Neutralino decay length measurement consistent with Neutrino masses and mixing in Bilinear R-parity violating MSSM at LHC

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`ongoing work`

in collaboration with
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Outline

1. Neutrino masses and mixing
2. R-parity violation (RpV)
3. Neutrino Masses from BRpV
4. Neutralino decay width, length and BR
5. Displaced Vertex
6. Uncertainty in Length measurement
7. Summary

Present status of the best-fitted Neutrino masses and mixing

parameter	best fit	2σ	3σ
Δm^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]

MSSM with R-parity violation (RpV)

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

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

General Superpotential of the Minimal Supersymmetric extension of the SM (MSSM):

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

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

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

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

- Explain the Neutrino masses and mixing.
- The lightest supersymmetric particle (LSP) is not stable anymore and decay inside the Inner Detector (ID) leads to displaced vertices.
- Sparticles masses, decay BR and cascade patterns changes.

Mixing...

It causes mixing in neutrino-Neutralino; charged lepton-Chargino; sneutrino-CP-even Higgs; anti-sneutrino-CP-odd Higgs; charged Higgs-sleptons; squarks (LR mixing through Slepton VEVs).

In $(-i\widetilde{\mathcal{B}}, -i\widetilde{\mathcal{W}}^{(3)}, \tilde{h}_u^0, \nu_\alpha)$ basis the mass-matrix:

$$\mathcal{M}_{\rm N} = \begin{pmatrix} M_1 & 0 & M_Z s_W \frac{v_u}{\sqrt{v_\gamma^2}} & -M_Z s_W \frac{v_\beta}{\sqrt{v_\gamma^2}} \\ 0 & M_2 & -M_Z c_W \frac{v_u}{\sqrt{v_\gamma^2}} & M_Z c_W \frac{v_\beta}{\sqrt{v_\gamma^2}} \\ M_Z s_W \frac{v_u}{\sqrt{v_\gamma^2}} & -M_Z c_W \frac{v_u}{\sqrt{v_\gamma^2}} & 0 & -\mu_\beta \\ -M_Z s_W \frac{v_\alpha}{\sqrt{v_\gamma^2}} & M_Z c_W \frac{v_\alpha}{\sqrt{v_\gamma^2}} & -\mu_\alpha & 0_{\alpha\beta} \end{pmatrix},$$

Neutrino Masses

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

$$\mathcal{M}_{\rm N} = \left(\begin{array}{cc} M_{\tilde{\chi}_0} & m \\ m^T & 0 \end{array} \right) ,$$

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

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

$$v_i, \, \epsilon_i \lesssim 1 \, {\rm MeV} \quad {\rm for} \quad M_{\rm SUSY} \lesssim 1 \, {\rm TeV}.$$

Neutrino Masses contd...

In BRpV the tree-level neutrino mass:

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

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

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

$$m_{\nu_2} \simeq c_1 \frac{(\vec{\epsilon} \times \vec{\Lambda})^2}{|\vec{\Lambda}|^2} \tag{3}$$

$$m_{\nu_3} \simeq c_0 |\vec{\Lambda}|^2 \tag{4}$$

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]

Solar and Atmospheric Neutrinos

6 parameters: 3 ϵ_i and 3 v_i
In generic model parameters:
$\rightarrow$ if $\epsilon^2/|\vec{\Lambda}| \ll 100$ leads to 1-loop corrections are small leads to

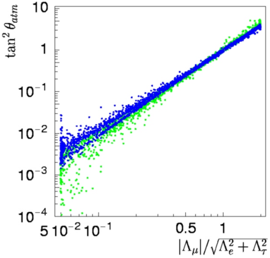
$$U_{\alpha 3} \approx \Lambda_\alpha / |\vec{\Lambda}| \tag{5}$$

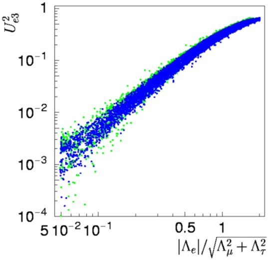
Atmospheric and reactor neutrino data: $\nu_\mu \rightarrow \nu_\tau$ preferred over $\nu_\mu \rightarrow \nu_e$.

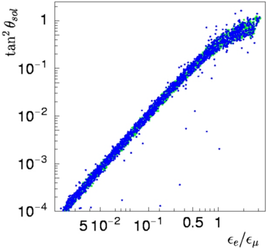
$$\Lambda_e \ll \Lambda_\mu \simeq \Lambda_\tau \tag{6}$$

are required to fit the recent Neutrino data

Angle







- 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

Probing Oscillation parameters at LHC

- 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 $\tilde{\nu}$-LSP in explicit RpV
[Dreiner hep-ph/9707435;
Bernhardt,SPD,Dreiner,Grab;PRD79:035003,2009, Dreiner,Grab PLB679(2009)45].

Generally DV is SM background free; if not Bgs simulation necessary.

