Neutrino mass and the invisible Higgs decays

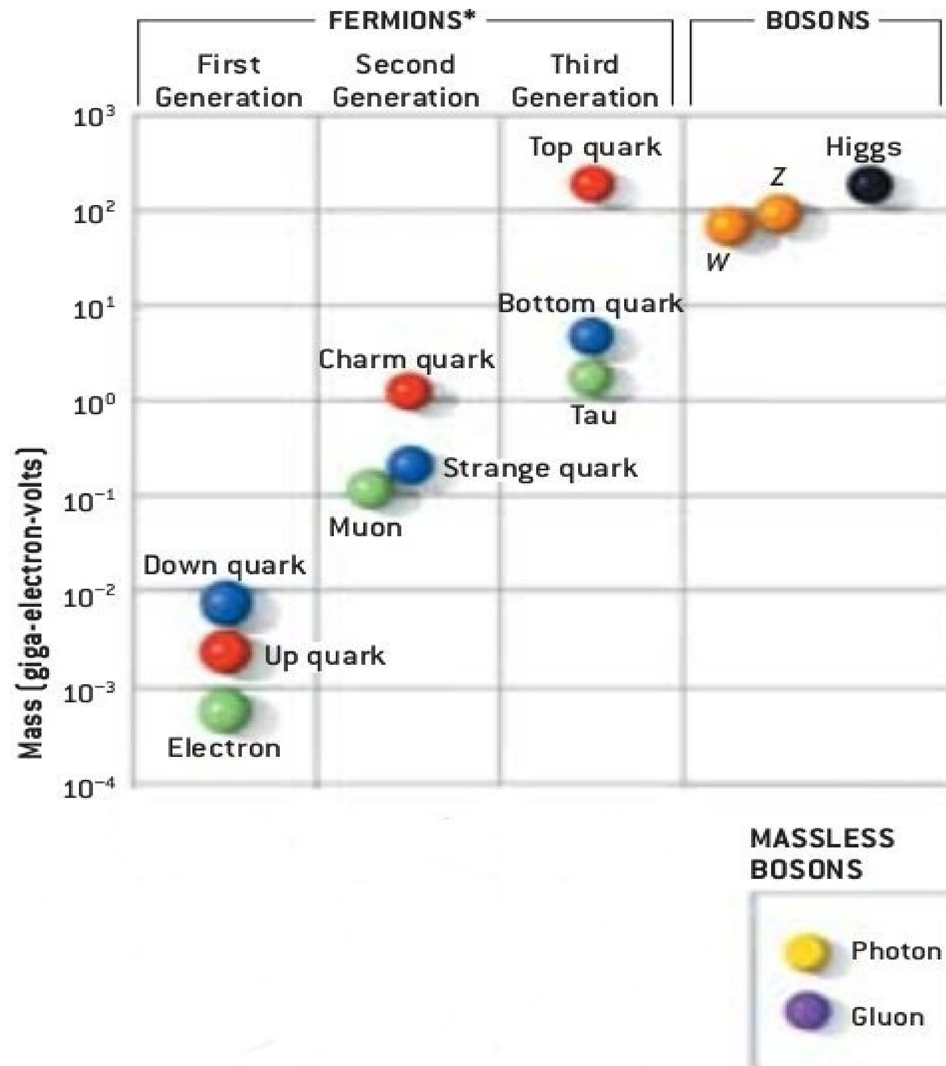
Cesar Bonilla

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

Particle content in the SM

- Neutrino mass
- Dark matter
- Flavor problem

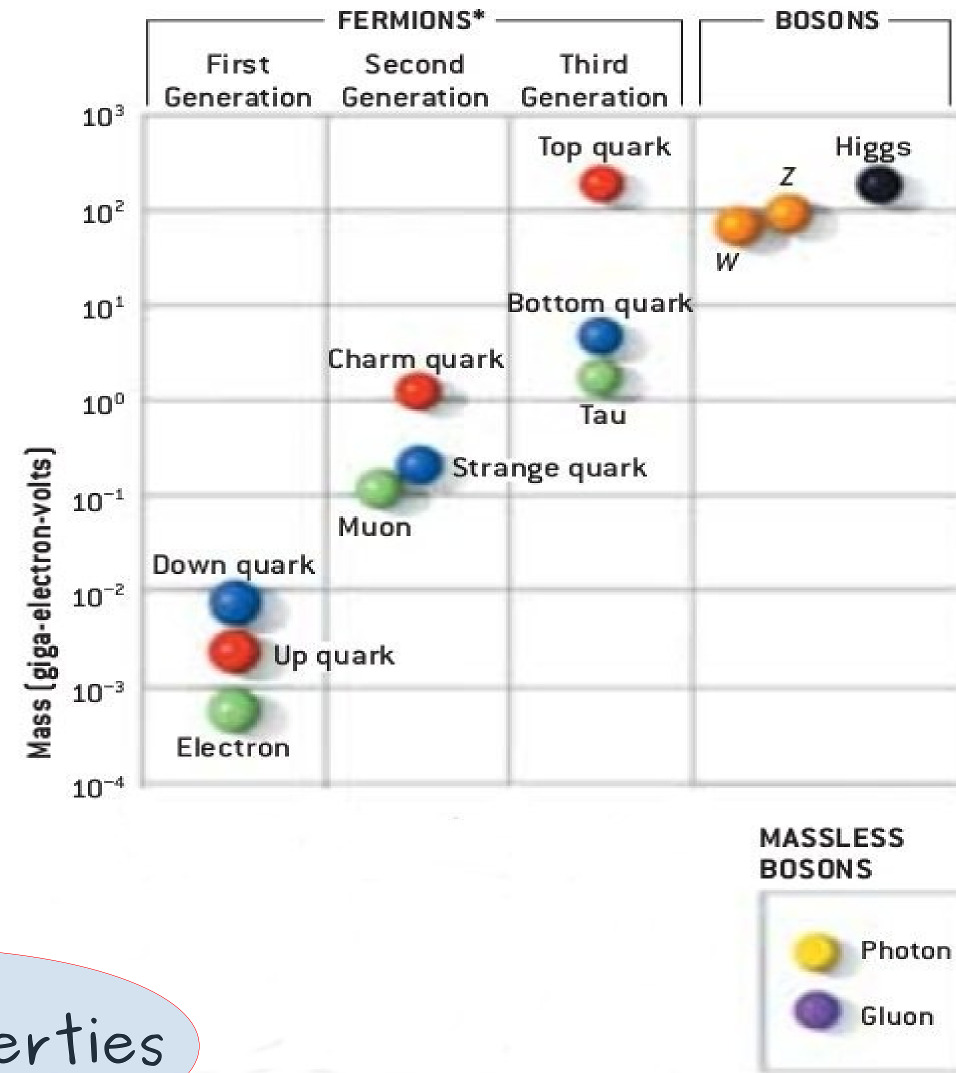


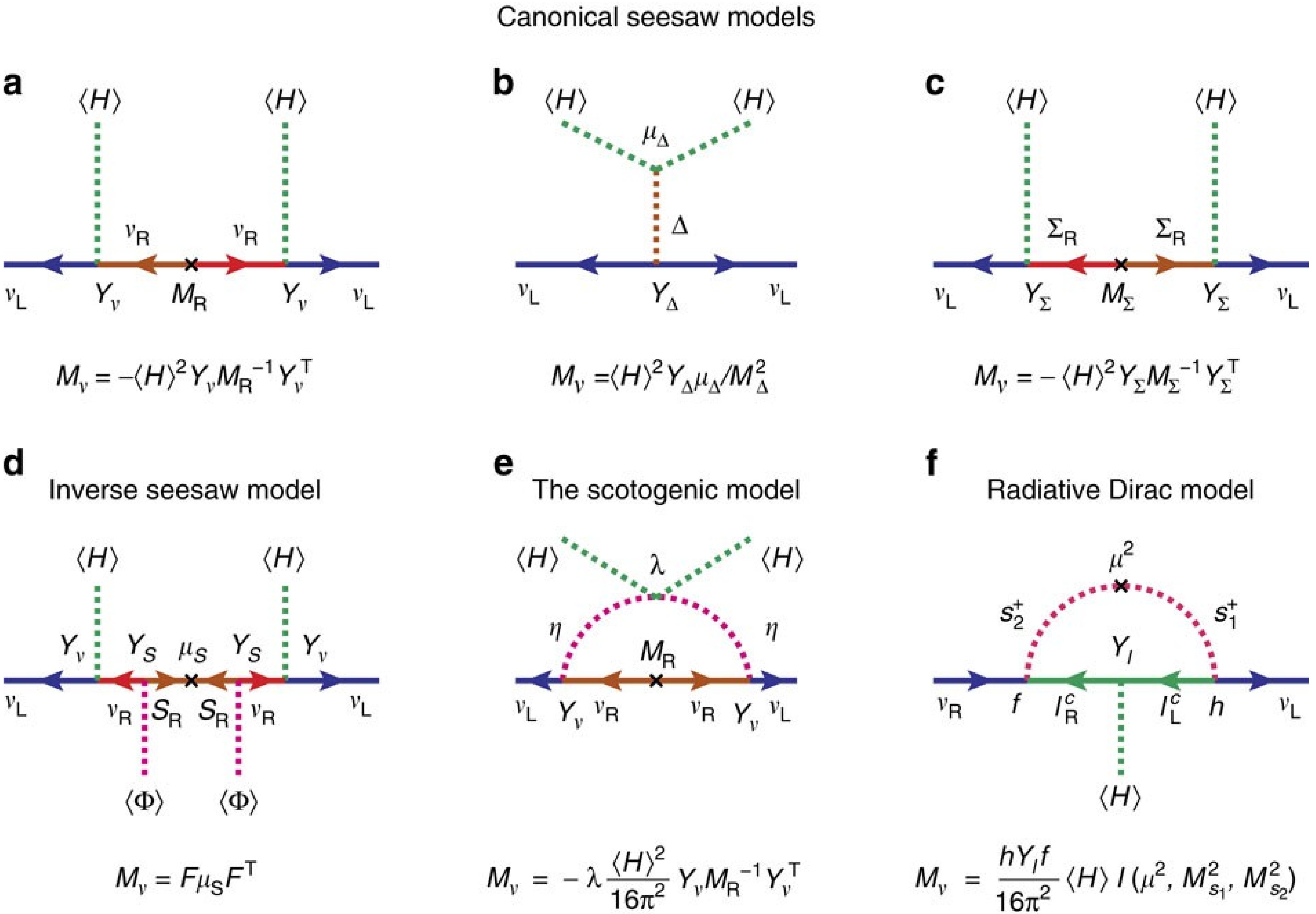
Aim of the work

?

- Neutrino mass
- Dark matter
- Flavor problem

Higgs properties




Canonical seesaw models
a
⟨H⟩
⟨H⟩
ν_R
ν_R
ν_L
Y_ν
M_R
Y_ν
ν_L
$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$
b
⟨H⟩
⟨H⟩
μ_Δ
Δ
ν_L
Y_Δ
ν_L
$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$
c
⟨H⟩
⟨H⟩
Σ_R
Σ_R
ν_L
Y_Σ
M_Σ
Y_Σ
ν_L
$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$
d
Inverse seesaw model
⟨H⟩
⟨H⟩
Y_ν
Y_S
μ_S
Y_S
Y_ν
ν_L
ν_R
S_R
S_R
ν_R
ν_L
⟨Φ⟩
⟨Φ⟩
$M_\nu = F\mu_S F^T$
e
The scotogenic model
⟨H⟩
λ
⟨H⟩
η
η
M_R
ν_L
Y_ν
ν_R
ν_R
Y_ν
ν_L
