Measuring Top-Quark Polarization in Top-Pair + Missing-Energy Events

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Based on the work PRL 109, 154002 (2012) in collaboration with Edmond L. Berger, Qing-Hong Cao, and Jiang-Hao Yu
Many New Physics Models

- Many new physics models have been developed in last thirty years.
  
  **Supersymmetry, Universal Extra Dimension, Warped Extra Dimension, Left-Right Symmetry Model, Little Higgs model ...**

- Many of them can explain hierarchy problem, have dark matter candidate and new particles which can be produced at high energy colliders.

- Many new physics models have similar signals at the LHC.

- When we discover those signals, there is another important question:

  Where is the signal from?

  SUSY?

  UED?

  Little Higgs?

  ...?
Distinguish New Physics Models

- To distinguish new physics models, we need more information of the new particles.
- Mass:
  - The difficulty of measuring the mass of the new particles are mainly from the missing transverse energy in the final state.
  - Many methods and variables are developed for mass measuring.

\[
m_T^2 \equiv m_{\text{vis}}^2 + m_\chi^2 + 2(E_{T_{\text{vis}}}E_{T_\chi} - p_{T_{\text{vis}}} \cdot p_{T_\chi})
\]

\[
m_{T2}^2 (m_\chi) \equiv \min_{p_{T_{\chi1}}+p_{T_{\chi2}} = \vec{p}_T} \left[ \max \left\{ m_T^2 (m_\chi, p_{T_{\chi1}}), m_T^2 (m_\chi, p_{T_{\chi2}}) \right\} \right]
\]
Distinguish New Physics Models

• Spin:
  • Measuring the angular distribution of the final state particles:
    • $Z'$, $W'$, Graviton, ...
  • Preliminary judgement with Landau-Yang theorem:
    • Higgs boson (on-shell)
  • It is also difficult when there is extra missing energy in the final state. Some sophisticated designed variables are proposed for spin measurement in that case.
Distinguish New Physics Models

- Chirality of the interaction:
  - It is even non-trivial in the SM!
  - To determine the chirality of the weak interaction, the results from neutrino scattering experiment, polarized electron-deuteron DIS experiment, fixed target polarized Møller scattering experiment and Z-pole experiments with polarized initial states at SLC and LEP are used.

- The key point is
  “The polarization of the initial state particles or final state particles should be known.”

- Question:
  How to measure particles’ polarization at the LHC?
• Using top quark!

• Mass: $\sim 172.5$ GeV, sensitive to TeV physics.

• Width: $\sim 1.5$ GeV.

• Lifetime: $\sim 0.5 \times 10^{-24}$ s << hadronization time scale!!

• Top quark will decay before hadronization.

• Its polarization information is well kept in the final states.
Top Quark Decay and Its Polarization


\[ \frac{d^2\Gamma}{dxd\cos\theta_{t\ell}} = \frac{\alpha_W^2 m_t}{32\pi AB} x(1 - x) \frac{1 + \lambda_t \cos\theta_{t\ell}}{2} \text{Arctan} \left[ \frac{Ax}{B - x} \right] \]

\[ A = \frac{\Gamma_W}{m_W}, \quad B = \frac{m_W^2}{m_t^2}, \quad x = \frac{2E_{t\ell}}{m_t} \]

\[ \text{Arctan}(x) = \begin{cases} \text{arctan} x, & x \geq 0 \\ \pi + \text{arctan} x, & x < 0 \end{cases} \]

- The “Arctan” function describes the finite width effect of the W boson.

- It is clear that 0 < x < 1.

- When x > B (~0.22), Ax/(B-x) < 0
Top Quark Decay and Its Polarization

- **Limitation of the traditional method**: Need top quark reconstruction. This is impossible when there is extra missing energy (dark matter candidate) in the final state.

