Spinning the Top

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based on work with Gilad Perez and Martin Schmaltz, **arXiv 1110.xxxx**

Top quark

Top quark is interesting because:

- 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 effects could randomize its polarization
- The anomalous $t\bar{t}$ forward-backward asymmetry is currently the **only** serious hint of new physics at the weak scale

Polarization and charged leptons

- 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:

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

  leading to $\sum_{s_f} |\mathcal{M}|^2 \sim (1 + \cos\theta)$ where θ is angle between lepton momentum and top spin in top rest frame
- Define charged lepton forward-backward asymmetry

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

- For completely top $A_{l+} = +50\%$ and for polarized antitops $A_{l-} = -50\%$

$$A_{FB}^{l} = \frac{N_l(q_l \cos\theta > 0) - N_l(q_l \cos\theta < 0)}{N_l(\cos\theta > 0) + N_l(\cos\theta < 0)}$$

New Idea...

- Huge literature on the subject, in particular on SM tests, sensitivity to new physics, spin correlations, stability wrt QCD corrections
- We're adding a simple observation; so intuitive that you'll probably say you have known that before
- But, as far as i know, never explicitly pointed out in a theory paper, and definitely no experimental results out there yet

Threshold Lepton Asymmetry

`IDEA:` *Look at the forward-backward lepton asymmetry at the $t\bar{t}$ 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 $A_l = +50\%$.
  - For events initiated by $q_L\bar{q}_L$, both t and $\bar{t}$ have spins anti-aligned with the quark beam, leading to $A_l = -50\%$.
- Therefore measuring A_{FB}^l 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

Threshold Lepton Asymmetry

- 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-quark jet in the other top) applies separately to top and anti-top decay products.
- New physics addressing anomalous top FB asymmetry requires new particles with **chiral** couplings to not only to top but **also to light quarks**

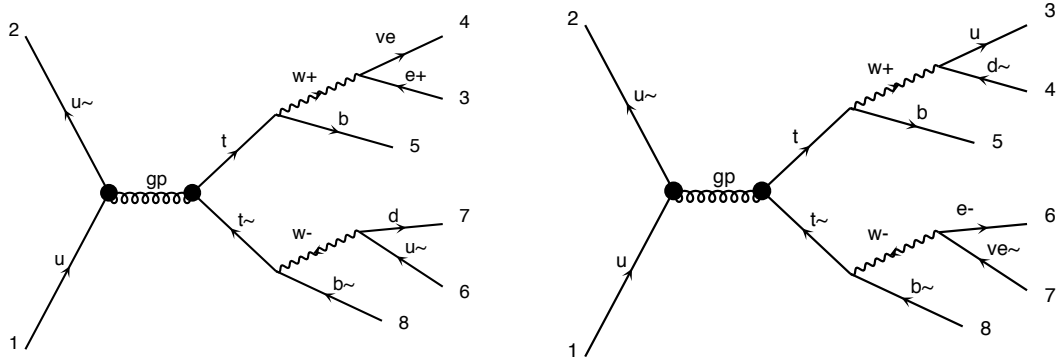
`Caveat`: Below, only TREE-LEVEL results. At the moment we don't know how this observable is affected by NLO QCD corrections (but in the inclusive case they do not change the picture dramatically Bernreuther,Si,Uwer [1003.3926])

Toy Model: χQCD

- Toy model to distil the effect : **Chiral QCD**
- Massless *chiral gluon* with general chiral couplings to quarks:

$$G^a_\mu \bar{q} \bar{\sigma}^\mu T^a (g_{q_R} P_R + g_{q_L} P_L) q + G^a_\mu \bar{t} \bar{\sigma}^\mu T^a (g_{t_R} P_R + g_{t_L} P_L) t$$

- Consider the process $q\bar{q} \to t\bar{t} \to l\nu jj$ 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

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

At the threshold only 2 spin-amplitudes non-zero

$$F(+,+|+,+) = -\frac{g_{q_R}(g_{t_L} + g_{t_R})}{2} \qquad F(-,-|-,-) = -\frac{g_{q_L}(g_{t_L} + g_{t_R})}{2}$$