$M_\nu = -\lambda \frac{\langle H\rangle^2}{16\pi^2} Y_\nu M_R^{-1} Y_\nu^T$
f
Radiative Dirac model
μ²
s₂⁺
s₁⁺
Y_l
ν_R
f
l_R^c
l_L^c
h
ν_L
⟨H⟩
$M_\nu = \frac{hY_l f}{16\pi^2} \langle H\rangle\, I(\mu^2, M_{s_1}^2, M_{s_2}^2)$

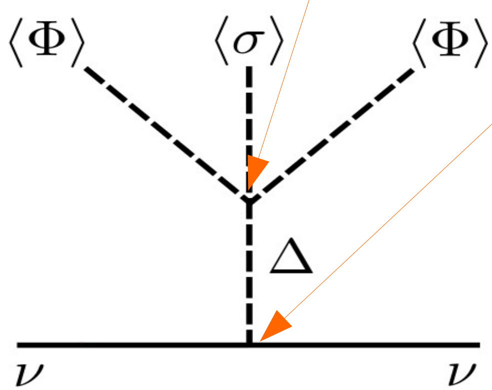
Nucl.Phys. B527, 44 (1998)

123 Model

$$L_Y \supset y^{\nu}_{ij} L^T_i C \Delta L_j + h.c.$$

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

	σ	Φ	Δ
$SU(2)$	**1**	**2**	**3**
$U(1)_L$	2	0	-2



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

Physical scalars

Neutral: H_1, H_2, H_3, J, A

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

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

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

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

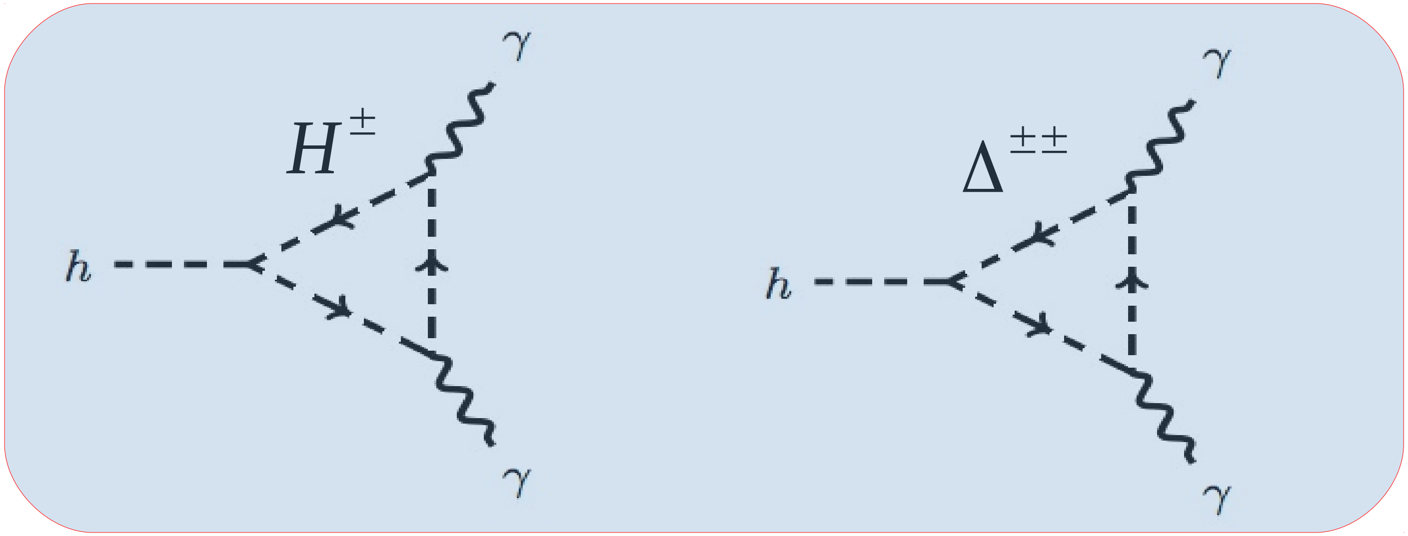
Non-SM Higgs decays

- Contribution to the invisible Higgs decays:

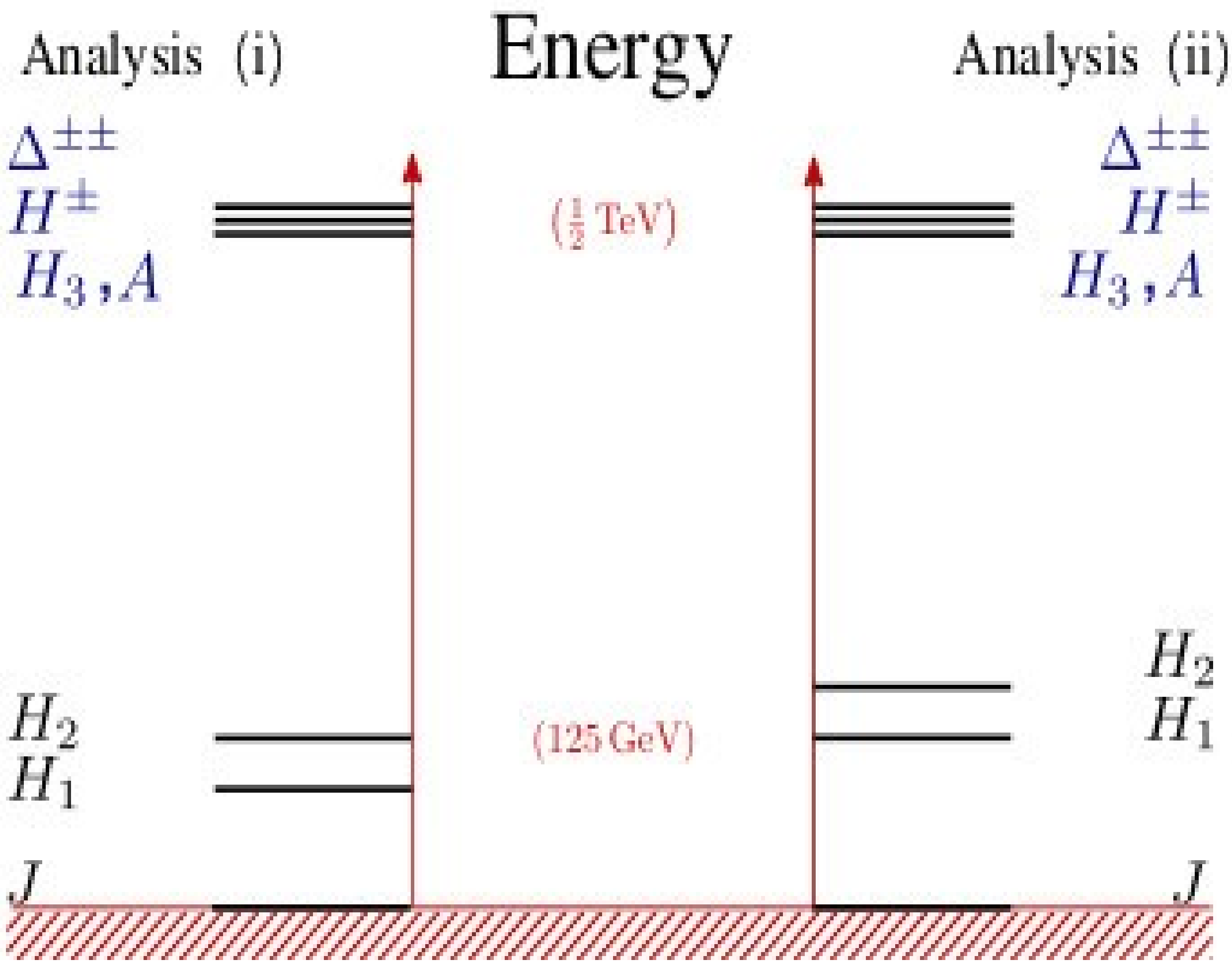
$$H_i \rightarrow J\,J$$

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

- Contribution to the visible Higgs decays:

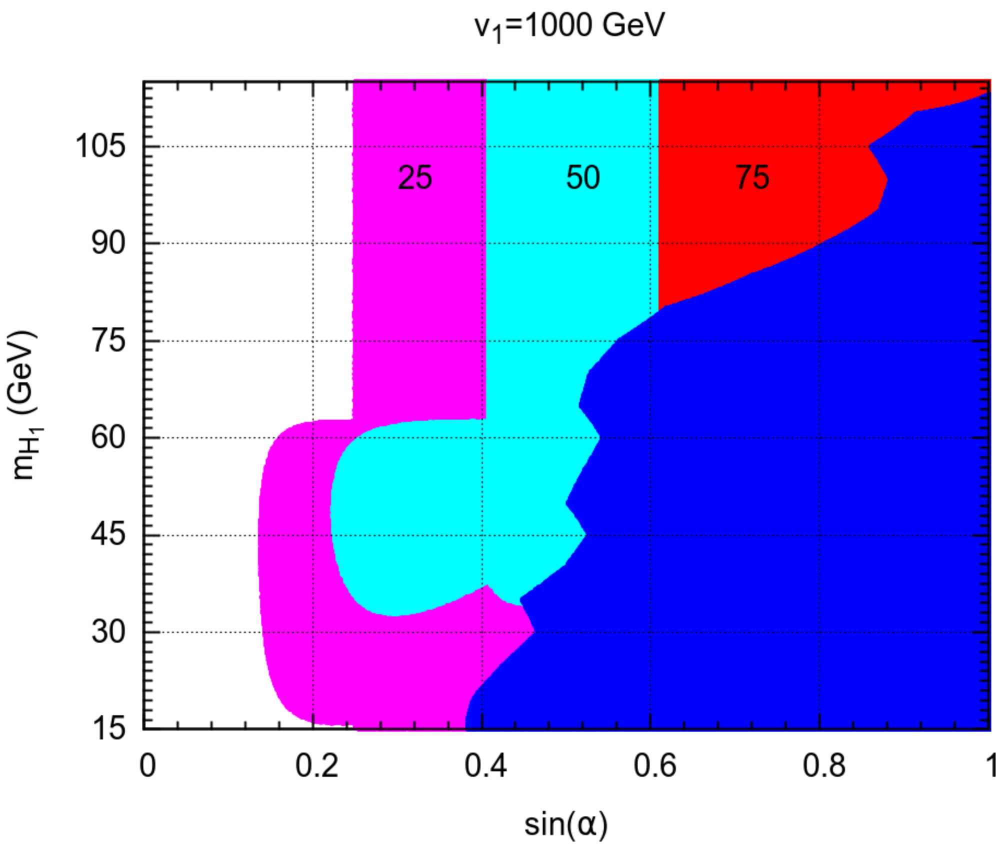


Studied cases



Experimental constraints from LEP (Light scalar)

$$e^+e^- \to Zh \to Zb\bar{b}$$



$BR(H \to Inv) < 0.25$

$BR(H \to Inv) < 0.50$

$BR(H \to Inv) < 0.75$

Forbidden by LEP

(DELPHI Collaboration), Eur.Phys.J. C38, 1 (2004)

