Neutrino masses in R-parity violating supersymmetry

Avelino Vicente
IFIC - CSIC/U. Valencia

In collaboration with M. Hirsch, J. Meyer and W. Porod

PRD 77, 075005 (2008) *[arXiv:0802.2896]*
PRD 79, 055023 (2009) *[arXiv:0902.0525]*

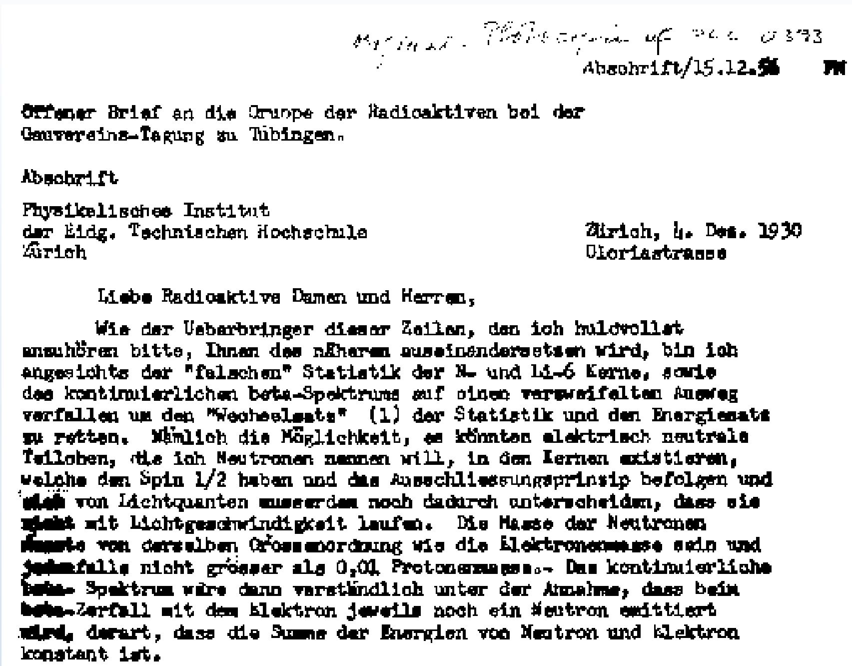
IPMU Seminar

May 20, 2009

Outline

Introduction

Dear radiactive Ladies and Gentlemen…



Abschrift/15.12.

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

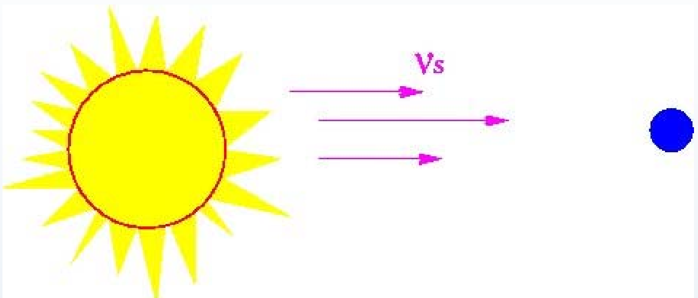
December 4th, 1930

Letter to his colleagues in Tübingen

1930

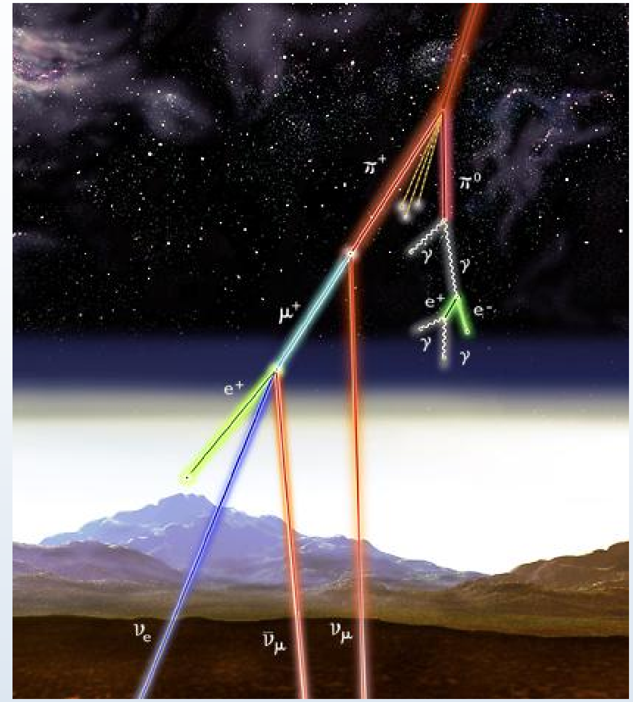
Pauli’s neutrino hypothesis

Solar Neutrino Problem



$$N_{obs} \simeq \frac{1}{3} N_{expected}$$

Atmospheric Neutrino Problem



$$\frac{N_\mu}{N_e} < 2$$

Where are the missing neutrinos?

Motivation

Nowadays there is a well stablished solution to these puzzles:

Neutrino oscillation

Idea: If neutrinos with definite flavor $(\nu_e, \nu_\mu, \nu_\tau)$ are not **mass eigenstates** they oscillate in their propagation

$$|i\rangle = |\nu_e\rangle \quad \longrightarrow \text{ Propagation } \longrightarrow \quad |f\rangle = C_e|\nu_e\rangle + C_\mu|\nu_\mu\rangle + C_\tau|\nu_\tau\rangle$$

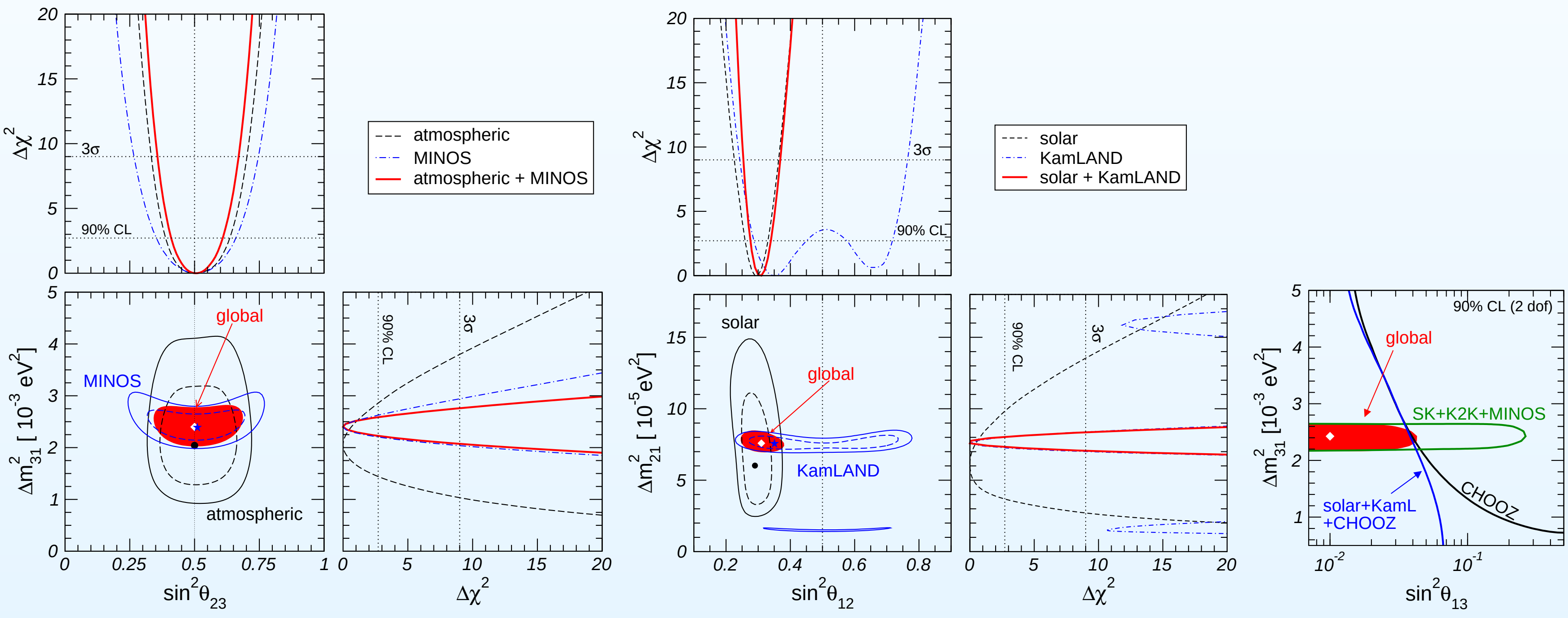
And then, when one does a measurement, the probability of finding a given flavor is

$$P(\nu_e \to \nu_i) \simeq \sin^2\theta_{ei}\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$\Longrightarrow$ **Neutrinos have to be massive!**

Motivation

Oscillation experiments have measured neutrino parameters with great accuracy.



Taken from Schwetz *et al*, New J. Phys. 10 (2008) 113011 *[arXiv:0808.2016v2]*

Motivation

Parameter	Best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	$\leq$ 0.040	$\leq$ 0.056

Taken from Schwetz *et al*, New J. Phys. 10 (2008) 113011 *[arXiv:0808.2016v2]*

- Hierarchy between atmospheric and solar mass scales
- Two large mixing angles
- One small (maybe zero?) mixing angle

Motivation

Many models. . .

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Many models...

