New Physics Implications of Vector Boson Fusion (VBF) Searches

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Outline

New physics implications of vector boson fusion searches exemplified through the Georgi-Machacek model *[PHYSICAL REVIEW D 109, 015016 (2024)]*

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- **Motivation**
- **Model**
- **Theoretical Constraints and decoupling limit**
- **Experimental Constraints**
- **Summary and Conclusion**

Motivation

- In the SM, electric charge $Q = T_{3L} + Y/2$ is conserved.
- Does there exist any additional scalar multiplets of $SU(2)_L$ beyond the SM that contribute to the mechanism of EWSB ?
- LHC searches for nonstandard scalar resonances in VBF production processes can potentially serve as a powerful tool to pin down any BSM contribution to the process of EWSB.
- **Georgi-Machacek** (GM) model can serve as the ideal candidate to illustrate the potential of VBF searches at the LHC in determining the basic ingredients of the electroweak VEV.
- In our analysis, we demonstrate how the VBF searches can provide complementary constraints to the theoretical bounds on the model parameter space.

Model

Extending the SM doublet (Y=1) with two triplets, withY=0 and Y=2[H. Georgi and M. Machacek, Nucl. Phys. B262, 463 (1985)].

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

The most general scalar scalar potential can be written as[H. E. Logan, Phys. Rev. D 90, 015007 (2014).]:

$$\begin{aligned} V(\Phi, X) = {}& \frac{\mu_\phi^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_X^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 + \lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) \\ & + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)\mathrm{Tr}(X^\dagger t_a X t_b) \\ & - M_1\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t_a X t_b)(UXU^\dagger)_{ab}, \end{aligned}$$

Model

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$$
\begin{aligned}
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& + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) + \lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)\mathrm{Tr}(X^\dagger t_a X t_b) \\
& - M_1\mathrm{Tr}(\Phi^\dagger\tau_a\Phi\tau_b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t_a X t_b)(UXU^\dagger)_{ab},
\end{aligned}
$$

With

$$
t_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad
t_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \quad
t_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \quad
U = \frac{1}{\sqrt{2}}\begin{pmatrix} -1 & 0 & 1 \\ -i & 0 & -i \\ 0 & \sqrt{2} & 0 \end{pmatrix}.
$$

Model

After EWSB, the neutral components of the bi-doublet and bi-triplet are expanded around their VEVs:

$$\phi^0 = \frac{1}{\sqrt{2}}(v_d + h_d + i\eta_d), \qquad \xi^0 = (v_t + h_\xi),$$

$$\chi^0 = \left(v_t + \frac{h_\chi + i\eta_\chi}{\sqrt{2}}\right).$$

The requirement of **equal VEVs** to the real and the complex triplets ensures that **custodial symmetry** in the scalar potential **remains intact**.

$$\sqrt{v_d^2 + 8v_t^2} = v = 246 \text{ GeV}.$$

Model

The two VEVs can be used to extract the bilinear coefficients:

$$\mu_\phi^2 = -4\lambda_1 v_d^2 - 3(2\lambda_2 - \lambda_5)v_t^2 + \frac{3}{2}M_1 v_t, \quad \mu_X^2 = -(2\lambda_2 - \lambda_5)v_d^2 - 4(\lambda_3 + 3\lambda_4)v_t^2 + \frac{M_1 v_d^2}{4v_t} + 6M_2 v_t.$$

The bilinear terms in the scalar potential can be diagonalized to obtain the physical Higgs scalars:

$$H_5^{\pm\pm} = \chi^{\pm\pm},$$

$$H_5^{\pm} = \frac{1}{\sqrt{2}}(\chi^{\pm} - \xi^{\pm}),$$

$$H_5^0 = \sqrt{\frac{2}{3}}h_\xi - \sqrt{\frac{1}{3}}h_\chi,$$

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

$$H_3^0 = -\sin\beta\,\eta_d + \cos\beta\,\eta_\chi,$$

$$h = \cos\alpha\,h_d + \sin\alpha\,H_5^{0\prime},$$

$$H = -\sin\alpha\,h_d + \cos\alpha\,H_5^{0\prime},$$

$$H_5^{0\prime} = \sqrt{\frac{1}{3}}h_\xi + \sqrt{\frac{2}{3}}h_\chi.$$

$$\tan\beta = \frac{2\sqrt{2}v_t}{v_d}.$$

Model

- We consider h to be the lightest CP-even scalar corresponding to the SM Higgs.
- GM model scalar potential has 9 parameters, namely, 2 bilinerars, 5 quartic couplings, and 2 trilinear couplings[N. Ghosh et al, Phys.Rev. D 101, 015029 (2020)].

