Carleton University
Department of Physics
www.physics.carleton.ca

Custodial Symmetry Violation in the Georgi-Machacek model

Ben Keeshan
Carleton University

Outline

- Introduction and Motivation
- The Georgi-Machacek Model (GM)
- Incorporating Custodial Violation
- Results

The Standard Model

- SM has a scalar $SU(2)_L$ doublet $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$
  - Isopin ½, hypercharge 1
- SM Lagrangian

$$\mathcal{L}_H = \left|D_\mu \phi\right|^2 - \left[-\mu^2 \phi^\dagger \phi + \lambda\left(\phi^\dagger \phi\right)^2\right] - [y_f \overline{f_R} \phi^\dagger F_L + h.c]$$

  - $\mu^2 < 0$: spontaneous symmetry breaking
    - non-zero vev; fixed by minimizing Higgs potential
    - Goldstones are gauged away (eaten by W and Z)

$$v^2 = \frac{\mu^2}{\lambda} \qquad m_H = 2\lambda v^2 \qquad \phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}$$

The Standard Model (Cont.)

- Higgs Couplings are proportional to generated mass

$$\mathcal{L}_H = \left|D_\mu \phi\right|^2 - \left[-\mu^2 \phi^\dagger \phi + \lambda\left(\phi^\dagger \phi\right)^2\right] - [y_f \bar{f}_R \phi^\dagger F_L + h.c]$$

  - W and Z:

$$M_W^2 = \frac{g^2 v^2}{4} \qquad hWW: 2i\frac{{M_W}^2}{v^2} g^{\mu\nu}$$

$$M_Z^2 = \frac{g^2 v^2}{4\cos^2(\theta_w)} \qquad hZZ: \frac{2iM_Z^2}{v^2} g^{\mu\nu}$$

  - Fermions:

$$m_f = \frac{y_f v}{\sqrt{2}} \qquad hf\bar{f}: \frac{im_f}{v}$$

Beyond the SM: Why Isospin triplets

- Gauge invariance -> Fermion masses only generated by doublet; W and Z can be generated by any isospin multiplet
  - Can use triplet models to limit exotic fraction of M_Z and M_W
- Can enhance hVV couplings compared to SM
  - Could mask non-SM contribution to measured Higgs branching ratios

Problems with Higher Isospin

- The ρ parameter: measure of relative strength of charged and neutral weak currents

$$\rho \equiv \frac{M_W^2}{M_Z^2 cos^2(\theta_w)} = \sum_k \frac{2\left[T_k(T_k+1) - \frac{Y_k^2}{4}\right] v_k^2}{\sum_k Y_k^2 v_k^2}$$

PDG 2014: $\rho = 1.00040 \pm 0.00024$

- With SM doublet ϕ, real triplet ξ (Y=0) and complex triplet χ (Y=1) ρ becomes:

$$\rho = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2}$$

Georgi-Machacek Model (GM)

Georgi & Machacek (1985); Chanowitz & Golden (1985)

- Impose global $SU(2)_L \times SU(R)_2$ symmetry on scalar potential (9 parameters)
  - EWSB: Breaks to custodial SU(2); fixes ρ=1 at tree level
- GM: $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}$ $\xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$
  - Where the neutral components decompose:

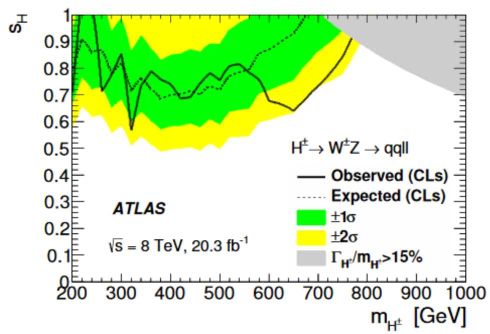
$$\phi^0 \to \frac{v_\phi}{\sqrt{2}} + \frac{\phi^{0,r} + i\phi^{0,i}}{\sqrt{2}} \quad \chi^0 \to v_\chi + \frac{\chi^{0,r} + i\chi^{0,i}}{\sqrt{2}} \quad \xi^0 \to v_\xi + \xi^0$$

