$t\bar{t}$ Production at the Tevatron I:

Event Selection and Cross Section Measurement

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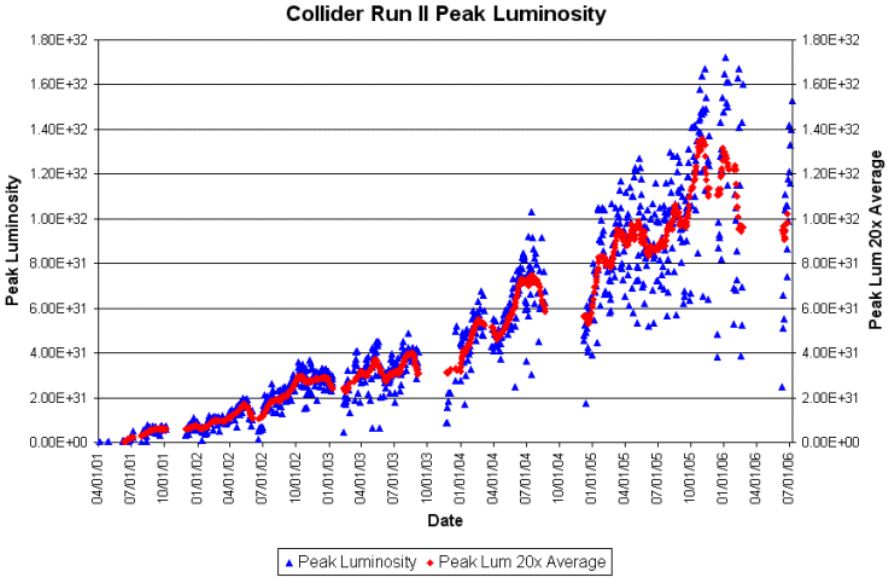
For the CDF and DØ Collaborations

Outline

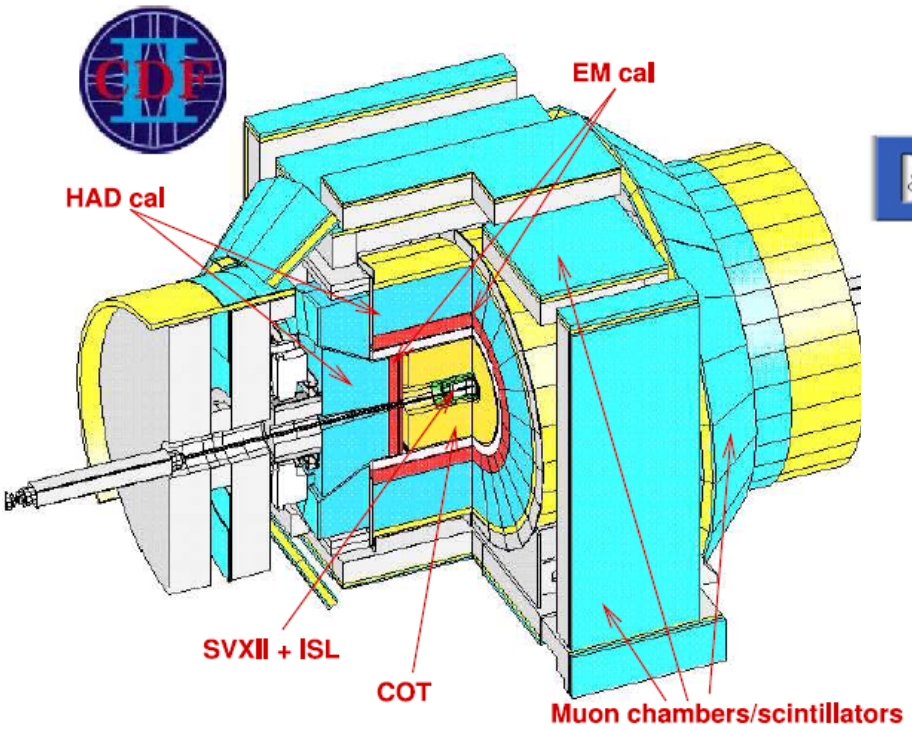
- The Tevatron Experiments
- Top Quark Pair Production and Decay
- Top Cross-Section Dilepton
- Top Cross-Section Lepton + Jet
- Top Cross-Section All-Hadronic
- Summary and Conclusions

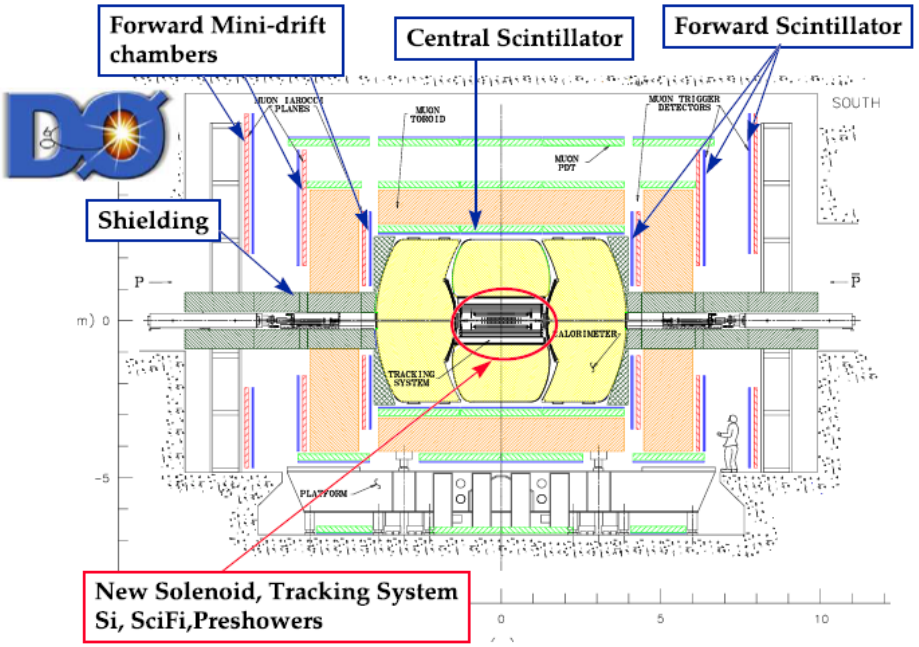
The Tevatron in Run II



- Run II began in March 2001
- 1.96 TeV proton-antiproton
- 396 ns bunch spacing
- Lumi up to $1.6 \times 10^{32} cm^{-2} s^{-1}$

