtx tagger
- Shown are distributions of some variables in 4-jet multiplicity bin









Systematic errors on kinematic ttbar cross section measurements

- ANN (CDF analysis)

CDF II Preliminary

Effect	Top Cross section neg shift	pos shift	symmetrised
Statistical top	-4.82	+4.88	4.85
Statistical Z	-0.32	+0.32	0.32
Jet E_T Scale	-2.90	+2.93	2.91
W+jets Q^2 Scale	-1.33	+1.33	1.33
Z+jets Q^2 Scale	-0.27	+0.27	0.27
$t\bar{t}$ IFSR	-0.42	+0.42	0.42
QCD shape	-0.48	+0.48	0.48
QCD fraction	-0.81	+0.81	0.81
$t\bar{t}$ generator	-2.50	+2.50	2.50
$t\bar{t}$ gen. branching ratio	-0.21	+0.95	0.58
$t\bar{t}$ PDF	-0.79	+1.10	0.94
$t\bar{t}$ Colour Reconnection	-0.16	+0.16	0.16
Other EWK	-1.00	+1.00	1.00
MC statistics	-0.14	+0.14	0.14
CEM ID SF	-0.48	+0.46	0.47
CMUP ID SF	-0.03	+0.03	0.03
CEM trigger efficiency	-0.25	+0.25	0.25
CMUP trigger efficiency	-0.39	+0.39	0.39
Z_{vtx} SF	-0.00	+0.00	0.00
nJet (NLO)	-0.02	+0.02	0.02
CEM energy Scale	-0.08	+0.08	0.08
CMUP energy Scale	-0.02	+0.02	0.02
Z Background	-0.04	+0.04	0.04
Track ID	-0.61	+0.60	0.60
Luminosity	-0.39	+0.00	0.19
Total systematic	-4.51	+4.67	4.57
Total uncertainty ratio	-6.60	+6.75	6.66
Z theory	-1.99	+1.99	1.99
Total uncertainty	**-6.89**	**+7.04**	**6.95**

- BDT (D0 analysis)

Summary of nuisance parameter likelihood with systematics on cross section			
Source	Offset	$+\sigma$	$-\sigma$
Statistical only	+7.05	+0.32	-0.32
Event preselection	+0.02	+0.13	-0.12
Muon identification	-0.03	+0.07	-0.05
Electron identification and smearing	+0.21	+0.18	-0.16
Luminosity reweighting	+0.00	+0.02	+0.00
$p_T(Z)$ reweighting	+0.01	+0.02	+0.00
signal modeling	-0.14	+0.14	-0.13
Color reconnection	-0.01	+0.05	-0.04
ISR/FSR variation	-0.00	+0.00	+0.00
EM triggers	-0.00	+0.00	+0.00
Muon triggers	-0.12	+0.12	-0.11
Jet energy scale	+0.21	+0.00	+0.00
Vertex confirmation	-0.20	+0.07	-0.04
b-Jet energy scale	-0.00	+0.03	-0.01
Jet energy resolution	+0.60	+0.07	-0.06
Jet reconstruction and identification	-0.08	+0.08	-0.07
b fragmentation	-0.03	+0.08	-0.07
Matrix method ϵ_{QCD} and ϵ_{sig}	-0.07	+0.00	+0.00
Monte Carlo background x-section	+0.01	+0.00	-0.01
Monte Carlo signal & bkg branching ratio	+0.00	+0.07	-0.05
Monte Carlo bkg scale factors	+0.05	+0.03	-0.01
Monte Carlo statistics	+0.00	+0.04	-0.02
W fractions matching + higher order effects	+0.08	+0.04	-0.04
PDF	+0.01	+0.09	-0.07
Luminosity	+0.30	+0.50	-0.43
Event statistics for matrix method	-0.00	+0.01	+0.00
Total systematics (quad sum of the above)	+0.82	+0.62	+0.53
Total error (nuisance parameter fit)	7.70	+0.79	-0.70

Systematics on b-tagging analysis

- CDF analysis

Systematic	$\Delta\sigma/\sigma$ %
Jet Energy Scale	4.0
Tagging Model	4.5
Mistag Model	1.1
W+HF Correction	4.0
Luminosity	0.3
QCD Fraction	0.2
MC Generator	2.7
W Branching Ratio	0.6
ISR/FSR	0.7
Trigger EFF/ID	0.6
Track ID	0.6
PDF	1.4
Z Background	0.1
NJet SF	0.0
Q^2	0.3
Color Recon	0.4
Total	8.05

