Top cross section and SM properties at CDF

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For the CDF collaboration
Tevatron Performance

- Accelerator complex breaking records all the time
- Peak Luminosity record $3.18 \times 10^{32}$ cm$^{-2}$sec
- Weekly integrated luminosity record 57 pb$^{-1}$
- Total integrated luminosity delivered $\sim 6.9$ fb$^{-1}$
  - $\sim 5.7$ fb$^{-1}$ recorded by each experiment

Thanks to the Accelerator Division!
Symmetric around beam axis
Front-back symmetric

1.4 Tesla solenoid

~100 tons

Dedicated silicon detector for secondary vertex tagging

Muon coverage up to |\eta| \sim 1.1

Electron reconstruction up to |\eta| \sim 2.8
Top Quark Production
- Top Pair Cross Section
- Forward-backward asymmetry
- Mechanism
- Resonances decaying to top
- EwK Production (single top)
- stop production

Top Properties
- Top Mass
- Top Quark Width
- Charge of Top Quark

Top Event Decays
- W helicity (V-A)
- Spin correlations
  - Branching ratios
  - Top to charged higgs
  - Top sample (W+c)
  - FCNC
Top Quark Pair Production Cross Section

New measurements since summer 2008

• All hadronic top cross section
• Ratio of top to Z cross section in lepton + jets channel

\[ \sigma_{t\bar{t}} = \frac{N_{\text{data}} - N_{\text{bck}}}{\epsilon \cdot A \cdot L} \]
All Hadronic

Event selection (same as used for the mass measurement)

- No lepton
- \( \geq 6\text{-}8 \) jets
  - \( \Delta R_{jj} > 0.5 \)
  - 1 or \( \geq 2 \) b-tags
- Low Missing \( E_T \)
- Neural Network output > fixed value
  - 13 input variables

- Obtain cross section from likelihood fit to reconstructed top mass

\[
\chi^2 = \frac{(m_{jj}^{(1)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj}^{(2)} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jjb}^{(1)} - m_{t}^{rec})^2}{\Gamma_t^2} + \frac{(m_{jjb}^{(2)} - m_{t}^{rec})^2}{\Gamma_t^2} + \sum_{i=1}^{6} \frac{(p_{T,i}^{fit} - p_{T,i}^{meas})^2}{\sigma_i^2}
\]
All Hadronic

- Systematic uncertainties evaluated from pseudo-experiments
  - Dominated by
    - Jet Energy Scale
    - Generator
- Fit performed at
  - New standard top mass point
    - $M_{\text{top}} = 172.5$ GeV/$c^2$
  - Top Mass and JES value from mass measurement
    - $M_{\text{top}} = 174.8^{+2.7}_{-2.8}$ GeV/$c^2$
    - $\Delta\text{JES} = -0.3$

$\sigma_{tt} = 7.2 \pm 0.5(\text{stat}) \pm 1.3(\text{syst}) \pm 0.4(\text{lumi})$ pb
Lepton + Jets

Event selection

• ≥ 3 jets
  ▪ $E_T \geq 20$
• 1 isolated electron or muon
  ▪ $p_T \geq 20 \text{ GeV}/c$
• High Missing $E_T$
  ▪ $M_{ET} \geq 20 \text{ GeV}$
Neural Network Fit

7 input variable
- $\Sigma E_T$ jets excl. first two
- $\Sigma$ reconstructed objects ($H_T$)
- Aplanarity

3 highest $E_T$ jets
- $\Sigma E_T/\Sigma p_T$
- Min dijet mass
- Min dijet separation
- Max $\eta$

- Tighten analysis cuts to remove most non-W (QCD) background
  - Missing $E_T > 35$ GeV
  - Leading jet $E_T > 35$ GeV
Neural Network Fit

Background model
- Non-W (QCD) from data
  - Normalisation constrained by fit to Missing transverse energy
- W+jets (ALPGEN) used to model all other backgrounds
  - Normalisation floated freely

\[ \sigma_{t\bar{t}} = 7.1 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb} \]

Dominant systematics (estimated from pseudo-experiments)
- Luminosity (5.8%)
- Jet Energy Scale (3.2%)
- t\bar{t} generator (2.7%)
Tighten event selection

