Reconstruction of tau leptons and prospects for SUSY in ATLAS

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Outline

I  Introduction and Motivation

II  Tau reconstruction and identification in ATLAS

III SUSY analyses with tau leptons
   ✤ Inclusive: discovery prospects
   ✤ Exclusive: measurement of properties

IV  Summary
Motivation

Why are taus interesting for SUSY?

- 3rd generation special in SUSY: mixing of $\tilde{\tau}_L$ and $\tilde{\tau}_R$ to $\tilde{\tau}_1$, $\tilde{\tau}_2$

  - $\tilde{\tau}_1$ and therefore $\tau$ production enhanced

- $\tilde{\tau}_1$ in many models lightest slepton

  - $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$ larger BR than analog $e/\mu$ decays, may even be only allowed (2body) decay

  - important discovery channel

- tau final states provide unique information not accessible otherwise, e.g. on stau masses

- tau decay offers opportunity to measure tau polarization

  - information about couplings of $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$
**Introduction: tau leptons**

**Tau characteristics:**
- \( m_\tau \approx 1.7 \text{ GeV}, \ c_\tau \approx 87 \mu m \)
- \( \rightarrow \) decay within detector, visible only via decay products:
  - **35% leptonically**
    - 17.8% \( \tau \rightarrow e\nu_\tau \nu_e \)
    - 17.4% \( \tau \rightarrow \mu\nu_\tau \nu_\mu \)
  - **65% hadronically**
    - 50.2% 1prong (1 charged track)
    - 15.2% 3prong
    - 0.1% 5prong

**Towards tau reconstruction:**
- \( e/\mu \) from \( \tau \) decay hard to distinguish from prompt \( e/\mu \)
- \( \rightarrow \) current algorithms focus on hadronic decays:
  - 1 prong (1p):
    - 22.4% \( \tau \rightarrow \pi^\pm \nu_\tau \)
    - 73.5% \( \tau \rightarrow \pi^\pm \nu_\tau + n\pi^0 \)
  - 3 prong (3p):
    - 61.6% \( \tau \rightarrow 3\pi^\pm \nu_\tau \)
    - 33.7% \( \tau \rightarrow 3\pi^\pm \nu_\tau + n\pi^0 \)

\( \rightarrow \) tau lepton in detector:
- jet of charged and neutral pions

\( \rho^\pm \rightarrow \pi^\pm + \pi^0 \)
\( a_1^\pm \rightarrow \pi^\pm + 2\pi^0 \)
\( \pi^0 \rightarrow \gamma\gamma \)
The ATLAS detector

Ingredients for tau identification:

Tracking

- $cT \approx 87 \mu m \rightarrow$ secondary vertex
- Tracking constraint for taus: $|\eta| < 2.5$

Calorimetry

- High granularity of sampling calorimeter allows
- Good shower profile reconstruction
- Reconstruction of $\pi^0$ subclusters

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\( \tau \)s from the detector's point of view

Two reconstruction algorithms:
- track based: seeded by high quality tracks
- calorimeter based: seeded by calorimeter clusters

Main background: QCD jets

Basic distinctive \( \tau \) features:
- collimated tracks and energy depositions
- low track multiplicity
- isolation
- impact parameter (1p), displaced vertex (3p)
- ratio of EM/HAD energy

\( \tau \) jet

3 prong \( \tau \) decay

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Reconstruction

use combination of track- and calorimeter-seeded algorithms

- Begin with track based algorithm
- search matching calorimeter seed
  - no match: track-only candidate (5%)
  - match: track+calorimeter seeded candidate (70%)
- remaining clusters: seeds for calorimeter-only candidates (25%)
Identification

Many discriminating variables, using calorimeter and tracking information:
- #tracks in isolation cone and invariant mass of track system
- shower radius in electromagnetic calorimeter
- #hits with certain energy deposit in certain calorimeter layer
- $E_T$ fraction in cone $0.1<\Delta R<0.2$ w.r.t. total energy in cone 0.4
- ...

