ATLAS discovery potential in the mSUGRA $\widetilde{\chi}_1^0 - \widetilde{\tau}$ coannihilation region

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Nordic Workshop on LHC and Beyond, Stockholm 12.06.08

Introduction

- Overview
- SUSY, mSUGRA and the coannihilation region
- End-point of $m_{\tau\tau}$ in the SU1 benchmark point
- Tau decay and tau reconstruction in ATLAS

Full simulation analysis of the SU1 benchmark point

- Samples used
- Invariant mass at generator level
- Background rejection
- Determination of an end-point

Results and conclusion

What and how

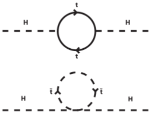
- The analysis performed is aimed to evaluate the potential for discovering SUSY in the mSUGRA coannihilation region.
- The SUSY decay chain $\widetilde{q} \rightarrow \widetilde{\chi}_2^0 q \rightarrow \widetilde{\tau}^{\pm}\tau^{\mp} q \rightarrow \tau^{\pm}\tau^{\mp} q \widetilde{\chi}_1^0$ has been studied.
- The invariant mass distribution of such taus has been investigated and a procedure to determine the end-point has been devised
- The cross section for this process is $O(10) >$ than for $\widetilde{\chi}_2^0 \rightarrow \widetilde{\ell}\ell$ ($\ell = e, \mu$)

- The work has been done using ATLAS full simulation CSC data sets
  - the background is statistically limited
- A detailed and inclusive study of background rejection has thus been performed with the available background.
- The study only consideres the mSUGRA benchmark point SU1, which lies in the coannihilation region

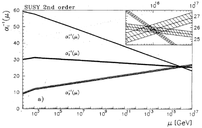
Why SUSY

MSSM provides elegant solutions to SM problems:

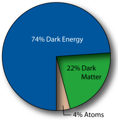
- If realized at the TeV-scale, SUSY provides a solution to the mass hierarchy problem;



- a unification of the SM couplings;



- if R-parity ($R = (-1)^{3(B+L)+2s}$) is conserved, the LSP is stable and hence a Dark Matter candidate (if el. neutral).



However, SUSY must be a broken symmetry

mSUGRA

- In order to make the MSSM manageable we make assumptions to constrain the parameter space based upon hypotheses of GUT:

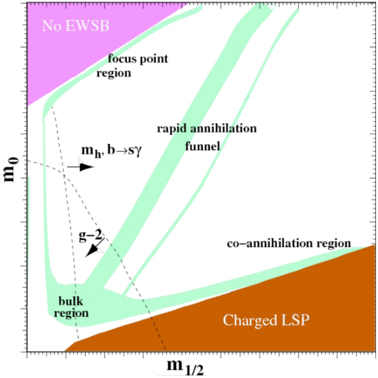
Unification of scalar and fermion superpartner masses	$\mathbf{m_0}, \mathbf{m_{1/2}}$
The Higgs mass parameter is fixed, but not the sign	**sgn**(μ)
The ratio between the two Higgs doublet VEVs	$\tan\beta$
A common value for all trilinear couplings in the Lagrangian	$\mathbf{A_0}$

Supersymmetry breaking mediated by gravity

- With these assumptions we are left with five parameters. Constraints upon these include DM relic density, the $b \rightarrow s\gamma$ branching ratio and the muon magnetic moment correction. These constraints exclude all but a few regions in the mSUGRA parameter space.

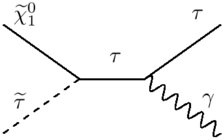
Why SU1

Quality plot of mSUGRA parameter space in $m_{1/2} - m_0$ plane



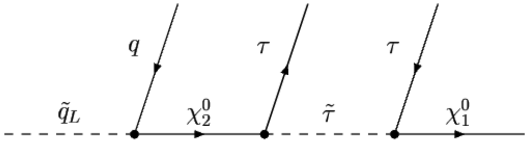
The coannihilation region is characterized by a small $\Delta m = m_{\tilde{\tau}} - m_{\tilde{\chi}_1^0} \leq 5 - 15$ GeV to allow the $\tilde{\tau}$'s to coannihilate with the $\tilde{\chi}_1^0$'s in the early universe to produce the amount of dark matter observed in the universe today.

▷ **One tau should be soft!**



The SU1 benchmark point

- LSP is χ_1^0 and is bino-like.
- The NLSP is the $\tilde{\tau}_1$ with a small mass difference to the LSP (9 GeV).
- χ_2^0, primarily produced in the decay of the left-handed squarks is wino-like.
- This leads to the decay chain studied:



- Taus important in this region as they are the most heavily produced.

