Fermionic decay of charged Higgs boson in low mass region in the Georgi Machacek Model

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Based on

- Fermionic decay of charged Higgs boson in low mass region in Georgi Machacek Model.
  SG. [arXiv:2205.03896 [hep-ph]]

The Georgi-Machacek (GM) model

Extended scalar sector in GM Model

- The SM Doublet ($Y = 1$)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \Rightarrow \quad \Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}$$

- One Real Triplet ($Y = 0$) and one Complex Triplet ($Y = 2$)

$$\xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix} \quad \Rightarrow \quad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

Extended scalar sector in GM Model

VEVs of the neutral fields

- $\langle \phi^0 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle \chi^0 \rangle = \langle \xi^0 \rangle = v_2,$
  $v_1{}^2 + 8v_2{}^2 = v^2 = \frac{4M_W{}^2}{g^2} \approx (246 \text{ GeV})^2$
- $\rho_{tree} = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$

Decomposition of the neutral fields

$$\phi^0 \to \frac{v_1}{\sqrt{2}} + \frac{\phi^{0R} + i\phi^{0I}}{\sqrt{2}}, \quad \chi^0 \to v_2 + \frac{\chi^{0R} + i\chi^{0I}}{\sqrt{2}}, \quad \xi^0 \to v_2 + \xi^0.$$

The doublet-triplet mixing angle

$$\tan\beta = \frac{2\sqrt{2}v_2}{v_1}$$

The GM Potential

Potential

$$V(\Phi, X) = \frac{{\mu_2}^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{{\mu_3}^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1\left[\mathrm{Tr}(\Phi^\dagger\Phi)\right]^2$$
$$+\lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4\left[\mathrm{Tr}(X^\dagger X)\right]^2$$
$$-\lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) - M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab}$$
$$-M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}$$

where $\tau^a = \sigma^a/2$, with σ^a being the three Pauli matrices.

$$t^1 = \frac{1}{\sqrt{2}}\begin{pmatrix}0 & 1 & 0\\ 1 & 0 & 1\\ 0 & 1 & 0\end{pmatrix}, t^2 = \frac{1}{\sqrt{2}}\begin{pmatrix}0 & -i & 0\\ i & 0 & -i\\ 0 & i & 0\end{pmatrix}, t^3 = \begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & -1\end{pmatrix}.$$

$$U = \frac{1}{\sqrt{2}}\begin{pmatrix}-1 & 0 & 1\\ -i & 0 & -i\\ 0 & \sqrt{2} & 0\end{pmatrix}.$$

The GM Potential

Potential at extrema

$$V(v_1, v_2) = \frac{{\mu_2}^2}{2}{v_1}^2 + 3\frac{{\mu_3}^2}{2}{v_2}^2 + \lambda_1 {v_1}^4 + \frac{3}{2}(2\lambda_2 - \lambda_5){v_1}^2{v_2}^2$$
$$+3(\lambda_3 + 3\lambda_4){v_2}^4 - \frac{3}{4}M_1{v_1}^2 v_2 - 6M_2{v_2}^3$$

The extremization conditions

$$\left({\mu_2}^2 + 4\lambda_1{v_1}^2 + 3(2\lambda_2 - \lambda_5){v_2}^2 - \frac{3}{2}M_1 v_2\right)v_1 = 0,$$
$$3{\mu_3}^2 v_2 + 3(2\lambda_2 - \lambda_5){v_1}^2 v_2 + 12(\lambda_3 + 3\lambda_4){v_2}^3 - \frac{3}{4}M_1{v_1}^2 - 18M_2{v_2}^2 = 0.$$

The physical fields of GM Model

- The Quintet
  - $H_5^{\pm\pm} = \chi^{\pm\pm}$,
  - $H_5^{\pm} = \frac{(\chi^{\pm} - \xi^{\pm})}{\sqrt{2}}$,
  - $H_5^0 = \sqrt{\frac{2}{3}}\xi^0 - \sqrt{\frac{1}{3}}\chi^{0R}$.
- The Triplet
  - $H_3^{\pm} = -\sin\beta\,\phi^{\pm} + \cos\beta\,\frac{(\chi^{\pm} + \xi^{\pm})}{\sqrt{2}}$,
  - $H_3^0 = -\sin\beta\,\phi^{0I} + \cos\beta\,\chi^{0I}$.
- Two Singlets
  - $H_1^0 = \phi^{0R}$,
  - $H_1^{0'} = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0R}$.

