Explorations of the Top Quark Forward-Backward Asymmetry at Tevatron

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References

“Explorations of the Top Quark Forward-Backward Asymmetry at the Tevatron”
J. Shu, T. M. P. Tait and K. Wang

“Axigluon as Possible Explanation for $p\bar{p} \rightarrow t\bar{t}$ Forward-Backward Asymmetry”
P. H. Frampton, J. Shu and K. Wang

“Top Quark Forward-Backward Asymmetry”
K. Cheung, W. Y. Keung and T. C. Yuan

“Top quark forward-backward asymmetry from new t-channel physics”
S. Jung, H. Murayama, A. Pierce and J. D. Wells

“Charge asymmetries of top quarks: a window to new physics at hadron colliders”
P. Ferrario and G. Rodrigo

“Chiral color symmetry and possible $G'$-boson effects at the Tevatron and LHC”
M. V. Martynov and A. D. Smirnov

“The forward-backward asymmetry of top quark production at the Tevatron in warped extra dimensional models”
A. Djouadi, G. Moreau, F. Richard and R. K. Singh
Top quark

- Top decays before it hadronizes so one can measure lepton sign, $m_t$, decay BR, polarization......
- Less constraints from flavor physics $B$-physics only $B \rightarrow KX$ ... but much less constraints then light quarks and leptons

Top quark may be the best place to study new physics ....

$A_{FB}^t$ at Tevatron

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$\sigma_{tt}^{\text{CDF combined}} = 7.50 \pm 0.31_{\text{stat}} \pm 0.34_{\text{syst}} \pm 0.15_{\text{th}} \text{ pb}$

$\sigma_{tt}^{\text{th}} = 7.5 + 0.5/ - 0.7 \text{ pb}$

$m_t = 172.5 \text{ GeV}$
Forward-Backward Asymmetry

\[ A_{FB}^t = \frac{N_t(p) - N_t(\bar{p})}{N_t(p) + N_t(\bar{p})} \]

Under CP \( N_{\bar{t}}(p) = N_t(\bar{p}) \) Charge Asymmetry

\[ A_{C}^t = \frac{N_t(p) - N_{\bar{t}}(p)}{N_t(p) + N_{\bar{t}}(p)} \]

\[ A_{FB}^t \text{ at Tevatron} \quad \text{Kai Wang, IPMU, U-Tokyo} \]
\( A_{FB}^t \): 0.20 ± 0.11 ± 0.047 (0.695 fb\(^{-1}\), CDF T. Schwaz Thesis)

\( : 0.19 ± 0.09 ± 0.02 \) (0.9 fb\(^{-1}\), D0 0712.0851)

\( : 0.193 ± 0.065 ± 0.024 \) (3.2 fb\(^{-1}\), CDF note 9724)

\( : 0.150 ± 0.050 ± 0.024 \) (5.3 fb\(^{-1}\), CDF note 10224)

persistently large at both CDF and D0
\(A_{FB}\)

- \(|\mathcal{M}|^2 \sim \cos \theta\)
- \(\theta \rightarrow \pi - \theta\)
Asymmetry due to QCD

J. Kuhn and G. Rodrigo, PRD 59, 054017 (1999); PRL 81, 49 (1998)

\[ A_{FB}^t(QCD) = 0.051 \pm 0.015 \text{ (lab frame)} \]

- ISR/FSR interference
- Box/Tree interference

6.2\% resummed result in \( t\bar{t} \) rest frame (Sterman)

3\( \sigma \) away from zero 2\( \sigma \) from SM prediction
Hints from Experimental Facts

Tevatron leading production: Color octet exchange in $s$-channel

\[ q\bar{q} \xrightarrow{g} t\bar{t}, \quad gg \xrightarrow{g} t\bar{t}, \quad q\bar{q} \xrightarrow{\gamma/Z} t\bar{t} \]

- Cross section is consistent with prediction
- Asymmetry is not

If asymmetry is due to new physics contribution

There will be interference between new physics and leading production.

- $s$-channel octet
- $t$-channel singlet/triplet/sextet/octet....
Hints from Experimental Facts

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- $s$-channel octet
- $t$-channel singlet/triplet/sextet/octet...
\[ \psi = \psi_L + \psi_R \]

\[ \bar{\psi} i \gamma^\mu D_\mu \psi = \bar{\psi}_L i \mathcal{D} \psi_L + \bar{\psi}_R i \mathcal{D} \psi_R \]

\[ -m \bar{\psi} \psi = -m (\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R) \]

\[ \psi^c = C \bar{\psi}^T, \quad \bar{\psi}^c = \psi^T C^{-1} \]

\[ \bar{\psi}^c \psi \]
$s$-channel $3 \otimes \bar{3} = 8 \oplus 1$

- $J = 0 \ (8, 2)_1$, $y_{uu}$ coupling

- $J = 1$
$t$-channel Physics
$Z'/W'$ with maximal flavor violation

S. Jung, H.Murayama, A.Pierce, J. Wess 0907.4112

K. Cheung, W. Keung, T. Yuan 0908.2589

\[
\frac{1}{t} : + \cos \theta,
\]

Large $\hat{s}$: take the $t$ massless limit, Rutherford singularity

$A_{FB}^t = 100\%$

$A_{FB}^t$ at Tevatron

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In the dilepton channel, the cross-sections inferred from our best point are less than 3 events per 2 fb. The asymmetry is high, and the cross-section is favored.