- ⋆ **Standard Seesaw.** Very natural explanation, but difficult to test

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Motivation

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- ⋆ **Standard Seesaw.** Very natural explanation, but difficult to test
- ⋆ **Electroweak scale models.**
  - Radiative neutrino masses
  - Low-scale seesaw
  - . . .
  - **Supersymmetry with R-parity violation**

    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)
    J. Ellis *et al*, Phys. Lett. B 150, 142 (1985)

    For comprehensive reviews see:

    M. Hirsch and J.W.F. Valle, New J. Phys. 6, 76 (2004)
    R. Barbier *et al*, Phys. Rept. 420, 1 (2005)

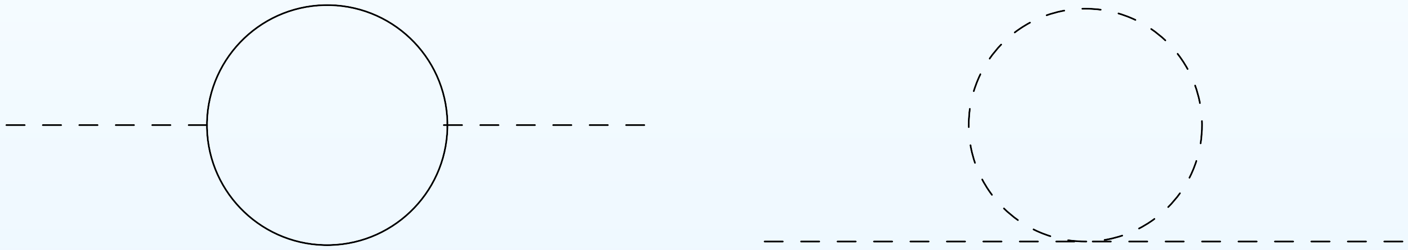
SUSY with R-parity violation

First of all . . . **why weak scale supersymmetry?**

SUSY with R-parity violation

First of all . . . **why weak scale supersymmetry?**

- Solves the **hierarchy problem**



$$\Delta m_H^2 = m_{SUSY}^2 \left(\frac{\lambda}{16\pi^2} \ln \frac{\Lambda}{m_{SUSY}} \right)$$

SUSY with R-parity violation

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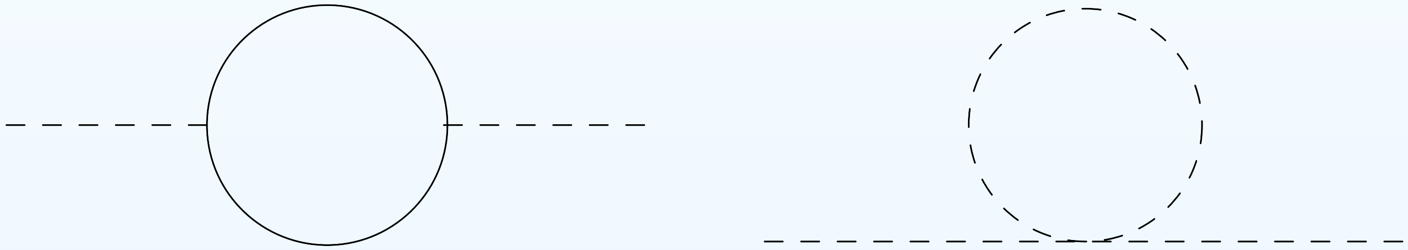


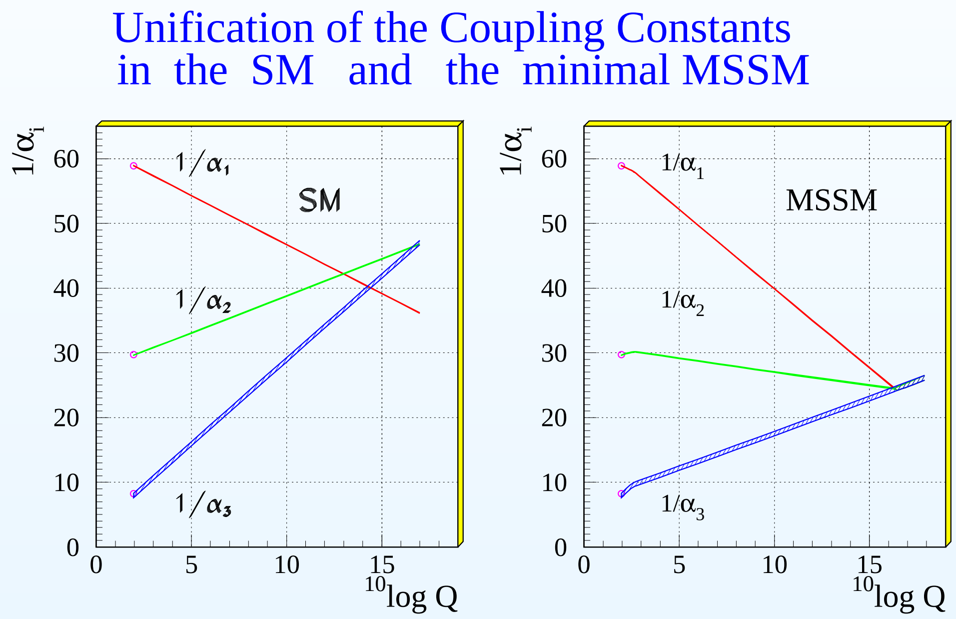
$$\Delta m_H^2 = m_{SUSY}^2 \left(\frac{\lambda}{16\pi^2} \ln \frac{\Lambda}{m_{SUSY}} \right)$$

- Naturally incorporates **electroweak symmetry breaking**

  Radiative symmetry breaking is a natural feature in supersymmetric models.

SUSY with R-parity violation

- Provides **gauge coupling unification**



Picture taken from D. Kazakov, hep-ph/0012288

SUSY with R-parity violation

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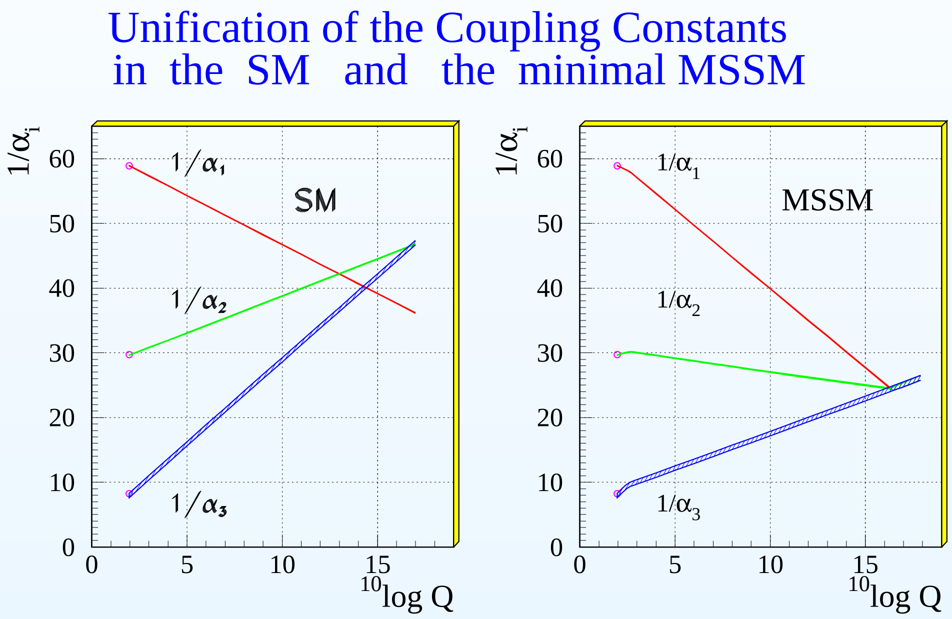


Picture taken from D. Kazakov, hep-ph/0012288

- **Other motivations**

SUSY with R-parity violation

It was soon realized that the **accidental** baryon and lepton number conservations in the Standard Model do not happen in its supersymmetric extension.

The most general superpotential allowed by gauge symmetry is

$$W = W^{MSSM} + W^{\not R_p}$$

with

$$W^{MSSM} = \epsilon_{ab}\left[h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_u^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_d^a + h_E^{ij}\widehat{L}_i^b\widehat{R}_j\widehat{H}_d^a - \mu\widehat{H}_d^a\widehat{H}_u^b\right]$$

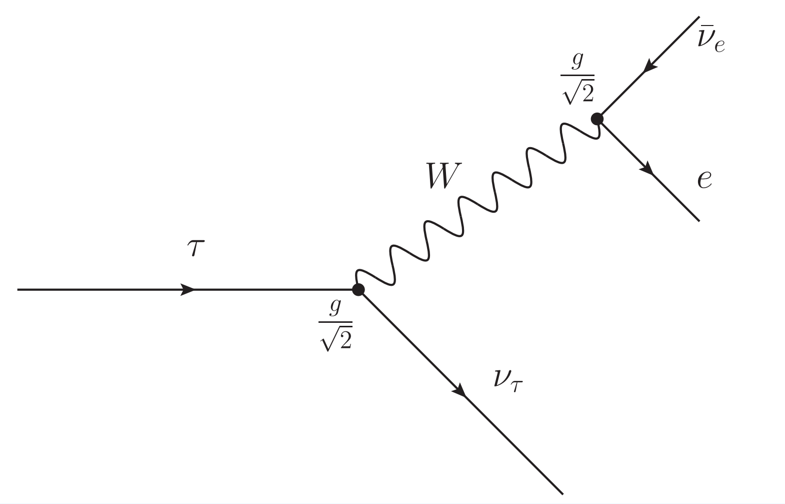
$$W^{\not R_p} = \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{R}_k + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{D}_k + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right] + \frac{1}{2}\lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k$$

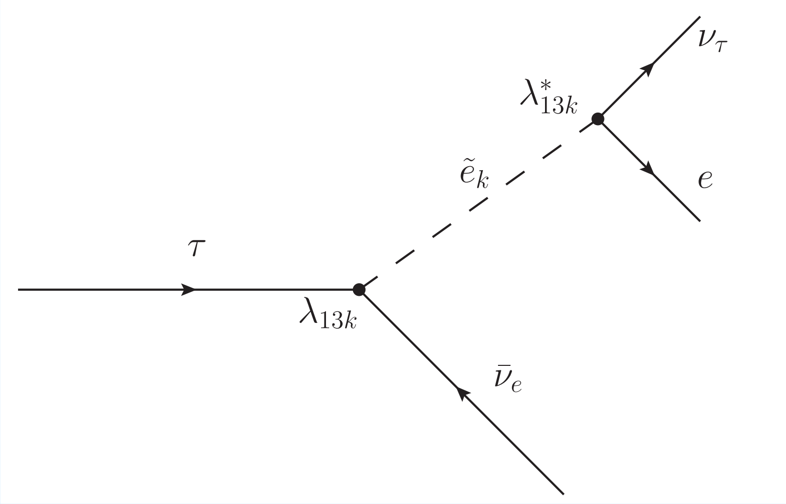
$W^{\not R_p}$ violates baryon and lepton numbers

