

Neutrino nature in mH-models and the invisible Higgs decays

Cesar Bonilla



In collaboration with *J.C.Romao, J.W.F.Valle.*

Based on [Phys.Rev.D91\(2015\)11,113015](#) and

[New J.Phys. 18 \(2016\) no.3, 033033](#)

Aim of the work

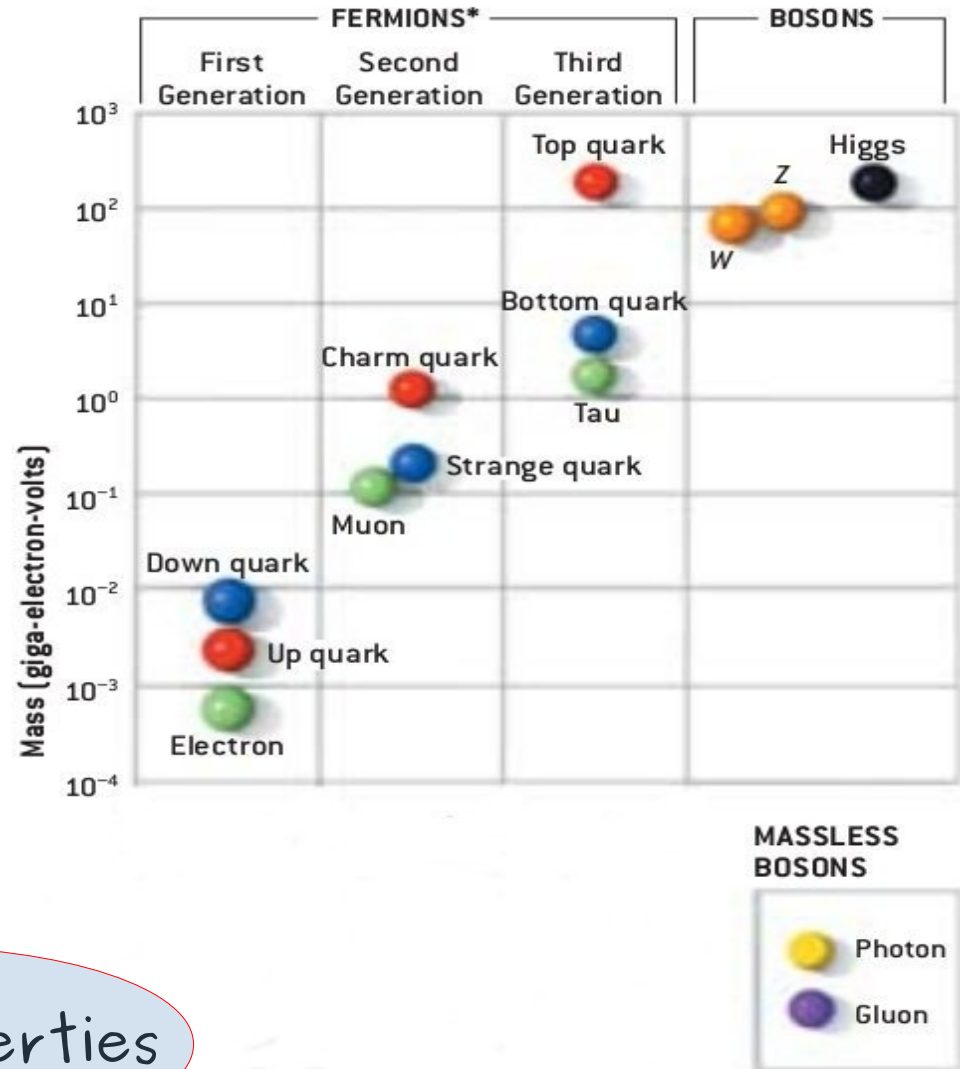


- Neutrino mass

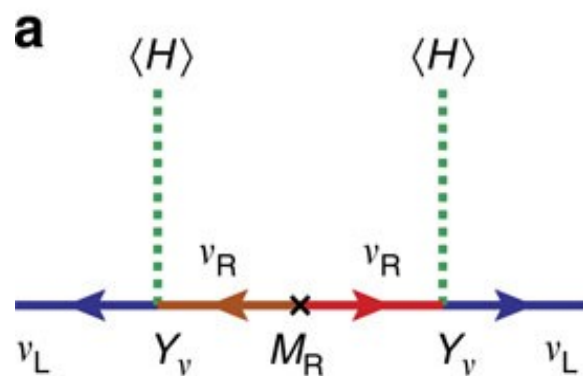
- Dark matter

- Flavor puzzle

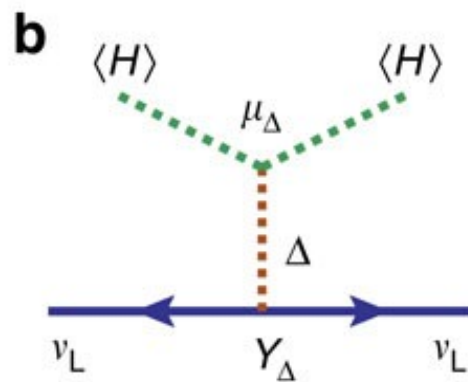
Higgs properties



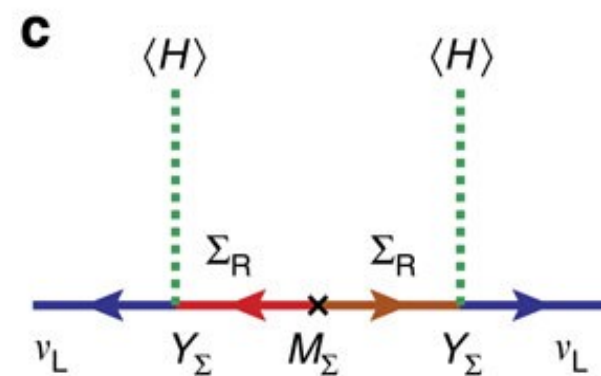
Canonical seesaw models



$$M_v = -\langle H \rangle^2 Y_v M_R^{-1} Y_v^T$$

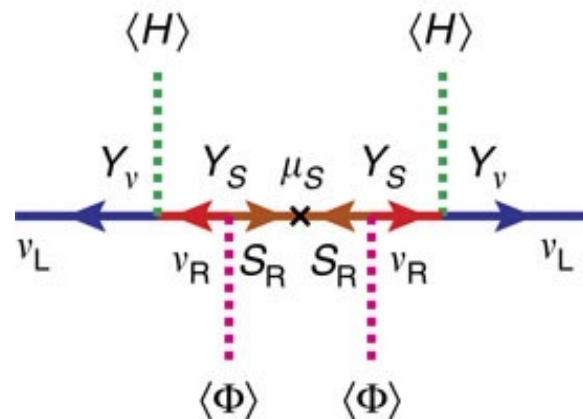


$$M_v = \langle H \rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$$



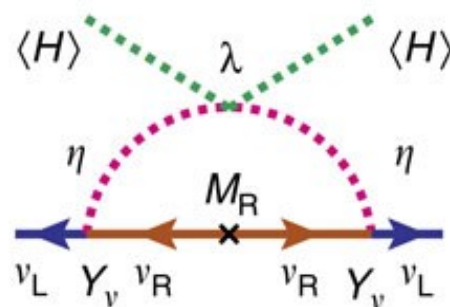
$$M_v = -\langle H \rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$$

d Inverse seesaw model



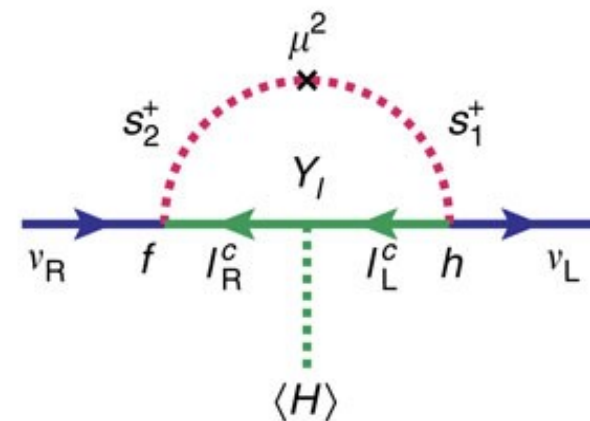
$$M_v = F \mu_S F^T$$

e The scotogenic model



$$M_v = -\lambda \frac{\langle H \rangle^2}{16\pi^2} Y_v M_R^{-1} Y_v^T$$

f Radiative Dirac model



$$M_v = \frac{h Y_I f}{16\pi^2} \langle H \rangle I(\mu^2, M_{s_1}^2, M_{s_2}^2)$$

