Top quark Production and Properties
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Outline

• Motivation
• Introduction to top production and decay
• Measurements of Top quark pair production cross section
  – Assume SM production and decay
• Studies of Top quark pair production mechanisms
  – Is the SM correct?
• Studies of Top quark production properties
  – Top Charge
• Conclusions and Outlook

Note: Top mass and decay properties and Single top production included in talks by J. Wagner and S. Jabeen, respectively.
Why study the Top Quark?

• Predicted by the SM and Discovered in 1995 by CDF and DØ
  – \( m_t \sim 170 \text{ GeV} \) vs \( m_b \sim 5 \text{ GeV} \)
• Top-Higgs Yukawa coupling \( \lambda_t \approx 1 \)
  • may help identify the mechanism of EWSB and mass generation.
  • may serve as a window to new physics that might couple preferentially to top.
• Until now, we knew very little about top
  • Indirect constraints from low energy data, or statistically limited direct measurements from the Tevatron
    • Plenty of room for new Physics
  • Even if we find no surprises, precision top measurements will allow for stringent tests of the SM.
The Fermilab Tevatron

- Highest-energy accelerator currently in operation
  - Only place where Top quarks can be produced
- Data delivered >2fb\(^{-1}\)
  - expect 4fb\(^{-1}\) by end of 2007

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Run IIa</th>
<th>Run IIb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunches in Turn</td>
<td>6 × 6</td>
<td>36 × 36</td>
<td>36 × 36</td>
</tr>
<tr>
<td>√s (TeV)</td>
<td>1.8</td>
<td>1.96</td>
<td>1.96</td>
</tr>
<tr>
<td>Peak L (cm(^{2})s(^{-1}))</td>
<td>1.6 × 10(^{30})</td>
<td>9 × 10(^{31})</td>
<td>3 × 10(^{32})</td>
</tr>
<tr>
<td>∫ Ldt (pb(^{-1})/week)</td>
<td>3</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td>Bunch crossing (ns)</td>
<td>3500</td>
<td>396</td>
<td>396</td>
</tr>
<tr>
<td>Interactions/ crossing</td>
<td>2.5</td>
<td>2.3</td>
<td>8</td>
</tr>
</tbody>
</table>

Results based on ~1fb\(^{-1}\)
Understanding the Top quark

• Tevatron Run I
  – Dataset: 100pb$^{-1}$
  – top mass and x-sec statistics-limited

• Tevatron Run IIA
  – Dataset: 1000pb$^{-1}$
  – top mass and x-sec systematics-limited
  – Precise measurements of top properties possible for the first time

• Is the Top really the Standard Model Top?
Top Quark Production at the Tevatron

- Top quarks are mainly produced in pairs, via the strong interaction
  \[ \sigma_{tt} = 6.8 \pm 0.6 \text{ pb} \text{ (Kidonakis, Vogt)} \]
  \[ \sigma_{tt} = 6.7^{+0.7}_{-0.9} \text{ pb} \text{ (Cacciari et al.)} \]
  (Calculated for top mass = 175 GeV)

- Recent evidence for EW Single Top production observed at DØ
  - Experimentally challenging due to large W+jets background in lower jet multiplicities than pair production

DØ result accepted by PRL
  \[ \sigma = 4.8 \pm 1.3 \text{ pb} \]
  Significance = 3.5 \( \sigma \)

Associated production tW too small at the Tevatron

see talk by Shabnam Jabeen
Top Quark Decay

- $m_t > m_W + m_b \Rightarrow$ dominant 2-body decay $t \rightarrow Wb$
- Assuming unitarity of 3-generation CKM matrix $\Rightarrow B(t \rightarrow Wb) \approx 100\%$
- $\Gamma_t^{SM} \approx 1.4$ GeV at $m_t = 175$ GeV
  - Top decays before top-flavored hadrons or $t\bar{t}$-quarkonium bound states can form
  - Top spin and kinematics is transferred to the final state

**tt decay modes**

- **Dilepton** (BR~5%, low bckg)
- **Lepton+jets** (BR~30%, moderate bckg)
- **All-hadronic** (BR~46%, huge bckg)

**DIS2007**

Cecilia Gerber (UIC)
Top Quark Pair Production Cross Section

- Test of pQCD at high $Q^2$
- Sensitive to new physics - Expect higher $x$-sec if resonant or non-SM production occurs
  - Measure in different channels
  - Measure with different techniques
    - $b$-tagging method assumes $\text{Br}(t \rightarrow Wb)=1$
    - Kinematic fit methods are free of this assumption
- Provides sample composition for other top properties measurements
- Gives input for searches for which top events are a dominant background.

- New results available for:
  - Dilepton (ee, $e\mu$, $\mu\mu$) $DØ$
    - Opposite sign leptons
    - $\geq$1 jet for $e\mu$
    - $\geq$2 jets for ee and $\mu\mu$
  - Lepton + track $CDF$
    - Increase acceptance by requiring $1$ lepton + $1$ isolated track (opposite charge)
    - $\geq$2 jets
  - Lepton + jets $DØ$
    - $1$ isolated lepton ($e$ or $\mu$)
    - $b$-tagged, $\geq$3 jets
    - Kinematic, $\geq$4 jets
  - All channels require significant Missing $E_T$
Cross Section Results (1)

Dileptons

\[ \sigma_{tt} = 6.8^{+1.2}_{-1.1} \text{ (stat)} ^{+0.9}_{-0.8} \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

\[ \delta\sigma/\sigma = 22\% \text{ (excluding luminosity)} \]

