Is The Top Quark Asymmetry Just Standard-Model Physics?

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Outline

• Top quark production at Tevatron and LHC
• Standard Model predictions
• Monte Carlo event generation
• Tevatron data
• QCD asymmetry as a coherence effect
• LHC data and prospects
• Conclusions
Top Production at Tevatron

- $p\bar{p}$ at 1.96 TeV
- CDF & D0
- $\sim 9$ fb$^{-1}$/expt
- $\sigma_{t\bar{t}} \sim 8$ pb

$\rightarrow \sim 70,000$ $t\bar{t}$

$t \rightarrow Wb$

$W \rightarrow ev_\ell, \mu\nu_\mu \rightarrow l + \not{E}$

($W \rightarrow \tau\nu_\tau$)

$W \rightarrow u\bar{d}, c\bar{s} \rightarrow jj$

$\rightarrow t\bar{t} \rightarrow b\bar{b}l\bar{l} + \not{E}$ (5%), $t\bar{t} \rightarrow b\bar{b}ljj + \not{E}$ (30%)
Top Production at LHC

- pp at 7,8 TeV
- ATLAS & CMS
- \( \sim 6 \text{ fb}^{-1}/\text{expt} \)
- \( \sigma_{t\bar{t}} \sim 160 \text{ pb} \)
- \( \sim 10^6 t\bar{t} \)
- Expect \( \sim 20 \text{ fb}^{-1} \) this run (2012)

But dominated by gg rather than q\bar{q} collisions
Parton distributions

- $u\bar{u} \rightarrow t\bar{t}$ dominates at Tevatron,
- $gg \rightarrow t\bar{t}$ at LHC

$x f(x)$

$Q=2m_t$

MSTW08
Standard Model Prediction

- Only $q\bar{q}$ asymmetric
- NLO effect $\sim 5\%$ at parton level
- $t$ prefers $q$ direction

\[ y \equiv \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \]

Expect $y_t > y_{\bar{t}}$

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

\[ A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} > 0 \]
QED/EW Contributions

\[ \Delta \sigma_{\text{QCD}}^{\text{FB}} \sim \]

\[ \Delta \sigma_{\text{QED}}^{\text{FB}} \sim \]

\[ = f_q^{\text{QED}} \times \Delta \sigma_{\text{FB}}^{\text{QCD}} \]

\[ f_q^{\text{QED}} = 3 \frac{\alpha_{\text{QED}} Q_t Q_q}{\alpha_S} = \frac{\alpha_{\text{QED}}}{\alpha_S} \frac{36}{5} Q_t Q_q \]

\[ f_{\text{Tevatron}}^{\text{QED}} = \frac{4 f_u^{\text{QED}} + f_d^{\text{QED}}}{5} = \frac{\alpha_{\text{QED}}}{\alpha_S} \frac{56}{25} \approx 0.18 \]

Kuhn & Rodrigo, JHEP01(2012)063

+5% from Z^0 contributions  →  23% increase

Bernreuther & Si, arXiv:1205.6580
Monte Carlo Event Generation

Hard subprocess

\[ u\bar{u} \rightarrow t\bar{t} \]
Monte Carlo Event Generation

Parton showering

→ JETS
Monte Carlo Event Generation

Top decays
Monte Carlo Event Generation

Hadronization
Monte Carlo Event Generation

Hadronization and decays
Including Next-to-Leading Order

Hard subprocess
Including Next-to-Leading Order

NLO Hard subprocess
(loop correction)
Including Next-to-Leading Order

NLO Hard subprocess
(real emission)
Monte Carlo Event Generation

NLO Hard subprocess
+ Parton showering
= Double counting?? need matching prescription
MC@NLO matching

\[ \frac{d\sigma_{\text{MC}}}{} = B(\Phi_B) \Phi_B \left[ \Delta_{MC}(0) + \frac{R_{MC}(\Phi_B, \Phi_R)}{B(\Phi_B)} \Delta_{MC}(k_T(\Phi_B, \Phi_R)) \right] d\Phi_R \]

\[ \equiv B(\Phi_B) d\Phi_B \left[ \Delta_{MC}(0) + (R_{MC}/B) \Delta_{MC}(k_T) d\Phi_R \right] \]

