Spinning the Top

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based on work with Gilad Perez and Martin Schmaltz, arXiv 1110.3796
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4 Lepton Asymmetry and New Physics

5 Summary
Why Bother with Top Quark

- Most recently discovered elementary fermion
- Its mass is of the order of the electroweak scale, so there are reasons it may couple strongly to the new physics sector that breaks the electroweak symmetry
- $\Gamma_t \gg \Lambda_{QCD}$, thus top decays before hadronization. Thanks to this we can experimentally access top polarization.
- The anomalous $t\bar{t}$ forward-backward asymmetry is currently the only serious hint of new physics at the weak scale
Measuring top quark

- Per experiment, about 75 thousand produced tops at Tevatron (about 2 thousand selected) and about 10 million produced at LHC so far.
- Most efficiently studied in semileptonic channel (easiest reconstruction and largest statistics) and dileptonic channel (cleaner but smaller statistics and more ambiguity in reconstruction).

We measure:

- Mass and Width
- (differential) Cross Sections
- Decay Branching Fractions
- Polarization and Asymmetries
Charged lepton from top decay is perfect analyzer of top spin

More precisely, amplitude square for top decay after averaging over spins of decay products:

$$\sum_{s_f} |M|^2 = \frac{2g^4}{(2k_l \cdot k_n - m_W^2)^2 + m_W^2 \Gamma_W^2} (k_b \cdot k_n) [\bar{x}(k_t, s_t) k_l \cdot \vec{\sigma} x(k_t, s_t)]$$

where $x(k_t, s_t)$ is a bi-spinor solving the equation of motion

In *top rest frame* one can choose $x(k_t, s_t)$ to be eigenstate of spin operator $\vec{S} \cdot \vec{\sigma}$, so $k_l \cdot \vec{\sigma} x(k_t, s_t) = E_l (1 + \cos \theta) x(k_t, s_t)$, leading to $\Gamma \sim (1 + \cos \theta)$ where $\theta$ is angle between lepton momentum and top spin

For anti-top $\Gamma \sim (1 - \cos \theta)$
Lepton Asymmetries

Rather than fitting $\cos \theta$ dependence, easier to measure asymmetries, e.g. in the LAB frame, $t \bar{t}$ rest frame, $t$ rest frame, etc

- Charged lepton forward-backward asymmetry

$$A_{FB}^{\ell+} = \frac{N_{l+}(\cos \theta > 0) - N_{l+}(\cos \theta < 0)}{N_{l+}(\cos \theta > 0) + N_{l+}(\cos \theta < 0)} \quad A_{FB}^{\ell-} = \frac{N_{l-}(\cos \theta > 0) - N_{l-}(\cos \theta < 0)}{N_{l-}(\cos \theta > 0) + N_{l-}(\cos \theta < 0)}$$

For a completely polarized top

$$A_{FB}^{\ell+} = \frac{\int_{0}^{1} (1 + \cos \theta) - \int_{-1}^{0} (1 + \cos \theta)}{\int_{-1}^{1} (1 + \cos \theta)} = +50\%$$

- For completely polarized antitops $A_{FB}^{\ell-} = -50\%$

- Another lepton asymmetry

$$A_{FB}^{\ell} = \frac{N_{l}(q_{l} \cos \theta > 0) - N_{l}(q_{l} \cos \theta < 0)}{N_{l}(\cos \theta > 0) + N_{l}(\cos \theta < 0)}$$

Useful to ameliorate statistics when $A_{FB}^{\ell+} = -A_{FB}^{\ell-}$, e.g. when both tops have spins along the same direction
Another asymmetry that can be defined in dileptonic $t\bar{t}$ events, (or in semi-leptonic if one attempts to identify the d/s quark originated jet from W decay)

- **Dilepton asymmetry**

  $$A_{FB}^{\ell\ell} = \frac{N(\eta_+ > \eta_-) - N(\eta_+ < \eta_-)}{N(\eta_+ > \eta_-) + N(\eta_+ < \eta_-)},$$

- When both top and anti-top polarized along the same direction, then $$\Gamma \sim (1 + \cos \theta_+) (1 - \cos \theta_-),$$ thus integrating one gets $A_{FB}^{\ell\ell} = 66.6\%$

