The alignment limit in the Georgi-Machacek model

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Work in progress with Pedro Ferreira, Howie Haber, and Yongcheng Wu, arXiv:18xx.xxxxx

Outline

Introduction

Basics of the Georgi-Machacek model

The alignment limit

Phenomenology

Conclusions & outlook

Introduction

LHC measurements of h_{125} couplings are consistent with SM, with uncertainties $\delta\kappa \sim 10\%$ and shrinking.

Relevant to study the alignment limit of extended Higgs models:
- Tree-level couplings of h_{125} become equal to their SM values
- Additional Higgs bosons can be weak-scale

(As distinct from alignment due to decoupling in which additional Higgs bosons are very heavy.)

Thoroughly studied in 2HDM: choose α so that $\sin(\beta - \alpha) \to 1$
- Useful for systematizing searches for additional Higgs bosons

This talk: alignment in the Georgi-Machacek model

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + triplets $(1,0)+(1,1)$ in a bi-triplet:

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

Global SU(2)$_L\times$SU(2)$_R$ $\rightarrow$ custodial symmetry $\langle\chi^0\rangle = \langle\xi^0\rangle \equiv v_\chi$

(ensures $\rho = 1$)

Most general scalar potential invariant under SU(2)$_L\times$SU(2)$_R$:

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

9 parameters, 2 fixed by G_F and m_h $\rightarrow$ 7 free parameters.

Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

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Global $SU(2)_L \times SU(2)_R \to$ custodial symmetry $\langle \chi^0 \rangle = \langle \xi^0 \rangle \equiv v_\chi$

Physical spectrum:

Bi-doublet: $2 \otimes 2 \to 1 \oplus 3$

Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\to h^0,\ H^0$ m_h, m_H, angle α
  Usually identify $h^0 = h(125)$

- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 + Goldstones
  Phenomenology very similar to $H^\pm, A^0$ in 2HDM Type I, $\tan\beta \to \cot\theta_H$

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{SM}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

Alignment limit: all tree-level couplings of $h_{125} \to$ SM values.

$$h = c_\alpha \phi^{0,r} - s_\alpha H_1^{0\prime}, \qquad H_1^{0\prime} \equiv \sqrt{\frac{1}{3}}\xi^{0,r} + \sqrt{\frac{2}{3}}\chi^{0,r}$$

Tree-level couplings of h:

$$\kappa_f^h = \frac{c_\alpha}{c_H}, \qquad \kappa_V^h = c_\alpha c_H - \sqrt{\frac{8}{3}} s_\alpha s_H$$

Alignment requires both $s_H \to 0^*$ and $s_\alpha \to 0$.

*I.e., triplet vevs $\to 0$.

Can show that

$$s_H = \frac{2\sqrt{2} M_1 v}{4 m_3^2 - 2\lambda_5 v^2}$$

Decoupling: $m_3 \to \infty$.

Alignment: $M_1 \to 0$.

Can also show that

$$s_\alpha^2 = \frac{\frac{3}{4} v_\phi^2 \left[4(2\lambda_2 - \lambda_5) v_\chi - M_1\right]^2}{(m_H^2 - m_h^2)(m_H^2 - 8\lambda_1 v_\phi^2)}$$

Decoupling: $m_H \to \infty$.
Alignment: $4(2\lambda_2 - \lambda_5) v_\chi - M_1 \to 0$.

No second alignment condition required:
$v_\chi \equiv s_H v/\sqrt{8}$ and $M_1 \to 0$ sends $s_\alpha \to 0$ automatically.

Spectrum in the alignment limit: (λ_5 can be positive or negative)

$$\begin{aligned} m_H^2 &= \mu_3^2 + (2\lambda_2 - \lambda_5) v^2 \\ m_3^2 &= m_H^2 + \frac{1}{2}\lambda_5 v^2 \\ m_5^2 &= m_H^2 + \frac{3}{2}\lambda_5 v^2 \end{aligned}$$

Mass spectrum controlled by 2 parameters: one overall scale m_H and one splitting parameter λ_5.

Phenomenology

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

Alignment limit: $M_1 \to 0$

Chanowitz & Golden 1985

Setting $M_1 = 0$ *and* $M_2 = 0$ preserves an exact Z_2 symmetry, unbroken when $v_\chi = 0 \longrightarrow$ lightest Z_2-odd particle is stable.

We do not want this! Keep $M_2 \neq 0$.
Alignment due to $M_1 \to 0$ is a fine-tuned accident, but this is also true in the 2HDM.

