Spontaneous R-parity violation and the origin of neutrino masses

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Outline

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- ⋆ The model
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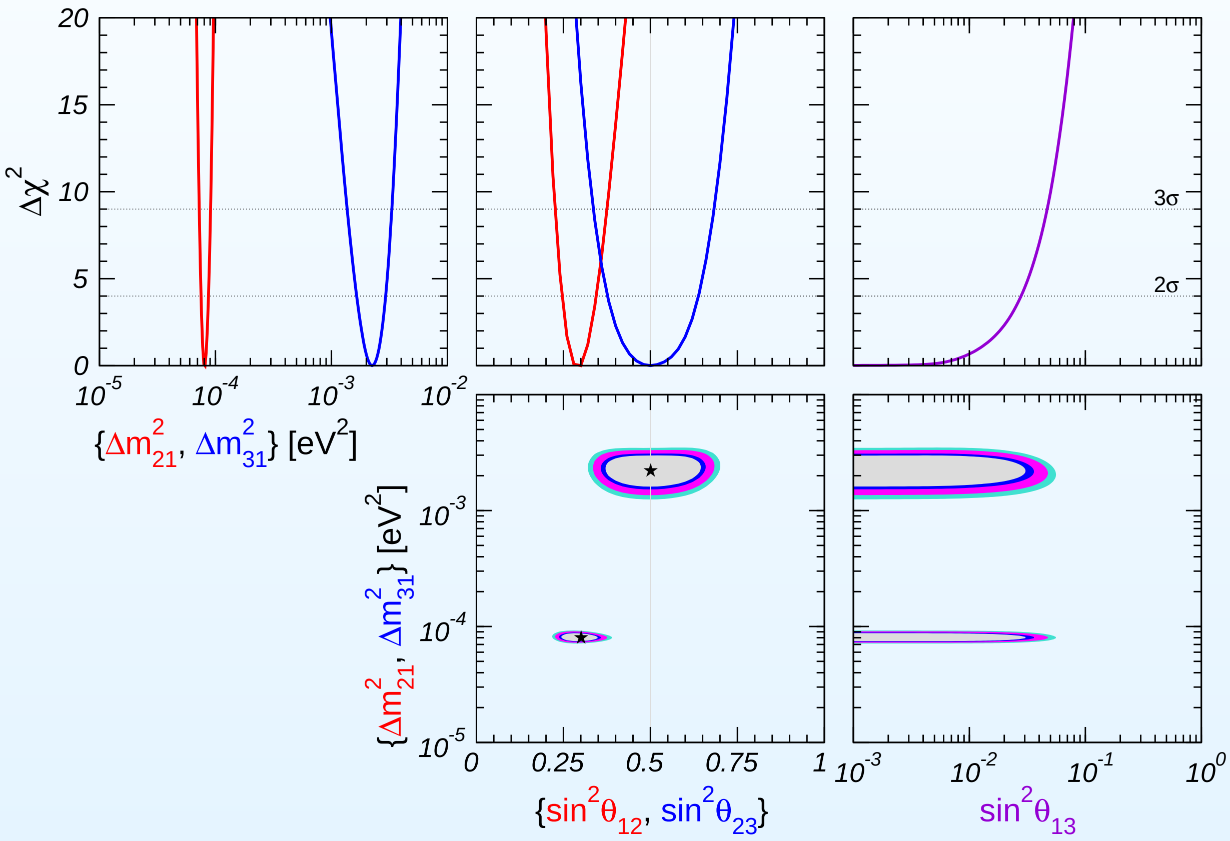
Introduction

Introduction

Oscillation experiments have demonstrated that neutrinos have non-zero masses and mixing angles.



Source: Maltoni et al, hep-ph/0405172v6 (online updated version)

Introduction

Many models. . .

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- ⋆ **See-Saw Type I.** Very natural explanation, but difficult to test

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    A. Zee, Phys. Lett. B 93, 389 (1980)

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  - . . .
  - **R-parity violation:** BRpV, TRpV, . . . **s-$\not{R}_p$**

    C.S. Aulakh and R.N. Mohapatra, Phys. Lett. B 119, 136 (1982)

    L.J. Hall and M. Suzuki, Nucl. Phys. B 231, 419 (1984)

    M. Hirsch and J.W.F. Valle, New J. Phys. 6, 76 (2004)

The model

Model basics

A. Masiero and J.W.F. Valle, Phys. Lett. B 251, 273 (1990)

J.C. Romao and J.W.F. Valle, Nucl. Phys. B 381, 87 (1992)

⋆ **Particle content**

			$\widehat{\nu}^c$	$\widehat{S}$	$\widehat{\Phi}$
MSSM	+	L:	-1	+1	0
			Singlets		

⋆ **Superpotential**

$$\begin{aligned}\mathcal{W} &= h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u + h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d \\ &+ \mathbf{h_\nu^i \widehat{L}_i \widehat{\nu}^c \widehat{H}_u} - h_0\widehat{H}_d\widehat{H}_u\widehat{\Phi} + h\widehat{\Phi}\widehat{\nu}^c\widehat{S} + \frac{\lambda}{3!}\widehat{\Phi}^3\end{aligned}$$

- Lepton number (and R_p) is conserved at the level of the superpotential
- $\mathcal{W}$ does not contain any terms with dimensions of mass, offering a potential solution to the **μ-problem**

