Top quark properties at the Tevatron

• Introduction
• Production
• Asymmetries & Polarization
• Spin correlations
• Conclusions & Outlook

Andreas Jung (Purdue)  August 4th, 2016
ICHEP, 3rd - 10th August, Chicago
Top quark introduction

- Top is the heaviest fundamental particle discovered so far
  \[ m_t = 173.34 \pm 0.76 \text{ GeV} \]

- Lifetime: \( \tau \sim 5 \times 10^{-25} \text{ s} \ll \Lambda_{\text{QCD}} \)
  
- Observe bare quark properties

- Large Yukawa coupling to Higgs boson
  \( \lambda_t \sim 1 \)
  special role in electroweak symmetry breaking?

- If we could calculate the Higgs mass:
  Large corrections to the Higgs mass from top quark “loops” (Hierarchy problem)

- High precision tests of QCD/SM
  Tops are background to many searches
  Top quarks as window to new physics

\( \text{[arxiv:1403.4427]} \)

\( \text{Degrassi et al.} \)
Is the top quark according to what we expect in the SM?
\[ \sqrt{s} = 1.96 \text{ TeV} \]

- Peak luminosities: \(3 - 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}\)
- \(~10 \text{ fb}^{-1}/\text{experiment recorded}\)
- Tevatron operation from 1983 till shutdown in September 2011

Properties of the top quark

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Properties of the top quark
Top quark production

- **Strong interaction: Top pairs**

  Tevatron vs. LHC (13 TeV):
  
  \[ \bar{q}q: 85\% \text{ vs } \sim 10\% \]
  \[ gg: 15\% \text{ vs. } \sim 90\% \]

- **Decay channels:**

  \[ gg \text{ fusion} \]

Top Pair Branching Fractions

Theory (NNLO+NNLL):

<table>
<thead>
<tr>
<th>Collider</th>
<th>( \sigma_{\text{tot}} \text{ [pb]} )</th>
<th>( \text{scales [pb]} )</th>
<th>( \text{pdf [pb]} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron</td>
<td>7.164</td>
<td>+0.110(1.5%)</td>
<td>+0.169(2.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−0.200(2.8%)</td>
<td>−0.122(1.7%)</td>
</tr>
<tr>
<td>LHC 7 TeV</td>
<td>172.0</td>
<td>+4.4(2.6%)</td>
<td>+4.7(2.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−5.8(3.4%)</td>
<td>−4.8(2.8%)</td>
</tr>
<tr>
<td>LHC 8 TeV</td>
<td>245.8</td>
<td>+6.2(2.5%)</td>
<td>+6.2(2.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−8.4(3.4%)</td>
<td>−6.4(2.6%)</td>
</tr>
<tr>
<td>LHC 13 TeV</td>
<td>( \sigma = 832^{+40}_{-46} \text{ pb} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Properties of the top quark
Top quark production

- Profile log-LH fit by D0 – final measurement at Tevatron
  - 3 individual log-LH fits for dilepton, l+jets and combination
  - Employ BDT (w gradients) discriminant, optimized to extract m(top)
  - Reduced uncertainties despite adding “hadronization” category

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D0 [arxiv:1605.06168]

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Properties of the top quark
Final Tevatron combination is work in progress  
Luminosity uncertainty: 4.3% (long effort in understanding paid of)

\[ \sigma = 7.26 \pm 0.13 \text{ (stat.)} \pm 0.57/0.50 \text{ (syst.) pb} \]

\[ \delta \sigma / \sigma = 7.6\% \]

Subm. to PRD

Theory (NNLO+NNLL, top++):

7.16 pb ± 3.5%

Pole mass extraction:
→ see Frederic Deliot

A. Jung  Properties of the top quark  7
New physics? e.g. $W'$

- $W' \rightarrow t\bar{b}$, CDF Run II Preliminary, $L = 9.5$ fb$^{-1}$

Events/0.04

- Data
- Single top
- $W'$
- $t\bar{t}$
- $VH$
- $V+Jets$
- QCD multijet

$M_{W'} = 300$ GeV/c$^2$

$\sigma \times BR = 3$ pb

→ missing $E_T$ and 2-3 jets
→ extending LHC exclusions into low mass region

No new physics....