- Dilepton asymmetry is invariant under longitudinal boosts (because rapidity difference is)
Another possible observable probing correlations between top spins

$$\Gamma \sim (1 - C \cos \theta_{\ell^+} \cos \theta_{\ell^-})$$

where angles usually measured in respective $t$ or $\bar{t}$ rest frame

- $C = +1$ for fully correlated spins, and $C = -1$ for fully anti-correlated spins
- Distinguishes correlated from anti-correlated top spins, but not spin direction
- Unlike asymmetries, spin correlations are predicted to be non-zero even at tree-level QCD, both at the Tevatron ($C \approx 0.78$ at NLO)
Our idea...
Huge literature on top polarization, in particular on SM tests, sensitivity to new physics, spin correlations, stability wrt QCD corrections

We’re adding a new twist, or rather a new spin; so simple and intuitive that you may say you have known that before

But, as far as I know, never explicitly pointed out in a theory paper, and definitely no experimental studies available yet
Our Proposal: *Study lepton forward-backward lepton at $t\bar{t}$ threshold*

- **At threshold**, tops have zero momentum $\rightarrow$ they don’t have angular momentum (neither has the beam)
- Thus, the sum of the spins of top and anti-top along beam directions equals the sum of the spins of the colliding light quarks
  - For events initiated by $q_R\bar{q}_R$, both $t$ and $\bar{t}$ have spins aligned with the quark beam, leading to $A_{FB}^{\ell} = +50\%$.
  - For events initiated by $q_L\bar{q}_L$, both $t$ and $\bar{t}$ have spins anti-aligned with the quark beam, leading to $A_{FB}^{\ell} = -50\%$.
- Therefore measuring $A_{FB}^{\ell}$ at threshold tells us the proportions of $q_R\bar{q}_R$ and $q_L\bar{q}_L$ that produce $t\bar{t}$ at threshold
Simple and clean experimental observable

Independent from *inclusive* lepton asymmetry and from $t\bar{t}$ forward-backward asymmetry. Easy to construct models where those have opposite signs from threshold lepton asymmetry.

Different from spin correlations. In fact, $C = +1$ for both $q_R\bar{q}_R$ and $q_L\bar{q}_L$ initiated top pairs.

(Unlike spin correlations that needs either dileptonic decay or identifying d/s quark jet) applies separately to top and anti-top decay products

Same spin argument applies to threshold *dilepton* asymmetry, in this case $A_{FB}^{\ell\ell} = +66.6\%$ for pure $q_R\bar{q}_R$ production, and $A_{FB}^{\ell\ell} = -66.6\%$ for pure $q_L\bar{q}_L$

New physics addressing anomalous top FB asymmetry requires new particles with *chiral* couplings to not only to top but also to light quarks

Caveat: Below, only TREE-LEVEL results. At the moment we don’t know how this observable is affected by NLO QCD corrections (but in the inclusive case they do not change the picture dramatically Bernreuther, Si, Uwer [1003.3926])
Lepton asymmetry in a toy model
• Toy model to distill the effect: **Chiral QCD**

• Massless *chiral gluon* with general chiral couplings to quarks:

\[
G^a_{\mu} \bar{q} \sigma^{\mu} T^a (g_{qR} P_R + g_{qL} P_L) q + G^a_{\mu} \bar{t} \sigma^{\mu} T^a (g_{tR} P_R + g_{tL} P_L) t
\]

• Consider the process \( q\bar{q} \rightarrow t\bar{t} \rightarrow l\nu jj \) at fixed CM energy \( \sqrt{s} \) (QLC = Quark Linear Collider :-)

• Consider spin amplitudes with the spin quantization axis along the beam direction
Toy model spin amplitudes

\[ \mathcal{M}(q_i \bar{q}_j \rightarrow t_k \bar{t}_l) = \left( \delta_{ik} \delta_{jl} - \frac{1}{3} \delta_{ij} \delta_{kl} \right) F(s_q, s_{\bar{q}}|s_t, s_{\bar{t}}) \]

At the threshold only 2 spin-amplitudes non-zero

\[ F(+, +|+, +) = -\frac{g_{q_R}(g_{t_L} + g_{t_R})}{2} \quad F(-, -|-,-, -) = -\frac{g_{q_L}(g_{t_L} + g_{t_R})}{2} \]

