Top Quark Measurements

29th Physics in Collisions
Kobe, August 31st, 2009

Results from the Tevatron, on behalf of the CDF and D0 Collaborations

Thank you to the following people in helping preparing these slides:
Florence Canelli, Veronica Sorin, Doug Glenzinski, Christian Schwanenberger
Discovery of top quarks in 1995 by CDF and D0 at the Tevatron

- **Indirect experimental/theoretical evidence emerged in 1970’s**
  - CP violation in Kaon system
  - Discovery of b-quark (1977) and it’s properties require SU(2) partner

- Precision EWK measurements in 1990’s indicated a heavy top quark
Why Study the Top Quark?

• Exciting physics!
The Tevatron observation in 1995 ended a 20 year quest for the top

• Unanswered question
Why is the top so heavy? $m_{\text{top}} \sim 175$ GeV $\sim m_{\text{Au-atom}}$?

• Mechanism for EWSB couples to mass
  - Top quarks are a good place to look for evidence of new physics - is top special?

• Large mass comes with interesting features
  - Decay through $t \rightarrow Wb$ kinematically allowed
  - Top quarks decay before they hadronize
  Study properties of a “bare quark”
• New Physics contributions

  – Might affect top-quark production

  – Might affect top-quark decay

  – Might affect top-quark properties

  – Might “contaminate” top-quark event samples

• Tevatron program explores all these possibilities
• Exploring top quark production
  – Top pair production
  – Single top production

• Exploring top quark decay
  – W boson helicity in top decays
  – Probe the W-t-b vertex

• Exploring top quark properties
  – Mass, width, charge, spin

• Explore exotic sources of top quarks
  – Resonant top production, \( t' \), squarks
  – Forward-backward asymmetries
Producing Top Quarks

- The Energy Frontier -

Fermilab

- 1.96 TeV pp collider
- Run II started in 2001
- Record Inst. Lum. $3.6 \cdot 10^{32}$ $[cm^{-2}sec^{-1}]$

CERN

- 14 TeV pp collider
- Restart in Nov 2009 at 7 TeV
- Inst. Lum. $10^{32}$-$10^{34}$ $[cm^{-2}sec^{-1}]$

Most of the results

Brief outlook
Tevatron Performance

Summer conference dataset
Data taking efficiency (~83%) ⇒ 5.3 fb⁻¹
Selecting good runs ⇒ 4.4 - 4.8 fb⁻¹

Summer 2009 shutdown

Run I: 1990-1995 110 pb⁻¹ / experiment
Run II: 2001-2010/11 up to 12 fb⁻¹ / experiment (delivered)

- 50 000 top quarks produced
Two Experiments: CDF and D0

Multipurpose collider detectors
Large international collaborations, 600+ members each
Tevatron Run II Detectors

- Silicon strip detector for precision vertexing
- Precision tracking
- Calorimetry (hermetic $\rightarrow$ missing $E_T$)
- Muon systems

D0 and CDF in very efficient data taking mode since 2002
Tevatron produces top, but that is *not* the only thing it makes..

Top quarks are rare!
1 in 10 billion inelastic collisions..

All other processes show up as “background” in one way or another..
Top Quark Production at the Tevatron

Production

In Pairs

$\sigma_{NLO} = 7.4^{+0.5}_{-0.7} \text{ pb}$

Single

$\sigma_{NLO} = 3.0 \pm 0.4 \text{ pb}$

Decay

BR($t \rightarrow Wb$) $\sim 100\%$

$m_{top} > m_W + m_b$

b-tagging

$\varepsilon_b = 45\text{-}55\%$

$\varepsilon_q = 0.5\text{-}1\%$

References:

JHEP 0809, 127 (2008)
Top Quark Pair Production

- **Dilepton** (lepton = e or μ) (6%)
  - Small rate, small backgrounds
  - Main background: Drell-Yan
  - Highest purity

- **Lepton+Jets** (lepton = e or μ) (34%)
  - Good rate and manageable backgrounds
  - Main background: W+jets,
  - Good purity “Golden Channel”

- **All-hadronic** (46%)
  - Large rate, large background
  - Main background: QCD multijet
  - Least purity

- **Hadronic Taus** (tau+lepton, tau+jets) (14%)
  - Small rate and large backgrounds
  - Main background: Multijets, W+jets
  - Challenging purity
Collision Event Display

