Lepton number violation at the ILC

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Outline

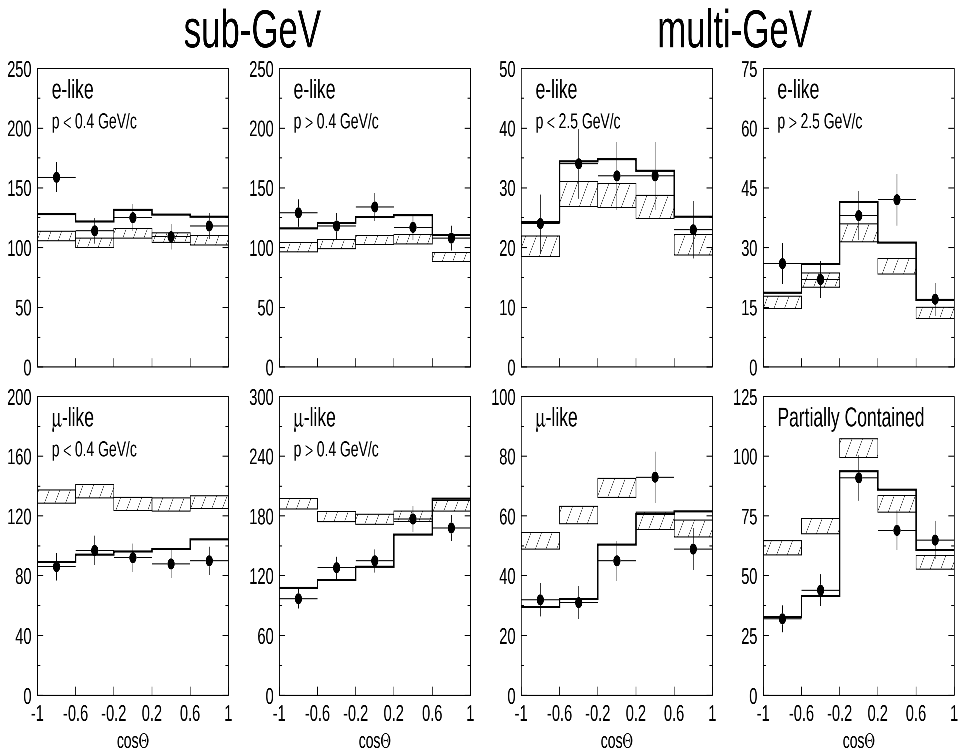
- 1. Motivation
- 2. Introduction to $\not{R}_p$ SUSY
- 3. Lightest SUSY particle decay
- 4. Dark matter
- 5. Spontaneous $\not{R}_p$ and the Higgs
- 6. Conclusion

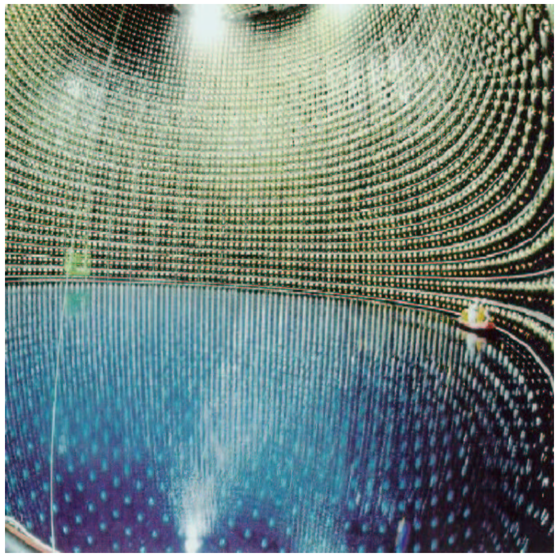
Motivation

Super-Kamiokande, PRL 81 (1998) 1562:

"Evidence for

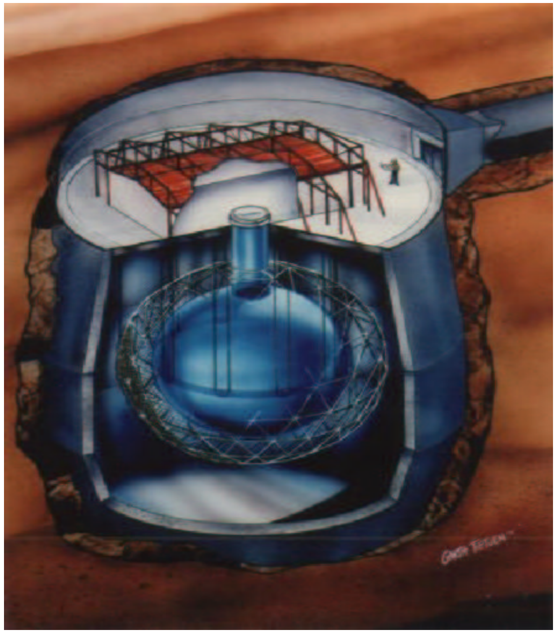
oscillation of atmospheric neutrinos"

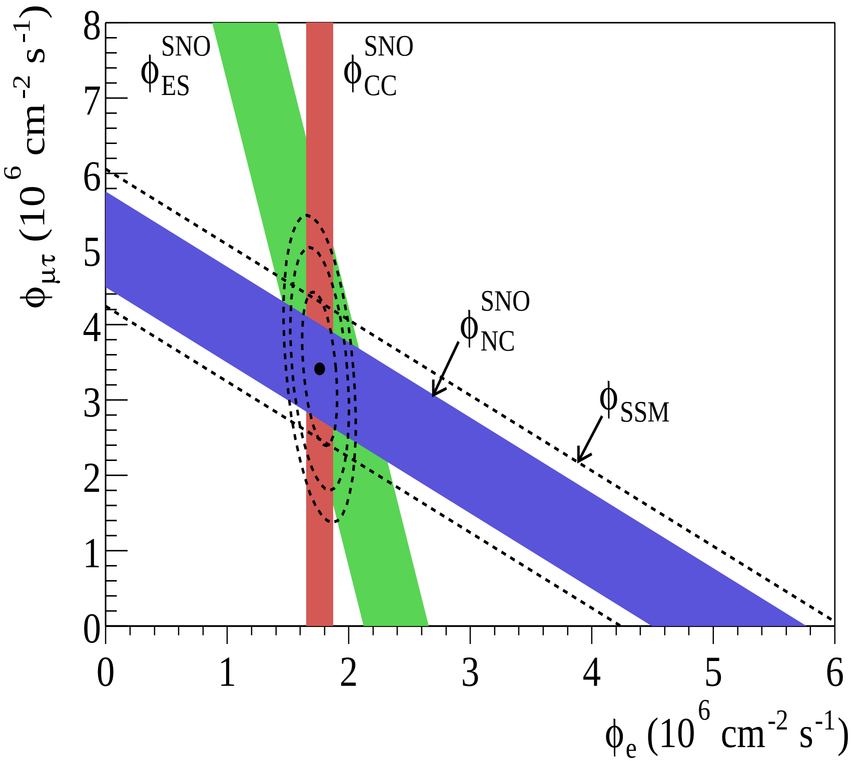




Motivation

SNO, PRL 89 (2002) 011301:

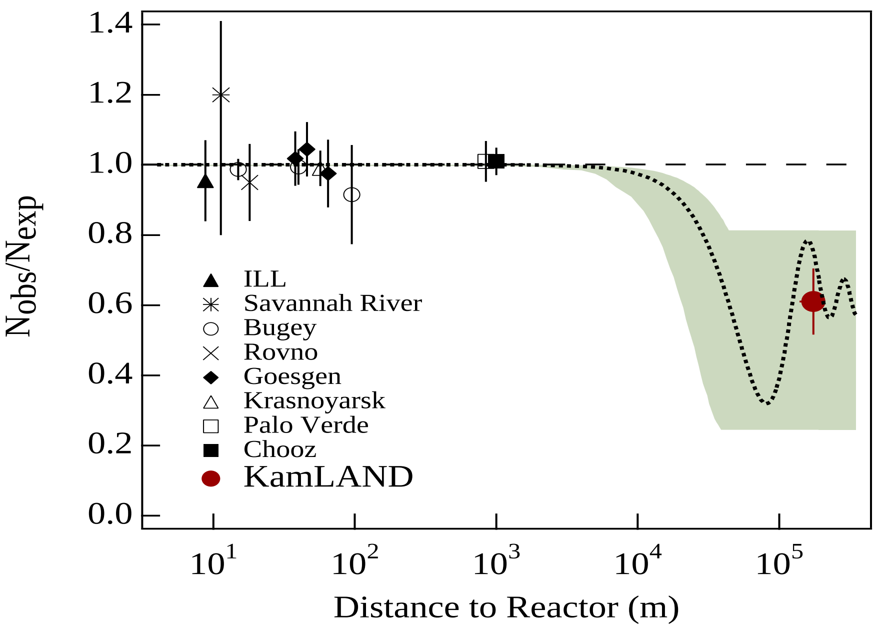


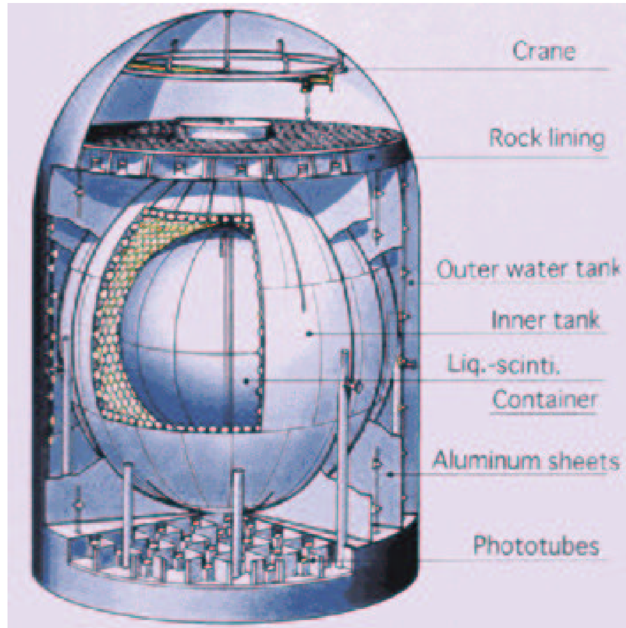


"The non-ν_e component is ... 5.3 σ greater than zero ..."

