Top pair production in ppbar collisions

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Why $t\bar{t}$bar production at Tevatron is still relevant?

Approximate numbers of events observed

<table>
<thead>
<tr>
<th>Quantity</th>
<th>LHC</th>
<th>TEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_1$: Background</td>
<td>75,000</td>
<td>4,500</td>
</tr>
<tr>
<td>$t\bar{t}$bar</td>
<td>300,000</td>
<td>4,500</td>
</tr>
<tr>
<td>$S: q\bar{q} \rightarrow t\bar{t}$bar</td>
<td>30,000</td>
<td>4,000</td>
</tr>
<tr>
<td>$B_2$: $gg \rightarrow t\bar{t}$bar</td>
<td>270,000</td>
<td>500</td>
</tr>
<tr>
<td>$S/\sqrt{S+B_1+B_2}$</td>
<td>49</td>
<td>43</td>
</tr>
<tr>
<td>$S$ purity$^2$</td>
<td>190</td>
<td>820</td>
</tr>
</tbody>
</table>

Gluon fusion production mechanism is a “background” to $t\bar{t}$bar production via $q\bar{q}$ annihilation.

To probe the properties of $q\bar{q} \rightarrow t\bar{t}$bar Tevatron is still relevant.

Relevant for top properties

Relevant for $q\bar{q} \rightarrow X \rightarrow t\bar{t}$ searches

Relevant for forward-backward asymmetry
Studies of the properties of $p\bar{p} \rightarrow t\bar{t}$ production provide a useful test of QCD at high energies and could give information about new physics.

- Production cross section can be divided into forward-backward (FB) symmetric and anti-symmetric contributions.
- Possible NP mediators would affect $M_{tt}$, $p_T^{top}$ and $y^{top}$ distributions.
- Mediator with axial coupling in s-channel would result in enhanced FB asymmetry (E.g. axigluon P. H. Frampton and S. L. Glashow, Phys. Lett. B {190} 157 (1987))

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Differential $t \bar{t}$ production cross section vs $M_{tt}$, $p_{T}^{\text{top}}, y^{\text{top}}$

Submitted to PRD: arXiv:/1401.5785
Data distributions in $M_{tt}$, $p_T^{top}$, $y^{top}$

Select events with one isolated lepton (e or $\mu$):

- $P_T(\text{lepton}) > 20$ GeV/c
- $|\eta_e| < 1.1$, $|\eta_{\mu}| < 2.0$
- Miss $E_T > 20$ GeV
- 4 jets: $P_T > (40, 3x20)$ GeV/c, $|\eta_{\text{jet}}| < 2.5$
- $\geq 1$ b-tag (MVA $\varepsilon=60\%$, fake=1.4%)

- $S/B=3.5$
- Total expected: 2484
- Total observed: 2540
Differential x-section vs $M_{tt}$, $p_{T}^{top}, y^{top}$

Raw data distributions are unfolded to production level using regularized unfolding.

Results are consistent with approx. NNLO (N. Kidonakis, PRD84, 011504(R) (2011)).
Forward-backward asymmetries in ttbar production cross section
Asymmetry defined in the rest frame

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

In proton-antiproton collisions \( \cos \theta \rightarrow y \)

\( \Delta y \) is invariant to boosts along \( z \)-axis

Asymmetry based on \( \Delta y \) is the same in lab and \( tt \) rest frame

Asymmetry based on rapidity of lepton from top decay
- Lepton angles are measured with a good precision
- Also sensitive to top polarization

\[ \Delta y = y_t - y_{\bar{t}} \]

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

\[ A_{FB}^{l} = \frac{N(q_{l}, y_{l} > 0) - N(q_{l}, y_{l} < 0)}{N(q_{l}, y_{l} > 0) + N(q_{l}, y_{l} < 0)} \]
A bit of 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, 2013
CDF, 9.4 fb$^{-1}$

PRL 81(1998)49
PRL100(2008)142002, 227 cit’s
PRL101(2008)202001, 222 cit’s
PRD83(2011)112003,409 cit’s
PRD84(2011)112005, 292 cit’s
PRD 86(2013), 034026
PRD87(2013)092002, 79 cit’s

Scaled with lum. the expected stat is 4.6%
Assuming the central value stays the same 5σ corresponds to 3.0%

Can we achieve 3.0%?
Based on $\sim 1/2$ of the dataset

- CDF reported a strong dependence on $M_{tt}$: $A_{FB}(M_{tt}>450 \text{ GeV})=47.5\pm11.4\%$

- D0 found a large asymmetry in lepton angular distribution $A_{FB}^{l}=15.2\pm4.0\%$

- Both observations are $>3\sigma$ deviations from the SM predictions

Could Nature be teasing us with the signs of new physics?
Forward-backward asymmetry of leptons from ttbar decay, $A_{FB}^l$

Submitted to PRD:

arXiv:1403.1294
Why 3 jets are worth fighting for?