SUSY with R-parity violation

Strong bounds on $\not{R}_p$ parameters

A simple **example**:



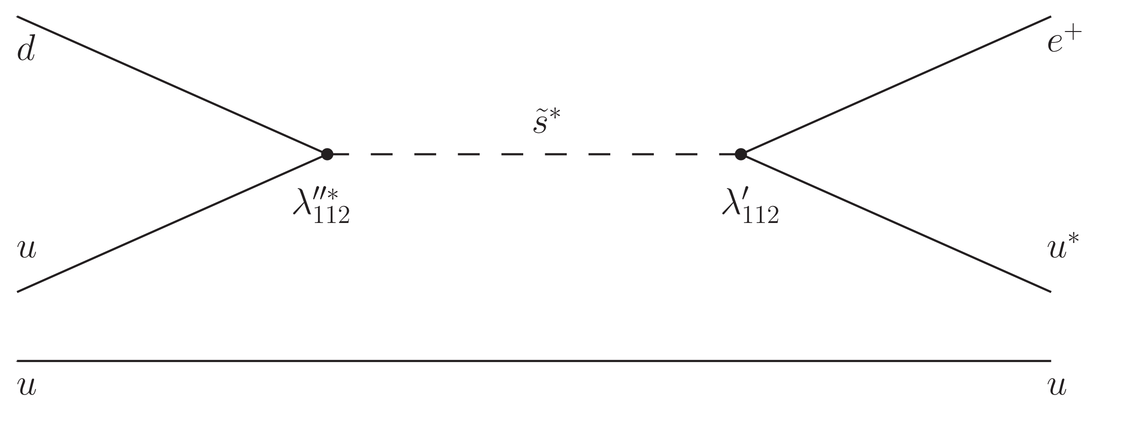


$$R_\tau \equiv \frac{\Gamma(\tau \to e \nu \bar{\nu})}{\Gamma(\tau \to \mu \nu \bar{\nu})} = R_\tau(SM)\left[1 + 2\frac{M_W^2}{g^2}\left(\frac{|\lambda_{13k}|^2}{\tilde{m}_k^2}\right)\right]$$

LEP: $R_\tau / R_\tau(SM) = 1.0006 \pm 0.0103 \Rightarrow |\lambda_{13k}| < 0.06\left(\frac{\tilde{m}_k}{100 GeV}\right)$

SUSY with R-parity violation

Moreover, $\not{R}_p$ terms induce **proton decay**



$$\Gamma_{p \to e^+ \pi^0} \sim m_p^5 \sum_{i=2,3} \frac{|\lambda'_{11i} \lambda''_{11i}|^2}{m^4_{\tilde{d}_i}}$$

$\Rightarrow$ If $\lambda' \sim \lambda'' \sim O(1)$ the **proton decays too fast**

Conventional solution: A new symmetry that forbids all terms in $W^{\not{R}_p}$

R-parity

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

SUSY with R-parity violation

R-parity consequences:

- ⋆ Sparticles are produced in even numbers
- ⋆ The **LSP** (Lightest Supersymmetric Particle) is absolutely stable

$\Rightarrow$ **Dark matter candidate**

- ⋆ Decay chains end always in final states including LSPs

$\Rightarrow$ **Good signal at colliders:** E_T^{miss}

SUSY with R-parity violation

However . . .

- **No theoretical argument** in favor of R_p

R_p is introduced *by hand* in the theory

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- In fact, $\boldsymbol{R_p}$ **does not solve fast proton decay**

L. E. Ibáñez and G. G. Ross, Nucl. Phys. B 368, 3 (1992)
S. Weinberg, Phys. Rev. D 26, 287 (1982)
N. Sakai and T. Yanagida, Nucl. Phys. B 197, 533 (1982)

Non-renormalizable operators can also induce fast proton decay and some of them are **not** forbidden by R-parity. Example:

$$\mathcal{O}_5 = \frac{f}{M} QQQL \quad \Rightarrow \quad \text{For } M = M_p, \;\; f < 10^{-7} \text{ is required}$$

SUSY with R-parity violation

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- Why must we forbid **all** $\not{R}_p$ **parameters**?

SUSY with R-parity violation

Why not allow for R-parity violation?

- Bilinear R-parity violation (BRpV)

$$W^{\not R_p} = \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{R}_k + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{D}_k + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right] + \frac{1}{2}\lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k$$

- Trilinear R-parity violation (TRpV)

$$W^{\not R_p} = \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{R}_k + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{D}_k + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right] + \frac{1}{2}\lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k$$

- Spontaneous R-parity violation (s-$\not R_p$)

SUSY with R-parity violation

Moreover, $\not{R}_p$ provides **an alternative explanation for neutrino masses**.

BRpV: Simplest extension of the MSSM that incorporates **lepton number violation**

$$W = W^{MSSM} + \epsilon_{ab}\, \boldsymbol{\epsilon_i} \widehat{L}_i^a \widehat{H}_u^b$$

$$\mathcal{L}_{soft} = \mathcal{L}_{soft}^{MSSM} - B_i \boldsymbol{\epsilon_i}\, \epsilon_{ab}\, \tilde{L}_i^a H_u^b$$

Neutrino mass is generated due to the **mixing between neutrinos and higgsinos**.

$\Longrightarrow$ **Electroweak scale seesaw**

SUSY with R-parity violation

However, **dimensionful SUSY-conserving parameters** are supposed to be at very high scales.

ϵ-problem Why the ϵ_i parameters are so small?

$\Updownarrow$

μ-problem Why the μ parameter is so small?

Same solution: Additional singlets

SUSY with R-parity violation

And what about Dark Matter?

Although the usual neutralino LSP is lost as a candidate for DM, there are other possibilities.

Super-WIMPs : Extremely weak interactions with matter $\Rightarrow$ Lifetimes longer than the age of the Universe

- Gravitino
- Axion
- Axino
- ...

Decaying DM : An explanation for Pamela, ATIC, Hess, Fermi ... results?

The model

Model basics

A. Masiero and J.W.F. Valle, Phys. Lett. B 251, 273 (1990)
J.C. Romão and J.W.F. Valle, Nucl. Phys. B 381, 87 (1992)

⋆ **Particle content**

			$\widehat{\boldsymbol{\nu}}^{\mathbf{c}}$	$\widehat{\mathbf{S}}$	$\widehat{\boldsymbol{\Phi}}$
MSSM	+	L:	-1	+1	0
			SU(2) singlets		

⋆ **Superpotential**

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

- 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 **$\boldsymbol{\mu}$-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

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

and then

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

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

$$\Downarrow$$

Goldstone boson

The majoron, J

Neutrino masses

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

$$\mathbf{M_N} = \begin{pmatrix} \mathbf{M_H} & \mathbf{m_{3\times7}} \\ \mathbf{m^T_{3\times7}} & 0 \end{pmatrix}$$

The 3×3 neutrino mass matrix is given in **seesaw approximation** by

$$\boldsymbol{m^{\text{eff}}_{\nu\nu}} = -\mathbf{m}_{3\times7} \cdot \mathbf{M_H}^{-1} \cdot \mathbf{m}^T_{3\times7}$$

Neutrino masses

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

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

where $\Lambda_i = \epsilon_i v_d + \mu v_i$ are the so-called *alignment parameters*.

Important:

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

The majoron

⋆ **Singlet character**

The **first models** of spontaneous R-parity violation broke lepton number by the **VEV of a left-handed sneutrino**

C.S. Aulakh and R.N. Mohapatra
Phys. Lett. B 119, 136 (1982)
MSSM with $\langle \tilde{\nu}_L^i \rangle = v_i \neq 0$ $\Rightarrow$ $\left\{ \begin{array}{l} \text{L violation} \\ \text{Neutrino masses} \\ \text{Goldstone boson, } J \end{array} \right.$

$$J = Im\left(\sum_i \frac{v_i}{v_L} \tilde{\nu}_L^i + \frac{v_L}{v^2} (v_d H_d^0 - v_u H_u^0) \right) \quad \Rightarrow \quad \textbf{Doublet majoron}$$

with $v^2 = v_d^2 + v_u^2$ and $v_L^2 = v_1^2 + v_2^2 + v_3^2$.

Ruled out by LEP: Large contribution to the **invisible Z^0 width**

The majoron

However, in the **Masiero-Valle model** lepton number is broken by the **VEV of a singlet**. With $V^2 = v_R^2 + v_S^2$ and $v_i \ll v_R, v_S, v$ one gets

$$J = Im\left(\frac{v_L^2}{V v^2}(v_u H_u^0 - v_d H_d^0) + \sum_i \frac{v_i}{V}\tilde{\nu}_L^i + \frac{v_S}{V}\tilde{S} - \frac{v_R}{V}\tilde{\nu}_R\right) \simeq Im\left(\frac{v_S}{V}\tilde{S} - \frac{v_R}{V}\tilde{\nu}_R\right)$$

$\Rightarrow$ **Singlet majoron**

This majoron does not couple to the Z^0, **evading the LEP bound.**

The majoron

⋆ **Stellar energy loss bound**

Majorons can be produced inside **stars**

$$\boxed{e\gamma \longrightarrow eJ}$$

and then escape due to their weak couplings to matter.

