Top Quark Physics at the Tevatron

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On behalf of the CDF and D0 Collaborations

Rencontres de Physique de la Vallée d'Aoste
La Thuile March 1st, 2018
The birthplace of the top quark, observed in 1995 by CDF and D0

Announcement of top quark discovery: March 2nd, 1995 ⇒ Top is fully grown up

Run II: $\sqrt{s} = 1.96$ TeV, 10 fb$^{-1}$ on tape
Tevatron stopped operating on September 2011 after a 26 years career

PRL 74 2626, PRL 74 2632 (1995)
Top Quark Production at Tevatron

- **QCD pair production**
  
  $\sigma_{SM} = 7.35^{+0.28}_{-0.33} \text{ pb}$

  (for $m_{Top} = 172.5 \text{ GeV}$)
  (PRL 110, 252004 (2013))

  Dominant process at Tevatron (~85%)
  Dominant process at LHC (~90%)

  Tevatron is the right place to study the $qq$ annihilation in $tt$ production.
QCD pair production

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Small cross section!

\[ \Rightarrow \text{Observation in } \sim 67 \text{ pb}^{-1} \Rightarrow \sim 500 \text{ } t\bar{t} \text{ pairs produced per experiment} \]

\[ \Rightarrow \text{In } 10 \text{ fb}^{-1} \Rightarrow \sim 73500 \text{ } t\bar{t} \text{ pairs produced} \]
**Top Quark Production at Tevatron**

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  Dominant process at Tevatron

  ~85%

  Dominant process at LHC (~90%)

  ~15%

  Tevatron is the right place to study the qq annihilation in tt production

- **EWK single-top production**
  
  first observed at Tevatron in 2009
  
  (PRL 103 092001, PRL 103 092002 (2009))

  - **s-channel**: \( \sigma_{SM} = 1.04 \pm 0.06 \, \text{pb} \)
  - **t-channel**: \( \sigma_{SM} = 2.1 \pm 0.1 \, \text{pb} \)

  (for \( m_{\text{Top}} = 173 \, \text{GeV} \))


- **Single top associated production Wt**: \( \sigma \sim 0.2 \, \text{pb} \), too small at the Tevatron
Top Quark Decay

SM predicts BR( t → Wb ) ≈ 100%

Event topology determined by the W decay mode

b quarks are always present

Top Pair Branching Fractions

- "alljets" 46%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons" ~4.5%
- "lepton+jets" ~30%

- Small rate
- Small background

- Golden channel:
- Good rate
- Manageable background

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More than 20 years ago, CDF & D0 assembled all the pieces needed to discover the top quark. The standard strategy to study the top quark remains the same today.

Top quark mass standard measurement:
- based on comparison of kinematic observables with MC generated at different top masses
- determination of the best-fit value of the MC top-quark mass parameter

On going theoretical work:
- to translate the MC top-quark mass into a mass in a well defined renormalization scheme

Experimental way to address the question of the top-quark mass definition:
- Use alternative methods to determine the top-quark mass
  - With less inputs from MC
  - With different sensitivity to systematics
  - Using theory computation with well defined mass (i.e. from cross section, single top events, $t\bar{t}+\text{jets}$ etc.)

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arXiv:1608.01881
D0 pole mass from inclusive cross section

- Compare the experimental $t\bar{t}$ cross section measurement with the theory computation

- From inclusive cross-section measurement in lepton+jets and dilepton channels:

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

  - Input top quark mass varied, MVA discriminant studied for each point
  - Dependence parametrized with a fourth-order polynomial function
  - Compared to NNLO+NNLL prediction
  - Extracting the most probable mass + uncertainty with normalized joint-likelihood function:

\[
m_{top} = 172.8 \pm 1.1 \text{ (theo.)} +3.3 \pm 3.1 \text{ (exp.) GeV}
\]

dominated by experimental uncertainties

Advantage: extract the top-quark mass in a well-defined renormalization scheme

Drawback: less precise than direct measurements

1.9% relative uncertainty
Using the differential $t\bar{t}$ cross section:
- Additional information coming from the shape of the distributions
- Possible since NNLO differential predictions are now available (JHEP 1605, 034 (2016))

