Invisible Higgs Boson Decays in Spontaneously Broken R-Parity

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Based on paper:

M. Hirsch, J. Romão, J. W. F. Valle and A. Villanova del Moral,
Phys. Rev. D **70** (2004) 073012.

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Universitat de València

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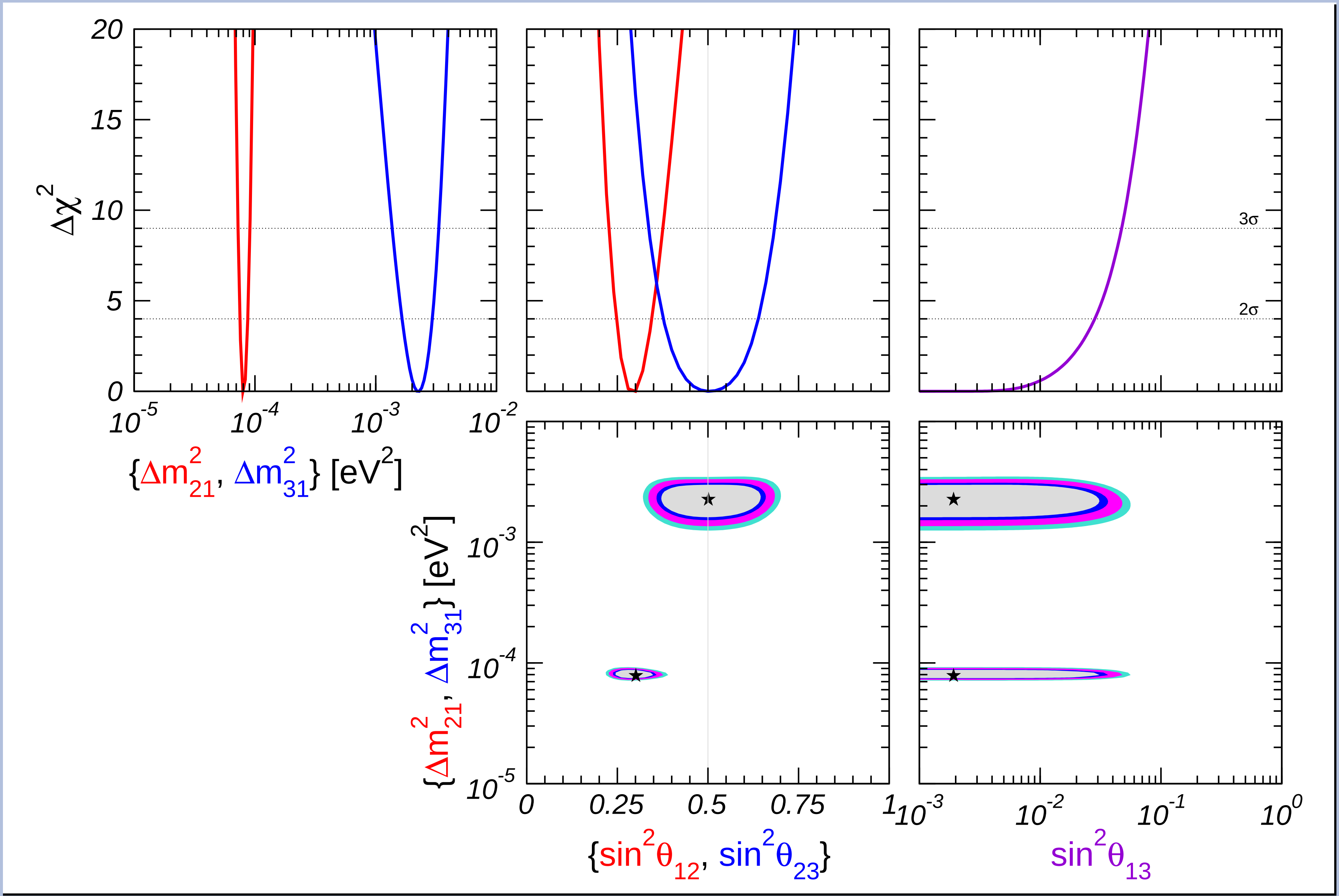
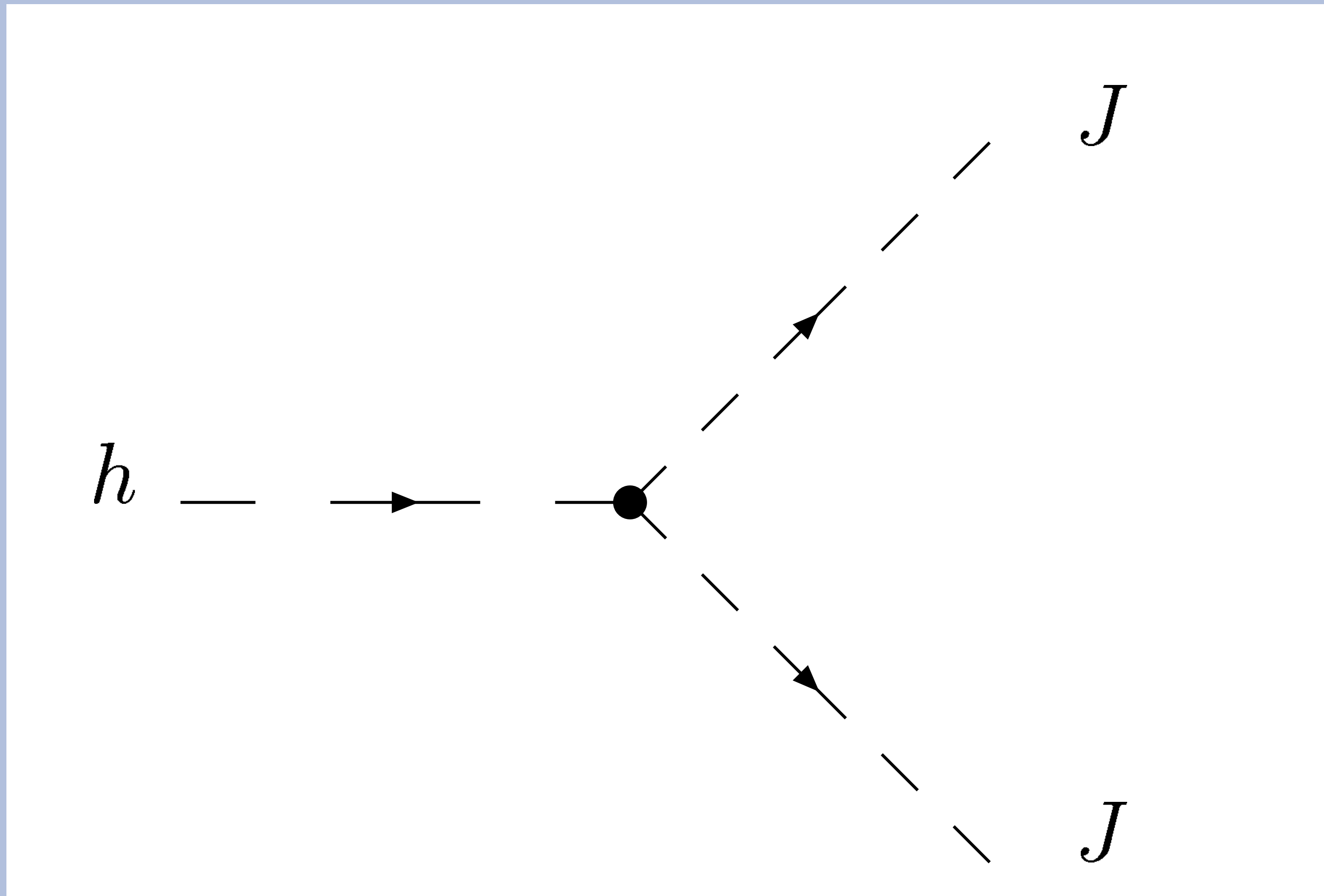
Motivation: Neutrino Oscillations



