Bilinear RPV and LHC at 7 TeV

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in collaboration with
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Outline

1. Neutrino masses and mixing
2. R-parity violation (RpV)
3. Neutrino Masses and Mixing from BRpV
4. Neutralino decay width, length and BR
5. Displaced Vertex
6. Uncertainty in Length measurement
   - 14 TeV with 100 fb^{-1}
   - 7 TeV with 1 fb^{-1}
7. Summary

Present status of best-fitted Neutrino masses-mixing

parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}] eV^2$	$7.59^{+0.23}_{-0.18}$	7.22–8.03	7.03–8.27
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}] eV^2$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.318^{+0.019}_{-0.016}$	0.29–0.36	0.27–0.38
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.013^{+0.013}_{-0.009}$	≤ 0.039	≤ 0.053

Tabelle: Best-fit values with 1σ errors, and 2σ and 3σ intervals for the three–flavor neutrino oscillation parameters from global data including solar (θ_{12}), atmospheric (θ_{23}), reactor (KamLAND and CHOOZ) and accelerator (K2K and MINOS) experiments.

[Schwetz,Tortola,Valle NJP10:113011,2008 arXiv:0808.2016]

$$\tan^2\theta_{23} \sim 1.0;\ \tan^2\theta_{12} \sim 0.47;\ U^2_{e3} \lesssim 0.013$$

MSSM with R-parity violation (RpV)

R-parity (R_p) is a discrete multiplicative symmetry,

$$R_p = (-\mathbf{1})^{2S+3B+L}$$

S=Spin; B (L) = Baryon (Lepton) Number; SM particle: +1 and Sparticle: -1

Superpotential of Minimal Supersymmetric of the SM (MSSM):

$$W_{R_p} = \varepsilon_{ab}[(\mathbf{Y}_E)_{ij} L_i^a H_d^b \bar{E}_j + (\mathbf{Y}_D)_{ij} Q_i^a H_d^b \bar{D}_j + (\mathbf{Y}_U)_{ij} Q_i^a H_u^b \bar{U}_j + \mu H_d^a H_u^b],$$

L, Q, H_d, H_u: SU(2) Doublet; $\bar{E}$, $\bar{D}$,$\bar{U}$: SU(2) Singlet; Y's are Yukawa ; μ = Higgsino Mass

$$W_{\not R_p} = \varepsilon_{ab} \underbrace{\epsilon_i L_i^a H_u^b}_{\Delta L \neq 0} \text{ (Bi-linear)}$$

[Masiero,Valle, PLB251 (1990) 273; Bhattacharyya,Pal,PRD82(2010)055013]

Bilinear R-parity Violation(BRpV)

- After REWSB, the effective potential parameterized by simple, bilinear soft breaking parameters.

$$V_{\mathrm{soft},\not{R}_p} = -\varepsilon_{ab} B_i \epsilon_i \widetilde{L}_i^a H_u^b$$

Hall,Suzuki NPB231(1984) 419

The number of parameters are just six (3 ϵ_i and 3v_i)

- Explain the Neutrino masses and mixing.
- The lightest supersymmetric particle (LSP) is not stable anymore.
- Sparticles masses, cascade patterns and decay BR changes.
- Mixing with same quantum number states: neutrino-Neutralino; charged lepton-Chargino; sneutrino-CP-even Higgs; anti-sneutrino-CP-odd Higgs; charged Higgs-sleptons; squarks (LR mixing through Slepton VEVs).

Neutrino Masses

$M_1, M_2, M_Z \gg v_i, \rightarrow$ see-saw formula

$$\mathcal{M}_{\mathrm{N}} = \begin{pmatrix} M_{\tilde{\chi}_0} & m \\ m^T & 0 \end{pmatrix},$$

$$\begin{aligned} M_{\tilde{\chi}_0} \equiv M_{\mathrm{SUSY}} \quad &\Longleftrightarrow \quad M_{\mathrm{Maj}}\,, \\ g v_i,\, \epsilon_i \quad &\Longleftrightarrow \quad M_{\mathrm{Dirac}} \end{aligned}$$

$$m_\nu \sim \frac{m^2}{M_{\mathrm{SUSY}}} \sim \frac{g^2 v_i^2}{M_{\mathrm{SUSY}}} \lesssim 1 \text{ eV}$$

$$\text{for} \quad M_{\mathrm{SUSY}} \lesssim 1\,\mathrm{TeV} \quad \text{leads to} \quad v_i,\, \epsilon_i \lesssim 1\,\mathrm{MeV}.$$

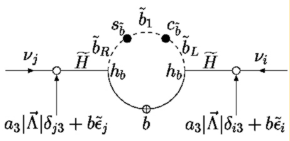
Neutrino Masses contd...