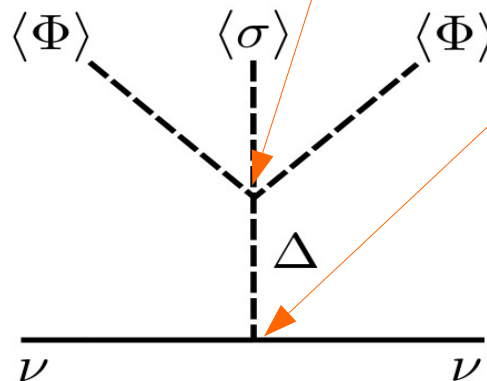
Majorana neutrinos @ low scale

123 Model

$$L_Y \supset y_{ij}^{\nu} L_i^T C \Delta L_j + h.c.$$

$$V \supset \kappa (\Phi^T \Delta \Phi \sigma + h.c.)$$

	σ	Φ	Δ
$SU(2)$	1	2	3
$U(1)_L$	2	0	-2



$$m_{\nu} = y^{\nu} \kappa v_1 \frac{v_2^2}{m_{\Delta}^2}$$

Physical scalars

Neutral: H_1, H_2, H_3, J, A

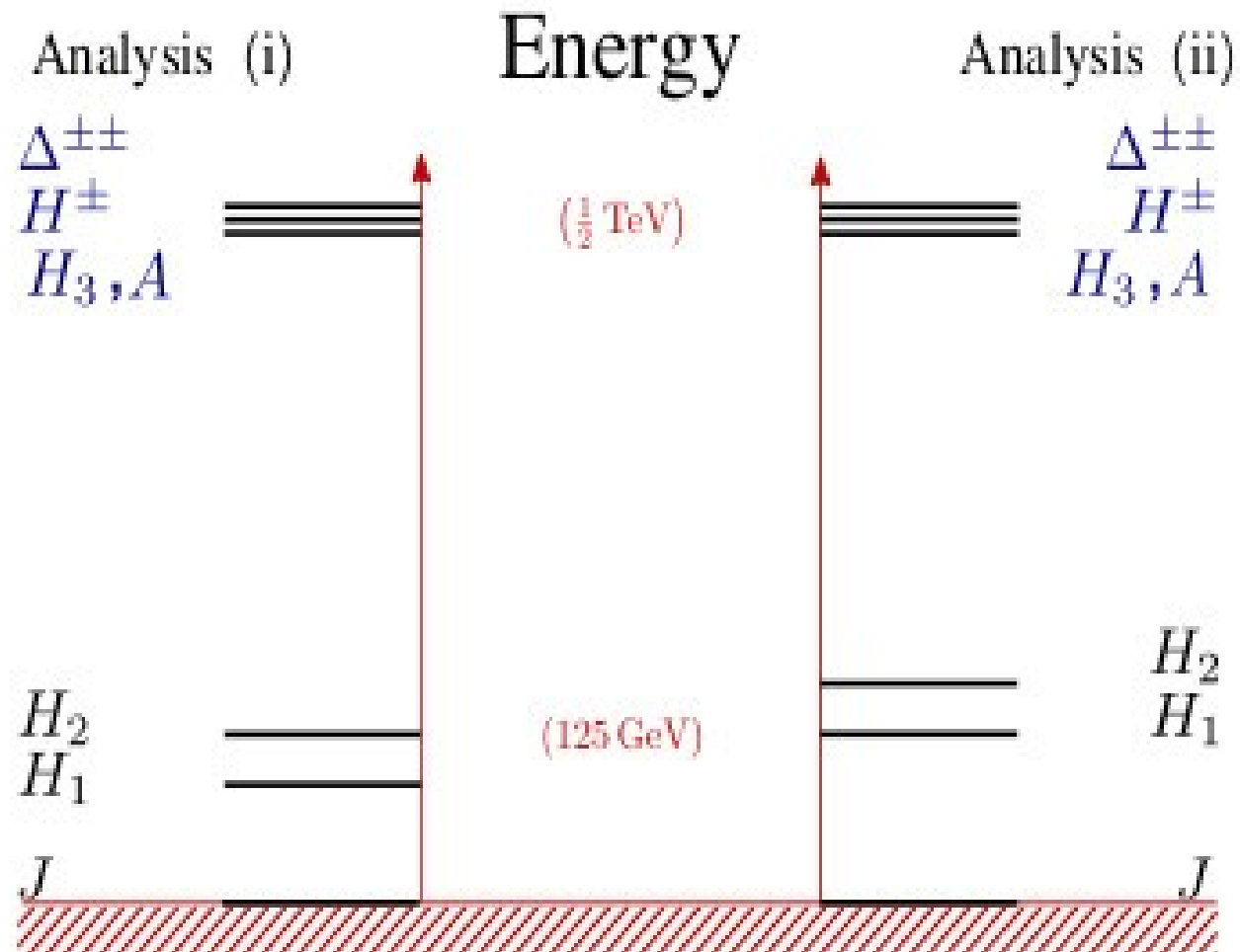
Charged: $H^{\pm}, \Delta^{\pm\pm}$

$$\langle \sigma \rangle = v_1$$

$$\langle \Phi \rangle = v_2$$

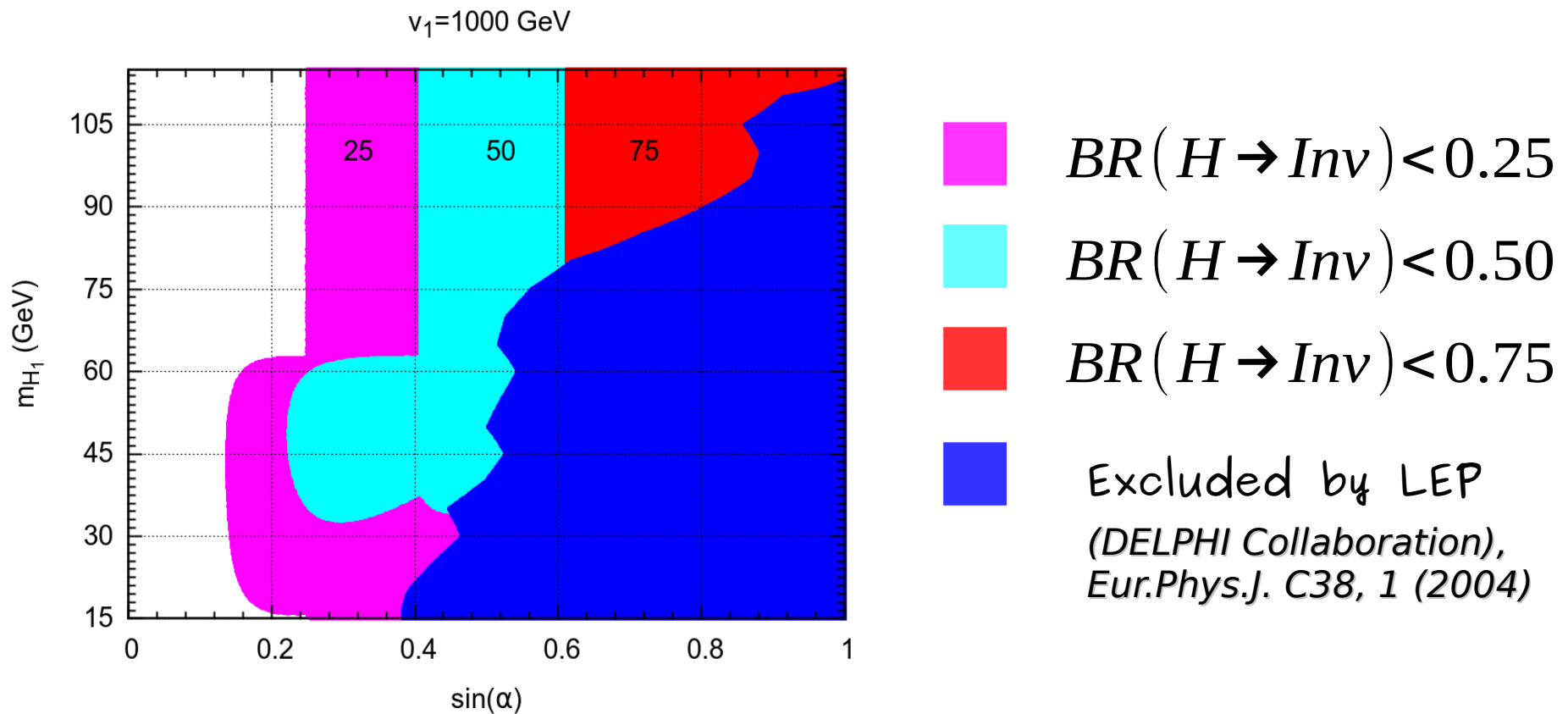
$$\langle \Delta \rangle = v_3$$

studied cases



Experimental constraints from LEP (Light scalar)

$$e^+ e^- \rightarrow Zh \rightarrow Z b \bar{b}$$



More details in, *Phys.Rev. D91(2015) 11, 113015*.