M. Maltoni, T. Schwetz, M. A. Tortola and J. W. F. Valle, New J. Phys. **6**, 122 (2004).

Motivation: Invisible Higgs Decay



In every model with spontaneous L breaking, there is a massless Goldstone boson: J (majoron)

Standard Model

SM neutrinos are massless since:

- Right-handed neutrinos do not exist
- Lepton number is “accidentally” conserved
- Higgs triplets do not exist

$\Rightarrow$ SM must be extended in some sector:

- Particles
- Symmetries
- or both

SM+SUSY

- The most general SUSY extension of the SM allows L and B violation $\Rightarrow$ Proton decay!!

- *Ad hoc* postulation of R-parity conservation $\Rightarrow$ MSSM

$$P_R = (-1)^{3B+L+2s}$$

  - Neutrinos remain massless

★ Postulation of P_R conservation is not inevitable!

- Postulation of P_R as an exact symmetry of the W, but which is spontaneously violated $\Rightarrow$ SBRP

Spontaneously Broken R-Parity Model

- Particle Content
- Superpotential
- Non-Zero Vacuum Expectation Values
- Neutral Fermion Sector
- Neutral Scalar Sector

Particle Content

MSSM superfields

+

3 Isosinglets

	$\widehat{\nu}^c$	$\widehat{S}$	$\widehat{\Phi}$
$L =$	-1	$+1$	0

$\widehat{\nu}^c$ $\Rightarrow$ neutrino Dirac mass term

$\widehat{S}$ $\Rightarrow$ large mass for $\widehat{\nu}^c$

$\widehat{\Phi}$ $\Rightarrow$ it enlarges invisible Higgs boson decay

$\Rightarrow$ possible solution to the μ problem

Superpotential

$$W = \varepsilon_{ab}\Big[h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_u^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_d^a + h_E^{ij}\widehat{L}_i^b\widehat{E}_j\widehat{H}_d^a -$$

$$- \mu\widehat{H}_d^a\widehat{H}_u^b\Big] +$$

$$+ \varepsilon_{ab}h_0\widehat{H}_d^a\widehat{H}_u^b\widehat{\Phi} - \alpha^2\widehat{\Phi} +$$

$$+ \varepsilon_{ab}h_\nu^i\widehat{L}_i^a\widehat{\nu}^c\widehat{H}_u^b + h\widehat{S}\widehat{\nu}^c\widehat{\Phi} +$$

$$+ M_R\widehat{S}\widehat{\nu}^c + \frac{1}{2}M_\Phi\widehat{\Phi}\widehat{\Phi} + \frac{1}{3!}\lambda\widehat{\Phi}^3$$

Solution to the μ problem

Vacuum Expectation Values

$$\langle H_u^0 \rangle \equiv v_u/\sqrt{2}, \quad \langle H_d^0 \rangle \equiv v_d/\sqrt{2},$$

$$\langle \widetilde{\nu}_i \rangle \equiv v_{Li}/\sqrt{2} \quad (i =, 1 \ldots, 3),$$

$$\langle \widetilde{\nu}^c \rangle \equiv v_R/\sqrt{2}, \quad \langle \widetilde{S} \rangle \equiv v_S/\sqrt{2}, \quad \langle \Phi \rangle \equiv v_\Phi/\sqrt{2}$$

$$v_{Li} \ll v_d, v_u \ll v_R, v_S, v_\Phi$$

Neutral Fermion Sector

Non-zero VEVs $\Rightarrow$

$$\Rightarrow \text{ mixing of } \begin{cases} \bullet \text{ neutrinos} \\ \bullet \text{ gauginos} \\ \bullet \text{ higgsinos} \\ \bullet \text{ singlet fermions} \end{cases}$$

In the basis

$$(\psi^0)^T = (\nu_1, \nu_2, \nu_3, -i\lambda', -i\lambda^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \nu^c, S, \widetilde{\Phi})$$

$$\mathcal{L} \supset -\frac{1}{2}(\psi^0)^T \mathbf{M_N} (\psi^0)$$

Neutral Fermion Mass Matrix

$$\mathbf{M_N} = \begin{pmatrix} \vec{\mathbf{0}}_{3\times3} & \mathbf{m}_{\nu\chi^0} & \mathbf{m}_{\nu\nu^c} & \vec{\mathbf{0}}_{3\times1} & \vec{\mathbf{0}}_{3\times1} \\ \mathbf{m}^T_{\nu\chi^0} & \mathbf{M}_{\chi^0} & \mathbf{m}_{\chi^0\nu^c} & \vec{\mathbf{0}}_{4\times1} & \mathbf{m}_{\chi^0\Phi} \\ \mathbf{m}^T_{\nu\nu^c} & \mathbf{m}^T_{\chi^0\nu^c} & 0 & m_{\nu^c S} & m_{\nu^c\Phi} \\ \vec{\mathbf{0}}_{1\times3} & \vec{\mathbf{0}}_{1\times4} & m_{\nu^c S} & 0 & m_{S\Phi} \\ \vec{\mathbf{0}}_{1\times3} & \mathbf{m}^T_{\chi^0\Phi} & m_{\nu^c\Phi} & m_{S\Phi} & M'_{\Phi} \end{pmatrix}$$

Mixing of the 10 neutral fermions

Effective Neutrino Mass Matrix

$$\mathbf{m}^{\mathbf{eff}}_{\nu\nu} = -\mathbf{m_{3\times 7}} \cdot \mathbf{M_7}^{-1} \cdot \mathbf{m_{3\times 7}}^T$$