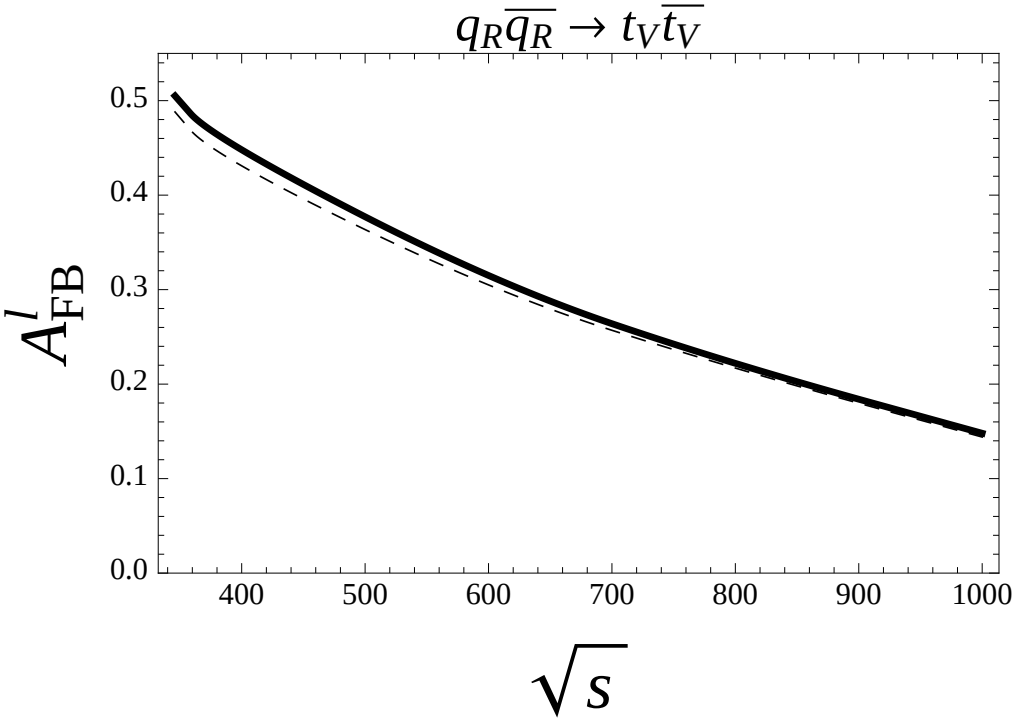
- Only **(++)** top spin state is possible if chiral gluon couples only to *right-handed* light quarks
- Only **(- -)** top spin state is possible if chiral gluon couples only to *left-handed* light quarks

Consider the **lepton asymmetry**

$$A_{FB}^{l} = \frac{N_l(q_l \cos\theta > 0) - N_l(q_l \cos\theta < 0)}{N_l(\cos\theta > 0) + N_l(\cos\theta < 0)}$$

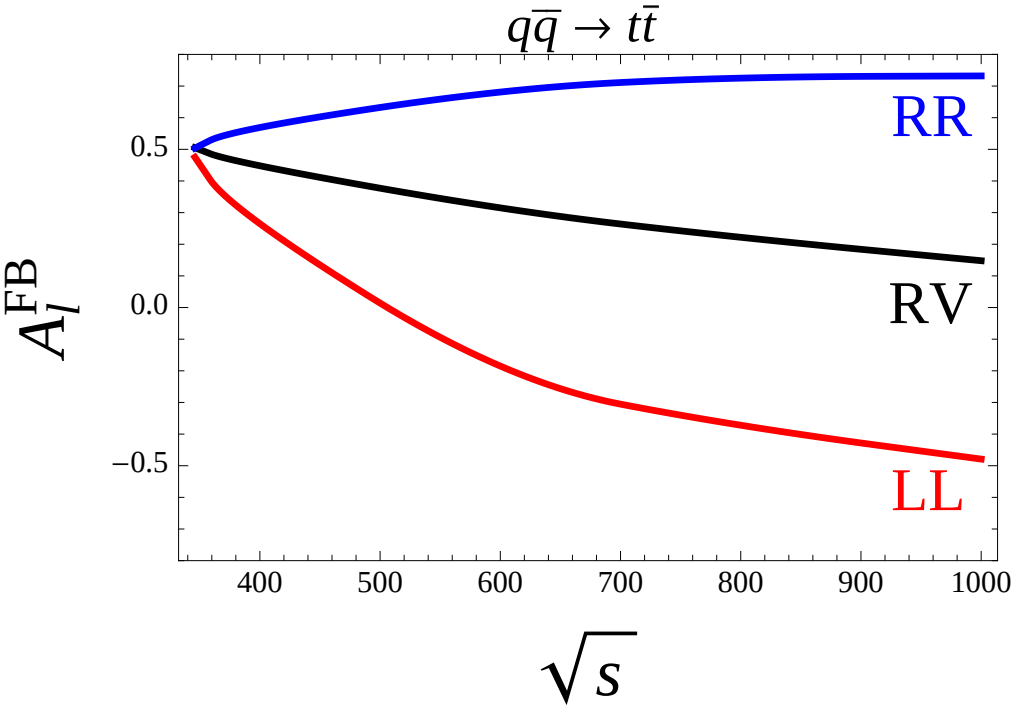
as a function of $t\bar{t}$ invariant mass $m_{tt} = \sqrt{s}$