Additional collider constraints.

Comparing the two panels of Fig. 2 indicates a potential simultaneous fit to a large region deviates by more than 2 standard deviations from the SM expectation. Re-measurements from D0, which use less data, and thus potentially dangerous. CDF has measured the ratio of events from, e.g., e+e− in the dilepton+jets channel. At CDF and D0, they reduce the dilepton top cross section relative to the SM expectation is also small but with large error: 2 ± 31 events from, e.g., e+e− production.

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Scalars in $t$-channel

In the massless limit, purely helicity states. Spin conservation at the Rutherford singularity. $\bar{\psi}\psi\phi$ must flip the helicity.

$$\sum |\mathcal{M}|^2 = 8g_S^4(1 + c_\theta^2 + 4m^2) +$$

$$2y^2 g_S^2 C_0 s \frac{(1 - c_\theta)^2 + 4m^2}{t_\phi} + y^4 C_2 \frac{s^2(1 - c_\theta)^2}{t_\phi^2}$$
$A_{FB}$ at Tevatron

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Color Singlet/Octet $\bar{\psi}\psi\phi$

$\sigma(pp \rightarrow t\bar{t})(pb)$

$A_{FB}$ at Tevatron

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Fermion Number Violating $\bar{\psi}^c \psi \phi$

$3 \otimes 3 = 6 \oplus \bar{3}$
Not a full story yet.... $M_{t\bar{t}}$

the same problem as $Z'$, $W'$ or our scalar model, all $t$-channel.....

May not be that worse....QCD correction may change the shape....
$qg \rightarrow \phi t$

$pp \rightarrow \phi \bar{t} + \phi^* t \rightarrow t\bar{t} + \text{mono-hard-jet}$
Almost Irrelevant at Tevatron but may change the LHC $t\bar{t}$ search
Maximal Flavor Violation

All three models rely on maximal flavor violations...

\[ \bar{t}\gamma_\mu(P_R + P_L)uZ^\mu \]
\[ \bar{t}\gamma_\mu(P_R + P_L)dW^\mu \]
\[ \bar{c}(P_R + P_L)u\phi + \bar{t}(P_R + P_L)u\Phi \]
\[ f_{ij}\phi_{\alpha\beta}\bar{u}_\alpha u_\beta + y_{ij}\epsilon_{\alpha\beta\gamma}\bar{u}_\alpha u_\beta j\phi'_{\gamma} \]
\[ f_{ij} = f_{ji}, \ y_{ij} = -y_{ji} \]
What we are interested in: $f_{13}$
particular dangerous: couplings to charm
safe under CKM rotation?

General Tricks in this business
- No coupling to charm $f_{12}, f_{22} = 0$
- Right-handed ONLY. (We don’t know right-handed rotation.)
\[ D_0 - \overline{D}_0 \text{ mixing/} D \rightarrow \pi \pi \]

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Same-sign Top quark pair at early LHC


- $pp$ vs $p\bar{p}$ collider
- $uu \rightarrow tt$ the most non-trivial final state with little background

Both scenarios may contribute to $uu \rightarrow tt$.

- $t$-channel exchange a neutral particle
- $s$-channel fermion number violating color sextet $f_{11}, f_{22}$

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Same-sign Top Production

$\alpha_s = 2.4 \times 10^{-2}$

$A_{FB}^t$ at Tevatron

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Color Sextet Diquark Pair Production at the LHC

W. Klemm, V. Rentala and KW, 2008

\[ g(p_1) + g(p_2) \rightarrow \Phi_6(k_1) + \Phi_6(k_2) \rightarrow t\bar{t}t\bar{t} \]
\[ q(p_1) + \bar{q}(p_2) \rightarrow \Phi_6(k_1) + \Phi_6(k_2) \rightarrow t\bar{t}t\bar{t} \]

Production of $\Phi_6 \Phi_6$ at the LHC and Tevatron $\mu_F = \mu_R = \sqrt{s}/2$, CTEQ6L

$A_{FB}^t$ at Tevatron

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Each diquark carries $B = 2/3$.

Pati-Salam Model to Left-Right Model

$$SU(2)_L \times SU(2)_R \times SU(4)_C \rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

$$(3, 1, 10) : \{ (3, 1, -2, 1) \oplus (3, 1, -2/3, 3) \oplus (3, 1, 2/3, 6) \} + L \leftrightarrow R$$

$B - L: \Delta L = 2 \leftrightarrow \Delta B = 2: n - \bar{n}$ oscillation

Electroweak Baryogenesis
Parity Violation and Axigluon
Is parity violated in strong interaction at higher energy?