- μ⁻
- MIP signal In calorimeter
- inside b Jet 1 interaction point
- inside b Jet 2 secondary vertex
- Muon + jets
<table>
<thead>
<tr>
<th>Property</th>
<th>Run II Measurement</th>
<th>SM prediction</th>
<th>Lumi (fb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_t$</td>
<td>CDF: 172.6 ± 0.9(stat) ± 1.2(syst) GeV</td>
<td></td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>D0: 174.2 ± 0.9(stat) ± 1.5(syst) GeV</td>
<td></td>
<td>3.6</td>
</tr>
<tr>
<td>$\sigma_{\text{ttbar}}$ (m_t=172.5 GeV)</td>
<td>CDF: 7.50 ± 0.31 (stat) ± 0.34 (syst) ± 0.15 (lumi) pb</td>
<td>7.4 ± 0.6 pb</td>
<td>4.5</td>
</tr>
<tr>
<td>$\sigma_{\text{ttbar}}$ (m_t=170 GeV)</td>
<td>D0: 7.84 *0.46-0.45 (stat) *0.56-0.54 (syst) *0.54-0.46 (lumi) pb</td>
<td>8.06 ± 0.6 pb</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{\text{singletop}}$ (@m_t=170 GeV)</td>
<td></td>
<td>2.86±0.8 pb</td>
<td>3.2-2.3</td>
</tr>
<tr>
<td>$</td>
<td>V_{tb}</td>
<td>$</td>
<td></td>
</tr>
<tr>
<td>$m_t - m_{\text{tbar}}$</td>
<td>D0: 3.8 ± 3.7 GeV</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma(t\to ll)/\sigma(t\to l+jets)$</td>
<td>D0: 0.86 ±0.17 (stat+syst)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma(t\to \tau l)/\sigma(t\to ll + l+jets)$</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\sigma_{\text{ttbar+jets}}$ (@m_t=172.5 GeV)</td>
<td>CDF: 1.6 ± 0.2 (stat) ± 0.5 (syst)</td>
<td>1.79+0.16 -0.31 pb</td>
<td>4.1</td>
</tr>
<tr>
<td>$c_{\text{top}}$</td>
<td>CDF: 52.5μm @ 95%C.L.</td>
<td>10⁻¹⁰μm</td>
<td>0.3</td>
</tr>
<tr>
<td>Top width</td>
<td>CDF: &lt;13.1 GeV @ 95%C.L.</td>
<td>1.5 GeV</td>
<td>1</td>
</tr>
<tr>
<td>BR(t-&gt;Wb)/BR(t-&gt;Wq)</td>
<td>CDF: &gt;-0.61 @ 95% C.L.</td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>D0: 0.97 ±0.09 ±0.08 (stat+syst)</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>$W$-boson Helicity</td>
<td>CDF: $F_0$=0.62 ± 0.11 $F_+ =-0.04 ± 0.05</td>
<td>$F_0 = 0.7$</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>D0: $F_0$=0.490±0.13 $F_+ =-0.110±0.059(stat)±0.052 (syst)$</td>
<td>$F_+ = 0$</td>
<td>2.7</td>
</tr>
<tr>
<td>Charge</td>
<td>CDF: 4e/3 excluded with 87% C.L.</td>
<td>2/3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>D0: 4e/3 excluded at 92% C.L.</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>Spin correlations</td>
<td>CDF: $\kappa = 0.32 ± 0.55 - 0.78, -0.46 &lt; K &lt; 0.87 @ 68%C.L.</td>
<td>0.78 -0.022</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>D0: $\kappa = -0.17 +0.65 -0.53 (stat + syst)$</td>
<td>+0.027</td>
<td>4.2</td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>CDF: 0.19 ± 0.07(stat) ± 0.02(syst) %</td>
<td>0.05 +- 0.015</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>D0: 12 ± 8 (stat) ± 1 (syst) %</td>
<td>0.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Top Quark Production
Analysis Strategies

• Counting Experiment
  \[ \sigma = \frac{N_{\text{observed}} - N_{\text{background}}}{\int \text{Luminosity} \, dt \cdot \epsilon} \]
  - Establish event selection and estimate background

• Template Analysis
  - Fit 1D signal + background distribution to data

• Matrix Element
  - Use tree level matrix elements to classify signal and background like events