$P_{T}^{top}$ and $m_{tt}$ sensitive to pole mass

Unfolded differential distributions from D0 paper PRD 90 092006 (2014)

Compared to NNLO QCD calc., four different PDF sets

$\chi^{2}$ fit to both distributions
  - $P_{T}$ vs. $m_{tt}$

$m_{top} = 169.1 \pm 2.5$ (total) GeV

Better uncertainty than inclusive (1.5%)
- Even with only lepton+jets
- Theory input not using NNLL

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D0 pole mass from diff. cross section

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  - Theory input not using NNLL
D0 legacy top mass combination

- All data analyzed
- Combined with BLUE
- $\chi^2$/ndof = 2.5/3, prob = 47%: good consistency between the measurements

D0 top quark mass combination:

$$m_{\text{top}} = 174.95 \pm 0.40 \, \text{(stat.)} \pm 0.64 \, \text{(syst.)} \, \text{GeV}$$

0.43% relative uncertainty

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QCD + EW theory predicts positive asymmetry from $qqbar \rightarrow ttbar$ annihilation: top quark tends to go in the same direction as incoming proton at Tevatron

- **NNLO+NNLL** predicts $\sim 9.5\%$ (arXiv:1411.3007) while $gg$ remains symmetric
- New physics can modify this asymmetry ($Z'$, axigluons,..)
- Experimentally, asymmetries based on fully reconstructed top quarks using the rapidity difference ($\Delta y$) of $t \rightarrow lvb$ and antitop $t \rightarrow jjb$, or using one or two leptons from top decay

In terms of frame-independent rapidity difference ($\Delta y$) between top and antitop:

In terms of rapidity of lepton(s) from top decay:
Lots of excitement in the past years!

→ First Tevatron l+jets analysis showed small deviations from SM
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More recent results show a lower value
→ More data and more refined analysis
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NNLO QCD + NLO EW expectations estimated to be higher
\[ A_{FB}^{tt} \text{ Tevatron Combination} \]

- Final Tevatron result
- CDF and D0 results combined using BLUE
- All correlations taken into account

Combined measurement:

\[ A_{FB}^{tt} = 0.128 \pm 0.025 \]

Prediction: \[ A_{FB}^{tt} = 0.095 \pm 0.007 \]

- **Agreement within: 1.3σ**

**Mass dependence**

- Tevatron combination:
  \[ \alpha = (9.71 \pm 3.28) \times 10^{-4} / \text{GeV}, \beta = 0.131 \pm 0.034 \]

- NNLO QCD + NLO EW prediction:
  \[ \alpha = (5.11^{+0.42}_{-0.64}) \times 10^{-4} / \text{GeV}, \beta = 0.087^{+0.005}_{-0.006} \]

- **Agreement within 1.3σ**

**|Δy_{tt}| dependence**

- Tevatron combination:
  \[ \alpha = 0.187 \pm 0.038 \]

- NNLO QCD + NLO EW prediction:
  \[ \alpha = 0.129^{+0.006}_{-0.012} \]

- **Agreement at the level of 1.5σ**

NEW! PRL 120, 042001 (2018)
Single lepton $A_{FB}^{l}$ Tevatron Combination

$A_{FB}^{l} = \frac{N(q\ell\eta\ell > 0) - N(q\ell\eta\ell < 0)}{N(q\ell\eta\ell > 0) + N(q\ell\eta\ell < 0)}$

- Combination of inclusive measurements:
  $A_{FB}^{l} = 0.073 \pm 0.020$

- NLO QCD + NLO EW inclusive prediction:
  $A_{FB}^{l} = 0.038 \pm 0.003$

- Agreement within 1.6$\sigma$

- No combination of differential measurements

NEW! PRL 120, 042001 (2018)
Combination of inclusive measurements: 
\( A_{FB}^{\|} = 0.108 \pm 0.046 \)

NLO QCD + NLO EW prediction: 
\( A_{FB}^{\|} = 0.048 \pm 0.004 \)

Consistency within 1.3\( \sigma \)

No combination of differential measurements

NEW! PRL 120, 042001 (2018)
The measurements and their combinations are consistent with each other and with the SM predictions.

