Higgs Bosons in SBRP: production modes and invisible decays

Albert Villanova del Moral

Based on papers:

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

and other work in preparation

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International Linear Collider Workshop

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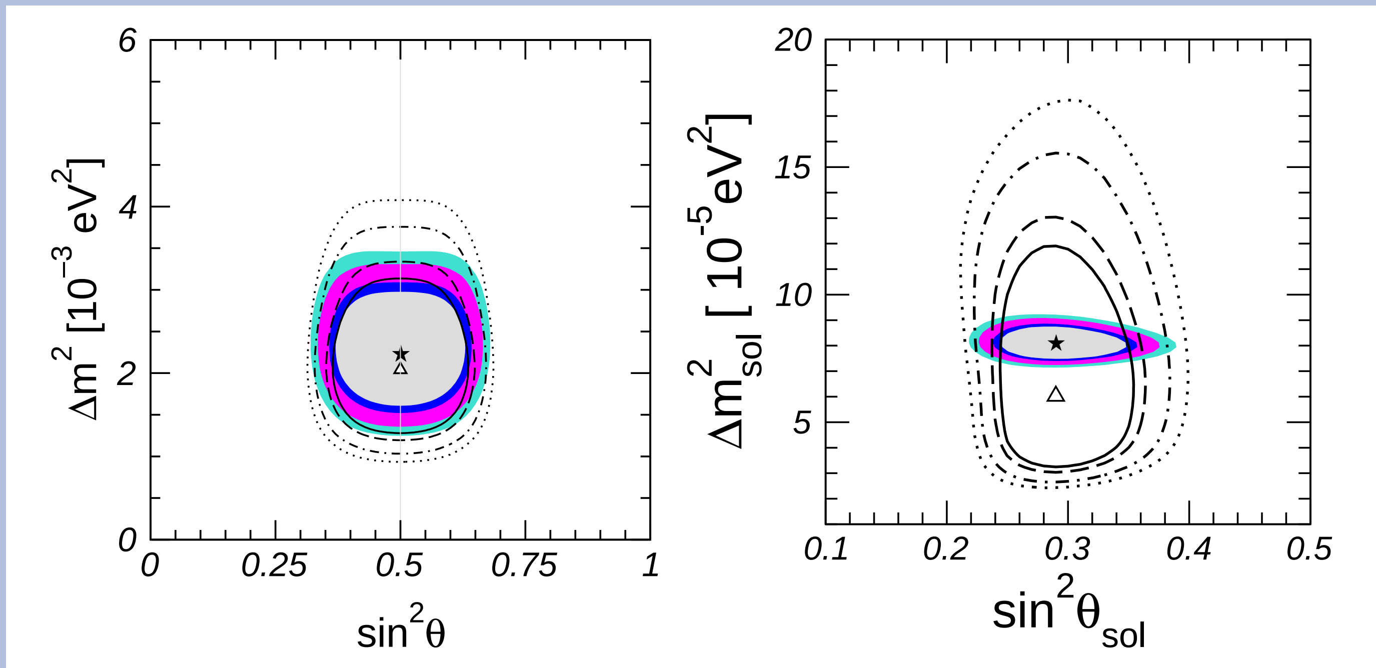
Neutrino Physics Data

★ Neutrinos are massive

- Allowed parameter region from all neutrino experimental data:



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

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Standard Model

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  - Right-handed neutrinos do not exist
  - Lepton number is “accidentally” conserved
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$\Rightarrow$ SM must be extended in some sector:
  - Particles
  - Symmetries
  - or both

SUSY extension of the SM

- The most general renormalizable and gauge invariant superpotential with minimal particle content is

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

where

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

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W_{\not B} &= \lambda''_{ijk}\widehat{U}_i\widehat{D}_j\widehat{D}_k
\end{aligned}$$

- It allows L and B violation $\Rightarrow$ Proton decay!!

Possible Solutions

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

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

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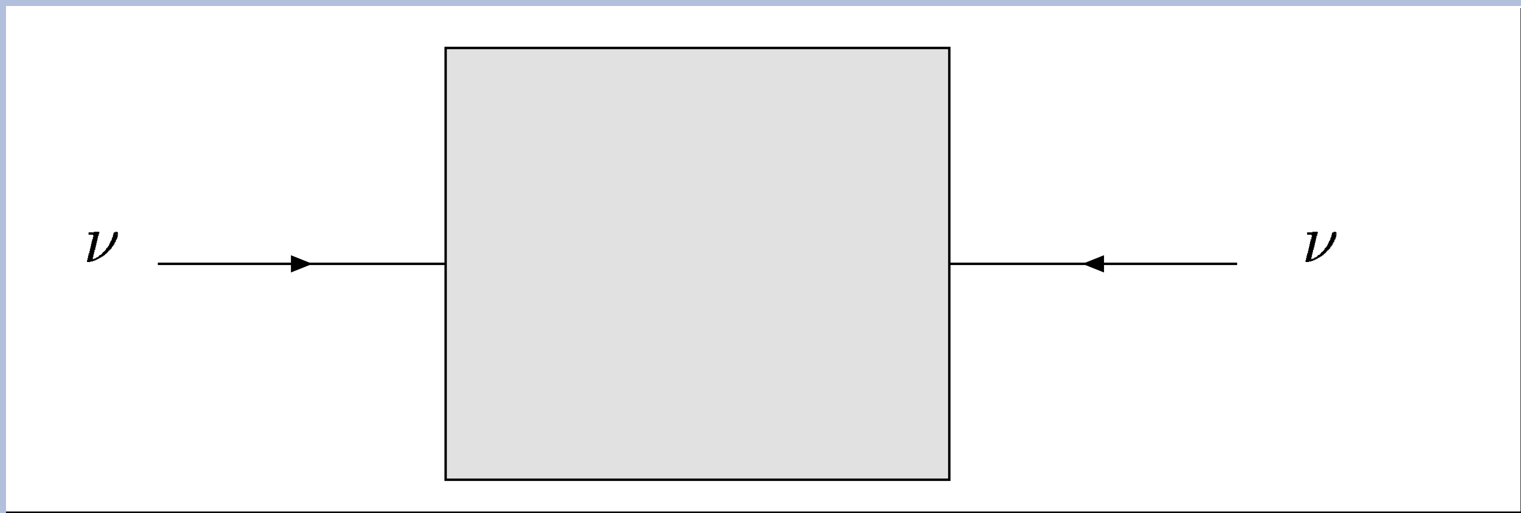
★ Postulation of R_P conservation is not inevitable!