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

Experimental constraints from the LHC

- Higgs h(125):

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

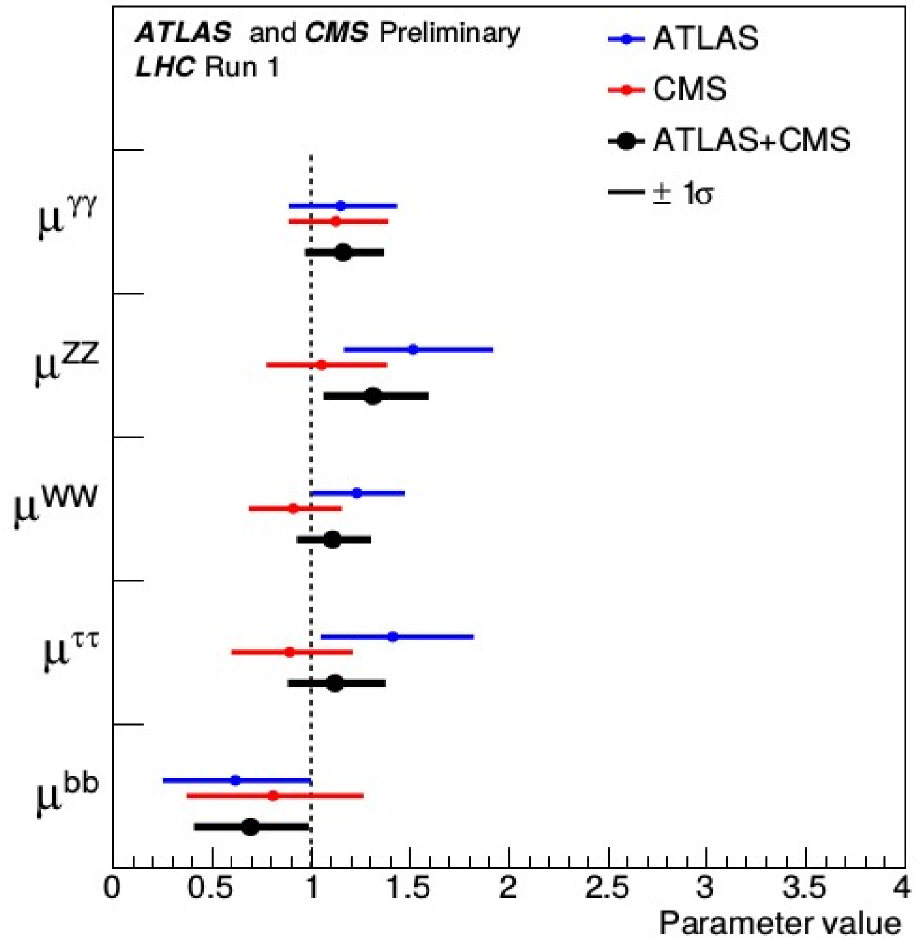


Figure taken from, *Technical Report ATLAS-CONF-2015-044, CERN, Geneva (2015).*

Experimental constraints from the LHC

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

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

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

$A \to Zh$ in the range [220–1000] GeV. *Phys. Lett. B744 (2015) 163-183*

- Doubly-charged:

$v_3 \leqslant 10^{-4} \Longrightarrow \Delta^{\pm\pm} \to l^{\pm} l^{\pm}$

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

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

$v_3 > 10^{-4} \Longrightarrow \Delta^{\pm\pm} \to W^{\pm} W^{\pm}$

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

- From the ρ-parameter:

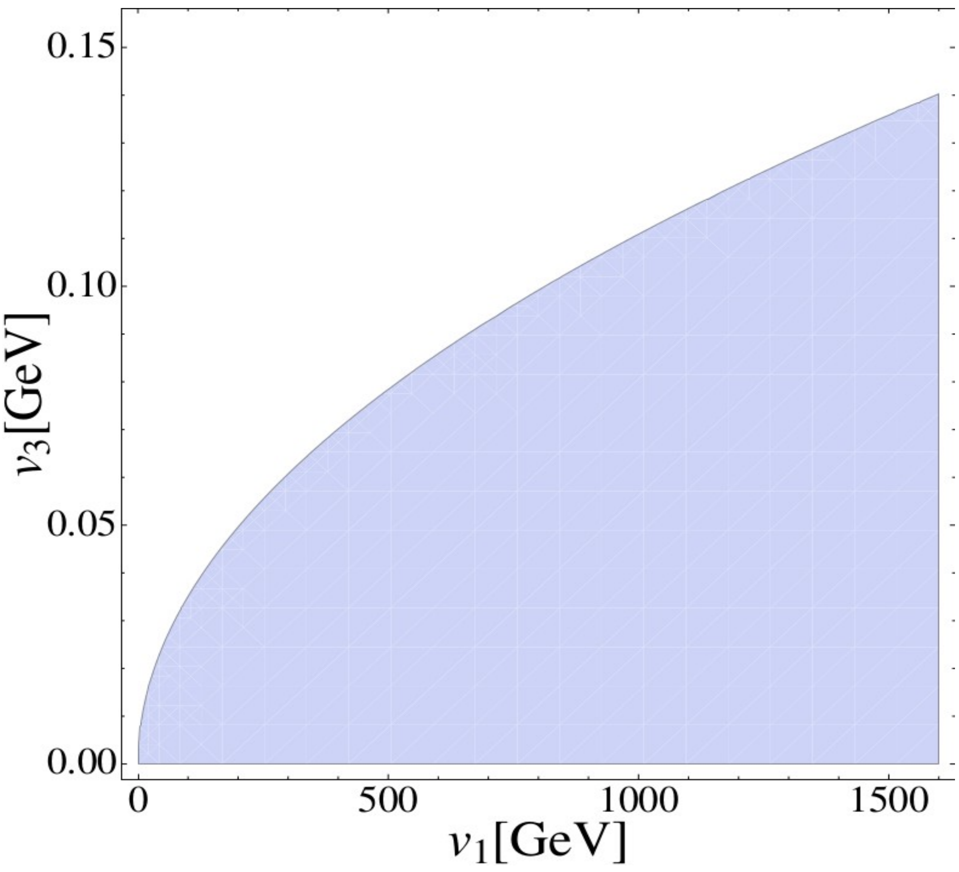
$$\rho = 1.0004 \mp 0.00024 \quad \rightarrow \quad v_3 \leqslant 7\,GeV$$