Toy model: RV case



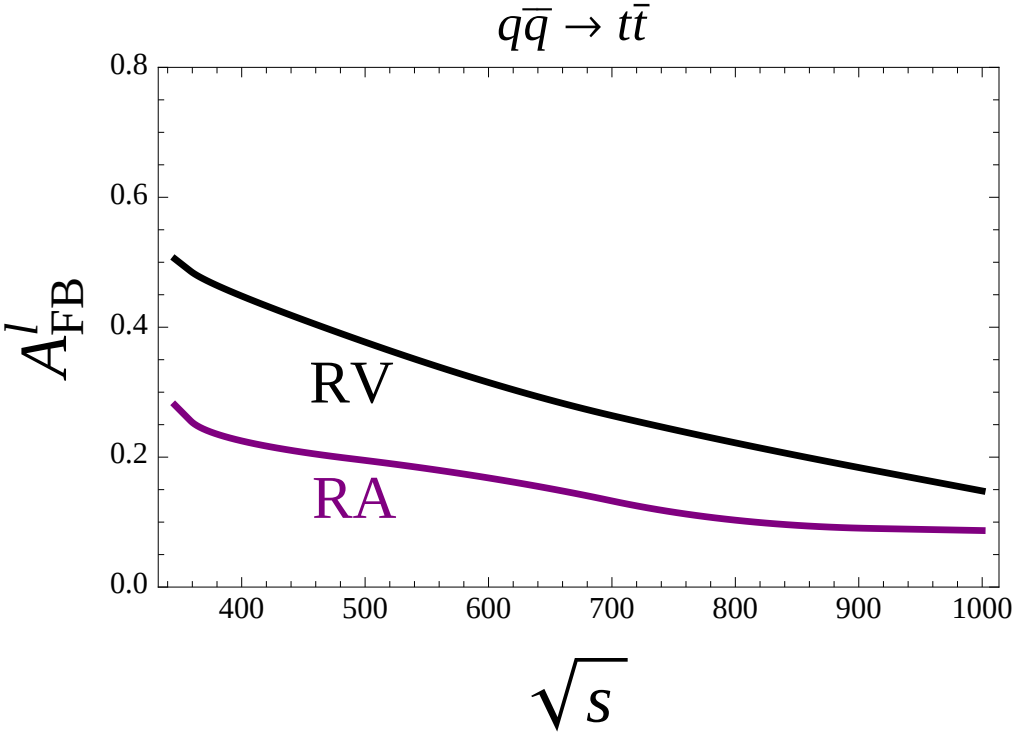
- Assume gluon coupling only to right-handed up quarks: $G^a_\mu \bar{u}\bar{\sigma}^\mu T^a P_R u$
- Assume vector coupling of the gluon to the top: $G^a_\mu \bar{t}\bar{\sigma}^\mu T^a t$
- Tops produced only by $q_R\bar{q}_R$, thus at threshold, $A^l_{FB} = 50\%$.
- Small effect of cutting on lepton rapidity $|\eta| < 2$ negligible (dashed line)
- At higher $\sqrt{s}$ tops not at rest $\to$ have angular momentum $\to$ spin of the tops no more along the beam $\to$ lepton asymmetry different than 50%
- At very high $\sqrt{s}$ lepton asymmetry approaches the $t\bar{t}$ asymmetry
- Note A^l_{FB} is independent of A^{FB}_{tt}; the latter is **zero** in this case for any $\sqrt{s}$