- Only \((++\)) top spin state is possible if chiral gluon couples only to \textit{right-handed} light quarks
- Only \((- -\)) top spin state is possible if chiral gluon couples only to \textit{left-handed} light quarks
- For \textit{scalar} gluons only \((-+\)) and \((-+\)) initial and final states would not vanish at threshold

Consider the \textbf{lepton asymmetry}

\[ A_{FB}^{\ell} = \frac{N_l(q_i \cos \theta > 0) - N_l(q_i \cos \theta < 0)}{N_l(\cos \theta > 0) + N_l(\cos \theta < 0)} \]

as a function of \(t\bar{t}\) invariant mass \(m_{tt} = \sqrt{s}\)
Assume gluon coupling only to right-handed up quarks: $G^a_\mu \bar{u} \bar{\sigma}^\mu T^a P_R u$

Assume vector coupling of the gluon to the top: $G^a_\mu \bar{t} \bar{\sigma}^\mu T^a t$

Tops produced only by $q_R \bar{q}_R$, thus at threshold, $A^\ell_{FB} = 50\%$

Small effect of cutting on lepton rapidity $|\eta| < 2$ negligible (dashed line)

At higher $\sqrt{s}$ tops not at rest → have angular momentum → spin of the tops no more along the beam → lepton asymmetry different than 50\%

At very high $\sqrt{s}$ lepton asymmetry approaches the $t\bar{t}$ asymmetry

Note $A^\ell_{FB}$ is independent from $A^{t\bar{t}}_{FB}$; latter is zero in this case for any $\sqrt{s}$
Varied gluon coupling to the top: \( G^a_{\mu} \bar{t}\bar{\sigma}^{\mu} T^a \mathcal{P}_X t \)

At the threshold, lepton asymmetry independent of the coupling to the top, in agreement with theoretical arguments.

At higher \( m_{tt} \), lepton asymmetry inherits from the \( t\bar{t} \) asymmetry.

Convoluting with Tevatron PDFs, inclusive asymmetry for RL case \( \sim 10\% \). One can easily miss the effect by looking inclusively!
Dilepton asymmetry displays similar $m_{tt}$ dependence
Threshold value $+66\%$ independently of chiral gluon coupling to tops
Axial gluon coupling to the top: $G_\mu^a \bar{t} \sigma^\mu T^a \gamma_5 t$

At the threshold, lepton asymmetry different than in the vector case, contrary to the theoretical arguments.

That’s because for axial couplings to the top, the $t \bar{t}$ production amplitude completely vanishes at the threshold. Then amplitude dominated by higher order terms in $\nu_{top}$ and the $(++)$ spin state is less dominant.
Lepton asymmetry vs $t\bar{t}$ asymmetry
Currently most exciting new physics models are those producing large $t\bar{t}$ forward-backward asymmetry without screwing up top quark cross section and its other measured properties

$$A_{FB}^{t\bar{t}} = \frac{N(\eta_t > \eta_{\bar{t}}) - N(\eta_t < \eta_{\bar{t}})}{N(\eta_t > \eta_{\bar{t}}) + N(\eta_t < \eta_{\bar{t}})},$$

Recall, both CDF and D0 observe inclusive $A_{FB}^{t\bar{t}} \approx (20 \pm 7)\%$, compared to the SM prediction $A_{FB}^{t\bar{t}} = 5 - 9\%$

Beside, CDF (not D0) observes a strong dependence on $t\bar{t}$ invariant mass

On the other hand, ATLAS and CMS measured a related charge asymmetry, and found no significant deviation (and opposite sign)

Summary from 1109.6830:
Many models (still) on the market:

- Heavy color octet vector \( (m_{G'} \gg 2m_t) \) with flavor non-universal large chiral couplings to light and top quarks in s-channel
- Light color octet vector \( (m_{G'} \lesssim 2m_t) \) with flavor universal moderate chiral couplings to light and top quarks in s-channel
- Light (complex) \( Z' \) vector boson with flavor violating coupling to up and top quarks in t-channel
- Light electroweak doublet scalar with flavor violating coupling to up and top quarks in t-channel
- Light color antitriplet scalar with flavor violating coupling to right-handed up and top quarks in u-channel
- ...
Light Color Octet

Choose light axigluon because it jives well with lepton asymmetry...

\[
\text{QCD} + \mathcal{G}^\prime \mu^a [\bar{q} \bar{\sigma}^\mu T^a (g_R P_R + g_L P_L) q + \bar{t} \bar{\sigma}^\mu T^a (g_R P_R + g_L P_L) t]
\]