  - The vevs are parameterized by $c_H = \frac{v_\phi}{v}$ $s_H = \frac{2\sqrt{2}v_\chi}{v}$

$$v_\phi^2 + 8v_\chi^2 = \mathrm{v}^2 \equiv \frac{1}{\sqrt{2}\mathrm{G_F}}$$

Georgi-Machacek Model (GM)

- Model gives 13 fields classified based their $SU(2)_C$ transformation properties
  - A 5-plet ($H_5^{\pm\pm}$,H_5^0,$H_5^{\pm}$) with mass m_5
  - A triplet ($H_3^{\pm}$,H_3^0) with mass m_3
  - 2 singlets (h^0, H^0) with mass m_h, m_H
  - 3 Goldstones that get eaten by W and Z

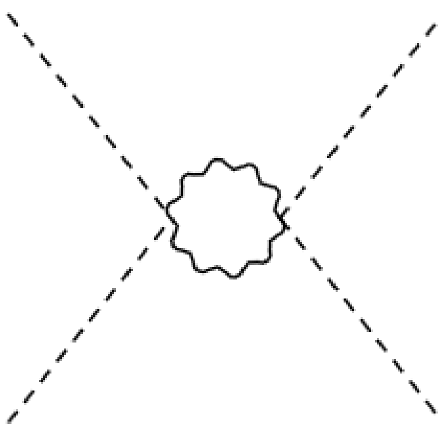


Search for $H_5^{\pm}$ in $H_5^{\pm} \rightarrow W^{\pm} Z \rightarrow qqll$
ATLAS 1503.04233

Custodial Violation in GM

- Has been known for many years that custodial symmetry is broken by the hypercharge loop effects (Gunion, Vega & Wudka 1991)
- Hypercharge loop diagrams -> parameters of the scalar potential run away from the custodial preserving relation

  (V now has 16 parameters)



Custodial Violation in GM

- Running of the parameters are described by the renormalization group equations (RGEs)
- Assume Custodial Symmetry holds exactly at some cutoff scale Λ use RGEs to run down to weak scale (parameterized by v)
- In general RGEs of the form:

$$\frac{d}{dt}\tilde{\lambda}(t) = \beta(\tilde{\lambda}) \qquad t = \log\left(\frac{p}{\Lambda}\right)$$

Custodial Violation in GM

- For small ratio of scales $\delta(t) \equiv t - t_0 = \log(v/\Lambda) < 0$ we have:

$$\tilde{X}(t) = X(t) + \frac{\beta_{\tilde{X}}^{Y}\delta t}{16\pi^2} \equiv X(t) + \delta_{\tilde{X}}$$

- i.e. Consider the custodial violating states as perturbations of the custodial symmetric states