**MC@NLO+HERWIG**

Lepton+3jet events double the statistics but have larger background contamination, mostly due to W+jets

**Problem:**
Forward-backward asymmetry in leptons from W boson decay
Calibrate using W+jets enriched sample: 3j 0b

<table>
<thead>
<tr>
<th></th>
<th>3j, ≥1 btag</th>
<th>≥4j, ≥1 btag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>2245</td>
<td>2222</td>
</tr>
<tr>
<td>BG</td>
<td>3841</td>
<td>705</td>
</tr>
<tr>
<td>S/N</td>
<td>0.6</td>
<td>3.2</td>
</tr>
</tbody>
</table>

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Asymmetry in W+jets background was calibrated on data (3jet 0 b-tag) in 3 lepton $p_T$ bins

- Black points – data
- Yellow points – MC@NLO, with CTEQ6.1M

Data-to-MC difference is not covered by pdf uncertainties $\Rightarrow$ we took the entire difference between data and MC as a source of systematic uncertainty
Summary of $A_{FB}^l$ measurements

All extrapolated to full acceptance, full Tevatron Run II dataset, combined by BLUE method

$A_{FB}^l (D0, l + jets, dileptons) = 4.7 \pm 2.7\%$

$A_{FB}^l (MC@NLO) = 2.3 \pm 0.2\%$

$A_{FB}^l (NLO + EW) = 3.8 \pm 0.2\%$

1st measurement of asymmetry vs lepton $p_T$ suggested in PRD 87 (2013)034039

Bernreuther and Si (PRD 86 034026)

The D0 results are smaller than originally observed value, consistent with calculations based on SM

$A_{FB}^l (CDF) = 9.0 \pm 2.8\%$

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[Graph showing distribution of $A_{FB}^l$ vs lepton $p_T$]
Forward-backward ttbar asymmetry $A_{FB}$

Submitted to PRD arXiv:1405.0421
Assumption: lost jet is from the “hadronic” top decay (True in 80% of the cases)

Procedure:
• Form a leptonically decaying top using $W \rightarrow l\nu$ and one of the jets.
• Form a proxy for hadronically decaying top using the other two jets.

Construct a likelihood of each assignment using b-tagging, “correct” and “wrong” masses.

Probability to correctly reconstruct the sign of $\Delta y$:

$P(l+\geq 4\text{jets}) = 77.6\%$

$P(l+3\text{jets}) = 74.5\%$
Reconstruction-level asymmetry

Data distributions in $\Delta y$ and $M_{tt}$ at reconstruction level are corrected to production level using regularized unfolding.

<table>
<thead>
<tr>
<th>$A_{FB}$ values, %</th>
<th>3j, 1b</th>
<th>3j, $\geq 2b$</th>
<th>$\geq 4j$, 1tag</th>
<th>$\geq 4j$, $\geq 2$tag</th>
<th>Inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>4.7</td>
<td>5.5</td>
<td>1.8</td>
<td>3.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Measured</td>
<td>$5.4 \pm 6.0^{+1.9}_{-3.4}$</td>
<td>$10.7 \pm 4.2^{+0.6}_{-0.8}$</td>
<td>$11.0 \pm 4.4^{+0.5}_{-0.7}$</td>
<td>$5.9 \pm 3.3 \pm 0.1$</td>
<td>$7.9 \pm 2.1^{+0.5}_{-0.8}$</td>
</tr>
</tbody>
</table>

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**Results: N(Δy), inclusive A_{FB}**

D0(9.7 fb^{-1}): A_{FB} = 10.6\pm2.7\text{(stat)}\pm1.3\text{(sys)}\%

D0 Results are consistent with SM predictions 8.8\% (Bernreuther. and Si, PRD 86, 034026)

CDF(9.4 fb^{-1}): A_{FB} = 16.4\pm3.9\text{(stat)}\pm2.6\text{(sys)}\%

Boxes show D0 data with stat uncertainty

Hatching shows total uncertainty on data
Results: $A_{FB}(\Delta y)$

Fit to $y=ax$

$a(D0) = 0.154\pm0.043$  \hspace{1cm} 1.7 $\sigma$

$a(MC@NLO) = 0.080$

$a(CDF) = 0.253\pm0.062$
Results: $A_{FB}(M_{tt})$

DØ, 9.7 fb$^{-1}$

Slope of $A_{FB}(M_{tt})$

$\alpha(D0) = (3.9 \pm 4.4) \times 10^{-4}$

$\alpha(MC&NLO) = 3.8 \times 10^{-4}$

$\alpha(CDF) = (15.5 \pm 4.8) \times 10^{-4}$
**History NOW**

**$t\bar{t}$ 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, 2013**
- **CDF, 9.4 fb$^{-1}$**
- **DØ, 9.7 fb$^{-1}$**

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**PRD83(2011)112003, 409 cit’s**

**PRD84(2011)112005, 292 cit’s**

Tevatron stopped taking data in Sep 2011

**PRD87(2013)092002, 79 cit’s**

**We achieved 3.0%**

**But the central value came down**
The differential cross section vs $M_{tt}$, $p_{T}^{\text{top}}$, $y^{\text{top}}$ is in agreement with the SM based (approx NNLO) calculation.