• Neural Networks, Decision Trees
  - Machine learning algorithm to classify signal and background events based on many input features mapped to a 1D distribution

Multivariate techniques are more sensitive but require careful validation work to evaluate systematics. Example: single top
CDF (4.5 fb⁻¹, m_t = 172.5 GeV), pre-tagged: \( \sigma_{tt} = 6.6 \pm 0.6 \text{(stat)} \pm 0.4 \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb} \)

CDF (4.5 fb⁻¹, m_t = 172.5 GeV), b-tagged: \( \sigma_{tt} = 7.3 \pm 0.7 \text{(stat)} \pm 0.4 \text{(syst)} \pm 0.4 \text{(lumi)} \text{ pb} \)

High purity sample, good test of signal model
Lepton + Jets Channel

- Measure top using b-tagging or using topological Neural Network
- Luminosity is the largest uncertainty in both measurements
  - Reduced by normalizing to Z cross section $\sigma = R \cdot \sigma_{Z}$

CDF (4.3 fb⁻¹, $m_t = 172.5$ GeV), b-tagged: $\sigma_{tt} = 7.1 \pm 0.3$(stat)±0.6(syst)±0.1(norm) pb

CDF (4.6 fb⁻¹, $m_t = 172.5$ GeV), topo NN: $\sigma_{tt} = 7.6 \pm 0.4$(stat)±0.3(syst)±0.1(norm) pb
- Measurement in background dominated sample - enormous multijet background
  - Data driven background model

- Topological Neural Network to purify the sample (and measure properties)

**D0 (1 fb⁻¹, \( m_t = 175 \text{ GeV} \)):**

\[
\sigma_{\text{tt}} = 6.9 \pm 1.3(\text{stat}) \pm 1.4(\text{sys}) \pm 0.4(\text{lumi}) \text{ pb}
\]

**CDF (2.9 fb⁻¹, \( m_t = 172.5 \text{ GeV} \)):**

\[
\sigma_{\text{tt}} = 7.2 \pm 0.5(\text{stat}) \pm 1.4(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}
\]
Combination has precision of 6.5%!

- Consistency among channels, experiments and with theory
- All channels limited by systematic uncertainties

- Tevatron combination underway -
Finding Single Top Quarks
• Predicted in ~1985
  – t-channel: Willenbrock and Dicus, PRD 34, 155 (1986)
  – s-channel: Cortese and Petronzio, PLB 253, 494 (1991)

• Not an easy measurement
  – Small cross section
  – Less striking signature compared to top pairs
  – Large backgrounds with large uncertainties

• Direct access to CKM element $|V_{tb}|$

• Need advanced techniques + $b$ tagging to separate dwarf signal from background
  – Likelihood Function
  – Neural Networks
  – Decision Trees
  – Matrix Elements
  – Neuro Evolution

EWK single top quark production

$\sigma_{NLO} = 2.05 \pm 0.22 \text{ pb}$
$\sigma_{NLO} = 0.95 \pm 0.08 \text{ pb}$

CDF Run II Preliminary, L=3.2fb$^{-1}$

Candidate Events

$\geq 1$ b-tag

signal region

S/B $\sim$ 1/20

m$_{\text{top}}$ = 172.5 GeV/c$^2$
CDF and D0 reported observation of single top quark production on March 4th 2009
Phys. Rev. Lett. 103, 092001
Phys. Rev. Lett. 103, 092002

<table>
<thead>
<tr>
<th>Data</th>
<th>Sensitivity</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>3.2 fb⁻¹</td>
<td>&gt;5.9 sd</td>
</tr>
<tr>
<td>D0</td>
<td>2.3 fb⁻¹</td>
<td>4.5 sd</td>
</tr>
</tbody>
</table>

CDF & D0 5σ Observation!

