Exclusive study of the mSUGRA co-annihilation region using a new soft tau identification method with the ATLAS detector

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Outline

• Introduction of mSUGRA co-annihilation region
• Phenomenology of this scenario at LHC, and the very soft taus which result from it.
• The standard tau identification algorithm in ATLAS, and the poor performance of it at low Pt.
• Introducing a new method which will increase the soft tau identification.
mSUGRA $\tilde{\chi}_1^0, \tilde{\tau}$ co-annihilation region

- In this region the LSP is $\tilde{\chi}_1^0$ and the NLSP is $\tilde{\tau}$
- The $\tilde{\chi}_1^0$ and $\tilde{\tau}$ are near degenerate in mass ($\Delta M \sim 5-15\text{GeV}$), which allows for the co-annihilation of them in the early universe.
- This co-annihilation can result in a $\tilde{\chi}_1^0$ density which agrees with the measured DM relic density.
- Once the SUSY mass scale has been determined the $\tilde{\chi}_1^0$ density must be calculated to check its consistency with the measured relic DM density.
\( \tilde{\chi}^0_2 \) decay phenomenology

\( \tilde{\chi}^0_2 \rightarrow \tilde{\tau} + \tau \rightarrow \tilde{\chi}^0_1 + \tau + \tau \) is the dominant visible decay mode

\[ \Delta m(\text{Chi1,Stau}) \approx 10 \text{GeV} \rightarrow \text{very soft taus} \]

264 GeV \( \tilde{\chi}^0_2 \)

147 GeV \( \tilde{\chi}^0_1 \)

137 GeV

“The HARD” tau: \( \sim 70 \text{GeV} \)  

“SOFT” tau: \( \sim 9 \text{GeV} \)

The endpoint of the \( M_{\tau,\tau} \) mass spectrum is sensitive to the masses of the SUSY particles in the chain. We wish to measure this.

\[
M_{\text{ll max}} = M(\tilde{\chi}_2^0) \sqrt{1 - \frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}} \sqrt{1 - \frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}
\]

\( = 78 \text{ GeV} \) for the ATLAS reference point

MC Truth

ATLAS work in progress
MC visible information of the signal taus

Signal “Soft” tau is somewhat confined around “Hard” tau.

Full simulation based on Geant4 @ 14TeV
Reconstruction of taus focuses on their hadronic modes only, since leptonic modes are too difficult to distinguish from primary leptons.

Hadronic taus need to be disentangled from copious QCD jet background by exploiting narrow jet shapes, track multiplicity etc.

Especially in busy SUSY environments discrimination against QCD jets is challenging, particularly so for low $P_T$ taus.
The present ATLAS algorithm focuses on the Pt>20GeV region, thus the performance for our signal soft taus is very poor (<10% of signal soft taus are identified).

THUS WE LOOK FOR ANOTHER METHODS FOR DISCRIMINATING THE SIGNAL SOFT TAU.
New method: Search for tau-like tracks around the hard tau

1. Select “hard tau candidates” using existing ATLAS algorithm.
2. Collect all good quality tracks within $dR<2$ of the hard tau candidate (call these “soft tau candidates”).
3. Apply $Pt>2\text{GeV}$ and track isolation (no tracks in $dR<0.1$) cuts on soft candidates.
4. If more than one soft candidate: apply likelihood (work in progress) to them to select the MOST TAU LIKE candidate.
5. Finally we will subtract same sign pairs from opposite sign pairs to reduce the uncorrelated background.
Classification of soft tau decay topology for likelihood

CASE 1. $\tau \rightarrow \pi^{+/-} + \pi^0$ (B.R=26%). Resolved
The $\pi^0$ causes an excess above the expected energy and there is an EM cluster in the vicinity of the $\pi^{+/-}$ impact in the calorimeter

CASE 2. $\tau \rightarrow \pi^{+/-} + \pi^0$. Unresolved
The $\pi^0$ causes an excess above the expected energy, but the clusters of the $\pi^{+/-}$ and $\pi^0$ are not resolved.

CASE 3. $\tau \rightarrow \pi^{+/-}$ (B.R=11%) 
The expected amount of energy is deposited in the calorimeter for the candidate track, and the cluster is ISOLATED

CASE 4. $\tau \rightarrow \pi^{+/-} + 2\pi^0$ (B.R=9%)
We will look at reconstructing this mode in the future.

CASE 5. $\tau \rightarrow 3\pi^{+/-} + n\pi^0$ (B.R=14%)
We believe that this mode would be very difficult to discriminate at low Pt so we are not studying it for now.

For now we focus only on $\tau \rightarrow \pi^{+/-} + \pi^0$ (26%) & $\tau \rightarrow \pi^{+/-}$ (11%)
Resolution of $\pi^{+/−}$ clusters

We want to know the resolution of a single $\pi^{+/−}$ in the calorimeter so that we can determine if the energy is greater than that expected from the track. This will separate “with $\pi^0$” soft tau candidates from “without $\pi^0$” soft tau candidates.