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

L Breaking

- Neutrinos are electrically neutral particles
- They can have Majorana mass terms



- Lepton number would be violated
- How can L be broken?
  - Explicitly
  - Spontaneously

The majoron

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  $\Rightarrow$ Associated massless Nambu-Goldstone boson: J (the majoron)

The majoron

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- The majoron cannot be mainly doublet or triplet
  - $\Leftarrow$ Ruled out by LEP measurement of Z invisible decay

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The majoron

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- The majoron must be mainly singlet
- New invisible Higgs boson decay channels

$$H_i \longrightarrow JJ$$

$$A_i \longrightarrow H_j J$$

$$A_i \longrightarrow JJJ$$

Spontaneously Broken R-Parity Model

- The Model
  - Particle Content
  - Superpotential
  - Non-Zero Vacuum Expectation Values
- Neutral Fermion Sector
- Neutral Higgs Boson Sector
  - Mass eigenstates
  - Production modes
  - Invisible decays

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

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

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

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

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

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

Superpotential

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

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

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

$$+\frac{1}{3!}\lambda\widehat{\Phi}^3$$

Solution to the μ problem

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Vacuum Expectation Values

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

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

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

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

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Neutral Fermion Sector

Non-zero VEVs $\Rightarrow$

$\Rightarrow$ mixing of
- neutrinos
- gauginos
- higgsinos
- singlet fermions

In the basis

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

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

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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

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Effective Neutrino Mass Matrix

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

Matrix elements:

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

where

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

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

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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 Higgs Boson Sector

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

$$\mathcal{L} \supset \frac{1}{2}(\boldsymbol{H'^0})^{\mathrm{T}} \cdot \boldsymbol{M}^2_{\boldsymbol{H^0}} \cdot \boldsymbol{H'^0}$$

Mass eigenstates are

$$\boldsymbol{H^0} = \boldsymbol{R}^{\boldsymbol{H^0}} \cdot \boldsymbol{H'^0}$$

with the following mass eigenvalues

$$\mathrm{diag}(m^2_{H_1}, \ldots, m^2_{H_8}) = \boldsymbol{R}^{\boldsymbol{H^0}} \cdot \boldsymbol{M}^2_{\boldsymbol{H^0}} \cdot (\boldsymbol{R}^{\boldsymbol{H^0}})^{\mathrm{T}}$$

Neutral CP-odd Higgs Boson Sector

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

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

Mass eigenstates are P_i^0, where

$$(\boldsymbol{P^0})^{\mathrm{T}} = (J, G^0, A_1, A_2, A_3, A_4, A_5, A_6)$$

$$\boldsymbol{P^0} = \boldsymbol{R}^{\boldsymbol{P^0}} \cdot \boldsymbol{P'^0}$$

with the following mass eigenvalues

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

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Majoron Components

- For

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

the majoron is given by the imaginary part of

$$\frac{\sum_i v_{Li}^2}{V v^2}(v_u H_u - v_d H_d) + \sum_i \frac{v_{Li}}{V}\tilde{\nu}_i + \frac{v_S}{V}\tilde{S} - \frac{v_R}{V}\tilde{\nu}^c$$