- **One benchmark point in the coannihilation region:**

SU1 parameters		
m_0	$=$	70 GeV
$m_{1/2}$	$=$	350 GeV
A_0	$=$	0
$\tan(\beta)$	$=$	10
sgn μ	$>$	0

$\longrightarrow$

SUSY masses		
$m_{\tilde{\chi}_2^0}$	$=$	262.0 GeV
$m_{\tilde{\tau}_1}$	$=$	147.7 GeV
$m_{\tilde{\chi}_1^0}$	$=$	136.7 GeV

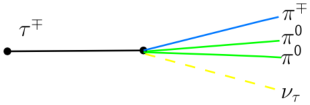
- **Masses are calculated with Isajet SUSY mass calculator**

$$m_{\tau\tau}^{max} = m_{\tilde{\chi}_2^0}\sqrt{1 - \frac{m_{\tilde{\tau}}^2}{m_{\tilde{\chi}_2^0}^2}}\sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\tau}}^2}} \simeq \mathbf{80\ GeV}$$

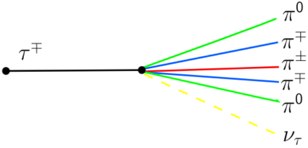
The τ-lepton

- Mean life time: $\tau_0 = 2.9 \cdot 10^{-13}$ s $\longrightarrow$ Flight distance of 87.11 μm
- Mass: 1.777 GeV $\longrightarrow$ Hadronic decay modes ($\sim$ 65%)

Tau reconstruction in ATLAS focuses on the hadronic decay modes



Single-prongs 76.4 %
$\rightarrow$ 23.5 % only charged $\pi^{\pm}$
$\rightarrow$ 76.5 % also neutral π^0



Three-prongs 22.5 %
$\rightarrow$ 64.6 % only charged $\pi^{\pm}$
$\rightarrow$ 35.4 % also neutral π^0

Tau reconstruction in ATLAS

- **Two algoritms:** `tauRec` **and** `tau1p3p`
  - → `tauRec`: calorimeter based, $E_T > 15\,\text{GeV}$
  - → `tau1p3p`: track based, $p_T^{\pi^\pm} > 9\,\text{GeV}$
- main difficulty is to distinguish tau-jets from QCD-jets
- tau-jet characteristics:
  - → low track multiplicity
  - → collimated jets
  - → strong EM component from π^0
- 1-prong τ's are easier to distinguish from QCD-jets than 3-prong τ's
- During winter/spring 2008 the two algorithms has been merged:
  - → lower p_T threshold in `tau1p3p`; $p_T^{\pi^\pm} > 6\,\text{GeV}$

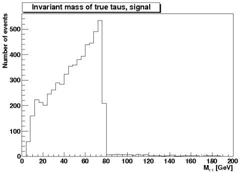
Full simulation analysis of the SU1 benchmark point

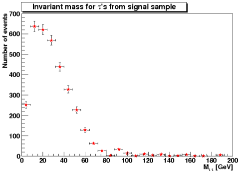
Sample	Number of events	Cross section [pb]	Data set	version
BACKGROUND:				
$t\bar{t}$	349 800	461	5200	12.0.6.4
$Z \rightarrow \tau\tau$	149 200	246	5188	12.0.6.1
$W \rightarrow \tau\nu$	338 700	5536	5107	12.0.6.1
QCD[1] $35 \leq p_T \leq 70$ GeV	153 750	$9.33 \cdot 10^7$	5011	12.0.6.1
QCD[2] $70 \leq p_T \leq 140$ GeV	335 550	$5.88 \cdot 10^6$	5012	12.0.6.1
QCD[3] $140 \leq p_T \leq 280$ GeV	10 000	$3.08 \cdot 10^5$	5013	12.0.6.1
SIGNAL:				
SUSY SU1	198600	11.86	5401	12.0.6.1
GENERATOR LEVEL				
$t\bar{t}$	10 000	11.66	5200	12.0.6
SUSY SU1	80 000	11.86	5401	12.0.6

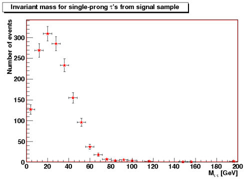
- The generator level samples are private productions, generated using Athena 12.06 with CSC jobOptions. All reconstructed nTuples were made using SUSYView. All taus are reconstructed with tau1p3p.