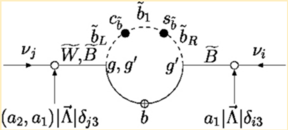
In BRpV the total neutrino mass:

$$m_\nu \simeq c_0 \Lambda_i \Lambda_j + c_1 \epsilon_i \epsilon_j \tag{1}$$

$$\Lambda_i = \mu v_i + v_d \epsilon_i$$

$$c_0 = \frac{M_1\, g^2 + M_2\, g'^2}{4\ \det(M_{\chi^0})} \quad ; \quad c_1 = \frac{3}{16\pi^2}\, m_b\, \sin 2\theta_b\, \frac{h_b^2}{\mu^2}\, \log \frac{m^2_{\tilde{b}_2}}{m^2_{\tilde{b}_1}} \tag{2}$$





Neutrino Masses contd...

$$m_{\nu_1} \simeq 0 \tag{3}$$

$$m_{\nu_2} \simeq c_1 \frac{(\vec{\epsilon} \times \vec{\Lambda})^2}{|\vec{\Lambda}|^2} \tag{4}$$

$$m_{\nu_3} \simeq c_0 |\vec{\Lambda}|^2 \tag{5}$$

One neutrino (m_{ν_3}) is massive(c_0): gauge couplings and VEVs;atmospheric
Other two from loop corrections(c_1): Yukawa coup,SUSY break param; solar
$H^{\pm}$ and $\tilde{\ell}$ loops are important.[Hirsch,Valle, NJP6(2004)76]
[Diaz et al PRD68 (2003) 013009, PRD62 (2000) 113008,PRD65 (2002) 119901; PRD61 (2000) 071703]

In generic model parameters: $\rightarrow$ if $\epsilon^2/|\vec{\Lambda}| \ll 100$ leads to 1-loop corrections are small leads to

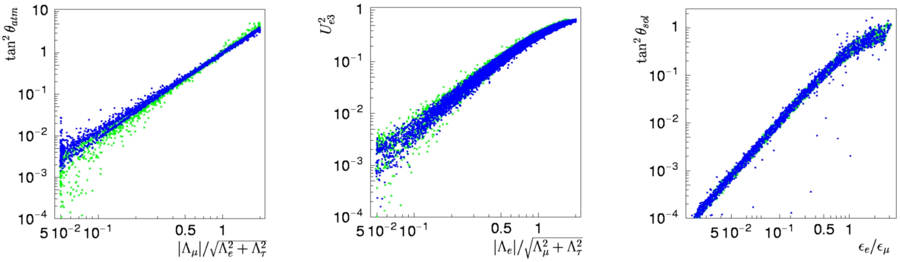
$$U_{\alpha 3} \approx \Lambda_\alpha / |\vec{\Lambda}| \tag{6}$$

Atmospheric and reactor neutrino data: $\nu_\mu \rightarrow \nu_\tau$ preferred over $\nu_\mu \rightarrow \nu_e$.

$$\Lambda_e \ll \Lambda_\mu \simeq \Lambda_\tau \tag{7}$$

are required to fit the recent Neutrino data

Angle



$$\tan^2\theta_{23} \sim 1.0; U_{e3}^2 \lesssim 0.013; \tan^2\theta_{12} \sim 0.47$$

- accommodate everything small deviations from Universality of soft parameters.
- $m_\nu^{\rm tree} \simeq \sqrt{\Delta m^2_{Atm}} \simeq 0.04 - 0.06$ eV $\Rightarrow |\vec{\Lambda}|/\sqrt{\det\mathcal{M}_{\tilde{\chi}^0}} \sim 10^{-6}$
- $m_\nu^{\rm 1lp} \simeq \sqrt{\Delta m^2_\odot} \simeq 0.009$ eV $\Rightarrow |\vec{\epsilon}|/\mu \sim 10^{-4}$
- This predictions are show up in the correlation studies at LHC

