Limits on exotic contributions to electroweak symmetry breaking

Heather Logan
Carleton University
Ottawa, Canada

Higgs as a Probe of New Physics 2019
Osaka, Japan, February 18–22, 2019

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.

Usual approach: models with custodial symmetry (Georgi-Machacek model) or a built-in cancellation (Scalar Septet Model) to ensure $\rho = 1$ at tree level. Experiment: $\rho_0 = 1.00039 \pm 0.00019$ (PDG 2018)

Otherwise, exotic vevs must be very small, or tuned between exotic mults to cancel contributions to ρ. [Chiang & Yagyu 1808.10152]

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

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

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

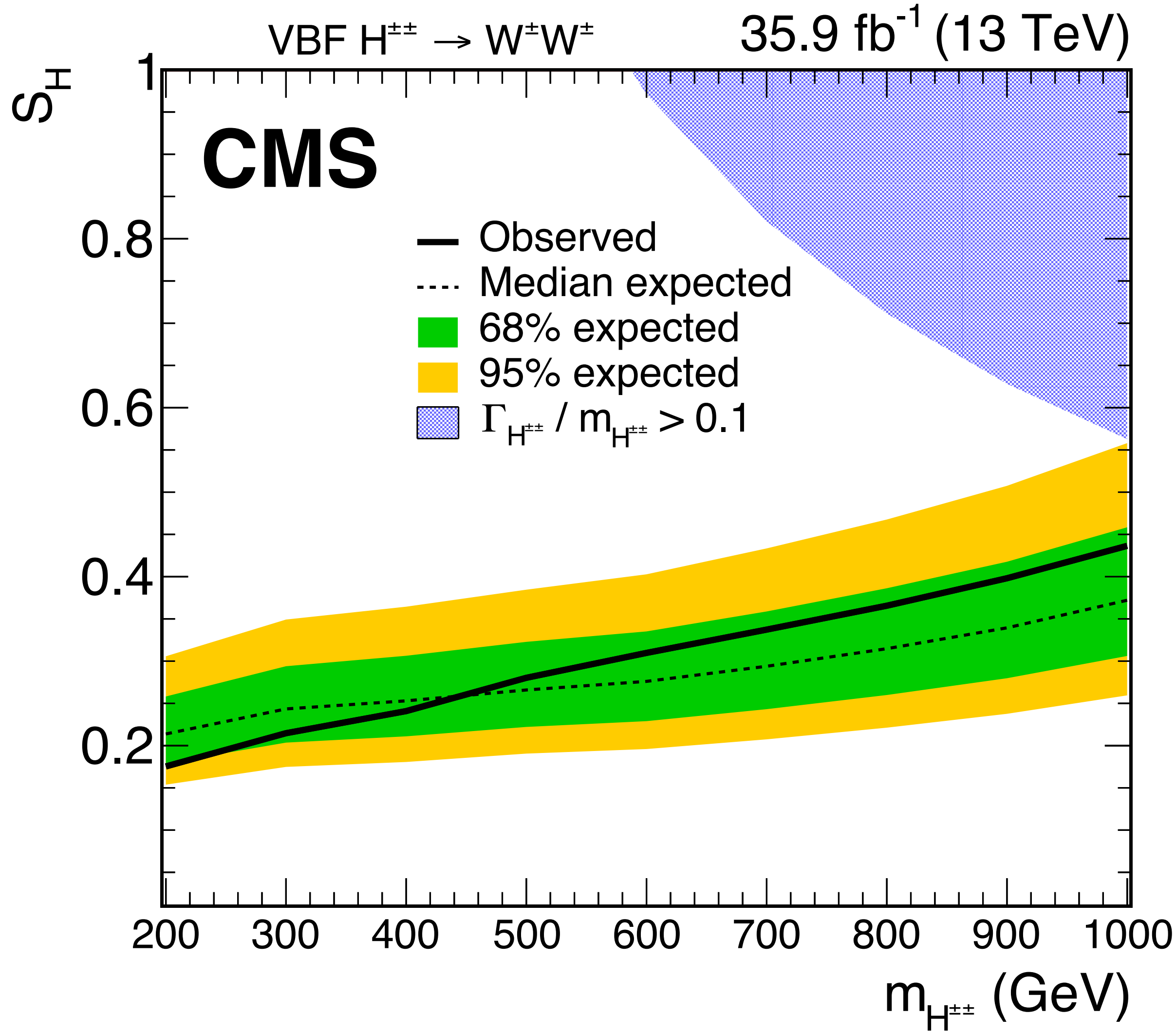
Global SU(2)$_L\times$SU(2)$_R$ $\to$ custodial symmetry $\langle\chi^0\rangle = \langle\xi^0\rangle \equiv v_\chi$