Matrix elements:

$$(\mathbf{m}^{\mathbf{eff}}_{\nu\nu})_{ij} = F^{\Lambda\Lambda}\Lambda_i\Lambda_j + F^{\epsilon\epsilon}\epsilon_i\epsilon_j + F^{\Lambda\epsilon}(\Lambda_i\epsilon_j + \Lambda_j\epsilon_i)$$

where

$$\Lambda_i \equiv \epsilon_i v_d + \mu v_{Li}$$

$$\epsilon_i \equiv \frac{1}{\sqrt{2}} h_i^\nu v_R$$

Mass Eigenstates

$$m_{\nu_1} = 0$$

$$m_{\nu_2} = \min(|m'_{\nu_2}|, |m'_{\nu_3}|) \quad \Rightarrow \text{SOL scale}$$

$$m_{\nu_3} = \max(|m'_{\nu_2}|, |m'_{\nu_3}|) \quad \Rightarrow \text{ATM scale}$$

where, approximately,

$$m'_{\nu_2} \propto |\vec{\Lambda}|^2$$

$$m'_{\nu_3} \propto |\vec{\epsilon}\,|^2$$

Neutral CP-even Scalar Sector

$$(h'^0)^T = (H_d^{0R}, H_u^{0R}, \widetilde{\nu}_1^R, \widetilde{\nu}_2^R, \widetilde{\nu}_3^R, \widetilde{\nu}^{cR}, \widetilde{S}^R, \Phi^R)$$

$$\mathcal{L} \supset \frac{1}{2}(h'^0)^T \mathbf{M^2_{h^0}} (h'^0)$$

Mass eigenstates are

$$h_i^0 = \mathbf{R}^{\mathbf{h^0}}_{ij} h_j'^0$$

with the following mass eigenvalues

$$\mathrm{diag}(m^2_{h_1}, \ldots, m^2_{h_8}) = \mathbf{R^{h^0}} \mathbf{M^2_{h^0}} (\mathbf{R^{h^0}})^T$$

We define $h \equiv h_1^0$

Neutral CP-odd Scalar Sector

$$(P'^0)^T = (H_d^{0I}, H_u^{0I}, \widetilde{\nu}_1^I, \widetilde{\nu}_2^I, \widetilde{\nu}_3^I, \widetilde{\nu}^{cI}, \widetilde{S}^I, \Phi^I)$$

$$\mathcal{L} \supset \frac{1}{2}(P'^0)^T \mathbf{M^2_{P^0}} (P'^0)$$

Mass eigenstates are P_i^0, where

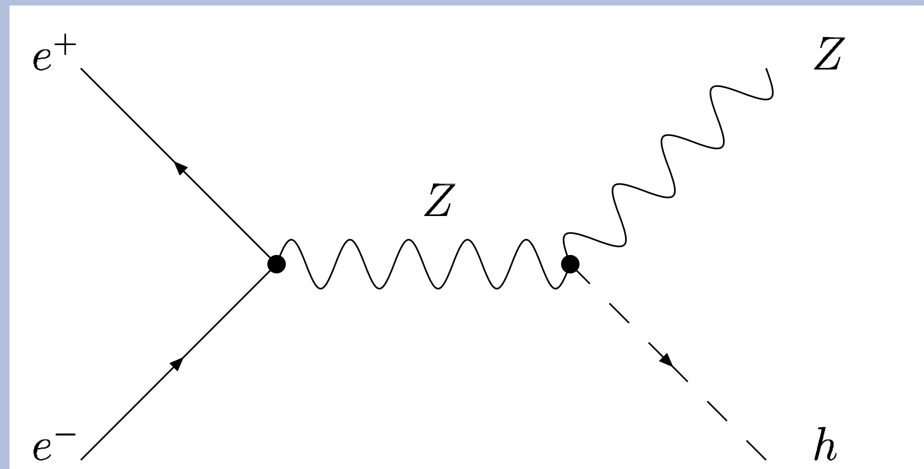
$$(P^0)^T = (J, G^0, A_1, A_2, A_3, A_4, A_5, A_6)$$

$$P_i^0 = \mathbf{R}_{ij}^{\mathbf{P^0}} P_j'^0$$

with the following mass eigenvalues

$$\mathrm{diag}(0, 0, m^2_{A_1}, \ldots, m^2_{A_6}) = \mathbf{R}^{\mathbf{P^0}} \mathbf{M^2_{P^0}} (\mathbf{R}^{\mathbf{P^0}})^T$$

Higgs Production

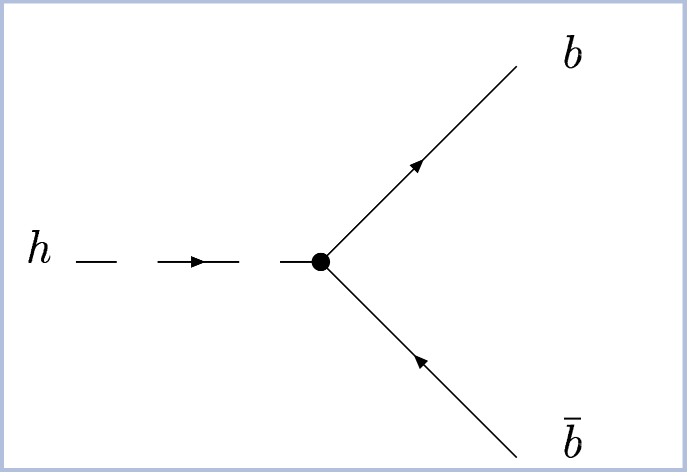


We define the following parameter:

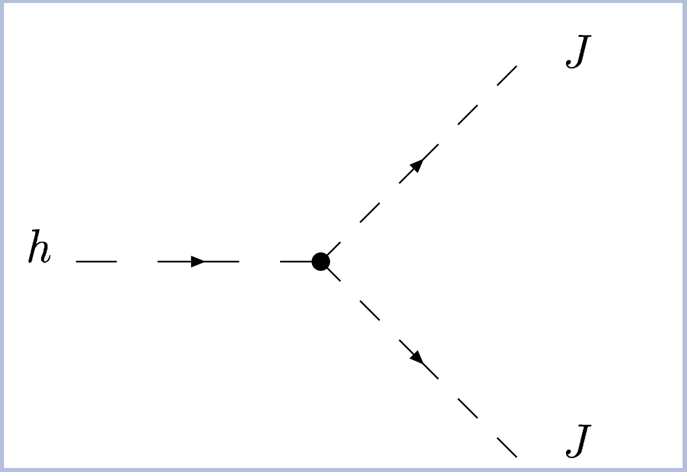
$$\eta \equiv \frac{g_{ZZh}}{g_{ZZh}^{\text{SM}}}$$

- If $\eta \sim 0 \Rightarrow h$ mainly isosinglet
- If $\eta \sim 1 \Rightarrow h$ mainly isodoublet (like MSSM h)

Higgs Decays



Visible Higgs decay



Invisible Higgs decay

Invisible Higgs decay

We define the following parameter:

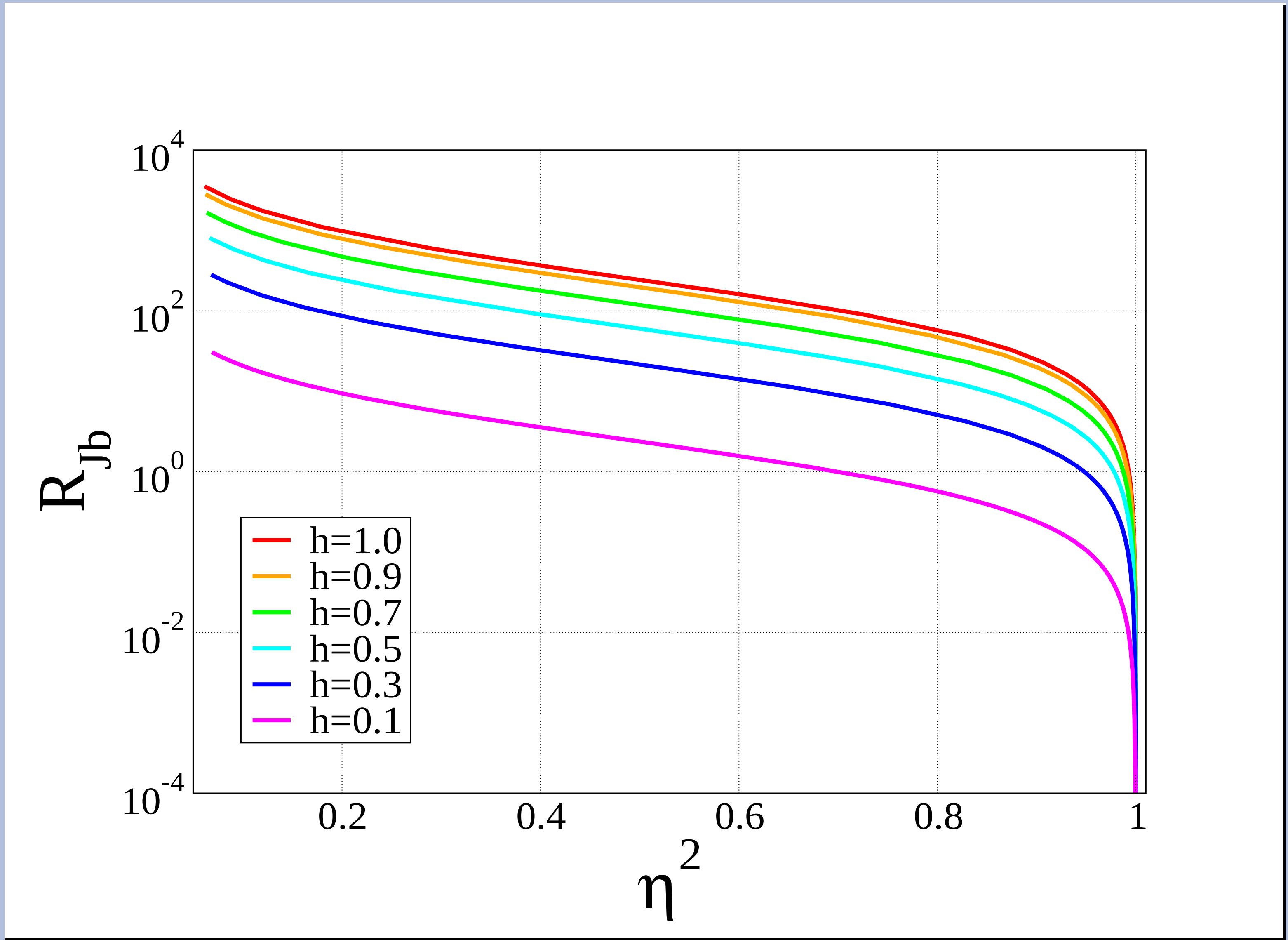
$$R_{Jb} \equiv \frac{\Gamma(h \to JJ)}{\Gamma(h \to b\bar{b})}$$

where

$$\Gamma(h \to b\bar{b}) \propto m_b^2$$

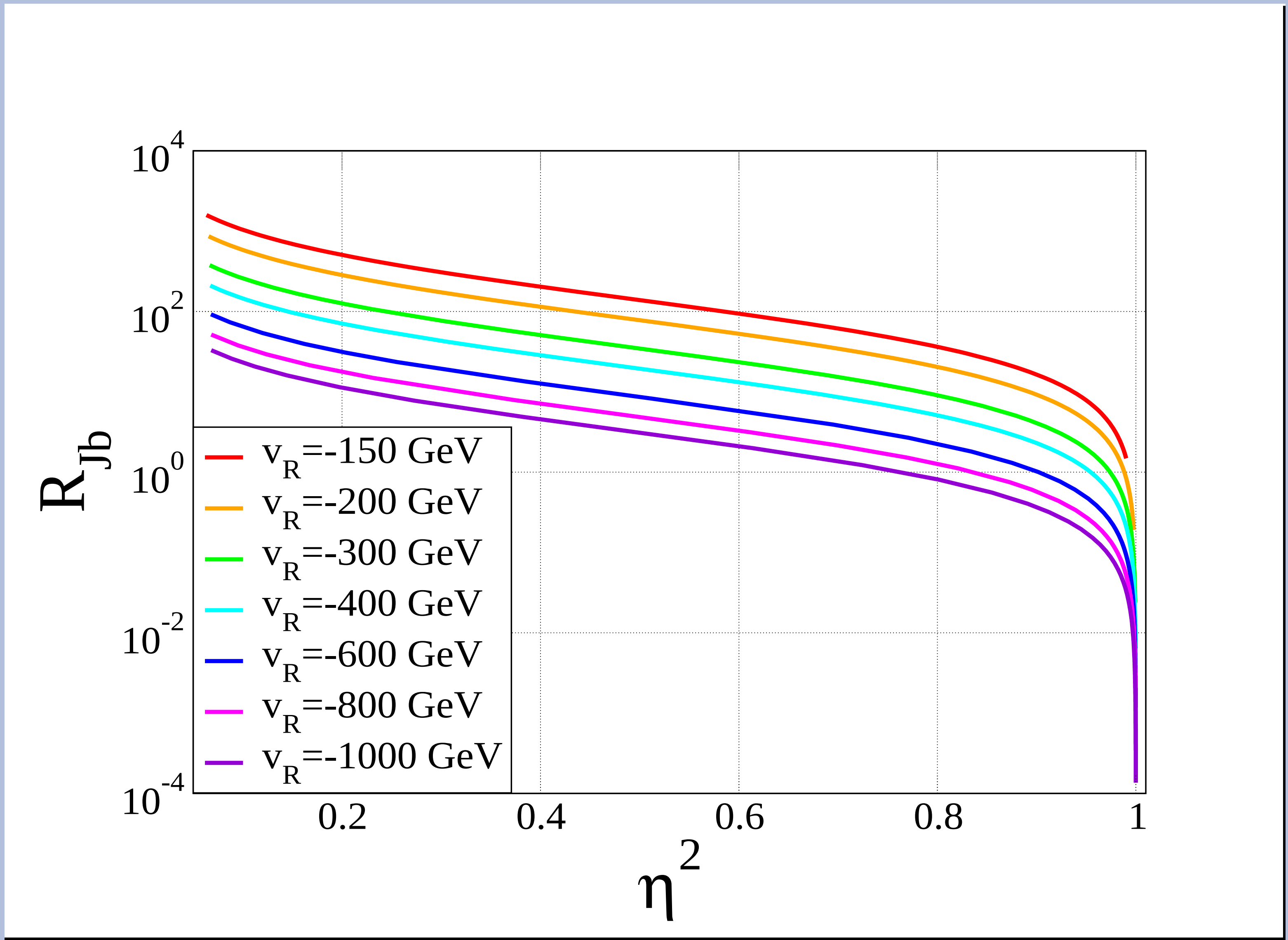
$$\Gamma(h \to JJ) = \frac{g_{hJJ}^2}{32\pi m_h}$$

