

SUSY Inverse Seesaw and its implications at the LHC

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Introduction

- Experimental results on neutrinos \implies non-zero neutrino masses and mixing angles
- The data can be explained well with

$$7.09 \times 10^{-5} \text{ eV}^2 \leq \Delta m_{21}^2 \leq 8.19 \times 10^{-5} \text{ eV}^2$$

$$2.14 \times 10^{-3} \text{ eV}^2 \leq \Delta m_{31}^2 \leq 2.76 \times 10^{-3} \text{ eV}^2,$$

$$0.27 \leq \sin^2 \theta_{12} \leq 0.36, \quad 0.39 \leq \sin^2 \theta_{23} \leq 0.64,$$

$$0.001 \leq \sin^2 \theta_{13} \leq 0.035, \quad \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

- One needs to go to a theory beyond the SM
- Tempting to see whether TeV scale SUSY can explain the observed pattern of neutrino masses and mixing

Introduction

- Cosmological studies show that a large fraction of the mass of the Universe is dark and must be nonbaryonic
- Generation of neutrino masses provide new insight on the nature of the DM
- Within the Inverse Seesaw mechanism for generating neutrino masses, mSUGRA provides sneutrino to be the LSP
- A Natural DM candidate
- New particles at the TeV scale – can be tested at the LHC

$\Delta L=2$ Majorana masses – seesaw mechanism

- In the context of MSSM, supplement $\hat{\nu}_i$ (contained in $SU(2)_L$ doublet \hat{L}_i) with gauge singlet $\hat{\nu}_i^c$

$$\delta W = Y_\nu^{ij} \hat{H}_u \hat{L}_i \hat{\nu}_j^c + m_M^{ij} \hat{\nu}_i^c \hat{\nu}_j^c$$

- couplings Y_ν determine the Dirac masses for the neutrinos – $m_D \ll m_M$
 - $m_M \rightarrow$ Majorana masses
 - light neutrino masses $m_\nu \sim \frac{m_D^2}{m_M}$
- $$Y_\nu \sim \mathcal{O}(1), m_M \sim 10^{15} \text{ GeV} \implies m_\nu \sim 10^{-2} \text{ eV}$$
- Very interesting possibility in the context of the attempts to connect the SM with GUTS with $M_{GUT} \sim 10^{15} \text{ GeV}$

Inverse seesaw

- The inverse seesaw is one of the viable alternatives with a seesaw mechanism operational at the TeV scale
- By proposal inverse seesaw mechanism relies on a new mass parameter ($\Delta L = 2$) and small enough to ensure small neutrino masses
- In the SUSY inverse seesaw model, R -parity is conserved ($\Delta L = 2$).
- LSP is stable for this class of models and can be a viable candidate for the cold dark matter of the Universe.

Mohapatra (1986), Mohapatra, Valle (1986)
Gonzalez-Garcia, Valle (1989)

SUSY Inverse seesaw (SISM)

- mSUGRA + Inverse seesaw \Rightarrow LSP is a sneutrino instead of the lightest neutralino
- Naturally reconciles
 - Small neutrino masses
 - Correct relic abundance of sneutrino DM
 - Experimentally accessible direct detection rates

SUSY Inverse seesaw (SISM) and LHC

- May also have important implications for SUSY particle searches at the LHC
- When one of the singlet sneutrinos is the LSP, particle spectra and decay chains modified
- Phenomenology at the LHC can be very interesting.
- The neutrino Yukawa coupling is large and can lead to LFV coupling of the sneutrinos with a charged lepton and the chargino.
- Couplings are related to the observed neutrino mixing angles – study the relation between neutrino physics and the physics at the high energy colliders.

Light Dark Matter

- Recent data from three DM direct detection experiment, namely DAMA, CoGeNT and CRESST suggested a light DM mass in the 10-100 GeV range
- Cross section in the range $10^{-3} - 10^{-6}$ pb for elastic scattering off nucleons
- Several other direct detection experiments do not see any such positive hints of a particle DM
- May not be premature to examine some BSM scenarios accommodating a light DM candidate in case any of these positive hints are confirmed in near future.

Light Neutralino Dark Matter in MSSM

- Gaugino mass unification in the MSSM $\Rightarrow m_{\tilde{\chi}_1^0} \gtrsim 50$ GeV (LEP SUSY search) and $\gtrsim 200$ GeV (LHC)
- In order to have a light neutralino LSP, one needs to go to a non-universal MSSM parameter space

D. Hooper, T. Plehn (2003)

S. Choi, S. Scopel, N. Fornengo, A. Bottino (2011)

N. Fornengo, S. Scopel, A. Bottino (2010)

Dark Matter and SUSY Inverse Seesaw

- MSSM needs to be extended to accommodate small neutrino masses
- Interesting to see if these extensions can also provide a viable light DM candidate while satisfying collider, relic density and other low energy constraints in the leptonic sector
- Three lepton number carrying neutral fermions per family
 - (ν_L, N^c, S)
- If a linear combination of the superpartners of these fields turns out to be the LSP, then it could be a scalar DM candidate

Arina, Bazzocchi, Fornengo, Romao, Valle, PRL 101, 161802 (2008)

Our approach

- We take a hybrid approach
- Top-down approach for the MSSM particle spectrum (mSUGRA)
- Low-energy inputs for the LNV soft SUSY breaking sector and the singlet neutrino sector

Can such a mSUGRA scenario with inverse seesaw give a light DM candidate ?

What the collider signals for such a scenario are ?

How to distinguish it from cMSSM at the LHC ?

Sneutrino Dark Matter

- The lightest sneutrino can have mass in the few GeV range without being in conflict with the collider bounds on gluino and chargino masses
- To check whether lightest sneutrino has the right admixture of the left and singlet sneutrino flavors to
 1. Reproduce the observed relic density
 2. Satisfy the constraints from direct and indirect detection experiments
 3. Satisfy constraints from other low energy sectors

Sneutrino Dark Matter

- We find that the lightest sneutrino mass has to be more than ~ 50 GeV
- Benchmark points we find around 50 GeV DM mass are all consistent with the recent measurement of the lightest Higgs mass around 125 GeV

The Model

The superpotential is

$$\mathcal{W}_{\text{SISM}} = \mathcal{W}_{\text{MSSM}} + \epsilon_{ab} y_\nu^{ij} \hat{L}_i^a \hat{N}_j \hat{H}_u^b + M_{R_{ij}} \hat{N}_i \hat{S}_j + \mu_{S_{ij}} \hat{S}_i \hat{S}_j$$

μ_S term is the only lepton-number breaking term in the superpotential

The soft SUSY breaking Lagrangian is

$$\begin{aligned} \mathcal{L}_{\text{SISM}}^{\text{soft}} &= \mathcal{L}_{\text{MSSM}}^{\text{soft}} - \left[m_N^2 \tilde{N}^\dagger \tilde{N} + m_S^2 \tilde{S}^\dagger \tilde{S} \right] \\ &- \left[\epsilon_{ab} A_\nu^{ij} \tilde{L}_i^a \tilde{N}_j H_u^b + B_{M_R}^{ij} \tilde{N}_i \tilde{S}_j + B_{\mu_S}^{ij} \tilde{S}_i \tilde{S}_j + \text{h.c.} \right] \end{aligned}$$

Neutrino mass

Tree-level 9×9 neutrino mass matrix in the basis
 $\{\nu_L, N^c, S\}$

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix}$$

$M_D = v_u y_\nu$ is the Dirac neutrino mass matrix.