Physical spectrum:

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 $\propto$ $s_H \equiv \sqrt{8}v_\chi/v_{\rm SM}$
  $s_H^2 \equiv$ exotic fraction of M_W^2, M_Z^2

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

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

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

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

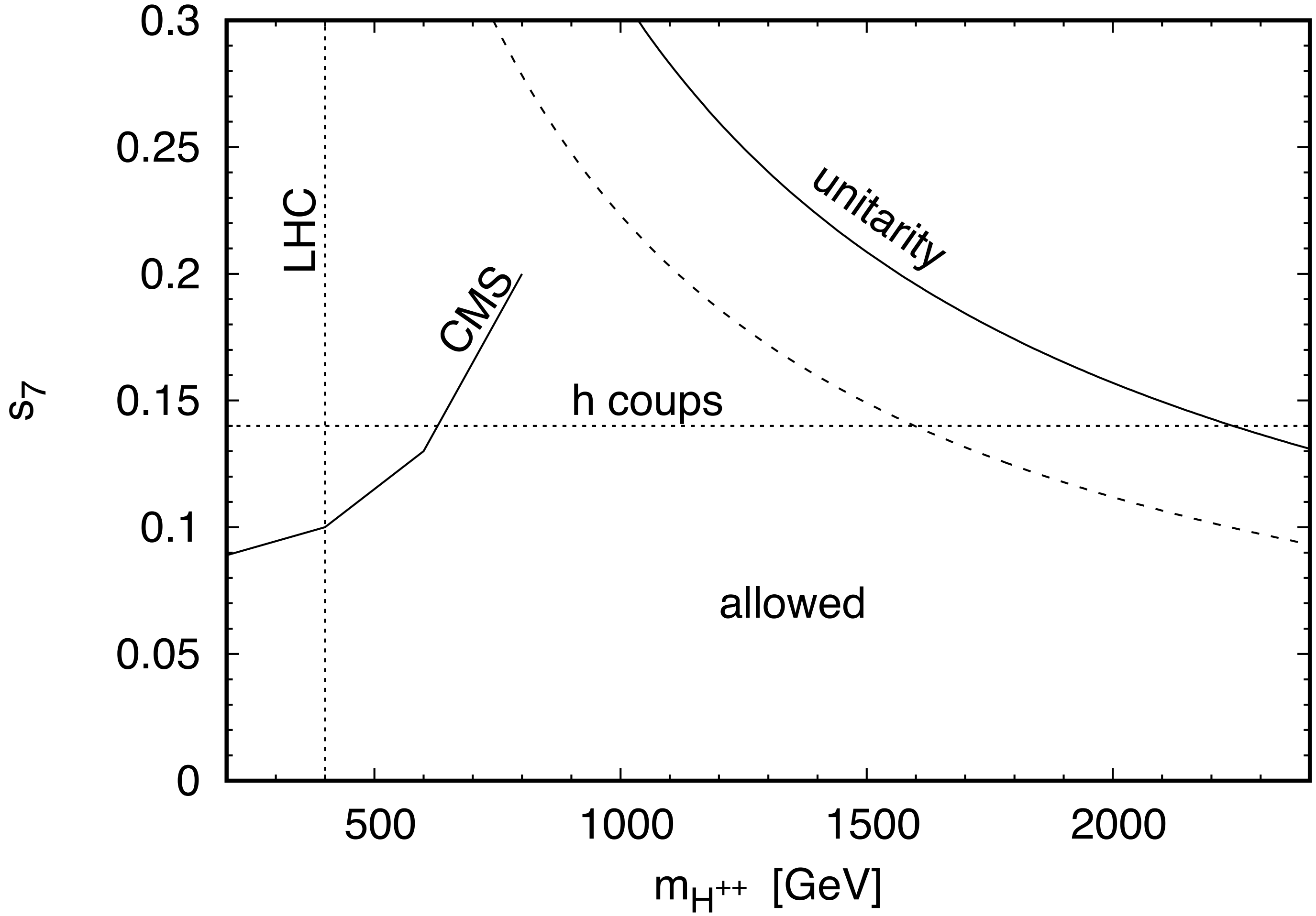
$\rho = 1$, yet there is no custodial symmetry in the scalar spectrum

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.

Models with potentially large exotic contributions to EWSB are getting significantly constrained by direct LHC searches and Higgs signal strength measurements.

