Higgs Boson Sector in Models with Spontaneously Broken R-Parity

Jorge C. Romão

Instituto Superior Técnico, Departamento de Física & CFTP

A. Rovisco Pais 1, 1049-001 Lisboa, Portugal

September 18^{th}, 2009

Summary

- Motivation
- The Model
- The Neutrino Mass Matrix
- The Scalars Mass Matrices and Spectra
- Higgs Boson Production and Decay
- Conclusions

Collaborators: J.W.F. Valle, M. Hirsch, A. Villanova del Moral

[Phys. Rev. D70 (2004) 073012 & Phys. Rev. D73 (2006) 055007.]

The Origin of Mass

- In the Standard Model all masses arise as a result of the spontaneous breaking of the SU(2) $\otimes$ U(1) gauge symmetry. This implies the existence of an elementary Higgs boson.
- Stabilizing the mass of the Higgs requires new physics. SUSY is the best candidate.
- Smallness of neutrino masses:
  - Seesaw mechanism
  - Radiative Generation
    - In such models the physics of neutrino mass is characterized by low scales, potentially affecting the decay properties of the Higgs boson.
    - This is especially so if neutrino masses arise due to the spontaneous violation of ungauged lepton number.
    - In this broad class of models the Higgs boson will have an important decay channel into the singlet Goldstone boson (called Majoron) associated to lepton number violation,

$$\boxed{h \to JJ}$$

Broken R–Parity Models

- Here we focus on the specific case of low-energy supersymmetry with spontaneous violation of R–parity, as the origin of neutrino mass.

$$R_P = (-1)^{2J+3B+L}$$

- In this case one of the neutral CP-odd scalars is identified with the majoron. In contrast with the seesaw majoron, ours is characterized by a small scale (TeV-like) and carries only one unit of lepton number.

Broken R–Parity Models ...

Relation to Bilinear R–Parity Violation Model

- This scheme leads to the Bilinear R–parity Violation (BRpV) model, the simplest effective description of R-parity violation.

  [M. A. Diaz, JCR, J.W.F. Valle, Nucl.Phys. B524(1998)23]

- The BRpV model accounts for the observed pattern of neutrino masses and mixings.

  [M.Hirsch, M. A. Diaz, JCR, J.W.F. Valle, Phys. Rev D62 (2000),113008]

- It makes predictions for the decay branching ratios of the lightest supersymmetric particle from the current measurements of neutrino mixing angles. So it can be tested at accelerators.

  [W.Porod, M. Hirsch, JCR, J.W.F. Valle, Phys. Rev D63 (2001),115004]

Broken R–Parity Models ...

Spontaneous Broken R-Parity Model

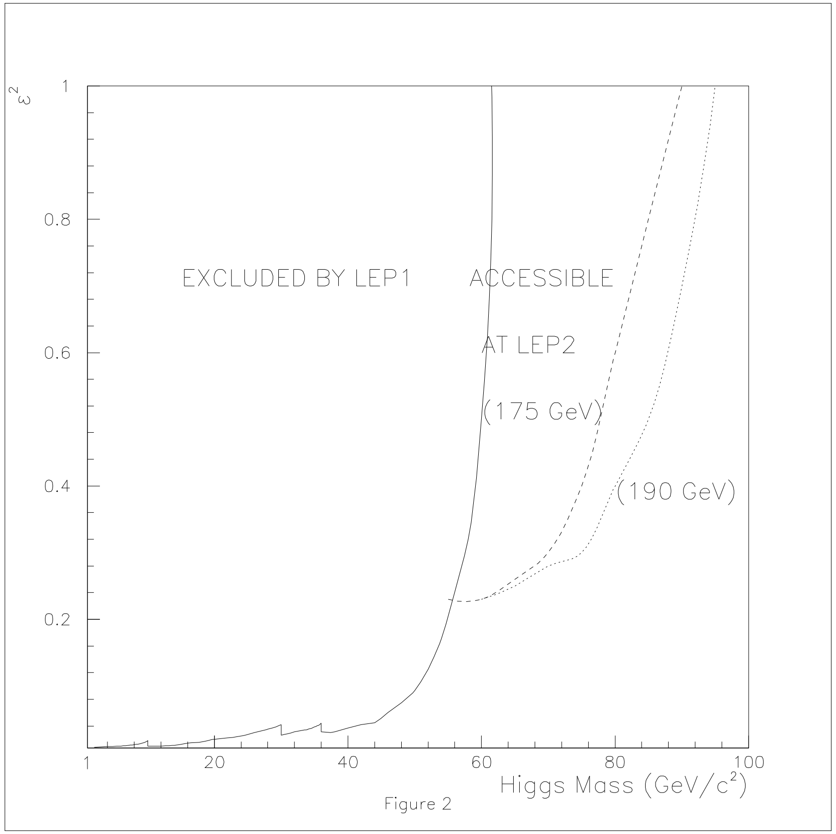
- Long ago

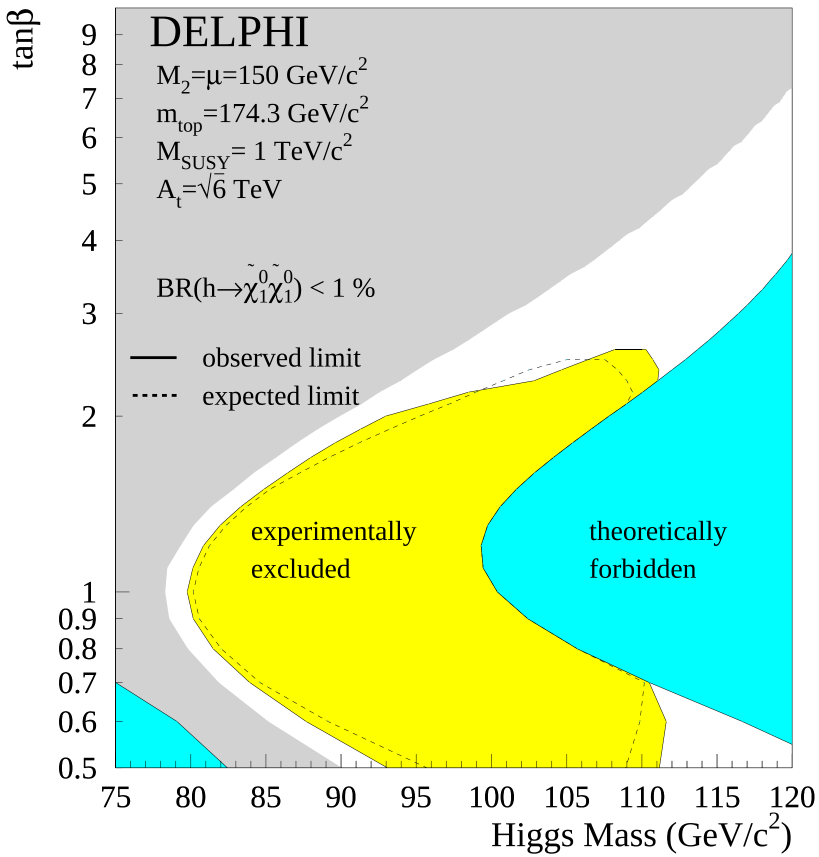
  [JCR, C.A. Santos, J.W.F. Valle, Phys. Lett. B288 (1992) 311]

  [JCR, F. de Campos, J.W.F. Valle, Phys. Lett. B292 (1992) 329]

  it was noted that the spontaneously broken R–parity (SBRP) model leads to the possibility of invisibly decaying Higgs bosons.
- At the time the upper limits on neutrino masses obtained from accelerators were very large, for instance the limit on m_{ν_τ} was a few MeV.
- In this work we reanalyse this issue taking into account the small masses indicated by current neutrino oscillation data. We focus on the lowest-lying neutral CP-even scalars bosons of the model, but also consider the lightest CP-odd scalar boson.

Invisible Decays: The Exp. Results





[A. Lopez-Fernandez, F. de Campos, JCR and J.W.F. Valle, Phys. Lett. B312 (1993) 240]

[DELPHI Collaboration, Eur. Phys. J. C25 (2002) 113]

The Model

- The most general superpotential is

$$\boxed{\begin{aligned}\mathcal{W} =& \varepsilon_{ab}\Big(h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_u^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_d^a + h_E^{ij}\widehat{L}_i^b\widehat{E}_j\widehat{H}_d^a \\ &+ h_\nu^{ij}\widehat{L}_i^a\widehat{\nu}_j^c\widehat{H}_u^b - \hat{\mu}\widehat{H}_d^a\widehat{H}_u^b - (h_0\widehat{H}_d^a\widehat{H}_u^b + \delta^2)\widehat{\Phi}\Big) \\ &+ h^{ij}\widehat{\Phi}\widehat{\nu}_i^c\widehat{S}_j + M_R^{ij}\widehat{\nu}_i^c\widehat{S}_j + \frac{1}{2}M_\Phi\widehat{\Phi}^2 + \frac{\lambda}{3!}\widehat{\Phi}^3\end{aligned}}$$

- The SU(2) ⊗ U(1) singlet superfields $(\nu^c{}_i, S_i, \Phi)$ carry a conserved lepton number assigned as $(-1, 1, 0)$.

The Model ...

- The singlets are essential in order to drive the EW symmetries and the spontaneous violation of $\boxed{R_P}$ in a phenomenologically consistent way.
- Like all other Yukawa couplings h_U, h_D, h_E we assume that $\boxed{h_\nu}$ is an arbitrary non-symmetric complex matrix in generation space.
- We take the simplest case with just one pair of lepton–number–carrying SU(2) $\otimes$ U(1) singlet superfields, $\widehat{\nu}^c$ and $\widehat{S}$.

$$\boxed{h_{ij} \longrightarrow h} \text{ and } \boxed{h_\nu^{ij} \longrightarrow h_\nu^i}$$

The full scalar potential is:

$$
\begin{aligned}
V =& |h\Phi\tilde{S} + h_\nu^i \tilde{\nu}_i H_u + M_R \tilde{S}|^2 + |h_0 \Phi H_u + \hat{\mu} H_u|^2 \\
&+ |h\Phi\tilde{\nu^c} + M_R \tilde{\nu^c}|^2 + |-h_0\Phi H_d - \hat{\mu} H_d + h_\nu^i \tilde{\nu}_i \tilde{\nu^c}|^2 \\
&+ |-h_0 H_u H_d + h\tilde{\nu^c}\tilde{S} - \delta^2 + M_\Phi \Phi + \frac{\lambda}{2}\Phi^2|^2 + \sum_{i=1}^{3} |h_\nu^i \tilde{\nu^c} H_u|^2 \\
&+ \Big[A_h h \Phi \tilde{\nu^c} \tilde{S} - A_{h_0} h_0 \Phi H_u H_d + A_{h_\nu} h_\nu^i \tilde{\nu}_i H_u \tilde{\nu^c} - B\hat{\mu} H_u H_d \\
&- C_\delta \delta^2 \Phi + B_{M_R} M_R \tilde{\nu^c}\tilde{S} + \frac{1}{2} B_{M_\Phi} M_\Phi \Phi^2 + \frac{1}{3!} A_\lambda \lambda \Phi^3 + h.c.\Big] \\
&+ \sum_\alpha \tilde{m}_\alpha^2 |z_\alpha|^2 + \frac{1}{8}(g^2 + g'^2)\Big(|H_u|^2 - |H_d|^2 - \sum_{i=1}^{3} |\tilde{\nu}_i|^2\Big)^2
\end{aligned}
$$