Invariant mass at generator level

- By plotting the invariant mass for *true* signal taus, we see that the end-point agrees with the theoretical calculation.
- For hardonically decaying single and three prong taus the distribution is smeared, but the end-point remains ∼same.
- In this analysis only single-prong decaying taus have been considered. Here, the end-point is slightly shifted.



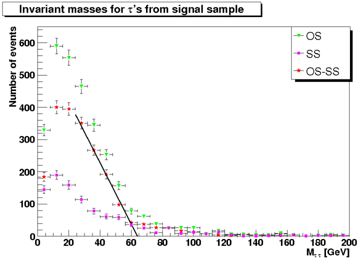




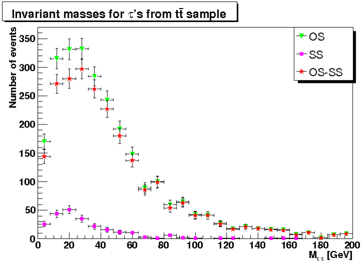
The τ's are here restricted to decay from $\tilde{\chi}_2^0$ or $\tilde{\tau}$

Invariant mass at generator level

- Combine all possible tau pairs and plot SS and OS tau pair distributions:



signal

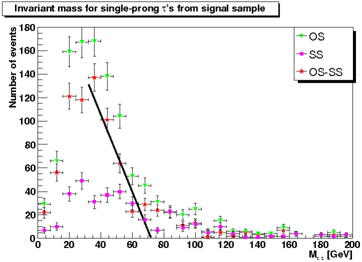


$t\bar{t}$ background

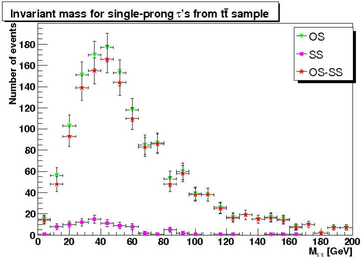
- By subtracting the invariant mass distribution for SS τ pairs from the one for OS tau pairs, we can reduce contributions from underlying processes and misidentified taus by assuming equal distributions.

Invariant mass at generator level

- Have used the `tau1p3p` algorithm for reconstructing taus in all samples used in this analysis. We introduce the cut $p_T^{\pi^\pm} = 9\,\mathrm{GeV}$ at generator level to see how much the shape of the invariant mass distributions are influenced by this cut:

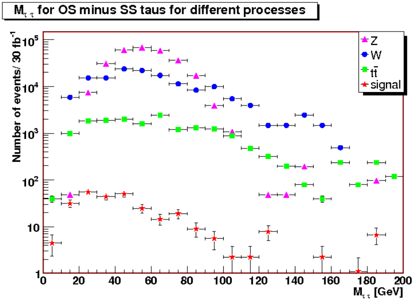


signal



$t\bar{t}$ background

After finding the shape of the desired signal, the big question is: Can the signal be observed over background?

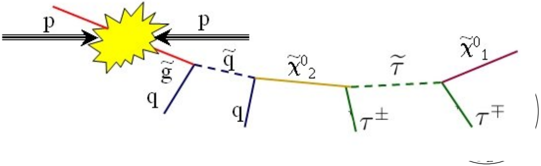


process	x-section [pb]
Z	246
W	5536
tt	461
SUSY	11.86

Need good cut methods!

Signal characteristics

- Two taus with OS
- High energetic jets
- Missing E_T
- One soft tau



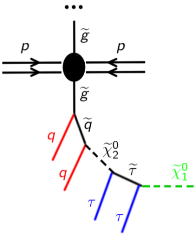
Process	Number of events	Passed cut 1	Passed cut 2	Passed cut 3
Z	149 200 (4 919 120)	6953 (229 240)	35 (1150)	32 (1055)
W	338 700 ($1.1 \cdot 10^8$)	651 (212 800)	6 (1960)	4 (1310)
$t\bar{t}$	349 300 (9 507 950)	870 (23 680)	161 (4380)	116 (3160)
SUSY	198 600 (236 330)	569 (677)	478 (568)	454 (540)

- Cut 1: Number of taus ≥ 2
- Cut 2: Number of taus $\geq 2 + E_T^{miss} > 100$ GeV
- Cut 3: Number of taus $\geq 2 + E_T^{miss} > 100$ GeV $+ E_T^{jet1} \geq 100$ GeV

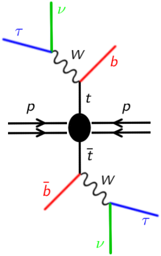
Numbers in parenthesis are normalized to 20 fb^{-1}