- But this happens in many popular new physics models!
  - Supersymmetry (with R-parity): stop-pair $\rightarrow$ top-pair + LSP-pair
  - Little Higgs model (with T-parity): T.-pair $\rightarrow$ top-pair + $A_H$-pair
  - Universal Extra Dimension (with KK-parity): $t^{(1)}$-pair $\rightarrow$ top-pair + LKP-pair
Top Quark Decay and Its Polarization

- The property of the top quark partner is very important in those new physics models.

- The top quark partner couples to the Higgs boson and plays a key role in the solutions to the hierarchy problem.

\[ \Delta m_h^2 = -\frac{|y_f|^2}{8\pi^2} \Lambda_{UV}^2 + ... \]

- The largest correction is from the top quark Yukawa interaction.

- This should be canceled by the “partner” of top quark in the new physics model.

SUSY

Little Higgs
Top Quark Decay and Its Polarization

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We need a new method to study the chirality and spin information!
Top Quark Decay and Its Polarization

Lepton energy fraction distribution ($t^{-1}$, $E_{top} = 200$ GeV)

Lepton energy fraction distribution ($t^{-1}$, $E_{top} = 600$ GeV)

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Lepton energy fraction distribution ($t^{-1}$, $E_{top} = 600$ GeV)
Top Quark Decay and Its Polarization

- The difference between the lepton energy fraction distribution from “left-handed” top quark and “right-handed” top quark can be used to measure the top quark polarization.
Top Quark Decay and Its Polarization

- We would like to define the quantity
  \[ R(x) \equiv \frac{1}{\Gamma} \int_0^x \frac{d\Gamma}{dx_\ell} dx_\ell = \frac{\Gamma(x_\ell < x)}{\Gamma} \]

- The analytic formula for \( R \) is

\[
\gamma \geq \frac{1+B}{2\sqrt{B}} \]

\[
\mathcal{R}(x_{\ell}) = \begin{cases} 
0 & x_{\ell} \in (0, B(1-\beta)) \\
\frac{f_1(x_{\ell})}{f_1(1-\beta) + f_2(x_{\ell})} & x_{\ell} \in (1-\beta, B(1-\beta)) \\
\frac{f_1(1-\beta) + f_2(B(1+\beta)) + f_3(x_{\ell})}{f_1(1-\beta) + f_2(B(1+\beta)) + f_3(x_{\ell})} & x_{\ell} \in (B(1-\beta), 1-\beta) \\
\frac{f_1(1-\beta) + f_2(B(1+\beta)) + f_3(x_{\ell})}{f_1(1-\beta) + f_2(B(1+\beta)) + f_3(x_{\ell})} & x_{\ell} \in (B(1+\beta), 1+\beta) \\
\end{cases}
\]

\[
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\[
\mathcal{R}(x_{\ell}) = \begin{cases} 
0 & x_{\ell} \in (0, B(1-\beta)) \\
g_1(x_{\ell}) & x_{\ell} \in (B(1-\beta), B(1+\beta)) \\
g_1(B(1+\beta)) + g_2(x_{\ell}) & x_{\ell} \in (B(1+\beta), 1-\beta) \\
g_1(B(1+\beta)) + g_2(B(1+\beta)) + g_3(x_{\ell}) & x_{\ell} \in (B(1+\beta), 1+\beta) \\
\end{cases}
\]

\[
g_1(x_{\ell}) = \frac{1+B}{12N\beta(1-\beta)} \left\{ B^2(1-\beta)^3(3-2B)[2\beta - h(1+\beta)] + x_{\ell}[6B(1-\beta)^2(2x_{\ell} + (2-B)(h(1+\beta))] + x_{\ell}^2[2\beta(3-3\beta - x_{\ell}) - h(9 + 2x_{\ell} - 4(3 + x_{\ell})\beta + 3\beta^2)] + 6hx_{\ell}(1-\beta)^2\ln\left(\frac{x_{\ell}}{B(1-\beta)}\right) \right\},
\]