At what point do we decide that these models are no longer interesting?

Our proposal: when the fraction of M_W^2 and M_Z^2 allowed in these models is no larger than can be achieved from any random exotic scalar multiplet, subject to the ρ parameter constraint.

J. Goodman & HEL, in progress

- Write down complete list of exotic multiplets with EWSB vevs
- Constrain vev using ρ parameter
- Compute maximum M_W^2 and M_Z^2 contributions

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

Upper bound on isospin of (perturbative!) exotic multiplets

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

Consider scattering of scalars into *transversely* polarized Ws & Zs (the ordinary gauge modes) and require tree-level unitarity:

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

$\chi\chi^* \leftrightarrow W_T^a W_T^a$ largest eigenvalue: 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 there is more than one large multiplet

Tree-level ρ parameter calculation

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]:

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

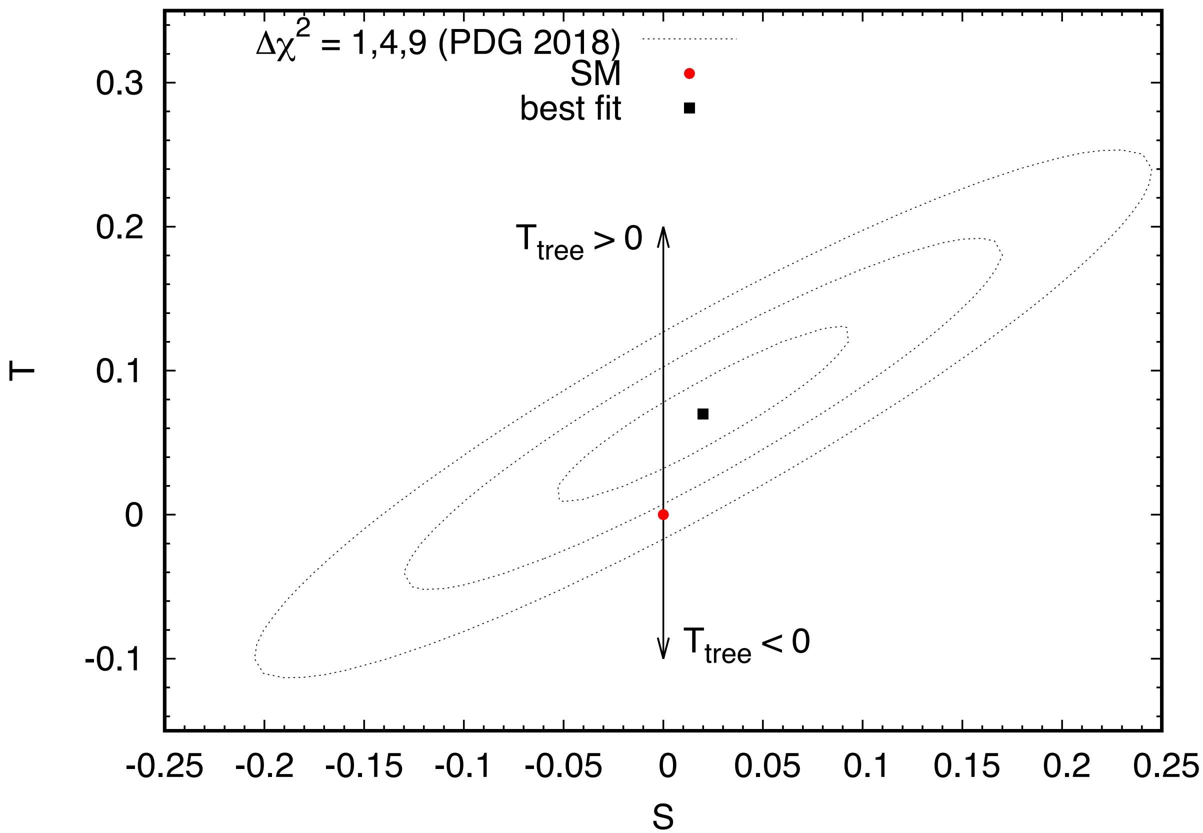
Correlations: S–T: $+92\%$, S–U: -66%, T–U: -86%