Numerical Results (general W)



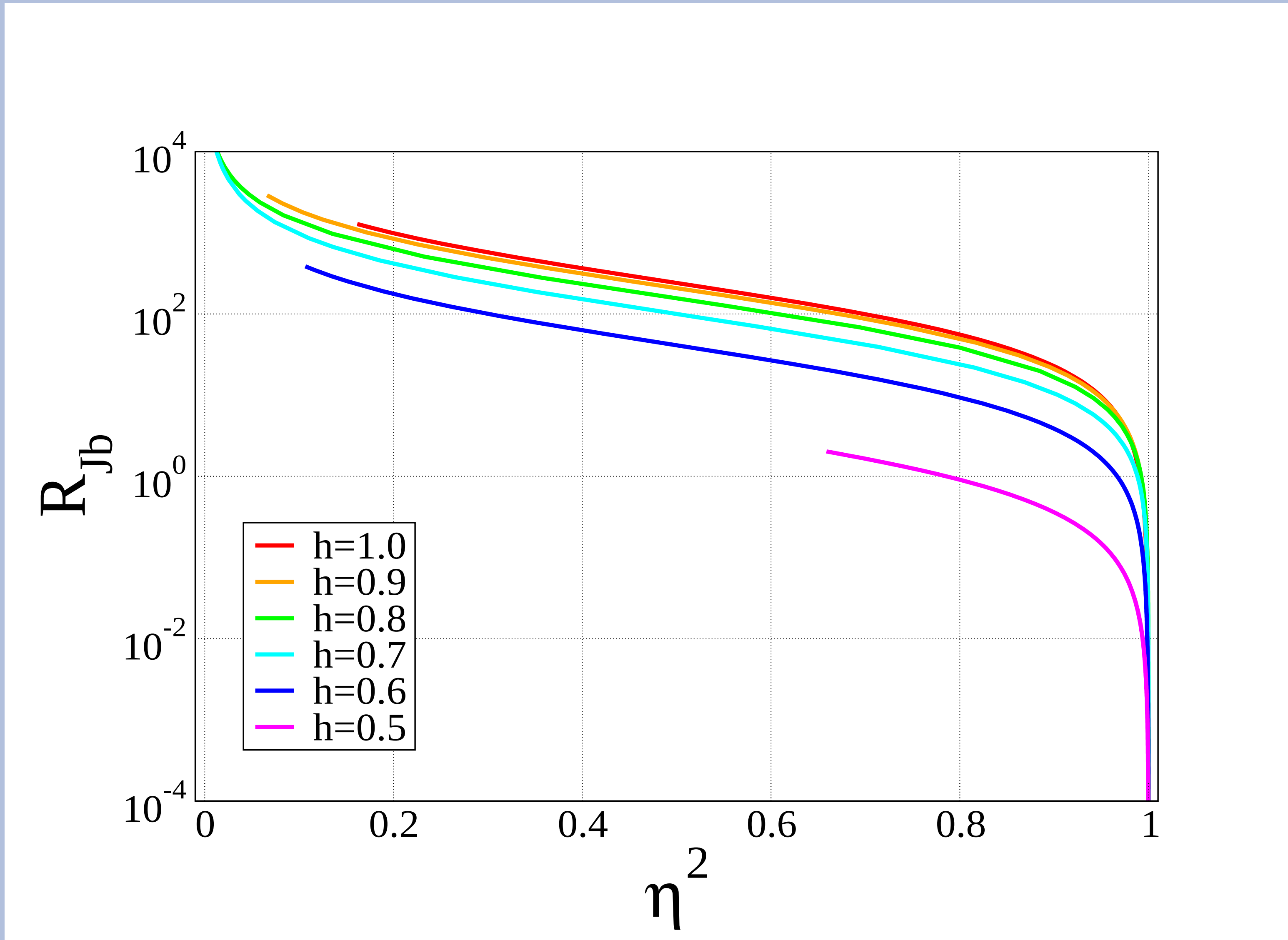
R_{Jb} as a function of η^2 for all the parameters fixed (SPS1a) except v_R, for different values of h

Numerical Results (general W)



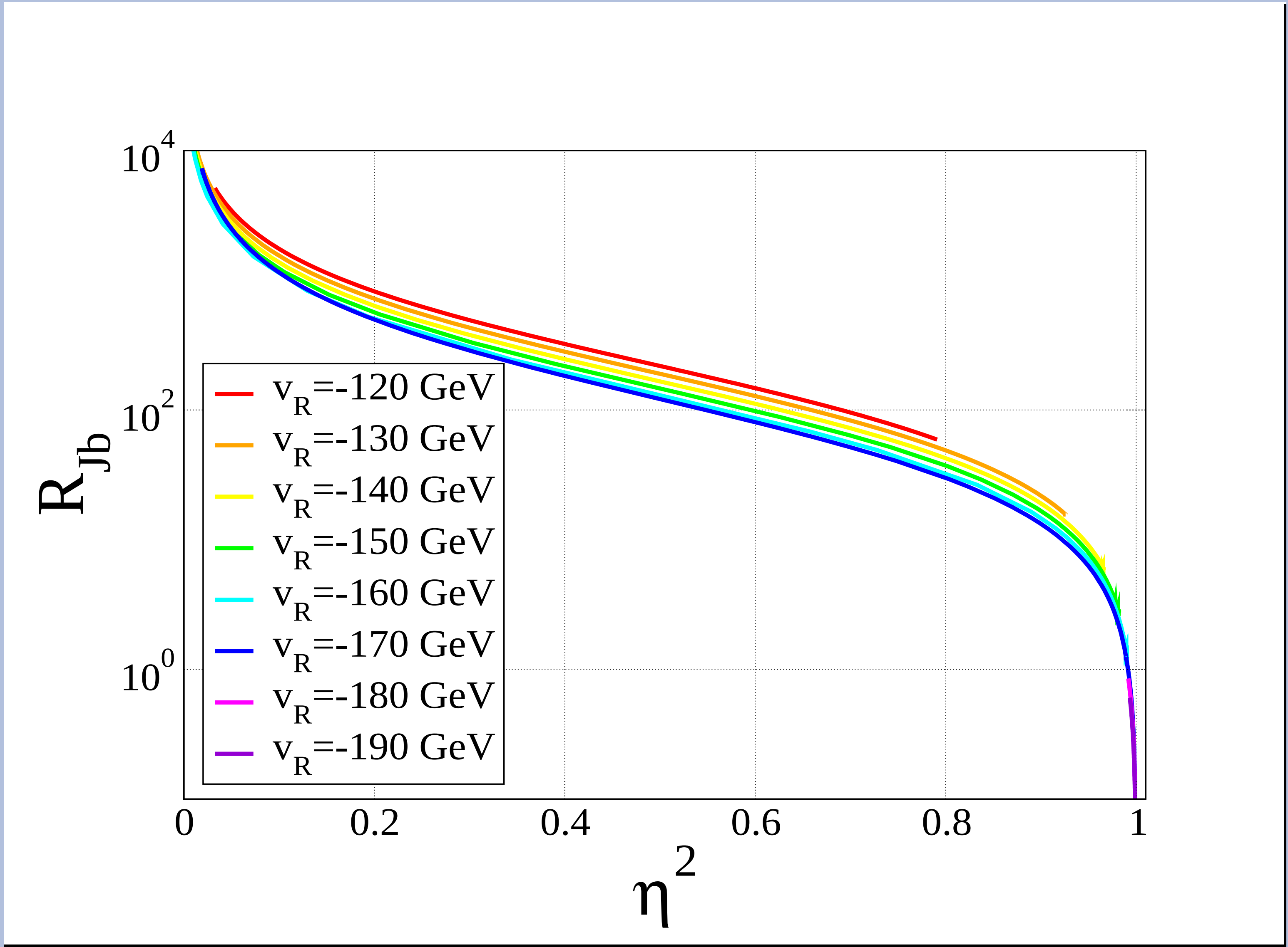
R_{Jb} as a function of η^2 for all the parameters fixed (SPS1a) except h, for different values of v_R