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

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

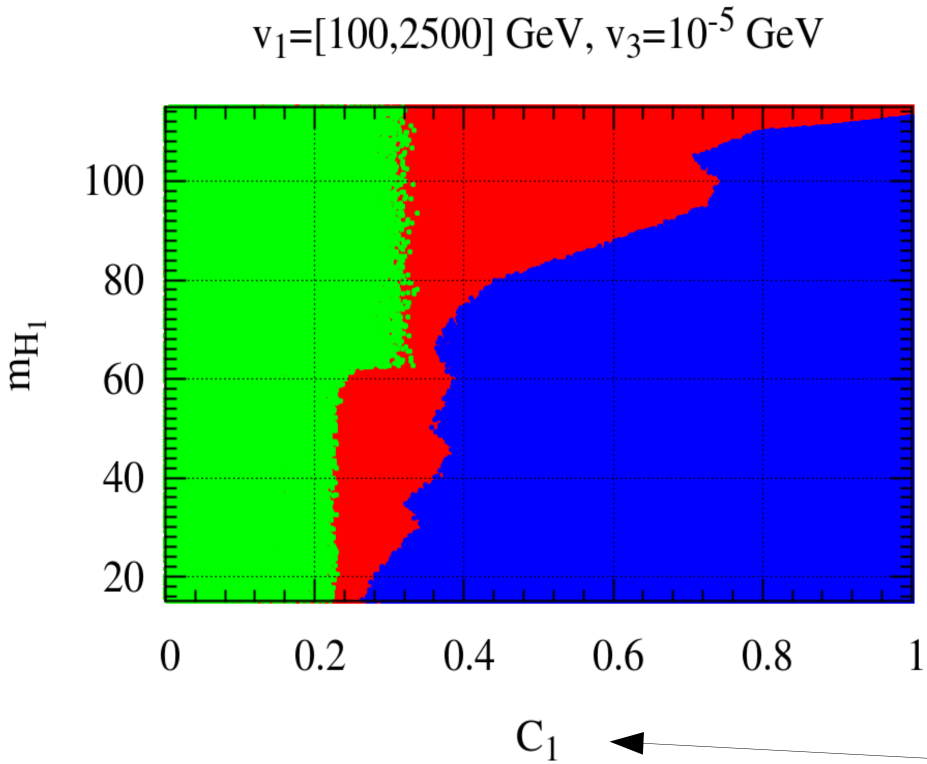
$$|g_{Jee}| < 10^{-13},$$

Phys.Rev. D42, 293 (1990)



Analysis i)

RESULTS



$0.8<\mu_{XX}<1.2$

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

Forbidden by LEP

$C_1=\cos\alpha_{13}\sin\alpha_{12}$

Mass spectrum

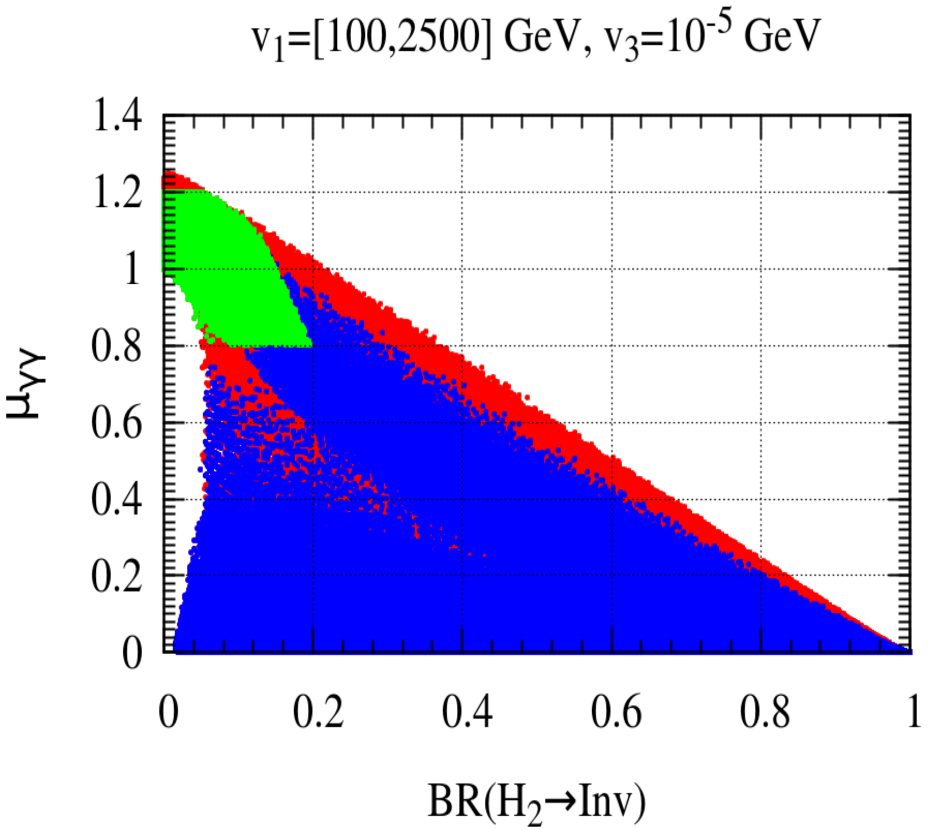
$m_{H_2}=125\,GeV$

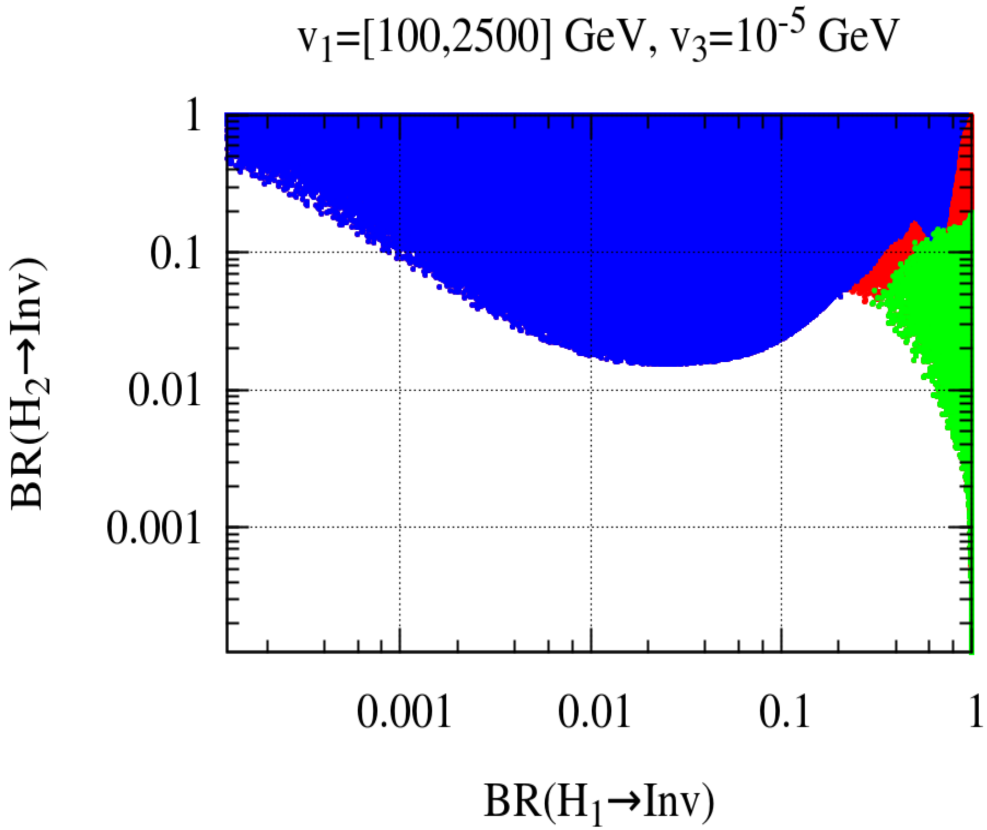
$m_{H_3}\simeq m_A\simeq m_{H^\pm}\simeq m_{\Delta^{\pm\pm}}=500\,GeV$

