Top Quark Cross-Section Measurements at the Tevatron in Run 2

Wolfgang Wagner

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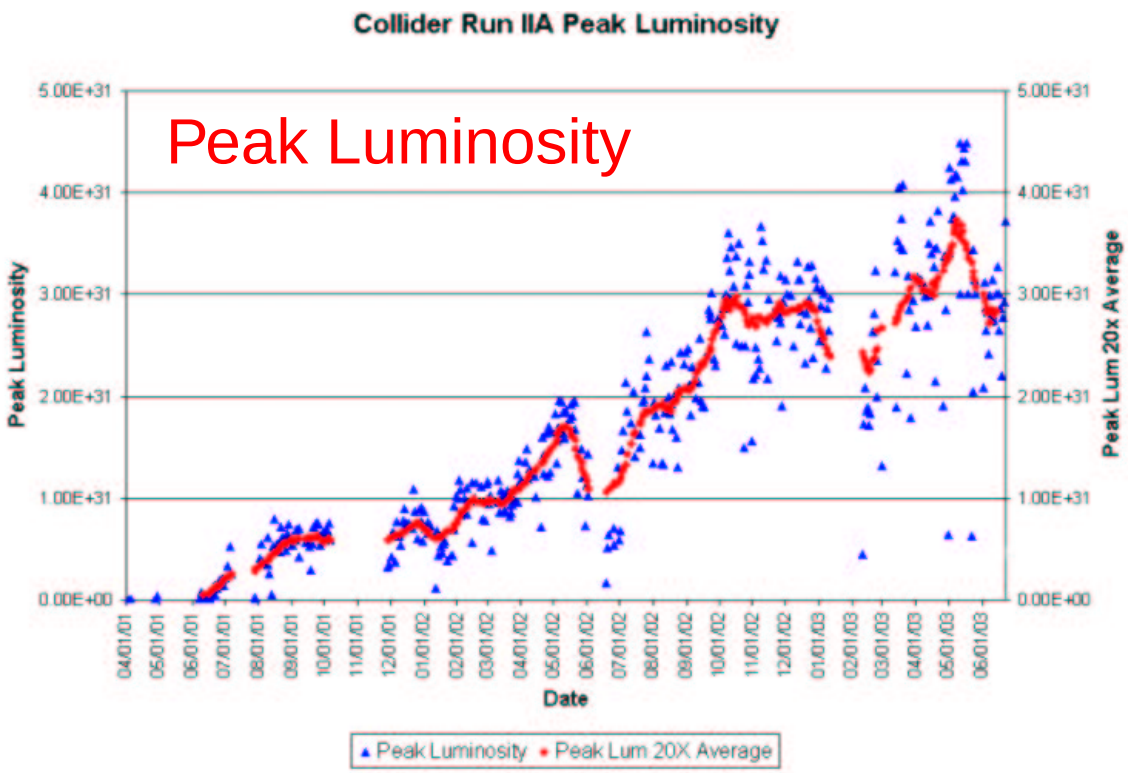
for the CDF and DØ Collaborations

Tevatron Upgrade for Run 2 and Luminosity Performance

- New accelerator rings: main injector and Recycler ($\overline{\mathrm{p}}$ storage).
- $\sqrt{\mathrm{s}} = 1.96\ \mathrm{TeV}$ (Run 1: 1.8 TeV).
- New bunch structure: 36×36 bunches ⇒ BX time 396 ns.



Highest luminosity so far:
$\mathcal{L} \simeq 4.7 \cdot 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
Aim for Run 2a:
$\mathcal{L} = 5 - 20 \cdot 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

$\int \mathcal{L}\, dt \approx 250\ \mathrm{pb}^{-1}$ delivered

Quality data for top physics:
CDF: $\int \mathcal{L}\ \mathrm{dt} = 107\ \mathrm{pb}^{-1}$

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Top Physics at the Tevatron: an Overview

$\sigma_{t\bar{t}}$	➜	test perturbative QCD
	➜	background to $\mathbf{W+H}$
spin: $\mathrm{s(t)}$ vs. $\mathrm{s(\bar{t})}$	➜	production mechanism
$\mathrm{h(W^{+/-})}$	➜	V-A structure of charged current
$\mathrm{m_{top}}$	➜	SM fits, $\mathrm{m_H}$
$\sigma(\mathrm{W \to tb})$	➜	$\lvert\mathrm{V_{tb}}\rvert$ / unitarity / polarization
$\sigma(\mathrm{p\bar{p} \to t + X})$	➜	production mechanism, FCNC
$\mathrm{t \to u/c + \gamma/Z/g}$	➜	FCNC, new physics
$\mathrm{t \to b + H^+}$	➜	SUSY

Please visit top quark Tevatron talks by T. Maruyama, P. Merkel, E. Shabalina and M. Warsinsky.

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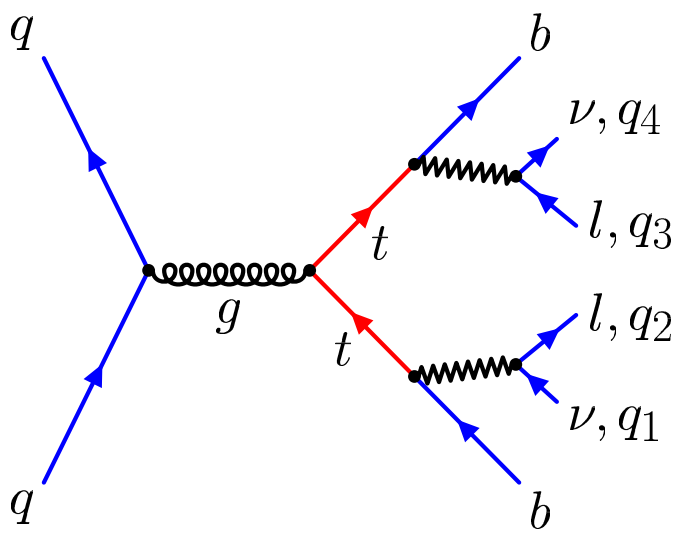
$t\bar{t}$ production at the Tevatron



- top quark does not hadronize

$$\tau_{\mathbf{top}} \sim \quad \mathbf{1/m^3_{top}} \quad \sim \mathbf{10^{-24}\ s}$$

$$\tau_{\mathbf{QCD}} \sim \quad \mathbf{1/\Lambda_{QCD}} \quad \sim \mathbf{10^{-23}\ s}$$

- SM: BR$(\mathbf{t \to W^+ + b}) \simeq \mathbf{100\%}$

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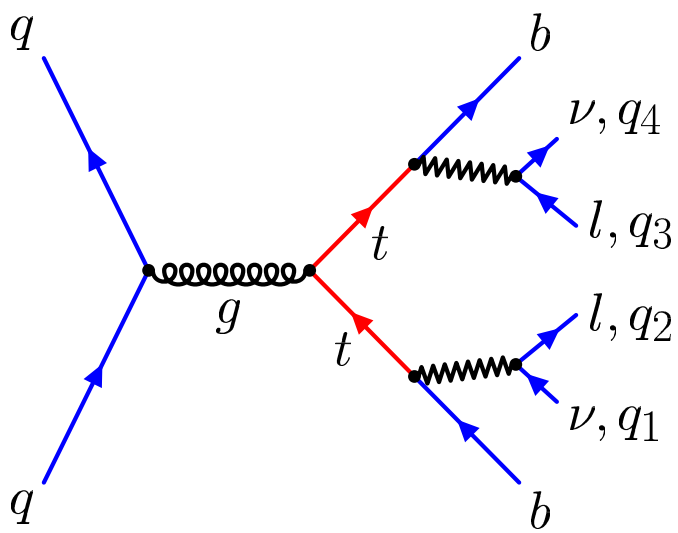