$$\lambda_1 = \frac{1}{8v^2\cos^2\beta}\left(m_h^2\cos^2\alpha + m_H^2\sin^2\alpha\right),$$

$$\lambda_2 = \frac{1}{12v^2\cos\beta\sin\beta}\left(\sqrt{6}(m_h^2 - m_H^2)\sin 2\alpha + 12m_3^2\sin\beta\cos\beta - 3\sqrt{2}v\cos\beta M_1\right),$$

$$\lambda_3 = \frac{1}{v^2\sin^2\beta}\left(m_5^2 - 3m_3^2\cos^2\beta + \sqrt{2}v\cos\beta\cot\beta M_1 - 3\sqrt{2}v\sin\beta M_2\right),$$

$$\lambda_4 = \frac{1}{6v^2\sin^2\beta}\left(2m_H^2\cos^2\alpha + 2m_h^2\sin^2\alpha - 2m_5^2 + 6\cos^2\beta m_3^2 - 3\sqrt{2}v\cos\beta\cot\beta M_1 + 9\sqrt{2}v\sin\beta M_2\right),$$

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

Theoretical Constraints and Decoupling Limit

$$\Lambda_1^2 = \frac{M_1 v}{\sqrt{2}\sin\beta} \equiv \frac{M_1 v^2}{4 v_t},$$

$$\Lambda_2^2 = 3\sqrt{2} v M_2 \sin\beta \equiv 12 v_t M_2.$$

Theoretical constraints from perturbative unitarity put upper bounds on the eigenvalues of the 2 → 2 scalar scattering amplitude matrix[H.E.Logan(Phys. Rev. D 90, 015007 (2014)), S.Kanemura(Phys. Rev. D 77, 095009 (2008))]:

$$x_1^\pm = 12\lambda_1 + 14\lambda_3 + 22\lambda_4 \pm \sqrt{(12\lambda_1 - 14\lambda_3 - 22\lambda_4)^2 + 144\lambda_2^2},$$

$$x_2^\pm = 4\lambda_1 - 2\lambda_3 + 4\lambda_4 \pm \sqrt{(4\lambda_1 + 2\lambda_3 - 4\lambda_4)^2 + 4\lambda_5^2},$$

$$y_1 = 16\lambda_3 + 8\lambda_4,$$

$$y_2 = 4\lambda_3 + 8\lambda_4,$$

$$y_3 = 4\lambda_2 - \lambda_5,$$

$$y_4 = 4\lambda_2 + 2\lambda_5,$$

$$y_5 = 4\lambda_2 - 4\lambda_5.$$

Theoretical Constraints and Decoupling Limit

In the decoupling limit ($v_t \ll v$), taking $|y_2| \leq 8\pi$,

$$\frac{1}{3}[m_5^2 + 2(m_h^2 \sin^2\alpha + m_H^2 \cos^2\alpha)] - m_3^2 \cos^2\beta \approx 0.$$

Similarly, $|y_3| \leq 8\pi$ gives to

$$\left| m_3^2 - \frac{\sqrt{2}}{\sqrt{3}}(m_H^2 - m_h^2)\frac{\sin 2\alpha}{\sin 2\beta} \right| \leq 4\pi v^2.$$

From these two equations, one can infer that unitarity conditions will be trivially satisfied for

$$\sin 2\alpha \approx \sqrt{\frac{3}{2}} \sin 2\beta \quad \text{with} \quad v_t \ll v$$

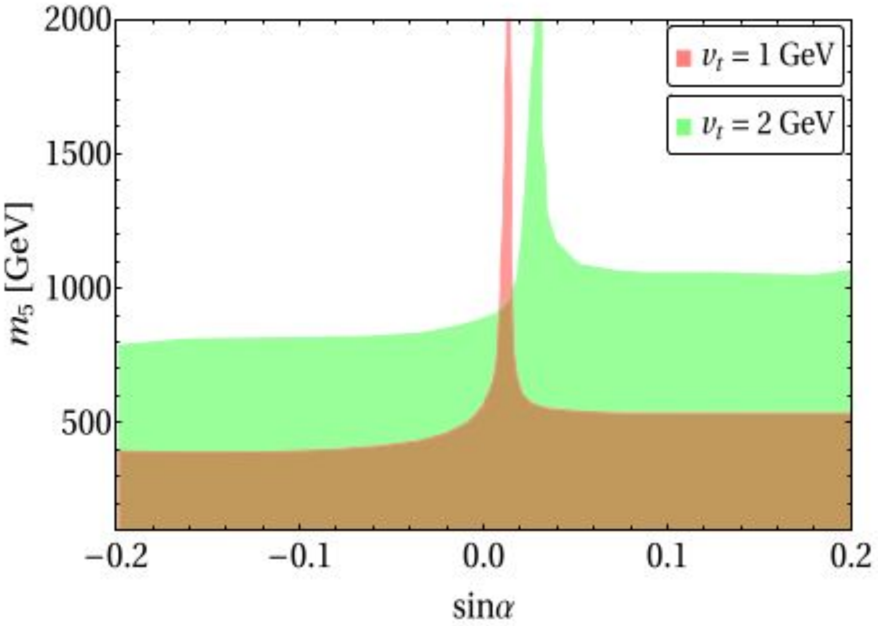
$$m_H^2 \approx m_3^2 \approx m_5^2 \approx \Lambda_1^2 \gg v^2; \qquad \Lambda_2^2 \ll v^2,$$