Motivation

KamLAND, PRL 90 (2003) 021802:

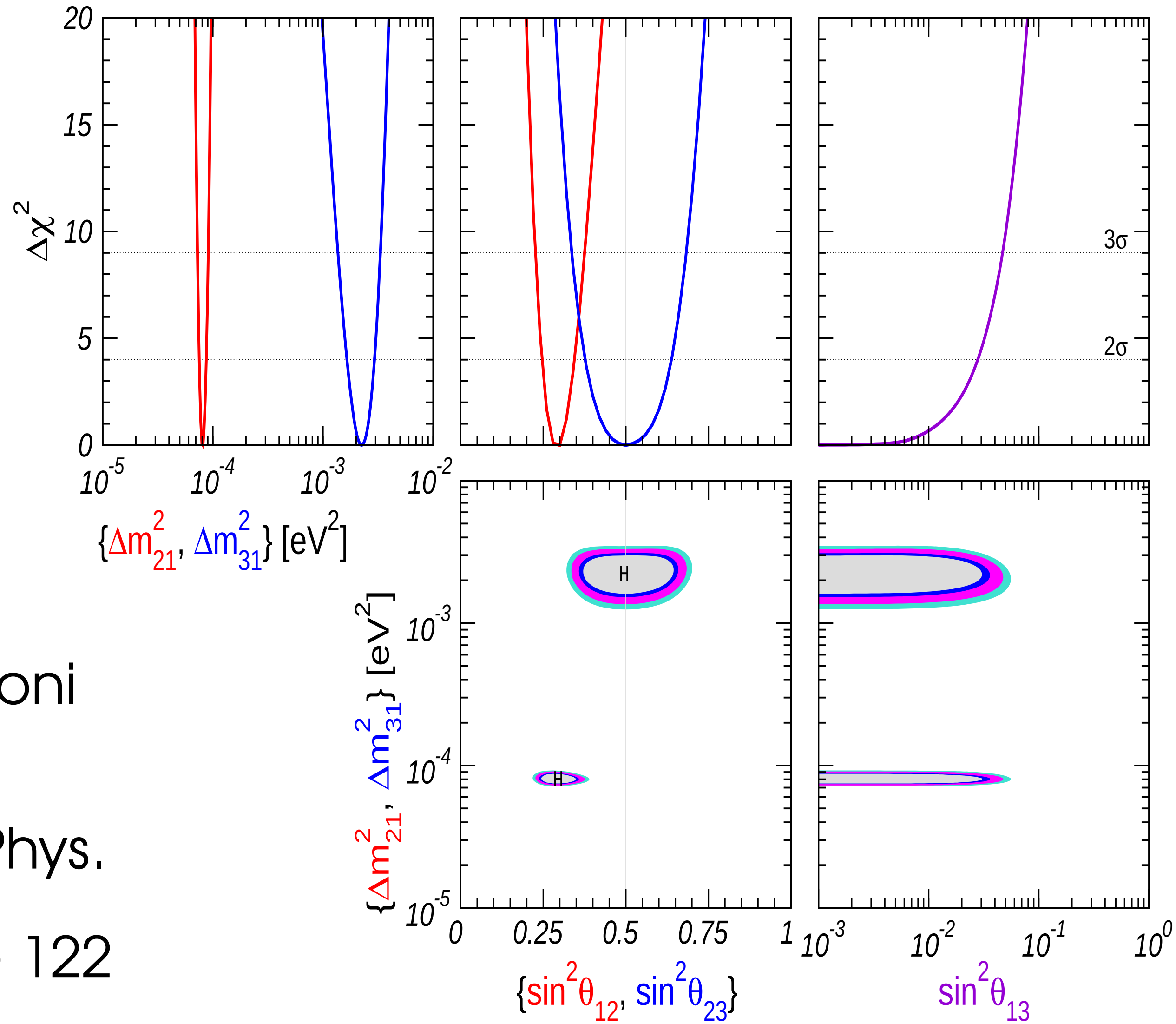




"...the ratio of ... observed ... to expected number of events is $0.611 \pm 0.085(\mathrm{stat}) \pm 0.041$ ..."

Current status of ν data

[⇚]



M. Maltoni
et. al,
New J.Phys.
6 (2004) 122

Neutrino masses

In the SM neutrinos are massless. In general, however:

	Majorana	Dirac
	$\Delta L = 2$	$\Delta L = 0$

$$\mathcal{L}^{\nu} \;=\; -m_M \overline{\nu_L^c} \nu_L \;-\; m_D \overline{\nu_L} \nu_R$$

Note:

- m_D requires ν_R
- m_M violates L

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Note:

- No experimental hint for Majorana mass
- " " " " scale of $\not{L}$ [⇚]

Introduction to $\not R_p$

MSSM superpotential:

$$W_{R_P} = + \ h_e^{ij}\hat{H}_d\hat{L}_i\hat{E}_j^C + h_d^{ij}\hat{H}_d\hat{Q}_i\hat{D}_j^C + h_u^{ij}\hat{H}_u\hat{Q}_i\hat{U}_j^C$$
$$- \ \mu\hat{H}_d\hat{H}_u$$

R-parity violating superpotential:

$$W_{\not R_P} = + \ \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}_k^C + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}_k^C$$
$$+ \ \epsilon_i\hat{L}_i\hat{H}_u + \lambda''_{ijk}\hat{U}_i^C\hat{D}_j^C\hat{D}_k^C$$

R-parity violation

The R-parity violating part:

$$W_{\not R_P} = \; + \; \lambda_{ijk}\hat{L}_i\hat{L}_j\hat{E}^C_k + \lambda'_{ijk}\hat{L}_i\hat{Q}_j\hat{D}^C_k$$
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$\Rightarrow$ λ_{ijk}, λ'_{ijk} and ϵ_i violate lepton number

$\Rightarrow$ λ''_{ijk} violate baryon number

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$\Rightarrow$ λ_{ijk}, λ'_{ijk} and ϵ_i violate lepton number

$\Rightarrow$ λ''_{ijk} violate baryon number

$\Rightarrow$ lepton number and baryon number violation can not be present at the same time because ...

Bilinear R-parity breaking

Consider:

$$W = W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u,$$

$$V_{\rm soft} = V_{\rm soft}^{MSSM} + B_i \epsilon_i \tilde{L}_i H_u.$$

$\Rightarrow$ Both terms violate lepon number

$\Rightarrow$ New terms in $V_{\rm soft}$ induce vevs v_{L_i}

$\Rightarrow$ $\Lambda_i = v_{L_i}\mu + \epsilon_i v_D$

$\Rightarrow$ Neutrinos mix with neutralinos

Tree-level mass matrix

In the basis:

$$\Psi_0'^T = (\nu_e, \nu_\mu, \nu_\tau, \tilde{B}, \tilde{W}, \tilde{H}_d, \tilde{H}_u)$$

The neutralino mass matrix can be written as:

$$\mathcal{M}_0 = \begin{pmatrix} 0 & m \\ m^T & \mathcal{M}_{\chi^0} \end{pmatrix}$$

Tree-level diagonalization

Only one neutrino mass non-zero at tree-level:

$$m_{\nu_3} = \frac{m_\gamma}{4det(\mathcal{M}_{\chi^0})} |\vec{\Lambda}|^2$$

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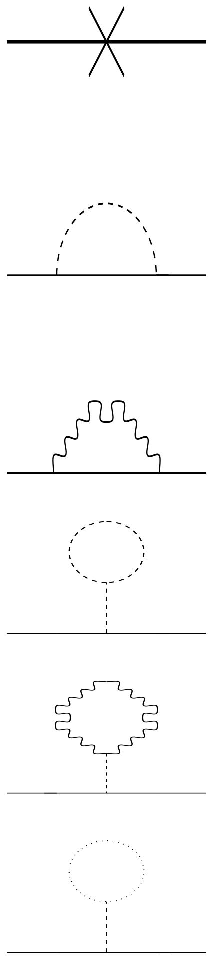
Only two angles defined at tree-level:

$$\tan\theta_{13} = -\frac{\Lambda_e}{(\Lambda_\mu^2 + \Lambda_\tau^2)^{\frac{1}{2}}},$$

$$\tan\theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau}.$$

1-loop contribution(s) to m_ν

$M^{1L} =$



$=$ tree-level

$+$ $d - \tilde{d}$ or $u - \tilde{u}$; $\chi^\pm - S^\pm$ or $\chi^0 - S^0$; $\chi^0 - P^0$

$+$ $W^\pm - \chi^\pm$ or $Z^0 - \chi^0$

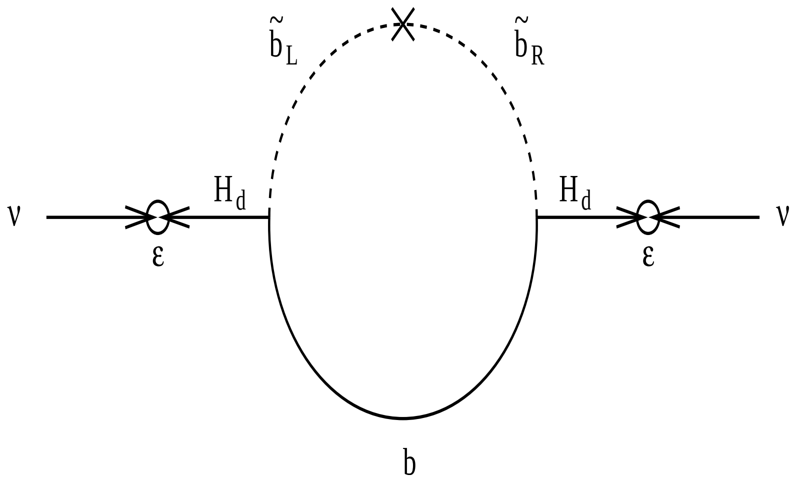
$+$ $S^0 - S^0$ or $S^0 - P^0$

$+$ $S^0 - W^\pm$ or $S^0 - Z^0$

$+$ $S^0 - c^\pm$ or $S^0 - c^0$

1-loop contribution(s) to m_ν

"Generically" most important loop(s):



Bottom squark loop

⇒ Mass:

$$m_\nu^{1lp} \sim \mathcal{F} \Delta B_0 \frac{(\tilde{\epsilon}_1^2 + \tilde{\epsilon}_2^2)}{\mu^2}$$

⇒ Angle:

$$\tan \theta_\odot \sim \tilde{\epsilon}_1 / \tilde{\epsilon}_2$$

[⇐]

LSP decay

With R-parity violated LSP decays, thus ...