Extra Higgs bosons consist entirely of SU(2) triplet and are still SM-phobic at tree level!

Trilinear coupling M_2 among SU(2) triplets $\Rightarrow$ scalar triangle diagrams induce decays of extra Higgs bosons to VV ($V = \gamma, Z, W$).

Phenomenology

Higgs-to-Higgs cascade decays (tree-level) will happen when kinematically allowed: $H \to H_3 \to H_5$ or $H_5 \to H_3 \to H$

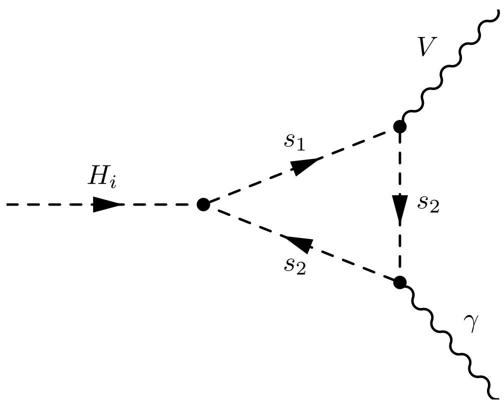
Lightest new scalar (H_5^0 or H) will decay via scalar loop diagram. Potential for large BR($H_i^0 \to \gamma\gamma$): easy to detect!

Production via Drell-Yan: cross section $\propto$ gauge coupling
- $pp \to H_5^0 H_5^\pm$, $H_5^0 H_3^\pm$, $H_5^0 H_3^0$
- $pp \to H H_3^\pm$, $H H_3^0$

Need to compute BR to $\gamma\gamma$.

H, $H_5^0 \to \gamma\gamma, Z\gamma$ are easy to compute.

$H, H_5^0 \to ZZ, W^+W^-$ are not so easy!



Phenomenology

Two approaches:

(1) Buckle down and calculate them. FeynRules/FormCalc $\Rightarrow$ numerical results (done by Yongcheng)

(2) Effective operator + gauge invariance (works when mass splittings can be neglected; Λ = mass of new scalars)

Only one dimension-5 operator: (+ many dimension-7 operators)

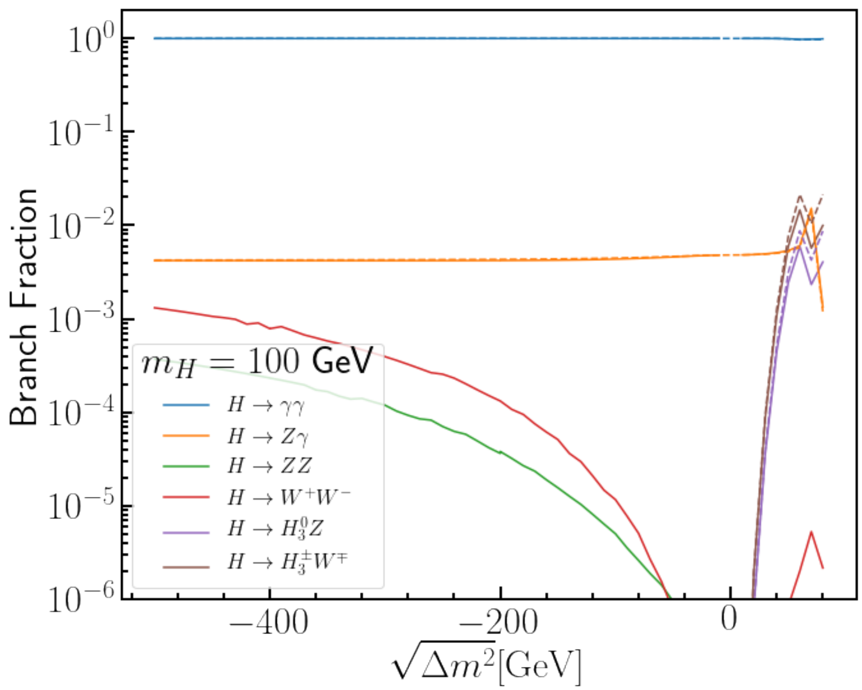
$$\mathcal{O}_5 = \frac{c_5}{\Lambda} \xi^a W^a_{\mu\nu} B^{\mu\nu}$$

