Top Quark Pair Production at the Tevatron

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on behalf of

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Moriond QCD
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What is the Top Quark?

- Discovered in 1995 by CDF and DØ at the Fermilab Tevatron
- Required by the Standard Model as the weak isospin partner of the bottom quark
- Extremely massive: $m_t \approx 170$ GeV vs. $m_b \approx 5$ GeV
- Mass near the electroweak symmetry breaking scale with a top–Higgs Yukawa coupling of $\lambda_t = \sqrt{2 \frac{m_t}{v}} \approx 1$
- $m_t > m_W$ so $t \rightarrow Wb$
  $\Gamma_t \approx 1.4$ GeV $\Rightarrow \tau_t \approx 4 \times 10^{-25}$ sec $\ll \frac{1}{\Lambda_{QCD}} \approx 3 \times 10^{-24}$ sec
  $\Rightarrow$ thus top quarks decay before interacting via strong force

Top quarks are effectively bare quarks!
The top quark exists at the interface between Electroweak and QCD physics. Its production and properties are sensitive to the existence of new physical phenomena and offer insights on the electroweak symmetry breaking mechanism.
$t\bar{t}$ Production

Top quarks are mainly produced in pairs via strong interactions. Measurement of the $t\bar{t}$ production rate provides precision tests of (N)NLO pQCD and is sensitive to the presence of new physical phenomena.

$\sigma_{NLO} = 7.46^{+0.66}_{-0.80}$ pb at $m_t = 172.5$ GeV and $\sqrt{s} = 1.96$ TeV

Cacciari et al
Classifying Top Events

$t \rightarrow Wb$ is $\approx 100\%$

It is important to measure all decay channels as they have different sensitivities to new physics (eg, $H^\pm$ in $\tau$)

Need to reconstruct electrons, muons, jets, $b$-jets, and missing transverse energy
Since last Moriond QCD...

- 4.6 fb$^{-1}$ Measurement of the $t \bar{t}$ Cross Section in the Lepton Plus Jets Channel Using Neural Networks in 4.6 fb$^{-1}$ of CDF Data
- 4.3 fb$^{-1}$ Measurement of the Ratio of the Top Pair Cross Section with the Z boson Cross Section in 4.3 fb$^{-1}$
- 4.3 fb$^{-1}$ Measurement of the Top Pair Production Cross Section using RomaNN in the Lepton Plus Jets Decay channel with 4.3 fb$^{-1}$
- 5.3 fb$^{-1}$ Measurement of the $t \bar{t}$ Production Cross-Section in Dilepton Final States at DØ using 5.3 fb$^{-1}$ of Data
- 4.5 fb$^{-1}$ Measurement of the $t \bar{t}$ Production Cross Section in Dilepton Channel using 4.5 fb$^{-1}$ of Run II Data
- 2.9 fb$^{-1}$ $t \bar{t}$ production cross section measurement in the all-hadronic channel
- 1.0 fb$^{-1}$ Measurement of the $t \bar{t}$ cross section using high-multiplicity jet events
- 2.2 fb$^{-1}$ Measurement of the $t \bar{t}$ production cross section in the $E_T$+jets channel with 2.2 fb$^{-1}$
- 4.6 fb$^{-1}$ Combination of the CDF top quark pair production cross section measurements with up to 4.6 fb$^{-1}$
- 1.0 fb$^{-1}$ Combination of the $t \bar{t}$ cross section measurements and constraints on the mass of the top quark and its decay into charged Higgs bosons
- 4.1 fb$^{-1}$ Measurement of the $t \bar{t}$+jet Cross Section with 4.1 fb$^{-1}$
- 1.0 fb$^{-1}$ Dependence of the $t \bar{t}$ production cross section on the transverse momentum of the top quark

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**$\ell +$ Jets Decay Channel**

- Use NN to separate signal from background
- Use $b$-tagging to suppress backgrounds

$\sigma_{t\bar{t}} = 7.63 \pm 0.37 \text{ (stat)} \pm 0.35 \text{ (sys)} \pm 0.15 \text{ (th)} \text{ pb}$ at $m_t = 172.5 \text{ GeV}$

$\Delta \sigma / \sigma \sim 7\% \ (8.6\% \text{ without using } \sigma_Z)$

$\sigma_{t\bar{t}} = 7.14 \pm 0.35 \text{ (stat)} \pm 0.58 \text{ (sys)} \pm 0.14 \text{ (th)} \text{ pb}$ at $m_t = 172.5 \text{ GeV}$

$\Delta \sigma / \sigma \sim 9.7\% \ (11\% \text{ without using } \sigma_Z)$

- Measure $\sigma_{t\bar{t}}$ in ratio with $\sigma_Z$ to reduce luminosity uncertainty
Dilepton Decay Channel

Dileptons offer great signal to background but with a small branching fraction
- count high purity $e\mu$
- separate signal from background in $e^+e^-$ & $\mu^+\mu^-$ with BDT

\[ \sigma_{tt} = 8.8 \pm 0.6 \text{ (stat)} \pm 1.0 \text{ (sys)} \pm 0.6 \text{ (lum)} \text{ pb} \]

at \( m_t = 172.5 \text{ GeV} (\mathcal{L} = 4.3 \text{ fb}^{-1}) \)

\[ \Delta \sigma/\sigma \sim 15\% \]