Mixing of two singlets

- Mass eigenstates :
  $h = \cos\alpha \;\; H_1^0 - \sin\alpha \;\; H_1^{0'}, \qquad H = \sin\alpha \;\; H_1^0 + \cos\alpha \;\; H_1^{0'}.$

- Mass-squared matrix : $\mathcal{M}^2 = \begin{pmatrix} \mathcal{M}_{11}{}^2 & \mathcal{M}_{12}{}^2 \\ \mathcal{M}_{21}{}^2 & \mathcal{M}_{22}{}^2 \end{pmatrix}$,

  with,
  $\mathcal{M}_{11}^2 = 8\lambda_1 v_1{}^2,$
  $\mathcal{M}_{12}^2 = \mathcal{M}_{21}^2 = \frac{\sqrt{3}}{2}\left[-M_1 + 4\left(2\lambda_2 - \lambda_5\right) v_2\right] v_1,$
  $\mathcal{M}_{22}^2 = \frac{M_1 v_1^2}{4 v_2} - 6 M_2 v_2 + 8(\lambda_3 + 3\lambda_4) v_2^2.$

- Mixing angle : $\tan 2\alpha = \frac{2\mathcal{M}_{12}{}^2}{\mathcal{M}_{22}{}^2 - \mathcal{M}_{11}{}^2}$

Masses of the physical states

The quintet mass m_5

$$m_5{}^2 = \frac{M_1}{4v_2} v_1{}^2 + 12 M_2 v_2 + \frac{3}{2}\lambda_5 v_1{}^2 + 8\lambda_3 v_2{}^2$$

The triplet mass m_3

$$m_3{}^2 = \left(\frac{M_1}{4v_2} + \frac{\lambda_5}{2}\right) v^2$$

The singlet masses $m_{h,H}$

$$m_{h,H}{}^2 = \frac{1}{2}\left[\mathcal{M}_{11}{}^2 + \mathcal{M}_{22}{}^2 \mp \sqrt{\left(\mathcal{M}_{11}{}^2 - \mathcal{M}_{22}{}^2\right)^2 + 4\left(\mathcal{M}_{12}{}^2\right)^2}\right]$$

The quartic couplings : λ_i s

- $\lambda_1 = \frac{m_h^2 \cos^2\alpha + m_H^2 \sin^2\alpha}{8v^2\cos^2\beta}$

- $\lambda_2 = \frac{\sqrt{6}\left(m_H^2 - m_h^2\right)\sin 2\alpha - 3\sqrt{2}v\cos\beta M_1 + 12 m_3^2 \sin\beta\cos\beta}{12v^2\cos\beta\sin\beta}$

- $\lambda_3 = \frac{m_5^2 - 3m_3^2\cos^2\beta + \sqrt{2}v\cos\beta\cot\beta M_1 - 3\sqrt{2}v\sin\beta M_2}{v^2\sin^2\beta}$

- $\lambda_4 = \frac{2m_h^2\sin^2\alpha + 2m_H^2\cos^2\alpha - 2m_5^2 + 6m_3^2\cos^2\beta - 3\sqrt{2}v\cos\beta\cot\beta M_1 + 9\sqrt{2}v\sin\beta M_2}{6v^2\sin^2\beta}$

- $\lambda_5 = 2\frac{m_3^2}{v^2} - \frac{\sqrt{2}M_1}{v\sin\beta}$

Theoretical constraints

Combined theoretical constraints on the quartic couplings

- $\lambda_1 \in (0, \pi/3) \simeq (0, 1.05)$
- $\lambda_2 \in (-2\pi/3, 2\pi/3) \simeq (-2.09, 2.09)$
- $\lambda_3 \in (-\pi/2, 3\pi/5) \simeq (-1.57, 1.88)$
- $\lambda_4 \in (-\pi/5, \pi/2) \simeq (-0.63, 1.57)$
- $\lambda_5 \in (-8\pi/3, 8\pi/3) \simeq (-8.38, 8.38)$