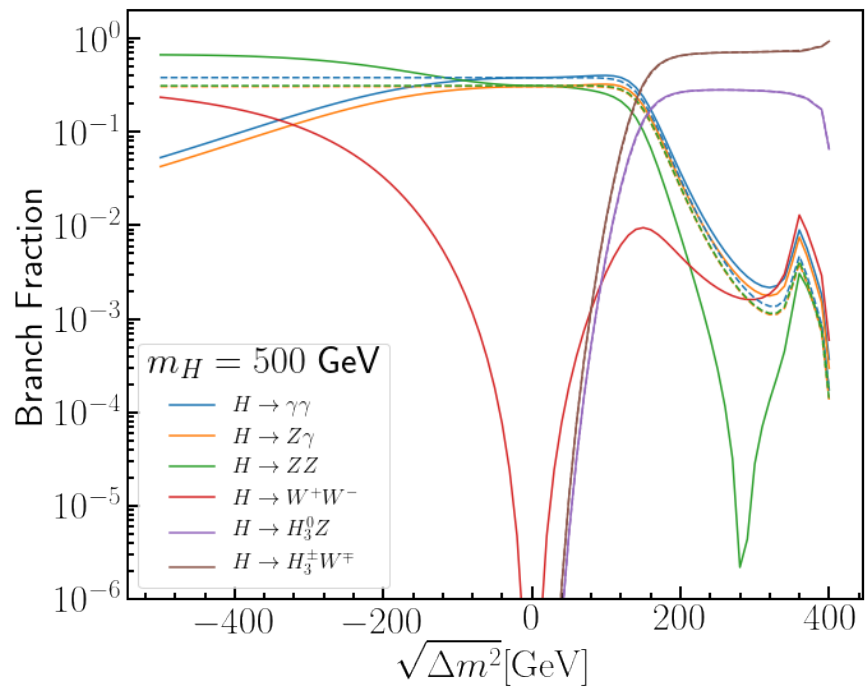
Use definitions of Z and γ to write *all* the effective couplings in terms of one (e.g., $H_5^0 \to \gamma\gamma$).

Notice $H, H_5^0 \to W^+W^- = 0$: true when mass splittings are zero.

Phenomenology

Branching ratios of H in alignment limit (blue $= \gamma\gamma$)





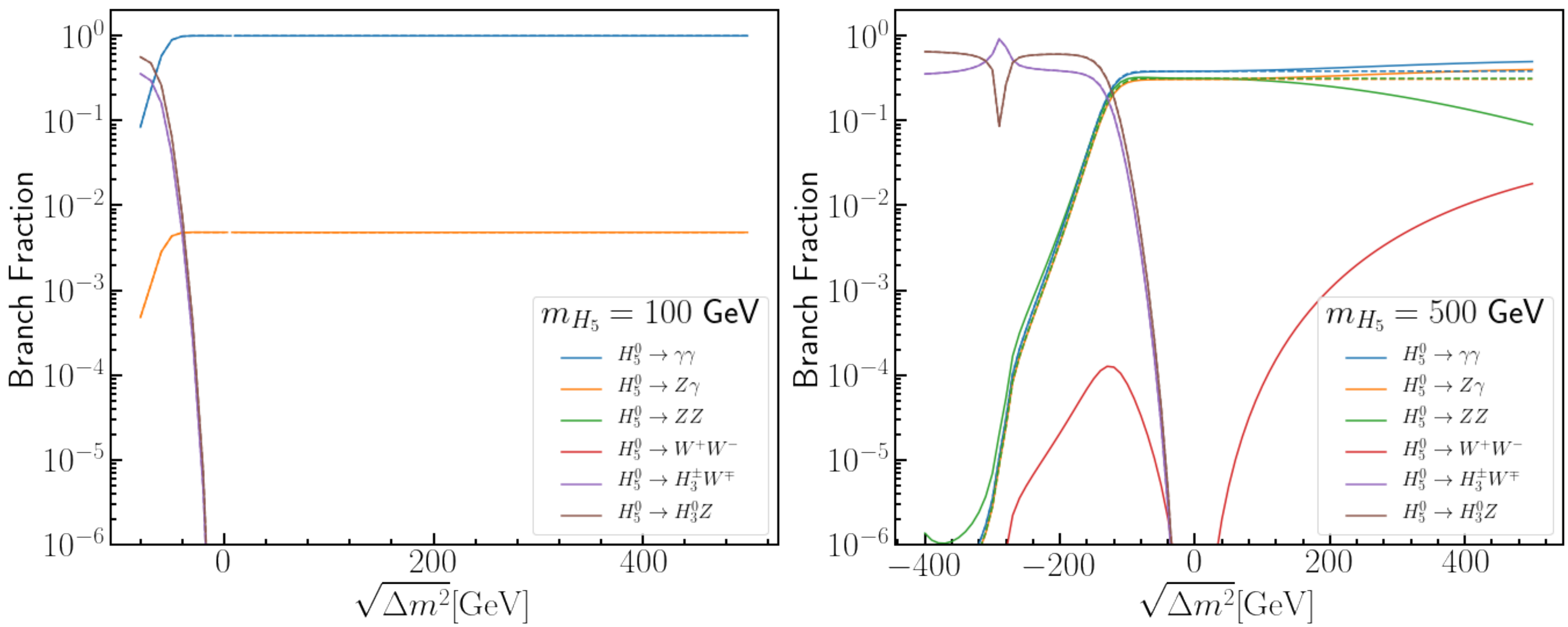
Dashed lines: single effective operator approximation

