Tau Lepton Identification
Using the CMS Detector at the LHC
(for SUSY Search)

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Motivation (SUSY Search)
Backgrounds
Search Strategy
Selection Cuts
- Jets, MHT, Tau ID
Selection Efficiencies and Sensitivity
Tasks/Plans
SUSY naturally provides a CDM candidate (LSP).

\[ \frac{dn}{dt} = -3Hn - \langle \sigma v \rangle (n^2 - n_{eq}^2) \]

**Standard Cosmology**

For earlier studies, see Arnowitt et al., PLB 649 (2007) 73; Arnowitt et al., PLB 639 (2006) 46

**Case 1** "Coannihilation (CA)" Region

Arnowitt, Dutta, Gurrola, Kamon, Krislock, Toback, PRL100 (2008) 231802

CDM Candidate!
Properties of Co-Annihilation Region

- **Properties**
  - Squark-gluino production dominant SUSY process
  - Squarks/gluinos decay to very high $p_T$ jets
    - Squark Mass $\sim 600$-$800$ GeV
    - Gluino Mass $\sim 850$ GeV
  - Squarks will decay primarily to $\tilde{\chi}_2^0$ & $\tilde{\chi}_1^\pm$
  - Branching ratio of $\tilde{\chi}_2^0 \rightarrow \tau \tilde{\nu}_\tau$ is $\sim 95$-$100\%$
  - Branching ratio of $\tilde{\chi}_1^\pm \rightarrow \nu \tau_1$ is $\sim 95$-$100\%$
  - Large MET from the CDM candidate
    - Mass of LSP $\sim 150$ GeV
  - Tau’s from $\tilde{\chi}_2^0$ decays are oppositely charged
  - One high energy tau from $\tilde{\chi}_2^0$ decay ($\sim 100$ GeV)
  - One low $p_T$ tau from the $\tau_1$ decay ($\Delta M \sim 15$ GeV)
Possible SM Backgrounds

- **Properties**

  - **Z->ττ**: two low $p_T$ taus
    - Does not contain large MET or high $p_T$ jets
    - Control region to show we can identify taus
  
  - **W+jets**: isolated lepton combined with a non-isolated lepton or jet
    - Has “small” MET from W, but low $p_T$ jets
    - Lepton fakes the tau, jet fakes the tau
  
  - **TTBar**: isolated leptons combined with high multiplicity of jets
    - Clean leptons from W’s fake the taus
    - High $p_T$ jets from top decays
  
  - **QCD**: non-isolated jets
    - Jets fake the taus
    - Can have high $p_T$ jets, but no real MET
  
  - **Z->Inv+Jets**
    - Real MET, jets fake the taus
Possible SUSY Backgrounds

- Combinatoric SUSY background
- A tau from the chargino can be paired with taus from a neutralino decay
- Example:
  - $\tau_1^+$ from chargino decay
  - $\tau_2^+$ from neutralino decay
  - $\tau_3^-$ from neutralino decay
  - Possible Pairs:
    - $\tau_1^+ \tau_2^+$
    - $\tau_1^+ \tau_3^-$
    - $\tau_2^+ \tau_3^-$
  - Incorrect Pairs:
    - $\tau_1^+ \tau_2^+$
    - $\tau_1^+ \tau_3^-$
  - Correct Pair
    - $\tau_2^+ \tau_3^-$
**OS-LS Method**

**Correct \( \tau\tau \) SUSY Combinations**

\(+\)-\( \) from \( \tau \)'s produced in the \( \tilde{\chi}_2^0 \) decay chain

**Wrong \( \tau\tau \) SUSY Combinations**

\(+\)-\( \) from \( \tau \)'s produced in different \( \tilde{\chi}_2^0 \) decays

\(++\), \((-\) from different \( \tilde{\chi}_2^0 \) decays

**"Fake" \( \tau\tau \) SM Combinations**

\(+\)-\( ,\)\(-+\), \(++\), and \((-\) are mostly observed with equal probability for SM processes such as QCD

**Good \( \tau\tau \) SM Combinations**

\(+\)-\( \) from \( \tau \)'s or e/\( \mu \)'s from different W's
Search Strategy

