Reconstruction of tau leptons and prospects for SUSY in ATLAS

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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 τ production enhanced
- * $\tilde{\tau}_1$ in many models lightest slepton
→ $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau$ **larger BR** than analog e/μ 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:

✱ $m_\tau \approx 1.7 \text{ GeV}$, $c\tau \approx 87 \mu\text{m}$
 → 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% 1 prong (1 charged track)

15.2% 3 prong

0.1% 5 prong

Towards tau reconstruction:

✱ e/μ from τ decay hard to
 distinguish from prompt e/μ
 → 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% $\tau \rightarrow 3\pi^\pm \nu_\tau + n\pi^0$

→ tau lepton
 in detector:
**jet of charged
 and neutral pions**

hadronic 1p
 $\rho^\pm \rightarrow \pi^\pm + \pi^0$
 $a_1^\pm \rightarrow \pi^\pm + 2\pi^0$
 $\pi^0 \rightarrow \gamma\gamma$

The ATLAS detector

Ingredients for tau identification:

Tracking

- * $c\tau \approx 87 \mu\text{m} \rightarrow$ secondary vertex
- * Tracking constraint for taus: $|\eta| < 2.5$

Calorimetry

High granularity of **sampling calorimeter** allows

- * good shower profile reconstruction
- * reconstruction of π^0 subclusters

τ 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 τ features: τ jet

- * collimated tracks and energy depositions
- * low track multiplicity
- * isolation
- * impact parameter (l_p), displaced vertex (3p)
- * ratio of EM/HAD energy

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

expected performance:

↑ calorimeter-based with likelihood selection

↓ track-based, NN selection

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

SUSY analyses with tau leptons

* Inclusive search strategy: cover all possible signatures

x jets + y leptons/taus + E_T^{miss} 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: 1fb^{-1} of 14 TeV data
- * τ 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 τ 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: $p_T > 100 \text{ GeV}$
- * $E_T^{\text{miss}} > 100 \text{ GeV}$, $E_T^{\text{miss}} > 0.2 * M_{\text{eff}}$
($M_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=1}^4 p_T^{\text{jet } i} + \sum_{i=1} p_T^{\text{lepton } i}$)
- * $\Delta\Phi(\text{jet}_{1,2,3}, E_T^{\text{miss}}) > 0.2$
- * transverse mass of hardest τ (vis. momentum)
and E_T^{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)

	S	B	$S/\sqrt{B}$
SU3	259	51	36.3
SU6	119	51	16.7

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: $\tilde{\chi}_1^0, \tilde{e}/\tilde{\mu}/\tilde{\tau}, \tilde{\chi}_2^0$

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

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

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Endpoint measurement

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

systematic error: includes fit uncertainty (binning, fit range) and 5% jet energy scale uncertainty

Endpoint measurement

Model independence of endpoint method

* use same fit function and calibration for **coannihilation point** (SUI):

- * 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^{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

Polarization dependence

Influence of τ polarization on $\tau\tau$ mass spectrum:

$\tau \rightarrow \pi^\pm \nu_\tau$: fixed neutrino handedness

$\rightarrow$ pion momentum boosted (anti)parallel to tau momentum, dependent on tau polarization

$\rightarrow$ mass spectra shifted for different τ polarizations:

* $\tau\tau$ spectrum depends on combination of near and far τ 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

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Endpoint and polarization measurement

SUSY masses and τ polarizations change spectrum in different way

→ fit spectrum with gaussian: more stable to polarization effects than log-normal function

→ measure both with 2 observables:

$x(f^{\max})$, $x(0.1 * f^{\max})$

→ 2dim calibration

Fast detector simulation

Implications for SUSY parameters

Constraints on mixing angle and stau mass:

assumption:
neutralino sector known
from other measurements
here: nominal values of SU1

Implication of measured values on
SUSY parameters

Improvement by separation of decay modes

Possible improvement by separation of τ decay modes:

* τ decay via **vector mesons** ρ , a_1 : direction of boost different for longitudinal/transversal mesons:

- * longitudinally polarized: same as pion
- * transversally polarized meson: opposite behaviour
- overall effect depends on relative branching ratio

$$\frac{1}{\Gamma_V} \frac{d\Gamma_V}{d\cos\vartheta} = \underbrace{\left(\frac{m_V^2}{m_\tau^2 + 2m_V^2} (1 - P_\tau \cos\vartheta) \right)}_{\text{transversal}} + \underbrace{\left(\frac{\frac{1}{2}m_\tau^2}{m_\tau^2 + 2m_V^2} (1 + P_\tau \cos\vartheta) \right)}_{\text{longitudinal}}$$

* a_1 : same amount of longitudinal and transverse states

→ inv. mass spectrum **not affect by polarization effects**

* ρ : more longitudinal than transverse states

→ inv. mass spectrum **shifted in same direction as for π decays**

* divide spectrum
in affected (π, K, ρ)/
not affected
→ 3x2 observables

* Assume **ideal** tau decay mode
separation
* Fake taus: assigned to decay
mode with probability of BR

Fast detector
simulation

Tau decay mode reconstruction

CERN-OPEN-2008-020

Reconstruction of π^0

subclusters:

✱ High granularity of ATLAS electromagnetic calorimeter allows reconstruction of isolated subclusters from π^0

1 prong candidates:

decay mode	no π^0 subclusters	1 π^0 subcluster	≥ 2 π^0 subclusters
$\tau \rightarrow \pi \nu_\tau$	65%	20%	15%
$\tau \rightarrow \rho \nu_\tau$	15%	50%	35%
$\tau \rightarrow a_1(\rightarrow 2\pi^0\pi)\nu_\tau$	9%	34%	57%

Invariant mass: candidates with at least one reconstructed π^0 subcluster, from $W \rightarrow \tau \nu_\tau$

Summary

- * Taus are important for SUSY
 - needed for searches and measurements
- * Endpoint of $\tau\tau$ invariant mass spectrum can be measured accurately with $\sim 1\text{fb}^{-1}$
 - constraint on $\tilde{\tau}_1$ mass
- * Sum of polarizations can be measured additionally with $\sim 35\text{fb}^{-1}$
 - 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 ($p_T > 6 \text{ GeV}$, requirements on #hits in subdetectors and χ^2/ndf)
- ✱ additional quality tracks ($p_T > 1 \text{ GeV}$) in cone $\Delta R < 0.2$
- ✱ η, ϕ reconstruction with p_T -weighting of tracks
- ✱ check charge consistency

✱ search matching calorimeter seed

- ✱ Jet “Cone4H I TopoJet” ($E_T > 10 \text{ GeV}$, $|\eta| < 2.5$) 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%)**

- ✱ η, ϕ reconstruction from cluster
- ✱ looser track quality selection ($p_T > 1 \text{ GeV}$)

Tau reconstruction and identification

Identification

Discriminating variables:

- * variance W_{tracks} (multiprong only)
- * invariant mass of track system
- * #tracks in isolation cone
- * electromagnetic radius R_{em}
- * # η 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
- * π^0 subclusters

safe variables:

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

SUSY analyses with tau leptons

mSUGRA benchmark points used:

	m_0 [GeV]	$m_{1/2}$ [GeV]	A_0 [GeV]	$\tan\beta$	$\text{sgn } \mu$
SU1 coannihilation	70	350	0	10	+
SU3 bulk	100	300	-300	6	+
SU6 funnel	320	375	0	50	+

Tau polarization

$$A_{j1L}^\tau = -\frac{m_\tau}{\sqrt{2}m_W \cos \beta} N_{j3}^* \sin \theta_{\tilde{\tau}} + \frac{1}{\sqrt{2}} (N_{j2}^* + N_{j1}^* \tan \theta_W) \cos \theta_{\tilde{\tau}}$$

$$A_{j1R}^\tau = -\frac{m_\tau}{\sqrt{2}m_W \cos \beta} N_{j3} \cos \theta_{\tilde{\tau}} - \sqrt{2} N_{j1} \tan \theta_W \sin \theta_{\tilde{\tau}},$$

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

Ditau mass spectrum for $\tau \rightarrow \pi^\pm \nu_\tau$

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

Endpoint and polarization measurement

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: $x(f^{\max})$, $x(0.1 * f^{\max})$
- 2dim calibration needed: