Sparticle mass reconstruction in supersymmetry with long-lived staus

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Talk at University of California, Davis

October 27, 2010

List of publications

1. *Neutralino reconstruction in supersymmetry with long-lived staus*, SB and Biswarup Mukhopadhyaya.
   Published in Phys. Rev. **D79:115009**, (2009), arXiv:0902.4349 [hep-ph]
2. *Chargino reconstruction in supersymmetry with long-lived staus*, SB and Biswarup Mukhopadhyaya.
   Published in Phys. Rev. **D81:015003**, (2010), arXiv:0910.3446 [hep-ph]
3. *Reconstruction of the left-chiral tau-sneutrino in supersymmetry with a right-sneutrino as the lightest supersymmetric particle*, SB.
   Accepted in Phys. Rev. D, arXiv:1002.4395 [hep-ph].

Outline

- Introduction
- Choice of mSUGRA parameters
- Basic strategy and results
    - Neutralino reconstruction
    - Chargino reconstruction
    - Left-chiral tau sneutrino reconstruction
- Conclusion

Introduction

- Standard Model of particle physics is incomplete...
  - The Higgs mass is unstable under the radiative correction
  - It does not explain the observed non-vanishing neutrino masses and mixing
  - It also does not explain the observed DM density and baryon asymmetry of the Universe.
- There are ample reasons to look for physics beyond the Standard Model.

- Physics beyond the Standard Model $\Rightarrow$ new particles.
- Supersymmetry: Bosons $\Longleftrightarrow$ Fermions
  $\rightarrow$ not an exception.
- Measuring mass and spin of these new particles are of paramount importance.

General features of SUSY at the LHC

- SUSY production is dominated by gluinos and squarks.
- the gluinos and squarks cascade down, generally in several steps, giving rise to the canonical SUSY signal,

  multi-jets and/or leptons and missing transverse energy ($\not{E}_T$) due to two invisible LSPs

  (in a R-parity, defined as $R = (-)^{3B+L+2S}$, conserving scenario.)
- Mass reconstruction is quite a difficult task at the LHC.

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But this possibility is not unique.

Alternative SUSY signal at the LHC

- One can have a charged particle as the NLSP and the decay of it into the LSP is suppressed $\Rightarrow$ NLSP becomes stable on the length scale of the detector.

  $\Rightarrow$ The essence of SUSY signal lies not in $\not{E}_T$, but in charged track due to massive particle, seen in the muon chamber.
- Additional kinematic information $\Rightarrow$ opens up the possibility of mass reconstruction

Right-handed sneutrino LSP scenario

- The scenario we have studied as an example is a right-handed sneutrino LSP and the NLSP is the superpartner of tau.
- In MSSM one can achieve this by the addition of a right-handed neutrino superfield for each family in the MSSM spectrum, assuming neutrino to be of Dirac type.
- The superpotential in this case is given by

$$W_{MSSM} = y_l \hat{L}\hat{H}_d\hat{E}^c + y_d\hat{Q}\hat{H}_d\hat{D}^c + y_u\hat{Q}\hat{H}_u\hat{U}^c + \mu\hat{H}_d\hat{H}_u + y_\nu\hat{H}_u\hat{L}\hat{\nu}_R^c$$

- These sneutrinos will have all their interactions proportional to y_ν

- It is possible to accommodate such a scenario in a high-scale framework of SUSY breaking:

mSUGRA

$$m_0,\ M_{1/2},\ A_0,\ sign(\mu),\ \tan\beta$$
$$\Downarrow$$

All the low energy parameters

- The RGE of the right-chiral sneutrino mass parameter at the one-loop level is given by-

$$\frac{dM^2_{\tilde{\nu}_R}}{dt} \simeq \frac{2}{16\pi^2} y_\nu^2\ A_\nu^2$$

- The small Dirac masses of the neutrinos $m_\nu = y_\nu \left\langle H_u^0 \right\rangle = y_\nu v\ \sin\beta \Rightarrow y_\nu \sim 10^{-13}$ such a small $y_\nu \Rightarrow M_{\tilde{\nu}_R}$ to remain frozen at m_0

- The soft SUSY breaking terms contributing to neutrino mass

$$-\mathcal{L}_{soft} \sim M_{\tilde{L}}^2 \tilde{L}^\dagger \tilde{L} + M_{\tilde{\nu}_R}^2 |\widetilde{\nu}_R|^2 + (y_\nu A_\nu H_u . \tilde{L} \widetilde{\nu}_R^c \ + \ h.c.)$$

- The sneutrino mass-squared matrix is of the form

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & y_\nu v (A_\nu \sin\beta - \mu \cos\beta) \\ y_\nu v (A_\nu \sin\beta - \mu \cos\beta) & M_{\tilde{\nu}_R}^2 \end{pmatrix}$$

- The lighter sneutrino mass eigenstate

$$\tilde{\nu}_1 = -\tilde{\nu}_L \sin\theta + \tilde{\nu}_R \cos\theta$$

where the mixing angle θ is given as

$$\tan 2\theta = \frac{2y_\nu v \sin\beta |\cot\beta\mu - A_\nu|}{m^2_{\tilde{\nu}_L} - m^2_{\tilde{\nu}_R}}$$

which for each family is dominated by the right-chiral state.

- Thus one naturally has RH-sneutrino LSP for a wide range of values of the gaugino mass parameter.

mSUGRA parameters

- The low energy mass spectrum is determined from the mSUGRA parameter set $(m_0, M_{1/2}, A_0, sign(\mu)$ and $\tan\beta)$ specified at some high scale value using the Spectrum Generator: `ISASUGRA v7.78`
- We have worked in the region of m_0-$M_{1/2}$ plane where a $\tilde{\tau}$ LSP occur in a usual mSUGRA scenario without the right handed sneutrino.
- The value of A_0 is fixed at 100 GeV without any loss of generality and $sign(\mu)$ has been taken to be $+$ve.

Input	BP-1	BP-2	BP-3	BP-4	BP-5	BP-6
mSUGRA	$m_0 = 100$ $m_{1/2} = 600$ $\tan\beta = 30$	$m_0 = 100$ $m_{1/2} = 500$ $\tan\beta = 30$	$m_0 = 100$ $m_{1/2} = 400$ $\tan\beta = 30$	$m_0 = 100$ $m_{1/2} = 350$ $\tan\beta = 30$	$m_0 = 100$ $m_{1/2} = 325$ $\tan\beta = 30$	$m_0 = 100$ $m_{1/2} = 325$ $\tan\beta = 25$
$m_{\tilde{\nu}_{iR}}$	100	100	100	100	100	100
$m_{\tilde{e}_L}, m_{\tilde{\mu}_L}$	418	355	292	262	247	247
$m_{\tilde{e}_R}, m_{\tilde{\mu}_R}$	250	214	183	169	162	162
$m_{\tilde{\nu}_{eL}}, m_{\tilde{\nu}_{\mu L}}$	408	343	279	247	232	232
$m_{\tilde{\nu}_{\tau L}}$	395	333	270	239	224	226
$m_{\tilde{\tau}_1}$	189	158	127	112	106	124
$m_{\chi_1^0}$	248	204	161	140	129	129
$m_{\chi_2^0}$	469	386	303	261	241	240
$m_{\chi_1^\pm}$	470	387	303	262	241	241
$m_{\tilde{g}}$	1362	1151	937	829	774	774
$m_{\tilde{t}_1}$	969	816	772	582	634	543
m_{h^0}	115	114	112	111	111	111

Table: *Proposed benchmark points (BP) for study of stau-NLSP scenario in the SUGRA with right-sneutrino LSP. All the values except* $\tan\beta$ *are given in GeV.*

Collider simulation

- We have used the event generator Pythia v6.4.16 for our simulation.
- *pp* collision has been simulated with a cm energy $E_{cm} = 14\ TeV$.
- CTEQ5L pdf used in the simulation.
- QCD renormalisation and factorisation scales set at the $\mu_{\mathbf{F}} = \mu_{\mathbf{R}} = \mathbf{m}^{\mathbf{final}}_{\mathbf{average}}$.
- Hadronisation has been done, using the fragmentation functions inbuilt in Pythia.
- The effects of ISR and FSR and finite detector resolution have been taken into account.

Neutralino reconstruction

- Neutralino are produced in cascade decay
  $\tilde{q} \to q\chi_i^0 \to q\tilde{\tau}^*\tau$
  $\tilde{g} \to \bar{q}\tilde{q} \to \bar{q}q\chi_i^0 \to \bar{q}q\tilde{\tau}^*\tau$

  $\Rightarrow 2\tau_j + 2\tilde{\tau}(\text{charged-track}) + \not{E}_T + X$
- We have not consider any isolated leptons
  $\Rightarrow$Minimize the contribution to $\not{E}_T$ of neutrinos other than from taus.

Event selection criteria

Events have been selected with the following basic criteria

$p_T^{lep,stau} > 10$ GeV

$p_T^{hardest-jet} > 75$ GeV

$p_T^{other-jets} > 50$ GeV

$\not{E}_T > 40\ GeV$

$|\eta| < 2.5$ for leptons, jets & stau

$\Delta R_{ll} > 0.2,\ \Delta R_{lj} > 0.4$

$\Delta R_{\tilde{\tau}l} > 0.2,\ \Delta R_{\tilde{\tau}j} > 0.4$

$\Delta R_{jj} > 0.7$

where, $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

Neutralino reconstruction

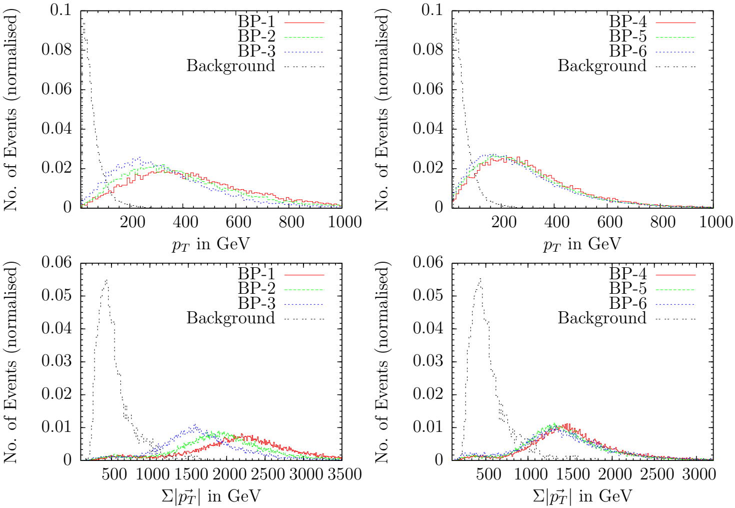

Fig. *p_T (top) and $\Sigma|\vec{p_T}|$ (bottom) distribution (normalised to unity) for the signal and the background for all benchmark points.*

Neutralino reconstruction

To reduce the SM background

- $p_T > 100\ GeV$ for each charged track
- $\Sigma|p_T| > 1\,TeV$

τ-reconstruction

- We have selected hadronic jets with $E_T > 50\ GeV$, assuming the identification efficiency of a true tau-jet to be 50%, and a non-tau jet rejection factor of 20.
- If x_i is the fraction of the parent τ-energy carried by each product jet, then one can write

$$P_{h_i} = x_i P_{\tau_i} \quad (i = 1, 2)$$

(in the collinear approx. $E_\tau >> m_\tau$)

$$\vec{\not{E}}_T = \vec{p}_T^{\,\nu_1} + \vec{p}_T^{\,\nu_2} = (\frac{1}{x_1} - 1)\ \vec{p}_{h1} + (\frac{1}{x_2} - 1)\ \vec{p}_{h2}$$

D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, Phys. Rev. D **59**, 014037 (1999)

- Reconstruction of the neutralinos in the channel $\chi_1^0\ (\chi_2^0)\ \rightarrow \tilde{\tau}\tau$ requires...
  The information about $\tilde{\tau}$ 4-momenta $\Leftarrow$ knowledge of $m_{\tilde{\tau}}$
- First we identify a correct $\tau\tilde{\tau}$-pair by using a seed value for $m_{\tilde{\tau}}$ (=100 GeV) and demand

$$|M_{\tau\tilde{\tau}}^{pair1} - M_{\tau\tilde{\tau}}^{pair2}| \text{ is min. and} < 50\ GeV$$

- Demand for the correct pairs

$$M_{\tau_1\tilde{\tau}_1} = M_{\tau_2\tilde{\tau}_2}$$
$$\Downarrow$$

$$\sqrt{m_{\tilde{\tau}}^2 + |\vec{p}_{\tilde{\tau}_1}|^2}.E_{\tau_1} - \sqrt{m_{\tilde{\tau}}^2 + |\vec{p}_{\tilde{\tau}_2}|^2}.E_{\tau_2} = \vec{p}_{\tilde{\tau}_1}.\vec{p}_{\tau_1} - \vec{p}_{\tilde{\tau}_2}.\vec{p}_{\tau_2}$$

- This method is effective when both pairs of $\tau\tilde{\tau}$ come from $\chi_1^0\chi_1^0$ or $\chi_2^0\chi_2^0$.