- No problems with constraints from the tail of \(d\sigma/dm_{tt}\) distribution
- Constraints from total \(\sigma_{tt}\) manageable
- Constraints from dijet resonances bypassed if \(G'\) is wide, Schmaltz, Tavares [1107.0978]
- Model specific prediction for inclusive lepton asymmetry which provides a handle to distinguish between different competing models, Krohn, Liu, Shelton, Wang [1105.3743]
- Assume purely axial couplings
- Correct $t\bar{t}$ asymmetry for $g_A \sim 0.5g_{\text{strong}}$
For axial couplings, no corrections to total $\sigma_{tt}$ from interference, thus weak constraints.
UA2 and Tevatron searches for dijet resonances exclude a narrow axigluon in the interesting parameter range.

Although some argue that a very light axigluon, $m_{G'} \sim 50 - 80$ GeV is allowed Krnjaic [1109.0648]
Stronger constraints from $\sigma_{t\bar{t}}$ for purely right-handed or left-handed couplings
3 benchmarks with $m_{G'} = 200$ GeV, $\Gamma_{G'} = 50$ GeV predicting $\Delta A_{t\bar{t}}^{FB} \approx 11\%$ in agreement with D0/CDF and without violating all other constraints

- **AxR**: $g_{q,R} = g_{t,R} = 0.8g_s$, $g_{q,L} = g_{t,L} = 0$
- **AxL**: $g_{q,R} = g_{t,R} = 0$, $g_{q,L} = g_{t,L} = 0.8g_s$
- **AxA**: $g_{q,R} = g_{t,R} = 0.4g_s$, $g_{q,L} = g_{t,L} = -0.4g_s$

Threshold lepton asymmetry at Tevatron (LAB/$t\bar{t}$ rest frame)

<table>
<thead>
<tr>
<th>Benchmark</th>
<th>$A_{FB}^\ell(\sqrt{s} &lt; 375 \text{ GeV})$</th>
<th>$A_{FB}^\ell(\sqrt{s} &lt; 450 \text{ GeV})$</th>
<th>$A_{FB}^\ell$ inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>AxR</td>
<td>18%</td>
<td>17%</td>
<td>17%</td>
</tr>
<tr>
<td>AxL</td>
<td>-13%</td>
<td>-8%</td>
<td>-7%</td>
</tr>
<tr>
<td>AxA</td>
<td>2%</td>
<td>3%</td>
<td>6%</td>
</tr>
<tr>
<td>$t\bar{t}$ fraction</td>
<td>17%</td>
<td>60%</td>
<td>100%</td>
</tr>
</tbody>
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- Inclusive lepton asymmetry provides discriminating power between benchmarks, as noticed by Krohn et al.
- But stronger discrimination by looking at $A_{FB}^\ell$ near the threshold
3 benchmarks with $m_{G'} = 200$ GeV, $\Gamma_{G'} = 50$ GeV predicting $\Delta A^\ell\ell_{t\bar{t}} \approx 11\%$ in agreement with D0/CDF and without violating all other constraints

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- **AxA**: $g_{q,R} = g_{t,R} = 0.4g_s$, $g_{q,L} = g_{t,L} = -0.4g_s$

### Threshold dilepton asymmetry at Tevatron

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<th>$A^\ell\ell_{FB}(\sqrt{s} &lt; 450 \text{ GeV})$</th>
<th>$A^\ell\ell_{FB}(\text{inclusive})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AxR</td>
<td>21%</td>
<td>21%</td>
<td>21%</td>
</tr>
<tr>
<td>AxL</td>
<td>-18%</td>
<td>-13%</td>
<td>-9%</td>
</tr>
<tr>
<td>AxA</td>
<td>2%</td>
<td>5%</td>
<td>7%</td>
</tr>
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- Inclusive lepton asymmetry provides discriminating power between benchmarks, as noticed by Krohn et al.
- But stronger discrimination by looking at $A^\ell\ell_{FB}$ near the threshold
• **Saavedra, Perez-Victoria [1107.0841]**: another possible model, weak doublet color singlet \( S = (S_+, S_0) \) coupled as

\[
y_R u^c Q_3 S + y_L t^c Q_1 S + \text{h.c.} \quad Q_3 = (t, b), \quad Q_1 = (u, d)
\]

- t-channel scalar exchange contributes to \( t\bar{t} \) production
- Either \( y_R \) or \( y_L \) non-zero; if both than model killed by same-sign top production
- Positive contributions to forward-backward top asymmetry, and constraints OK for \( m_S \sim m_{\text{top}} \) and \( y_{R,L} \sim 1 \)
- New twist here because of destructive interference with QCD
Light, $m_S \lesssim 170$ GeV electroweak doublet scalar can produce enough $A_{FB}^{tt}$ without violating constraints from $t\bar{t}$ cross section at Tevatron.

