Top quark production and properties from the Tevatron, where else?

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The top quark
TOP
TURNS
TEN
ELEVEN
TWELVE
Top quarks exist, what do we do with them?

- QCD
- Prod. kinematics
- Resonances
- Spin correlation

- W-helicity

- Mass
- Width
- Charge
- Lifetime
- $t'$

- $|V_{tb}|$
- Branching ratios
- Anomalous couplings
- $t \rightarrow H^+b$

New Physics
Outline

- Top quark production and identification
- Cross section measurements
- Properties of the top quark
- $Wtb$: branching ratio, $W$ helicity
- Top and new physics
Top quark production

Top quark pair production via strong interaction

- 85% 6.7 pb (1.96TeV, mt=175GeV/c²)
- 15%


Single top quark production via weak interaction

See talk by A. Juste

- s-channel: 1.0 pb
  - NNNLO, mt=175 GeV

- t-channel: 2.2 pb

Top quark decay & identification

$t \rightarrow Wb \cong 100\%$

Need to reconstruct and identify Electrons, muons, jets, b-jets and missing transverse energy

decay products have:
- good angular separation in the lab frame
- high transverse momentum
Production cross section

\[
\sigma = \frac{N_{\text{events}} - N_{\text{background}}}{\text{Luminosity} \times \varepsilon}
\]

- Test of QCD at high \(Q^2\)
- Higher cross section than predicted could be a sign of new physics: resonant state \(X \rightarrow t\bar{t}\) OR anomalous couplings in QCD?
- Lower cross section could also mean new physics: we make assumptions on the expected decay mode
- Important to measure all decay channels and topologies: different sensitivities to new physics possibilities
- Provides samples for properties measurements
Lepton + jets channel

Golden channel:
manageable backgrounds branching fraction 29%

Backgrounds:
W+jets
fake leptons in multijets
Lepton+jets cross section

Ultra pure top sample:
≥4 jets, 2 tags
0.6±0.4±0.1 BG expected
19 observed

Combining 1,2 tags; 3, >4 jets; e, µ:

\[ \sigma_{t\bar{t}} = 6.6 \pm 0.9 \text{(stat + syst)} \pm 0.4 \text{(lumi)} \text{pb} \]

@ \( m_t = 175 \text{ GeV} \)

PRD 74, 112004 (2006)
Dilepton cross section

low BG, but also low branching fraction (4.5%)

Increase efficiency by requiring one fully reconstructed lepton, and require an additional track

Backgrounds:
WW/WZ, Z/γ*→ττ→ll
fake MET in DY or fake leptons in multijet

\[ \sigma_{tt} = 8.6^{+1.9}_{-1.7} \text{(stat)}^{+1.1}_{-1.1} \text{(syst)} \text{pb} \]

Combined with e-μ (which has both leptons fully reconstructed)

\[ \sigma_{tt} = 9.0 \pm 1.3 \text{(stat)} \pm 0.5 \text{(syst)} \text{pb} \]

March 5 2007, 1.1fb⁻¹
All-hadronic cross section

- Large branching fraction (46%)
- Huge multijet background (S/B~1/300)
- Need b-jet tagging

**NN-based analysis**

\[ \sigma_{\bar{t}t} = 8.3 \pm 1.0\text{(stat)}^{+2.0}_{-1.5}\text{(syst)} \pm 0.5\text{(lumi)} \text{ pb} \]

1.02 fb\(^{-1}\)
CDF

LaThuile 2007

lepton+track in the plot by next week…

CDF Preliminary

**Dilepton**

\( L = 750 \text{ pb}^{-1} \)

8.3 \( \pm 1.5 \) \( \pm 1.0 \) \( \pm 0.5 \)

**Lepton+Jets: Kinematic ANI**

\( L = 760 \text{ pb}^{-1} \)

6.0 \( \pm 0.6 \) \( \pm 0.9 \) \( \pm 0.3 \)

**Lepton+Jets: Vertex Tag**

\( L = 695 \text{ pb}^{-1} \)

8.2 \( \pm 0.6 \) \( \pm 0.9 \) \( \pm 0.5 \)

**Lepton+Jets: Soft Muon Tag**

\( L = 760 \text{ pb}^{-1} \)

7.8 \( \pm 1.7 \) \( \pm 1.0 \) \( \pm 0.5 \)

**MET+Jets: Vertex Tag**

\( L = 311 \text{ pb}^{-1} \)

6.1 \( \pm 1.2 \) \( \pm 1.4 \) \( \pm 0.4 \)

**All-hadronic: Vertex Tag**

\( L = 1020 \text{ pb}^{-1} \)

8.3 \( \pm 1.0 \) \( \pm 2.0 \) \( \pm 0.5 \)

**Combined(old SLT, all-had)**

\( L = 760 \text{ pb}^{-1} \)

7.3 \( \pm 0.5 \) \( \pm 0.6 \) \( \pm 0.4 \)

(stat) \( \pm \) (syst) \( \pm \) (lumi)
Production mechanism \((gg \rightarrow tt)/(pp \rightarrow tt)\)

The number of low-pt tracks (0.3-3.0 GeV) scales with the gluon content of the sample

\[
\sigma(gg \rightarrow tt) \quad \frac{\sigma(gg \rightarrow tt)}{\sigma(pp \rightarrow tt)} = 0.01 \pm 0.16(\text{stat}) \pm 0.07(\text{syst})
\]

March 5, 2007

Consistent with SM expectation of 0.18
Is the ‘top’ the SM top?

