Constraining exotic sources of electroweak symmetry breaking

Heather Logan
Carleton University

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The Standard Model as written down by Weinberg in 1967 implements electroweak symmetry breaking using a spin-zero doublet of $SU(2)_L$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad \langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

This is the simplest possible option – the minimum nontrivial "charge" under $SU(2)_L$.

$\langle\Phi\rangle \neq 0$ breaks electroweak symmetry ($Y = 1/2$, $T^a = \sigma^a/2$):

$$\mathcal{L} \supset (\mathcal{D}_\mu\Phi)^\dagger(\mathcal{D}^\mu\Phi) \qquad \mathcal{D}_\mu = \partial_\mu - ig' B_\mu Y - ig W_\mu^a T^a$$

$$= \frac{g^2}{2}\left\{\langle\Phi\rangle^\dagger(T^+T^- + T^-T^+)\langle\Phi\rangle\right\} W_\mu^+ W^{-\mu}$$

$$+\frac{(g^2+g'^2)}{2}\left\{\langle\Phi\rangle^\dagger(T^3T^3 + Y^2)\langle\Phi\rangle\right\} Z_\mu Z^\mu + \cdots$$

$\langle\Phi\rangle$ is in the $Q = 0$ component $\rightarrow$ use $Q = T^3 + Y$

$$\mathcal{L} \supset \frac{g^2v^2}{2}\left\{T(T+1) - Y^2\right\} W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)v^2}{4}\left\{2Y^2\right\} Z_\mu Z^\mu + \cdots$$

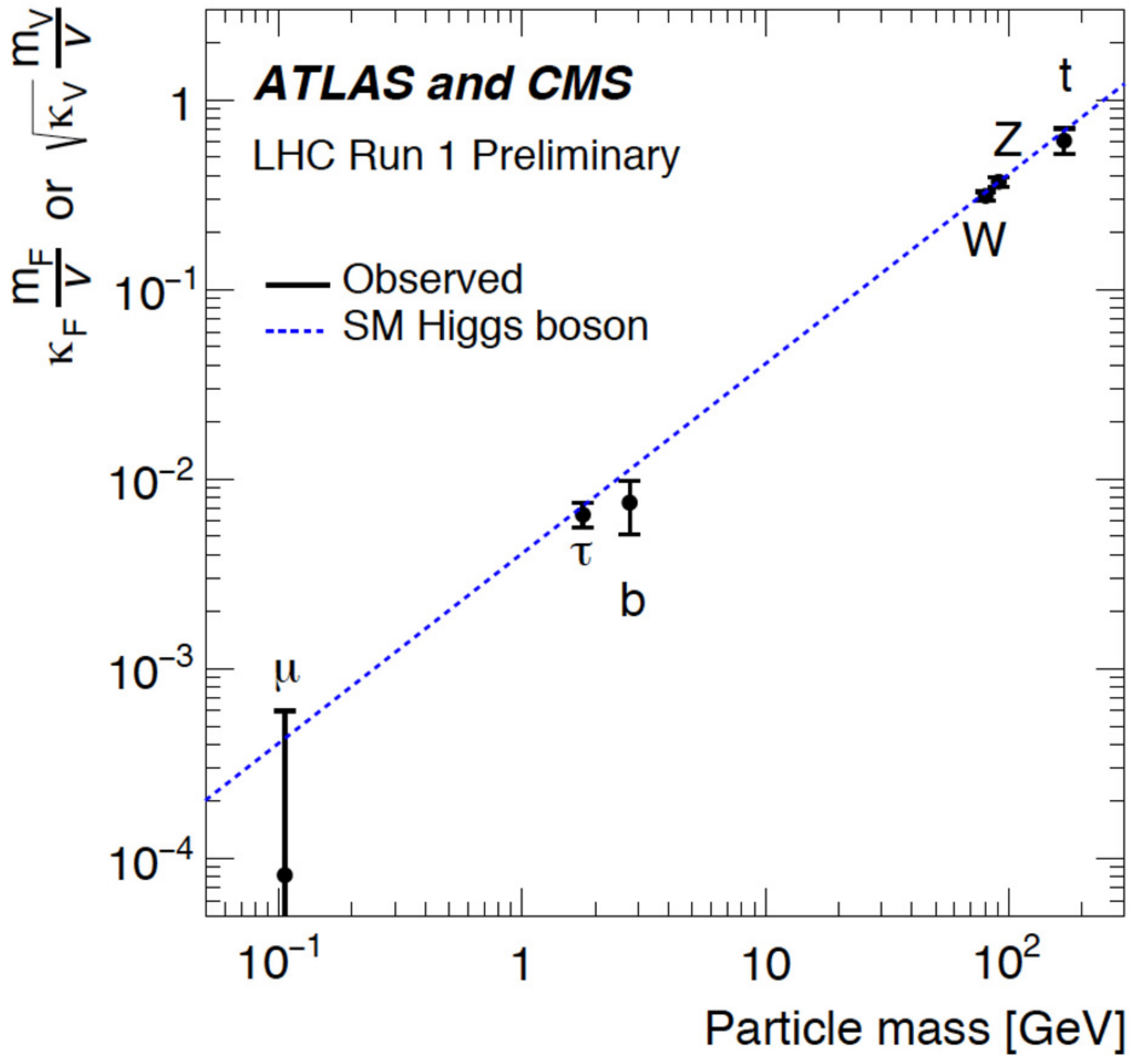
$$= \frac{g^2v^2}{4} W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)v^2}{8} Z_\mu Z^\mu + \cdots$$

So $M_W^2 = g^2v^2/4$ and $M_Z^2 = (g^2+g'^2)v^2/4$.

Fermion masses come as a bonus (doublet Φ marries left-handed fermion doublets):

$$\mathcal{L} \supset -y_e \bar{e}_R \Phi^\dagger L_L + \text{h.c.} = -\frac{y_e v}{\sqrt{2}}\bar{e}e + \cdots = -m_e\bar{e}e + \cdots$$

Higgs boson measurements agree with the single doublet Standard Model so far:



The Standard Model as written down by Weinberg in 1967 implements electroweak symmetry breaking using a spin-zero doublet of SU(2)$_L$:

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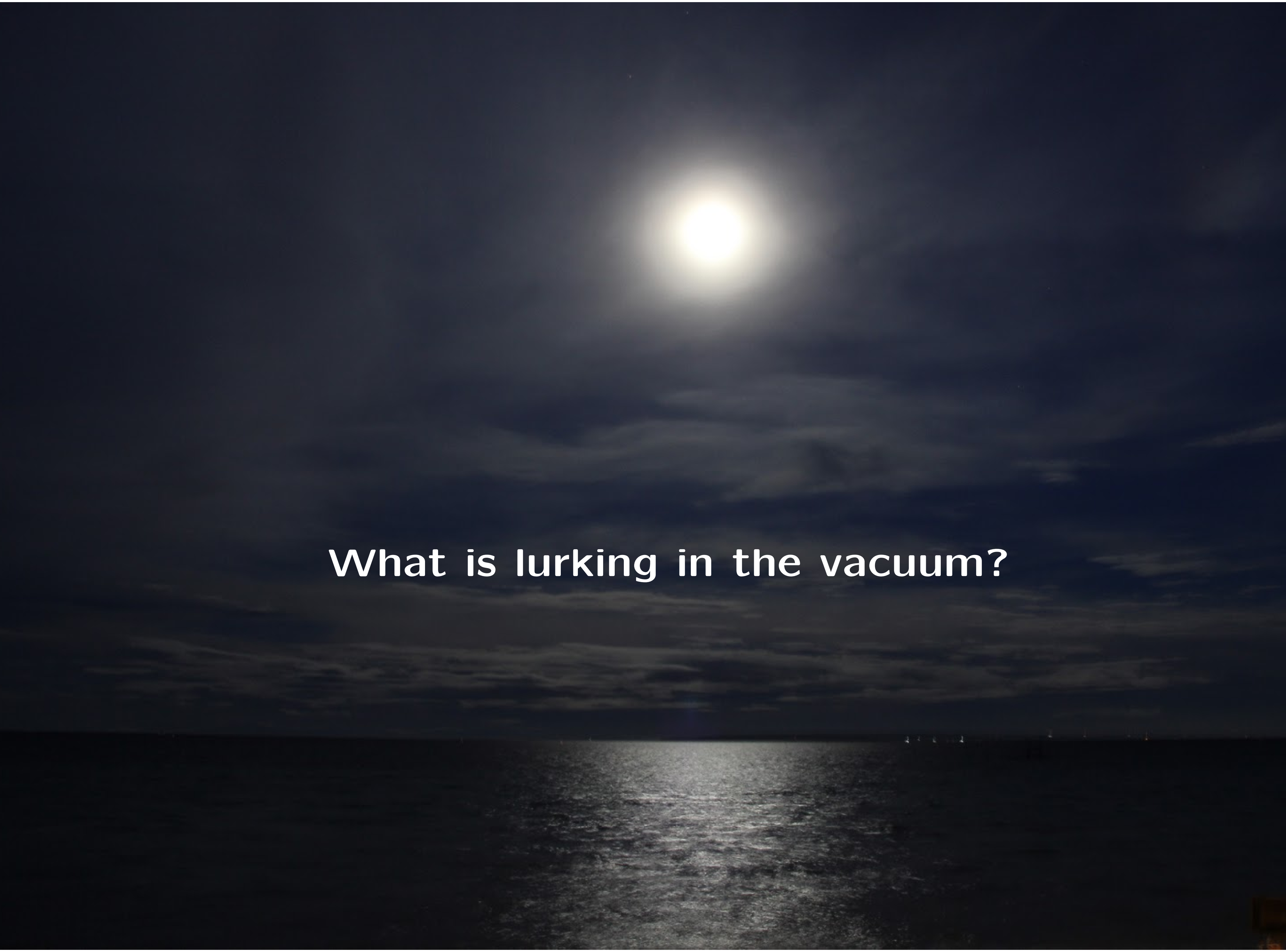
Q: Could there be contributions to electroweak symmetry breaking from scalars in larger ("exotic") representations of SU(2)$_L$?


What is lurking in the vacuum?

Outline

Requirements for a sensible theory
- allowed reps from perturbative unitarity
- allowed vevs from rho parameter
- some model building

Georgi-Machacek model and constraints from VBF $\rightarrow H_5 \rightarrow VV$

Constraining other models (GM-like; septet)

Promising channels at lower masses

Conclusions

How high an isospin is ok?

Higher isospin → higher maximum "weak charge" (gT^3, etc.)
Higher isospin → higher multiplicity of scalars

Unitarity of the scattering matrix:

$$|\mathrm{Re}\, a_\ell| \leq 1/2, \qquad \mathcal{M} = 16\pi \sum_\ell (2\ell + 1) a_\ell P_\ell(\cos\theta)$$

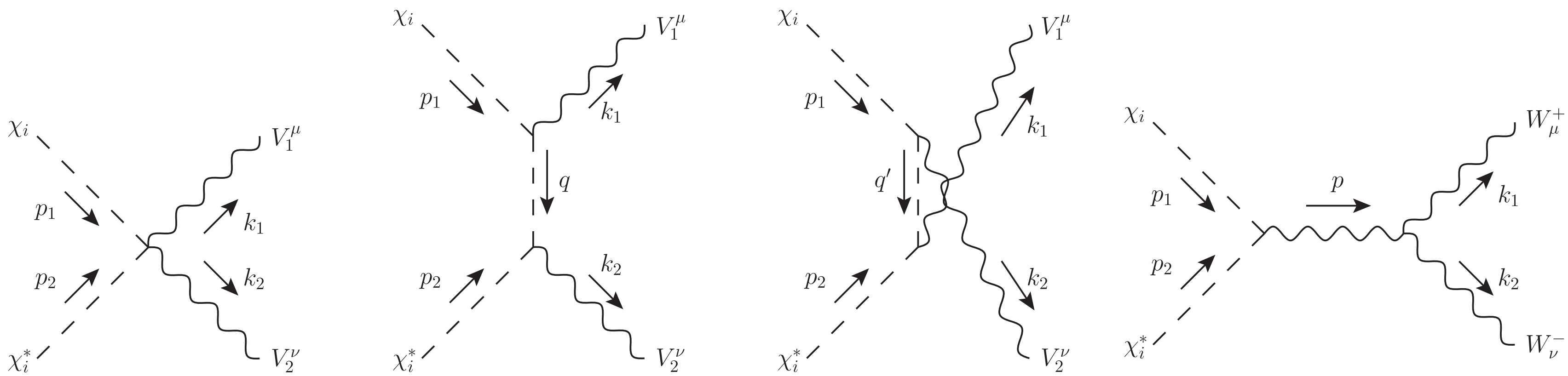
Scattering of longitudinally-polarized Ws & Zs famously used to put upper bound on Higgs mass Lee, Quigg & Thacker 1977

To bound the strength of the weak charge, consider *transversely* polarized Ws & Zs (the ordinary gauge modes).

Too strong a charge → nonperturbative

$\chi\chi \leftrightarrow W_T^a W_T^a$:

Hally, HEL, & Pilkington 1202.5073



$$a_0 = \frac{g^2}{16\pi}\frac{(n^2-1)\sqrt{n}}{2\sqrt{3}} \qquad \text{complex } \chi, \; n = 2T+1$$

- Real scalar multiplet: divide by $\sqrt{2}$ to account for smaller multiplicity
- More than one multiplet: add a_0's in quadrature

- Complex multiplet $\Rightarrow$ $T \leq 7/2$ (8-plet)
- Real multiplet $\Rightarrow$ $T \leq 4$ (9-plet)
- Constraints tighter if more than one large multiplet

T	Y
1/2	1/2
1	0
1	1
3/2	1/2
3/2	3/2
2	0
2	1
2	2
5/2	1/2
5/2	3/2
5/2	5/2
3	0
3	1
3	2
3	3
7/2	1/2
7/2	3/2
7/2	5/2
7/2	7/2
4	0

Complete list of (perturbative) scalars that can contribute to EWSB:

- Must have a neutral component ($Q = T^3 + Y = 0$)

- $Y \to -Y$ is just the conjugate multiplet

- Singlet $T = 0$, $Y = 0$ doesn't contribute to EWSB

How much can these contribute to EWSB?

$$\mathcal{L} \supset \frac{g^2}{2}\left\{\langle X\rangle^\dagger(T^+T^- + T^-T^+)\langle X\rangle\right\} W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)}{2}\left\{\langle X\rangle^\dagger(T^3T^3 + Y^2)\langle X\rangle\right\} Z_\mu Z^\mu + \cdots$$

Must have at least one doublet to give masses to SM fermions

$$M_W^2 = \left(\frac{g^2}{4}\right)[v_\phi^2 + a\langle X_0\rangle^2]$$
$$M_Z^2 = \left(\frac{g^2+g'^2}{4}\right)[v_\phi^2 + b\langle X_0\rangle^2]$$

where $\langle \Phi_{\rm SM}\rangle = (0, v_\phi/\sqrt{2})^T$ and

$$a = 4\left[T(T+1) - Y^2\right] c$$
$$b = 8Y^2$$

$c = 1$ for complex and $c = 1/2$ for real multiplet

SM Higgs doublet: $a = b = 2$ (cancels $(1/\sqrt{2})^2$ in $\langle \Phi_0\rangle^2$)

Extremely strong constraint from low-energy weak interaction strength measurements:

$$\rho \equiv \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v_\phi^2 + a\langle X_0\rangle^2}{v_\phi^2 + b\langle X_0\rangle^2}$$

$$\begin{aligned} a &= 4\left[T(T+1) - Y^2\right] c \\ b &= 8Y^2 \end{aligned}$$

Experiment: (Moriond 2017, Erler 1704.08330)

$$\rho = 1.000\,36 \pm 0.000\,19$$

T	Y	a	b	$\delta\rho$	$\delta M_W^2\vert_{\rm max}$	$\delta M_Z^2\vert_{\rm max}$
1/2	1/2	2	2	0	–	–
1	0	4	0	+	0.068%	0
1	1	4	8	–	0.021%	0.042%
3/2	1/2	14	2	+	0.079%	0.011%
3/2	3/2	6	18	–	0.011%	0.032%
2	0	12	0	+	0.068%	0
2	1	20	8	+	0.113%	0.045%
2	2	8	32	–	0.007%	0.028%
5/2	1/2	34	2	+	0.072%	0.004%
5/2	3/2	26	18	+	0.221%	0.153%
5/2	5/2	10	50	–	0.005%	0.026%
3	0	24	0	+	0.068%	0
3	1	44	8	+	0.083%	0.015%
3	2	32	32	0	–	–
3	3	12	72	–	0.004%	0.025%
7/2	1/2	62	2	+	0.070%	0.002%
7/2	3/2	54	18	+	0.102%	0.034%
7/2	5/2	38	50	–	0.067%	0.088%
7/2	7/2	14	98	–	0.004%	0.025%
4	0	40	0	+	0.068%	0

work in progress

with Jesi Goodman

T	Y	a	b	$\delta\rho$	$\delta M_W^2\vert_{\text{max}}$	$\delta M_Z^2\vert_{\text{max}}$	
1/2	1/2	2	2	0	–	–	doublet
1	0	4	0	+	0.068%	0	
1	1	4	8	–	0.021%	0.042%	
3/2	1/2	14	2	+	0.079%	0.011%	
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HIGGS BOSON TRIPLETS WITH $M_W = M_Z \cos\theta_w$ ☆

Michael S. CHANOWITZ and Mitchell GOLDEN

Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Received 23 September 1985

‡1 The requirement that an irreducible representation of $SU(2)_L$ give $\rho = 1$ in tree approximation yields [4] a Diophantine equation in the isospin t and hypercharge y, $t^2 + t - 3y^2 = 0$, which has 11 solutions for $t < 1\,000\,000$, the largest being $t, y = 489060\frac{1}{2}, 282359\frac{1}{2}$. We are offering a prize for the most original model based on this representation.

$$a_0 = \frac{g^2}{16\pi}\frac{(n^2-1)\sqrt{n}}{2\sqrt{3}} \simeq 2.3 \times 10^{12}$$

T	Y	a	b	$\delta\rho$	$\delta M_W^2\|$max	$\delta M_Z^2\|$max
1/2	1/2	2	2	0	–	–
1	0	4	0	+	0.068%	0
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7/2	7/2	14	98	–	0.004%	0.025%
4	0	40	0	+	0.068%	0

Include both reps with $v_1 = v_2$:

$$\rho = \frac{v_\phi^2 + a_1 v_1^2 + a_2 v_2^2}{v_\phi^2 + b_1 v_1^2 + b_2 v_2^2}$$

$\sum a = 8$

$\sum b = 8$

T	Y	a	b	$\delta\rho$	$\delta M_W^2\vert$max	$\delta M_Z^2\vert$max
1/2	1/2	2	2	0	–	–
1	0	4	0	+	0.068%	0
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$$\rho = \frac{v_\phi^2 + a_1 v_1^2 + a_2 v_2^2}{v_\phi^2 + b_1 v_1^2 + b_2 v_2^2}$$

$\sum a = 20$

$\sum b = 20$

T	Y	a	b	$\delta\rho$	$\delta M_W^2\|$max	$\delta M_Z^2\|$max
1/2	1/2	2	2	0	–	–
1	0	4	0	+	0.068%	0
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7/2	7/2	14	98	–	0.004%	0.025%
4	0	40	0	+	0.068%	0

Include all 3 reps with $v_1 = v_2 = v_3$:

$$\rho = \frac{v_\phi^2 + \sum a_i v_i^2}{v_\phi^2 + \sum b_i v_i^2}$$

$\sum a = 40$

$\sum b = 40$

T	Y	a	b	$\delta\rho$	$\delta M_W^2\vert_{\max}$	$\delta M_Z^2\vert_{\max}$
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1	0	4	0	+	0.068%	0
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4	0	40	0	+	0.068%	0

Include all 3 reps with $v_1 = v_2 = v_3$:

$$\rho = \frac{v_\phi^2 + \sum a_i v_i^2}{v_\phi^2 + \sum b_i v_i^2}$$

$\sum a = 70$

$\sum b = 70$

Complete list of models with sizable exotic sources of EWSB:

1) Doublet + septet $(T, Y) = (3, 2)$: Scalar septet model

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

2) Doublet + triplets $(1, 0) + (1, 1)$: Georgi-Machacek model

(ensure triplet vevs are equal using a global "custodial" symmetry)

Georgi & Machacek 1985; Chanowitz & Golden 1985

3) Doublet + quartets $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$: Generalized Georgi-
4) Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$: Machacek models
5) Doublet + sextets $\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)$:

(ensure exotics' vevs are equal using a global "custodial" symmetry)

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

Larger than sextets $\rightarrow$ too many large multiplets, violates perturbativity!

Can also have duplications, combinations $\rightarrow$ ignore that here.

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Georgi-Machacek model and constraints from VBF $\to H_5 \to VV$

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Promising channels at lower masses

Conclusions

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

Physical spectrum:

Bidoublet: $2 \otimes 2 \to 1 \oplus 3$

Bitriplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\to h^0,\ H^0$ $m_h,\ m_H$

  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 $\longleftarrow \bigstar$

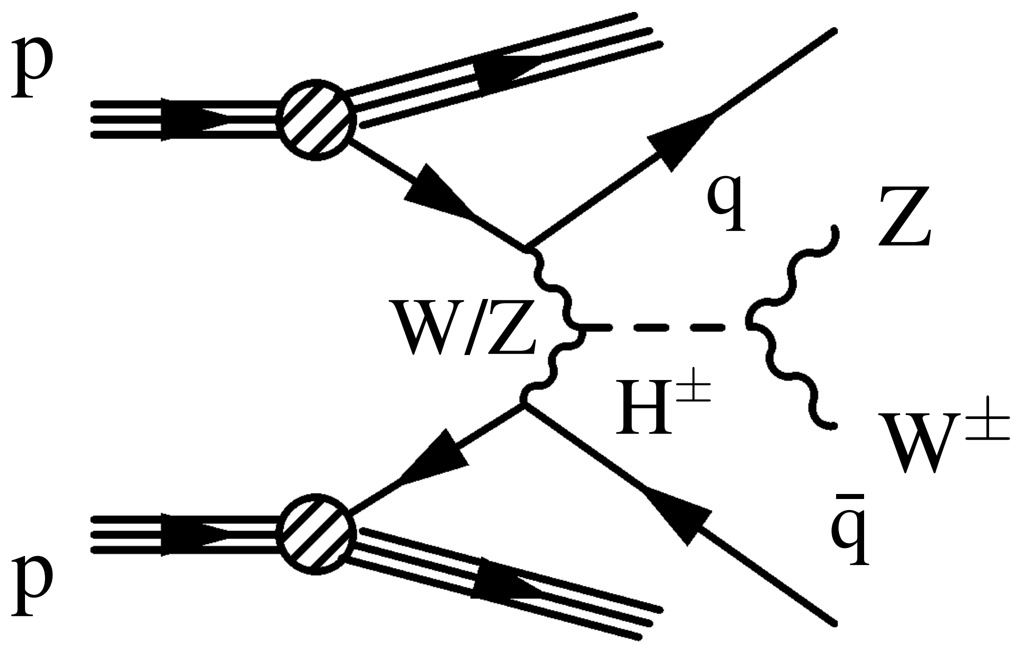
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{SM}$

  $s_H^2 \equiv$ exotic fraction of $M_W^2,\ M_Z^2$

Smoking-gun processes:

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

VBF $\rightarrow H_5^{\pm} \rightarrow W^{\pm}Z$ 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

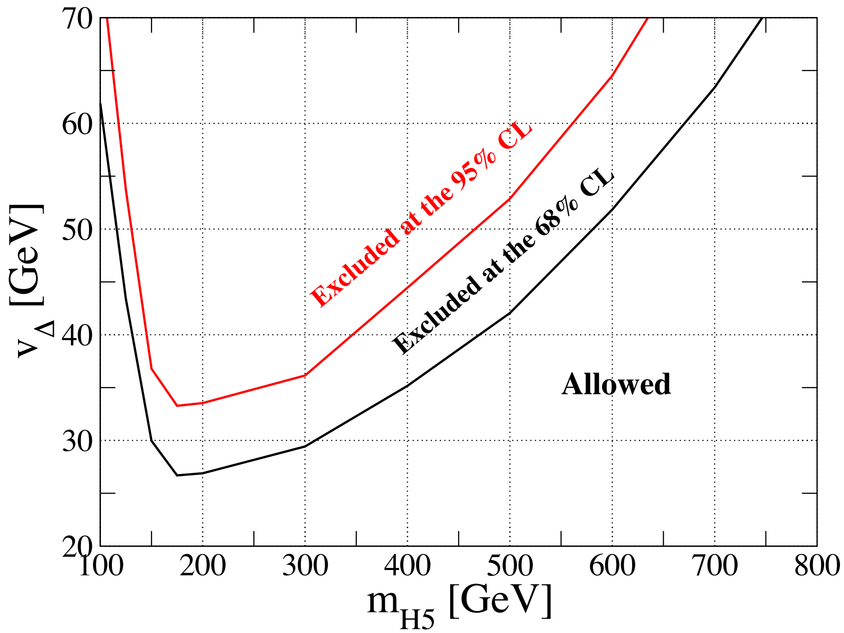
Searches

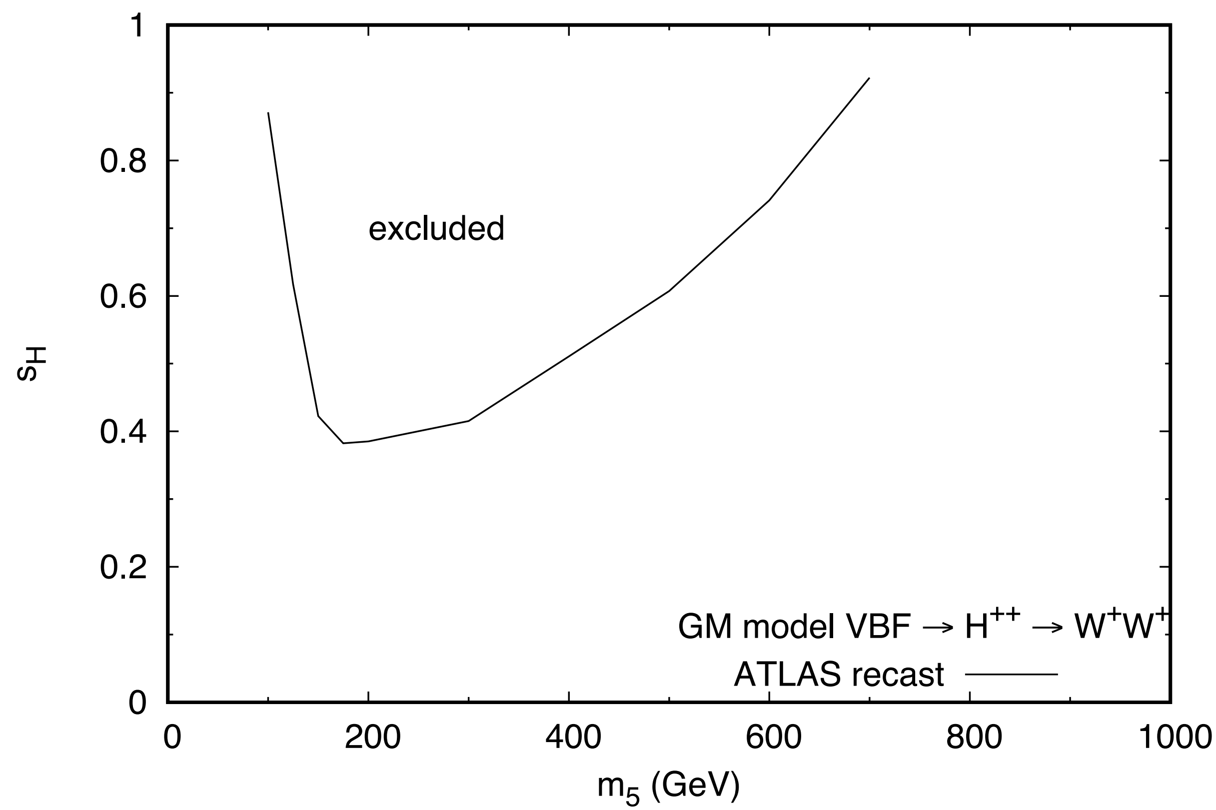
SM VBF $\to W^\pm W^\pm \to \ell^\pm \ell^\pm$ + MET cross section measurement

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

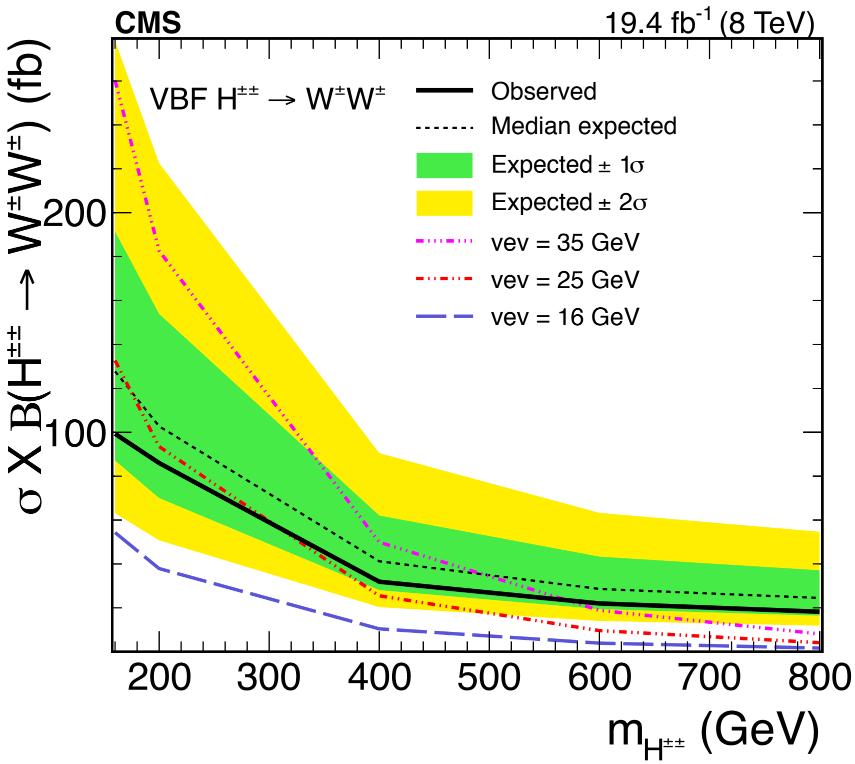


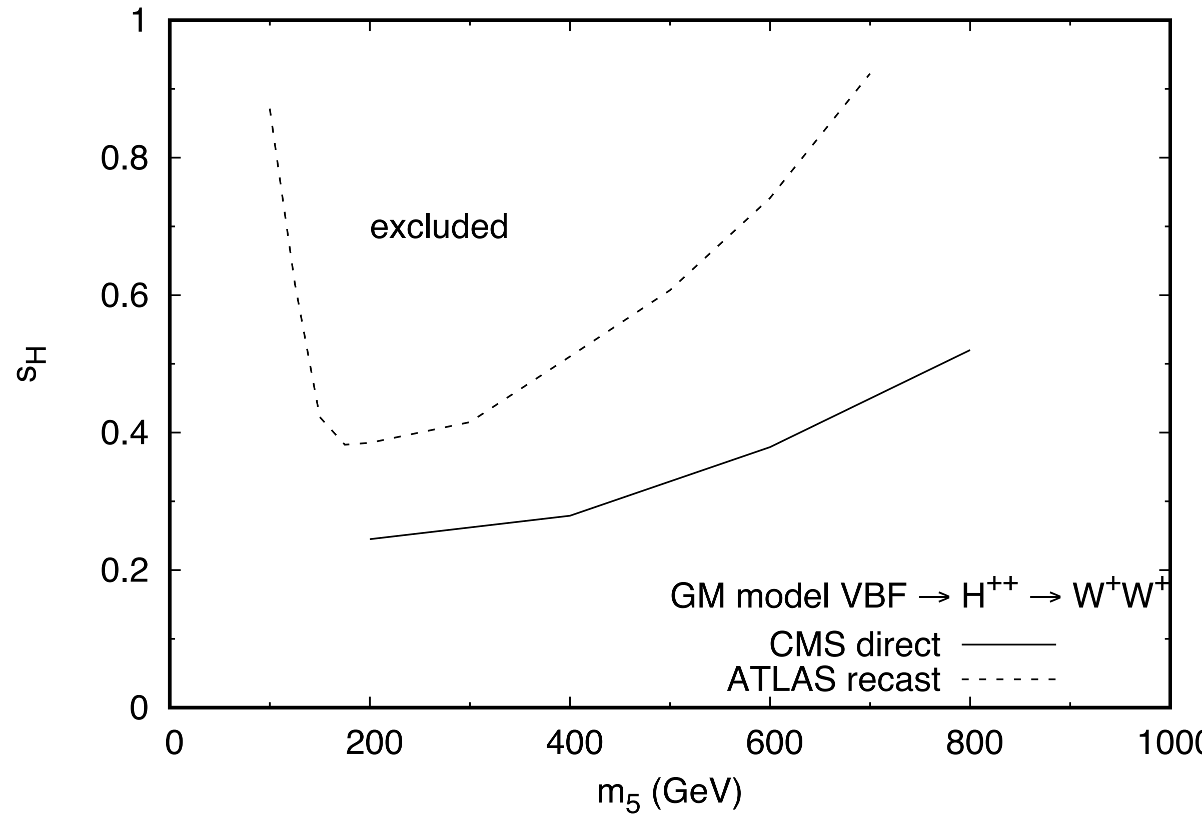


Searches

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

CMS 1410.6315, PRL 2015



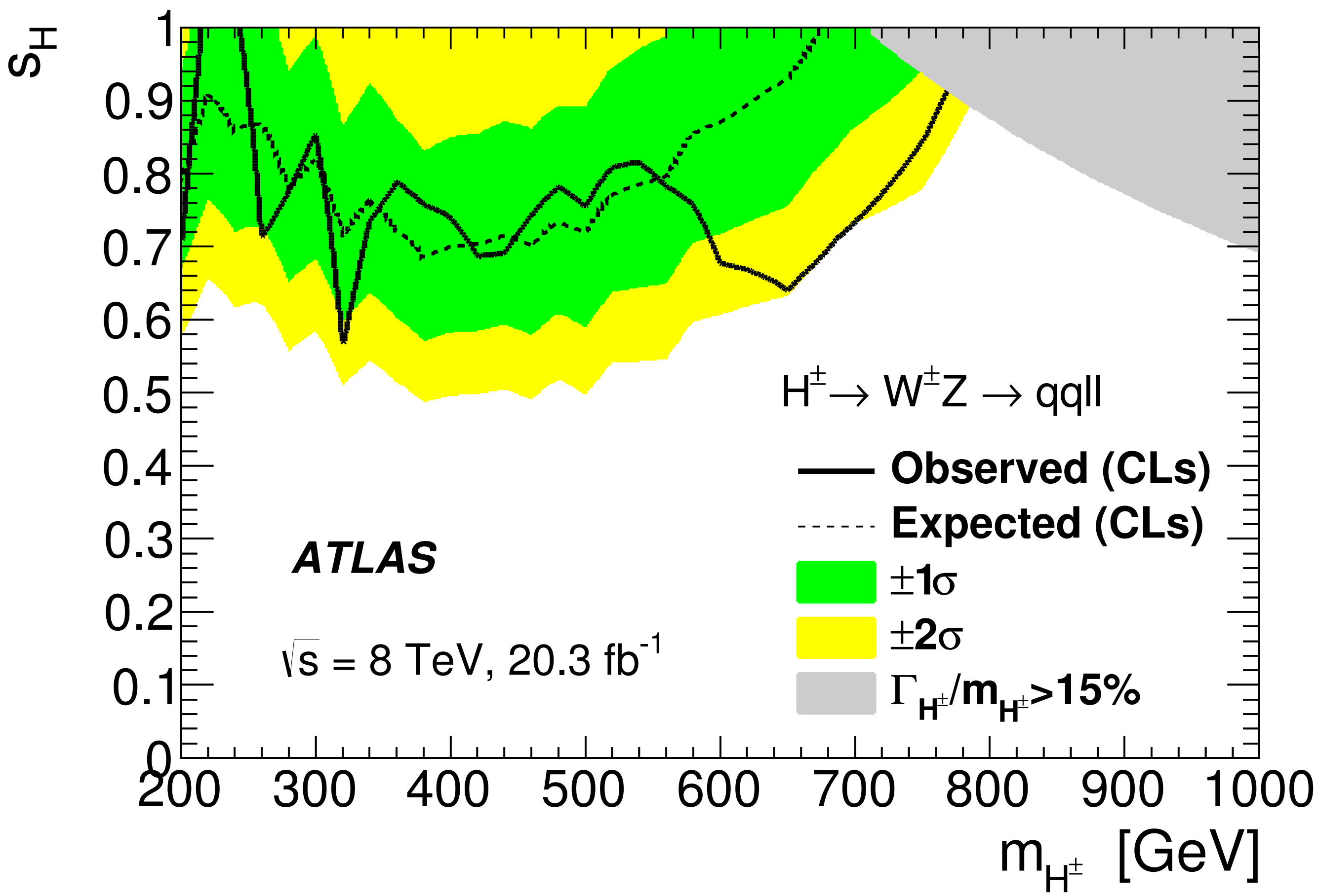


Translated using VBF → $H^{\pm\pm}$ cross sections from LHCHXSWG-2015-001

Searches

VBF $H_5^{\pm} \to W^{\pm}Z \to qq\ell\ell$ (ATLAS Run 1)

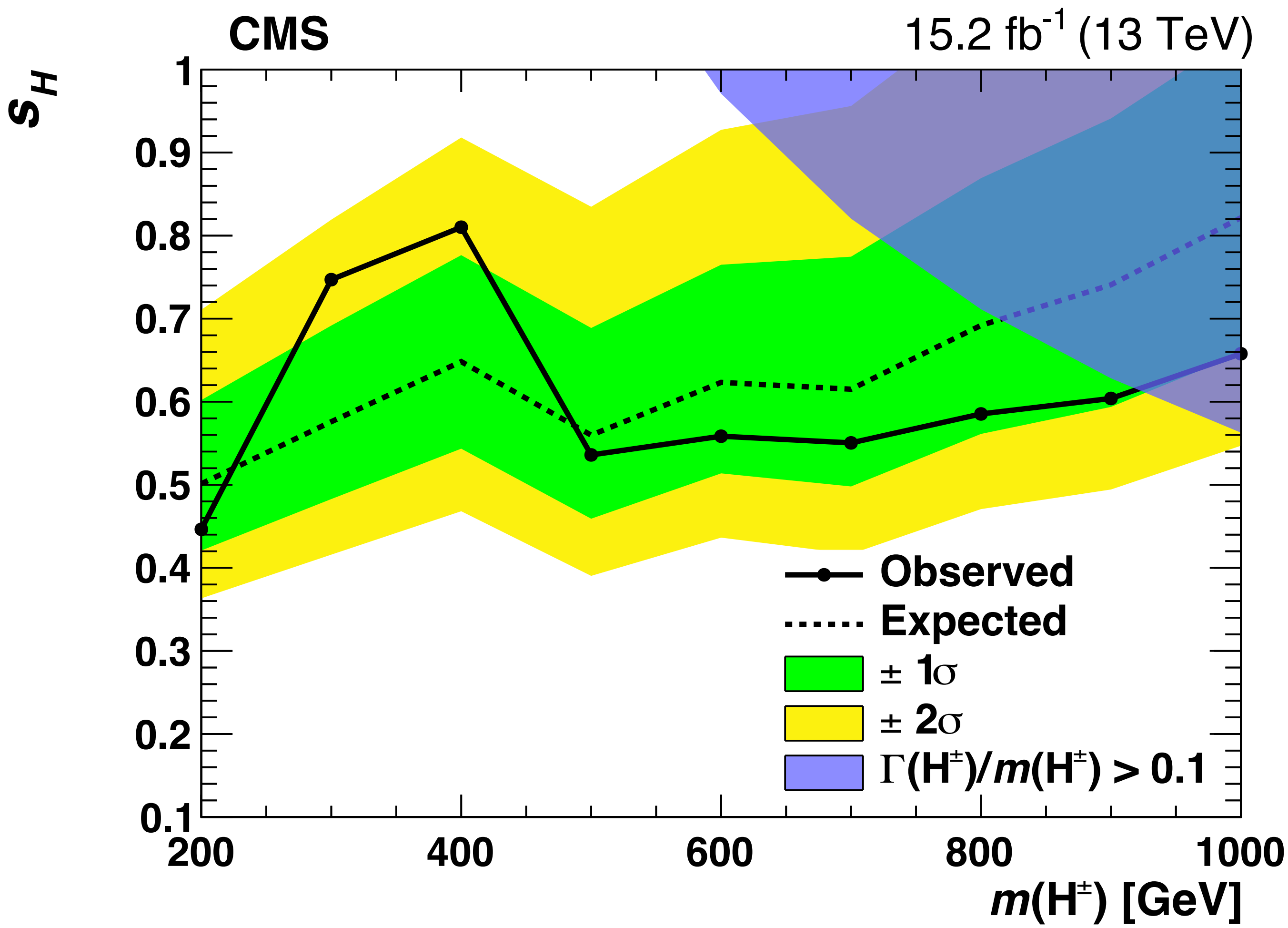
ATLAS 1503.04233, PRL 2015



Searches

VBF $H_5^\pm \to W^\pm Z \to 3\ell$ + MET (CMS Run 2)

CMS 1705.02942, PRL 2017



One more constraint from $VV \to H_5 \to VV$: unitarity!

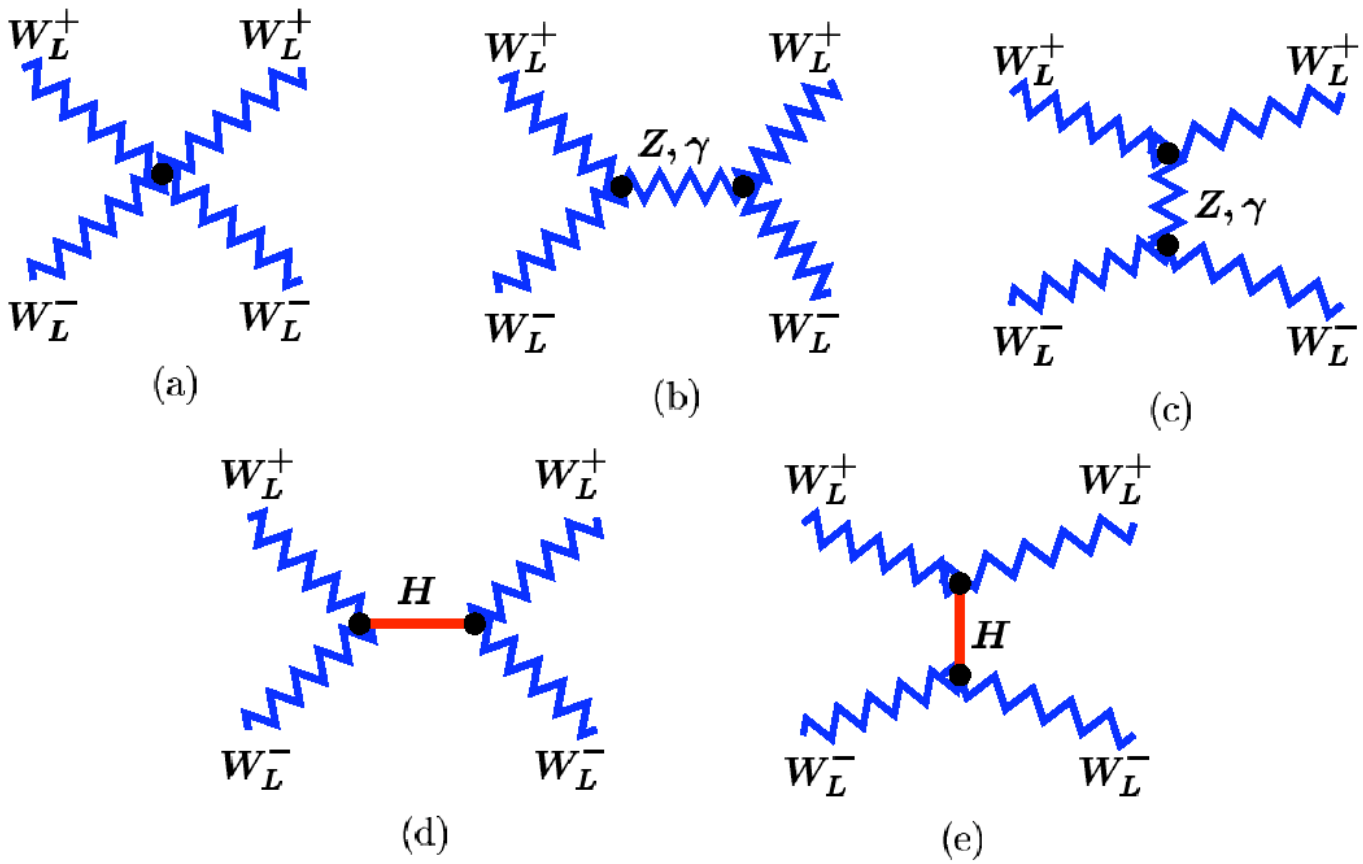
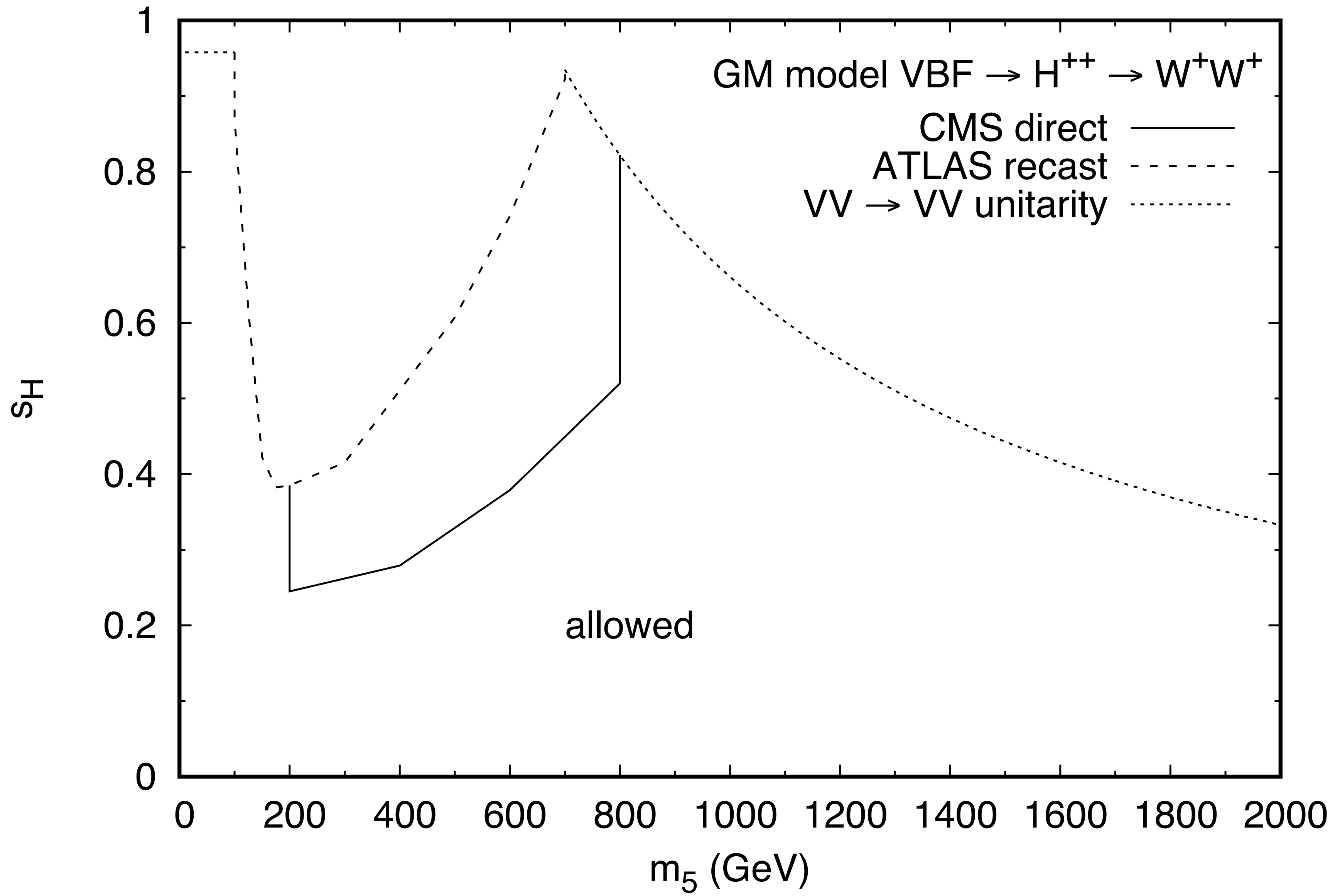


figure: S. Chivukula

SM: $m_h^2 < 16\pi v^2/5 \simeq (780 \text{ GeV})^2$ Lee, Quigg & Thacker 1977

GM: $s_H^2 < 12\pi v^2/5m_5^2 \simeq (675 \text{ GeV}/m_5)^2$

One more constraint from $VV \to H_5 \to VV$: unitarity!



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- allowed vevs from rho parameter
- some model building

Georgi-Machacek model and constraints from VBF $\to H_5 \to VV$

Constraining other models (GM-like; septet)

Promising channels at lower masses

Conclusions

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

3) Doublet + quartets $\left(\frac{3}{2}, \frac{1}{2}\right) + \left(\frac{3}{2}, \frac{3}{2}\right)$
4) Doublet + quintets $(2, 0) + (2, 1) + (2, 2)$
5) Doublet + sextets $\left(\frac{5}{2}, \frac{1}{2}\right) + \left(\frac{5}{2}, \frac{3}{2}\right) + \left(\frac{5}{2}, \frac{5}{2}\right)$

Replace the GM bi-triplet with a bi-n-plet $\Longrightarrow$ "GGMn"

Original GM model ("GM3"): $(1, 0) + (1, 1)$ in a bi-triplet

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

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

3) Doublet + quartets $\left(\frac{3}{2},\frac{1}{2}\right)+\left(\frac{3}{2},\frac{3}{2}\right)$
4) Doublet + quintets $(2,0)+(2,1)+(2,2)$
5) Doublet + sextets $\left(\frac{5}{2},\frac{1}{2}\right)+\left(\frac{5}{2},\frac{3}{2}\right)+\left(\frac{5}{2},\frac{5}{2}\right)$

Replace the GM bi-triplet with a bi-n-plet $\Longrightarrow$ "GGMn"

"GGM4": $\left(\frac{3}{2},\frac{1}{2}\right)+\left(\frac{3}{2},\frac{3}{2}\right)$ in a bi-quartet

$$X_4 = \begin{pmatrix} \psi_3^{0*} & -\psi_1^{-*} & \psi_1^{++} & \psi_3^{+3} \\ -\psi_3^{+*} & \psi_1^{0*} & \psi_1^{+} & \psi_3^{++} \\ \psi_3^{++*} & -\psi_1^{+*} & \psi_1^{0} & \psi_3^{+} \\ -\psi_3^{+3*} & \psi_1^{++*} & \psi_1^{-} & \psi_3^{0} \end{pmatrix}$$

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

3) Doublet + quartets $\left(\frac{3}{2},\frac{1}{2}\right)+\left(\frac{3}{2},\frac{3}{2}\right)$
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Replace the GM bi-triplet with a bi-n-plet $\Longrightarrow$ "GGMn"

"GGM5": $(2,0)+(2,1)+(2,2)$ in a bi-quintet

$$X_5 = \begin{pmatrix} \pi_4^{0*} & -\pi_2^{-*} & \pi_0^{++} & \pi_2^{+3} & \pi_4^{+4} \\ -\pi_4^{+*} & \pi_2^{0*} & \pi_0^{+} & \pi_2^{++} & \pi_4^{+3} \\ \pi_4^{++*} & -\pi_2^{+*} & \pi_0^{0} & \pi_2^{+} & \pi_4^{++} \\ -\pi_4^{+3*} & \pi_2^{++*} & -\pi_0^{+*} & \pi_2^{0} & \pi_4^{+} \\ \pi_4^{+4*} & -\pi_2^{+3*} & \pi_0^{++*} & \pi_2^{-} & \pi_4^{0} \end{pmatrix}$$

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

3) Doublet + quartets $\left(\frac{3}{2},\frac{1}{2}\right)+\left(\frac{3}{2},\frac{3}{2}\right)$
4) Doublet + quintets $(2,0)+(2,1)+(2,2)$
5) Doublet + sextets $\left(\frac{5}{2},\frac{1}{2}\right)+\left(\frac{5}{2},\frac{3}{2}\right)+\left(\frac{5}{2},\frac{5}{2}\right)$

Replace the GM bi-triplet with a bi-n-plet $\Longrightarrow$ "GGMn"

"GGM6": $\left(\frac{5}{2},\frac{1}{2}\right)+\left(\frac{5}{2},\frac{3}{2}\right)+\left(\frac{5}{2},\frac{5}{2}\right)$ in a bi-sextet

$$X_6 = \begin{pmatrix} \zeta_5^{0*} & -\zeta_3^{-*} & \zeta_1^{--*} & \zeta_1^{+3} & \zeta_3^{+4} & \zeta_5^{+5} \\ -\zeta_5^{+*} & \zeta_3^{0*} & -\zeta_1^{-*} & \zeta_1^{++} & \zeta_3^{+3} & \zeta_5^{+4} \\ \zeta_5^{++*} & -\zeta_3^{+*} & \zeta_1^{0*} & \zeta_1^{+} & \zeta_3^{++} & \zeta_5^{+3} \\ -\zeta_5^{+3*} & \zeta_3^{++*} & -\zeta_1^{+*} & \zeta_1^{0} & \zeta_3^{+} & \zeta_5^{++} \\ \zeta_5^{+4*} & -\zeta_3^{+3*} & \zeta_1^{++*} & \zeta_1^{-} & \zeta_3^{0} & \zeta_5^{+} \\ -\zeta_5^{+5*} & \zeta_3^{+4*} & -\zeta_1^{+3*} & \zeta_1^{--} & \zeta_3^{-} & \zeta_5^{0} \end{pmatrix}$$

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

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

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

Bi-quartet: $4 \otimes 4 \to 1 \oplus 3 \oplus 5 \oplus 7$

Bi-pentet: $5 \otimes 5 \to 1 \oplus 3 \oplus 5 \oplus 7 \oplus 9$

Bi-sextet: $6 \otimes 6 \to 1 \oplus 3 \oplus 5 \oplus 7 \oplus 9 \oplus 11$

Larger bi-n-plets forbidden by perturbativity of weak charges!

- Two custodial singlets mix $\to h^0$, H^0

- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstones

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ $\longleftarrow \star$

- Additional states

Compositions & couplings of fiveplet states are determined by the global symmetry!

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

Custodial-fiveplet is fermiophobic; couples to VV:

$$H_5^0 W_\mu^+ W_\nu^- : \qquad -i\frac{2M_W^2}{v}\frac{g_5}{\sqrt{6}}g_{\mu\nu},$$

$$H_5^0 Z_\mu Z_\nu : \qquad i\frac{2M_Z^2}{v}\sqrt{\frac{2}{3}}g_5 g_{\mu\nu},$$

$$H_5^+ W_\mu^- Z_\nu : \qquad -i\frac{2M_W M_Z}{v}\frac{g_5}{\sqrt{2}}g_{\mu\nu},$$

$$H_5^{++} W_\mu^- W_\nu^- : \qquad i\frac{2M_W^2}{v}g_5 g_{\mu\nu},$$

$$\text{GM3}: \qquad g_5 = \sqrt{2}s_H$$

$$\text{GGM4}: \qquad g_5 = \sqrt{24/5}s_H$$

$$\text{GGM5}: \qquad g_5 = \sqrt{42/5}s_H$$

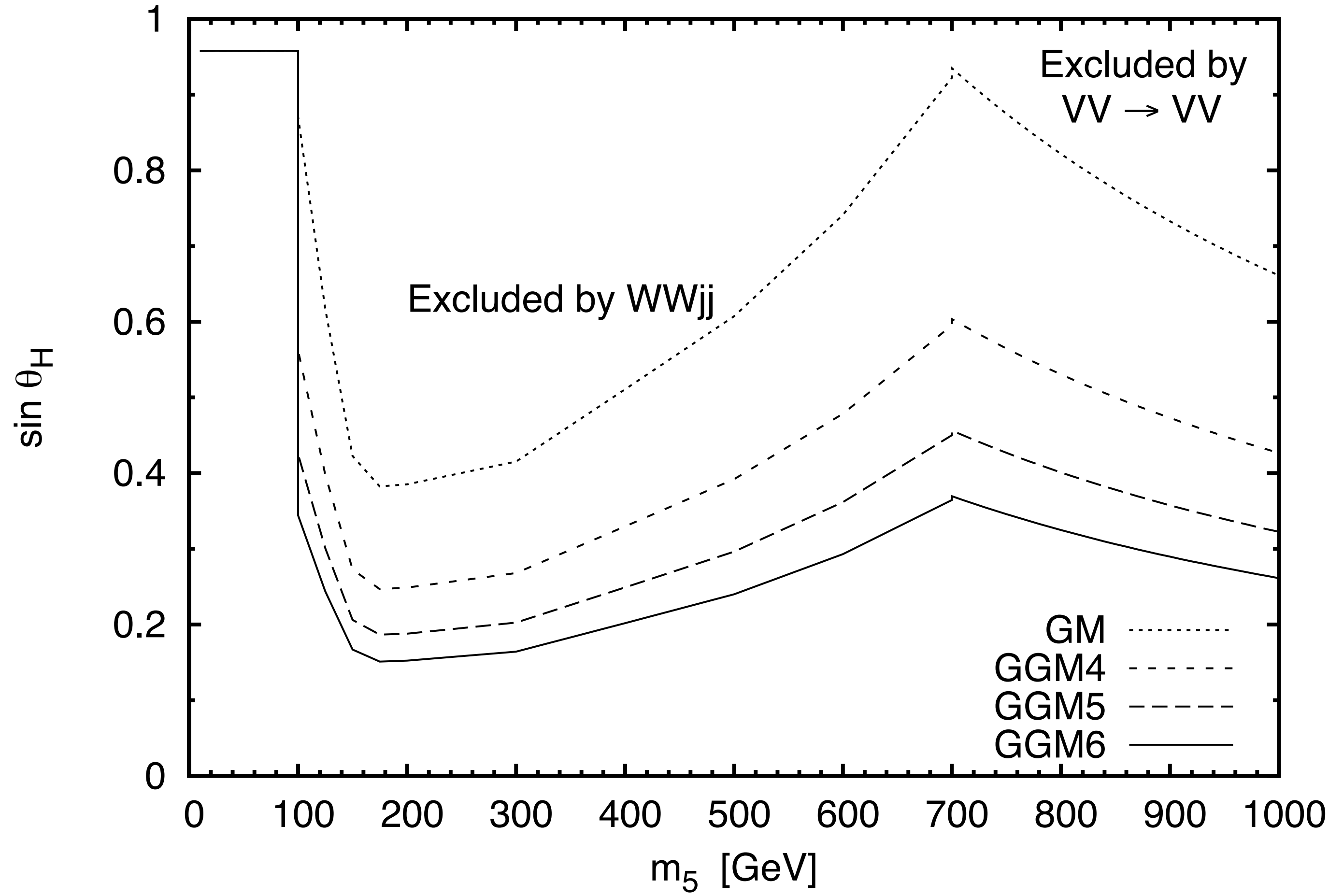
$$\text{GGM6}: \qquad g_5 = \sqrt{64/5}s_H$$

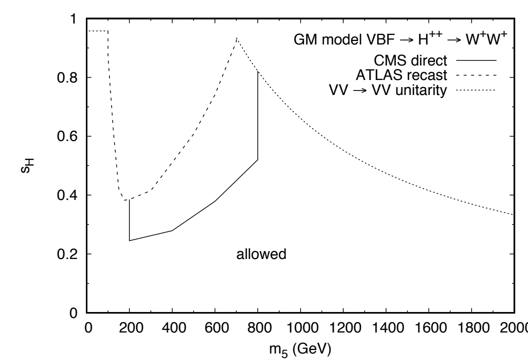
s_H^2 = fraction of M_W^2, M_Z^2 from exotic scalars

Generalized Georgi-Machacek models

Galison 1984; Robinett 1985; HEL 1999; Chang et al 2012; HEL & Rentala 2015

VBF $\rightarrow H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ and $VV \rightarrow VV$ unitarity





HEL & Rentala, 1502.01275

(old plot: CMS Run 1 direct-search constraint not shown)

Scalar septet model $(T, Y) = (3, 2)$

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{+5} \\ \chi^{+4} \\ \chi^{+3} \\ \chi^{+2} \\ \chi^{+1} \\ \chi^0 \\ \chi^{-1} \end{pmatrix}.$$

Detailed pheno study in Alvarado, Lehman & Ostdiek, 1404.3208:

- h^0 couplings $\rightarrow$ upper bound on septet vev

- S and T parameters $\rightarrow$ septet states must be fairly degenerate

- LHC SUSY searches (2SSL, 3L) + inclusive septet pair production $\rightarrow$ lower bound on common septet mass

Scalar septet model $(T, Y) = (3, 2)$

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \qquad X = \begin{pmatrix} \chi^{+5} \\ \chi^{+4} \\ \chi^{+3} \\ \chi^{+2} \\ \chi^{+1} \\ \chi^0 \\ \chi^{-1} \end{pmatrix}.$$

$\rho = 1$, yet there is no custodial symmetry in the scalar spectrum

- $H^{++} = \chi^{+2}$: analogue of H_5^{++}
- ϕ^+, χ^{+1}, $(\chi^{-1})^*$ mix: no purely fermiophobic analogue of H_5^+
- Only 2 CP-even neutral scalars (h^0, H^0): no analogue of H_5^0

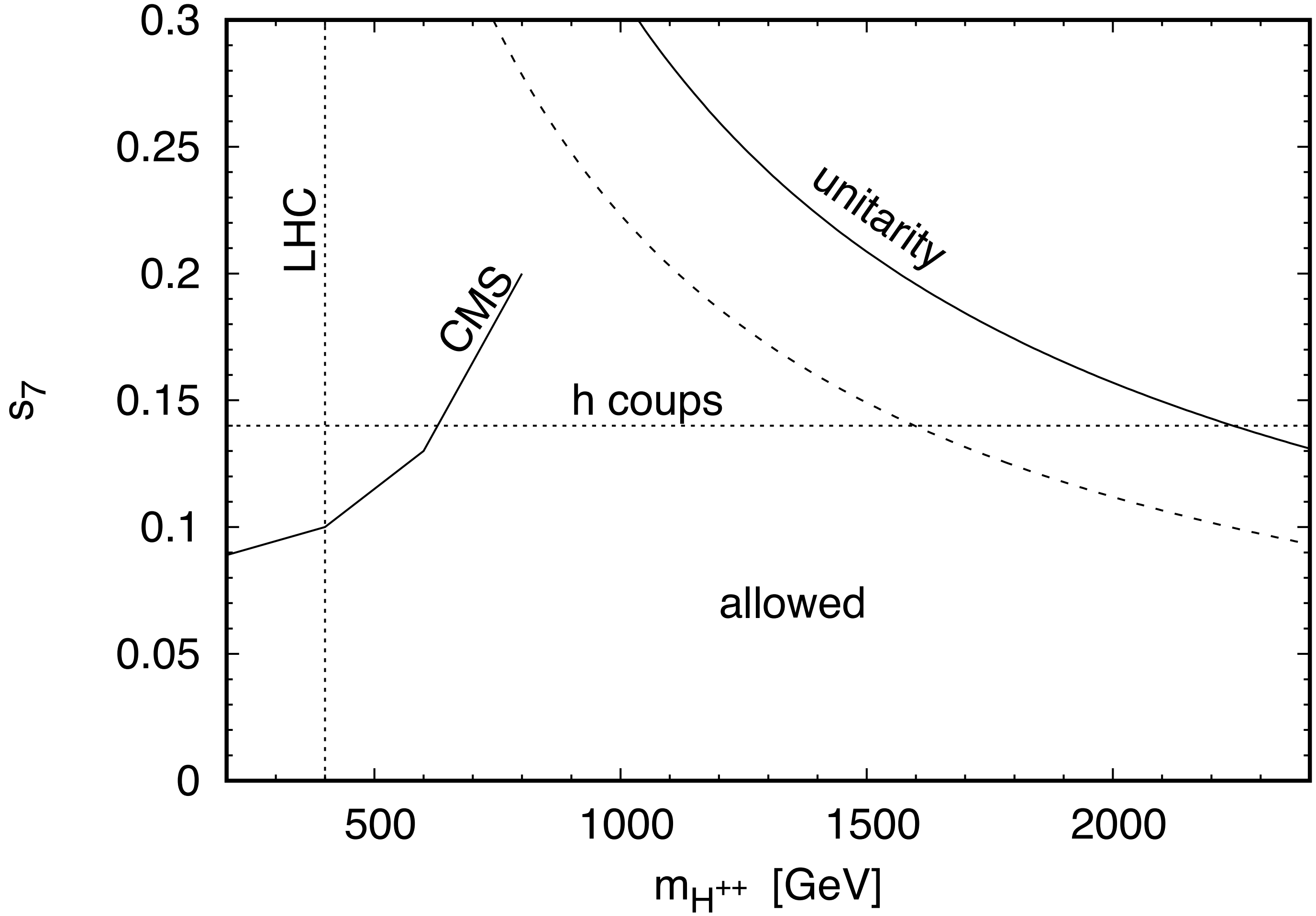
$$H^{++} W_\mu^- W_\nu^- : \quad i \frac{2 M_W^2}{v} \sqrt{15} s_7 g_{\mu\nu},$$

$s_7^2 =$ fraction of M_W^2, M_Z^2 from septet vev

Scalar septet model $(T,Y)=(3,2)$

Hisano & Tsumura, 1301.6455; Kanemura, Kikuchi & Yagyu, 1301.7303

Translate CMS VBF $\to H^{++} \to W^+W^+$ direct search,
$VV \to VV$ unitarity constraint: Harris & HEL, 1703.03832



$VV \to VV$ unitarity bound:

solid H^{++} only;

dashed assumes degenerate H_1^+, H_2^+, H^0

$s_7^2 < 2\%$!

Dots: LHC SUSY searches, h^0 couplings Alvarado, Lehman & Ostdiek, 1404.3208

Outline

Requirements for a sensible theory
- allowed reps from perturbative unitarity
- allowed vevs from rho parameter
- some model building

Georgi-Machacek model and constraints from VBF $\to H_5 \to VV$

Constraining other models (GM-like; septet)

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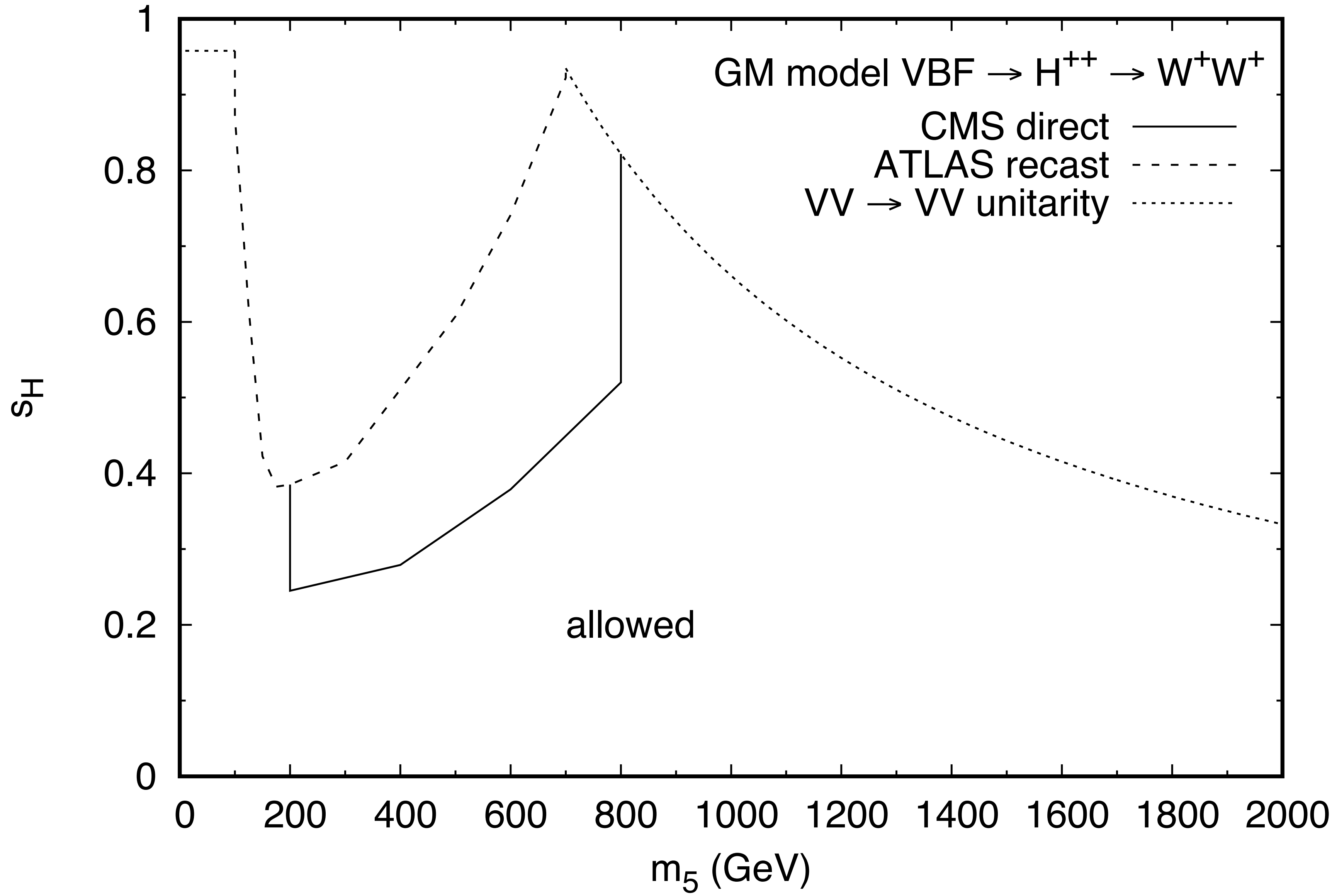
Constraints on GM model at low mass?



Constraints on GM model at low mass?

Studied already:

- Drell-Yan $pp \to H_5^{++}H_5^{--} + H_5^{\pm\pm}H_5^{\mp}$, $H_5^{\pm\pm} \to$ like-sign dimuons

- LEP $e^+e^- \to ZH_5^0$, recoil method (independent of H_5^0 decay)

- LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$ (fermiophobic!)

For the future:

- Drell-Yan $pp \to H_5^0 H_5^{\pm}$, $H_5^0 \to \gamma\gamma$

- Drell-Yan $pp \to H_5^{\pm}H_5^0 + H_5^{\pm}H_5^{\mp} + H_5^{\pm}H_5^{\mp\mp}$, $H_5^{\pm} \to W^{\pm}\gamma$

Drell-Yan $pp \to H_5^{++} H_5^{--} + H_5^{\pm\pm} H_5^{\mp}$, $H_5^{\pm\pm} \to$ like-sign dimuons

ATLAS Run 1 anomalous like-sign dimuon search ATLAS, 1412.0237

Recast for $pp \to H^{\pm\pm} H^{\mp\mp} + H^{\pm\pm} H^{\mp}$ in Higgs Triplet Model

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

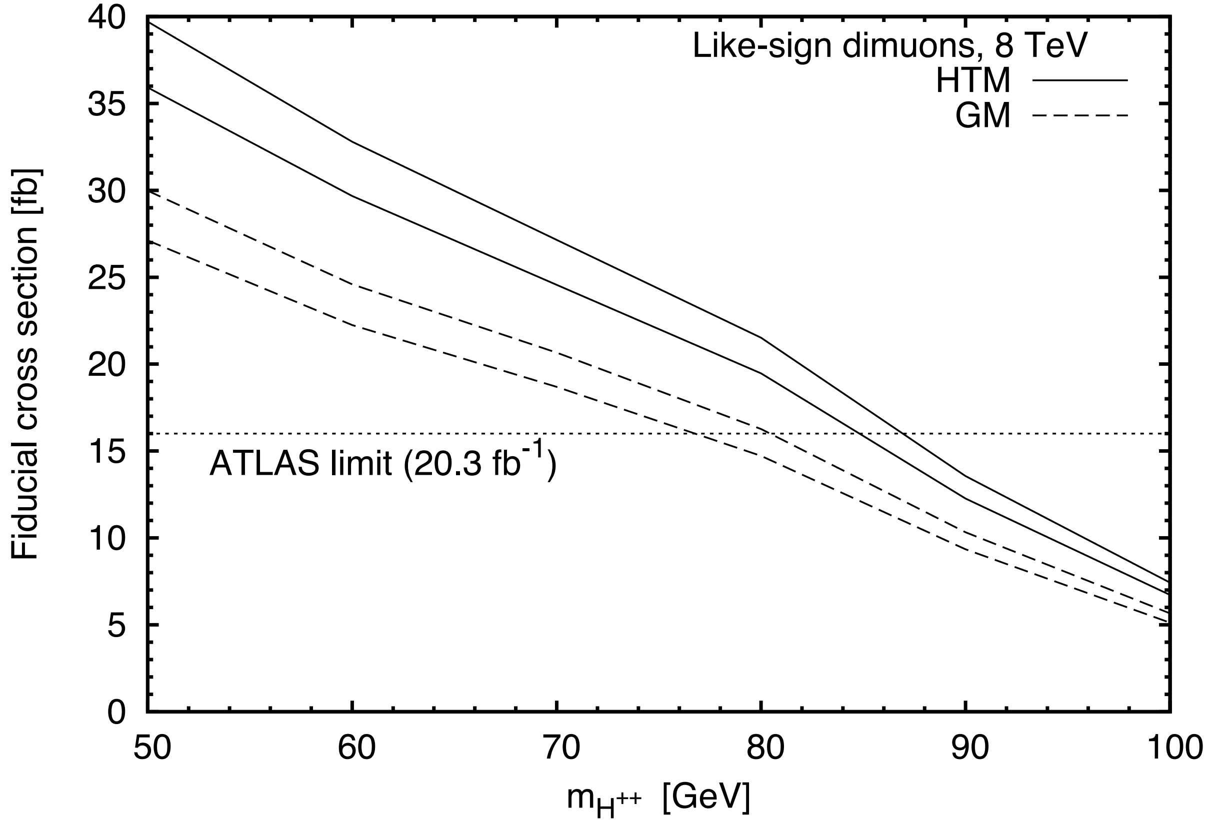
Adapt to generalized GM models using

$$\begin{aligned} \sigma_{\rm tot}^{\rm NLO}(pp \to H_5^{++} H_5^{--})_{\rm GM} &= \sigma_{\rm tot}^{\rm NLO}(pp \to H^{++} H^{--})_{\rm HTM}, \\ \sigma_{\rm tot}^{\rm NLO}(pp \to H_5^{\pm\pm} H_5^{\mp})_{\rm GM} &= \frac{1}{2} \sigma_{\rm tot}^{\rm NLO}(pp \to H^{\pm\pm} H^{\mp})_{\rm HTM}. \end{aligned}$$

HEL & Rentala, 1502.01275

Take advantage of mass degeneracy of all H_5 states.

Drell-Yan $pp \to H_5^{++} H_5^{--} + H_5^{\pm\pm} H_5^{\mp}$, $H_5^{\pm\pm} \to$ like-sign dimuons



$\Rightarrow$ $m_5 \gtrsim 76$ GeV, no s_H dependence! HEL & Rentala, 1502.01275

Assumes no decays $H_5^{\pm\pm} \to H_3^{\pm} W^{\pm}$:

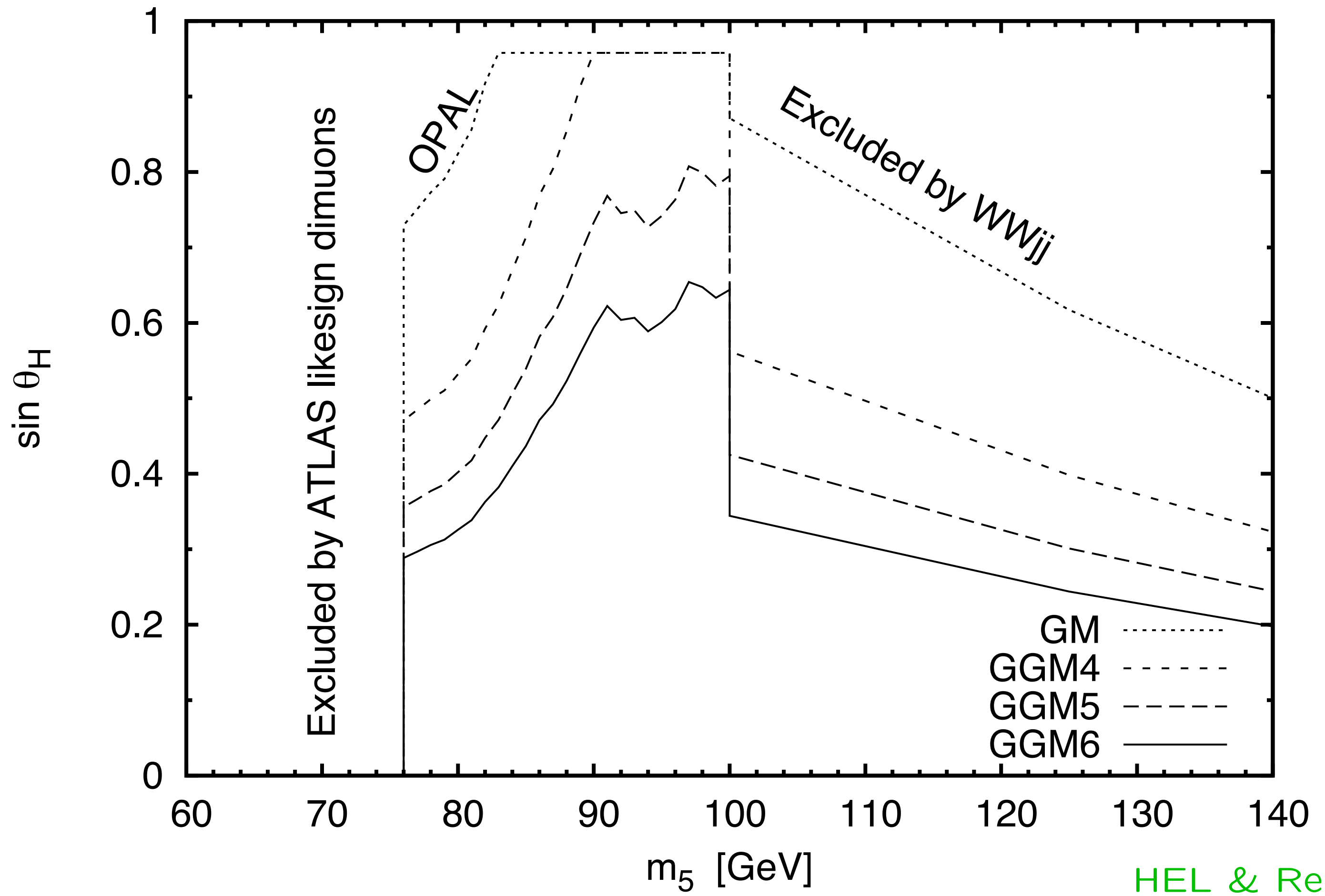
Constraint on $e^+e^- \to H_3^+ H_3^-$ in Type-I 2HDM LEP, hep-ex/0107031

