Top production at the Tevatron

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Top production at the Tevatron

- Top mass from differential cross section
- Polarization
- $t\bar{t}$ asymmetry (Tevatron combination)

Tevatron Run II data taking (2001-2011):
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
- $\sim 12$ fb$^{-1}$ delivered per experiment
- $\sim 10$ fb$^{-1}$ for analysis
Top quark production

At the Tevatron top mostly produced in pairs via $q\bar{q}$ annihilation
→ a unique data set for the top quark studies
LHC: 80-90% gluon fusion

Cross-section (NNLO +NNLL QCD for $m_t=172.5$ GeV):

$\sigma_{t\bar{t}} = 7.35^{+0.23}_{-0.27}$ pb

Czakon, Fiedler and Mitov, PRL 110 (2013) 252004
Top pair production signatures

Well known decay signatures

Effective event ID using:
- isolated high $p_T$ lepton(s), missing $p_T$
- high mass (kinematic selections)
- heavy flavor jet tagging

### Other Signatures

- $\tilde{c}s$
- $\bar{t}d$
- $\tilde{t}$
- $e^+\mu^+$
- $e^+\mu^-$
- dilepton ($e/\mu$)
- $e/\mu+jets$
- $\ell+jets$
- $\ell\ell$
- $c\bar{s}$
- all-hadronic
- tau+jets
- electron+jets
- muon+jets
**Signal and Background**

**tt simulation: ALPGEN + PYTHIA** (parton showering + hadronization)

- Systematic uncertainty studies: MC@NLO+HERWIG, different PYTHIA versions
- Acceptance 10-20\% (4 – 6 reconstructed objects in the final state)

**Lepton + Jets**
- W+jets (Wbbj, Wccj, Wjjj)
- Multijet events with misidentified leptons
- Dibosons (WW, WZ, ZZ) +jets

**Dominant backgrounds**

- Z → μμ, ee, ττ + jets (D-Y)
- Dibosons (WW, WZ, ZZ) + jets
- W+jets and multijet events with misidentified leptons

**Dileptons**
- Z → μμ, ee, ττ + jets (D-Y)
- Dibosons (WW, WZ, ZZ) + jets
- W+jets and multijet events with misidentified leptons
Signal and Background

Example S/B performance (from D0 inclusive $t\bar{t}$ cross section analysis)

**Lepton + Jets**
(MET)

- Data
- $t\bar{t}$(l+jet)
- $t\bar{t}$(ll)
- Diboson

**Dileptons**
(b-tag MVA)

- Singletop
- $Z$+jets
- Whf+jets
- Wlf+jets
- Multijet

Good signal purity, high statistics, 1 neutrino in reconstruction

Very good signal purity, more limited statistics, 2 neutrinos

Top pole mass from differential cross sections

Kinematic distributions: Top quark momentum, $t\bar{t}$ invariant mass, etc. are sensitive to the top quark mass

- Expect improved sensitivity vs extraction from total cross-section

- Use the D0 lepton+jets measurement:

- Compare differential distributions to NNLO QCD calculation of $\text{TOP}++$ using the pole mass:
  Czakon, Fiedler, Heymes and Mitov, JHEP 1605, 034 (2016)
Ratios of NNLO calculation to data

NNLO QCD scale uncertainties < 5\% for $p_T^{\text{top}}$
10\% maximum for $m(t\bar{t})$

Sensitivity

Good

Better
Top pole mass from differential cross sections

- Unfolded cross sections
- Use $\chi^2$ fit to measure the mass
- Include full 2-D correlation matrix in $m(tt), p_T^{\text{top}}$

\[
m_t^{\text{pole}} \text{ extractions}
\]

(b) D0 Preliminary, 9.7fb\(^{-1}\)

- NLO vs. $d\sigma/dX$
  [This article] \hspace{1cm} 167.3 \pm 2.6
- NNLO vs. $d\sigma/dX$
  [This article] \hspace{1cm} 169.1 \pm 2.5
- D0 (NNLO+NNLL $\sigma_{\text{tot}})$
  [arXiv:1605.06168] \hspace{1cm} 172.8 \pm 3.3
- ATLAS ($t\bar{t}+1j$)
  [JHEP 10 (2015)] \hspace{1cm} 173.7 \pm 2.2
- CMS (NNLO+NNLL $\sigma_{\text{tot}})$
  [PLB 728 (2014)] \hspace{1cm} 176.7 \pm 2.9