Positive $\Delta m^2 \longrightarrow H \to H_3 V$ decays open up

$m_3^2 = m_H^2 - \frac{1}{2}\Delta m^2 \qquad m_5^2 = m_H^2 - \frac{3}{2}\Delta m^2$

Phenomenology

Branching ratios of H_5^0 in alignment limit (blue $= \gamma\gamma$)



Dashed lines: single effective operator approximation

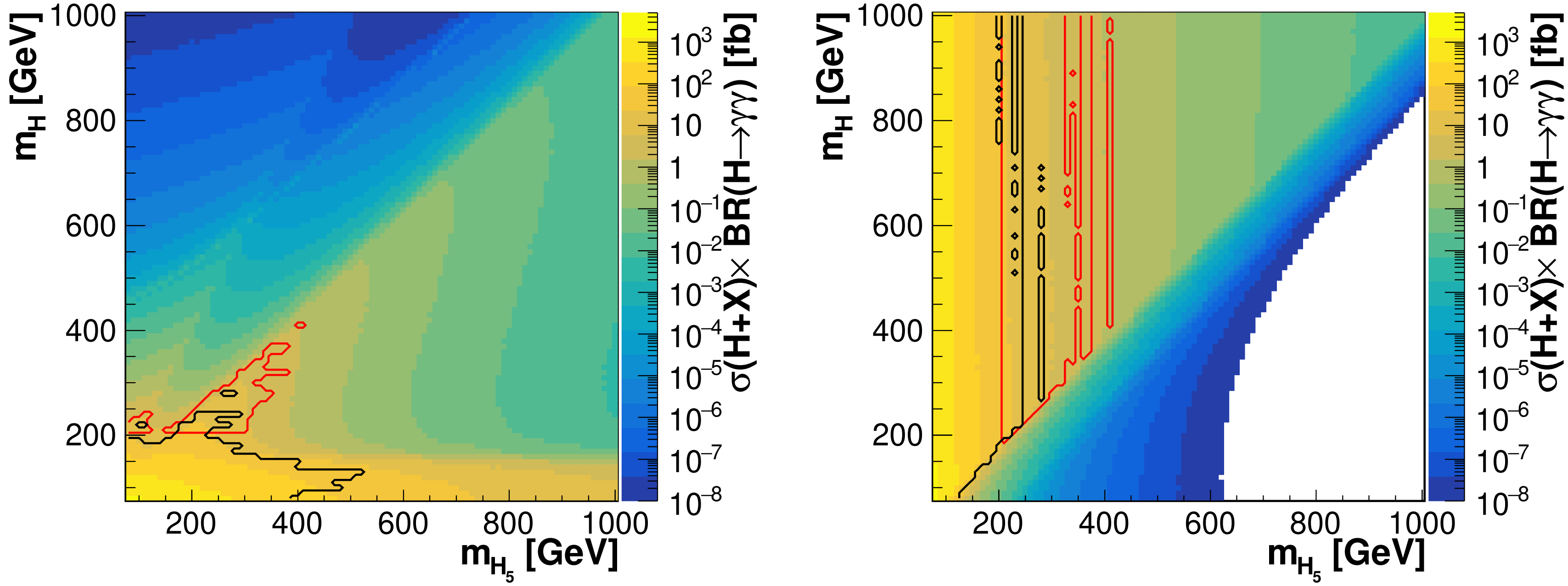
Negative $\Delta m^2 \longrightarrow H_5^0 \to H_3 V$ decays open up

$m_3^2 = m_5^2 + \Delta m^2 \qquad m_H^2 = m_5^2 + \frac{3}{2}\Delta m^2$

Phenomenology

$pp \to HH_3^\pm,\ HH_3^0$ $\quad\quad$ $pp \to H_5^0 H_5^\pm,\ H_5^0 H_3^\pm,\ H_5^0 H_3^0$

PRELIMINARY



$H \to \gamma\gamma$ $\quad\quad$ $H_5^0 \to \gamma\gamma$

LHC diphoton resonance searches, black = 8 TeV; red = 13 TeV

Color scale = $\sigma\times$BR at 13 TeV

Interesting exclusions for masses up to $\sim$ 400 GeV!