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... any superpartner can be the LSP!

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... any superpartner can be the LSP!

$\Rightarrow$ Neutralino

$\Rightarrow$ Chargino

$\Rightarrow$ Gluino

$\Rightarrow$ Charged scalar

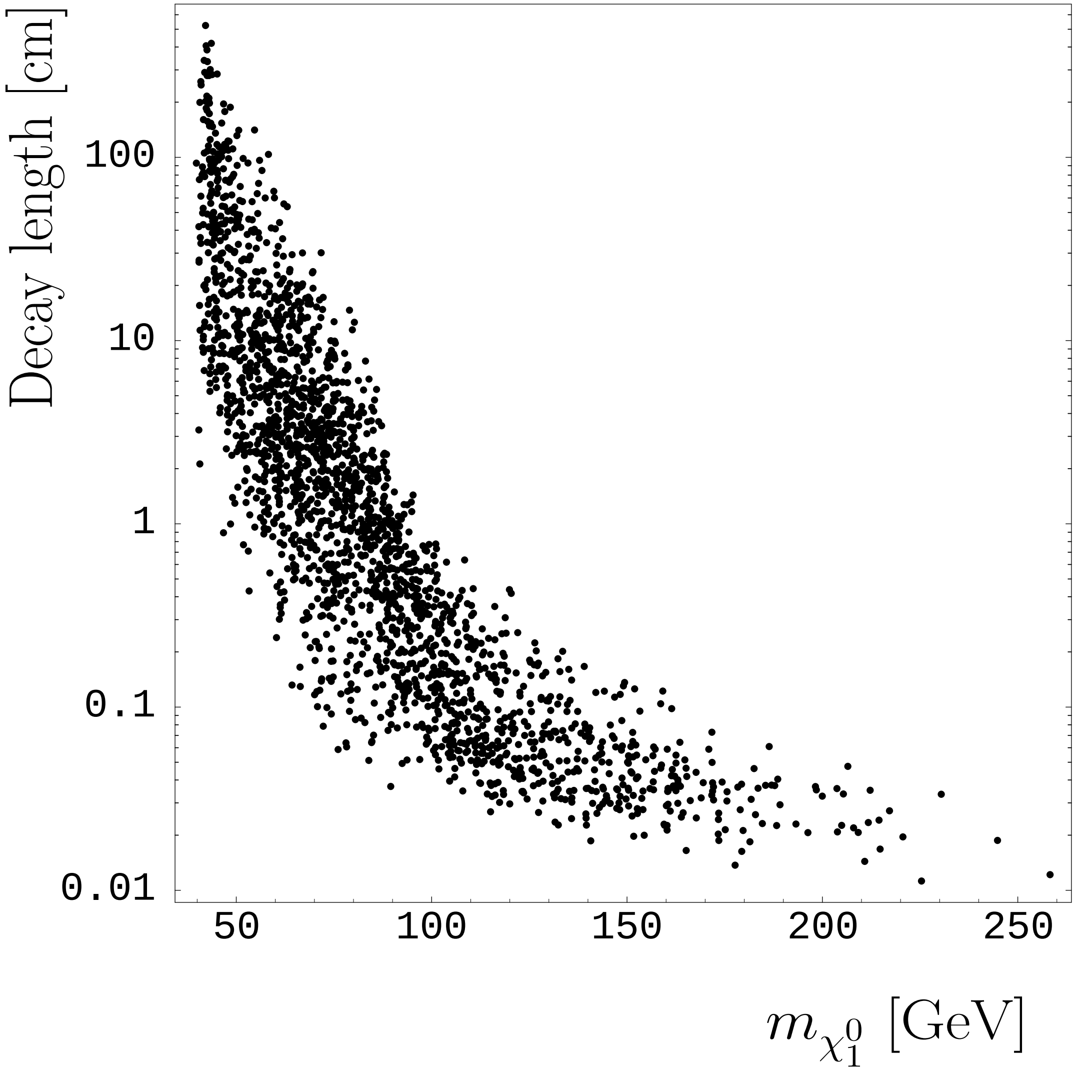
$\Rightarrow$ Scalar neutrino

$\Rightarrow$ Scalar quark

[$\Leftarrow$]

Neutralino decay length

All Points with correct $\Delta m^2_{\rm Atm}$ and $\Delta m^2_{\odot}$:



Neutralino decay

Consider, for example, the decay $\chi_1^0 \to W^{\pm} l_i$:

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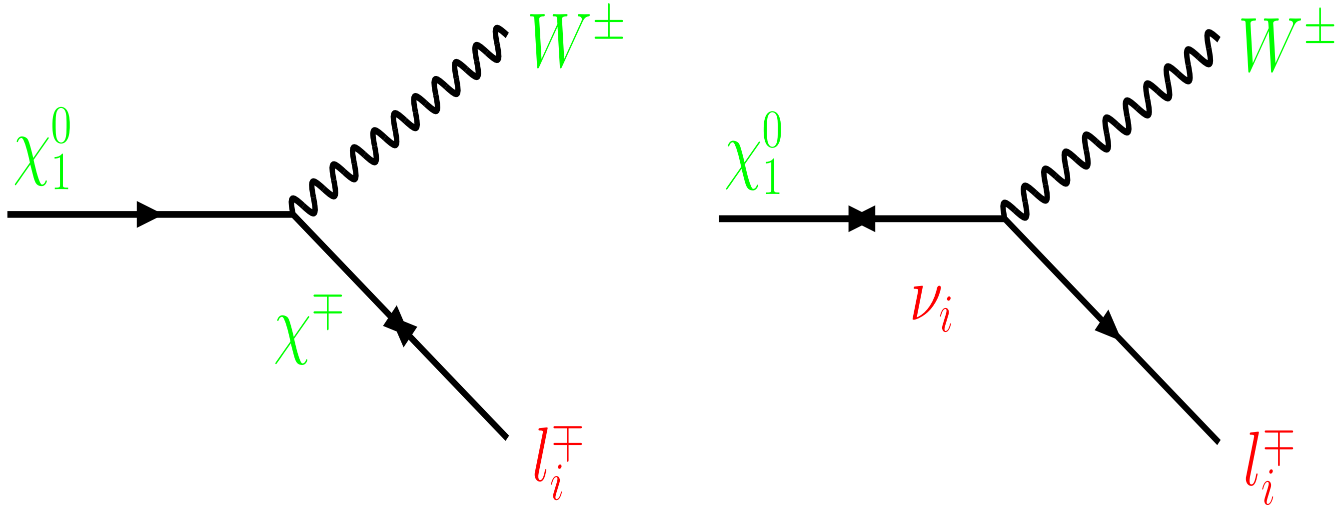

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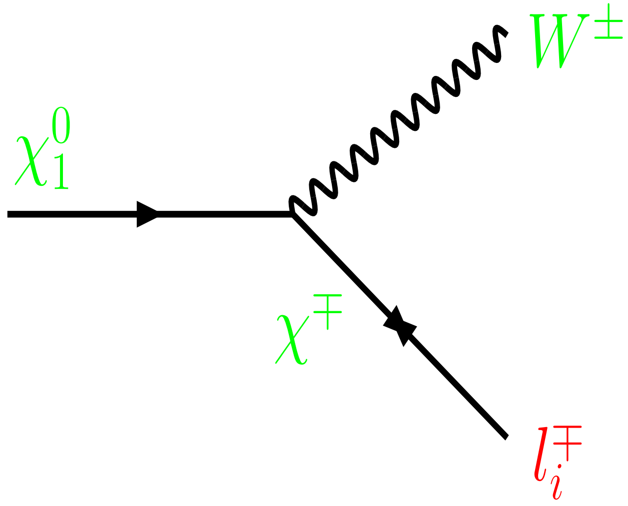


