On New Physics Explanations of the Tevatron Top Forward-Backward Asymmetry

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work in collaboration with
Ian-Woo Kim and Kathryn Zurek
at the University of Michigan
[arXiv:1103.3501]

Implications of EWSB Workshop
May 7-8, 2011

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incoming proton → outgoing top

incoming anti-proton → outgoing anti-top

forward:

backward:

(top forward-backward asymmetric) = 

(#{forward forward tops}) - (#{backward backward tops})

(total # of tops)
Let \( y = \text{rapidity with respect to forward direction.} \)

\[(\text{lab frame})\]

\[
A^{p\bar{p}} = \frac{N(y_t^{p\bar{p}} > 0) - N(y_t^{p\bar{p}} < 0)}{N(y_t^{p\bar{p}} > 0) + N(y_t^{p\bar{p}} < 0)}
\]

\[(t\bar{t} \text{ CM frame})\]

\[
A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}
\]

\[
\Delta y \equiv y_t - y_{\bar{t}} = 2y_t^{t\bar{t}}
\]

Mass-dependent asymmetry:

\[
A^{t\bar{t}}(m_{t\bar{t},i}) = \frac{N(\Delta y > 0, m_{t\bar{t},i}) - N(\Delta y < 0, m_{t\bar{t},i})}{N(\Delta y > 0, m_{t\bar{t},i}) + N(\Delta y < 0, m_{t\bar{t},i})}
\]
Standard Model asymmetry is zero at leading order.

Small, positive asymmetry at NLO.

image credit: CDF arXiv:1101.0034
Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production (CDF, [arXiv:1101.0034])

• Reconstructed tops in events with semileptonic top pair decay signature.
• Assumed:

\[ y_t^{p\bar{p}} = -qy_h \quad \Delta y = q(y_l - y_h) \]

where

\[ y_h = y_{\text{hadronic top}} \quad y_l = y_{\text{leptonic top}} \]
\[ q = \text{sign of lepton} \]

• Provided raw, background-subtracted and unfolded “parton level” results
### CDF [arXiv:1101.0034]

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<tr>
<th>$A_{FB}^{tt}$</th>
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<td>bkd-sub data</td>
<td>$-0.022 \pm 0.039 \pm 0.017$</td>
<td>$0.266 \pm 0.053 \pm 0.032$</td>
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<td>MC@NLO</td>
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$\Delta = -1\sigma$

1260 events passed selection, 283+/− 91 estimated background
CDF [arXiv:1101.0034]

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$\Delta = 1.4\sigma$ \hspace{1cm} $\Delta = 2.3\sigma$
The predicted Standard Model top asymmetry is significantly lower than the measured asymmetry, especially for $t\bar{t}$ events with large invariant mass ($m_{t\bar{t}} > 450$ GeV).
Independent confirmation:

Measurement of the Forward Backward Asymmetry in Top Pair Production in the Dilepton Decay Channel using 5.1 fb
(CDF, March 2011)

\[
\begin{align*}
A_{\text{obs}}^{<450 \text{ GeV}} &= 0.104 \pm 0.066 \text{(stat.)} \quad \text{(Pred. : } 0.003 \pm 0.031) \\
A_{\text{obs}}^{>450 \text{ GeV}} &= 0.212 \pm 0.096 \text{(stat.)} \quad \text{(Pred. : } -0.040 \pm 0.055)
\end{align*}
\]

Measurement of the forward-backward production asymmetry of \( t \) and \( \bar{t} \) quarks in \( p\bar{p} \rightarrow tt \) events (D0, July 2010)

\[
A_{fb} = (8 \pm 4 \text{ (stat)} \pm 1 \text{ (syst)})\% \quad \text{and} \quad A_{fb}^{\text{pred}} = (1^{+2}_{-1} \text{ (syst)})\%.
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Measurement of the Forward Backward Asymmetry in Top Pair Production in the Dilepton Decay Channel using 5.1 fb (CDF, March 2011)

$$A_{\text{obs}} < 450 \text{ GeV} = 0.104 \pm 0.066(\text{stat.})$$  \hspace{1cm} (Pred. : $0.003 \pm 0.031$)

$$A_{\text{obs}} > 450 \text{ GeV} = 0.212 \pm 0.096(\text{stat.})$$  \hspace{1cm} (Pred. : $-0.040 \pm 0.055$)

$$\Delta = 1.4\sigma$$

$$\Delta = 2.3\sigma$$

Measurement of the forward-backward production asymmetry of $t$ and $\bar{t}$ quarks in $p\bar{p} \rightarrow tt$ events (D0, July 2010)

$$A_{fb} = (8 \pm 4\, (\text{stat}) \pm 1\, (\text{syst}))\%$$  \hspace{1cm} $A_{fb}^{\text{pred}} = (1^{+2}_{-1}\, (\text{syst}))\%$. 
How to produce a large asymmetry:

**s channel**
- nonzero axial couplings

![Diagram of s channel](image)

**t channel**

- Top flavor-carrying...
- Color octet (with maximally axial couplings to light quarks and to top quarks) aka an axigluon
- ...
Main goals:

• Reassess the viability of new physics models proposed to explain the top forward-backward asymmetry in light of new CDF measurements.