The 3×3 light neutrino mass matrix, in the approximation
 $\mu_S \ll M_D < M_R$ is given by

$$M_\nu = (M_D M_R^{-1}) \mu_S (M_D M_R^{-1})^T \equiv F \mu_S F^T$$

- Small neutrino mass is ascribed to the small μ_s parameter

Neutrino mixing

The full (non-unitary) light neutrino mixing matrix is (to leading order in $F = M_D M_R^{-1}$)

$$\mathcal{U} \simeq \left(\mathbf{1} - \frac{1}{2} F F^\dagger \right) U \equiv (1 - \eta) U$$

$\eta = \frac{1}{2} F F^\dagger$ measures the non-unitarity of the light neutrino mixing matrix.

U diagonalizes the light neutrino mass matrix:

$$U^T M_\nu U = \text{diag}(m_1, m_2, m_3)$$

Sneutrinos

- The doublet and singlet sneutrinos mix after the EWSB.
- Thus the sneutrino mass squared matrix, $M_{\tilde{\nu}}^2$ is now a 10×10 matrix for SISM
- Assuming CP conservation this matrix can be decomposed into two 5×5 block matrices for CP -even and CP -odd sneutrino fields.

The sneutrino mass term in the Lagrangian, then looks

like, $\mathcal{L}_{\tilde{\nu}} = \frac{1}{2} (\phi^R, \phi^I) \begin{pmatrix} M_+^2 & 0 \\ 0 & M_-^2 \end{pmatrix} \begin{pmatrix} \phi^R \\ \phi^I \end{pmatrix}$, where,

$$\phi^R = (\tilde{\nu}_i^R, \tilde{N}^{cR}, \tilde{S}^R), \phi^I = (\tilde{\nu}_i^I, \tilde{N}^{cI}, \tilde{S}^I).$$

Sneutrinos

- The two mass squared matrices M_{\pm}^2 are given by

$$M_{\pm}^2 =$$

$$\begin{pmatrix} (M_{\tilde{L}_i}^2 + \frac{1}{2}M_Z^2 \cos 2\beta + m_{D_i}^2)\delta_{ij} & \pm(A_{h_\nu}^j v_u - \mu m_{D_j} \cot \beta) & m_{D_j} M_R \\ \pm(A_{h_\nu}^i v_u - \mu m_{D_i} \cot \beta) & m_{\nu^c}^2 + M_R^2 + \sum m_{D_k}^2 & \mu_S M_R \pm B_{M_R} \\ m_{D_i} M_R & \mu_S M_R \pm B_{M_R} & m_S^2 + \mu_S^2 + M_R^2 \pm B_{\mu_S} \end{pmatrix},$$

$$\mathbf{G} M_{\tilde{\nu}}^2 \mathbf{G}^T = \text{diag}(m_{\tilde{N}_1}^2, \dots, m_{\tilde{N}_{10}}^2), \text{ with } m_{\tilde{N}_1}^2 < \dots < m_{\tilde{N}_{10}}^2.$$

Diagonalizing the CP -even and CP -odd mass matrices M_{\pm}^2 separately by $\mathbf{G}_{\pm} M_{\pm}^2 \mathbf{G}_{\pm}^T = \text{diag}(m_{\tilde{N}_{i\pm}}^2)$, $i = 1, \dots, 5$, where \tilde{N}_{i+} and \tilde{N}_{i-} denote the i -th CP -even and CP -odd sneutrino mass eigenstates

Some benchmark points

Goal is to find a sparticle spectrum with light sneutrino LSP
in the cMSSM scenario with ($m_0, m_{1/2}, \tan \beta, A_0, \text{sgn } \mu$)
and the inverse seesaw parameters $\mu_S, M_R, M_D, B_{\mu_S}$ and B_{M_R}

$$123 \text{ GeV} \leq m_h \leq 127 \text{ GeV}$$

Various experimental constraints

Quantity	Value
$\Omega_{\text{CDM}} h^2$	0.112 ± 0.006
σ_{SI}	$< 5 \times 10^{-9} \text{ pb}$
$\langle \sigma_A v \rangle$	$< 10^{-26} \text{ cm}^3 \text{s}^{-1}$
Δa_μ	$(26.1 \pm 8.0) \times 10^{-10}$
Δa_e	$(109 \pm 83) \times 10^{-14}$
$\text{BR}(B \rightarrow X_s \gamma)$	$(3.21 \pm 0.33) \times 10^{-4}$
$\text{BR}(B_s^0 \rightarrow \mu^+ \mu^-)$	$< 4.5 \times 10^{-9}$
$\text{BR}(\mu \rightarrow e \gamma)$	$< 2.4 \times 10^{-12}$
$\text{BR}(\tau \rightarrow e \gamma)$	$< 3.3 \times 10^{-8}$
$\text{BR}(\tau \rightarrow \mu \gamma)$	$< 4.4 \times 10^{-8}$

Quantity	Value
$\text{BR}(\mu \rightarrow 3e)$	$< 1.0 \times 10^{-12}$
$\text{BR}(\tau \rightarrow 3e)$	$< 2.7 \times 10^{-8}$
$\text{BR}(\tau \rightarrow 3\mu)$	$< 2.1 \times 10^{-8}$
$\text{BR}(\tau \rightarrow e\mu\mu)$	$< 1.7 \times 10^{-8}$
$\text{BR}(\tau \rightarrow ee\mu)$	$< 1.5 \times 10^{-8}$
$ \eta _{ee}$	0.002 ± 0.005
$ \eta _{\mu\mu}$	0.003 ± 0.005
$ \eta _{\tau\tau}$	0.003 ± 0.005
$ \eta _{e\mu}$	$< 7.2 \times 10^{-5}$
$ \eta _{e\tau}$	$< 1.6 \times 10^{-2}$
$ \eta _{\mu\tau}$	$< 1.3 \times 10^{-2}$

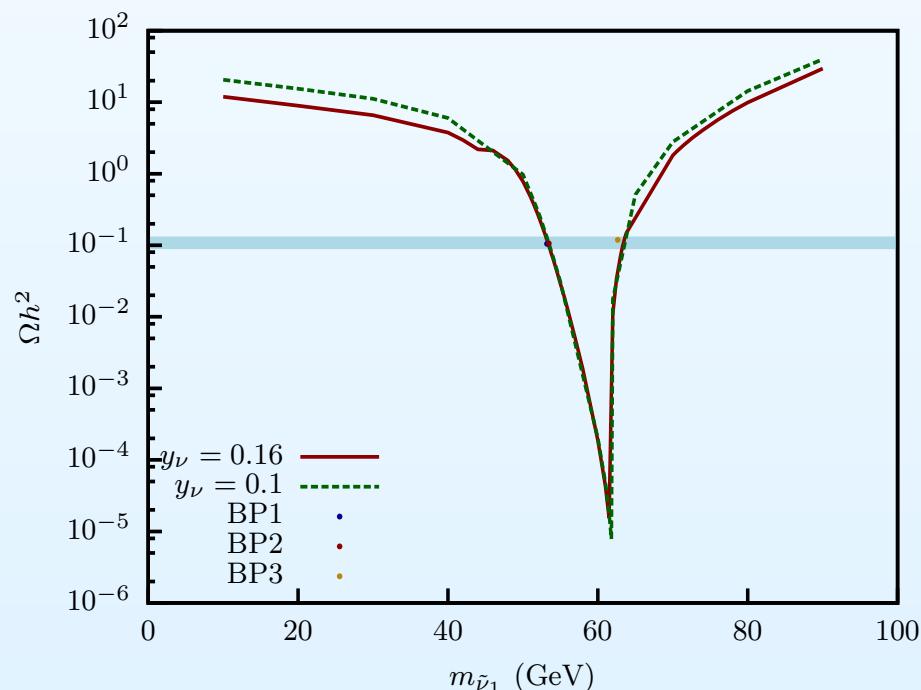
Fitting neutrino masses and mixing

- Low energy values of y_ν and M_R satisfy DM and other constraints
- Neutrino mass and mixing parameter can be fit using appropriate values for the mass matrix μ_S
- Use the latest global fit values for the neutrino oscillation parameters including the most recent θ_{13} results from Double CHOOZ, Daya Bay and RENO experiment
- One obtains the values for μ_S in the range $\sim 10\text{-}100 \text{ eV}$