1. Target the overall global SUSY scale
   - Select high $p_T$ jets and use quantities that are designed to select $\sim 500\text{GeV}-1\text{TeV}$ objects
   - Allows us to filter out models/scenarios that are not consistent with the global scale
   - Should be very effective at removing significant contamination from SM background

2. Identify the smoking-gun signature
   - Look for co-annihilation region: identify taus
   - Must be able to identify low $p_T$ taus!!!
   - Different points in SUSY parameter space can allow for similar global scales. We need to find the “smoking-gun” variables to discriminate between them

3. Excess in OS-LS DiTau Mass
   - use OS-LS method to remove remaining contamination from QCD and/or other SUSY backgrounds
Technical Details

- Privately produced patTuples (7TeV) using the HighMassAnalysis/Configuration framework w/ CMSSW_3_8_6:
  - https://twiki.cern.ch/twiki/bin/view/Sandbox/SUSYJetsMETTausAnalysis
  - LM2 is our signal sample

- HighMassAnalysis/Analysis framework used to carry out the actual analysis (used for plots and efficiencies shown today).

- Samples are skimmed using the following selections:
  - At least 2 PFTaus with leading pion \( p_T > 5 \text{ GeV} \)
  - At least 1 ditau pair with \( \Delta R(\tau_1,\tau_2)>0.7 \)

- Particle Flow is used for MET
- Particle Flow is used for taus
- Calorimeter based jets are used
1\textsuperscript{st} and 2\textsuperscript{nd} Leading Jet Distributions

- **Event Selection for Lead Jet Plot**
  - At least 1 jet with $p_T > 15$ GeV
  - $1\textsuperscript{st}$ Leading Jet $|\eta|<3$

- **Event Selection for 2\textsuperscript{nd} Lead Jet Plot**
  - At least 1 jet with $p_T > 15$ GeV
  - $1\textsuperscript{st}$ Leading Jet $p_T > 100$ GeV
  - $1\textsuperscript{st}$ Leading Jet $|\eta|<3$
  - $2\textsuperscript{nd}$ Leading Jet $|\eta|<3$

- **Define our 1\textsuperscript{st} and 2\textsuperscript{nd} jet cuts:**
  - $1\textsuperscript{st}$ Leading Jet $p_T > 100$ GeV
  - $2\textsuperscript{nd}$ Leading Jet $p_T > 50$ GeV

- One could apply larger thresholds, but at the risk of losing a large part of phase space … the proper cut will be determined during optimization.
Event Selections:
- At least 1 jet with $p_T > 15$ GeV
- 1st Leading Jet $p_T > 100$ GeV
- 1st Leading Jet $|\eta| < 3$
- 2nd Leading Jet $p_T > 50$ GeV
- 2nd Leading Jet $|\eta| < 3$

Define MHT Selection:
- $MHT > 150$ GeV
- We plan on using unprescaled MHT triggers (e.g. pfMht150)
- Final cut value will be determined by optimization

$$\vec{H} = - \sum_{i=jets \; w/ \; p_T > 15} \vec{p}_i$$

$$MHT = \sqrt{H_x^2 + H_y^2}$$
**Standard Tau Identification Cones**

- **Definition:** Seed track – highest $P_T$ track
  - For $\tau$ jets, a seed track (with $P_T > X$) is required within some matching cone from the jet axis

- **Track signal cone**
  - Defined relative to the seed track
  - Signal cone/annulus
    - $\Delta R = \text{"5.0/ET"}$ with max $\Delta R=0.15$ and min $\Delta R=0.07$

- **Track isolation annulus**
  - Region between the track signal cone and an outer isolation cone
  - Tracker isolation cones: $\Delta R=0.5$
Standard Tau Identification Cones

- Neutral pions from the tau will decay to $\gamma$'s
- $\gamma$'s will decay to electrons that bend in the B field
- Define the Ecal signal cone as an elliptical region in $\eta$–$\phi$ space
  - $R_\phi = 2R_\eta$
  - Ecal isolation cone: $\Delta R = 0.5$

$$
\left( \frac{\Delta \phi}{R_\phi} \right)^2 + \left( \frac{\Delta \eta}{R_\eta} \right)^2 < 1
$$