Couplings and scaling factors of h/H to f/V

- h to VV
  $ig_{hWW} = ic_W^2 g_{hZZ} = -i\frac{e^2}{6s_W^2}(8\sqrt{3}s_\alpha v_2 - 3c_\alpha v_1)$,
  $\kappa_V^h = -\frac{1}{3v}(8\sqrt{3}s_\alpha v_2 - 3c_\alpha v_1)$.
- H to VV
  $ig_{HWW} = ic_W^2 g_{HZZ} = i\frac{e^2}{6s_W^2}(8\sqrt{3}c_\alpha v_2 + 3s_\alpha v_1)$,
  $\kappa_V^H = \frac{1}{3v}(8\sqrt{3}c_\alpha v_2 + 3s_\alpha v_1)$
- h to $\overline{f}f$
  $g_{h\overline{f}f} = -i\frac{m_f}{v}\frac{c_\alpha}{c_\beta}$,
  $\kappa_f^h = \frac{v}{v_1}c_\alpha$.
- H to $\overline{f}f$
  $g_{H\overline{f}f} = -i\frac{m_f}{v}\frac{s_\alpha}{c_\beta}$,
  $\kappa_f^H = \frac{v}{v_1}s_\alpha$.

Relevant couplings for $h/H \to \gamma\gamma$

- $-ig_{hH_3^+H_3^-} = -i(64\lambda_1 c_\alpha \frac{v_2^2 v_1}{v^2} - \frac{8}{\sqrt{3}} \frac{v_1^2 v_2}{v^2} s_\alpha(\lambda_3 + 3\lambda_4) - \frac{4}{\sqrt{3}} \frac{v_2 M_1}{v^2}(s_\alpha v_2 - \sqrt{3} c_\alpha v_1) - \frac{16}{\sqrt{3}} \frac{v_2^3}{v^2} s_\alpha(6\lambda_2 + \lambda_5) - c_\alpha \frac{v_1^3}{v^2}(\lambda_5 - 4\lambda_2) + 2\sqrt{3} M_2 \frac{v_1^2}{v^2} s_\alpha - \frac{8}{\sqrt{3}} \lambda_5 \frac{v_1 v_2}{v^2}(s_\alpha v_1 - \sqrt{3} c_\alpha v_2))$
- $-ig_{HH_3^+H_3^-} = -i(64\lambda_1 s_\alpha \frac{v_2^2 v_1}{v^2} + \frac{8}{\sqrt{3}} \frac{v_1^2 v_2}{v^2} c_\alpha(\lambda_3 + 3\lambda_4) + \frac{4}{\sqrt{3}} \frac{v_2 M_1}{v^2}(c_\alpha v_2 + \sqrt{3} s_\alpha v_1) + \frac{16}{\sqrt{3}} \frac{v_2^3}{v^2} c_\alpha(6\lambda_2 + \lambda_5) + s_\alpha \frac{v_1^3}{v^2}(4\lambda_2 - \lambda_5) - 2\sqrt{3} M_2 \frac{v_1^2}{v^2} c_\alpha + \frac{8}{\sqrt{3}} \lambda_5 \frac{v_1 v_2}{v^2}(c_\alpha v_1 + \sqrt{3} s_\alpha v_2))$
- $-ig_{hH_5^+H_5^-} = -ig_{hH_5^{++}H_5^{--}} = -i(-8\sqrt{3}(\lambda_3 + \lambda_4) s_\alpha v_2 + (4\lambda_2 + \lambda_5) c_\alpha v_1 - 2\sqrt{3} M_2 s_\alpha)$
- $-ig_{HH_5^+H_5^-} = -ig_{HH_5^{++}H_5^{--}} = -i(8\sqrt{3}(\lambda_3 + \lambda_4) c_\alpha v_2 + (4\lambda_2 + \lambda_5) s_\alpha v_1 + 2\sqrt{3} M_2 c_\alpha)$