P.S. Bhupal Dev, S. Mondal, B. Mukhopadhyaya, SR, arXiv:1207.6542

Sneutrino DM in SISM

- The correct relic density is obtained near the resonant enhancement region of the annihilation cross-section in the Higgs-mediated *s*-channel process
- All our benchmark points have the LSP mass close to $m_h/2$



SUSY at the LHC

- SUSY particle searches from the 4.7 fb^{-1} (4.98 fb^{-1}) data, collected by ATLAS (CMS) at $\sqrt{s} = 7 \text{ TeV}$, found no significant signal over the expected SM background.
- In the context of the CMSSM, searches by ATLAS exclude squarks and gluinos with masses below 1360 GeV at 95% C.L.
- The results from CMS obtain similar mass limits
- In the $(m_0, m_{1/2})$ -plane, $m_{1/2} \lesssim 600 \text{ GeV}$ and $m_0 \lesssim 1 \text{ TeV}$ is already excluded by the LHC SUSY searches
- We choose to work with m_0 value close to 1 TeV and the $m_{1/2}$ value close to 600 GeV

The input parameters for three chosen BPs

Input parameter	BP1	BP2	BP3
m_0 (GeV)	993.68	996.84	815.79
$m_{1/2}$ (GeV)	600	650	600
A_0 (GeV)	-2712.11	-2858.42	-2442.11
$\tan \beta$	35	25	30
y_ν	(0.16,0.16,0.18)	(0.10,0.10,0.08)	(0.10,0.10,0.10)
M_R (GeV)	(300,1000,1000)	(200,1000,1000)	(610,1000,1000)
B_{μ_S} (GeV 2)	10	10	10
B_{M_R} (GeV 2)	10^6	10^6	10^6

P.S. Bhupal Dev, S. Mondal, B. Mukhopadhyaya, SR, arXiv:1207.6542

Sparticle masses in GeV

Notation	BP1	BP2	BP3
$(\tilde{\nu}_{I_1}, \tilde{\nu}_{R_1})$	(53.2155, 53.3030)	(53.4623, 53.5529)	(62.6587, 62.7365)
\tilde{e}_1	1018.4	1025.3	846.1
\tilde{e}_2	1039.4	1069.0	893.6
$\tilde{\mu}_1$	1016.6	1024.4	844.9
$\tilde{\mu}_2$	1036.4	1068.6	893.2
$\tilde{\tau}_1$	513.4	769.3	493.4
$\tilde{\tau}_2$	856.0	973.0	768.0
\tilde{u}_1	1535.0	1607.5	1434.0
\tilde{u}_2	1569.3	1645.7	1471.2
\tilde{c}_1	1535.0	1607.5	1433.9
\tilde{c}_2	1569.1	1645.6	1471.0

Sparticle masses in GeV

Notation	BP1	BP2	BP3
\tilde{t}_1	634.2	625.0	613.8
\tilde{t}_2	1151.6	1247.1	1125.3
\tilde{d}_1	1531.6	1603.4	1430.2
\tilde{d}_2	1571.1	1647.4	1473.1
\tilde{s}_1	1531.5	1603.3	1430.1
\tilde{s}_2	1570.9	1647.3	1473.0
\tilde{b}_1	1087.8	1194.3	1061.8
\tilde{b}_2	1304.0	1460.0	1265.4
\tilde{g}	1401.4	1505.3	1392.6

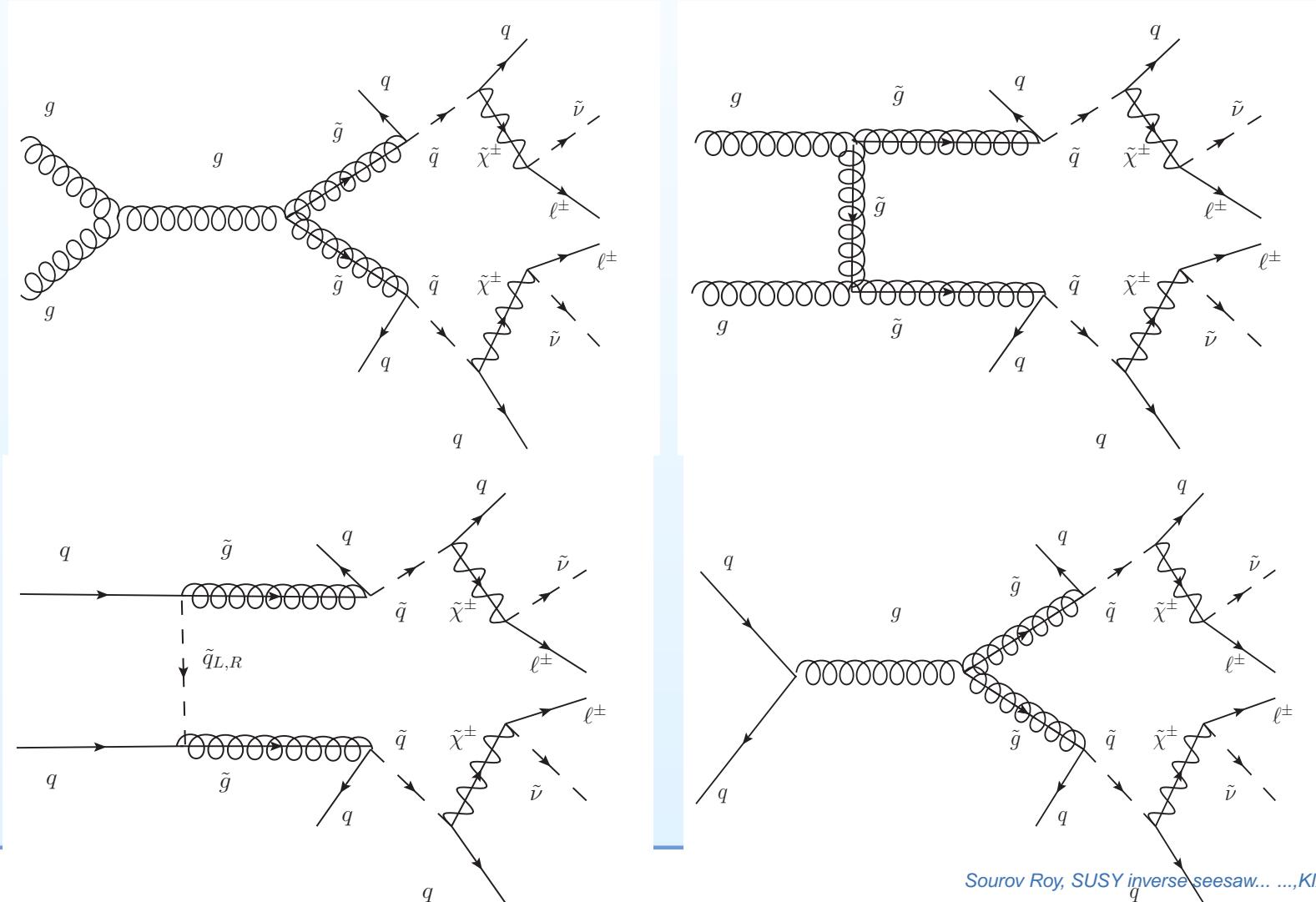
Notation	BP1	BP2	BP3
$\tilde{\chi}_1^0$	264.3	286.2	261.8
$\tilde{\chi}_2^0$	499.2	539.8	495.2
$\tilde{\chi}_3^0$	-1376.5	-1464.4	-1295.3
$\tilde{\chi}_4^0$	1379.5	1467.5	1298.7
$\tilde{\chi}_1^\pm$	499.4	540.0	495.4
$\tilde{\chi}_2^\pm$	1380.1	1467.9	1299.2

