Boosted Top quark polarization.

Aravind H. Vijay

EPS-HEP, 12th July, 2019

Department of High Energy Physics, TIFR

[1902.08096]

Rohini Godbole, Monoranjan Guchait,
Charanjit K. Khosa, Jayita Lahiri,
Seema Sharma, Aravind H. Vijay

Motivation

Studying top quark polarization:

- Helps to determine nature of couplings in BSM models.
- Probe anomalous *Wtb* coupling:

$$\Gamma^\mu = \frac{-ig}{\sqrt{2}}\left[\gamma^\mu\left\{(1+f_{1L})\,\mathbf{P}_L + f_{1R}\mathbf{P}_R\right\}\right] - \frac{g\sigma^{\mu\nu}}{\sqrt{2}m_W}\left[(p_t-p_b)_\nu\left(f_{2L}\mathbf{P}_L + f_{2R}\mathbf{P}_R\right)\right]$$

(some recent progress in this [1809.06285 (Peskin M., et. al.)]).

- Lepton from top decay is already established as a very good spin analyzer.
- Top from massive BSM particles are boosted ⇒ **leptons not well isolated**.
- Additional sources of p_T^{miss} can also **prevent** complete top reconstruction
- Boosted hadronic tops are well reconstructed
- Hadronic branching fraction larger than leptonic.

Hence, polarization measurement of boosted hadronically decaying top is an interesting problem.

SM top quark decay kinematics

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1+\mathcal{P}_0\kappa_f\cos\theta_f\right)$$

$\theta_f \Rightarrow$ Angle between top spin and decay product momentum.

$\mathcal{P}_0 \Rightarrow$ Polarization of the produced top.

$\kappa_f \Rightarrow$ Spin analyzing power.

$$\kappa_b \approx -0.4 = -\kappa_{W^\pm}$$

$$\kappa_{\bar{d}} = 1$$

[hep-ph/0205023 (Brandenburg A. et. al.)]

$$\kappa_u \approx -0.3$$

- $\bar{d}$ (or ℓ) has largest spin analyzing power.
- NLO QCD correction to spin analyzing power extremely small.
- Tends to form smaller invariant mass with b.

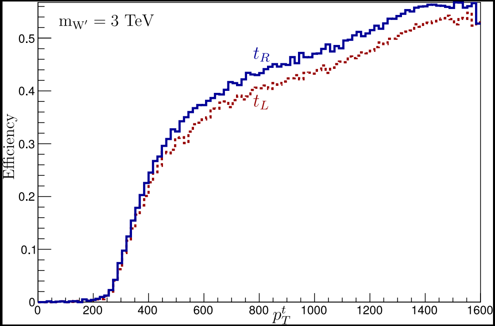
(throughout this study, spin of top quantized parallel or anti-parallel to top momentum in lab frame, t decay kinematics according to SM).

Benchmark process $W' \to tb$

- Studied effective W' model.

$$\mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} \bar{f}_i \gamma^\mu \left(g_R (1+\gamma_5) + g_L (1-\gamma_5) \right) W'_\mu f_j + h.c.$$

- Difference in kinematics of final state particles leads to tiny difference in top tagging efficiency

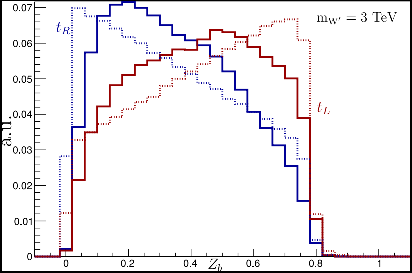


- Tagged top using `HEPTopTagger` `[1503.05921 (Plehn T. et. al.)]` but similar observations by ATLAS [1801.07893] using shower deconstruction `[1211.3140 (Soper, D. et. al.)]`.

Matrix elements for hard event (including t and W decay) generated using `MadGraph5` (not factorizing production & decay) and showered using `Pythia8`.