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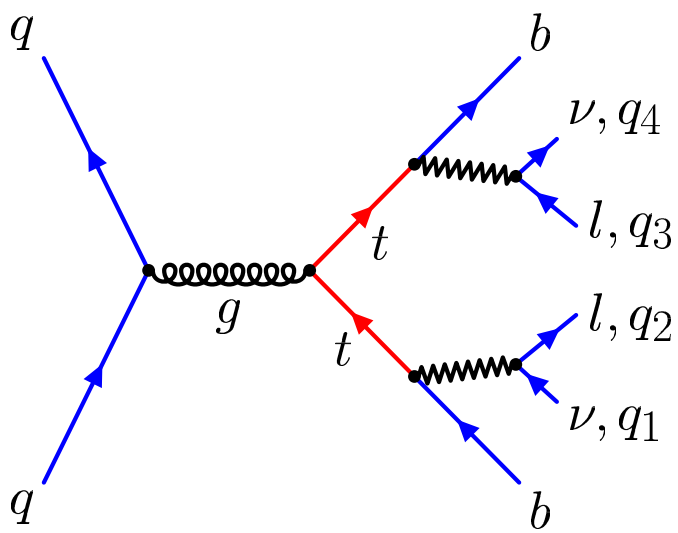
$t\bar{t}$ event classification:

1. Dilepton channel:
   $\ell_1\nu_1 + \ell_2\nu_2 + b\bar{b}$
2. Lepton + Jets:
   $\ell\nu + q_1\overline{q_2} + b\bar{b}$
3. All hadronic:
   $q_1\overline{q_2} + q_3\overline{q_4} + b\bar{b}$

$t\bar{t}$ production at the Tevatron



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Run 1 cross-section results:

CDF combined: $\mathbf{6.5^{+1.7}_{-1.4}\ pb}$

DØ combined: $\mathbf{5.9 \pm 1.6\ pb}$

Run 2: $\sqrt{s}$ = 1.96 TeV $\Rightarrow$
$\sigma_{t\bar{t}}$: +30%

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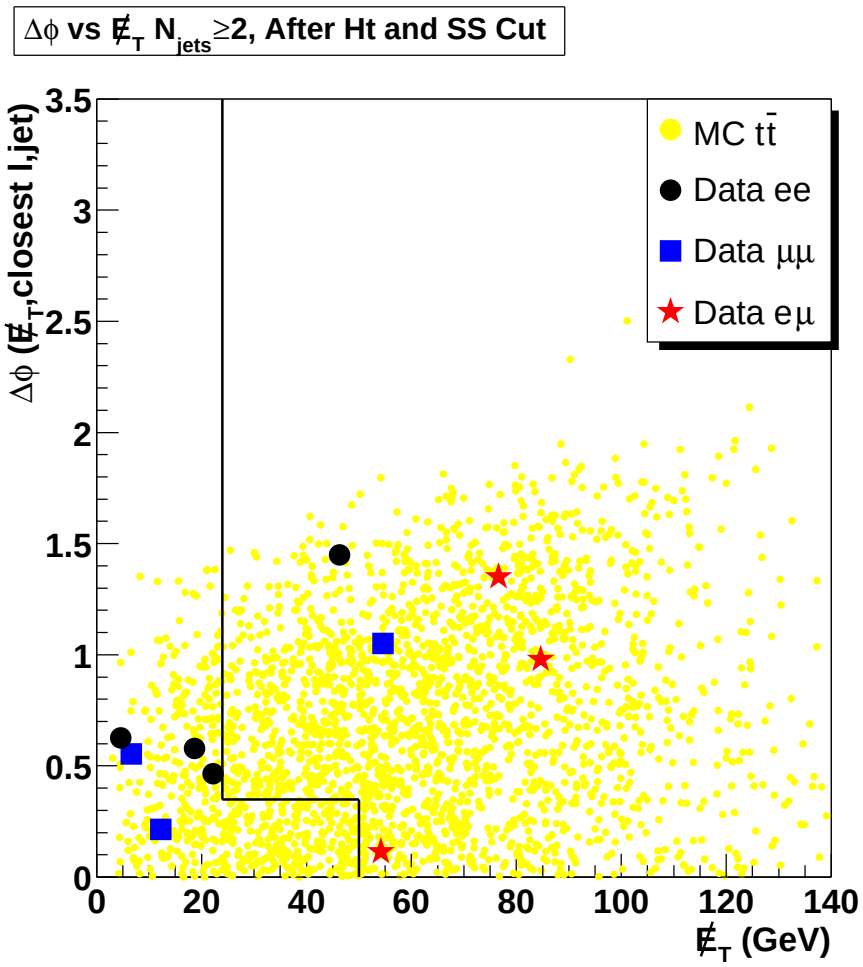
$t\bar{t}$ Events in the Dilepton Channel

Event selection:

- 2 isolated leptons (e or μ), Opp. charge, $\mathbf{p_t} > \mathbf{20}$ GeV
- Z veto: $\mathbf{m_{\ell\ell}} < \mathbf{76}$ GeV or $\mathbf{m_{\ell\ell}} > \mathbf{106}$ GeV
- neutrinos: $|\not{\mathbf{E}}_\mathbf{T}| > \mathbf{25}$ GeV
- ≥ 2 jets with $|\mathbf{E_T}| > \mathbf{10}$ GeV
- $H_t \equiv |\not{E}_T| + |E_T(\ell_1)| + |E_T(\ell_2)| + \sum |E_t(\,\mathrm{jets}\,)| \geq 200$ GeV
- $\Delta\phi(\not{\mathbf{E}}_\mathbf{T}\,, \mathrm{nearest}\ \ell\ \mathrm{or\ j}) > 20^\circ$ if $\not{\mathbf{E}}_\mathbf{T} < \mathbf{50}$ GeV



5 candidate events over background of 0.30 ± 0.12

$\sigma(\mathrm{t\bar{t}})$ in the Dilepton Channel

CDF results:

A counting experiment:

$$\sigma(\mathrm{t\bar{t}}) = \frac{\mathrm{N}_{obs} - \mathrm{N}_{\mathrm{bkg}}}{\mathrm{A} \int \mathcal{L}\, \mathrm{dt}}$$

$\int \mathcal{L}\, dt$	Accep.
$72\ \mathrm{pb}^{-1}$	0.64%

Cross section: Preliminary !

$$\sigma(\mathrm{t\bar{t}}) = 13.2 \pm 5.9_{\mathrm{stat}} \pm 1.5_{\mathrm{sys}} \pm 0.8(\mathrm{lum})\ \mathrm{pb}$$

DØ results:

- No Z-mass window cut. Raise $\not{E}_T$ cut in Z window.
- 7 candidate events observed (4 ee, 2 $\mu\mu$, 1 e μ).
- Background: 1.7 ± 0.6

Combined dilepton cross section:

$$\sigma = 29.9^{+21.0}_{-15.7}(\mathrm{stat})^{+14.1}_{-6.1}(\mathrm{sys}) \pm 3.0(\mathrm{lum})\ \mathrm{pb}$$

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Strategies to Identify $t\bar{t}$ Events

1. Topological cuts
   Kinematic and event shape variables, e.g. $\mathbf{H_T}$ or aplanarity $\mathcal{A}$.
2. Identification of b-jets via lifetime information
   - Secondary vertex
   - Track impact parameter significance
3. Identification of b-jets by searching for leptons from semileptonic b-decays. (Soft muon/electron tagger).

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Topological $t\bar{t}$ analysis (1)

Preselection

- One electron or muon with $\mathbf{p_T} > \mathbf{20}$ GeV
- $\not{\mathbf{E}}_\mathbf{T} > \mathbf{20}$ GeV
  μ-analysis:
  $\not{\mathbf{E}}_\mathbf{T}\,(\mathbf{cal}) > \mathbf{20}$ GeV
- Veto soft muons ➜
  sample disjoint with b-tagged analysis

The preselected sample is used to estimate the backgrounds.