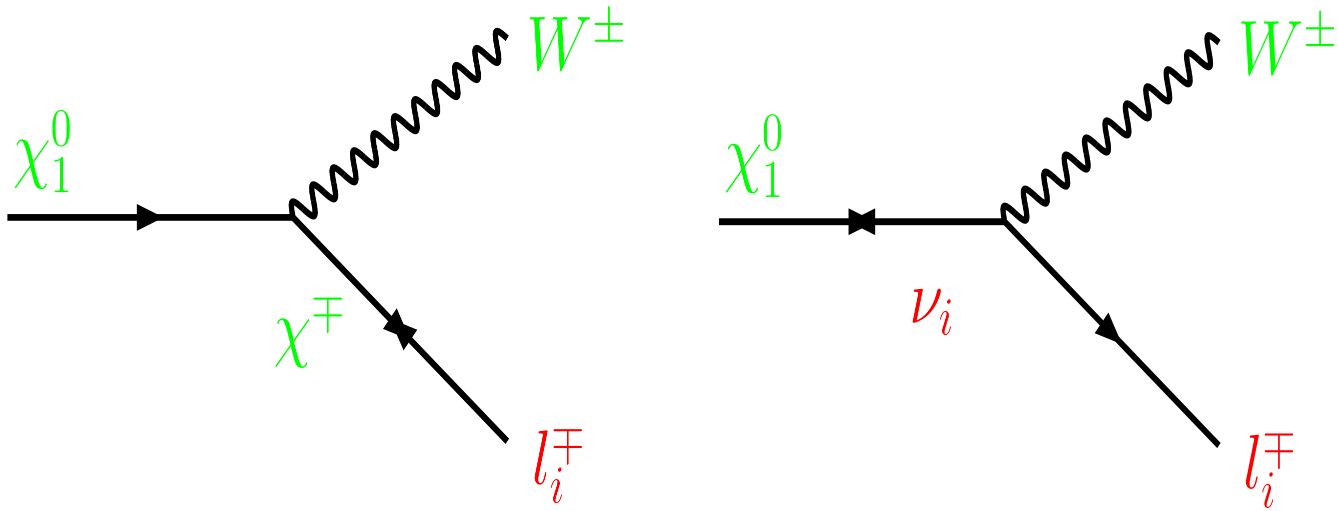
$\Rightarrow$ Couplings are complicated functions:

$$f \equiv f(g, g', M_1, M_2, ..., \epsilon_i, \Lambda_i)$$

$\Rightarrow$ But: Same functions for all generations

Neutralino decay

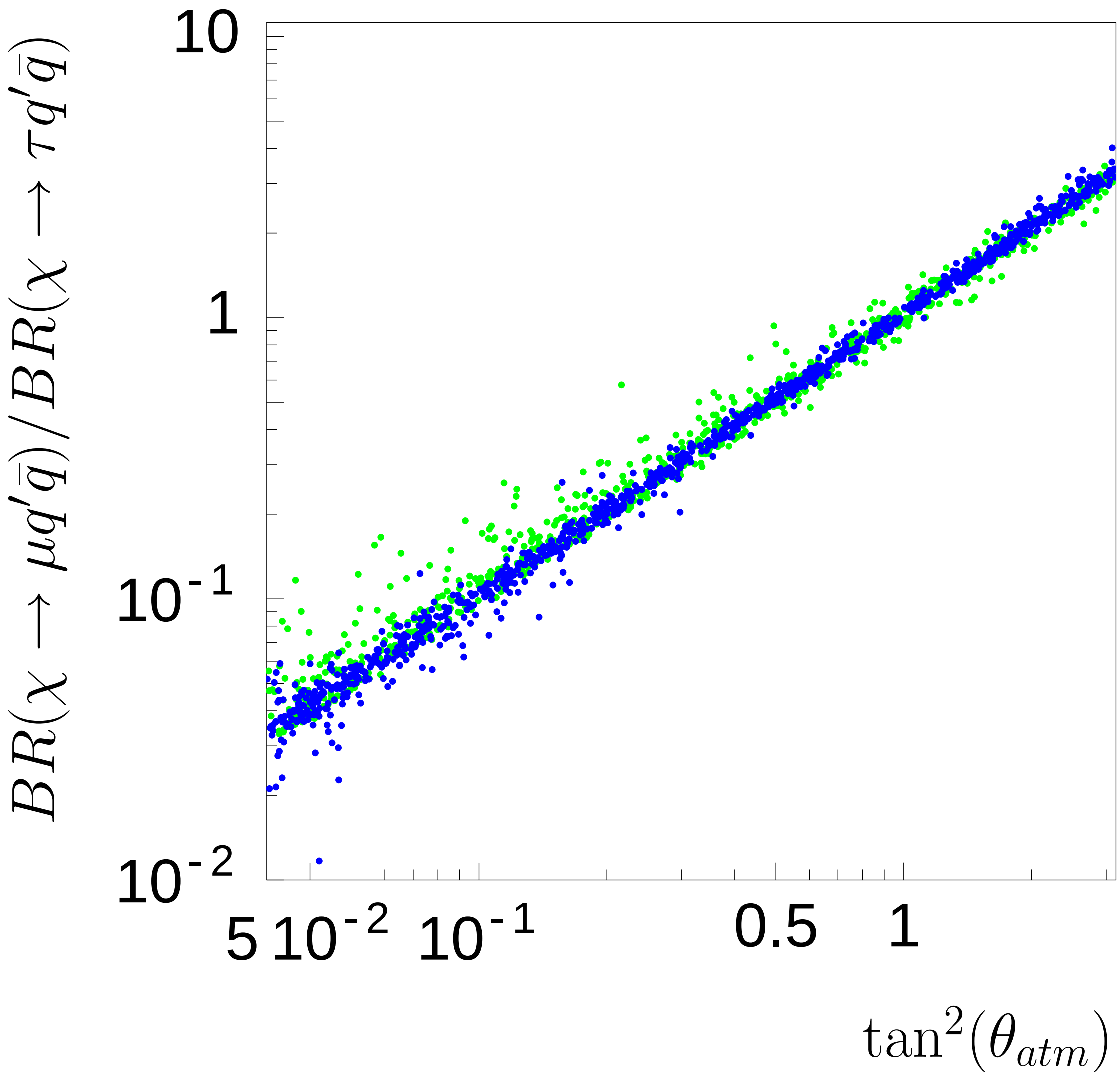
Consider, for example, the decay $\chi_1^0 \to W^\pm l_i$:



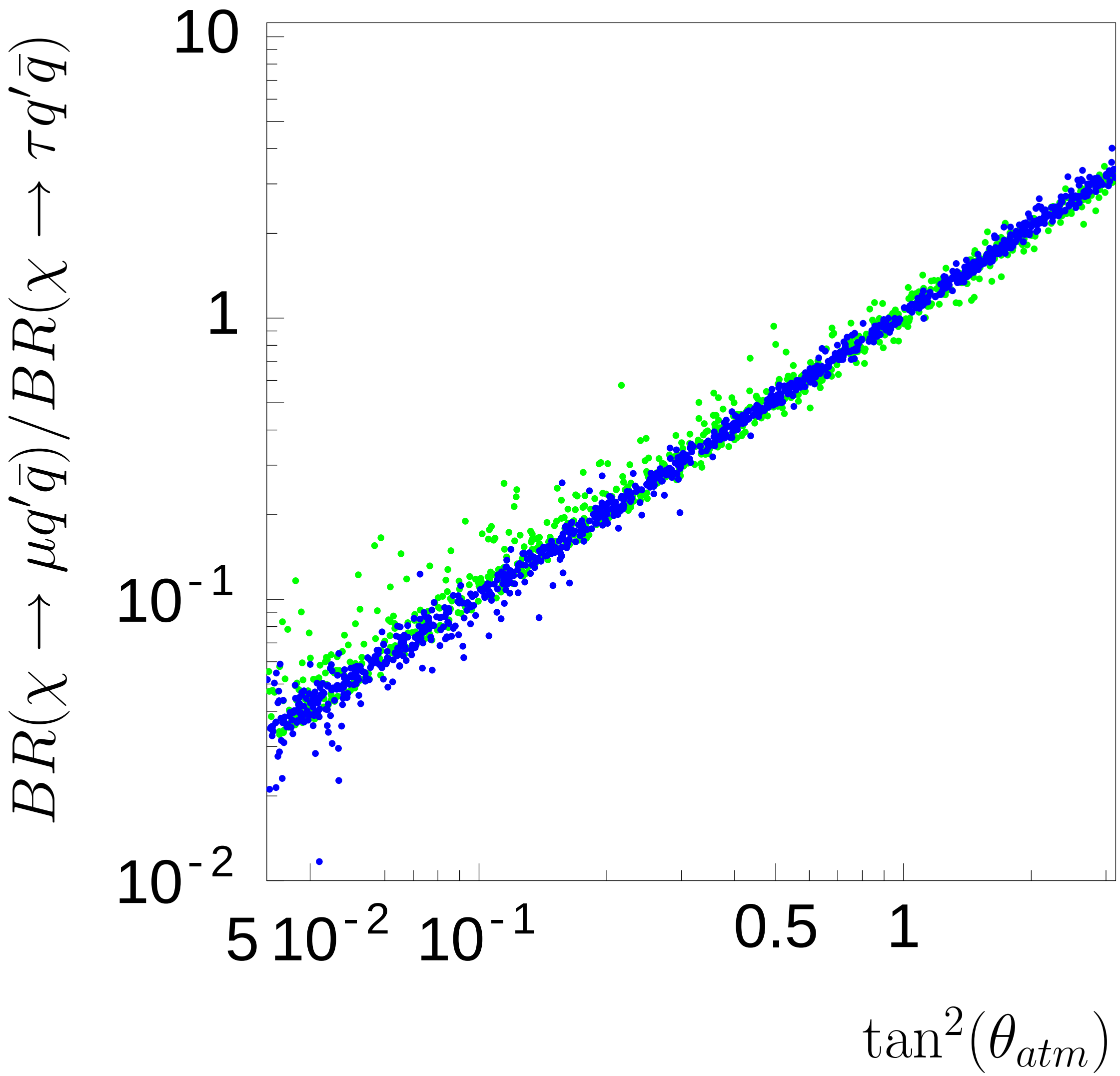
$\Rightarrow$ Try:

$$\frac{Br(\chi^0 \to l_i W)}{Br(\chi^0 \to l_j W)} \simeq \left(\frac{f(\ldots, \epsilon_i, \Lambda_i)}{f(\ldots, \epsilon_j, \Lambda_j)}\right)^2 \sim \left(\frac{\Lambda_i}{\Lambda_j}\right)^2 \quad or \quad \left(\frac{\epsilon_i}{\epsilon_j}\right)^2$$

