Limits on exotic contributions to electroweak symmetry breaking

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Outline

Introduction and motivation

Exotic electroweak symmetry breaking?

Constraints from precision electroweak data

Some model-building

Constraints from direct searches: $H^{\pm\pm}$!

Conclusions and outlook

Introduction and motivation

The electroweak part of the Standard Model is an SU(2)×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.

Introduction and motivation

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

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?

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:

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

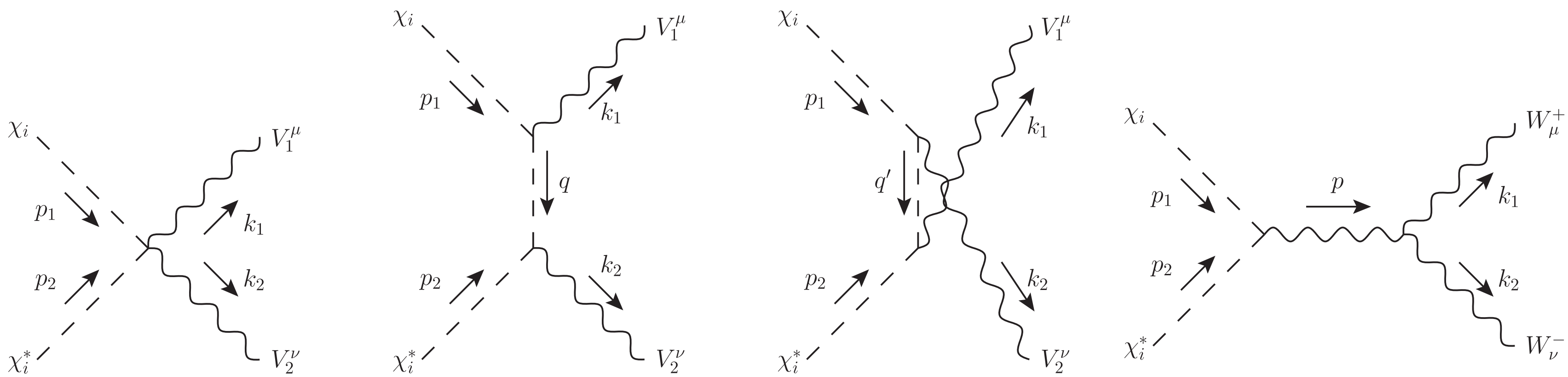
Scattering of longitudinally-polarized Ws & Zs famously used to put upper bound on Higgs mass Lee, Quigg & Thacker 1977

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

Too strong a charge → nonperturbative

How high an isospin is ok?

$\chi\chi \leftrightarrow W_T^a W_T^a$: Hally, HEL, & Pilkington 1202.5073



$$a_0 = \frac{g^2}{16\pi}\frac{(n^2-1)\sqrt{n}}{2\sqrt{3}}$$

complex χ, $n = 2T+1$

- 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

How high an isospin is ok?

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

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

- 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%

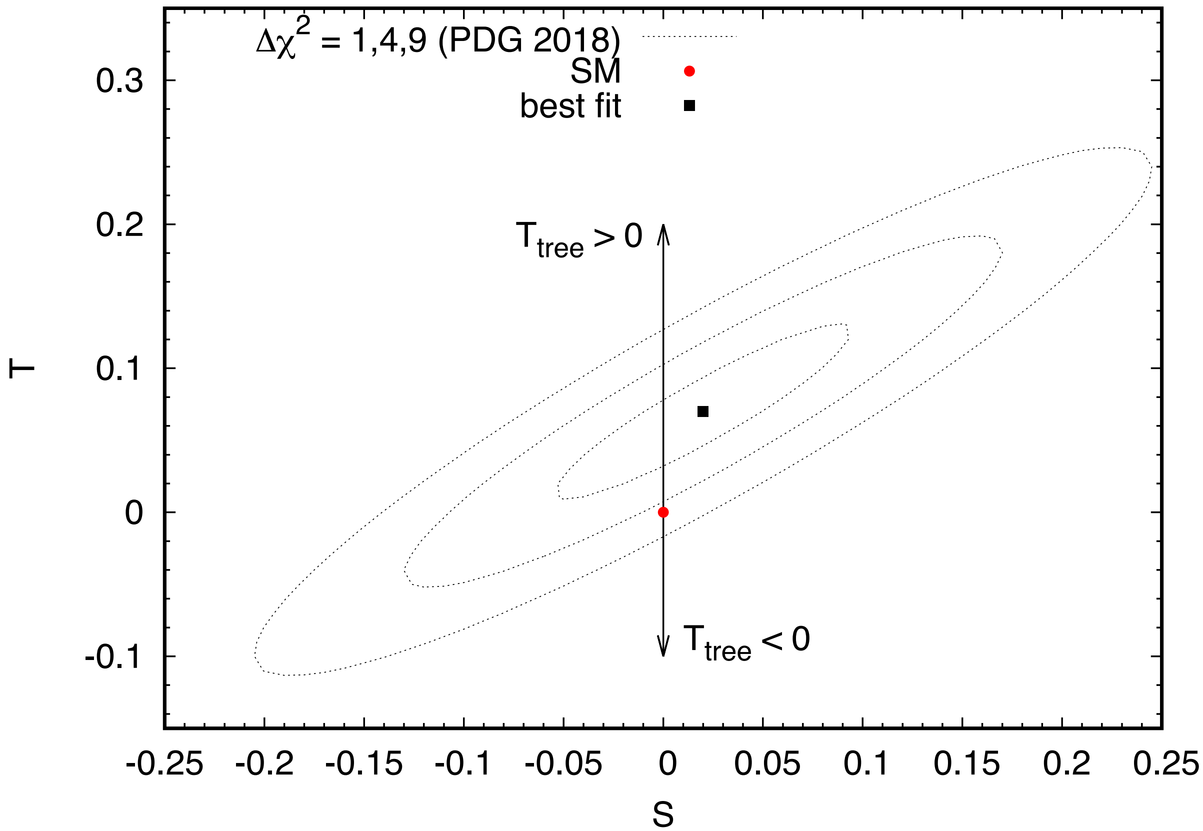
Peskin & Takeuchi, 1990, 1992

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

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

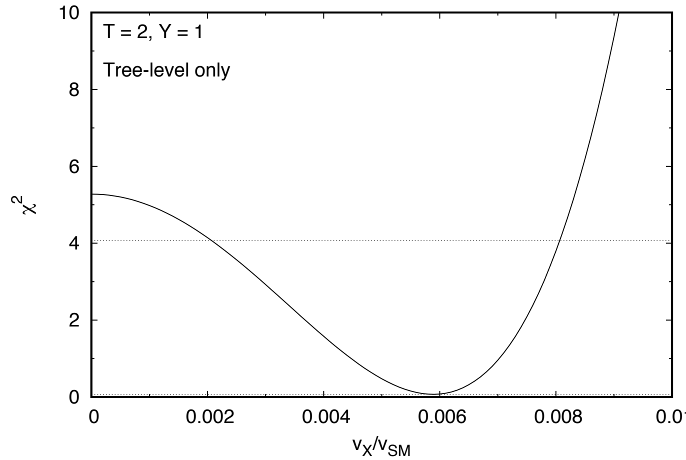
How much can these contribute to EWSB?

Tree-level ρ_0 parameter versus S, T, U

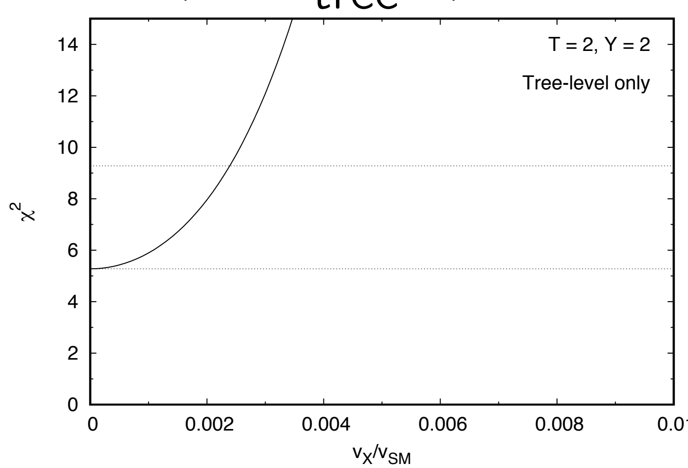


Jesi Goodman & HEL, in progress

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



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



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

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

			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
→ Handle this by constraining renormalized vev (choose counterterm to cancel tadpole).