Sudakov factor =
\[ P(\text{no emission above } p_T) \]

\[ \Delta_{MC}(p_T) = \exp \left[ - \int \Phi_R \frac{R_{MC}(\Phi_B, \Phi_R)}{B(\Phi_B)} \theta(k_T(\Phi_B, \Phi_R) - p_T) \right] \]

\[ \frac{d\sigma_{\text{MC}\oplus NLO}}{} = B + V + \int (R_{MC} - C) d\Phi_R \] 

\[ \equiv B(\Phi_B) \Phi_B \left[ \Delta_{MC}(0) + (R_{MC}/B) \Delta_{MC}(k_T) d\Phi_R \right] \]

\[ + (R - R_{MC}) \Delta_{MC}(k_T) d\Phi_B d\Phi_R \]

- Expanding gives NLO result

S Fratone & BV, JHEP 06(2002)029
POWHEG matching

\[ d\sigma_{MC} = B(\Phi_B) \, d\Phi_B \left[ \Delta_{MC}(0) + \frac{R_{MC}(\Phi_B, \Phi_R)}{B(\Phi_B)} \, \Delta_{MC}(k_T(\Phi_B, \Phi_R)) \, d\Phi_R \right] \]

\[ d\sigma_{PH} = \overline{B}(\Phi_B) \, d\Phi_B \left[ \Delta_R(0) + \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} \, \Delta_R(k_T(\Phi_B, \Phi_R)) \, d\Phi_R \right] \]

\[ \overline{B}(\Phi_B) = B(\Phi_B) + V(\Phi_B) + \int \left[ R(\Phi_B, \Phi_R) - \sum_i C_i(\Phi_B, \Phi_R) \right] \, d\Phi_R \]

\[ \Delta_R(p_T) = \exp \left[ - \int d\Phi_R \frac{R(\Phi_B, \Phi_R)}{B(\Phi_B)} \, \theta(k_T(\Phi_B, \Phi_R) - p_T) \right] \]

- NLO with (almost) no negative weights
- High \( p_T \) always enhanced by \( K = \overline{B}/B = 1 + \mathcal{O}(\alpha_S) \)

Use exact \( R \) in Sudakov factor for hardest emission

- arbitrary NNLO

Lepton+jets mode

- CDF: 2498 events
- Acceptance/selection cuts reduce asymmetry
  - Lepton and at least 4 jets (inc. 1 b-jet)
    with $p_T > 20 \text{ GeV}/c$, $|\eta| < 2$ ($|\eta|_b < 1$)
  - Missing $E_T \geq 20 \text{ GeV}$
- Simulate SM with MC@NLO or POWHEG
CDF Results

- CDF report a large effect, increasing with $t\bar{t}$ invariant mass
- SM predicts a smaller NLO effect
- MC@NLO and POWHEG in good agreement
- CDF claim $P_{NLO}=0.0065$

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

\[
A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]
CDF data: low vs high mass

\[ M_{tt} < 450 \text{ GeV/c}^2 \]

\[ M_{tt} > 450 \text{ GeV/c}^2 \]

- No significant asymmetry below \( M_{t\bar{t}} = 450 \text{ GeV} \)
Dilepton decay mode

$A^\Delta \eta_i = 0.138 \pm 0.054$

$A^\Delta \eta_i^{\text{pred}} = -0.022 \pm 0.022$

$A^\Delta y_t = 0.138 \pm 0.054$

$A^\Delta y_t^{\text{pred}} = -0.015 \pm 0.023$

- Consistent with lepton+jets mode
- Results from 8.7 fb$^{-1}$ coming soon
D0 Results

<table>
<thead>
<tr>
<th>$A_{FB}(%)$</th>
<th>$l+ \geq 4$ jets</th>
<th>$l+ 4$ jets</th>
<th>$l+ \geq 5$ jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>9.2±3.7</td>
<td>12.2±4.3</td>
<td>-3.0±7.9</td>
</tr>
<tr>
<td>$\text{mc@nlo }A_{FB} (%)$</td>
<td>2.4±0.7</td>
<td>3.9±0.8</td>
<td>-2.9±1.1</td>
</tr>
</tbody>
</table>