Neutralino decay and θ_{Atm}



Neutralino decay and $\theta_{\rm Atm}$

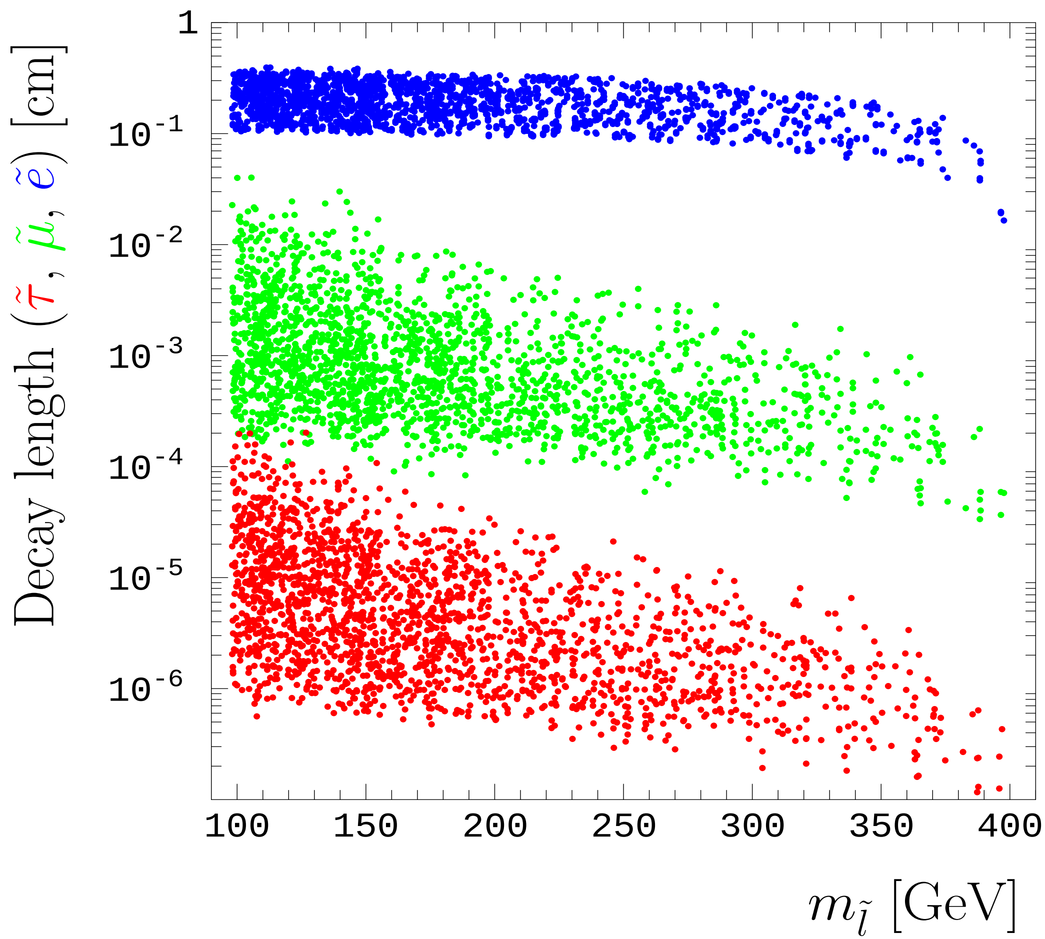


Ratio of branching ratios predicted from atmospheric neutrino measurement

[⇚]

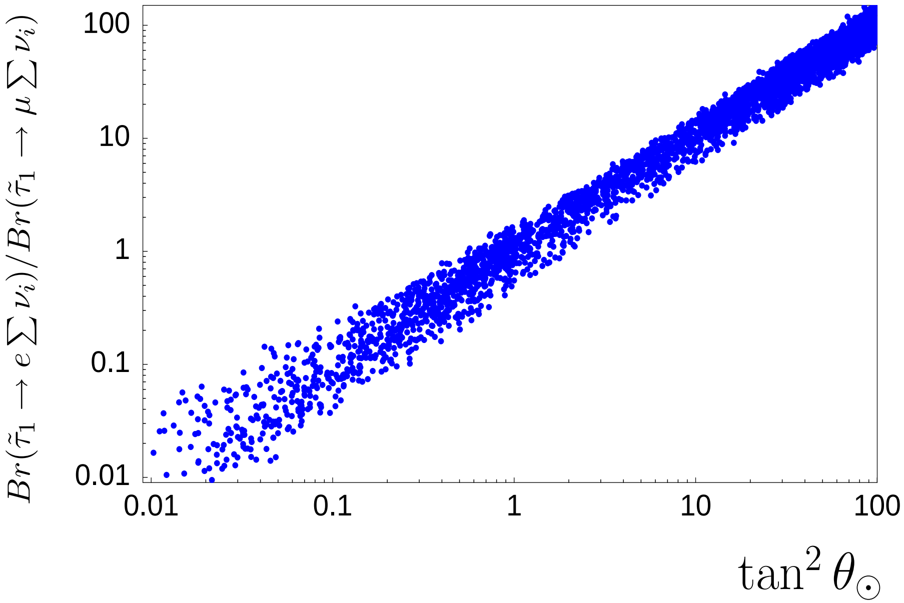
Charged scalar decay

mSugra-like: charged sleptons have similar mass at weak scale:



$\tilde{\tau}$, $\tilde{\mu}$ and $\tilde{e}$ all decay through $\not{R}_p$ modes

Charged scalars and $\theta_\odot$



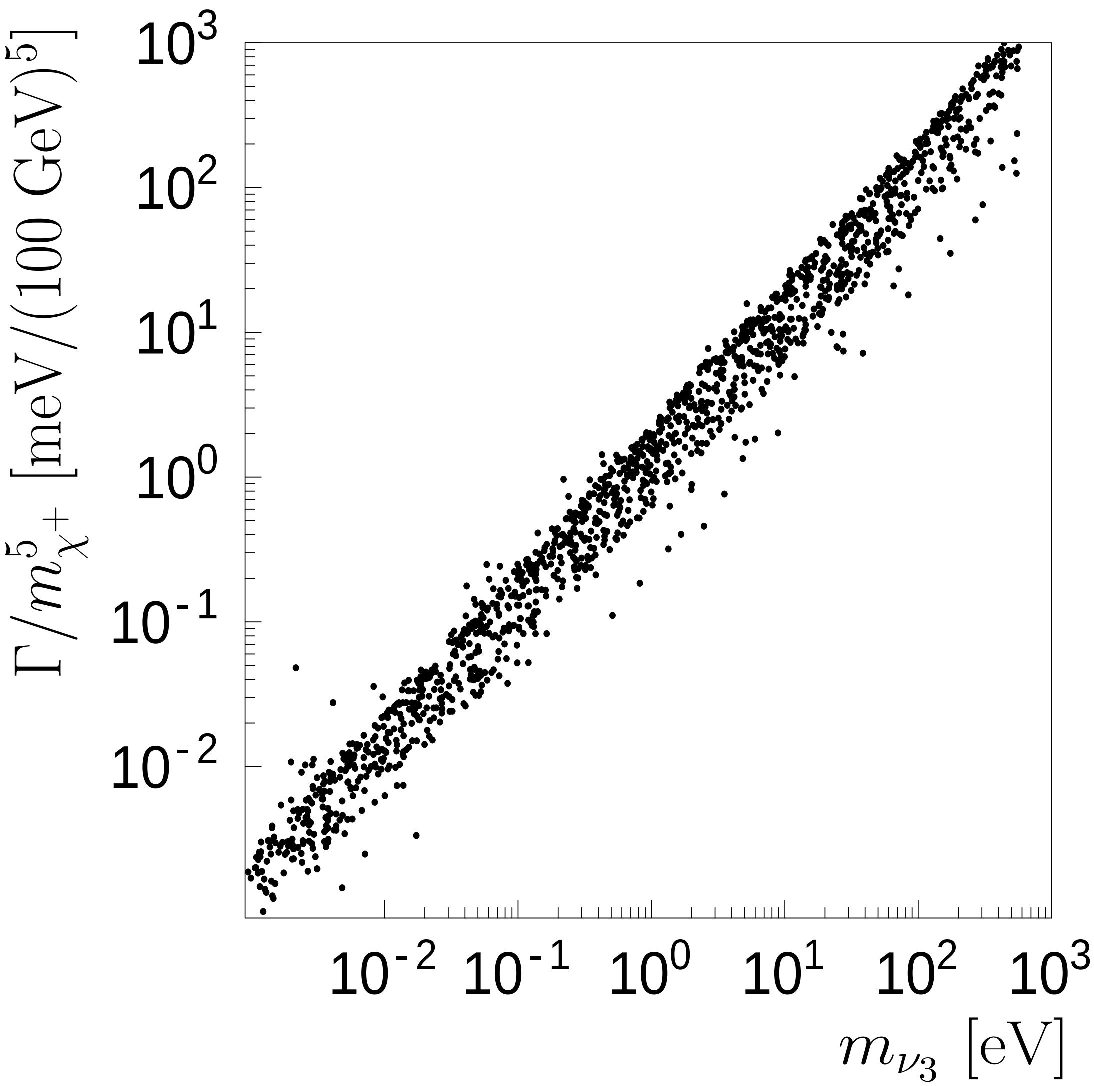
[$\Lleftarrow$]