- Majoron is mainly singlet

$$\frac{1}{V}(v_S \tilde{S} - v_R \tilde{\nu}^c)$$

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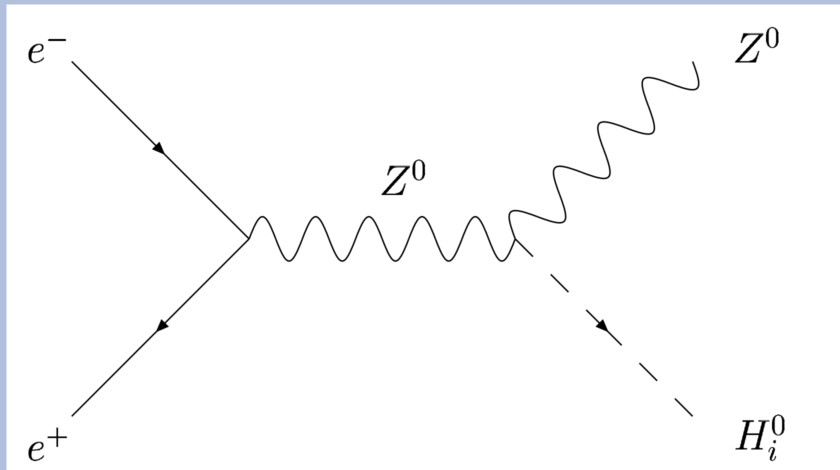
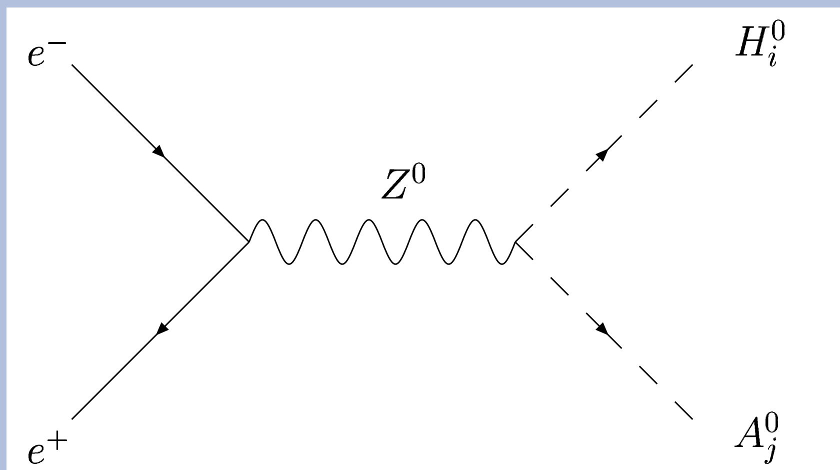
Neutral Higgs Boson Production

- Direct Production (Bjorken process)



- Associated production



Direct Production

$$\mathcal{L}_{ZZH} = \sum_{i=1}^{8} (\sqrt{2} G_F)^{1/2} M_Z^2 Z_\mu Z^\mu \, \eta_i H_i^0$$

Direct production parameter

$$\eta_i \equiv \frac{g_{ZZH_i^0}}{g^{\rm SM}_{ZZH_i^0}} = \frac{v_d}{v} R^{H^0}_{i1} + \frac{v_u}{v} R^{H^0}_{i2} + \sum_{j=1}^{3} \frac{v_{Lj}}{v} R^{H^0}_{i\,j+2}$$

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- If $\eta_i \sim 0 \Rightarrow H_i^0$ mainly isosinglet
- If $\eta_i \sim 1 \Rightarrow H_i^0$ mainly isodoublet (like MSSM)

Direct Production of H_1^0

- Upper bound on $m_{H_1^0}$

$$m_{H_1^0} \leq 150 \text{ GeV}, \quad \eta_1 \in [0, 1]$$

- If $\eta_1 \sim 0 \Rightarrow H_1^0$ is NOT produced!
- What about H_2^0?

Direct Production of H_2^0

- If $\eta_1 \sim 0 \quad \Rightarrow \quad$ What about η_2?

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Direct Production of H_2^0

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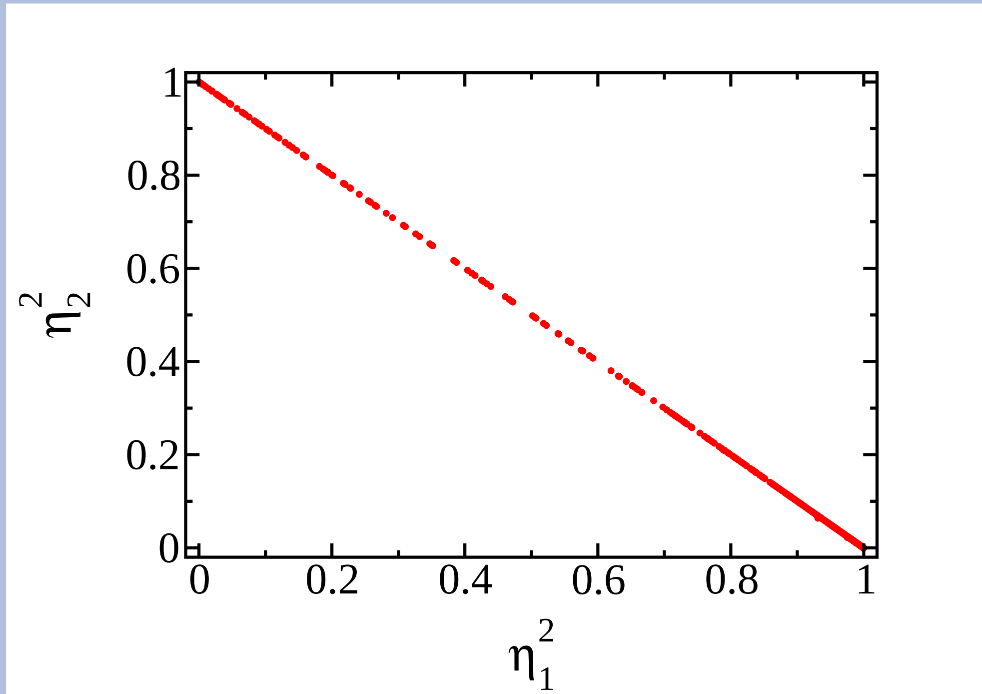

