Decoding the Georgi-Machacek Scenario

Insights from the LHC and Future Possibilities

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Extended Scalar Sectors from All Angles
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Based on

1. *Some new observations for the Georgi-Machacek scenario with triplet Higgs scalars*, Phys. Rev. D **107**, (2023) - by **R Ghosh** , B. Mukhopadhyaya

2. *Diphoton signals for the Georgi-Machacek scenario at the Large Hadron Collider*, arXiv:2407.07776 [hep-ph] - by S. Bhattacharya , **R Ghosh** , B. Mukhopadhyaya

Introduction

- The Standard Model (SM) of particle physics best describes nature in terms of elementary particles. Still it suffers from a few theoretical as well as observational dissatisfactions.
- Also it does not have any fundamental principle to dictate the structure of the electroweak symmetry breaking sector. Moreover many well motivated theoretical scenarios that solves the puzzles around SM, predicts an extended scalar sector.
- Two important questions: 1. How much is λ ? 2. What about other multiplets of $SU(2)$?.
- Non-doublet vevs are tightly constrained by the ρ parameter. However, what if substantial non-doublet vevs could be realized consistently with the ρ parameter constraint?
- What is the status of such a scenario ? What could we do more in this framework ?

An Illustration : The Georgi-Machacek Model

- Georgi and Machacek proposed a scenario whose Higgs sector consists of a doublet $\phi = (\phi^+ \;\; \phi^0)^T$, complex triplet $\chi = (\chi^{++} \;\; \chi^+ \;\; \chi^0)^T$ and real triplet $\xi = (\xi^+ \;\; \xi^0 \;\; \xi^-)^T$
  Nucl. Phys. B **262** (1985), 463, Phys. Lett. B **165** (1985), 105
- To proceed further let us denote the doublet ϕ as a bi-doublet Φ, and combine χ and ξ in a bi-triplet X

$$\Phi = \begin{pmatrix} \phi^{0\star} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \quad X = \begin{pmatrix} \chi^{0\star} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix} \tag{1}$$

- Under a $SU(2)_L \times SU(2)_R$ symmetry Φ transforms as, $\Phi \to U_L \Phi U_R^\dagger$ and X transforms as $X \to U_L X U_R^\dagger$
- After EWSB the vacuum remains invariant under the subgroup $U_L = U_R$. This symmetry is called as custodial $SU(2)$ and is ensured by $v_\chi = v_\xi$. This in turn preserves $\rho = 1$ at the tree-level.

The Scalar Sector

- The corresponding scalar potential is,

$$
\begin{aligned}
V(\Phi, X) &= \frac{\mu_2^2}{2} Tr(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2} Tr(X^\dagger X) + \lambda_1 [Tr(\Phi^\dagger \Phi)]^2 \\
&+ \lambda_2 Tr(\Phi^\dagger \Phi) Tr(X^\dagger X) + \lambda_3 Tr(X^\dagger X X^\dagger X) \\
&+ \lambda_4 [Tr(X^\dagger X)]^2 - \lambda_5 Tr(\Phi^\dagger \tau^a \Phi \tau^b) Tr(X^\dagger t^a X t^b) \\
&- M_1 Tr(\Phi^\dagger \tau^a \Phi \tau^b)(U X U^\dagger)_{ab} \\
&- M_2 Tr(X^\dagger t^a X t^b)(U X U^\dagger)_{ab}
\end{aligned}
$$

- The physical spectrum : a quintet $(H_5^{\pm\pm}, H_5^{\pm}, H_5^0)$, a triplet $(H_3^{\pm}, H_3^0)$, and two singlets (H, h).
- In the absence of $\Delta L = 2$ Yukawa coupling, the quintet couples to gauge bosons only, triplet couples to fermions only, and the singlets couple to both.