$\Rightarrow$ measured solar angle currently predicts

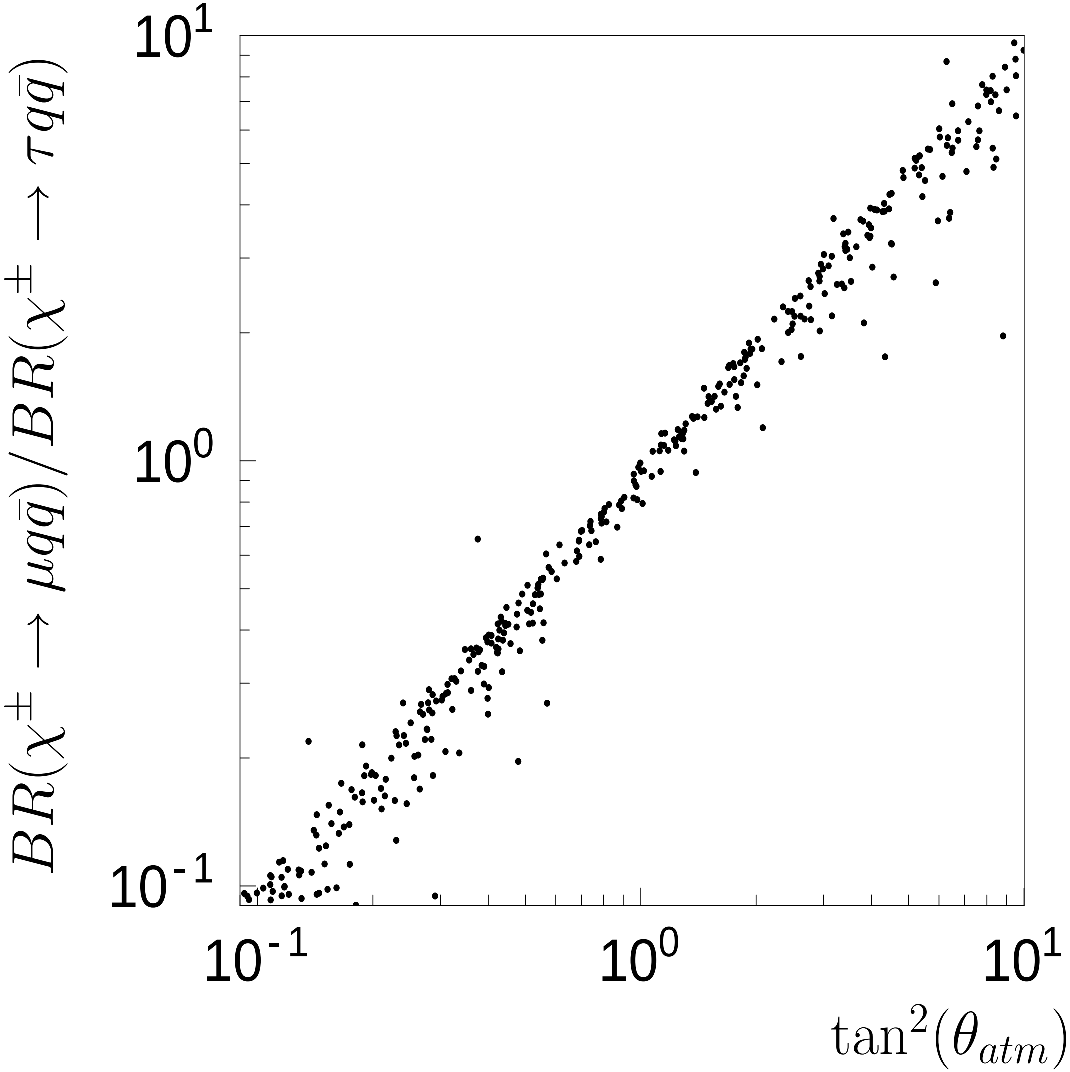
$$\frac{Br(\tilde{\tau}_1 \to e \sum \nu_i)}{Br(\tilde{\tau}_1 \to \mu \sum \nu_i)} \simeq [0.09, 1.8]$$

Chargino decay

Neutrino mass and decay width related:



Chargino decay and θ_{Atm}



[⇚]

Cosmological parameters

Source: http://pdg.lbl.gov/

Parameter	Value
Hubble parameter	$h = 0.71 \pm 0.03$
Total matter density	$\Omega_M h^2 = 0.135 \pm 0.009$
Baryon density	$\Omega_B h^2 = 0.0224 \pm 0.0009$
Cosmological constant	$\Omega_\Lambda = 0.73 \pm 0.04$
Radiation density	$\Omega_r h^2 = 2.47 \times 10^{-5}$
Neutrinos	$\Omega_\nu \geq 0.001$

Gravitino dark matter

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Gauge Mediated Supersymmetry Breaking (GMSB) generically predicts the gravitino is LSP ...

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Pagels and Primack (1982):

$$\Omega_{\tilde{G}} h^2 \simeq 0.11\,\mathcal{F}\left(\frac{m_{3/2}}{100\ \mathrm{eV}}\right)\left(\frac{100}{g_*}\right)$$

$\Rightarrow$ “warm dark matter”

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$\Rightarrow$ “warm dark matter”

If R-parity violated, gravitino decays, but ...

Gravitino half-live

$$\Gamma(\tilde{G} \to \sum_i \nu_i \gamma) \simeq \frac{1}{32\pi} |U_{\gamma\nu}|^2 \frac{m_{3/2}^3}{M_{Pl}^2}.$$

Here,

$$|U_{\gamma\nu}|^2 \;=\; \sum_{i=1}^{3} |\cos\theta_W N_{i1} + \sin\theta_W N_{i2}|^2$$

$$\sim 3.5 \times 10^{-14} \frac{m_\nu}{0.05\,\mathrm{eV}}$$

$\Rightarrow$ Gravitino half-live $\sim 10^{31}\, t_{H_0} \left(\frac{0.1\mathrm{keV}}{m_{3/2}}\right)^3$

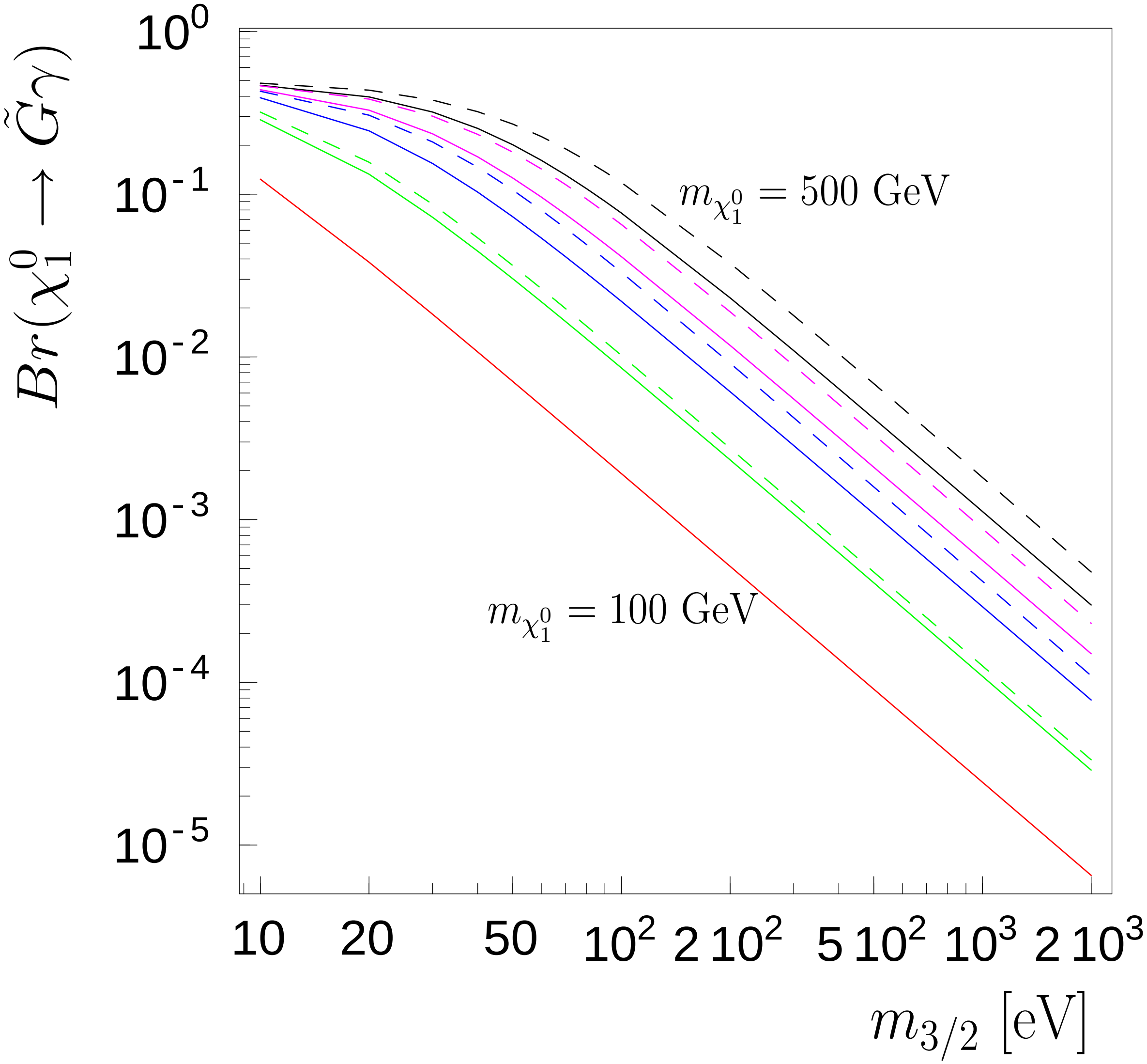
Neutralino decay

Neutralino decay width to gravitino + photon:

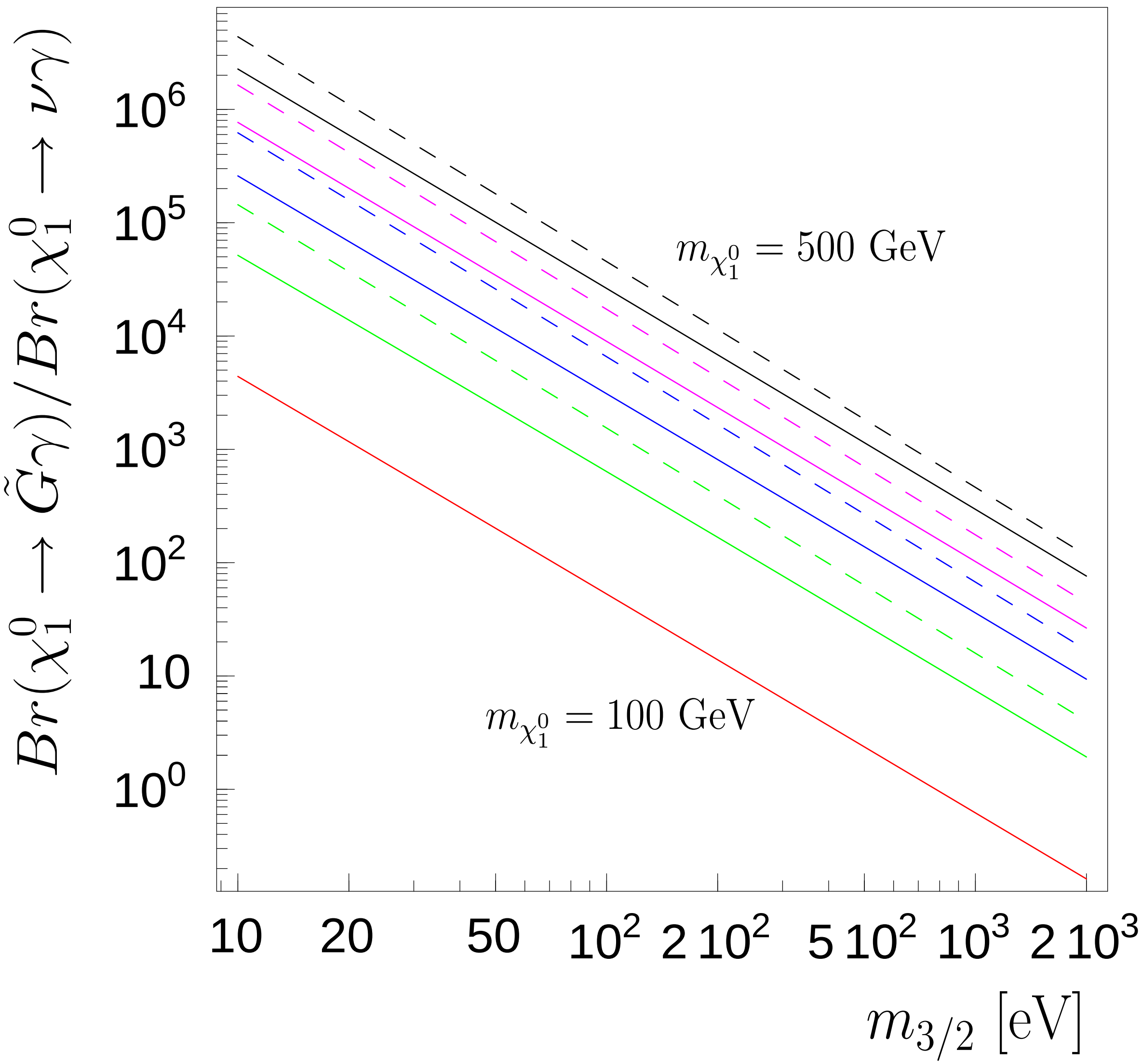
$$\Gamma(\tilde{\chi}_1^0 \to \tilde{G}\gamma) = \frac{\kappa_\gamma^2 m_{\tilde{\chi}_1^0}^5}{48\pi m_{3/2}^2 M_{Pl}^2}$$

$$\simeq 1.2 \times 10^{-6} \kappa_\gamma^2 \left(\frac{m_{\tilde{\chi}_1^0}}{100\ \mathrm{GeV}}\right)^5 \left(\frac{100\ \mathrm{eV}}{m_{3/2}}\right)^2 \mathrm{eV}$$

Accelerator test?



Background?



$Br(\chi_1^0 \to \tilde{G}\gamma)/Br(\chi_1^0 \to \nu\gamma)$
10^6
10^5
10^4
10^3
10^2
10
10^0
$m_{\chi_1^0} = 500$ GeV
$m_{\chi_1^0} = 100$ GeV
10
20
50
10^2
$2\,10^2$
$5\,10^2$
10^3
$2\,10^3$
$m_{3/2}$ [eV]

[⇚]

Spontaneous $\not{R}_p$

$$\mathcal{W} = h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u + h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d + \mu\widehat{H}_d\widehat{H}_u$$

Spontaneous $\not R_p$

$$\mathcal{W} = h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u \;+\; h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d$$
$$+h_\nu^{ij}\widehat{L}_i\widehat{\nu}_j^c\widehat{H}_u \;+\; \mu\widehat{H}_d\widehat{H}_u$$

$\Rightarrow$ Conserves L at level of $\mathcal{W}$

$\Rightarrow$ If scalar singlet gets vacuum expectation value:

$$\epsilon_i = h_i^\nu\langle\tilde{\nu}^c\rangle$$

$\Rightarrow$ Spontaneous breaking of lepton number, Goldstone boson: Majoron

Spontaneous $R\!\!\!/_p$

$$\mathcal{W} = h_U^{ij}\widehat{Q}_i\widehat{U}_j\widehat{H}_u \ + \ h_D^{ij}\widehat{Q}_i\widehat{D}_j\widehat{H}_d + h_E^{ij}\widehat{L}_i\widehat{E}_j\widehat{H}_d$$
$$+h_\nu^{ij}\widehat{L}_i\widehat{\nu}^c_j\widehat{H}_u \ - \ h_0\widehat{H}_d\widehat{H}_u\widehat{\Phi} + h^{ij}\widehat{\Phi}\widehat{\nu}^c_i\widehat{S}_j$$

As before, plus:

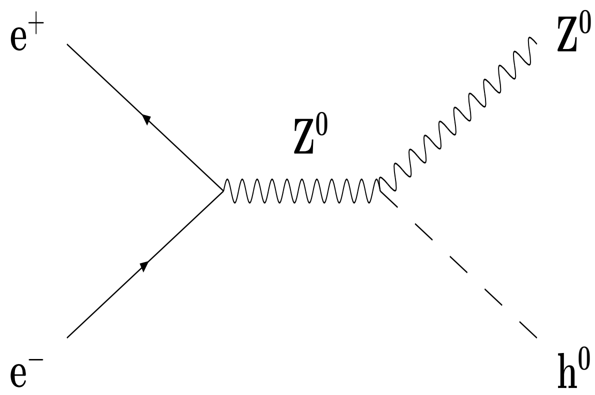
$\Rightarrow$ $\widehat{\Phi}$ potentially solves μ-problem á la NMSSM

$\Rightarrow$ Dirac mass term for $\widehat{\nu}^c$ through $v_\Phi\widehat{S}$

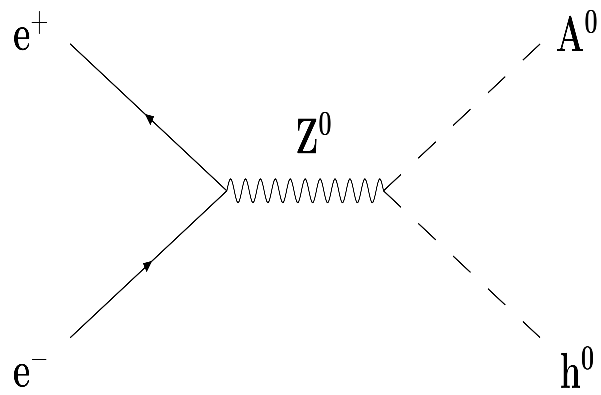
$\Rightarrow$ Many variants possible ...

Higgs production

In the MSSM:



$\sim \sin(\beta - \alpha)$



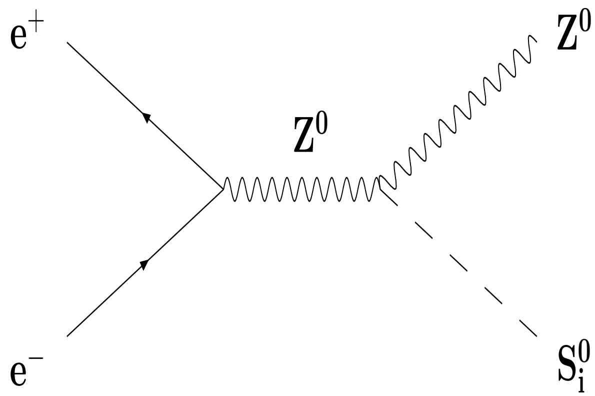
$\sim \cos(\beta - \alpha)$

$\Rightarrow$ For h^0 and h^0-A production

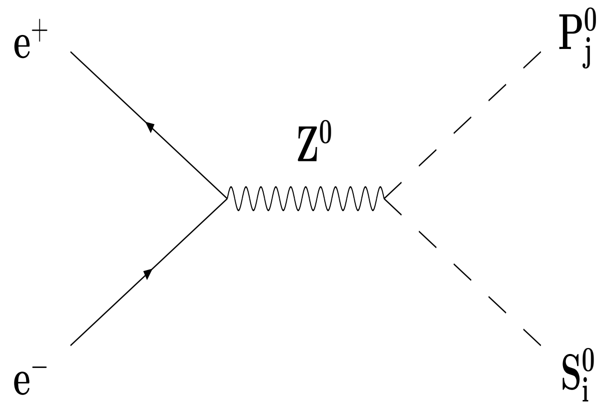
$\Rightarrow$ H^0: exchange $\sin(\beta - \alpha) \leftrightarrow \cos(\beta - \alpha)$

Higgs production

In spontaneous $\not{R}_p$:



$\sim \eta_{B_i}$



$\sim \eta_{A_{ij}}$

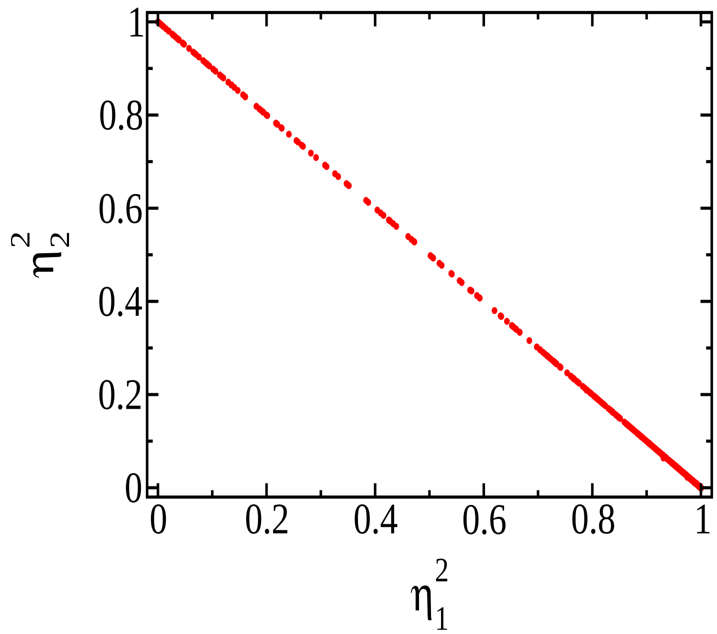
"Higgses":

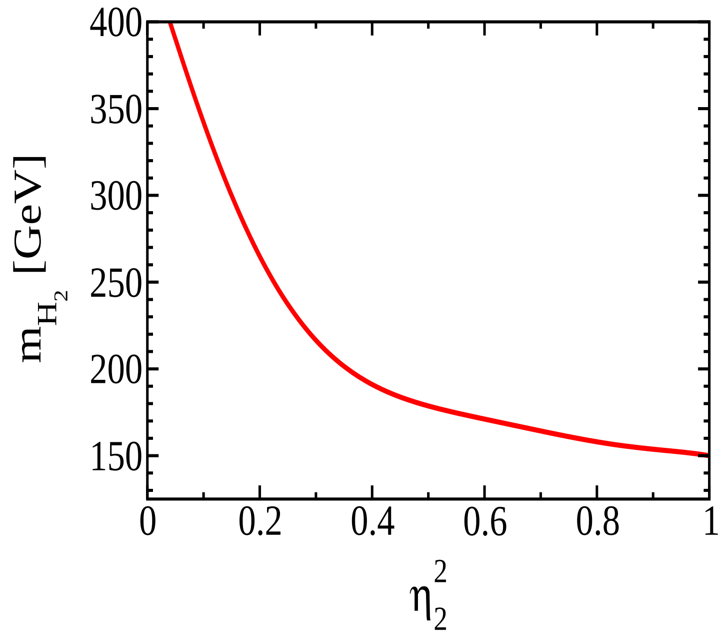
$$\left(P^0\right)^T = \left(J, G^0, P_{A^0}, P_{J_\perp}, P_\Phi, P_{\tilde{\nu}_i}\right)$$

$$\left(S^0\right)^T = \left(S_{h^0}, S_{H^0}, S_J, S_{J_\perp}, S_\Phi, S_{\tilde{\nu}_i}\right)$$

Higgs mass bound

If there is a light singlet (typically S_J):

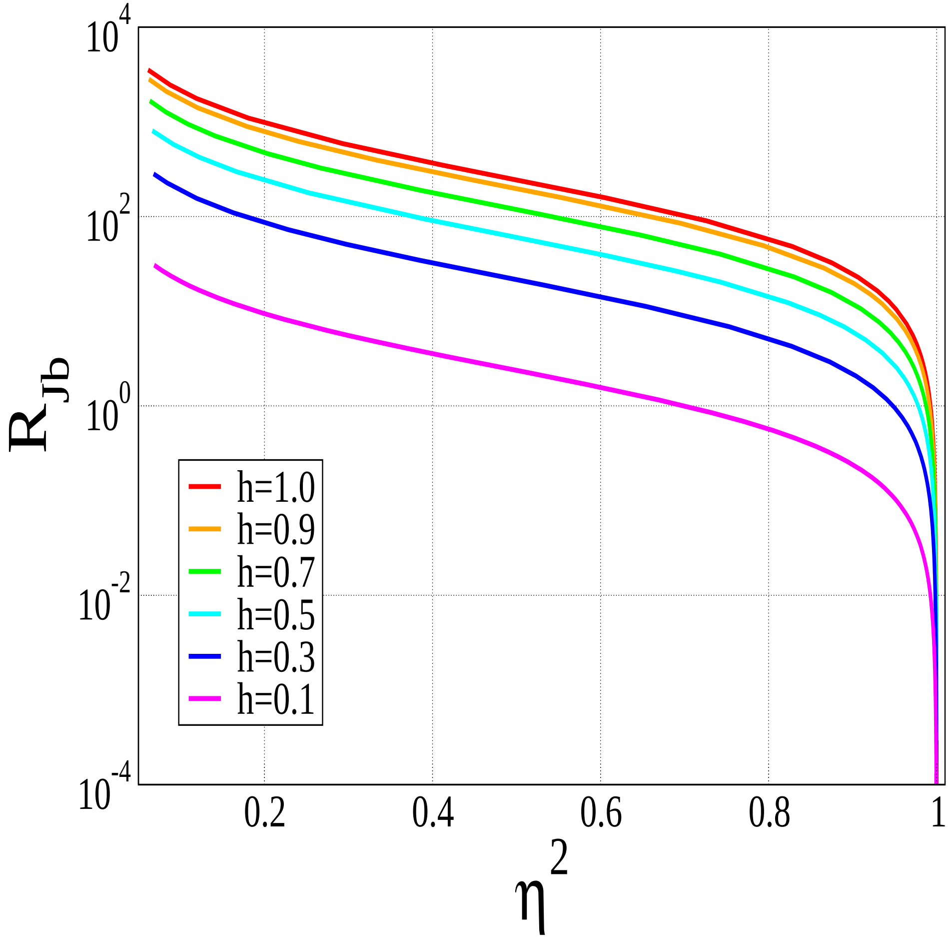




$\Rightarrow$ One CP-even Higgs necessarily light

$\Rightarrow$ Note: $\eta_{B_1}^2 + \eta_{B_2}^2 = 1$

Higgs in spontaneous $\not{R}_p$



$$R_{Jb} = \frac{\Gamma(h \to JJ)}{\Gamma(h \to b\bar{b})}$$

CP-even Higgs can decay invisibly!

[⇚]

Conclusion

“... after all, you are measuring just another bunch of Yukawas!”

Nick Evans

[⇚]

Neutrino masses

Add right-handed neutrino to SM:

$$\mathcal{L}^{\nu} = \frac{1}{\sqrt{2}} Y_{ij} h^0 \overline{\nu_{L_i}} \nu_{R_j}$$

With (example only, in units of 10^{-13}):

$$Y_{ee} = 0.5 \qquad Y_{e\mu} = -0.78 \qquad Y_{e\tau} = 0.65$$

$$Y_{\mu\mu} = 1.2 \qquad Y_{\mu\tau} = -1.0 \qquad Y_{\tau\tau} = 1.7$$

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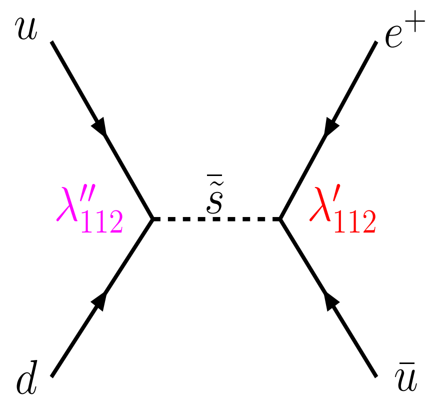
$\Rightarrow$ Fit to data, not a theory!

[$\Leftarrow$]

Proton Decay



Estimate decay width:

$$\Gamma(p \to e^+\pi^0) \approx \frac{(\lambda'_{11k})^2(\lambda''_{11k})^2}{(4\pi^2)^2\tilde{m}^4_{dk}} M^5_{proton}$$

Given that $\tau(p \to e\pi) > 10^{32}\, yr$:

$$\lambda'_{11k} \cdot \lambda''_{11k} \lesssim 2 \cdot 10^{-27} \left(\frac{\tilde{m}_{dk}}{100\text{Gev}}\right)^2 .$$

[⇚]

Alternatives to R_p

As R_p: matter parity

$$\begin{aligned}(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i) &\longrightarrow -(L_i, \bar{E}_i, Q_i, \bar{U}_i, \bar{D}_i),\\ (H_1, H_2) &\longrightarrow (H_1, H_2).\end{aligned}$$

Forbids $\not{B}$: baryon-parity

$$\begin{aligned}(Q_i, \bar{U}_i, \bar{D}_i) &\longrightarrow -(Q_i, \bar{U}_i, \bar{D}_i),\\ (L_i, \bar{E}_i, H_1, H_2) &\longrightarrow (L_i, \bar{E}_i, H_1, H_2).\end{aligned}$$

Spontaneous $\not\!R_p$

$$\mathcal{W} = \mathcal{W}_{MSSM} \; + \; h_\nu^{ij} \widehat{L}_i \widehat{\nu}_j^c \widehat{H}_u + \cdots$$

$\Rightarrow$ If scalar singlet gets vacuum expectation value:

$$\epsilon_i = h_i^\nu \langle \tilde{\nu}^c \rangle$$

$\Rightarrow$ Produces only bilinear $\not\!R_p$ terms

[$\Leftarrow$]

WDM and Entropy

⇒ "Problem": Matter power spectrum at (1-40) Mpc very sensitive to WDM, M. Viel et al, PRD71 (2005):

$$m_{WDM} > 550 eV$$

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⇒ "Solution": Produce entropy after gravitino decoupling (Baltz & Murayama (2001), Fujii & Yanagida (2002)) through late messenger decay:

$$\mathcal{F} \geq (5 - 10)$$

[⇐]