Direct Production of H_2^0

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  i.e., if H_1^0 has small production, then H_2^0 is largely produced

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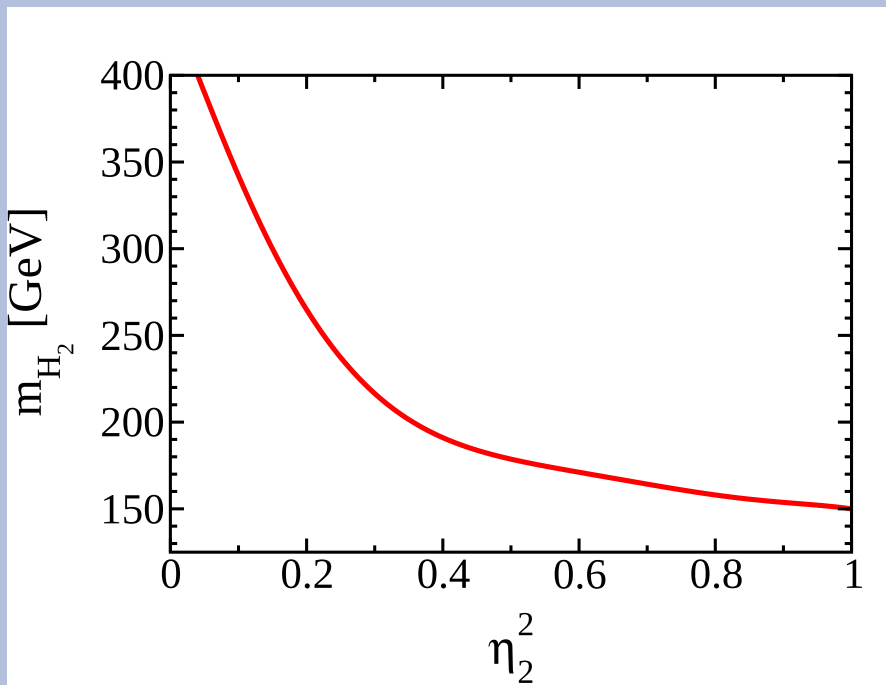

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- If $\eta_2 \sim 1 \quad \Rightarrow \quad m_{H_2^0} \leq 150$ GeV
  i.e., for H_2^0 largely produced, its mass is bounded from above

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- If $\eta_2 \sim 1 \quad \Rightarrow \quad m_{H_2^0} \leq 150$ GeV
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★ One Higgs boson, whose mass is bounded from above at around 150 GeV, will be produced, independently of whether this boson is the lightest or the next-to-lightest one

Associated Production

$$\mathcal{L}_{ZHA} = \sum_{i,j=1}^{8} (\sqrt{2}G_F)^{1/2} M_Z \, \zeta_{ij} \left(Z^\mu H_i^0 \overleftrightarrow{\partial_\mu} P_j^0 \right)$$

Associated production parameter

$$\zeta_{ij} \equiv R^{S^0}_{i1} R^{P^0}_{j1} - R^{S^0}_{i2} R^{P^0}_{j2} + \sum_{k=1}^{3} R^{S^0}_{ik+2} R^{P^0}_{jk+2}$$

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★ At least one state will be produced

CP-even Higgs Boson Decays

- Main dacay channels for either H_1^0 or H_2^0

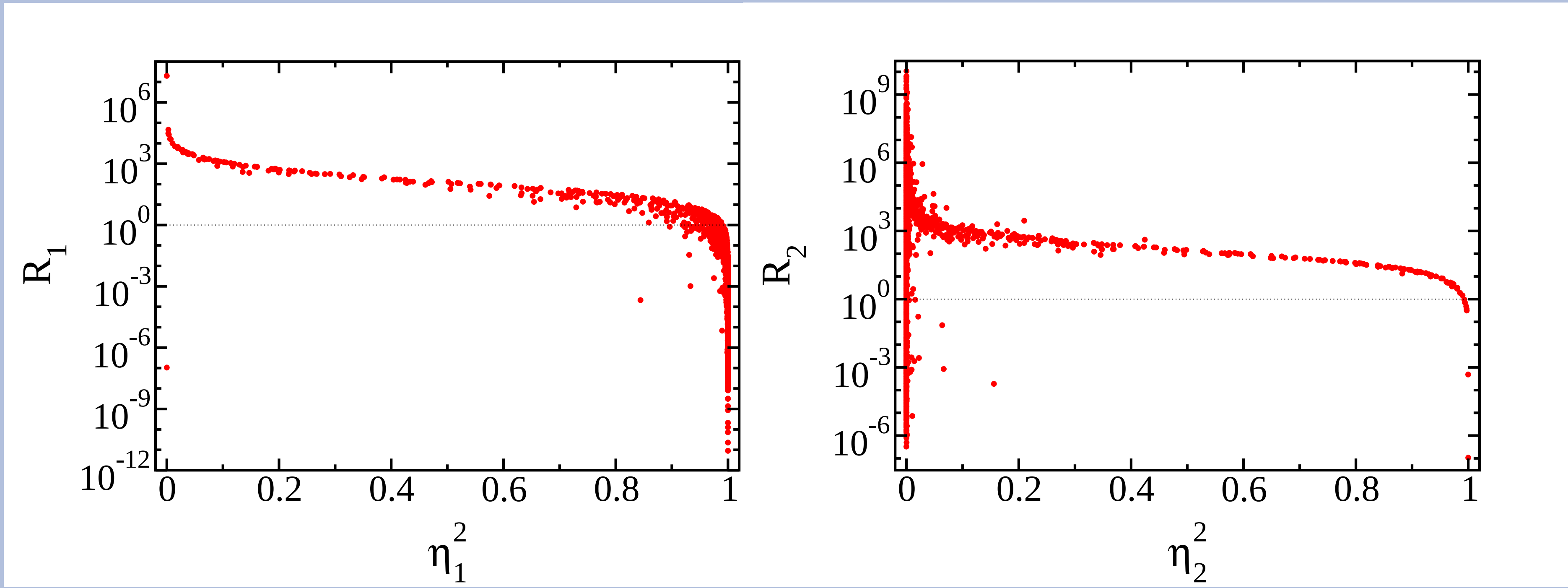
$$H_{1,2}^0 \to f_i \bar{f}_i \qquad \text{if} \qquad m_{H_{1,2}^0} > 2m_{f_i}$$