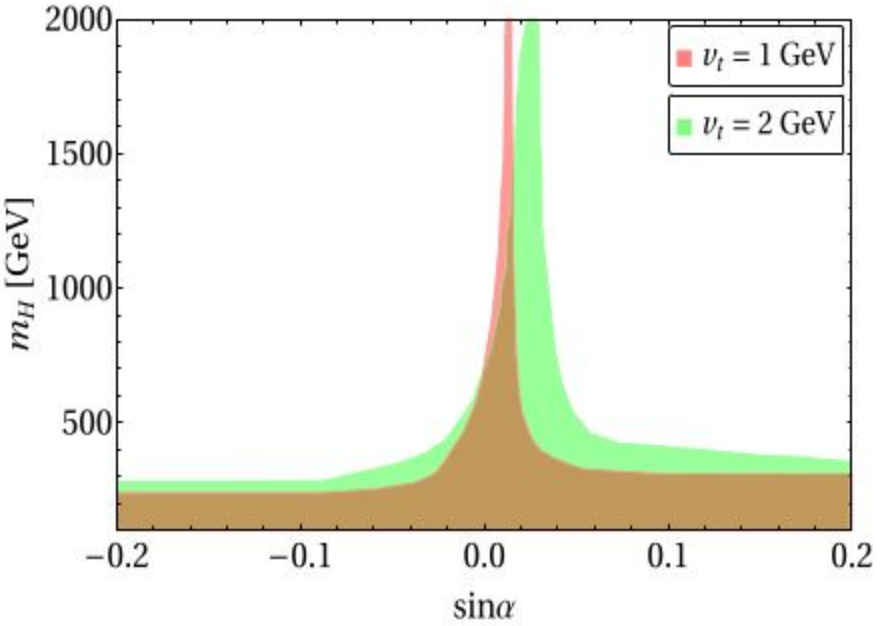
Decoupling limit of the GM Model !!

This can be more simplified as: $$\sin\alpha \approx 2\sqrt{3}\frac{v_t}{v},$$

Theoretical Constraints and Decoupling Limit

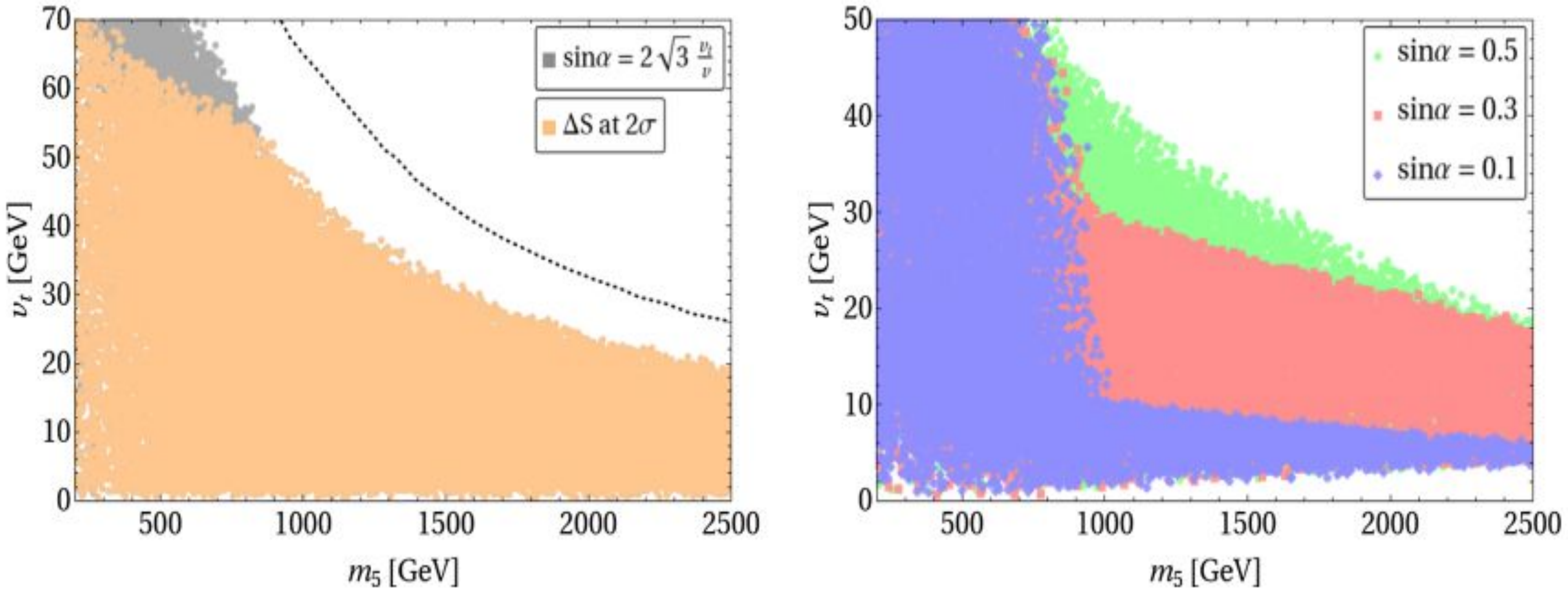
In the decoupling limit, the unitarity and BFV restricts the parameter space as:





The location of the peak corresponds to: $$\sin\alpha \approx 2\sqrt{3}\,\frac{v_t}{v}\,,$$

Theoretical Constraints and Decoupling Limit



The Lee-Quicker-Thacker bound on the Higgs masses[H. B. Thacker et al,Phys. Rev. D 16, 1519 (1977)]

$$(\kappa_W^h)^2 m_h^2 + (\kappa_W^H)^2 m_H^2 + \left[(\kappa_W^{H_5})^2 + \frac{1}{2}(\kappa_2)^2\right] m_5^2 \leq 4\pi v^2.$$

Theoretical Constraints and Decoupling Limit

We recall that the oblique S parameter has been known to put important constraints on the parameter space of the GM model. ΔS constraints(-0.01 ± 0.07) start becoming important for $v_t \gtrsim 50$ GeV.

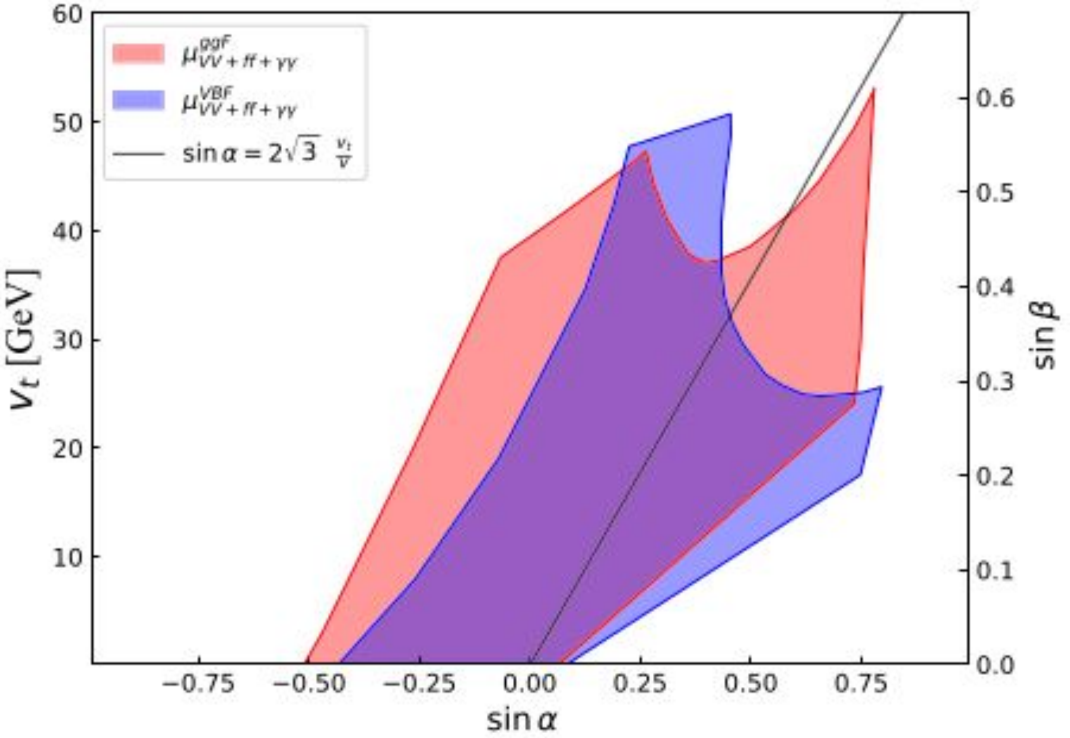
The coupling modifier for the trilinear Higgs self-coupling can be written as:

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{(\lambda_{hhh})^{\mathrm{SM}}} = \cos^3\alpha \sec\beta + \frac{2\sqrt{2}}{\sqrt{3}} \sin^3\alpha \csc\beta + \frac{2\Lambda_1^2}{m_h^2} \sin^2\alpha \cos\beta \left(\cos\alpha - \frac{\sqrt{2}}{\sqrt{3}} \sin\alpha \cot\beta \right) + \frac{\sqrt{2}}{3\sqrt{3}} \frac{\Lambda_2^2}{m_h^2} \sin^3\alpha \csc\beta.$$

Experimental Constraints

A. Higgs Signal Strength:

$$\mu_j^i = \frac{\sigma^i}{(\sigma^i)_{\rm SM}} \times \frac{{\rm BR}_j}{({\rm BR}_j)_{\rm SM}}$$



Experimental Constraints

B. Direct search constraints from the LHC:

- The ATLAS collaboration has performed searches for the VBF production of a neutral heavy resonance decaying to Z-boson pairs in the leptonic final states[*Eur. Phys. J. C 81, 332 (2021)*]. This data can be effective in constraining the neutral member of the custodial fiveplet H^0_5 as well as the custodial singlet H.

- Searches for a charged Higgs boson have been performed in VBF production mode and its subsequent decay into WZ modes[*ATLAS-CONF-2022-066, 2022*].This bound can be crucial to constrain the properties of the charged Higgs state $H^{\pm}_5$.

Experimental Constraints

B. Direct search constraints from the LHC:

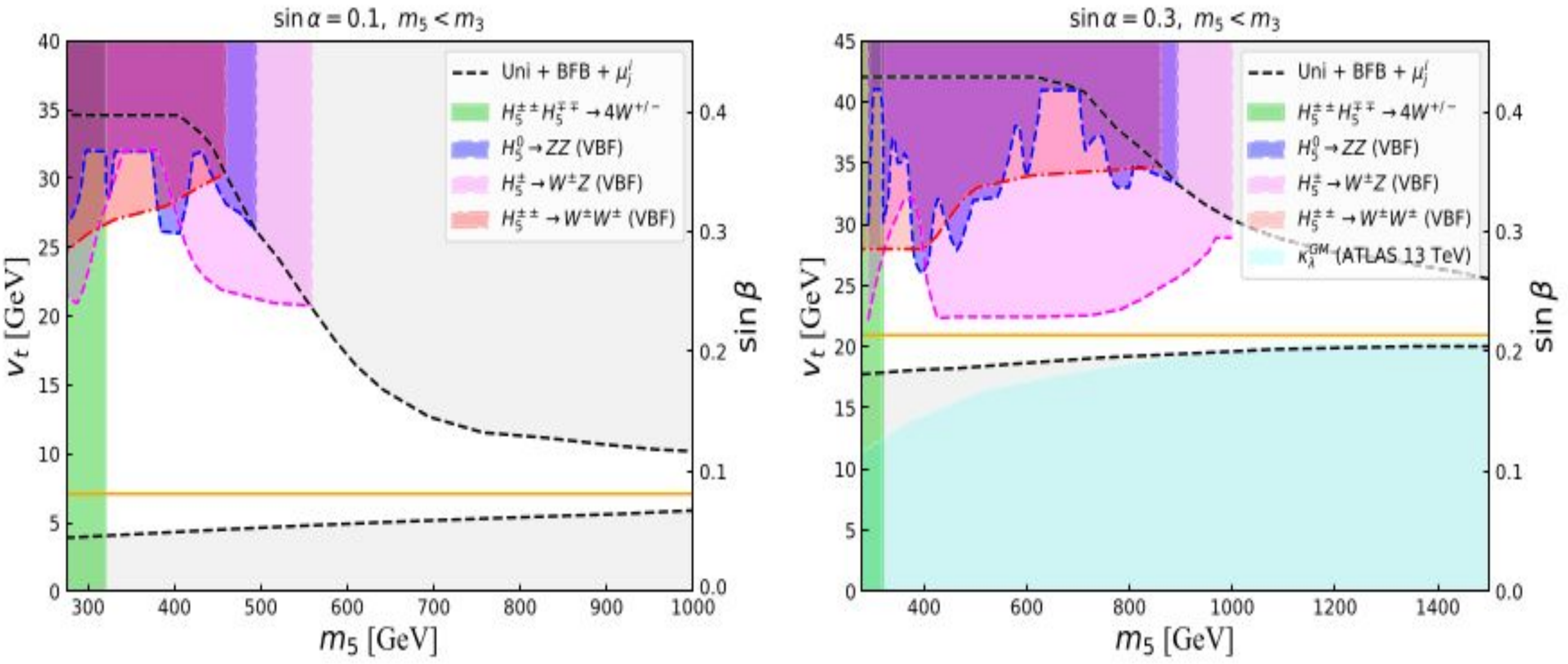
- The CMS collaboration has looked for a doubly charged scalar in like-sign WW final states, producing model independent bounds on the corresponding signal strength as a function of doubly charged Higgs mass [*Eur. Phys. J. C 81, 723(2021)*]. Additionally, the Drell-Yan production of a pair of doubly charged Higgs bosons with decays to WW pairs has been investigated by the ATLAS collaboration [*J. High Energy Phys. 06 (2021) 146*]. We employ these data to constrain the properties of the $H^{\pm\pm}_5$ particle.