Numerical Results (cubic-only W)



R_{Jb} as a function of η^2 for all the parameters fixed (SPS1a) except v_R, for different values of h

Numerical Results (cubic-only W)



R_{Jb} as a function of η^2 for all the parameters fixed (SPS1a) except h, for different values of v_R

Conclusions

- Experimental data: Neutrino oscillations
  $\Rightarrow$ SM must be extended
- The Spontaneously Broken R-Parity Model explains neutrino properties
- It can give a solution to the μ problem
- Moreover it predicts large invisible Higgs decay (for Higgs mainly isodoublet)

SM+SUSY

- The SUSY extension of the SM allows L and B violation
- The most general superpotential which is renormalizable and invariant under $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$ is

$$W = W_{\mathrm{MSSM}} + W_{\not{L}} + W_{\not{B}}$$

where

$$\begin{aligned}
W_{\mathrm{MSSM}} &= \varepsilon_{ab}\left[h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_u^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_d^a + h_E^{ij}\widehat{L}_i^b\widehat{E}_j\widehat{H}_d^a - \mu\widehat{H}_d^a\widehat{H}_u^b\right] \\
W_{\not{L}} &= \varepsilon_{ab}\left[\epsilon_i\widehat{L}_i^a\widehat{H}_u^b + \lambda_{ijk}\widehat{L}_i^a\widehat{L}_j^b\widehat{E}_k + \lambda'_{ijk}\widehat{L}_i^a\widehat{Q}_j^b\widehat{D}_k\right] \\
W_{\not{B}} &= \lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k
\end{aligned}$$

- $W \Rightarrow$ Proton decay!!

Possible Solutions

- Postulation of L and B conservation
  - Disadvantage respect to the SM
  - They are violated by non-perturbative EW effects

- Postulation of R-parity conservation:

$$P_R = (-1)^{3B+L+2s}$$

  - It can be an exact symmetry
  - Stable LSP $\Rightarrow$ candidate to dark matter
  - $\Rightarrow$ MSSM
  - Neutrinos remain massless

★ Postulation of P_R conservation is not inevitable

Possible Solutions

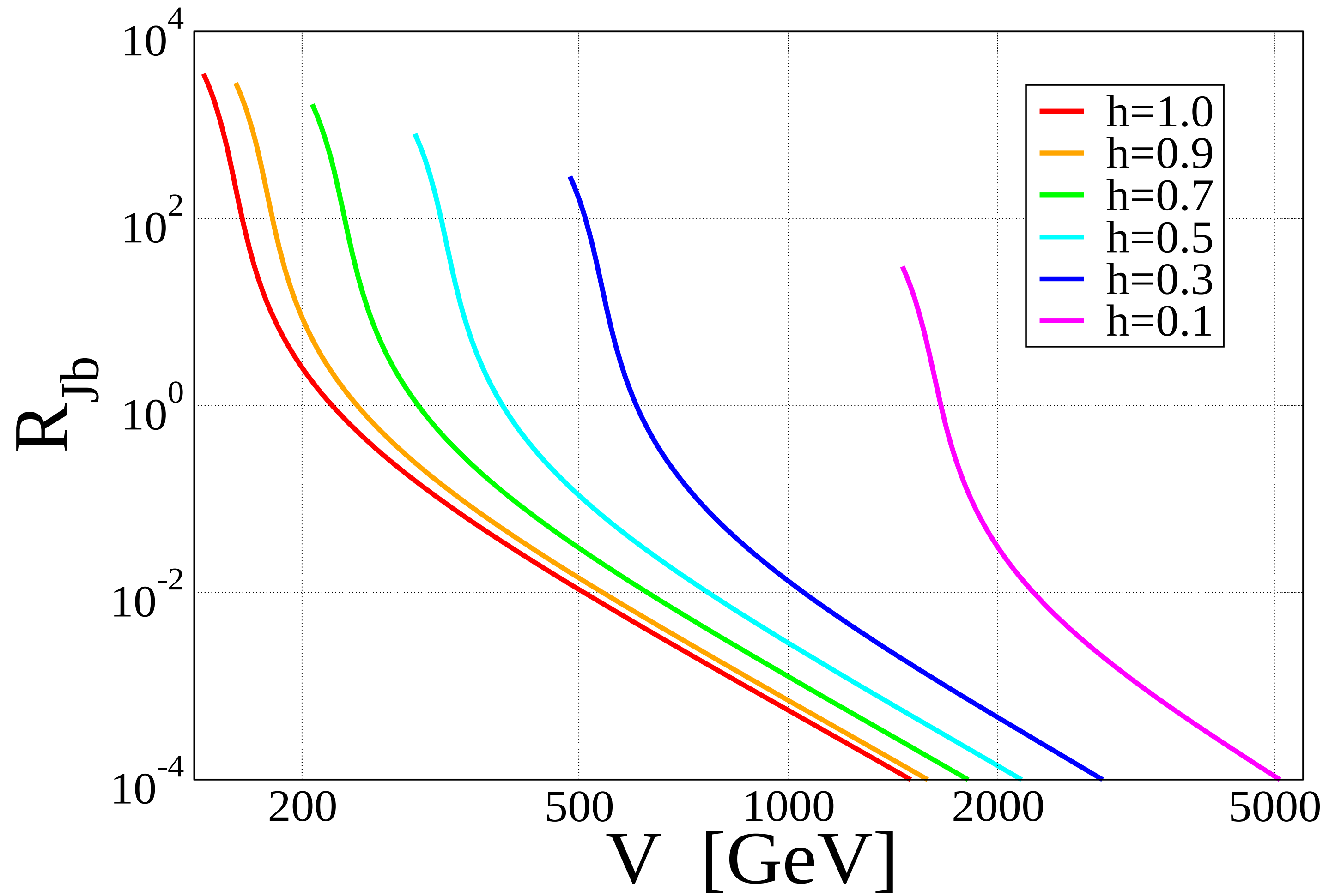
- Postulation of baryonic parity conservation:

$$Z_3^B = e^{\frac{2\pi i}{3}(B-2Y)}$$

- Postulation of P_R as an exact symmetry of the W, but which is spontaneously violated
  $\Rightarrow$ SBRP