$\langle\sigma\rangle=v_1$

$\langle\Phi\rangle=v_2$

$\langle\Delta\rangle=v_3$





$0.8<\mu_{XX}<1.2$

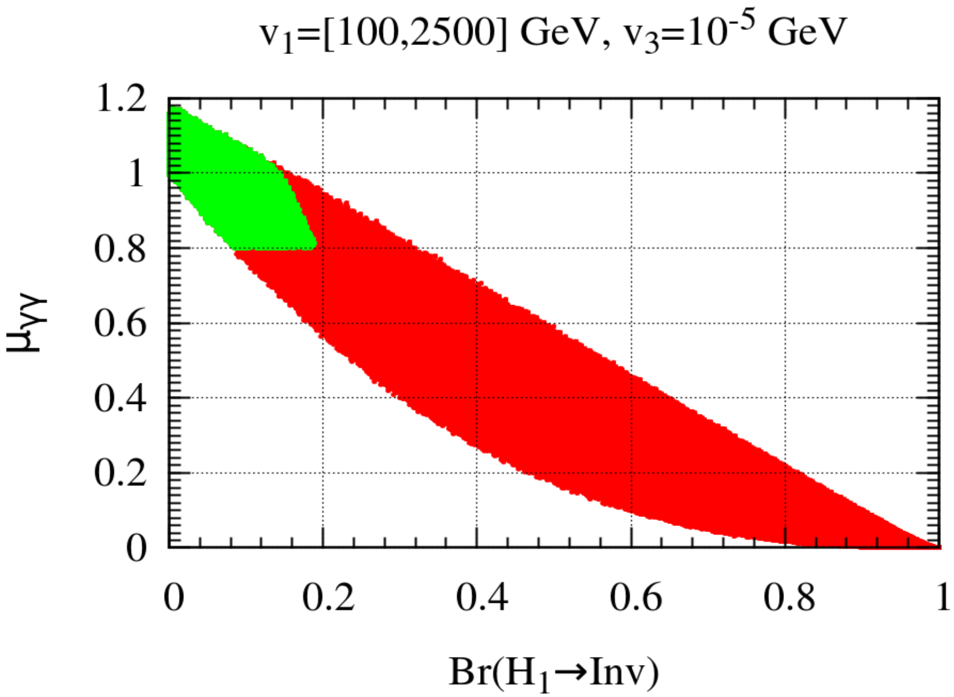
$\mu_{XX} \notin 1 \pm 0.2$

Forbidden by LEP

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

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

Analysis ii)



$0.8<\mu_{XX}<1.2$

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

Mass spectrum

$m_{H_1}=125\,GeV$

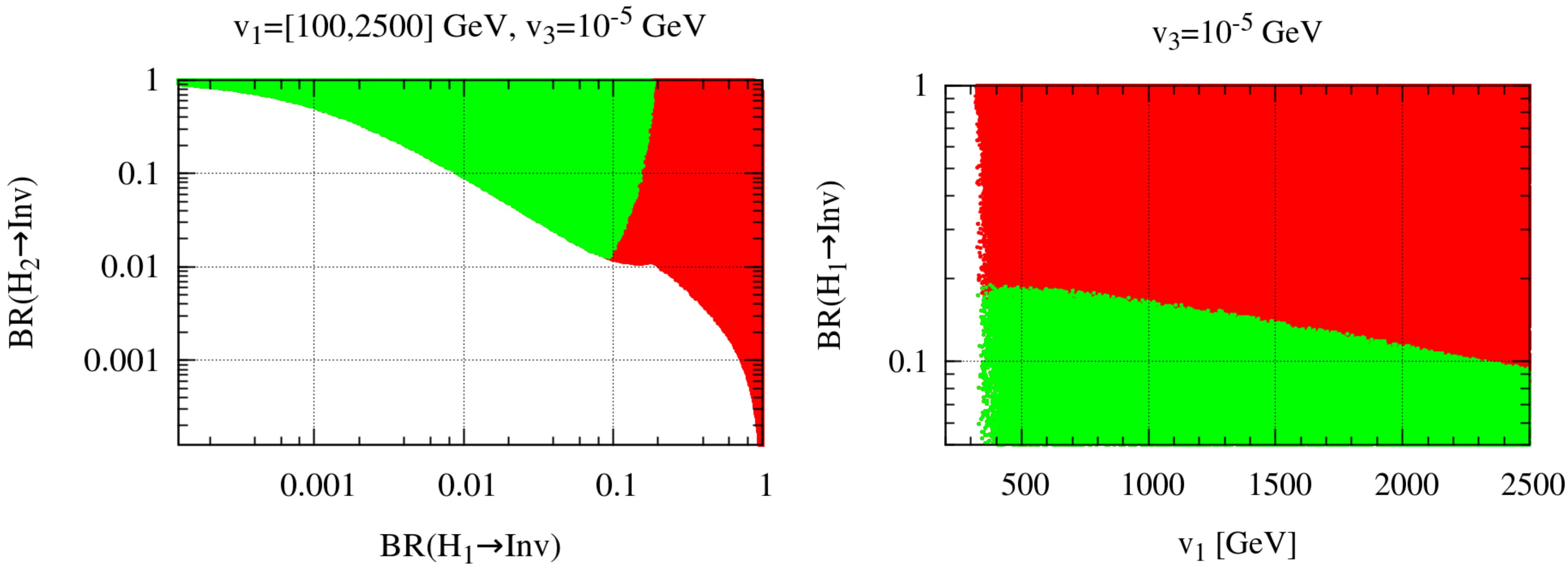
$m_{H_2}=[150{,}500]\,GeV$

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

$\langle\sigma\rangle=v_1$

$\langle\Phi\rangle=v_2$

$\langle\Delta\rangle=v_3$



$0.8 < \mu_{XX} < 1.2$

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

The green region satisfy:

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

CONCLUSIONS

- Invisible Higgs decays connected to neutrino mass generation.
- neutrino physics is a nice "portal to PBSM"
- LFVP, e.g. $\mu \to e\, J$?. Work in progress in collab with N. Rojas, J. Romao, J. Valle

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

$$\mathcal{L}_Y = y^d_{ij}\overline{Q}_i u_{R_j}\Phi + y^u_{ij}\overline{Q}_i d_{R_j}\tilde{\Phi} + y^\ell_{ij}\overline{L_i}\ell_{R_j}\Phi + y^\nu_{ij}L_i^T C\Delta L_j + \text{h.c.}$$

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

Nucl.Phys. B527, 44 (1998)

123 Model

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

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

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

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

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

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

Physical scalars

Neutral: H_1, H_2, H_3, J, A

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

Nucl.Phys. B527, 44 (1998)

Theoretical constraint (BFB conditions)

$$\lambda_1 > 0, \quad \beta_1 > 0, \quad \lambda_{24} > 0, \quad \hat{\lambda} \equiv \beta_2 + 2\sqrt{\beta_1 \lambda_1} > 0,$$