The Model: Symmetry Breaking

Pattern of spontaneous symmetry breaking

- The spontaneous breaking of R_P is driven by nonzero vevs for the scalar neutrinos. The scale characterizing R_P breaking is set by the isosinglet vevs

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

- We also have very small left-handed sneutrino vacuum expectation values

$$\langle \tilde{\nu}_{Li} \rangle = \frac{v_{Li}}{\sqrt{2}}$$

The Model: Symmetry Breaking

- The electroweak breaking is driven by

$$\langle H_u \rangle = \frac{v_u}{\sqrt{2}}, \quad \langle H_d \rangle = \frac{v_d}{\sqrt{2}}$$

with $v^2 = v_u^2 + v_d^2 + \sum_i v_{Li}^2$ and $m_W^2 = \frac{g^2 v^2}{4}$

- The spontaneous breaking of R–parity also entails the spontaneous violation of total lepton number. This implies that the Majoron

$$\boxed{J = Im\left[\frac{v_L^2}{V v^2}(v_u H_u - v_d H_d) + \sum_i \frac{v_{Li}}{V}\tilde{\nu}_i + \frac{v_S}{V} S - \frac{v_R}{V}\tilde{\nu^c}\right]}$$

remains massless, as it is the Nambu-Goldstone boson associated to the breaking of lepton number.

Neutrino-Neutralino-Singlino mass matrix

In the basis $(-i\lambda', -i\lambda^3, \tilde{H}_d, \tilde{H}_u, \nu_e, \nu_\mu, \nu_\tau, \nu^c, S, \tilde{\Phi})$

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

10×10 matrix

Neutrino-Neutralino-Singlino mass matrix

$\mathbf{M}_{\chi^0}$ is the MSSM neutralino mass matrix:

$$\mathbf{M}_{\chi^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & +\frac{1}{2}g'v_u \\ 0 & M_2 & +\frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & +\frac{1}{2}gv_d & 0 & -\mu \\ +\frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{pmatrix}$$

$$\mu = \hat{\mu} + h_0 v_\Phi/\sqrt{2}$$

$$\mathbf{m}^{\mathbf{T}}_{\chi^0\nu} = \begin{pmatrix} -\frac{1}{2}g'v_{Le} & \frac{1}{2}gv_{Le} & 0 & \epsilon_e \\ -\frac{1}{2}g'v_{L\mu} & \frac{1}{2}gv_{L\mu} & 0 & \epsilon_\mu \\ -\frac{1}{2}g'v_{L\tau} & \frac{1}{2}gv_{L\tau} & 0 & \epsilon_\tau \end{pmatrix}$$

$$\epsilon_i = \frac{1}{\sqrt{2}} h_\nu^i v_R$$

$$(\mathbf{m_D})_i = \frac{1}{\sqrt{2}} h_\nu^i v_u$$

and so on ...

From the full neutral fermion mass matrix, one calculates the effective 3×3 neutrino mass matrix $(\mathbf{m}_{\nu\nu}^{\text{eff}})$ as

$$\boxed{\mathbf{m}_{\nu\nu}^{\text{eff}} = -\mathbf{M}_{\mathbf{D}}^{\mathbf{T}} \mathbf{M}_{\mathbf{H}}^{-\mathbf{1}} \mathbf{M}_{\mathbf{D}}}$$

where $\mathbf{M}_{\mathbf{H}}$ is the 7×7 matrix of all other neutral fermion states, and the 3×7 matrix $\mathbf{m}_{\mathbf{D}}^{\mathbf{T}}$ is given as

$$\mathbf{M}_{\mathbf{D}}^{\mathbf{T}} = \begin{pmatrix} \mathbf{m}_{\chi^0\nu}^{\mathbf{T}} & \mathbf{m}_{\mathbf{D}} & \mathbf{0} & \mathbf{0} \end{pmatrix}$$

$\mathbf{M}_{\mathbf{H}}$ is too long to be given explicitly here.

The effective neutrino mass matrix

- The effective neutrino mass matrix can be cast into a very simple form

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

- The effective bilinear R–parity violating parameters are

$$\epsilon_i = h_\nu^i \frac{v_R}{\sqrt{2}} \qquad \text{and} \qquad \Lambda_i = \epsilon_i v_d + \mu v_{L_i}$$

Here the parameter μ is

$$\mu = \hat{\mu} + h_0 \frac{v_\Phi}{\sqrt{2}} \,, \tag{1}$$

- This equation resembles very closely the result for the BRpV model once the dominant 1-loop corrections are taken into account.

Neutrino Masses: Some comments

- The tree-level result of the explicit bilinear model can be recovered in the limit $M_R, M_\Phi \to \infty$.

$$\boxed{a = \frac{g^2 M_1 + g'^2 M_2}{4 \mathrm{Det} \mathbf{M}_{\chi^0}}, \quad b = 0, \quad c = 0}$$

In this limit only one non-zero neutrino mass remains.

- The relative size of the coefficient c compared to the corresponding 1-loop coefficient dictates if the 1-loop corrections or the contribution from the singlet fields are more important.

- Both extremes can be realized in our model. Large branching ratios of the Higgs into invisible final states require sizeable values of h and h_0. Then the "singlino" contribution dominates.

The Neutral Scalar Mass Matrix

The 8×8 scalar mass matrix is a symmetric matrix that in the basis $(H_d^0, H_u^0, \tilde{\nu}_i, \Phi, \tilde{S}, \tilde{\nu}^c)$ takes the form

$$M^{S^2} = \begin{bmatrix} M^{S^2}_{HH} & M^{S^2}_{H\widetilde{L}} & M^{S^2}_{HS} \\ M^{S^2\,T}_{H\widetilde{L}} & M^{S^2}_{\widetilde{L}\widetilde{L}} & M^{S^2}_{\widetilde{L}S} \\ M^{S^2\,T}_{HS} & M^{S^2\,T}_{\widetilde{L}S} & M^{S^2}_{SS} \end{bmatrix}$$

2×3

2×2

3×3

The pseudo–scalar mass matrix has a similar form.

Two Massless Goldstone Bosons

- In the CP-odd sector we found both the Goldstone "eaten" by the Z^0 as well as the Goldstone boson corresponding to the SBRP, the Majoron J.
- In the basis $A'_0 = (H_d^{0I}, H_u^{0I}, \tilde{\nu}^{1I}, \tilde{\nu}^{2I}, \tilde{\nu}^{3I}, \Phi^I, \tilde{S}^I, \tilde{\nu}^{cI})$

$$\boxed{G_0 = (N_0\, v_d, -N_0\, v_u, N_0\, v_{L1}, N_0\, v_{L2}, N_0\, v_{L3}, 0, 0, 0)}$$

$$\boxed{J = (-N_1 v_d, N_1 v_u, N_2 v_{L1}, N_2 v_{L2}, N_2 v_{L3}, 0, N_3 v_S, -N_3 v_R)}$$

where the N_i are normalization constants.

- It can easily be checked that they are orthogonal

$$G_0 \cdot J = 0$$

Approximate Eigenvalues

- Since these mass matrices are too complicated for analytic diagonalization, we will solve the exact eigensystems numerically. However, it is useful to consider some simplifying approximations. This allows us to gain some insight into the nature of the spectra.
- We introduce the naming convention:

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

- In the region of parameters where the model accounts for the observed neutrino masses we must have that $\epsilon_i = h_\nu^i v_R/\sqrt{2}$ is necessarily a small number and therefore $h_\nu^i \ll 1$. In this limit $S_{\tilde{\nu}_i}$ and $P_{\tilde{\nu}_i}$ decouple.
- Recall the pseudoscalar mass matrix

$$\boldsymbol{M^{P^2}} = \begin{bmatrix} \boldsymbol{M^{P^2}_{HH}} & \boldsymbol{M^{P^2}_{H\tilde{L}}} & \boldsymbol{M^{P^2}_{HS}} \\ \boldsymbol{M^{P^2\,\mathrm{T}}_{H\tilde{L}}} & \boldsymbol{M^{P^2}_{\tilde{L}\tilde{L}}} & \boldsymbol{M^{P^2}_{\tilde{L}S}} \\ \boldsymbol{M^{P^2\,\mathrm{T}}_{HS}} & \boldsymbol{M^{P^2\,\mathrm{T}}_{\tilde{L}S}} & \boldsymbol{M^{P^2}_{SS}} \end{bmatrix}$$

CP-odd States: G_0 and P_{A^0}

- Neglecting terms proportional to h_ν^i

$$\boldsymbol{M^{P^2}_{HH}} = \begin{bmatrix} \Omega \frac{v_u}{v_d} & \Omega \\ \Omega & \Omega \frac{v_d}{v_u} \end{bmatrix}$$

$$\boxed{\Omega = B\hat{\mu} - \delta^2 h_0 + \frac{\lambda}{4} h_0 v_\Phi^2 + \frac{1}{2} h h_0 v_R v_S + \frac{\sqrt{2}}{2} A_{h_0} h_0 v_\Phi + \frac{\sqrt{2}}{2} h_0 M_\Phi v_\Phi}$$

- The eigenvalues are

$$\boxed{m^2_{1,2} = \left(0, \Omega(\frac{v_u}{v_d} + \frac{v_d}{v_u})\right)}$$

identified as the Goldstone boson, G^0, and the other state resembling the pseudo-scalar Higgs A^0 of the MSSM, which we call P_{A^0}, with

$$\boxed{m^2_{A^0} = \frac{2\Omega}{\sin 2\beta}}$$

CP-odd States: J, $P_{J_\perp}$ and P_Φ

- The sub-matrix $\boldsymbol{M^{P^2}_{SS}}$, in the limit $h^i_\nu = 0$ is,

$$\boldsymbol{M^{P^2}_{SS}} = \begin{bmatrix} M^{P^2}_{SS_{11}} & M^{P^2}_{SS_{12}} & M^{P^2}_{SS_{13}} \\ M^{P^2}_{SS_{12}} & -\Gamma\frac{v_R}{v_S} & -\Gamma \\ M^{P^2}_{SS_{13}} & -\Gamma & -\Gamma\frac{v_S}{v_R} \end{bmatrix},$$

$$\boxed{\Gamma = B_{M_R} M_R - \delta^2 h + \frac{1}{4} h\lambda v_\Phi^2 - \frac{1}{2} h h_0 v_u v_d + \frac{\sqrt{2}}{2} h \left(A_h + M_\Phi\right) v_\Phi \,.}$$

- We have one zero eigenvalue, identified with the majoron, J, and two non-zero eigenvalues.