Conclusions and outlook

The Georgi-Machacek model possesses an alignment limit, toward which we are increasingly being driven as measurements constrain h_{125} couplings to their SM values.

Exact alignment has dramatic phenomenological consequences, with $H \to \gamma\gamma$ or $H_5^0 \to \gamma\gamma$ leading to strong exclusions below about 400 GeV.

Next step: study approach to alignment: how far can we go from exact alignment until the $\gamma\gamma$ decays are no longer significant?

An interesting tangent: the approach to alignment in the Z_2-symmetric model. Must generate v_χ through spontaneous symmetry breaking – as $v_\chi \to 0$, $m_H \to 0$ too! Can we *completely* exclude this version of the model?

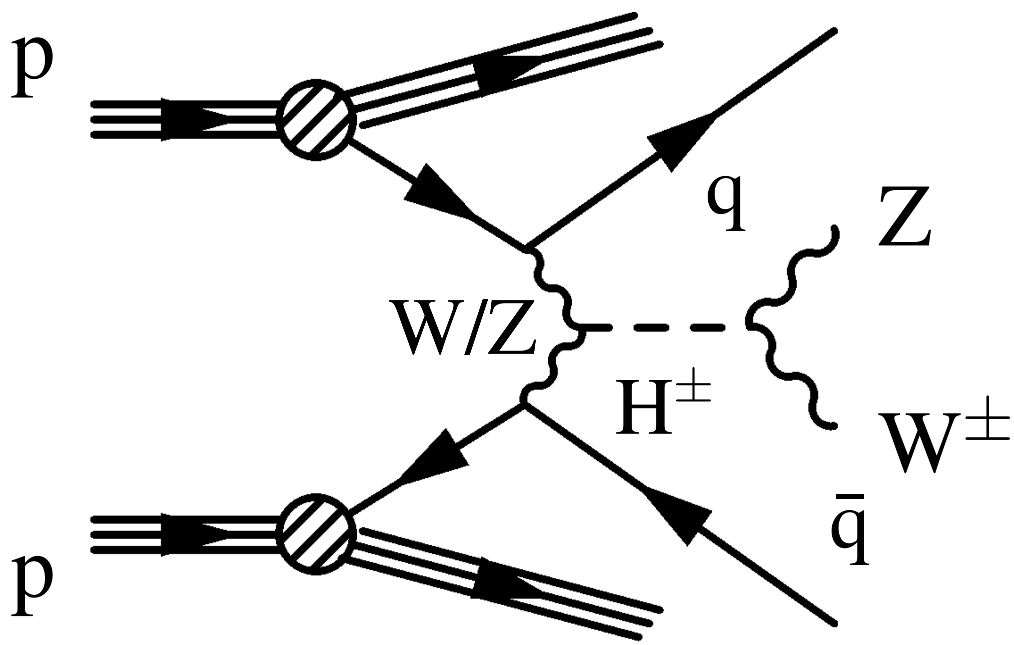
BACKUP SLIDES

Distinctive processes:

N.B. Not useful in alignment limit!

VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ — VBF + like-sign dileptons + MET

VBF $\to H_5^{\pm} \to W^\pm Z$ — VBF + $qq\ell\ell$; VBF + 3ℓ + MET



Cross section $\propto s_H^2 \equiv$ fraction of M_W^2, M_Z^2 due to exotic scalars