→ input for different discriminants: cut method, likelihood, neural network, boosted decision trees, PDRS

Identification in early data: “safe variables”
Reduce complex set of input variables to a few, well understood “safe” variables and use cut-based identification method for early data taking
Inclusive search strategy: cover all possible signatures

\[ x \text{ jets} + y \text{ leptons/taus} + \mathcal{E}_{T}^{\text{miss}} \text{ modes} \]

→ defined complementary to simplify combination

* development of selection cuts in chosen benchmark points in mSUGRA-like models
* scans of subsets of SUSY parameter space with fast detector simulation

Exclusive studies: focus on special signatures

* often very little background
* main goal: measurement of SUSY properties

Plots and numbers here: 1 fb\(^{-1}\) of 14 TeV data

\( \tau \) identification: track- and calorimeter-based algorithms used separately, safe variables not implemented yet

mSUGRA examples → R-parity conservation
Inclusive searches: tau mode

**Tau mode:**

*leptonic \( \tau \) decays: part of lepton modes*

**Event selection:**

- \( \geq 1 \ \tau \) (\( p_T > 40 \text{GeV} \), |\( \eta | < 2.5 \), calorimeter-based)
  → efficiency \( \approx 50\% \), purity \( \approx 80\% \) (SU3)
- no isolated lepton
- 4 jets: \( p_T > 50 \text{GeV} \), leading jet: \( p_T > 100 \text{GeV} \)
- \( E_T^{\text{miss}} > 100 \text{GeV} \), \( E_T^{\text{miss}} > 0.2 * \text{Meff} \)
  (\( \text{Meff} = E_T^{\text{mis}} + \sum_{i=1}^{4} p_T^{\text{jet } i} + \sum_{i=1} E_T^{\text{lepton } i} \))
- \( \Delta \Phi(\text{jet}_{1,2,3}, E_T^{\text{miss}}) > 0.2 \)
- transverse mass of hardest \( \tau \) (vis. momentum) and \( E_T^{\text{miss}} \): \( M_T > 100 \text{GeV} \)

**Trigger:** 97-100% efficiency expected when triggering on 1 jet (\( p_T > 70 \text{GeV} \)) plus \( E_T^{\text{miss}} > 70 \text{GeV} \)

(trigger rate: \( \sim 20 \text{ Hz} \) (for \( 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} \)))

→ Expected events at 1fb\(^{-1}\)

after tau mode selection cuts:
(S: signal, B: background)

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>B</th>
<th>S/\sqrt{B}</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU3</td>
<td>259</td>
<td>51</td>
<td>36.3</td>
</tr>
<tr>
<td>SU6</td>
<td>119</td>
<td>51</td>
<td>16.7</td>
</tr>
</tbody>
</table>

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**Exclusive studies:**

- For SUSY discovery: show it **is** SUSY
  - need to measure properties
- no mass peaks because of missing LSPs
  - kinematic edges
- dilepton mass spectrum holds information about **SUSY masses** involved in the decay chain: $\tilde{\chi}_1^0$, $\tilde{e}/\tilde{\mu}/\tilde{\tau}$, $\tilde{\chi}_2^0$

$$m_{\tau\tau}^{max} = \sqrt{\frac{(m(\tilde{\chi}_2^0)^2 - m(\tilde{\tau}_1)^2)(m(\tilde{\tau}_1)^2 - m(\tilde{\chi}_1^0)^2)}{(m(\tilde{\tau}_1)^2)}}$$

- shape of ditau mass spectrum also holds information about **stau mixing angle**

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Endpoint measurement

**ττ Invariant mass spectrum:** triangular shape washed out due to tau decay

- fit trailing edge with log-normal function
- measure inflection point
- use calibration (obtained with fast detector simulation) to derive endpoint

Event selection for bulk region point (SU3):
- $\geq 2\tau$ (calorimeter-seeded reconstruction)
- 4 jets: $p_T>220/50/50/30\text{GeV}$
- $E_T^{\text{miss}} > 230\text{GeV}$
- $\Delta R_{\tau\tau} < 2$

→ measured endpoint: (nominal value: 99 GeV)

$$m_{\tau\tau}^{\text{max}} = 102 \pm 17^{\text{stat}} \pm 5.5^{\text{syst}} \text{GeV} \ (1 \text{ fb}^{-1})$$

systematic error: includes fit uncertainty (binning, fit range) and 5% jet energy scale uncertainty
Model independence of endpoint method

- use same fit function and calibration for coannihilation point (SU1):
  - lower cross section (factor 0.4)
  - far tau very soft, hard to reconstruct

→ different event selection:

- \( \geq 2\tau \) (track-seeded reconstruction)
- 2 jets: \( p_T > 100/50 \text{GeV} \)
- \( E_T^{\text{miss}} > 100 \text{GeV} \)
- elliptical cut in \( (E_T^{\text{miss}}, p_T^{\text{jet1}} + p_T^{\text{jet2}}) \) plane
  (semi-axes 450 GeV (\( E_T^{\text{miss}} \)), 500 GeV (sum jet \( p_T \)))

→ measured endpoint: (nominal value: 78 GeV)

\[
m_{\tau\tau}^{\text{max}} = 70 \pm 6.5^{\text{stat}} \pm 5^{\text{syst}} \text{ GeV} \ (18 \text{ fb}^{-1})
\]