CDF Preliminary Single Top Summary
For M_{top} = 175 GeV/c²

<table>
<thead>
<tr>
<th>Method</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neural Network (3.2 fb⁻¹)</td>
<td>1.8 ± 0.6</td>
</tr>
<tr>
<td>Matrix Element (3.2 fb⁻¹)</td>
<td>2.5 ± 0.7</td>
</tr>
<tr>
<td>Likelihood Function (3.2 fb⁻¹)</td>
<td>1.6 ± 0.8</td>
</tr>
<tr>
<td>Boosted Decision Tree (3.2 fb⁻¹)</td>
<td>2.1 ± 0.7</td>
</tr>
<tr>
<td>Combination (Lepton+Jets) (3.2 fb⁻¹)</td>
<td>2.1 ± 0.6</td>
</tr>
<tr>
<td>MET+Jets (2.1 fb⁻¹)</td>
<td>4.9 ± 2.2</td>
</tr>
<tr>
<td>Combination (All Channels) (3.2 fb⁻¹)</td>
<td>2.3 ± 0.6</td>
</tr>
</tbody>
</table>

CDF and D0 reported observation of single top quark production on March 4th 2009

Phys. Rev. Lett. 103, 092001
Phys. Rev. Lett. 103, 092002

CDF Run II Preliminary, 3.2 fb⁻¹

Signal region S/B ~ 1/20

Consistency among results using different techniques

D0 2.3 fb⁻¹

<table>
<thead>
<tr>
<th>Method</th>
<th>March 2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decision Trees</td>
<td>3.74 ±0.95</td>
</tr>
<tr>
<td>Bayesian NNs</td>
<td>4.70 ±1.19</td>
</tr>
<tr>
<td>Matrix Elements</td>
<td>4.30 ±0.99</td>
</tr>
<tr>
<td>BLUE Combination</td>
<td>4.16 ±0.84</td>
</tr>
<tr>
<td>BNN Combination</td>
<td>3.94 ±0.88</td>
</tr>
</tbody>
</table>

CDF Single Top

S/B ~ 5

D0 Single Top

2.3 fb⁻¹

Consistency among results using different techniques

CDF Combination Output

D0 Combination Output

PIC 2009 - Kobe, Japan
Bernd Stelzer, Simon Fraser University
Tevatron Combination and $|V_{tb}|$

- Combination of CDF and D0 results

**Single Top Quark Cross Section**

- **CDF** Lepton+jets 3.2 fb$^{-1}$
  - $\sigma_{s+t} = 2.17^{+0.56}_{-0.55}$ pb
- **CDF** MET+jets 2.1 fb$^{-1}$
  - $\sigma_{s+t} = 5.0^{+2.6}_{-2.3}$ pb
- **DØ** Lepton+jets 2.3 fb$^{-1}$
  - $\sigma_{s+t} = 3.94^{+0.88}_{-0.88}$ pb

**Tevatron Combination**

- $\sigma_{s+t} = 2.76^{+0.58}_{-0.47}$ pb

Assume:

- a) $|V_{ts}|, |V_{td}| \ll |V_{tb}|$ (from top BR measure)
- b) Pure (V-A) coupling

**Tevatron Preliminary, August 2009**

- $\sigma_{s+t} = 2.76^{+0.58}_{-0.47}$ (stat+syst) pb
- $|V_{tb}| = 0.91 \pm 0.08$ (stat+syst)
• Extract t-channel and s-channel contribution to single top signal

• New physics scenario can affect single top channels differently
  – s-channel sensitive to new resonances
  – t-channel sensitive to FCNC

**D0 (2.3 fb⁻¹):**

\[ \sigma_t = 3.14 + 0.94 - 0.81 \text{(all)} \text{ pb} \]

Strong evidence with 4.8 sd!
Top Quark Mass
Top Quark Mass

- Top quark mass is a fundamental parameter of the Standard Model.

- Since $m_{\text{top}}$ is very large, quantum loops involving top quarks are important when calculating precision observables ($\sin^2 \theta_W$, $R_b$, $m_W$, ...).

- Measuring the $W$ boson mass and top quark mass precisely allows for prediction of the mass of the Higgs boson and constrain new physics.
• Measured in 3 channels:
  - Dilepton (kinematics underconstraint)
  - Lepton+jets
  - All-hadronic

• Experimental Challenges
  - Measure jets not partons
  - Jet-parton assignment
  - QCD radiation

• Jet energy scale uncertainty dominates (~3%)
  - Can be reduced via in situ measurement from W mass

• Techniques
  - Top reconstruction templates
  - Matrix Element Technique
  - “Indirect” top cross-section vs mass
  - “Subset of information” Lepton $p_T$, $b$-tag
Most Precise from Single Channel