- If $M^{P^2}_{SS_{12}}, M^{P^2}_{SS_{13}} \ll M^{P^2}_{SS_{11}} + \Gamma$ then the eigenvalues are approximately

$$\boxed{\begin{aligned} m^2_{1,2,3} = \Bigg(0, \quad - \quad & \Gamma\Big(\frac{v_R}{v_S} + \frac{v_S}{v_R}\Big) - \frac{1}{2}\frac{h^2(A_h - \hat{M}_\Phi)^2 v_R^2 v_S^2}{M^{P^2}_{SS_{11}} v_R v_S + \Gamma(v_R^2 + v_S^2)} + \cdots, \\ & M^{P^2}_{SS_{11}} + \frac{1}{2}\frac{h^2(A_h - \hat{M}_\Phi)^2 v_R v_S (v_R^2 + v_S^2)}{M^{P^2}_{SS_{11}} v_R v_S + \Gamma(v_R^2 + v_S^2)} + \cdots \Bigg) \end{aligned}}$$

CP-even States: S_{h^0}, S_{H^0}, S_J, $S_{J_\perp}$ and S_Φ

- Consider the scalar sector of the model,

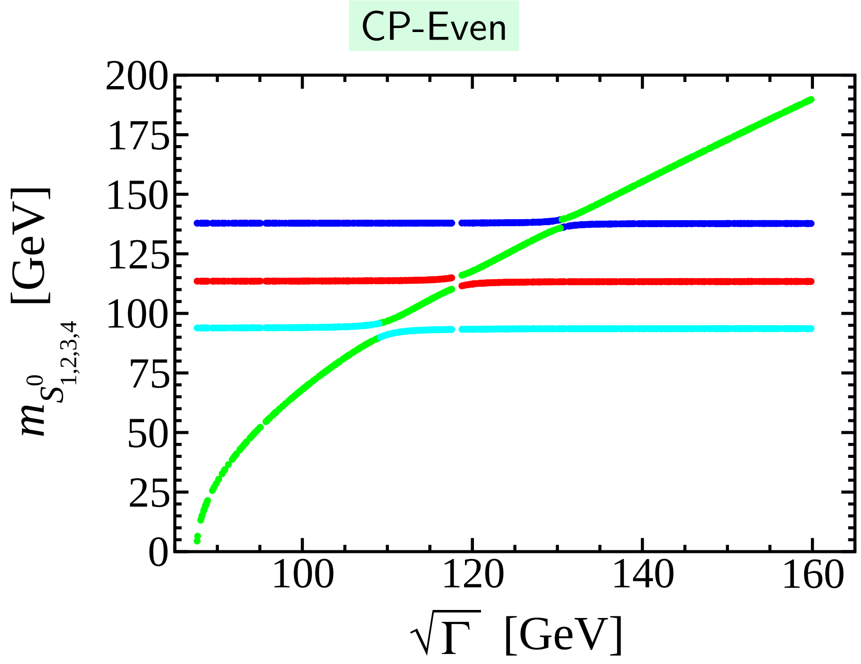
$$\boldsymbol{M^{S^2}} = \begin{bmatrix} \boldsymbol{M^{S^2}_{HH}} & \boldsymbol{M^{S^2}_{H\widetilde{L}}} & \boldsymbol{M^{S^2}_{HS}} \\ \boldsymbol{M^{S^2}_{H\widetilde{L}}}^{\mathrm{T}} & \boldsymbol{M^{S^2}_{\widetilde{L}\widetilde{L}}} & \boldsymbol{M^{S^2}_{\widetilde{L}S}} \\ \boldsymbol{M^{S^2}_{HS}}^{\mathrm{T}} & \boldsymbol{M^{S^2}_{\widetilde{L}S}}^{\mathrm{T}} & \boldsymbol{M^{S^2}_{SS}} \end{bmatrix}$$

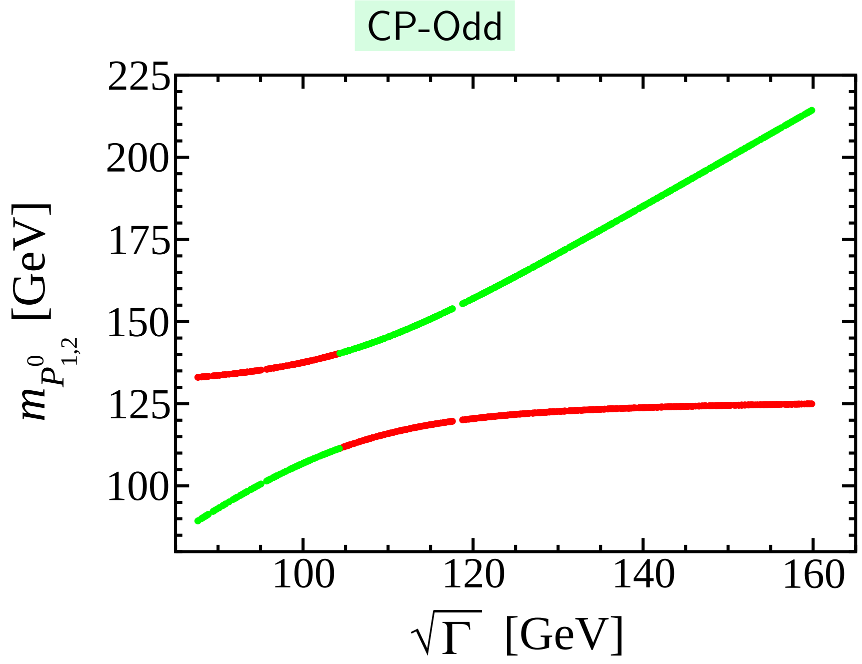
$\boldsymbol{M^{S^2}_{HH}}$ contains two eigenvalues which, in the limit of zero mixing, would be the MSSM states h^0 and H^0. These states are S_{h^0} and S_{H^0}.

- The sub-matrix $\boldsymbol{M^{S^2}_{SS}}$ has three non-zero eigenvalues. One can find an approximate analytic expression for them in the limit that the state S_Φ is much heavier than the remaining two eigenstates (called S_J and $S_{J_\perp}$).

$$\boxed{m^2_{1,2} = \left(2h^2 \frac{v_R^2 v_S^2}{(v_R^2+v_S^2)} + \cdots, -\Gamma\left(\frac{v_R}{v_S}+\frac{v_S}{v_R}\right) - 2h^2 \frac{v_R^2 v_S^2}{(v_R^2+v_S^2)} + \cdots\right)}$$

Example of Spectra





Typical CP-even (left) and CP-odd (right) Higgs masses as function of the parameter Γ. In this example there are four light CP-even states and two light massive CP-odd states (plus two massless states, G^0 and J, not shown). Just as in the MSSM there is always one light doublet state, coinciding with h^0 in the limit of zero mixing. Other states can (but need not) be light, depending on the parameters Ω and Γ.

Higgs Boson Production: Couplings

- SUSY Higgs bosons can be produced at an e^+e^- collider through their couplings to Z^0, via the so–called Bjorken process $(e^+e^- \to Z^0 S_i^0)$, or via the associated production mechanism $(e^+e^- \to S_i^0 P_j^0)$.
- The couplings are

$$\boxed{\mathcal{L} \supset \sum_{i=1}^{8} (\sqrt{2} G_F)^{1/2} M_Z^2 Z_\mu^0 Z^{0\mu} \, \eta_{\mathrm{B}_i} S_i^0 + \sum_{i,j=1}^{8} (\sqrt{2} G_F)^{1/2} M_Z \, \eta_{\mathrm{A}_{ij}} \left(Z^{0\mu} S_i^0 \overleftrightarrow{\partial_\mu} P_j^0 \right)}$$

with

$$\boxed{\begin{aligned} \eta_{\mathrm{B}_i} &= \frac{v_d}{v} R_{i1}^{S^0} + \frac{v_u}{v} R_{i2}^{S^0} + \sum_{j=1}^{3} \frac{v_{Lj}}{v} R_{ij+2}^{S^0} \\ \eta_{\mathrm{A}_{ij}} &= R_{i1}^{S^0} R_{j1}^{P^0} - R_{i2}^{S^0} R_{j2}^{P^0} + \sum_{k=1}^{3} R_{ik+2}^{S^0} R_{jk+2}^{P^0} \end{aligned}}$$

where the subscripts B and A refer, respectively, to the Bjorken process or associated production mechanisms.

Higgs Boson Production: Sum Rules

- In the MSSM, there are two sum rule rules, one in the CP even sector

$$\boxed{\eta^2_{\mathrm{B}_{h^0}} + \eta^2_{\mathrm{B}_{H^0}} = 1}$$

and another relating the Bjorken and the associated production mechanisms,

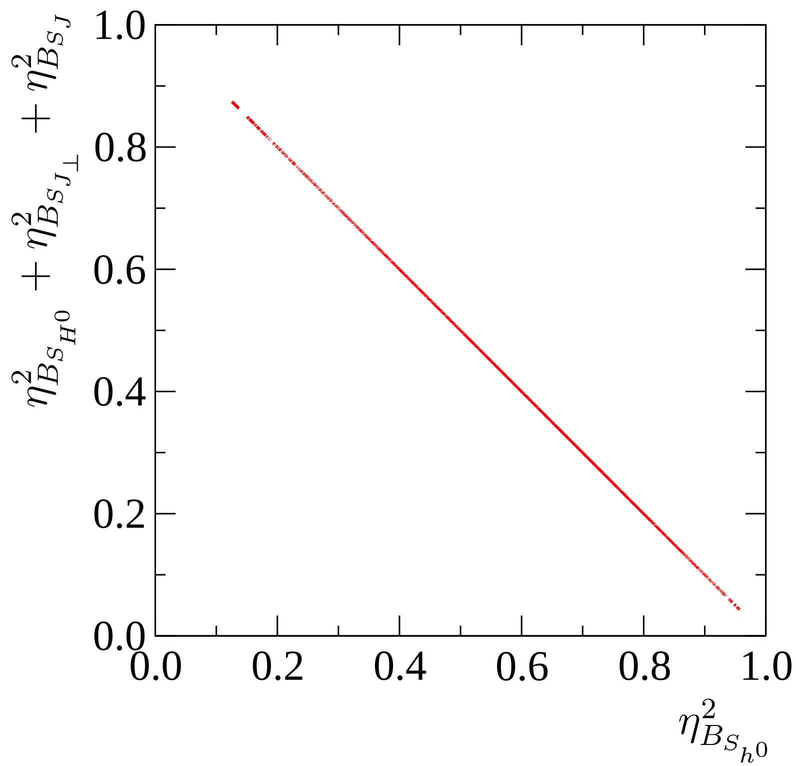
$$\boxed{\eta^2_{\mathrm{B}_{h^0}} + \eta^2_{\mathrm{A}_{h^0 A^0}} = 1}$$

with $\eta_{\mathrm{B}_{h^0}} = \sin(\alpha - \beta)$ and $\eta_{\mathrm{A}_{h^0 A^0}} = \eta_{\mathrm{B}_{H^0}} = \cos(\alpha - \beta)$.