Full calculation of 1-loop S, T, U in these models is quite involved.
→ Work in a double expansion:
1st order in exotic vev ($T_{\rm tree}$) and 1st order in $\alpha_{\rm EM}$ (1-loop)
Can use 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:

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

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	$\delta\rho$	$\delta M_W^2\vert_{\text{max}}$	$\delta M_Z^2\vert_{\text{max}}$
*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.

How much can these contribute to EWSB?

J. Goodman & HEL, in progress

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

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

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

T	Y	$\delta\rho$	$\delta M_W^2\|_{\rm max}$	$\delta M_Z^2\|_{\rm max}$
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%

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?

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!

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

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

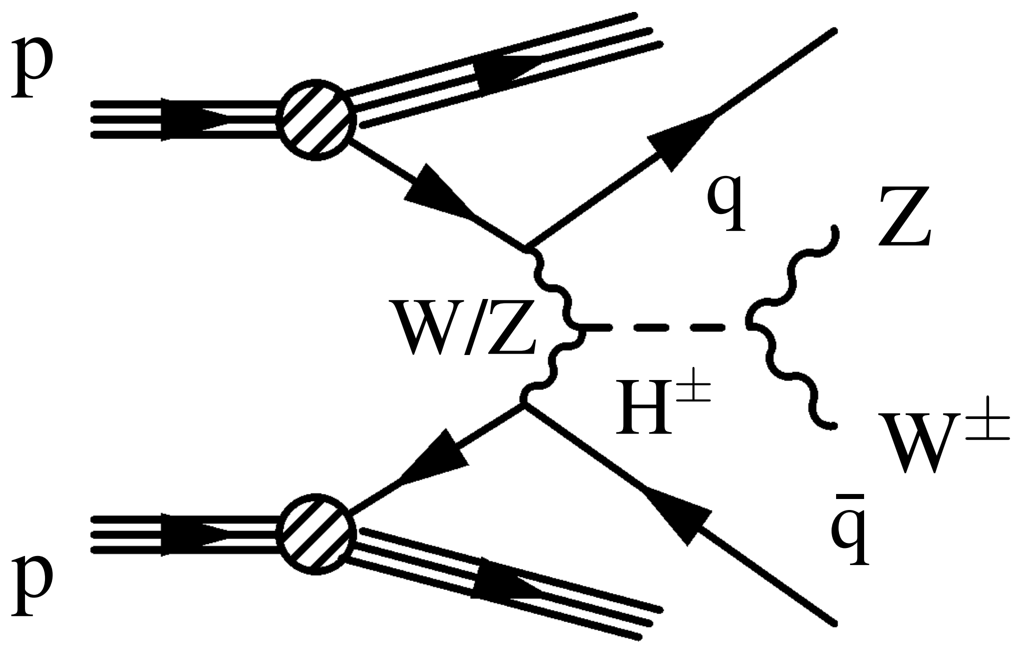
  Fermiophobic; H_5VV couplings $\propto s_H \equiv \sqrt{8} v_\chi / v_{\mathrm{SM}}$

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

Smoking-gun processes:

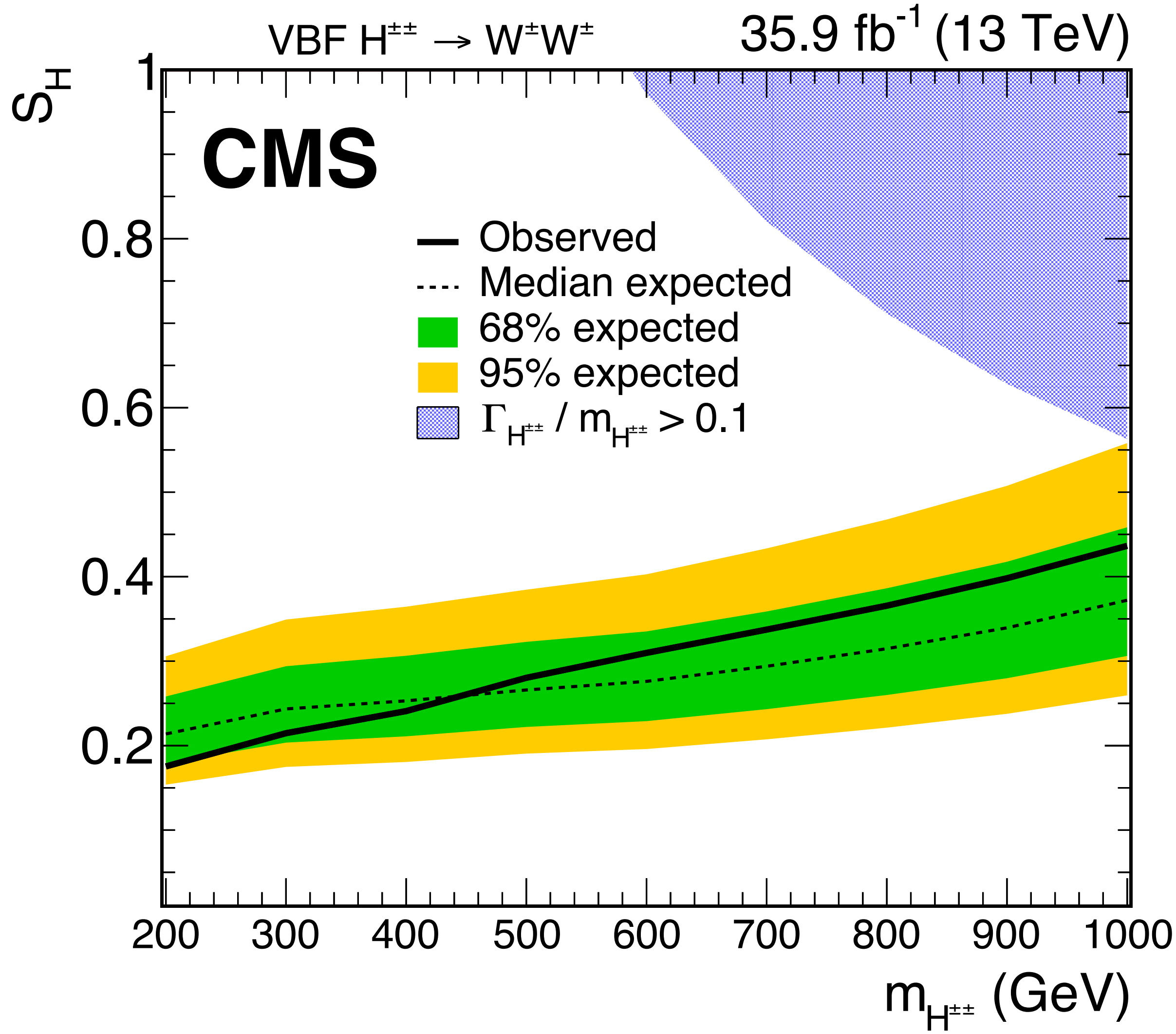
VBF $\to H_5^{\pm\pm} \to W^\pm W^\pm$ VBF + like-sign dileptons + MET

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 $\Rightarrow$ $s_H \leq 0.5$ at $m_{H^{++}} = 1000$ GeV.

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: $\sim 4\% - 20\%$

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"

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!

All models contain custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$

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:

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

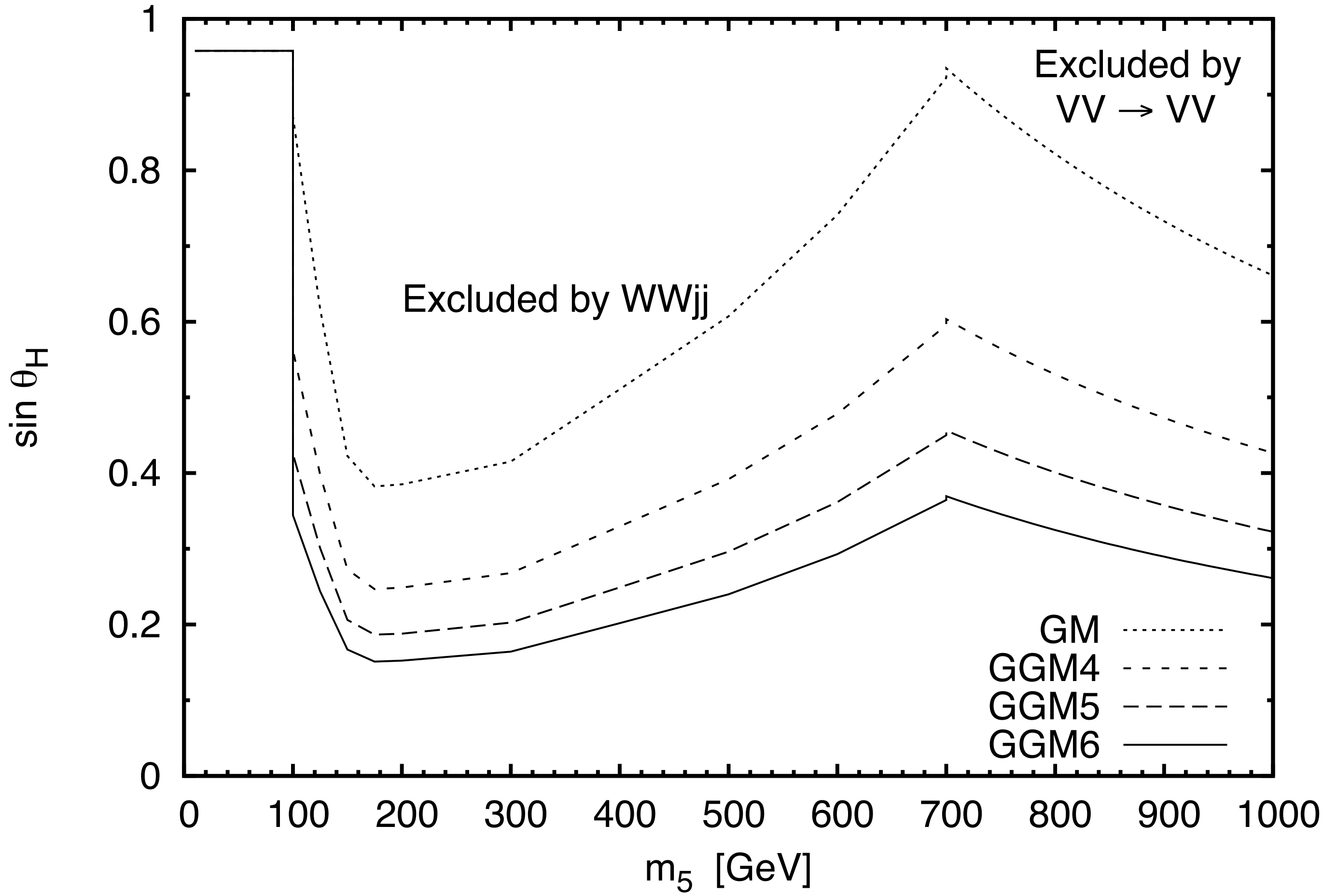
$$
\begin{aligned}
\text{GM3} &: \quad g_5 = \sqrt{2}s_H \\
\text{GGM4} &: \quad g_5 = \sqrt{24/5}s_H \\
\text{GGM5} &: \quad g_5 = \sqrt{42/5}s_H \\
\text{GGM6} &: \quad g_5 = \sqrt{64/5}s_H
\end{aligned}
$$

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 $\to H_5^{\pm\pm} \to W^\pm W^\pm$ and $VV \to VV$ unitarity



HEL & Rentala, 1502.01275

All VBF and unitarity constraints stronger than original GM!

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

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

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

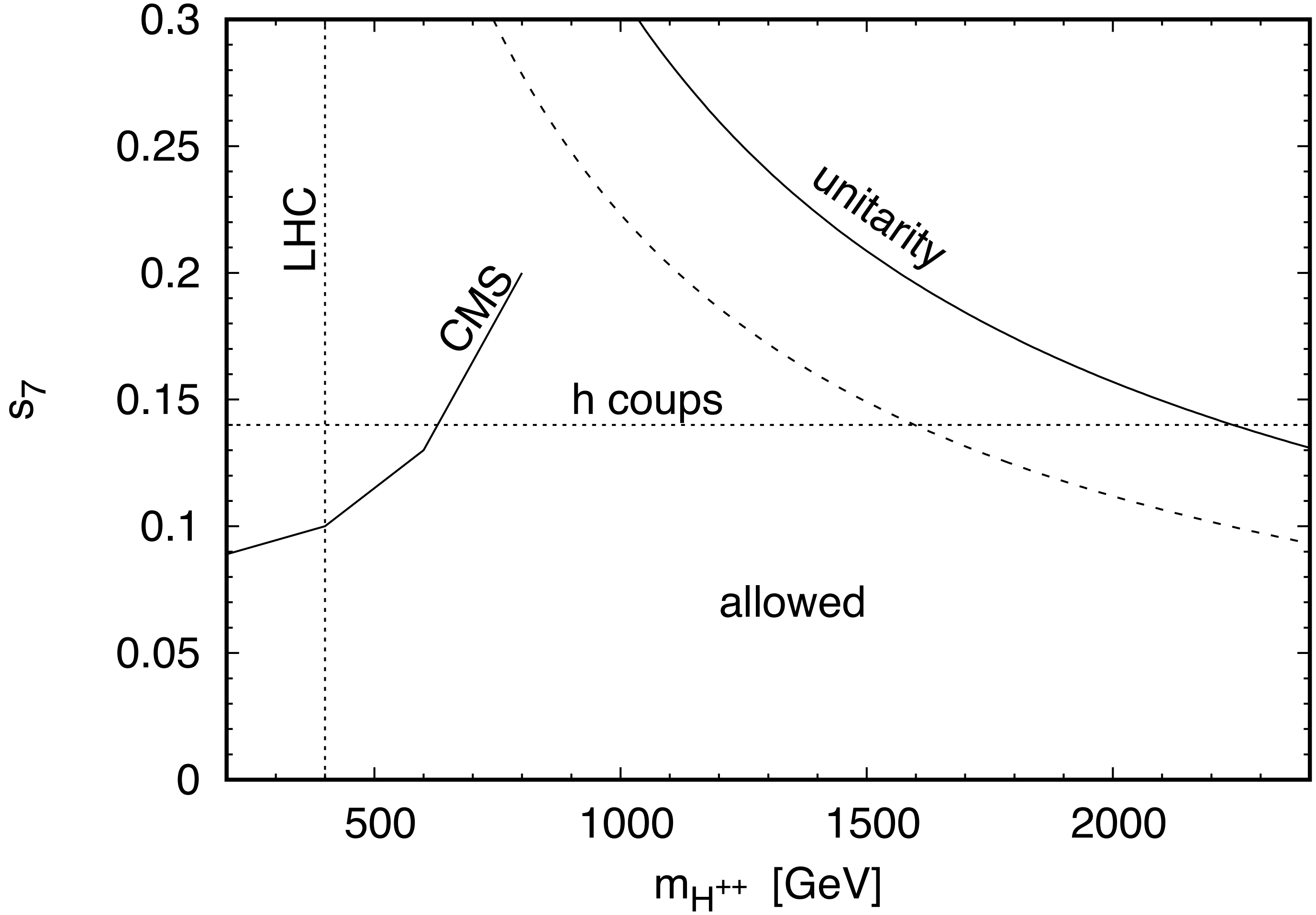
$\rho = 1$, yet there is no custodial symmetry in the scalar spectrum

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

$H^{++} = \chi^{+2}$ completely analogous to GM model:
apply direct search for VBF $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$
$\rightarrow$ constrain $s_7^2 =$ fraction of M_W^2, M_Z^2 from septet vev

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 $\equiv s_7^2 < 2\%$!

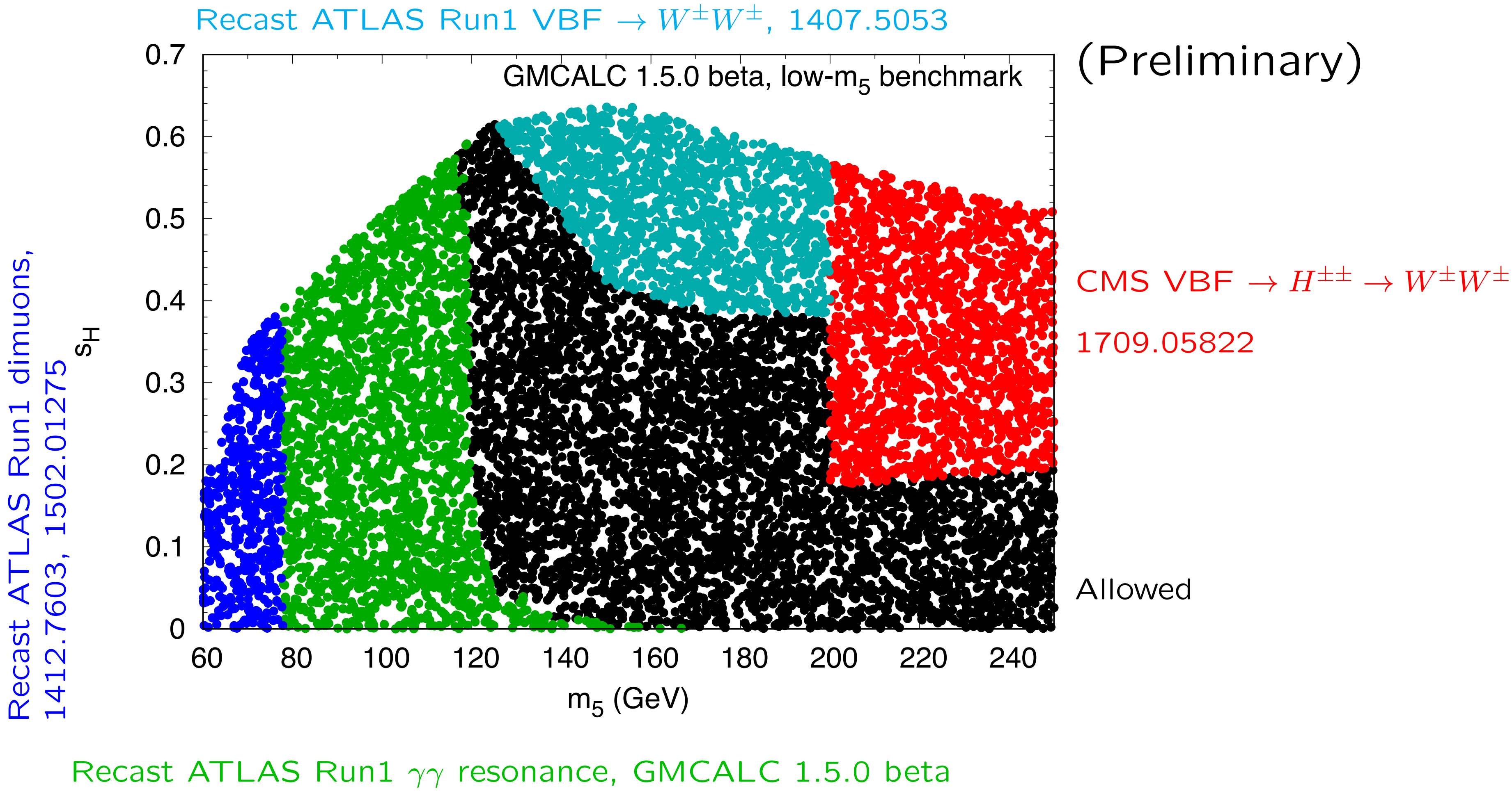
Dots: LHC SUSY searches, h^0 couplings Alvarado, Lehman & Ostdiek, 1404.3208

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

$H_5^{\pm\pm}$ below 200 GeV? Constraints are mainly theory-recast.

new "low-m_5" benchmark in GM model

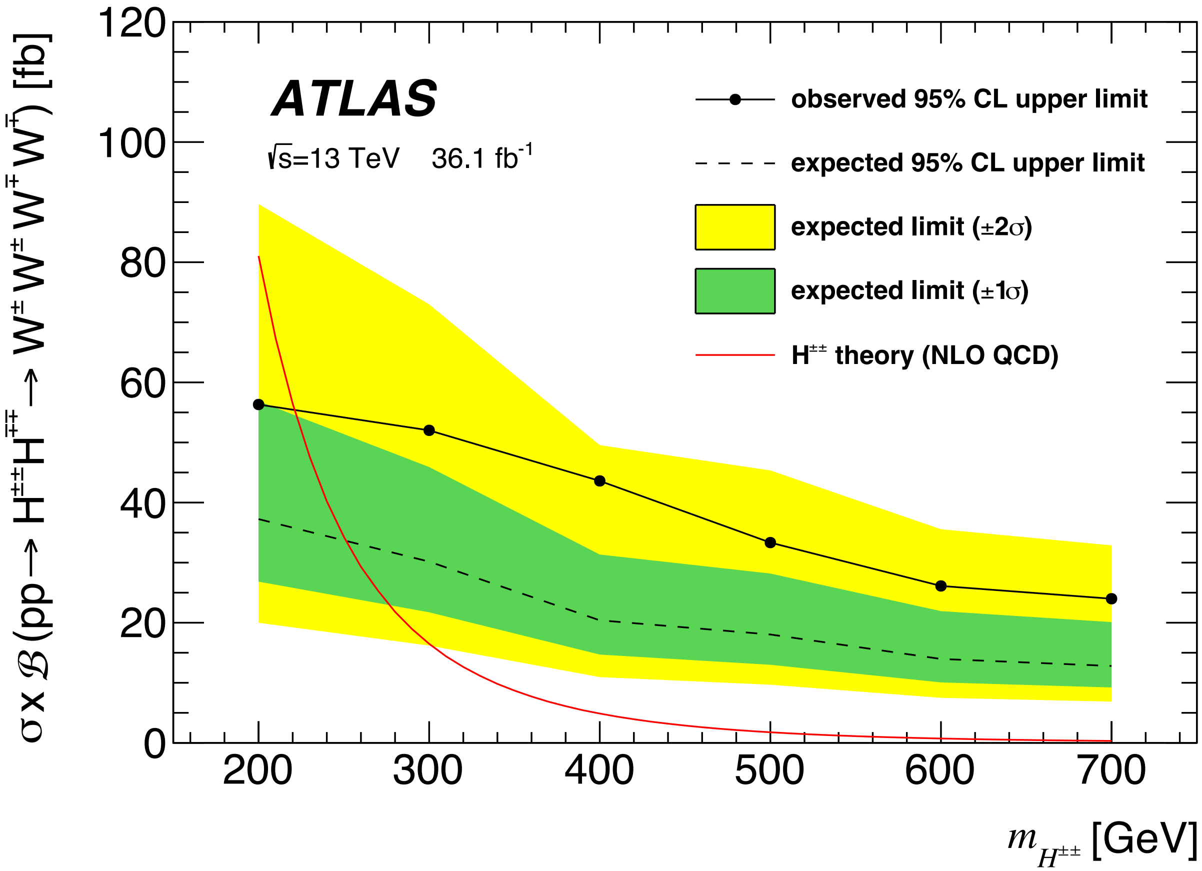
Ben Keeshan, LHC HXSWG WG3 Extended Scalars meeting, 2018-10-24



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

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

Drell-Yan $H^{\pm\pm} \to W^\pm W^\pm$ search was done for the first time in Run 2 but with Ws on shell, above 200 GeV only.



ATLAS, arXiv:1808.01899

Extending to masses below 200 GeV (with offshell Ws) could exclude the entire low-m_5 region!

Conclusions and outlook

Exotic contributions to electroweak symmetry breaking are quite strongly constrained by precision electroweak (ρ_0 parameter).

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 $\to H^{\pm\pm} \to W^{\pm}W^{\pm}$: direct upper bound on $\delta M^2_{W,Z}$ (depends on $m_{H^{\pm\pm}}$).

Low-mass region ($m_{H^{\pm\pm}} < 200$ GeV) could be fully tested by Drell-Yan $pp \to H^{++}H^{--} \to W^+W^+W^-W^-$, but analysis must take into account off-shell Ws.

BACKUP

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

Mass splitting in the exotic multiplet

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

$$V \supset \lambda_1(\Phi^\dagger \tau^a \Phi)(X^\dagger T^a X) + \left[\lambda_2(\tilde{\Phi}^\dagger \tau^a \Phi)(X^\dagger T^a \tilde{X}) + \text{h.c.}\right]$$

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

λ_1 term generates a uniform m^2 splitting among T^3 eigenstates:

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

λ_1 term is absent for real $Y = 0$ mults:
$S_{\text{loop}} = T_{\text{loop}} = U_{\text{loop}} = 0$, constraints same as tree level.

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

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

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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

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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 $\left(\frac{3}{2},\frac{1}{2}\right)+\left(\frac{3}{2},\frac{3}{2}\right)$
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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

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

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

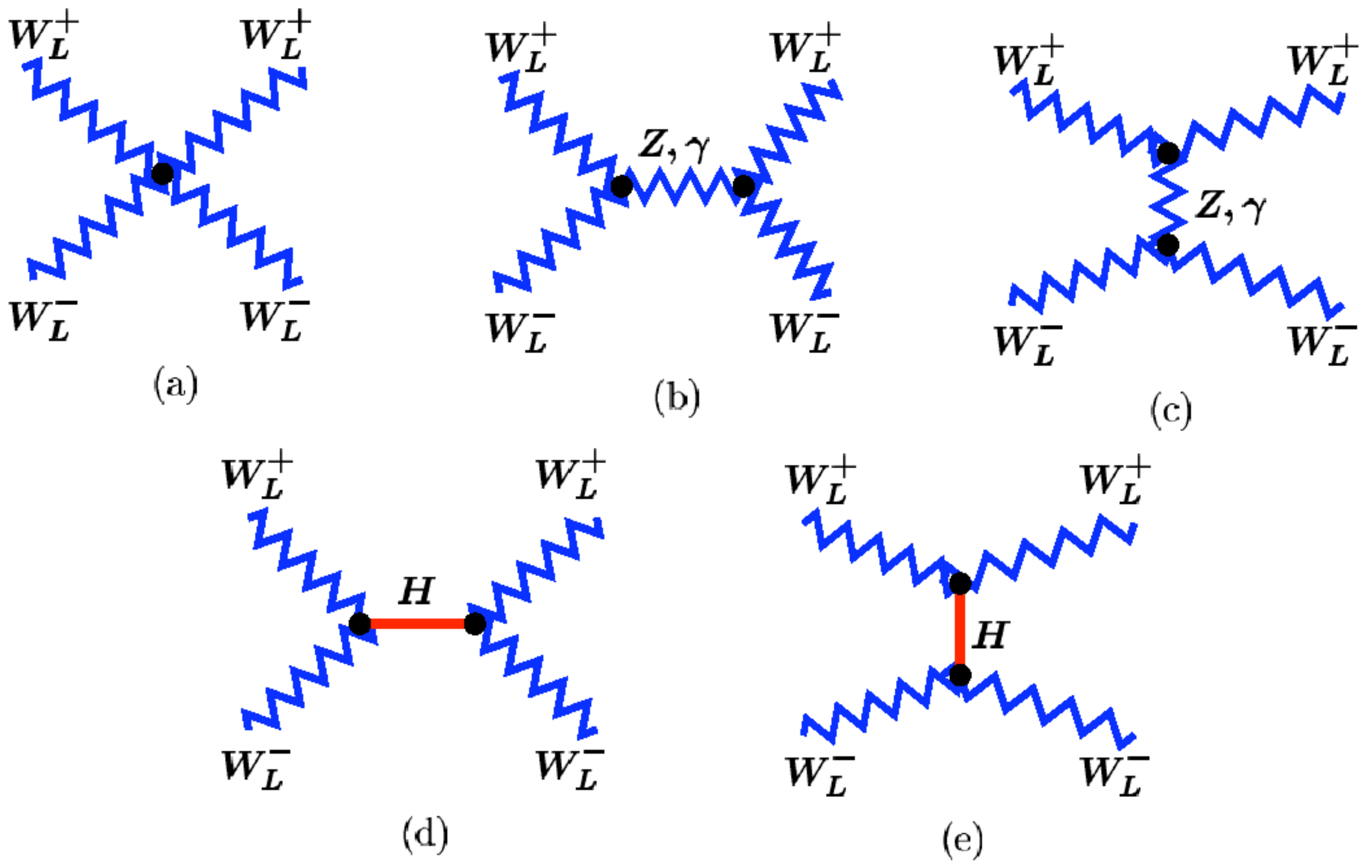
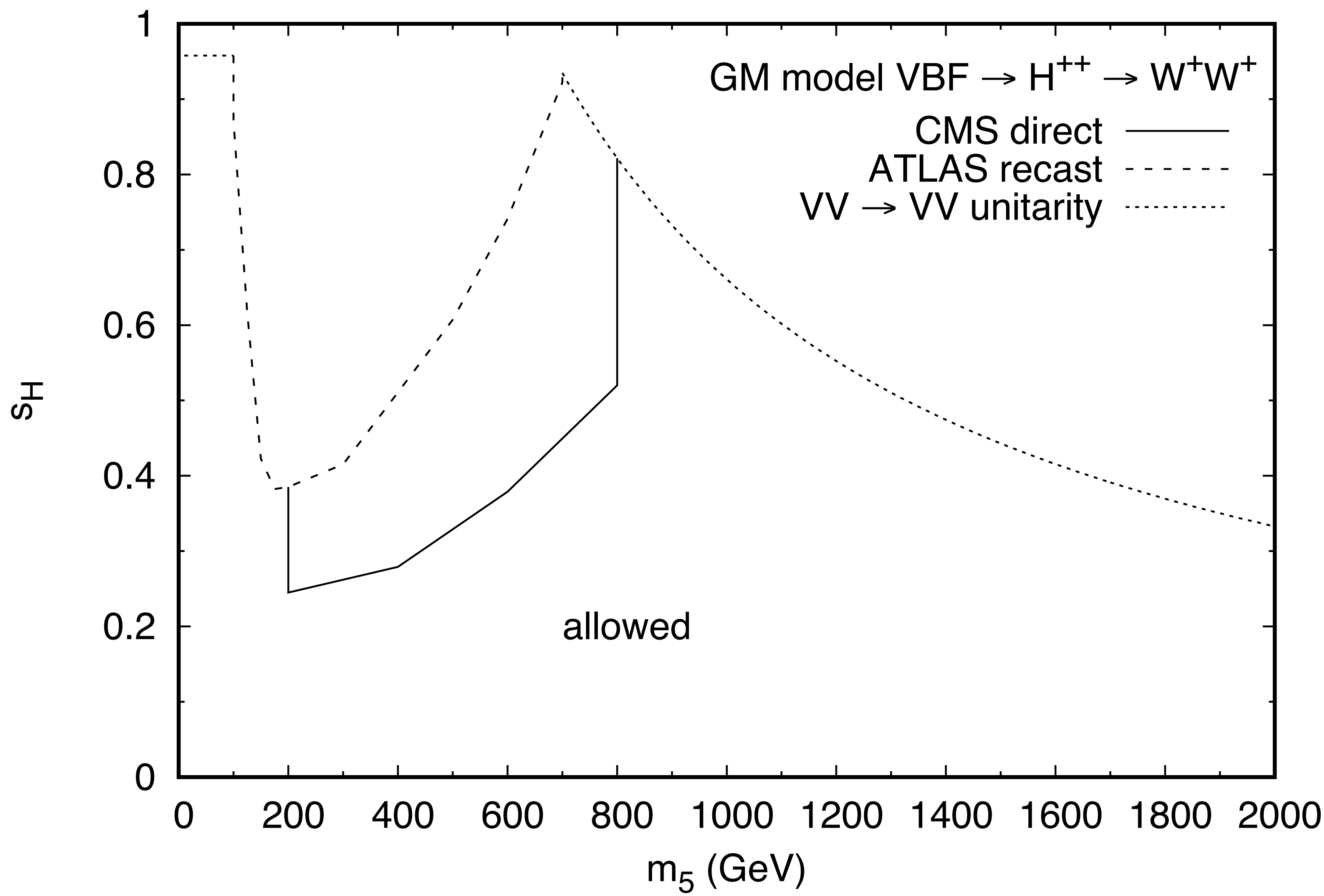


figure: S. Chivukula

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

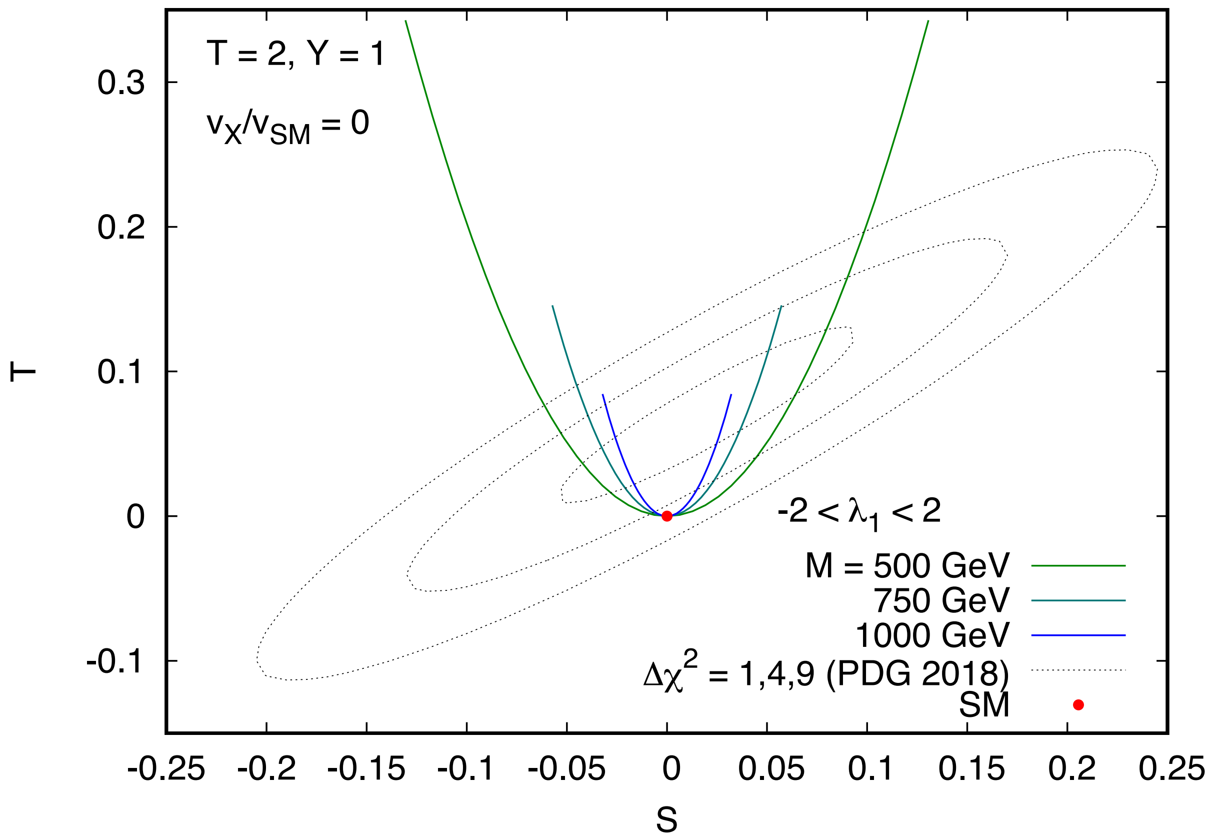
- $H^{++} = \chi^{+2}$: analogue of H_5^{++}
- ϕ^+, χ^{+1}, $(\chi^{-1})^*$ mix: no purely fermiophobic analogue of H_5^+
- Only 2 CP-even neutral scalars (h^0, H^0): no analogue of H_5^0

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

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

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

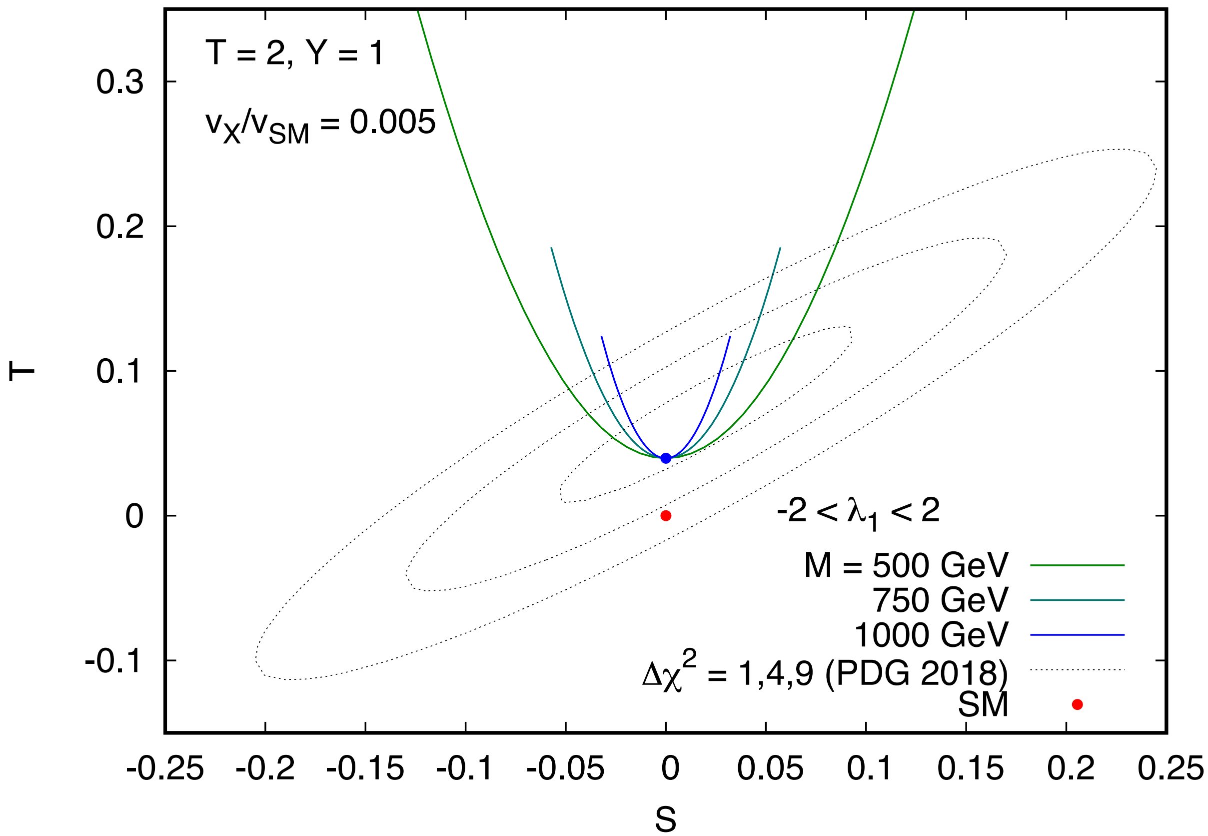
Take advantage of correlation between S and T to try to ease the constraint.



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

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.



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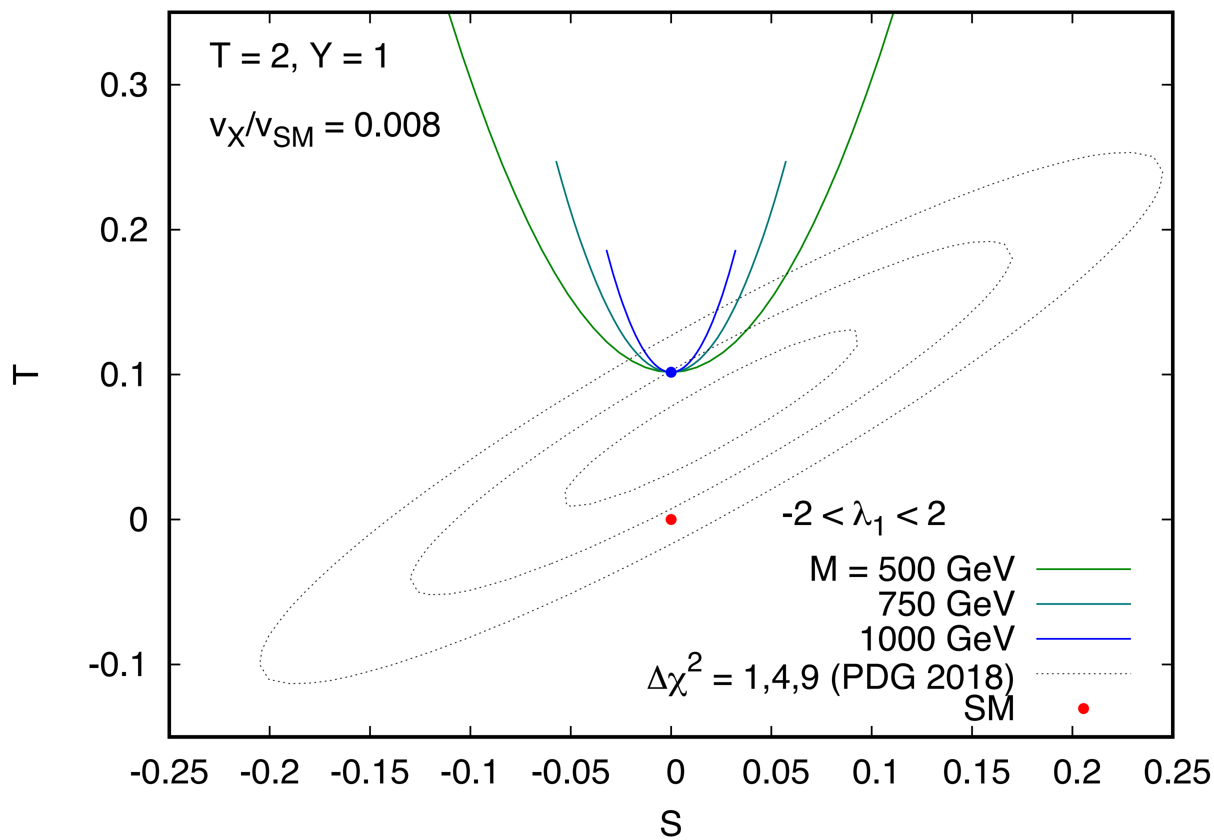

