Spinning the Top

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based on work with Gilad Perez and Martin Schmaltz, **arXiv 1110.3796**

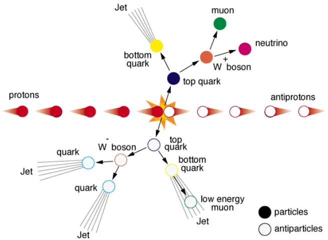
Outline

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

Buy one or a quark 6-pack at http://particlezoo.net/

Measuring top quark



A Top Antitop Quark Event from the D-Zero Detector at Fermilab

- 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

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:

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

  where $x(k_t, \mathbf{s_t})$ is a bi-spinor solving the equation of motion
- In *top rest frame* one can choose $x(k_t, \mathbf{s_t})$ to be eigenstate of spin operator $\vec{S} \cdot \vec{\sigma}$, so $k_l \cdot \bar{\sigma}\, x(k_t, \mathbf{s_t}) = E_l(1 + \cos\theta) x(k_t, \mathbf{s_t})$, leading to $\Gamma \sim (1 + \cos\theta)$ where θ is angle between lepton momentum and top spin
- For anti-top $\Gamma \sim (1 - \cos\theta)$

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

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

  For a completely polarized top
  $A_{\rm FB}^{\ell+} = [\int_0^1 (1+\cos\theta) - \int_{-1}^0 (1+\cos\theta)]/[\int_{-1}^1 (1+\cos\theta)] = +50\%$

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

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

  Useful to ameliorate statistics when $A_{\rm FB}^{\ell+} = -A_{\rm FB}^{\ell-}$, e.g. when both tops have spins along the same direction

Dilepton Asymmetries

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

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

- When both top and anti-top polarized along the same direction, then $\Gamma \sim (1 + \cos\theta_{\ell_+})(1 - \cos\theta_{\ell_-})$, thus integrating one gets $A_{\rm FB}^{\ell\ell} = 66.6\%$
- Dilepton asymmetry is invariant under longitudinal boosts (because rapidity difference is)

Spin Correlations

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)

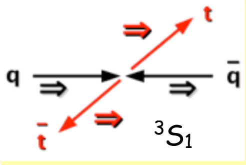
Our idea...

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

Threshold Lepton Asymmetry

`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 $A^{\ell}_{\mathrm{FB}} = +50\%$.
  - For events initiated by $q_L\bar{q}_L$, both t and $\bar{t}$ have spins anti-aligned with the quark beam, leading to $A^{\ell}_{\mathrm{FB}} = -50\%$.
- Therefore measuring A^{ℓ}_{FB} 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/s quark jet) applies separately to top and anti-top decay products
- Same spin argument applies to threshold *dilepton* asymmetry, in this case $A_{\mathrm{FB}}^{\ell\ell} = +66.6\%$ for pure $q_R\bar{q}_R$ production, and $A_{\mathrm{FB}}^{\ell\ell} = -66.6\%$ 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])

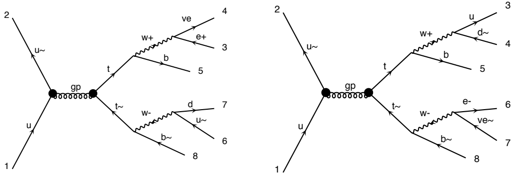
Lepton asymmetry in a toy model

Toy Model: χQCD

- Toy model to distill 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

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

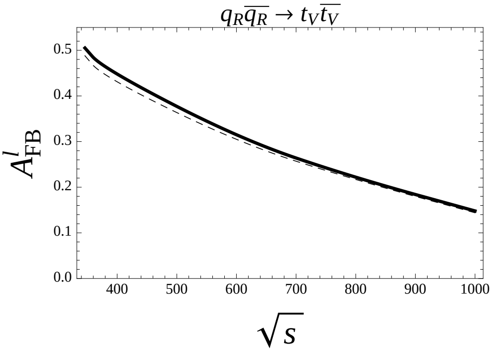
- Only **(++)** top spin state is possible if chiral gluon couples only to *right-handed* light quarks
- Only **(- -)** top spin state is possible if chiral gluon couples only to *left-handed* light quarks
- For *scalar* gluons only $(+-)$ and $(-+)$ initial and final states would not vanish at threshold

Consider the **lepton asymmetry**

$$A^{\ell}_{\mathrm{FB}} = \frac{N_l(q_l \cos\theta > 0) - N_l(q_l \cos\theta < 0)}{N_l(\cos\theta > 0) + N_l(\cos\theta < 0)}$$