- We will see that to have a sizeable invisible branching ratio we need the doublets to be close in mass to the singlet states related to the majoron and orthogonal combinations. This means that, in the CP-even sector, the first four states are $(S_{h^0}, S_{H^0}, S_{J_\perp}, S_J)$, while in the CP-odd sector we should have $(P_{A_0}, P_{J_\perp}, J, G^0)$. If this situation happens then we can very easily find a generalization of the sum rule of the CP-even sector, as

$$\boxed{\eta^2_{\mathrm{B}_{S_{h^0}}} + \eta^2_{\mathrm{B}_{S_{H^0}}} + \eta^2_{\mathrm{B}_{S_{J_\perp}}} + \eta^2_{\mathrm{B}_{S_J}} = 1}$$

Higgs Boson Production: Sum Rules ...



- If the lightest Higgs boson has a very small coupling to the Z^0 and hence a small production cross section, there should be another state nearby that has a large production cross section.
- The other sum rule, relating the CP-even and CP-odd sectors, is more difficult to generalize. In fact the P_{A_0} state will now mix with the $P_{J_\perp}$.
- However, qualitatively the sum rule still holds in the sense that if the parameters are such that the production of the CP-odd states is reduced one always gets a CP-even state produced.

Types of Parameters

- First, there are the MSSM parameters $\tan\beta, \mu, m_0, m_{1/2}$ and A_0 and the soft SUSY breaking terms. These are partially restricted by SUSY searches.
- The second group of parameters are the ϵ_i and left-handed sneutrino vevs v_{L_i}. We trade the latter for the parameters Λ_i. These six parameters occur also in BRpV model. They are constrained by neutrino data.
- Finally, there are the parameters of the singlet sector, namely singlet vevs $v_R,\ v_S$ and v_Φ, Yukawa couplings $h,\ h_0$ and λ and the singlet mass terms $M_R,\ M_\Phi,\ \delta^2$, as well as the corresponding soft terms.

Scanning Strategy: The MSSM

- We have checked by a rather generous scan that the results presented below do not depend, qualitatively, on the choice of MSSM parameters.
- For definiteness we will fix the MSSM parameters to the SPS1a benchmark point:

$$\boxed{\begin{array}{c} m_0 = 100\text{GeV}, \quad \mathrm{M}_{1/2} = 250\text{GeV}, \quad \tan\beta = 10 \\ A_0 = -100\text{GeV}, \quad \mu < 0 \end{array}}$$

- We have run down this set of parameters to the EW scale using the program package SPheno [W. Porod, Comput. Phys. Commun. 153 (2003) 275].

Scanning Strategy: The Singlet Sector

- For the singlet parameters we choose as a starting point

$$\boxed{\begin{array}{c} v_R = v_S = v_\Phi = -150 \text{ GeV} \\ M_R = -M_\Phi = \delta = 10^3 \text{ GeV}, \\ h = 0.8,\ h_0 = -0.15,\ \lambda = 0.1 \end{array}}$$

- We have tried other values of parameters and obtained qualitatively similar results to the ones we will discuss below.

Scanning Strategy: The $\not{R}_P$ Sector

- The explicit bilinear parameters, ϵ_i and Λ_i, are then fixed approximately such that neutrino masses and mixing angles are in agreement with experimental data.
- Slightly different values of parameters are found, depending on whether the first or the third term in the mass matrix

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

is responsible for the atmospheric neutrino mass scale.

- Both possibilities lead to very similar results for the invisible decay of the Higgs.

Higgs Boson Decays: What to look for?

- We are interested here in the ratio

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

of the invisible decay to the SM decay into b-jets

- These decay widths are

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

and

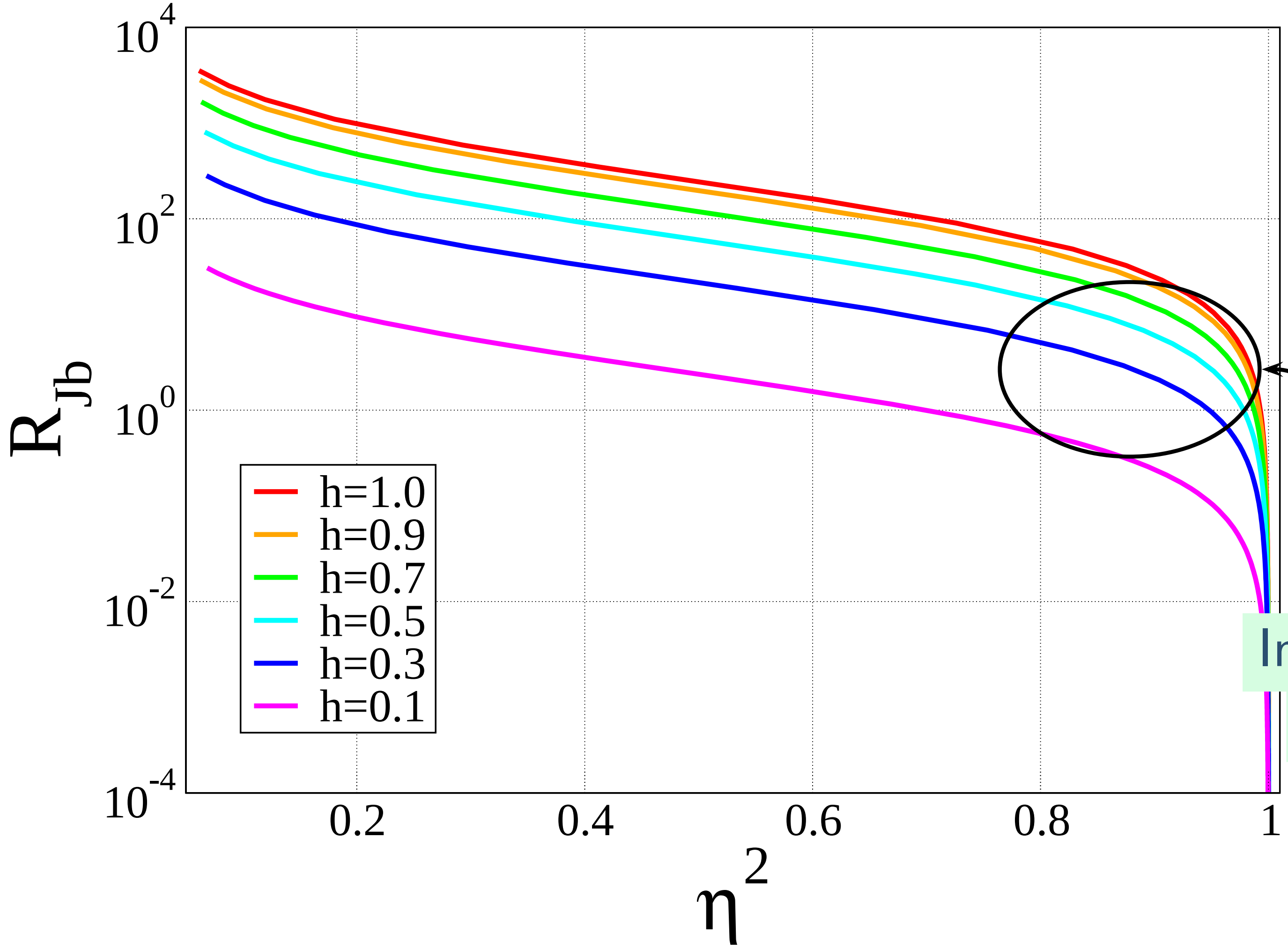
$$\boxed{\Gamma(h \to b\bar{b}) = \frac{3G_F\sqrt{2}}{8\pi}\,\left(R_{11}^S\right)^2\, m_h\, m_b^2\left[1 - 4\left(\frac{m_b}{m_h}\right)^2\right]^{3/2}}$$

Observables: Some Comments

- If the lightest Higgs boson is mainly a combination of the $\tilde{\nu}^c$ and $\tilde{S}$ fields not only g_{hJJ} will be large, but also $\Gamma(h \to b\bar{b})$ will be small suppressing $h \to b\bar{b}$. Unfortunately the production would be suppressed, as singlets do not couple to the Z.
- The phenomenologically novel and interesting situation is when h and h_0 are large. In this case the Higgs boson behaves as the lightest MSSM Higgs boson (with moderately reduced production cross section) but with a large branching to the invisible channel $h \to JJ$.
- The sensitivities of LEP experiments to the invisible channel $h \to JJ$ have been discussed since long ago.
- We will limit ourselves to the discussion of light states, i.e. Higgs bosons with masses below the $2W$ threshold. As discussed below, the decays of heavier CP-odd states will be similar to the situation encountered in the (N)MSSM.