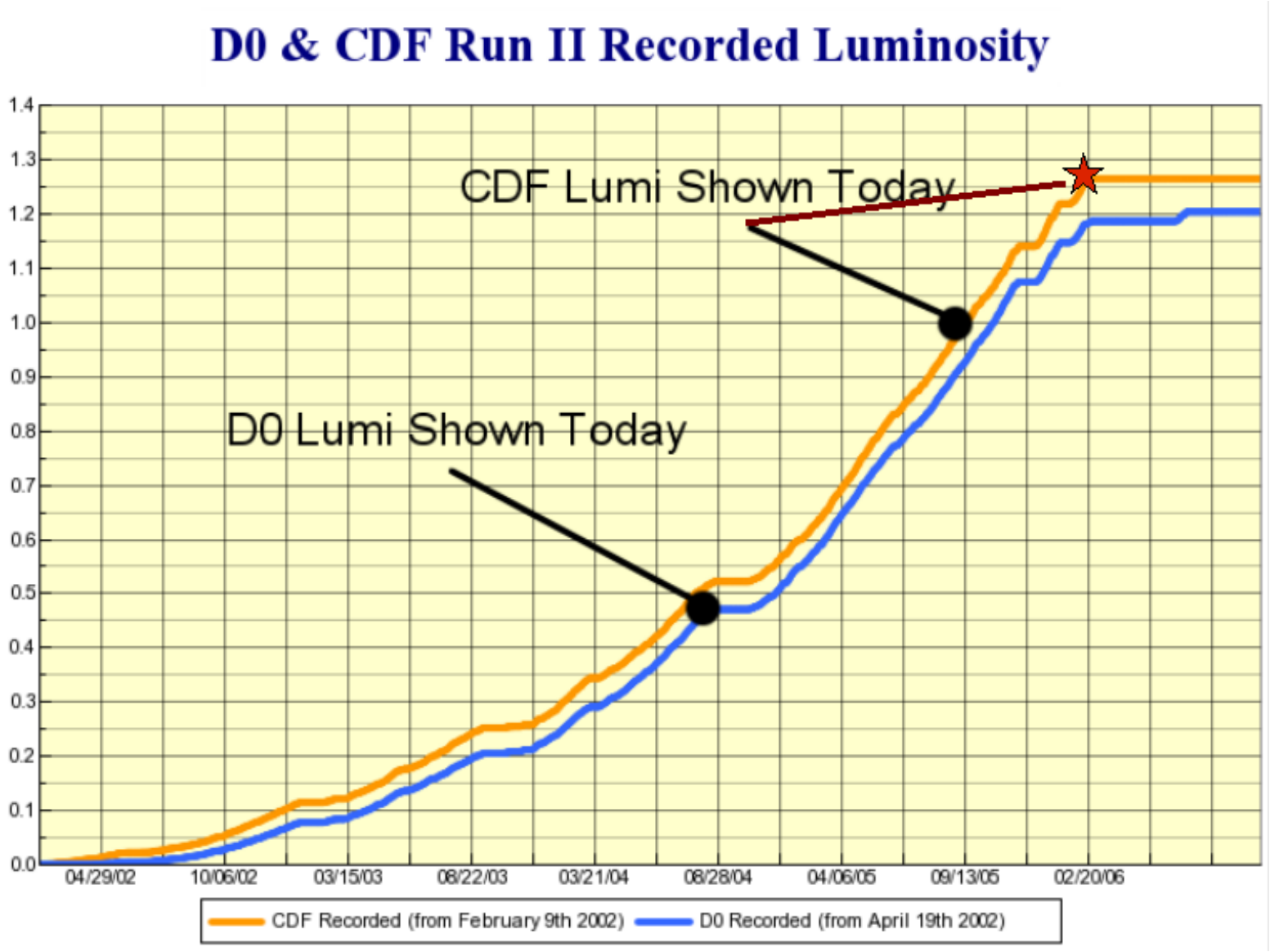
The Experiments



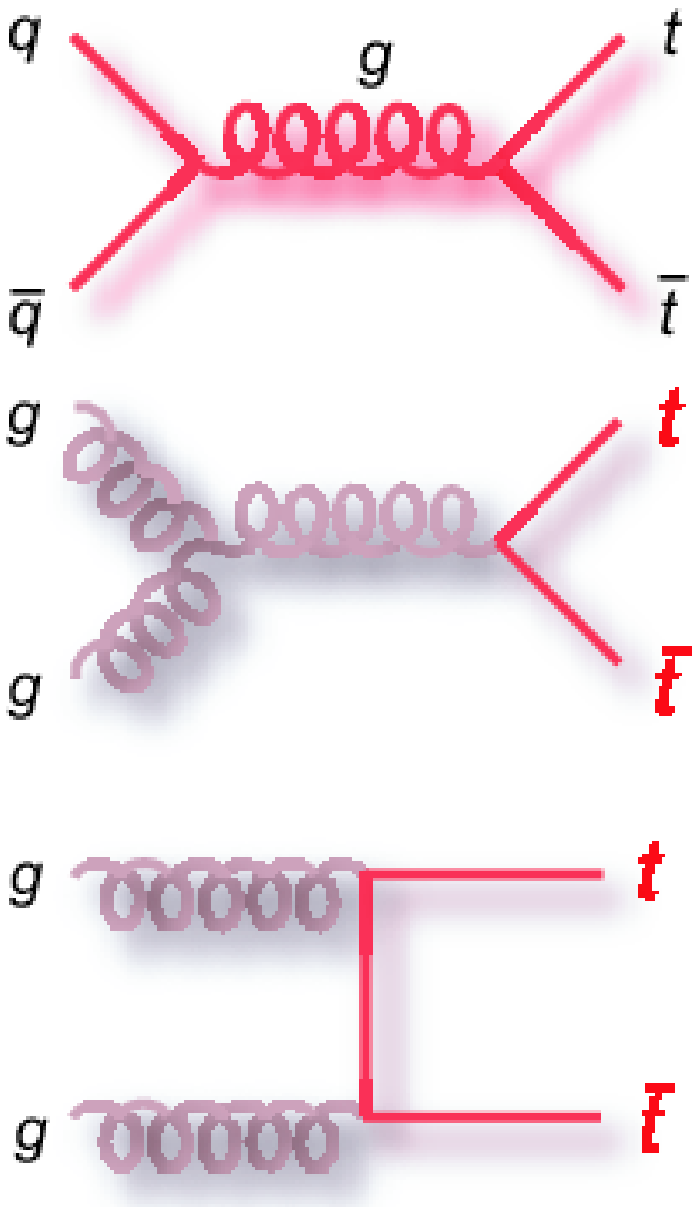


Top quark measurements rely on the whole detector for electrons, jets, muons, $\not\!\!E_T$ and b-tagging!

Data-Taking Status

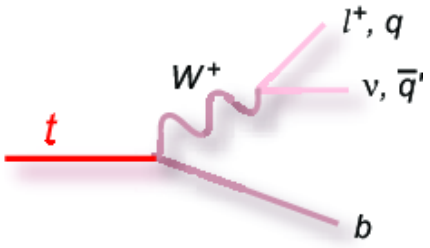


Top Quark Production



- At Tevatron $q\bar{q} \to t\bar{t}$ dominates ($\sim$85%), $gg \to t\bar{t}$ ($\sim$15%)
- NLO QCD (12% uncertainty)
  - 6.8 ± 0.8pb (Kidonakis, Vogt)
  - $6.8^{+0.7}_{-0.9}$pb (Cacciari et al.)
- Run I measurement $\sim$ 25%
- Test QCD prediction to at least theoretical precision, look for new physics (example $t\bar{t}$ resonance).