- Missing $E_T \geq 25$ GeV
- $\geq 1$ heavy flavour tagged jet
- $H_T \geq 250$ GeV

Background estimation

- Estimate backgrounds for a given $\sigma_{tt}$
- Vary $\sigma_{tt}$ by small amount
- Iterate until find minimum of log likelihood distribution as a function of $\sigma_{tt}$

$\sigma_{tt} = 7.2 \pm 0.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 0.4 \text{ (lumi)} \text{ pb}$
Ratio: $\sigma_{tt} / \sigma_{Z}$

- $\sigma_{Z}$ well known theoretically
  - $\sigma_{Z\rightarrow ll}$ (theory) = 251.3 ± 5.0 pb
- $Z$ well modeled in data
  - Small background
  - $\sigma_{Z\rightarrow ll} = 256.8 \pm 1.1$(stat) ±7.0(sys)±15.1(lumi)
- Luminosity uncertainty cancels out in ratio of $tt\bar{t}$ to $Z$ cross section if use same triggers and data periods
  - $\sigma_{tt\bar{t}} = 7.0 \pm 0.4$ (stat) ± 0.4 (sys) ± 0.4 (lumi) pb
  - $\sigma_{Z\rightarrow ll} / \sigma_{tt\bar{t}} = 37.1\pm2.2$(stat) ±2.1(sys)

$\sigma_{tt} = 6.8 \pm 0.4$(stat) ± 0.4 (syst) ± 0.1 (theory) pb

$\sigma_{tt\bar{t}}$ (b-tagged) = 7.0 ± 0.4(stat) ± 0.6 (syst) ± 0.1 (theory) pb

$\Delta\sigma_{tt} / \sigma_{tt} = 8\%$

$\Delta\sigma_{tt} / \sigma_{tt} = 10\%$

Single measurement better than summer 2008 combination (same luminosity)

Similar total uncertainty to theoretical predictions
Spin Correlations
Dilepton Channel

2.8 fb$^{-1}$
Spin-Spin Correlations

- Top quarks do not hadronise before they decay
  - Can observe original polarization from when they are produced
- Spin-spin correlations at $t\bar{t}$ production can be observed through correlations between flight direction of decay products
- Can measure $\kappa$ from angular distribution of $\theta^+$ vs $\theta^-$ and $\theta_b$ vs $\theta_{\bar{b}b}$

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta^+ d \cos \theta^-} = \frac{1 + \kappa \cos \theta^+ \cos \theta^-}{4}
\]

- Standard Model
  - $qq\bar{q} \rightarrow g \rightarrow t\bar{t}$: $\kappa = 1$
  - At Tevatron expect $\kappa \sim 0.8$
Spin-Spin Correlations

Event selection
- 2 electrons or muons
  - $p_T / E_T > 20$ GeV
  - $\geq 1$ isolated
  - $\geq 1$ central
  - Opposite charge
- Missing $E_T > 25$
  - MET $> 50$ if angle MET-lepton/jet $< 20^\circ$
- $\geq 2$ jets ($E_T > 15$ GeV)
- $H_T > 200$ GeV

Dominant backgrounds
- WW/ZZ/WZ
- Drell-Yan
- W+jets
  - 1 jet fakes a lepton
  - Can ignore W$\gamma$

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Results

• Minimum unbinned likelihood fit to obtain \( \kappa \)
• Feldman-Cousins confidence intervals
• Statistics limited

\( \kappa = 0.32^{+0.55}_{-0.78} \)

-0.455 < \( \kappa \) < 0.865 (68% CL)

Dominant systematics
• Background uncertainty
• PDFs
  \( M_{\text{top}} = 175 \) GeV/c\(^2\)
• \( \kappa \) value flat wrt top mass
W-Helicity Measurements + Combination

W-boson Helicity in Top Quark Decays

- Decay products preserve helicity content of underlying weak interaction
- Probe the V-A structure of the weak interaction in the top-quark decay
- Helicity fractions $\neq$ SM $\Rightarrow$ new physics
- e.g. V+A component in weak interaction, anomalous couplings in top-decay.