On the other hand, we need $m_S > 160$ GeV to avoid too large branching fraction $t \rightarrow Su$, so window rather small.
Even though $S$ couples to right-handed up quarks, threshold lepton asymmetry is negative for moderate $y_R$

This is because the color-octet part of the scalar exchange amplitude interferes *destructively* with the QCD amplitude, thus it may suppress the $u_R \bar{u}_R$ contribution wrt to $u_L \bar{u}_L$

For very large $y_R$ the scalar exchange wins QCD and one gets positive threshold lepton asymmetry

Other way around for $y_L > 0$, where $u_L \bar{u}_L$ contribution gets suppressed wrt $u_R \bar{u}_R$ and one ends up with positive threshold asymmetry for moderate $y_L$
Light Scalar Doublet Benchmarks

- **SdR:** $m_S = 170$ GeV and $y_R = 1.5$, $y_L = 0$, leading to $\Delta A_{FB}^{tt} \approx 5\%$
- **SdL:** $m_S = 170$ GeV and $y_L = 1.5$, $y_R = 0$, leading to $\Delta A_{FB}^{tt} \approx 5\%$

**Threshold lepton and dilepton asymmetry at Tevatron**

<table>
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<th>$A_{FB}(\sqrt{s} &lt; 450\text{ GeV})$</th>
<th>$A_{FB}$ inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>SdR</td>
<td>-10/-13%</td>
<td>-7/-9%</td>
<td>-4/-4%</td>
</tr>
<tr>
<td>SdL</td>
<td>10/14 %</td>
<td>10/12%</td>
<td>11/13%</td>
</tr>
<tr>
<td>$\bar{t}t$ fraction</td>
<td>17 %</td>
<td>60 %</td>
<td>100 %</td>
</tr>
</tbody>
</table>
The \textit{threshold lepton} asymmetry not studied experimentally so far

D0 measured inclusive lepton asymmetry in semileptonic $t\bar{t}$ events

$$A^\ell_{FB} = (15.2 \pm 4.0)\%,$$

compared to 2\% predicted by the SM at the NLO. In the same sample $A^{t\bar{t}}_{FB} = 19.6 \pm 6.5\%$.

CDF measured inclusive lepton asymmetry in dileptonic $t\bar{t}$ events

$$A^\ell_{FB} = (21 \pm 7)\%,$$

(at reconstruction level). In the same sample at parton level $A^{t\bar{t}}_{FB} = (42 \pm 15)\%$.

These results strongly disfavor a domination of $q_L\bar{q}_L$ contribution to $t\bar{t}$ production, such as AxL and SdR benchmarks before.

Given large $A^{t\bar{t}}_{FB}$ in these samples, they slightly prefer comparable $q_L\bar{q}_L$ and $q_R\bar{q}_R$ contributions over $q_R\bar{q}_R$ domination.

Measuring threshold lepton and dilepton asymmetry would immensely clarify the situation.
Take Away Points

- We point out it is interesting to study the threshold lepton asymmetry, that is $A_{FB}^\ell$ in $t\bar{t}$ events near the production threshold
- Simple and clean observable, with a simple and intuitive theoretical interpretation
- Probes slightly different physics than other commonly studied measures of top polarization
- Applies separately to top and anti-top decay products, in semileptonic or dileptonic channel
- This observable is a direct measure of the polarization of the light quarks that produce the tops
- It’s zero in the SM at tree-level, but is non-zero in many new physics model addressing the anomalous forward-backward $t\bar{t}$ asymmetry
- Threshold dilepton asymmetry has similar properties
To Do List

- Effects of NLO corrections
- $t\bar{t}$ bound state corrections
- Dilution due to showering and detector effects
- Prospects at the LHC
どうもありがとうございました！