What we know about top

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A survey of measurements of top-quark properties from the Tevatron

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The big picture

- We now know a lot about the top quark:
  - It completes the 3 generations of quarks
  - Its mass is 171.4 GeV/c$^2$ to $\sim$1.2%
  - Many other properties with increasing precision

- But there remain open questions:
  - Why did the universe settle for this “picture” $\sim$$10^{-32}$s after the Big Bang?
  - Why is top so heavy?
  - Is there a close connection between the top quark and mass generation itself (and EWSB)?
  - Can it lead us to new symmetries of the Universe?

- A better understanding of the properties of the top quark could shed some light on such questions

- And the Tevatron is the only place for these studies for a couple more years still!
Results presented use between 200pb\(^{-1}\) and 1fb\(^{-1}\) of Tevatron Run 2 data.
Top quark production at the Tevatron

**In pairs via the strong interaction**

- Production Cross Section
  - Tevatron (2 TeV): 85% 6.7 pb
  - LHC (14 TeV): 5% 800 pb

**Singly via the electroweak interaction**

- Production Cross Section
  - Tevatron (2 TeV): 15% 2.1 pb
  - LHC (14 TeV): 95% 10.2 pb

- Total single top production cross-section about 3 pb

See talk by Y. Caudou

In 1 fb⁻¹ about 7000 tt events produced (assumes $m_{\text{top}} = 175$ GeV)
Top quark decay

The SM $t \rightarrow Wb$ decay has $\tau \sim 10^{-25}$s
- No time to form bound states!

$\text{BR}(W \rightarrow l \nu) = 3/9$
$\text{BR}(W \rightarrow qq') = 6/9$

Measurements are made using distinct decay channels

- **Dilepton** $\rightarrow$ 2 high-$p_T$ e's or $\mu$'s, 2 high-$E_T$ jets, large missing $E_T$ ($E_T$)
  $\rightarrow$ Branching Ratio (BR) = 5%

- **Tau-Dilepton** $\rightarrow$ 1 high-$p_T$ e or $\mu$, 1 high-$E_T \tau$, 2 high-$E_T$ jets, large $E_T$
  $\rightarrow$ BR = 5%

- **Lepton (or tau) + jets** $\rightarrow$ 1 high-$p_T$ e, $\mu$ (or $\tau$), 4 jets (2 b's), large $E_T$
  $\rightarrow$ BR = 30% (15%)

- **All-hadronic** $\rightarrow$ 6 jets (2 b's)
  $\rightarrow$ BR = 45%
Identifying b-quarks helps reduce backgrounds (crucial for many top analyses)

- Measure secondary vertex: B's travel ~3 mm before decay
- Identify low-$P_T$ muon in jet: $BR(b \rightarrow l \nu c) \sim 20\%$
- $\bar{t}t$ event b-tag efficiency ~$15\%$
- False tag rate ~$4\%$
- $\bar{t}t$ event b-tag efficiency ~$55\%$
- False tag rate ~$0.5\%$
- Relies heavily on excellent performance and understanding of the silicon tracker

Other algorithms also used and being developed for greater efficiency
Extracting the Physics from Collisions

Collision rate
~ 2.5 MHz

Events written to tape at ~100 Hz

3 Tiered Trigger Systems to select “interesting” events

E.g. about 1 in $10^{10}$ collisions produces a top quark event:
- dilepton and lepton+jet data samples trigger on high-$P_T$ leptons
- all-hadronic channel uses a multi-jet trigger
In 1 fb$^{-1}$ of integrated luminosity:

- 7000 tt events produced
- 200 dilepton
- 1000 lepton + jets
- 2000 all-hadronic

Event selection:

- 50 dilepton $S/B \sim 2:1$
- 200 lepton + jets (with b-tag) $S/B \sim 3:1$
- 300 all-hadronic (with b-tag) $S/B \sim 1:5$

Main backgrounds:
- W+jets, WW, WZ, DY
- mistag, W+hf, VV, non-W
- QCD multijets

To first order these are the samples of top events with which we make measurements.
Measurements

- **Top quark production**
  - Cross sections
  - Production mechanism
  - Resonance production (see talk by R. Erbacher)
  - Single top production (see talk by Y. Coadou)

- **Top quark decay**
  - Lifetime
  - Branching fractions
  - W helicity
  - Rare decays (see talk by R. Erbacher)

- **Top quark characteristics**
  - Charge
  - Spin
  - Mass (see talk by R. Wallny)
Production cross sections of top quark pairs

- Tests QCD in very high $Q^2$ regime
- Measurements across all decay channels and topologies have different sensitivities to new physics possibilities
- Provides important sample composition for all other top property measurements

\[
\sigma(p\bar{p} \rightarrow t\bar{t}) = \frac{N_{\text{observed}} - N_{\text{background}}}{A_{\text{tot}} \int L \, dt}
\]
Top cross section measurements

Many analyses across all decay channels
No surprises yet!
Global technique to extract dilepton cross sections
(hep-ex/0612058)

- Likelihood fit performed on the data to SM templates in the missing-$E_T$ - $N_{jet}$ space:
  - $\sigma(t\bar{t})$, $\sigma(W^+W^-)$, $\sigma(Z \rightarrow \tau\tau)$ float
  - Extract $t\bar{t}$, $WW$, and $Z \rightarrow \tau\tau$ cross sections simultaneously

- Provides different test of the SM than single cross section measurements
- Utilizes full statistical power of the data

Results:

<table>
<thead>
<tr>
<th>Process</th>
<th>$e\mu$</th>
<th>$ee + \mu\mu + e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(t\bar{t})$</td>
<td>9.3 ± 0.7</td>
<td>2.6 ± 0.7</td>
</tr>
<tr>
<td>$\sigma(W^+W^-)$</td>
<td>11.4 ± 0.5</td>
<td>5.1 ± 0.8</td>
</tr>
<tr>
<td>$\sigma(Z^0 \rightarrow \tau^+\tau^-)$</td>
<td>291 ± 6</td>
<td>-</td>
</tr>
</tbody>
</table>

SM prediction
- $6.7 \pm 0.9$ pb
- $12.4 \pm 0.8$ pb
- $251 \pm 5$ pb

360 pb$^{-1}$ $e\mu$ data (103 events)
Top pair production mechanism

- $gg \rightarrow tt$ versus $qq \rightarrow tt$: tests pQCD and sensitive to new production mechanisms
- Discrimination is tough, but can use # of tracks in underlying event:
  - $gg$ initial state tends to have greater underlying event activity

- Use # low $p_T$ tracks in event as discriminator (0.3 – 3 GeV)
- Calibrate $<N_{\text{trk}}> \text{ vs. } <N_g>$ correlation using $W+$jets and dijet data
- Fit $W+$jets(b-tagged) data to gluon-rich and no-gluon $<N_{\text{trk}}>$ templates

$$\frac{\sigma(gg \rightarrow tt)}{\sigma(qq \rightarrow tt)} = 0.25 \pm 0.24\text{(stat)} \pm 0.10\text{(syst)}$$

(SM predicts 0.18)
Under the SM assumption of a V-A $tWb$ coupling, and $|V_{tb}| \sim 1$, the partial width for $t \rightarrow Wb$ is $\Gamma \sim 1.5$ GeV giving $\tau \sim 10^{-25}$ s ($c\tau \sim 10^{-10}$ $\mu$m).

Deviations from these assumptions can give very different predictions.

Using lepton + 3-jet data:
- require 1 $b$-tag
- measure impact parameter ($d_0$) of lepton tracks
- determine resolution from lepton trigger data

Obtain: $c\tau < 52.5$ $\mu$m (95% CL)
In the SM, \( R = \frac{\text{BR}(t \rightarrow Wb)}{\text{BR}(t \rightarrow Wq)} = 0.998 \sim |V_{tb}|^2 \)

- \( R \) determines the fraction of \( tt \) events with 0, 1 and 2 b-jets
- Use this to extract \( R \) from fits to the 0, 1 and 2 b-tagged samples

\[ R = 1.03^{+0.19}_{-0.17} \]
\[ R > 0.61 @ 95\% \text{ CL} \]
\[ |V_{tb}| > 0.78 @ 95\% \text{ CL} \]

Still need a lot more data to really test the SM, but a nice technique for doing so
Top quark decay: W helicity

- The helicity of the W can be:
  - Longitudinal (fraction $F_0$)
  - Right-handed (fraction $F_-$)
  - Left-handed (fraction $F_+$)

- The V-A character of the decay $\Rightarrow F_0 = 0.70$, $F_- = 0.30$, $F_+ = 0$
  (if the decay vertex was V+A then $F_0 = 0.70$, $F_- = 0$, $F_+ = 0.30$)

- The W helicity fractions can be measured using variables sensitive to the angular distributions of the W decay products:
  - Lepton $p_T$
  - $M_{lb}^2$
  - $\cos(\theta^*)$
W helicity measurements

Using $\cos(\theta^*)$:

- (370 pb$^{-1}$, dilepton and lepton + jets):
  - $F_+ = 0.06 \pm 0.10$
  - $F_+ < 0.23$ @ 95% CL

- (1 fb$^{-1}$, lepton + jets):
  - $F_0 = 0.59 \pm 0.12 \pm 0.07$
  - $F_+ = -0.03 \pm 0.07$
  - $F_+ < 0.1$ @ 95% CL

Using $M_{lb}^2$ (700 pb$^{-1}$, dilepton and lepton + jets):

- $F_0 = 0.59 \pm 0.12 \pm 0.07$
- $F_+ = -0.03 \pm 0.07$
- $F_+ < 0.1$ @ 95% CL

Within large errors, consistency observed with SM.
New analyses underway.

(hep-ex/0609045)
(hep-ex/0612011)
(hep-ex/0608062)
In the SM top is $+2/3$ partner to the $-1/3$ bottom

But how do we know that this is what we've been measuring?

For example:

In lepton + 4-jet sample:
- require 2 $b$-tags
- use a jet-charge algorithm to discriminate between $b$ and $b\bar{b}$
- pair to charged lepton to infer $Q_{\text{top}}$

$Q_{\text{top}} = 4/3e$ excluded at 94% CL
Summary of our knowledge of top

Aside from the top mass, the precision on all other measurements is still relatively poor (the next best being $\sigma_{tt}$ at ~12%)
Closing remarks

The Tevatron is currently running very well and making important strides in precision top quark measurements.

By the end of Run 2 (~6 fb\(^{-1}\))
- Mass measured to <1% precision (further constraining Higgs sector)
- Cross-sections to be measured to ~7%
- All other top properties to better precision, not just due to more data, but also greater effort to optimally utilize the data and control systematic uncertainties.

The LHC will take over where the Tevatron leaves off, with its comparatively huge top samples available....(at LHC design luminosity of 10\(^{33}\) cm\(^{-2}\)s\(^{-1}\), 1 day at LHC \(\equiv\) 3 years at Tevatron!)

**Top** may be getting on in years, but it remains our most mysterious particle, and a greater understanding of it could lead to what lies beyond the SM.