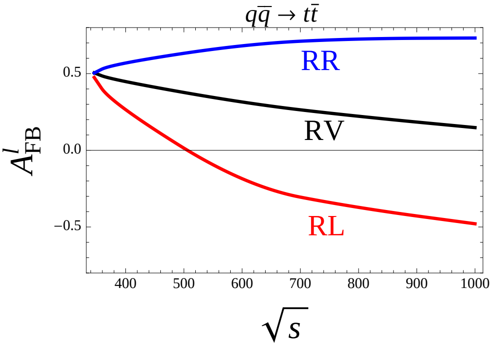
as a function of $t\bar{t}$ invariant mass $m_{tt} = \sqrt{s}$

Toy model: RV case



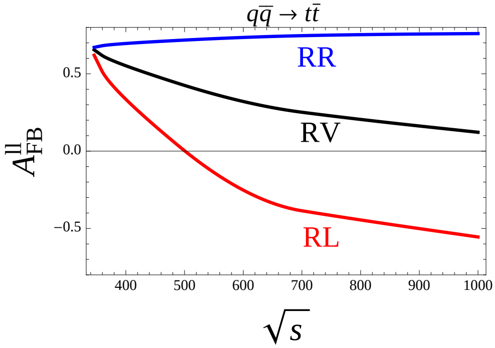
- Assume gluon coupling only to right-handed up quarks: $G^a_\mu \bar{u}\bar{\sigma}^\mu T^a P_R u$
- Assume vector coupling of the gluon to the top: $G^a_\mu \bar{t}\bar{\sigma}^\mu T^a t$
- Tops produced only by $q_R\bar{q}_R$, thus at threshold, $A^\ell_{\rm FB} = 50\%$.
- Small effect of cutting 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 $A^\ell_{\rm FB}$ is independent from $A^{t\bar{t}}_{\rm FB}$; latter is **zero** in this case for any $\sqrt{s}$

Independence of top coupling



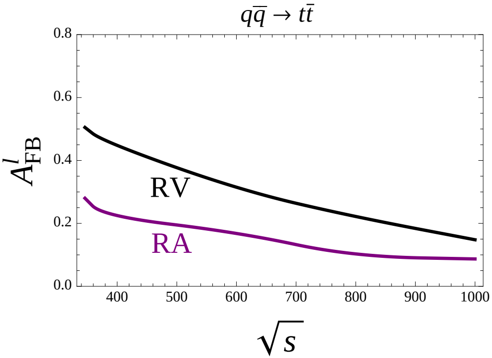
- Varied gluon coupling to the top: $G^a_\mu \bar{t}\bar{\sigma}^\mu T^a P_X t$
- At the threshold, lepton asymmetry independent of the coupling to the top, in agreement with theoretical arguments
- At higher m_{tt}, lepton asymmetry inherits from the $t\bar{t}$ asymmetry
- Convoluting with Tevatron PDFs, inclusive asymmetry for RL case $\sim 10\%$. One can easily miss the effect by looking inclusively!

Compare to dilepton asymmetry



- Dilepton asymmetry displays similar m_{tt} dependence
- Threshold value $+66\%$ independently of chiral gluon coupling to tops

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 v_{top} and the $(++)$ spin state is less dominant

Lepton asymmetry vs $t\bar{t}$ asymmetry

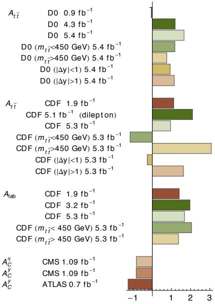
Back to reality

- 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

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

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



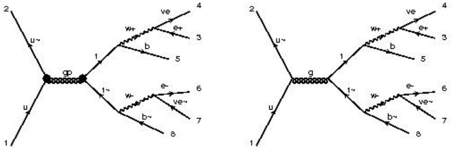
Models for A_{FB}^{tt}

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

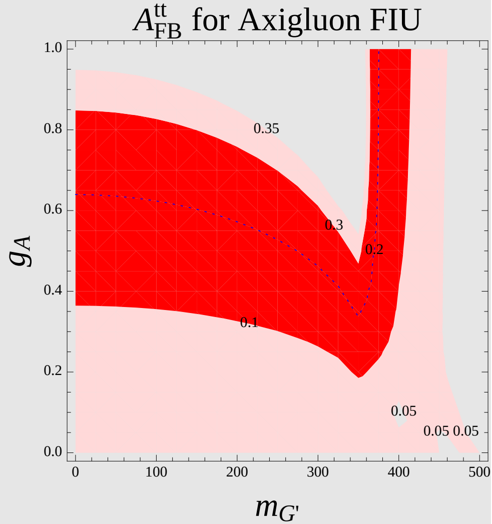
Choose light axigluon because it jives well with lepton asymmetry...