Lepton + Track

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

\[ \delta\sigma/\sigma = 15\% \text{ (excluding luminosity)} \]
Cross Section Results (2)

(1) $l+\text{jets with b-tagging}$

$\sigma_{tt} = 6.3^{+0.9}_{-0.8} \pm 0.7 \text{ (stat)} \pm 0.4 \text{ (lumi)} \text{ pb}$

(2) $l+\text{jets kinematic}$

$\sigma_{tt} = 8.3^{+0.6}_{-0.5} \text{ (stat)}^{+0.9}_{-1.0} \text{ (syst)} \pm 0.5 \text{ (lumi)} \text{ pb}$

$\sigma_{tt} = 6.3^{+0.9}_{-0.8} \text{ (stat)} \pm 0.7 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb}$

(3) Published result 425 pb$^{-1}$ PRD D 74, 112004

$\sigma_{tt} = 6.6 \pm 0.9 \text{ (stat+syst)} \pm 0.4 \text{ (lumi)} \text{ pb}$

$\delta \sigma/\sigma = (1): 15\%; (2) 19\%; (3) 14\%$
Experimental results reaching theoretical precision of ~12%
Expect ~10% with 2fb⁻¹
Top Quark Pair Production Mechanism (1)

- NLO Theoretical predictions have large uncertainties:
  - $q\bar{q}$ annihilation: $0.85\pm0.5$
  - Gluon fusion: $0.15\pm0.5$
- Top quark decays before hadronization
  - Different production processes retain their kinematic characteristics in the final state

**Method 1:**
Build a NN using 2 production and 6 decay variables & generate templates for $q\bar{q}$, $gg$ and $W$+jets
Simulate Top samples with different fractions of $gg$ & fit samples to the templates.
Output of fit is mapped to the known $gg$ content of the samples.

![Diagram](image)

Red line is NN fit obtained from data

\[
\frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(pp \rightarrow t\bar{t})} < 0.51 \quad 95\% \text{ C.L.}
\]
Top Quark Pair Production Mechanism (2)

Method 2:

- **Multiplicity of low $p_T$ tracks correlated with number of gluons**
  - Calibrate average number of tracks in collider data with gluon content in sample as predicted by MC
  - Obtain track multiplicity templates from data
    - W+0jets (no-gluon)
    - dijet events (gluon-rich)
  - Measure the gluon-rich fraction of tagged W+4 jets events by fitting the track multiplicity to the templates.
  - Extract the gluon-rich fraction of $t\bar{t}$ events using the known fractions of top and W+jets events in the sample.

\[
\frac{\sigma(gg \rightarrow t\bar{t})}{\sigma(pp \rightarrow t\bar{t})} = 0.01 \pm 0.16\text{(stat)} \pm 0.07\text{(syst)}
\]
Search for $t\bar{t}$ Resonances

- Top pairs could be produced by the decay of a heavy particle into a $t\bar{t}$ pair: $X \rightarrow t\bar{t}$
- Study invariant mass spectrum of the $l+jets$ b-tagged data sample and compare with SM predictions
  - Spectrum is consistent with the SM expectations and shows no evidence for additional resonant production mechanisms
- Model resonant $t\bar{t}$ production by a narrow heavy neutral boson
  - Set model-dependent limits on resonant production
    - Topcolor leptophobic $Z'$ excluded with $M(Z') < 725$ GeV
Top Quark Charge (1)

- Fundamental property of particle
  - has not been determined yet
- One possible scenario
  - The discovered top quark is an exotic quark of charge $-4e/3$
  - The top quark with charge $2e/3$, mass 270GeV not observed yet
  - Model accounts for precision Z data (including $R_b$ and $A_{FB}$)

Analysis technique:

- $W$ charge from charge of lepton
- Associate lepton with b-jet using constrained kinematic fit for l+jets double tagged & $M^2(lb)$ for dilepton tagged events
- $b$ charge obtained from momentum-weighted sum of charged tracks associated to b-jet, calibrated on data

Jet Charge Calibration

- Select $b\bar{b}$ dijet events
- Muon gives “true” charge
- Measure charge in away-jet
  - ~ 60% correct assignment
Top Quark Charge (2)

**CDF:**
Use Hypothesis testing with Null Hypothesis “SM is correct” & define a-priori probability of incorrectly rejecting SM to 0.01
If measured p-value is <0.01, exclude SM at 99% C.L.
If exotic model (XM) is true, 81% of all p-values are below 0.01. Measured p-value 0.35 (>0.01) ⇒ XM excluded at 81% C.L.

**DØ:**
Likelihood ratio test
Measured p-value = 0.078 (probability of obtaining measured value if the sample has 100% XM tops is 7.8%) ⇒ XM excluded up to max 92.2% C.L.

- C.L. Not directly comparable -

**CDF:** Measured p-value using DØ’s method is 0.002 ⇒ XM excluded at max 99.8% C.L.

Bayes Factor (odds of SM vs XM) = 8.54 (CDF), 4.3(DØ)
“Strong” “Positive”

Both CDF & DØ Data strongly favor the SM over XM
Conclusions and Outlook

• Entering a new era of precision top properties measurements
  – Cross section measurements soon to reach precision of theoretical predictions
  – Comparisons across channels and methods interesting

• Series of new top properties measurements becoming available with larger samples
  – Production mechanisms
  – Top charge

STILL NO SIGN OF NEW PHYSICS

Expect results based on 2fb\(^{-1}\) by Summer
Expect to have collected 4fb\(^{-1}\) by the end of 2007.