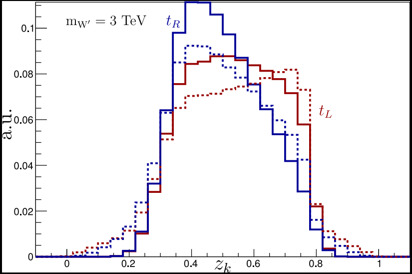
Polarization sensitive (energy fraction based) observables

- b-quark energy fraction (in the lab frame), E_b/E_t



- Spin analyzing power of b $-$ve $\Rightarrow$ b momentum opposite to top spin direction.
- $\Rightarrow$ Soft for right handed, hard for left handed.

- Closest subjet energy fraction (z_k) [0909.3855 (Krohn D. et. al.)]

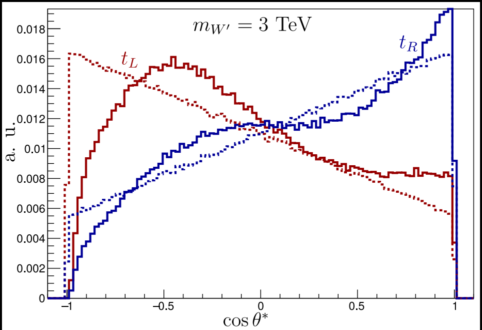


$$z_k = \frac{\max(E_i, E_j)}{E_t}$$

where d_{ij} (k_T distance) is minimum.

Angle based observable $\cos\theta^*$

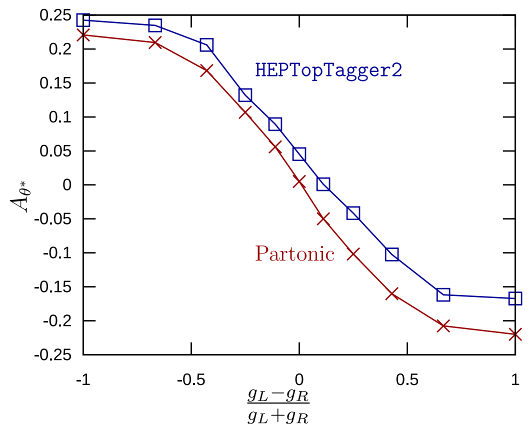
- Label 3 subjets as b, j_1, j_2 such that $m_{bj_1} < m_{bj_2}$.
- $\Lambda^{\mu}{}_{\nu} \Rightarrow$ Lorentz boost to top rest frame.
- $\vec{T} \equiv$ Top momentum in lab frame.
- $p^{\mu}_{j_1} \to p'^{\mu}_{j_1} \equiv \lambda^{\mu}{}_{\nu} p^{\nu}_{j_1}$
- $\cos\theta^* \equiv \frac{\vec{T}\cdot\vec{p}_{j_1}{}'}{\left|\vec{T}\right|\left|\vec{p}_{j_1}{}'\right|}$



- Dashed $\Rightarrow$ at matrix element level (not showered).
- Solid $\Rightarrow$ After jet cluster and top tagging.
- $b-$jets identified by W mass reconstruction criterion. Subjet $b-$tagging also viable.

Event Asymmetry

$$A_{\theta^*} \equiv \frac{N_{\cos(\theta^*)>0} - N_{\cos(\theta^*)<0}}{N_{\cos(\theta^*)>0} + N_{\cos(\theta^*)<0}}$$



Event asymmetry for W'

- Helps in determining model coupling parameters.
- Useful for benchmarking polarization sensitive observables.
- $A_{\theta^*} < 0$ for left handed t. $A_{\theta^*} > 0$ for right handed t.

Apllication to MSSM $\tilde{t}\,(\textbf{stop}) \to t\chi_1^0$ - I

- t_L and t_R of SM supersymmetrized into $\tilde{t}_L$ and $\tilde{t}_R$ (flavor eigen states)
  - Mix to give light mass eigen state: $\tilde{t}_1 = \cos(\theta_{\tilde{t}})\,\tilde{t}_L + \sin(\theta_{\tilde{t}})\,\tilde{t}_R$.