\[
g_2(x_{\ell}) = \frac{1}{12N\beta(1-\beta)} \left\{ B^2(1-\beta)^3(3-2B)[2\beta - h(1+\beta)] + x_{\ell}[6B(1-\beta)^2(2x_{\ell} + (2-B)(h(1+\beta))] + x_{\ell}^2[2\beta(3-3\beta - x_{\ell}) - h(9 + 2x_{\ell} - 4(3 + x_{\ell})\beta + 3\beta^2)] + 6hx_{\ell}(1-\beta)^2\ln\left(\frac{x_{\ell}}{B(1-\beta)}\right) \right\},
\]

\[
g_3(x_{\ell}) = \frac{1-B}{12N\beta(1+\beta)} \left\{ (x_{\ell} - \beta - 1)[2\beta((1-x_{\ell})^2 + 4(1-x_{\ell})\beta + 7\beta^2)] + h(2x_{\ell}^2(1 + 2\beta) + x_{\ell}(5 + 2\beta - 7\beta^2) + \beta(7\beta^2 - 15\beta - 15) - 1)] - 6h(1+\beta)^2\left[2(1-\beta)^2\arctanh\beta + x_{\ell}^2\ln\left(\frac{x_{\ell}}{1+\beta}\right) \right] \right\},
\]

\[
N = \frac{\beta}{3}(1-\beta)^2(1+2B)(1-B)^2.
\]
Top Quark Decay and Its Polarization (II)

- We would like to define the quantity

\[ R(x) \equiv \frac{1}{\Gamma} \int_0^x \frac{d\Gamma}{dx_\ell} \, dx_\ell = \frac{\Gamma(x_\ell < x)}{\Gamma} \]
Measuring stop-top-neutralino Interaction

- As an example, we consider the stop pair production process in supersymmetry model.

- The interaction Lagrangian is

\[ \mathcal{L}_{\tilde{t}t\tilde{\chi}} = g\tilde{t}\tilde{\chi} (P_L \cos \theta + P_R \sin \theta) t \]

- In this work, we choose the benchmark point (After our work, this parameter point has been ruled out.)

\[ m_{\tilde{t}} = 350 \text{GeV}, \quad m_{\tilde{\chi}} = 50 \text{GeV} \]

- 8TeV LHC

- top leptonic decay and anti-top hadronic decay

- Signal: lepton + (>3) jets + missing transverse energy
Measuring stop-top-neutralino Interaction

- The dominant SM backgrounds are top-pair and top-pair + Z productions.

- We generate both the signal and the backgrounds using MadGraph/MadEvent with CTEQ6L1 parton distribution function.

- The renormalization and factorization scales are chosen to be the mass of top quark.

- We only generate events using LO cross section.

- Momentum smearing effects are included through a Gaussian-type energy resolution.

- The basic cuts are

\[
p_T(\ell) > 20\text{GeV}, \quad |\eta_\ell| < 2.5
\]
\[
p_T(j) > 20\text{GeV}, \quad |\eta_j| < 2.5, \quad \Delta R_{jj,\ell} > 0.4
\]
\[
\not{E}_T > 25\text{GeV}
\]
Measuring stop-top-neutralino Interaction

- The dominant SM top-pair background is still huge after the basic cuts.

- Because the signal events have two extra massive invisible particles, the missing transverse energy and the scalar sum of the transverse energy of all objects are larger than the top-pair events.

- We impose harder cuts on the events which pass the basic cuts
  \[ p_T(j_{\text{leading}}) > 50\text{GeV}, \quad p_T(j_{\text{sub-leading}}) > 40\text{GeV} \]
  \[ \not{E}_T > 100\text{GeV}, \quad H_T > 500\text{GeV} \]
  at least one b-tagged jet

- After the hard cuts, the SM top-pair + Z background is negligible. But the SM top-pair background is still large.