- Disagreement with SM = 3.4 s.d.
- CDF $M_{t\bar{t}}$ dependence not confirmed (?)
### $t\bar{t}$ $A_{FB}$ at Tevatron

<table>
<thead>
<tr>
<th>Selection</th>
<th>NLO (QCD+EW)</th>
<th>CDF, 5.3 fb(^{-1})</th>
<th>D0, 5.4 fb(^{-1})</th>
<th>CDF, 8.7 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>6.6</td>
<td>15.8 ± 7.4</td>
<td>19.6 ± 6.5</td>
<td>16.2 ± 4.7</td>
</tr>
<tr>
<td>$M_{tt} &lt; 450$ GeV/c(^2)</td>
<td>4.7</td>
<td>$-11.6 ± 15.3$</td>
<td>$7.8 ± 4.8$ (Bkg. Subtracted)</td>
<td>$7.8 ± 5.4$</td>
</tr>
<tr>
<td>$M_{tt} ≥ 450$ GeV/c(^2)</td>
<td>10.0</td>
<td>47.5 ± 11.2</td>
<td>$11.5 ± 6.0$ (Bkg. Subtracted)</td>
<td>$29.6 ± 6.7$</td>
</tr>
<tr>
<td>$</td>
<td>Δy</td>
<td>&lt; 1.0$</td>
<td>4.3</td>
<td>2.6 ± 11.8</td>
</tr>
<tr>
<td>$</td>
<td>Δy</td>
<td>≥ 1.0$</td>
<td>13.9</td>
<td>61.1 ± 25.6</td>
</tr>
</tbody>
</table>

- CDF/D0 disagreement?

D. Mietlicki, Moriond, 2012
NLO+NNLL Prediction

Ahrens, Ferroglia, Neubert, Pecjak, Yang, PRD84(2011)074004

- Stable w.r.t. soft gluon resummation
- Could still be hard HO effects
tt inv. mass at Tevatron

- CDF/D0 in agreement with SM

Is Top Asymmetry Just SM Physics?

Bryan Webber, ETH, Oct 2012
**t\bar{t} p_T at Tevatron**

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**FIG. 5:** Comparison of D0 measurement with theoretical NLO QCD prediction. The data points are obtained from Ref. [44] after background subtraction. The bands correspond to the variation of renormalization and factorization scales in the interval $m_t/2 < \mu < 2m_t$. The experimental distribution and the theoretical distribution are normalized in such a way that their integrals equal to one.

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CDF Run II Preliminary $L = 8.7$ fb$^{-1}$

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* Melnikov, Scharf, Schulze, PRD85(2012)034025

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* CDF/D0 disagreement

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Is Top Asymmetry Just SM Physics?

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Bryan Webber, ETH, Oct 2012
$t\bar{t}$ $p_T$ dependence of asymmetry

- Pure NLO (MCFM) has delta-function at $p_T = 0$
- CDF data disagree with MC@NLO
- Asymmetry should change sign at $\sim 25$ GeV
$A_{FB}$ in LO Monte Carlos

- Leading-order Monte Carlo = Born process + parton showers
- Born process has no asymmetry
- Hence LO MC has no asymmetry?

Wrong!

- LO MCs with coherent showering do!
What’s going on?

- QCD radiation controlled by colour flow
- Backward top $\rightarrow$ more radiation
- More radiation $\rightarrow$ bigger recoils
  $\rightarrow$ bigger $p_T(t\bar{t})$
Soft gluon limit

\[
\frac{d^2 \hat{\sigma}_A / dp_T \, d \cos \hat{\theta}}{2 \, d\hat{\sigma}_B / d \cos \hat{\theta}} = \frac{\alpha_S}{2\pi} \frac{16}{p_T} \frac{(N^2 - 4)}{2N} \log \left( \frac{1 - \beta \cos \hat{\theta}}{1 + \beta \cos \hat{\theta}} \right) \quad (0 < \cos \hat{\theta} < 1)
\]

\[
\beta = \sqrt{1 - \frac{4m_t^2}{\hat{s}}} \quad , \quad \frac{1 - \beta \cos \hat{\theta}}{1 + \beta \cos \hat{\theta}} = \frac{p_q \cdot p_t}{p_q \cdot p_{\bar{t}}}
\]