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Properties of the top quark
Properties of the top quark

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- Measurements at Tevatron & LHC are complementary
- Variety of models with wide parameter space still allowed \( W', G, T, Z' \)

\[ \begin{align*}
A_C & = 0.08 \\
A_{FB} & = 0.06 \\
\end{align*} \]

Models from PRD 84, 115013; JHEP 1109, 097

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Properties of the top quark
Interference appears at NLO QCD:

Only occurs in $q\bar{q}$ initial state; $gg$ is fwd-bwd symmetric

This is a forward-backward asymmetry at Tevatron
No valence anti-quarks at LHC $\tilde{t}$ more central

SM predictions at NLO (QCD+EWK)

Tevatron: $A_{FB} \sim 10\%$ vs. LHC: $A_{C} \sim 1\%$

NNLO+NNLL

Experimentally: Asymmetries based on decay leptons
or fully reconstructed top quarks “easier”
“harder”
Differential measurements by CDF and D0:
- PRD 87 092002

- NNLO+NNLL agrees with differential measurements by D0
- CDF agrees within < 2 s.d.

Results at aN3LO by Kidonakis agree with D0 (same caveat for CDF)
- PRD 91 071502

Scale choice can have large impact on size of Afb
- Keep in mind for LHC ?!
Top quark asymmetries

- Dilepton channel: Likelihood per event for correct $\Delta y$ assignment

\[ \sum L_z(\Delta y_{\bar{t}t}) \text{ vs } \Delta y_{\bar{t}t} \text{ true} \]

- Simultaneous 2D measurement:

\[ A_{FB}^{} = 15.0 \pm 8.0 \text{ (tot.) \%} \]
\[ \kappa P = 7.2 \pm 11.3 \text{ (tot.) \%} \]
\[ \text{Constrain } P \text{ to SM value: } A_{FB}^{} = 17.5 \pm 6.4 \text{ (tot.) \%} \]

(SM polarization essentially 0)

Reconstruct in $A_{FB}$ in dilepton events

- Likelihood based kin. Reconstruction
- Probability density dist for each solution

$A_{FB} = 12 \pm 11 \text{ (stat.)} \pm 7 \text{ (syst.) \%}$

$A_{FB} = 12 \pm 13 \text{ (tot.) \%}$

Slope in $|\Delta y|$ agrees with theory and D0 result in l+jets

CDF note 11161 (2015)

Agreement with the SM
Top quark asymmetries

Latest combinations:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Combination</th>
<th>Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Lepton+jets (9.4 fb⁻¹)</td>
<td>16.4 ± 4.7</td>
<td></td>
</tr>
<tr>
<td>CDF Dilepton (9.1 fb⁻¹)</td>
<td>12 ± 13</td>
<td></td>
</tr>
<tr>
<td>CDF Combination (9.4 fb⁻¹)</td>
<td>16.0 ± 4.5</td>
<td></td>
</tr>
<tr>
<td>D0 Lepton+jets (9.7 fb⁻¹)</td>
<td>10.6 ± 3.0</td>
<td></td>
</tr>
<tr>
<td>D0 Dileptons (9.7 fb⁻¹)</td>
<td>17.5 ± 6.3</td>
<td></td>
</tr>
<tr>
<td>D0 Combination (9.7 fb⁻¹)</td>
<td>11.8 ± 2.8</td>
<td></td>
</tr>
</tbody>
</table>

→ Agreement with SM
→ Tevatron combination is underway!