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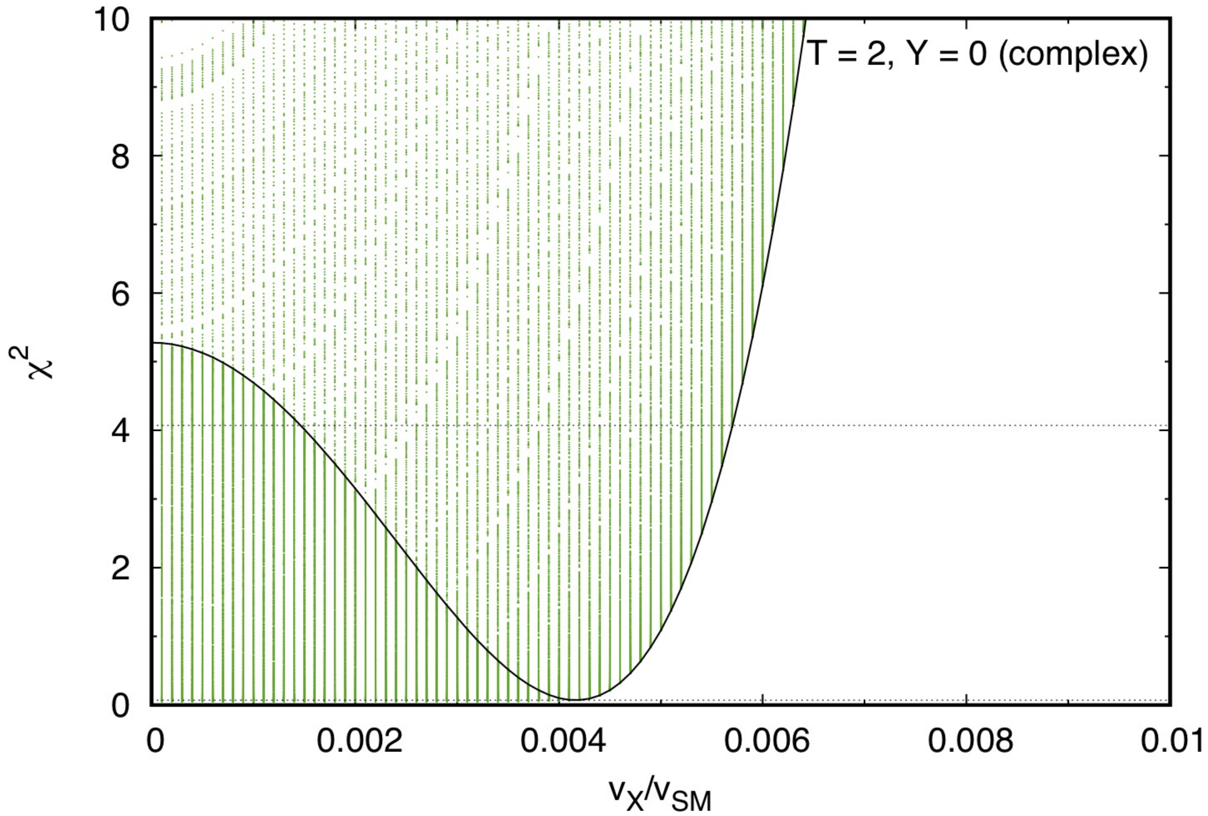
Results: complex multiplets with $Y = 0$ ($T_{\rm tree} > 0$)

$T_{\rm tree} > 0$, $T_{\rm loop} \geq 0$, $S_{\rm loop} \propto Y = 0$:
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 $T_{\text{tree}} < 0$

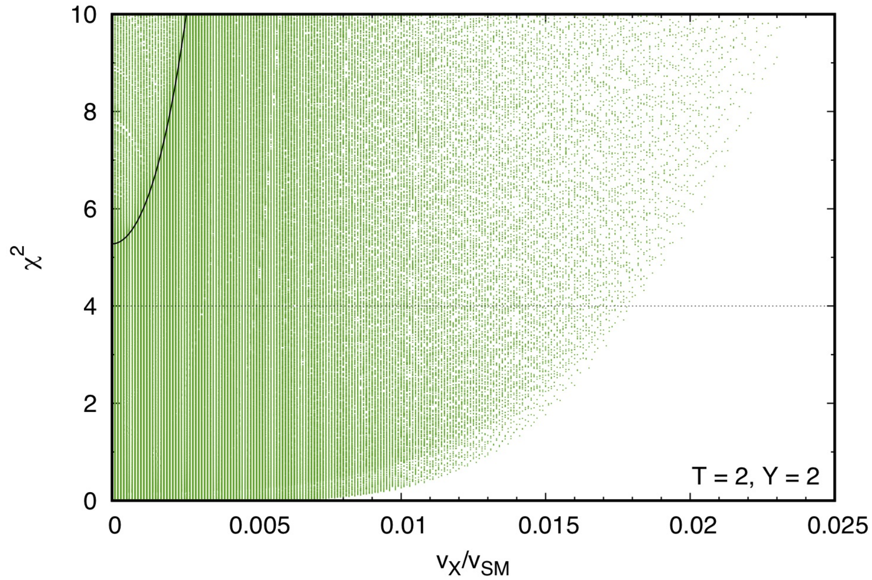
$T_{\text{loop}} > 0$: can cancel negative T_{tree}!

Ultimately S_{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_{loop} while minimizing S_{loop}. (Sign of λ_1 doesn't matter much.)

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

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



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	$\delta\rho$	$\delta M_W^2\vert_{\text{max}}$	$\delta M_Z^2\vert_{\text{max}}$
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%