Constraints on the parameter space

- Theoretical constraints: Unitarty, Vacuum stability, Custodial symmetric vacuum be the global one.
- Indirect constraints: EWPT, $b \to s\gamma$, $B_s \to \mu^+\mu^-$ K. Hartling, K. Kumar and H. E. Logan, Phys. Rev. D **91**, 015013 (2015)
- Direct constraints: Searches for BSM scalars, measurements of 125 GeV scalar.
- Most stringent:

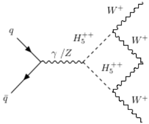


Figure 1: **Drell-Yan production of H_5^{++}**

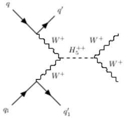


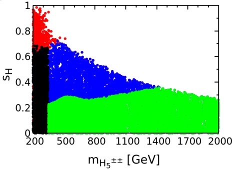
Figure 2: **VBF production of H_5^{++}**

- Input parameters: m_5 , $s_H = \frac{2\sqrt{2}v_\chi}{v}$, $m_3, M_2, \lambda_3, \lambda_4, \lambda_2$
- Codes used: GMCALC, HiggsSignals, HiggsBounds. P. Bechtle, O. Brein, S. Heinemeyer, G. Weiglein and K. E. Williams, Eur. Phys. J. C **75**, 421 (2015)

Allowed Triplet vev : The custodial case

$\underline{m_5 < m_3}$

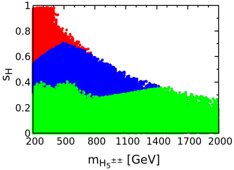
$H_5^{\pm\pm} \to W^\pm W^\pm$



- $s_H|_{max} = 0.4 \implies v_\chi \approx$ 35 GeV at around $m_5 = 1400$ GeV.

$\underline{m_3 < m_5 < 2m_3}$

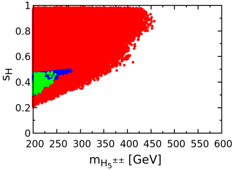
$H_5^{\pm\pm} \to W^\pm W^\pm$
$H_5^{\pm\pm} \to W^\pm H_3^\pm$



- $s_H|_{max} = 0.4 \implies v_\chi \approx$ 35 GeV in the range $m_5 = 200 - 500$ GeV.

$\underline{m_5 > 2m_3}$

$H_5^{\pm\pm} \to W^\pm W^\pm$
$H_5^{\pm\pm} \to W^\pm H_3^\pm$
$H_5^{\pm\pm} \to H_3^\pm H_3^\pm$



- $s_H|_{max} = 0.48 \implies v_\chi \approx 42$ GeV at around $m_5 = 200$ GeV.

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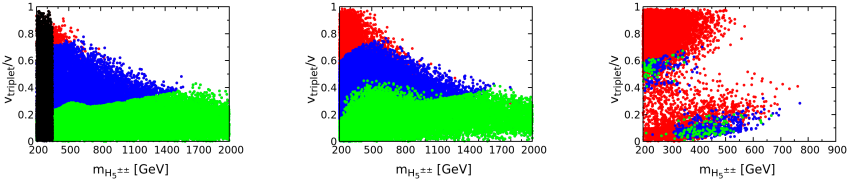
Allowed Triplet vev : The non-custodial case

- In the full lagrangian of the GM scenario, the custodial $SU(2)$ is broken by the hypercharge interaction.
- Hence, upon inclusion of quantum corrections, this symmetry is broken and the 1-loop effective potential is $SU(2)_L \times U(1)_Y$ invariant general potential with this scalar content.
  J. F. Gunion, R. Vega and J. Wudka Phys. Rev. D **43** (1991)
- Treating the non-custodial effects completely in a phenomenological manner, and taking $|\frac{v_\chi - v_\xi}{v_\chi}| \leq 0.3$, the allowed parameter space turns out to be:



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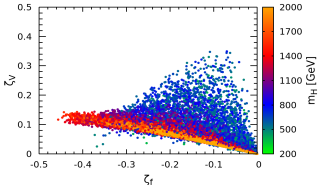
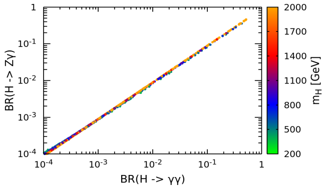
Signature Other than $H^{\pm\pm}$

- Now, what if $s_H < 0.2$? or $m_5 < 200$ GeV ? Is there any signature of such a scenario other than $H^{\pm\pm}$? $\rightarrow$ Look at H.
- The coupling strength modification factors of H to gauge boson pairs and charged fermion pairs are denoted by ζ_V and ζ_f respectively.

$$\zeta_F = \frac{\sin\alpha}{\sqrt{1-\frac{8v_\chi^2}{v^2}}} \ , \ \zeta_V = \frac{v_\phi}{v}\sin\alpha + \frac{8v_\chi}{\sqrt{3}v}\cos\alpha \qquad (2)$$