Independence of top coupling



- Varied gluon coupling to the top: $G_\mu^a \bar{t} \bar{\sigma}^\mu T^a P_X t$
- 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
- Inclusive asymmetry for left-handed top couplings only 9%. One can easily miss the effect by looking inclusively!

Caveat: axial coupling

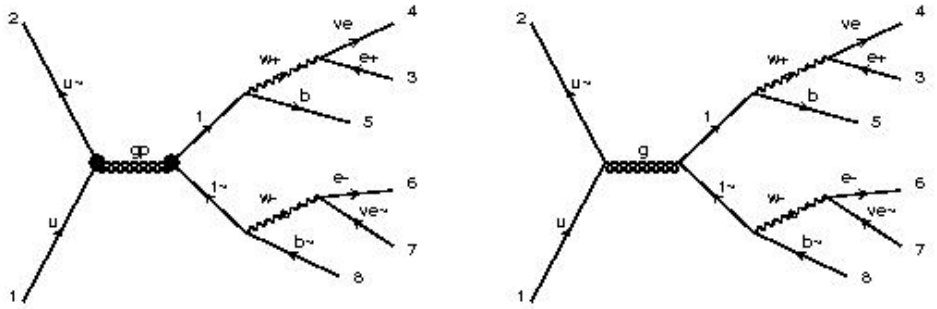


- Axial gluon coupling to the top: $G^a_\mu \bar{t} \bar{\sigma}^\mu T^a \gamma_5 t$
- At the threshold, lepton asymmetry different than in the vector case, contrary to the theoretical arguments
- That's because for axial couplings to the top, the $t\bar{t}$production amplitude completely vanishes at the threshold Then amplitude dominated by higher order terms in β_{top} and the $++$ spin state is less dominant

Back to reality

- Currently most exciting examples are those producing a large $t\bar{t}$ forward-backward asymmetry without screwing up the top quark cross section and its other measured properties
- Many models on the market:
  - Heavy axigluon (> 1 TeV) with flavor non-universal large chiral couplings to light and top quarks in s-channel
  - Light axigluon (< 450 GeV) 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
  - ...
- Model specific prediction for inclusive lepton asymmetry which provides a handle to distinguish between different competing models
  Krohn,Liu,Shelton,Wang [1105.3743]

Light Axigluon Model



QCD + $G'^{a}_{\mu}[\bar{q}\bar{\sigma}^{\mu}T^{a}(g_{q_R}P_R + g_{q_L}P_L)q + \bar{t}\bar{\sigma}^{\mu}T^{a}(g_{t_R}P_R + g_{t_L}P_L)t]$
3 benchmarks with $m_{G'} = 300$ GeV, $\Gamma_{G'} = 100$ GeV predicting $\Delta A_{t\bar{t}}^{FB} \approx 15\%$ 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

Benchmark	$A_{FB}^{l}(\sqrt{s} < 375\,\mathrm{GeV})$	$A_{FB}^{l}(\sqrt{s} < 450\,\mathrm{GeV})$	A_{FB}^{l} inclusive
AxR	19 %	19 %	19 %
AxL	-15 %	-12 %	-8 %
AxA	2 %	4 %	7 %
$t\bar{t}$ fraction	20 %	60 %	100 %