Generic BRpV signature at Colliders

- LSP decays deplete $\not{E}_T$, however increases multiplicities
- Leaving Displaced Vertices (DV)
- Decay pattern correlates with oscillation
- Simulation reveals that atmospheric angle can be extracted

Similar features in some other SUSY breaking scenario and hence with any LSP profile, e.g., scalar top, scalar tau
[Restrepo etal. PRD64(2001)055011; Hirsch etal. PRD66(2002)095006]

and scalar neutrino: $\tilde{\nu}$-LSP in explicit (Tri-linear) RpV model
[Dreiner, hep-ph/9707435]
[Bernhardt,SPD,Dreiner,Grab, PRD79:035003,2009]

Generally DV is SM background free

Decay widths

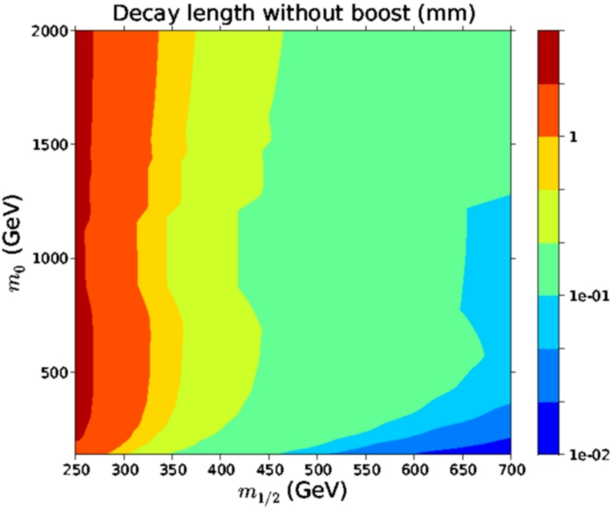
$$\Gamma(\tilde{\chi}_1^0 \to \sum_i W^{\pm} l^{\mp}) \sim \frac{g^2 g'^2 M_2 m_{\tilde{\chi}_1^0}}{(16\pi M_1 m_\gamma)} f(m_W^2/m_{\tilde{\chi}_1^0}^2) m_\nu^{\mathrm{Tree}} \sim \frac{\Lambda_i^2}{det(\mathcal{M}_{\tilde{\chi}'})} \quad (8)$$

$$\Gamma(\tilde{\chi}_1^0 \to \sum_i Z^0 \nu_i) \sim 0.5\ \Gamma(\tilde{\chi}_1^0 \to \sum_i W^{\pm} \ell_i^{\mp}) \quad (9)$$

$$\Gamma(\tilde{\chi}_1^0 \to \nu \tau^+ \ell_i^-) \sim \frac{\epsilon_i^2}{\mu^2} \quad (10)$$

The Gauge boson final states are more important if the $m_{\tilde{\ell}}$ are heavier
$\Gamma \simeq 2 \times 10^{-4} \frac{m_\nu}{0.05\mathrm{eV}} f(m_W^2/m_{\tilde{\chi}_1^0}^2)$ eV
$\Gamma \approx \mathcal{O}(10^{-4}) - \mathcal{O}(10^{-2})$ eV leads to decay length $\sim \mathcal{O}$(few mm)

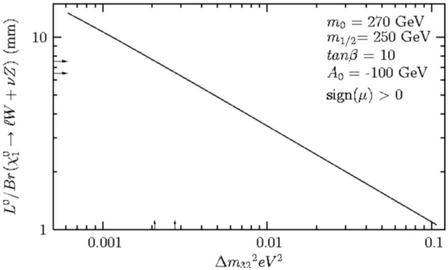
Decay Length Profile in BRpV mSUGRA scenario



$A_0 = -100\,\text{GeV}$, $\tan\beta = 10$ and $\text{sgn}(\mu) = +1$

Length over Br

$$\frac{L^0}{Br} \sim \frac{1}{\Gamma_{Gauge}} \sim \frac{1}{m_\nu^{\rm Tree}}$$



L^0 over Br is related with Atmospheric Mass scale

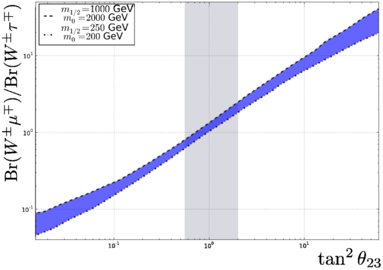
$m_{\tilde{\chi}_1^0} \sim 98$ GeV $L^0 \sim 8$ mm
$W^\pm\mu^\mp$=23.0 % ; $W^\pm\tau^\mp$= 29.4 % ; $W^\pm e^\mp$= 0.36%
$e^\pm\tau^\mp\nu$ = 7.62%; $\mu^\pm\tau^\mp\nu$= 7.62 %; $\tau^\pm\tau^\mp\nu$= 14.8%;