Model basics

⋆ **Electroweak symmetry breaking**

After electroweak symmetry breaking various fields acquire vevs:

$$\langle H_d^0 \rangle = \frac{v_d}{\sqrt{2}} \text{ and } \langle H_u^0 \rangle = \frac{v_u}{\sqrt{2}}$$

but also

$$\langle \Phi \rangle = \frac{v_\Phi}{\sqrt{2}} \quad \langle \tilde{\nu}^c \rangle = \frac{v_R}{\sqrt{2}} \quad \langle \tilde{S} \rangle = \frac{v_S}{\sqrt{2}} \quad \langle \tilde{\nu}_i \rangle = \frac{v_{L_i}}{\sqrt{2}}$$

and then

$$\left. \begin{array}{c} \mathcal{W} \supset -h_0 \widehat{H}_d \widehat{H}_u \widehat{\Phi} \; \longrightarrow \; -\mu \widehat{H}_d \widehat{H}_u \\ \boldsymbol{\mu = h_0 \frac{v_\Phi}{\sqrt{2}}} \end{array} \right\} \Rightarrow \quad \mu\text{-term}$$

$$\left. \begin{array}{c} \mathcal{W} \supset h_\nu^i \widehat{L}_i \widehat{\nu}^c \widehat{H}_u \; \longrightarrow \; \epsilon_i \widehat{L}_i \widehat{H}_u \\ \boldsymbol{\epsilon_i = h_\nu^i \frac{v_R}{\sqrt{2}}} \end{array} \right\} \Rightarrow \quad \text{Spontaneous } \mathrm{R_p} \text{ breaking}$$

$\Downarrow$

Goldstone boson

The majoron, J

Neutrino masses

After some straightforward algebra, $\boldsymbol{m_{\nu\nu}^{\text{eff}}}$ can be cast into a very simple form

$$-(\boldsymbol{m_{\nu\nu}^{\text{eff}}})_{ij} = a\Lambda_i\Lambda_j + b(\epsilon_i\Lambda_j + \epsilon_j\Lambda_i) + c\epsilon_i\epsilon_j$$

where $\Lambda_i = \epsilon_i v_d + \mu v_{L_i}$ are the so-called *alignment parameters*.

Important:

- ⋆ The matrix $\boldsymbol{m_{\nu\nu}^{\text{eff}}}$ has two non-zero eigenvalues
- ⋆ **Two possibilities** to fit neutrino data:
  - **Case (c1):** $\vec{\Lambda}$ generates the atmospheric scale, $\vec{\epsilon}$ the solar scale
  - **Case (c2):** $\vec{\epsilon}$ generates the atmospheric scale, $\vec{\Lambda}$ the solar scale

Neutralino phenomenology

Bino vs Singlino

The spectra of the seven heavy states depends on many unknown parameters:

$$\mathbf{M_H} = \begin{pmatrix} \mathbf{M}_{\chi^0} & \mathbf{0} & \mathbf{0} & \mathbf{m}_{\chi^0\mathbf{\Phi}} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{\nu^c\mathbf{S}} & \mathbf{M}_{\nu^c\mathbf{\Phi}} \\ \mathbf{0} & \mathbf{M}_{\nu^c\mathbf{S}} & \mathbf{0} & \mathbf{M}_{\mathbf{S\Phi}} \\ \mathbf{m}^{\mathbf{T}}_{\chi^0\mathbf{\Phi}} & \mathbf{M}_{\nu^c\mathbf{\Phi}} & \mathbf{M}_{\mathbf{S\Phi}} & \mathbf{M}_{\mathbf{\Phi}} \end{pmatrix}$$

But typically

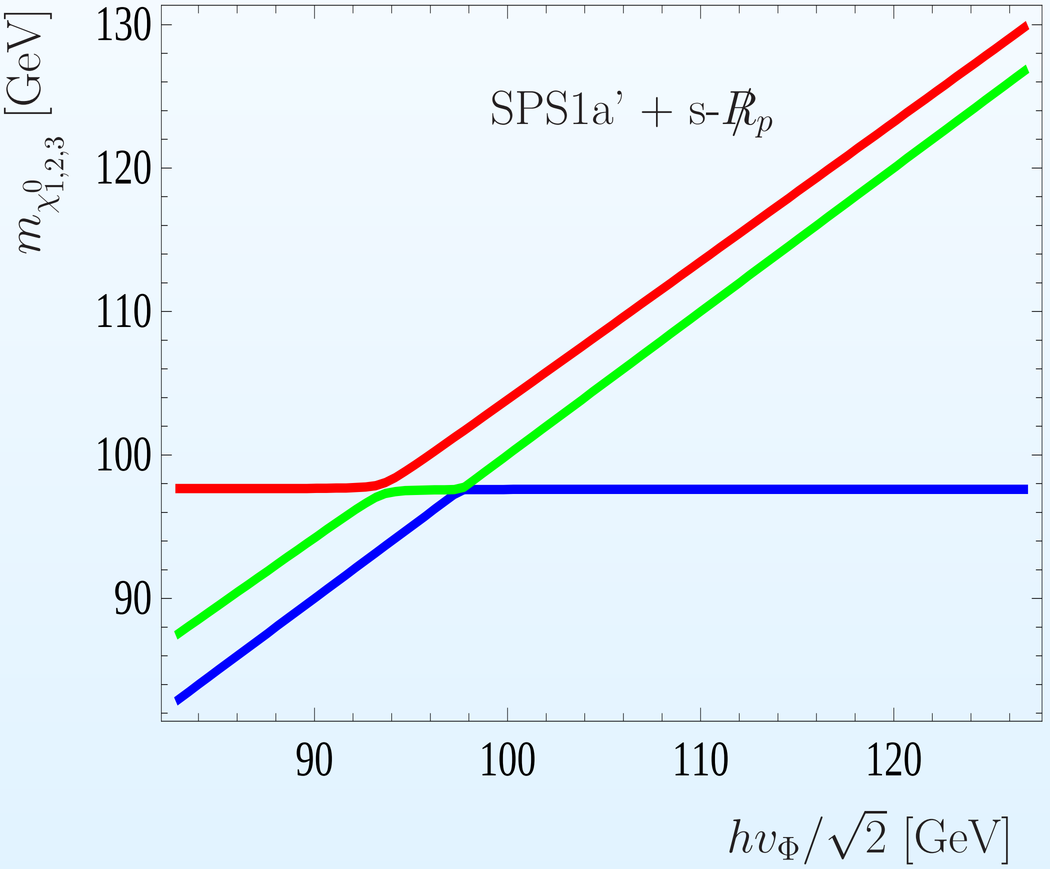
- There are four states very close to the MSSM neutralinos
- ν^c and S form a quasi-Dirac pair, **the Singlino**, $\mathcal{S}_{\mathbf{1,2}} \simeq \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(\boldsymbol{\nu}^{\mathbf{c}} \mp \mathbf{S})$
- The remaining state is the phino, $\tilde{\Phi}$

Bino vs Singlino

Which one is the lightest?