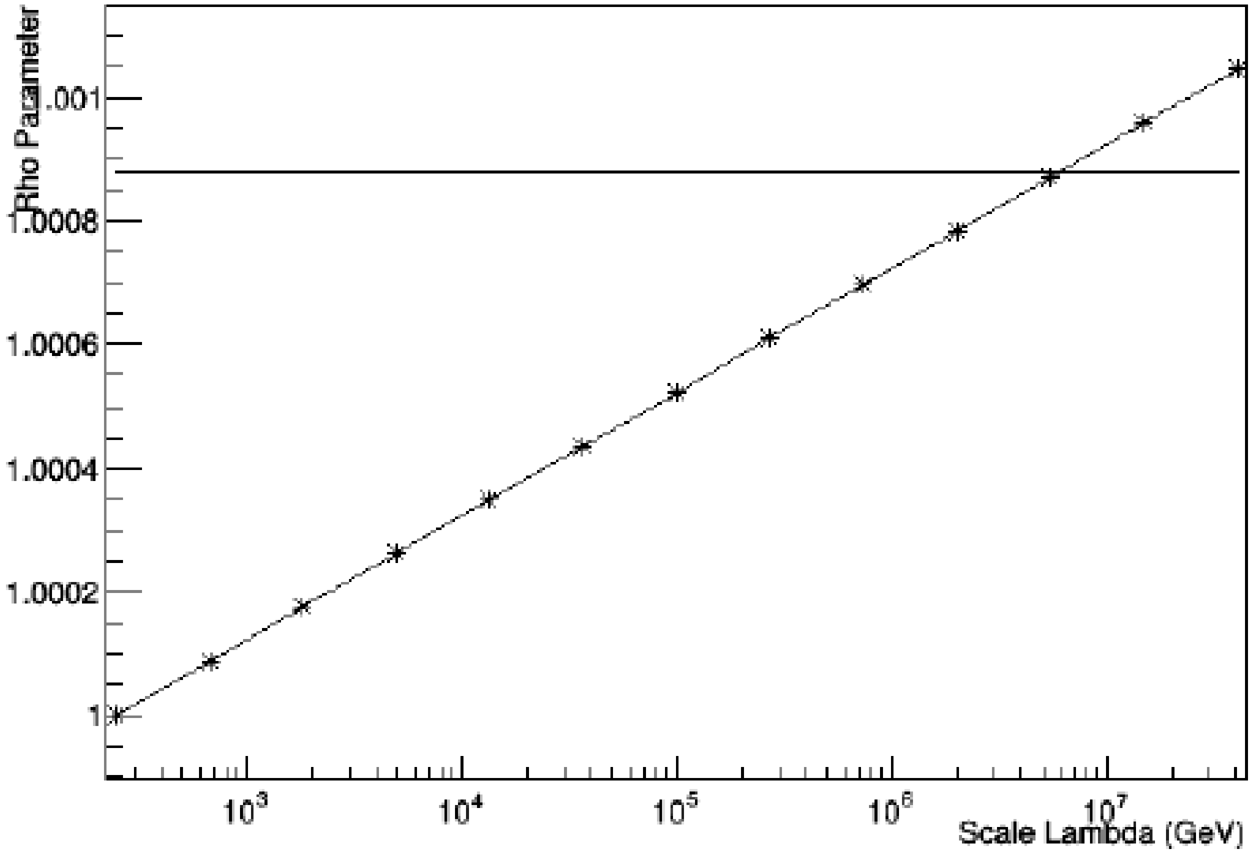
$$\begin{pmatrix} H_5^+ \\ H_3^+ \\ G^+ \end{pmatrix} : \begin{pmatrix} m_5^2 & 0 & 0 \\ 0 & m_3^2 & 0 \\ 0 & 0 & 0 \end{pmatrix} \rightarrow \begin{pmatrix} m_5^2 + O(\delta) & O(\delta) & O(\delta) \\ O(\delta) & m_3^2 + O(\delta) & O(\delta) \\ O(\delta) & O(\delta) & 0 \end{pmatrix}$$

Running of the Rho Parameter

- The running of rho parameter limits the size of the allowed cut-off scale
- For given test point can find largest possible cut-off scale that still preserves rho parameter within 2σ of measured value
- Running causes mixing between states and splits degenerate multiplets