Numerical results: General Superpotential

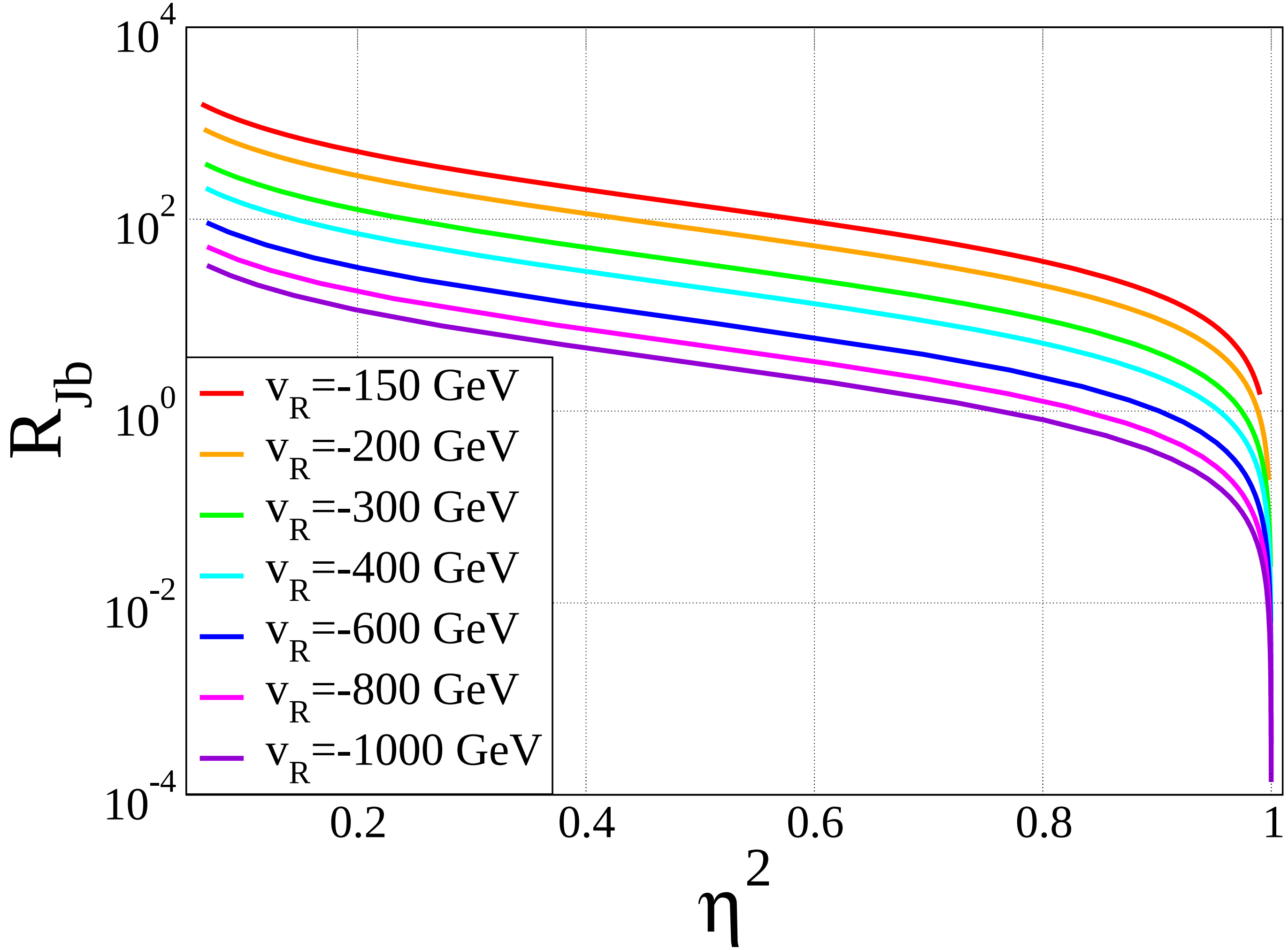
R_{Jb} vs η^2 for fixed h



Important region

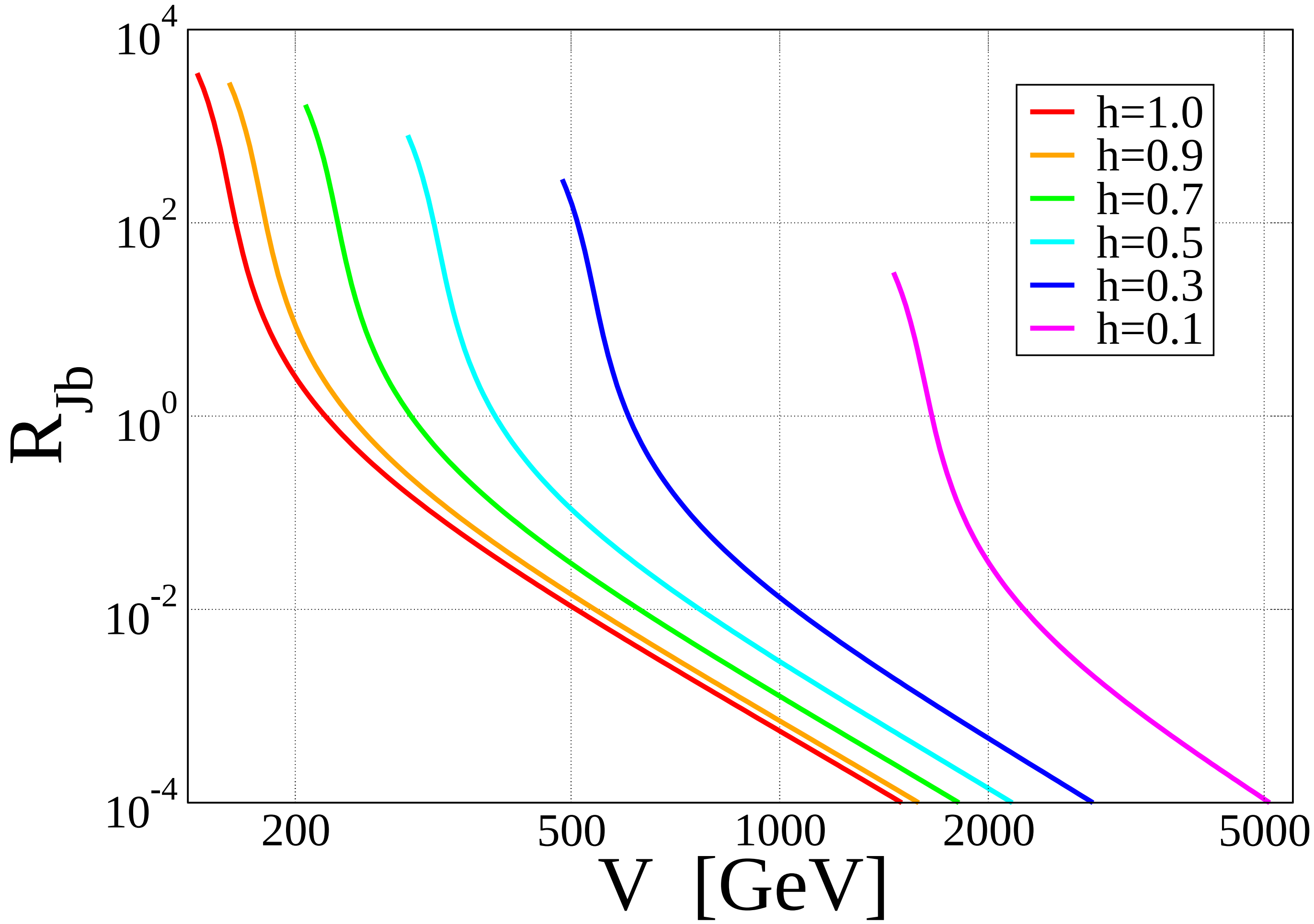
Numerical results: General Superpotential

R_{Jb} vs η^2 for fixed $v_R = v_S$



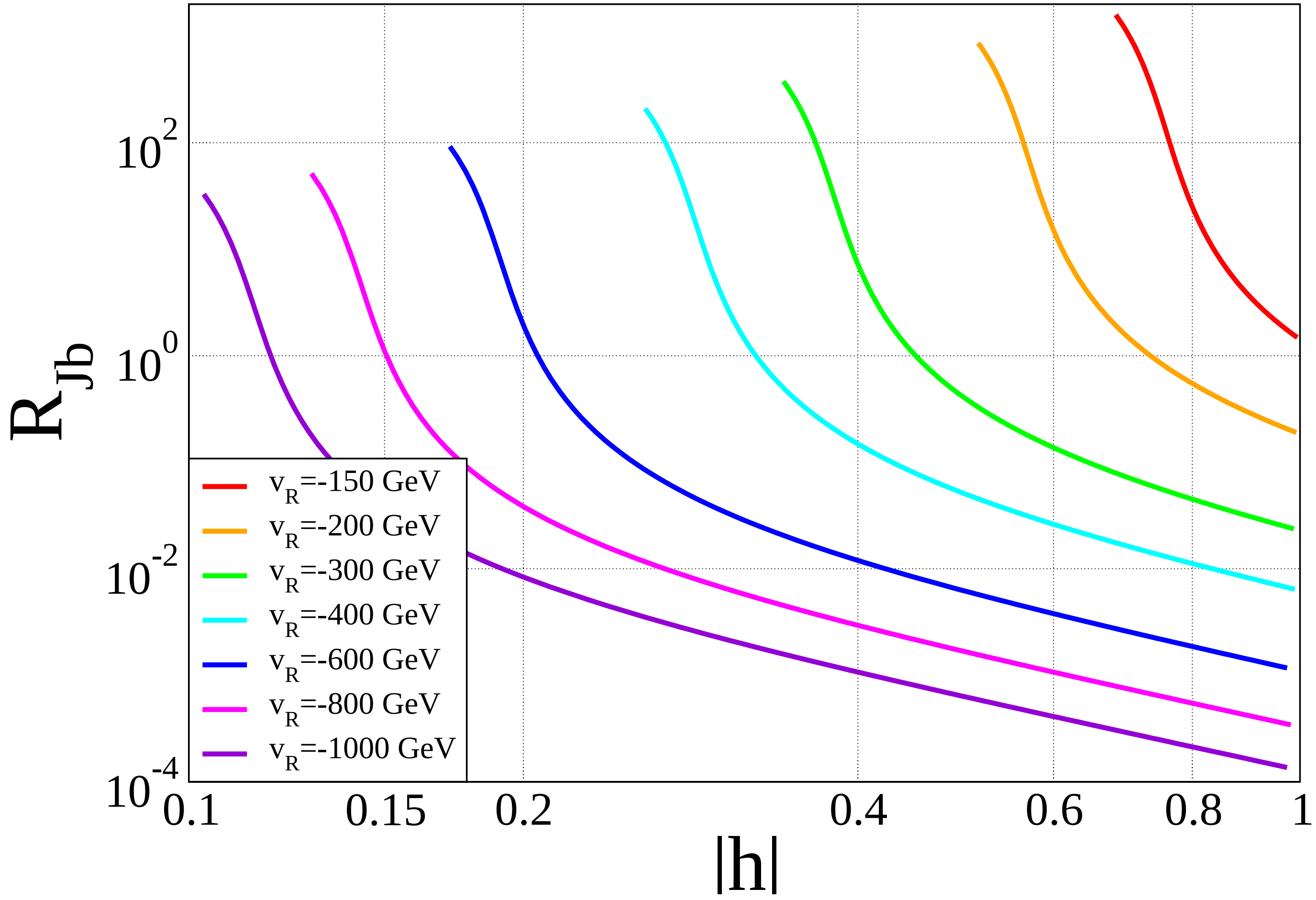
Numerical results: General Superpotential

