Lepton versus Top Asymmetry

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Based on:

- an old work with Gilad Perez and Martin Schmaltz, **arXiv 1110.3796**,
- and one in progress with Adam Martin, Gilad Perez, Jan Winter.

Two important top asymmetry observables at Tevatron

- *Belle de Jour:* top (Δy) asymmetry

$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_t < y_{\bar{t}})}{N(y_t > y_{\bar{t}}) + N(y_t < y_{\bar{t}})}$$

- *Poor Cousin:* lepton asymmetry

$$A_\ell = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

Parton level results for lepton+jets channel

CDF with 8.7 fb^{-1}

- $A_{t\bar{t}} = 16.2 \pm 4.7\%$
- $A_\ell = 6.6 \pm 2.5\%$ (folded!)

D0 with 5.4 fb^{-1}

- $A_{t\bar{t}} = 19.6 \pm 6.5\%$
- $A_\ell = 15.2 \pm 4.0\%$

SM

- $A_{t\bar{t}} =$ 7-9%
- $A_\ell = 2\%$

- So far more spotlight on $A_{t\bar{t}}$,
- That's because naively one expects that the 2 are correlated: by kinematics, the lepton follows the parent top direction.
- That is true, `unless polarization enters the game`

Polarization and charged leptons

- Charged lepton from top decay is perfect analyzer of top spin
- More precisely, amplitude square for $t \to l^+ \nu b$ 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

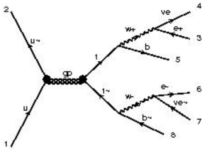
$$\frac{d\Gamma_{l^+}}{d\cos\theta} \sim (1 + \cos\theta)$$

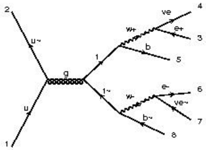
  where θ is angle between lepton momentum and top spin
- For anti-top

$$\frac{d\Gamma_{l^-}}{d\cos\theta} \sim (1 - \cos\theta)$$

Light Color Octet

Illustrative model: `light axigluon` (similar story in other BSM models)



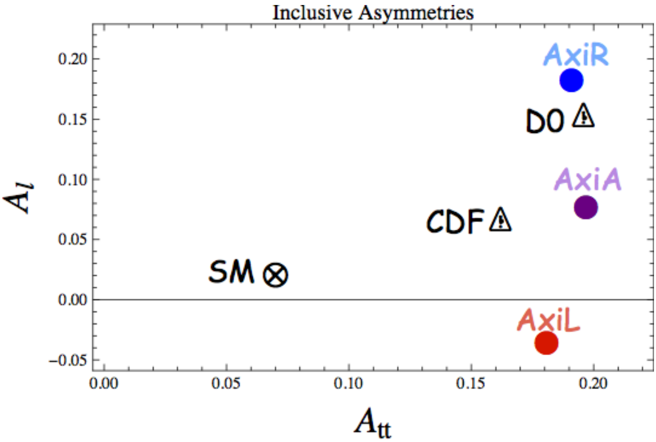


QCD $+ \, G'^{a}_{\mu}[\bar{q}\bar{\sigma}^{\mu}T^{a}(g_{q,R}P_R + g_{q,L}P_L)q + \bar{t}\bar{\sigma}^{\mu}T^{a}(g_{t,R}P_R + g_{t,L}P_L)t]$

- 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,

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

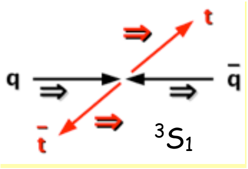
- AxiR: $g_{q,R} = g_{t,R} = 0.8 g_s$, $g_{q,L} = g_{t,L} = 0$
- AxiL: $g_{q,R} = g_{t,R} = 0$, $g_{q,L} = g_{t,L} = 0.8 g_s$
- AxiA: $g_{q,R} = g_{t,R} = 0.4 g_s$, $g_{q,L} = g_{t,L} = -0.4 g_s$



- $A_{t\bar{t}}$ and A_ℓ are in fact independent observables!
- They can even have different signs!