$$\text{Coupling} \quad \Rightarrow \quad \bar{\tilde{\chi}}_1^0 (g^{\tilde{t}_{1L}} P_L + g^{\tilde{t}_{1R}} P_R) t \tilde{t}_1 + h.c,$$

$$g^{\tilde{t}_{1L}} = -\sqrt{2} g_2 \left[\frac{1}{2} Z_{12}^* + \frac{1}{6} \tan(\theta_W) Z_{11}^*\right] \cos\theta_{\tilde{t}} - \left[\frac{g_2 m_t Z_{14}^*}{\sqrt{2} m_W \sin(\beta)}\right] \sin\theta_{\tilde{t}}$$

$$g^{\tilde{t}_{1R}} = \left[\frac{2\sqrt{2}}{3} g_2 \tan(\theta_W) Z_{11}\right] \sin\theta_{\tilde{t}} - \frac{g_2 m_t Z_{14}}{\sqrt{2} m_W \sin(\beta)} \cos\theta_{\tilde{t}}.$$

- Supersymmetric (fermionic) neutral components of B, W, H_u and H_d mix: $\chi_1^0 = Z_{11} B + Z_{12} W_3 + Z_{13} H_d + Z_{14} H_u$.
- Gaugino component of χ_1^0 preserves chirality (gauge interactions) of stop decay, Higgs components flip it (Yukawa interactions).

Apllication to MSSM $\tilde{t}$ (stop) $\rightarrow t\chi_1^0$ - II

- Polarization of t determined by composition of $\tilde{t}$ and χ_1^0

χ_1^0	$\tilde{t}_1$	t chirality
Bino like or Wino Like	$\tilde{t}_L$	t_L
	$\tilde{t}_R$	t_R
Higgsino like	$\tilde{t}_L$	t_R
	$\tilde{t}_R$	t_L

$$\mathcal{P}_0 = \frac{\left(\left|g^{\tilde{t}_{1L}}\right|^2 - \left|g^{\tilde{t}_{1R}}\right|^2\right)\mathcal{K}^{1/2}\left(1, \frac{m_t^2}{m_{\tilde{t}_1}^2}, \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{t}_1}^2}\right)}{\left(\left|g^{\tilde{t}_{1L}}\right|^2 + \left|g^{\tilde{t}_{1R}}\right|^2\right)\left(1 - \frac{m_t^2}{m_{\tilde{t}_1}^2} - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{t}_1}^2}\right) - 4\frac{m_t m_{\tilde{\chi}_1^0}}{m_{\tilde{t}_1}^2}\mathrm{Re}\left(g^{\tilde{t}_{1L}} g^{\tilde{t}_{1R*}}\right)}$$

$$\mathcal{K}(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$$

- **Events studied:**

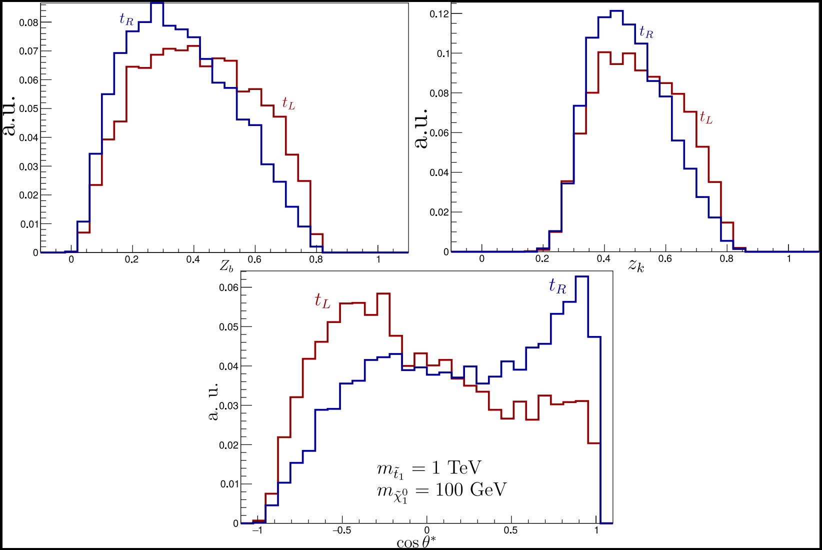
$$pp \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1 \rightarrow t\bar{t}\chi_1^0\chi_1^0 \rightarrow (bjj)(b\ell\nu_\ell)\chi_1^0\chi_1^0$$

with

$$m_{\chi_1^0} = 100 \text{ GeV} \quad ; \quad m_{\tilde{t}_1} = 1 \text{ TeV} \quad ; \quad \tan\beta = 10$$