Tevatron Top Asymmetry

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Lepton+jets (9.4 fb⁻¹)</td>
<td>16.4 ± 4.7</td>
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<td>CDF Dilepton (9.1 fb⁻¹)</td>
<td>12 ± 13</td>
</tr>
<tr>
<td>D0 Lepton+jets (9.7 fb⁻¹)</td>
<td>10.6 ± 3.0</td>
</tr>
<tr>
<td>D0 Dileptons (9.7 fb⁻¹)</td>
<td>17.5 ± 6.3</td>
</tr>
</tbody>
</table>

Lepton q₁ Asymmetry (A₁⁻)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Lepton+jets (9.4 fb⁻¹)</td>
<td>9.4 ± 3.2</td>
</tr>
<tr>
<td>CDF Dilepton (9.1 fb⁻¹)</td>
<td>7.2 ± 6.0</td>
</tr>
<tr>
<td>D0 Lepton+jets (9.7 fb⁻¹)</td>
<td>5.0 ± 3.4</td>
</tr>
<tr>
<td>D0 Dileptons (9.7 fb⁻¹)</td>
<td>4.4 ± 3.9</td>
</tr>
</tbody>
</table>

Lepton Δη Asymmetry (A_η⁻)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF Dileptons (9.1 fb⁻¹)</td>
<td>7.6 ± 8.2</td>
</tr>
<tr>
<td>D0 Dileptons (9.7 fb⁻¹)</td>
<td>12.3 ± 5.6</td>
</tr>
</tbody>
</table>

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Properties of the top quark
Measure polarization of the top quark: 

- **spin** analysing basis
- **charged lepton**
- **b jet**
- **neutrino**

1\textsuperscript{st} measurement of the transverse polarization

- SM expectation is 0
- SM almost 0 for helicity and beam as well

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measured polarization $P_{\ell\tau}$</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>$+0.070 \pm 0.055$</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Helicity</td>
<td>$-0.102 \pm 0.060$</td>
<td>$-0.004$</td>
</tr>
<tr>
<td>Transverse</td>
<td>$+0.040 \pm 0.034$</td>
<td>$+0.011$</td>
</tr>
</tbody>
</table>

→ dilepton & l+jets combination:

\[ P = 0.081 \pm 0.048 \]

→ In agreement with the SM
Top quark physics

Top mass (difference)
Top width, Lifetime
Top Charge

Production cross sections
Top kinematics
Production via resonance
New particles

Branching Ratios $|V_{tb}|$
Anomalous couplings
Rare decays

Spin Correlations
Production Asymmetries

W helicity
Top quark spin correlations

- This is a different quantity at Tevatron and LHC:
  - Production at threshold and well above pp versus $p\bar{p}$ collisions

- Complementary to the LHC results
  - e.g. light top quark partners modifies SM spin correlation expectation

- Matrix element technique (ll + l+jets)
  - Optimized off-diagonal basis

\[ O_{\text{off}} = 0.89 \pm 0.22 \text{ (tot.)} \quad \text{Evidence for spin correlation:} \quad 4.2 \text{ s.d. (observed)} \]

\[ O_{\text{off, MC@NLO}} = 0.766 \]
Very successful Tevatron top quark program

Precision measurements of Top Quark properties at Tevatron (all employing full Run II data set)
All results at 1.96 TeV in $p\bar{p}$ confirm that top quark behaves as expected in SM

Complementary results at different energy and initial state!

More legacy Tevatron combinations (mass, Afb, cross section) to come...plus a new mass extraction from differential cross sections

Only small limited selection of results shown, more information:

CDF Top Web pages
D0 Top Web pages

Thank you!
List of systematic uncertainties, dominant are luminosity, hadronization, jet modeling, signal generator