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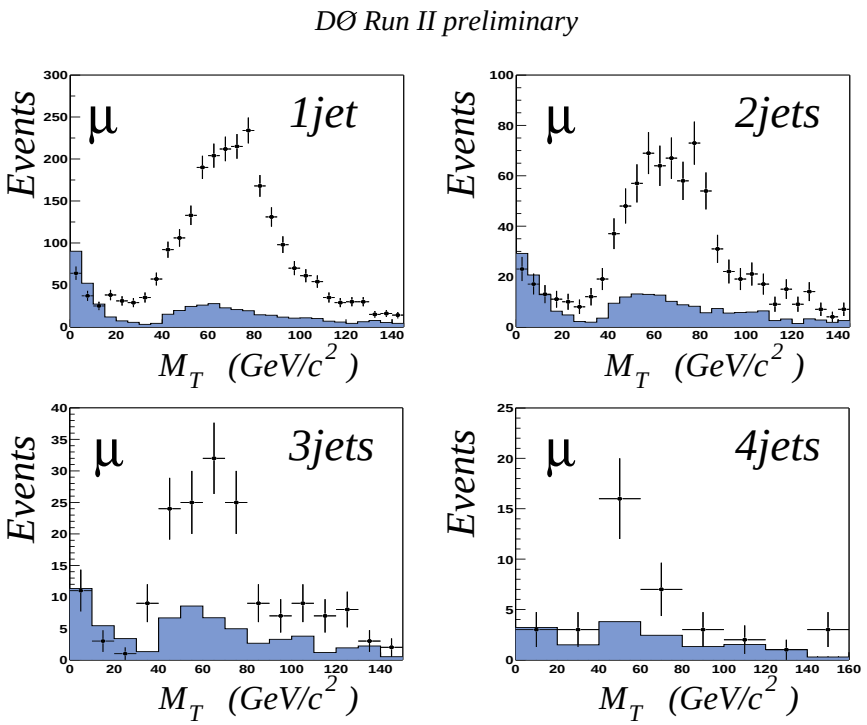
Multi-Jet Background Estimate

- Isolation cut ➜ tight sample.
- $\epsilon_{\mathbf{MJT}}$ and $\epsilon_{\mathbf{W+J}}$ from control samples.



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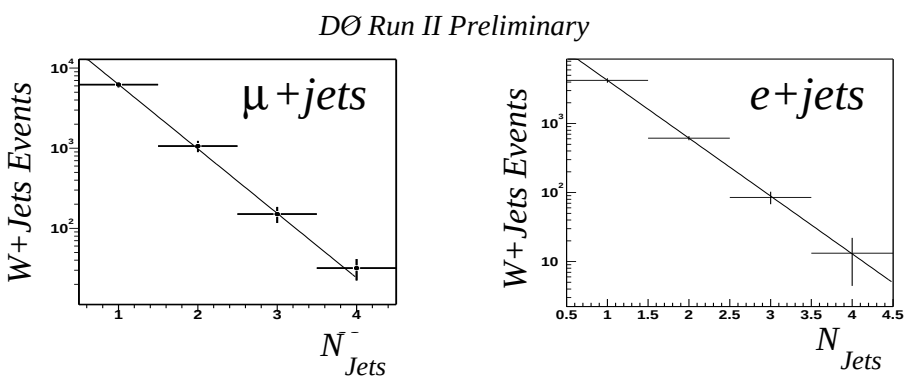
Topological $t\bar{t}$ analysis (2)

W+Jet Background Estimate

Empirical Berends scaling law:

$$\frac{\sigma\left(\mathbf{W}+(\mathbf{n}+\mathbf{1})\ \mathbf{jets}\right)}{\sigma\left(\mathbf{W}+\mathbf{n}\ \mathbf{jets}\right)}=\alpha$$

- Subtract multi-jet background
- Determine α from a fit



- Predict N (4 jets)

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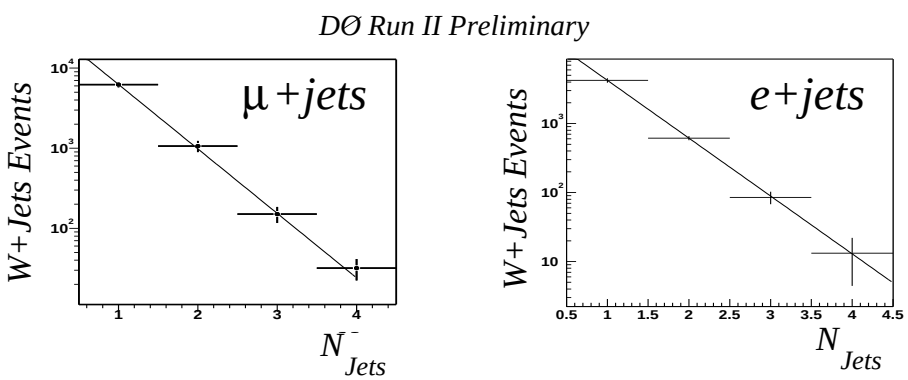

- Predict N (4 jets)

Topological Cuts

- Aplanarity $\mathcal{A} > 0.065$ (elect.)
  μ+jets: $\mathcal{A} > 0.0065$
- $\sum E_T(jet) >$ 180 GeV (ele.)
  μ+jets: $\mathbf{H_T} >$ 220 GeV

	e+jets	μ+jets
Bkg.	2.7±0.6	2.7±1.1
Sig. exp.	1.8±0.4	2.4±0.4
Observed	4	4

Cross-Section Results

$$\sigma_{\mathbf{t\bar{t}}}(\mathbf{e}) = \mathbf{5.2}^{+\mathbf{9.4}}_{-\mathbf{6.7}}(\mathbf{sta})^{+\mathbf{9.1}}_{-\mathbf{3.1}}(\mathbf{sys})\ \text{pb}$$

$$\sigma_{\mathbf{t\bar{t}}}(\mu) = \mathbf{3.8}^{+\mathbf{6.9}}_{-\mathbf{4.9}}(\mathbf{sta})^{+\mathbf{3.9}}_{-\mathbf{5.4}}(\mathbf{sys})\ \text{pb}$$

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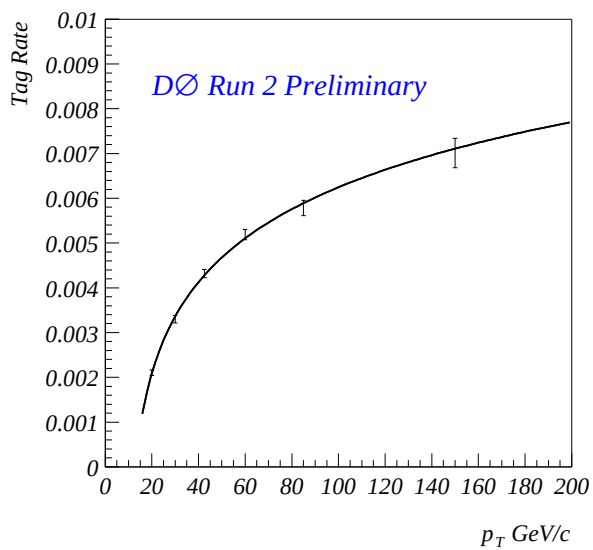
$\sigma_{t\bar{t}}$ using Soft Muon b-Jet Tagging at DØ

- Identify muon from b-decay with jets.
  $\mathbf{p_T}(\mu) > \mathbf{4}$ GeV, $|\eta(\mu)| < \mathbf{2}$
  $\mathbf{\Delta R}(\mu, \mathbf{jet}) < \mathbf{0.5}$
- Jet tagging probability from multi-jet events:



- Standard lepton ID: e or μ
- $\not{E}_T > \mathbf{20}$ GeV
- Jet definition: $\mathbf{E_T} > \mathbf{20}$ GeV, $|\eta| < \mathbf{2}$ $\mathbf{N_{jets}} \geq \mathbf{3}$
- Loose topological cuts:
  $\mathbf{H_T} > \mathbf{110}$ GeV
  Aplanarity > 0.04

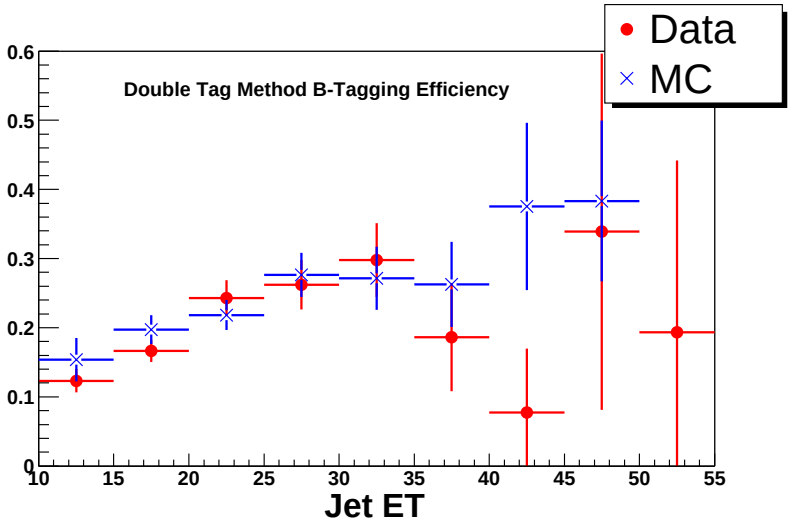
$\mathbf{N_{obs}}$	$\mathbf{N_{bkg}}$	$\mathbf{N_{t\bar{t},exp.}}$
2	$\mathbf{0.9 \pm 0.39}$	1.36

