# Search for a charged Higgs boson decaying into a heavy neutral Higgs boson and a W boson in the Georgi-Machacek Model

(*Work is in progress and soon to be arXived*)

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# Overview

- The Georgi-Machacek Model
- Couplings and Scaling factors
- Allowed parameter space
- Experimental result from CMS
- Production cross-section of $H_3^{\pm}$
- Decay of $H_3^{\pm}$ to one gauge boson and one scalar
- $pp \to tbH_3^{\pm}$, $H_3^{\pm} \to W^{\pm}H$, $H \to \tau^+\tau^-$
- Conclusions

# Extended scalar sector in GM Model

- The SM Doublet

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

- One Real Triplet and one Complex Triplet

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

## VEVs of the neutral fields

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

## 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 $\sigma^a$ 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

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

## The extremization conditions

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

# The physical fields of GM Model

## One quintet $H_5 = \left(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}\right)^T$

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

$H_5^{++} = \chi^{++}, H_5^{+} = \frac{(\chi^{+} - \xi^{+})}{\sqrt{2}}, H_5^{0} = \sqrt{\frac{2}{3}}\xi^{0} - \sqrt{\frac{1}{3}}\chi^{0R}$

## One triplet $H_3 = \left(H_3^{+}, H_3^{0}, H_3^{-}\right)^T$

degenerate mass $m_3$, with $m_3{}^2 = \left(\frac{M_1}{4v_2} + \frac{\lambda_5}{2}\right) v^2$.

$H_3^{+} = -\sin\beta\ \ \phi^{+} + \cos\beta \frac{(\chi^{+} + \xi^{+})}{\sqrt{2}}, H_3^{0} = -\sin\beta\ \ \phi^{0I} + \cos\beta\ \ \chi^{0I}$

## Two singlets : $H_1^0$ and $H_1^{0'}$

$H_1^{0} = \phi^{0R}, H_1^{0'} = \sqrt{\frac{1}{3}}\xi^{0} + \sqrt{\frac{2}{3}}\chi^{0R}$

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

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

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

# 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 $\bar{f}f$
  $g_{h\bar{f}f} = -i\frac{m_f}{v}\frac{c_\alpha}{c_\beta}$,
  $\kappa_f^h = \frac{v}{v_1}c_\alpha$.
- H to $\bar{f}f$
  $g_{H\bar{f}f} = -i\frac{m_f}{v}\frac{s_\alpha}{c_\beta}$,
  $\kappa_f^H = \frac{v}{v_1}s_\alpha$.

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

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

# The quartic couplings : $\lambda_i$ 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

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

# Theoretical constraints and LHC data

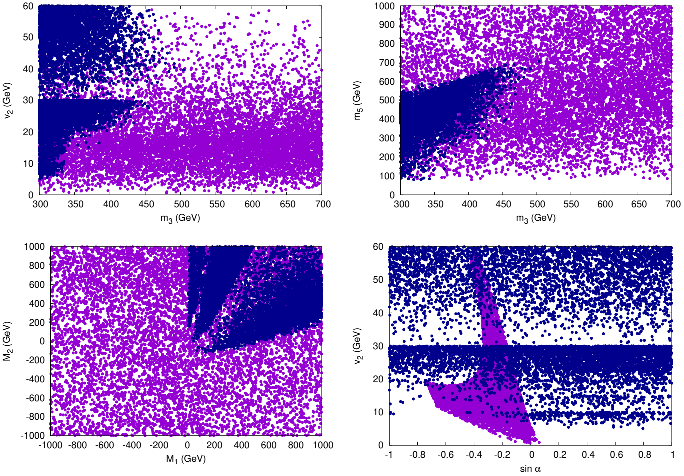
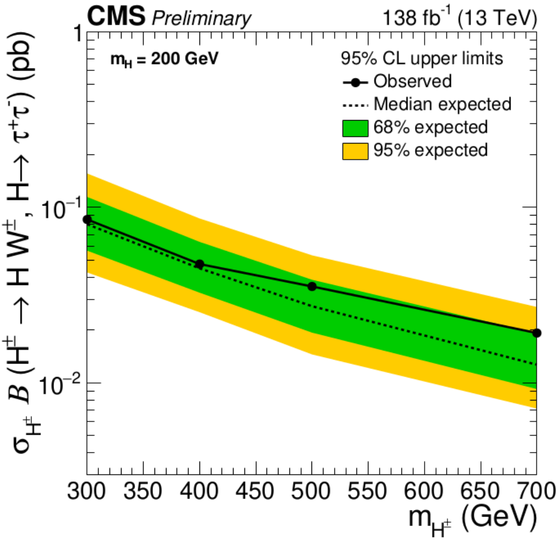
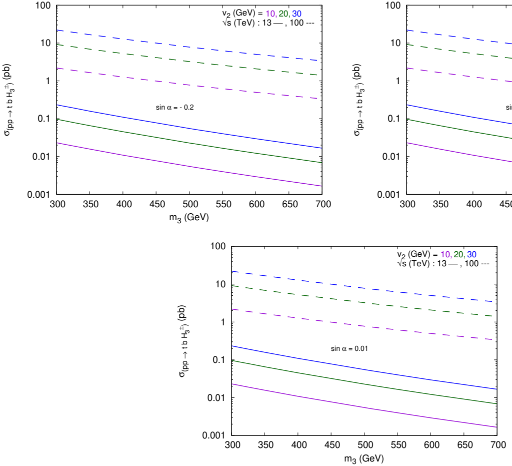



Figure: Allowed parameter space in the $m_3 - v_2$, $m_3 - m_5$, $M_1 - M_2$, $\sin\alpha - v_2$ plane from theoretical constraints (blue points) and LHC data at $\sqrt{s} = 13$ TeV (violet points) at $m_H = 200$ GeV.