• Investigate subtleties associated with unfolding the “raw” asymmetry to a “parton level” asymmetry for more direct comparison to theory.
Mass-dependent asymmetry unfolding

\[ \vec{n}_{\text{signal}} = S A \vec{n}_{\text{parton}} \]

- \( \Delta y \)
- +

\[
\begin{array}{cc}
   n_{LB} & n_{LF} \\
   n_{HB} & n_{HF} \\
\end{array}
\]

A : Acceptance (diagonal)
S : Bin-to-bin migration

(derived through simulations (of SM events... and checked against axigluon events). CAUTION)

\[ \vec{n}_{\text{parton}} = A^{-1} S^{-1} (\vec{n}_{\text{data}} - \vec{n}_{\text{bkg}}) \]
Mass-dependent asymmetry unfolding

\[ \vec{n}_{\text{signal}} = SA \vec{n}_{\text{parton}} \]

- \( \Delta y \) +

\[ \begin{array}{cc}
  n_{LB} & n_{LF} \\
  n_{HB} & n_{HF} \\
\end{array} \]

\( A \) : Acceptance (diagonal)

\( S \) : bin-to-bin migration

(derived through simulations (of SM events... and checked against axigluon events). CAUTION)

\[ \vec{n}_{\text{parton}}^{\text{CDF}} = A^{-1}_{\text{SM}} S^{-1}_{\text{SM}} (\vec{n}_{\text{data}} - \vec{n}_{\text{bkg}}) \]
\( A_{FB}(m_{\bar{t}t} > 450 \text{ GeV}) \)

\( \sigma \) (pb, leading order, no K factor)
Parton level mass- and rapidity-dependent asymmetries
Parton level mass- and rapidity-dependent asymmetries
Parton level differential cross section
Conclusions after parton level comparison:

• $Z'$ does best at getting a steep rise in the asymmetry as a function of $m_{\bar{t}t}$.

• Sextets and triplets do marginally better than the SM at producing the asymmetry, but to produce these larger asymmetries the total production cross-section must be quite large.

• Axigluons with large enough mass to avoid dijet constraints can produce an asymmetry only slightly larger the the SM asymmetry, though the total cross-section looks ok.

• The differential cross-section for all models producing reasonably large asymmetries appears to be in conflict with measurement.
But...
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benchmark models (piped through Pythia/PGS)

$A_{FB}(m_{t\bar{t}} > 450 \text{ GeV})$

$\sigma (\text{pb, leading order, no K factor})$

$\text{SM}$

$Z_{H'}$

$W$

Triplet

Sextet

Axigluon

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CM frame mass-dependent asymmetry
Jet multiplicity dependence of asymmetry
Mass-dependent asymmetry partitioned by lepton charge
Frame dependence of asymmetry

- 400 GeV $Z_{h'}$, $g=1.75$, 400 GeV $W$, $g=2.55$
- 600 GeV Triplet, $g=4.4$, 1.4 TeV Sextet, $g=4.0$
- 2 TeV Axigluon, $g_a=-g_{a'}=2.4$, 800 GeV $Z_{h'}$, $g=3.4$
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Conclusions after data level comparison:

• $Z'$ and $W'$ benchmark models do the best at matching the mass-dependent asymmetry data, though the axigluon and triplet benchmarks don’t look so bad.

• None of the benchmark models get the frame-dependent asymmetry quite right.

• The invariant mass spectrum for triplet and high mass $Z'$ events differs substantially from the CDF measurement.

• The invariant mass spectrum for the low mass $Z'$ and $W'$ benchmark events agrees reasonably well with measurement at high invariant mass.

• It appears as if efficiency effects indeed brought the $Z'$ and $W'$ into agreement with measurement even though these models appeared to disagree with the invariant mass spectrum measurement at parton level.
If there’s time...
If: 

\[ \begin{align*} &q \\ &\bar{q} \end{align*} \rightarrow \begin{align*} &\tilde{t} \\ &\tilde{t} \end{align*} \]

(M: top flavor-carrying mediator)

then there necessarily exists:

(colored states only)
$\bar{t}j$ resonance in $t\bar{t}j$ events ($Z'$, $W'$)

$tj$ resonance in $tt\bar{t}j$ events (triplet, sextet)
LHC Reach [arXiv:1102.0018]