SM prediction for $m_t=175$ GeV/c$^2$, $m_b=0$

$$F_0 = \frac{m_t^2}{2m_W^2 + m_t^2} = 0.7$$
$$F_- = 0.3$$
$$F_0 = 0.0$$

- Angle between direction of charged lepton in the W-boson rest frame and direction of W-boson in the top-quark rest frame
- To calculate $\theta^*$ we have to reconstruct the four-vectors of top-quark, W-boson, and charged lepton
**cosθ* Reconstruction**

- Unbinned likelihood fit to expected distributions
- Then correct for acceptance effects

Use theoretically predicted # events in each bin at particle level

Convolute acceptance and resolution effects

Get expected number events at detector level

\[
\frac{dN}{d\cos\theta^*} = F_- \cdot \frac{3}{8} \left(1 - \cos\theta^*\right)^2 + F_0 \cdot \frac{3}{4} \left(1 - \cos^2\theta^*\right) + F_+ \cdot \frac{3}{8} \left(1 + \cos\theta^*\right)^2
\]
Fit Results

F^0 with F^+ = 0.0
- Template: F^0 = 0.59 ± 0.11 ± 0.04
- Convolution: F^0 = 0.66 ± 0.10 ± 0.06
- Combination: F^0 = 0.62 ± 0.10 ± 0.05

F^+ with F^0 = 0.7
- Template: F^+ = -0.04 ± 0.04 ± 0.03
- Convolution: F^+ = 0.01 ± 0.05 ± 0.03
- Combination: F^+ = -0.04 ± 0.04 ± 0.03

Simultaneous fit of F^0 and F^+
- Template
  - F^0 = 0.65 ± 0.19 ± 0.04
  - F^+ = -0.03 ± 0.07 ± 0.03
- Convolution
  - F^0 = 0.38 ± 0.21 ± 0.07
  - F^+ = 0.15 ± 0.10 ± 0.05
- Combination
  - F^0 = 0.66 ± 0.16 ± 0.05
  - F^+ = -0.03 ± 0.06 ± 0.03

All values consistent with SM predictions
<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Lum fb&lt;sup&gt;-1&lt;/sup&gt;</th>
<th>SM value</th>
<th>SM-like</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_{\text{top}} )</td>
<td>…have to wait until tomorrow 😊</td>
<td></td>
<td>N/A</td>
<td>Yes</td>
</tr>
<tr>
<td>( \sigma_{\text{ttbar}} )</td>
<td>(7.0 \pm 0.3 \pm 0.4 \pm 0.3 \pm 0.4 \text{ pb} @ M_{\text{top}} = 175 \text{ GeV/c}^2)</td>
<td>2.8</td>
<td>6.7</td>
<td>Yes</td>
</tr>
<tr>
<td>W-helicity</td>
<td>( F^0 = 0.66 \pm 0.16 \pm 0.05 ) ( F^+ = -0.03 \pm 0.06 \pm 0.03 )</td>
<td>1.9</td>
<td>( F^0 = 0.7 ) ( F^+ = 0.0 )</td>
<td>Yes</td>
</tr>
<tr>
<td>Spin Correlations</td>
<td>(-0.455 &lt; \kappa &lt; 0.865 ) (68% CL)</td>
<td>2.8</td>
<td>( \kappa = 0.8 )</td>
<td>Yes</td>
</tr>
<tr>
<td>( A_{\text{FB}} )</td>
<td>( A_{\text{FB}} = 0.19 \pm 0.07 \text{(stat)} \pm 0.02 \text{(syst)} )</td>
<td>3.2</td>
<td>( A_{\text{FB}} = 0.05 ) (NLO)</td>
<td>Yes</td>
</tr>
<tr>
<td>Width</td>
<td>( \Gamma_{\text{top}} &lt; 13.1 \text{ GeV} ) @ 95% confidence level</td>
<td>1.0</td>
<td>1.5 GeV</td>
<td>Yes</td>
</tr>
<tr>
<td>Lifetime</td>
<td>( c\tau_t &lt; 52.5 \mu\text{m} @ 95% \text{ C.L.} )</td>
<td>0.3</td>
<td>~10&lt;sup&gt;-16&lt;/sup&gt; m</td>
<td>Yes</td>
</tr>
<tr>
<td>Branching Ratio</td>
<td>( \text{BR}(t\rightarrow Wb)/\text{BR}(t\rightarrow Wq) &gt; 0.61 ) @ 95% C.L.</td>
<td>0.2</td>
<td>~100%</td>
<td>Yes</td>
</tr>
<tr>
<td>Gluon fusion fraction</td>
<td>( F_{\text{gg}} = 0.53 \pm 0.36 \pm 0.08 )</td>
<td>2.0</td>
<td>~15% (NLO)</td>
<td>Yes</td>
</tr>
<tr>
<td>Top charge</td>
<td>Exclude top charge of -4/3 with 87% C.L.</td>
<td>1.5</td>
<td>2/3</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Top Physics is “obviously” THE sexiest topic at the Tevatron
Extras..
Combination: Summer 08