We use the $\tau \rightarrow \pi^{+/−}$ mode to determine the calorimeter resolution for $\pi^{+/−}$ as a function of $P_T$.

The width of the gaussian fit of

$$\frac{(E_{\text{calo}}-P_{\text{track}})}{P_{\text{track}}}$$

$\pi^{+/−}$ identified as having excess energy

RED: $(E_{\text{calo}}-P_{\text{track}})/P_{\text{track}}$ for $\pi^{+/−}$ from 0 $\pi^0$ mode

BLACK: $(E_{\text{calo}}-P_{\text{track}})/P_{\text{track}}$ for $\pi^{+/−}$ from 1 $\pi^0$ mode (when the $\pi^0$ is close to the $\pi^{+/−}$)
Classifying the soft tau candidate

- **CASE1**: If there is an energy excess around the $\pi^{+/−}$ candidate then look for an EM cluster (the $\pi^0$) in the vicinity of it ($dR<0.4$).
  - ➔ If there is one, CLASSIFY AS 1-PI0 MODE

- **CASE2**: If there is an excess of energy around the $\pi^{+/−}$ candidate in the calorimeter, but no EM cluster was found,
  - ➔ ATTEMPT TO RESOLVE $\pi^0$: we are working on a better clustering resolution using fine granularity strip layer of calorimeter

- **CASE3**: For $\pi^{+/−}$ candidates with no excess, and no $\pi^0$ candidate, require isolation (no hadronic cluster in $0.2<dR<0.4$).
  - ➔ If it is isolated CLASSIFY AS 0$\pi^0$ MODE
  - ➔ If not isolated classify as jet and discard

- **CASE4**: If there are n $\pi^0$, CLASSIFY as n$\pi^0$ mode (for now we will not study this case any further).
**Algorithm applied to signal and QCD jet BG**

<table>
<thead>
<tr>
<th></th>
<th>$\tau \rightarrow \pi^{+/−} + 1\pi^0$ [16fb$^{-1}$]</th>
<th>$\tau \rightarrow \pi^{+/−} + 0\pi^0$ [16fb$^{-1}$]</th>
<th>QCD Jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passes hard tau selection cuts</td>
<td>1447</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BRANCHING FRACTION</strong></td>
<td>357</td>
<td>194</td>
<td></td>
</tr>
<tr>
<td>$\pi^{+/−}$ track reconstructed within dR&lt;2.0 of hard tau</td>
<td>226</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Track quality, pt, isolation cuts</td>
<td>89</td>
<td>87</td>
<td></td>
</tr>
<tr>
<td><strong>CASE1:</strong> Classified as 1 $\pi^0$ mode</td>
<td>29 (33%)</td>
<td>5 (6%)</td>
<td>30%</td>
</tr>
<tr>
<td><strong>CASE2:</strong> Excess but no EM cluster</td>
<td>14 (16%)</td>
<td>3 (3%)</td>
<td>21%</td>
</tr>
<tr>
<td><strong>CASE3:</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isolation $\rightarrow$ Classified as 0 $\pi^0$ mode</td>
<td>29 (33%)</td>
<td>70 (80%)</td>
<td>13%</td>
</tr>
<tr>
<td>no isolation $\rightarrow$ Classified as jet</td>
<td>9 (10%)</td>
<td>7 (8%)</td>
<td>16%</td>
</tr>
<tr>
<td><strong>CASE4:</strong> more than 1 EM cluster</td>
<td>8 (9%)</td>
<td>2 (2%)</td>
<td>21%</td>
</tr>
</tbody>
</table>

Many $\pi^0$ clusters lost due to being too close/far from $\pi^{+/−}$ or being classified as hadronic.
Work in progress: Using $\pi^0$ to discriminate against jets

For signal, the invariant mass of the $\pi^+/\pi^-$ and $\pi^0$ peaks at the mass of their parent $\rho$ (775 MeV)

We are presently building a likelihood to choose the most tau like candidate
Conclusion

• The mSUGRA co-annihilation region is a good new physics candidate and would explain the observed dark matter density.

• The existing ATLAS tau identification algorithm performs poorly for the low Pt taus that result from this scenario.

• A new method is proposed that will boost the soft tau identification efficiency.
  – We have investigated the resolution of $\pi^0$ from the $\tau \rightarrow \pi^{+/−} + 1\pi^0$ mode and have reconstructed it 33% of the time. The parent $\rho$ mass has been reconstructed.
  – We are currently working on a likelihood method to select the soft tau from the soft tau candidates.