Neutralino reconstruction

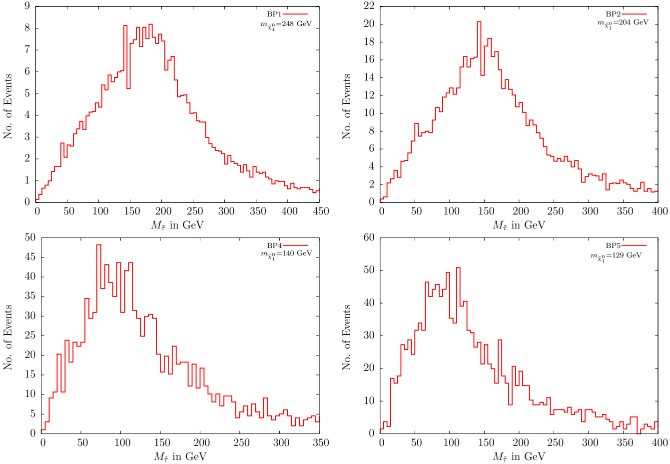

Fig. *The $\tilde{\tau}$ mass peak obtained from eventwise reconstruction of $m_{\tilde{\tau}}$.*

Neutralino reconstruction

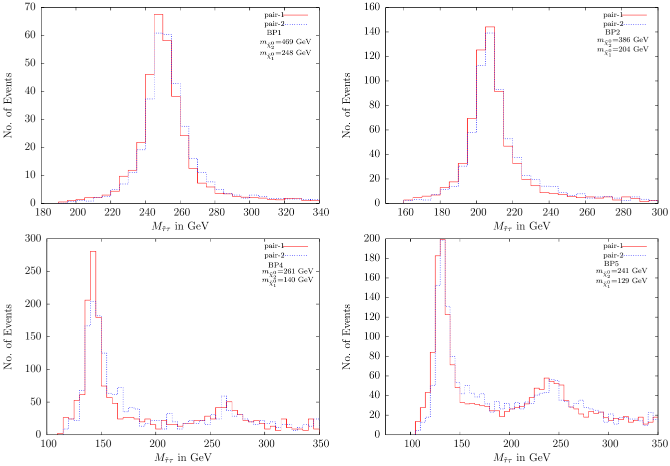

Fig. *$M_{\tilde{\tau}\tau}$ distribution for BP1, BP2, BP4 and BP5.*

CUTS	SIGNAL				BACKGROUND
	BP1	BP2	BP4	BP5	
Basic Cuts	1765	4143	20889	28864	4180
$+P_T$ Cut	1588	3631	15526	20282	214
$+\Sigma\lvert P_T\rvert$ Cut	1442	3076	9538	11266	63
$+\lvert M_{\tilde{\tau}\tau}^{pair1} - M_{\tilde{\tau}\tau}^{pair2}\rvert$ Cut	408	887	2004	2244	6

Table: *Number of signal and background events for* $2\tau_j + 2\tilde{\tau} + \not{E}_T + X$ *final state with an integrated luminosity of* 300 fb^{-1}.

Chargino reconstruction

- $\chi_1^\pm$ is produced in association with χ_1^0/χ_2^0 and hard jets.
- The $\chi_1^\pm$ subsequently decays into a $\tilde{\tau}^{(*)}$-$\nu_\tau^{(-)}$ pair, while the χ_1^0 (or χ_2^0) decays into a $\tilde{\tau}$-τ pair.
- The final state consists of $\tau_j + 2\tilde{\tau}(opposite - sign\ charged\ tracks) + \not{E}_T + X$
- Since the decay of $\chi_1^\pm$ involves an invisible particle (ν_τ), a transverse mass distribution, rather than invariant mass distribution, will give us information of $m_{\chi_1^\pm}$.