$m_3 > 78.6$ GeV assuming no decays $H_3 \to H_5 V$

$\Rightarrow$ take $m_3 > 76$ GeV also ($m_5 > 76$ GeV guarantees no competing decays)

LEP $e^+e^- \to ZH_5^0$, recoil method (independent of H_5^0 decay)

OPAL search for $Z + S^0$ production OPAL hep-ex/0206022
$\to$ upper bound on $H_5^0 ZZ$ coupling $\propto s_H^2$ as a function of m_5

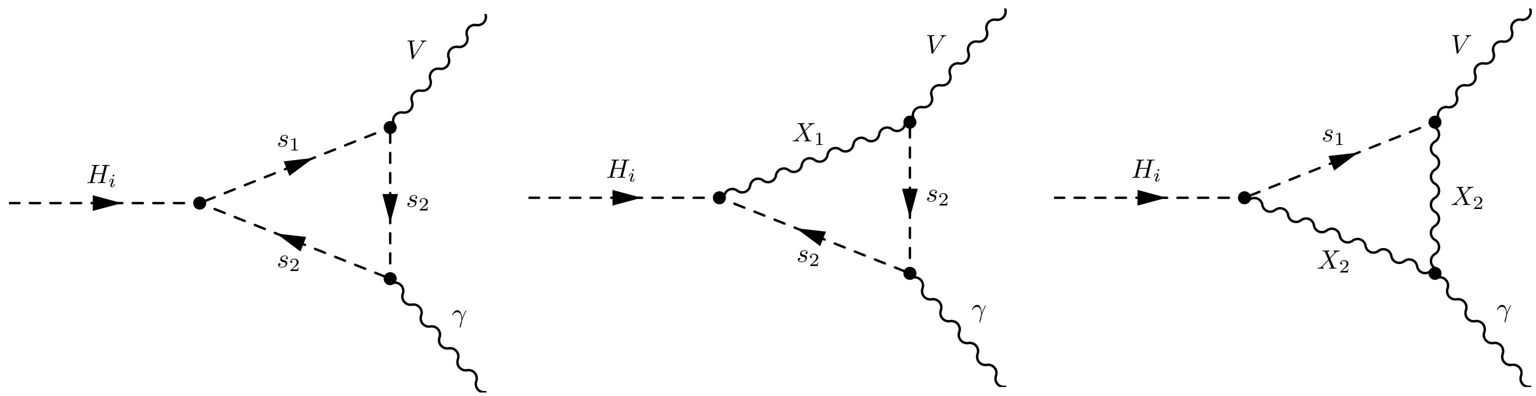


HEL & Rentala, 1502.01275

LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$ (fermiophobic!)

Below $H_5^0 \to VV$ threshold: tree-level decays suppressed

$H_5^0 \to W^+W^-, ZZ$ calculated including doubly off-shell effects
$H_5^0 \to \gamma\gamma$ calculated as usual
$H_5^0 \to Z\gamma$ (competing mode): new diagrams with $m_1 \neq m_2$

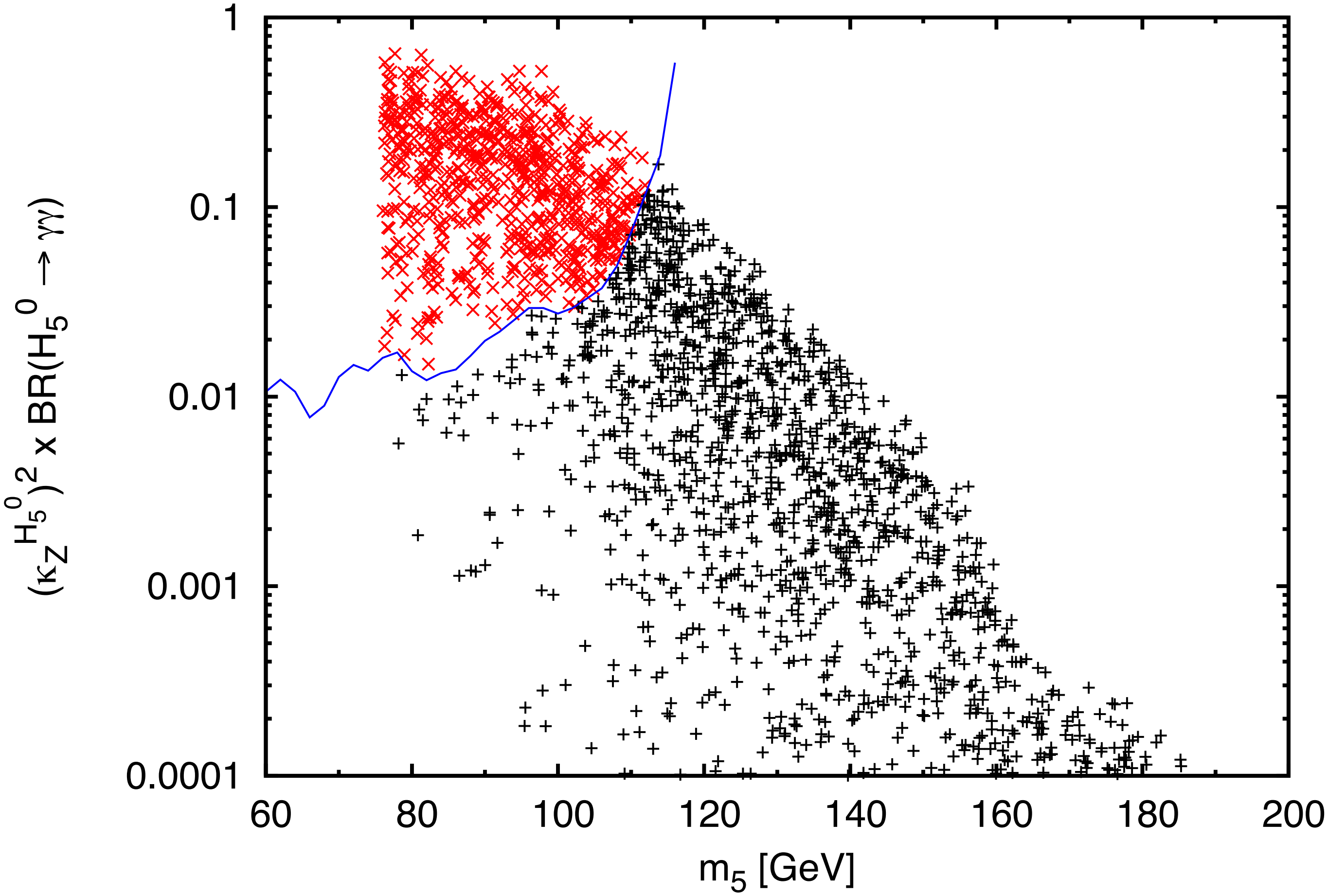


Degrande, Hartling & HEL, 1708.08753

Implemented in GMCALC 1.3.0

LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$ (fermiophobic!) LHWG Note 2002-02

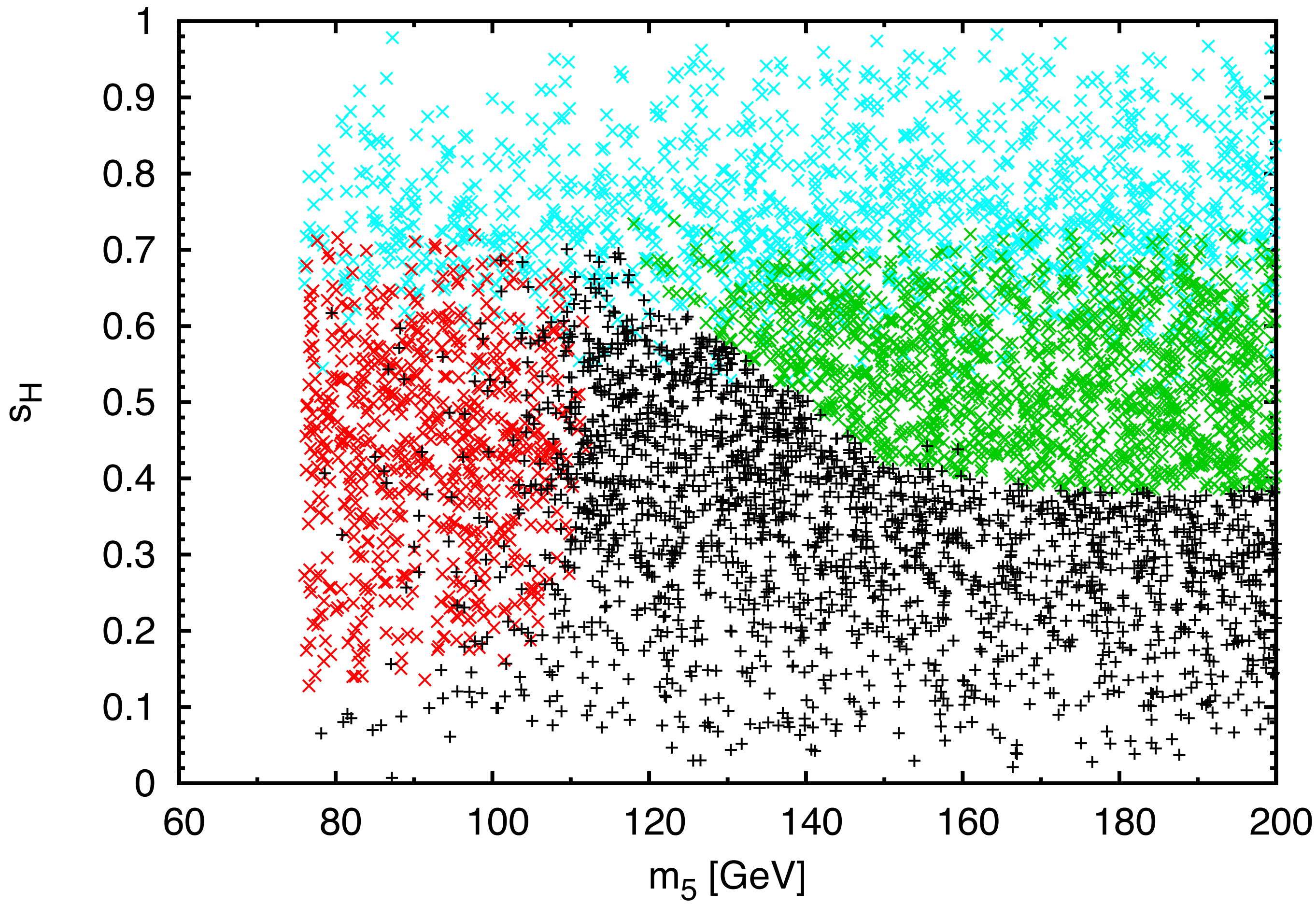
Numerical limit is in HiggsBounds 4.2.0 Bechtle et al., 1507.06706

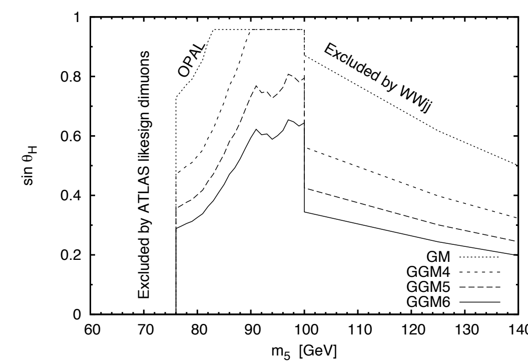


Degrande, Hartling & HEL, 1708.08753

Production cross section $\propto s_H^2$

LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$ (fermiophobic!)