$\Rightarrow$ **Stellar energy loss**

In order to leave stellar evolution unchanged we get the **bound**

$$\frac{v_L^2}{v_R m_W} \lesssim 10^{-7}$$

Naturally fulfilled due to neutrino masses

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

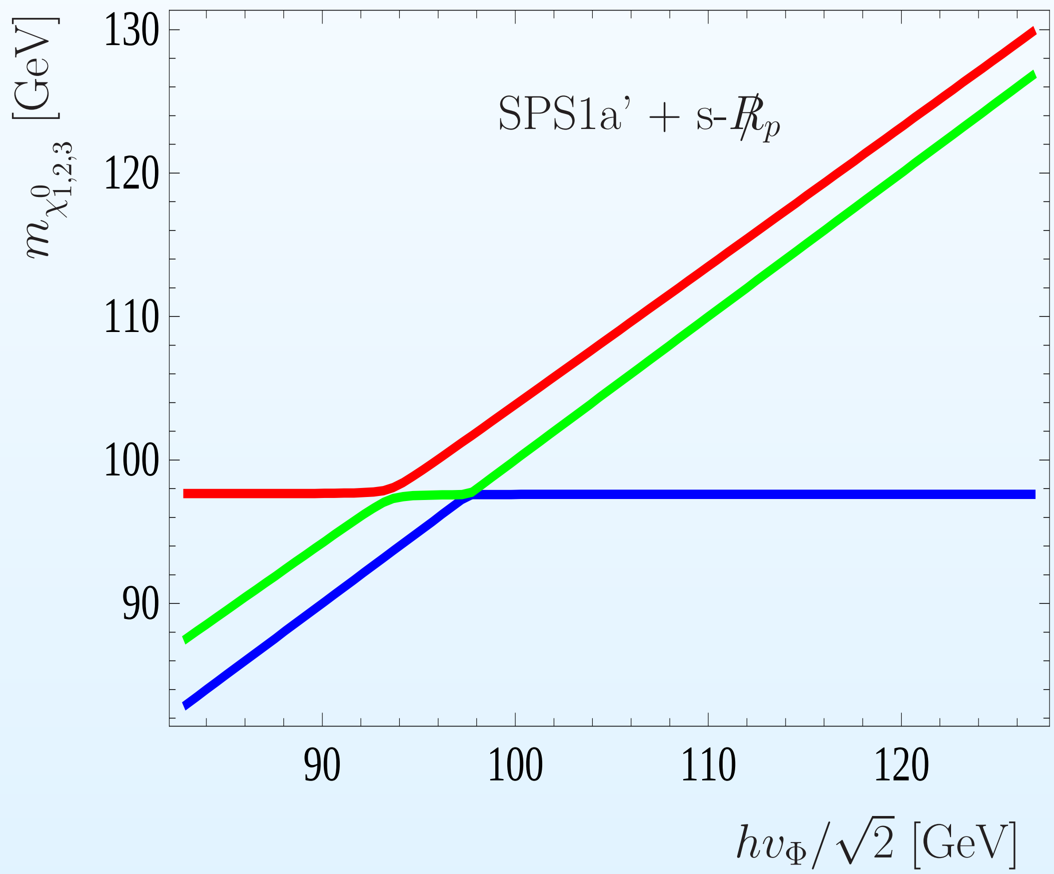
- There are four states very close to the MSSM neutralinos
- ν^c and S form a quasi-Dirac pair, **the Singlino**, $\mathcal{S}_{\mathbf{1,2}} \simeq \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}(\boldsymbol{\nu}^{\mathbf{c}} \mp \mathbf{S})$
- The remaining state is the phino, $\tilde{\Phi}$

Bino vs Singlino

Which one is the lightest?

We study two cases

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



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

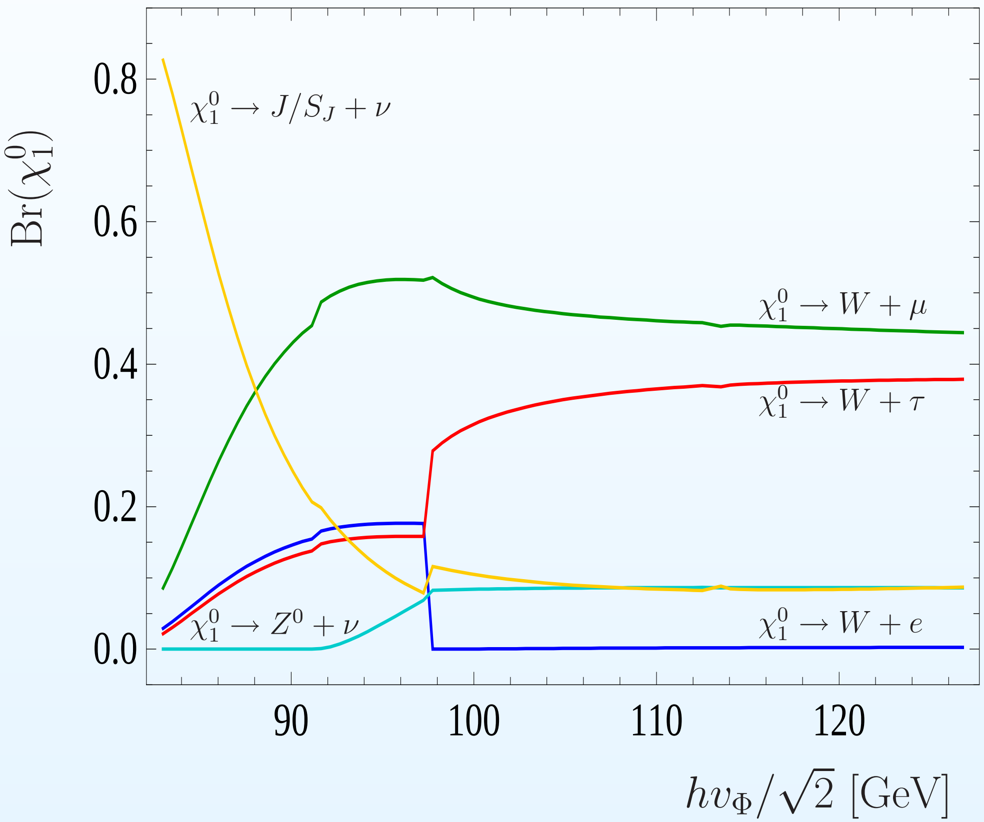
- ⋆ The lightest neutralinos (bino or singlino) **will appear** as “final” (since R_p is broken, the LSP can decay to SM particles) states of the decay chains

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

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

Neutralino decays

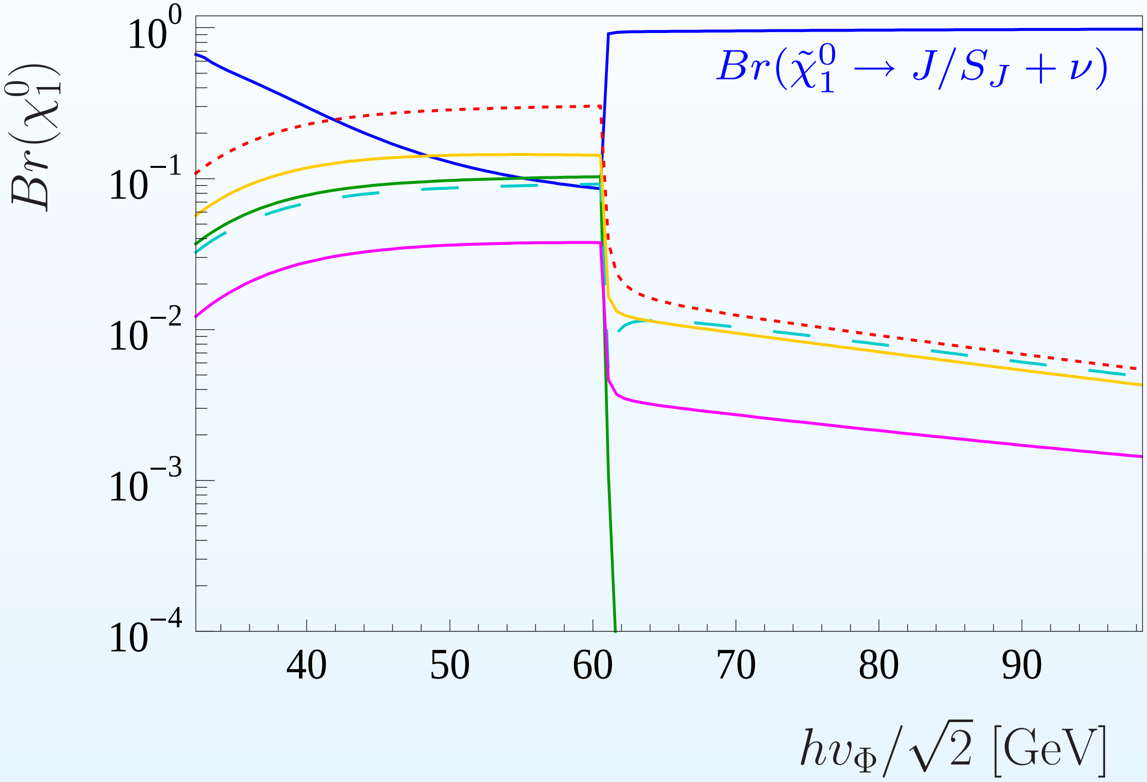
⋆ **Most important decay channels:** $\mathbf{m_{\chi_1^0} \geq m_{W^\pm}}$



- **Invisible channels** typically have measurable branching ratios, 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 $\tilde{\chi}_1^0 \longrightarrow \nu\mu\tau$) are as important as the LF conserving ones (like $\tilde{\chi}_1^0 \longrightarrow \nu\mu\mu$).