$$H_{1,2}^0 \to JJ$$

- Ratio between the invisible decay width and the visible one as

$$R_{1,2} \equiv \frac{\Gamma(H_{1,2}^0 \to JJ)}{\sum_j \Gamma(H_{1,2}^0 \to f_j \bar{f}_j)}$$

CP-even Higgs Boson Decays



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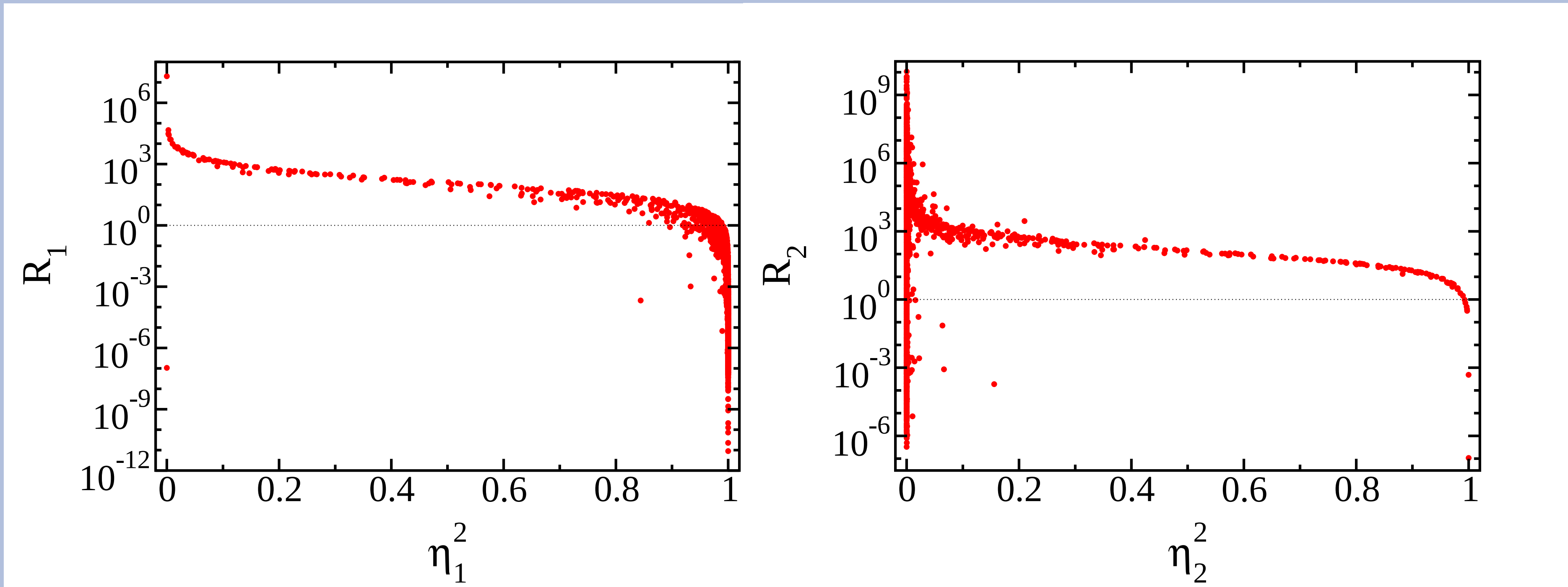

★ Both can have dominant invisible decay for large values of their direct production parameters