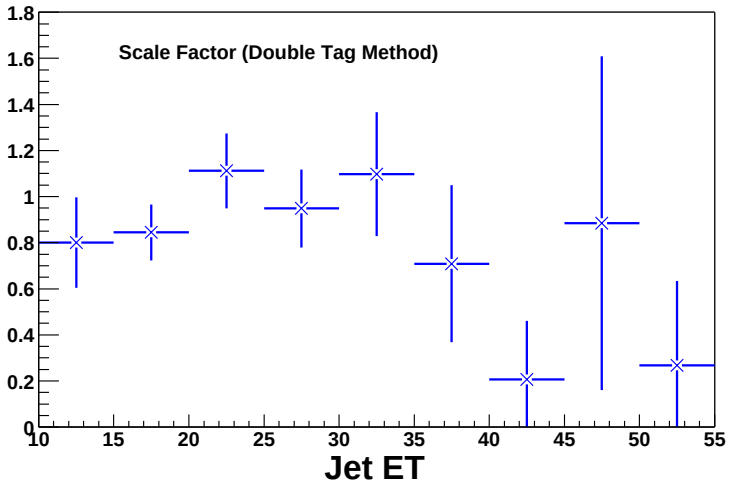
SLT + Topological combined:

$$\sigma_{t\bar{t}} = \mathbf{5.8^{+4.3}_{-3.4}(stat)^{+4.1}_{-2.6}(sys)} \pm \mathbf{0.6(lumi)\ pb}$$

Tagging of b-Quark Jets at CDF

- Objective: suppression of W + multijet background. Only 2% of events have b-quarks.
- B hadrons fly macroscopic distances: $\Delta L = c\tau \cdot \beta\gamma$ with $c\tau \simeq 450\ \mu\mathrm{m}$
- Secondary Vertex Tag:
  - → 2D decay length
  - → beamline $\oplus$ primary vertex
- Event tagging eff. for $\mathrm{t\bar{t}}$: 45% $\pm$ 1%(stat.) $\pm$ 5%(syst.)

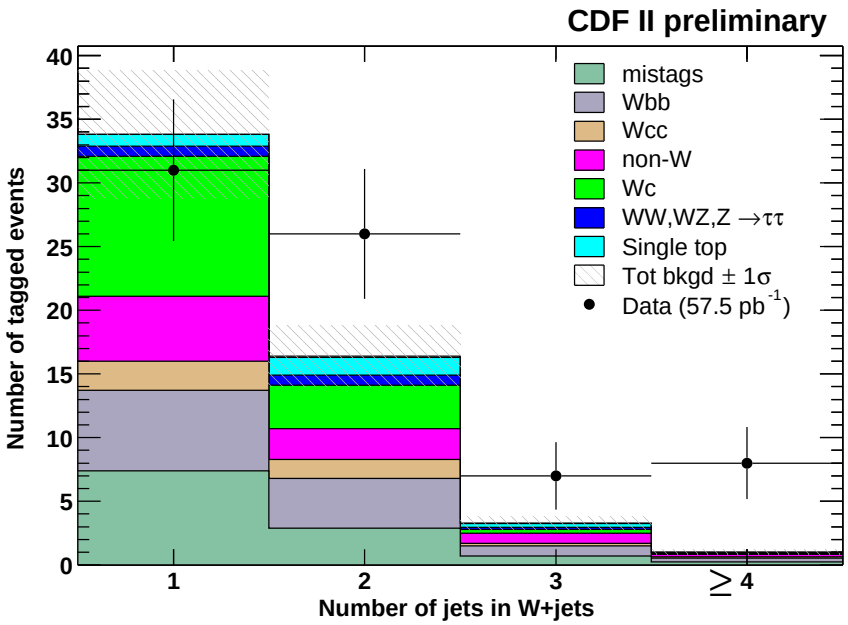




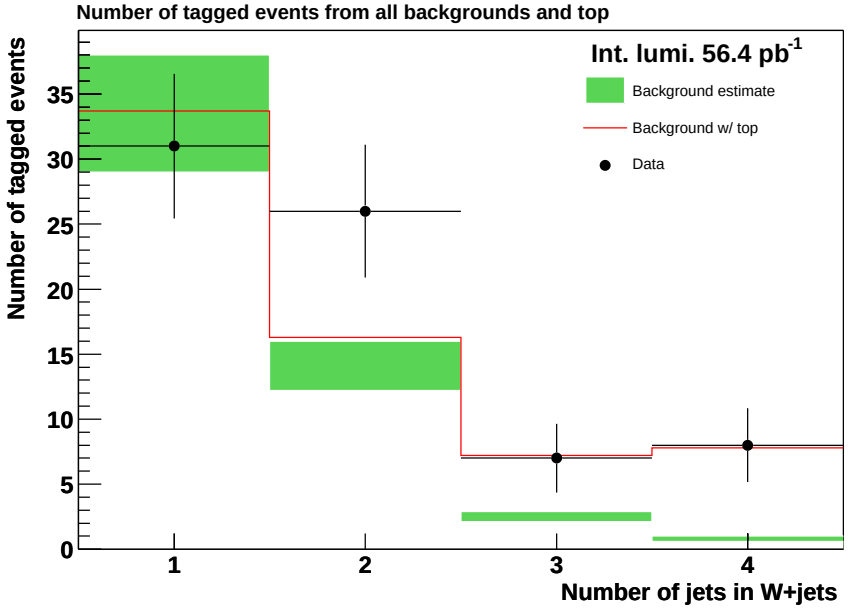
b-Tagging efficiency per jet

Cross Section Measurement in Lepton + Jets at CDF

- $\int \mathcal{L}\, dt = 57.5\ \mathrm{pb}^{-1}$ ($\pm 6\%$)
- Signal region:
  W+3 and W+4 jet bin
  $\mathbf{E_T} > \mathbf{15}$ GeV, $|\eta| < \mathbf{2.0}$



15 candidate events /
4.1 background events



Cross section:

$$\sigma(\mathrm{t\bar{t}}) = (\mathbf{5.3} \pm \mathbf{1.9} \pm \mathbf{0.8_{sys}})\ \mathbf{pb}$$

+ 6% luminosity uncertainty

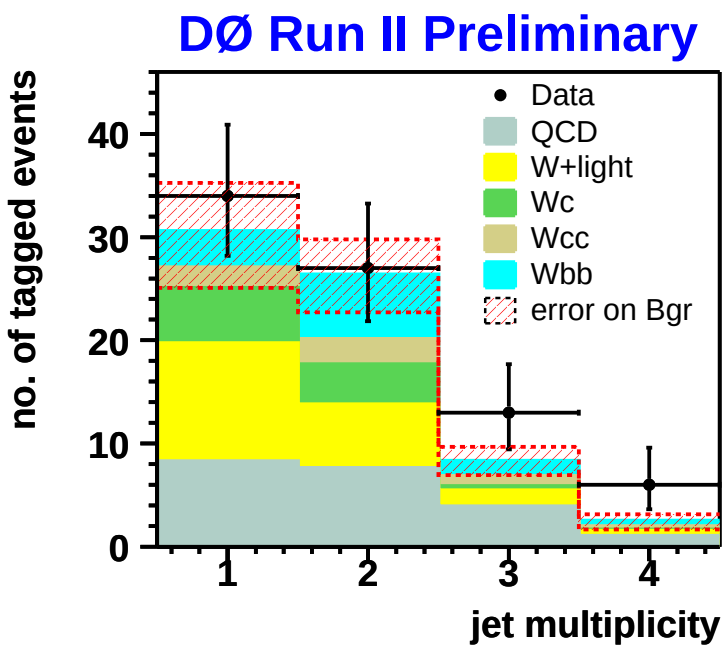
$\sigma(t\bar{t})$ with Lifetime b-Tagging at DØ

Two different algorithms:

- SVT – based on secondary vertex resonstruction
- CSIP – uses impact parameter significance

Analysis uses standard preselection and topological cuts.