Scaling factor for $h/H \to \gamma\gamma$

- Loop function :
  - SM : $F_1(\tau_W) + N_c Q_f^2 F_{\frac{1}{2}}(\tau_f)$
  - GM : $\kappa_V^{h,H} F_1(\tau_W) + \kappa_f^{h,H} N_c Q_f^2 F_{\frac{1}{2}}(\tau_f) + \sum_s \beta_s^{h,H} Q_s^2 F_0(\tau_s)$

  with, $Q_f \Rightarrow$ Charge of the fermion f,

  $\beta_s^{h,H} = g_{h(H)ss}/2m_s^2$, $m_s \Rightarrow$ mass of charged scalar s.
- Loop factors
  - $F_1(\tau) = 2 + 3\tau + 3\tau(2-\tau)f(\tau)$
  - $F_{\frac{1}{2}}(\tau) = -2\tau[1 + (1-\tau)f(\tau)]$
  - $F_0(\tau) = \tau[1 - \tau f(\tau)]$

  where, $f(\tau) = \left[\sin^{-1}\left(\sqrt{\frac{1}{\tau}}\right)\right]^2$ for $\tau \geq 1$

  $$f(\tau) = -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right)\right]^2 \text{ for } \tau < 1$$
- $\tau_i = 4m_i^2/m_{h(H)}^2$

Vertices involving a charged scalar and two fermions

- $H_3^+ \overline{u} d$: - i $\sqrt{2}\, V_{ud} \tan\beta \left(\frac{m_u}{v} P_L - \frac{m_d}{v} P_R \right)$
- $H_3^- \overline{d} u$: - i $\sqrt{2}\, V_{ud}^* \tan\beta \left(\frac{m_u}{v} P_R - \frac{m_d}{v} P_L \right)$
- $H_3^+ \overline{\nu} l$: i $\sqrt{2} \tan\beta \, \frac{m_l}{v} P_R$
- $H_3^- \overline{l} \nu$: i $\sqrt{2} \tan\beta \, \frac{m_l}{v} P_L$

Here V_{ud} is the CKM matrix element and $P_{R,L} = \frac{(1 \pm \gamma_5)}{2}$ are the projection operators.

Theoretical constraints and LHC data

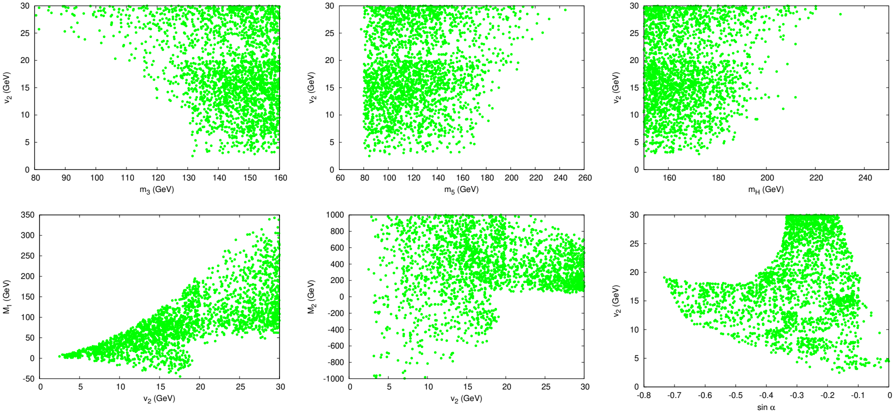


Figure: Allowed parameter space in the $m_3 - v_2$, $m_5 - v_2$, $m_H - v_2$, $v_2 - M_1$, $v_2 - M_2$, $\sin\alpha - v_2$ plane from theoretical constraints and LHC data at $\sqrt{s} = 13$ TeV.