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

Neutralino decays

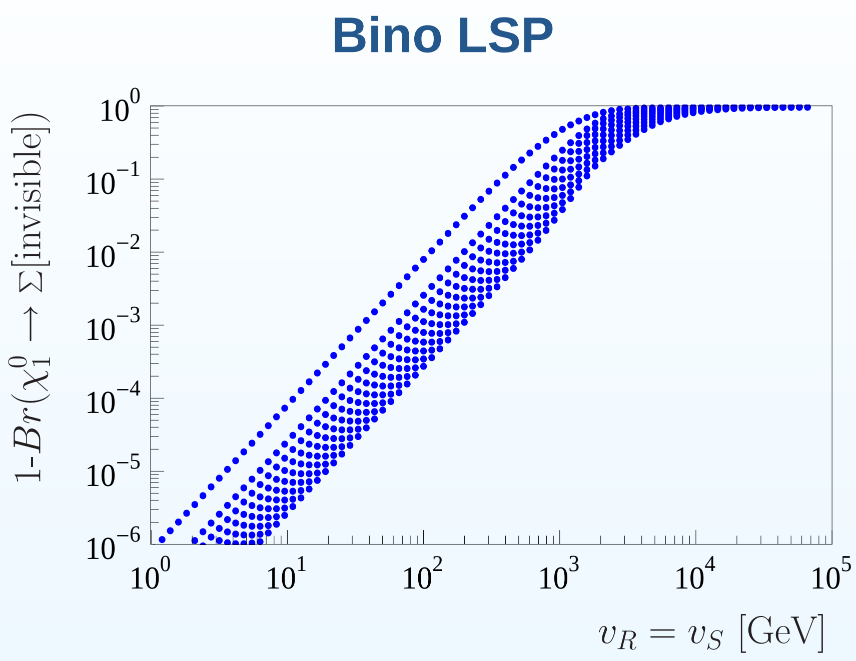
⋆ **Invisible decays**

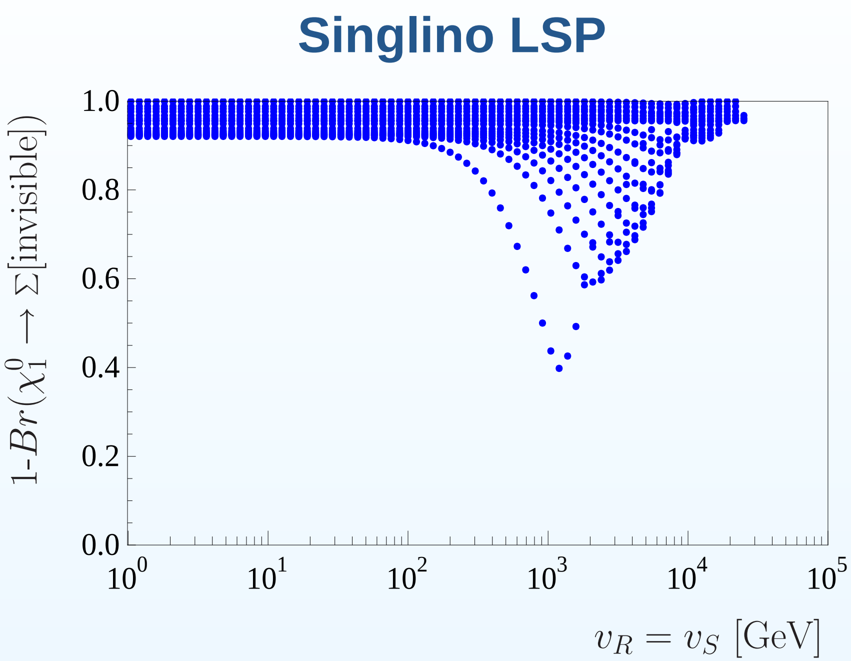
The lightest neutralino can decay to **completely invisible final states**, thanks to the existence of **the majoron**.

- 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



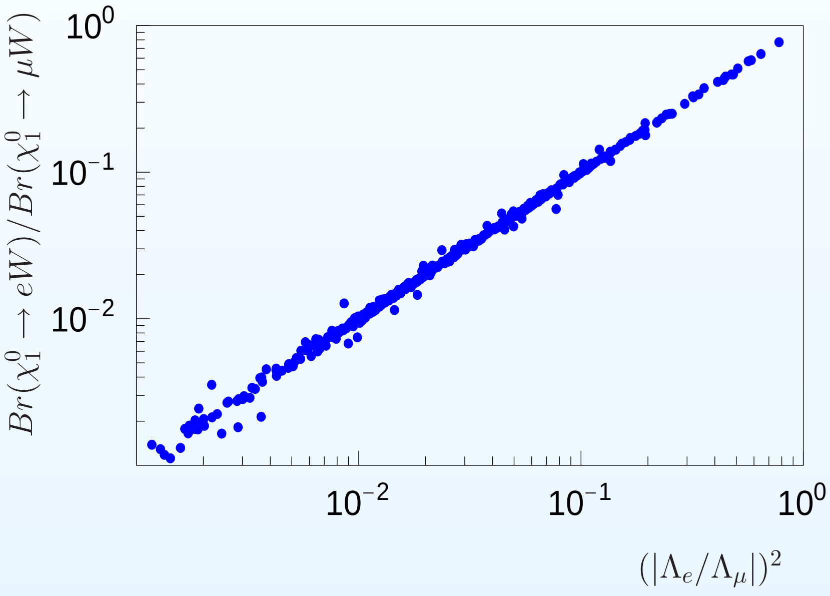


- In the case of a **Bino LSP**, low values of v_R lead to $Br(\tilde{B} \to invisible)$ very close to 100%.
  $\Rightarrow$ This scenario can resemble the MSSM
  $\Rightarrow$ Large stadistics will be necessary to prove R_p breaking
- On the other hand, in the case of a **Singlino LSP**, $Br(\mathcal{S}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

Neutralino decays

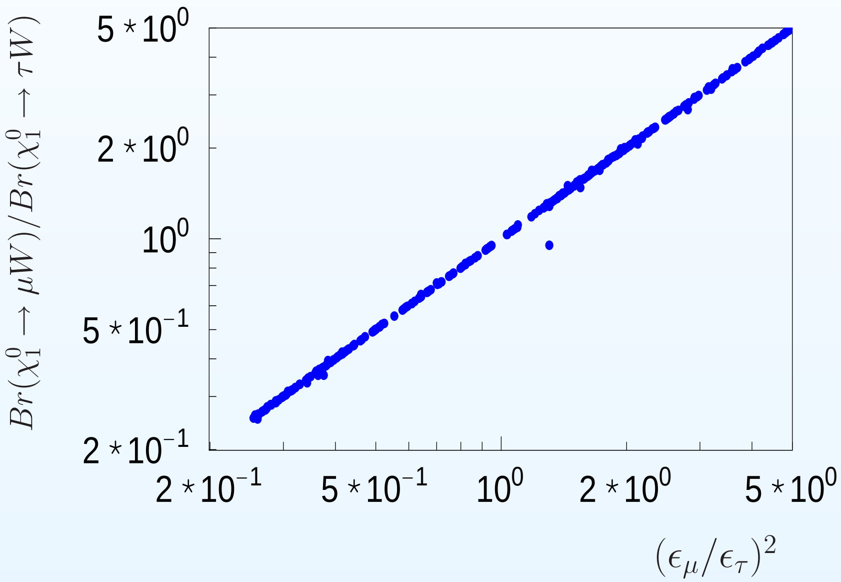
⋆ **Correlations between neutralino decays and neutrino mixing angles**

Bino LSP



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

Singlino LSP



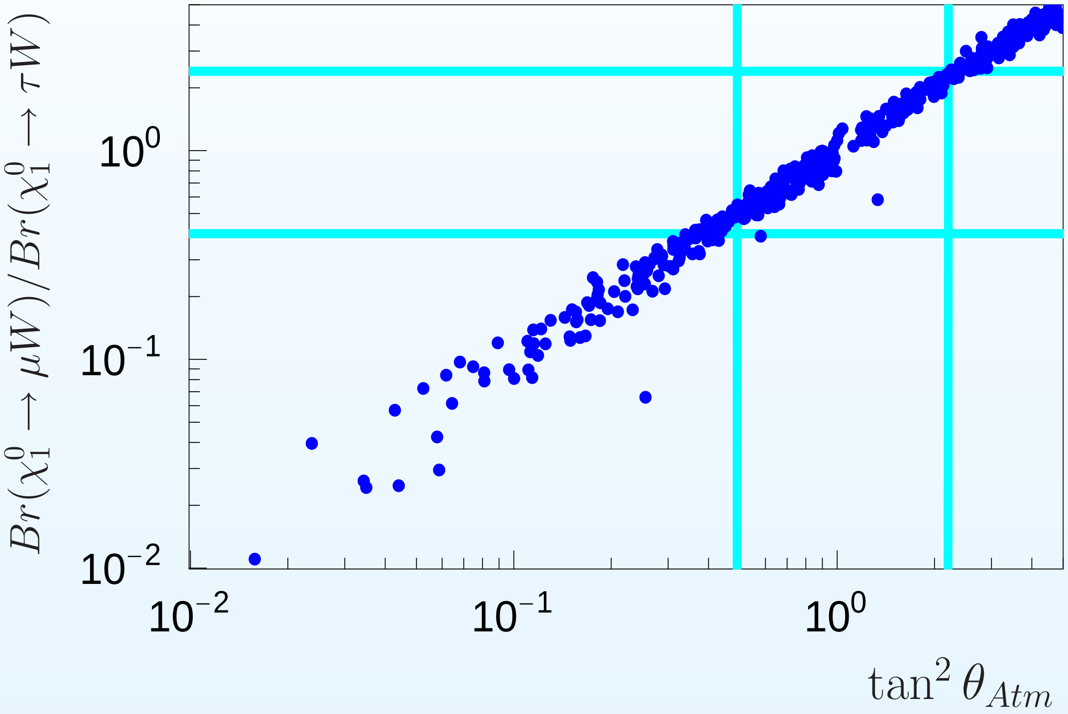
$$\mathbf{Br(\tilde{\chi}_1^0 \to W\, l_i) \propto \epsilon_i{}^2}$$

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)