NEW! PRL 120, 042001 (2018)
SM: top quark is produced almost unpolarized in ttbar pair production

Top polarization can be measured through angular distributions of decay products:

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

- \( P_{\hat{n}} \) – polarization
- \( k_i \) – spin-analyzing power (~1 for leptons)

\( \theta \) angle between decay product (in parent top rest frame) and quantization axis (in tt rest frame)

- 3 quantization axes used: beam, helicity, transverse axis
- Sample composition determined using kinematic discriminant based on likelihood ratio of various variables
- Template fit to \( \cos \theta \) distributions with top polarizations \( P = \pm 1 \) for lepton + >=4 jet events
Top polarization in lepton + jets channel

<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>$+0.040 \pm 0.035$</td>
<td>$+0.011$</td>
</tr>
</tbody>
</table>

- Performed also combination with D0 dilepton channel
- Results consistent with theory at the level of 1-2σ

PRD 95, 011101(R) (2017)
Top polarization in dilepton channel

- Top dilepton final state channels $ee, e\mu, \mu\mu$
- The methods of estimating the signal and backgrounds follow $A_{FB}$ measurement analysis
- Examine $(\cos \theta^+, \cos \theta^-)$ 2D distribution:

$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta^+ d \cos \theta^-} = \frac{1}{4} \left(1 + \alpha_+ P_+ \cos \theta^+ + \alpha_- P_- \cos \theta^- - C \cos \theta^+ \cos \theta^-\right)$$

- $\alpha_{\pm}$: the lepton spin-analyzing power ($\approx 1$ @NLO)
- $P_{\pm}$: the degree of polarization of the top quark
- $C$: the $t\bar{t}$ spin correlation coefficient

- weight signal templates using double differential angular distribution formula

We consider two special cases:
1. CP Conserved (CPC): $\alpha P^{CPC} = \alpha_+ P_+ = \alpha_- P_-$
2. CP Maximally Violated (CPV): $\alpha P^{CPV} = \alpha_+ P_+ = -\alpha_- P_-$

In SM $\alpha P = 0$ at tree level and negligible in higher order

- Consider two spin quantization bases and the two assumption of top quark production mechanism: (helicity basis, transverse basis) x (CPC, CPV)
As an example, two extreme $\alpha P$ allowed in the physical region are shown for CPC in helicity and transverse frame.
Top polarization in dilepton channel

Example of signal + backgrounds 2-dim templates in Helicity and Transverse base

Data distributions

CDF Run II Prelim (9.1 fb⁻¹)

Helicity

CPC(\alpha P = 0.0)

+ Backgrounds

CDF Run II Prelim (9.1 fb⁻¹)

Transverse

CPC(\alpha P = 0.0)

+ Backgrounds

CDF Run II Prelim (9.1 fb⁻¹)

Helicity

Data

CDF Run II Prelim (9.1 fb⁻¹)

Transverse

Data
Top polarization in dilepton channel

- Likelihood fit with 2 dimensional distribution

\[
\begin{align*}
\alpha P_{\text{helicity}}^{\text{CPC}} &= -0.130 \pm 0.114 \text{ (stat.)} \pm 0.111 \text{ (syst.)} \\
\alpha P_{\text{helicity}}^{\text{CPV}} &= -0.046 \pm 0.123 \text{ (stat.)} \pm 0.040 \text{ (syst.)} \\
\alpha P_{\text{transverse}}^{\text{CPC}} &= -0.077 \pm 0.177 \text{ (stat.)} \pm 0.098 \text{ (syst.)} \\
\alpha P_{\text{transverse}}^{\text{CPV}} &= -0.111 \pm 0.146 \text{ (stat.)} \pm 0.055 \text{ (syst.)} 
\end{align*}
\]

The measured polarizations are consistent with the SM predictions.