R_{Jb} vs $V = \sqrt{v_R^2 + v_S^2}$ for fixed h



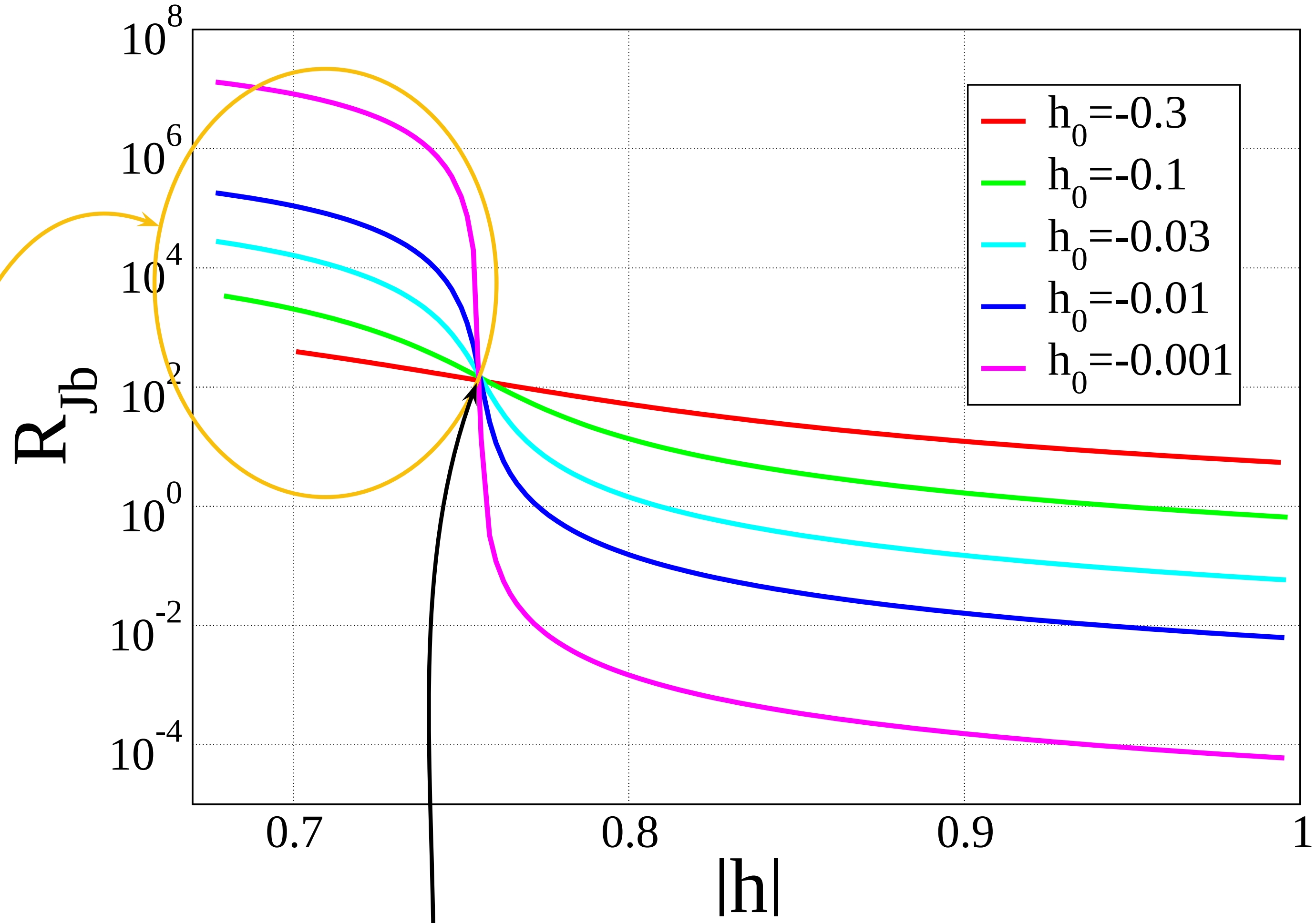
Numerical results: General Superpotential

R_{Jb} vs $|h|$ for fixed $v_R = v_S$



Numerical results: General Superpotential

R_{Jb} vs $|h|$ for fixed h_0



H^0 singlet

level crossing

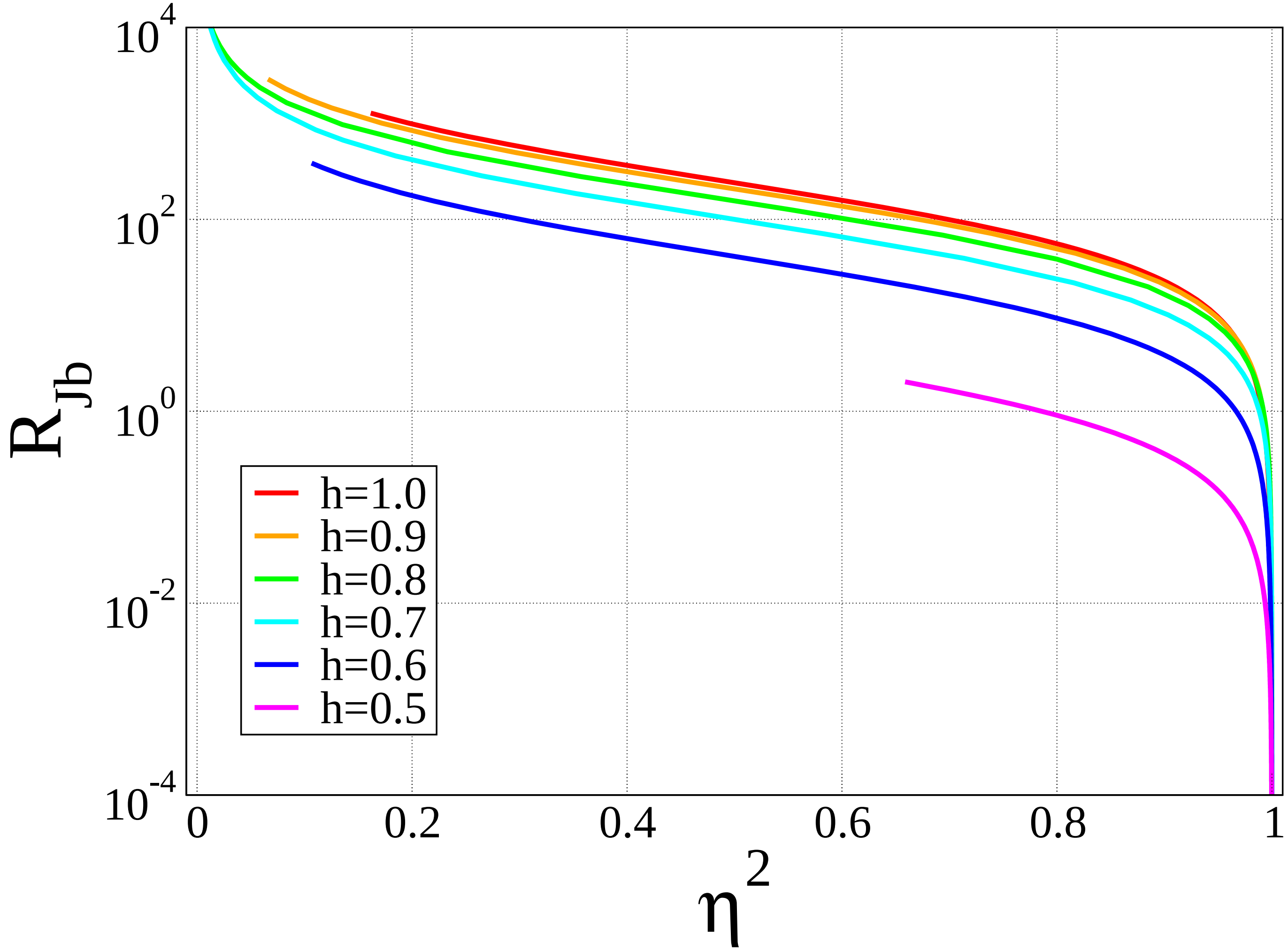
Numerical results: Cubic-Only Case

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

- The restricted model provides a potential “solution” to the μ problem in the context of SBRpV.
- We give results for the same parameter choices as above, except that no mass parameters are now present in the basic superpotential.