Tagging efficiency of $t\bar{t}$ events with $N_{jet} = 4$:
SVT: 42.4±4.7%
CSIP: 45.8±4.9%



Cross-Sections:

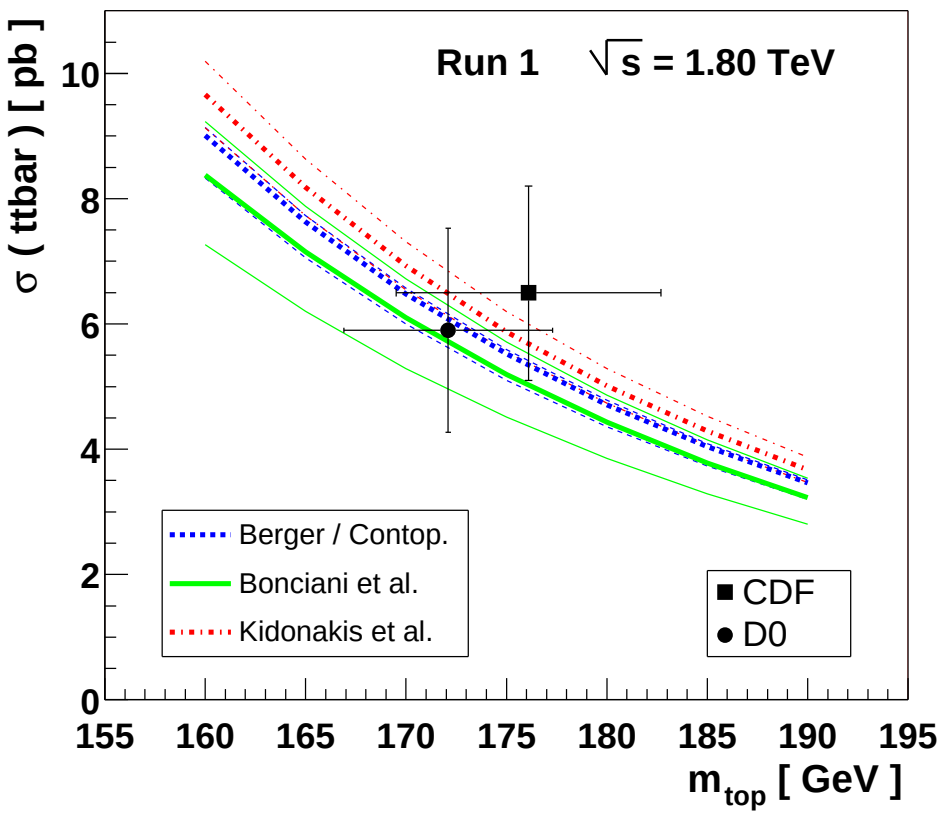
SVT: $\sigma_{t\bar{t}}(\mu) = 10.8^{+4.9}_{-4.0}(\mathrm{stat})$
$^{+2.1}_{-2.0}(\mathrm{sys}) \pm 1.1$(lum) pb

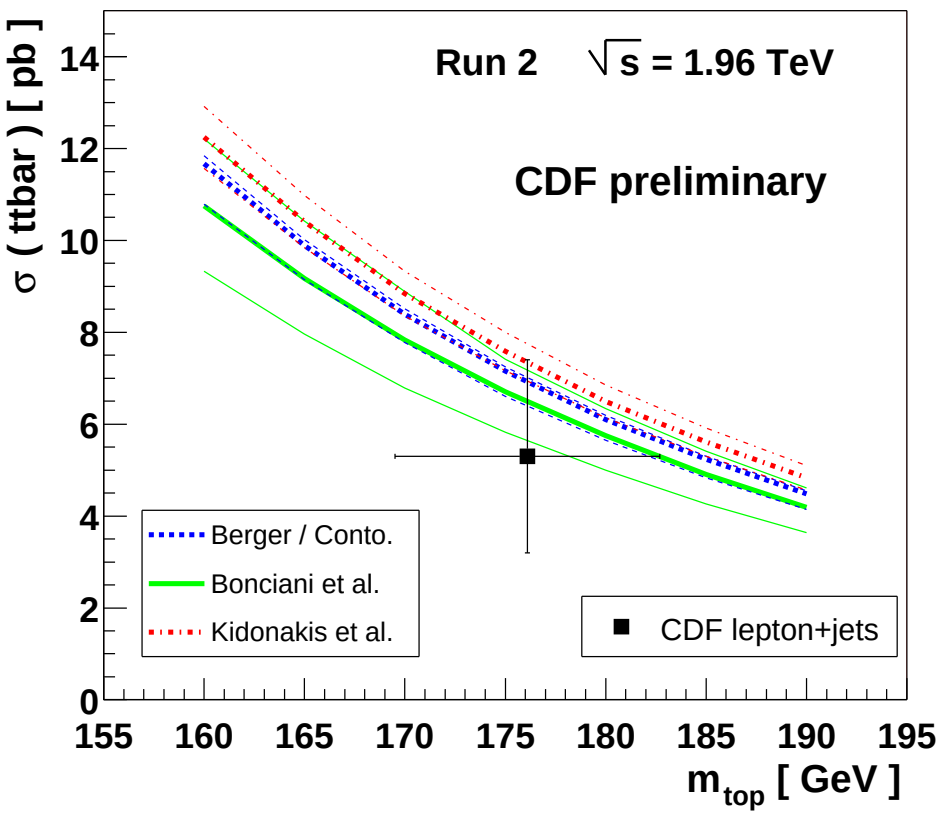
CSIP:
$\sigma_{t\bar{t}} = 7.4^{+4.4}_{-3.6}(\mathrm{stat})^{+2.1}_{-1.8}(\mathrm{sys})$
± 0.7(lum) pb

Cross-Section Summary and Comparison with Theory

CDF lepton+jets: $\sigma(\mathrm{t\bar{t}}) = (5.3 \pm 1.9 \pm 0.8(\mathrm{sys}) \pm 0.3(\mathrm{lum}))\ \mathrm{pb}$

DØ combined: $\sigma = \left(8.5^{+4.5}_{-3.6}(\mathrm{stat})^{+6.3}_{-3.5}(\mathrm{sys}) \pm 0.8(\mathrm{lum})\right)\ \mathrm{pb}$





For the Run 2 plot we used the Run 1 top mass.

Measurement of $\mathrm{R_{tb}}$ with $\mathrm{t\bar{t}}$ Events in Run 1

- Standard Model:
  BR$(\mathbf{t \to W^+ + b}) \simeq \mathbf{100\%}$
- experimental test: measure

$$\mathbf{R_{tb}} \equiv \frac{\mathbf{BR\ (t \to W + b)}}{\mathbf{BR\ (t \to W + q)}}$$

- use two CDF $\mathrm{t\bar{t}}$ data sets:
  di-lepton and lepton+jets
  $\int \mathcal{L}\ \mathbf{dt} = \mathbf{109}\ \mathrm{pb}^{-1}$
- two tagging algorithms:
  SECVTX and Soft Lepton

- likelihood fit to tagging multiplicity

Sample	00	01	1	2
ℓ + jets	126	14	18	5
di-lepton	6	n/a	3	0

$$|\mathbf{R_{tb}}| = \mathbf{0.94}^{\mathbf{+0.31}}_{\mathbf{-0.24}}$$
$$> \mathbf{0.56}\ @\ \mathbf{95\%C.L.}$$

Phys. Rev. Lett. 86 3233 (2001)

- w/ unitarity: $|\mathbf{V_{tb}}| = 0.97^{+0.16}_{-0.12}$
- Expectation for Run 2a:
  $\delta|\mathbf{R_{tb}}|/|\mathbf{R_{tb}}| = \mathbf{3\%}$