Top Quark Decay



Top Pair Decay Channels

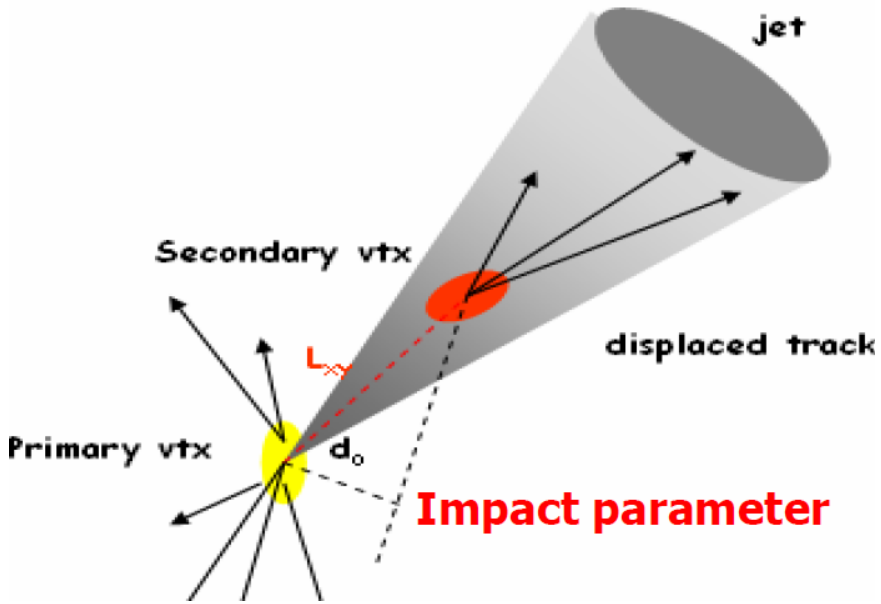
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
e^-	ee	$e\mu$	$e\tau$	electron+jets	
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$

dileptons

- Top decay BR defined by W decays
  - Dilepton: $ee, e\mu, \mu\mu$, BR=6%
  - l+jets: e, μ + jets, BR=34%
  - All Hadronic: BR=46%
  - Tau: $\tau + X$, BR=14%
- Measurements in each channel, multiple techniques, 2 experiments

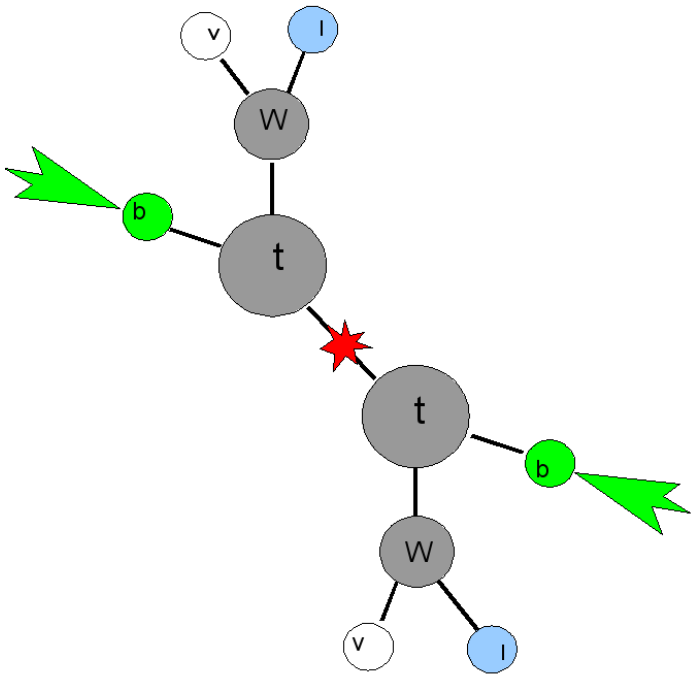
$t\bar{t}$ Event Selection

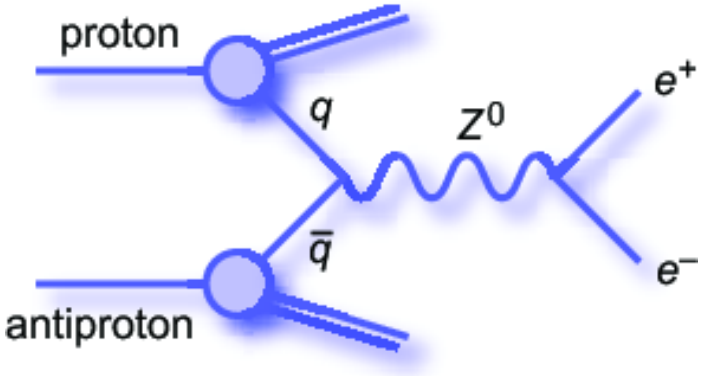
- Central, spherical, energetic
- Instrumental backgrounds from (eg.) jets faking electrons in QCD multijet or W+jets
- Physics backgrounds from (eg.) di-boson production (dilepton)
- Common distinguishing variables:
  - number of energetic jets, leptons
  - H_T - scalar sum of transverse momenta of a subset of objects
  - event shape: aplanarity, sphericity
  - $\not{E}_T$
  - b-tagging



Dilepton Channel

- 3 final states: ee or $\mu\mu$ or $e\mu$
- Signature: 2 high-Pt leptons, 2 b-jets, large $\not{E}_T$
- Smaller BR than states with more jets, but distinct signature, favourable S/B.
- Backgrounds:
  - $Z/\gamma^* \rightarrow ee, \mu\mu$
  - $Z/\gamma^* \rightarrow \tau\tau$
  - WW/WZ
  - W+jets
  - QCD Multijet





Dilepton Channel Selection

- 2 leptons (opposite charge) $E_T > 20\text{GeV}$
- 2 jets, $E_T > 15\text{GeV}$
- $\not{E}_T > 25\text{GeV}$ (object $< 20^\circ$ and $\not{E}_T > 50\text{GeV}$), in/out of Z window
- $H_T > 200\text{GeV}$

- lepton + track (opposite charge) $E_T > 15\text{GeV}$
- at least 1 jet above 20GeV
- $\not{E}_T$ for ee, $\mu\mu$ in/out of Z window (15-35GeV)
- at least one b-tag
- $e\mu$ vetoed & combined

CDF Dilepton - 750pb^{-1}

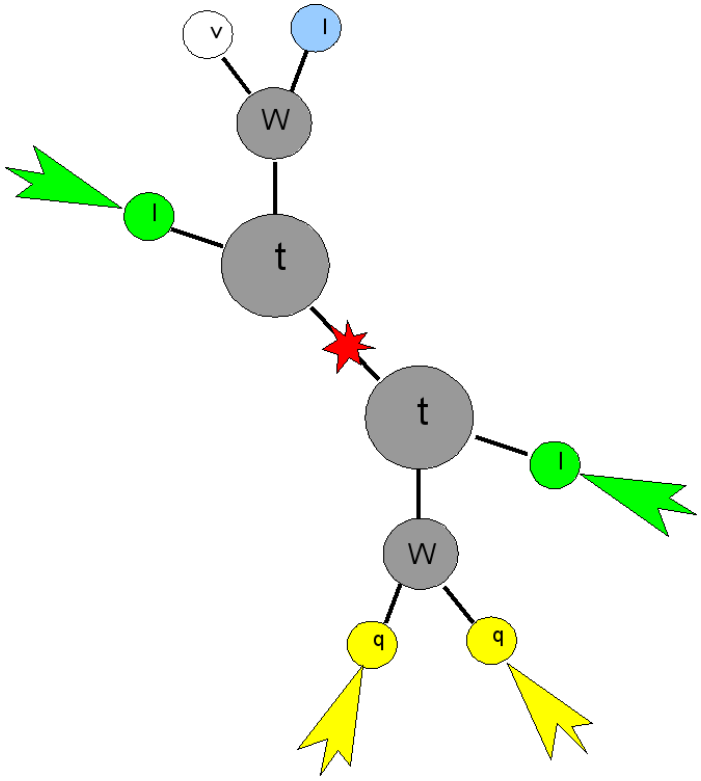
$\sigma_{t\bar{t}} = 8.3 \pm 1.5(stat) \pm 1.0(syst) \pm 0.5(lumi)pb$