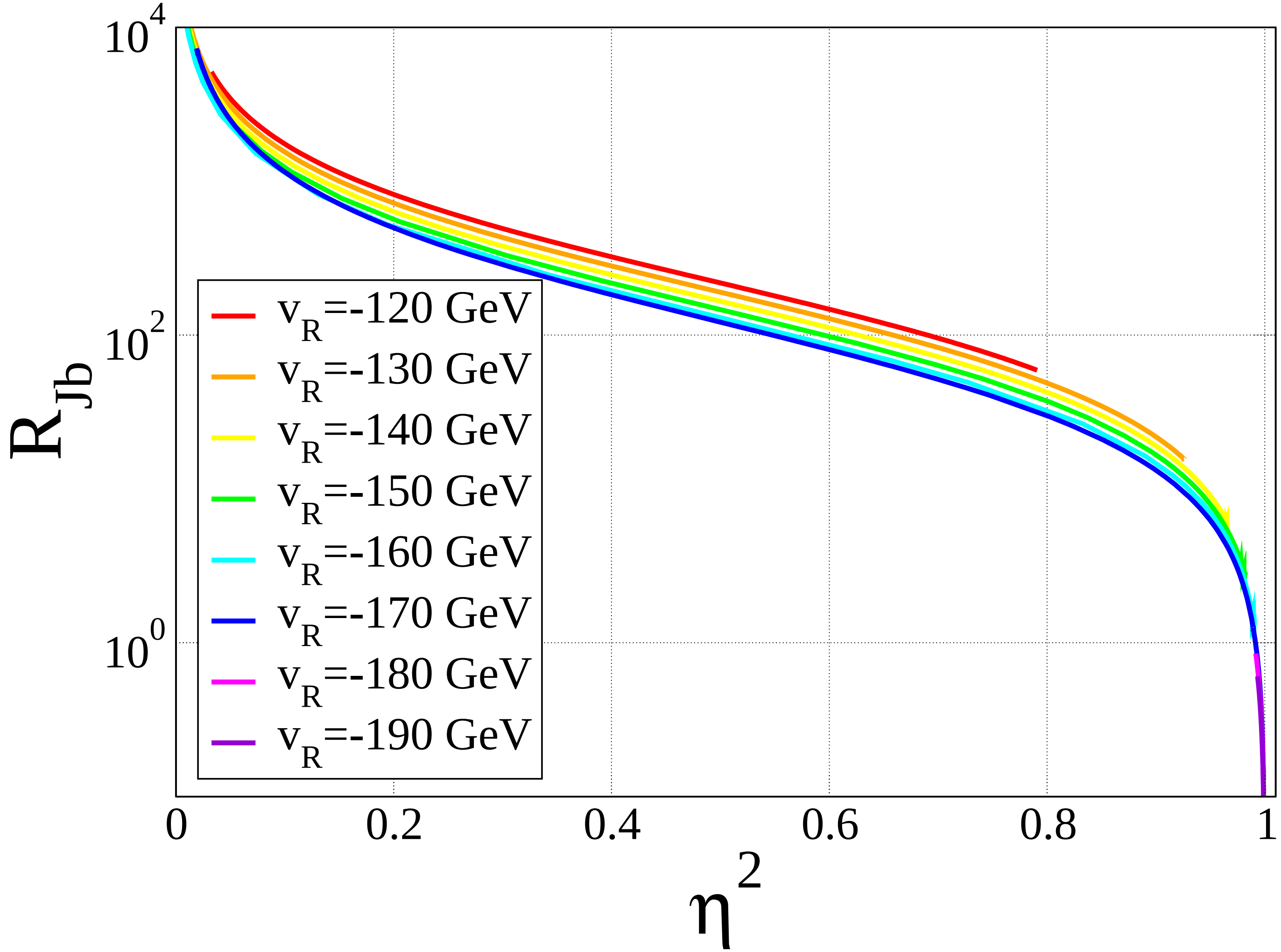
Numerical results: Cubic-Only Case

R_{Jb} vs η^2 for fixed $|h|$



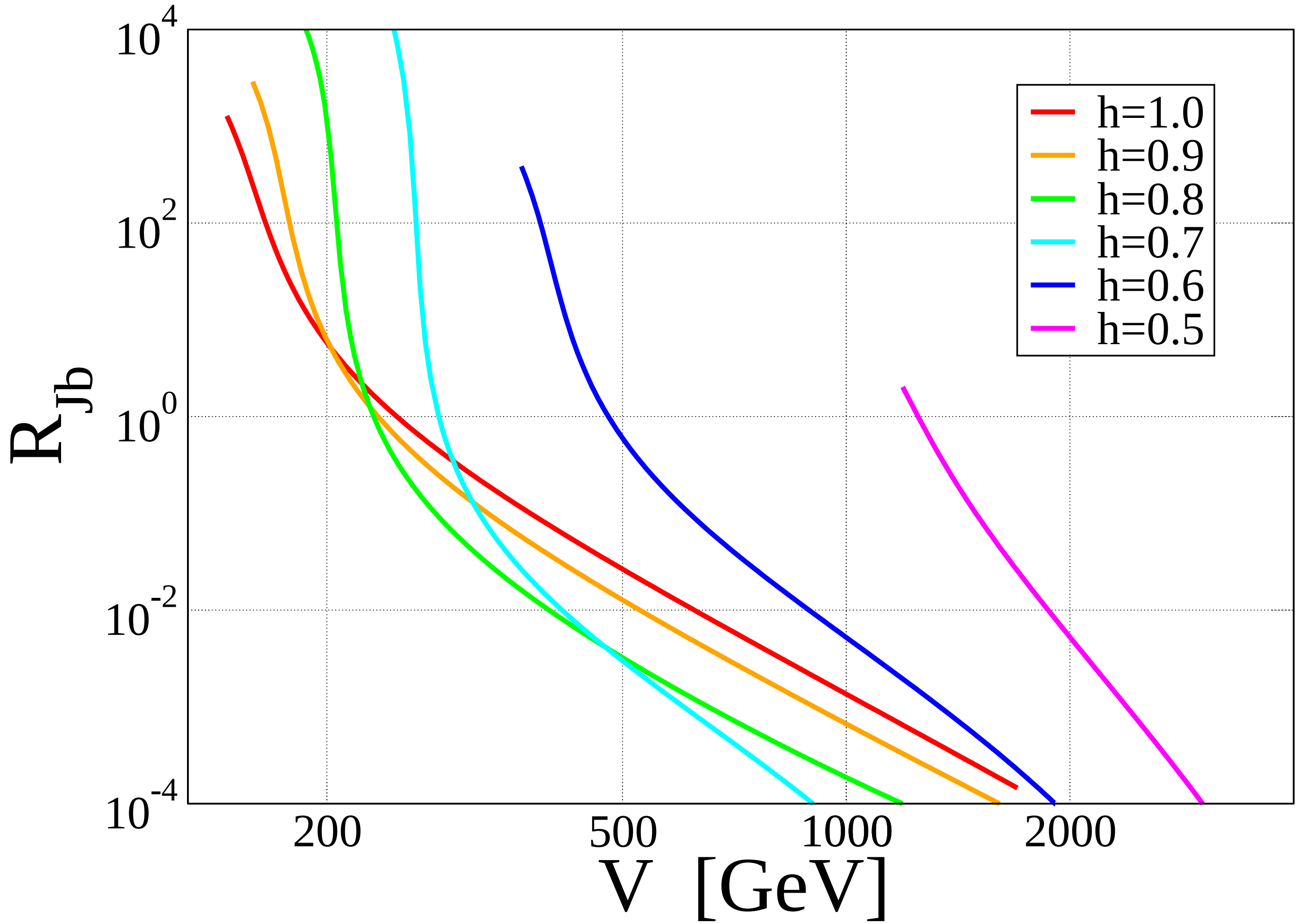
Numerical results: Cubic-Only Case

R_{Jb} vs η^2 for fixed $v_R = v_S$



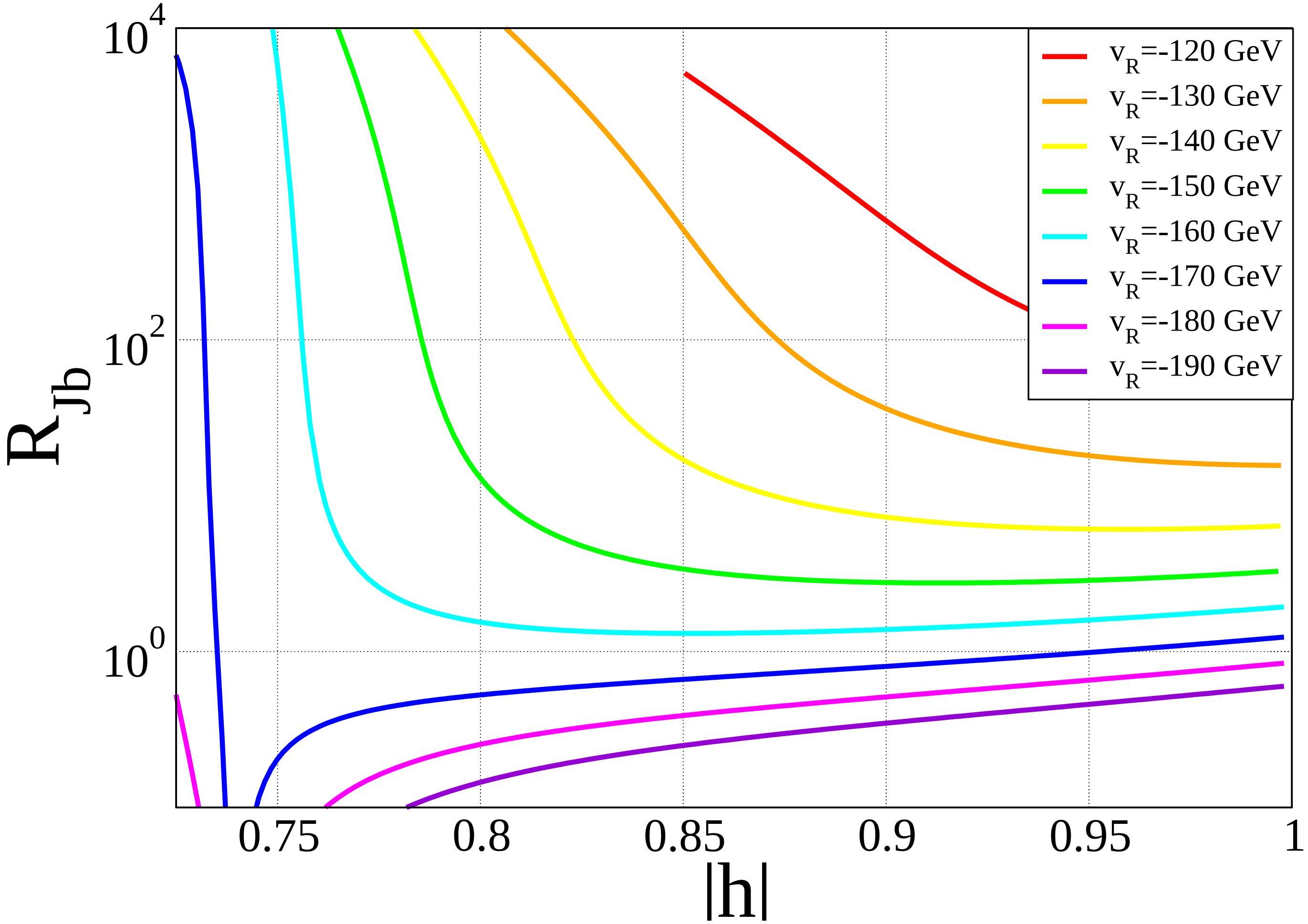
Numerical results: Cubic-Only Case

R_{Jb} vs $V = \sqrt{v_R^2 + v_S^2}$ for fixed h



Numerical results: Cubic-Only Case

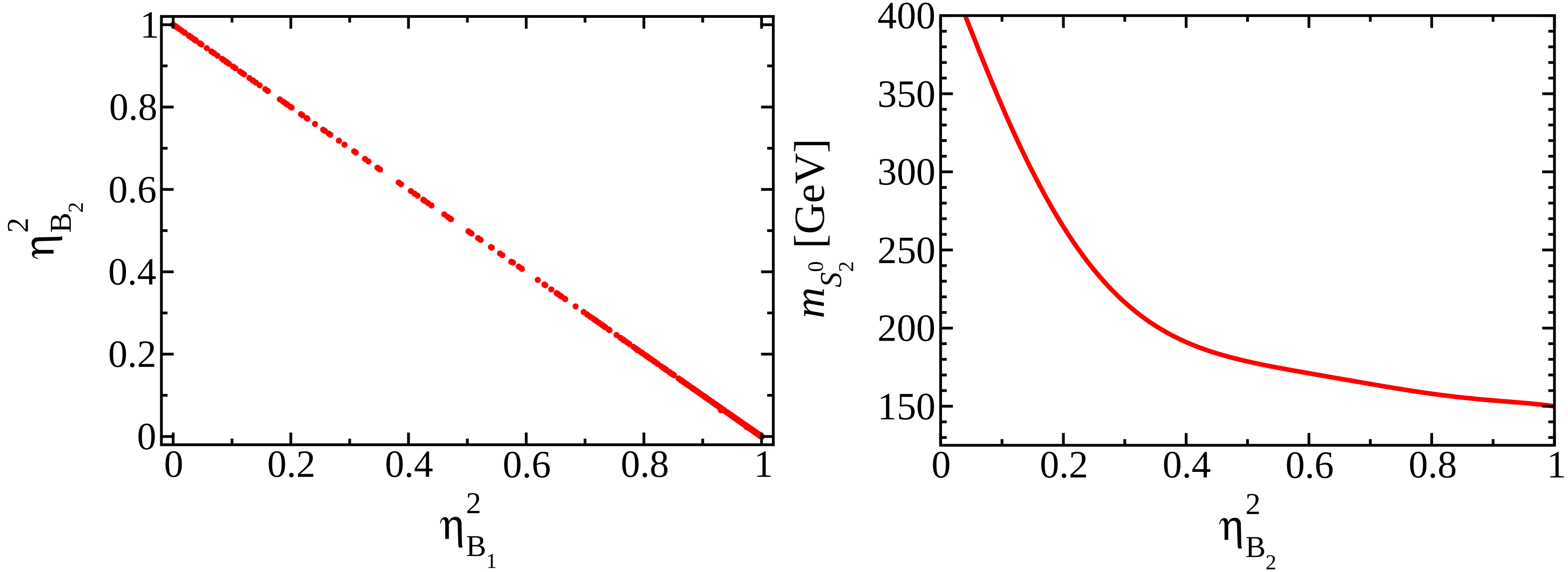
R_{Jb} vs $|h|$ for fixed $v_R = v_S$



CP-even Higgs Boson Decays: The 2^{nd} Eigenstate

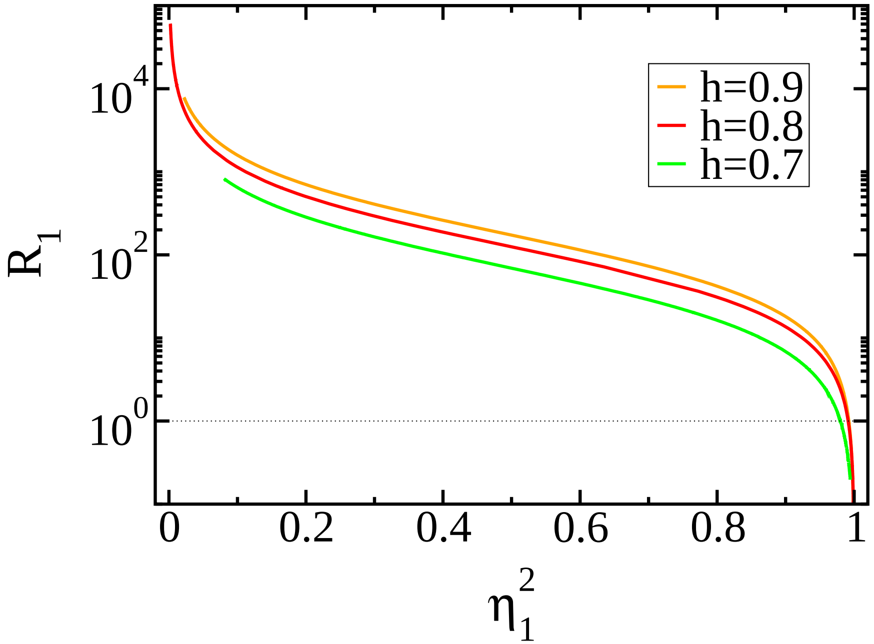
- It is well known that, in contrast to the Standard Model, in the MSSM (and in the NMSSM) the mass of the lightest CP-even supersymmetric Higgs boson obeys an upper bound that follows from the D-term origin of the quartic terms in the scalar potential. This mass acquires a contribution from the top-stop quark exchange, a fact that modifies the numerical value of this upper bound.
- In the SBRP model it is possible that the lightest CP-even Higgs is mainly a singlet. However, if this happens, there must exist a light, mainly doublet Higgs, to which the NMSSM bounds apply.

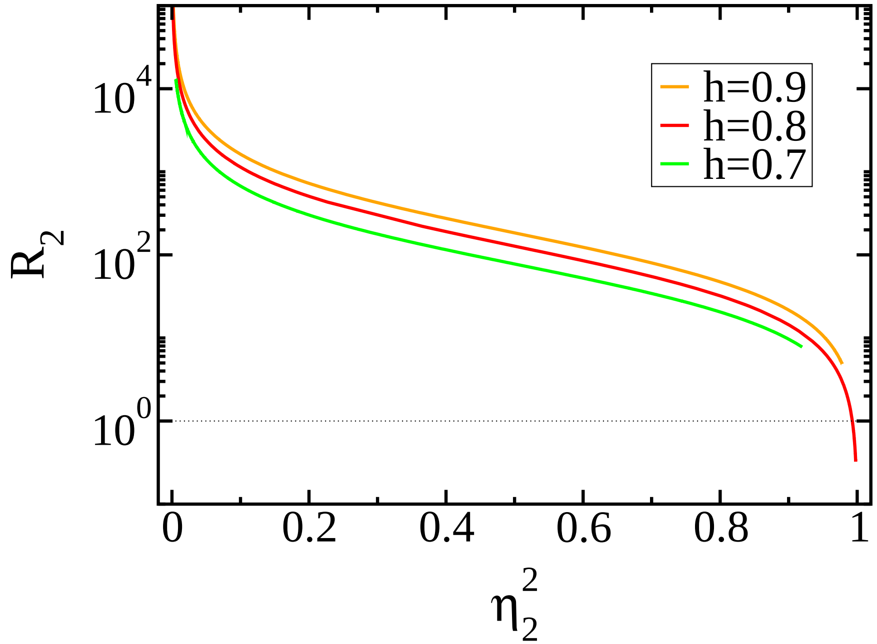
CP-even Higgs Boson Decays: The $2^{\rm nd}$ Eigenstate ...



In the left panel we show the parameter characterizing direct production of the second lightest neutral CP-even Higgs boson, $\eta^2_{\rm B_2}$, as function of the corresponding one for the first lightest neutral CP-even Higgs boson, $\eta^2_{\rm B_1}$. To the right: Upper limit on the mass of the second lightest CP-even Higgs as a function of $\eta^2_{\rm B_2}$. As is seen, if the lightest state is mainly singlet, $\eta^2_{\rm B_1} \simeq 0$, therefore $\eta^2_{\rm B_2} \simeq 1$, then there is an upper bound on the second lightest state mass. Vice versa the upper bound applies to the lightest state if it is mainly doublet.

CP-even Higgs Boson Decays: The 2^{nd} Eigenstate ...





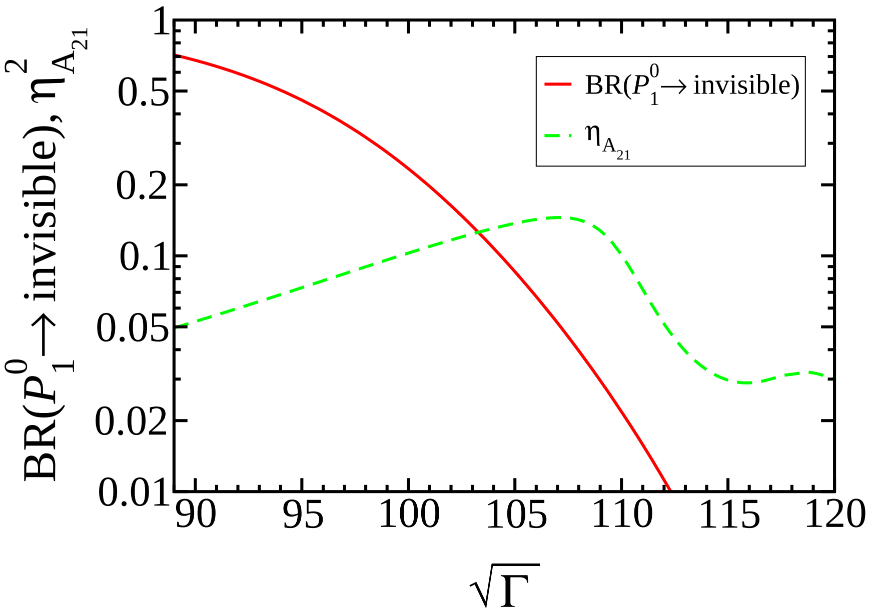
To the left (right): Ratio R_1 (R_2) as a function of the direct production parameter, $\eta^2_{\mathrm{B}_1}$ ($\eta^2_{\mathrm{B}_2}$), for the first (second) lightest neutral CP-even Higgs boson.

In summary, we have seen that in the SBRP model there is always at least one light state, which is mainly doublet, and therefore can be produced at future colliders. Irrespectively of whether this state is the lightest or second-lightest Higgs state, it can decay with very large branching ratio to an invisible final state.

CP-odd Higgs Boson Decays

- Light CP-odd Higgs bosons in the MSSM decay according to $P_i^0 \to f\bar{f}$.
- The WW channel becomes dominant as soon as kinematically allowed, however we will not include it as we are mainly interested in the possibility of invisible decays of the lowest-lying pseudoscalar.
- The formulas for the CP-even and CP-odd Higgs boson MSSM decay branching ratios, are totally analogous to those of the MSSM, except for the prefactors which are determined by the diagonalizing matrices of our model. The corresponding matrix elements replace the familiar $\sin(\beta-\alpha)$ and $\cos(\beta-\alpha)$ factors.