Higgs boson invisible decay

- Since the sneutrino LSP is sufficiently light, the lightest neutral Higgs can in principle decay into a pair of LSP's thus giving rise to an invisible decay width of the Higgs
- The LHC signatures of these decays are relatively clean, and very large branching ratios to invisible decay channel are disfavored by the current LHC searches
- The branching ratio depends, among other things, on the neutrino Yukawa coupling y_ν
- The present LHC Higgs data can indeed accommodate an invisible branching ratio for the Higgs
- May lead to an estimate of the bounds on the neutrino Yukawa couplings in the inverse seesaw models

Collider Signatures

- The production channels are $\tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$, and $\tilde{q}\tilde{q}$
- Cascade decays to $\tilde{\chi}^0$, $\tilde{\chi}^\pm$ ending up in stable LSP



Gluino, Squark decays

- Multiple jets in the final state
- $\tilde{g} \rightarrow q\bar{q}$ if kinematically allowed

Three-body decay modes $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_i^\pm$, $q\bar{q}\tilde{\chi}_j^0$ with virtual squarks.

- squarks decay to two-body modes $\tilde{q} \rightarrow q\bar{g}$ if kinematically allowed, or $\tilde{q}_L \rightarrow q'\tilde{\chi}_i^\pm$, $q\tilde{\chi}_j^0$, while $\tilde{q}_R \rightarrow q\tilde{\chi}_j^0$ only

LHC signals

- The LHC signals of our scenario can differ considerably from those of the pure cMSSM situation.

Chargino ($\tilde{\chi}_1^+$) decay	BP1	BP2	BP3
$W^+ \tilde{\chi}_1^0$	0.23	0.45	0.31
$\ell^+ \tilde{\nu}_1$	0.77	0.55	0.69

- Consequently, the leptonic branching ratio of the $\tilde{\chi}_1^+$ is remarkably enhanced
- Thus the SUSY cascades lead to a highly boosted rate of dileptons, of which the same-sign dileptons (SSD) are more spectacular being relatively background-free.

LHC signals

- This scenario exhibit a rise in the SSD rate with respect to that of purely (jets+ E_T) events, as compared to a pure cMSSM spectrum of comparable heaviness.
- In our SISM scenario, the E_T distribution is expected to be much harder compared to the cMSSM scenario

Event Generation and background analysis

SUSY spectrum and decay branching fractions calculated using SPheno

PYTHIA for event generation and showering. Initial and final state radiation, decay, hadronization, fragmentation and jet formation are implemented following the standard procedures in PYTHIA

Factorization and renormalization scales are set at $\sqrt{\hat{s}}$ (i.e
 $\mu_R = \mu_F = \sqrt{\hat{s}}$

Event Generation and background analysis

To find same-sign di-leptons+ n jets+ E_T (with $n \geq 2$) in the final states, we impose the following selection criteria:

- $p_T^\ell > 10$ GeV and $|\eta^\ell| < 2.4$ for both leptons. For same-flavor dilepton final states, we raise it to $p_T^\ell > 15$ GeV.
- Lepton-lepton separation $\Delta R_{\ell\ell} > 0.2$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.
- Lepton-jet separation $\Delta R_{\ell j} > 0.4$.
- The sum of E_T deposits of the hadrons which fall within a cone of $\Delta R \leq 0.2$ around a lepton, must be less than $0.2p_T^\ell$.
- Jet-jet separation $\Delta R_{jj} > 0.4$.

r-Ratio

- Illustrate the SSD enhancement effect

$$r = \frac{\sigma(\ell^\pm \ell^\pm + \geq 2j + E_T)}{\sigma(0\ell + \geq 3j + E_T)}$$

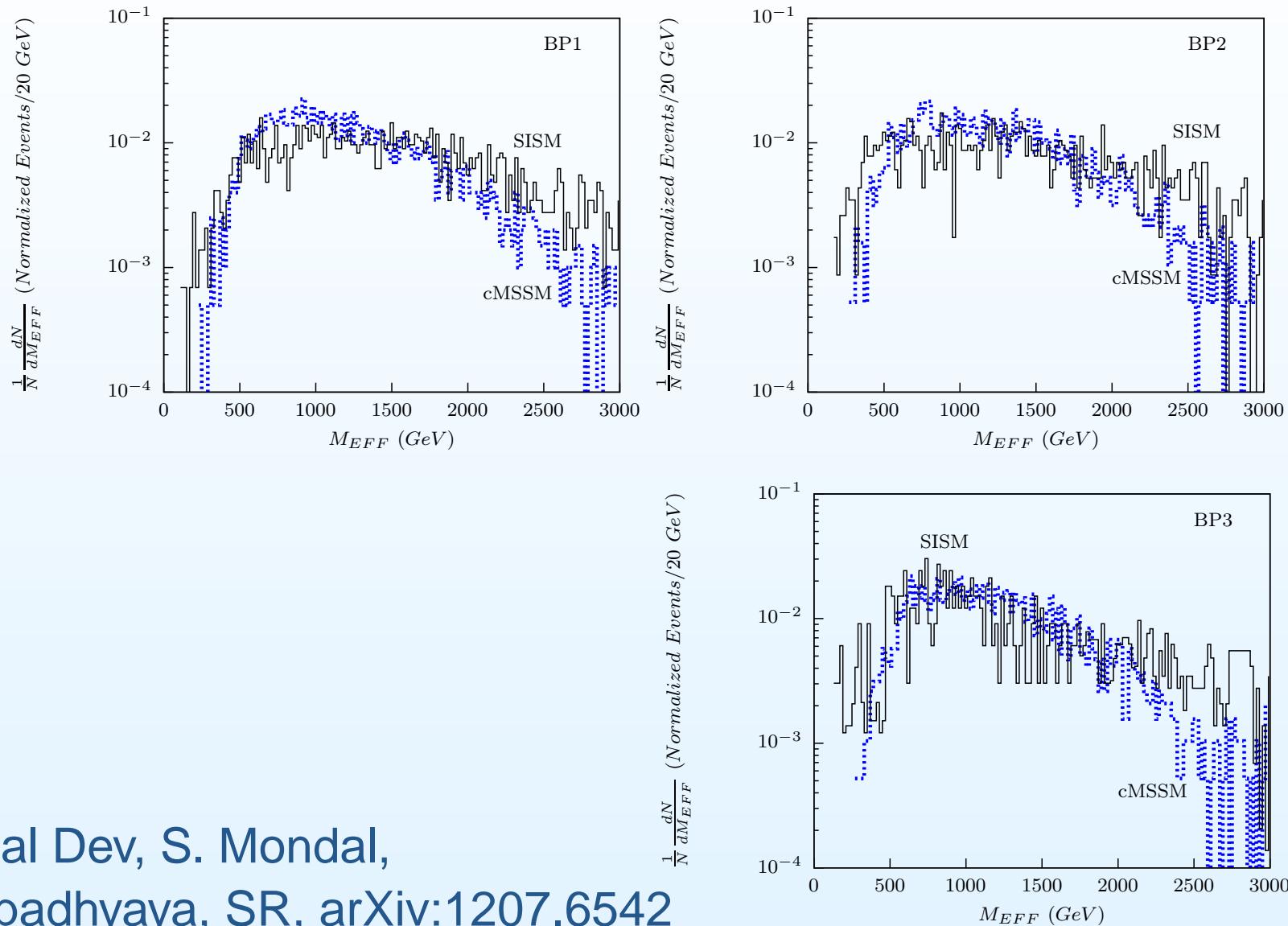
r	BP1	BP2	BP3
SISM	0.19	0.15	0.11
cMSSM	0.04	0.03	0.03