$A_{FB}^{l}$ extrapolated to full leptonic acceptance:

\[ A_{FB}^{l}(D0, l + \text{jets}, \text{dileptons}) = 4.7 \pm 2.7\% \]
\[ A_{FB}^{l}(MC @ NLO) = 2.3 \pm 0.2\% \]
\[ A_{FB}^{l}(NLO + EW) = 3.8 \pm 0.2\% \]

Fully reconstructed $A_{FB}$:

\[ A_{FB}(D0, l + \text{jets}) = 10.6 \pm 3.0\% \]
\[ A_{FB}(MC @ NLO) = 5\% \]
\[ A_{FB}(NLO + EW) = 8.8\% \]

The results are largely consistent with SM-based calculations.
• Using full $t\bar{t}b$ reconstruction in $l+jets$ channel and identifying the $b$-jet charge using the jet charge algorithm DØ was able to exclude the $Q=\frac{-4}{3}$ hypothesis at $>5\sigma$ level.
Backup slides
ttbar production in SM QCD

\[
\text{Born}(\alpha_s^2) \quad \text{and box}(\alpha_s^4)
\]

- Coulomb-like repulsion of top and quark and attraction of antitop and quark in QCD
- **Positive asymmetry**
- Final state with no extra partons \( \rightarrow \) small transverse momentum of the tt system

\[
\text{ISR}(\alpha_s^3) \quad \text{and FSR}(\alpha_s^3)
\]

- **Negative asymmetry**
- Final state with extra gluons \( \rightarrow \) large transverse momentum of the tt system
- Possible extra jets

- Forward and backward events differ in jet multiplicity, transverse momentum of ttbar system and thus in acceptance

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**$A_{FB}^l$ by channel**

**Forward-Backward Lepton Asymmetry, %**

<table>
<thead>
<tr>
<th>Events/Exp</th>
<th>Events/Exp</th>
<th>Events/Exp</th>
<th>Events/Exp</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>150</td>
<td>250</td>
<td>350</td>
<td>450</td>
</tr>
<tr>
<td>DØ, 9.7fb⁻¹</td>
<td>DØ, 9.7fb⁻¹</td>
<td>DØ, 9.7fb⁻¹</td>
<td>DØ, 9.7fb⁻¹</td>
</tr>
</tbody>
</table>

3j- New channels

Was high in 5.4fb⁻¹

Now has higher weight because of higher purity

\[
A_{FB}^l (9.7 fb^{-1}) = 4.7 \pm 2.3 \pm 1.7 \%
\]

\[
A_{FB}^l (MC @ NLO) = 2.3 \pm 0.2\%
\]

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### Consistency in reco-level $A_{FB}$

<table>
<thead>
<tr>
<th>Run period</th>
<th>3j, 1b</th>
<th>3j, 2b</th>
<th>4j, 1b</th>
<th>4j, 2b</th>
<th>Total</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 5.4 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Combined</td>
<td>9.2±3.7%</td>
</tr>
<tr>
<td>First 5.4 fb$^{-1}$</td>
<td>12.0±5.4</td>
<td>8.3±4.1</td>
<td></td>
<td></td>
<td>9.9±3.4%</td>
<td>9% improvement in uncertainty due to split channels, b-tagging</td>
</tr>
<tr>
<td>First 5.4 fb$^{-1}$</td>
<td>7.0±7.3</td>
<td>12.0±6.0</td>
<td>12.0±5.4</td>
<td>8.3±4.1</td>
<td>10.1±2.7</td>
<td>26% improvement - add 3j</td>
</tr>
<tr>
<td>Sec 4.3 fb$^{-1}$</td>
<td>2.4±9.1</td>
<td>9.1±6.0</td>
<td>9.2±6.4</td>
<td>2.9±5.0</td>
<td>6.0±3.1</td>
<td></td>
</tr>
<tr>
<td>Total 9.7 fb$^{-1}$</td>
<td>5.4±6.0</td>
<td>10.7±4.2</td>
<td>11.0±4.4</td>
<td>5.9±3.3</td>
<td>7.9±2.1</td>
<td>29% improvement (exp 34%) due to $L$</td>
</tr>
</tbody>
</table>

Better resolution has a more significant effect at the unfolding level because it minimizes migrations.
We studied the effect of various sources of systematics via 102(!) nuisance parameters by performing ensemble testing.

<table>
<thead>
<tr>
<th>Category</th>
<th>Reco-level</th>
<th>Prod. level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bg model</td>
<td>+0.7/-0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Signal model</td>
<td>&lt;0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Unfolding</td>
<td>N/A</td>
<td>0.5</td>
</tr>
<tr>
<td>PDF/pile up</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Detector model</td>
<td>+0.1/-0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Sample composition</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>+0.8/-0.9</strong></td>
<td><strong>1.3</strong></td>
</tr>
</tbody>
</table>

The asymmetry in W+jets, ISR/FSR jet reco systematics are reduced compared to previous publication because of inclusion of l+3 jet events.