We study two cases

- **Bino-like $\tilde{\chi}^0_1$**: Typical mSUGRA point
- **Singlino-like $\tilde{\chi}^0_1$**: When $\mathbf{M_{\nu^c S}} = \frac{1}{\sqrt{2}} h v_\Phi \lesssim M_1$



Neutralino production

- ⋆ Neutrino physics requires that the $\not{R}_p$ parameters are small

  $\Longrightarrow$ Production cross sections are very similar to the corresponding MSSM values

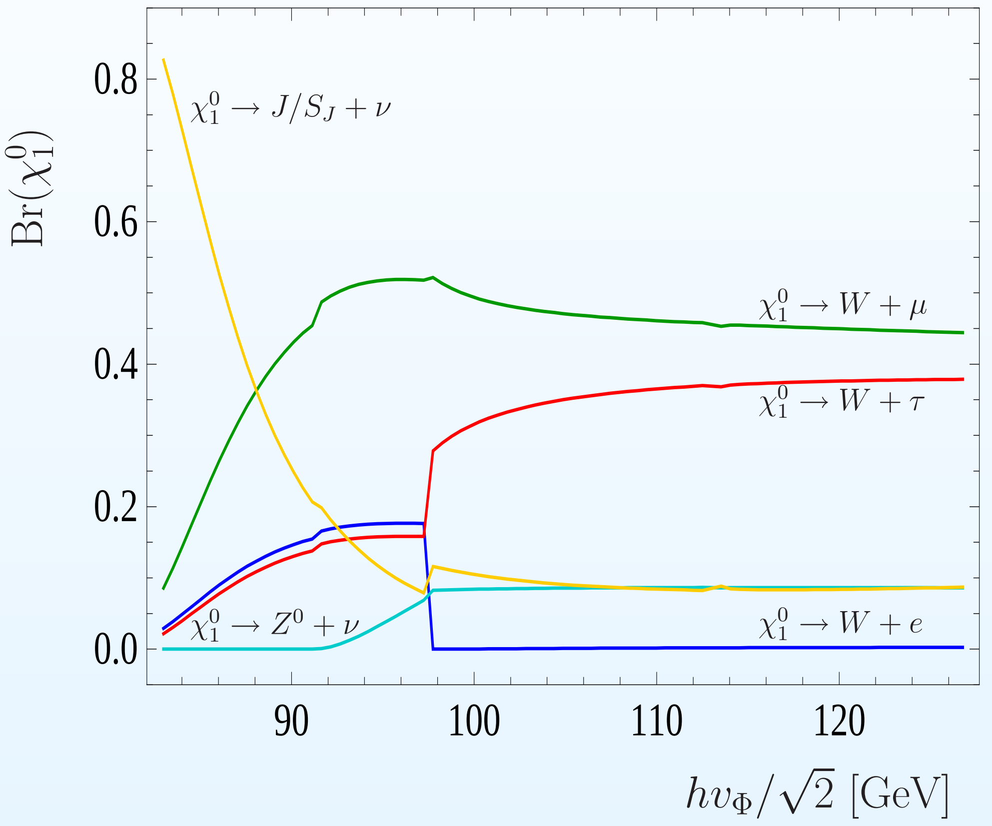
- ⋆ The lightest neutralinos (bino or singlino) **will appear** as “final” (since R_p is broken, the LSP can decay to SM particles) states of the decay chains

$$\tilde{q} \to q + \tilde{\mathbf{B}} \to q + \mathcal{S}_{\mathbf{1},\mathbf{2}} + J \to \ldots$$

- ⋆ Singlinos can be **produced and studied** at accelerators

Neutralino decays

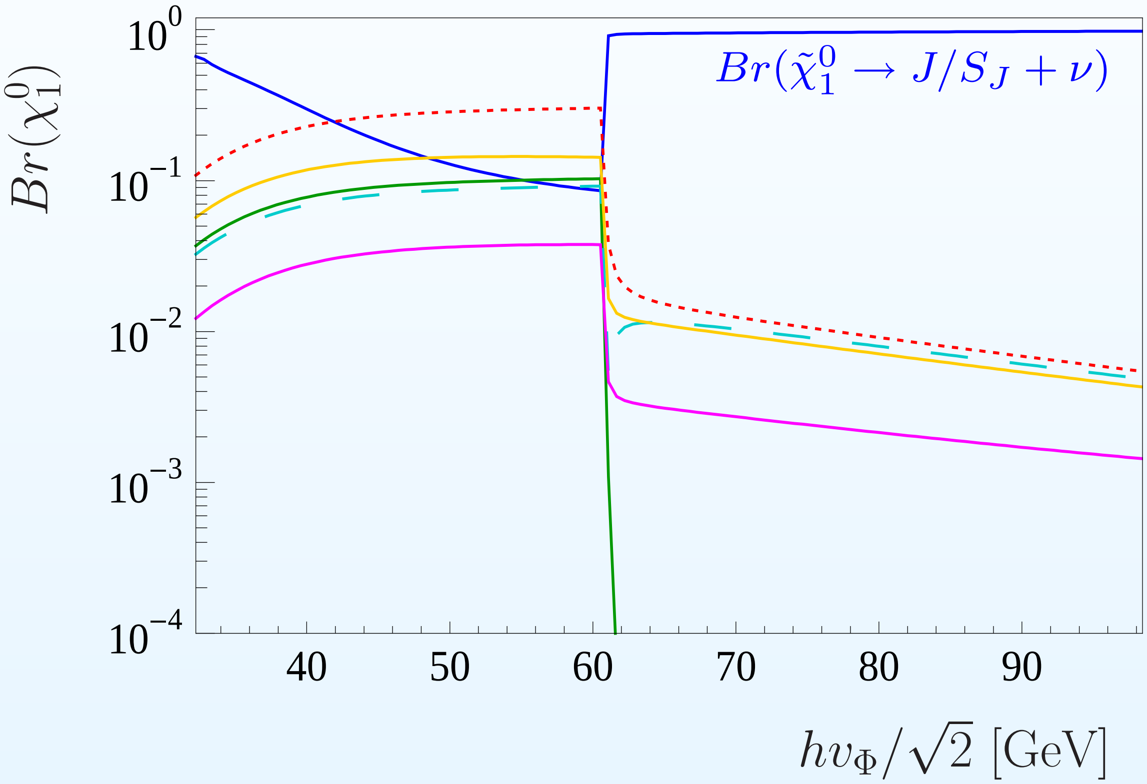
⋆ **Most important decay channels:** $\mathbf{m_{\chi_1^0} \geq m_{W^\pm}}$