Apart from the direct LHC searches, we also take the constraints coming from 125 GeV Higgs boson trilinear self-coupling measurements [-1 , 6.6] at the LHC[*Nature (London) 607, 60 (2022)*].

We checked our parameter space against the constraints on the quartic gauge-Higgs coupling modifier[0.55 , 1.49] [*Englert et al, J. High Energy Phys. 11(2023) 158*] from di-Higgs production process [*Phys. Rev. D 108, 052003 (2023)*]. This provides a much weaker bound compared to other constraints, excluding only $\sin\alpha \gtrsim 0.81$.

Experimental Constraints

B. Direct search constraints from the LHC:



Experimental Constraints

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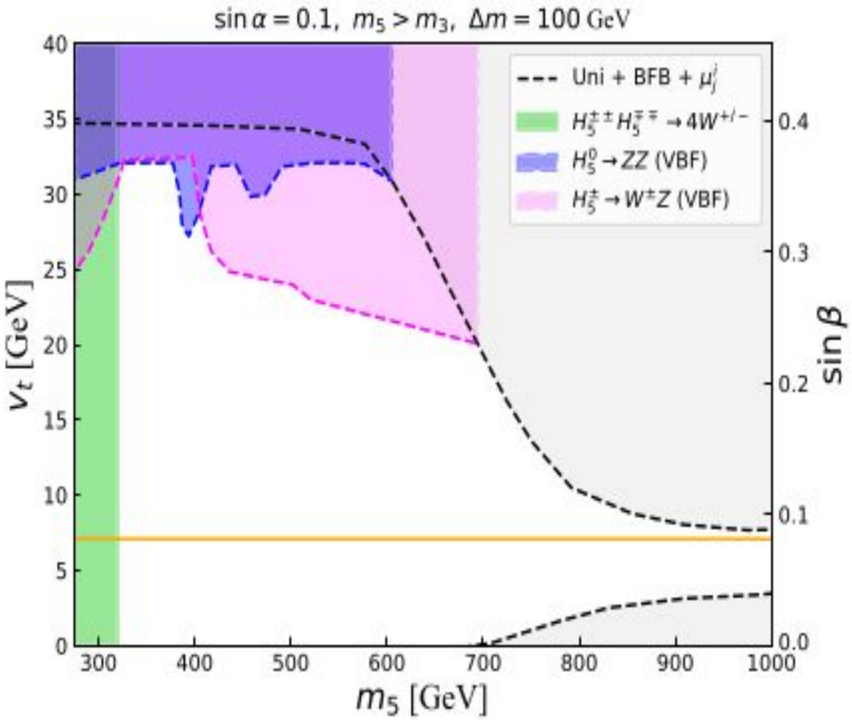