- Assuming top mass of 175 GeV/c²
- Total CDF uncertainty 9%
- Latest theory uncertainty 8%

New measurements since then
- All hadronic top cross section
- Ratio of top to Z cross section in lepton + jets channel
  - Neural Network fit
  - B-tagged

Will be updated soon...
Forward-Backward Asymmetry in $t\bar{t}bar$ Production

Update of measurement in ppbar rest frame using top/anti-top rapidity rather than $\theta$
SM

Asymmetry caused by interference of ME amplitudes for same final state

- Predictions in parton rest frame
  - $tt$ (general)
    - $A_{\text{NLO}} = 4\text{-}7\%$
    - $A_{\text{LO}} = 0\%$
  - $tt + g$
    - $A_{\text{NLO}} = -(0\text{-}2)\%$
    - $A_{\text{LO}} = - (9\text{-}10)\%$
- Test of discrete symmetries of strong interaction at high energy
- Significant deviations would be an indication of new physics
  - E.g. $Z'$ or axigluons
- Assume CP invariance
  - $A_{\text{FB}}$ asymmetry $\rightarrow$ charge asymmetry

$$A_{fb} = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})}$$

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• Fully reconstruct L+J events
  - ≥1 b-tag
  - Minimum chi\(^2\) fit
• Look at angle between hadronically decaying top and proton direction
• Multiply by charge of lepton on other side
• \(A_{FB} > 0\) means net top current in the proton direction

Unfold observed distribution
- Subtract backgrounds
  - Some have asymmetry
- Unfold for trigger and acceptance effects
- Unfold for detector bias
  - Bin migration roughly symmetric

\[ A_{FB} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (sys)} \]
Dependence of $A_{FB}$ on $M_{ttbar}$ cut

- Do forward and backward events have different $M_{ttbar}$ distributions?
  - NLL calculations predict some small dependence on $M_{ttbar}$
  - Presence of structure ("bump"/enhancement) in spectrum could be sign of new physics

### Rapidity for $t\bar{t}$ Tagged Events

<table>
<thead>
<tr>
<th>$A_{fb}^{data}$</th>
<th>$A_{fb}^{cp}$</th>
<th>$A_{fb}^{bg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.098 \pm 0.036$</td>
<td>$-0.008 \pm 0.003$</td>
<td>$-0.059 \pm 0.0079$</td>
</tr>
</tbody>
</table>

### $M_{tt}$ Invariant Mass for Tagged Events

- CDF II Preliminary
- Data $L=3.2$ fb$^{-1}$
- Top (7.1 pb)
- Bkg.
Dependence of $A_{FB}$ on $M_{ttbar}$ cut

- Look at $A_{FB}$ as a function of the minimum/maximum cut on $M_{ttbar}$

- No significant sign of $M_{ttbar}$ dependence…. Yet 😊

- e.g. $Z'$ would have an invariant mass dependence
Results

- Cross check observed distribution with parametrisation of asymmetry
  - $1 + A \cos(\theta)$
  - Min log likelihood as a function of asymmetry
    - $A_{FB} = 0.173 \pm 0.052$
    - Consistent with measurement

$A_{FB} = 0.193 \pm 0.065 \text{ (stat)} \pm 0.024 \text{ (sys)}$

Previous result (1.9 fb$^{-1}$)

$A_{FB} = 0.17 \pm 0.08$