$t\bar{t}$ background most challenging

where each top decays as $t \to Wb \to b\tau\nu$



Signal

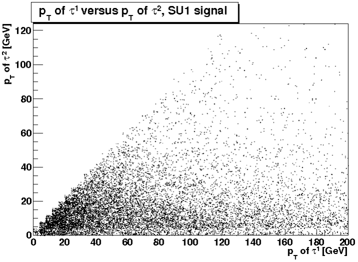


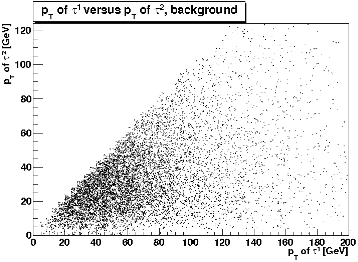
Background

- Different colours indicate similarities:
  - Two OS tau leptons
  - Two high energetic jets
  - Missing E_T
- $t\bar{t}$ cross section $\sim 40 \times$ larger

Cuts to optimise sensitivity:

1) Exploiting the feature of a soft tau:



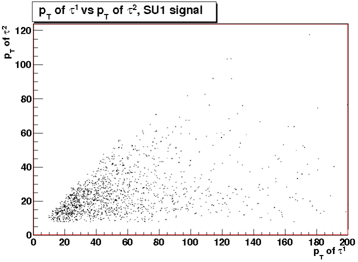


Signal **Background**

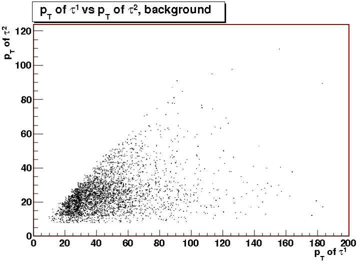
Generator level

Cuts to optimise sensitivity:

1) Exploiting the feature of a soft tau:



Signal

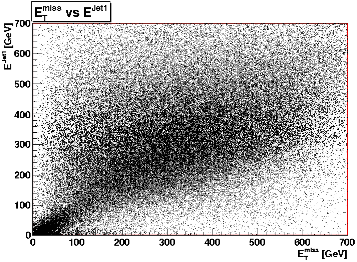


Background

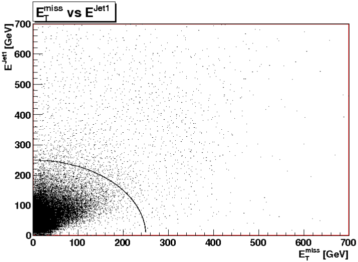
Reconstructed level

Cuts to optimise sensitivity:

2) Missing energy versus jet-energy:



Signal

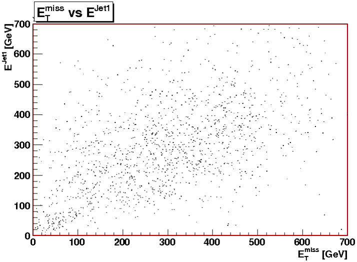


Background

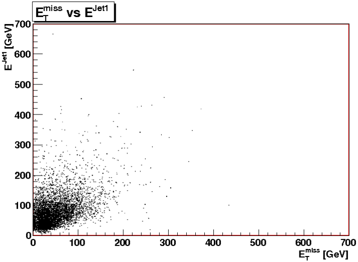
before requiring two taus

Cuts to optimise sensitivity:

2) Missing energy versus jet-energy:



Signal

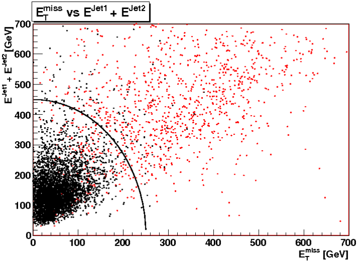


Background

after requiring two taus

Cuts to optimise sensitivity:

3) Missing energy versus sum of jet-energy:



Elliptic cuts in this plane give good results

Cut methods and sensitivity

- 4) Elliptic cut in the plane spanned by E_T^{miss} and p_T of next-to-leading τ

$$S = \frac{\text{\# of signal events}}{\sqrt{\text{\# of background events} + \text{\# of signal events}}},$$