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Diphoton in the GM Scenario

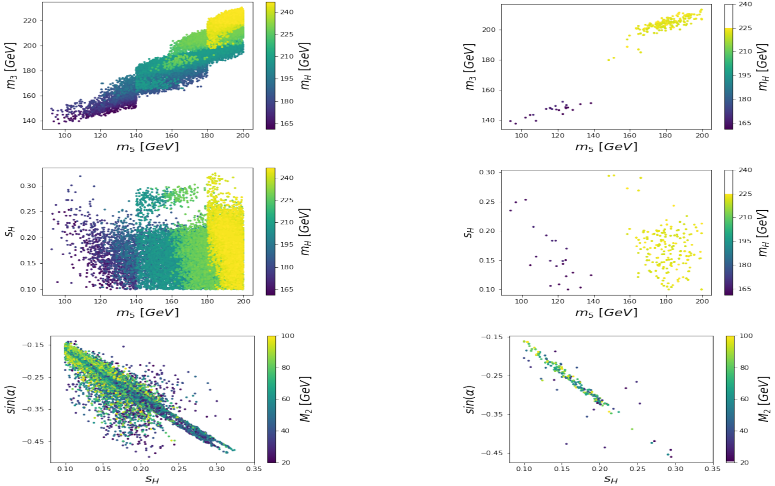
- A detailed analysis of resulting diphoton signal has been carried out taking into account the irreducible $\gamma\gamma$ and reducible $j\gamma$ and jj background.

- The corresponding significance has been calculated using likelihood ratio method.

- The production rate will be controlled by mass of the doubly and singly charged scalars, the doublet content of $H(\sin\alpha)$, the triplet vev, the trilinear coupling. Hence the results have been shown in terms of $(m_H, m_5, m_3, s_H, \sin\alpha, M_2)$

arXiv:2407.07776 [hep-ph] - by S. Bhattacharya , **RG** , B. Mukhopadhyaya

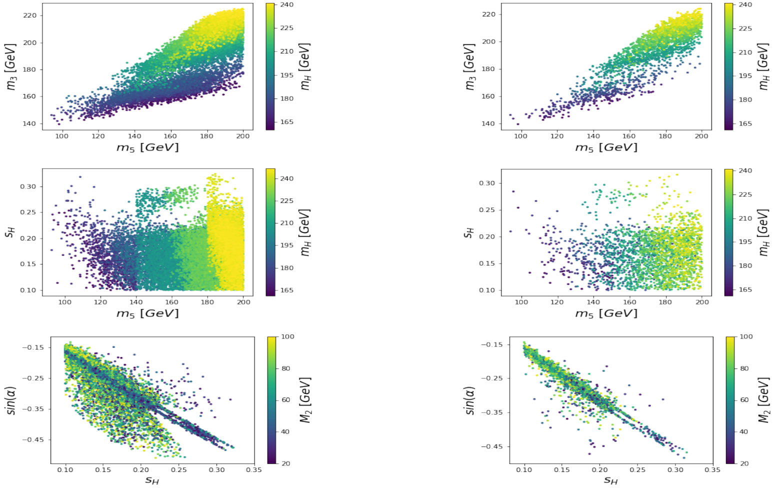
Results of a cut-based analysis



Left: Regions of the parameter space that can be probed with a significance $\geq 3\sigma$ at the LHC, with $\int \mathcal{L}dt = 3000\ fb^{-1}$ in presence of 10% systematics. Right: Same as left but at $300\ fb^{-1}$.

Results based on a neural-network

Improvements achieved based on a neural-network with input variables: $\sum_{i,\Delta R \leq 0.5} \frac{p_{T_i}}{p_T^\gamma}$, $\frac{p_T^l}{m_{\gamma\gamma}}$, $\frac{p_T^{sl}}{m_{\gamma\gamma}}$, $\frac{E^l}{m_{\gamma\gamma}}$, $\frac{E^{sl}}{m_{\gamma\gamma}}$, $\Delta|\eta|_{\gamma\gamma}$, $\Delta|\phi|_{\gamma\gamma}$, $\Delta\theta_{\gamma\gamma}$



Summary

- Given all the experimental constraints, a triplet vev upto 40 GeV is allowed.
- Besides $H^{\pm\pm}$, H also has a significant role in probing the scenario at the LHC, due to high loop induced branching ratio to $\gamma\gamma$ and $Z\gamma$.
- Demanding the production mode to be gluon-fusion restricts the explorable range of m_H to 160-250 GeV. But, it would be interesting to search for other production modes to exploit the high branching ratio of $H \to \gamma\gamma$, $Z\gamma$.
- Such a diphoton signal can be probed even with $\int L dt = 300\ fb^{-1}$ for some region of the parameter space if an analysis based on a neural-network is carried out.