Peskin & Takeuchi, 1990, 1992

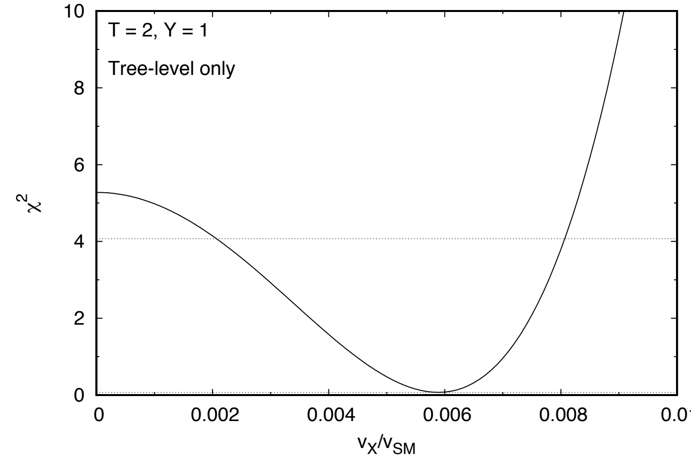
ρ parameter is extracted by setting $S = U = 0$ and using

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

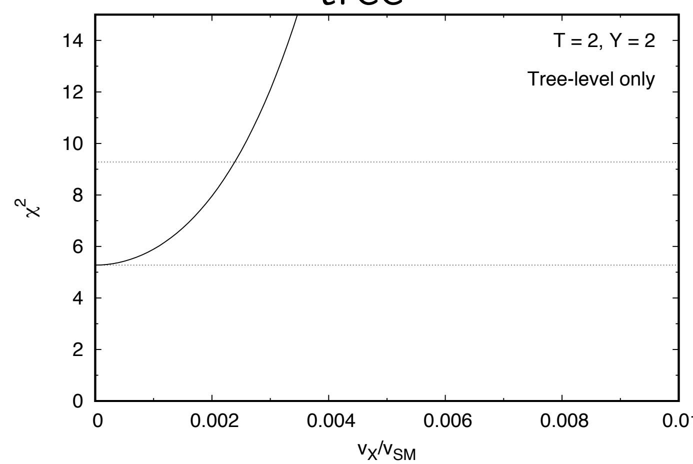
Tree-level ρ parameter versus S, T, U



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



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



Jesi Goodman & HEL, in progress

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

Tree-level ρ parameter constraints (S, T, U fit) J. Goodman & HEL

			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%]

$\Rightarrow$ our target M_W^2 fraction sensitivity is $\sim 0.25\%$.

Beyond tree level

T parameter calculation involving exotic mults is subtle: have to renormalize T_{tree}. Chankowski, Pokorski & Wagner, hep-ph/0605302
$\rightarrow$ 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.
$\rightarrow$ Work in a double expansion:
1st order in exotic vev (T_{tree}) and 1st order in α_{EM} (1-loop)
Can use existing results for $(S, T, U)_{\text{loop}}$ from a scalar electroweak multiplet with zero vev.

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

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

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:

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

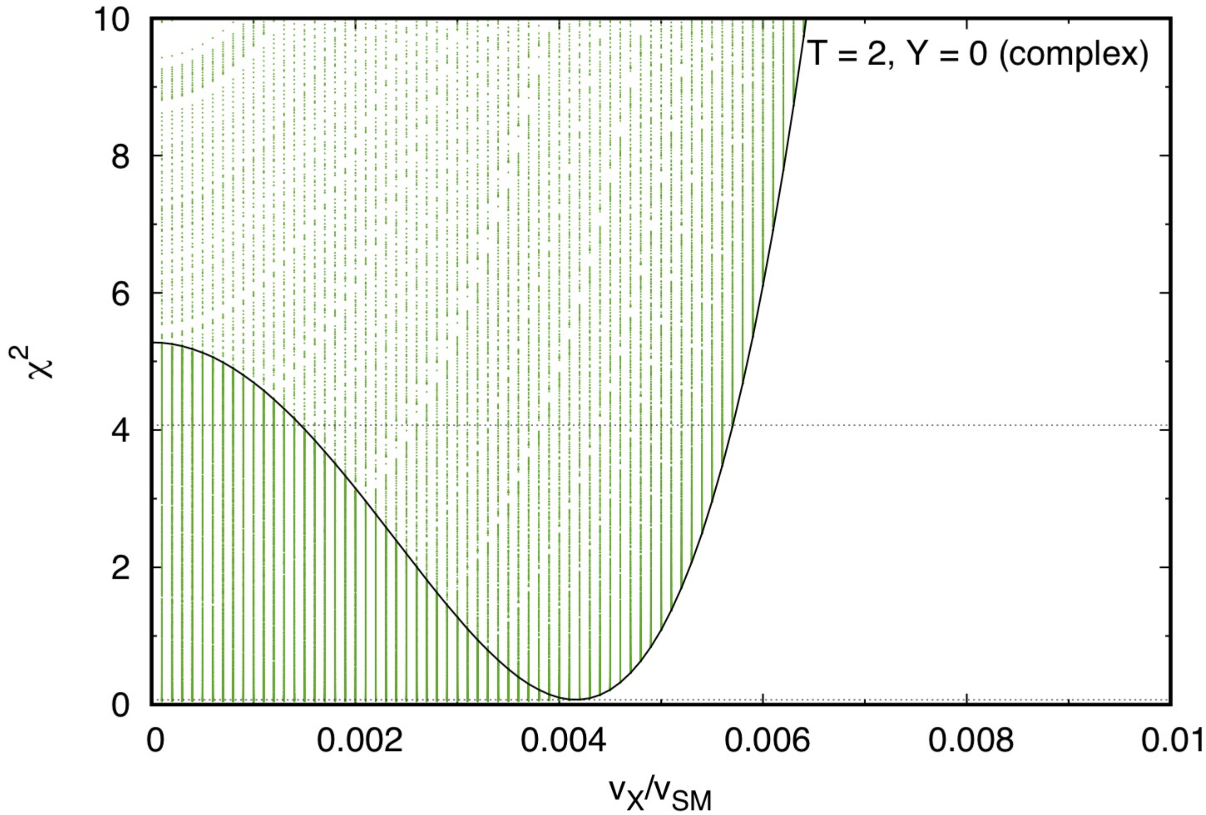
λ_1 term is absent for real $Y = 0$ mults:
$S_{\text{loop}} = T_{\text{loop}} = U_{\text{loop}} = 0$, constraints same as tree level.

Modulo M.J. Ramsey-Musolf's talk... have to check this!

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.

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

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

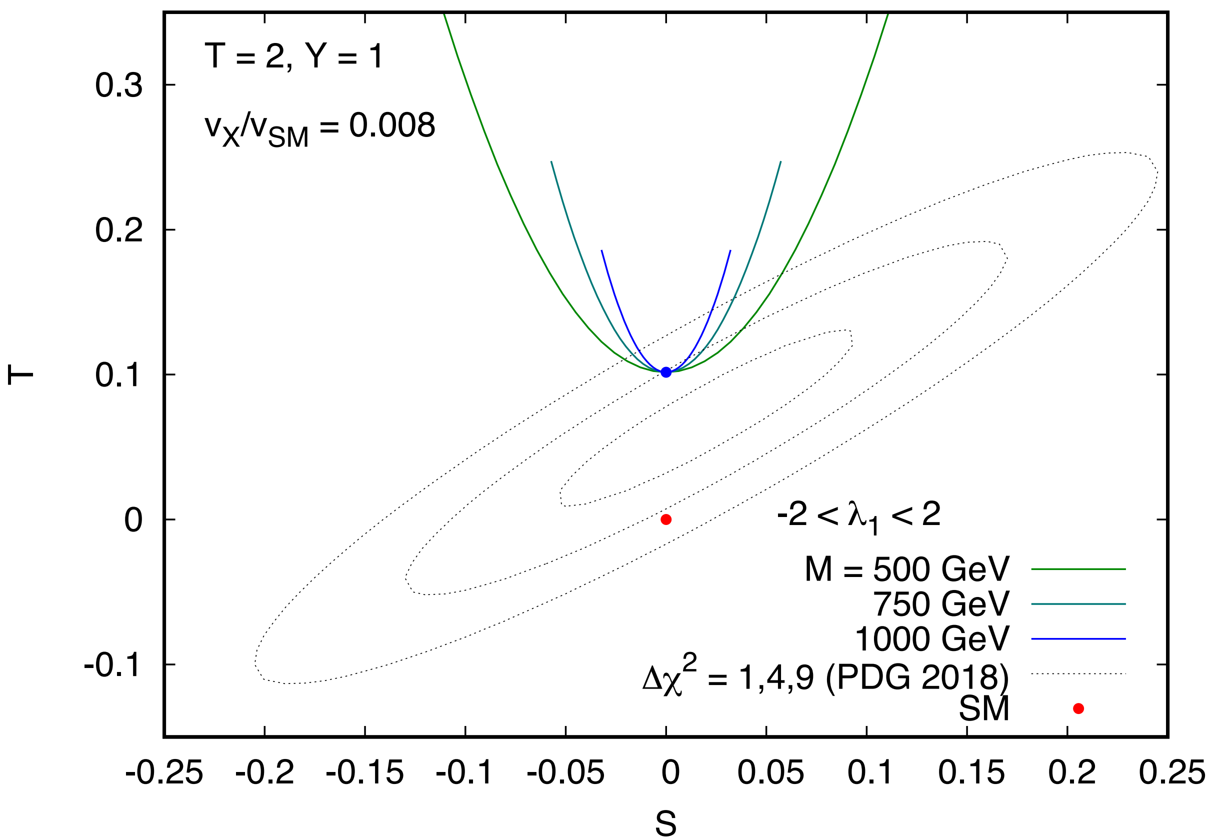


J. Goodman & HEL, in progress

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

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

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



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

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

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

T	Y	$\delta\rho$	$\delta M_W^2\|_{\rm max}$	$\delta M_Z^2\|_{\rm max}$
*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 $T_{\text{tree}} < 0$

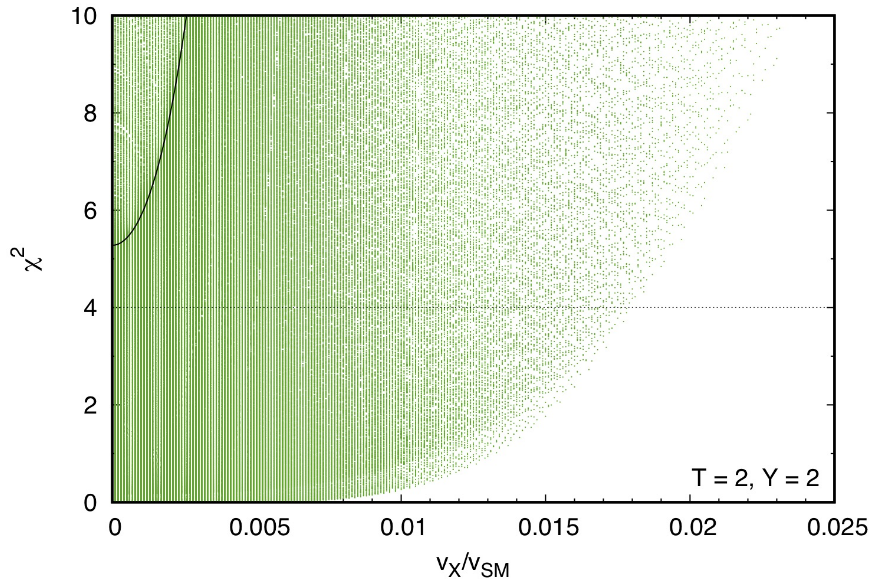
$T_{\text{loop}} > 0$: can cancel negative T_{tree}!

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 $T_{\rm tree} < 0$



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

J. Goodman & HEL, in progress

Conclusions

Tree-level contribution to the ρ parameter limits M_W^2 contribution from a single exotic multiplet to at most 0.25%.

But the ρ parameter constraint is so tight that one should really consider 1-loop contributions along with tree-level.

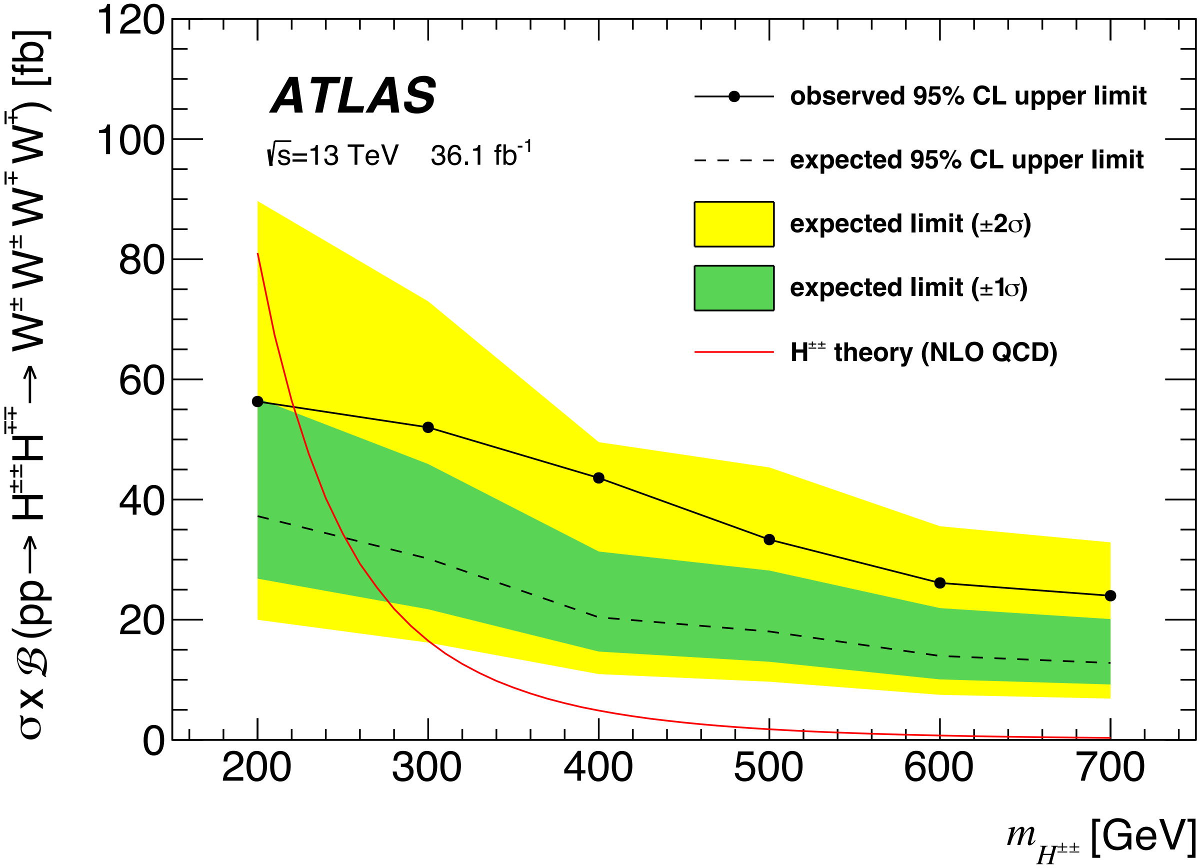
Mass-splitting effects within exotic multiplet can loosen tree-level bound on vev significantly:
Tree-level contributions to M_W^2 and M_Z^2 up to 3.6% and 7.0% (respectively) are still allowed for $Y = 1$ triplet.

Compare direct-search and Higgs-coupling constraints that limit $M_{W,Z}^2$ contribution to $\sim 4\% - 20\%$ in GM model and to $\sim 2\%$ in septet model.

Still working on the cases with mixing of T^3 eigenstates: S, T, U interdependence qualitatively different. (Ex: $T_{\rm loop} < 0$ possible.)

BACKUP

$\chi^{\pm\pm} \to W^{\pm}W^{\pm}$ search done for first time in Run 2 (Ws on shell)



ATLAS, arXiv:1808.01899

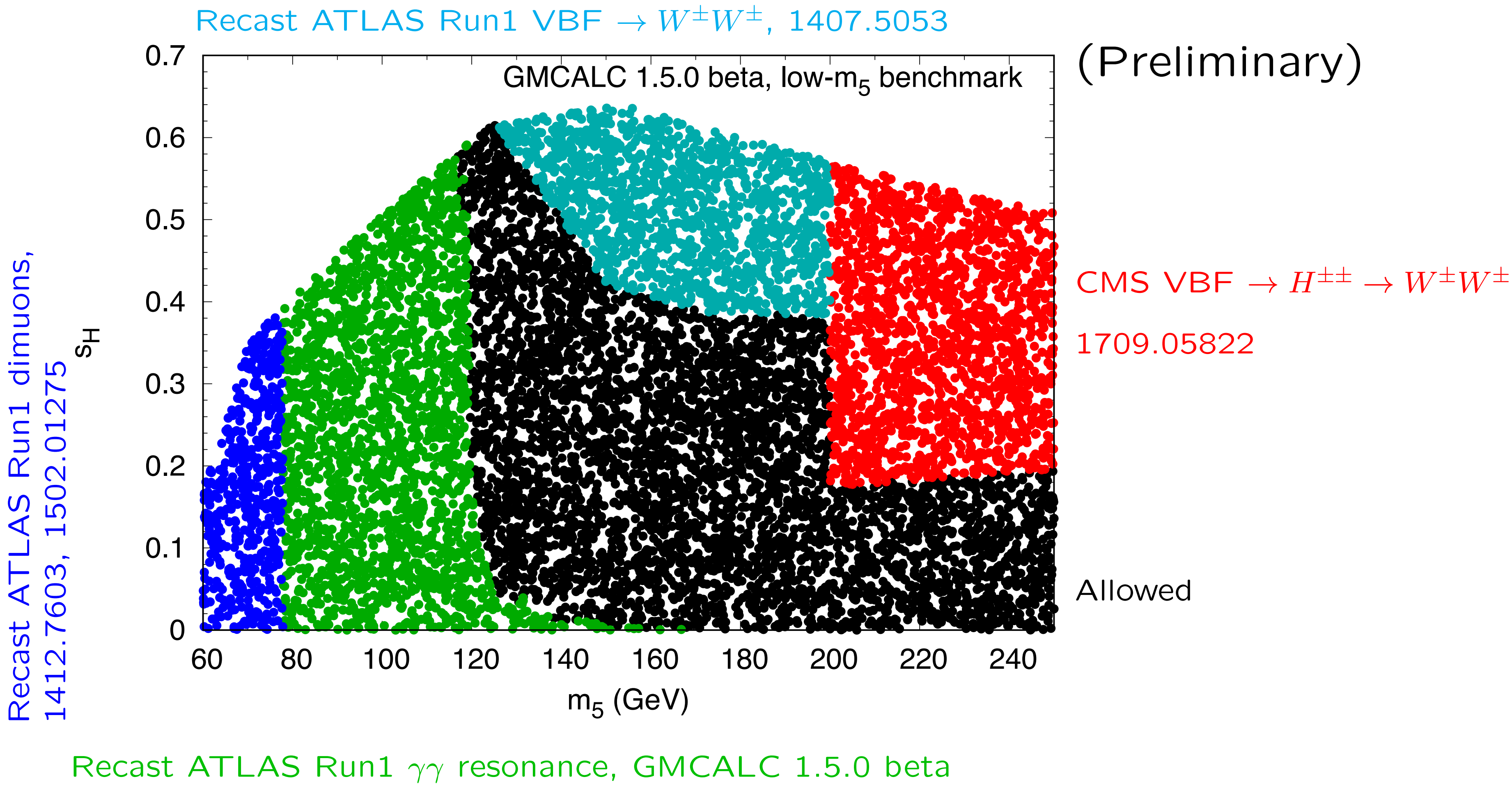
Theorist recast of ATLAS Run-1 like-sign dimuon data sets lower bound $m_{\chi^{++}} \gtrsim 84$ GeV Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Gap at intermediate masses < 200 GeV: need offshell Ws!