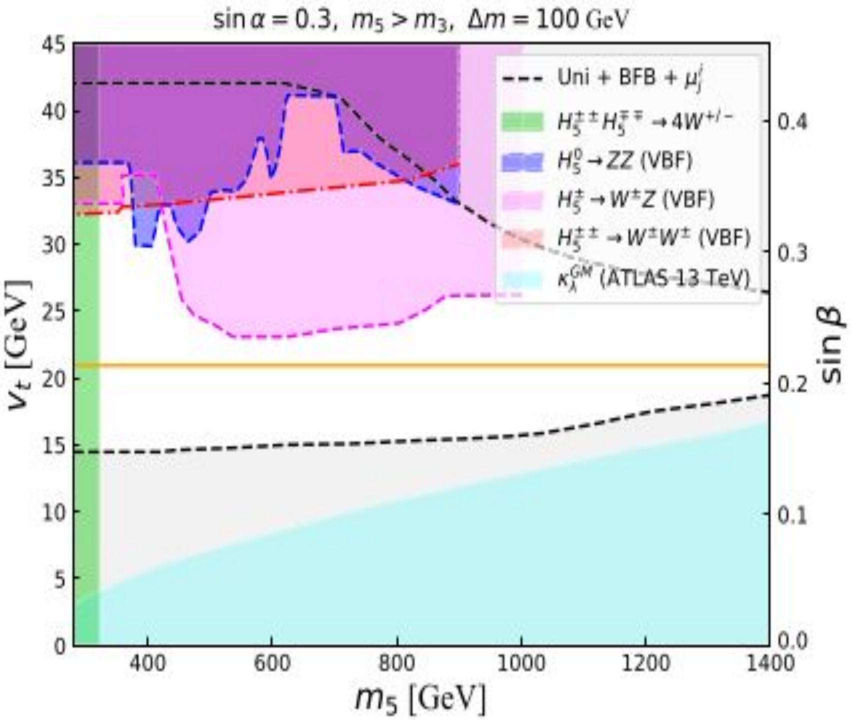

Experimental Constraints

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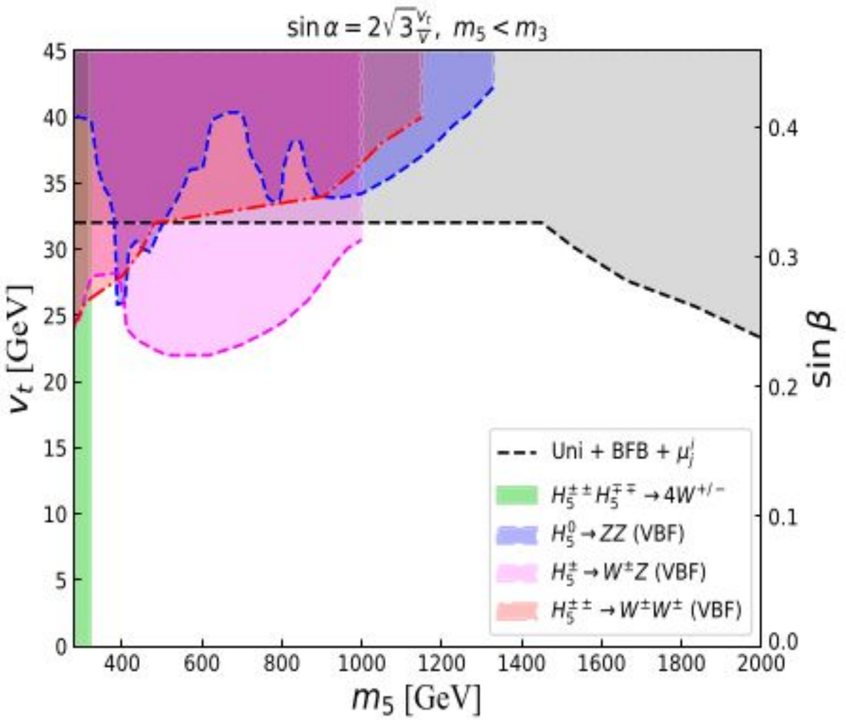
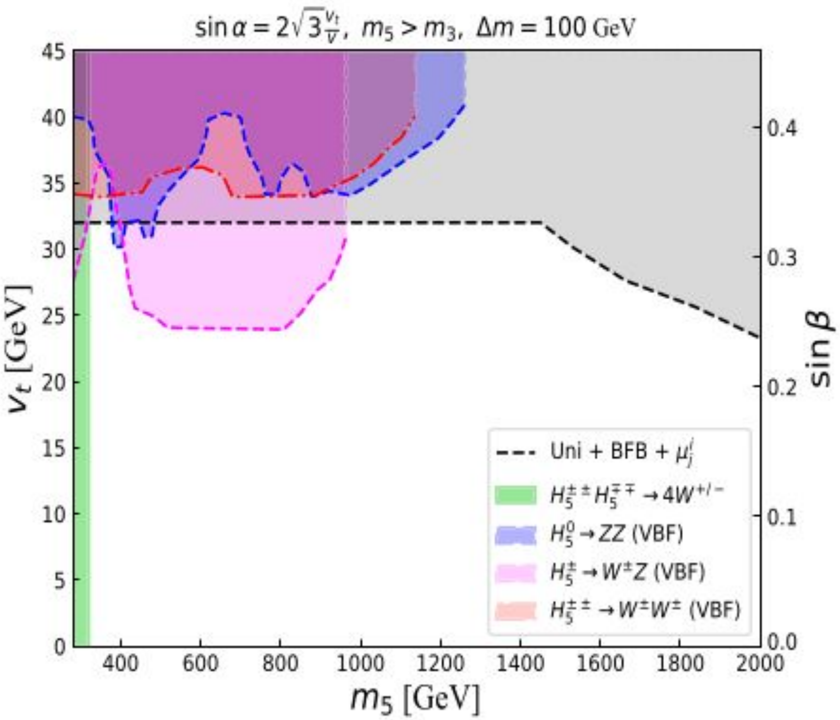
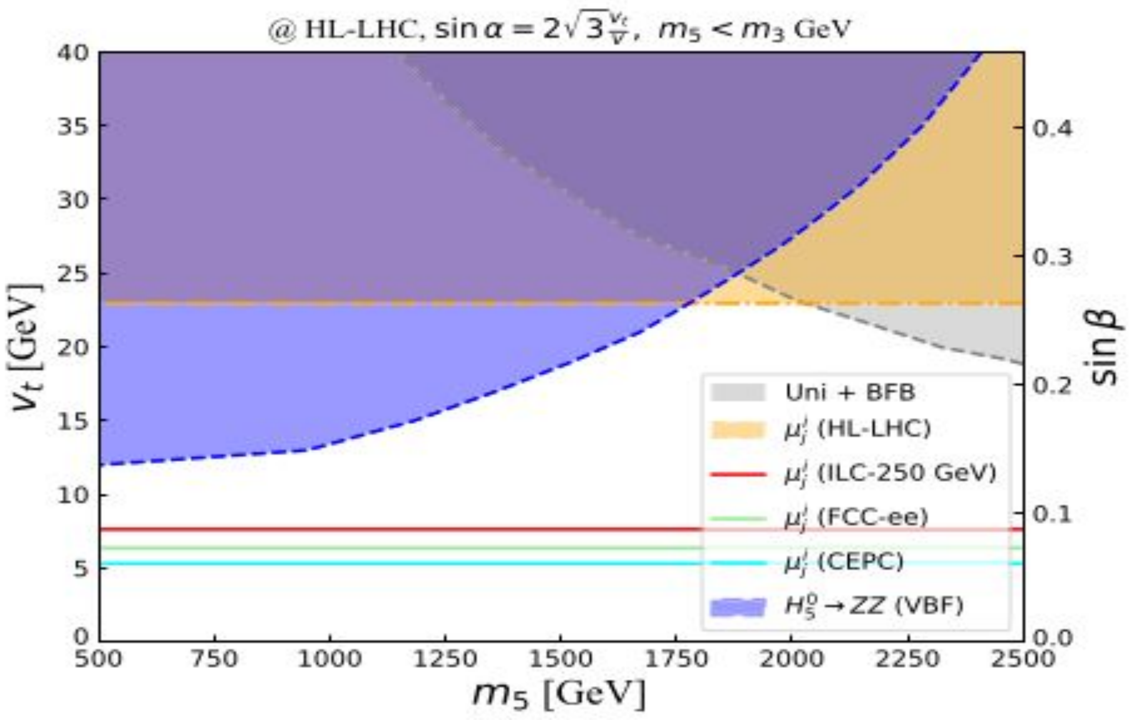