- The $\vec{\not{E}}_T$ is comprises of $\vec{\not{E}}_T = \vec{P}^T_{\nu_1} + \vec{P}^T_{\nu_2}$
- The transverse momenta of the neutrino ($\vec{P}^T_{\nu_2}$), out of a tau decay, is first reconstructed in the collinear approximation

$$P_{\tau_j} = xP_\tau$$

- Following the decay χ^0_1 (or, χ^0_2)$\longrightarrow \tilde{\tau}^\pm \tau^\mp$ one can write

$$m^2_{\chi^0_i} = (P_{\tilde{\tau}} + P_\tau)^2 = (P_{\tilde{\tau}} + P_{\tau_j}/x)^2 \quad (i = 1, 2)$$

- One can solve this to obtain

$$\vec{P}^T_{\nu_2} = \vec{P}^T_\tau - \vec{P}^T_{\tau_j} = \frac{1-x}{x}.\vec{P}^T_{\tau_j}$$

- The transverse momenta of the neutrino, out of $\chi_1^{\pm}$-decay can be extracted from the knowledge of $\vec{\not{E}}_T$ of that particular event

$$\vec{P}^T_{\nu_1} = \vec{\not{E}}_T - \vec{P}^T_{\nu_2}$$

- From the transverse mass distribution of the $\tilde{\tau}$-ν_τ pair, defined by,

$$M^T_{\tilde{\tau}\nu_\tau} = \sqrt{(E^T_{\tilde{\tau}} + E^T_{\nu_\tau})^2 - (\vec{P}^T_{\tilde{\tau}} + \vec{P}^T_{\nu_\tau})^2}$$

one can obtain the value of $m_{\chi_1^{\pm}}$

SUSY backgrounds

- SUSY processes in this scenario itself are serious than SM backgrounds
- The dominant contributions come from

$$\chi_i^0 \chi_j^0 + X \rightarrow (\tilde{\tau}\tau)(\tilde{\tau}\tau) + X$$

$$\searrow \swarrow$$

one of the τ not being identified

$$\tilde{\nu}_{\tau_L} \chi_i^0 + X \rightarrow (\tilde{\tau}W)(\tilde{\tau}\tau) + X$$

$$\downarrow$$

with the W not being identified

- Cut X: look at the invariant mass distribution of the $\tilde{\tau}$ (having same charge as that of the τ) with each jet in the final state and veto that event if

$$m_{\chi_i^0} - 20 < M_{\tilde{\tau}j} < m_{\chi_i^0} + 20$$

- Cut Y: veto event with W being identified in its hadronic decay if

$$M_W - 20 < M_{jj} < M_W + 20 \text{ and } \Delta R_{\tilde{\tau}j_r} < 0.8$$

Chargino reconstruction

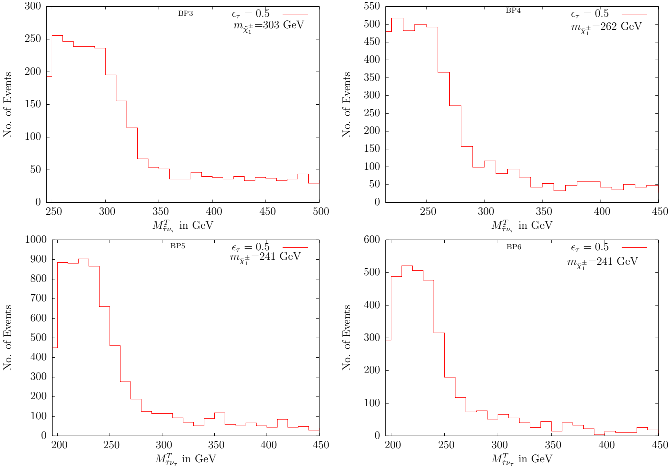

Fig. *$M^T_{\tilde{\tau}\nu_\tau}$ distribution for BP3, BP4, BP5 and BP6.*

BP4	Signal $(\chi^0_{1/2}-\chi^\pm_1)$	SM backgrounds	SUSY backgrounds $\chi^0_i-\chi^0_j$	SUSY backgrounds $\chi^0_{1/2}-\tilde{\nu}_{\tau L}$
Basic cuts	18194	65588	44580	10613
With $p_T + \Sigma\|p_T\|$ Cut	10697	202	31256	5713
Cut X+cut Y	4875	202	9872	1480
$M^T_{\tilde{\tau}\nu_\tau} > \frac{3}{4} m_{\chi^0_2}$	2345	1	1754	231
$\|M_{edge} - M^T_{\tilde{\tau}\nu_\tau}\| \leq 20$	1076	1	381	58

