Limits on exotic contributions to electroweak symmetry breaking

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Motivation: exotic EWSB?

In the SM we break the electroweak symmetry with a scalar doublet – the minimal nontrivial representation of $SU(2)_L$.

Fermion weak charges are directly measured – need a doublet to generate fermion masses. (except maybe neutrinos)

But the multiplet structure of the Higgs sector is not yet determined.

There could be contributions to the vacuum condensate from "exotic" scalars = scalars with higher isospin.

$\Rightarrow$ How can we constrain this class of models, theoretically and experimentally?

Motivation: exotic EWSB?

Theoretical motivation: who knows?
- Triplet scalar $(\chi^{++}, \chi^{+}, \chi^{0})$ gives Majorana neutrino masses.
- Global symmetries of composite Higgs models can yield larger SU(2) representations.
- If LHC discovered it, we would come up with a good reason.

Instead, take a phenomenological approach:

1) Perturbative unitarity (a matter of taste) $\rightarrow$ what models are allowed

2) Precision electroweak constraint (mostly ρ parameter); model building to evade it

3) Direct search for $\langle X^\dagger \rangle X W_\mu^a W^{a\mu}$ (to constrain exotic vevs)

How high an isospin is ok?

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

Unitarity of the scattering matrix:

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

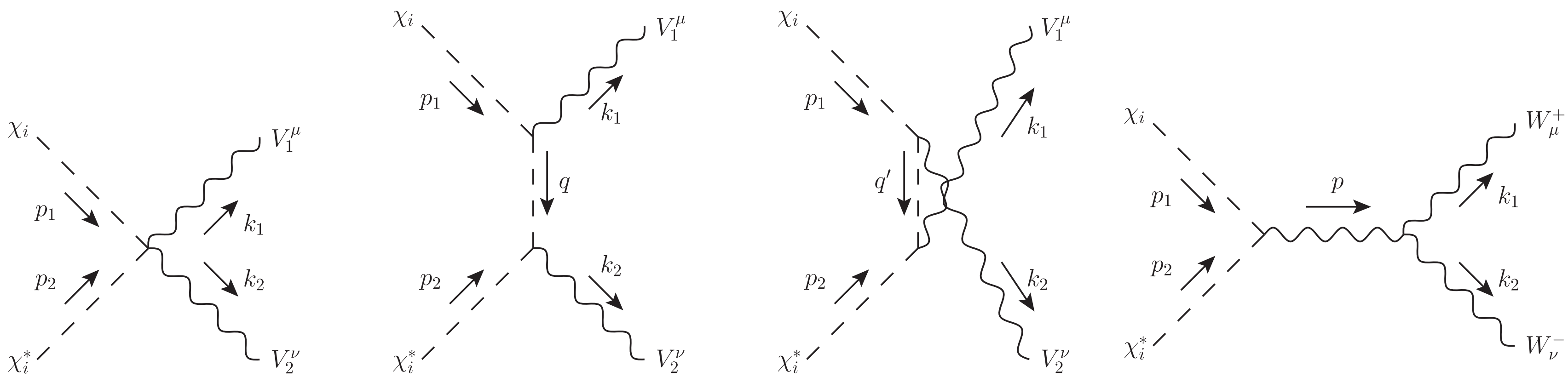
To bound the strength of the weak charge, consider *transversely* polarized Ws & Zs (the ordinary gauge modes).

Too strong a charge $\rightarrow$ nonperturbative

Different from scattering of longitudinally-polarized Ws & Zs that puts an upper bound on Higgs mass Lee, Quigg & Thacker 1977

How high an isospin is ok?

Hally, HEL, & Pilkington 1202.5073



Compute largest eigenvalue of scattering matrix for $\chi\chi \leftrightarrow W_T^a W_T^a$:

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

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

- Single complex multiplet $\Rightarrow T \leq 7/2$ (8-plet)
- Single real multiplet $\Rightarrow T \leq 4$ (9-plet)
- Constraints are tighter if $\exists$ more than one large multiplet

How high an isospin is ok?

Here's the complete list of perturbative scalars that can contribute to EWSB:

- Y values are determined by requiring that X must have a neutral component $(Q = T^3 + Y = 0)$

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

How much can these contribute to EWSB?

Extremely strong constraint on exotic multiplet vevs from precision electroweak data:

$$\rho_0 = \frac{\text{weak neutral current}}{\text{weak charged current}} = \frac{(g^2 + g'^2)/M_Z^2}{g^2/M_W^2} = \frac{v_\phi^2 + a\langle X^0\rangle^2}{v_\phi^2 + b\langle X^0\rangle^2}$$

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

Complex mult: $c = 1$. Real mult: $c = 1/2$. Doublet: $Y = 1/2$

Electroweak fit: PDG June 2018, Erler & Freitas

$$S = 0.02 \pm 0.10 \qquad T = 0.07 \pm 0.12 \qquad U = 0.00 \pm 0.09$$

Correlations: S–T: $+92\%$, S–U: -66%, T–U: -86%

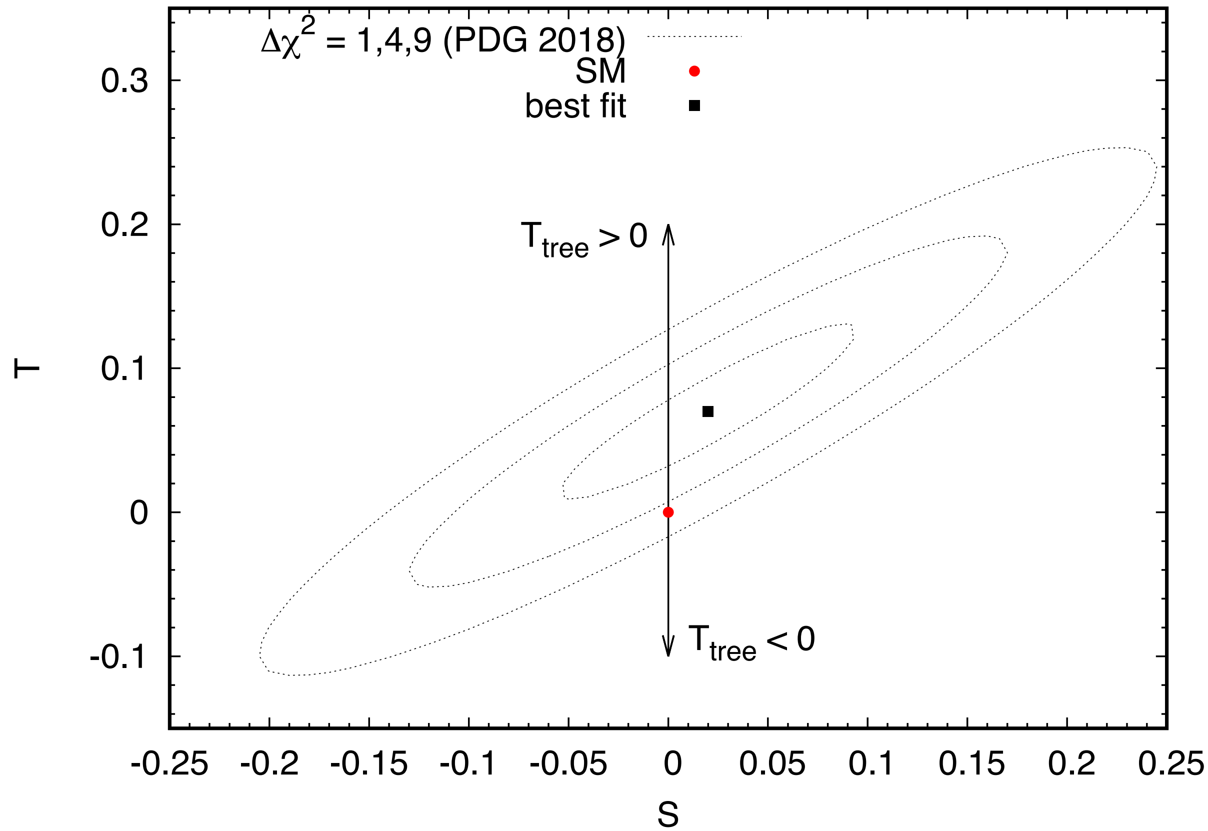
Peskin & Takeuchi, 1990, 1992

ρ_0 parameter is extracted by setting $S = U = 0$ and using

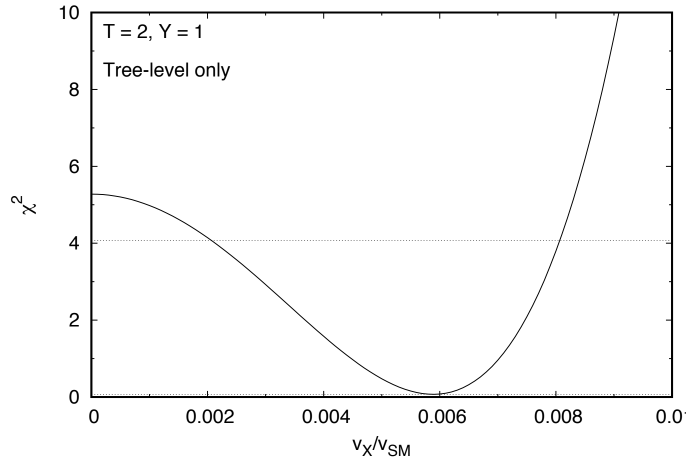
$$\rho_0 - 1 = \frac{1}{1 - \hat{\alpha}(M_Z)T_{\text{tree}}} - 1 \simeq \hat{\alpha}(M_Z)T_{\text{tree}}$$

How much can these contribute to EWSB?

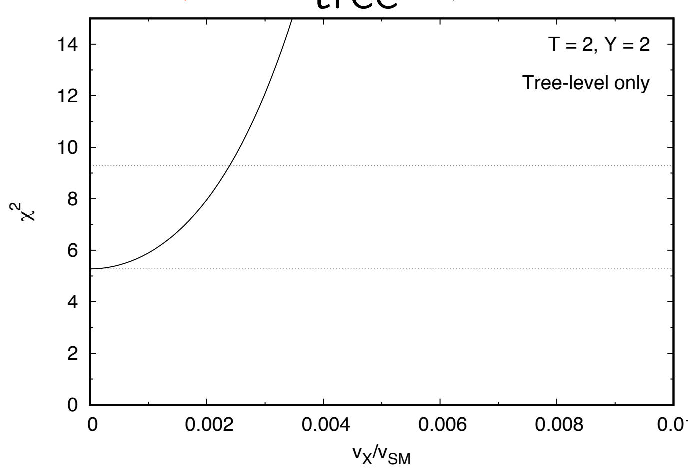
Tree-level ρ_0 parameter versus S, T, U



$a > b$: $T_{\text{tree}} > 0$



$a < b$: $T_{\text{tree}} < 0$



Jesi Goodman & HEL, in progress

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

How much can these contribute to EWSB? J. Goodman & HEL, in prog.

			Best fit		Allowed range ($\Delta\chi^2 \leq 4$)	
T	Y	$\delta\rho$	δM_W^2	δM_Z^2	δM_W^2	δM_Z^2
1/2	1/2	0	–	–	–	–
1	0	+	0.042%	0.000%	[0.005%, 0.078%]	[0.000%, 0.000%]
1	1	−	0.000%	0.000%	[0.000%, 0.014%]	[0.000%, 0.027%]
3/2	1/2	+	0.049%	0.007%	[0.006%, 0.091%]	[0.001%, 0.013%]
3/2	3/2	−	0.000%	0.000%	[0.000%, 0.007%]	[0.000%, 0.021%]
2	0	+	0.042%	0.000%	[0.005%, 0.078%]	[0.000%, 0.000%]
2	1	+	0.069%	0.028%	[0.009%, 0.130%]	[0.003%, 0.052%]
2	2	−	0.000%	0.000%	[0.000%, 0.005%]	[0.000%, 0.018%]
5/2	1/2	+	0.044%	0.003%	[0.005%, 0.083%]	[0.000%, 0.005%]
5/2	3/2	+	0.135%	0.093%	[0.017%, 0.253%]	[0.012%, 0.175%]
5/2	5/2	−	0.000%	0.000%	[0.000%, 0.003%]	[0.000%, 0.017%]
3	0	+	0.042%	0.000%	[0.005%, 0.078%]	[0.000%, 0.000%]
3	1	+	0.051%	0.009%	[0.006%, 0.095%]	[0.001%, 0.017%]
3	2	0	–	–	–	–
3	3	−	0.000%	0.000%	[0.000%, 0.003%]	[0.000%, 0.016%]
7/2	1/2	+	0.043%	0.001%	[0.005%, 0.080%]	[0.000%, 0.003%]
7/2	3/2	+	0.062%	0.021%	[0.008%, 0.117%]	[0.003%, 0.039%]
7/2	5/2	−	0.000%	0.000%	[0.000%, 0.043%]	[0.000%, 0.057%]
7/2	7/2	−	0.000%	0.000%	[0.000%, 0.002%]	[0.000%, 0.016%]
4	0	+	0.042%	0.000%	[0.005%, 0.078%]	[0.000%, 0.000%]

$\Rightarrow$ Maximum exotic M_W^2 contribution is $\sim$ 0.25% (tree-level ρ_0).

How much can these contribute to EWSB?

J. Goodman & HEL, in progress

Complication: experimental bound on ρ_0 is so tight that one-loop contributions can be as large as the tree-level vev contribution.

T parameter calculation involving exotic mults is subtle:
have to renormalize $T_{\rm tree}$. Chankowski, Pokorski & Wagner, hep-ph/0605302
$\rightarrow$ Handle this by quoting constraint on renormalized vev (choose counterterm to cancel tadpole).

Full calculation of 1-loop S, T, U in these models is quite involved.
$\rightarrow$ Work in a double expansion:
1st order in exotic vev ($T_{\rm tree}$) and 1st order in $\alpha_{\rm EM}$ (1-loop)
Can use (mostly) existing results for $(S, T, U)_{\rm loop}$ from a scalar electroweak multiplet with zero vev.

Nonzero $(S, T, U)_{\rm loop}$ driven by mass splitting in exotic multiplet:

$$S_{\rm loop} \sim Y \times \frac{-\delta m^2}{M^2} \qquad T_{\rm loop} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\rm loop} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Details: Mass splitting in the exotic multiplet

Ignore exotic multiplet's vev (consistent with double expansion). Mass splitting is due to EWSB and is driven by doublet vev:

$$
\begin{aligned}
V \;\supset\; & \lambda_0 \Phi^\dagger \Phi X^\dagger X + \lambda_1 (\Phi^\dagger \tau^a \Phi)(X^\dagger T^a X) \\
& + \left[\lambda_2 (\tilde{\Phi}^\dagger \tau^a \Phi)(X^\dagger T^a \tilde{X}) + \text{h.c.}\right] + \left[\lambda_3 \Phi^\dagger \Phi \tilde{X}^\dagger X + \text{h.c.}\right]
\end{aligned}
$$

$\tilde{\Phi}$, $\tilde{X}$ = conjugate multiplets

λ_0 term gives universal mass^2 contribution to all members of X.
λ_1 term generates a uniform m^2 splitting among T^3 eigenstates:
(absent for real $Y = 0$ mults)

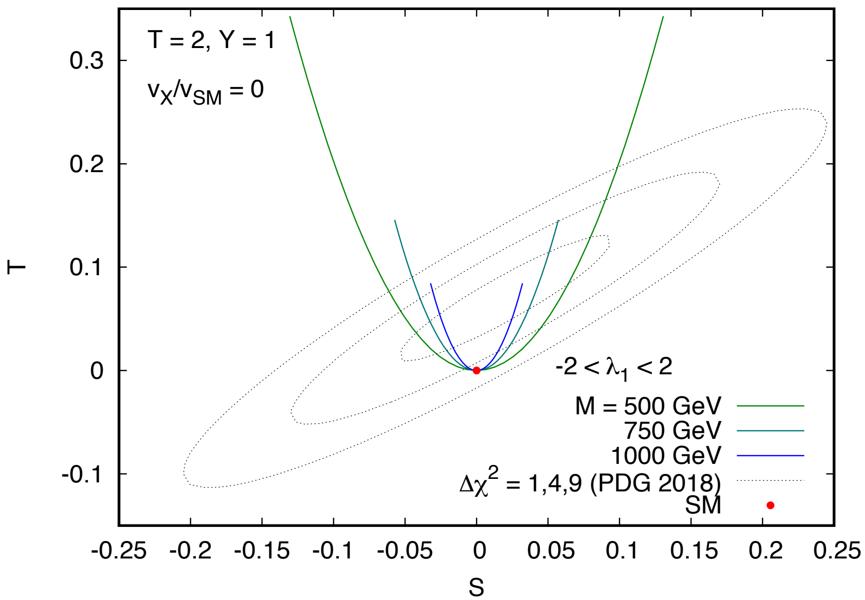
$$m^2_{T^3} = M^2 - \frac{1}{4}\lambda_1 v_\phi^2 T^3 \equiv M^2 + \delta m^2 T^3.$$

λ_2 term is present only for $Y = 1/2$ and $T = 3/2, 5/2, 7/2$;
λ_3 term is present only for complex mults with $Y = 0$:
These mix states with different T^3 but same electric charge.
Calculation still in progress: set $\lambda_2 = \lambda_3 = 0$ for now.

How much can these contribute to EWSB?

J. Goodman & HEL, in progress

Uniform m^2 splitting among T^3 eigenstates gives simple pattern:



$$S_{\text{loop}} \sim -\frac{\delta m^2}{M^2}$$

$$T_{\text{loop}} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2}$$

$$U_{\text{loop}} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Constraint on (renormalized) tree-level vev is loosened the most when positive T_{loop} compensates negative T_{tree}.

T	Y	$\delta\rho$	$\delta M_W^2\|_{\text{max}}$	$\delta M_Z^2\|_{\text{max}}$
1	1	–	3.609%	6.967%

← largest allowed (preliminary)

A *single* exotic multiplet: up to ∼0.25% of $M_{W,Z}^2$ at tree level; up to 3.5–7% including loop effects. ...Model-building?

T	Y	a	b	$\delta\rho$	
1/2	1/2	2	2	0	doublet
1	0	4	0	+	
1	1	4	8	−	
3/2	1/2	14	2	+	
3/2	3/2	6	18	−	
2	0	12	0	+	
2	1	20	8	+	
2	2	8	32	−	
5/2	1/2	34	2	+	
5/2	3/2	26	18	+	
5/2	5/2	10	50	−	
3	0	24	0	+	
3	1	44	8	+	
3	2	32	32	0	septet
3	3	12	72	−	
7/2	1/2	62	2	+	
7/2	3/2	54	18	+	
7/2	5/2	38	50	−	
7/2	7/2	14	98	−	work in progress
4	0	40	0	+	with Jesi Goodman

T	Y	a	b	$\delta\rho$
1/2	1/2	2	2	0
1	0	4	0	+
1	1	4	8	−
3/2	1/2	14	2	+
3/2	3/2	6	18	−
2	0	12	0	+
2	1	20	8	+
2	2	8	32	−
5/2	1/2	34	2	+
5/2	3/2	26	18	+
5/2	5/2	10	50	−
3	0	24	0	+
3	1	44	8	+
3	2	32	32	0
3	3	12	72	−
7/2	1/2	62	2	+
7/2	3/2	54	18	+
7/2	5/2	38	50	−
7/2	7/2	14	98	−
4	0	40	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	$\delta\rho$
1/2	1/2	2	2	0
1	0	4	0	+
1	1	4	8	−
3/2	1/2	14	2	+
3/2	3/2	6	18	−
2	0	12	0	+
2	1	20	8	+
2	2	8	32	−
5/2	1/2	34	2	+
5/2	3/2	26	18	+
5/2	5/2	10	50	−
3	0	24	0	+
3	1	44	8	+
3	2	32	32	0
3	3	12	72	−
7/2	1/2	62	2	+
7/2	3/2	54	18	+
7/2	5/2	38	50	−
7/2	7/2	14	98	−
4	0	40	0	+

Include both reps with $v_1 = v_2$:

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

$\sum a = 20$

$\sum b = 20$

T	Y	a	b	$\delta\rho$
1/2	1/2	2	2	0
1	0	4	0	+
1	1	4	8	−
3/2	1/2	14	2	+
3/2	3/2	6	18	−
2	0	12	0	+
2	1	20	8	+
2	2	8	32	−
5/2	1/2	34	2	+
5/2	3/2	26	18	+
5/2	5/2	10	50	−
3	0	24	0	+
3	1	44	8	+
3	2	32	32	0
3	3	12	72	−
7/2	1/2	62	2	+
7/2	3/2	54	18	+
7/2	5/2	38	50	−
7/2	7/2	14	98	−
4	0	40	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	$\delta\rho$
1/2	1/2	2	2	0
1	0	4	0	+
1	1	4	8	−
3/2	1/2	14	2	+
3/2	3/2	6	18	−
2	0	12	0	+
2	1	20	8	+
2	2	8	32	−
5/2	1/2	34	2	+
5/2	3/2	26	18	+
5/2	5/2	10	50	−
3	0	24	0	+
3	1	44	8	+
3	2	32	32	0
3	3	12	72	−
7/2	1/2	62	2	+
7/2	3/2	54	18	+
7/2	5/2	38	50	−
7/2	7/2	14	98	−
4	0	40	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!

Is there a common piece of phenomenology that we can use to constrain the exotic $\delta M_{W,Z}^2$ in ALL of these?

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

Physical spectrum:

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

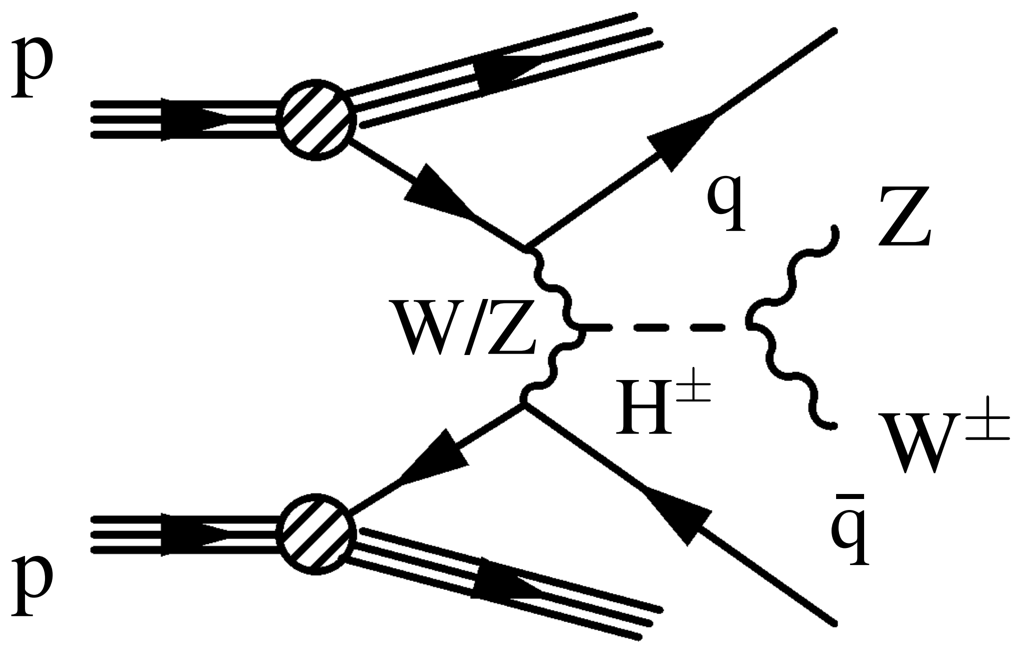
Bi-triplet: $3 \otimes 3 \to 1 \oplus 3 \oplus 5$

- Two custodial singlets mix $\to h$, H m_h, m_H, angle α
  - Usually identify $h = h(125)$
- 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 $\propto$ $\sin\theta_H \equiv s_H = \sqrt{8} v_\chi / v_{\mathrm{SM}}$
  - $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

Smoking-gun processes:

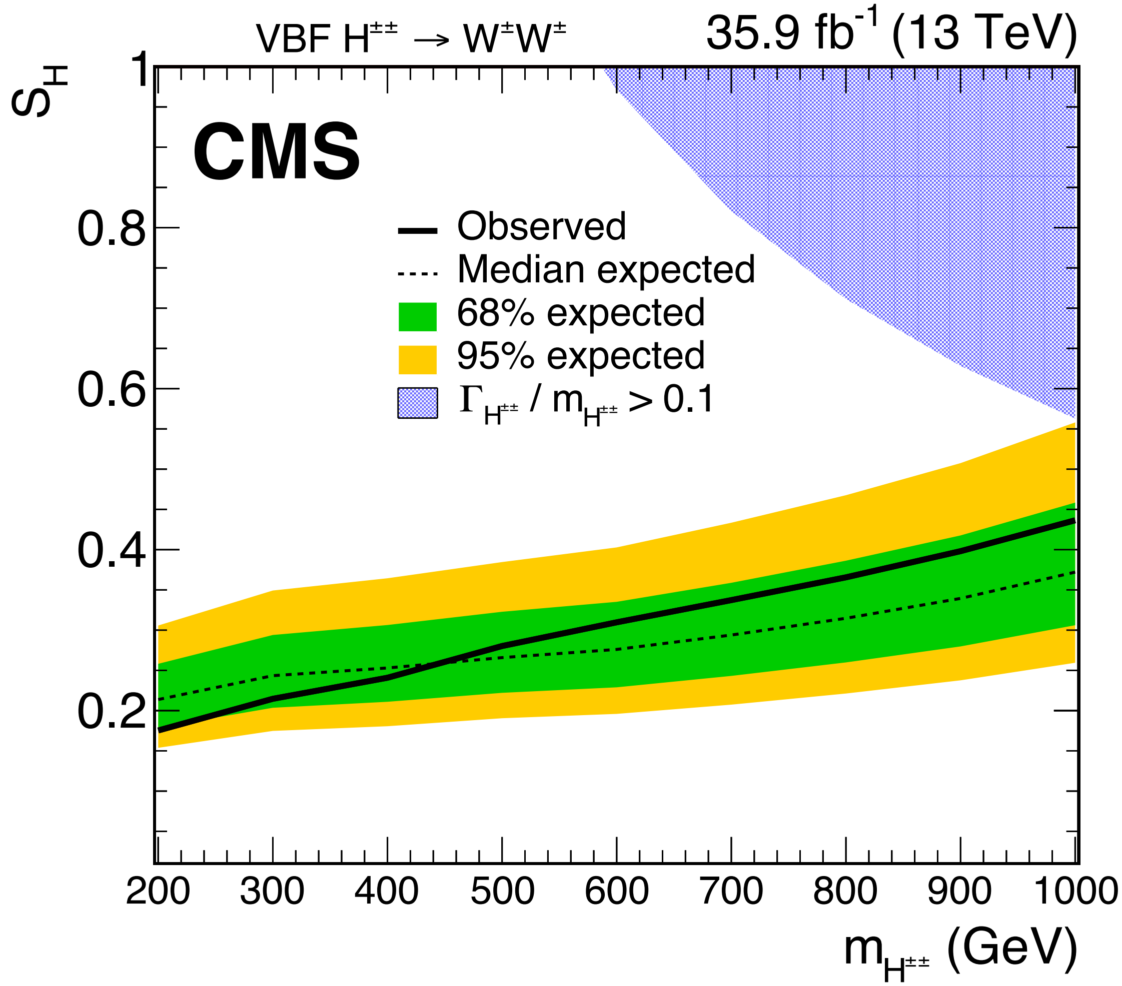
VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ — VBF + like-sign dileptons + MET

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

Most stringent constraint: VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ CMS, arXiv:1709.05822



Also ATLAS + CMS searches for VBF $H_5^\pm \to W^\pm Z$

For $m_{H^{++}} > 1000$ GeV, theory upper bound on s_H from unitarity of quartic couplings takes over $\Rightarrow$ $s_H \leq 0.5$ for $m_{H^{++}} > 1000$ GeV $\Rightarrow$ $\delta M^2_{W,Z} \lesssim 25\%$.

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

Probed by direct searches in GM model: $\sim 4\% - 20\%$

Compare a single exotic multiplet + loop effects: $\delta M^2_{W,Z} \lesssim$ 3.5–7%.

Generalized Georgi-Machacek models

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

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

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!

Common feature is the custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$

Key $H_5^{\pm\pm} W_\mu^\mp W_\nu^\mp$ coupling $= i g_{\mu\nu} (2\sqrt{2} M_W^2/v) C_n s_H$
GM: $C_3 = 1$;
Generalized GMs: $C_4 = \sqrt{12/5}$, $C_5 = \sqrt{21/5}$, $C_6 = \sqrt{32/5}$.

VBF $\to H_5^{\pm\pm}$ cross section $\propto C_n^2 s_H^2$; C_n grows with increasing n.
Constraints on $\delta M_{W,Z}^2$ in GGMs tighter by a factor of C_n^2!

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

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

pheno: Alvarado, Lehman & Ostdiek, 1404.3208

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

Spectrum:

$\mathrm{Re}\phi^0, \mathrm{Re}\chi^0 \to h, H$

$\mathrm{Im}\phi^0, \mathrm{Im}\chi^0 \to G^0, A^0$

$\phi^+, \chi^{+1}, \chi^{-1*} \to G^+, H_1^+, H_2^+$

$\chi^{+2} = H^{++}$ (etc.)

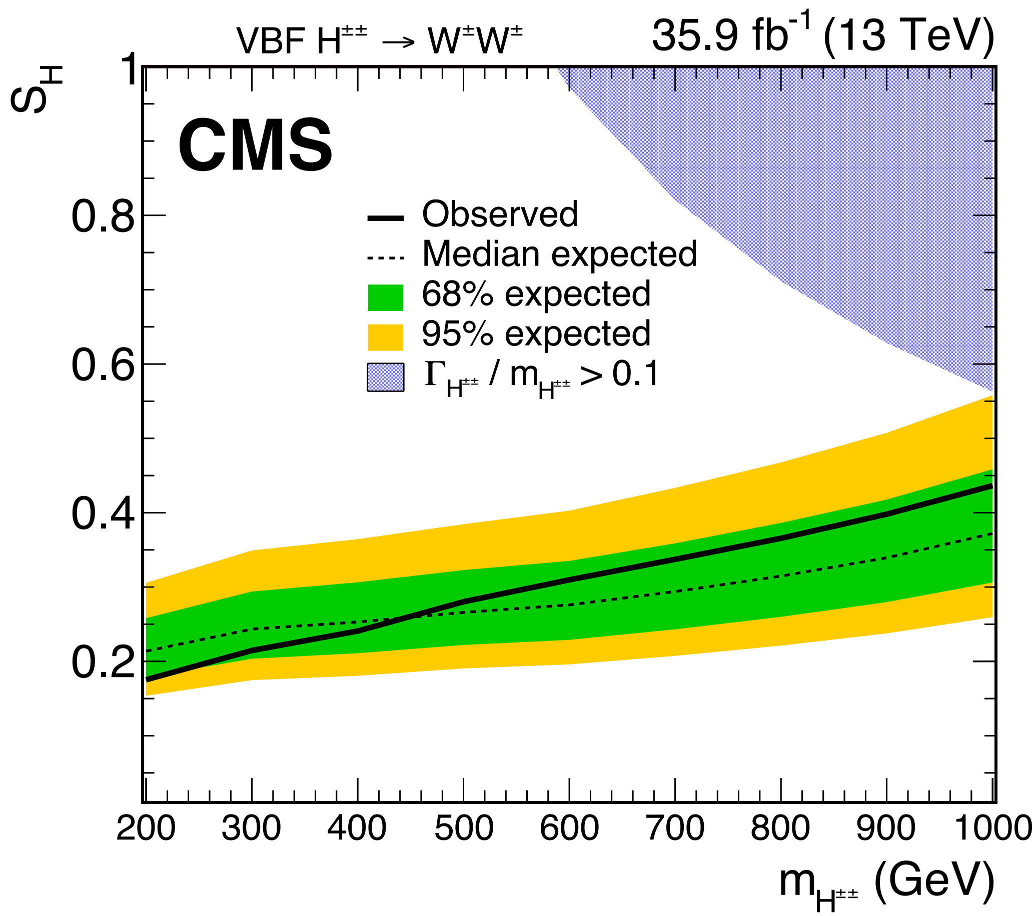
$\rho = 1$, yet there is no custodial symmetry in the scalar spectrum!

Only $H^{++} = \chi^{+2}$ is entirely analogous to GM model.
Apply direct search for VBF $H^{\pm\pm} \to W^\pm W^\pm$: $C_7 = \sqrt{15/2} > 1$

Harris & HEL, 1703.03832

Constraint on $\delta M^2_{W,Z}$ again stronger than GM.

LHC searches for VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ (and VBF $\to H_5^\pm \to W^\pm Z$) start at $m_5 = 200$ GeV, so that the final-state vector bosons can be taken on-shell.