Carleton University
Department of Physics
www.physics.carleton.ca

Running of Rho Parameter

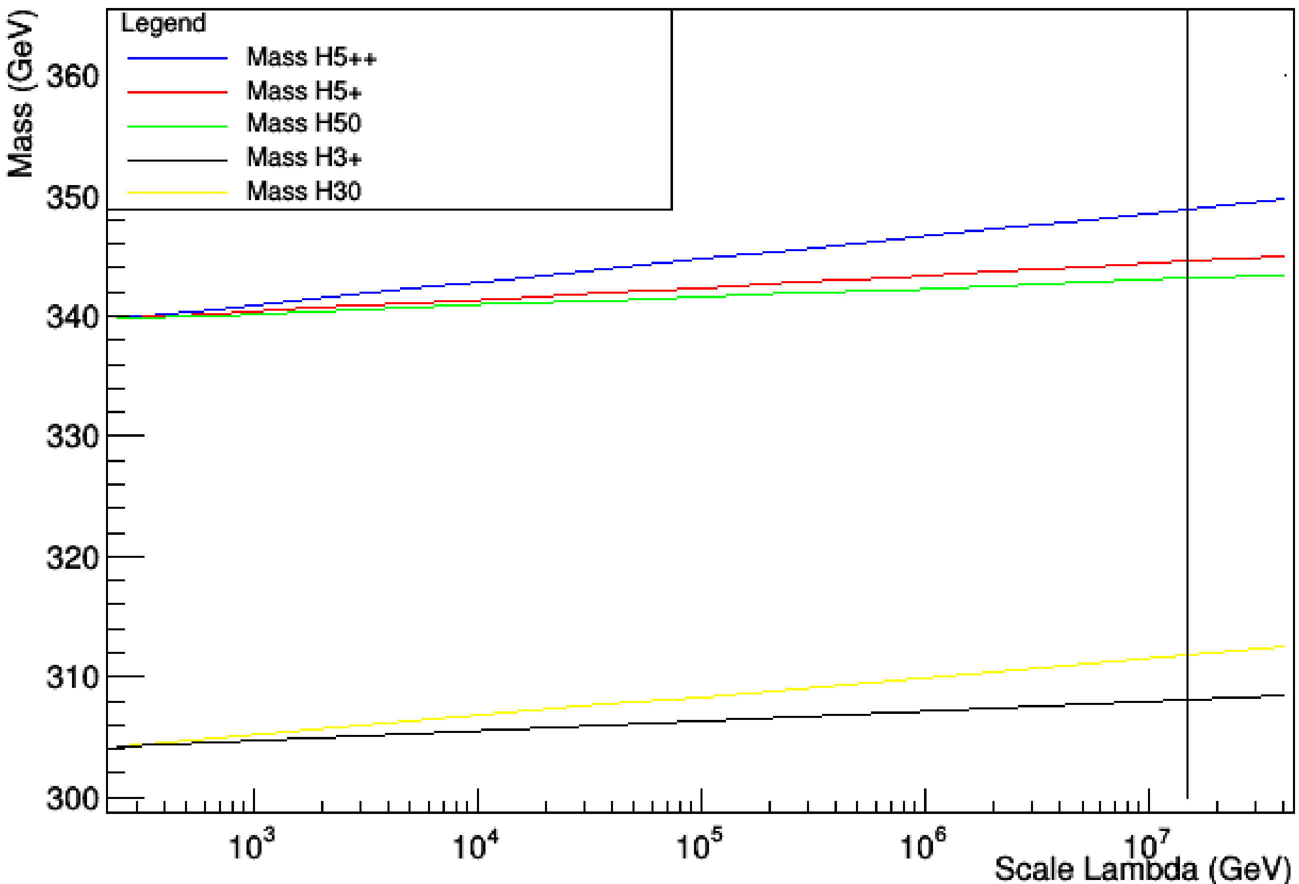


Test Pt: λ_i=0.1, M_i=100 GeV, μ_2^2=-8462 GeV^2, μ_3^2 =90000, GeV^2
V_χ=17 GeV

FIG. 1. ρ Parameter

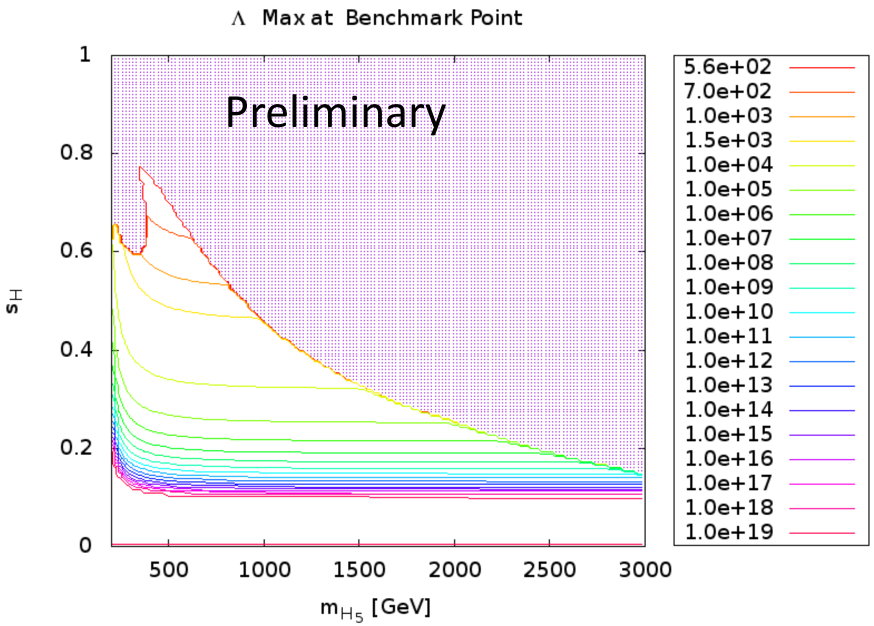
Carleton University
Department of Physics
www.physics.carleton.ca