<table>
<thead>
<tr>
<th>Basic</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>22.26</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>4347.08</td>
</tr>
<tr>
<td>( t\bar{t}Z )</td>
<td>1.25</td>
</tr>
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Measuring stop-top-neutralino Interaction

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<th>recon.</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>22.26</td>
<td>18.46</td>
<td></td>
<td>8.87</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>4347.08</td>
<td>3596.75</td>
<td></td>
<td>154.47</td>
</tr>
<tr>
<td>(t\bar{t}Z)</td>
<td>1.25</td>
<td>1.03</td>
<td></td>
<td>0.34</td>
</tr>
</tbody>
</table>
Measuring stop-top-neutralino Interaction

- How to suppress the SM top-pair background?
- The missing transverse energy of background events is from neutrino.
- The missing transverse energy of signal events is from neutrino and neutralino.

Assuming the missing energy of the event is from a single neutrino, solving the longitudinal momentum of the neutrino using $W$ boson mass-shell equation, we have

$$p_{\nu L} = \frac{1}{2p_{\ell T}^2} \left( A p_{\ell T} \pm E_{\ell} \sqrt{A^2 - 4p_{\ell T}^2 E_T^2} \right)$$

$$A = m_W^2 + 2 \vec{p}_{\ell T} \cdot \vec{E}_T$$

- It is unphysical more often in the signal than the background (T. Han, R. Mahbubani, D. Walker, and L.-T, Wang, JHEP 05 (2009) 117).
Measuring stop-top-neutralino Interaction

- We require the events to satisfy

\[ A^2 - 4p_T^2 \sqrt{E_T^2} \leq 0 \]

\[ m_T = \sqrt{2p_T E_T (1 - \cos \Delta\phi)} \geq 100\text{GeV} \]

- After those cuts, the SM top-pair background is highly suppressed.

<table>
<thead>
<tr>
<th></th>
<th>Basic</th>
<th>( t_{\text{had recon.}} )</th>
<th>Hard</th>
<th>( \not{E}_T \text{ sol.} )</th>
<th>( \epsilon_{\text{cut}} )</th>
</tr>
</thead>
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<tr>
<td>Signal</td>
<td>22.26</td>
<td>18.46</td>
<td>8.87</td>
<td>6.51</td>
<td>11.6%</td>
</tr>
<tr>
<td>( \bar{t}t )</td>
<td>4347.08</td>
<td>3596.75</td>
<td>154.47</td>
<td>0.91</td>
<td>0.00 556%</td>
</tr>
<tr>
<td>( t\bar{t}Z )</td>
<td>1.25</td>
<td>1.03</td>
<td>0.34</td>
<td>0.22</td>
<td>5.9%</td>
</tr>
</tbody>
</table>

- If we consider 8 TeV LHC with 20 fb\(^{-1}\) integrated luminosity, there is 130 signal events and 22 background events.

- The signal significance is \( S/\sqrt{B} = 28 \).
Measuring stop-top-neutralino Interaction

- Another question: how to estimate the energy of the leptonic decay top quark?

- In this work, we mimic top quark energy using the energy of the hadronic decay antitop.

\[ x'_\ell \equiv \frac{2E_\ell}{E_\ell} \]

\[ R'(x) \equiv \frac{1}{\sigma} \int_0^x \frac{d\sigma}{dx'_\ell} dx'_\ell \equiv \frac{\sigma(x'_\ell < x)}{\sigma} \]

- To reconstruct the antitop, we select the three jets from antitop decay by minimizing

\[ \chi^2 = \frac{(m_W - m_{jjj})^2}{\Gamma_W^2} + \frac{(m_t - m_{jjjj})^2}{\Gamma_t^2} \]

- The efficiency of this method is \( \sim 84\% \).
Measuring stop-top-neutralino Interaction

- Cut dependence: Not sensitive to cuts!
- $R$ will be smaller because the lepton transverse momentum cut will select large lepton energy fraction events.
Measuring stop-top-neutralino Interaction

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Measuring stop-top-neutralino Interaction

- Cut dependence: Not sensitive to cuts!
- $R$ will be smaller because the lepton transverse momentum cut will select large lepton energy fraction events.
Little Higgs model with T-parity


- The simulation shows that the right-handed nature of the interaction can be measured very well.