cyan $b \to s\gamma$ SuperIso + 2HDMC — Degrande, Hartling & HEL, 1708.08753

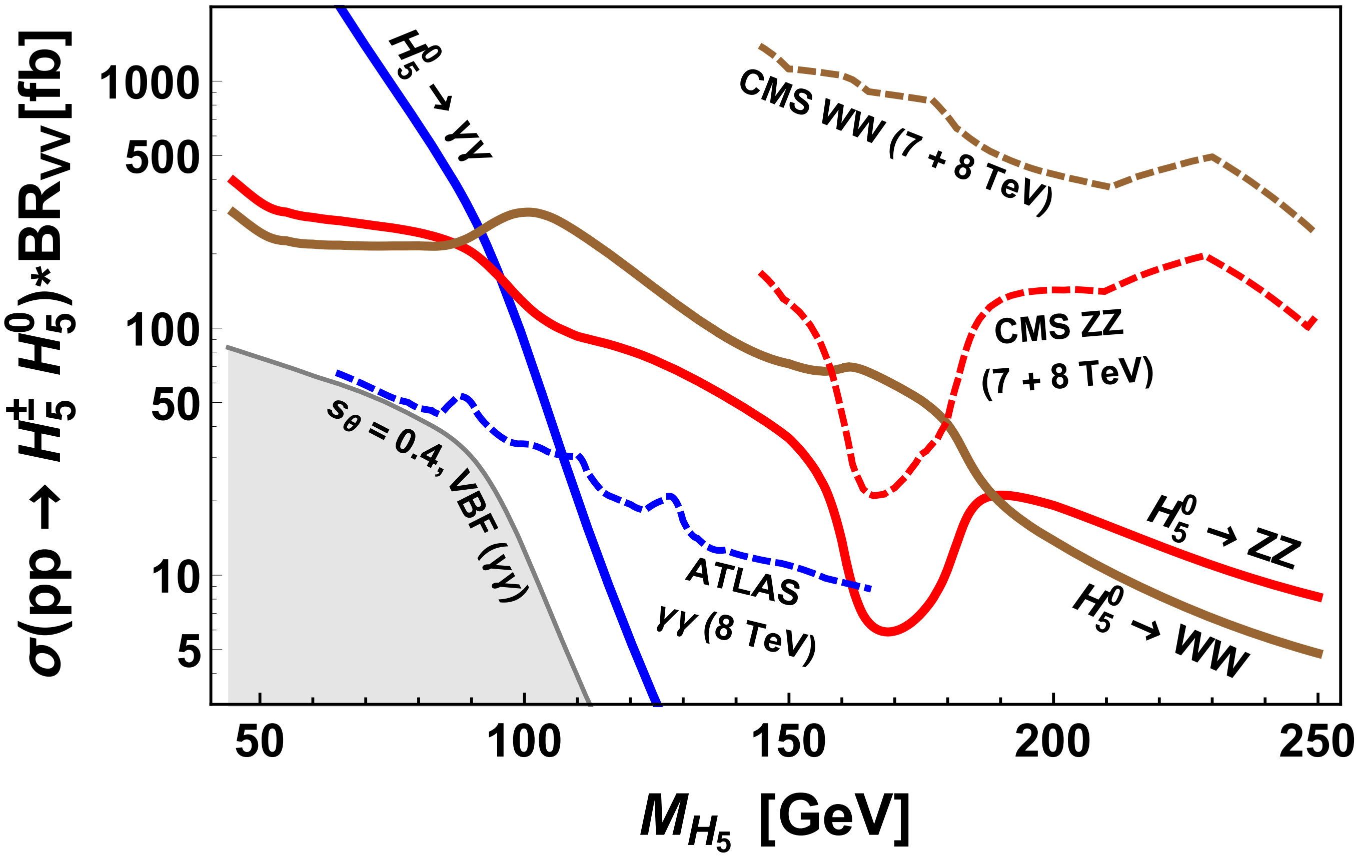
green $H_5^{\pm\pm} \to W^\pm W^\pm$ ATLAS recast

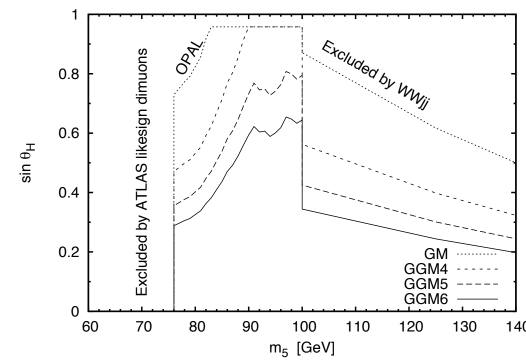
red LEP $H_5^0 \to \gamma\gamma$ — GMCALC Hartling, Kumar & HEL, 1412.7387

For the future:

- Drell-Yan $pp \to H_5^0 H_5^\pm$, $H_5^0 \to \gamma\gamma$

Drell-Yan cross section depends only on m_5 and gauge couplings!





Delgado, Garcia-Pepin, Quiros, Santiago & Vega-Morales, 1603.00962

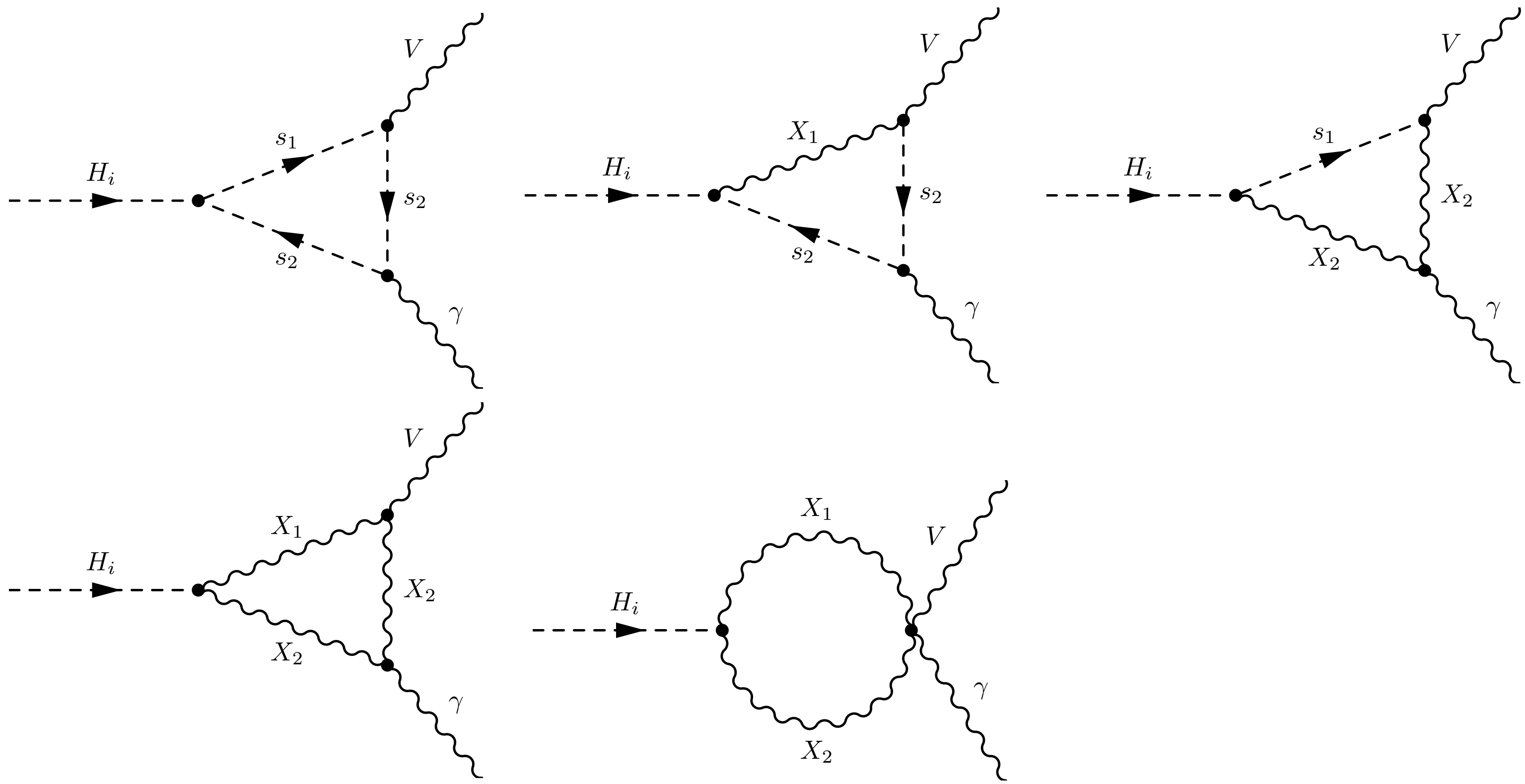
Projection: only W loop included in $H_5^0 \to \gamma\gamma, Z\gamma$ calculation.

For the future: fermiophobic!

- Drell-Yan $pp \to H_5^\pm H_5^0 + H_5^\pm H_5^\mp + H_5^\pm H_5^{\mp\mp}$, $H_5^\pm \to W^\pm \gamma$

Below $H_5^\pm \to W^\pm Z$ threshold: tree-level decays suppressed

Calculation of $H_5^\pm \to W^\pm \gamma$ involves nonstandard diagrams:

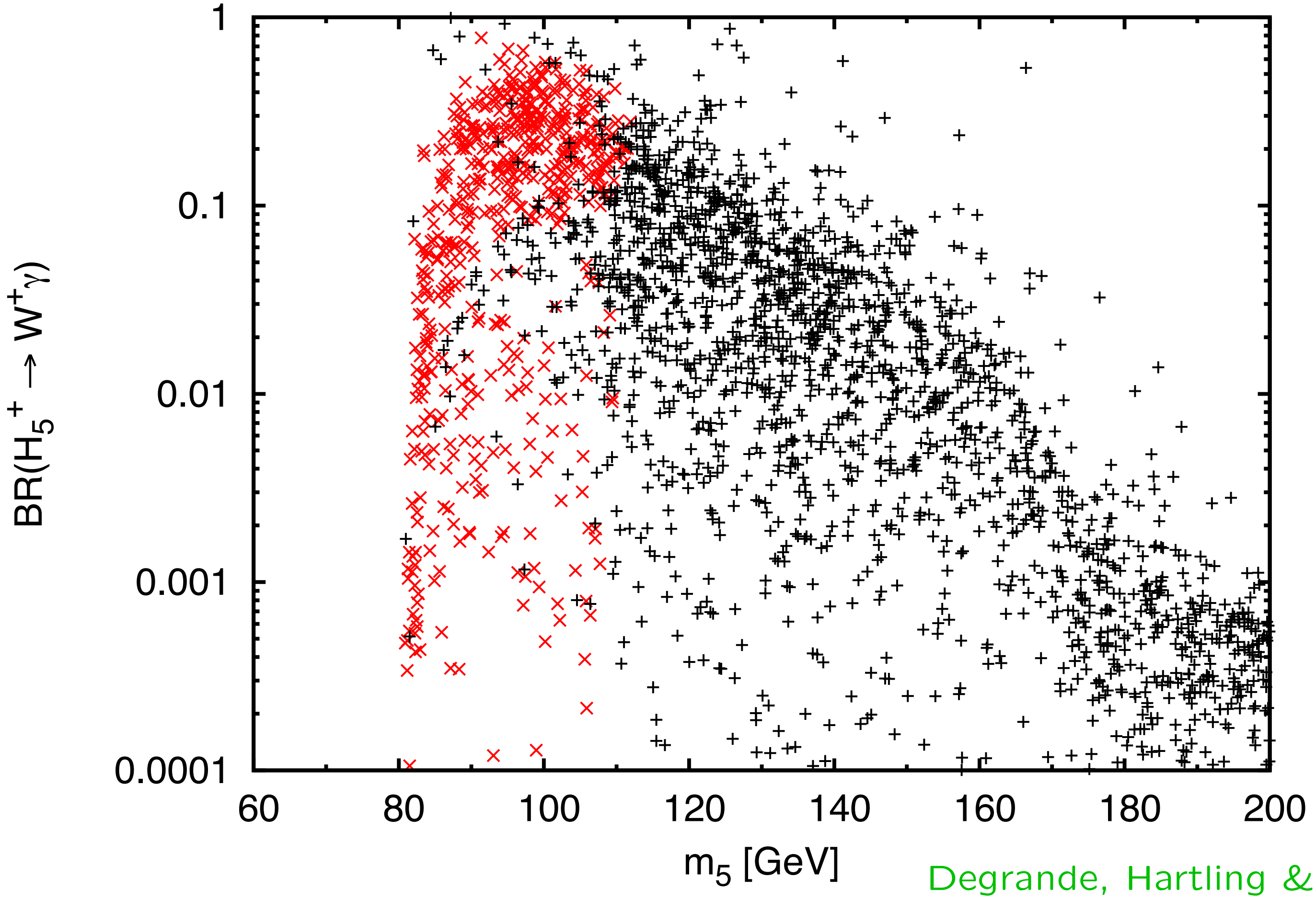


Degrande, Hartling & HEL, 1708.08753

Implemented in GMCALC 1.3.0

For the future:

- Drell-Yan $pp \to H_5^\pm H_5^0 + H_5^\pm H_5^\mp + H_5^\pm H_5^{\mp\mp}$, $H_5^\pm \to W^\pm \gamma$



Degrande, Hartling & HEL, 1708.08753

Red points excluded by LEP $e^+e^- \to ZH_5^0$, $H_5^0 \to \gamma\gamma$

Drell-Yan cross section depends only on m_5 and gauge couplings!

For the future:

- Drell-Yan $pp \to H_5^0 H_5^\pm$, $H_5^0 \to \gamma\gamma$
- Drell-Yan $pp \to H_5^\pm H_5^0 + H_5^\pm H_5^\mp + H_5^\pm H_5^{\mp\mp}$, $H_5^\pm \to W^\pm \gamma$

MadGraph model file with effective vertices for $H_5^0 \gamma\gamma$, $H_5^0 Z\gamma$, $H_5^\pm W^\mp \gamma$ in preparation

Specific to Georgi-Machacek model: detailed predictions for loop-induced BRs can't be applied to generalized GM models without dedicated calculations.

Drell-Yan $pp \to H_5 H_5$ cross sections are generic to all generalized GM models.

H_5^0 BR$(WW + ZZ + Z\gamma + \gamma\gamma) = 1$ and $H_5^\pm$ BR$(WZ + W\gamma) = 1$ are generic: combination of complementary searches useful.

Don't forget Drell-Yan $H_5^{\pm\pm}$: BR$(H_5^{\pm\pm} \to W^\pm W^\pm) = 1$!

Conclusions

Goal:
- Enumerate the possibilities for exotic contributions to EWSB
- Find ways to constrain their contributions to M_W^2, M_Z^2

VBF $\rightarrow H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ very generic:
constrains GM, its generalizations, & septet model

VBF $\rightarrow H^{\pm} \rightarrow W^{\pm}Z$ also pretty generic:
constrains GM & its generalizations

Low mass region $m_5 \lesssim 2M_V$ is finicky:
Drell-Yan probably our best bet – depends only on m_5
Loop decays to $\gamma\gamma$, $Z\gamma$, $W^{\pm}\gamma$ become interesting
$H_5^{\pm\pm}$ decays to like-sign dileptons still very generic