Combined with PLB 679, 177 (2009):
\[ \sigma_{tt} = 8.4 \pm 0.5^{+0.9}_{-0.8} \pm 0.7 \text{ pb} \]

at \( m_t = 172.5 \text{ GeV} (\mathcal{L} = 5.3 \text{ fb}^{-1}) \)
Dilepton Decay Channel

Pre-b-tagged:
\[ \sigma_{\tilde{t}\tilde{t}} = 6.56 \pm 0.65 \text{ (stat)} \pm 0.41 \text{ (sys)} \pm 0.38 \text{ (lum)} \text{ pb} \]
at \( m_t = 172.5 \text{ GeV} \)

requiring at least one b-tagged jet improves signal-to-background

\[ \Delta \sigma / \sigma \sim 13\% \]

\[ b\text{-tagged:} \]
\[ \sigma_{\tilde{t}\tilde{t}} = 7.27 \pm 0.71 \text{ (stat)} \pm 0.46 \text{ (sys)} \pm 0.42 \text{ (lum)} \text{ pb} \]
at \( m_t = 172.5 \text{ GeV} \)

\[ \Delta \sigma / \sigma \sim 13\% \]
All Jets Decay Channel

Backgrounds extracted from data:

- combine jets from different double $b$-tagged events that had low jet multiplicities
- validated with 4- and 5-jet events

$\sigma_{t\bar{t}} = 6.9 \pm 1.3\text{ (stat)} \pm 1.4\text{ (sys)} \pm 0.4\text{ (lum)}$ pb
at $m_t = 175$ GeV

$\Delta\sigma/\sigma \sim 28\%$

arXiv:0911.4286 [hep-ex]
All Jets Decay Channel

Backgrounds extracted from data:

- apply probability for jet to be $b$ tagged to an untagged sample
- validated in 4-jet events with low NN values

$$\sigma_{tt} = 7.2 \pm 0.5 \text{ (stat)} \pm 1.1 \text{ (sys)} \pm 0.4 \text{ (lum)} \text{ pb}$$ at $m_t = 172.5 \text{ GeV}$

$$\frac{\Delta \sigma}{\sigma} \sim 18\%$$
$E_T^{\pm} + \text{jets}$ Decay Channel

Recover events that don’t satisfy lepton requirements but have significant $E_T$

- data-driven background from low jet-multiplicity bins

$\sigma_{t\bar{t}} = 7.99 \pm 0.55 \text{ (stat)} \pm 0.76 \text{ (sys)} \pm 0.46 \text{ (lum)} \text{ pb}$

at $m_t = 172.5 \text{ GeV}$

$\Delta \sigma / \sigma \sim 13\%$

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CDF Run II Preliminary $L=2.2 \text{fb}^{-1}$

$\chi^2/\text{ndf} = 95.28/54$

$N_{\text{jets}} \geq 4$

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Combined Measurements

CDF


Combined Measurements

CDF combined

\[ \sigma(\bar{p}p \rightarrow t\bar{t}) (pb) \]

\[ \chi^2/DOF = 0.60 \]

\[ m_t = 172.5 \text{ GeV}/c^2 \]

\[ \sigma(\bar{p}p \rightarrow t\bar{t} + X) [pb] \]

Lepton+Jets (SVX)

\[ \sigma = 7.14 \pm 0.35 \pm 0.58 \pm 0.14 \]

Dilepton

\[ \sigma = 7.27 \pm 0.71 \pm 0.46 \pm 0.42 \]

(stat) (syst) (lumi)

Lepton+Jets (ANN)

\[ \sigma = 7.63 \pm 0.37 \pm 0.35 \pm 0.15 \]

All-hadronic

\[ \sigma = 7.21 \pm 0.50 \pm 1.10 \pm 0.42 \]

Inclusive \( t\bar{t} \) production cross section known to \( \sim 6.5\% \)

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\[ \sigma(\bar{p}p \rightarrow t\bar{t}) (pb) \]

Run II * = preliminary

CDF

\[ m_{\text{top}} = 175 \text{ GeV} \]

CTEQ6.6M

M. Cacciari et al., JHEP 0806, 127 (2008)
S. Moch and P. Uwer, PRD 78, 034003 (2008)
**tt+jet Cross Section**

Measurements of jets associated with $t\bar{t}$ provide important tests of NLO pQCD

- initial- & final-state radiation
- diagrams not present in LO+PS event generators

$$\sigma_{t\bar{t}j} = 1.6 \pm 0.2 \text{ (stat.)} \pm 0.5 \text{ (sys.)} \text{ pb}$$

at $m_t = 172.5 \text{ GeV}$

NLO pQCD: $\sigma_{t\bar{t}j} = 1.79^{+0.16}_{-0.31} \text{ pb}$

Differential Cross Sections

Measurements of differential $t\bar{t}$ cross sections probe QCD more deeply than inclusive measurements

- top quarks are effectively bare quarks!
- test pQCD calculations

deviations can provide model-independent indications of new physical phenomena

arXiv:1002.4594 [hep-ex]

PRL 102, 222003 (2009)
Differential Cross Sections

Measure the inclusive differential $t\bar{t}$ cross section binned in top-quark $p_T$.

Distribution must be
- background subtracted
- unfolded for experimental effects

rough equivalent of inclusive jet cross section

The Tevatron continues to produce impressive results in the top-quark sector:

- inclusive $t\bar{t}$ production cross section known to $\sim 6.5\%$
- first measurement of $t\bar{t}+\text{jet}$ production cross section
- first measurements of differential cross sections binned in top-quark $p_T$ and $t\bar{t}$ mass

see the next several talks for further exciting results...