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\delta_{\ell+\text{jets}}, \text{ pb}$</th>
<th>$\delta_{\ell\ell}, \text{ pb}$</th>
<th>$\delta_{\text{comb.}}, \text{ pb}$</th>
<th>Shift, pb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal modeling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Signal generator</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.05$</td>
<td>$\pm 0.17$</td>
<td>$+0.08$</td>
</tr>
<tr>
<td>Hadronization</td>
<td>$\pm 0.26$</td>
<td>$\pm 0.33$</td>
<td>$\pm 0.25$</td>
<td>$+0.12$</td>
</tr>
<tr>
<td>Color reconnection</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.05$</td>
<td>$\pm 0.09$</td>
<td>$+0.02$</td>
</tr>
<tr>
<td>ISR/FSR variation</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.06$</td>
<td>$-0.05$</td>
</tr>
<tr>
<td><strong>PDF</strong></td>
<td>$\pm 0.04$</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.02$</td>
<td>$-0.01$</td>
</tr>
<tr>
<td><strong>Detector modeling</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet modeling &amp; ID</td>
<td>$\pm 0.11$</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.04$</td>
<td>$+0.07$</td>
</tr>
<tr>
<td>$b$-jet modeling &amp; ID</td>
<td>$\pm 0.27$</td>
<td>$\pm 0.26$</td>
<td>$\pm 0.23$</td>
<td>$-0.15$</td>
</tr>
<tr>
<td>Lepton modeling &amp; ID</td>
<td>$\pm 0.20$</td>
<td>$\pm 0.26$</td>
<td>$\pm 0.17$</td>
<td>$-0.11$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$\pm 0.32$</td>
<td>$\pm 0.08$</td>
<td>$\pm 0.16$</td>
<td>$+0.01$</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$\pm 0.30$</td>
<td>$\pm 0.30$</td>
<td>$\pm 0.27$</td>
<td>$+0.10$</td>
</tr>
<tr>
<td><strong>Sample Composition</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MC cross sections</td>
<td>$\pm 0.07$</td>
<td>$\pm 0.13$</td>
<td>$\pm 0.09$</td>
<td>$+0.01$</td>
</tr>
<tr>
<td>Multijet contribution</td>
<td>$\pm 0.11$</td>
<td>$\pm 0.02$</td>
<td>$\pm 0.10$</td>
<td>$+0.10$</td>
</tr>
<tr>
<td>$W+\text{jets}$ scale factor</td>
<td>$\pm 0.21$</td>
<td>$\pm 0.01$</td>
<td>$\pm 0.15$</td>
<td>$-0.50$</td>
</tr>
<tr>
<td>$Z/\gamma^*+\text{jets}$ scale factor</td>
<td>$\pm 0.07$</td>
<td>$\pm 0.11$</td>
<td>$\pm 0.12$</td>
<td>$+0.12$</td>
</tr>
<tr>
<td><strong>MC statistics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty (quadratic sum)</td>
<td>$\pm 0.70$</td>
<td>$\pm 0.64$</td>
<td>$\pm 0.60$</td>
<td></td>
</tr>
<tr>
<td>Total systematic uncertainty (central COLLIE)</td>
<td>$\pm 0.67$</td>
<td>$\pm 0.73$</td>
<td>$\pm 0.55$</td>
<td></td>
</tr>
</tbody>
</table>
Top quark asymmetries

- Measurements at Tevatron & LHC are complimentary
- Variety of models with wide parameter space still allowed
  \( > W', G, T, Z/ \)
- MARK-J at \( s = 34.6 \) GeV

Properties of the top quark

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Top quark asymmetries

- Updated D0 measurement (improvements beyond “lumi-scaling”)
- Existing CDF measurement in l+jets decay channel also measured kinematic dependence of $A_{FB}$

$A_{FB} = 10.6 \pm 3.0 \text{ (tot.) \%}$

CDF: $A_{FB} = 16.4 \pm 4.5 \text{ (tot.) \%}$

D0 agrees with SM within uncertainties
CDF higher than SM predictions

Kinematic dependencies larger than “currently” predicted by SM
Reminder: Leptonic asymmetries less affected by reconstruction effects

- lepton+jets, updated measurement of leptonic asymmetries
- Discriminant $D_c$ to determine sample composition
- **Final measurements**, need to maximize acceptance & precision
  - Include the 3 jet bin
  - Larger contribution of backgrounds in 3 jet bin
  - Need to calibrate $W$+jets, use 0 $b$-tag

![Graph showing event distribution by jet bin and $D_c$]

0 $b$-tags not used in measurement of lepton asymmetry
Lepton asymmetries

- Lepton+jets, updated measurement of leptonic asymmetries
- Discriminant $D_c$ to determine sample composition
- Need to calibrate W+jets, use 0 $b$-tag

Asymmetry in W+jets control region (CR) different from MC
- PDF uncertainty shown by yellow bars
- Full difference between data and MC slope taken as systematic uncertainty