- ongoing work: use method in non-mSUGRA scenario
Influence of $\tau$ polarization on $\tau\tau$ mass spectrum:

\[ \tau_R^+ \rightarrow \pi^+ \]
\[ \tau_R^- \rightarrow \pi^- \]
\[ \tau_L^+ \rightarrow \pi^+ \]
\[ \tau_L^- \rightarrow \pi^- \]

$\tau \rightarrow \pi^+ \bar{\nu}_\tau$ : fixed neutrino handedness

→ pion momentum boosted (anti)parallel to tau momentum, dependent on tau polarization

→ mass spectra shifted for different $\tau$ polarizations:

* $\tau\tau$ spectrum depends on combination of near and far $\tau$ polarization $P_n + P_f$ and $P_n * P_f$

* Sum $P_n + P_f$ has far more impact than product

* Product $P_n * P_f \rightarrow$ variation bands
SUSY masses and $\tau$ polarizations change spectrum in different way

$\rightarrow$ fit spectrum with gaussian: more stable to polarization effects than log-normal function

$\rightarrow$ measure both with 2 observables:
$x(f_{\max})$, $x(0.1 \times f_{\max})$

$\rightarrow$ 2dim calibration

Fast detector simulation

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Implications for SUSY parameters

Constraints on mixing angle and stau mass:

- Sum of polarizations as function of stau mixing angle
  \[ P_n + P_f \]
  \[ \theta_{\tilde{\tau}} \]
  assumption: neutralino sector known from other measurements here: nominal values of SUSY

- Endpoint as function of stau mass
  \[ m_{\tilde{\tau}} \text{[GeV]} \]

Implication of measured values on SUSY parameters

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Improvement by separation of decay modes

Possible improvement by separation of $\tau$ decay modes:

- $\tau$ decay via vector mesons $\rho$, $a_1$: direction of boost different for longitudinal/tranversal mesons:
  - Longitudinally polarized: same as pion
  - Transversally polarized meson: opposite behaviour
  → Overall effect depends on relative branching ratio

$$\frac{1}{\Gamma_v} \frac{d\Gamma_v}{d\cos\theta} = \left( \frac{m_v^2}{m_T^2 + 2m_v^2} (1 - P_\tau \cos\theta) \right) + \left( \frac{\frac{1}{2} m_v^2}{m_T^2 + 2m_v^2} (1 + P_\tau \cos\theta) \right)$$

- $a_1$: same amount of longitudinal and transverse states
  → Inv. mass spectrum not affect by polarization effects
- $\rho$: more longitudinal than transverse states
  → Inv. mass spectrum shifted in same direction as for $\pi$ decays

- $P_n + P_f$ divide spectrum in affected ($\pi, K, \rho$)/not affected → 3x2 observables
- Assume ideal tau decay mode separation
- Fake taus: assigned to decay mode with probability of BR

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Fast detector simulation
Reconstruction of $\pi^0$ subclusters:

High granularity of ATLAS electromagnetic calorimeter allows reconstruction of isolated subclusters from $\pi^0$

I prong candidates:

<table>
<thead>
<tr>
<th>decay mode</th>
<th>no $\pi^0$ subclusters</th>
<th>1 $\pi^0$ subcluster</th>
<th>$\geq 2 \pi^0$ subclusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow \pi \nu_\tau$</td>
<td>65%</td>
<td>20%</td>
<td>15%</td>
</tr>
<tr>
<td>$\tau \rightarrow \rho \nu_\tau$</td>
<td>15%</td>
<td>50%</td>
<td>35%</td>
</tr>
<tr>
<td>$\tau \rightarrow a_1(\rightarrow 2 \pi^0 \pi) \nu_\tau$</td>
<td>9%</td>
<td>34%</td>
<td>57%</td>
</tr>
</tbody>
</table>

Invariant mass: candidates with at least one reconstructed $\pi^0$ subcluster, from $W \rightarrow \tau \nu_\tau$
Taus are important for SUSY
→ needed for searches and measurements
Endpoint of $\tau\tau$ invariant mass spectrum can be measured accurately with $\sim 1$ fb$^{-1}$
→ constraint on $\tilde{\tau}_1$ mass
Sum of polarizations can be measured additionally with $\sim 35$ fb$^{-1}$
→ constraint on $\tilde{\tau}$ mixing angle $\theta_{\tilde{\tau}}$
Performance of tau reconstruction and identification crucial
→ high reconstruction efficiency for visible signals
→ high purity for meaningful signals
→ information about tau decay could improve measurements significantly
backup
**Reconstruction**