Table: *Number of signal and background event at an integrated luminosity of 300fb^{-1} for BP4.*

Left-chiral tau-sneutrino reconstruction

- The $\tilde{\nu}_{\tau_L}$ is produced predominantly via the decay of lightest chargino or second lightest neutralino .

$$\chi_1^{\pm} \rightarrow \tilde{\nu}_{\tau_L}^{(*)} \tau^{\pm}$$
$$\chi_2^0 \rightarrow \tilde{\nu}_{\tau_L} \bar{\nu}_\tau$$

- It has a sizeable decay branching fraction into a $W\tilde{\tau}$-pair (ranging from 34% to 80%).

Chargino reconstruction

- To reconstruct the left-chiral τ-sneutrino we have consider the following final state: $\tau_j + W + 2\tilde{\tau} + \not{E}_T + X$
- $\tilde{\nu}_{\tau_L}$ is produced mainly in association with $\chi^0_{1,2}$ in cascade decay of squarks and gluinos-
  $\chi^0_2 - \chi^0_{1,2} \to (\tilde{\nu}_{\tau_L}\nu_\tau)(\tilde{\tau}\tau) \to (W\tilde{\tau}\nu_\tau)(\tilde{\tau}\tau)$
  $\chi^\pm_1 - \chi^0_{1,2} \to (\tilde{\nu}_{\tau_L}\tau)(\tilde{\tau}\tau) \to (W\tilde{\tau}\tau)(\tilde{\tau}\tau)$
- W has been reconstructed in its hadronic decay mode.

- We have adopted two different method to identify correct $\tilde{\tau}W$-pair
  - Using opposite sign charged track-
    the W has been combined with the *stau* having same charge as that of the τ
  - Using chargino-neutralino mass information-
    W has been combined with the $\tilde{\tau}$ for which either of the following criteria is satisfied:
    $|M_{\tilde{\tau}\tau_j} - m_{\chi_i^0}| > 20 GeV$ or $|M_{\tilde{\tau}\tau_j W} - m_{\chi_i^\pm}| < 20 GeV$

Chargino reconstruction

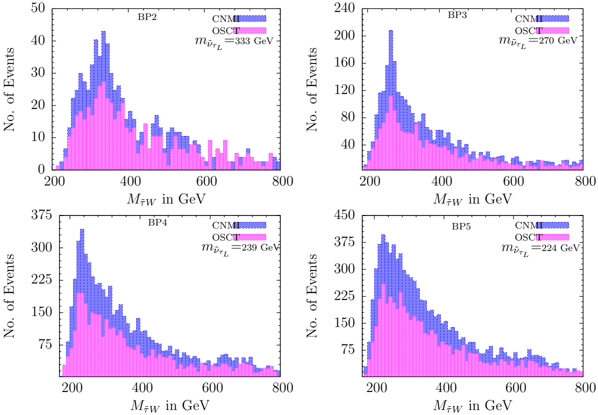

Fig. *$M_{\tilde{\tau}W}$ distribution for BP2, BP3, BP4 and BP5.*

Conclusion

- The mSUGRA scenario, with conserved *R*-parity, can eminently lead to a situation in which the right-chiral sneutrino is the LSP and stau is long-lived.
- The right-chiral sneutrino becomes a viable dark-matter candidate, due to its very small neutrino Yukawa coupling.
- The stau being long-lived, the signal of SUSY consists of charged tracks in the muon chamber.

- This feature can be used to reconstruct the mass of the SUSY particle in such a scenario.
- The method of reconstruction we have suggested is not limited to scenario with right-handed sneutrino LSP alone. It can be applied to all those scenarois in which stau is long-lived. (*e.g.* GMSB,..)
- The existence of quasi-stable massive charged particles is an interesting possibility to look for at the LHC...

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It not only offers a distinct SUSY signal, but also opens a new vista in the reconstruction of the superparticle masses.

Thank you!