$b\bar{b}\nu$ = 10.5%; $Z\nu$ = 0.06%

Atmospheric Angle and Ratio of Branching ratio

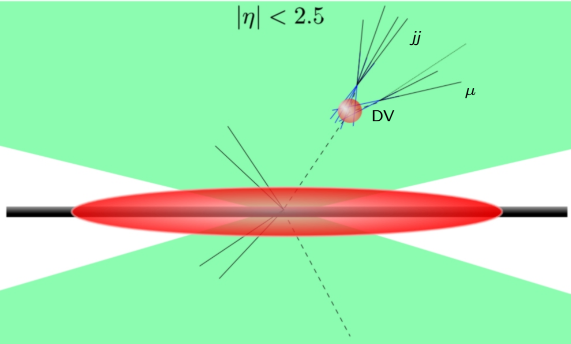
$\tilde{\chi}^0_1$-W-l_i coupling O^L_i is given by: $O^L_i = \Lambda_i f(M_1, M_2, \mu, \tan\beta, v_d, v_u)$
f only depends on MSSM parameters but not on the BRpV parameters (in the limit slepton/squarks contributions are small)

$$\tan^2\theta_{\rm atm} \simeq \left|\frac{\Lambda_2}{\Lambda_3}\right|^2 \simeq \frac{BR(\tilde{\chi}^0_1 \to \mu^\pm W^\mp)}{BR(\tilde{\chi}^0_1 \to \tau^\pm W^\mp)} \simeq \frac{BR(\tilde{\chi}^0_1 \to \mu^\pm \bar{q}q')}{BR(\tilde{\chi}^0_1 \to \tau^\pm \bar{q}q')} \simeq \frac{N_\mu}{N_\tau}, \quad (11)$$



Counting different flavors of lepton from LSP at Colliders

Displaced Vertex (DV)



$$\left(\frac{x}{5\delta_{xy}}\right)^2 + \left(\frac{y}{5\delta_{xy}}\right)^2 + \left(\frac{z}{5\delta_z}\right)^2 = 1$$

ATLAS: $\delta_{xy} = 20$ μm and $\delta_z = 500$ μm

B-meson ($m \sim 5$ GeV) typical ($p_T > 5$ GeV) decay length ~ 0.5 mm

sparticle production and cascades to $\tilde{\chi}_1^0(M \sim \mathcal{O}(100)$ GeV$) \to e/\mu/\tau$ W

Trigger

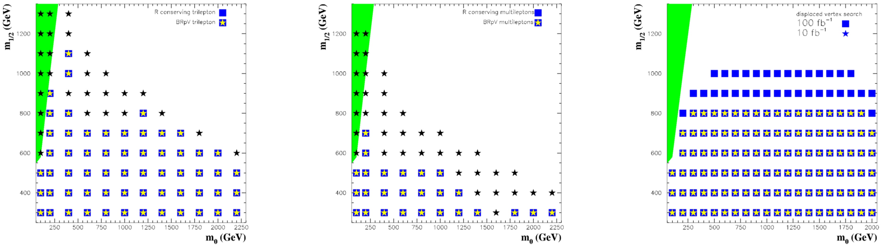
LHC experiments not yet defined any specific strategy to trigger DV for high Invariant masses.

At least one of the neutralinos in the event, the *signal vertex*, decays beyond the primary vertex point, outside the ellipsoid
And at least one from below:

- one isolated electron or a photon with $p_T > 20$ GeV and $\eta < 3$;
- one isolated muon with $p_T > 6$ GeV and $\eta < 3$;
- two isolated electrons or photons with $p_T > 15$ GeV and $\eta < 3$;
- At least one jet with $p_T > 100$ GeV and $\eta < 5$;
- Missing transverse energy ($\not{E}_T$) > 100 GeV (if all fails).