Effective mass

$$M_{\text{eff}} = \sum |p_T^\ell| + \sum |p_T^j| + E_T$$

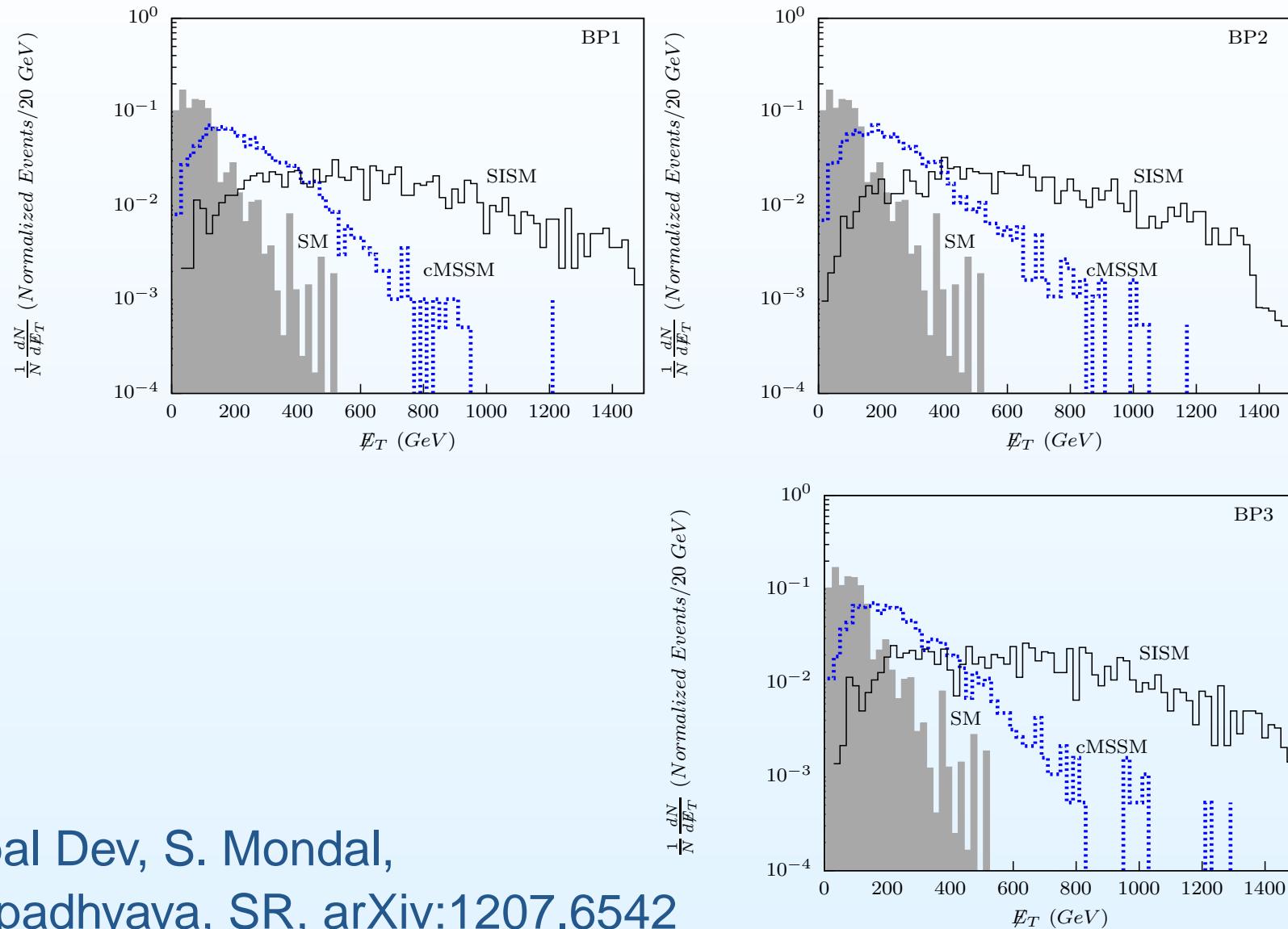
- Check that the effective mass distributions are similar for both cMSSM and SISM

The effective mass distribution of the final states



P.S. Bhupal Dev, S. Mondal,
B. Mukhopadhyaya, SR, arXiv:1207.6542

E_T distribution for the SISM (with $\tilde{\nu}$ LSP) and cMSSM



P.S. Bhupal Dev, S. Mondal,
B. Mukhopadhyaya, SR, arXiv:1207.6542

Additional cuts

- SISM case has a much harder \cancel{E}_T tail compared to the cMSSM case
- This can be used as a distinguishing feature
- Combined SM background falls rapidly for $\cancel{E}_T > 300 \text{ GeV}$
- To suppress the SM background we need two relevant cuts

(a) $p_T^j > 50 \text{ GeV}$ for all jets and $p_T^j > 100 \text{ GeV}$ for the leading jet

(b) $\cancel{E}_T > 300 \text{ GeV}$

which reduce the background significantly

Number of events for 30 fb^{-1} @ 14 TeV

Channel	After basic selection criteria		
	$\mu\mu$	$e\mu$	ee
BP1	33.24	125.18	144.01
BP2	39.95	32.44	97.26
BP3	35.94	88.94	102.84
WWW	16.86	12.36	29.64
$WWjj$	140.01	75.39	193.86
WZ	84.60	16.92	186.06
ZZ	0.33	0.33	0.66
$Wb\bar{b}$	29.25	5.85	29.25
$Wt\bar{t}$	81.33	66.84	147.54 8
$t\bar{t}$	2109.00	754.80	2331.00
$Zb\bar{b}$	0.00	6.99	19.38

Number of events for 30 fb^{-1} @ 14 TeV

Channel	After jet p_T cut		
	$\mu\mu$	$e\mu$	ee
BP1	30.73	112.66	127.45
BP2	34.38	26.86	84.34
BP3	34.15	80.05	91.49
WWW	3.18	2.49	6.00
$WWjj$	75.39	43.08	96.93
WZ	33.84	0.00	51.00
ZZ	0.000	0.000	0.03
$Wb\bar{b}$	0.00	0.00	0.00
$Wt\bar{t}$	38.70	31.89	69.75
$t\bar{t}$	710.4	222.00	466.2
$Zb\bar{b}$	0.00	0.00	1.62

Number of events for 30 fb^{-1} @ 14 TeV

Channel	After \cancel{E}_T cut		
	$\mu\mu$	$e\mu$	ee
BP1	24.30	90.13	114.69
BP2	28.54	23.35	64.87
BP3	32.44	78.48	86.76
WWW	0.39	0.24	0.24
$WWjj$	0.00	0.00	0.00
WZ	0.00	0.00	0.00
ZZ	0.00	0.00	0.00
$Wb\bar{b}$	0.00	0.00	0.00
$Wt\bar{t}$	1.83	1.59	3.18
$t\bar{t}$	0.00	0.00	0.00
$Zb\bar{b}$	0.00	0.00	0.00