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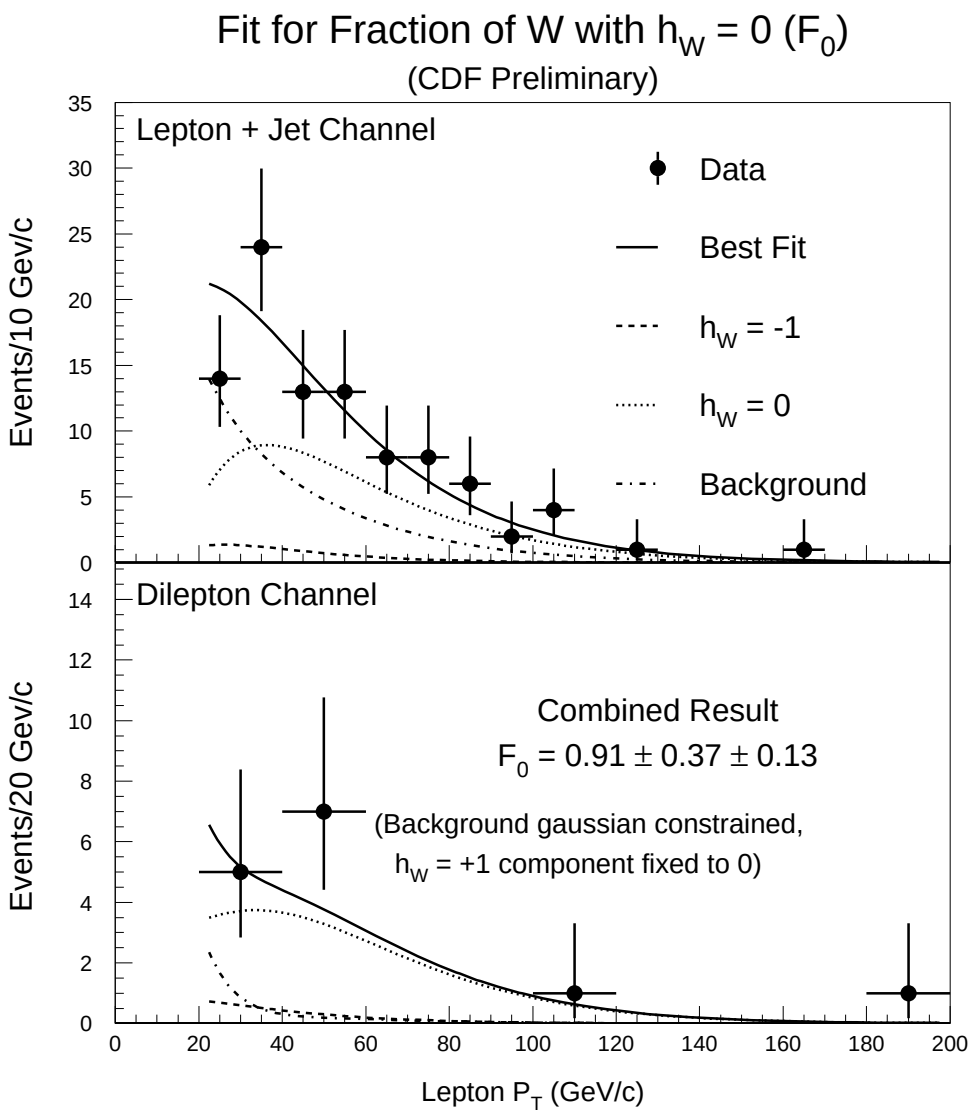
W helicity Measurements
Testing V-A Theory



Fitting Lepton $\mathbf{p_T}$ Spectrum

Longitudinal Fraction:

$\mathcal{F}_0 = \mathbf{0.91 \pm 0.37 \pm 0.13(sys)}$

SM: $\mathcal{F}_0 = \mathbf{0.701 \pm 0.016}$

V+A test: $\mathcal{F}_+$

$\mathcal{F}_+ = \mathbf{0.11 \pm 0.15}$

SM: $\mathcal{F}_+ < \mathbf{0.04}$ (b-mass)

Fitting $\mathbf{M_{\ell b}}$

$$\mathbf{M^2_{\ell b} = (M^2_T - M^2_W) \cdot (1 + \cos\theta^*)}$$

New CDF result (2003):

$$\mathcal{F}_+ = \mathbf{-0.21^{+0.42}_{-0.25} \pm 0.21(sys)}$$

Conclusions

- Run 2 data sets are now exceeding those of Run 1.
  Soon we will have exciting results superseding those of Run 1.

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$\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} < 7\%$	Δm_{top} = 2 – 3 GeV/c^2
W polarization	Single Top Production
R_{tb} measurement	$t\bar{t}$ spin correlations
Search for FCNC top decays	Gluon radiation in top decays

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Backup Slides

1. CDF Detector Upgrade
2. $\mathbf{D\emptyset}$ Detector Upgrade
3. CDF dilepton event candidate
4. $\mathrm{D\emptyset}$: $t\bar{t}$ cross section with soft muon tag

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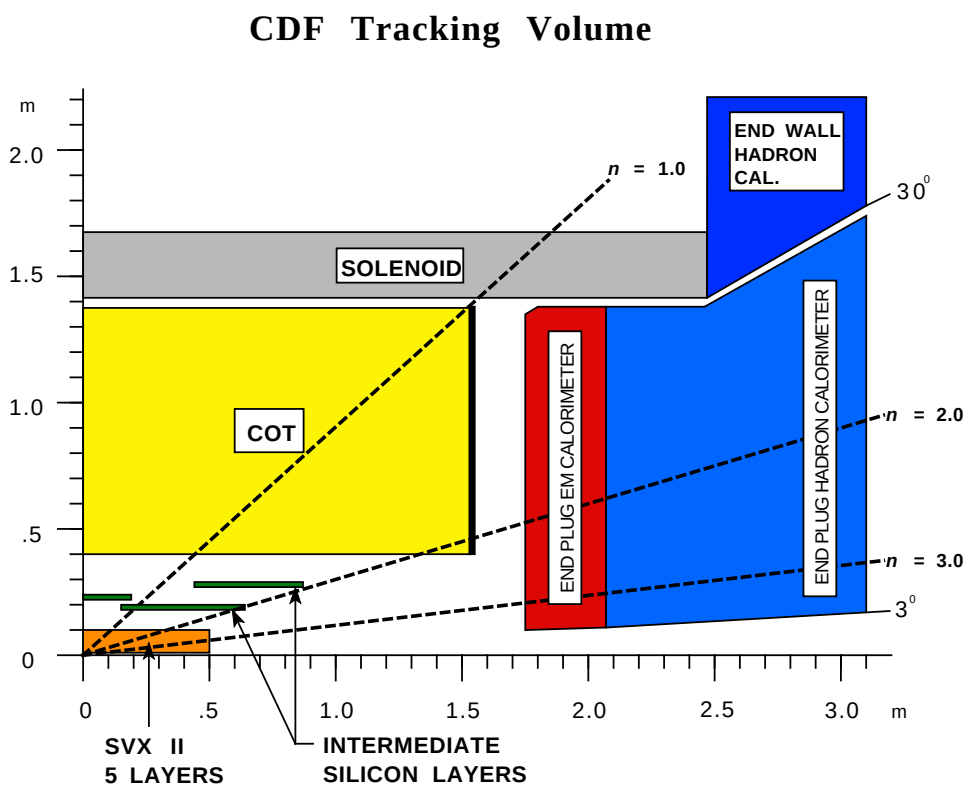
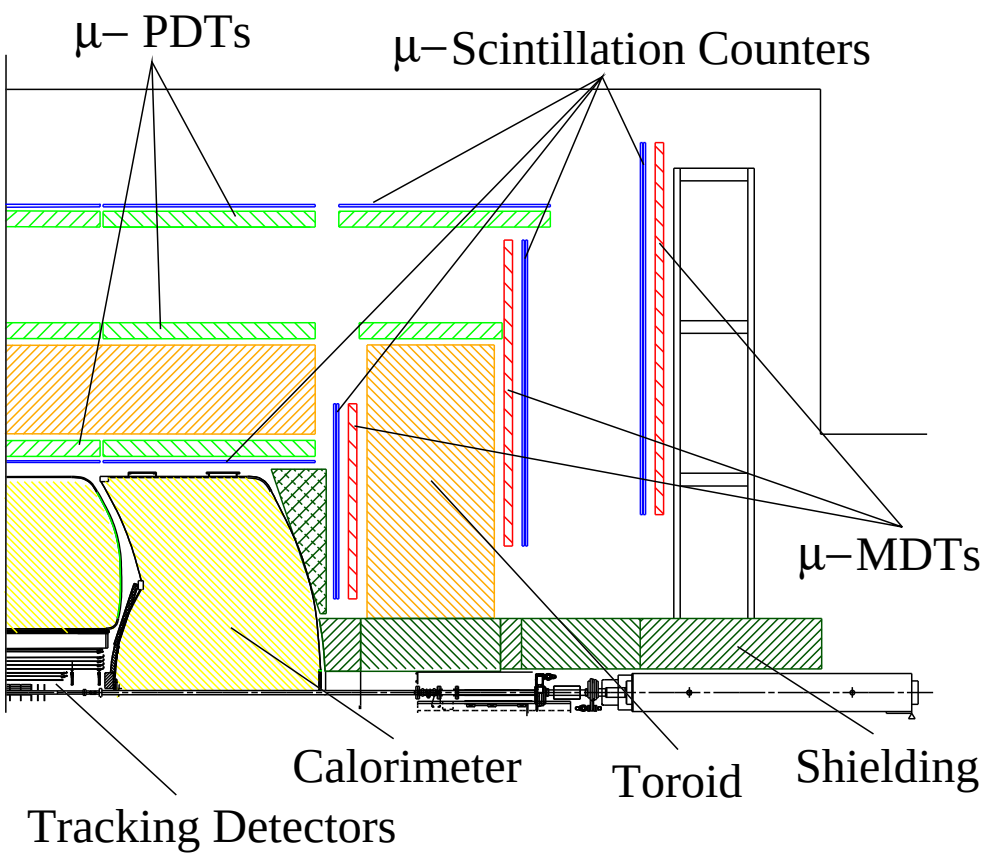
CDF Upgrade for Run 2