- **Begin with track based algorithm**
  - Seed: high quality track ($p_T > 6$ GeV, requirements on #hits in subdetectors and $\chi^2$/ndf)
  - additional quality tracks ($p_T > 1$ GeV) in cone $\Delta R < 0.2$
  - $\eta$, $\phi$ reconstruction with $p_T$-weighting of tracks
  - check charge consistency

- **search matching calorimeter seed**
  - Jet “Cone4H1 TopoJet” ($E_T > 10$ GeV, $|\eta| < 2.5$) within $\Delta R < 0.2$

  → **no match:** track-only candidate (5%)
  - $E_T$ from EnergyFlow algorithm

  → **match:** track+calorimeter seeded candidate (70%)
  - $E_T$ from cells of calorimeter based algorithm

- **remaining clusters:** seeds for calorimeter-only candidates (25%)
  - $\eta$, $\phi$ reconstruction from cluster
  - looser track quality selection ($p_T > 1$ GeV)
Tau reconstruction and identification

Identification

Discriminating variables:

- variance $W_{\text{tracks}}$ (multiprong only)
- invariant mass of track system
- #tracks in isolation cone
- electromagnetic radius $R_{\text{em}}$
- # $\eta$ strips with certain energy deposit
- width of the energy deposit
- $E_T$ fraction in cone $0.1 < \Delta R < 0.2$ w.r.t. total energy in cone $0.2$
- transverse energy at EM scale in core cone and isolation cone $E_T^{\text{core}}, E_T^{\text{isol}}, E_T^{\text{isolHAD}}$
- hadronical $E_T$ fraction in core region w.r.t. sum $p_T$ of tracks
- visible mass
- transverse impact parameter
- transverse flight path
- $\pi^0$ subclusters

Calorimeter-based:

- radius in EM calorimeter
- isolation fraction
- width in strip layer
- $E_T(\text{EM})/E_T$
  → uses only calorimeter information

Additional for track+calorimeter-based:

- width of track momenta
- $E_T/p_T$ of leading track
- electromagnetic and hadronic $E_T$ fraction w.r.t. sum $p_T$ of tracks
- sum $p_T$ of tracks / $E_T$

Safe variables:
SUSY analyses with tau leptons

mSUGRA benchmark points used:

<table>
<thead>
<tr>
<th>SU1 coannihilation</th>
<th>$m_0$ [GeV]</th>
<th>$m_{1/2}$ [GeV]</th>
<th>$A_0$ [GeV]</th>
<th>$\tan\beta$</th>
<th>$\text{sgn} , \mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>70</td>
<td>350</td>
<td>0</td>
<td>10</td>
<td>+</td>
</tr>
<tr>
<td>SU3 bulk</td>
<td>100</td>
<td>300</td>
<td>-300</td>
<td>6</td>
<td>+</td>
</tr>
<tr>
<td>SU6 funnel</td>
<td>320</td>
<td>375</td>
<td>0</td>
<td>50</td>
<td>+</td>
</tr>
</tbody>
</table>
**Tau polarization**

\[ A_{j1L} = -\frac{m_\tau}{\sqrt{2}m_W \cos \beta} N_j^* \sin \theta_\tau + \frac{1}{\sqrt{2}} (N_j^* + N_{j1}^* \tan \theta_W) \cos \theta_\tau, \]

\[ A_{j1R} = -\frac{m_\tau}{\sqrt{2}m_W \cos \beta} N_j^* \cos \theta_\tau - \sqrt{2}N_{j1} \tan \theta_W \sin \theta_\tau, \]

→ polarization: \[ P = \frac{(A_{j1R})^2 - (A_{j1L})^2}{(A_{j1R})^2 + (A_{j1L})^2}, \]

Ditau mass spectrum for \( \tau \rightarrow \pi^\pm \nu_\tau \)

\[ N(m_{\pi\nu}) = 4m \left\{ (P_n \cdot P_f) \left[ \ln m (\ln m + 4m^2 + 4) + 4 (1 - m^2) \right] + \right. \]

\[ + (P_n + P_f) \left[ m^2 - 2 \ln m - 1 - \ln^2 m \right] + \ln^2 m \} \]
SUSY masses and τ polarizations change spectrum in different way
→ fit spectrum with gaussian: more stable to polarization effects than log-normal function
→ possible to measure both with 2 observables: \( x(f_{\text{max}}), x(0.1 \times f_{\text{max}}) \)
→ 2dim calibration needed:

Red plane: calibration function
Blue lines: equipotential lines

Fast detector simulation