Experimental constraints from the LHC

● Higgs $h(125)$:

$$0.8 \leq \mu_{XX} \leq 1.2$$

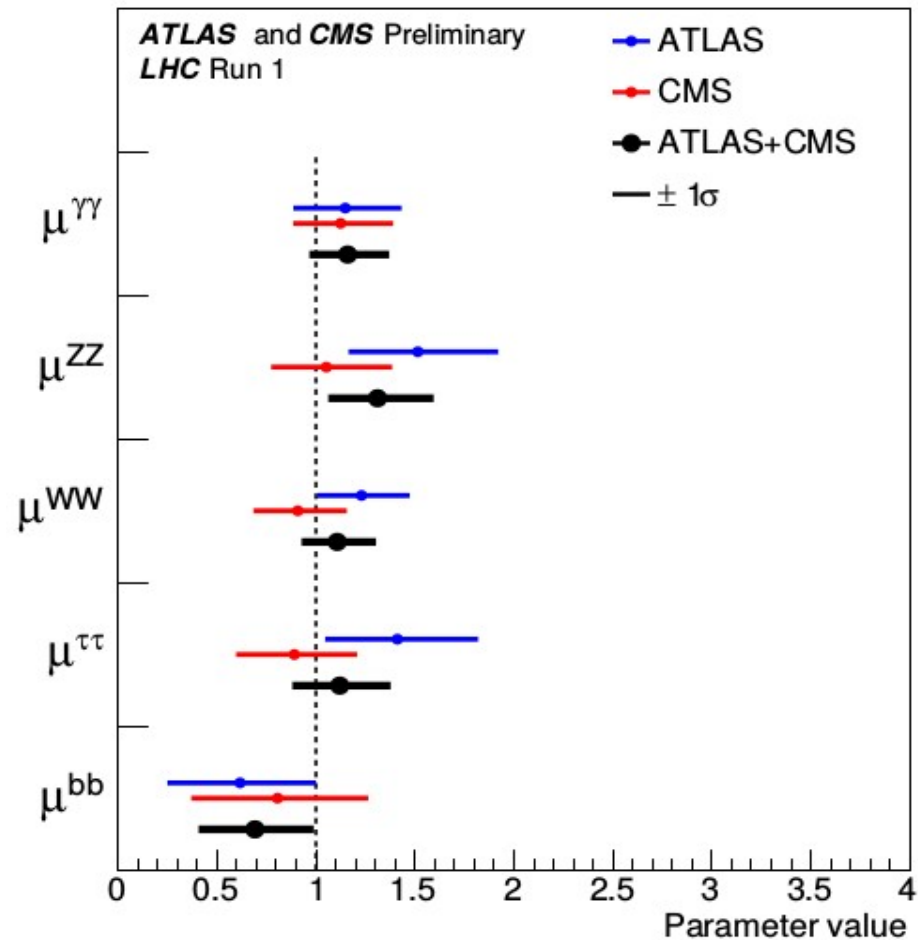


Figure taken from, *Technical Report ATLAS-CONF-2015-044, CERN, Geneva (2015)*.

Experimental constraints from the LHC

- bounds set by the search for a heavy Higgs in the decay channels:

$H \rightarrow VV$ in the range [145–1000] GeV. *JHEP* 1510 (2015) 144.

$H \rightarrow \tau\tau$ in the range [100–1000] GeV. *JHEP* 10 (2014) 160.

$A \rightarrow Zh$ in the range [220–1000] GeV. *Phys. Lett. B* 744 (2015) 163–183

- Doubly-charged:

$$v_3 \leq 10^{-4} \implies \Delta^{\pm\pm} \rightarrow l^{\pm} l^{\pm}$$

Doubly-charged masses in the range [200–400] GeV are excluded @ 95% C.L.

Eur. Phys. J. C72(2012) 2244.

$$v_3 > 10^{-4} \implies \Delta^{\pm\pm} \rightarrow W^{\pm} W^{\pm}$$

Constraint on $\langle \Delta \rangle = v_3$

- From the ρ -parameter:

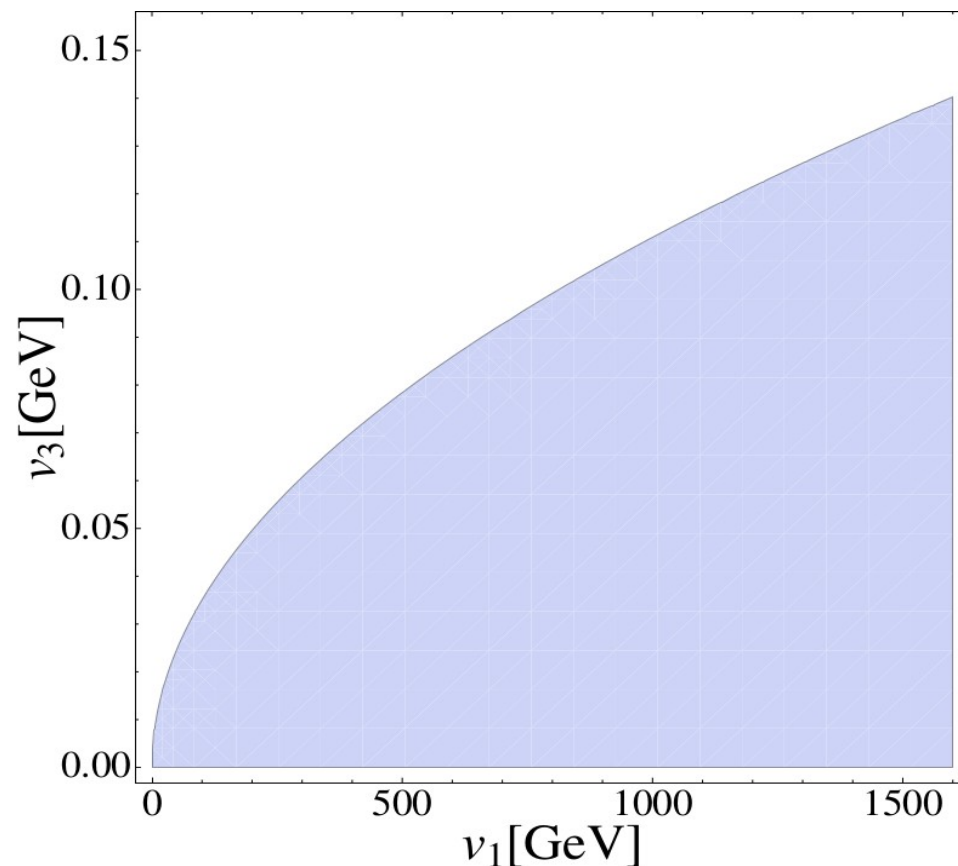
$$\rho = 1.0004 \pm 0.00024 \quad \longrightarrow \quad v_3 \leq 7 \text{ GeV}$$

(Particle Data Group), *Chin. Phys.* C38, 090001 (2014)

- From astrophysics (stellar cooling, $\gamma + e \rightarrow J + e$):

$$|g_{Jee}| < 10^{-13},$$

*Phys.Rev. D*42, 293 (1990)



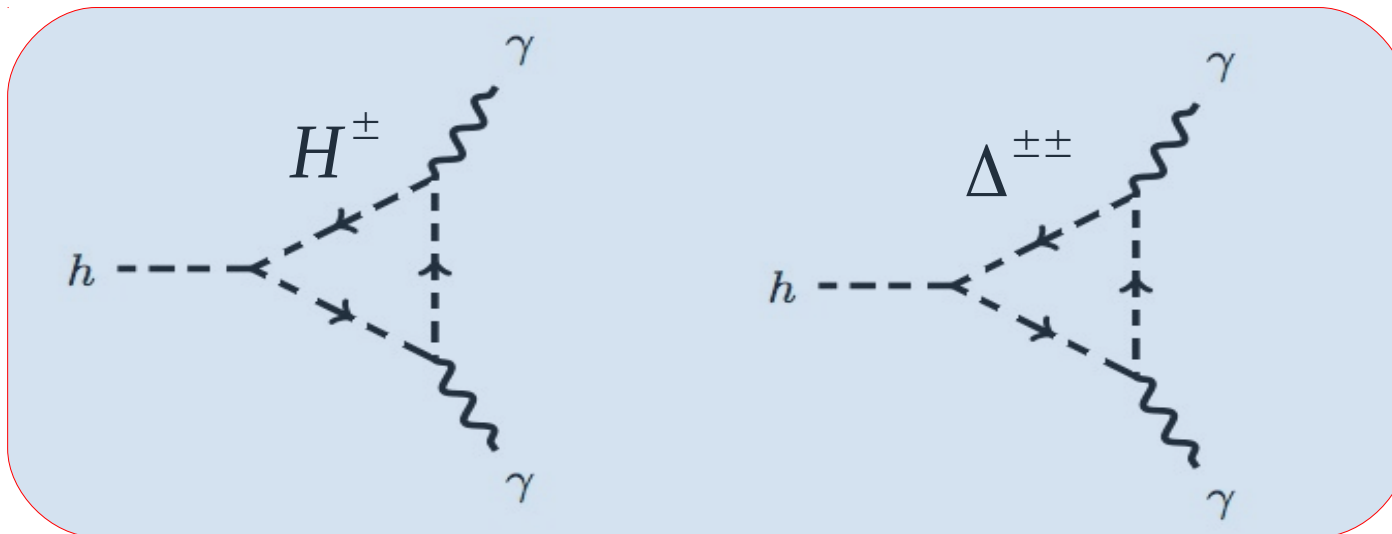
Non-SM Higgs decays

- Contribution to the invisible Higgs decays:

$$H_i \rightarrow J J$$

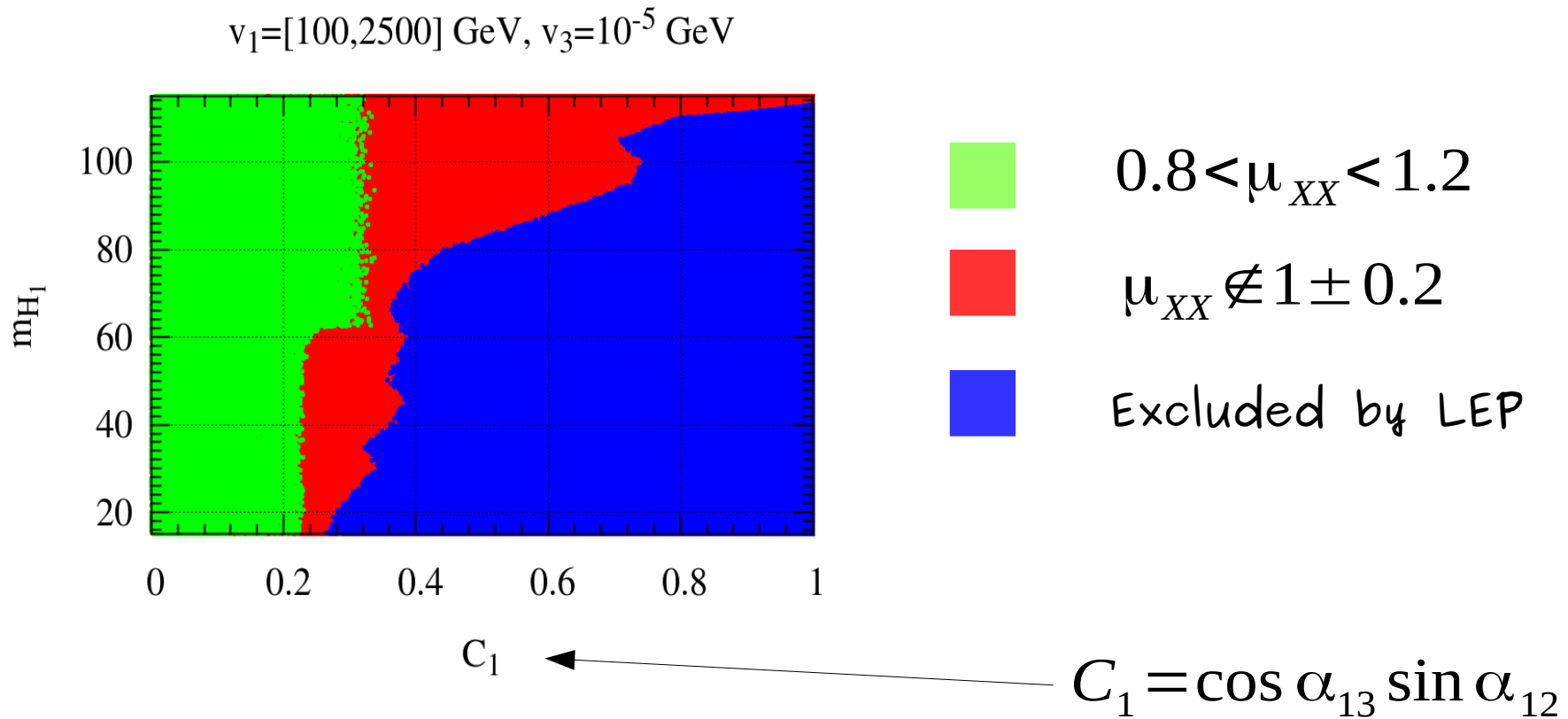
$$H_i \rightarrow H_j H_j \rightarrow 4 J \quad (i \neq j)$$

- Contribution to the visible Higgs decays:



Analysis i)

RESULTS



Mass spectrum

$$m_{H_2} = 125 \text{ GeV}$$

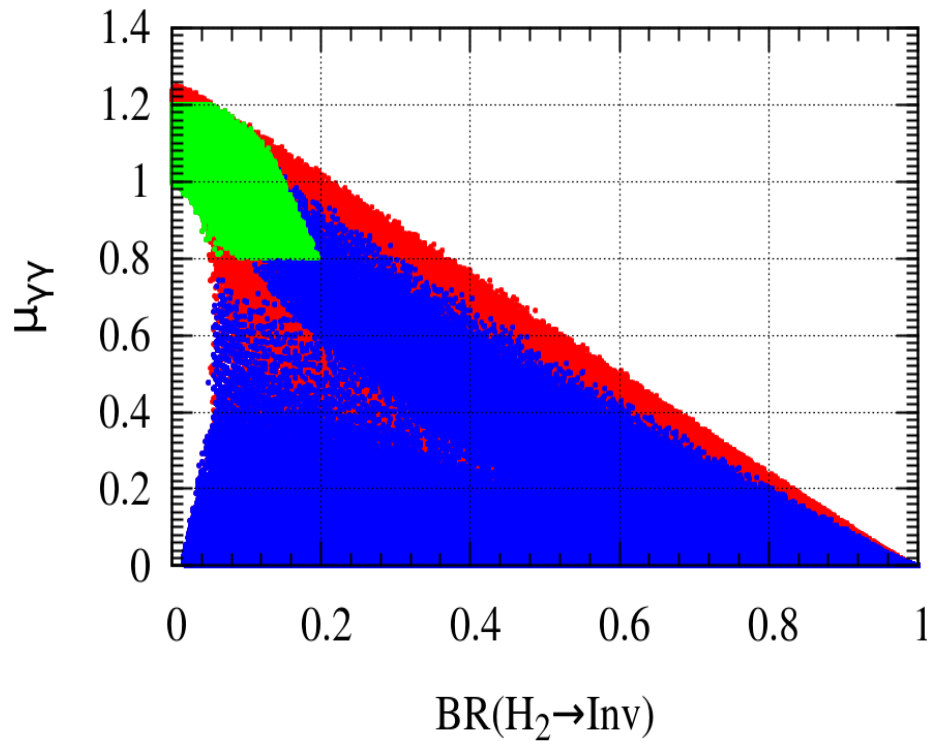
$$m_{H_3} \simeq m_A \simeq m_{H^\pm} \simeq m_{\Delta^{\pm\pm}} = 500 \text{ GeV}$$