- Faster front end electronics
- Trigger/DAQ pipelined, 70 Hz to tape

- New silicon vertex detector:
  Layer 00 + SVX II + ISL
  Full silicon coverage: $|\eta| < 2$
  13 (15) views: $r\phi$, rz, stereo
- New Drift Chamber
  Central Outer Tracker (COT)
- Secondary Vertex Trigger
- Extended muon systems in ϕ and η
- New calorimeter endplugs
- Time of Flight (K/π Id)

DØ Run 2 Upgrade

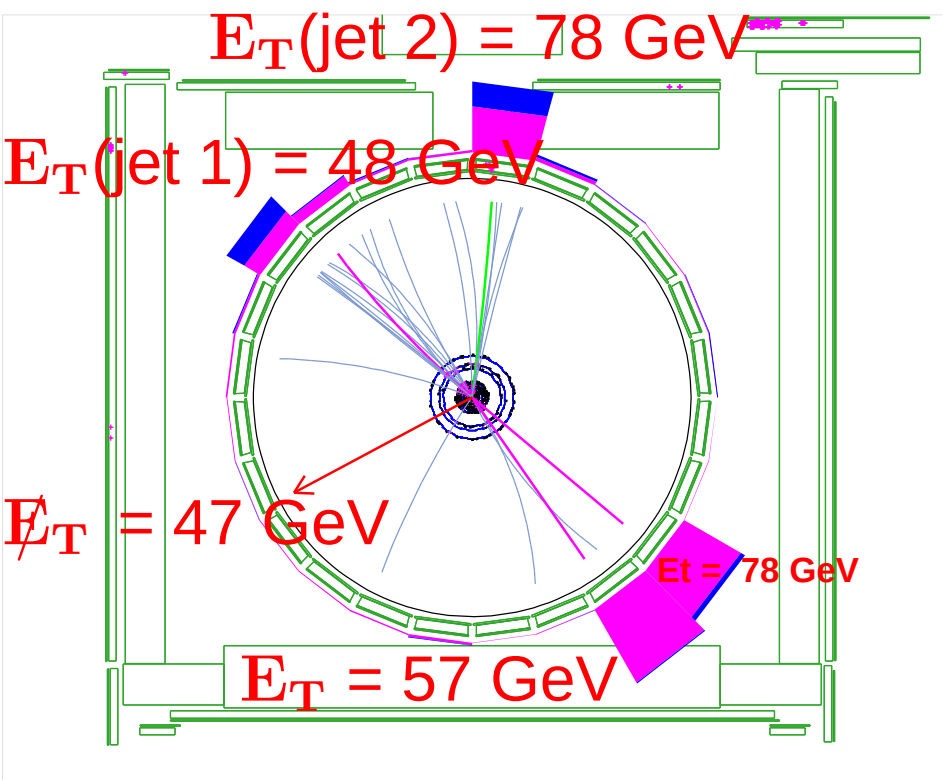


- New tracking system:
  - + silicon tracker
  - + fiber tracker
  - + 2 T solenoid
- Upgraded muon systems.
- New trigger and DAQ system.
  Displaced track trigger coming soon.

Example Dilepton $t\bar{t}$ Candidate in the e^+e^- Channel

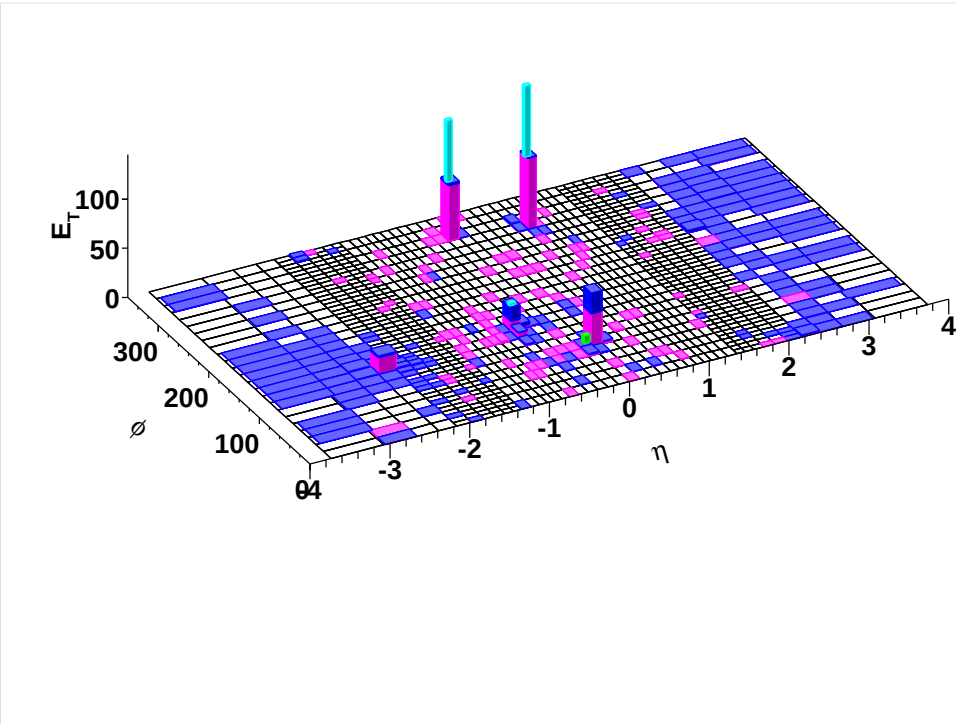
Run 153374 Event 2276742

taken on October 27, 2002



M_{ee} = 59 GeV, H_t = 302 GeV

- E_T on calorimeter $\eta \times \phi$ grid



- $\Delta\phi(\not{E}_T$, nearest ℓ or j$) = 79°$

Lepton + Jets: the Golden Sample for $\mathrm{m_{top}}$ and $\sigma(\mathrm{t\bar{t}})$

CDF top mass in Run 1:

$\mathbf{m_{top} = (176.1 \pm 6.6)}$ GeV
dominated by ℓ + jets.