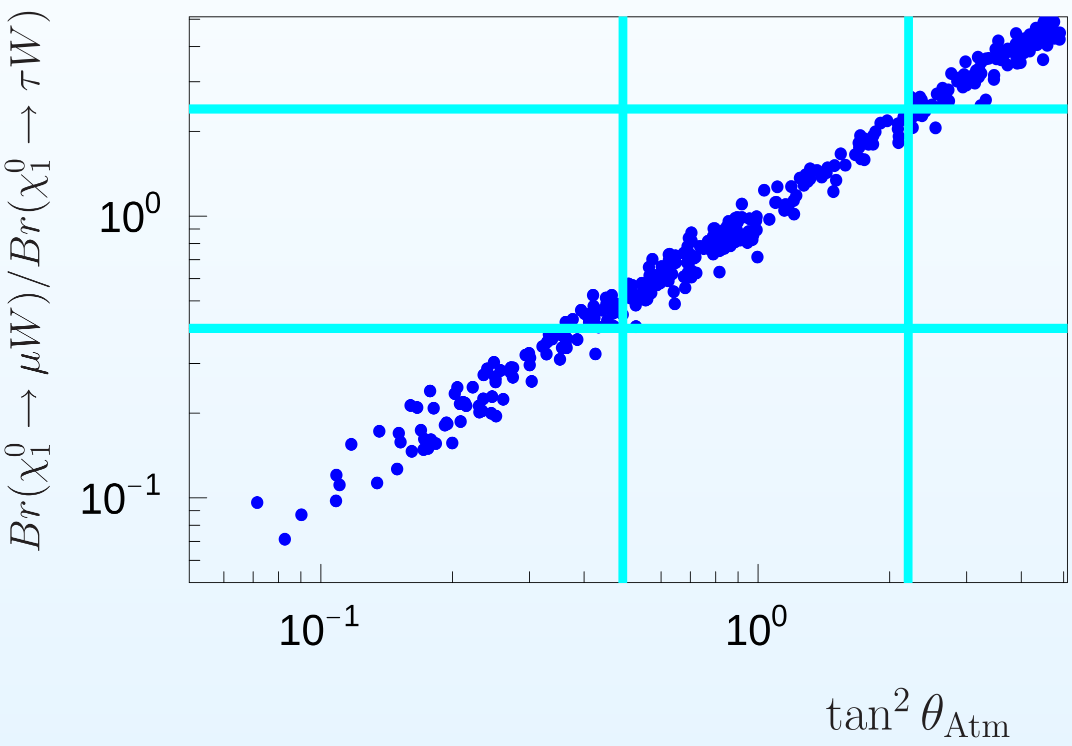


$$\tan^2\theta_{atm} \in [0.5, 2.0] \quad \Rightarrow \quad \frac{Br(\chi_1^0 \to \mu W)}{Br(\chi_1^0 \to \tau W)} \in [0.4, 2.1]$$

Neutralino decays

Singlino LSP

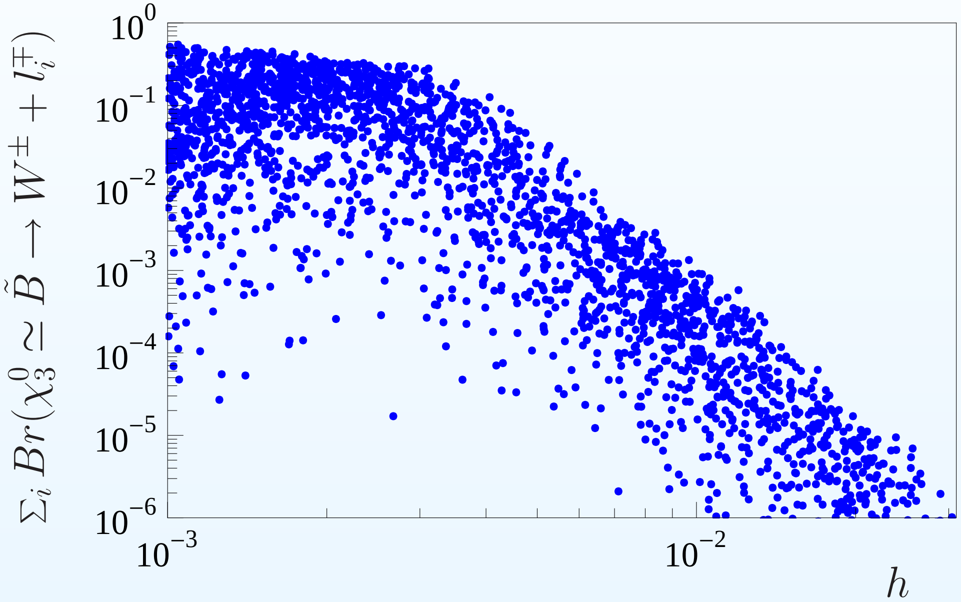
Case (c2)



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

Neutralino decays

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 both $\vec{\Lambda}$ and $\vec{\epsilon}$.
- If $\mathcal{S} =$ LSP and the $\tilde{B}$ NLSP has a measurable Br to SM particles (a low value for h is required), **one can measure simultaneously both sets of parameters**.
- This could also give us some clue about the nature of the LSP.

Neutralino decays

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

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

would rule it out.

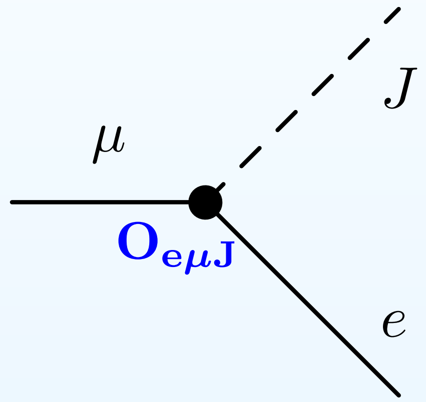
- Since we don't know whether **case (c1)** or **case (c2)** is realized, the decay of the lightest neutralino is not sufficient to know **the nature of the LSP**. We need to reconstruct the complete decay chains and use kinematical variables to obtain some information about the intermediate states.

Exotic muon decays

Exotic muon decays

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

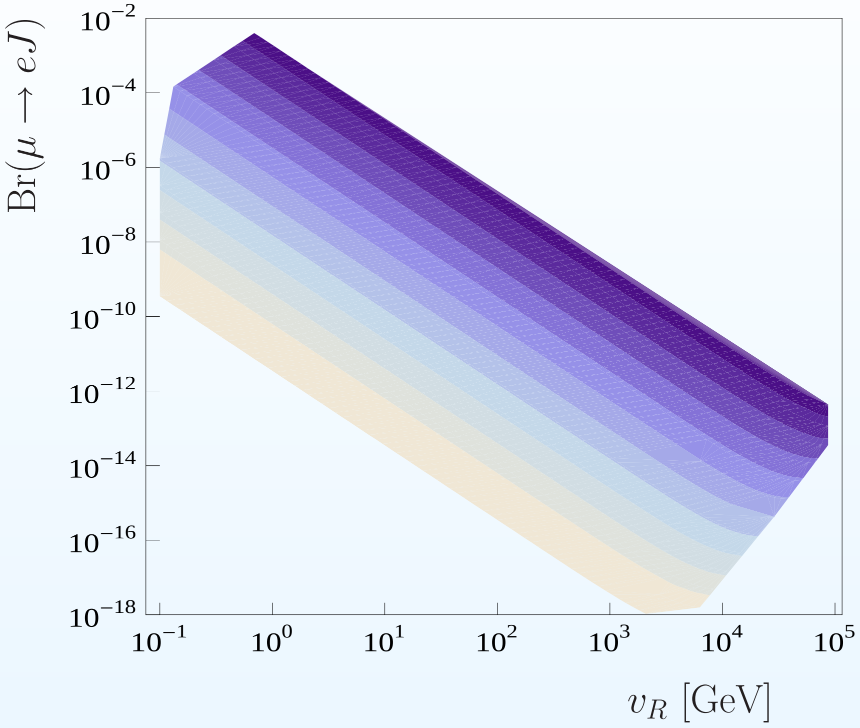
$$\boldsymbol{\mu \longrightarrow eJ}$$

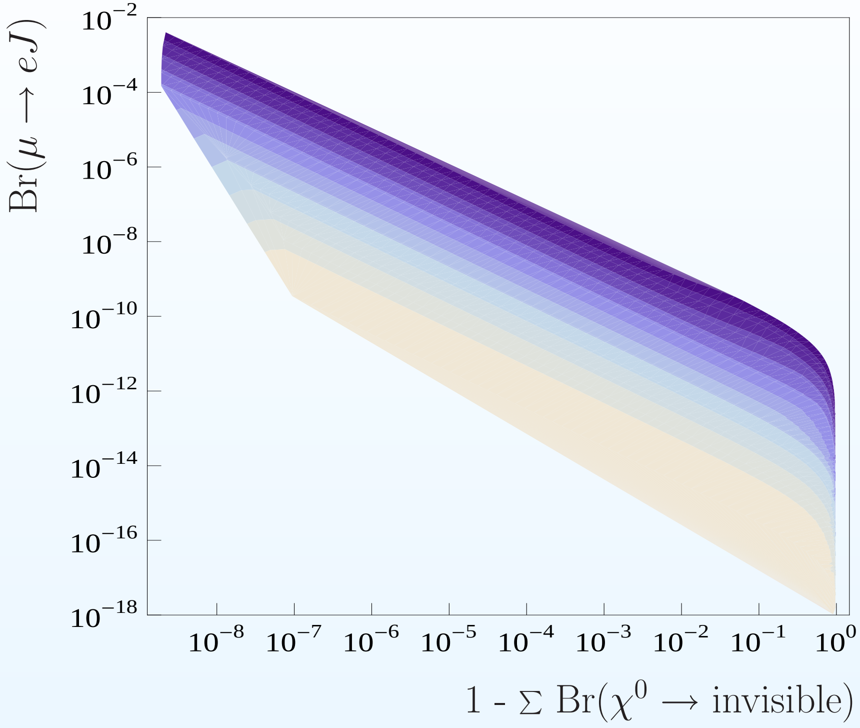


$$\mathbf{O_{e\mu J}} \sim \frac{1}{v_R} \times \not{R}_p \text{parameters}$$

- 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 $\boldsymbol{\mu \longrightarrow e\nu\bar{\nu}}$

Exotic muon decays





- 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

Question: Any improvement with $\mu \longrightarrow eJ\gamma$?

MEG experiment?