$0 b$-tags not used in measurement

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Properties of the top quark
Lepton asymmetries

- lepton+jets, updated measurement of leptonic asymmetries
- Discriminant $D_c$ to determine sample composition
- Differential measurement of the leptonic asymmetry

In agreement with SM:

$$A_l = 4.2 \pm 2.3 \text{ (stat.)} \pm 1.7 \text{ (syst)}$$

Combined $l+$jets & dilepton:

$$A_l = 4.2 \pm 2.0 \text{ (stat.)} \pm 1.4 \text{ (syst.)} \%$$

MC@NLO: 2%
**Top quark asymmetries**

**Properties of the top quark**

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Lots of effort went into maximizing expected significance:
- Reduce systematic uncertainties
- Increase available sample size

Full Run II expected statistical uncertainty 4.6%, need 3% for 5 s.d. Discovery (given central value does not move) Can we get to 3%?

Partial $tt$ reconstruction:
- Lost jet is from hadronic top decay (80%)
- Reconstruct leptonically decaying top and one jet
- Use a proxy for hadronically decaying top using two other jets
- Construct a likelihood & correctly reconstruct sign of $\Delta y$:

\[
P_C (\geq 4j) = 77.6 \%
\]
\[
P_C (= 3j) = 74.5 \%
\]
Top quark asymmetries

- Shares same selection as the one for the leptonic asymmetry
- Get the mass dependence of $A_{FB}$:
  - Need 2D regularized unfolding
Top quark asymmetries

- New measurement by D0 in the dilepton channel employing the matrix element method:
  assign a likelihood per event for most probably $\Delta y$ value

\[
\sum_{events} L_{z_i}(\Delta y_{\ell\ell}) \text{ vs } \Delta y_{\ell\ell \text{ true}}
\]

- Control distributions show reasonable data modeling by MC; extract asymmetries

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Properties of the top quark
Top quark polarization

DØ, 9.7 fb⁻¹

Measurements:
- Standard Model
- Z'
- Axigluon models
- m200R
- m200L
- m2000A
- m2000R

Regions:
- 68% CL region
- 95% CL region
- 99.7% CL region

Table of uncertainties:

<table>
<thead>
<tr>
<th>Source</th>
<th>Beam</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet reconstruction</td>
<td>±0.010</td>
<td>±0.008</td>
<td>±0.008</td>
</tr>
<tr>
<td>Jet energy measurement</td>
<td>±0.010</td>
<td>±0.023</td>
<td>±0.006</td>
</tr>
<tr>
<td>b tagging</td>
<td>±0.009</td>
<td>±0.014</td>
<td>±0.005</td>
</tr>
<tr>
<td>Background modeling</td>
<td>±0.007</td>
<td>±0.021</td>
<td>±0.004</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>±0.016</td>
<td>±0.020</td>
<td>±0.008</td>
</tr>
<tr>
<td>PDFs</td>
<td>±0.013</td>
<td>±0.011</td>
<td>±0.003</td>
</tr>
<tr>
<td>Methodology</td>
<td>±0.013</td>
<td>±0.007</td>
<td>±0.004</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>±0.030</td>
<td>±0.042</td>
<td>±0.015</td>
</tr>
<tr>
<td>Total statistical uncertainty</td>
<td>±0.046</td>
<td>±0.044</td>
<td>±0.030</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>±0.055</td>
<td>±0.061</td>
<td>±0.034</td>
</tr>
</tbody>
</table>
Various axi gluon models with different couplings, differential cross section predictions provided by A. Falkowicz

Remarks:
- Models with masses of 0.2 to 2 TeV and L (left), R (right), A (axial)
- Large masses highly constrained by LHC measurement
- Low masses not so much, but tough as effects are small