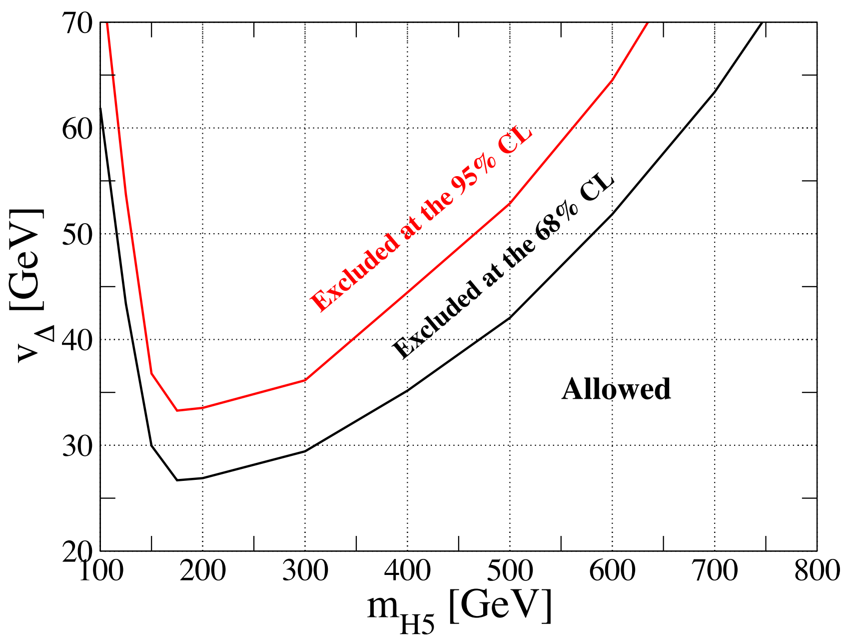
Searches

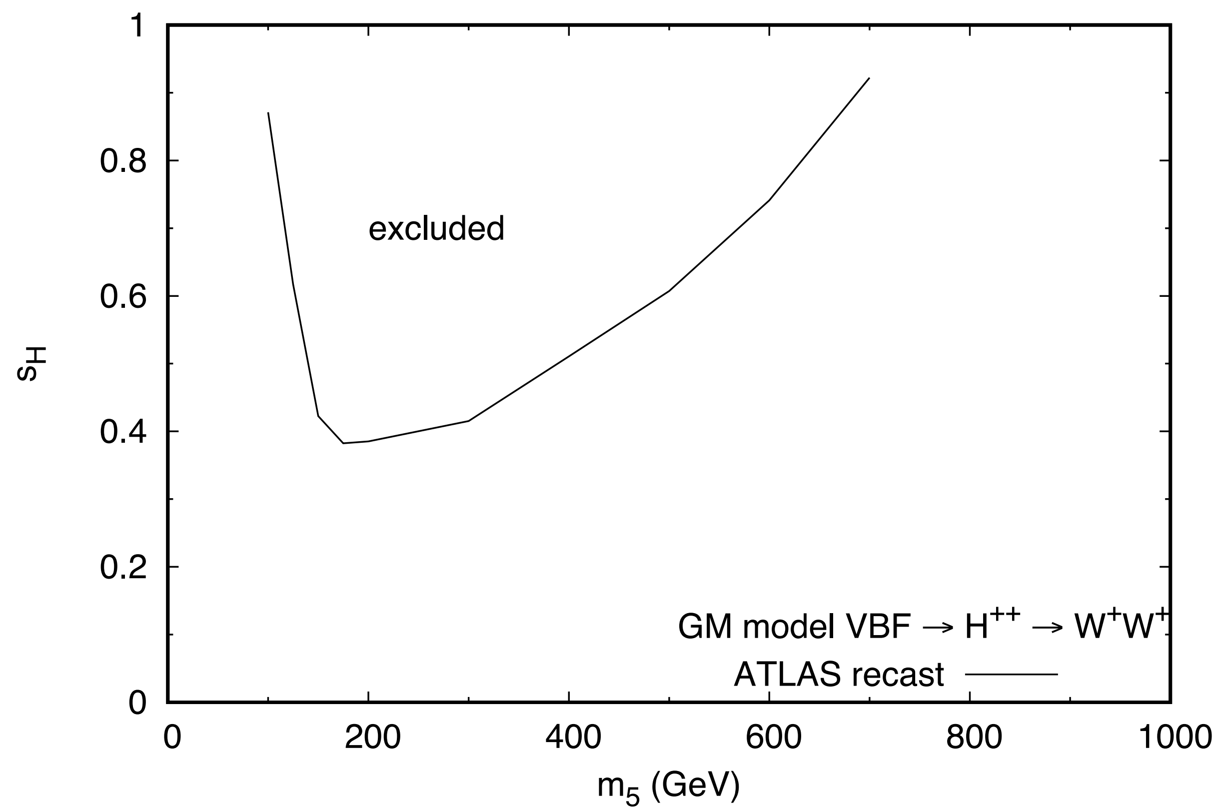
SM VBF $\to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET cross section measurement

ATLAS Run 1 1405.6241, PRL 2014

Recast to constrain VBF $\to H_5^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET

Chiang, Kanemura, Yagyu, 1407.5053

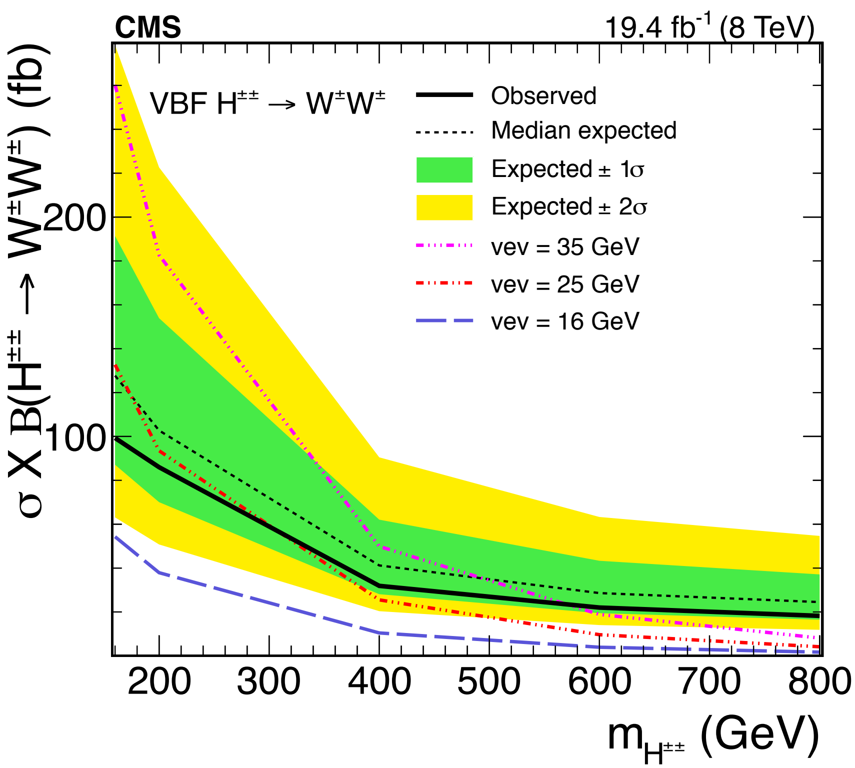


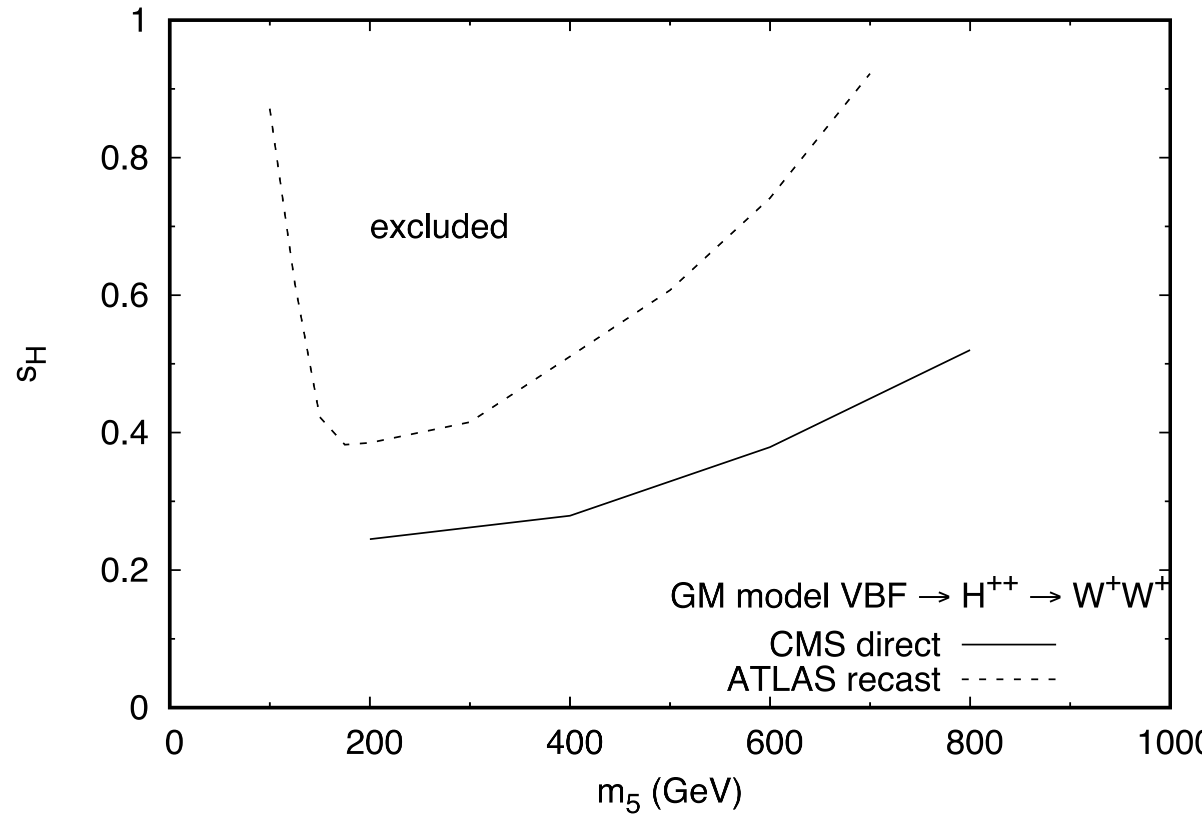


Searches

VBF $H_5^{\pm\pm} \to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET (CMS Run 1)

CMS 1410.6315, PRL 2015



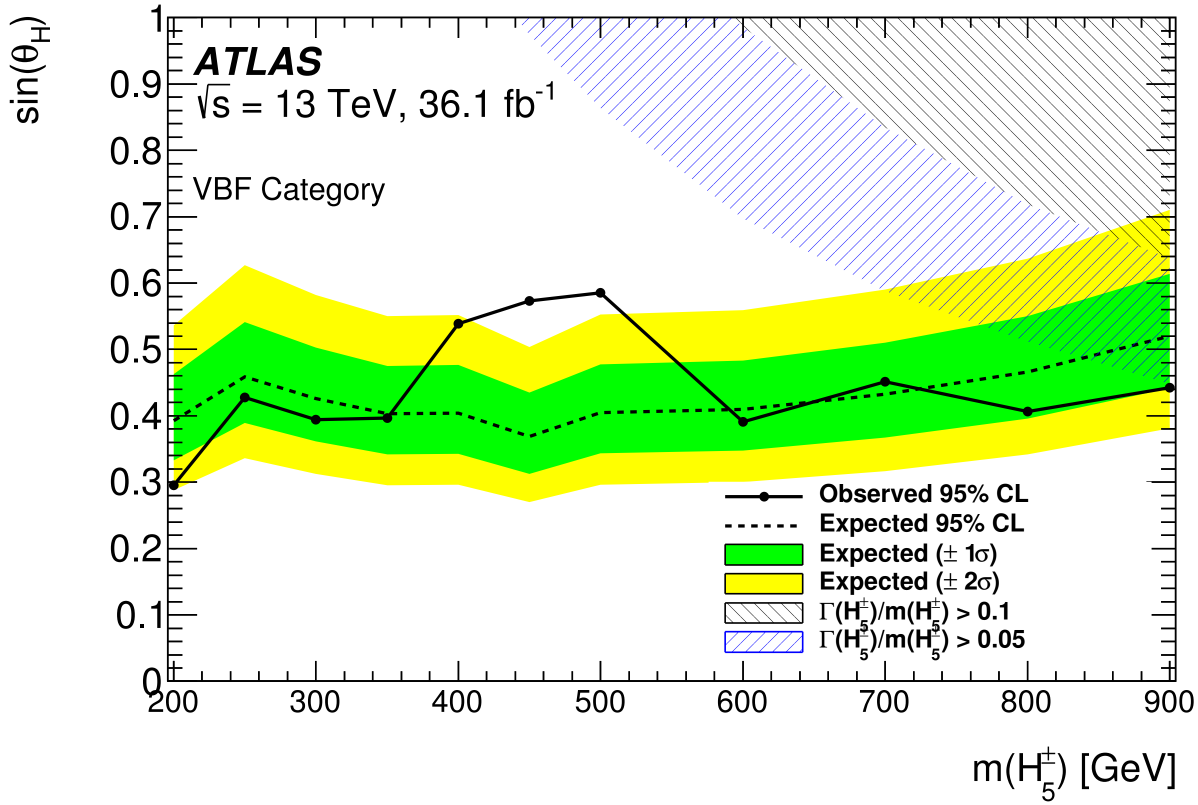


Translated using VBF $\to H^{\pm\pm}$ cross sections from LHCHXSWG-2015-001

 New this summer!

VBF $H_5^\pm \to W^\pm Z \to \ell^\pm\ell^+\ell^- +$ MET (ATLAS Run 2)

ATLAS 1806.01532



Stronger upper bound on s_H for $m_5 \in (700, 900)$ GeV compared to $H_5^{\pm\pm}$