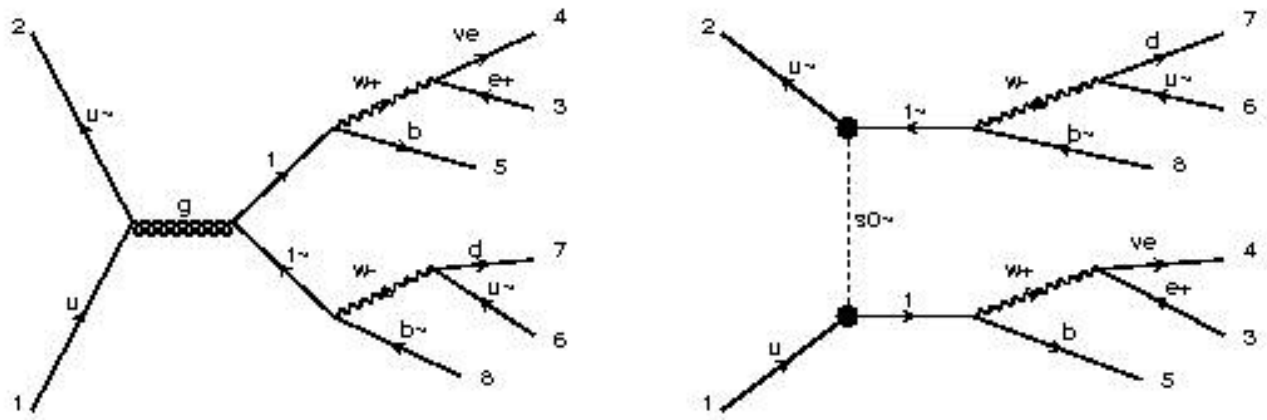
- Inclusive lepton asymmetry provides discriminating power between benchmarks, as noticed by Krohn et al.
- But stronger discrimination by looking at A_{FB}^{l} near the threshold

Light Scalar Doublet

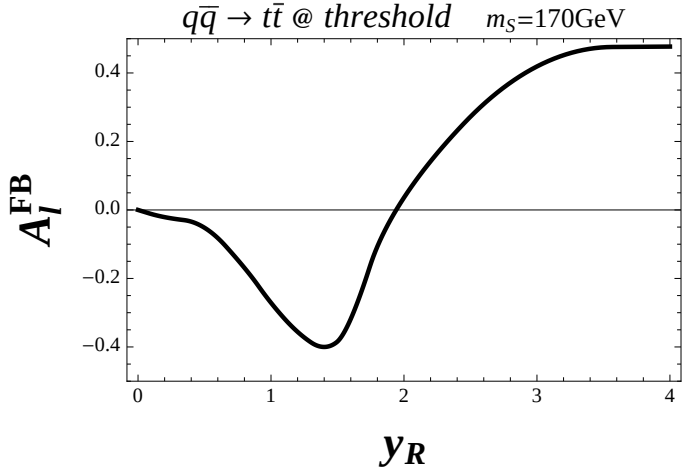
- Saavedra,Perez-Victoria [1107.0841] : another possible model, weak doublet color singlet $S = (S_+, S_0)$ coupled as

$$y_R u^c Q_3 S + \text{h.c.} \qquad Q_3 = (t, b)$$

- t-channel scalar exchange contributes to $t\bar{t}$ production,
- Positive contributions to forward-backward top asymmetry, and constraints OK for $m_S \sim m_{top}$ and $y_R \sim 1$
- New twist here because of destructive interference with QCD



Light Scalar Doublet



- 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 swamps QCD and one gets positive threshold lepton asymmetry

Benchmark $m_S = 170$ GeV and $y_R = 1.5$ leading to $\Delta A_{FB}^{tt} \approx 5\%$. Threshold lepton asymmetry at Tevatron

Benchmark	$A_{FB}^l(\sqrt{s} < 375\,\mathrm{GeV})$	$A_{FB}^l(\sqrt{s} < 450\,\mathrm{GeV})$	A_{FB}^l inclusive
SdR	- 7%	- 6 %	-3 %
$t\bar{t}$ fraction	20 %	60 %	100 %

Take Away Points

- We propose to measure the lepton asymmetry A_{FB}^{l} in $t\bar{t}$ events at the production threshold
- Simple and clean observable, with a simple and intuitive theoretical interpretation
- 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
- Of course, even more information if statistics and systematics allow us to measure the full dA_{FB}^{l}/dm_{tt} distribution