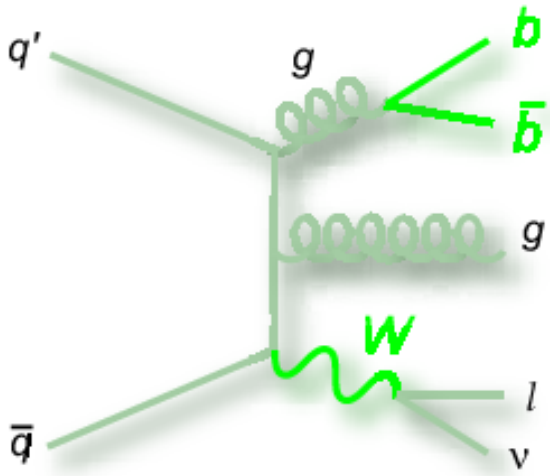
DØ lepton + track (including eμ) - 370pb^{-1}

$\sigma_{t\bar{t}} = 8.6^{+1.9}_{-1.7}(stat) \pm 1.1(syst) \pm 0.6(lumi)pb$

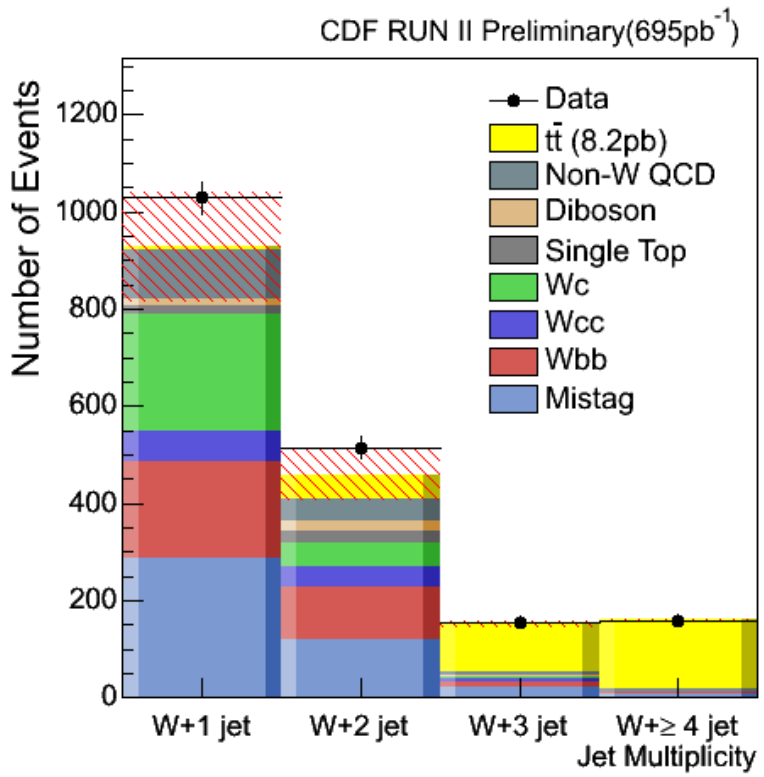
Lepton + Jets Channels

- Signature: 1 high-Pt lepton, 2 b-jets, 2 light jets, large $\not{E}_T$
- Larger BR, still one high-Pt lepton
- Backgrounds: W+jets, QCD multijet, Z+jets, Z$\rightarrow \tau\tau$, WW/WZ
- Use kinematics in NN or topological discriminant and/or use b-tag information





Lepton + Jets Channels - b-tagging CDF



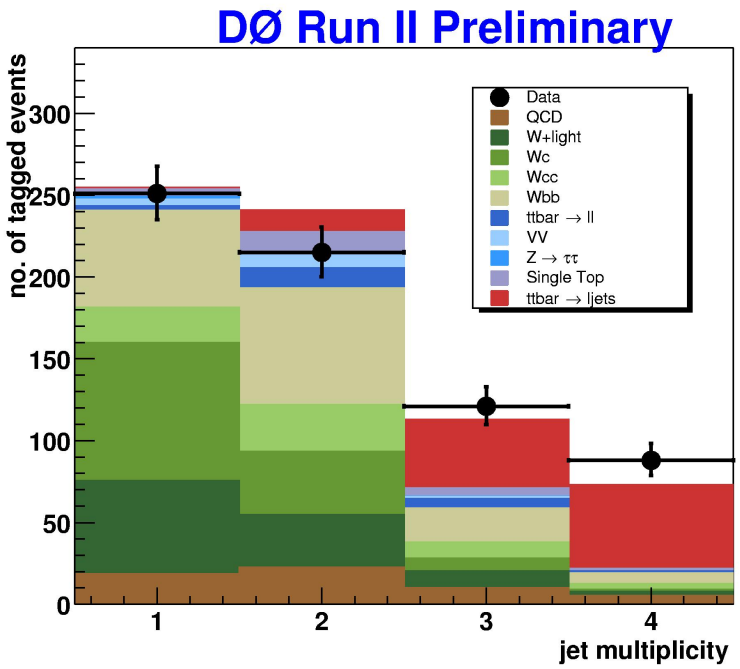
- Requirements:
  - 1 isolated lepton $E_t > 20GeV$
  - ≥ 3 jets $E_t > 15GeV$
  - $\not{E}_T > 20$GeV
  - 1 b-jet
  - $H_T > 200$GeV
- Cross-check with 2b sample

Njets	1	2	3	≥ 4
Pretag	68183	10647	846	402
Mistag	286.0 ± 42.3	119.2 ± 17.7	21.0 ± 3.2	6.6 ± 1.0
$Wb\bar{b}$	201.1 ± 62.3	109.0 ± 32.3	13.0 ± 3.5	3.3 ± 0.9
$Wc\bar{c}$	61.5 ± 18.0	40.9 ± 12.8	5.2 ± 1.6	1.5 ± 0.5
Wc	242.1 ± 62.0	50.4 ± 13.3	3.3 ± 0.9	0.4 ± 0.1
Single Top	17.2 ± 1.7	24.1 ± 2.4	2.1 ± 0.2	0.4 ± 0.1
Diboson	13.3 ± 2.1	19.2 ± 3.0	[illegible]	[illegible] ± 0.2
non-W QCD	99.9 ± 16.4	45.0 ± 7.5	[illegible] ± 1.1	4.1 ± [illegible]
Total	921.1 ± 113.3	407.8 ± 5[illegible]	53.0 ± 6.3	17.2 ± 1.9
Data	1029	514	156	158