$$\langle \sigma \rangle = v_1$$

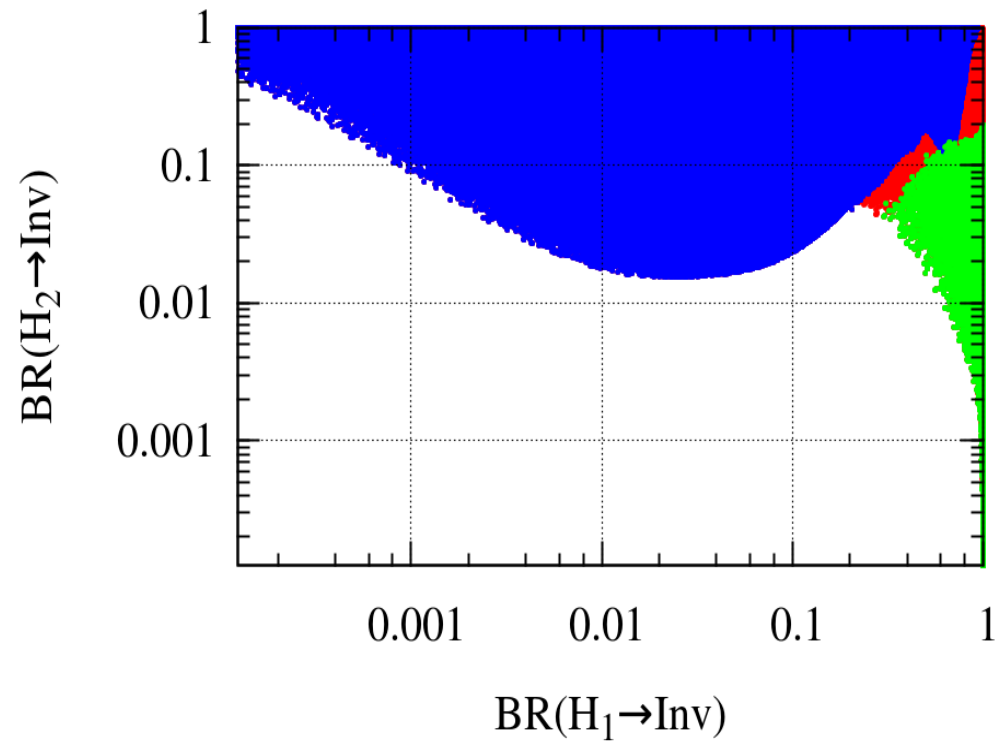
$$\langle \Phi \rangle = v_2$$

$$\langle \Delta \rangle = v_3$$

$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



$0.8 < \mu_{XX} < 1.2$

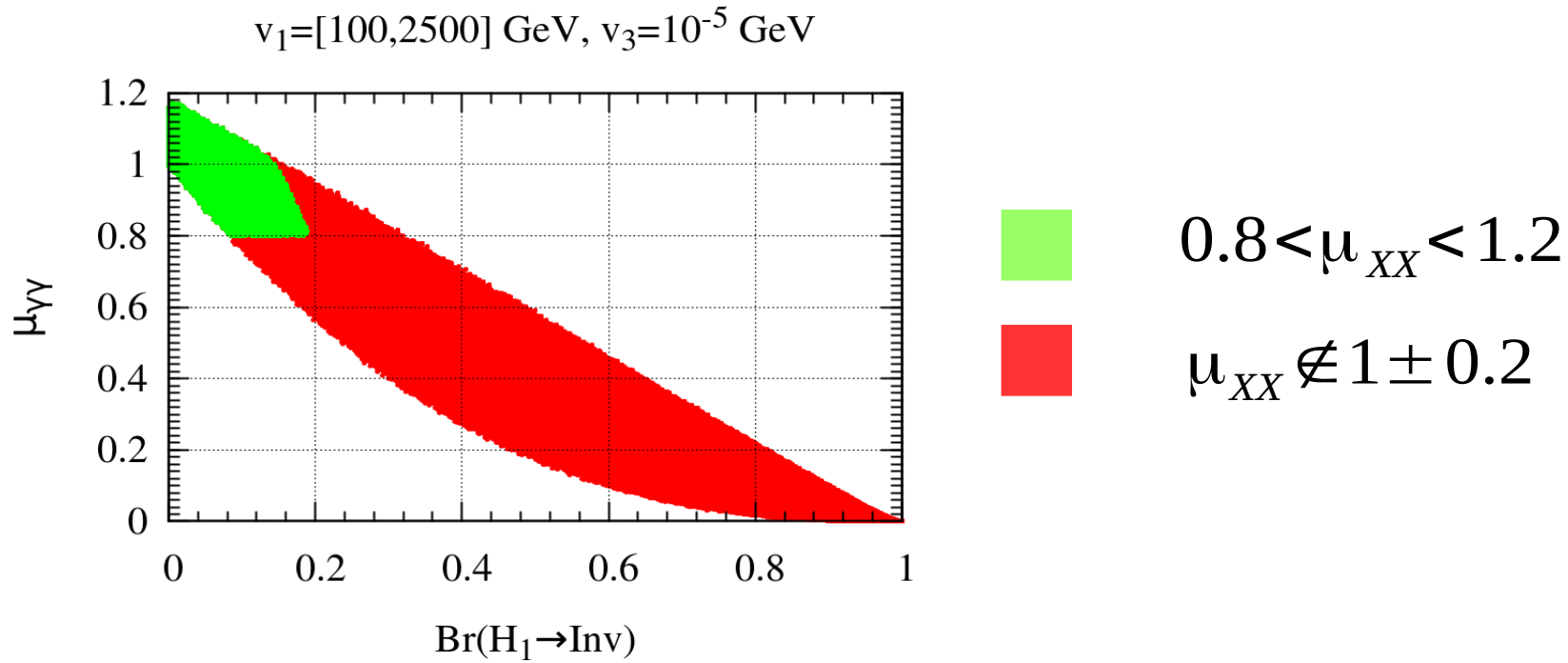
$\mu_{XX} \notin 1 \pm 0.2$

Excluded by LEP

ATLAS: $BR(H \rightarrow \text{Inv}) < 0.28$, JHEP 01 (2016) 172.

See also, Eur. Phys. J. C 74 (2014) and JHEP 1411 (2014) 039.

Analysis ii)



Mass spectrum

$$m_{H_1} = 125 \text{ GeV}$$

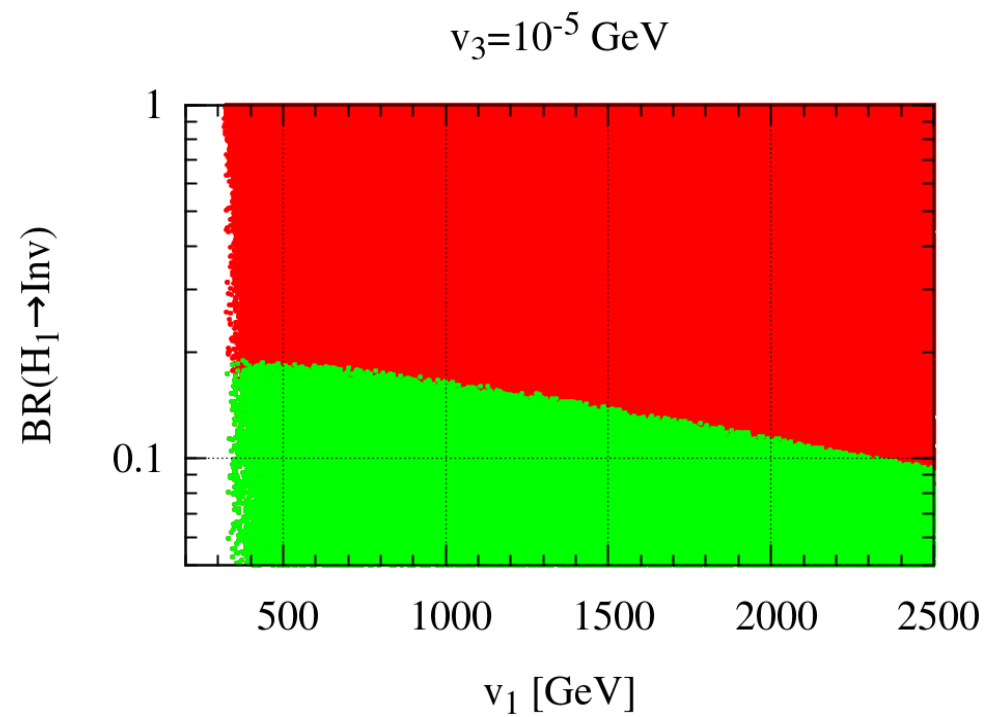
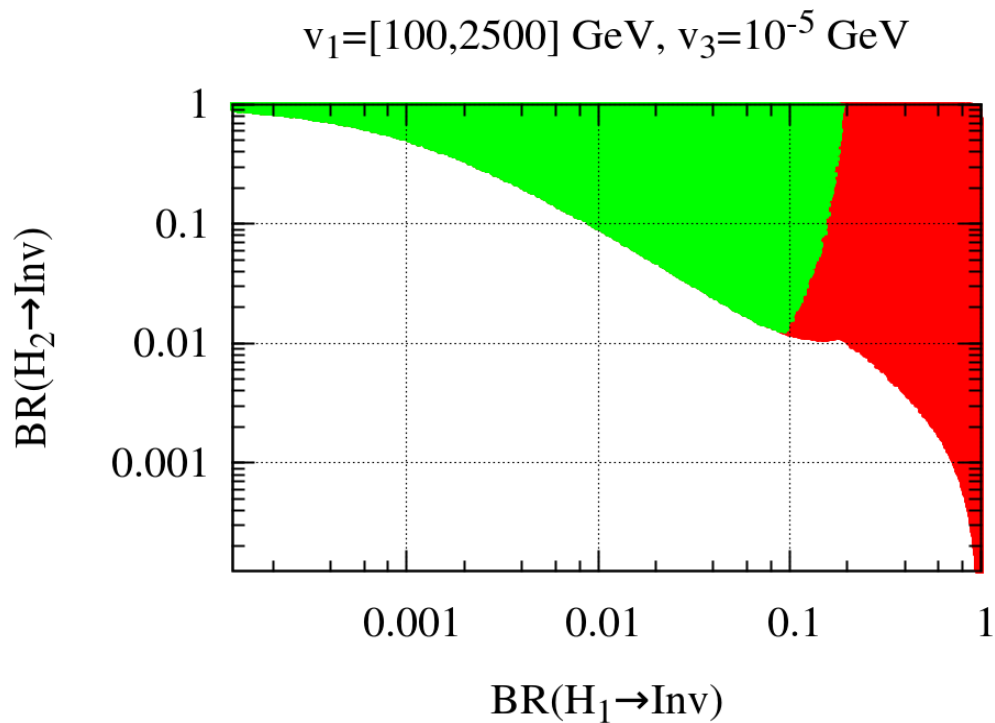
$$m_{H_2} = [150, 500] \text{ GeV}$$