The contribution of charged Higgs in the $h \to \gamma\gamma$ loop

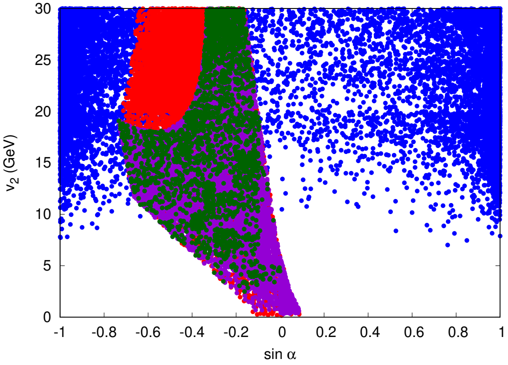


Figure: The $v_2 - \sin\alpha$ parameter space. Blue points : forbidden by LHC Higgs signal strength at $\sqrt{s} = 13$ TeV, with and without considering the charged Higgs contributions in the $h \to \gamma\gamma$ loop. Red points : forbidden by the contribution of charged Higgs in the $h \to \gamma\gamma$ loop. Violet points : allowed by the LHC Higgs signal strength data. Dark-Green points : allowed by the theoretical and LHC Higgs signal strength data at $\sqrt{s} = 13$ TeV after considering the charged Higgs contributions in the $h \to \gamma\gamma$ loop.

Branching ratios

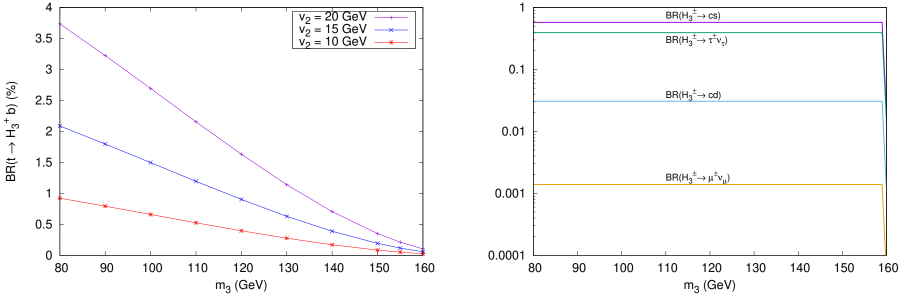
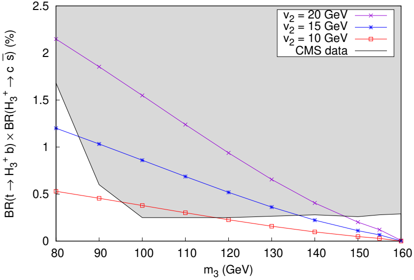
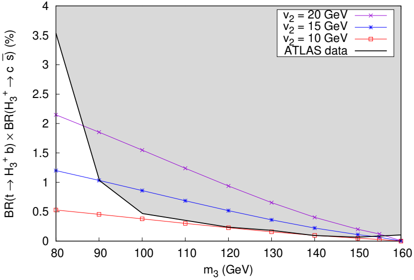
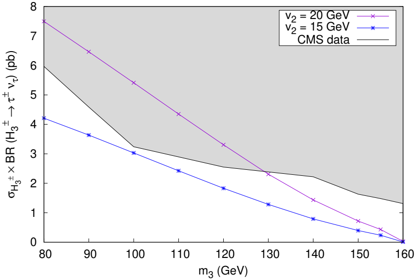


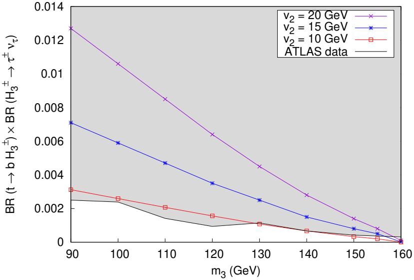
Figure: Branching ratio of $t \to H_3^+ b$ for $v_2 = 10, 15, 20$ GeV (left), and $H_3^\pm$ for $v_2 = 10$ GeV (right) as a function of m_3 (GeV). We choose $m_H = 200$ GeV, $m_5 = 80$ GeV, $\sin\alpha$ =-0.2, $M_1 = M_2 = 100$ GeV for the plots.