CDF l+jets with b-tag - 695pb^{-1}

$\sigma_{t\bar{t}} = 8.2 \pm 0.6(stat) \pm 1.0(syst)$pb

Lepton + Jets Channels - b-tagging DØ



- Requirements:
  - 1 isolated central lepton $E_T > 20 GeV$
  - ≥ 1 jets $E_t > 15 GeV$
  - $\not{E}_T > 20$GeV
  - 1 or 2 b-jet

	W+1jet	W+2jets	W+3jets	W+$\geq$4jets
W+light	57.1±1.1	32.0±1.1	10.2±0.5	2.46±0.20
Wc	84.4±0.9	38.5±0.8	7.8±0.3	1.34±0.11
$Wc\bar{c}$	21.5±0.2	28.8±0.6	9.73±0.3	3.32±0.28
$Wb\bar{b}$	59.1±0.6	71.3±1.2	20.9±0.7	6.67±0.54
W+jets	222.0±1.6	170.6±1.7	48.6±0.8	13.8±0.5
QCD	18.5±2.6	22.8±2.9	10.2±1.9	5.4±1.5
single top	4.66±0.08	13.2±0.1	5.19±0.09	1.34±0.04
$t\bar{t} \to ll$	3.11±0.05	12.1±0.1	5.9±0.1	1.26±0.03
diboson	3.67±0.17	8.29±0.27	1.04±0.09	0.08±0.02
$Z \to \tau^+\tau^-$	1.79±0.25	0.86±0.16	0.18±0.08	< 0.01
background	253.8±3.1	227.8±3.4	71.1±2.1	21.8±1.6
syst.	+35.96-40.73	+30.15-32.0	+8.37-8.79	+2.45-2.52
$t\bar{t} \to l$+jets	1.05±0.05	13.3±0.2	41.9±0.3	51.3±0.3
total predicted.	254.8±3.1	241.0±3.4	113.0±2.1	73.2±1.6
syst.	+35.96-40.75	+30.36-32.15	+8.77-9.15	+5.73-6.79
observed	251	215	121	88

Get cross section via likelihood:

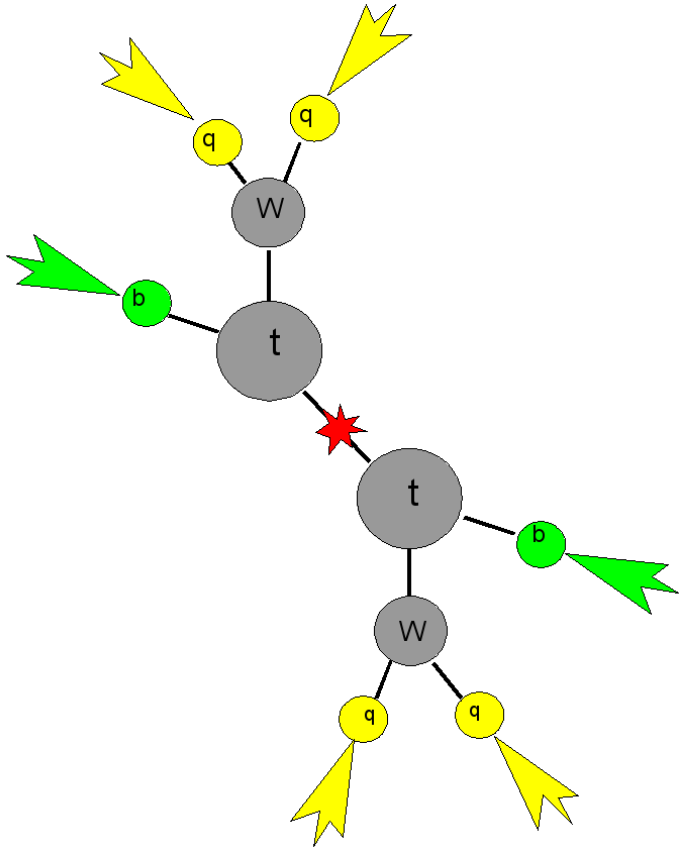
$$\mathcal{L} = \prod_i P(N_i^{obs}, N_i^{pred}(\sigma_{t\bar{t}}))$$