- This is a powerful check of the model.
Conclusion

- The top quark polarization can be sensitive to the new physics beyond the SM. The traditional method which is used to measure the top quark polarization can not be used when there is extra invisible particles in the final state.

- We propose a novel method based on the charged lepton energy fraction and illustrate the method with a detailed simulation of top-quark pairs produced in supersymmetric top squark pair production.

- **Advantage:**
  - Sensitive to the top-quark polarization
  - Insensitive to the precise measurement of the top-quark energy
  - Insensitive to the energy distribution of the top-quark
Comment

- After this work finished, the ATLAS and CMS collaboration updated their results of stop search. The benchmark point we used has been excluded by current data.

- But the method proposed in our work is also powerful for the allowed region.
Comment

- The higher order QCD correction is small and will not change the result significantly. (J. Gao, C. S. Li, and H.-X. Zhu, arXiv: 1210.2808 [hep-ph])
Thank you!
back up
Top Quark Decay and Its Polarization (I)

- Dominant decay mode: $t \rightarrow Wb$, $\Gamma(t \rightarrow Wb)/\Gamma(t \rightarrow Wq)=91\pm4\%$
- Final states of events top-pair:
  - hadronic mode: 45.7\%
  - semi-leptonic mode: 43.8\%
  - leptonic mode: 10.5\%

From F. Hubaut, E. Monnier, P. Pralavorio, TEV4LHC Workshop, CERN, April 28-30, 2005
Angular correlations in top quark decay

\[ \frac{d\Gamma}{\Gamma d\cos \theta_i} = \frac{1 + \alpha_i \cos \theta_i}{2} \]

<table>
<thead>
<tr>
<th>(i)</th>
<th>(\alpha_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>down quarks, charged leptons</td>
<td>1.00</td>
</tr>
<tr>
<td>up quarks, neutrinos</td>
<td>-0.318</td>
</tr>
<tr>
<td>W boson</td>
<td>0.406</td>
</tr>
<tr>
<td>bottom quark</td>
<td>-0.406</td>
</tr>
</tbody>
</table>

Top Quark Decay and Its Polarization (I)

- For massive free particle (top quark), helicity is not a frame-independent quantity but a good quantum number.

- In the top quark helicity base, the charged lepton angular distribution can be rewritten as

\[
\frac{d\Gamma}{\Gamma d\cos \theta_{t\ell}} = \frac{1 + \lambda_t \cos \theta_{t\ell}}{2}
\]

- \( \lambda_t \) is the top quark helicity.

- \( \theta_{t\ell} \) is the angular between the top 3-momentum and the charged lepton 3-momentum.
Top Quark Decay and Its Polarization (I)

- Traditional method: Measuring the distribution of $\cos\theta_{\ell}$, comparing it with the helicity amplitudes, we can get the information of the chirality of the interaction and the spin of the exotic particle.

Top Quark Decay and Its Polarization (II)

- In the narrow width limit of the W boson ($A \rightarrow 0^+$), we have
  \[
  \arctan \left( \frac{Ax}{B-x} \right) \rightarrow \pi \theta (x - B)
  \]

- After angular integral, we can get the charged lepton energy fraction in the top quark rest frame.
Top Quark Decay and Its Polarization (II)

- To calculate the differential distribution in the laboratory frame, we need to translate the formula from the top-rest frame coordinate \((x', z' = \cos\theta_w)\) to the lab frame coordinate \((x, z)\).

- It is easy to get

\[
x' = x\gamma^2(1 - z\beta), \quad z' = \frac{z - \beta}{1 - z\beta},
\]

- Because the differential distribution is a two-form, its transformation property is

\[
\frac{d^2\Gamma}{dx'dz'} = \frac{\partial (x', z')}{\partial (x, z)} \frac{d^2\Gamma}{dx'dz'}
\]

\[
\frac{d^2\Gamma}{dx'dz'} = \frac{\alpha_W^2 m_t^2 \gamma^2}{64\pi A B} x [1 - x\gamma^2 (1 - z\beta)] \left(1 + \lambda_t \frac{z - \beta}{1 - z\beta}\right)
\]

\[
\times \text{Arctan} \left[ \frac{A x\gamma^2 (1 - z\beta)}{B - x\gamma^2 (1 - z\beta)} \right]
\]
Top Quark Decay and Its Polarization (II)

- The lepton energy fraction ($x$) distribution ($d\Gamma/dx$) is top-polarization-independent in the top-rest frame. This is a result of the vanished angular integral

$$\int_{-1}^{1} \lambda_t \cos \theta_{t\ell} d \cos \theta_{t\ell}$$

- This is no longer the case in the lab frame!