Decay widths

$\tilde{\chi}_1^0$ (mostly bino) and the width:

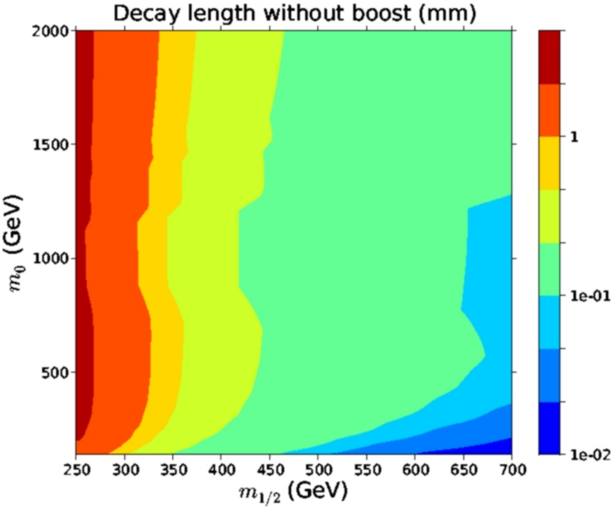
$$\Gamma(\tilde{\chi}_1^0 \to \sum_i W^{\pm} l^{\mp}) \sim \frac{g^2 g'^2 M_2 m_{\tilde{\chi}_1^0}}{(16\pi M_1 m_\gamma)} f(m_W^2/m_{\tilde{\chi}_1^0}^2) m_\nu^{\mathrm{Tree}} \sim \frac{\Lambda_i^2}{det(\mathcal{M}_{\tilde{\chi}'})} \tag{7}$$

$$\Gamma(\tilde{\chi}_1^0 \to \sum_i Z^0 \nu_i) \sim 0.5\ \Gamma(\tilde{\chi}_1^0 \to \sum_i W^{\pm} \ell_i^{\mp}) \tag{8}$$

$$\Gamma(\tilde{\chi}_1^0 \to \nu \tau^+ \ell_i^-) \sim \qquad \frac{\epsilon_i^2}{\mu^2} \tag{9}$$

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

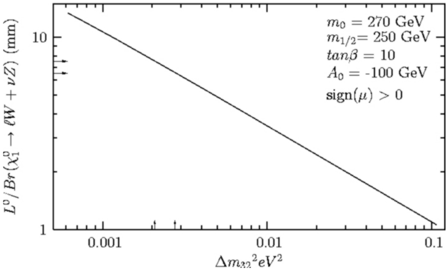
Decay Length Profile in BRpV mSUGRA scenario



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

Length over Br

$$\frac{L^0}{Br} \sim \frac{c}{\Gamma_{Gauge}} \sim \frac{c}{m_\nu^{\mathrm{Tree}}}$$



The uncertainties in L^0 and Br can be projected onto Atmospheric uncertainty

$m_{\tilde{\chi}_1^0}$ = 97.8 GeV L^0= 8.8 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

Couplings

$\tilde{\chi}^0_1$-W-l_i coupling O^L_i is given by

$$O^L_i = \Lambda_i f(M_1, M_2, \mu, \tan\beta, v_d, v_u) \tag{10}$$

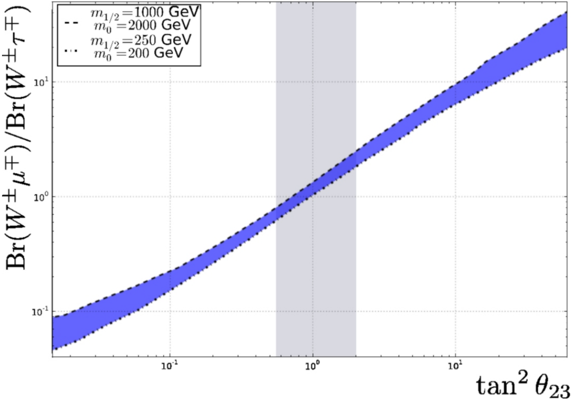
f only depends on MSSM parameters but not on the BRpV parameters

BR ratio

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

if the slepton/squarks contributions are small.

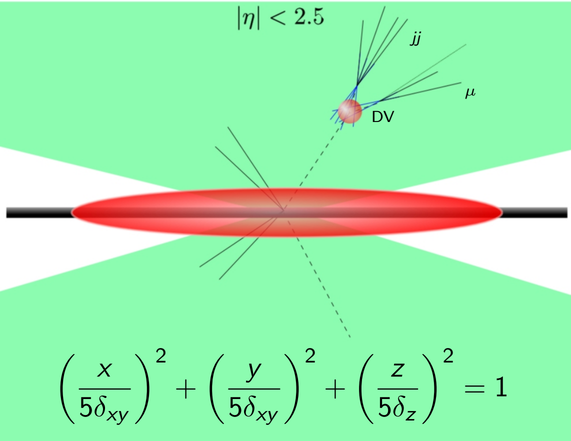
Atmospheric Angle and Ratios of Branching ratios



$A_0 = -100\,\mathrm{GeV}$, $\tan\beta = 10$, and $\mathrm{sgn}(\mu) = +1$
Neutrino Masses and mixing angles fit within 3σ

How can that be tested at the Collider?