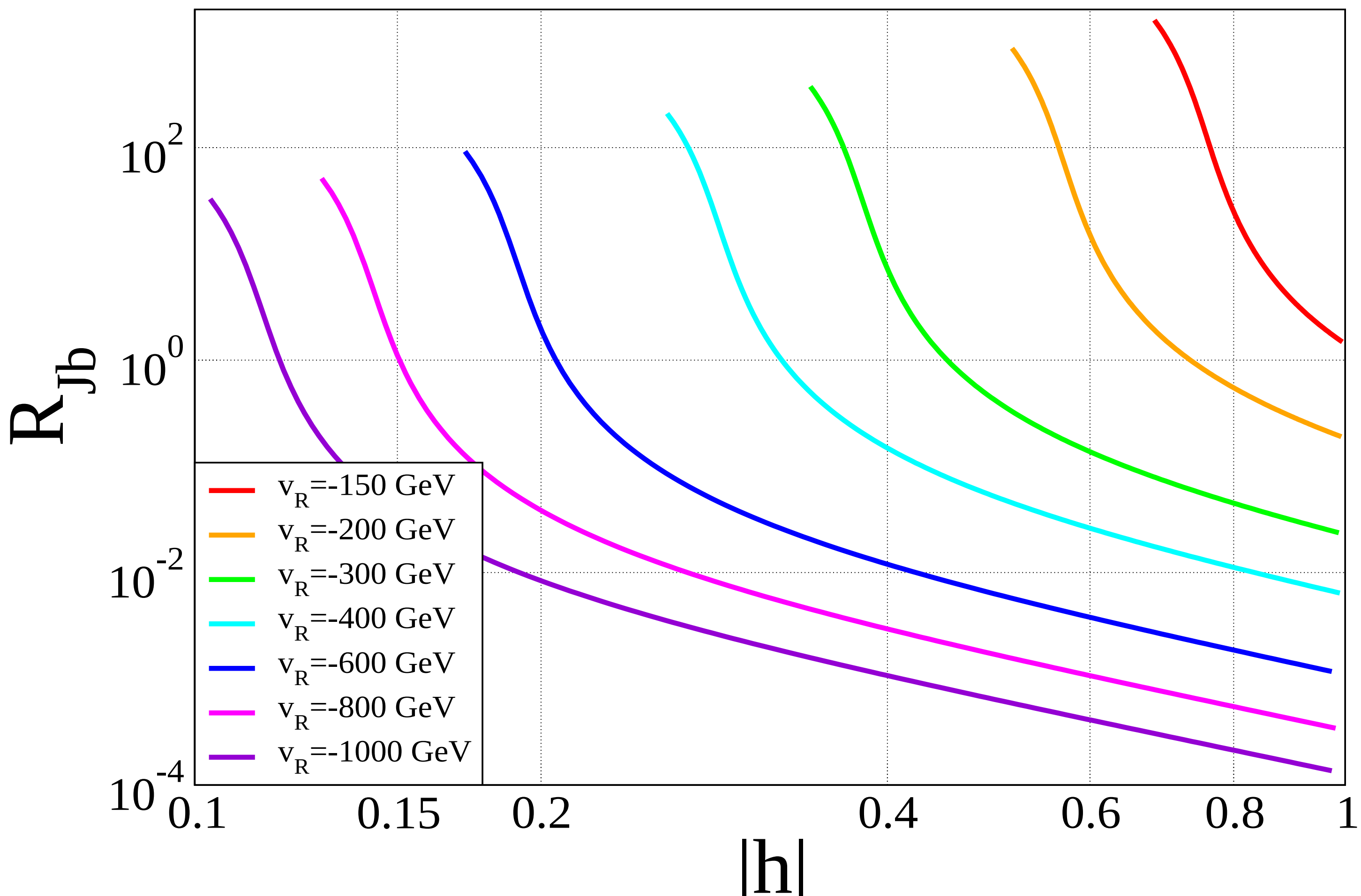
★ Z_3^B and SBRP let L violation
$\Rightarrow$ open door to massive neutrinos

Numerical Results (general W)