$$\text{QCD} + G'^{\,a}_{\mu}[\bar{q}\bar{\sigma}^{\mu} T^a (g_R P_R + g_L P_L) q + \bar{t}\bar{\sigma}^{\mu} T^a (g_R P_R + g_L P_L) t]$$

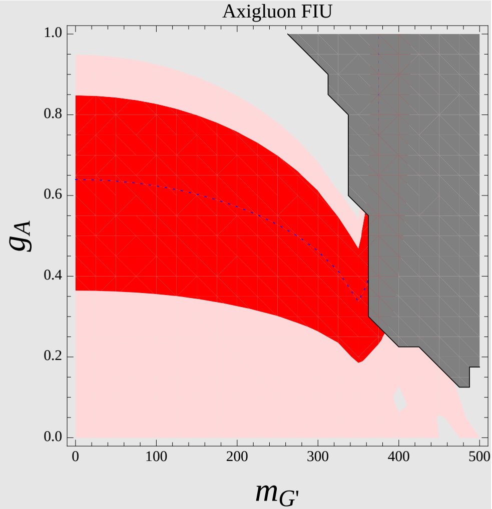
- No problems with constraints from the tail of $d\sigma/dm_{tt}$ distribution
- Constraints from total σ_{tt} manageable
- Constraints from dijet resonances bypassed if G' is wide, Schmaltz,Tavares [1107.0978]
- Model specific prediction for inclusive lepton asymmetry which provides a handle to distinguish between different competing models Krohn,Liu,Shelton,Wang [1105.3743]

Light Axigluon: Parameter Space



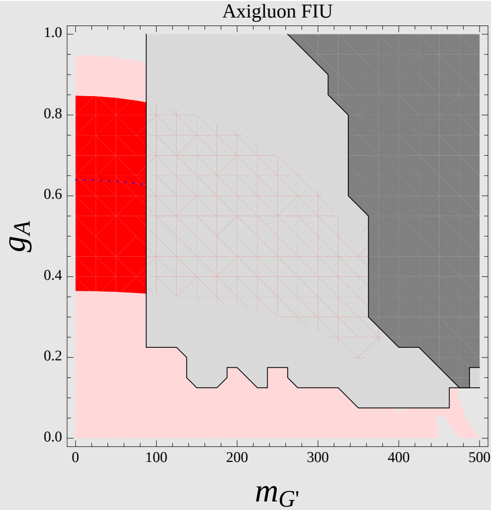
- Assume purely axial couplings
- Correct $t\bar{t}$ asymmetry for $g_A \sim 0.5 g_{\mathrm{strong}}$

Light Axigluon: Parameter Space



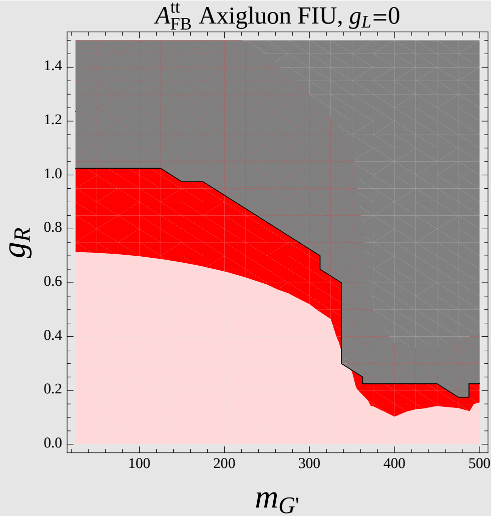
- For axial couplings, no corrections to total σ_{tt} from interference, thus weak constraints

Light Axigluon: Parameter Space



- UA2 and Tevatron searches for dijet resonances exclude a narrow axigluon in the interesting parameter range
- Although some argue that a very light axigluon, $m_{G'} \sim 50 - 80\,\mathrm{GeV}$ is allowed Krnjaic [1109.0648]

Right Color Octet Vector: Parameter Space



- Stronger constraints from $\sigma_{t\bar{t}}$ for purely right-handed or left-handed couplings

Light Axigluon Model: Lepton asymmetry

3 benchmarks with $m_{G'} = 200$ GeV, $\Gamma_{G'} = 50$ GeV predicting $\Delta A^{FB}_{t\bar{t}} \approx 11\%$ in agreement with D0/CDF and without violating all other constraints