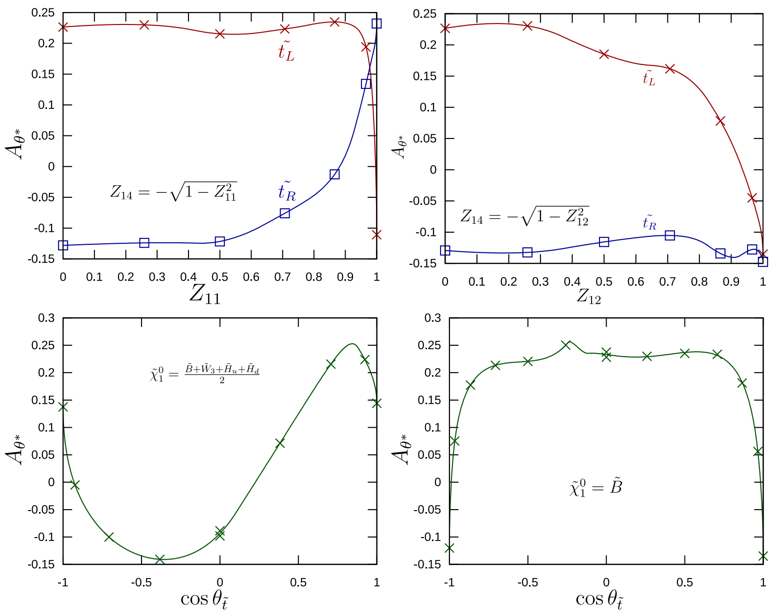
- **Selection:** 1 isolated lepton ($p_T^\ell > 20$ GeV), $p_T^{\text{miss}} > 30$ GeV

Polarization sensitive observables for $\tilde{t}$



$\cos\theta^*$ performs better than other two variables.

Asymmetry observables for $\tilde{t}$



Conclusion

Summary:

- Studied observables to discriminate polarization of top quarks.
- Studied simple application:
  - Event asymmetry as a function of model parameters.
  - Polarized tops from decay of $\tilde{t}$ squark of MSSM.
- In [1902.08096], we also studied the application of our observables to RS models.
- Sor far, the observable seems robust.

Outlook:

- Explore applications of machine learning and deep neural networks in observables for top polarization.
- Explore the robustness of our observables in realistic experimental scenario with background and contamination.

Thank You!

References I

- **Rohini M. Godbole, Michael E. Peskin, Saurabh D. Rindani, Ritesh K. Singh:**
  Why the angular distribution of the top decay lepton is unchanged by anomalous tbW coupling.
  arXiv:1809.06285 [hep-ph]
- **Brock Tweedie:**
  Better Hadronic Top Quark Polarimetry.
  arXiv:1401.3021 [hep-ph]
- **Rohini Godbole, Monoranjan Guchait, Charanjit K. Khosa, Jayita Lahiri, Seema Sharma, Aravind H. Vijay:**
  Boosted Top quark polarization.
  arXiv:1902.08096 [hep-ph]

References II

- **David Krohn, Jessie Shelton, Lian-Tao Wang:**
  Measuring the Polarization of Boosted Hadronic Tops.
  `arXiv:0909.3855 [hep-ph]`
- **A. Brandenburg, Z.G. Si, P. Uwer:**
  QCD-corrected spin analysing power of jets in decays of polarized top quarks.
  `arXiv:hep-ph/0205023`
- **ATLAS Collaboration:**
  Search for $W' \to tb$ decays in the hadronic final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
  `arXiv:1801.07893 [hep-ex]`

References III

- **Gregor Kasieczka, Tilman Plehn, Torben Schell, Thomas Strebler, Gavin P. Salam:**
  Resonance Searches with an Updated Top Tagger.
  arXiv:1503.05921 [hep-ph]
- **Davison E. Soper, Michael Spannowsky:**
  Finding top quarks with shower deconstruction.
  arXiv:1211.3140 [hep-ph]