Direct techniques

- Tevatron average
  [arxiv:1608.01881] \hspace{1cm} 174.30 \pm 0.65
- ATLAS average
  [arxiv:1606.02179] \hspace{1cm} 172.84 \pm 0.70
- CMS combination
  [PRD 93 (2016)] \hspace{1cm} 172.44 \pm 0.49

\[m_t = 169.1 \pm 1.4\text{(theo.)} \pm 2.2\text{(exp)} \text{ GeV}\]

Precision: 1.5% ~ 25% improvement over using inclusive XS
SM top quark production at Tevatron is nearly unpolarized

- Any top quark polarization at production is undiluted by hadronization (small $\tau_{\text{top}}$)
- BSM models predict enhanced polarization (e.g., $Z'$, Axigluon)

Polarization $P_{\hat{n}}$ measured from angular distribution ($\theta$) of decay products wrt quantization axis $\hat{n}$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2} \left( 1 + P_{\hat{n}} \kappa_i \cos\theta_{i,\hat{n}} \right)$$

$\kappa_i$ – analyzing power

~1 for leptons

- **Beam basis**: use proton beam direction boosted in $t\bar{t}$ rest frame as quantization axis
- **Helicity basis**: use $t\bar{t}$ axis in $t\bar{t}$ rest frame
- **Transverse basis**: cross product (beam axis, top direction) in $t\bar{t}$ rest frame
Top quark polarization

Beam and transverse polarizations expected to be larger in pp vs pp
Sensitive to BSM models with nonzero polarization

- use angular distribution of lepton from W decay => best analyzing power
- kinematic discriminant to separate top signal and dominant W+jets bkg
- l+3jets, l+4jets samples analyzed
- lepton angles from kinematic reconstruction of t\bar{t} event

**cosθ_{l,\bar{t}} distributions**

beam basis  

helicity basis  

transverse basis
Polarization Results

Measure polarization by fit to reconstructed $\cos\theta_{i,n}$ distribution using $t\bar{t}$ templates of $P_{n} = \pm 1$ and background templates normalized to the expected event yield

- **World’s 1\textsuperscript{st} measurement wrt transverse axis**
- Combined w/ dilepton result wrt beam axis
- Most precise polarization measured in $pp$
- Results consistent w/ SM and 0 polarization
- Comparison w/ various non-SM scenarios

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measured polarization</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>Beam - D0 comb.</td>
<td>$+0.081 \pm 0.048$</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Helicity</td>
<td>$-0.102 \pm 0.061$</td>
<td>$-0.004$</td>
</tr>
<tr>
<td>Transverse</td>
<td>$+0.040 \pm 0.034$</td>
<td>$+0.011$</td>
</tr>
</tbody>
</table>

Longitudinal polarizations

Phys. Rev. D 95, 011101(R) (2017)
Forward-backward production asymmetries have been discussed extensively since 2012.

Initial MC predictions suggested very small asymmetry, increasing significantly from higher order corrections.

CDF and D0 have completed extensive studies and recently provided combined Tevatron results.
\( \bar{t}t \) production asymmetry

\[ A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \]

SM predicts asymmetry in \( \bar{t}t \) production at NLO from events with q\( q \) initial states (gg is symmetric)

SM asymmetry is small, \( \sim 9.5\% \) (NNLO)

=> sensitive to test new physics contributions

Contrast with pp collisions (charge asym. \( \sim 1\% \))

Czakon, Fiedler and Mitov, PRL 115, 5, 052001 (2015)
Asymmetry measurement

Measured either wrt:

- reconstructed (anti)top direction
- location of lepton in $ll, \ell+\text{jets}$ events (correlated with direction of top quark)

Reconstruction of the $\Delta y$ distribution

$$\Delta y = y_t - y_\bar{t}$$

$$q \cdot \eta = q_\ell, (\eta_\ell > 0) - q_\ell, (\eta_\ell < 0)$$

$$\Delta \eta = \eta_\ell - \eta_\ell$$

- Background subtraction
- $A_{\text{top}}$: unfolding
- $A_{\text{lep}}$: correction
  - affected by the top polarization
  - $A_{\text{lep}} \sim A_{\text{top}}/2$ at 1.96 TeV