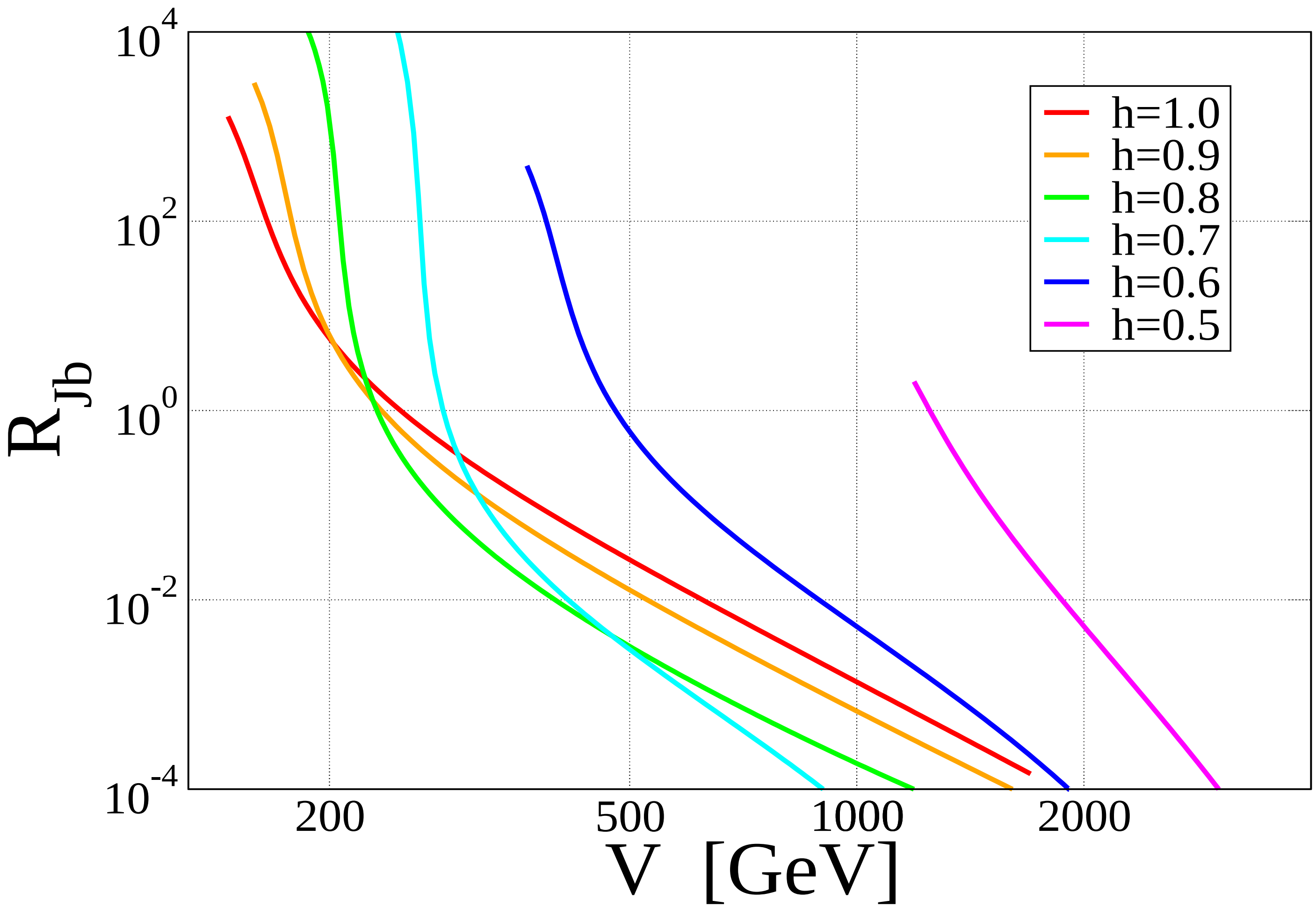
R_{Jb} as a function of $V = \sqrt{v_R^2 + v_S^2}$ for all the parameters fixed (SPS1a), for different values of h.

Numerical Results (general W)



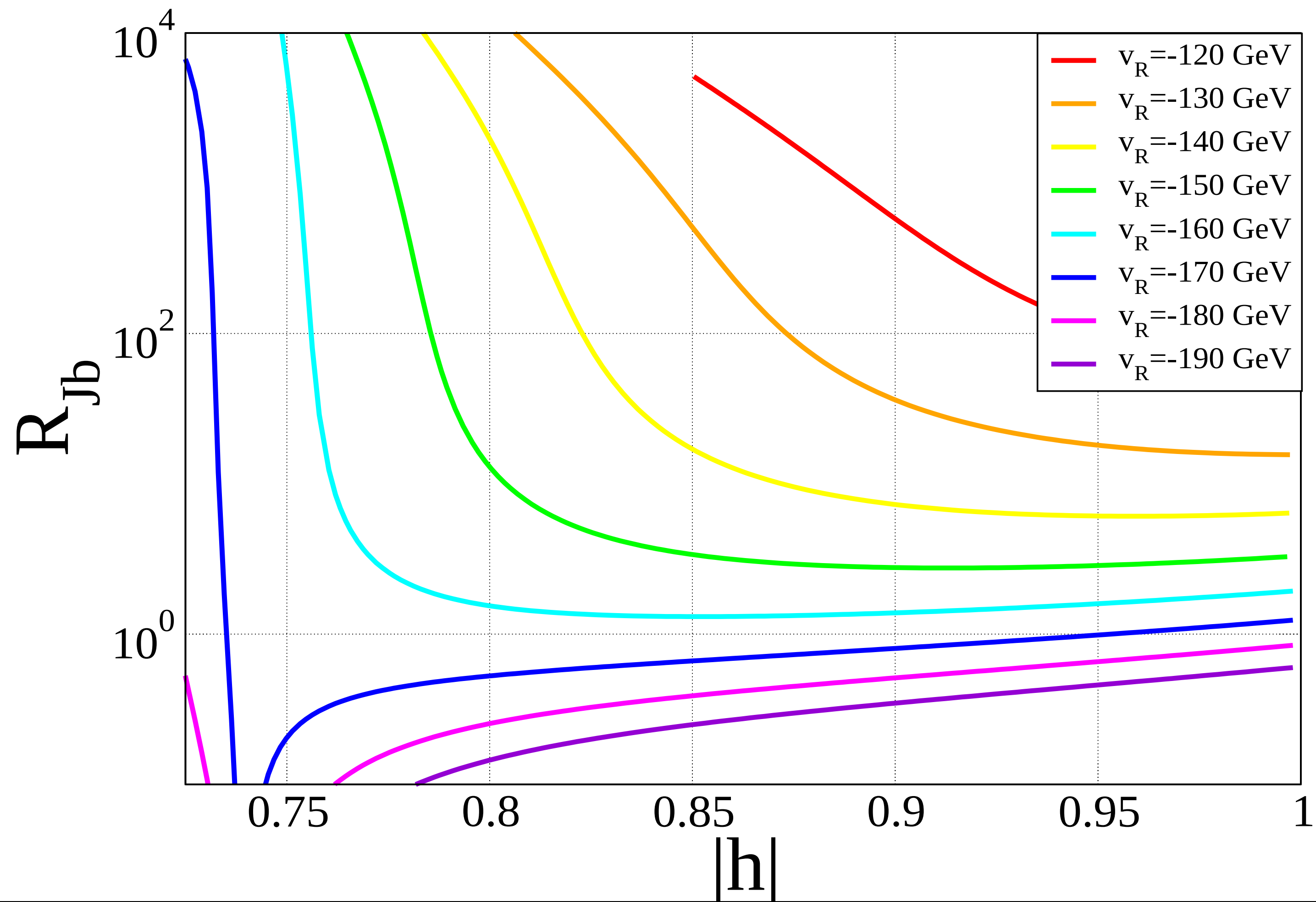
R_{Jb} as a function of $|h|$ for all the parameters fixed (SPS1a), for different values of v_R.

Numerical Results (cubic-only W)



R_{Jb} as a function of $V = \sqrt{v_R^2 + v_S^2}$ for all the parameters fixed (SPS1a), for different values of h.

Numerical Results (cubic-only W)



R_{Jb} as a function of $|h|$ for all the parameters fixed (SPS1a), for different values of v_R.

Motivation: Neutrino Oscillations

- Atmospheric Neutrinos

$$\Delta m^2_{\mathrm{ATM}} = 2.2 \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(\theta_{\mathrm{ATM}}) = 0.50$$

- Solar Neutrinos

$$\Delta m^2_{\mathrm{SOL}} = 8.1 \times 10^{-5}\ \mathrm{eV}^2$$

$$\tan^2(\theta_{\mathrm{SOL}}) = 0.41$$

- Reactor Neutrinos

$$\sin^2(\theta_{\mathrm{CHOOZ}}) \leq 0.022$$