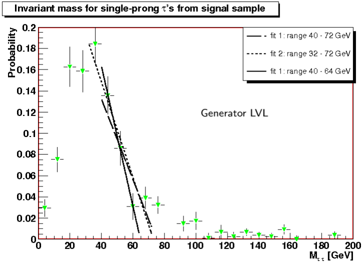
- Tried different elliptic shapes by varying semi minor and semi major axis in the ellipse to obtain the best sensitivity
- **Method 4 gave best results: sensitivity of 15.6 for 20 fb^{-1}**

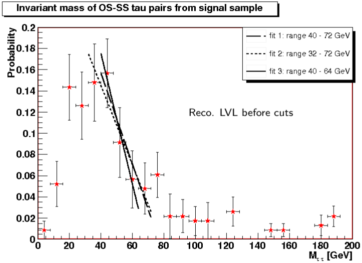
So we know the theoretical shape of $m_{\tau\tau}$ and we manage (to some extent) to reduce the SM background

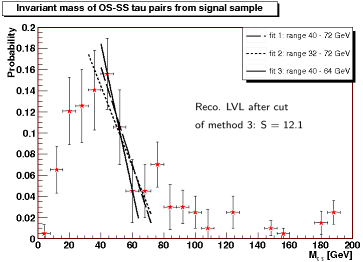
How can we determine an end-point?

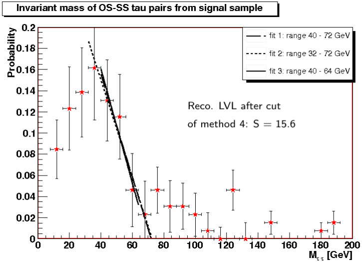
- Have applied a linear fit from the upper edge of the distribution to the region where we expect to locate the end-point, and obtain an end-point where the intersection point of the fit with the x-axis
- Not ideal, depends on fit range and of the binning of the histogram
- Due to low statistics we could not vary the bin size of the histogram
- Have selected three different fit ranges

Invariant mass of $\tau\tau$ (OS-SS)







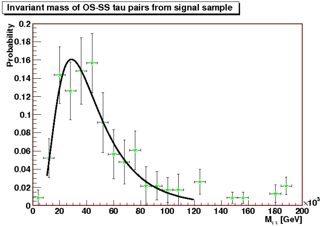


Results

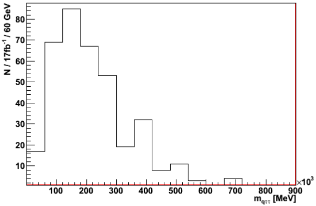
Distribution at:	slope a $[-10^{-3}\ \mathrm{GeV}^{-1}]$	end-point [GeV]	S
Generator level:			
fit region 1: 40- 72 GeV	3.7 ± 0.4	75.0 ± 3.6	
fit region 2: 32- 72 GeV	4.5 ± 0.3	73.0 ± 2.5	
fit region 3: 40- 64 GeV	6.6 ± 1.3	64.8 ± 2.5	
Reco. level before cuts:			
fit region 1: 40- 72 GeV	4.3 ± 1.6	76.7 ± 7.7	
fit region 2: 32- 72 GeV	3.7 ± 1.2	78.8 ± 8.2	
fit region 3: 40- 64 GeV	6.1 ± 2.2	68.6 ± 7.3	
Reco. level after cut 1:			
fit region 1: 40- 72 GeV	4.6 ± 1.7	75.2 ± 6.9	
fit region 2: 32- 72 GeV	3.8 ± 1.2	78.4 ± 8.2	12.1
fit region 3: 40- 64 GeV	6.9 ± 2.2	66.7 ± 6.3	
Reco. level after cut 2:			
fit region 1: 40- 72 GeV	4.9 ± 2.0	72.1 ± 6.9	
fit region 2: 32- 72 GeV	4.6 ± 1.5	72.6 ± 6.9	15.6
fit region 3: 40- 64 GeV	5.4 ± 3.2	69.9 ± 11.0	

Work in progress:

- **Try other fit functions:**
  See CSC note SUSY 6



- **Construct $m_{\tau\tau q}$:**



Remarks, conclusion and further work

- Background is statistically limited
  $\rightarrow$ this may in future be solved with combining full and fast simulation
- High sensitivities (15.6) was achieved
- Limited statistics of signal surviving background rejection
  $\rightarrow$ balance between high sensitivity and surviving signal
- Fit parameters for three different fit ranges are in good agreement after cuts
- Lowering p_T threshold in tau1p3p should improve statistics
- Signal passes the trigger chain
- Construct invariant mass distribution for several points in the coannilhilation region and repeat the procedure to determine end-point
- Find way to convert measured to theoretical end-point