CMS, arXiv:1709.05822

Also ATLAS + CMS searches for VBF $H_5^\pm \to W^\pm Z$

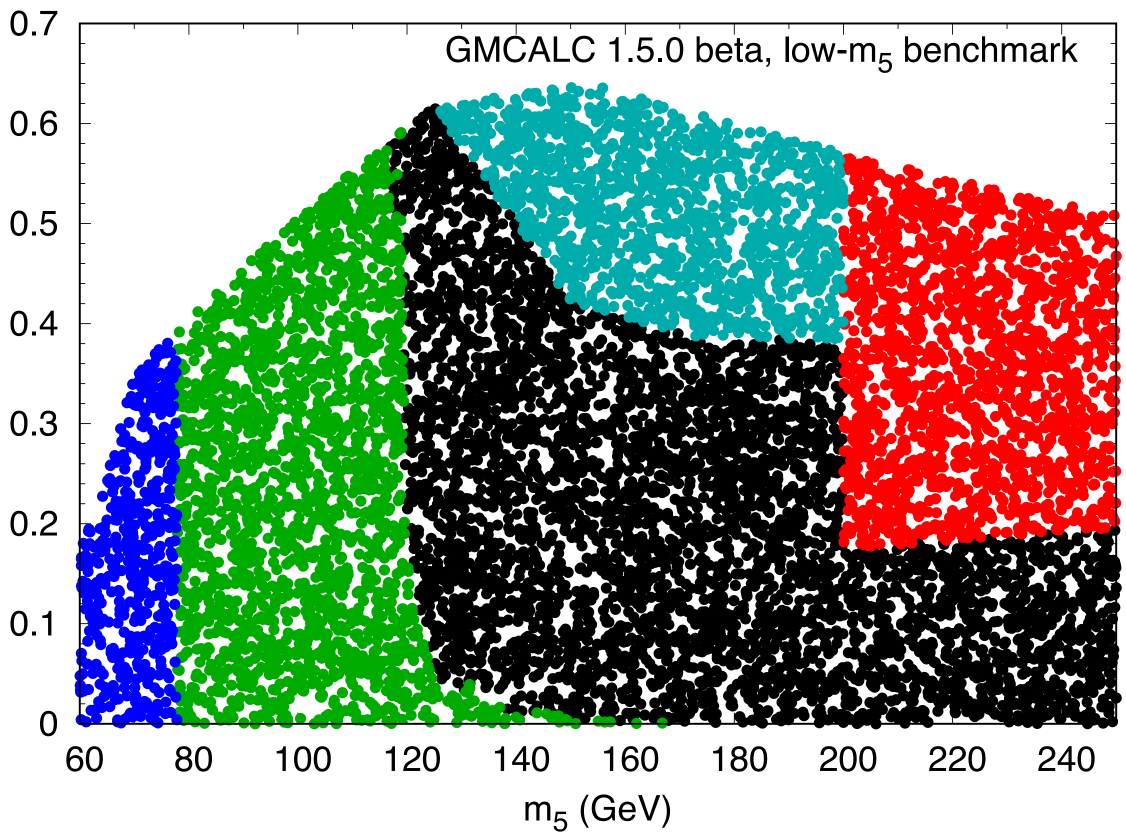
What about $H_5^{\pm\pm}$ below 200 GeV?

For $H_5^{\pm\pm}$ below 200 GeV, constraints are mainly theory-recast.

Plot: new "low-m_5" benchmark in GM model

Ben Keeshan, LHC HXSWG WG3 Extended Scalars meeting, 2018-10-24

Recast ATLAS Run1 VBF $\to W^\pm W^\pm$, 1407.5053



(Preliminary)

CMS VBF $\to H^{\pm\pm} \to W^\pm W^\pm$

1709.05822

Allowed

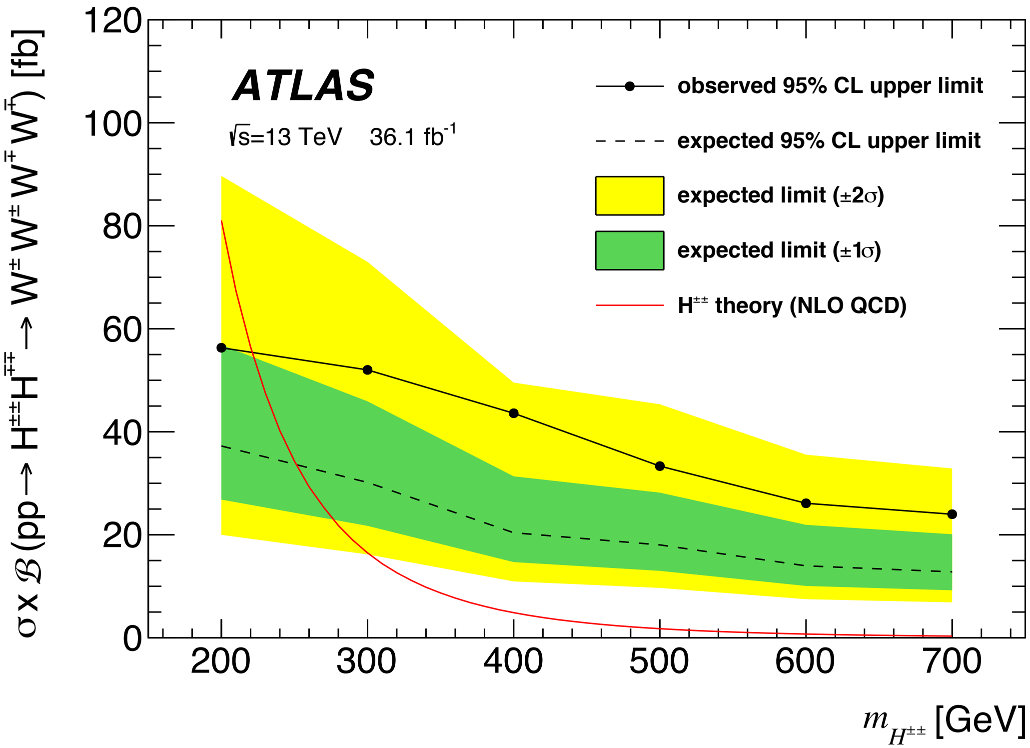
Recast ATLAS Run1 dimuons, 1412.7603, 1502.01275

Recast ATLAS Run1 $\gamma\gamma$ resonance, GMCALC 1.5.0 beta (Keeshan, HEL, Wu, in prep)

$s_H \lesssim 0.6 \to$ fraction of $M_{W,Z}^2 \lesssim 36\%$ still allowed in GM model!

Best way to probe $H_5^{\pm\pm}$ below 200 GeV:

Drell-Yan $q\bar{q} \to H_5^{++} H_5^{--}$ (xsec independent of s_H),
with $H_5^{\pm\pm} \to W^\pm W^\pm$ (BR = 1 unless $H_3^\pm$ is significantly lighter).



Search done for the first time in Run 2! But only for $H_5^{\pm\pm}$ mass above 200 GeV: W's on shell.

ATLAS, arXiv:1808.01899

Extending to masses below 200 GeV (with offshell W's) could exclude the entire low-m_5 region! Large xsec! Very promising!

Conclusions and outlook

Exotic contributions to electroweak symmetry breaking are quite strongly constrained by precision electroweak (ρ_0 parameter).
- Including cancellations against 1-loop contributions, exotic vev can contribute at most $\delta M_{W,Z}^2 \lesssim 3.5$–7%. (preliminary)

Exception is exotic models in which $\rho_0 = 1$ at tree level:
Georgi-Machacek, generalized GM, scalar septet.

Key direct search in all these models is VBF $\to H^{\pm\pm} \to W^{\pm}W^{\pm}$:
xsec bound directly constrains $\delta M_{W,Z}^2$ (as a function of $m_{H^{\pm\pm}}$).
- $\delta M_{W,Z}^2 \lesssim 25\%$ in GM model for $m_{H^{\pm\pm}} > 200$ GeV; others more constrained.
- More luminosity will continue to push this down.

Low-mass region ($m_{H^{\pm\pm}} < 200$ GeV) still allows $\delta M_{W,Z}^2 \lesssim 36\%$; could be fully tested by Drell-Yan $pp \to H^{++}H^{--} \to W^+W^+W^-W^-$, taking into account off-shell W's.

BACKUP

How much can these contribute to EWSB?

J. Goodman & HEL, in progress

Multiplets with $Y = 0$:

$T_{\text{tree}} > 0$, $T_{\text{loop}} \geq 0$, $S_{\text{loop}} \propto Y = 0$: loop effect can't ease constraint. Limits same as tree level.*

Multiplets with $Y \neq 0$ and $T_{\text{tree}} > 0$:

Take advantage of correlation between S and T to try to ease the constraint.

T	Y	$\delta\rho$	$\delta M_W^2\|_{\text{max}}$	$\delta M_Z^2\|_{\text{max}}$
*3/2	1/2	+	0.112%	0.016%
2	1	+	0.207%	0.083%
*5/2	1/2	+	0.111%	0.007%
5/2	3/2	+	0.442%	0.307%
3	1	+	0.159%	0.029%
*7/2	1/2	+	0.114%	0.004%
7/2	3/2	+	0.208%	0.069%

Compare tree-level
0.253%, 0.175%

*To be revisited including operators that mix T^3 eigenstates: in progress.

How much can these contribute to EWSB?

J. Goodman & HEL, in progress

Multiplets with $Y \neq 0$ and $T_{\text{tree}} < 0$:

$T_{\text{loop}} > 0$: can cancel negative T_{tree}!

Size of cancellation ultimately limited by S_{loop} generated at the same time.

T	Y	$\delta\rho$	$\delta M_W^2\|_{\text{max}}$	$\delta M_Z^2\|_{\text{max}}$
1	1	–	3.609%	6.967%
3/2	3/2	–	0.755%	2.232%
2	2	–	0.258%	1.025%
5/2	5/2	–	0.116%	0.578%
3	3	–	0.060%	0.361%
7/2	5/2	–	0.930%	1.221%
7/2	7/2	–	0.033%	0.234%

Preliminary

Compare tree-level
0.014%, 0.027%

The bottom line: a *single* exotic multiplet can contribute up to $\sim$0.25% of $M_{W,Z}^2$ at tree level; 3.5–7% when maximal cancellations against loop effects are allowed.

Can we get around this by model-building?

Introduction and motivation

The electroweak part of the Standard Model is an SU(2)$\times$U(1) gauge theory: Weinberg 1967

- Isospin SU(2)$_L$ gauge bosons W^a_μ, $a = 1, 2, 3$

- Hypercharge U(1)$_Y$ gauge boson B_μ

- Chiral fermions, left-handed transform as doublets under SU(2)$_L$, right-handed as singlets, hypercharge quantum numbers assigned according to electric charge $Q = T^3 + Y$.

Gauge invariance requires that the gauge bosons are massless.

To account for massive $W^\pm$ and Z, incorporate the Higgs mechanism of spontaneous symmetry breaking.

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 $\langle\Phi^0\rangle^2$)

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

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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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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"

"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

Custodial-fiveplet is fermiophobic; couples to VV:

$$
\begin{aligned}
H_5^0 W_\mu^+ W_\nu^- : &\qquad -i\frac{2M_W^2}{v}\frac{g_5}{\sqrt{6}}g_{\mu\nu}, \\
H_5^0 Z_\mu Z_\nu : &\qquad i\frac{2M_Z^2}{v}\sqrt{\frac{2}{3}}g_5 g_{\mu\nu}, \\
H_5^+ W_\mu^- Z_\nu : &\qquad -i\frac{2M_W M_Z}{v}\frac{g_5}{\sqrt{2}}g_{\mu\nu}, \\
H_5^{++} W_\mu^- W_\nu^- : &\qquad i\frac{2M_W^2}{v}g_5 g_{\mu\nu},
\end{aligned}
$$

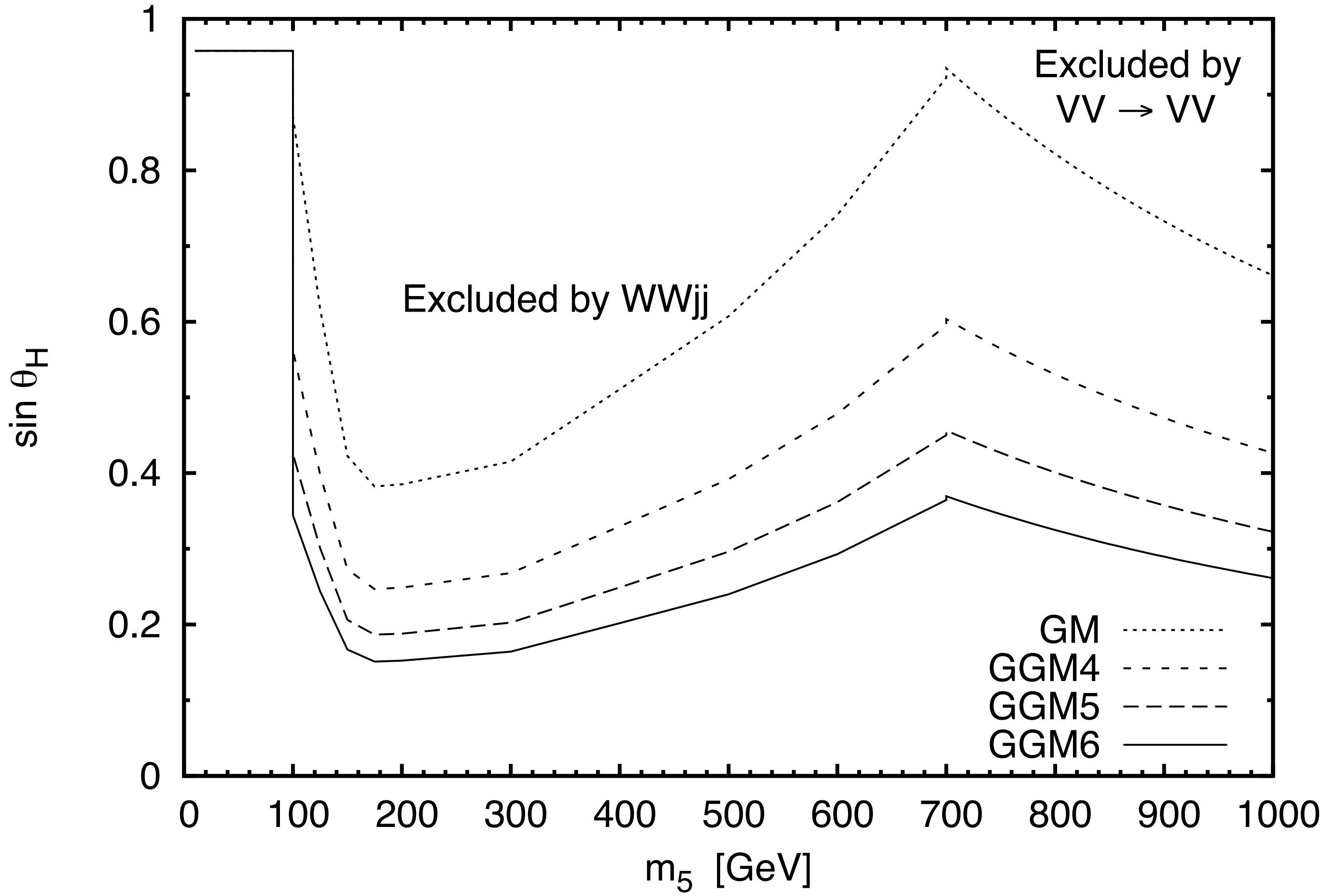
$$
\begin{aligned}
\text{GM3}: &\qquad g_5 = \sqrt{2}s_H \\
\text{GGM4}: &\qquad g_5 = \sqrt{24/5}s_H \\
\text{GGM5}: &\qquad g_5 = \sqrt{42/5}s_H \\
\text{GGM6}: &\qquad g_5 = \sqrt{64/5}s_H
\end{aligned}
$$

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

All VBF and unitarity constraints stronger than original GM!

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

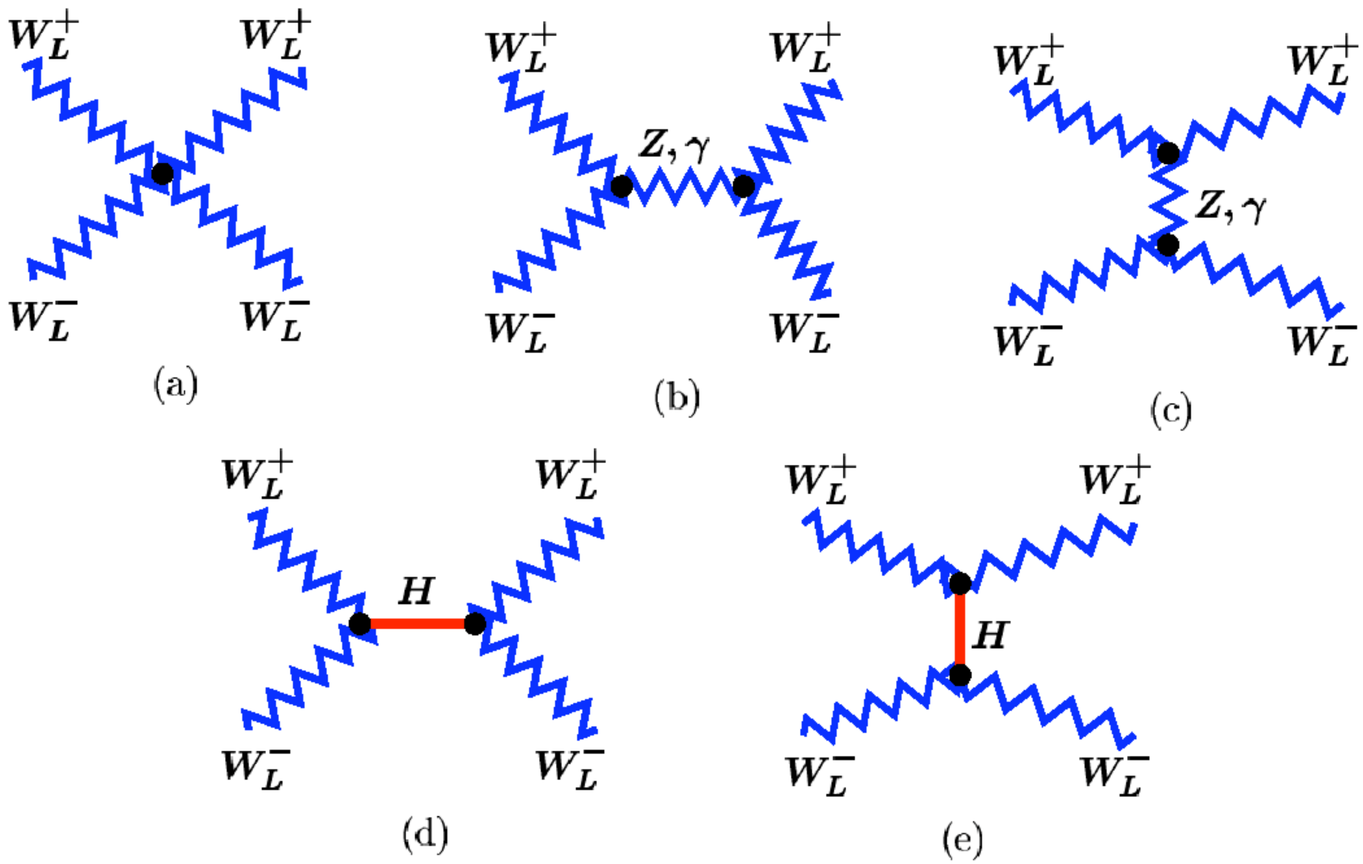
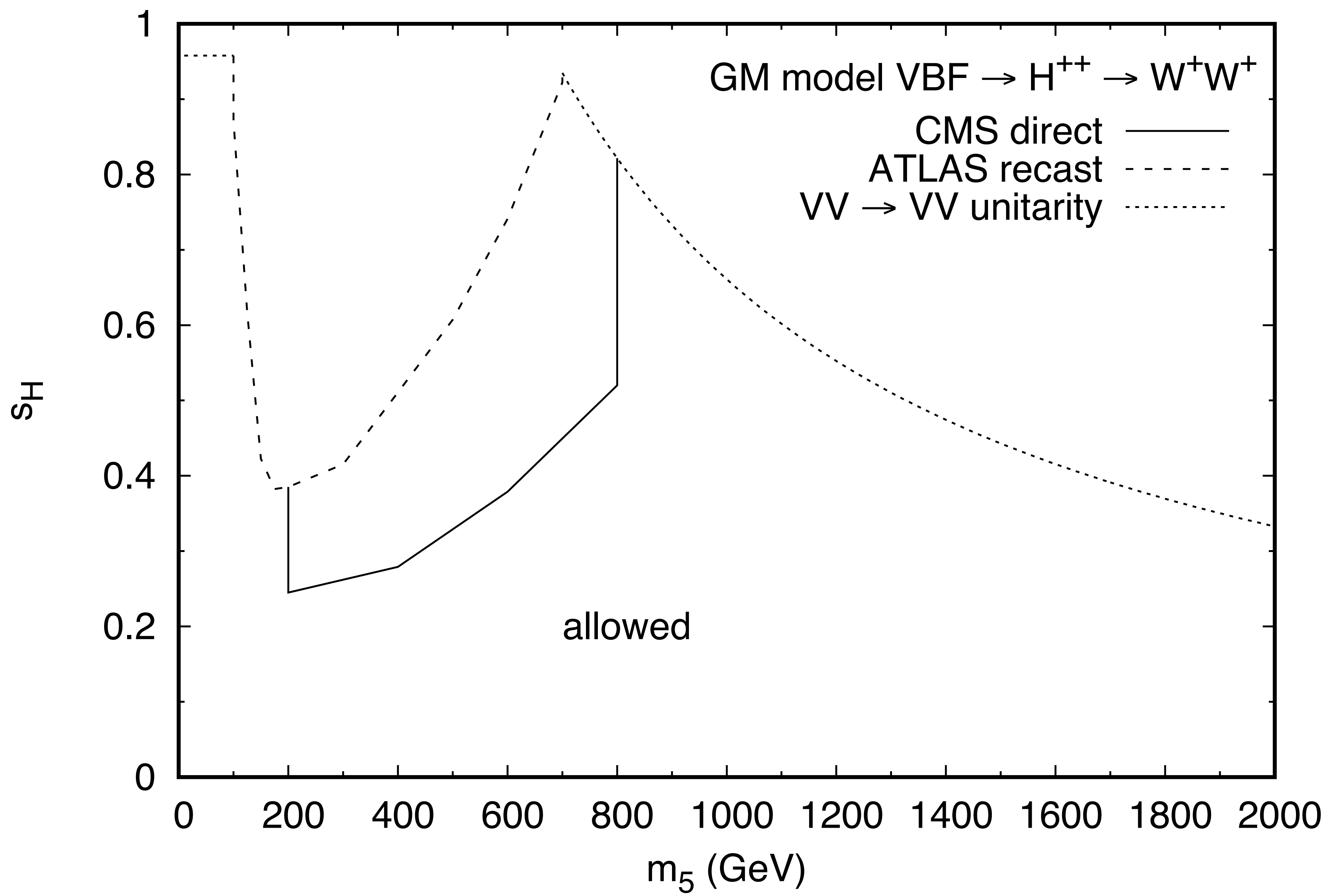


figure: S. Chivukula

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!



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

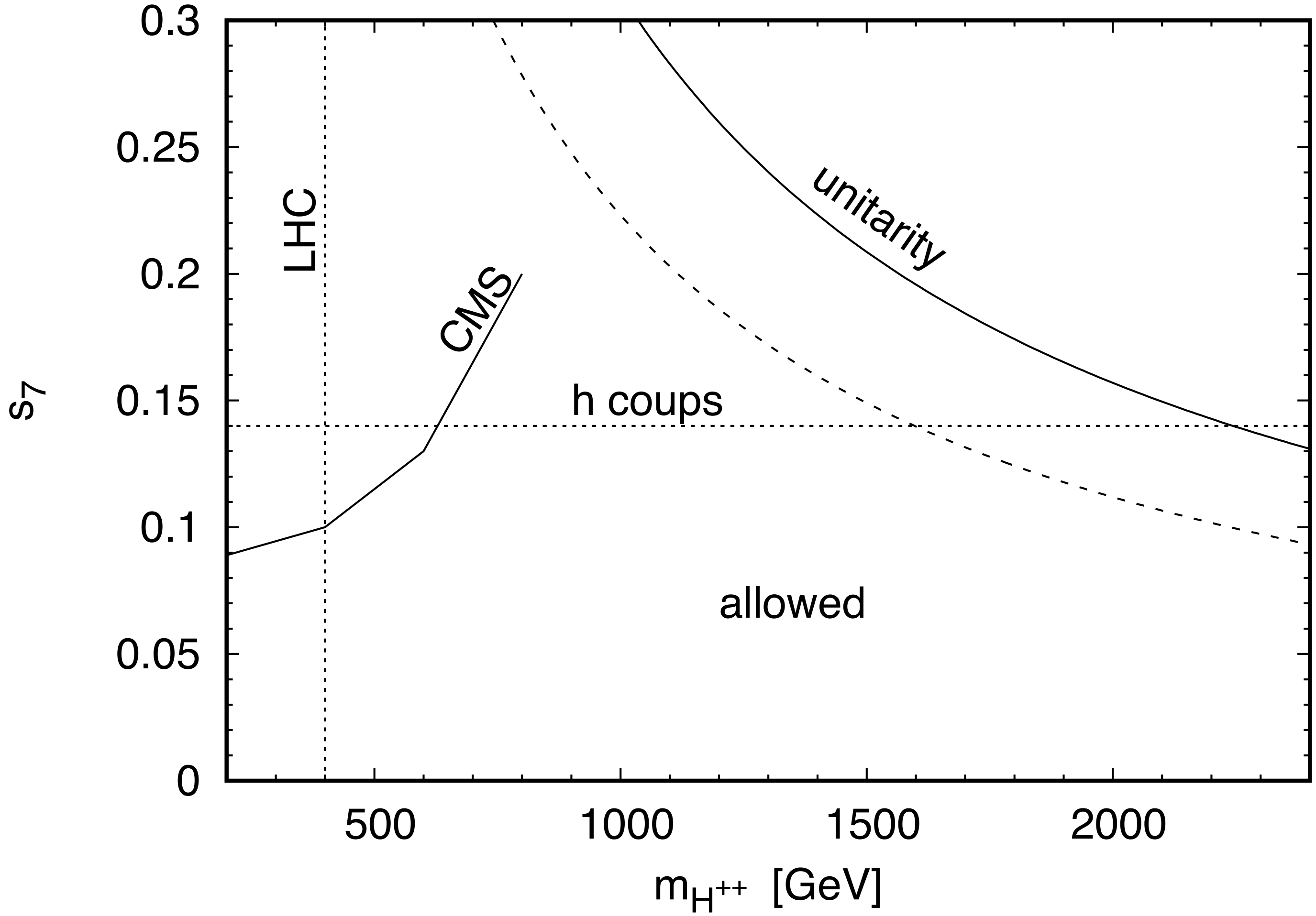
$$H^{++} W_\mu^- W_\nu^- : \quad i \frac{2 M_W^2}{v} \sqrt{15} s_7 g_{\mu\nu},$$

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

Detailed pheno study in Alvarado, Lehman & Ostdiek, 1404.3208:
- h^0 couplings $\rightarrow$ upper bound on septet vev $\Leftarrow$
- LHC SUSY searches (2SSL, 3L) + inclusive septet pair production $\rightarrow$ lower bound on common septet mass

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

CMS VBF $\to H^\pm \to W^\pm W^\pm$ and $VV \to VV$ unitarity constraint



Harris & HEL, 1703.03832

$VV \to VV$ unitarity bound:

solid H^{++} only;

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

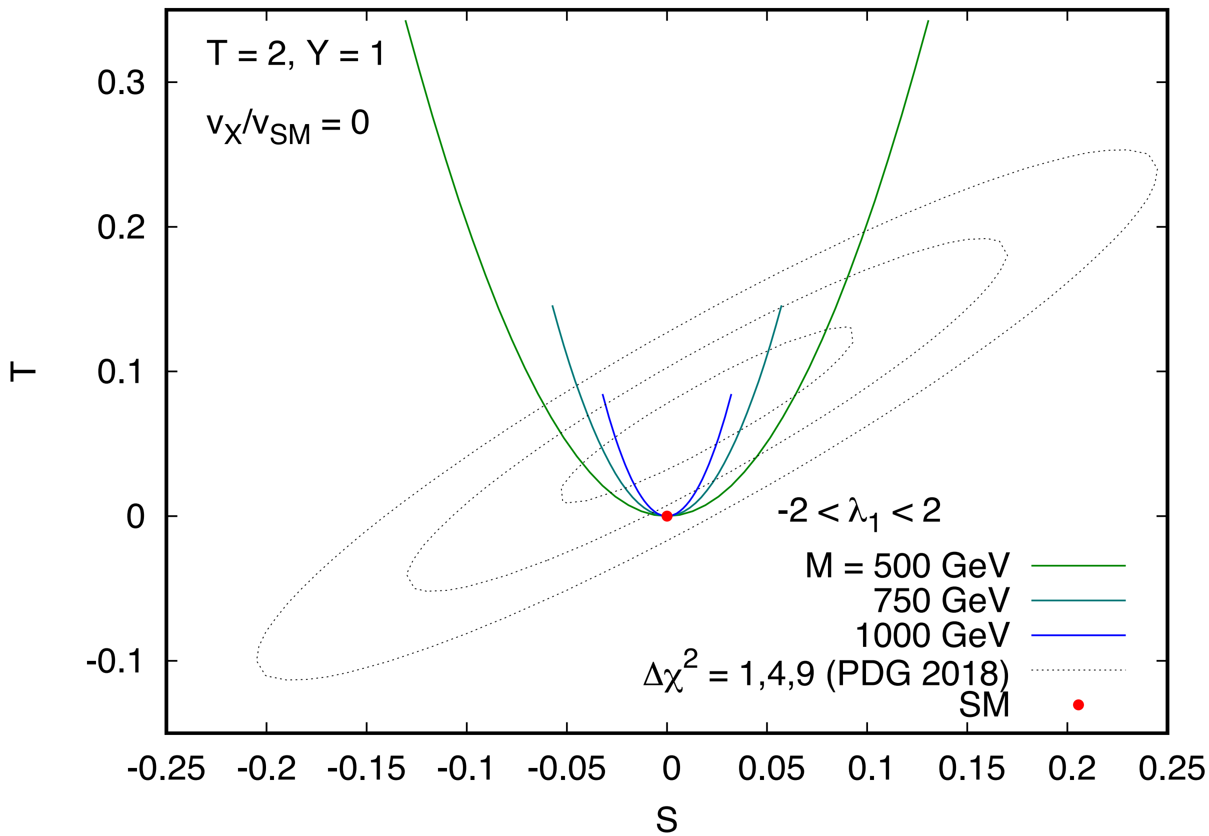
Fraction of M_W^2 and M_Z^2 from exotic vev $\equiv s_7^2 < 2\%$!

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

Plot based on LHC Run 1 constraints only – now even stronger.

Results: multiplets with $T_{\rm tree} > 0$ and $Y \neq 0$

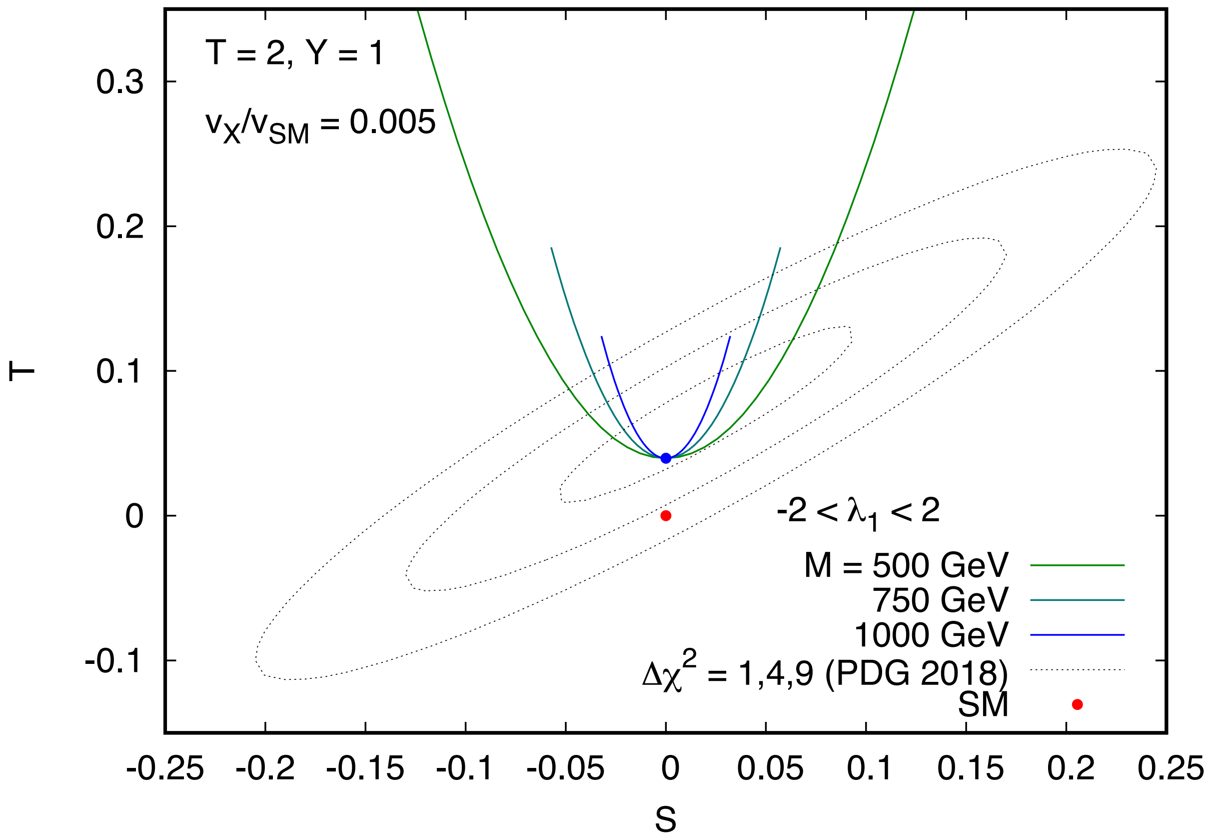
Take advantage of correlation between S and T to try to ease the constraint.