![Diagram of Standard Tau Identification Cones](image-url)
Tau Identification

- **Tau Jets vs. Standard Jets**
  - **Main differences:**
    - On average, standard jets have higher density of tracks
    - Taus have narrow energy profiles
    - Taus have fewer tracks (prongs) within a narrow cone (signal cone) around the jet axis

\[
\frac{1}{3} \text{Tracks} \quad \text{Larger Track Multiplicity}
\]
Isolation definition: 

\[ I = \sum_{tracks/gammas} P_T \]

Thresholds on tracks and gammas:

- \( P_T \) of tracks and gammas > 1 GeV

Define our selection: 

\[ I = \sum_{tracks/gammas} P_T < 1 \]

- Exotica Tau Definition
- Correct cut value will be determined by optimization
Summary of Current Event Selections

- **Acceptance**
  - Leading Jet $p_T > 100$ GeV and Jet $|\eta| < 3$
  - Second Leading Jet $p_T > 50$ GeV and Jet $|\eta| < 3$
  - At least 2 Taus $w/ p_T > 15$ and $|\eta| < 2.1$
  - MHT $> 150$ GeV
  - At least 2 ditau pairs with $\Delta R(\tau_1, \tau_2) > 0.7$

- **Tau ID**
  - At least 2 Taus passing the Electron and Muon vetos
  - At least 2 Taus with 1 or 3 prongs
  - At least 2 Taus passing Isolation
  - Identify specific decay modes (e.g. $a_1$ resonance)

- **Jet ID**
  - Jet-Tau cross-cleaning, ...

- **Topology**
  - Alpha
  - $\Delta \phi$(jet,MET)
  - ...

- **Final Reconstruction of Masses**
  - OS – LS to remove fake pairs and reconstruct endpoint

Cuts are chosen to stay away from systematic effects (e.g. track isolation not well understood at the edge of the tracker region)

Do NOT consider any jets with $\Delta R($jet, $\tau) < 0.5$

Not applying this criteria ... still studying discriminating power, etc.
Selection Efficiencies and Sensitivity

<table>
<thead>
<tr>
<th>Selection</th>
<th>LM2</th>
<th>Wjets</th>
<th>TTBar</th>
<th>ZinvJets</th>
<th>QCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Jet $\eta$</td>
<td>99.9 +/- 0.01</td>
<td>98.8 +/- 0.01</td>
<td>99.7 +/- 0.01</td>
<td>99.2 +/- 0.03</td>
<td>99.3 +/- 0.01</td>
</tr>
<tr>
<td>Lead Jet $p_T$</td>
<td>83.3 +/- 0.07</td>
<td>9.23 +/- 0.02</td>
<td>58.7 +/- 0.05</td>
<td>15.0 +/- 0.14</td>
<td>95.3 +/- 0.01</td>
</tr>
<tr>
<td>2nd Jet $\eta$</td>
<td>99.6 +/- 0.02</td>
<td>95.8 +/- 0.05</td>
<td>99.4 +/- 0.01</td>
<td>98.8 +/- 0.11</td>
<td>99.1 +/- 0.01</td>
</tr>
<tr>
<td>2nd Jet $p_T$</td>
<td>95.6 +/- 0.05</td>
<td>70.4 +/- 0.11</td>
<td>96.8 +/- 0.02</td>
<td>64.9 +/- 0.48</td>
<td>99.6 +/- 0.01</td>
</tr>
<tr>
<td>MHT &gt; 150</td>
<td>86.1 +/- 0.09</td>
<td>6.32 +/- 0.07</td>
<td>7.05 +/- 0.03</td>
<td>19.7 +/- 0.49</td>
<td>0.001 +/- 2e-4</td>
</tr>
<tr>
<td>N @ 1 fb$^{-1}$</td>
<td>385 +/- 1</td>
<td>1.4e4 +/- 164</td>
<td>5788 +/- 28</td>
<td>2652 +/- 73</td>
<td>7849 +/- 1327</td>
</tr>
<tr>
<td>Tau $\mu$ Veto</td>
<td>98.6 +/- 0.13</td>
<td>85.4 +/- 0.44</td>
<td>92.4 +/- 0.13</td>
<td>99.1 +/- 0.30</td>
<td>62.5 +/- 8.56</td>
</tr>
<tr>
<td>Tau e Veto</td>
<td>75.4 +/- 0.49</td>
<td>75.5 +/- 0.58</td>
<td>86.1 +/- 0.18</td>
<td>84.3 +/- 1.12</td>
<td>95.0 +/- 4.87</td>
</tr>
<tr>
<td>Tau Prongs</td>
<td>69.8 +/- 0.60</td>
<td>19.0 +/- 0.61</td>
<td>32.3 +/- 0.26</td>
<td>19.0 +/- 1.32</td>
<td>15.8 +/- 8.37</td>
</tr>
<tr>
<td>Tau Iso.</td>
<td>31.7 +/- 0.73</td>
<td>1.80 +/- 0.48</td>
<td>0.59 +/- 0.08</td>
<td>0.60 +/- 0.60</td>
<td>0.00</td>
</tr>
<tr>
<td>N @ 1 fb$^{-1}$</td>
<td>10.2 +/- 0.3</td>
<td>5.7 +/- 1.48</td>
<td>1.2 +/- 0.2</td>
<td>0.0 +/- 2.05</td>
<td>0 +/- 1e-4</td>
</tr>
</tbody>
</table>