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

$$\sqrt{\beta_1 \lambda_1 \lambda_{24}} + [\lambda_3 + \theta(-\lambda_5)\lambda_5]\sqrt{\beta_1} + \beta_2\sqrt{\lambda_{24}} + \beta_3\sqrt{\lambda_1} + \sqrt{\hat{\lambda}\tilde{\lambda}\bar{\lambda}} > 0,$$

Eur.Phys.J. C72, 2093 (2012)

Experimental constraints from the LHC

- Higgs h(125): $0.8 \leqslant \mu_{XX} \leqslant 1.2$
- bounds set by the search for a heavy Higgs in the decay channels:
  - $H \to VV$ in the range [145−1000] GeV.
  - $H \to \tau\tau$ in the range [100−1000] GeV.
  - $A \to Zh$ in the range [220−1000] GeV.
- Doubly-charged:

$$\Delta^{\pm\pm} \to (l^{\pm} l^{\pm}, W^{\pm} W^{\pm}, W^{\pm} H^{\pm}, H^{\pm} H^{\pm})$$

SUM RULE

Sum rules (like in the TypeII seesaw model):

$$m^2_{H^+} - m^2_{\Delta^{++}} \approx m^2_A - m^2_{H^+} \approx \frac{\lambda_5 v_2^2}{4}$$

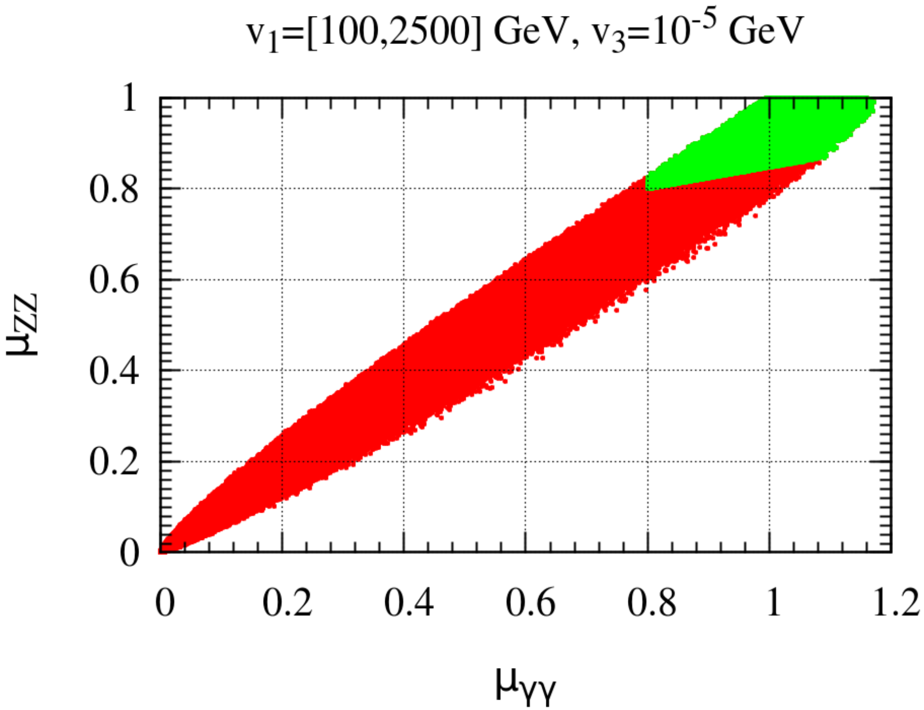
Because the smalless of the triplet's vev:

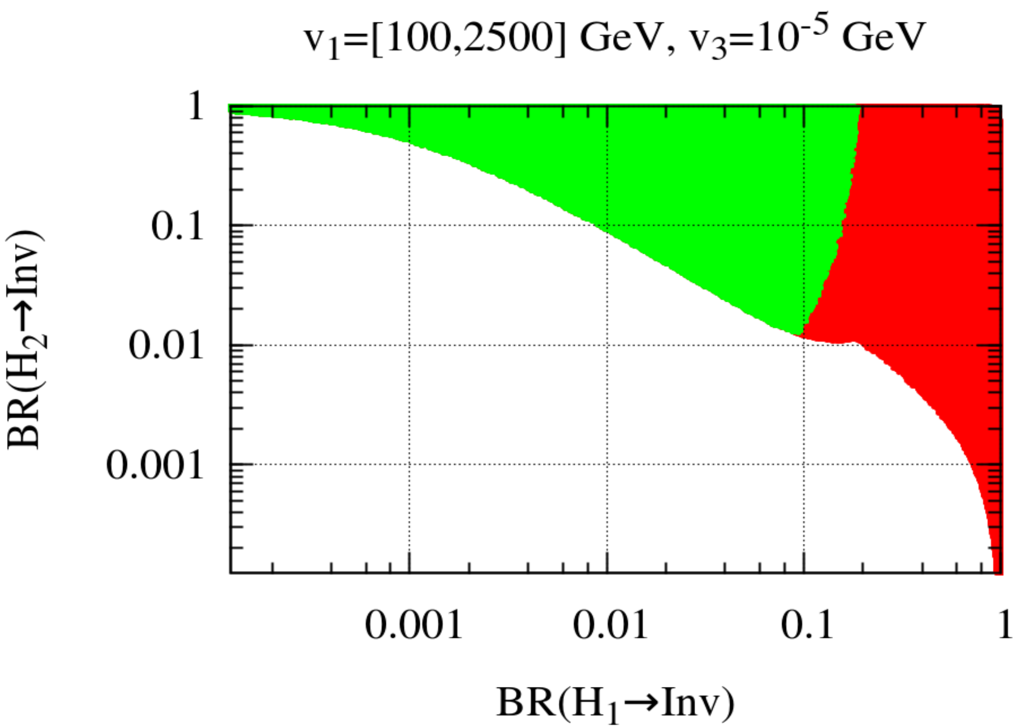
$$m^2_{H_3} - m^2_A \approx 2\lambda_2 v_3^2 \Rightarrow m_{H_3} \approx m_A$$

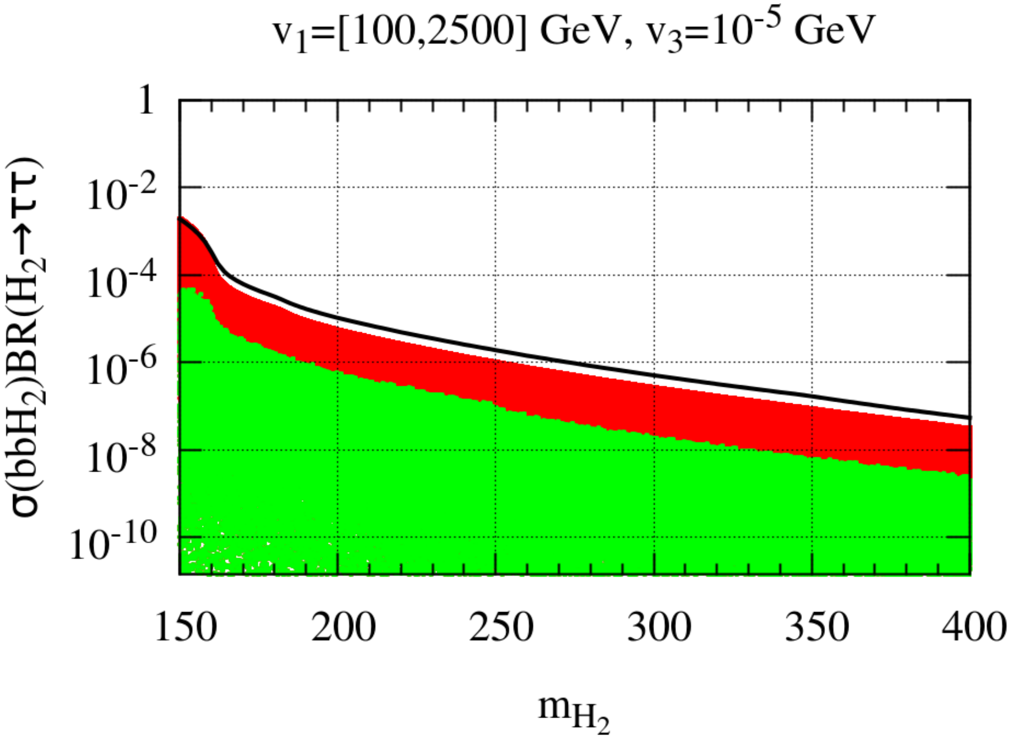
The coupling of H3 to the SM is very small in both cases:

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

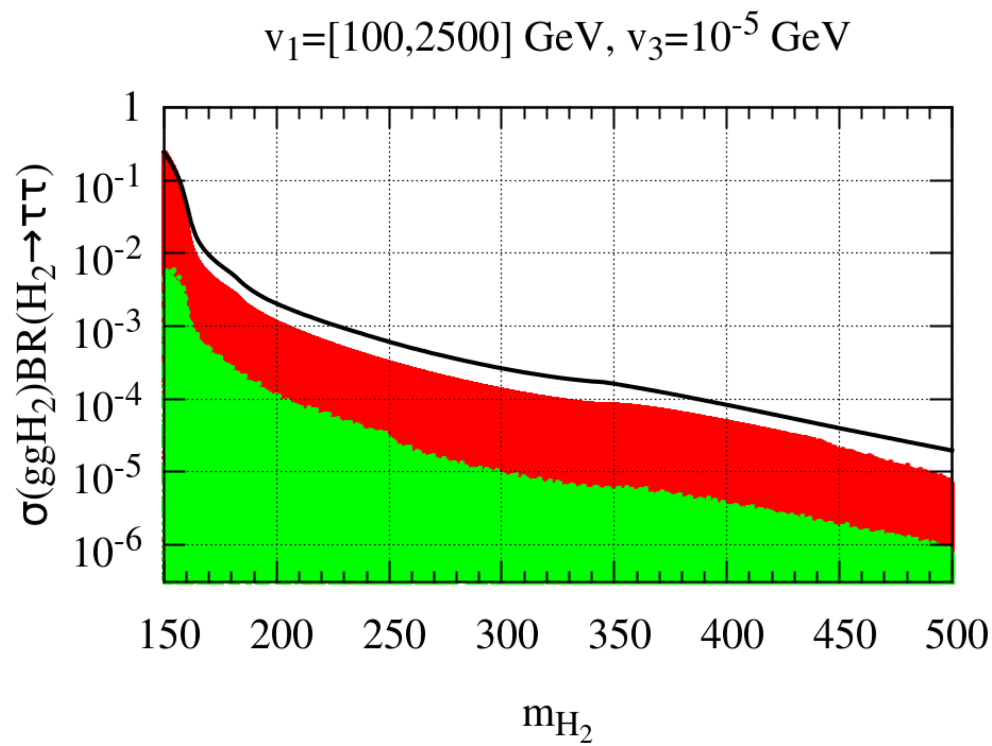
CASE II : Heavies







v1=[100,2500] GeV, v3=10-5 GeV
σ(bbH2)BR(H2→ττ)
1
10-2
10-4
10-6
10-8
10-10
150
200
250
300
350
400
mH2



v1=[100,2500] GeV, v3=10-5 GeV
σ(ggH2)BR(H2→ττ)
1
10-1
10-2
10-3
10-4
10-5
10-6
150
200
250
300
350
400
450
500
mH2

Experimental constraints on v_3

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

$$|g_{Jee}| = |O^I_{12} m_e / v_2|,$$

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

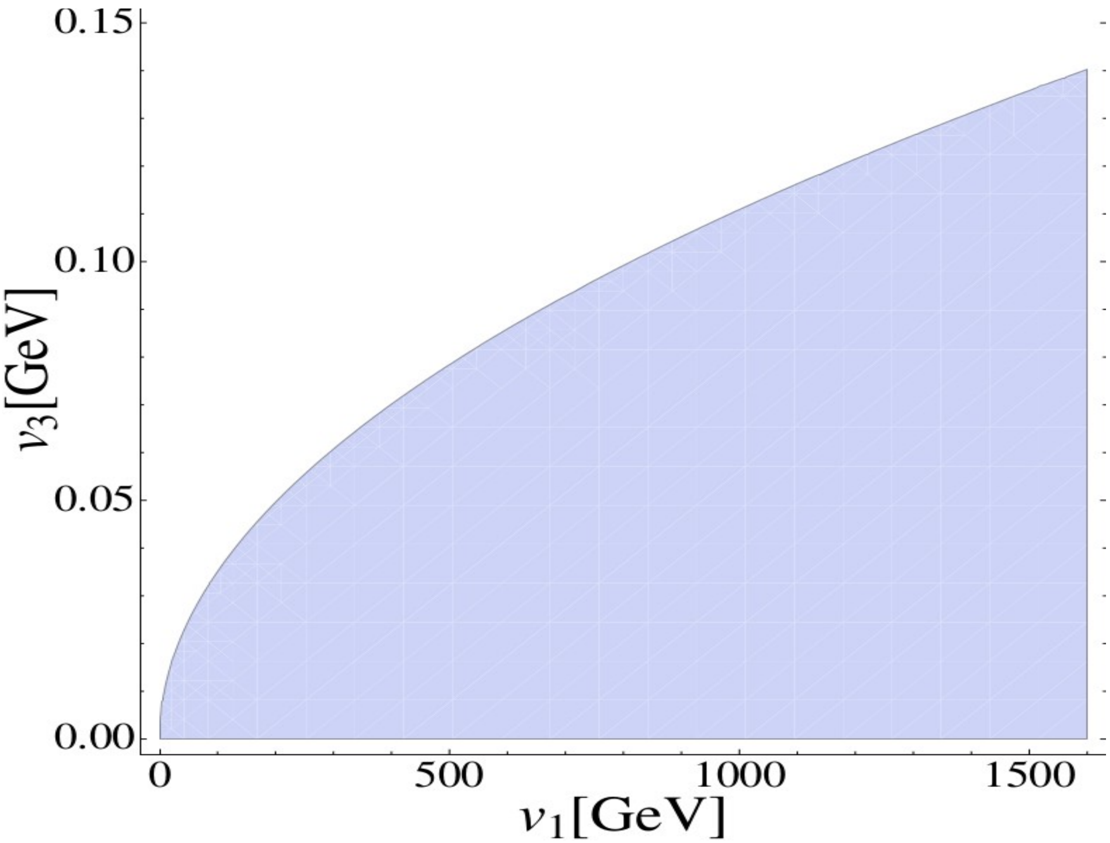
Other bounds on invisible decays

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

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

Experimental constraints on v_3

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



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

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