- The charged lepton energy fraction distribution is top-quark-helicity-dependent.

- The charged lepton energy fraction distribution is the integral

$$\frac{d\Gamma}{dx} = \int_{z_{\text{min}}}^{z_{\text{max}}} \frac{\alpha_W^2 m_t \gamma^2}{64 \pi A B} x \left[ 1 - x \gamma^2 (1 - z \beta) \right] \left( 1 + \lambda_t \frac{z - \beta}{1 - z \beta} \right)$$

$$\times \arctan \left[ \frac{A z \gamma^2 (1 - z \beta)}{B - x \gamma^2 (1 - z \beta)} \right] dz$$

- The key point is to make sure the integral region, the value of $z_{\text{min}}$ and $z_{\text{max}}$. 
Top Quark Decay and Its Polarization (II)

- We list the value of $z_{\text{min}}$ and $z_{\text{max}}$ without derivation.

$$z_1 \equiv \frac{1}{\beta} \left(1 - \frac{1}{x \gamma^2}\right), \quad z_2 \equiv \frac{1}{\beta} \left(1 - \frac{B}{x \gamma^2}\right)$$

<table>
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<th>$\gamma &gt; \frac{1+B}{2\sqrt{B}}$</th>
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<tbody>
<tr>
<td>$x \in {B(1+\beta), 1+\beta}$</td>
<td>$z \in {z_1, 1}$</td>
</tr>
<tr>
<td>$x \in {(1-\beta), B(1+\beta)}$</td>
<td>$z \in {z_1, z_2}$</td>
</tr>
<tr>
<td>$x \in {B(1-\beta), 1-\beta}$</td>
<td>$z \in {-1, z_2}$</td>
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<tr>
<td>$x \in {0, B(1-\beta)}$</td>
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Top Quark Decay and Its Polarization (II)

- Why the integral region is different as the velocity of the top quark and the lepton energy fraction?
- There is a pictural explanation.
- The 3-momentum of the charged lepton in the top-rest frame distributes between two spheres with same center.
- The 3-momentum of the charged lepton in lab frame distributes between two ellipsoids with same focus.
- The surface with same $x$ is a sphere (in the top-rest frame or lab frame) with radius which is proportional to the absolute value of $x$. 
Top Quark Decay and Its Polarization (II)

\[
\frac{|p_\perp|}{E_t}, \quad \frac{\hat{p}_z}{E_t}
\]

\[\beta = 0.3\]

Points labeled as B(1-\beta) and B(1+\beta).

Axes: \(\frac{\hat{p}_z}{E_t}\) and \(|p_\perp|/E_t\).
Top Quark Decay and Its Polarization (II)
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Top Quark Decay and Its Polarization (II)
Measuring stop-top-neutralino Interaction

- Can we use the antitop energy to mimic the top energy?
- Some difference, but essential features are preserved.
Measuring stop-top-neutralino Interaction

- How many events do we need to distinguish the pure right-handed theory and the pure left-handed theory?

- Using binomial distribution, we have

\[
\delta R' (x') = \frac{1}{N_{\text{tot}}} \sqrt{\frac{N (x'_{\ell} < x') N (x'_{\ell} > x')}{N_{\text{tot}}}}
\]

- We need 87 (101) signal events to distinguish a pure left-handed (right-handed) new physics model from an unpolarized new physics model.

- To distinguish pure left-handed from pure right-handed new physics model, 23 signal events is enough.