Trilepton channel and correlation

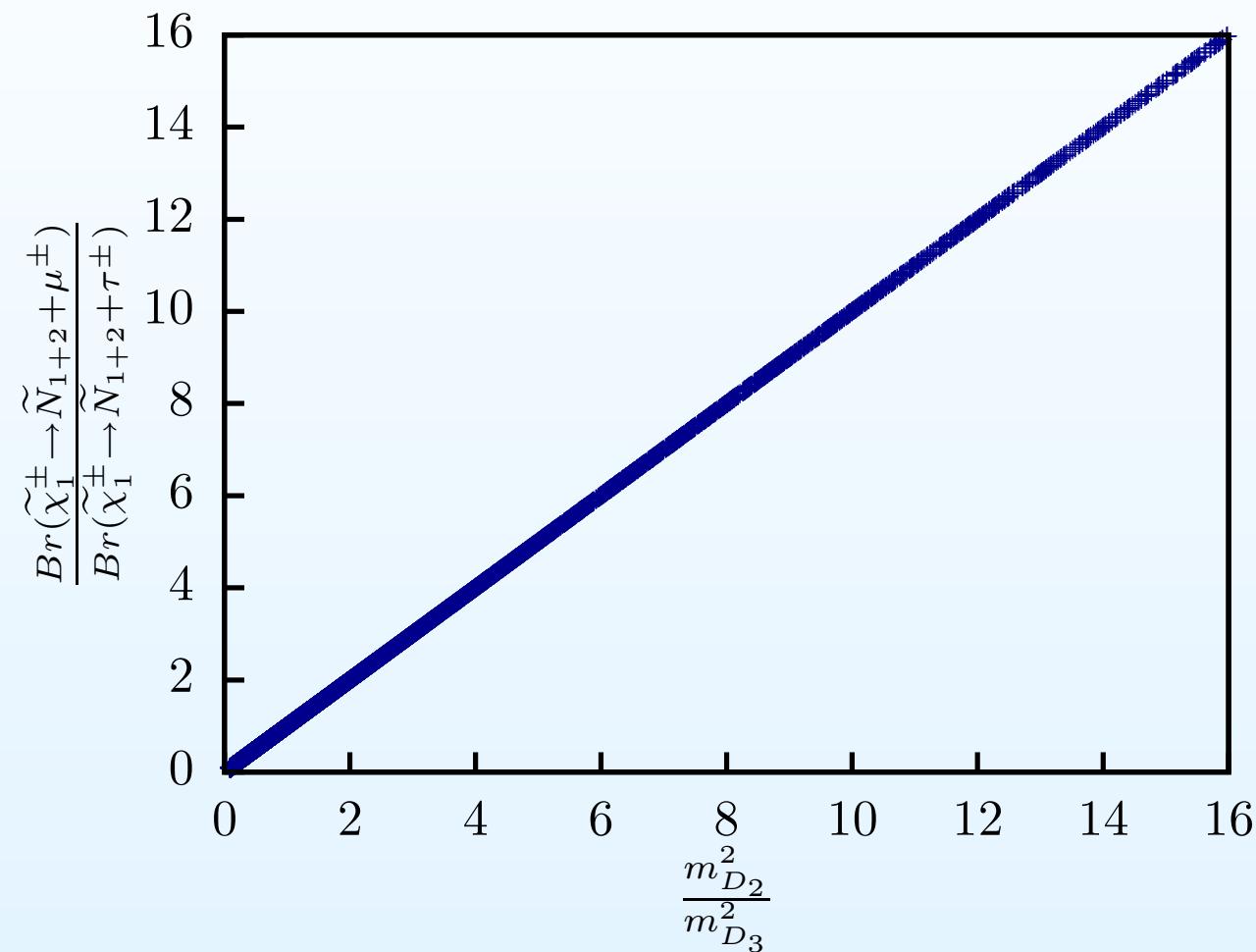
- Trilepton signals ($3l$, with or without τ s) – extensively studied as an important probe for supersymmetric models.
- If in the production or in the decay chain $\tilde{\chi}_1^\pm$ appears then it can have a decay $\tilde{\chi}_1^\pm \rightarrow l^\pm + \tilde{N}$, where \tilde{N} is the LSP.
- The ratios of the decay branching ratios into different charged lepton flavors correlate with the neutrino mixing angles
- Look at these correlations by studying the trilepton + E_T signature from the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production at the LHC.

M. Hirsch, T. Kernreiter, J.C. Romao, A. Villanova del Moral,
JHEP 1001 (2010) 103, arXiv:0910.2435

Decays of chargino

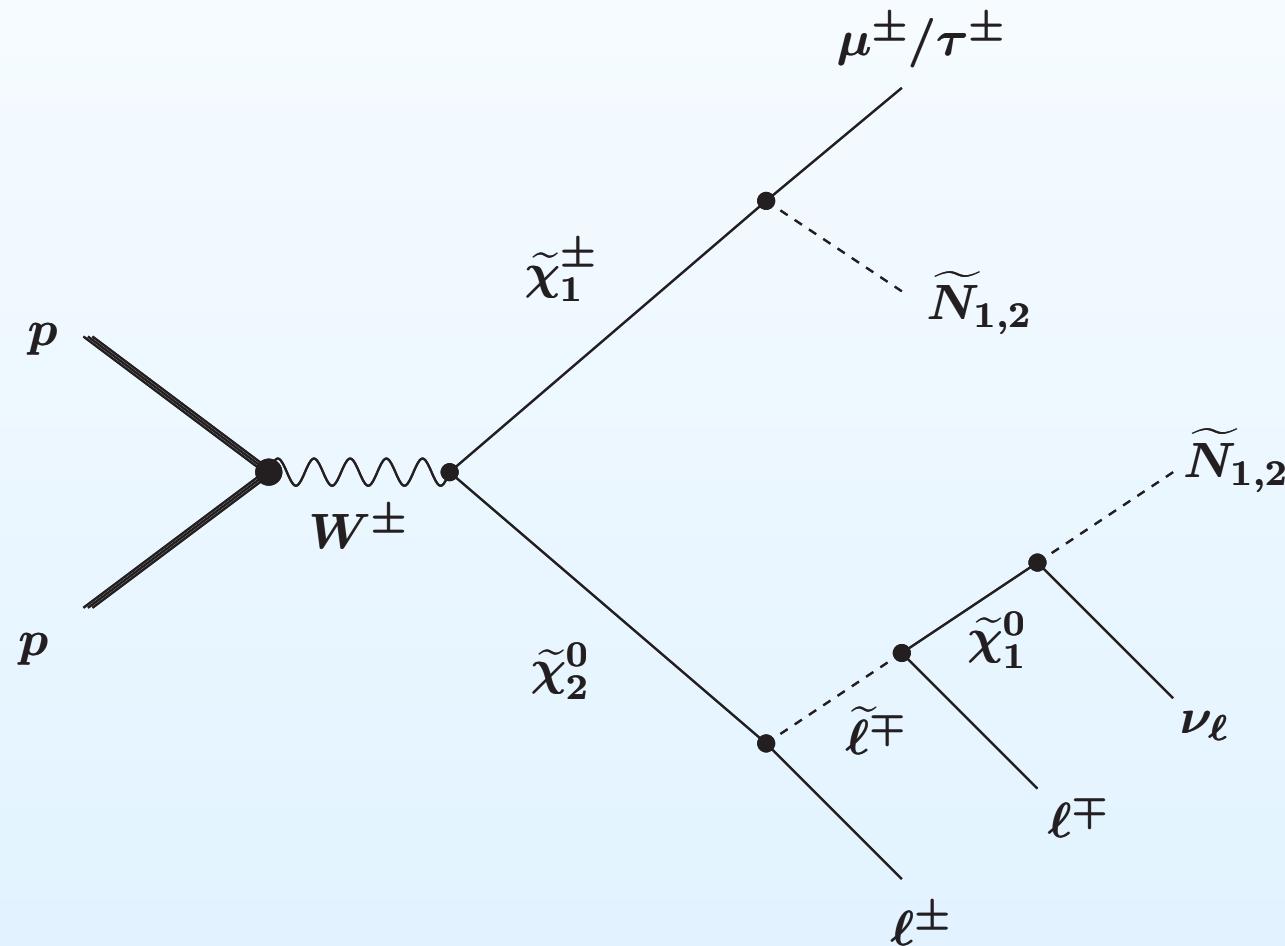
- Small reactor neutrino mixing angle and maximal atmospheric neutrino mixing angle $\implies m_{D_1} \ll m_{D_2}, m_{D_3}$ and simultaneously, $m_{D_2} \sim m_{D_3}$.
- $\Gamma(\tilde{\chi}_1^\pm \rightarrow \tilde{N}_{1+2} + l_i^\pm)$ correlates with $m_{D_i}^2$.
- Also $\tan^2 \theta_{23} \sim \frac{m_{D_2}^2}{m_{D_3}^2}$. Hence, $\frac{Br(\tilde{\chi}_1^\pm \rightarrow \tilde{N}_{1+2} + \mu^\pm)}{Br(\tilde{\chi}_1^\pm \rightarrow \tilde{N}_{1+2} + \tau^\pm)}$ correlate with the ratio $\frac{m_{D_2}^2}{m_{D_3}^2}$.