Analysis: `SPheno, SLHA, Pythia`

Trilepton, Multilepton and Displaced Vertex Signatures

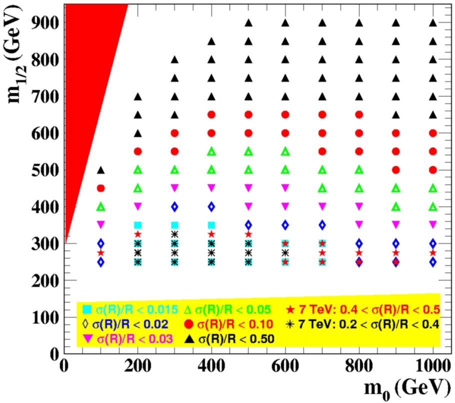


$A_0 = -100$ GeV, $\tan\beta = 10$ and $\mu > 0$ for 100 fb^{-1} at LHC

Compare to RpC the reach is more in RpV scenario
In RpV the reach is even more by exploiting the DV

[de Campos etal. hep-ph/07122156]

$$\frac{\Delta R}{R} = \sqrt{\left(\frac{1}{N_\mu} + \frac{1}{N_\tau}\right)}$$



$\sigma_{LHC} \sim$ 30 pb at 14 TeV [$\sim$ 3 pb at 7 TeV]

$\Rightarrow$ 100 fb^{-1} for 14 TeV and 1 fb^{-1} for 7 TeV: overall $\mathcal{O}(3)$ suppression

$\Rightarrow N_\tau > 5$

$\Rightarrow$ The statistical issue is the major factor at 7 TeV

[arXiv:1006.5075[hep-ph]]

LSP decay length

- $L^0 = \frac{L^{lab}}{\beta\gamma}$
- $\beta\gamma$ is the average boost factor.
- $\gamma = E/m$ and $\beta = |\vec{p}|/E$.
- $m_{\tilde{q},\tilde{g}} \sim 500$ GeV with $m_{\tilde{\chi}_1^0} \sim 100$ GeV at LHC $\beta\gamma$ is $\mathcal{O}$(3-4).

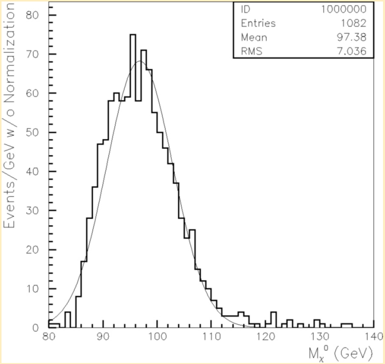
$$L^0 = \frac{L^{lab}}{p^{reco}_{\tilde{\chi}_1^0}} m^{reco}_{\tilde{\chi}_1^0}$$

$\tilde{\chi}_1^0 \rightarrow \mu$ W

Reconstructing $m^{reco}_{\tilde{\chi}_1^0}$ and $\frac{L^{lab}}{p^{reco}_{\tilde{\chi}_1^0}}$

[work in progress]

Mass reco and $\frac{L^{lab}}{p^{reco}_{\tilde{\chi}^0_1}}$ measurement at 14 TeV

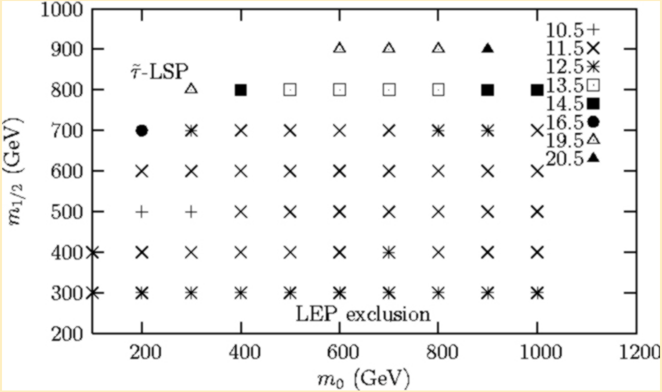


at least 1-μ with $p_T > 20$ GeV and $\eta < 2.5$; 2-jets with $|M_{jj} - M_W| < 10$ GeV

$\frac{\delta M}{M} = 0.057$, $\frac{\delta(L/p)}{(L/p)}$=0.06 with δL^{lab} =10%

overall 12.9% (w/o stat) [N_μ=76000] and unchanged with stat.