$$m_{H_3} \simeq m_A \simeq m_{H^\pm} \simeq m_{\Delta^{\pm\pm}} = 600 \text{ GeV}$$

$$\langle \sigma \rangle = v_1$$

$$\langle \Phi \rangle = v_2$$

$$\langle \Delta \rangle = v_3$$



$0.8 < \mu_{XX} < 1.2$

$\mu_{XX} \notin 1 \pm 0.2$

The green region satisfy:

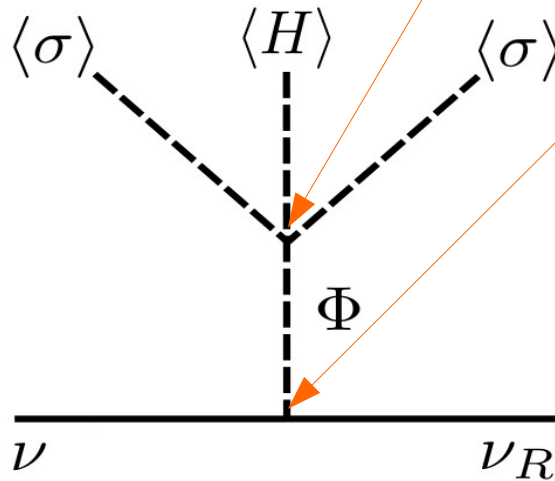
- Scalar potential is bounded from below.
- All experimental constraints, including the Bounds on searches of heavy scalars.

Dirac neutrinos @ low scale

122 Model

$$L_Y \supset y_{ij}^{\nu} \bar{L}_i \nu_{R_j} \Phi + h.c.$$

$$V \supset \kappa (\tilde{H}^+ \Phi \sigma^2 + h.c.)$$



$$m_{\nu} = y^{\nu} \kappa v_{\sigma}^2 \frac{v_H}{m_{\Phi}^2}$$

Physical scalars

Neutral: $H_1, H_2, H_3, D, A.$

Charged: $H^{\pm}.$

$$\langle \sigma \rangle = v_{\sigma}$$

$$\langle \Phi \rangle = v_{\Phi}$$

$$\langle H \rangle = v_H$$

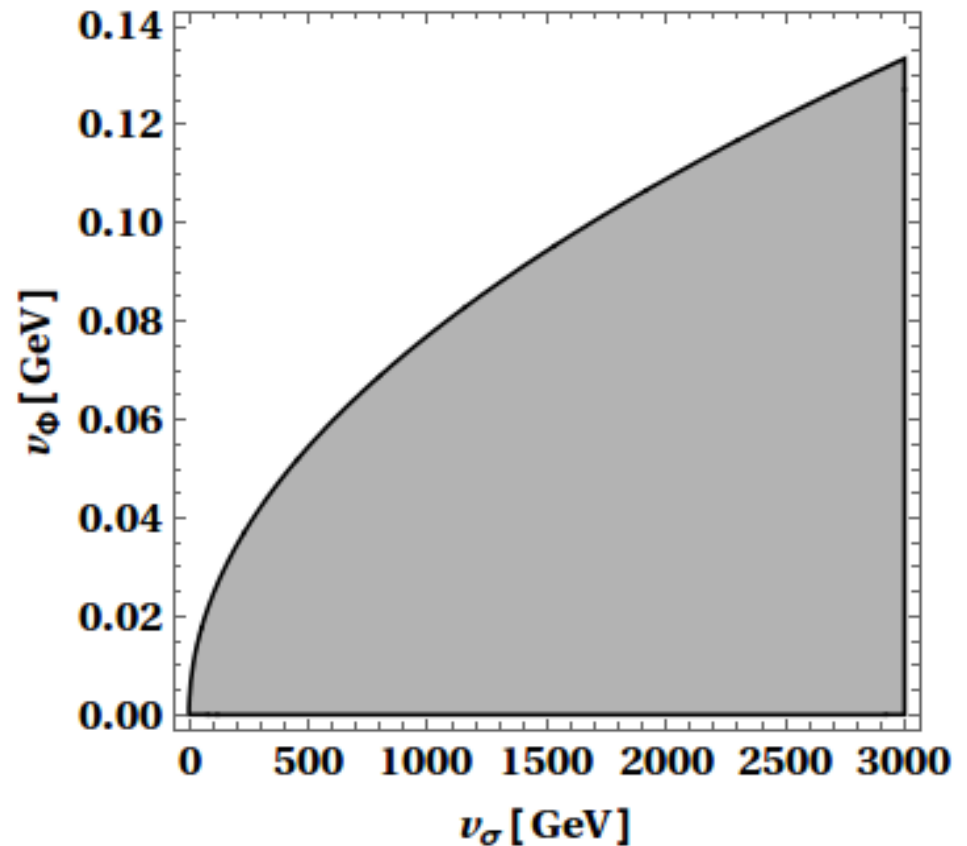
	σ	Φ	H
$SU(2)$	1	2	2
Z_5	α	α^3	1
Z_3	1	1	1

Constraint on $\langle \Phi \rangle = v_\Phi$

- No contribution to the ρ -parameter @ tree-level
- From astrophysics (stellar cooling, $\gamma + e \rightarrow D + e$):

$$|g_{Dee}| < 10^{-13},$$

Phys.Rev. D42, 293 (1990)



Features of the model

- Invisible Higgs decays connected to neutrino mass generation.
- LNC in the neutrino sector. No $\nu 0 \beta \beta$
- Flavor model?
- Other interesting signal in the Higgs sector?

SUMMARY

- neutrino physics is a nice “portal to PBSM”
@ low scale

Thank you!

BACKUP

123 Model

$$\Phi = \begin{bmatrix} \phi^0 \\ \phi^- \end{bmatrix} \quad \text{and} \quad \Delta = \begin{bmatrix} \Delta^0 & \frac{\Delta^+}{\sqrt{2}} \\ \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \end{bmatrix}$$

	σ	Φ	Δ
SU(2)	1	2	3
U(1)	2	0	-2

$$\mathcal{L}_Y = y_{ij}^d \bar{Q}_i u_{R_j} \Phi + y_{ij}^u \bar{Q}_i d_{R_j} \tilde{\Phi} + y_{ij}^\ell \bar{L}_i \ell_{R_j} \Phi + y_{ij}^\nu L_i^T C \Delta L_j + \text{h.c.}$$

$$\begin{aligned} V = & \mu_1^2 \sigma^* \sigma + \mu_2^2 \Phi^\dagger \Phi + \mu_3^2 \text{tr}(\Delta^\dagger \Delta) + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 [\text{tr}(\Delta^\dagger \Delta)]^2 \\ & + \lambda_3 \Phi^\dagger \Phi \text{tr}(\Delta^\dagger \Delta) + \lambda_4 \text{tr}(\Delta^\dagger \Delta \Delta^\dagger \Delta) + \lambda_5 (\Phi^\dagger \Delta^\dagger \Delta \Phi) + \beta_1 (\sigma^* \sigma)^2 \\ & + \beta_2 (\Phi^\dagger \Phi) (\sigma^* \sigma) + \beta_3 \text{tr}(\Delta^\dagger \Delta) (\sigma^* \sigma) - \kappa (\Phi^T \Delta \Phi \sigma + \text{h.c.}). \end{aligned}$$