Correlation plot for the ratio of the branching ratios



Trilepton signal and the benchmark points

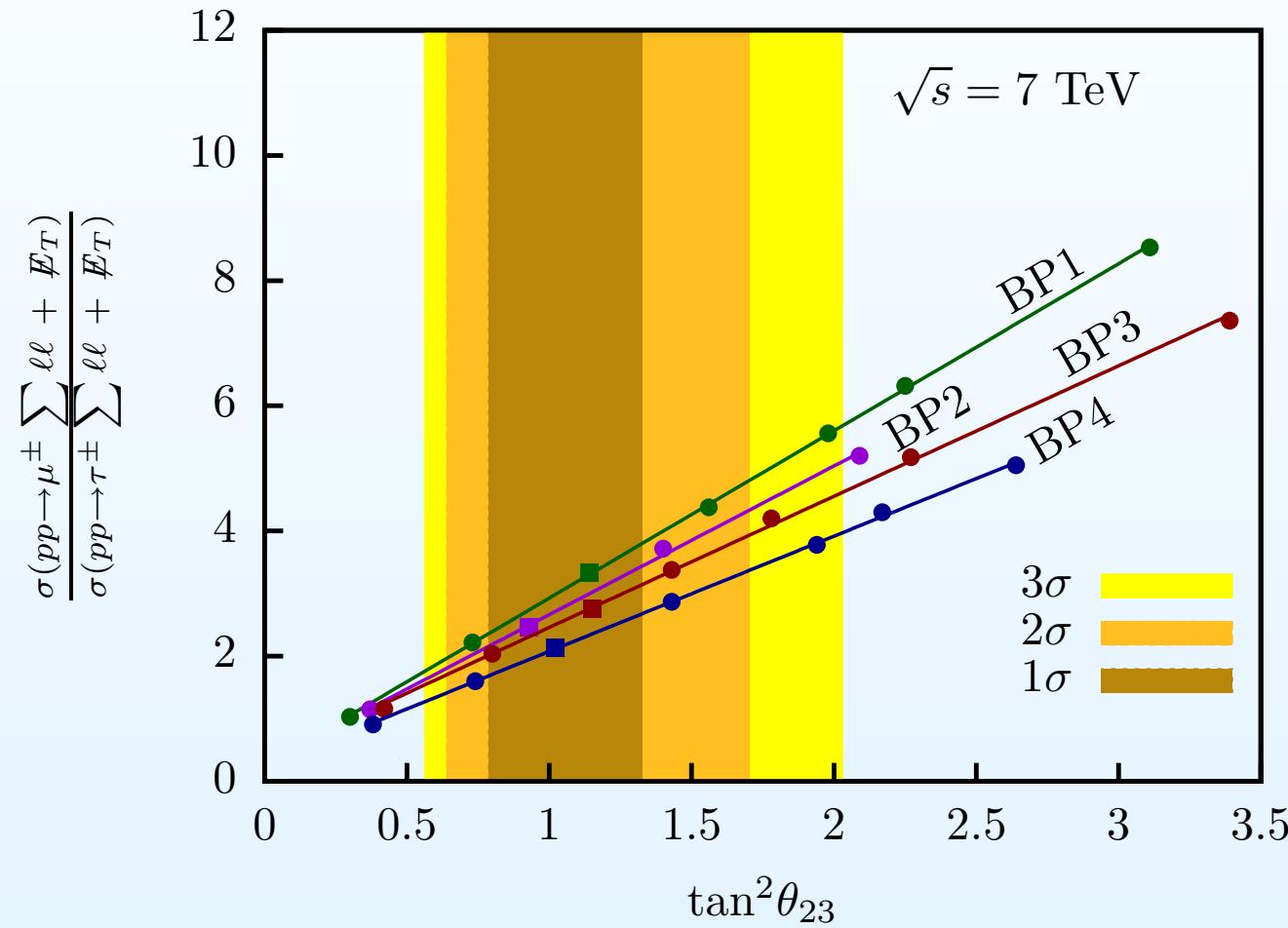
We simulate $\tilde{\chi}_2^0 \tilde{\chi}_1^\pm$ production followed by their two-body decays to produce $3\ell + \cancel{E}_T$ or $2\ell + \tau - \text{jet} + \cancel{E}_T$ final states, where $\ell = e, \mu$.



Results

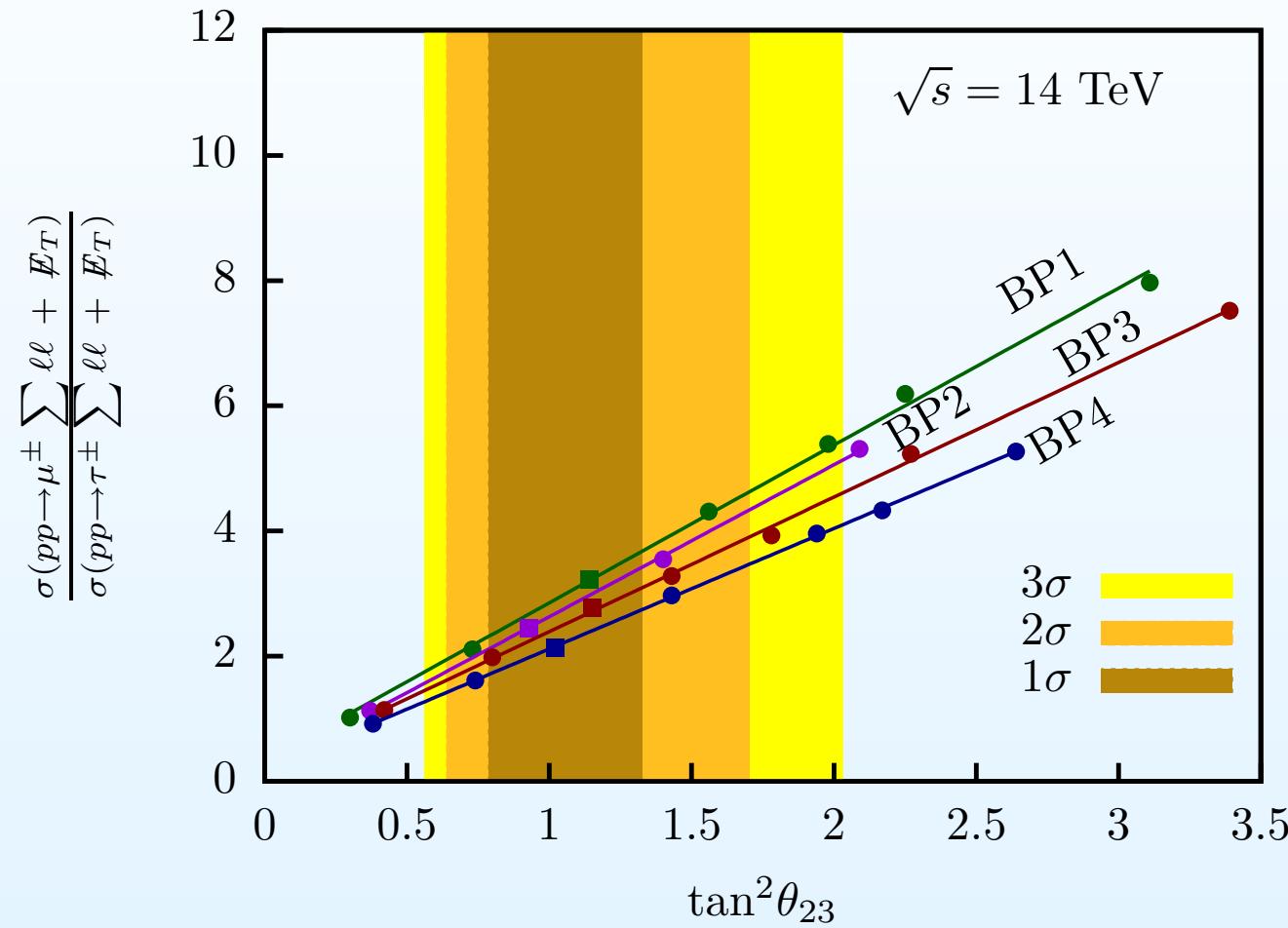
- To study the correlation between θ_{23} and the final states with trilepton + E_T at the LHC, we look at the ratio of cross sections $\frac{\sigma(pp \rightarrow \mu \sum \ell\ell + E_T)}{\sigma(pp \rightarrow \tau \sum \ell\ell + E_T)}$
- In the denominator the τ must always come from the decay of $\tilde{\chi}_1^\pm$
- In the numerator one μ must always also come from the decay of $\tilde{\chi}_1^\pm$.
- Naively we would expect that this ratio of cross sections will also show nice correlation with the atmospheric neutrino mixing angle θ_{23} .