- **Invisible channels** have typically a measurable branching ratio, being dominant in some cases.
- Decays to $\mathbf{W + l}$ have large branching ratios.

Neutralino decays

⋆ **Most important decay channels:** $\mathbf{m_{\chi_1^0} < m_{W^\pm}}$



- Again, **invisible channels** can be dominant.
- LFV decays (like $\tilde{\chi}_1^0 \to \nu \mu \tau$) are as important as the LF conserving ones (like $\tilde{\chi}_1^0 \to \nu \mu \mu$).

$\Rightarrow$ Good chances for **LFV signals**

Neutralino decays

⋆ **Invisible decays**

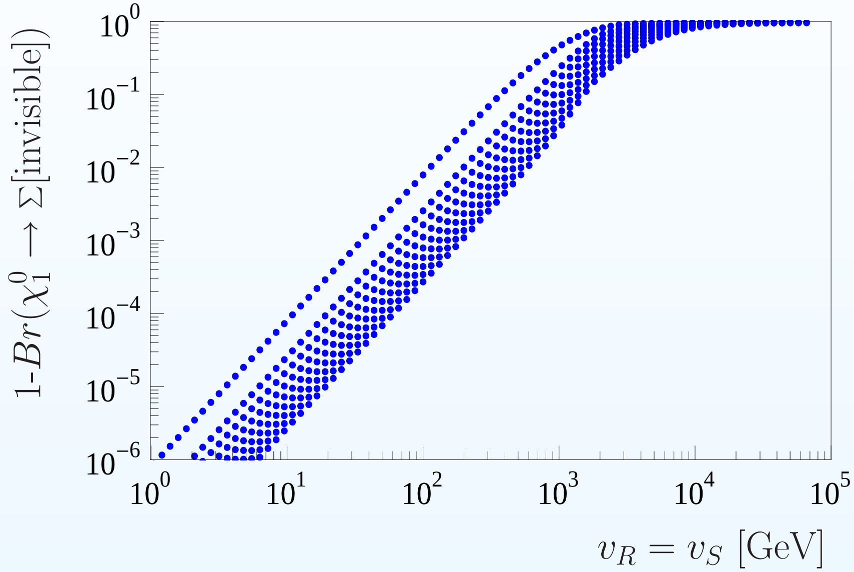
The lightest neutralino can decay to **completely invisible final states**, thanks to the existence of **the majoron**.

- Despite the smallness of the $\not{R}_p$ parameters, the LSP typically decays inside the detector
- But, if the decay products are invisible... **it would look like conserved $\mathbf{R_p}$**

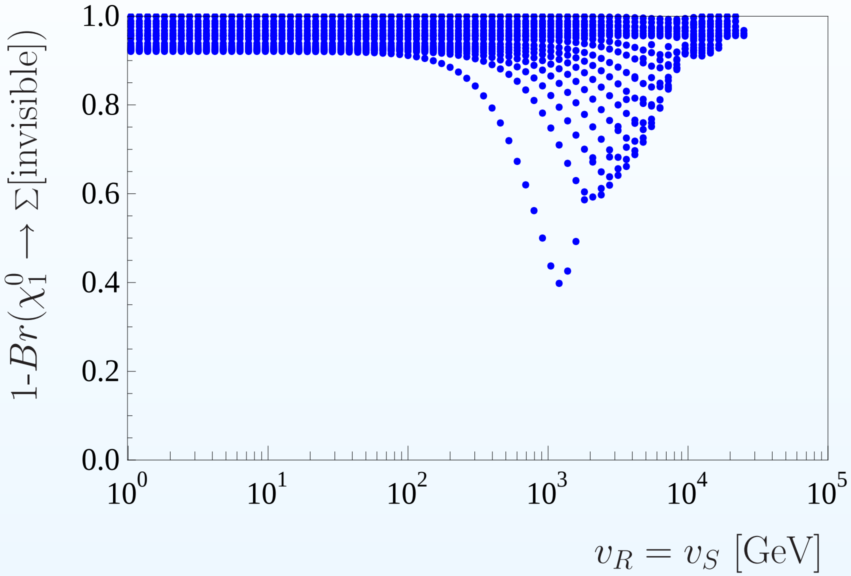
We need additional information
$\Rightarrow$ **Exotic muon decays**