Cross-sec. times Branching ratios









The $m_3 - v_2$ plot

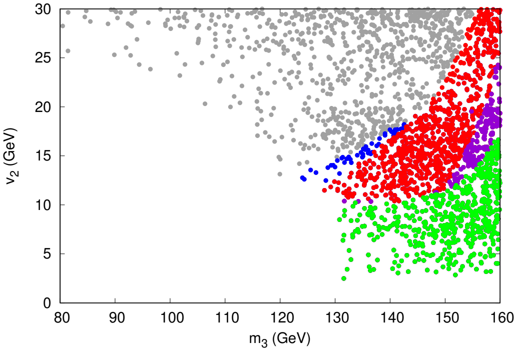


Figure: The $m_3 - v_2$ parameter space. All points are allowed from theoretical constraints as well as LHC data at $\sqrt{s} = 13$ TeV. The gray points are excluded from all the $H_3^{\pm} \to cs, \tau\nu$ data of CMS and ATLAS experiments. The blue points are excluded by $H_3^{\pm} \to \tau\nu$ ATLAS, $H_3^{\pm} \to cs$ CMS as well as ATLAS data. The red points are excluded by $H_3^{\pm} \to cs, \tau\nu$ ATLAS data. The violet points are excluded by $H_3^{\pm} \to \tau\nu$ ATLAS data. The green points are allowed by all the $H_3^{\pm} \to cs, \tau\nu$ CMS and ATLAS data.

The $m_3 - v_2$ plot

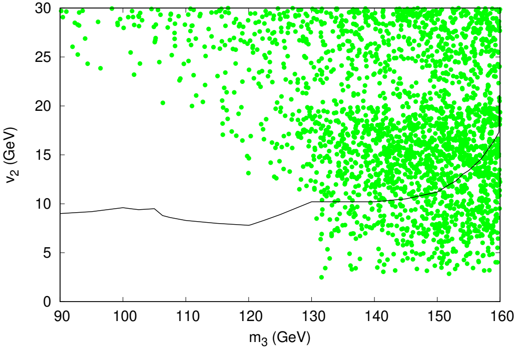


Figure: The $m_3 - v_2$ plane. The green points are allowed by theoretical constraints and LHC data. The solid line corresponds to the data obtained from the $H^{\pm} \to \tau\nu$ decay observed by ATLAS while fixing m_H = 200 GeV, m_5 = 80 GeV, $\sin\alpha$ = -0.2, $M_1 = M_2$ = 100 GeV in the GM model.

Allowed parameter space

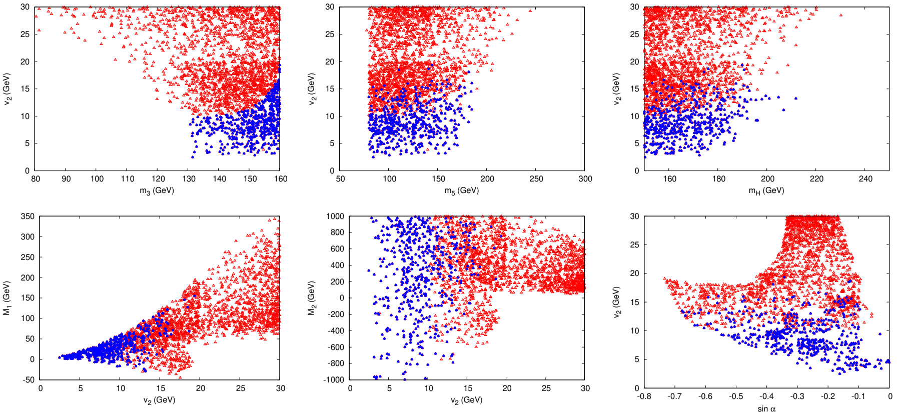


Figure: Allowed parameter space in the $m_3 - v_2$, $m_5 - v_2$, $m_H - v_2$, $v_2 - M_1$, $v_2 - M_2$, $\sin\alpha - v_2$ plane. Red points are allowed by theoretical constraints and LHC data at $\sqrt{s} = 13$ TeV. Blue points are allowed also by all the $H^{\pm} \to ff'$ data.

Conclusions

- The most stringent bound on the triplet vev is coming from the decay of the low mass charged Higgs to $\tau\nu$ observed by ATLAS.

- Simultaneous adoption of the theoretical constraints, LHC data and the observed data also curb the parameter space of the GM model.


Thank you