Experimental Constraints

C. Future prospects: HL-LHC projected limits:

[Blas et al.J. High Energy Phys. 01 (2020) 139]



Summary and Conclusion

- We studied the implications of the nonstandard scalar (neutral as well as charged) searches in the VBF production channel at the LHC, taking the GM model as an illustrative example.

- In our study of the GM model, we have first analyzed the theoretical constraints from unitarity and BFB. Here we observe that, for low values of the triplet VEV, we need to have a correlation between sin α and v_t to allow for very heavy nonstandard scalars decoupled from the electroweak scales.

- We have found that the LHC constraints can be complementary to the theoretical constraints from unitarity and BFB to constrain the triplet VEV as a function of the custodial fiveplet mass. For $m_5 < m_3$,the upper bound on the triplet VEV can be as strong as $v_t \lesssim 25$ GeV.

Summary and Conclusion

- With the improved sensitivity projected for the HL-LHC, more stringent constraints on the triplet VEV are expected from the VBF searches, implying that the combination of the direct HL-LHC collider limits and the theoretical constraints will enforce the decoupling limit of the GM model if no deviation from the SM is found in future.

- Our analysis thus goes to show that the VBF searches for nonstandard scalars can be really useful in restricting the nondoublet contributions to the electroweak VEV and thereby providing valuable intuitions into the constructional aspects of new BSM scenarios. This observation, in turn, underscores the fact that ***the null results for the BSM searches at the LHC are a lot more than just upper bounds on cross sections as they can be translated into practical insights regarding the anatomy of EWSB.***

Picture taken from ：www.google.com