- In the SBRP we must take into account in addition the decays $P_i^0 \to JJJ$ and, if kinematically allowed, also $P_i^0 \to S_j^0 J$, $P_i^0 \to S_j^0 P_k^0$, $P_i^0 \to P_j^0 JJ$, $P_i^0 \to P_j^0 P_k^0 J$ and $P_i^0 \to P_j^0 P_k^0 P_m^0$.
- For the lightest Higgs boson we are interested only in $P_i^0 \to JJJ$ and $P_i^0 \to S_j^0 J$.

Numerical results: CP-odd Higgs Boson



Production cross section (green/dashed curve) and invisible final states decay branching ratio (red/solid curve) for the lightest CP-odd Higgs boson.

- To find sizeable branching ratios for the decays of the lightest massive pseudoscalar P_1^0, mixing between doublet and singlet states is therefore required.
- In order to have sizeable mixing between doublet and singlet CP-odd Higgs bosons, we must require that at least one of the singlet states is light, i.e. the parameter Γ should be very roughly of order $\Gamma \sim \Omega$.
- In summary, the CP-odd Higgs bosons in the SBRP model usually behave very similar to the situation discussed in the (N)MSSM. However, sizeable branching ratios to invisible final states are possible when there are light CP-odd Higgs bosons from both, the doublet and the singlet sectors.

Conclusions

- We have carefully analyzed the mass spectra, production and decay properties of the lightest supersymmetric CP-even and CP-odd Higgs bosons in models with spontaneously broken R-parity. We have compared the resulting mass spectra with what is predicted in the Minimal Supersymmetric Standard Model, stressing the validity of the upper bound on the lightest CP-even Higgs boson mass.
- The main difference with respect to the MSSM case comes from the fact that the spontaneous breaking of lepton number necessarily implies the existence of the majoron, and this opens new decay channels for supersymmetric Higgs bosons into "invisible" final states.
- The singlet superfield Φ plays a triple role:
  - Neutrino masses are obtained from first principles, even when radiative corrections are negligible.
  - it solves the μ-problem *a la NMSSM*
  - it makes the invisible Higgs boson decay potentially the most important mode of Higgs boson decay.

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Conclusions ...

- We have found that the invisible decays of CP-even Higgses can be dominant, despite the small values of the neutrino masses indicated by neutrino oscillation data. In contrast, although the decays of the CP-odd bosons into invisible final states can also be sizeable, this situation is not generic.
- Therefore the existence of invisibly decaying Higgs bosons should be taken seriously in the planning of future accelerators, like the LHC and the ILC. These decays may signal the weak-scale violation of lepton number in a wide class of theories. Within the supersymmetric context they are a characteristic feature of the SBRP models. These can account for the observed pattern of neutrino masses and mixings in a way which allows the neutrino mixing angles to be cross checked at high energy accelerators like LHC/ILC.

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