- charge
- lifetime
Top charge

- A most fundamental quantity characterizing a particle
- Possible alternative to $+2/3e$ (D.Chang et al PRD59, 091503 (1999))
  - Introduce an exotic 4th family $(Q_1, Q_4)_R$, with charge $(-1/3, -4/3)$
  - $Q_4$ is the "discovered top quark"
- True top quark has a mass of $\sim 270$ GeV and escaped detection

![Diagram of SM and Exotic models](image-url)
Top charge

Use a likelihood ratio method

\[ \Lambda = \frac{\prod_i p^{\text{sm}}(q_i)}{\prod_i p^{\text{ex}}(q_i)} \]

92% \( \Lambda_{\text{EX}} < \Lambda_{\text{data}} \)

Exclude exotic 4/3e top at 92% C.L.

*PRL 98, 041801 (2007)
top lifetime

Lepton + jets channel with one b tagged jet

• Primary Vertex constrained by jets
• Measure the lepton impact parameter

CDF Run II  Preliminary

Likelihood fit

Maximum likelihood for $c\tau_{\text{top}} = 0 \, \mu m$

$c\tau_{\text{top}} < 52.5 \, \mu m$ at 95% CL

SM: $3 \times 10^{-10} \, \mu m$
Probing the Wtb vertex

- $t \rightarrow Wb$ / $t \rightarrow Wq$
- $W$ helicity in top events
Probing the assumption $t \rightarrow Wb$

$$R = \frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.9980 \text{ to } 0.9984$$

(True in SM with three quark generations)

Measurement: count b-jets. The number of b-jets depends strongly on $R$ and the tagging efficiency.

→ Result is obtained from a binned maximum likelihood fit to data for $N_{jet} = 3$ and $N_{jet} = 4$

→ Simultaneous fit to $R$ and cross section

$Br(t \rightarrow Wb) = 1$ and $\sigma_{tt} = 7 \text{ pb}$
Probing $t \rightarrow Wb$

$$\sigma_{t\bar{t}} = 7.9^{+1.7}_{-1.5} \text{(stat + syst)} \text{ pb}$$

Also allows for a model independent cross section measurement:

$$B = \frac{Br(t \rightarrow Wb)}{Br(t \rightarrow Wq)} = 1.03^{+0.19}_{-0.17} \text{(stat + syst)}$$

Assuming CKM unitarity $|V_{tb}| > 0.78$ @ 95% CL

Direct $|V_{tb}|$ measurement with single top $\rightarrow$ see talk by Juste

PRL 95, 102002 (2005)
W Helicity from $t \rightarrow Wb$ Decays

- Examines the nature of the tWb vertex, probing the structure of weak interactions at energy scales near EWSB
- Stringent test of SM and its V-A type of interaction.
- Uses boosted W from top decays

\[ M_{l+b}^2 = \frac{1}{2} \cdot (M_T^2 - M_W^2)(1 + \cos \psi_l^*) \]
Results (2 selected)

lepton+jets and dilepton

F+ = 0.056 ± 0.080 (stat) ± 0.057 (syst)
F+ < 0.23 @ 95% C.L.

(Earlier result with 0.7 fb⁻¹:
PRD 75, 031102(R) (2007))

CDF Run II Preliminary

lepton+jets

F0 = 0.59 ± 0.12 (stat) ± 0.07 (syst)
F+ < 0.10 @ 95% C.L.

(Earlier result with 0.7 fb⁻¹:
PRL 98, 072001 (2007))
Is there more than the top?

- t-prime
- Resonant top production
Search for a heavy 4th generation quark (He et al. Hep-ph/0102144)

Template fit in \((H_T, M_T)\)

Lower limit on the t’ mass of 258 GeV/c² at 95% C.L.

Expect \(m(t') > 300\) GeV/c² with 2 fb⁻¹, unless...
t-tbar resonances in $l+jets$

Search for a resonance in the t-tbar invariant mass spectrum

Model exclusion:
- narrow leptophobic $Z'$ $\Gamma = 1.2\% M_{Z'}$
  - CDF: exclude $M(Z') < 725$ GeV/c$^2$
  - D0: exclude $M(Z') < 680$ GeV/c$^2$
Conclusions

- Top production and properties are consistent with the standard model expectation
- There is still space for new physics
- A lot of physics from the Tevatron: 15 D0 or CDF papers on top physics in 2006

Understanding top quark production and properties will be crucial for success at LHC. What we learn at the Tevatron, both physics and analysis tools, extends directly to LHC!
- 8 layer silicon
- 16 layers scintillating fibers
- 2T Solenoid
- Calorimeter: Central + EndCap
- 1.8T Toroid
- 3 layers muon scintillator + drift tubes

- Silicon detector
- COT: drift chamber
- Solenoid
- Calorimeters: Central, wall, plug
- Muon: scintillator + chamber
b-jet tagging

Secondary Vertex b-tagging algorithm
Separates b jets from light quark and gluon jets

→ B hadrons travel 
~3 mm before decay

NN tagger

b Jets
(Real b-tags)

<table>
<thead>
<tr>
<th>Tagger applied to MC</th>
<th>TRF applied to MC</th>
<th>TRF after scaling to match tagger on data</th>
</tr>
</thead>
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Transverse Momentum [GeV]

NN Tagger Efficiency

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
20 30 40 50 60 70 80 90 100
Mass dependence

All cross sections are measured at $m_t=175$ GeV

Dependence on mass is studied both for measurement (detection) and theory (production)
Discoveries...

Year Discovered

Number of Physicists

12 years ago!