123 Model

$$M_R^2 = \begin{bmatrix} 2\beta_1 v_1^2 + \frac{1}{2}\kappa v_2^2 \frac{v_3}{v_1} & \beta_2 v_1 v_2 - \kappa v_2 v_3 & \beta_3 v_1 v_3 - \frac{1}{2}\kappa v_2^2 \\ \beta_2 v_1 v_2 - \kappa v_2 v_3 & 2\lambda_1 v_2^2 & (\lambda_3 + \lambda_5) v_2 v_3 - \kappa v_1 v_2 \\ \beta_3 v_1 v_3 - \frac{1}{2}\kappa v_2^2 & (\lambda_3 + \lambda_5) v_2 v_3 - \kappa v_1 v_2 & 2(\lambda_2 + \lambda_4) v_3^2 + \frac{1}{2}\kappa v_2^2 \frac{v_1}{v_3} \end{bmatrix}.$$

$$M_I^2 = \kappa \begin{bmatrix} \frac{1}{2} v_2^2 \frac{v_3}{v_1} & v_2 v_3 & \frac{1}{2} v_2^2 \\ v_2 v_3 & 2v_1 v_3 & v_1 v_2 \\ \frac{1}{2} v_2^2 & v_1 v_2 & \frac{1}{2} v_2^2 \frac{v_1}{v_3} \end{bmatrix}.$$

$$M_{H^\pm}^2 = \begin{bmatrix} \kappa v_1 v_3 - \frac{1}{2}\lambda_5 v_3^2 & \frac{1}{2\sqrt{2}} v_2 (\lambda_5 v_3 - 2\kappa v_1) \\ \frac{1}{2\sqrt{2}} v_2 (\lambda_5 v_3 - 2\kappa v_1) & \frac{1}{4v_3} v_2^2 (-\lambda_5 v_3 + 2\kappa v_1) \end{bmatrix}.$$

$$m_A^2 = \kappa \left(\frac{v_2^2 v_1^2 + v_2^2 v_3^2 + 4v_3^2 v_1^2}{2v_3 v_1} \right).$$

$$m_{H^\pm}^2 = \frac{1}{4v_3} (2\kappa v_1 - \lambda_5 v_3) (v_2^2 + 2v_3^2).$$

Physical scalars

Neutral: H_1, H_2, H_3, J, A

Charged: $H^\pm, \Delta^{\pm\pm}$

$$m_{\Delta^{++}}^2 = \frac{1}{2v_3} (\kappa v_1 v_2^2 - 2\lambda_4 v_3^3 - \lambda_5 v_2^2 v_3).$$

Nucl.Phys. B527, 44 (1998)

Theoretical constraint (BFB conditions)

$$\begin{aligned} \lambda_1 > 0, \quad \beta_1 > 0, \quad \lambda_{24} > 0, \quad \hat{\lambda} \equiv \beta_2 + 2\sqrt{\beta_1 \lambda_1} > 0, \\ \tilde{\lambda} \equiv \beta_3 + 2\sqrt{\beta_1 \lambda_{24}} > 0, \quad \bar{\lambda} \equiv \lambda_3 + \theta(-\lambda_5)\lambda_5 + 2\sqrt{\lambda_1 \lambda_{24}} > 0, \quad \text{and} \\ \sqrt{\beta_1 \lambda_1 \lambda_{24}} + [\lambda_3 + \theta(-\lambda_5)\lambda_5] \sqrt{\beta_1} + \beta_2 \sqrt{\lambda_{24}} + \beta_3 \sqrt{\lambda_1} + \sqrt{\hat{\lambda} \tilde{\lambda} \bar{\lambda}} > 0, \end{aligned}$$

Experimental constraints from the LHC

- Higgs $h(125)$: $0.8 \leq \mu_{XX} \leq 1.2$
- bounds set by the search for a heavy Higgs in the decay channels:
 - ✗ $H \rightarrow VV$ in the range $[145-1000]$ GeV.
 - ✗ $H \rightarrow \tau\tau$ in the range $[100-1000]$ GeV.
 - ✗ $A \rightarrow Zh$ in the range $[220-1000]$ GeV.
- Doubly-charged:
 $\Delta^{\pm\pm} \rightarrow (l^{\pm} l^{\pm}, W^{\pm} W^{\pm}, W^{\pm} H^{\pm}, H^{\pm} H^{\pm})$

SUM RULE

Sum rules (like in the TypeII seesaw model):

$$m_{H^+}^2 - m_{\Delta^{++}}^2 \approx m_A^2 - m_{H^+}^2 \approx \frac{\lambda_5 v_2^2}{4}$$

Because the smallness of the triplet's vev:

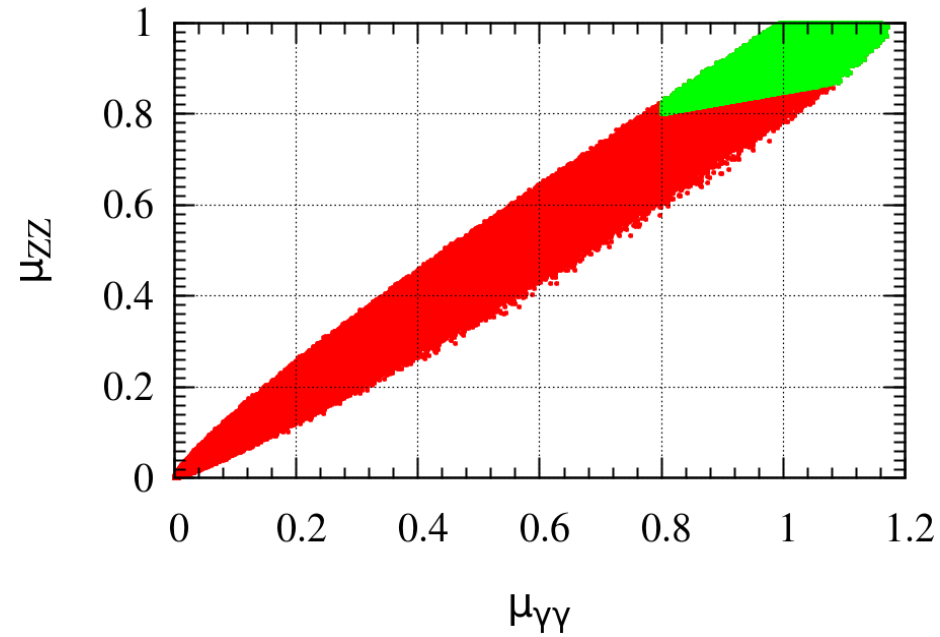
$$m_{H_3}^2 - m_A^2 \approx 2\lambda_2 v_3^2 \Rightarrow m_{H_3} \approx m_A$$

The coupling of H_3 to the SM is very small in both cases:

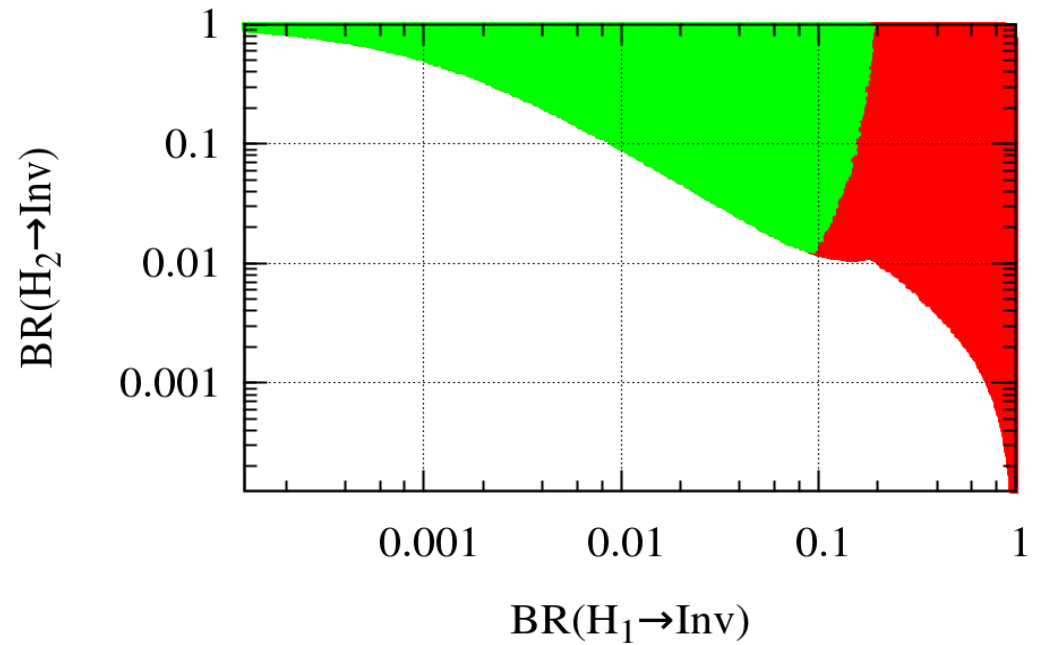
$$\frac{g_{H_3 ff}^{SM}}{g_{hff}^{SM}} = \frac{g_{H_3 VV}^{SM}}{g_{hVV}^{SM}} = C_3 \sim 10^{-7}$$