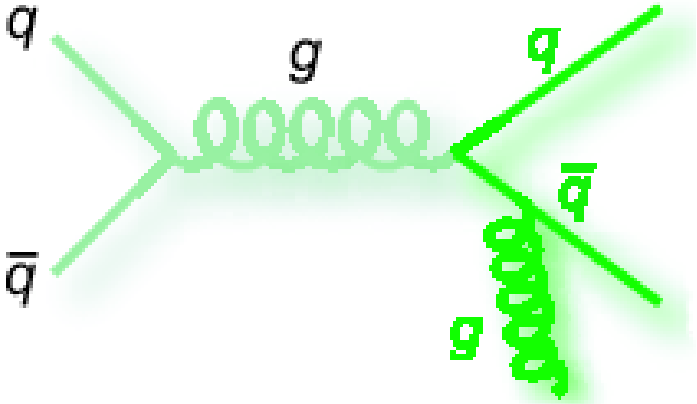
D0 l+jets with b-tag - 365pb^{-1}

$$\sigma_{t\bar{t}} = 8.1^{+1.3}_{-1.2}(stat + syst) \pm 0.5(lumi)\text{pb}$$

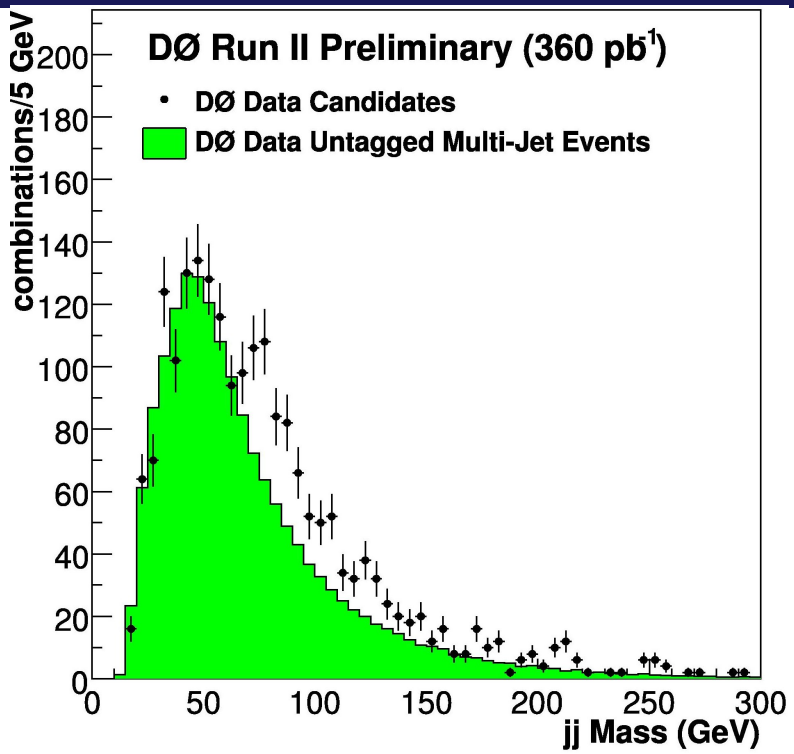
All-Hadronic Channel

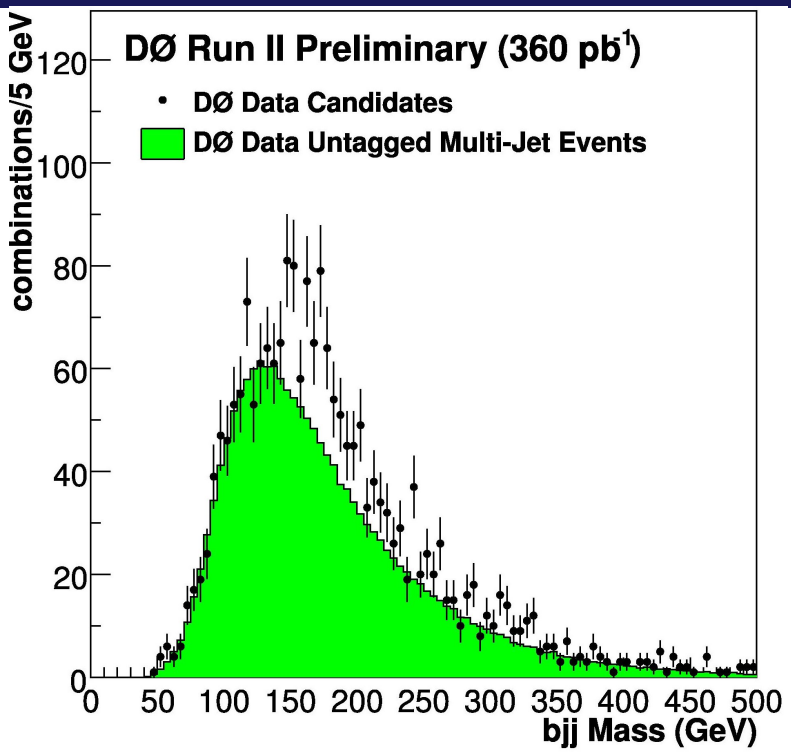
- Signature: 6 high-Pt jets!, 2 b's
- Large BR
- Backgrounds: QCD multijets, W+jets
- No neutrinos! Low $\not{E}_T$, reconstruct the whole event.





Multi-Jet Channel - DØ



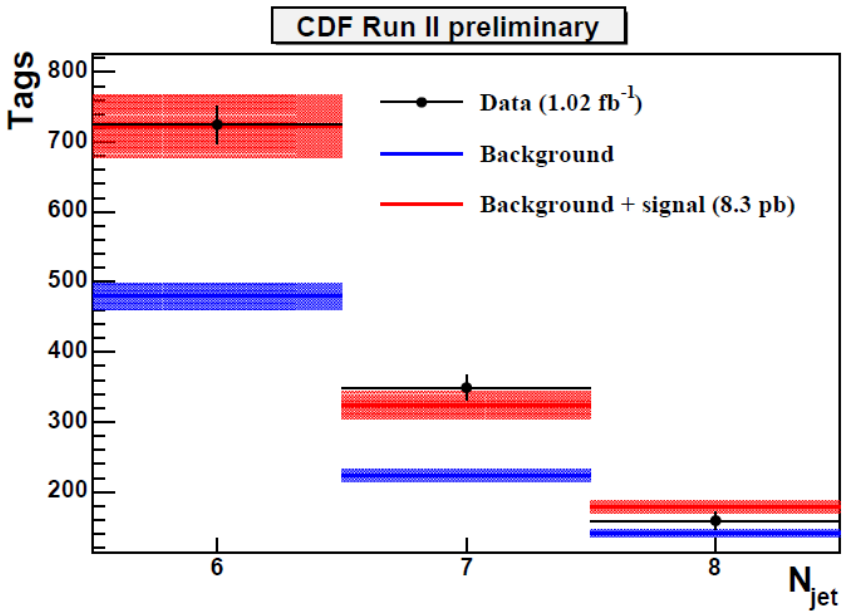


- Requirements:
  - 6 jets, exactly 2 b-tags (45,25,15GeV)
  - Do NOT veto on leptons or $\not\!\!E_T$.
  - All jets "taggable" (2 tracks point to PV)

DØ Multi-Jet - 360pb^{-1}

$\sigma_{t\bar{t}} = 12.1 \pm 4.9(stat) \pm 4.6(syst)$pb

All-Hadronic Channel - CDF NEW



- Requirements:
  - veto isolated leptons, $\not\!\!E_T$
  - 6-8 Jets $E_T > 15$GeV
  - Topological NN on 11 inputs
  - 1 or more b-jet

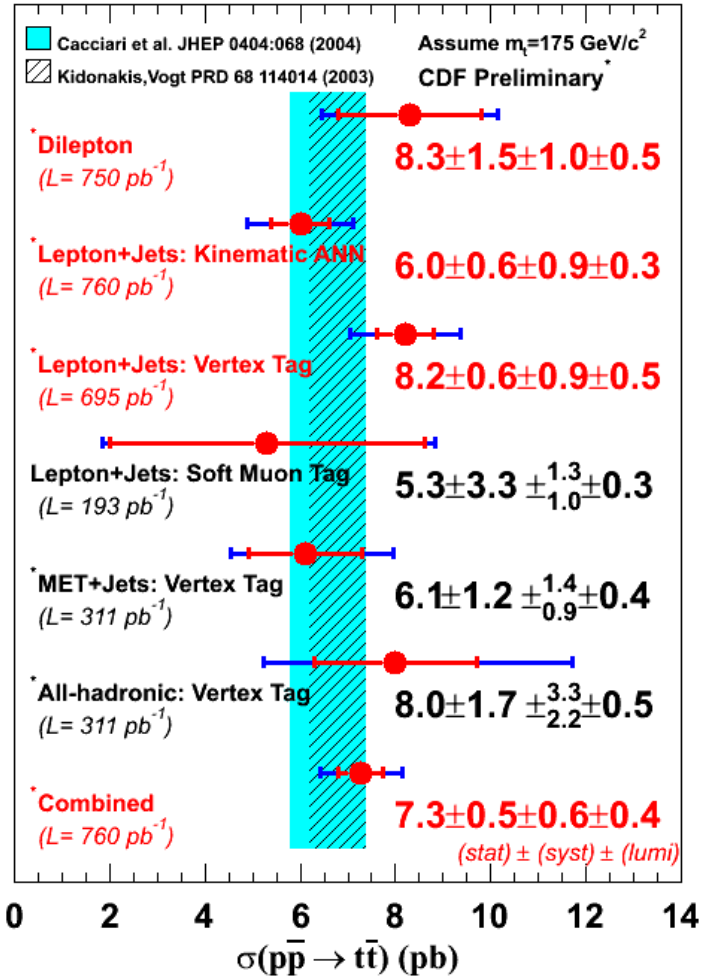
N$_{jet}$	6-8
Events	4205
Background	846 ± 37
$t\bar{t}(\sigma = 8.3pb)$	381 ± 65
Background + $t\bar{t}$	1227 ± 76
Observed Tags	1233