• This soft tau reconstruction could be useful for other studies including VBF H-$\rightarrow$tau,tau.
Standard ATLAS tau reconstruction algorithm discrimination 1

1. \[ R_{em} = \frac{\sum_{i=1}^{n} E_{T,i} \sqrt{(\eta_i - \eta_{\text{cluster}})^2 + (\phi_i - \phi_{\text{cluster}})^2}}{\sum_{i=1}^{n} E_{T,i}} \]

2. \[ \Delta \eta = \sqrt{\frac{\sum_{i=1}^{n} E_{\text{strip}i} (\eta_i - \eta_{\text{cluster}})^2}{\sum_{i=1}^{n} E_{Ti}}} \]

3. \[ \Delta E_T^2 = \frac{\sum_{i=1}^{j} E_{T,i}}{\sum_{j} E_{T,j}} \]

4. $E_T$ over $p_T$ of the leading track:
Standard ATLAS tau reconstruction algorithm discrimination 2

Discrimination variables are combined to form a likelihood

“Medium” discrimination cut

Figure 12: Left: The log likelihood (LLH) distribution for $\tau$ leptons (solid) and jets from QCD production (dashed). The likelihood is applied after a preselection on the number of associated tracks, i.e. requiring $1 \leq N_\tau \leq 3$. (Candidates with LLH $< -10$ had variables outside the boundaries of histograms used when obtaining the PDFs for the likelihood calculation). Right: Efficiency for $\tau$ leptons and rejection against jets for different $E_T$ ranges, achieved with the likelihood selection.
Standard ATLAS tau reconstruction algorithm applied to mSUGRA co-annihilation events

Reconstructed == hadronic MC tau with $|\text{Eta}|<2.5$ matched to a reconstruction object within $dR<0.2$

Identified == Reconstructed + passes discrimination cut
Track quality cuts for soft tau search

**Pixel +SCT hits (secondary track cut)**

**RED:** \( \pi^+/\pi^- \) track
**BLACK:** Other soft candidates

**TRT hits (secondary track cut, \(|\eta|<1.9\) only)**

**High thresh TRT hits (loose electron veto)**

**Norm. \( \chi^2 \) (fake track cut)**

**ATLAS work in progress**
Isolation and $P_T$ of $\pi^{+/0}$ from $\tau \rightarrow \pi^{+/0} + 0\pi^0$ compared to other soft tau candidates

**RED:** $\pi^{+/0}$ track

**BLACK:** Other soft tau candidates

**ATLAS work in progress**
Isolation and $P_T$ of $\pi^{+/0}$ from $\tau \rightarrow \pi^{+/0} + 1\pi^0$ compared to other soft tau candidates

- RED: $\pi^{+/0}$ track
- BLACK: Other soft tau candidates

ATLAS work in progress
$\tau \rightarrow \pi^{+/−} + 1\pi^0$ mode:
loss of $\pi^0$ cluster in algorithm

The ATLAS topological clustering algorithm uses clusters shape to classify clusters as either EM or hadronic.

$\pi^0$ too far from $\pi^{+/−}$ get lost by algorithm

30% of $\pi^0$ clusters are classified as hadronic
Source of taus in mSUGRA co-annihilation region (MC Truth)

<table>
<thead>
<tr>
<th>Source</th>
<th>No Pt cut</th>
<th>Pt&gt;40</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1SS-&gt;tau</td>
<td>30%</td>
<td>16.3%</td>
</tr>
<tr>
<td>W1SS-&gt;Stau1-&gt;tau</td>
<td>24%</td>
<td>2.0%</td>
</tr>
<tr>
<td>W1SS-&gt;Stau2-&gt;tau</td>
<td>1.2%</td>
<td>4.4%</td>
</tr>
<tr>
<td>W1SS-&gt;W-&gt;tau</td>
<td>1.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Chi^0_2-&gt;tau <strong>SIGNAL</strong></td>
<td>12%</td>
<td>40%</td>
</tr>
<tr>
<td>+Stau1-&gt;tau</td>
<td>12%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Chi^0_2-&gt;tau</td>
<td>1.0%</td>
<td>3.6%</td>
</tr>
<tr>
<td>+Stau2-&gt;tau</td>
<td>1.0%</td>
<td>0</td>
</tr>
<tr>
<td>W-&gt;tau (other than 4)</td>
<td>6.5%</td>
<td>13%</td>
</tr>
<tr>
<td>Z-&gt;tau</td>
<td>0.4%</td>
<td>1.0%</td>
</tr>
<tr>
<td>B-&gt;tau</td>
<td>6.1%</td>
<td>3.5%</td>
</tr>
<tr>
<td>Other sources</td>
<td>4.7%</td>
<td>10.7%</td>
</tr>
</tbody>
</table>
Effect of Pt cut on $dR_{\tau\tau}$ and $M_{\tau\tau}$

ATLAS work in progress