- Negative asymmetry (for $p_T > 0$)
- Dipole shower gives \( \frac{\alpha_S}{2\pi} \frac{16}{p_T} C_F \log \left( \frac{p_q \cdot p_t}{p_q \cdot p_{\bar{t}}} \right) \), i.e. $N^2 - 1$ in place of $N^2 - 4$

→ 60% overestimate
Forward tops left at low $p_T$
\[ A_{FB} > 0 \]

Backward tops moved to high $p_T$
\[ A_{FB} < 0 \]
Inclusive $A_{FB}$ vs $m(t\bar{t})$

- Less radiation from forward tops
- Sudakov factor is larger: $\Delta_+ > \Delta_-$
- Migration from F to B is smaller: $P_{+-} < P_{--}$

\[
\Delta\sigma_{+-} = \int d\sigma^{LO}_{\Delta y>0} \left[ \Delta_+ + (1 - \Delta_+)(P_{++} - P_{+-}) \right] \\
- \int d\sigma^{LO}_{\Delta y<0} \left[ \Delta_- + (1 - \Delta_-)(P_{--} - P_{-+}) \right]
\]

\[
= -2 \int d\sigma^{LO}_{\Delta y>0} (1 - \Delta_+)P_{+-} + 2 \int d\sigma^{LO}_{\Delta y<0} (1 - \Delta_-)P_{-+} > 0
\]
Inclusive $A_{FB}$ vs $m(t\bar{t})$

- Sherpa coherent dipole shower
- Herwig++ coherent parton shower
- QCD loop effects reproduced (approximately) by Sudakov factors in coherent showering
- Shows importance of higher order recoil effects (not yet computed exactly)
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{tt}$ (q vs $\bar{q}$)
- SM effect is small

$$\Delta y = y_t - y_{\bar{t}} \, , \quad Y_{tt} = \frac{1}{2}(y_t + y_{\bar{t}})$$
Top quark asymmetry at LHC

- LHC is a pp collider → no effect??
- No! Effect should increase with $Y_{t\bar{t}}$ ($q$ vs $\bar{q}$)
- Rapidity correlation should be as shown below
- Top rapidity distribution should be wider

\[ \Delta y = y_t - y_{\bar{t}} , \quad Y_{t\bar{t}} = \frac{1}{2}(y_t + y_{\bar{t}}) \]

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

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

\[ \Delta |y| \equiv |y_t| - |y_{\bar{t}}| > 0 \quad \leftrightarrow \quad \Delta y \cdot Y_{t\bar{t}} > 0 \]
\[ A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \]

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

- Much smaller than \( A_{FB} \)
- Good SM agreement (so far)
- EAG = effective axigluon, fits CDF
Comparisons with BSM Models

For all $M_{tt}$

- $A_C$ vs $A_{FB}$

For $M_{tt}>450$ GeV

- $A_C$ vs $A_{FB}$

- Not clear that any model is much better than SM
Other backgrounds are estimated from simulation. The unfolding procedure is used to separate the data sample into two bins with roughly equal number of events.

The expected and observed distributions for the invariant mass \(m_{\ell\ell}\) of the reconstructed \(t\bar{t}\) system are shown in Fig. 1 (a) and (c) for the electron channel, while in the muon channel are shown in Fig. 1 (b) and (d). The background contributions from diboson, \(W+\)jets, \(Z+\)jets, single top, and multijets are visible, with the signal contribution and uncertainty on the combined signal and background estimate included. An additional cut on the value of the likelihood for a badly reconstructed candidate is required in the two-dimensional unfolding, since a large fraction of simulated events with low acceptance likelihood value.

The left hand panels show distributions in the electron channel, while the right hand panels show distributions in the muon channel. The data is shown as a function of the reconstructed top-antitop invariant mass \(m_{\ell\ell}\) as a function of the reconstructed top-antitop invariant mass \(p_t\) and \(m_{\ell\ell}\). The expected and observed distributions are shown for the inclusive, semi-inclusive, and two-jet samples.