- $A_{t\bar{t}}$ and A_ℓ are independent observables when there is net polarization of top quarks
- A_ℓ can discriminate between BSM models predicting same $A_{t\bar{t}}$ Krohn,Liu,Shelton,Wang [1105.3743]
- We can understand these examples as manifestation of *threshold lepton asymmetry* AA,Perez,Schmaltz [1110.3796]

Threshold Lepton Asymmetry



- *At threshold*, tops have zero momentum → 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 $A_\ell = +50\%$.
  - For events initiated by $q_L\bar{q}_L$, both t and $\bar{t}$ have spins anti-aligned with the quark beam, leading to $A_\ell = -50\%$.
- Therefore measuring A_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

Light Axigluon Model: Lepton asymmetry

Threshold lepton asymmetry at Tevatron (LAB frame)

Benchmark	$A_\ell(\sqrt{s} < 375\,\mathrm{GeV})$	$A_\ell(\sqrt{s} < 450\,\mathrm{GeV})$	A_ℓ inclusive
AxR	14%	14%	14%
AxL	–10%	–8%	–6%
AxA	2%	3%	6%
$t\bar{t}$ fraction	17%	60%	100%

- In this case, stronger discrimination by measuring $A_{\ell\ell}$ near threshold
- Theoretically, even stronger discrimination provided by lepton asymmetry in $t\bar{t}$ rest frame

Light Axigluon Model: Dilepton Asymmetry

$$A_{\ell\ell} = \frac{N(y_{\ell_+} > y_{\ell_-}) - N(y_{\ell_+} < y_{\ell_-})}{N(y_{\ell_+} > y_{\ell_-}) + N(y_{\ell_+} < y_{\ell_-})},$$

- When both top and anti-top polarized along the same direction, then $\Gamma \sim (1 + \cos\theta_{\ell_+})(1 - \cos\theta_{\ell_-})$
- Dilepton asymmetry is invariant under longitudinal boosts (because rapidity difference is)

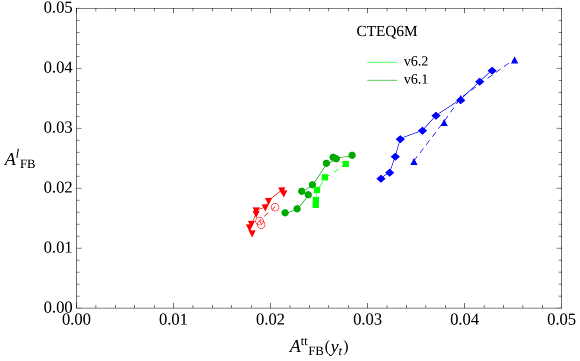
Threshold dilepton asymmetry at Tevatron

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

- In this case, stronger discrimination by measuring $A_{\ell\ell}$ near threshold

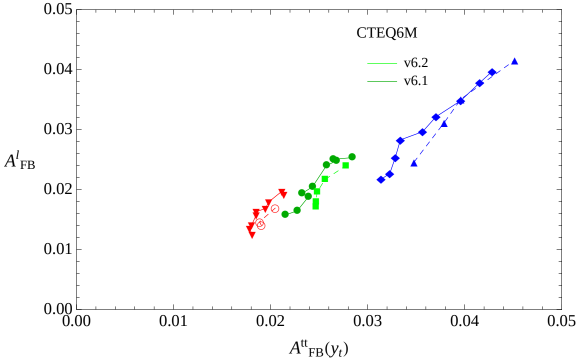
New results on p_T(lepton) dependence of top-related asymmetries
AA,Martin,Perez,Winter [1205.xxxx]

$p_T(l)$ dependence in SM

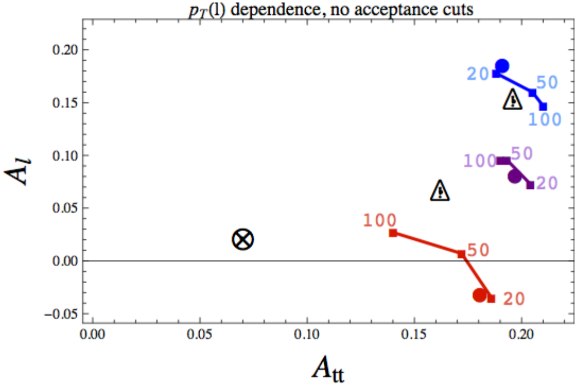


- Study effect of varying lepton p_T cut between 20 and 100 GeV
- Using latest MCFM v6.2 to derive SM predictions Campbell,Ellis [1204.1513]
- CDF-like kinematic cuts on rest of event: $|\eta|_l < 1.1$, $p_T(j) > 20$ GeV, $|\eta(j)| < 2$, $\eta(b) < 1$, $p_T^{\mathrm{miss}} > 20$ GeV, ...
- Small upward shift of $A_{t\bar{t}}$ compared to v6.1
- Studied effect of varying $\mu_{fac} = \mu_{ren}$ between $0.5m_t$ and $2m_t$