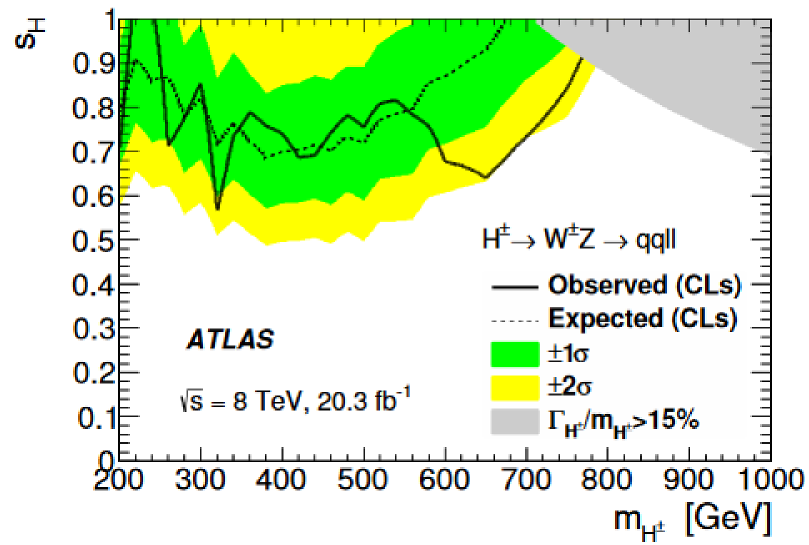
Mass Splitting



Test Pt: λ_i=0.1, M_i=100 GeV, μ_2^2=-8462 GeV^2, μ_3^2 =90000, GeV^2
V_χ=17 GeV

Some Contours





Bench Mark Pt: m_h =125 GeV
$\lambda_2 = 0.4(m_5/1000\text{GeV})$
$\lambda_3 = -0.1$
$\lambda_4 = 0.2$
$M_1 = \sqrt{2}\, s_H\, (m_5^2 + v^2)/v$
$M_2 = M_1/6$

Search for $H_5^{\pm}$ in $H_5^{\pm} \rightarrow W^{\pm} Z \rightarrow qqll$
ATLAS 1503.04233C

