Stop Search in the Compressed Region via Semileptonic Decays

~t~ production, ~t→ t \tilde{\chi}^0_1 / c \tilde{\chi}^0_1

Based on arXiv:1604.00007
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Motivation

- A light Higgs boson puts tension on naturalness.
- A light stop is preferred to cancel the top loop contribution to $m_H$.
- Stop mass excluded up to $\sim 750$ GeV on LHC.
- Traditional search techniques using $M_{T2}$, $H_T^{miss}$ ... are not sensitive for stop in the compressed region.  
  \[(m_{\tilde{t}} \approx m_t + m_{\tilde{\chi}})\]

We need to fill the gap in the compressed region where a light stop is still possible.
Motivation (Continued)

Why do we prefer semileptonic decays ($WW \rightarrow \ell + \nu + \text{jets}$)?

- Less SM background (e.g. QCD multi-jets, unidentified leptons)
- Considerable cross session (BR $\approx 44\%$)
  - Similar to fully hadronic decays (BR $\approx 46\%$)
  - Much bigger than dileptonic ones (BR $\approx 11\%$)
We consider $\tilde{t} \rightarrow t\tilde{\chi}$ decay here.

Other SUSY objects decoupled.

What happens when $m_{\tilde{t}} \approx m_t + m_{\tilde{\chi}}$?
In the compressed region, the decay products of stop decay ($t$ and $\tilde{\chi}$) are both static in stop reference frame.

When boosted, the two decay products becomes **comoving** in the lab frame. Therefore, their momentums would have the same ratio as their masses.

$$\frac{p_{\tilde{\chi}}}{p_{\tilde{t}}} \approx \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} \quad (1)$$

When the stop pair are produced nearly back-to-back, the event looks like a SM $t$ pair production.
New topology: stop pair produced with a hard initial state radiation (ISR) jet. \( p_{T\tilde{\chi}_1} + p_{T\tilde{\chi}_2} \approx \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} (p_{T\tilde{t}_1} + p_{T\tilde{t}_2}) \)

\[ R_M \equiv \frac{p_T^{\text{miss}}}{p_T(\text{ISR})} \approx \begin{cases} \frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} & (\text{stop}) \\ 0 & (\text{SM}) \end{cases} \]

Hadronic Analysis (arXiv:1506.00653 [hep-ph]).
In order to recover the LSP momentum sum, need to solve for neutrino momentum ($p_\nu$) and subtract it from the MET. ($R_M \rightarrow \bar{R}_M$)

Requires 4 relations.

3 mass-shell relation

$$p_\nu^2 = 0$$

$$ (p_\ell + p_\nu)^2 = m_w^2 $$

$$(p_\ell + p_\nu + p_b)^2 = m_t^2$$

perpendicular part:

$$p_{T\nu}^\perp = \not{p}_T$$
Cut Selection

- $p_T(\text{ISR}) \geq 475$ GeV
- MET $\geq 200$ GeV.
- $|\phi_\ell - \phi_{\text{MET}}| > 0.9$
- Others...
Background and Signal Simulation

SM background
- $t\bar{t}$ (semileptonic)
- $t\bar{t}$ (dileptonic)
- single top production (small Xsec.)
- (Multi)vector boson with jets (small Xsec.)
- $t\bar{t}$ production with an extra vector boson. (low signal efficiency)

Compressed Region signal
- Stop pair (semileptonic)
The significance is 8.4 for $m_{\tilde{t}} = 400$ GeV.
Compared with Fully Hadronic Analysis

- $p_T(ISR) \geq 700 \text{ GeV}$
- $p_T(J_2, J_3, J_4) \geq 60 \text{ GeV}$.
- $|\phi_{ISR} - \phi_{MET} - \pi| \leq 0.15$.
- At least one $b$ tag.
- $|\phi_{J_i} - \phi_{MET}| > 0.2, \ i = 2, 3, 4$