Neutralino decays

Bino LSP



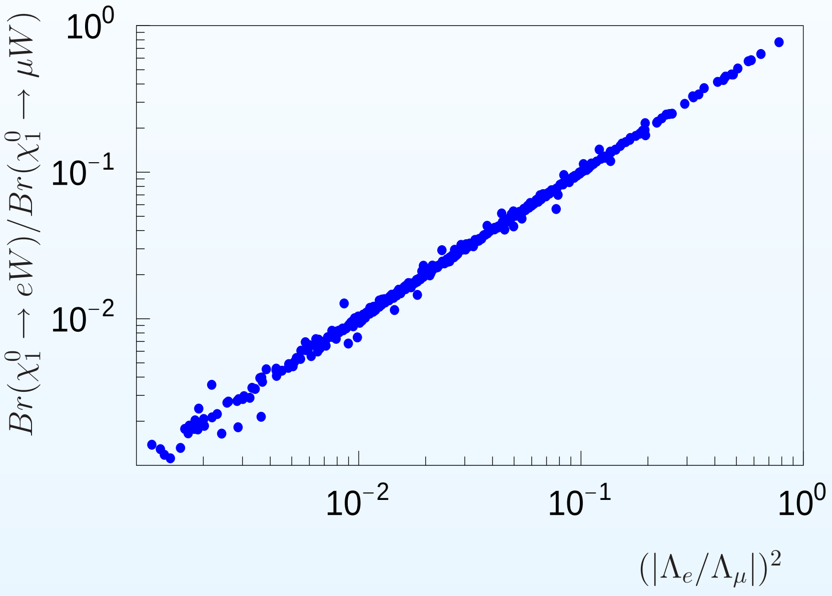
Singlino LSP



- In the case of a **Bino LSP**, low values of v_R lead to $Br(\tilde{B} \to invisible)$ very close to 100%.
  $\Rightarrow$ This scenario can resemble the MSSM
  $\Rightarrow$ Large stadistics will be necessary to prove R_p breaking
- On the other hand, in the case of a **Singlino LSP**, $Br(\mathcal{S} \to invisible)$ never approaches 100%.

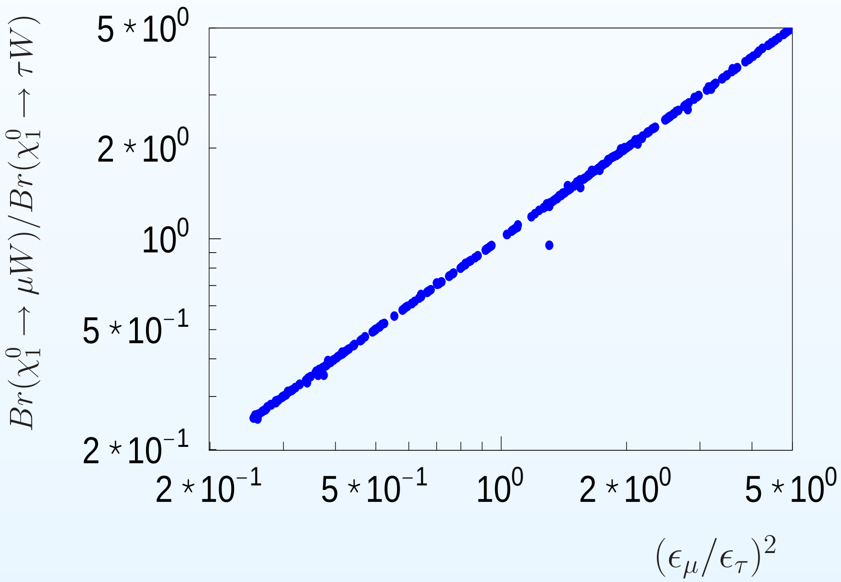
⋆ **Correlations between neutralino decays and neutrino mixing angles**

Bino LSP



$$\mathbf{Br(\tilde{\chi}_1^0 \to W\, l_i) \propto \Lambda_i{}^2}$$

Singlino LSP



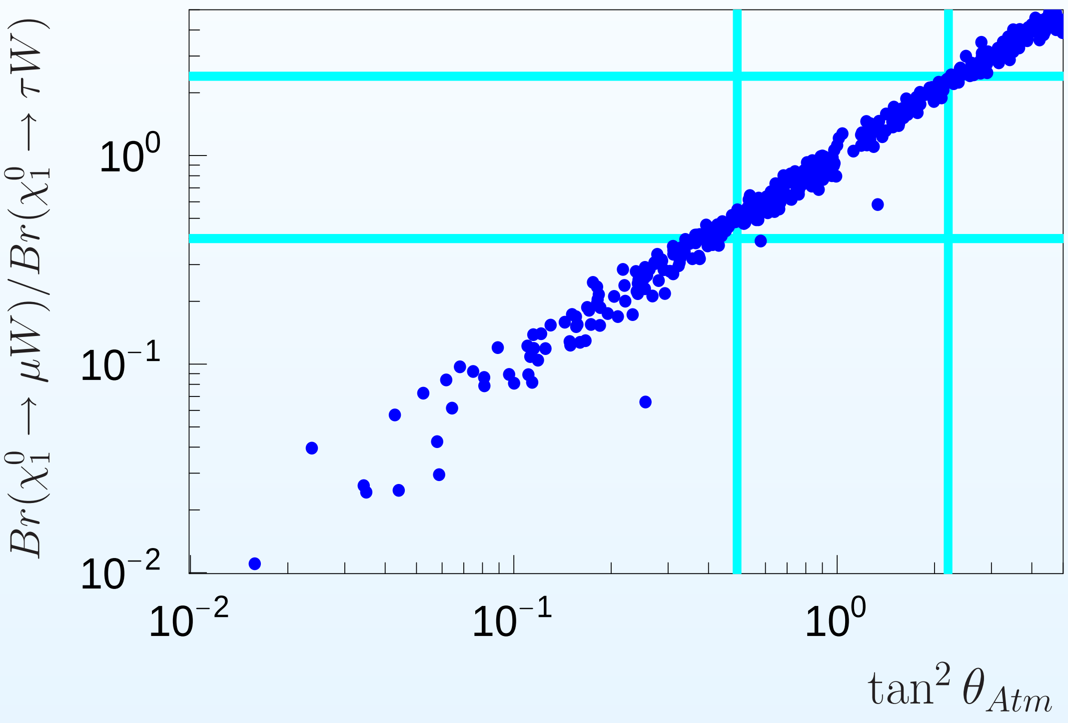
$$\mathbf{Br(\tilde{\chi}_1^0 \to W\, l_i) \propto \epsilon_i{}^2}$$

Since the structure of $m_{\nu\nu}^{\text{eff}}$ is given by $\vec{\Lambda}$ and $\vec{\epsilon}$, this implies **correlations between some combinations of branching ratios and neutrino mixing angles**.