Correlation plot ($\frac{\sigma(pp \rightarrow \mu^\pm \sum \ell\ell + E_T)}{\sigma(pp \rightarrow \tau^\pm \sum \ell\ell + E_T)}$ vs $\tan^2 \theta_{23}$) LHC at $\sqrt{s} = 7$ TeV



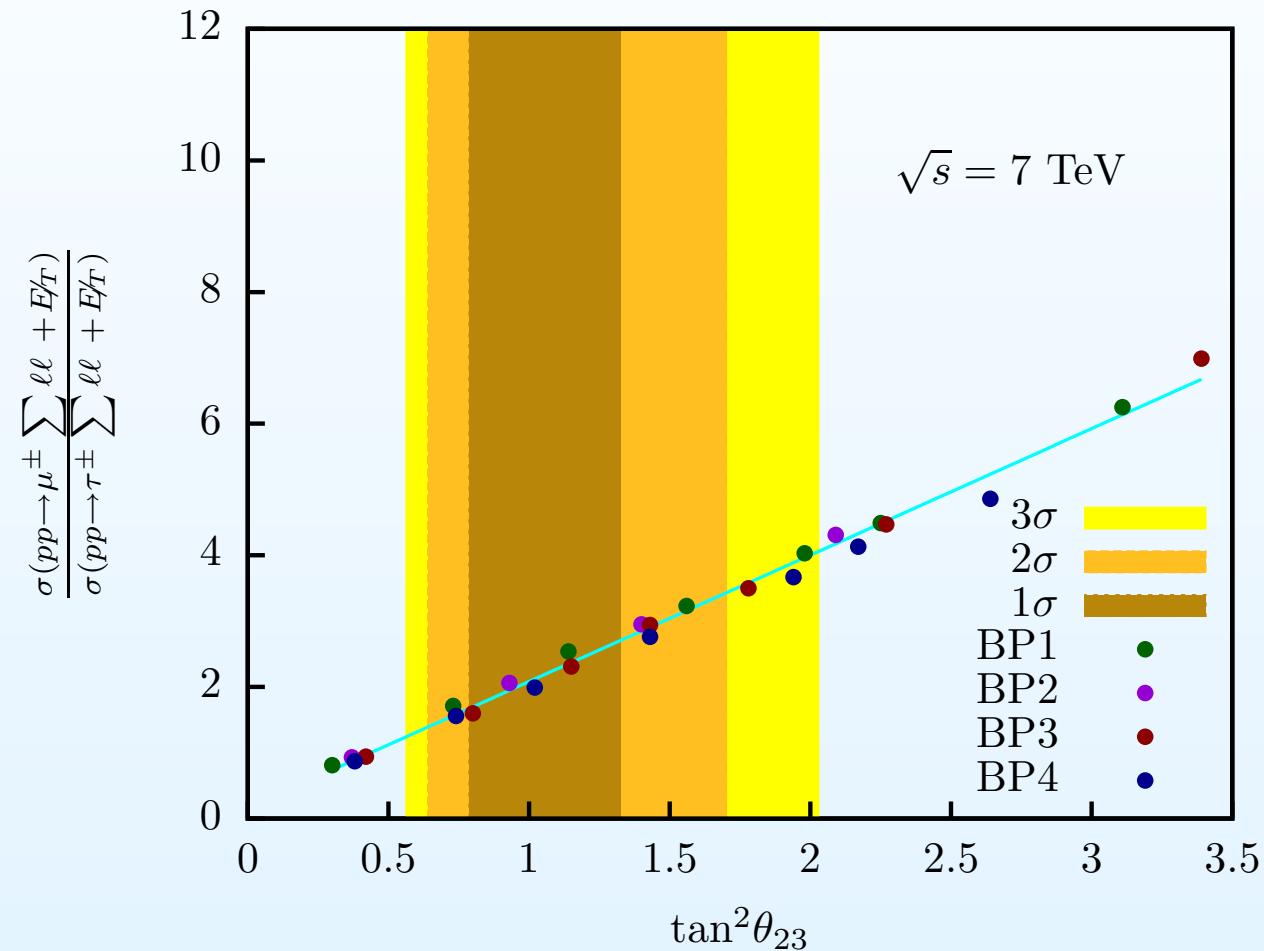
S. Mondal, S. Biswas, P. Ghosh, SR, JHEP 1205 (2012) 134,
arXiv:1201.1556

Correlation plot ($\frac{\sigma(pp \rightarrow \mu^\pm \sum \ell\ell + E_T)}{\sigma(pp \rightarrow \tau^\pm \sum \ell\ell + E_T)}$ vs $\tan^2 \theta_{23}$) LHC at $\sqrt{s} = 14$ TeV



S. Mondal, S. Biswas, P. Ghosh, SR, JHEP 1205 (2012) 134,
arXiv:1201.1556

$\frac{\sigma(pp \rightarrow \mu^\pm \sum \ell\ell + E_T)}{\sigma(pp \rightarrow \tau^\pm \sum \ell\ell + E_T)}$ vs $\tan^2 \theta_{23}$ for LHC 7 TeV ($\epsilon_\tau \sim 0.5$
 and same p_T cut for both μ and τ .)



Conclusions

- SUSY inverse seesaw mechanism is one possibility of neutrino mass generation
- A very small $\Delta L = 2$ mass term (of the order \sim keV) is required.
- Can account for neutrino masses and mixing
- Leads to an LSP dominated by right chiral sneutrino states
- Sneutrino LSP can act as a DM candidate of mass around 50 GeV

Conclusions

- Can be distinguished from the usual mSUGRA scenario with a neutralino LSP, through a study of the **same-sign dilepton signals** at the LHC
- Also from the \cancel{E}_T spectra
- Might be able to put useful bounds on the Dirac Yukawa coupling from the invisible decay width of the lightest neutral Higgs boson
- The ratio $\frac{\sigma(\mu^\pm + \sum \ell\ell)}{\sigma(\tau^\pm + \sum \ell\ell)}$, with $\ell = e, \mu$ shows nice correlation with $\tan^2\theta_{23}$
- High energy redetermination of neutrino mixing angle at the LHC