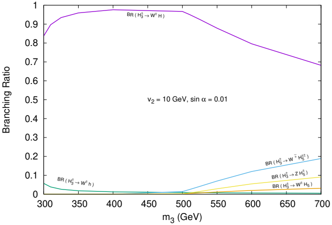
# HIG-21-010-PAS

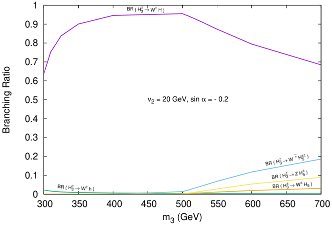


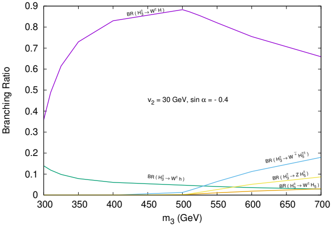
# $pp \to tbH_3^{\pm}$ in GM Model



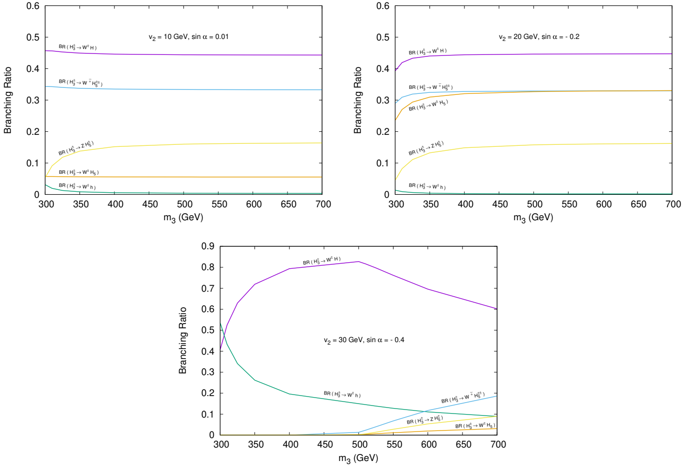
# $H_3^{\pm} \to VS,\ V = W^{\pm}, Z,\ S = h, H, H_5, H_5^{+}, H_5^{\pm}$ with $m_H =$ 200 GeV, $m_5 = 400$ GeV in GM Model



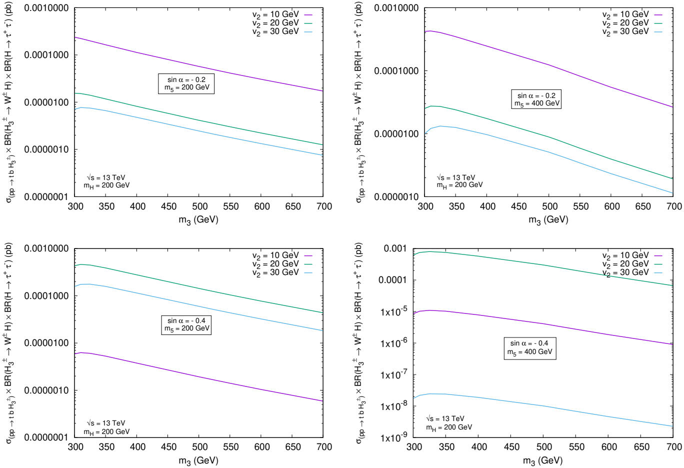



# $H_3^\pm \to VS$, $V = W^\pm, Z$, $S = h, H, H_5, H_5^+, H_5^\pm$ with $m_H = m_5 = 200$ GeV in GM Model



# $pp \to tbH_3^\pm$, $H_3^\pm \to W^\pm H$, $H \to \tau^+\tau^-$ in GM Model



# Conclusions

- There are two types of singly charged scalars ($H_3^{\pm}, H_5^{\pm}$) in GM model, but the production cross-section of $H_3^{\pm}$ is preffered over that of $H_5^{\pm}$.
- Considering all the possible decays of $H_3^{\pm}$ to one gauge boson and scalar, $H_3^{\pm} \rightarrow W^{\pm}H$ is preffered in terms of branching ratio.
- GM model can well accomodate the CMS result of the process $pp \rightarrow tbH^{\pm} \rightarrow tbW^{\pm}H \rightarrow tbW^{\pm}\tau^{+}\tau^{-}$.


Thank you