Neutralino decays

Bino LSP

Case (c1)

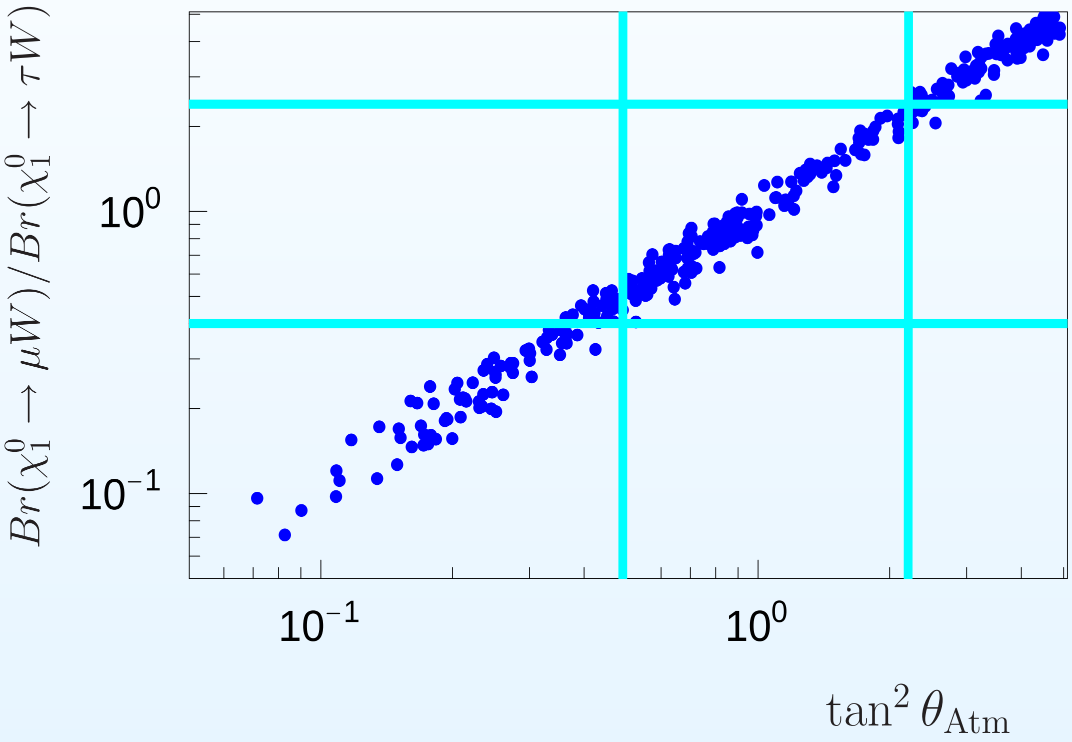


$$\tan^2\theta_{atm} \in [0.5, 2.0] \quad \Rightarrow \quad \frac{Br(\chi_1^0 \to \mu W)}{Br(\chi_1^0 \to \tau W)} \in [0.4, 2.1]$$

Neutralino decays

Singlino LSP

Case (c2)



$$\tan^2\theta_{atm} \in [0.5, 2.0] \quad \Rightarrow \quad \frac{Br(\chi_1^0 \to \mu W)}{Br(\chi_1^0 \to \tau W)} \in [0.4, 2.1]$$

Neutralino decays

- The model is **testable** at the inminent LHC. For instance, finding experimentally

$$\frac{Br(\chi_1^0 \to eW)}{\sqrt{Br(\chi_1^0 \to \mu W)^2 + Br(\chi_1^0 \to \tau W)^2}} >> 1$$

  would rule it out.

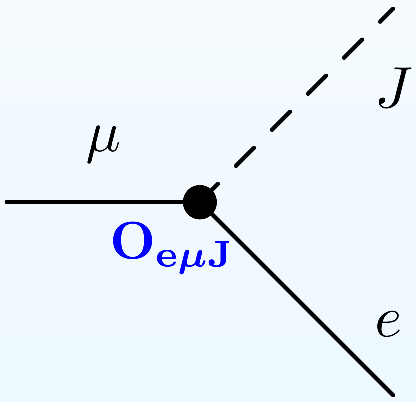
- Since we don't know whether case (c1) or case (c2) is realized, the decay of the lightest neutralino is not sufficient to know **the nature of the LSP**. We need to reconstruct the complete decay chains and use kinematical variables to obtain some information about the intermediate states.

Exotic muon decays

Exotic muon decays

N. Rius, J.C. Romao and J.W.F. Valle, Nuc. Phys. B 363, 369 (1991)
TRIUMF experiment: A. Jodidio *et al*, Phys. Rev. D 34, 1967 (1986)