Matrix Element Technique in Lepton + Jets
- Event likelihood based on differential cross section, parameterized in $m_{\text{top}}$ and JES
- Use Transfer Functions to model detector effects

$$P_{ii}(x;m_t,JES) = \frac{1}{\sigma} \int \frac{f(q_1)f(q_2)}{|q_1||q_2|} \sum_{\text{comb}} |M(m_t,y)|^2 \text{TF}(x,y,JES) \, d\phi(y)$$

DØ Run IIb Preliminary, L=2.6 fb$^{-1}$

CDF Run II Preliminary 4.3 fb$^{-1}$

DØ (3.6 fb$^{-1}$):
173.7±0.8(stat)±0.8(JES)±1.4(syst) GeV

CDF (4.3 fb$^{-1}$):
172.6±0.9(stat)±0.7(JES)±1.1(syst) GeV
### Tevatron Results

**Tevatron (Winter 09):**

\[ m_t = 173.1 \pm 0.6 \text{(stat)} \pm 1.1 \text{(syst)} \text{ GeV} \]

**Results from different channels are consistent**

**Different techniques to measure** \( m_{\text{top}} \)**

produce consistent results**

**Ongoing work on improving systematic uncertainties (CDF+D0+theory community)**

- Are all sources of uncertainty covered?
- Is there overlap?

\[ \chi^2/\text{ndof} = 6.3/10 \Rightarrow 79 \% \text{ probable} \]

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<table>
<thead>
<tr>
<th>Channel</th>
<th>( m_t ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF-I di-l</td>
<td>167.4 ± 10.3 ± 4.9</td>
</tr>
<tr>
<td>D0-I di-l</td>
<td>168.4 ± 12.3 ± 3.6</td>
</tr>
<tr>
<td>CDF-II di-l</td>
<td>171.2 ± 2.7 ± 2.9</td>
</tr>
<tr>
<td>D0-II di-l</td>
<td>174.7 ± 2.9 ± 2.4</td>
</tr>
<tr>
<td>CDF-I I+j</td>
<td>176.1 ± 5.1 ± 5.3</td>
</tr>
<tr>
<td>D0-I I+j</td>
<td>180.1 ± 3.9 ± 3.6</td>
</tr>
<tr>
<td>CDF-II I+j</td>
<td>172.1 ± 0.9 ± 1.3</td>
</tr>
<tr>
<td>D0-II I+j</td>
<td>173.7 ± 0.8 ± 1.6</td>
</tr>
<tr>
<td>CDF-I all-j</td>
<td>186.0 ± 10.0 ± 5.7</td>
</tr>
<tr>
<td>CDF-II all-j</td>
<td>174.8 ± 1.7 ± 1.9</td>
</tr>
<tr>
<td>CDF-II trk</td>
<td>175.3 ± 6.2 ± 3.0</td>
</tr>
</tbody>
</table>

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*Mass of the Top Quark (*Preliminary)*

- Tevatron March'09
- hep-ex/0903.2503

- arXiv:0903.2503
Magnitude of systematic uncertainties are comparable. Top quark mass precision for single measurement approaches 1 GeV.
Top Quark Decay
トップクォークの崩壊
W Boson Helicity in Top Quark Decay

- Standard Model predicts purely left handed $t$-$W$-$b$ coupling
- Directly probe $t$-$W$-$b$ vertex at high $Q^2$
- In SM, the helicity of $W$ boson:
  - longitudinal fraction $f_0 \sim 70\%$
  - left-handed fraction $f_- \sim 30\%$
  - right-handed fraction $f_+ \sim 0\%$

- Can use $\cos \theta^*$ to measure $f_0$, $f_+$, $f_-$
Measure $f_0$ and $f_+ \text{ simultaneously}$

$\Rightarrow$ Model independent

$D0$ Lepton$\text{+Jets + Dilepton (2.7 fb}^{-1})$

$f_0 = 0.49 \pm 0.11 \text{ (stat) } \pm 0.09 \text{ (syst)}$

$f_+ = 0.11 \pm 0.06 \text{ (stat) } \pm 0.05 \text{ (syst)}$

$\text{CDF Lepton+Jets (2.0 fb}^{-1}, \text{ } m_t = 172.5 \text{ GeV):}$

$f_0 = 0.65 \pm 0.19 \text{ (stat) } \pm 0.03 \text{ (syst)}$

$f_+ = -0.03 \pm 0.07 \text{ (stat) } \pm 0.03 \text{ (syst)}$

Consistent with the Standard Model
Top Quark Properties
Mass difference would imply \textit{CPT-violation}