CDF Run II Prelim

| Top Quark Polarization Measurement in Dilepton Channel at Tevatron | CDF (9.1 fb\(^{-1}\)) | CDF (9.1 fb\(^{-1}\)) | D0 (9.4 fb\(^{-1}\)) **
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Helicity Basis</strong></td>
<td>(\alpha P_{\text{SM}} = -0.0039 \pm 0.0004 )**</td>
<td>(\alpha P_{\text{CPC}} = -0.130 \pm 0.114 \text{ (stat.)} \pm 0.111 \text{ (syst.)} )</td>
<td>(\alpha P_{\text{CPC}} = 0.072 \pm 0.105 \text{ (stat.)} \pm 0.042 \text{ (syst.)} ) (without (A_{R_{tb}}) constraint)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\alpha P_{\text{CPV}} = -0.046 \pm 0.123 \text{ (stat.)} \pm 0.040 \text{ (syst.)} )</td>
<td>(\alpha P_{\text{CPV}} = 0.113 \pm 0.091 \text{ (stat.)} \pm 0.019 \text{ (syst.)} ) (with (A_{R_{tb}}) constraint)</td>
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- \(\alpha P_{\text{transverse}}^{\text{CPC}} = -0.077 \pm 0.177 \text{ (stat.)} \pm 0.098 \text{ (syst.)} \)
- \(\alpha P_{\text{transverse}}^{\text{CPV}} = -0.111 \pm 0.146 \text{ (stat.)} \pm 0.055 \text{ (syst.)} \)

Conclusion

- Several years after the end of RunII the Tevatron continues providing valuable top physics results.
- Many top quark areas of study (i.e. cross sections, single top s-channel, spin correlations, $A_{FB}$) are complementary to LHC measurements.
- CDF & D0 are in the process of making the last Tevatron legacy measurements:
  - The final Tevatron $A_{FB}$ combination just published.
  - D0 published the top quark pole mass meas. from cross sections.
  - CDF approved last week a new top polarization measurement in the dilepton channel.
- All measurements are in agreement with SM prediction.
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- All new measurements in agreement with SM prediction

Thank you!

For more details:
- http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/
- http://tevewwg.fnal.gov
Top polarization in dilepton channel

We build a binned likelihood function with Gaussian constraints on the numbers of the signal and backgrounds. minimize (−log L) to find the best fit αP.
Systematic uncertainties are evaluated using pseudoexperiments with varied $\alpha_P$ values

<table>
<thead>
<tr>
<th>Sources</th>
<th>Helicity CPC</th>
<th>Helicity CPV</th>
<th>Transverse CPC</th>
<th>Transverse CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(-0.130)</td>
<td>(-0.046)</td>
<td>(-0.077)</td>
<td>(-0.111)</td>
</tr>
<tr>
<td>PDF</td>
<td>$\pm 0.015$</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.006$</td>
<td>$\pm 0.002$</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>$\pm 0.018$</td>
<td>$\pm 0.015$</td>
<td>$\pm 0.030$</td>
<td>$\pm 0.012$</td>
</tr>
<tr>
<td>JES</td>
<td>$\pm 0.045$</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.005$</td>
</tr>
<tr>
<td>Renormalization Scale</td>
<td>$\pm 0.013$</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.020$</td>
<td>$\pm 0.031$</td>
</tr>
<tr>
<td>Top Quark Mass</td>
<td>$\pm 0.050$</td>
<td>$\pm 0.006$</td>
<td>$\pm 0.047$</td>
<td>$\pm 0.014$</td>
</tr>
<tr>
<td>MC Generator</td>
<td>$\pm 0.076$</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.049$</td>
<td>$\pm 0.016$</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>$\pm 0.009$</td>
<td>$\pm 0.013$</td>
<td>$\pm 0.011$</td>
<td>$\pm 0.022$</td>
</tr>
<tr>
<td>Parton Showering</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.012$</td>
<td>$\pm 0.045$</td>
<td>$\pm 0.012$</td>
</tr>
<tr>
<td>Background Shape</td>
<td>$\pm 0.029$</td>
<td>$\pm 0.028$</td>
<td>$\pm 0.039$</td>
<td>$\pm 0.028$</td>
</tr>
<tr>
<td>Total Syst.</td>
<td>$\pm 0.111$</td>
<td>$\pm 0.040$</td>
<td>$\pm 0.098$</td>
<td>$\pm 0.055$</td>
</tr>
<tr>
<td>Stat.</td>
<td>$\pm 0.114$</td>
<td>$\pm 0.123$</td>
<td>$\pm 0.177$</td>
<td>$\pm 0.146$</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>$\pm 0.159$</td>
<td>$\pm 0.129$</td>
<td>$\pm 0.203$</td>
<td>$\pm 0.156$</td>
</tr>
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