$$\boxed{\mu \longrightarrow eJ}$$

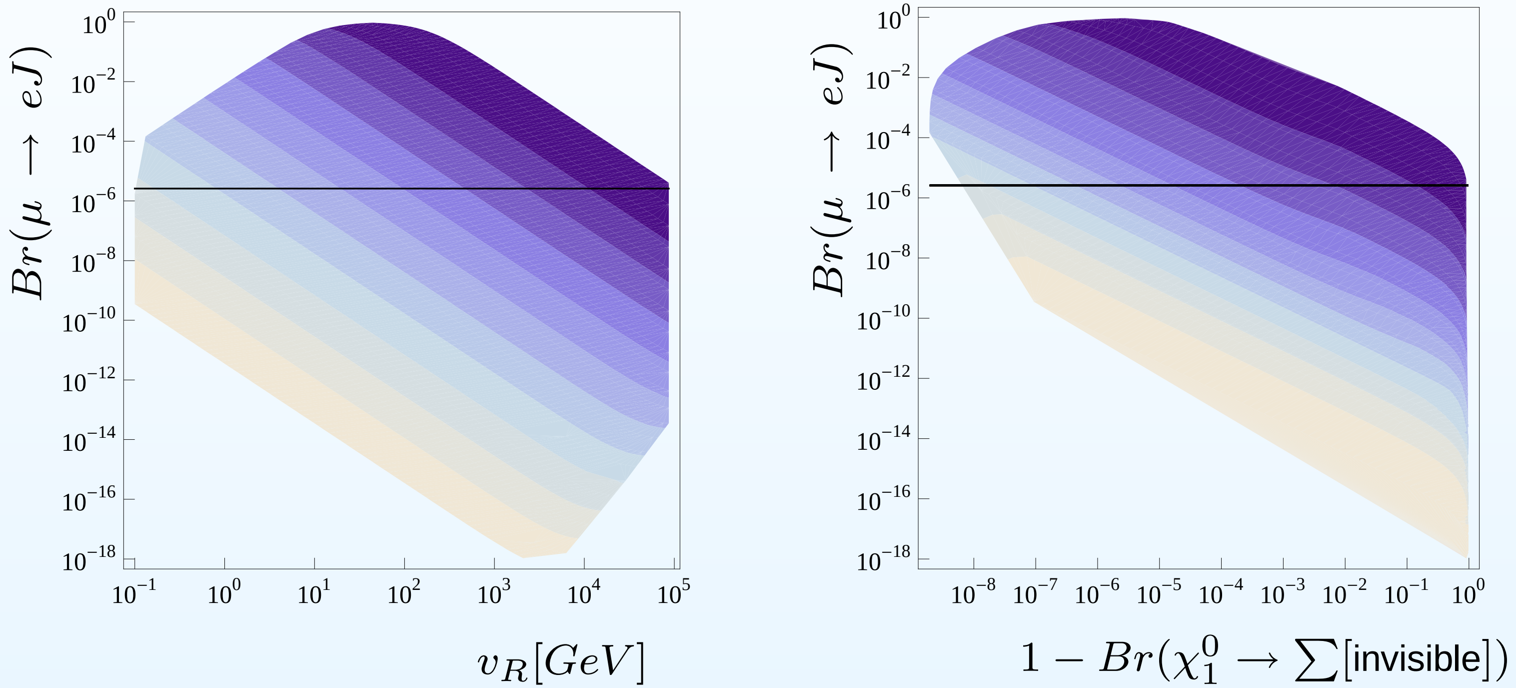


$$\mathbf{O_{e\mu J}} \sim \frac{1}{v_R} \times \not{R}_p \text{parameters}$$

- The branching ratio can be measurable for **low values of $\mathbf{v_R}$**
- Additional information where it is needed
  Remember: a bino LSP decays mainly to invisible channels if v_R is low
- Possible improvement:
  $\boldsymbol{\mu \longrightarrow eJ\gamma}$ does not have the background coming from $\mu \longrightarrow e\nu\bar{\nu}$

Exotic muon decays

Preliminary results . . .



- If this decay is not observed we can exclude a large part of parameter space
- The model can be ruled out if there is tension with the invisible BR of the LSP
- Much better with $\mu \to eJ\gamma$: **MEG experiment**

(Work in progress . . .)

Summary

Summary

- ⋆ Nowadays it is well established that neutrinos are massive.
- ⋆ We have presented a supersymmetric model based on the spontaneous breaking of R-parity, where the neutrinos get masses through their mixing with the heavy neutralinos.
- ⋆ Neutralino decays can be used to ckeck the model. In particular, the correlations between neutralino decays and neutrino mixing angles are very good for this purpose. Therefore, the LHC is potentially able to rule out the model.
- ⋆ Exotic muon decays, like $\mu \to eJ$ and $\mu \to eJ\gamma$, can constrain the model and give us additional information about the scale of lepton number breaking.

Backup slides

Neutralino-Neutrino mixing

Neutrino masses are generated via **neutralino-neutrino mixing**.

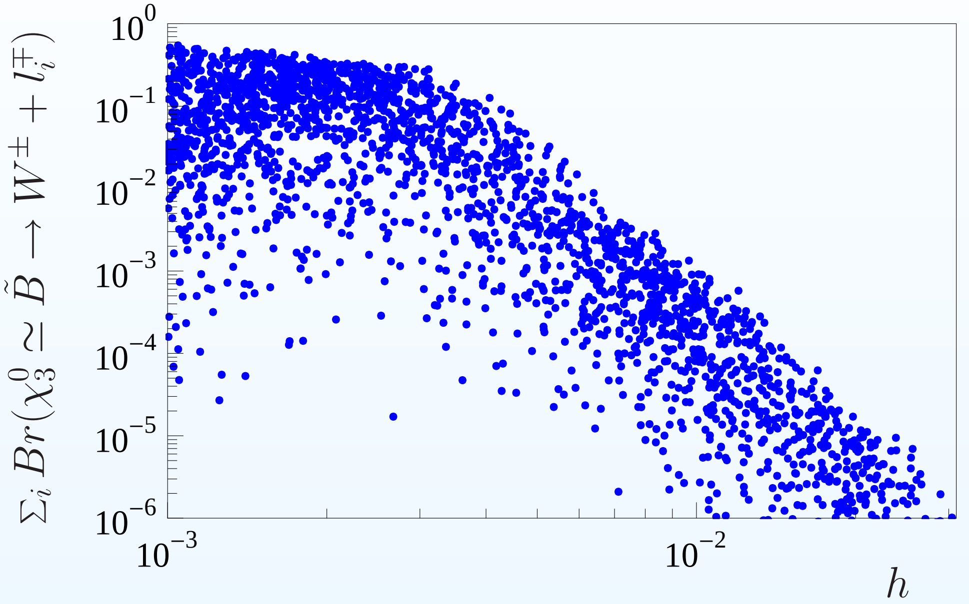
In the basis $(-i\lambda', -i\lambda^3, \tilde{H}_d, \tilde{H}_u, \nu^c, S, \tilde{\Phi}, \nu_e, \nu_\mu, \nu_\tau)$ the 10×10 neutral fermion mass matrix can be written as

$$\mathbf{M_N} = \begin{pmatrix} \mathbf{M_H} & \mathbf{m}_{3\times 7} \\ \mathbf{m}_{3\times 7}^T & 0 \end{pmatrix}$$

The 3×3 neutrino mass matrix is given in 'see-saw approximation' by

$$\boldsymbol{m}_{\boldsymbol{\nu\nu}}^{\mathbf{eff}} = -\mathbf{m}_{3\times 7} \cdot \mathbf{M_H}^{-1} \cdot \mathbf{m}_{3\times 7}^T$$

Is it possible to measure $\vec{\Lambda}$ and $\vec{\epsilon}$ at the same time?