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CP-odd Higgs Boson Decays

- Main dacay channels for A_1^0

$$A_1^0 \to f_i \bar{f}_i \qquad \text{if} \quad m_{A_1^0} > 2m_{f_i}$$

$$A_1^0 \to H_j^0 J \qquad \text{if} \quad m_{A_1^0} > m_{H_j^0}$$

$$A_1^0 \to JJJ$$

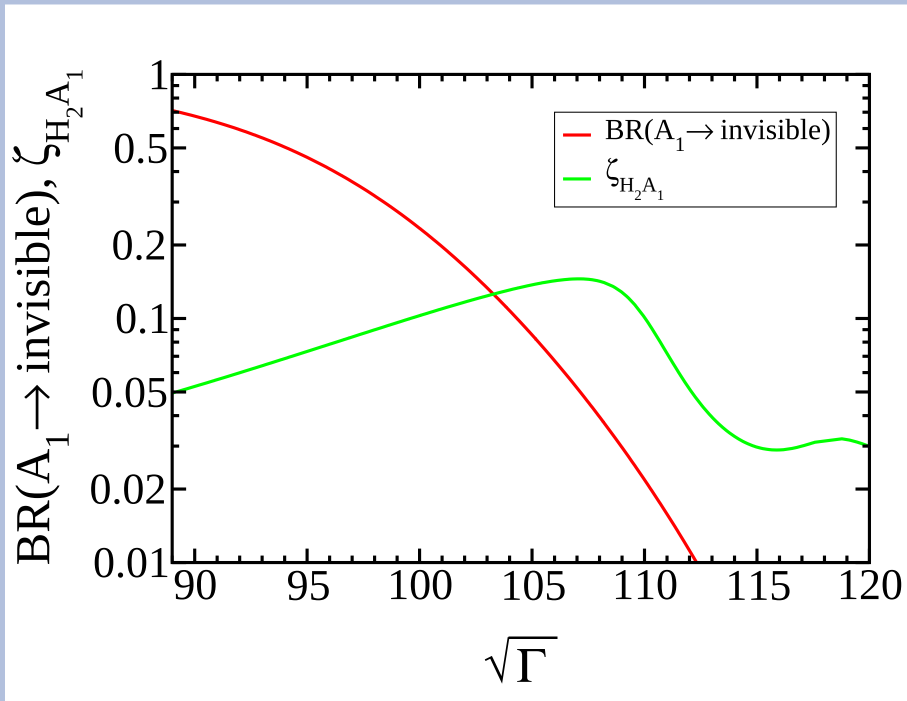
CP-odd Higgs Boson Decays

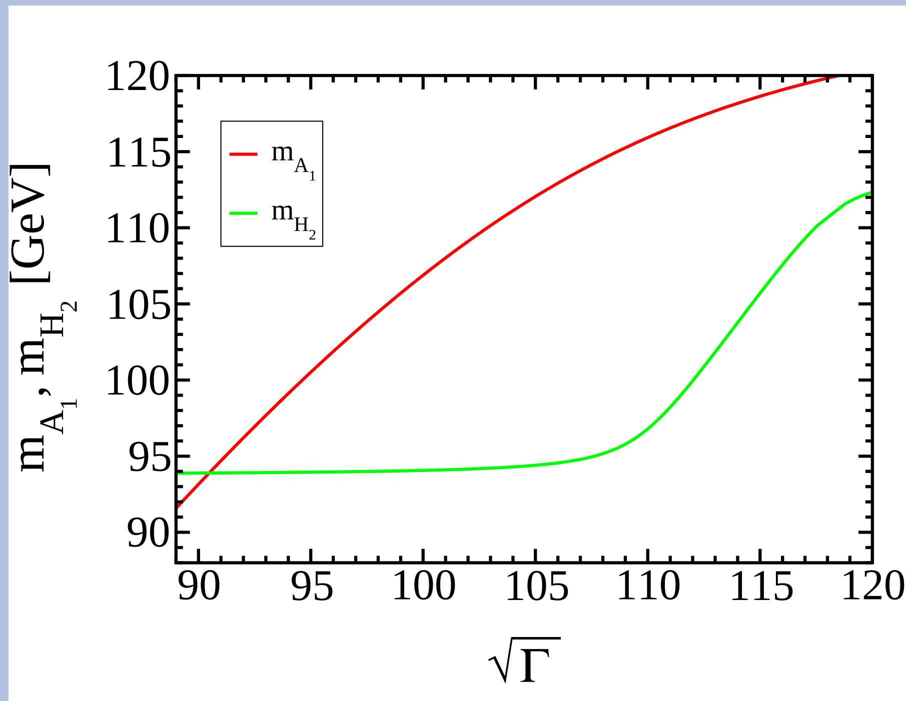
- Problem: in most of the parameter space the lightest CP-odd Higgs boson that is largely produced via the associated production mechanism will have these invisible decay channels suppressed

CP-odd Higgs Boson Decays

- Problem: in most of the parameter space the lightest CP-odd Higgs boson that is largely produced via the associated production mechanism will have these invisible decay channels suppressed
- Solution: to find a compromise between its degree of "doubletness" (so that it will be produced) and "singletness" (so that it has a sizable invisible decay through majorons)