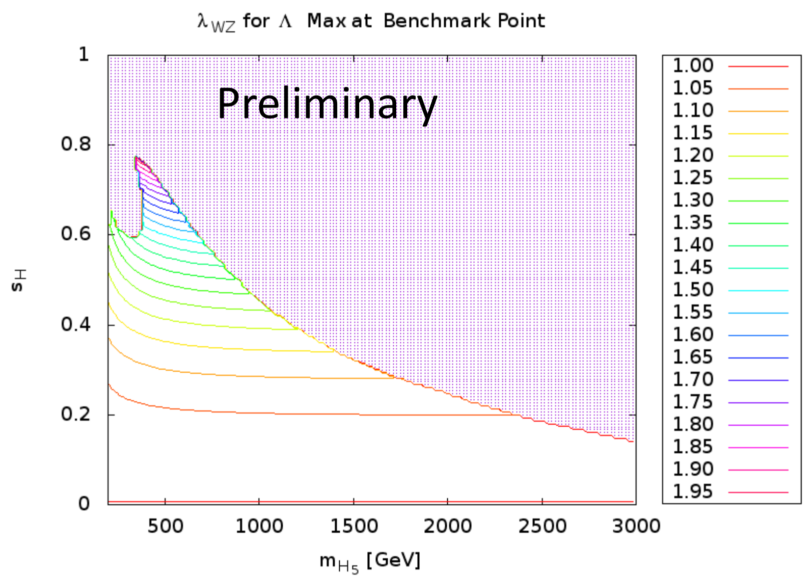
Coupling to Vector Bosons

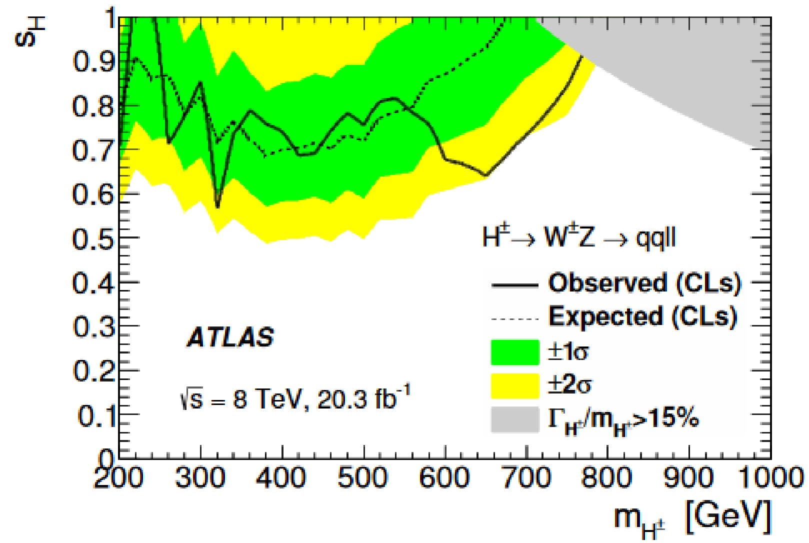
- Can parameterize BSM couplings as:

$$hWW: 2i\frac{{M_W}^2}{v^2}\kappa_W^h g^{\mu\nu} \qquad hZZ: \frac{2iM_Z^2}{v^2}\kappa_z^h g^{\mu\nu}$$

- Can use these to define: $\lambda_{WZ}^h = \frac{\kappa_W^h}{\kappa_Z^h}$
  - Measure of BSM physics
  - λ^h_{WZ} =1 in GM but not with custodial violation
  - Due to H_5^0 mixing and difference between v_ξ and v_χ
- $\lambda_{WZ}^h = 0.9 \pm 1$ at 1 sigma (ATLAS and CMS, 1606.02266)

Some Contours





Bench Mark Pt: m_h =125 GeV

$\lambda_2 = 0.4(m_5/1000\text{GeV})$

λ_3 =-0.1

λ_4 =0.2

$M_1=\sqrt{2}\, s_H\, (m_5^2 + v^2)/v$

$M_2= M_1/6$

Search for $H_5^\pm$ in $H_5^\pm \to W^\pm Z \to qqll$

ATLAS 1503.04233C

Carleton University
Department of Physics
www.physics.carleton.ca

Conclusions

- GM interesting benchmark of higher isospins
  - Custodial symmetry imposed at tree level
- Hypercharge gauge interaction violates custodial symmetry
  - Custodial symmetric scale can be quite large
- Running leads custodial violation in SM-like Higgs couplings to VBs
  - λ^{h}_{WZ} becomes greater than 1

Carleton University
Department of Physics
www.physics.carleton.ca

Backup Slides

GM Potential

- Write in terms of bidoublet and bitriplet

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

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

$$\tilde{\lambda}_1 = 4\lambda_1$$
$$\tilde{\lambda}_2 = 2\lambda_3$$
$$\tilde{\lambda}_3 = -2\lambda_5$$
$$\tilde{\lambda}_4 = -\sqrt{2}\lambda_5$$
$$\tilde{\lambda}_5 = 4\lambda_2$$
$$\tilde{\lambda}_6 = 2\lambda_2$$
$$\tilde{\lambda}_7 = 2\lambda_3 + 4\lambda_4$$
$$\tilde{\lambda}_8 = \lambda_3 + \lambda_4$$
$$\tilde{\lambda}_9 = 4\lambda_3$$
$$\tilde{\lambda}_{10} = 4\lambda_4$$
$$\widetilde{M}_1^1 = M_1$$
$$\widetilde{M}_1 = M_1$$

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

$$\widetilde{M}_2 = M_2$$

GM BenchMark Point

- parameterize (μ^2_1, μ^2_2, λ_1, λ_5) as (G_F,m_5,m_h,s_H)
- m_5, s_H parameters most related to direct searches for H_5
- maximum possible theoretical allowed parameter space
- $m_3 > m_5$ so no H_5->H_3VB i.e BR(H5->VBs) = 1 at tree level