Early History

- $t\bar{t}$ forward-backward asymmetry
  - SM, 2006
  - DØ, 0.9 fb$^{-1}$
  - CDF, 1.9 fb$^{-1}$
  - CDF, 5.3 fb$^{-1}$
  - DØ, 5.4 fb$^{-1}$
Asymmetry measurement

Measured either wrt:

- reconstructed (anti)top direction \( \Delta y = y_t - y_{\bar{t}} \)
- location of lepton in \( ll, l+\text{jets} \) events (correlated with direction of top quark) \( q \cdot \eta = q_{\ell},(\eta_\ell > 0) - q_{\ell},(\eta_\ell < 0) \)

\( \Delta \eta = \eta_{\bar{\ell}} - \eta_\ell \)

**Early History**

\( t\bar{t} \) forward-backward asymmetry

- SM, 2006
- DØ, 0.9 fb\(^{-1}\)
- CDF, 1.9 fb\(^{-1}\)
- CDF, 5.3 fb\(^{-1}\)
- DØ, 5.4 fb\(^{-1}\)

- SM, 2014
- CDF, 9.4 fb\(^{-1}\)
- DØ, 9.7 fb\(^{-1}\)
Asymmetry: Tevatron Combination

- Use BLUE to combine measurements
- Standardize and combine systematic uncertainties.
  - All results are limited by the statistical uncertainty
- Consistency:
  - $t\bar{t}$ asymmetry vs NNLO prediction: **1.3 SD**
  - Lepton $q\eta$ asymmetry vs NLO prediction: **1.6 SD**
  - Lepton $\Delta\eta$ asymmetry vs NLO prediction: **1.3 SD**

Note: the three asymmetry measurements are correlated!
Differential asymmetry combinations

Work in progress on slopes
- Determine combination bins
- Account for bin-to-bin correlations
- Combine systematic uncertainties

Slope $\alpha$ of $A_{\text{FB}}^{tt}(\Delta y)$
Compared w/ SM NNLO predictions

Bob Hirosky, UNIVERSITY of VIRGINIA
Conclusion

Twenty years after discovery, Tevatron data still providing valuable insight into top quark physics

Precise measurements, complementary to LHC’s pp initial state (production asym., transverse polarization, s-chan single top, $m_{\text{top}}$, ...)

- $A_{FB}^{tt}$ in agreement with Standard Model
  Final measurements of the top-quark production asymmetry and more refined predictions are in better agreement ($\sim 1.5\sigma$)

- top quark polarization consistent with expectations

- New, more precise method of top pole mass using differential cross sections demonstrated

Latest measurements and combinations to finalize Tevatron legacy
Additional slides
## Typical Event Selections

### Lepton + Jets
- Trigger: single lepton and lepton+jets
  - $p_T > 20$ GeV
  - $|\eta(\mu)| < 2.0$, $|\eta(e)| < 1.1$
- At least 3 jets $p_T > 20$ GeV
- Missing transverse momentum $> 20$ GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections

### Dileptons
- Trigger: dileptons
- Two isolated leptons (electrons and/or muons)
  - $p_T > 15$ GeV
  - $|\eta(\mu)| < 2.0$
  - $|\eta(e)| < 1.1$ and $1.5 < |\eta(e)| < 2.5$
- At least 2 jets $p_T > 20$ GeV
- Missing transverse momentum $> 20$ GeV
- Additional selections:
  - Use of the b-jet identification
  - Event kinematic selections
Direct measures shown based on $m_t^{MC} \approx m_t^{pole}$ (but close $\Delta < \sim 1\text{GeV}$)
Can not be used directly for precise NLO / NNLO theoretical predictions

$m_t^{pole}$ can be extracted from inclusive cross-section measurement

Well defined mass parameter in QFT

Use l+jets and dilepton channel data
MVA method, simultaneous template fit for XS
$m_t^{\text{pole}}$ determined using experimental dependence of $\sigma_{tt}$ on $m_t$.

Most probable $m_t$ and uncertainty calculated via joint likelihood of data, NNLO pQCD, and related uncertainties.