CASE II : Heavies

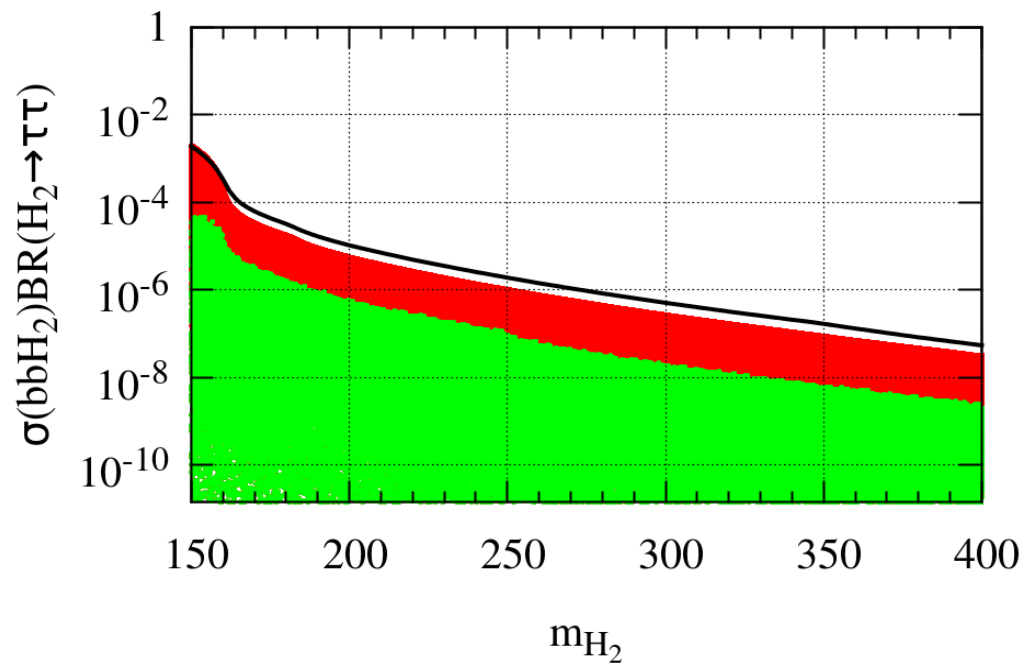
$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



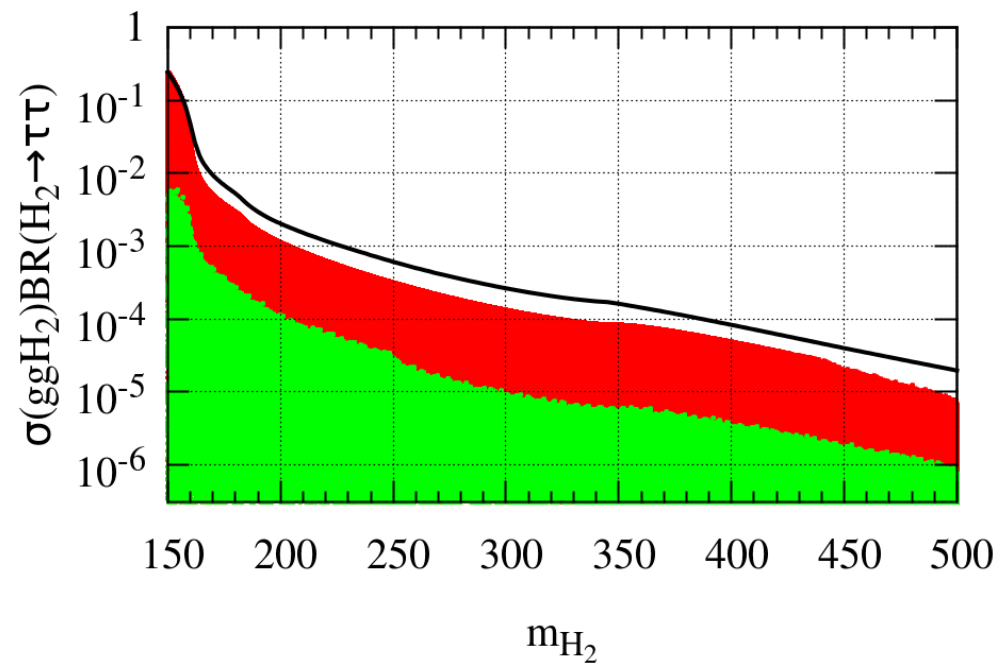
$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



$v_1=[100,2500]$ GeV, $v_3=10^{-5}$ GeV



Experimental constraints

ON ν_3

- From astrophysics (stellar cooling, $\gamma + e \rightarrow J + e$)

$$|g_{Jee}| = |O_{12}^I m_e / \nu_2|,$$

$$|\langle J | \phi \rangle| = \frac{2|\nu_2| \nu_3^2}{\sqrt{\nu_1^2 (\nu_2^2 + 4\nu_3^2)^2 + 4\nu_2^2 \nu_3^4 + \nu_2^4 \nu_3^2}} \lesssim 10^{-7}.$$

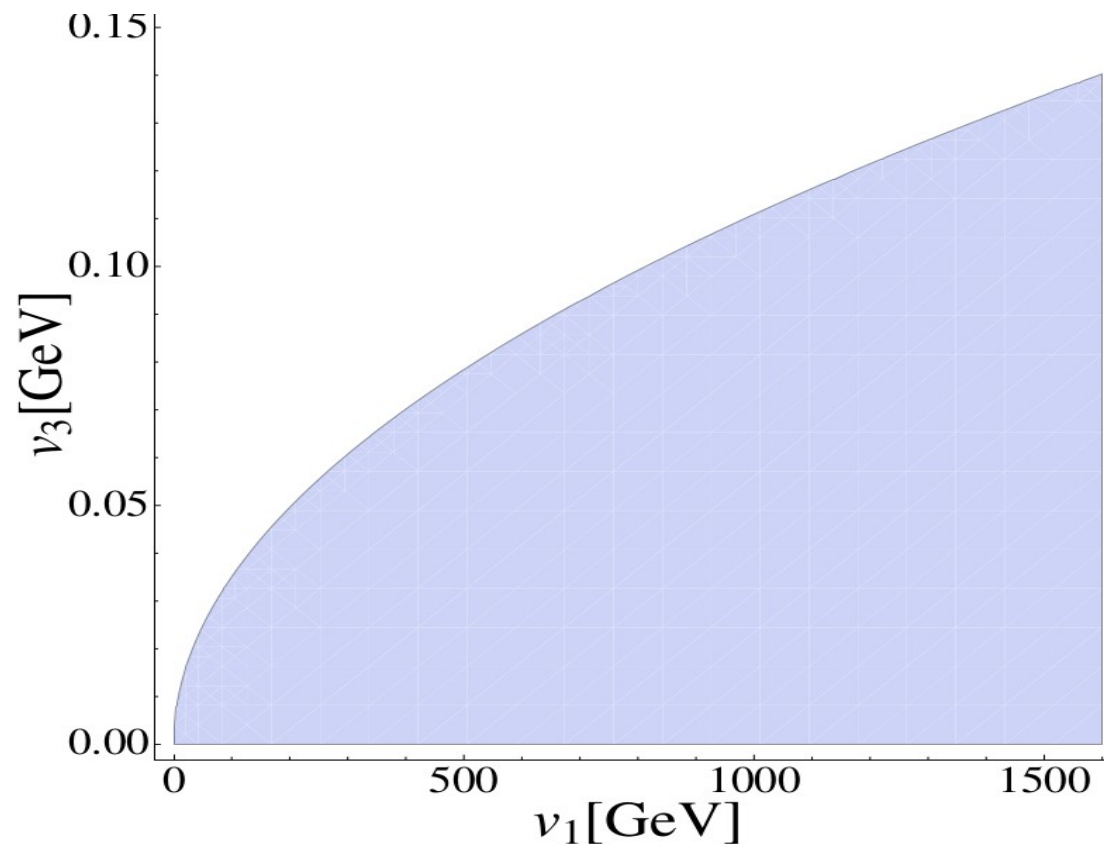
Other bounds on invisible decays

CMS: $BR(H \rightarrow Inv) < 0.58$, Eur. Phys. J. C 74 (2014) 2980.

Fit: $BR(H \rightarrow Inv) < 0.39$, JHEP 1411 (2014) 039.

Experimental constraints on v_3

$$|\langle J|\phi\rangle| = \frac{2|v_2|v_3^2}{\sqrt{v_1^2(v_2^2 + 4v_3^2)^2 + 4v_2^2v_3^4 + v_2^4v_3^2}} \lesssim 10^{-7}.$$



$$\Delta m_{31}^2 = 2.5_{-0.16}^{+0.09} \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 = 7.59_{-0.18}^{+0.20} \times 10^{-5} \text{ eV}^2$$