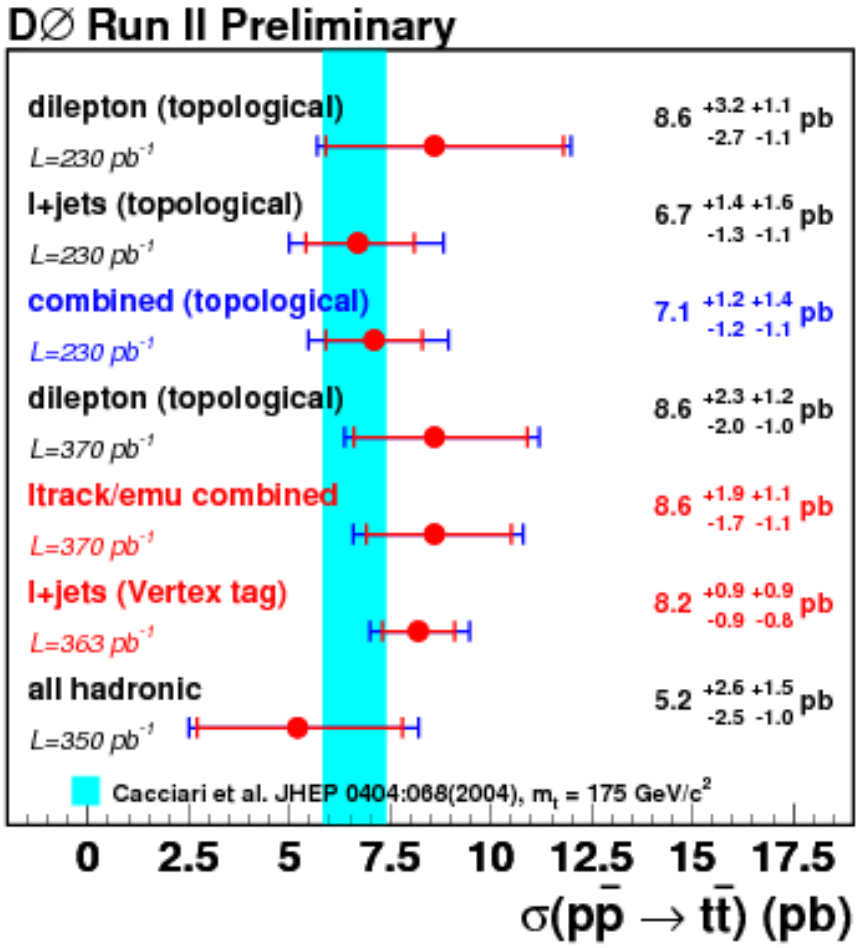
- Data-driven background estimation
- Cross section extracted from tags, not events

CDF All Hadronic - 1.02fb^{-1}

$$\sigma_{t\bar{t}} = 8.3 \pm 1.0(stat)^{+2.3}_{-1.9}(syst) \pm 0.5(lumi)$$

Summary





CDF All Hadronic - 1.02fb^{-1}

$$\sigma_{t\bar{t}} = 8.3 \pm 1.0(stat)^{+2.3}_{-1.9}(syst) \pm 0.5(lumi)$$

Summary

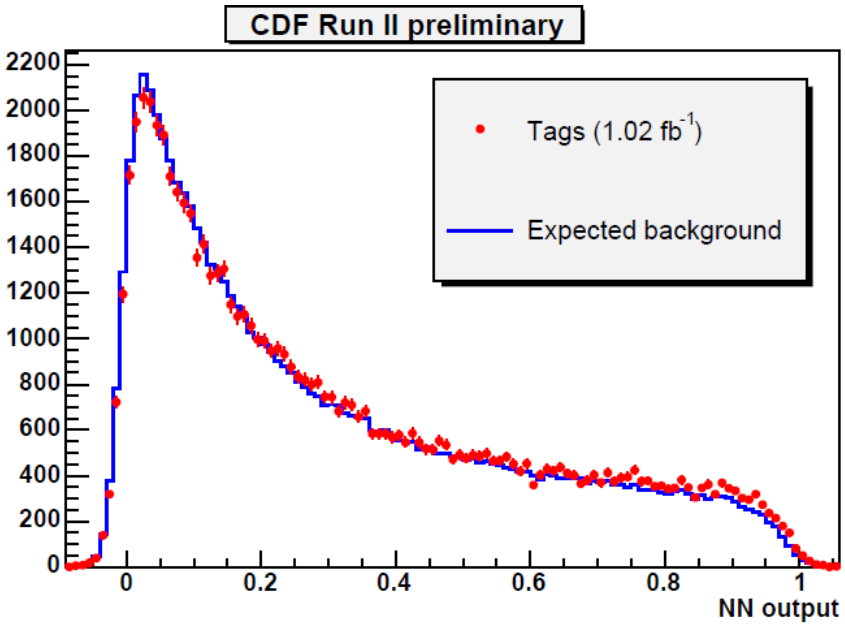
- Precision cross section measurement now rivals theory (12% uncertainty)
  - 6.8 ± 0.8pb (Kidonakis, Vogt)
  - $6.8^{+0.7}_{-0.9}$pb (Cacciari et al.)
  - CDF combined: 7.3 ± 0.9pb - 12%
- I only sampled the analyses in each channel
- Data is still accumulating!