In agreement with world average MC mass of 173.34±0.76 GeV

Most precise determination of $m_t^{\text{pole}}$ at the Tevatron.

$172.8 \pm 1.1(\text{theo})^{+3.3}_{-3.1}(\text{exp})$ GeV

$\delta m_t / m_t = 1.9\%$

PRD 94, 092004 (2016)
Helicity bases

lab frame

\[ n_{\text{helicity}} \times n_{\text{beam}} = n_{\text{transverse}} \]

\[ \theta_\ell, \text{ helicity} \]

top rest frame

\[ \theta_\ell, \text{ beam} \]
\( \bar{t}t \) production asymmetry

Top and tbar show a forward-backward asymmetry in pp collisions

\[ \begin{array}{c}
\text{positive asymmetry} \\
\text{negative asymmetry}
\end{array} \]

- NLO 2\( \rightarrow \)2 (interference between Born and box diagrams), LO 2\( \rightarrow \)3: expect (5—10)% asymmetry (higher order corrections are small)
- NLO 2\( \rightarrow \)3 (ISR/FSR interference): has the negative asymmetry and reduce expected asymmetry significantly \( \Rightarrow \) strong dependence from phase space region
- gg initiated processes are symmetric

SM asymmetry is small, \(~9.5\%\) (NNLO) \(\Rightarrow\) sensitive to test new physics contributions

Czakon, Fiedler and Mitov, PRL 115, 5, 052001 (2015)
Asymmetry measurement

$t\bar{t}$ forward-backward asymmetry

<table>
<thead>
<tr>
<th></th>
<th>time</th>
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<tbody>
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<td>SM, 2006</td>
<td></td>
</tr>
<tr>
<td>DØ, 0.9 fb$^{-1}$</td>
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$\Delta y$ Asymmetry ($A_{FB}^{\Delta y}$)

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<tr>
<th>Experiment</th>
<th>95% C.L.</th>
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<tbody>
<tr>
<td>CDF Lepton+jets (9.4 fb$^{-1}$)</td>
<td>$16.4 \pm 4.7$</td>
</tr>
<tr>
<td>CDF Dileptons (9.1 fb$^{-1}$)</td>
<td>$12 \pm 13$</td>
</tr>
<tr>
<td>DØ Lepton+jets (9.7 fb$^{-1}$)</td>
<td>$10.6 \pm 3.0$</td>
</tr>
<tr>
<td>DØ Dileptons (9.7 fb$^{-1}$)</td>
<td>$17.5 \pm 6.3$</td>
</tr>
<tr>
<td>Tevatron combination</td>
<td>$12.8 \pm 2.5$</td>
</tr>
</tbody>
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$\Delta\eta$ Asymmetry ($A_{FB}^{\Delta\eta}$)

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<tbody>
<tr>
<td>CDF Lepton+jets (9.4 fb$^{-1}$)</td>
<td>$10.5 \pm 3.2$</td>
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<tr>
<td>CDF Dileptons (9.1 fb$^{-1}$)</td>
<td>$7.2 \pm 6.0$</td>
</tr>
<tr>
<td>DØ Lepton+jets (9.7 fb$^{-1}$)</td>
<td>$5.0 \pm 3.4$</td>
</tr>
<tr>
<td>DØ Dileptons (9.7 fb$^{-1}$)</td>
<td>$4.4 \pm 3.9$</td>
</tr>
<tr>
<td>Tevatron combination</td>
<td>$7.3 \pm 2.0$</td>
</tr>
</tbody>
</table>

$\eta$ Asymmetry (NLO SM)

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<tr>
<td>CDF Dileptons (9.1 fb$^{-1}$)</td>
<td>$7.6 \pm 8.2$</td>
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Forward Backward Asymmetry at D0

\[ \frac{1}{N_{\text{tot}}} \frac{dN}{dy} \]

tt asymmetry in l+jets channel

\[ \Delta y \]


Leptonic asymmetry in l+jets chan.

\[ \frac{1}{N_{\text{tot}}} \frac{dN}{dy} \]


Leptonic asymmetry in l+jets chan.

\[ \frac{1}{N_{\text{tot}}} \frac{dN}{dy} \]


\[ \Delta y \]