J. Goodman & HEL, in progress

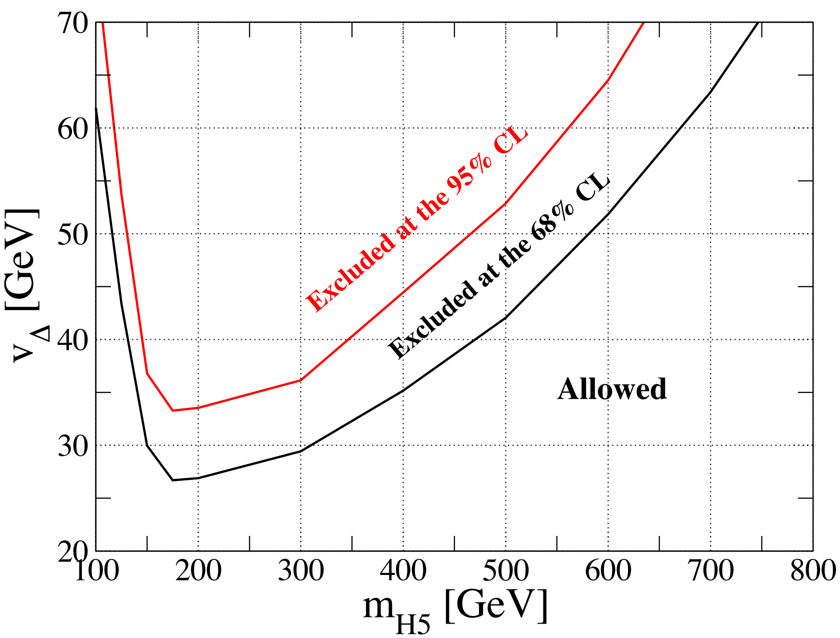
Searches

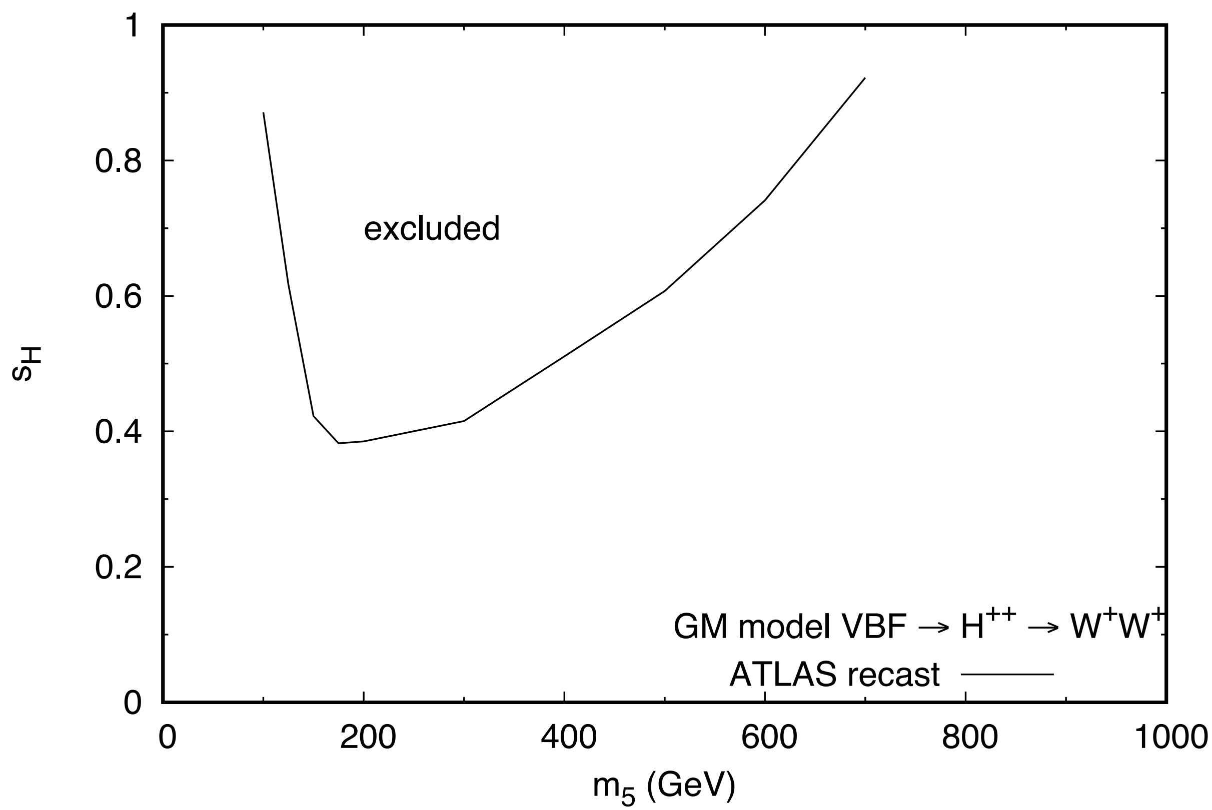
SM VBF $\to W^{\pm}W^{\pm} \to \ell^{\pm}\ell^{\pm}$ + MET cross section measurement

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

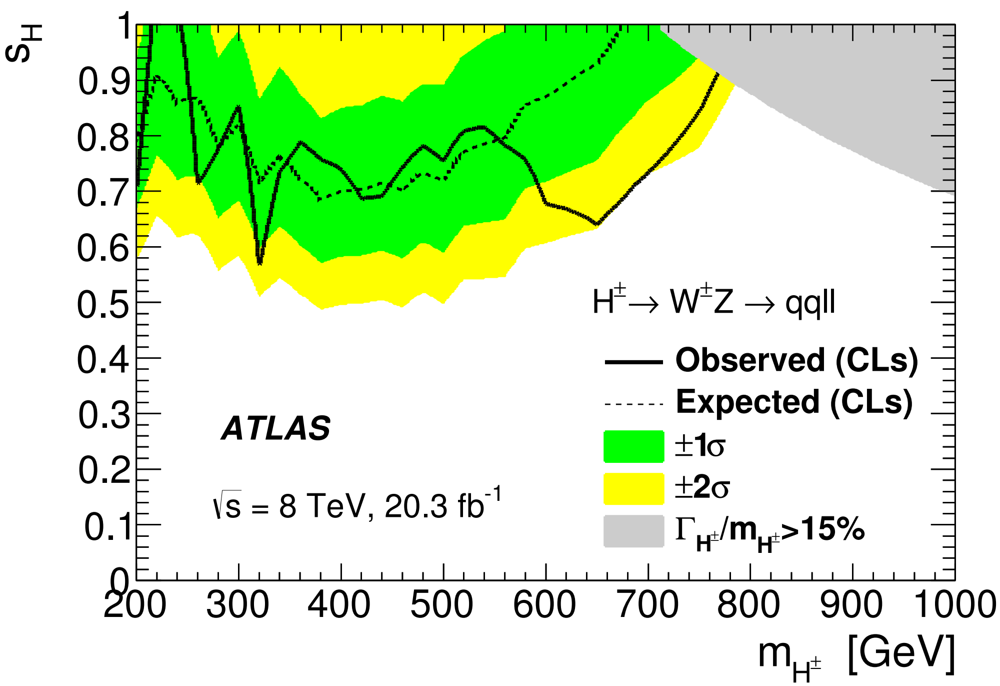
Chiang, Kanemura, Yagyu, 1407.5053





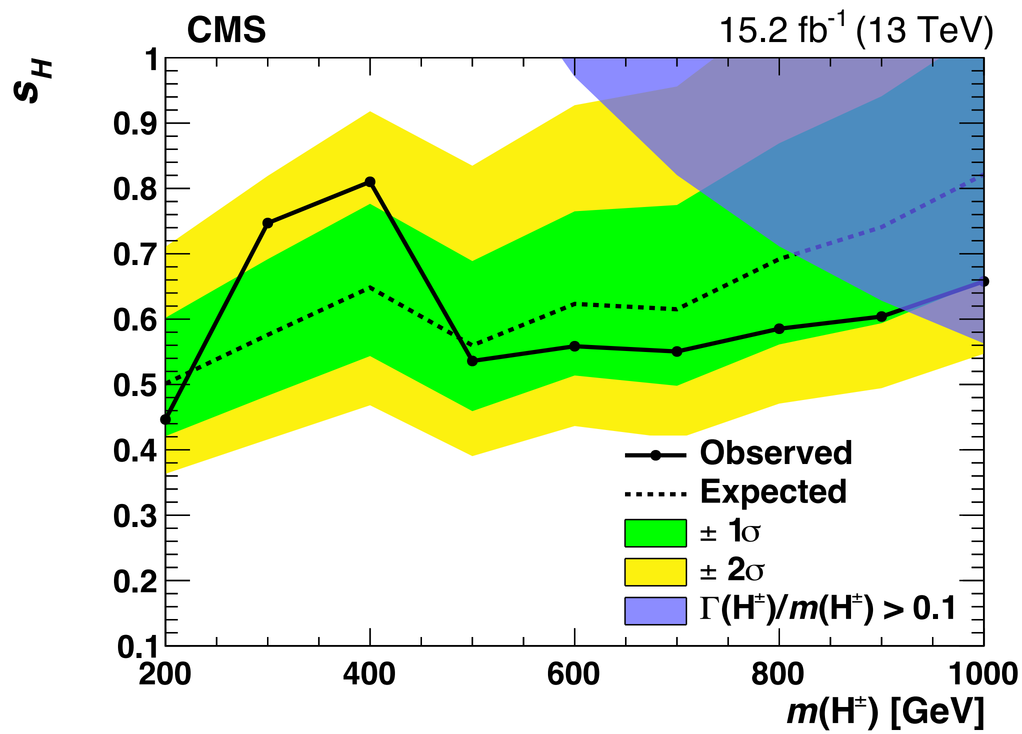
Searches

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



ATLAS 1503.04233, PRL 2015

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



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)