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

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

Benchmark	$A^{\ell}_{\rm FB}(\sqrt{s} < 375\,{\rm GeV})$	$A^{\ell}_{\rm FB}(\sqrt{s} < 450\,{\rm GeV})$	$A^{\ell}_{\rm FB}$ inclusive
AxR	18%	17%	17%
AxL	–13%	-8%	–7%
AxA	2%	3%	6%
$t\bar{t}$ fraction	17%	60%	100%

- Inclusive lepton asymmetry provides discriminating power between benchmarks, as noticed by Krohn et al.
- But stronger discrimination by looking at $A^{\ell}_{\rm FB}$ near the threshold

Light Axigluon Model: Dilepton Asymmetry

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

Threshold dilepton asymmetry at Tevatron

Benchmark	$A_{\rm FB}^{\ell\ell}(\sqrt{s} < 375\,{\rm GeV})$	$A_{\rm FB}^{\ell\ell}(\sqrt{s} < 450\,{\rm GeV})$	$A_{\rm FB}^{\ell\ell}$(inclusive)
AxR	21%	21%	21%
AxL	-18%	-13%	-9%
AxA	2%	5%	7%
$t\bar{t}$ fraction	17%	60%	100%

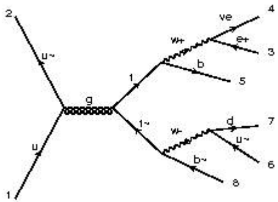
- Inclusive lepton asymmetry provides discriminating power between benchmarks, as noticed by Krohn et al.
- But stronger discrimination by looking at $A_{\rm FB}^{\ell\ell}$ near the threshold

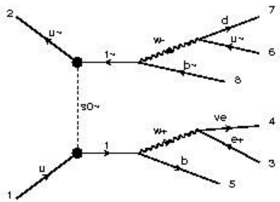
Light Scalar Doublet

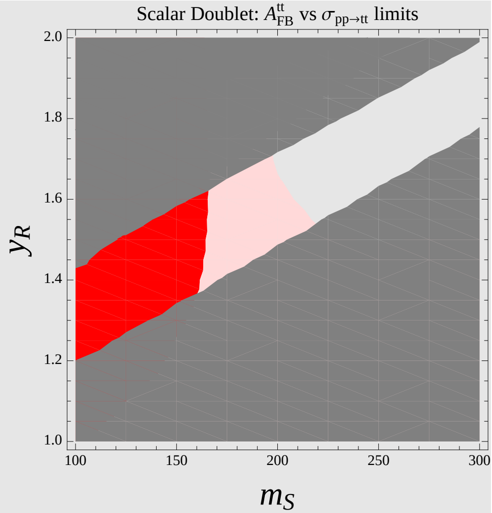
- Saavedra,Perez-Victoria [1107.0841] : another possible model, weak doublet color singlet $S = (S_+, S_0)$ coupled as

$$y_R u^c Q_3 S + y_L t^c Q_1 S + \mathrm{h.c.} \qquad Q_3 = (t, b),\ \ Q_1 = (u, d)$$

- 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 $m_S \sim m_{top}$ and $y_{R,L} \sim 1$
- New twist here because of destructive interference with QCD

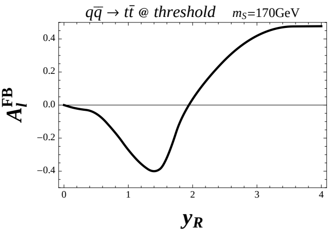






- Light, $m_S \lesssim 170$ GeV electroweak doublet scalar can produce enough $A_{\rm FB}^{t\bar{t}}$ without violating constraints from $t\bar{t}$ cross section at Tevatron
- On the other hand, we need $m_S > 160$ GeV to avoid too large branching fraction $t \to Su$, so window rather small

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 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

Benchmark	$A_{FB}(\sqrt{s} < 375\,\mathrm{GeV})$	$A_{FB}(\sqrt{s} < 450\,\mathrm{GeV})$	A_{FB} inclusive
SdR	-10/-13%	-7/-9%	-4/-4%
SdL	10/14 %	10/12%	11/13%
$t\bar{t}$ fraction	17 %	60 %	100 %

Data so far...

- The *threshold lepton* asymmetry not studied experimentally so far
- D0 measured inclusive lepton asymmetry in semileptonic $t\bar{t}$ events

$$A^{\ell}_{\mathrm{FB}} = (15.2 \pm 4.0)\%,$$

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

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

$$A^{\ell}_{\mathrm{FB}} = (21 \pm 7)\%,$$

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

- 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 $A^{t\bar{t}}_{\mathrm{FB}}$ 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^{ℓ}_{FB} 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！