Exotic muon decays

$$Br(\mu \to eJ\gamma) = \frac{\alpha}{2\pi}\mathcal{I}(x_{min}, y_{min}) Br(\mu \to eJ)$$

$\mathcal{I}(x_{min}, y_{min})$ is a phase space integral that depends on

- Kinematics
- Experimental cuts ($x_{min} \equiv \frac{2E_e^{min}}{m_\mu}$ and $y_{min} \equiv \frac{2E_\gamma^{min}}{m_\mu}$)

$\mu \to eJ$

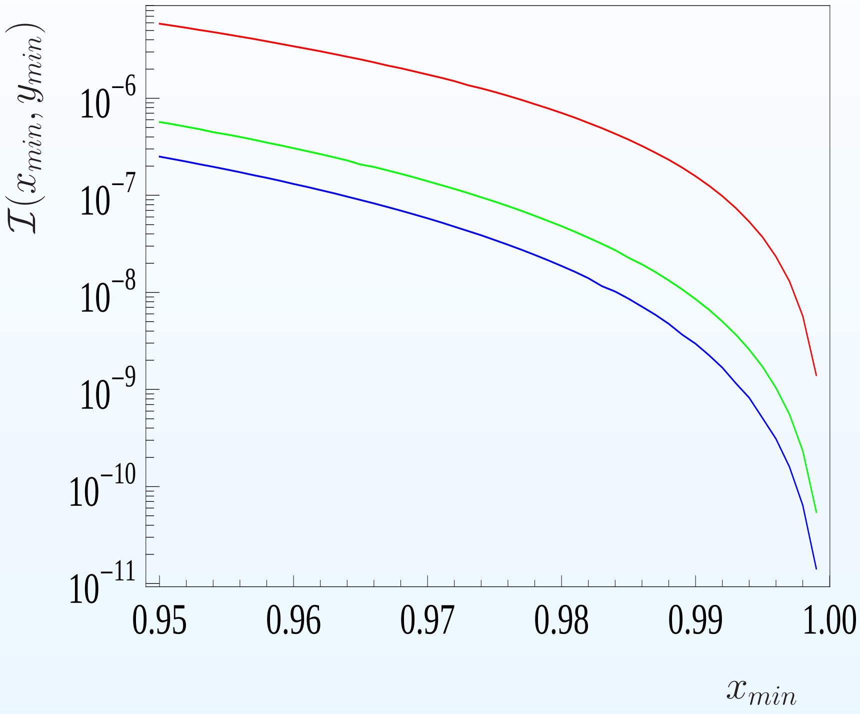
- Higher branching ratio
- Strong background suppression from $\mu \to e\nu\bar{\nu}$
- No available experiments
- Current upper limit $\sim 10^{-5}$

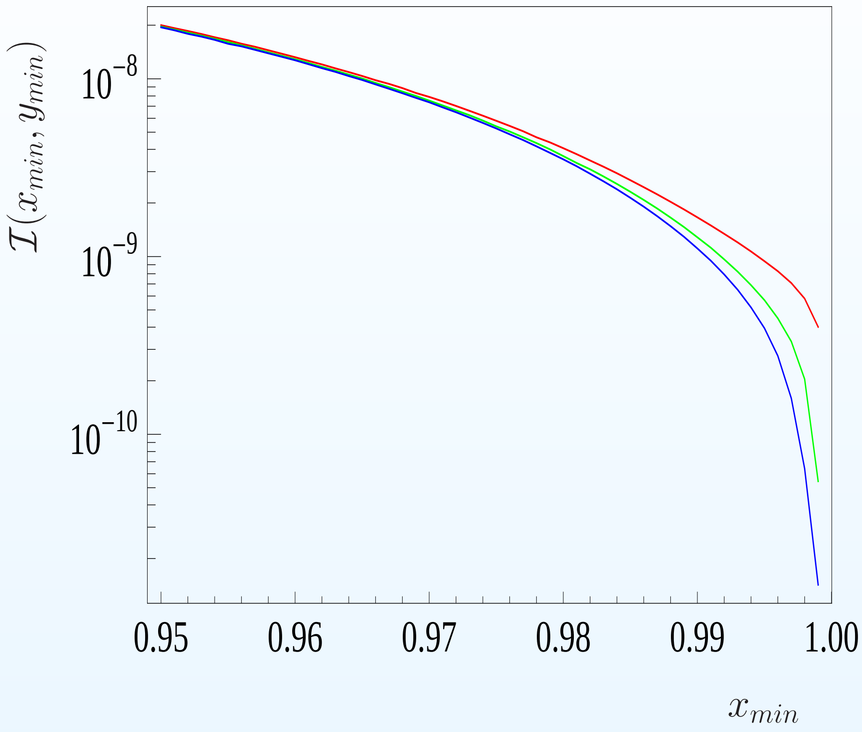
vs

$\mu \to eJ\gamma$

- Lower branching ratio
- Lower background
- Available experiments but with strong phase space suppression
- Current upper limit $\sim 10^{-9}$ but it leads to Br($\mu \to eJ$) $\lesssim 10^{-3}$

Exotic muon decays





MEG experiment :

$$\left.\begin{array}{c} x_{min} = 0.995 \\ y_{min} = 0.99 \\ \cos\theta_{e\gamma}^{max} = -0.99997 \\ (|\pi - \theta_{e\gamma}| \leq 8.4 \text{ mrad}) \end{array}\right\} \Rightarrow \quad \boldsymbol{\mathcal{I} \simeq 6 \cdot 10^{-10}}$$

MEG suffers from small value of phase space integral

Summary

Summary

- ⋆ Solar and atmospheric neutrino problems are nowadays very well understood in terms of neutrino oscillations. This mechanism implies 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.

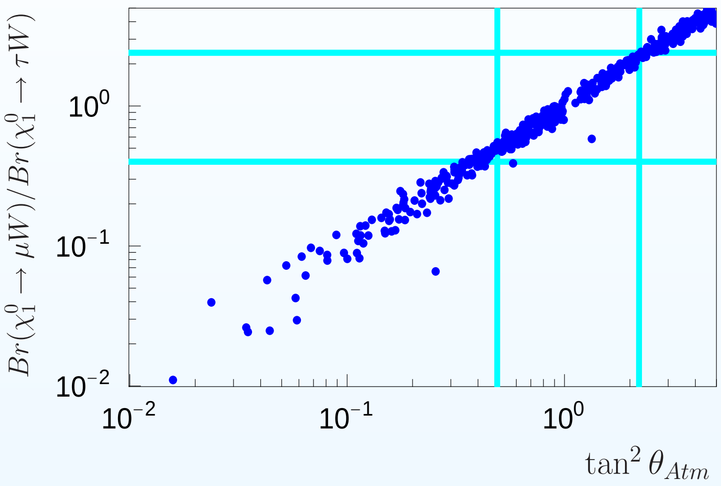
- ⋆ Exotic muon decays, like $\mu \to eJ$ and $\mu \to eJ\gamma$, can constrain the model and give us additional information about the scale of lepton number breaking.

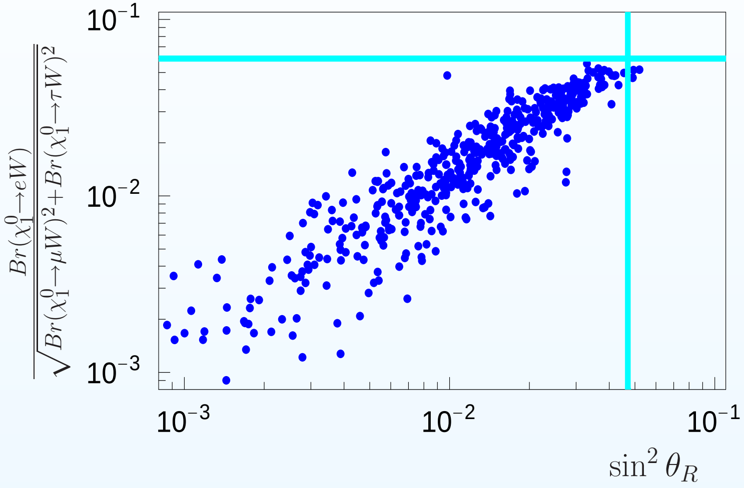
Backup slides

Correlations

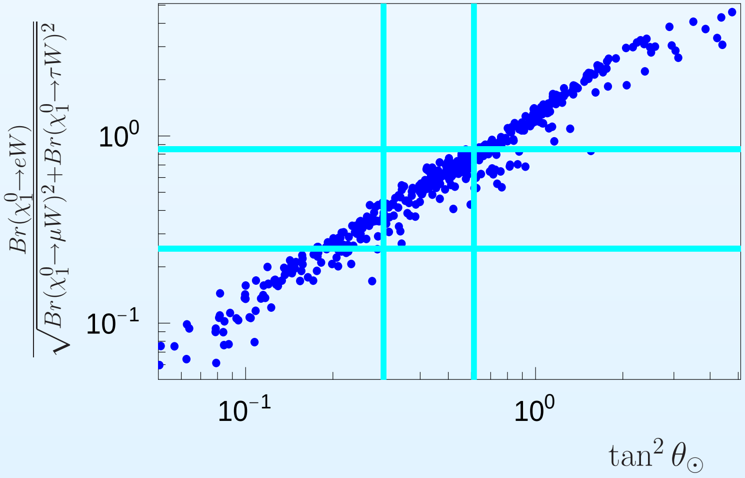
Bino LSP

Case (c1)





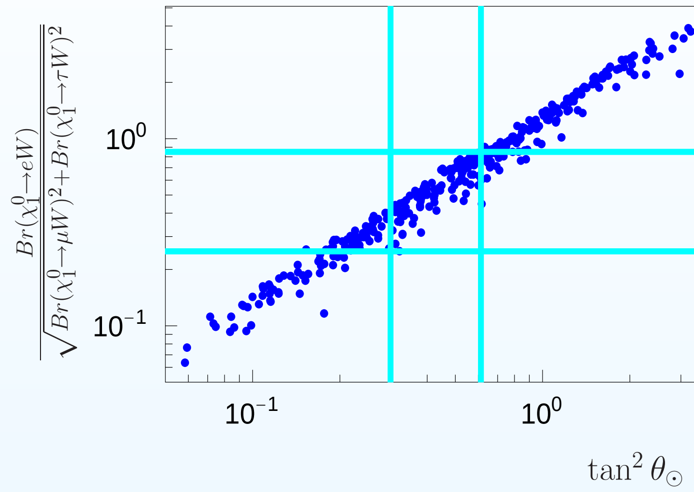
Case (c2)