CP-odd Higgs Boson Decays





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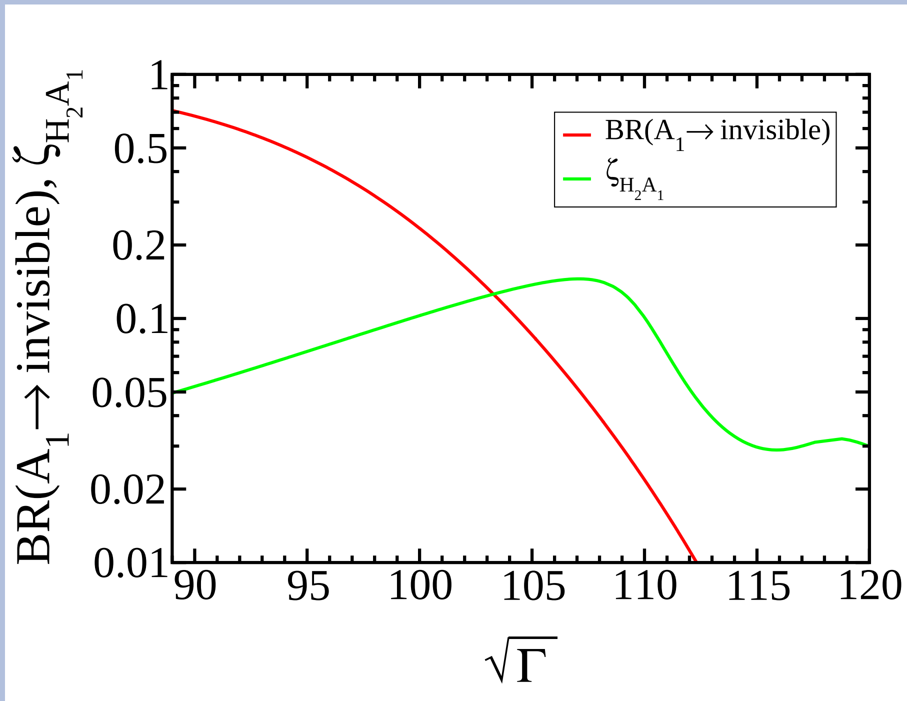

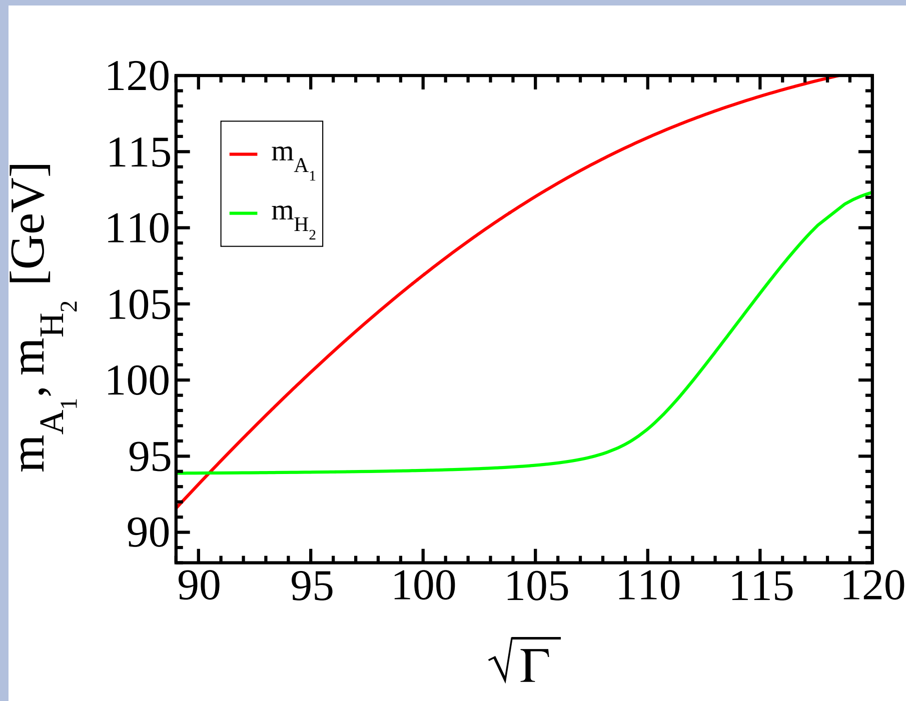

★ We can get a compromise of 10% invisible branching ratio and 0.1 associated production parameter