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: $\delta_{xy} = 20\ \mu$m and $\delta_z = 500\ \mu$m

All possible sparticle production at LHC at 14 TeV

Eventually cascades to $\tilde{\chi}_1^0$ which decays into e/μW

Trigger

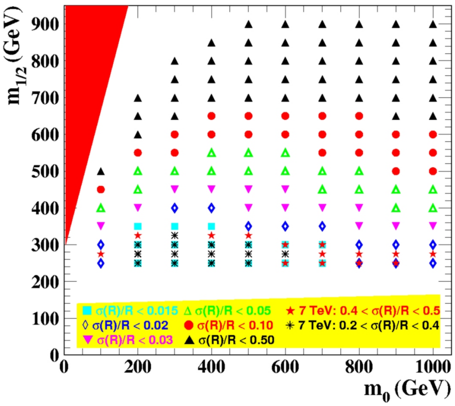
LHC experiments not yet defined any specific strategy to trigger DV for high Invariant masses.

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.

Analysis: `SPheno, SLHA, Pythia`

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



$\Rightarrow N_\tau > 5$

$\Rightarrow$ 100 fb^{-1} for 14 TeV and 1 fb^{-1} for 7 TeV (cross-section $\mathcal{O}(1)$ less)

$\Rightarrow$ overall $\mathcal{O}(3)$ suppression 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).

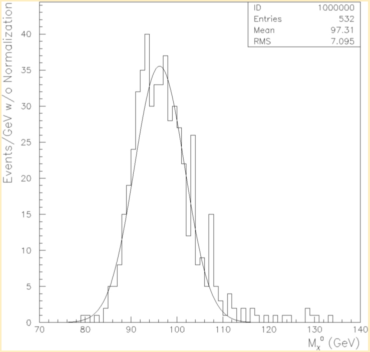
$$L^0 = \frac{L^{lab}}{p^{reco}_{\tilde{\chi}_1^0}} m^{reco}_{\tilde{\chi}_1^0}$$

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

[work in progress]

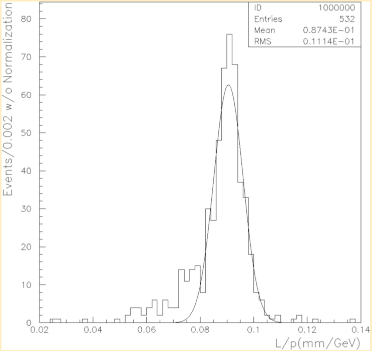
Mass reconstruction

SPheno → SLHA → Pythia $\Rightarrow \sigma_{LHC} = 30$ pb



at least one μ with $p_T > 20$ GeV and $\eta < 2.5$
at least two jets with $|M_{jj} - M_W| < 10$ GeV
overall eff. 0.007 and Gaussian fits: $\delta M = 5.5$ GeV; $\frac{\delta M}{M} = 0.057$

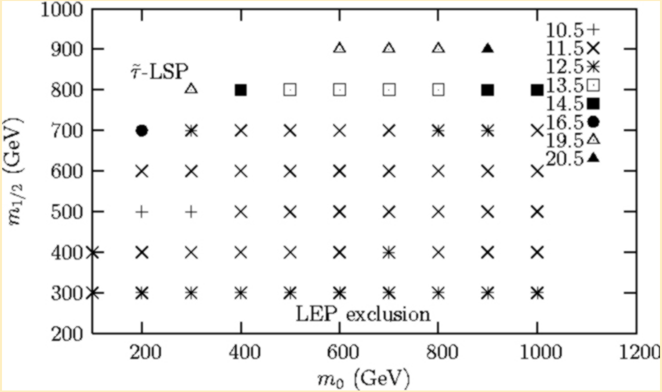
$\frac{L^{lab}}{p^{reco}_{\tilde{\chi}^0_1}}$ measurement



$$\delta(L/p) = 0.0055\ (\mathrm{mm/GeV});\ \frac{\delta(L/p)}{(L/p)} = 0.06$$

Assuming $\delta L^{lab} = 10\%$; leads to overall 12.9% (without statistics).

Total Uncertainties



⇒ including statistics ($>$ 5 event) 12% in large parameter space
⇒ Maximum 20%

⇒ BR uncertainties can also be measurable from simulation
⇒ Then L^0/Br can explain the atmospheric uncertainties

Summary

Summary

- R-parity is a discrete symmetry and 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 (almost background free) and correlation among Branching ratios.
- Decay length (L^0) uncertainties approx. 10-13% (max. 3% from simulation).
- With Statistical uncertainties the max uncertainties $< 20\%$.
- Together with BR uncertainties (i.e., L^0/Br) one can project the Atmospheric Angle uncertainties.
- ATLAS triggers are designed to exploit $\not{E}_T$ and isolated-lepton. Displaced vertex with such high invariant masses (~ 100 GeV) are not really included. If included and if this signal can be observed then it proves that BRpV is the theory behind the origin of Neutrino masses and mixing.
- LSP decay ratio to $e\tau\nu$ and $\mu\tau\nu$: $\frac{\epsilon_e}{\epsilon_\mu} \to \theta_{solar}$ [work in progress].