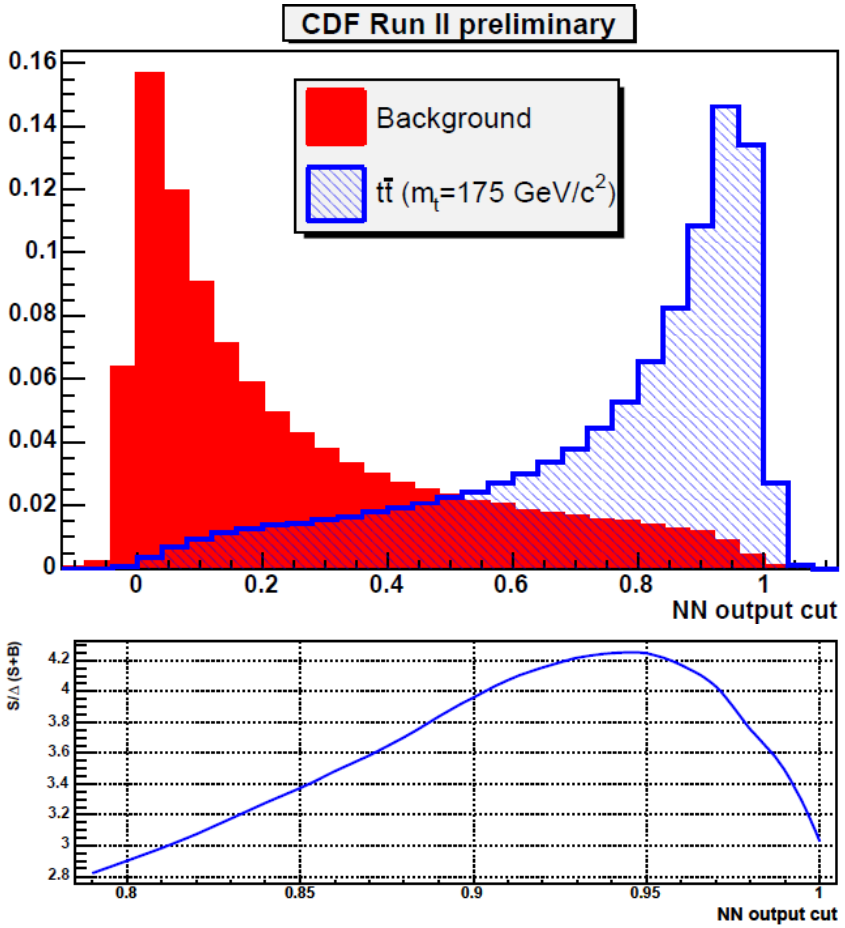
Backup Slides

Backup Slides

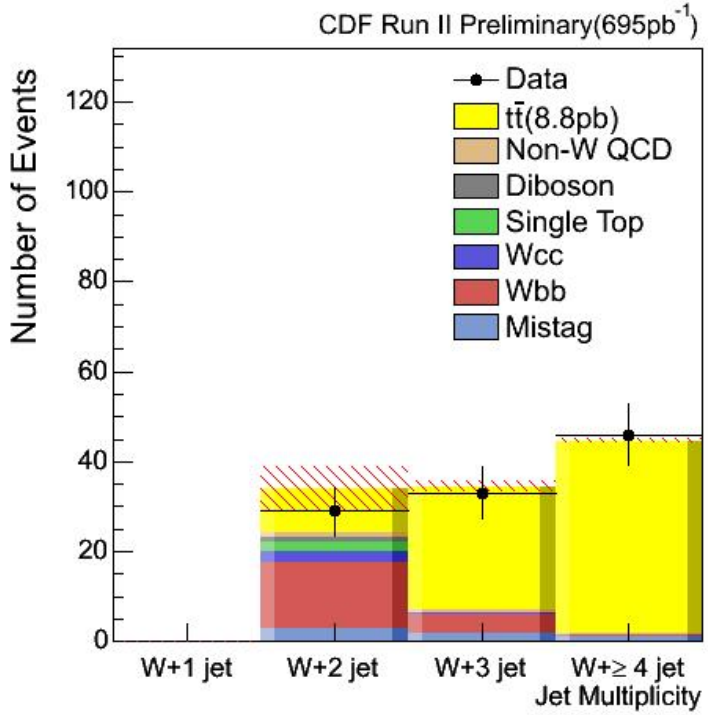
All-Hadronic Channel - CDF NEW - Details

- NN: $\sum E_T, \sum E_T - E_T^1 - E_T^2$, centrality, aplanarity, min dijet mass, max dijet mass, min trijet mass, max trijet mass, $E_T^1 \cdot \sin^2\theta_1^*, E_T^2 \cdot \sin^2\theta_2^*, < E_T^* >_{3N}$





CDF l+jets with b-tagging

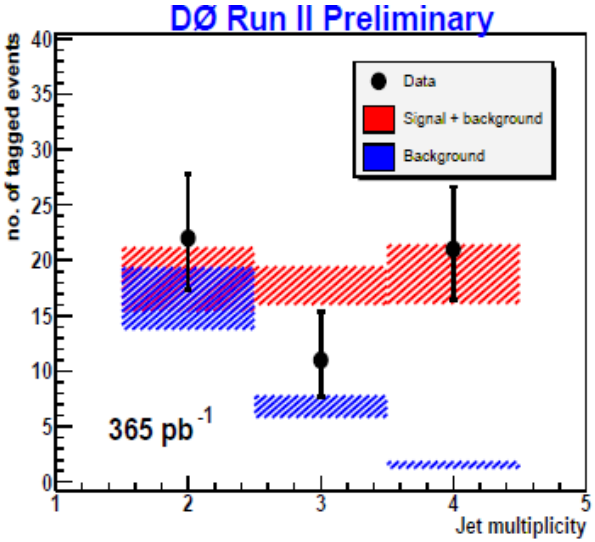


Jet multiplicity	2 jets	3 jets	$\geq$ 4 jets
Mistags	2.9 ± 0.5	1.7 ± 0.4	1.0 ± 0.5
Wbb	14.8 ± 4.0	4.7 ± 1.2	1.4 ± 0.4
Wcc	2.3 ± 0.8	0.4 ± 0.1	0.2 ± 0.1
Single Top	2.4 ± 0.5	0.1 ± 0.0	0.0 ± 0.0
Diboson	0.9 ± 0.2	0.2 ± 0.1	0.1 ± 0.0
Non-W QCD	1.0 ± 0.2	0.6 ± 0.1	0.2 ± 0.1
Total Pred	24.3 ± 4.8	7.7 ± 1.4	2.9 ± 0.7
Corrected Total	24.2 ± 4.8	7.2 ± 1.3	1.9 ± 0.5
Top(6.7±0.8 pb)	7.3 ± 1.6	20.4 ± 4.5	31.9 ± 7.1
Observed	29	33	46

Source	Systematic (%)
b-tagging	6.5
Luminosity	6.0
PDF	5.8
Jet Energy Scale	3.0
ISR/FSR	2.6
Lepton Identification	2.0
Total	11.5

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bckg}}{\epsilon_{t\bar{t}} \times \int \mathcal{L} dt}$$

DØ l+jets



	W+2jets	W+3jets	W+$\geq$4jets
W+light	0.043±0.004	0.028±0.003	0.010±0.001
Wc	0.081±0.003	0.031±0.002	< 0.01
$Wc\bar{c}$	0.77±0.03	0.30±0.02	0.12±0.01
$Wb\bar{b}$	10.1±0.3	3.25±0.14	1.04±0.09
W+jets	10.9±0.2	3.60±0.14	1.18±0.08
QCD	< 0.01	0.32±0.36	< 0.01
single top	1.82±0.03	1.00±0.02	0.31±0.01
$t\bar{t} \to ll$	3.27±0.03	1.75±0.02	0.38±0.01
diboson	0.92±0.05	0.12±0.01	0.011±0.004
$Z \to \tau^+\tau^-$	0.03±0.03	0.02±0.02	< 0.01
background	16.9±0.3	6.8±0.4	1.88±0.38
syst.	+2.81-2.79	+1.00-0.99	+0.31-0.31
$t\bar{t} \to l$+jets	1.70±0.04	10.9±0.1	17.4±0.1
total predicted	18.6±0.3	17.7±0.4	19.3±0.4
syst.	+2.94-2.86	+1.74-1.73	+2.51-2.83
observed	22	11	21

Source	Offset	σ^+	σ^-
Muon preselections	+0.02	+0.18	-0.15
Electron preselections	-0.02	+0.18	-0.15
Muon triggers	+0.07	+0.34	-0.28
Jet energy scale	-0.07	+0.24	-0.21
Jet reco and jet ID	-0.09	+0.23	-0.18
SML b-tag eff in MC	+0.03	+0.15	-0.14
Semileptonic b-tagging efficiency in data	+0.18	+0.40	-0.35
Heavy quark mass on W fractions	-0.00	+0.18	-0.19
W fractions matching + higher order effects	+0.01	+0.44	-0.44
Event statistics for matrix method	-0.02	+0.15	-0.15

$$\mathcal{L} = \prod_i P(N_i^{obs}, N_i^{pred}(\sigma_{t\bar{t}}))$$

DØ All-Hadronic

Source	Uncertainty (%)
background model & subtraction	± 25
b ID scale factor	± 18
jet energy scale	± 15
Monte Carlo simulation	± 10
trigger	$^{+12}_{-3}$
luminosity	± 6.5
total	± 38