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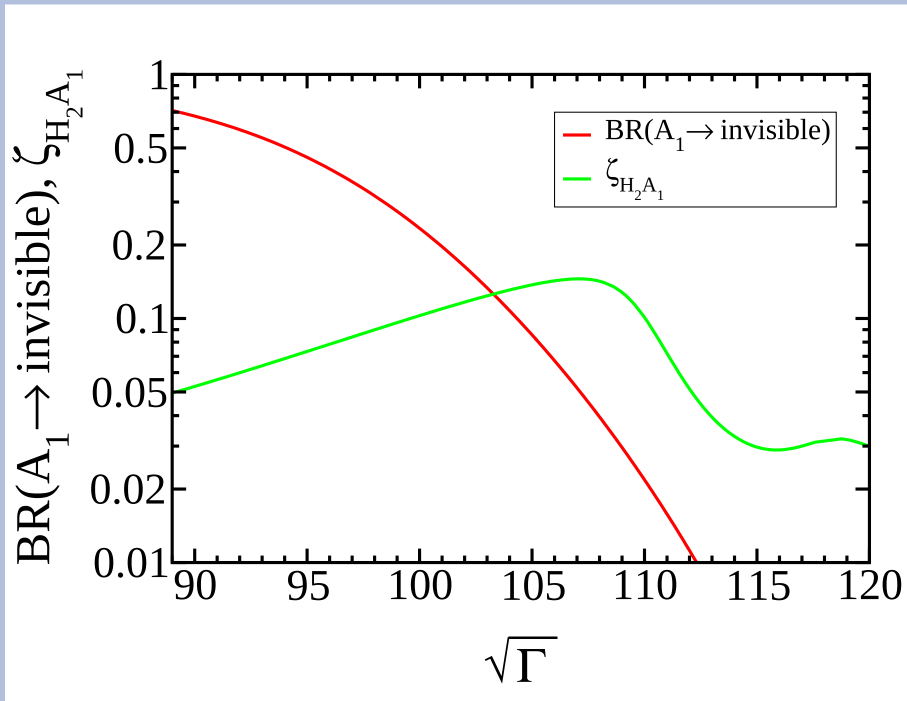
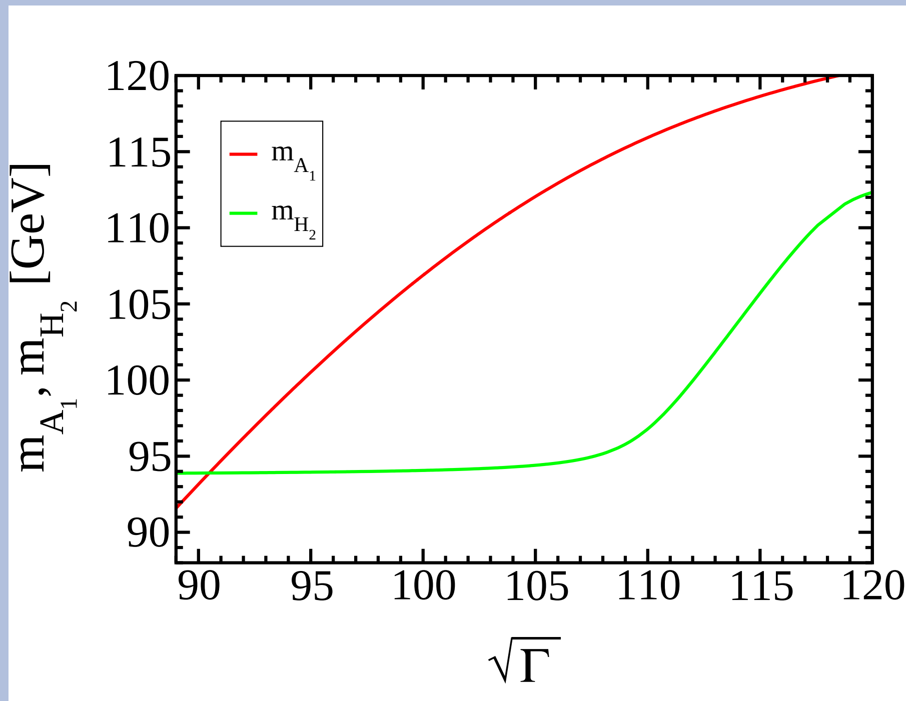
CP-odd Higgs Boson Decays





- ★ We can get a compromise of 10% invisible branching ratio and 0.1 associated production parameter
- ★ Masses are accessible for the next generation of colliders

Conclusions

- Experimental data: Neutrino oscillations

  $\Rightarrow$ Neutrinos are massive

  $\Rightarrow$ SM must be extended

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    - Mixing angles
  - Can give a solution to the μ problem
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  - It can have dominant invisible decay
  - Is is possible to have sizeable both production and invisible decay for the CP-odd Higgs boson

The End

g_{hJJ} Coupling

For

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

$$g_{H_d^{0R}JJ} = hh_0 v_u \frac{v_S v_R}{V^2}$$

$$g_{H_u^{0R}JJ} = hh_0 v_d \frac{v_S v_R}{V^2} - \frac{2v_u}{V^2} \sum_i \epsilon_i^2$$

where

$$V^2 = v_R^2 + v_S^2$$

★ For large h and h_0 $\Rightarrow$ Large $g_{H_i^0 JJ}$ coupling for H_i^0 mainly H_d^{0R} and H_u^{0R} (MSSM-like h)

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Three-neutrino Oscillation Parameters

- Neutrino mass squared differences:

$$\Delta m^2_{\mathrm{SOL}} \equiv \Delta m^2_{21} \equiv m^2_2 - m^2_1$$

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- Neutrino mixing angles:

$$\theta_{\rm SOL} \equiv \theta_{12}$$
$$\theta_{\rm ATM} \equiv \theta_{23}$$
$$\theta_{\rm CHOOZ} \equiv \theta_{13}$$

Experimental Values of the Parameters

Allowed intervals (at 3σ C.L.) for the 3-flavour neutrino oscillation parameters from global data (except LSND):

$$\Delta m^2_{21} = [\,7.2,\ 9.1\,] \times 10^{-5}\mathrm{eV}^2$$

$$\Delta m^2_{31} = [\,1.4,\ 3.3\,] \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{12} = [\,0.23,\ 0.38\,]$$

$$\sin^2\theta_{23} = [\,0.34,\ 0.68\,]$$

$$\sin^2\theta_{13} \leq 0.047$$

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:

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

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

★ Postulation of R_P conservation is not inevitable

Possible Solutions

- Postulation of baryonic parity conservation:

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

- Postulation of R_P 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