Parity violation

\[ \overline{t}_\alpha \gamma_\mu \gamma_5 t_\beta T^a_{\alpha\beta} G^\mu_a \]

Chiral Color Models (Frampton-Glashow, 1987)

\[ SU(3)_L \times SU(3)_R \rightarrow SU(3)_C \] with massive axigluon

QCD strength, color octet but with \( \gamma^5 \)
No light color resonance in $s$-channel
Direct search bound from Tevatron 1.13 TeV 95%CL for $g_s$
General $V - A$ structure

\[
\sum |\mathcal{M}|^2 = g_s^4 (1 + c^2 + 4m^2) \\
+ \frac{2g_s^2 \hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ g_V^q g_V^t (1 + c^2 + 4m^2) \\
+ 2 g_A^q g_A^t c \right] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ ((g_V^q)^2 + (g_A^q)^2) \\
\times ((g_V^t)^2(1 + c^2 + 4m^2) + (g_A^t)^2(1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c \right],
\]

c = \beta \cos \theta

$A_{FB}^t$ at Tevatron

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<table>
<thead>
<tr>
<th>Field</th>
<th>$Q_i$</th>
<th>$u_i^c$</th>
<th>$d_i^c$</th>
<th>$Q_j$</th>
<th>$u_j^c$</th>
<th>$d_j^c$</th>
<th>$\Sigma$</th>
<th>$H_q$</th>
<th>$L_k$</th>
<th>$e_k^c$</th>
<th>$H_l$</th>
</tr>
</thead>
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<td>1</td>
<td>1</td>
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<td>3</td>
<td>3</td>
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<td>1</td>
<td>1</td>
<td>1</td>
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<tr>
<td>SU(3)$_B$</td>
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<td>$\bar{3}$</td>
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<tr>
<td>SU(2)$_L$</td>
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<tr>
<td>U(1)$_Y$</td>
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<td>0</td>
<td>1</td>
<td>-1</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Table: Charge assignment of all the quark, lepton fields and the Higgs fields under $SU(3)_A \times SU(3)_B \times SU(2)_L \times U(1)_Y$. The flavor indices are as $i = 1, 2$, $j = 3, 4$ and $k = 1, 2, 3, 4$. The hypercharge is defined as the convention of electric charge $q = I^3_L + Y/2$ where $I^3_L$ is the third component of $SU(2)_L$ isospin. All the $SU(2)_L$ singlet fields are defined in their conjugate forms.
$A^t_{FB}$ at Tevatron

Kai Wang, IPMU, U-Tokyo
General $V - A$ structure

$$
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+ \frac{2g_s^2 \hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ g_V^q g_V^t (1 + c^2 + 4m^2) 
+ 2 g_A^q g_A^t c \right] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} \left[ ((g_V^q)^2 + (g_A^q)^2) \times ((g_V^t)^2 (1 + c^2 + 4m^2) + (g_A^t)^2 (1 + c^2 - 4m^2))
+ 8 g_V^q g_A^q g_V^t g_A^t c \right],
$$

$$
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$$
$A_{FB}^t$ at Tevatron

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Parton Level $A^{pp}_{FB}$ below $M_{tt}$ Edge

CDF II Preliminary $L=3.2$ fb$^{-1}$

$A_{FB} \pm \sigma_{\text{stat}}$

$\pm \sigma_{\text{stat+syst}}$

Integral $A_{FB} = 19.3\%$

with flat mass dependence

NLO Model

$A_{FB}$ at Tevatron

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Parton Level $A_{FB}^{pp}$ Above $M_{tt}$ Edge

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$\pm \sigma_{stat+syst}$

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$A_{FB}$ at Tevatron

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FIG. 1: $A_{FB}^{t}$ vs. $M_{tt}$ with $M_{tt}$ integrated over each 150 GeV of $M_{tt}$ using the benchmark point, $M_{G} = 1525$ GeV, $g_{qV} = -0.577$, $g_s$ and $g_{qA} = g_{tA} = -1.155$. The solid line corresponds to our model with $g_{qV} = g_{tV}$ and dashed line is a comparison plot with $g_{qV} = -g_{tV}$, as explained in the text.
Conclusions

- Top quark forward/backward asymmetry may provide a hint to new physics.
- It is possible to accommodate the large asymmetry in new physics while keeping the total cross section unchanged through $t$-channel new physics but hard to fit the $M_{t\bar{t}}$.
- $s$-channel color octet with $V-A$ coupling may not be able to generate a large asymmetry but can provide a better fit to every constraint.
- It will be useful to improve the measurement of $A_{FB}^{t}$ vs $M_{t\bar{t}}$ to confirm or rule out models.