- Good agreement with MC@NLO
Conclusions

• Asymmetry larger than NLO SM seen by CDF in several independent data sets
• D0 also see this but no mass dependence
• D0 top pair $p_T$ also inconsistent with SM
• HO SM prediction not yet clear (recoils)
• Asymmetry at CDF (not SM) level could be seen at LHC in this run
• So far no sign of BSM at LHC
\( A_C \) vs \( A_{FB} \) in various models

- NB: \( A^{\text{new}} \) is deviation from SM (so SM is 0,0)

Adapted from J Aguilar-Saavedra, arXiv:1202:2382
“Axigluon” model

Ferrario & Rodrigo, PRD80(09) 051701

- sample “Octet A”
  - \( g_v = 0, |g_A| = 3 \|
  - \( g^q_A = - g^t_A \)
  - \( M_G = 2.0 \text{ TeV} \)
  - xsec ratio: \( \sigma/\sigma_{\text{sm}} = 1.02 \)
  - \( M_{\bar{t}t} \) spectrum ~ compares to Pythia
  - Model: Parton \( A_{\bar{t}t} = 0.16 \)  Reco \( A_{\bar{t}t} = 0.08 \)
  - Data: Parton \( A_{\bar{t}t} = 0.15 \), Reco \( A_{\bar{t}t} = 0.06 \)

- Can fit CDF \( A_{\bar{t}t} \) data
- \( M_{\bar{t}t} \) spectrum will differ
Axigluon search in dijets

ATLAS, arXiv:1103.3864

- Resonance bump would be similar to $q^*$
- Exclude $0.6 < M_G < 2.1$ TeV

Is Top Asymmetry Just SM Physics?

Bryan Webber, ETH, Oct 2012
Z’ exchange models

- Rutherford scattering → asymmetry
- Interferes with QCD $u\bar{u} \rightarrow g^* \rightarrow t\bar{t}$
- RH coupling avoids FCNC constraints
- Data favour light Z’ mass, below top
- BUT...
  - Also get $u\bar{u} \rightarrow t\bar{t}$
  - and $u\bar{u} \rightarrow Z'Z' \rightarrow t^*\bar{u}t^*\bar{u}$
  - need mixing so $Z' \rightarrow u\bar{u}$
Nonabelian $Z'$ model

Jung, Pierce, Wells, arXiv:1103.4835

- SU(2)$_L$ doublet $\begin{pmatrix} t_R \\ u_R \end{pmatrix}$
- Gauge triplet $Z'_\pm, Z'_0$ (they call $W', Z'$)
- Don’t get $uu \rightarrow tt$ (when unbroken)
- Flavour mixing reduces $Z'_0 \rightarrow u\bar{u}$
- Data favour $m_t < m_{Z'} < 2m_t$ (point A)

Is Top Asymmetry Just SM Physics?

Bryan Webber, ETH, Oct 2012
Z’ model asymmetry

- Jung-Pierce-Wells nonabelain model (point A) can fit data:
CDF asymmetry at LHC?

- LHC is a pp collider → no effect??
- **No!** Effect should increase with $Y_{t\bar{t}}$ ($q$ vs $\bar{q}$)
- Jung-Pierce-Wells model (point A) → smaller effect ($u\bar{u}$ only)
CDF Wjj anomaly

CDF, arXiv:1104.0699

- No anomaly in $\gamma jj \rightarrow$ flavour-changing $Z'$?

Is Top Asymmetry Just SM Physics?
W' model

A Papaefstathiou, in prep.

- Includes simulation of CDF detector

Tevatron, Delphes CDF sim., 5.3 fb^{-1}

\[ A_{\bar{t}t} \]

- CDF data
- MC@NLO (CDF)
- MC@NLO (Hw++/Delphes)

\[ M_{t\bar{t}} \ (GeV/c^2) \]

Tevatron, Delphes CDF sim., 5.3 inv. fb

\[ A_{tt} \]

- CDF data
- MC@NLO (CDF)
- MC@NLO (Hw++/Delphes)
- Hw++ Wprime (gR=2,400 GeV)