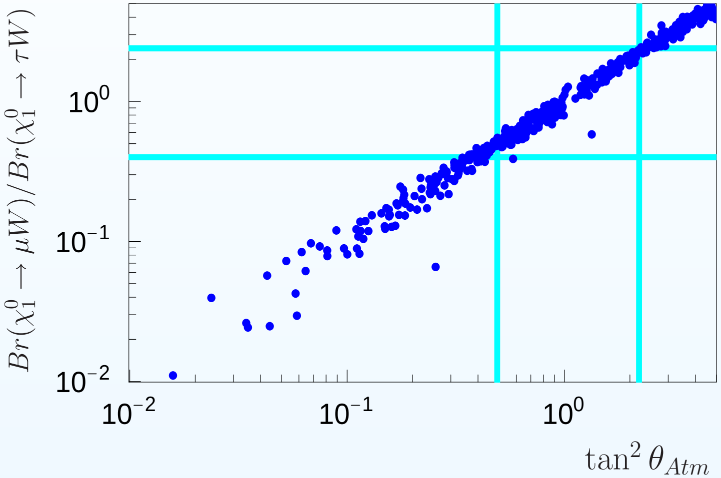


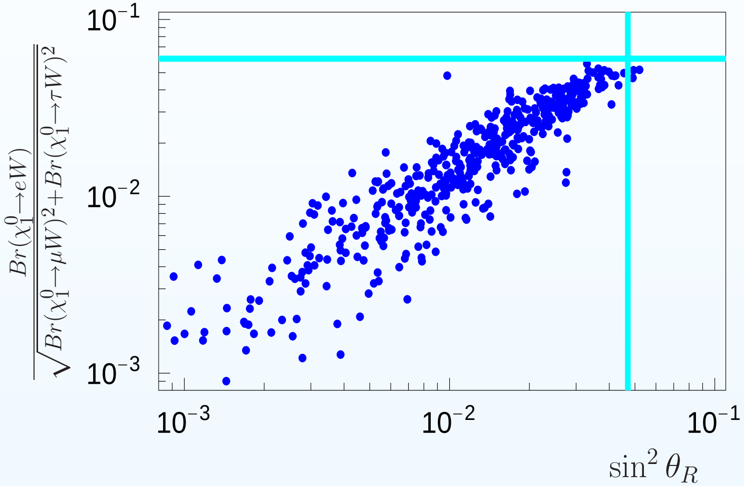
- Typically, the NLSP decays to the LSP and J or $2J$ with $Br \simeq 100\%$.
- Therefore, in most cases it is impossible to measure $\vec{\Lambda}$ **and** $\vec{\epsilon}$, but there is a chance.
- If the $\mathcal{S}$ is the LSP and the $\tilde{B}$ NLSP has a measurable Br to SM particles (that needs a low value for h), we can measure simultaneously both set of parameters.
- This could also give us some clue about the nature of the LSP.

Correlations

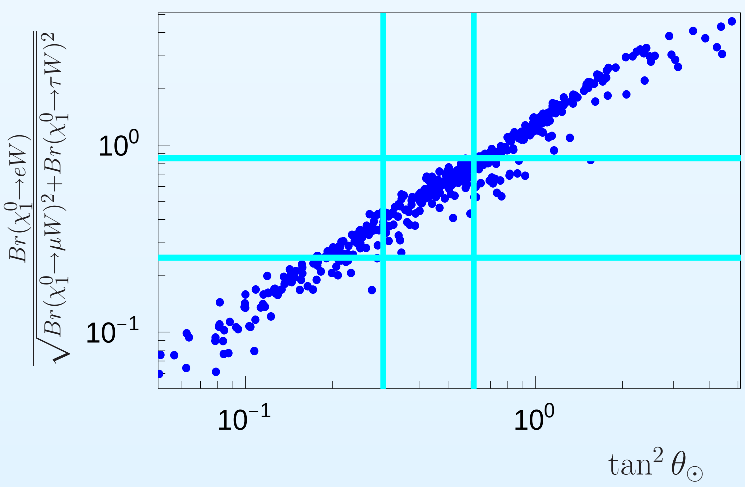
Bino LSP

Case (c1)





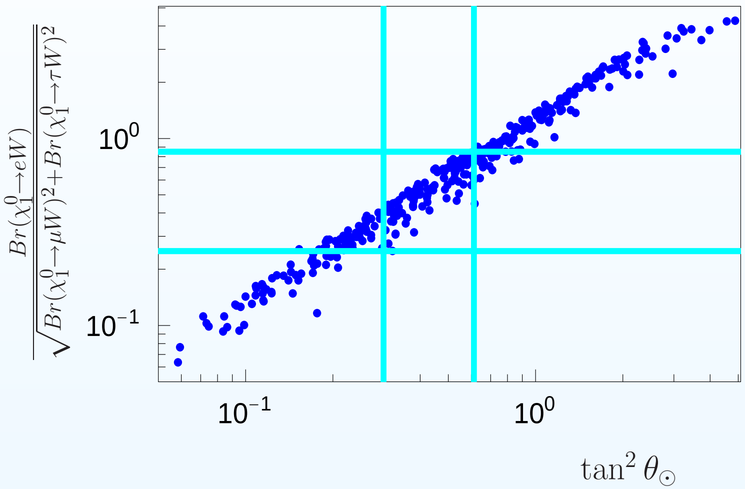
Case (c2)



Correlations

Singlino LSP

Case (c1)



Case (c2)