CDF $\oplus$ $\mathbf{D\emptyset}$:
$\mathbf{m_{top} = (174.3 \pm 5.1)}$ GeV

Systematic uncertainties:

Jet energy scale	4.4 GeV
ISR / FSR	2.6 GeV
Background model	1.3 GeV
b-tagging	0.4 GeV
PDFs	0.3 GeV
MC generators	0.1 GeV
Total	5.3 GeV

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CDF $\oplus$ $\mathbf{D\emptyset}$:
$\mathbf{m_{top} = (174.3 \pm 5.1)}$ GeV

Systematic uncertainties:

Jet energy scale	4.4 GeV
ISR / FSR	2.6 GeV
Background model	1.3 GeV
b-tagging	0.4 GeV
PDFs	0.3 GeV
MC generators	0.1 GeV
Total	5.3 GeV

- Run 2 increase:
  $20 \times 1.3 \times 1.6 \approx 40$
  $\approx$ 800 single-tagged lepton + jets events
  ➜ stat. uncertainty $\approx$ 1 GeV
- reducing the syst. uncertainty to $\approx$ 2 GeV
  ➜ control samples:
  Z + jets, $\mathbf{Z \to b\bar{b}}$, $\mathbf{W \to q\bar{q}}$
  ➜ experimental study of soft gluon radiation

Lepton + Jets: the Golden Sample for $\mathbf{m_{top}}$ and $\sigma(\mathbf{t\bar{t}})$

CDF top mass in Run 1:

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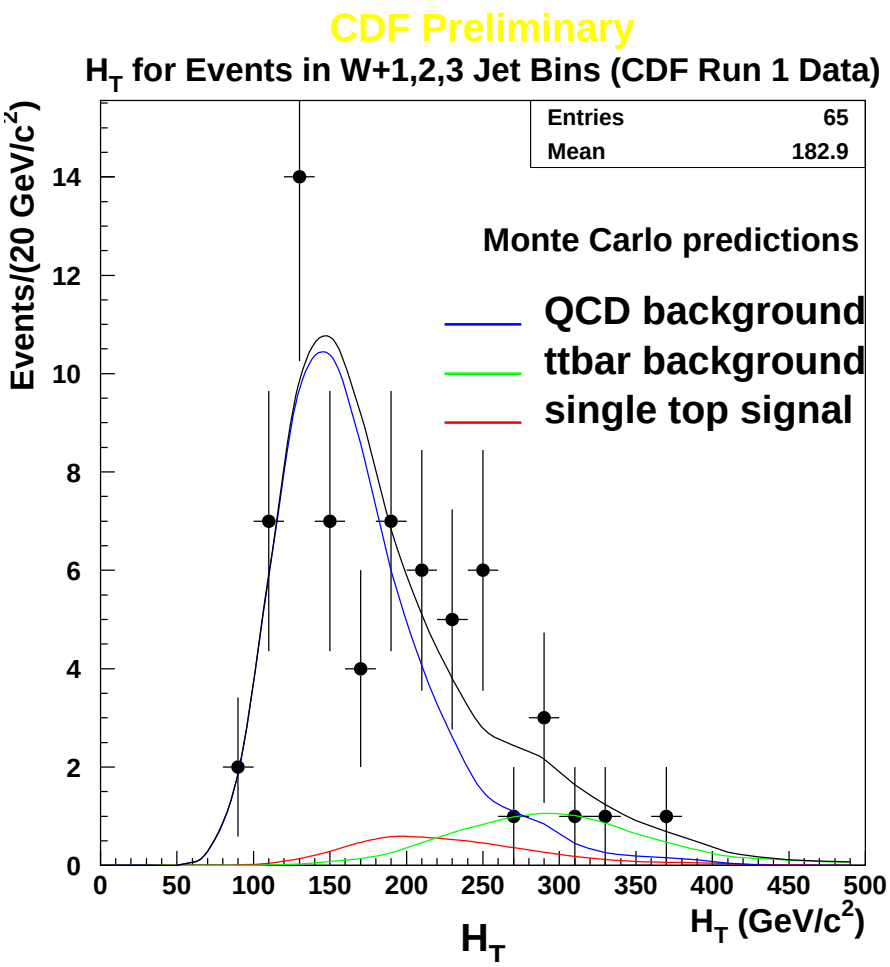
- $\mathbf{\delta M_{top} = 2}$ to $\mathbf{3}$ GeV/$\mathbf{c^2}$
  per experiment

Run I Single Top Search (1): Combined Limit

- reconstruct $\mathbf{M_{\ell\nu b}}$, apply W mass constraint
- $\mathbf{140 < M_{\ell\nu b} < 210\ GeV}$
- <u>event numbers:</u>

Wg	W^*	$t\bar{t}$	non-top	total	obs.
3.0	1.3	8.4	54	67	65

- $H_t \equiv |\not{E}_T| + |E_t(\ell)| + \sum |E_t(\text{ all jets })|$
- unbinned maximum likelihood fit to $\mathbf{H_t}$ distribution



Upper Limit

$\sigma(\mathbf{Wg} + \mathbf{W}^*) < \mathbf{14}$ pb

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Run I Single Top Search (2): Separate Limits

- Use only W+2-jets sample.
- Sample 1:
  exactly 1 b-tagged jet
  Binned ML fit to $\mathbf{Q} \times \eta$ distribution ➜ extract Wg content

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Run I Single Top Search (2): Separate Limits

- Use only W+2-jets sample.
- Sample 1:
  exactly 1 b-tagged jet
  Binned ML fit to $\mathbf{Q} \times \eta$ distribution ➜ extract Wg content
- Sample 2:
  exactly 2 b-tagged jets
  Binned ML fit to reconstructed top mass $\mathbf{M}_{\ell\nu\mathbf{b}}$
  ➜ $7.6^{+5.9}_{-4.8}$ W^* events

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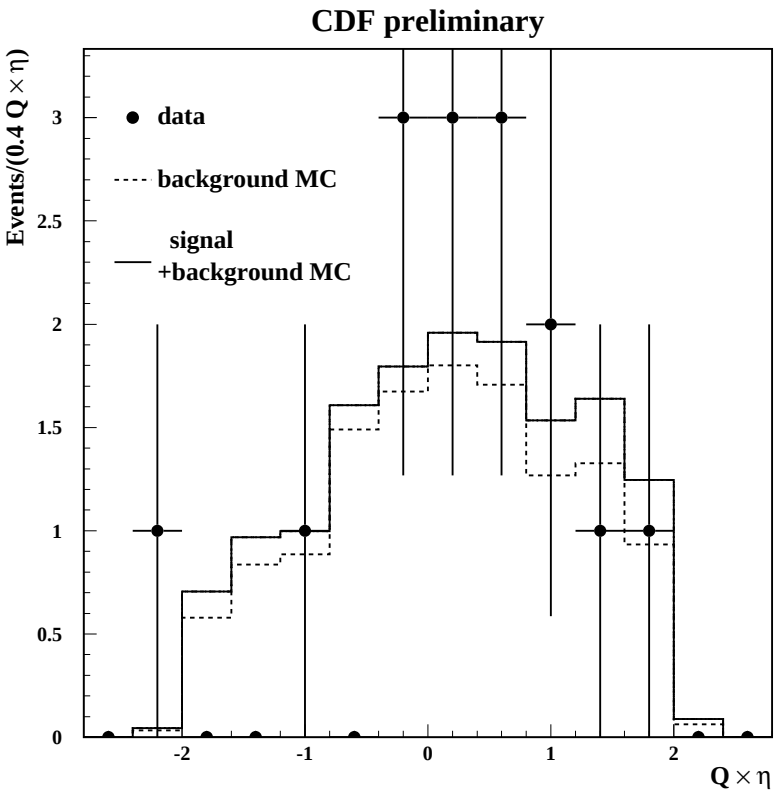

Cross Section Limits

$\sigma(Wg) < 13$ pb

$\sigma(W^*) < 18$ pb

Run I Single Top (3): NN Search

Results are preliminary !

Additional selection criteria:

1. If $\mathbf{N_{jets} = 1}$ ($\mathbf{E_t > 15}$ GeV):
   $\geq$ 1 jet with $\mathbf{E_T > 8}$ GeV
2. If $\mathbf{N_{jets} = 3}$ ($\mathbf{E_t > 15}$ GeV):
   no additional jet with
   $\mathbf{E_T > 8}$ GeV

- 3-layer network
- 7 input variables:
  $\mathbf{E_T(jet1)}$, $\mathbf{E_T(jet2)}$, $\mathbf{E_T}(\ell)$,
  $\mathbf{H_t}$, $\mathbf{p_T(jet1 + jet2)}$ and
  $\mathbf{Q} \times \eta$

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Event numbers:

Wg + W^*	$t\bar{t}$	QCD	expec.	obs.
4.2	7.4	43.3	54.9	64

NN output:

Wg + $\mathbf{W}^*$	$\mathbf{t\bar{t}}$	QCD
$\mathbf{22.9 \pm 7.6}$	$\mathbf{7.6 \pm 2.0}$	$\mathbf{36.1 \pm 6.2}$

- 2.5 σ effect
- Further checks are ongoing.
- Resolve issue in Run 2a: more data and better background simulation.