$$S_{\rm loop} \sim -\frac{\delta m^2}{M^2} \qquad T_{\rm loop} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\rm loop} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Results: multiplets with $T_{\text{tree}} > 0$ and $Y \neq 0$

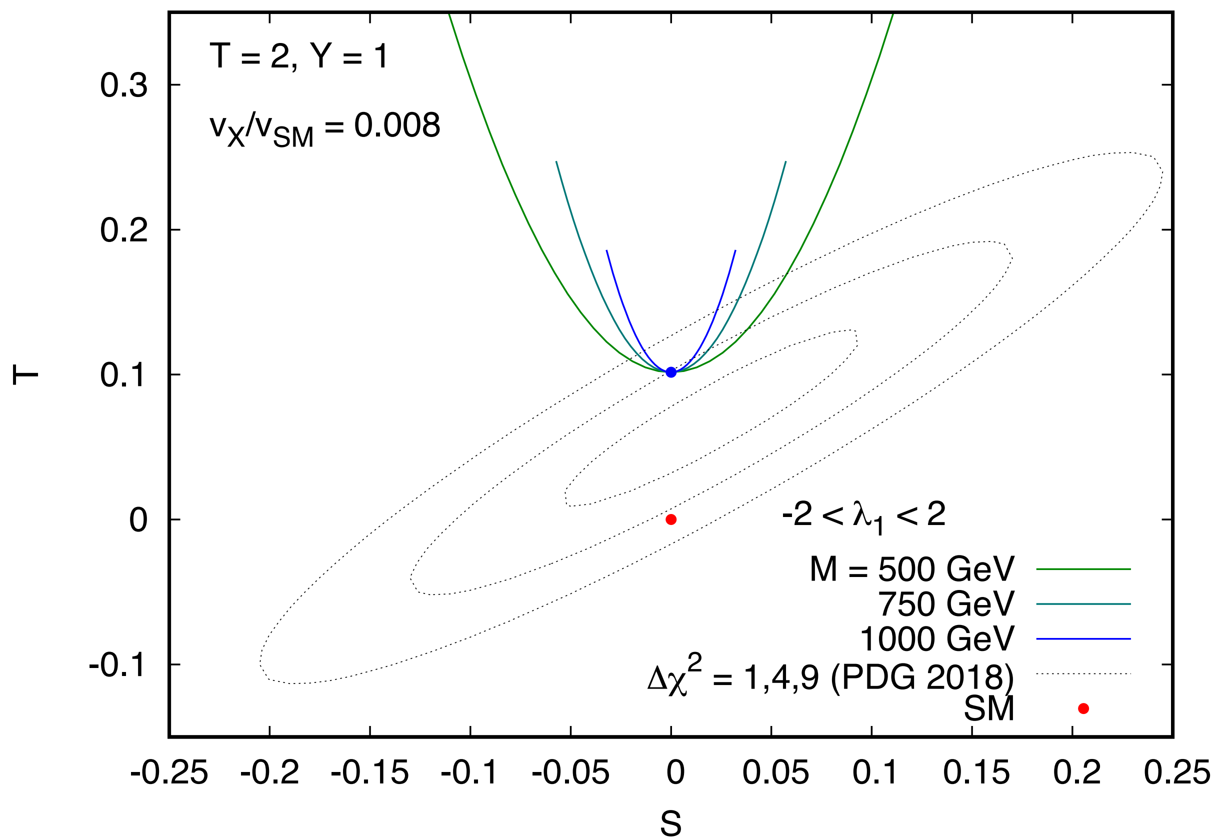
Take advantage of correlation between S and T to try to ease the constraint.



$$S_{\text{loop}} \sim -\frac{\delta m^2}{M^2} \qquad T_{\text{loop}} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\text{loop}} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Results: multiplets with $T_{\text{tree}} > 0$ and $Y \neq 0$

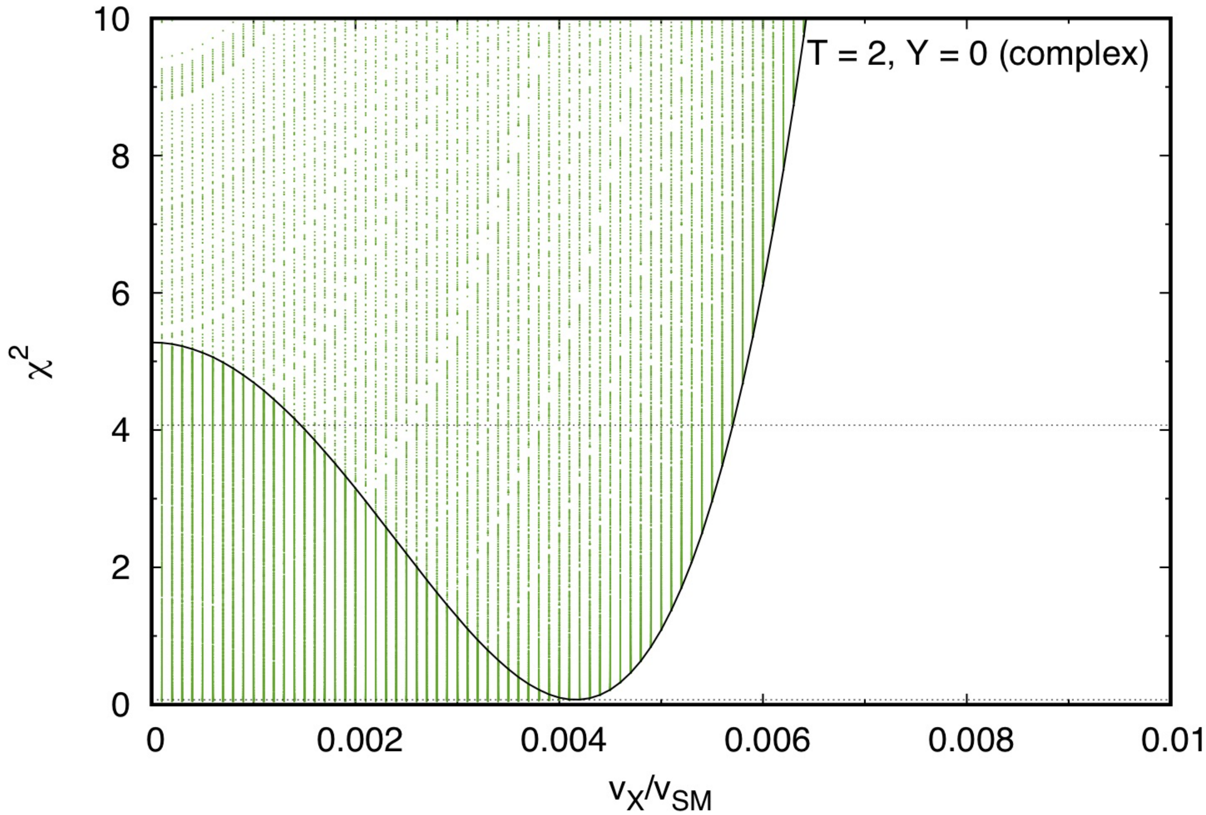
Take advantage of correlation between S and T to try to ease the constraint.



$$S_{\text{loop}} \sim -\frac{\delta m^2}{M^2} \qquad T_{\text{loop}} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\text{loop}} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Results: complex multiplets with $Y = 0$ ($T_{\rm tree} > 0$)

$T_{\rm tree} > 0$, $T_{\rm loop} \geq 0$, $S_{\rm loop} \propto Y = 0$:
Bound is loosest when δm^2 splitting $= 0$.



J. Goodman & HEL, in progress

Upper bounds unchanged from tree-level: $\delta M_W^2 \leq 0.078\%$.

Results: multiplets with $T_{\text{tree}} > 0$ and $Y \neq 0$

Best to take M^2 as small as possible and λ_1 small and positive to generate positive S_{loop} while minimizing additional positive T_{loop}. (Physically, positive λ_1 means that the member of the multiplet with the highest electric charge is lightest.)

T	Y	$\delta\rho$	$\delta M_W^2\vert_{\text{max}}$	$\delta M_Z^2\vert_{\text{max}}$
*3/2	1/2	+	0.112%	0.016%
2	1	+	0.207%	0.083%
*5/2	1/2	+	0.111%	0.007%
5/2	3/2	+	0.442%	0.307%
3	1	+	0.159%	0.029%
*7/2	1/2	+	0.114%	0.004%
7/2	3/2	+	0.208%	0.069%

Compare tree-level 0.253%, 0.175%

*To be revisited including λ_2 effect mixing T^3 eigenstates: in progress

J. Goodman & HEL, in progress

Results: multiplets with $T_{\rm tree} < 0$

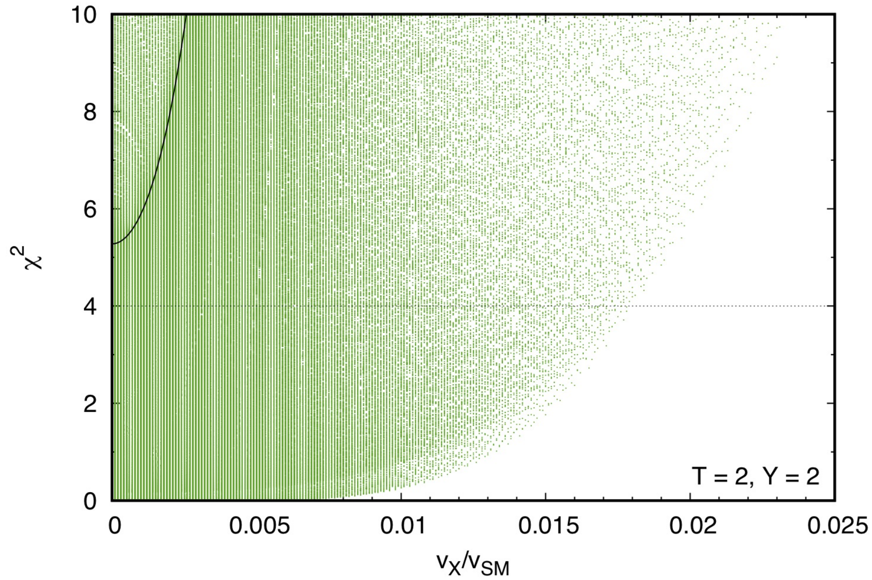
$T_{\rm loop} > 0$: can cancel negative $T_{\rm tree}$!

Ultimately $S_{\rm loop}$ generated at the same time will limit size of cancellation, along with perturbative unitarity bound on λ_1.

Best to take M^2 rather large and $|\lambda_1|$ as large as possible to maximize $T_{\rm loop}$ while minimizing $S_{\rm loop}$. (Sign of λ_1 doesn't matter much.)

$$S_{\rm loop} \sim Y \times \frac{-\delta m^2}{M^2} \qquad T_{\rm loop} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\rm loop} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

Results: multiplets with $T_{\text{tree}} < 0$



Constraint on the tree-level (renormalized) vev is significantly loosened!

Also, can get $\chi^2 = 0$: models no longer disfavoured by positive central value of T.

T	Y	$\delta\rho$	$\delta M_W^2\|_{\max}$	$\delta M_Z^2\|_{\max}$
1	1	–	3.609%	6.967%
3/2	3/2	–	0.755%	2.232%
2	2	–	0.258%	1.025%
5/2	5/2	–	0.116%	0.578%
3	3	–	0.060%	0.361%
7/2	5/2	–	0.930%	1.221%
7/2	7/2	–	0.033%	0.234%

J. Goodman & HEL, in progress

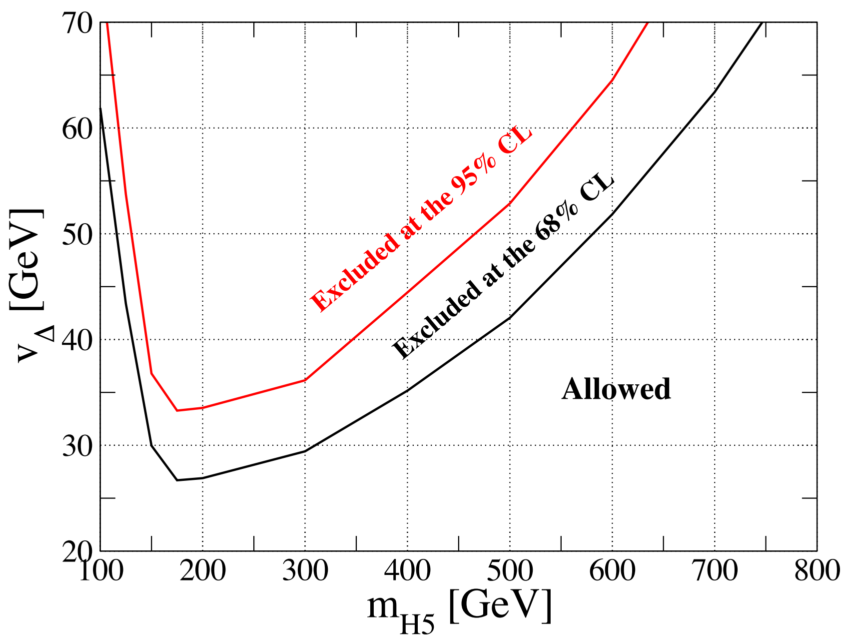
Searches

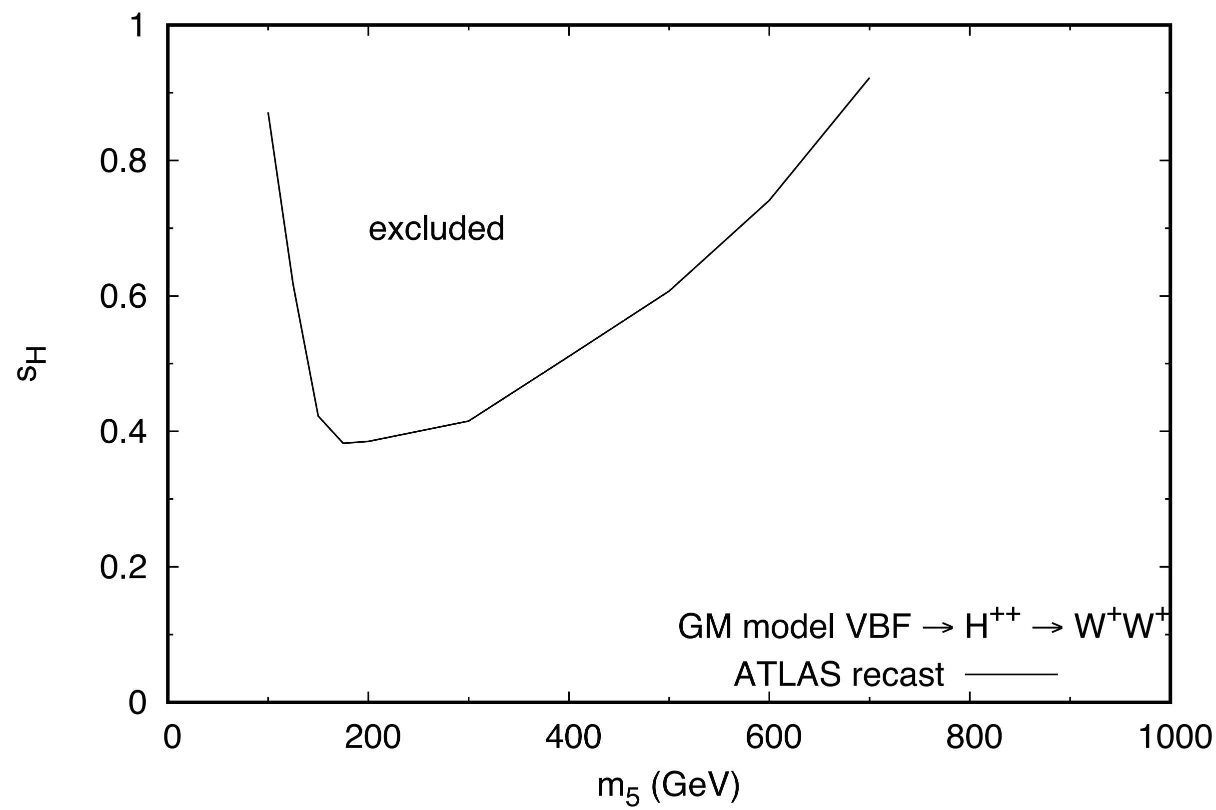
SM VBF $\to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET cross section measurement

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

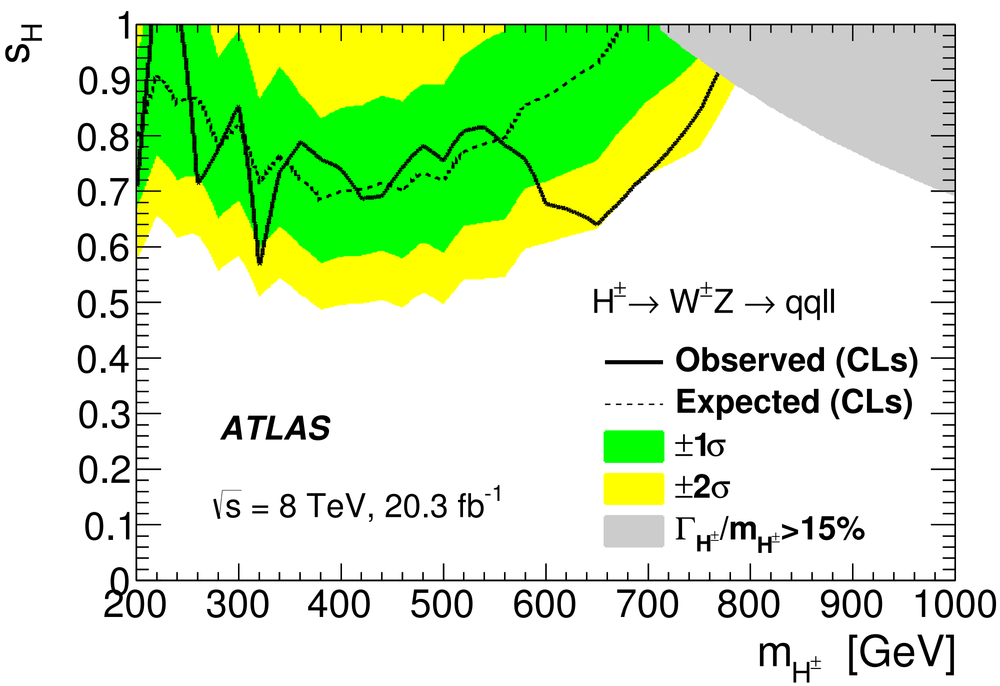


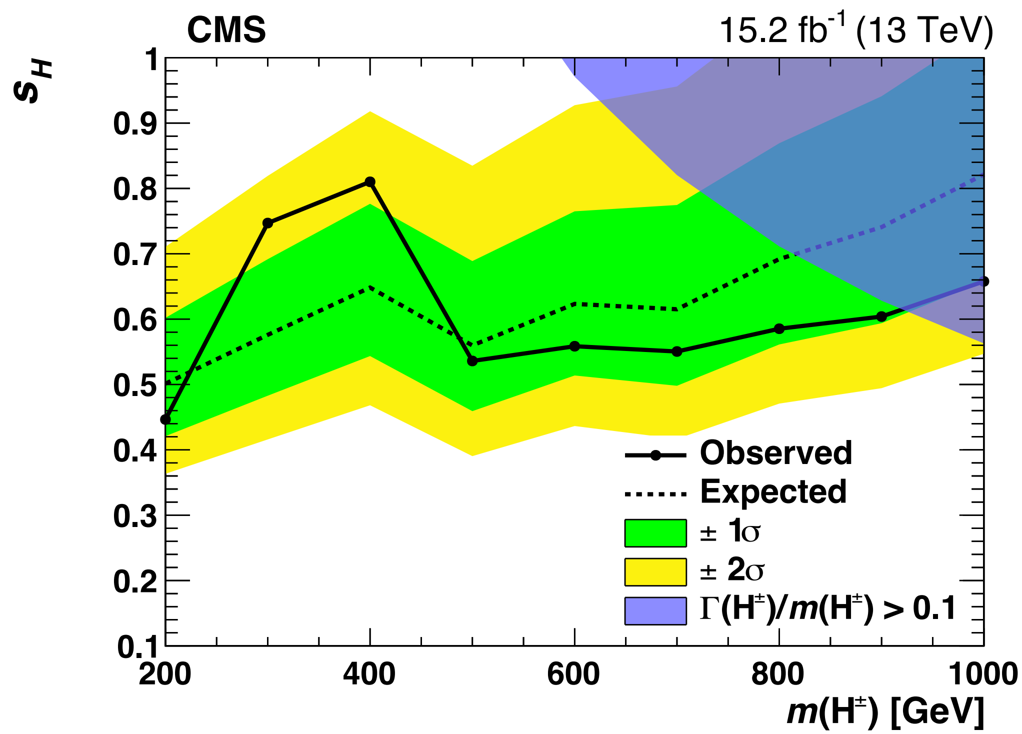


Searches

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

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





ATLAS 1503.04233, PRL 2015

CMS 1705.02942, PRL 2017

(Not yet as constraining as VBF $H_5^{\pm\pm} \to W^\pm W^\pm \to \ell^\pm \ell^\pm$ + MET)