$p_T(l)$ dependence in SM

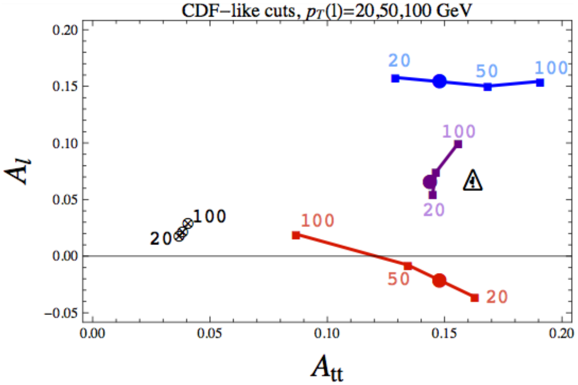


- Study effect of varying lepton p_T cut between 20 and 100 GeV
- In SM, $p_T(l)$ obviously correlated with $m_{t\bar{t}}$.
- A linear growth of both $A_{t\bar{t}}$ and A_ℓ as function of $p_T(l)$

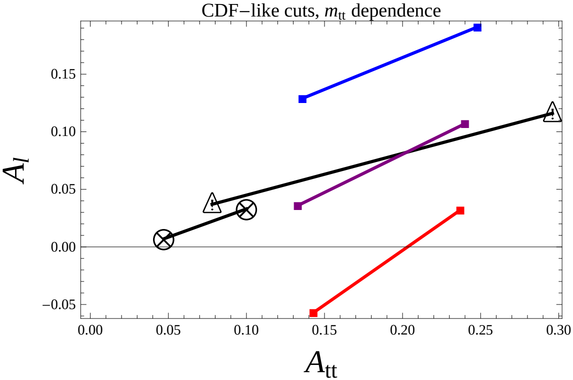


- In BSM models, due to interplay of kinematics and polarization effect, non-trivial dependence of asymmetries on $p_T(l)$
- Slope on the $A_{t\bar{t}}$-A_ℓ plane can be completely different than in the SM!

$p_T(l)$ dependence in BSM

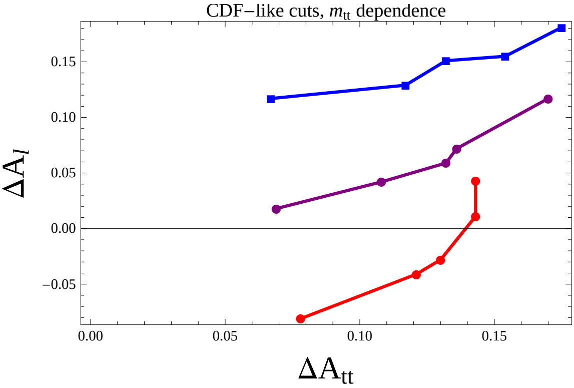


- In BSM models, due to polarization effect, non-trivial dependence of observables on $p_T(l)$
- Slope on the $A_{t\bar{t}}$-A_ℓ may depend on acceptance effects



- $p_T(l)$ dependence more striking than $m_{t\bar{t}}$ dependence

$m_{t\bar{t}}$ dependence in BSM



- $p_T(l)$ dependence more striking than $m_{t\bar{t}}$ dependence

Take Away Points

- ⋆ $A_{t\bar{t}}$ and A_ℓ are independent observables, both are important to test the SM and discriminate between BSM models
- ⋆ A_ℓ at threshold is a direct measure of the polarization of the *light quarks* that produce the tops
- ⋆ $p_T(l)$ trajectory in the $A_{t\bar{t}}$-A_ℓ is another test of the SM and may give us indications of new physics