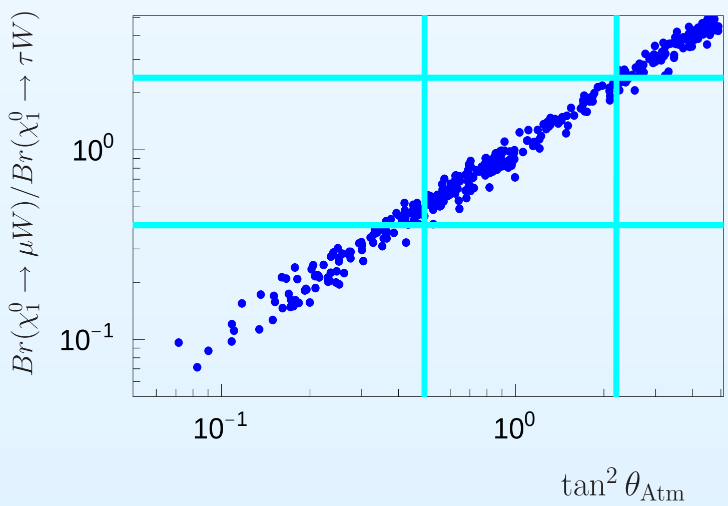
Correlations

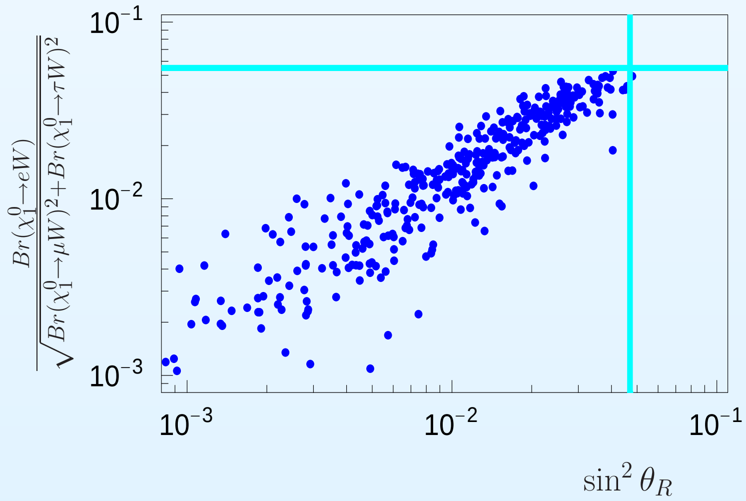
Singlino LSP

Case (c1)



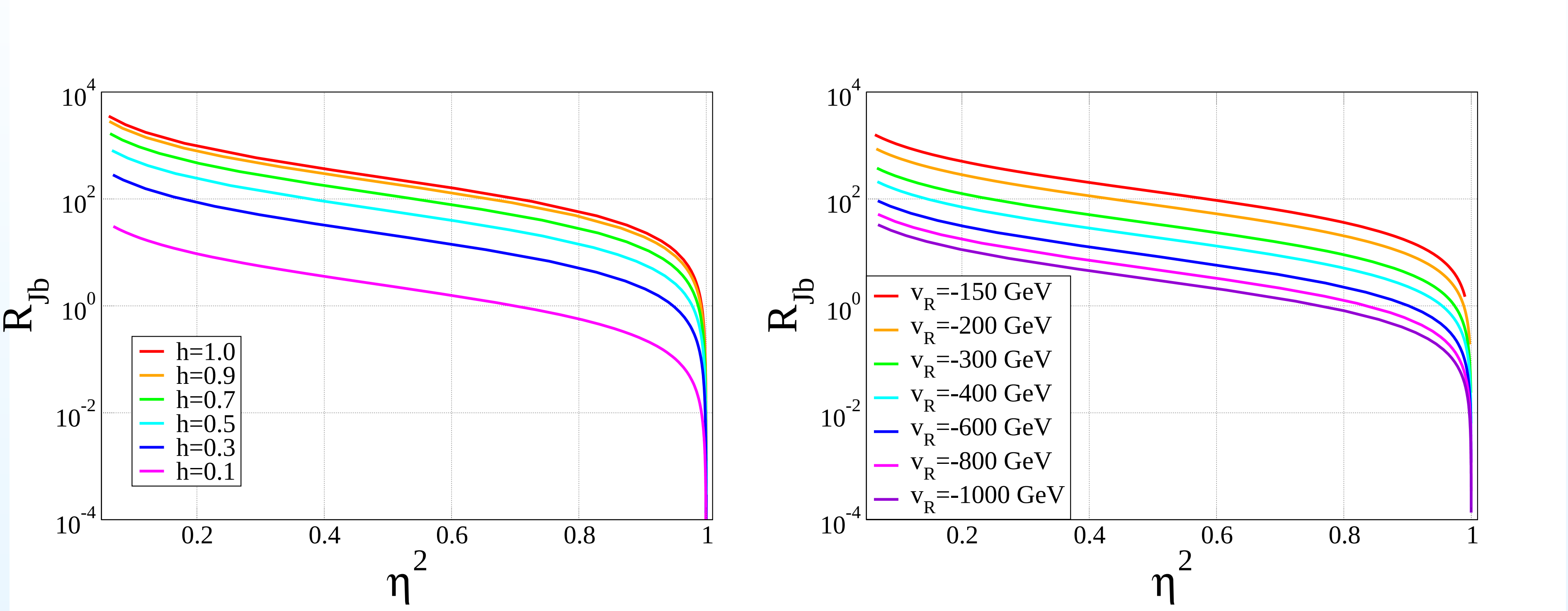
Case (c2)





Invisible Higgs boson decays

M. Hirsch *et al*, Phys. Rev. D 70, 073012 (2004)

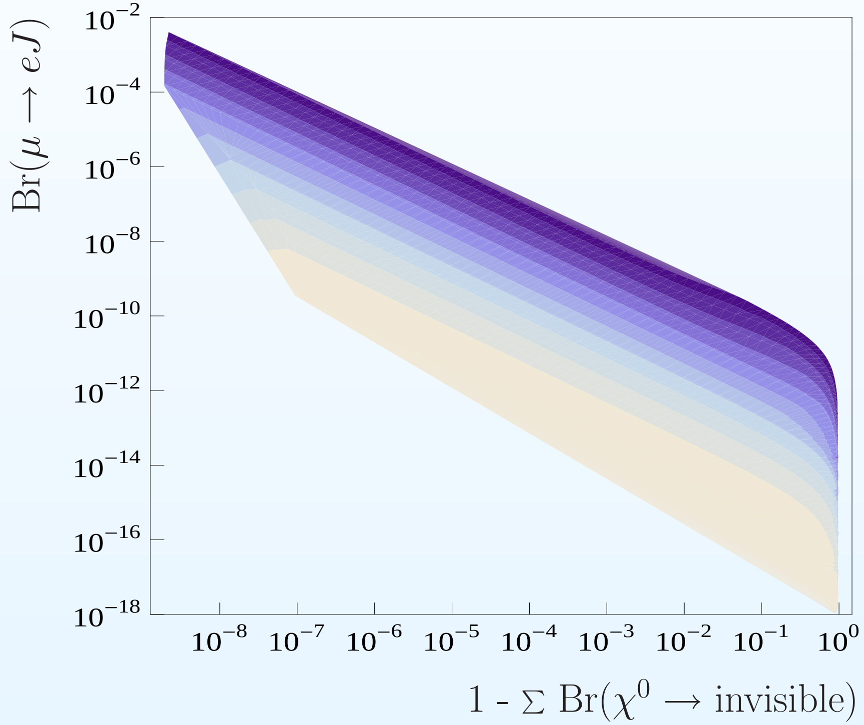


$$R_{Jb} = \frac{Br(h \to JJ)}{Br(h \to b\bar{b})} \qquad \eta = \text{doublet component of } S_1^0$$

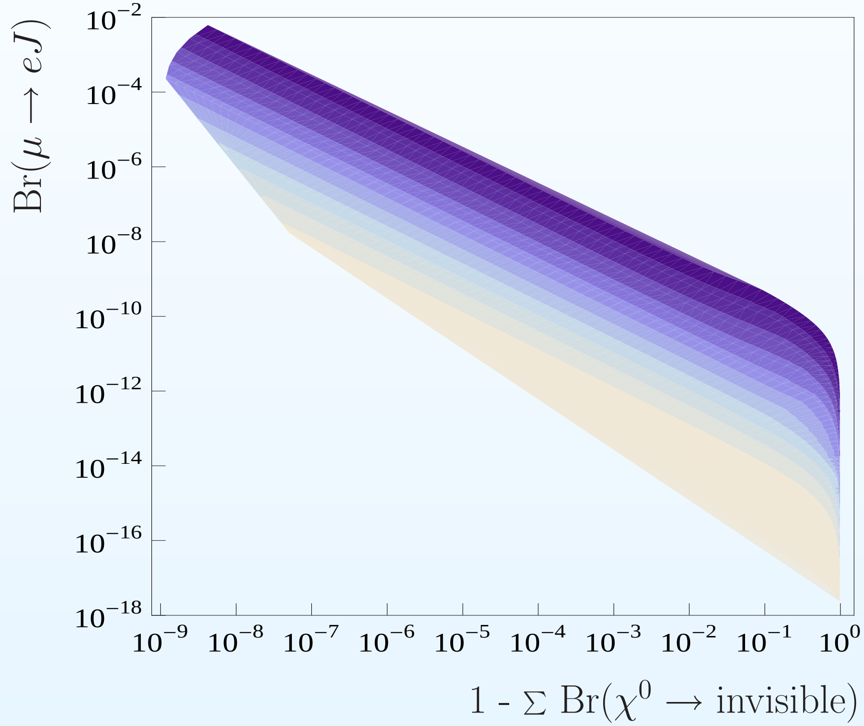
The invisible Higgs decay mode $h \to JJ$ can be dominant

$Br(\mu \to eJ)$ vs $Br(\chi_1^0 \to visible)$

$\Omega_{\chi_1^0} h^2 = 1$



SPS1a'



The anti-correlation depends very weakly on the mSUGRA point