Thank You

Back up

More info on diphoton

Reasons of high BR($H \to \gamma\gamma$)

- Contributions of the doubly and singly-charged scalar loops
- Suppression of the destructively interfering fermion loops
- Presence of the trilinear scalar couplings, especially M_2
- Suppression of the tree-level fermion and gauge boson pair decays due to the dominant $SU(2)_L$ triplet composition of H as compared to h

What about production?

- The gluon fusion cross-section is proportional to ζ_f^2
- Hence the production mode is driven by the doublet content of H whereas the decay into diphoton is driven mainly by triplet content of H.
- As a result there exists a competing as well as compensating effect between the production and decay mode.

More info on diphoton

Relevant trilinear couplings

$$g_{HH_5H_5} = 8\sqrt{3}(\lambda_3 + \lambda_4)v_\chi \cos\alpha + (4\lambda_2 + \lambda_5)v_\phi \sin\alpha + 2\sqrt{3}M_2\cos\alpha \quad (3)$$

$$g_{HH_3H_3} = 64\lambda_1\frac{v_\chi^2 v_\phi}{v^2}\sin\alpha + \frac{8}{\sqrt{3}}(\lambda_3 + 3\lambda_4)\frac{v_\phi^2 v_\chi}{v^2}\cos\alpha + \frac{4}{\sqrt{3}}M_1\frac{v_\chi}{v^2}(v_\chi\cos\alpha + \sqrt{3}v_\phi\sin\alpha) + \frac{16}{\sqrt{3}}(6\lambda_2 + \lambda_5)\frac{v_\chi^3}{v^2}\cos\alpha + (4\lambda_2 - \lambda_5)\frac{v_\phi^3}{v^2}\sin\alpha - 2\sqrt{3}M_2\frac{v_\phi^2}{v^2}\cos\alpha + \frac{8}{\sqrt{3}}\lambda_5\frac{v_\chi v_\phi}{v^2}(v_\phi\cos\alpha + \sqrt{3}v_\chi\sin\alpha) \quad (4)$$

More info on diphoton

The cut flow table

m_H[GeV]	cuts applied	signal [fb]	$\gamma\gamma$ [pb]	$j\gamma$ [pb]	jj [pb]
200	initial cross section	4.95	9.17	4.89×10^3	2.01×10^7
	acceptance	3.17	6.08	3.97	2.87
	$p_T^l \geq 70\ GeV$, $p_T^{sl} \geq 60\ GeV$	2.72	2.02	1.35	0.64
	$170\ GeV \leq m_{\gamma\gamma} \leq 230\ GeV$	2.72	0.79	0.46	0.08

Significance as obtained from cut-based analysis

	$cut1$	$cut2$	significance without systematics	significance with 10% systematics
BP1	$p_T^l > 55$, $p_T^{sl} > 45$	$130 < m_{\gamma\gamma} < 180$	10	9.4
BP2	$p_T^l > 65$, $p_T^{sl} > 55$	$150 < m_{\gamma\gamma} < 210$	5.7	5.3
BP3	$p_T^l > 70$, $p_T^{sl} > 60$	$170 < m_{\gamma\gamma} < 230$	7.6	7.1
BP4	$p_T^l > 80$, $p_T^{sl} > 70$	$190 < m_{\gamma\gamma} < 250$	10.4	10
BP5	$p_T^l > 90$, $p_T^{sl} > 80$	$210 < m_{\gamma\gamma} < 270$	9.1	8.7
BP6	$p_T^l > 90$, $p_T^{sl} > 80$	$210 < m_{\gamma\gamma} < 270$	6.7	6.4

More info on diphoton

Significance as obtained from an ANN-based analysis

BP	Significance (Cut-based) with 10% systematics	$\int \mathcal{L}dt$ $[fb^{-1}]$ for 5σ (cut based)	significance (ANN) with 10% systematics	$\int \mathcal{L}dt$ $[fb^{-1}]$ for 5σ (ANN)
BP1	9.4	849	17.4	248
BP2	5.3	2670	15.6	308
BP3	7.1	1488	13.7	399
BP4	10	750	15.9	297
BP5	8.7	990	13.6	405
BP6	6.8	1622	9.9	750