Measured in lepton + jets events (ME technique)

First time measured for a “bare quark”

Consistent with SM expectations

$\Delta m_t = 3.8 \pm 3.7$ GeV

\textit{D0} (1 fb$^{-1}$)

\textit{statistics limited}

arXiv:0906.1172
Top Quark Spin-Spin Correlations

- Top spins are correlated only if \textit{top lifetime is short enough}
- Spin-spin correlation is observable in the top quark decay products

\[ \kappa = \frac{N(\uparrow \uparrow) + N(\downarrow \downarrow) - N(\uparrow \downarrow) - N(\downarrow \uparrow)}{N(\uparrow \uparrow) + N(\downarrow \downarrow) + N(\uparrow \downarrow) + N(\downarrow \uparrow)} \]

SM predicts \( \kappa = 0.78 \) \cite{Nucl.Phys.B690, 81 (2004)}

CDF (2.8 fb\(^{-1}\)): \( \kappa = 0.32^{+0.55}_{-0.78} \)

D0 (4 fb\(^{-1}\)): \( \kappa = -0.17^{+0.64}_{-0.53} \)

First CDF and D0 RunII result, agreement with SM within 1\( \sigma \) (CDF), 2\( \sigma \) (DØ)
Top Quark Spin Polarization

- Single top offers a source of ~100% polarized top quarks

\[ \cos(\theta_{tq}) \]

(V±A)

- Extract single top under left handed (V-A) and right handed (V+A) production hypothesis

- Data prefers (V-A) production

\[ \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.0^{+1.5}_{-0.0} \]
Top Quarks as a Window to New Physics
Search for Narrow Resonance in $M_{tt}$

- Resonance production of $t\bar{t}$ is predicted by several new physics models
  - Top color assisted technicolor with leptophobic $Z'$
  - Randall Sundrum KK-gluons, colorons, etc..

- Search for bumps in $M_{tt}$
  - Assume narrow width (1.3%), dominated by resolution

**Lepton+Jets**

**All Hadronic**

**CDF Run II preliminary, $L=2.8fb^{-1}$**

- Data
- $Z'$ (650 GeV)
- $t\bar{t}$
- W+jets
- Other MC
- Multijet

**D0 (3.6 fb$^{-1}$):**
>820 GeV/$c^2$ at 95% CL

**CDF (2.8 fb$^{-1}$):**
>805 GeV/$c^2$ at 95% CL
Forward Backward Asymmetry

\[ A_{fb} = \frac{F - B}{F + B} \]

- New physics could give rise to a asymmetry (Z’, axigluons, ..)
- NLO QCD: \( A_{fb} = 0.05 \pm 0.015 \% \)

CDF (3.2 fb\(^{-1}\)):
\[ A_{fb} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (syst)} \]

D0 (1.0 fb\(^{-1}\)):
\[ A_{fb}^{\text{det}} = 0.12 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)} \]

PRL 100, 062004 (2008)
• Heavy $t'$ production
  - suggested in 4th generation models, little Higgs, 2HD models, Beautiful mirrors etc.

• Search for $t'$ in Lepton + Jets

CDF Run 2 (2.8 fb$^{-1}$)
Preliminary
$t'\rightarrow Wq$, ≥ 4 jets
$H_T$ vs $M_{reco}$

CDF (2.8 fb$^{-1}$):
$M(t') > 311$ GeV/c$^2$ at 95% C.L.
Search for Charged Higgs in Top Decay

- If kinematically allowed, $t \rightarrow H^+b$ happens in SUSY
- Charged Higgs decay: $H^+ \rightarrow cs$ or $H^+ \rightarrow \tau\nu$
  - Branching ratios depend on $\tan\beta$
- Observable:
  Altered rates in final states: L+jets to Dilepton to $\tau + X$

$m_{H^+} = 80$ GeV

$D\bar{O}$, L=1.0 fb$^{-1}$

$B(H^+ \rightarrow \tau\nu) = 1$

- Data
  - $t\bar{t}$ Br$(t \rightarrow H^+b) = 0.0$
  - $t\bar{t}$ Br$(t \rightarrow H^+b) = 0.3$
  - $t\bar{t}$ Br$(t \rightarrow H^+b) = 0.6$
- SM

$N_{\text{event}} \times 10^3$

$B(t \rightarrow H^+b)$

$M_{H^+}$ [GeV]

Deercrease $\uparrow \downarrow$ $\downarrow$ $\downarrow$ $\downarrow$ Increase

arXiv:0908.1811
Could top quark SUSY partner (stop) hide in the top quark samples?