The significance is around 4 for $m_{\tilde{t}} = 400 \text{ GeV}$.
## Results

<table>
<thead>
<tr>
<th>$m_\tilde{t}$ (GeV)</th>
<th>250</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{m_\tilde{t}-(m_\tilde{\chi}+m_t)=0}$</td>
<td>19.7</td>
<td>15.8</td>
<td>11.0</td>
<td>8.4</td>
<td>5.8</td>
<td>5.1</td>
<td>3.8</td>
<td>2.1</td>
</tr>
<tr>
<td>$\sigma_{m_\tilde{t}-(m_\tilde{\chi}+m_t)=-30}$</td>
<td>22</td>
<td>19</td>
<td>13</td>
<td>11</td>
<td>7.2</td>
<td>4.7</td>
<td>3.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$\sigma_{m_\tilde{t}-(m_\tilde{\chi}+m_t)=30}$</td>
<td>$-$</td>
<td>7.6</td>
<td>5.3</td>
<td>3.3</td>
<td>2.4</td>
<td>1.7</td>
<td>1.3</td>
<td>0.9</td>
</tr>
</tbody>
</table>
Significance in $m_t - m_{\tilde{\chi}}$ plane, $\sqrt{s} = 13$ TeV, $L = 300$ fb$^{-1}$

- $\tilde{t} \rightarrow t + \tilde{\chi}, 95\%$ CL
- $\tilde{t} \rightarrow Wb + \tilde{\chi}, 95\%$ CL
We have studied the stop search from direct $\tilde{t}\tilde{t}j$ production in the compressed region, using the semileptonic decay mode.

For 300 fb$^{-1}$ integrated luminosity at LHC 13 TeV, the semileptonic channel can have a discovery reach for the stop mass up to about 500 GeV, in comparison to $\sim 400$ GeV for the fully hadronic channel.
The End (Time For Questions)
Lepton Energy

- MET $\geq$ 200 GeV
- Choose the solution with bigger $E_\nu$
MET and $p_T(ISR)$ should be back-to-back without $\nu$

- $|\phi_{J_{ISR}} - \phi_{MET}| \geq 2$

What about the relation between the lepton and the MET?

- For SM, high MET indicates a highly boosted $W$, $p_{T\ell}$ and $p_{T}^{miss}$ tends to be collinear.
- For signal, $p_{T}^{miss}$ could be separated from $p_{T\ell}$

**Need to cut $\Delta\phi_{\ell,MET}$!**
Azimuthal Distribution (Continued)

- Green points/curve: semileptonic $t\bar{t}$ background
- Red points/curve: dileptonic $t\bar{t}$ background
At least 4 jets with non-zero $b$ jets. Events with $\tau$ jets are vetoed.

- $p_{T\nu} < 180$ GeV, $p_{T\nu} < 6p_{T\ell}$.
- $p_T(J_2, J_3) \geq 60$ GeV.
- For more than 1 $b$ jet that give solutions, choose the one with a smaller $\bar{R}_M$.
- Pick the greater $E_\nu$ among two solutions.
- $|\phi_{ISR} - \phi_{MET}| \geq 2$. 
$\bar{R}_M$ expectation changes with $\frac{m_{\tilde{\chi}}}{m_{\tilde{t}}}$.
Moving away from the Compressed Region

If the spectrum deviates from $m_{\tilde{t}} \approx m_t + m_{\tilde{\chi}}$.  

▶ If $m_{\tilde{\chi}} > m_{\tilde{t}} - m_t$, $t$ becomes off-shell.

▶ If $m_{\tilde{\chi}} < m_{\tilde{t}} - m_t$, decay products will not be comoving.
Criteria for signal region

- If $m_{\tilde{\chi}} \geq m_{\tilde{t}} - m_t$, choose $\frac{m_{\tilde{\chi}}}{m_{\tilde{t}}} - 0.15 < \bar{R}_M < 1$
- If $m_{\tilde{\chi}} < m_{\tilde{t}} - m_t$, choose $\frac{m_{\tilde{t}} - m_t}{m_{\tilde{t}}} - 0.15 < \bar{R}_M < 1$

The significance is given by

$$\sigma = \sqrt{2 \left[ (S + B) \log \left( \frac{S + B}{B} \right) - S \right]}$$  \hspace{1cm} (2)
Significance as a function of the fractional background uncertainty for the case study.