Good S/B with only Acceptance, Tau ID, and Jet-Tau Cross-Cleaning!!!

Tau $p_T$ cut is ~ 15% efficient for LM2!!!!

Sensitivity will only improve with optimization and addition of topological cuts!
Tasks and Plans

- A lot of work to be done for this analysis:
  - Begin studying RA2 and RA2b cuts
    - Can some of those cuts improve our sensitivity?
    - It would be ideal to have similar acceptance criteria, so that it can be easier to untangle any discrepancies.
  - Need to include other topology cuts
    - Study $\alpha$, $\Delta \phi(MET,jets)$, $R_1$, $R_2$, ...
  - Need to study PU effect on taus, MET, etc.
    - DataMixer
  - Develop a plan for control regions and background extraction
  - Optimization of cuts
  - Systematics
  - Analysis needs a lot of cleaning up (e.g. don’t use taus as jets).
  - Are we including all backgrounds?
For now, our group is currently using a modified “Shrinking Cone” approach for the reconstruction and identification of $\tau$’s.

TanC and HPS $\tau$’s can be more difficult to understand.

Much more difficult to measure $\tau$ efficiencies for TanC and HPS

RA2 Tau Plan:

- Shrinking cone approach for signal track multiplicity and isolation
  - Very well developed and verified with 2010 collision data.

- Use pion reconstruction to identify $\tau$ decay modes (e.g. rho resonance, $a_1$ resonance, etc.)
  - Work in progress!
Backup
Establishing the Discovery

Expected Kinematics

\[ \tilde{\chi}_2^0 \rightarrow \tau^+ + \tilde{\tau}_1^- \rightarrow \tau^+ + \tau^- \tilde{\chi}_1^0 \]

\[ M_{\tau\tau}^{\text{max}} = M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}} \]

How to Establish the Discovery

[1] \( N_{\text{OS–LS}} \) (Number of OS–LS counts) > 0

[2] Clear peak (\( M_{\text{peak}} \)) and end-point (\( M_{\text{max}} \)) for OS–LS pairs

[3] \( M_{\text{peak}} \) related to \( \Delta M \), where \( \Delta M = M_{\tilde{\tau}_1} - M_{\tilde{\chi}_1^0} \)
CMS Detector
Topology

\[ H_T = \sum_{i=\text{jets with } p_T > 15} p_T^i \]

\[ E_T = \left[ - \sum_{i=\text{PFCandidates}} \vec{p}_i \right]_T \]

We are currently studying these variables as well as other topological variables …
Topology

No significant discriminating power

\[ \alpha = \frac{E_{T}^{\text{jet2}}}{M_{\text{DiJet}}} \]

We are currently studying these variables as well as other topological variables …
Angular variables are effective at discriminating signal from backgrounds such as QCD.

MET in QCD mostly points in the direction opposite to the leading jet.

\[ \delta \phi_2 = \phi_{MET} - \phi_{Jet2} \]

\[ \delta \phi_1 = \phi_{MET} - \phi_{Jet1} \]