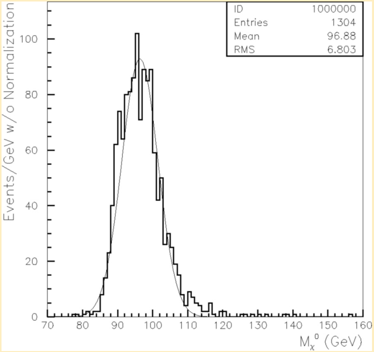
Total Uncertainties

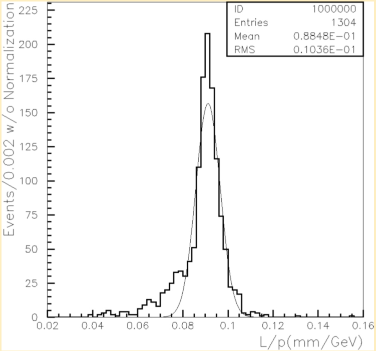


With stat. ($>$ 5 event) within 12% uncertainty one can probe $M_{1/2} < 700$ GeV

One can probe large regions of model parameters

Mass reco and $\frac{L^{lab}}{p^{reco}_{\tilde{\chi}^0_1}}$ measurement at 7 TeV



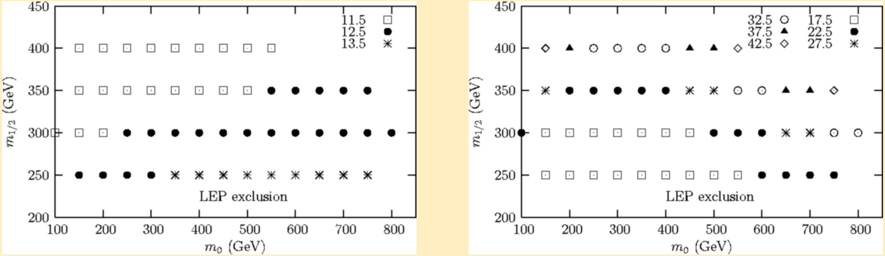


$\frac{\delta M}{M}$= 0.053 and $\frac{\delta(L/p)}{(L/p)}$=0.061

δL^{lab} =10%; overall 12.86% (w/o stat); N_μ=75 thus 17.27% (with stat)

5% increases; again we see that stat. is the major issue

Sensitivity at parameter space at 7 TeV



$N_\mu > 5$ for both ; Left (Right) panel with(out) stat.
Uncertainty $< 14\%$ (without stat) until $M_{1/2} < 400$ GeV and $M_0 < 800$ GeV.
With stat., one can probe $< 20\%$ until $M_{1/2} < 300$ GeV and $M_0 < 600$ GeV.

One can probe very restricted regions of model parameters

Summary

- BRpV is the simplest extension of SUSY to describe ν-masses and mixing.
- In BRpV model parameters, consistent with recent ν-data, LSP decays within the detector leads to Displaced vertex (background free) and correlation among Branching ratios (leads to Atmospheric angle).
- At 14 TeV with 100 fb^{-1}, decay length (L^0) uncertainties approx. 10-13% (max. 3% from simulation); with $< 14\%$ uncertainties one can probe $M_{1/2} < 700$ GeV (almost M_0 independent).
- At 7 TeV with 1 fb^{-1}, the number of event is small. With $N_\mu > 5$, one can probe with $<$ 14% (without stat.) in $M_{1/2} < 400$ GeV and $M_0 < 800$ GeV.
  With stat., one can probe $< 20\%$ until $M_{1/2} < 300$ GeV and $M_0 < 600$ GeV.
- Together with BR uncertainties (by counting explicit event structure) one can have overall L^0/Br and hence test the Atmospheric Mass scale.
- ATLAS triggers are designed to exploit $\not{E}_T$ and isolated-lepton. DV with $M_{inv} \sim 100$ GeV are not included. If included and if this signal can be observed then it establish BRpV is theory behind the Neutrino masses and mixing (LHCb is very promising in the Higgs channel ($\tilde{\chi}_1^0 \rightarrow \nu H$) by exploiting b-tagging).
- LSP decay ratio to $e\tau\nu$ and $\mu\tau\nu$: $\frac{\epsilon_e}{\epsilon_\mu} \rightarrow \theta_{solar}$
  [work in progress].