Assume:
1. $\tilde{\chi}_1^0$ is the LSP
2. $m_{\tilde{t}_1} \lesssim m_t$
3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$

Reconstructed Stop Mass, B-Tagged Channel

<table>
<thead>
<tr>
<th>$M_{\tilde{t}_1}$</th>
<th>Events/20 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>155 GeV</td>
<td>25</td>
</tr>
<tr>
<td>125.8 GeV</td>
<td>20</td>
</tr>
<tr>
<td>43.9 GeV</td>
<td>15</td>
</tr>
</tbody>
</table>

Observed 95% CL

CDF Run II Preliminary (2.7 fb$^{-1}$)

$BR(\tilde{\chi}_1^0 \rightarrow \chi_1^0 l^+ l^-) = 1.0$
$BR(\tilde{t}_1 \rightarrow \tilde{\chi}_1^0 b) = 1$

$BR(\tilde{\chi}_1^0 \rightarrow \chi_1^0 l^+ l^-) = 0.50$

$BR(\tilde{\chi}_1^0 \rightarrow \chi_1^0 l^+ l^-) = 0.25$

Excluded by LEP
Could top quark SUSY partner (stop) hide in the top quark samples?

Assume:
1. $\tilde{\chi}_1^0$ is the LSP
2. $m_{\tilde{t}_1} \lesssim m_t$
3. $m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$
Top Quark Physics at the LHC
Large Hadron Collider

$LHC$

$E_{CM} = 7\text{ TeV initially}$
$= 10\text{ TeV in summer 2010 ?}$
$= 14\text{ TeV in 2011 ?}$

$\sigma_{tt} \sim 830\text{ pb}$
$\sigma_{\text{single top}} \sim 315\text{ pb}$ ($\sim 100 \times \text{Tevatron}$)

Expect 200 pb$^{-1}$ by end of 2010.
Top Cross Section at LHC

14 TeV → 10 TeV:
\(\sigma_{tt}\) ↓ factor 2.3
\(\sigma_W\) ↓ factor 1.4

Rediscover top quarks with \( \sim 10 \text{ pb}^{-1} \)
Possibly first in dilepton channel

\[
\Delta \sigma_{tt} = 15\% \text{ (stat)} \pm 10\% \text{ (syst)} \pm 10\% \text{ (lumi)}
\]

Top quarks are an excellent testbed
- Understand lepton ID (incl. taus)
- Efficiency of b-tagging
- Jet energy scale

Single Top at the LHC
- \( t \)-channel most sensitive channel
- Requires b-tagging + MVA
- See Patrick Ryan, MSU (poster)

\( \Delta |V_{tb}| = 12\% \text{ (stat + syst + theo)} \)

\( \Delta |V_{tb}| = 10 \% \)
• Searches for resonant top pair production at very high mass will suffer from “jet merging” because of highly boosted top quarks

• Traditional top reconstruction works up to ~0.75 - 1 TeV
• Efficiency drops rapidly

• New development: Tagging of boosted top jets

⇒ CMS: ~ 46% efficiency, ~ 2% fake rate for $p_T$(top) = 600 GeV

Using constraints on top/W mass
Conclusions

- The discovery of the top quark opened up a rich field in HEP
- A broad top physics program is underway at the Tevatron
  
  *So far, the data seems consistent with the SM*
  
  *Tevatron expects to double data sets if running through 2011*

- Single top quarks have been observed!
  
  *Most precise direct determination of $V_{tb}$ to date*

- The precision on the top quark mass has reached 0.75 %

- With the LHC, an enormous top quark factory is beginning operations - continue to explore the truth about the top…
Further Information

Top Physics Results from the Tevatron

http://www-cdf.fnal.gov/physics/new/top/top.html

http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm

Top Physics Projections for the LHC

https://twiki.cern.ch/twiki/bin/view/Atlas/TopPublicResults

https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults#TOP_physics
Thank You!
ご静聴ありがとうございました。