Boosted Top quark polarization.

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[1902.08096]
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Motivation

Studying top quark polarization:

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

$$\Gamma^{\mu} = \frac{-ig}{\sqrt{2}} [\gamma^{\mu} \{(1 + f_{1L})P_L + f_{1R}P_R\}]$$

$$- \frac{g\sigma^{\mu\nu}}{\sqrt{2}m_W} [(p_t - p_b)_{\nu} (f_{2L}P_L + f_{2R}P_R)]$$

(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 $\Rightarrow$ leptons not well isolated.
- Additional sources of $p_T^{\text{miss}}$ 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

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_f} = \frac{1}{2} \left( 1 + P_0 \kappa_f \cos \theta_f \right)
\]

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

\(P_0\) \(\Rightarrow\) Polarization of the produced top.

\(\kappa_f\) \(\Rightarrow\) Spin analyzing power.

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

\(\kappa_{\bar{d}} = 1\)

\(\kappa_u \approx -0.3\)

- \(\bar{d}\) (or \(\ell\)) 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 $W' \rightarrow tb$

- Studied effective $W'$ model.
  \[
  \mathcal{L} = \frac{V_{ij}}{2\sqrt{2}} \bar{f}_i \gamma^\mu (g_R (1 + \gamma_5) + g_L (1 - \gamma_5)) W_{\mu}^\prime f_j + h.c.
  \]

- 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 $b$ nev $\Rightarrow b$ momentum opposite to top spin direction.

  - $\Rightarrow$ Soft for right handed, hard for left handed.

- Closest subjet energy fraction ($z_k$) \[0909.3855 \text{(Krohn D. et. al.)}\]

  \[z_k = \max(E_i, E_j) / E_t\]

  where $d_{ij}$ ($k_T$ distance) is minimum.
Angle based observable $\cos \theta^*$

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

- 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

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

- 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 \( t \).
Application to MSSM \( \tilde{t} (\text{stop}) \to t\chi^0_1 - 1 \)

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

Coupling \( \Rightarrow \tilde{\chi}^0_1 (g_{\tilde{t}_1L} P_L + g_{\tilde{t}_1R} P_R) t \tilde{t}_1 + h.c. \)

\[
\begin{align*}
g_{\tilde{t}_1L} &= -\sqrt{2} g_2 \left[ \frac{1}{2} Z^*_{12} + \frac{1}{6} \tan(\theta_W) Z^*_{11} \right] \cos \theta_{\tilde{t}} - \left[ \frac{g_2 m_t Z^*_{14}}{\sqrt{2} m_W \sin(\beta)} \right] \sin \theta_{\tilde{t}} \\
g_{\tilde{t}_1R} &= \left[ \frac{2\sqrt{2}}{3} g_2 \tan(\theta_W) Z_{11} \right] \sin \theta_{\tilde{t}} - \frac{g_2 m_t Z_{14}}{\sqrt{2} m_W \sin(\beta)} \cos \theta_{\tilde{t}}.
\end{align*}
\]

- Supersymmetric (fermionic) neutral components of \( B, W, H_u \) and \( H_d \) mix: \( \chi^0_1 = Z_{11} B + Z_{12} W_3 + Z_{13} H_d + Z_{14} H_u \).
- Gaugino component of \( \chi^0_1 \) preserves chirality (gauge interactions) of stop decay, Higgs components flip it (Yukawa interactions).
Application to MSSM $\tilde{t} (\text{stop}) \rightarrow t \chi^0_1$ - II

- Polarization of $t$ determined by composition of $\tilde{t}$ and $\chi^0_1$

<table>
<thead>
<tr>
<th>$\chi^0_1$</th>
<th>$\tilde{t}_1$</th>
<th>$t$ chirality</th>
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<tbody>
<tr>
<td>Bino like or Wino Like</td>
<td>$\tilde{t}_L$, $\tilde{t}_R$</td>
<td>$t_L$, $t_R$</td>
</tr>
<tr>
<td>Higgsino like</td>
<td>$\tilde{t}_L$, $\tilde{t}_R$</td>
<td>$t_L$, $t_R$</td>
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$$P_0 = \frac{\left(g_{\tilde{t}_L}^2 - g_{\tilde{t}_R}^2\right)^2 K^{1/2} \left(1, \frac{m_{\tilde{t}_L}^2}{m_{\tilde{t}_1}^2}, \frac{m_{\chi^0_1}^2}{m_{\tilde{t}_1}^2}\right)}{\left(g_{\tilde{t}_L}^2 + g_{\tilde{t}_R}^2\right) \left(1 - \frac{m_{\tilde{t}_L}^2}{m_{\tilde{t}_1}^2} - \frac{m_{\chi^0_1}^2}{m_{\tilde{t}_1}^2}\right) - 4 \frac{m_{\tilde{t}_L} m_{\chi^0_1}}{m_{\tilde{t}_1}^2} \text{Re} (g_{\tilde{t}_L} g_{\tilde{t}_R}^*)}$$

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

- Events studied:

$$pp \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow t \bar{t} \chi^0_1 \chi^0_1 \rightarrow (b j j) (b l \nu_l) \chi^0_1 \chi^0_1$$

with

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

- Selection: 1 isolated lepton ($p_T^l > 20$ GeV), $p_T^{\text{miss}} > 30$ GeV
Polarization sensitive observables for $\tilde{t}$

- $t_R$ and $t_L$ are plotted against $Z_b$.
- $t_R$ and $t_L$ are plotted against $Z_k$.
- $t_R$ and $t_L$ are plotted against $\cos \theta^*$.

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

$m_{\tilde{t}_1} = 1 \text{ TeV}$

$m_{\tilde{\chi}_1^0} = 100 \text{ GeV}$
Asymmetry observables for $\tilde{t}$

$Z_{14} = -\sqrt{1 - Z_{11}^2}$

$Z_{14} = -\sqrt{1 - Z_{12}^2}$

$\chi_1^0 = \frac{\bar{b} \bar{W}_3 + \bar{H}_u + \bar{H}_d}{2}$

$\chi_1^0 = \tilde{B}$
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.
• So 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!
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.

Brock Tweedie:
Better Hadronic Top Quark Polarimetry.

Rohini Godbole, Monoranjan Guchait, Charanjit K. Khosa, Jayita Lahiri, Seema Sharma, Aravind H. Vijay:
Boosted Top quark polarization.
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.

ATLAS Collaboration:
Search for $W' \rightarrow tb$ decays in the hadronic final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
arXiv:1801.07893 [hep-ex]
Gregor Kasieczka, Tilman Plehn, Torben Schell, Thomas Strebler, Gavin P. Salam:  
Resonance Searches with an Updated Top Tagger.  

Davison E. Soper, Michael Spannowsky:  
Finding top quarks with shower deconstruction.  