<table>
<thead>
<tr>
<th>Model</th>
<th>$\sigma_{\text{tot}}(p\bar{p} \rightarrow tt)$ [pb]</th>
<th>$\Delta \sigma_{\text{tot}}(p\bar{p} \rightarrow tt)$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>$8.27^{+0.92}_{-0.91}$ (stat. + syst.)</td>
<td></td>
</tr>
<tr>
<td>NNLO pQCD (SM)</td>
<td>$7.24^{+0.23}_{-0.27}$ (scales + pdf)</td>
<td></td>
</tr>
<tr>
<td>axi200L</td>
<td>$0.97 \pm 0.06$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi200R</td>
<td>$0.97 \pm 0.06$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi200A</td>
<td>$0.06 \pm 0.04$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi400A</td>
<td>$0.26 \pm 0.04$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi800A</td>
<td>$0.22 \pm 0.04$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi2000L</td>
<td>$0.87 \pm 0.15$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi2000R</td>
<td>$0.55 \pm 0.06$ (scale)</td>
<td></td>
</tr>
<tr>
<td>axi2000A</td>
<td>$0.05 \pm 0.06$ (scale)</td>
<td></td>
</tr>
<tr>
<td>Z’220</td>
<td>$-1.00 \pm 0.06$ (scale)</td>
<td></td>
</tr>
</tbody>
</table>

Phys. Rev. D 84, 112005 (2011)
CDF Conf. 11035

Acc. by PRD [arxiv:1309.7570]

CMS [arxiv:1309.2030]
D0 [arxiv:1401.5785]
CDF PRL 102 222003
Axi gluon & $Z'$ models

Compare various models to unfolded cross section data.

Reminder: High tail is used to constrain models.

Reminder: Bins are correlated, needs to be taken into account: $\mathcal{U}$ based on full covariance matrix.

Clearly some models are in tension with the presented data!

$Z'$

Various axi gluons
Axi gluon & Z' models

- Compare various models to unfolded cross section data
- Reminder: High tail is used to constrain models

- Reminder: Bins are correlated, needs to be taken into account:
  \[ \chi^2 = \sum_{i,j} (y - \mu)_i \cdot \text{cov}_{i,j}^{-1} \cdot (y - \mu)_j \]

| Model     | $M(t\bar{t})$ [\(\chi^2/\text{ndf}\)] | $p_T^{\text{top}}$ [\(\chi^2/\text{ndf}\)] | $|y^{\text{top}}|$ [\(\chi^2/\text{ndf}\)] |
|-----------|---------------------------------|---------------------------------|---------------------------------|
| axi200L   | 0.96                            | 1.07                            | 1.20                            |
| axi200R   | 0.96                            | 1.07                            | 1.20                            |
| axi200A   | 0.85                            | 3.55                            | 3.88                            |
| axi400A   | 0.44                            | 2.65                            | 3.26                            |
| axi800A   | 0.97                            | 2.86                            | 3.23                            |
| axi1200L  | 0.58                            | 1.27                            | 3.78                            |
| axi1200R  | 0.43                            | 1.94                            | 2.75                            |
| axi1200A  | 0.88                            | 3.56                            | 4.11                            |
| Z'220     | 4.95                            | 8.27                            | 7.48                            |

Tevatron data adds sensitivity at low mass
Specific models heavily constrained
Top quark width

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-top quark t-channel cross section</td>
<td>9.2</td>
</tr>
<tr>
<td>$\mu_R/\mu_F$</td>
<td>0.3</td>
</tr>
<tr>
<td>$</td>
<td>\Delta</td>
</tr>
<tr>
<td>pileup</td>
<td>0.8</td>
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<tr>
<td>ME-PS</td>
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<tr>
<td>$\mu_R/\mu_F$</td>
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<tr>
<td>top-quark mass</td>
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<tr>
<td>Other sources</td>
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</tr>
<tr>
<td>Total systematic</td>
<td>10.4</td>
</tr>
</tbody>
</table>

$$\Gamma_t = 1.36 \pm 0.02\,(\text{stat.})^{+0.14}_{-0.11}\,(\text{syst.})\,\text{GeV}$$
**Top charge**

- Fully reconstruct top pairs in lepton+jets decay channel
- Identify $b$-jet charge by jet charge algorithm
- Exclude -4/3 hypothesis by 5 s.d.

**Properties of the top quark**

A. Jung

Confirmed earlier measurements

\[ F_{BSM} < 0.46 \text{ @ 95\% C.L.} \]