CDF Run II Preliminary $\mathcal{L} = 4.3$ fb^{-1}

- D0 Analysis

Summary of nuisance parameter likelihood with systematics on cross section			
Source	Offset	$+\sigma$	$-\sigma$
Statistical only	+7.83	+0.28	-0.28
Event preselection	-0.00	+0.14	-0.13
Muon identification	-0.06	+0.07	-0.07
Electron identification and smearing	+0.24	+0.18	-0.17
Luminosity reweighting	-0.00	+0.02	+0.00
$p_T(Z)$ reweighting	-0.00	+0.00	-0.00
signal modeling	+0.11	+0.16	-0.15
Color reconnection	-0.01	+0.07	-0.06
ISR/FSR variation	-0.00	+0.00	-0.03
EM triggers	+0.03	+0.06	-0.06
Muon triggers	-0.20	+0.13	-0.12
Jet energy scale	+0.08	+0.12	-0.12
Vertex confirmation	+0.07	+0.22	-0.21
b-Jet energy scale	+0.00	+0.04	-0.04
Jet energy resolution	-0.01	+0.02	-0.02
Jet reconstruction and identification	+0.04	+0.12	-0.11
Taggability in data	-0.01	+0.10	-0.09
b-tag TRF	-0.21	+0.33	-0.32
c-tag TRF	+0.00	+0.00	+0.00
light tag TRF	-0.01	+0.10	-0.11
b fragmentation	+0.00	+0.02	-0.02
Matrix method ϵ_{QCD} and ϵ_{sig}	+0.01	+0.04	-0.04
Monte Carlo background x-section	-0.00	+0.02	-0.02
Monte Carlo signal & bkg branching ratio	-0.00	+0.07	-0.07
Monte Carlo bkg scale factors	-0.00	+0.04	-0.04
Monte Carlo statistics	-0.01	+0.12	-0.12
PDF	-0.00	+0.19	-0.17
Luminosity	-0.02	+0.53	-0.46
Event statistics for matrix method	-0.00	+0.06	-0.06
Total systematics (quad sum of the above)	-0.04	+0.84	+0.77
Total error (quad sum of all above)	7.93	+1.04	-0.91

Systematics on dilepton analyses

- CDF
  - Pretag analysis

Source	Systematic Error (%)
Lepton ID	2.2
MC Generator	1.9
ISR/FSR	1.3
PDF's	0.6
Color Reconnection	1.2
Jet corrections	3.3
Total	4.8

  - B-tag analysis

Source	Systematic Error (%)
Lepton ID	2.2
MC Generator	1.9
ISR/FSR	1.3
PDF's	0.6
Color Reconnection	1.2
Jet corrections	3.3
b-tagging	4.1
Total	6.3

- D0

	ee, %	$e\mu$, %	$\mu\mu$, %	$\ell\ell$, % (Run IIb)	$\ell\ell$, % (Run II)
Signal modeling	4.9	4.8	4.8	$^{+5.0}_{-4.7}$	$^{+4.9}_{-4.6}$
MC background normalisation	5.8	2.3	11.1	$^{+3.4}_{-3.3}$	$^{+3.1}_{-3.0}$
Instrumental background	0.4	2.3	1.7	1.6	$^{+1.4}_{-1.4}$
Electron ID	8.9	3.9		$^{+4.2}_{-3.9}$	$^{+3.3}_{-3.2}$
Muon ID		1.7	4.9	$^{+1.9}_{-1.9}$	$^{+1.6}_{-1.5}$
Jet ID and resolution	6.5	3.2	$^{+5.9}_{-9.3}$	$^{+4.2}_{-3.9}$	$^{+3.4}_{-3.2}$
Jet energy scale	6.9	4.9	7.6	$^{+5.6}_{-5.2}$	$^{+5.2}_{-4.9}$
Trigger	0.6	5.5	7.9	$^{+4.1}_{-3.7}$	$^{+3.2}_{-3.1}$
Others	3.8	2.5	3.4	$^{+2.8}_{-2.7}$	$^{+2.7}_{-2.6}$
Total:	± 15.5	± 11.1	$^{+18.4}_{-19.8}$	$^{+11.5}_{-10.9}$	$^{+10.3}_{-9.8}$