For $H_5^{\pm\pm}$, $H_5^{\pm}$, H_5^0 masses below 200 GeV, constraints are mainly theory-recast:

new "low-m_5" benchmark in GM model,

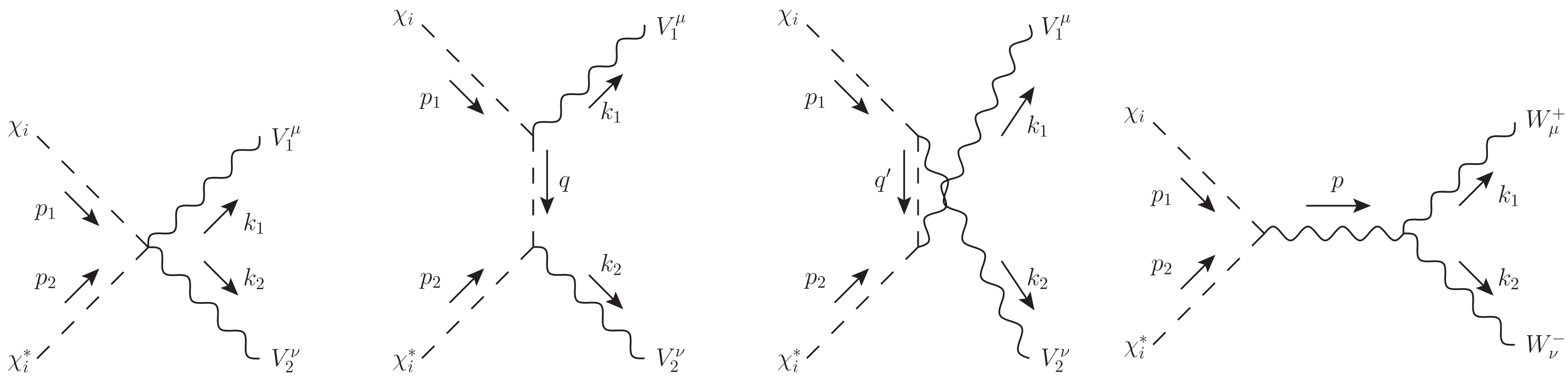
Ben Keeshan, WG3 Extended Scalars meeting, 2018-10-24



Extending Drell-Yan $H^{\pm\pm} \to W^\pm W^\pm$ search to masses below 200 GeV (w/ offshell Ws) could exclude entire low-m_5 region!

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

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 there is more than one large multiplet

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

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

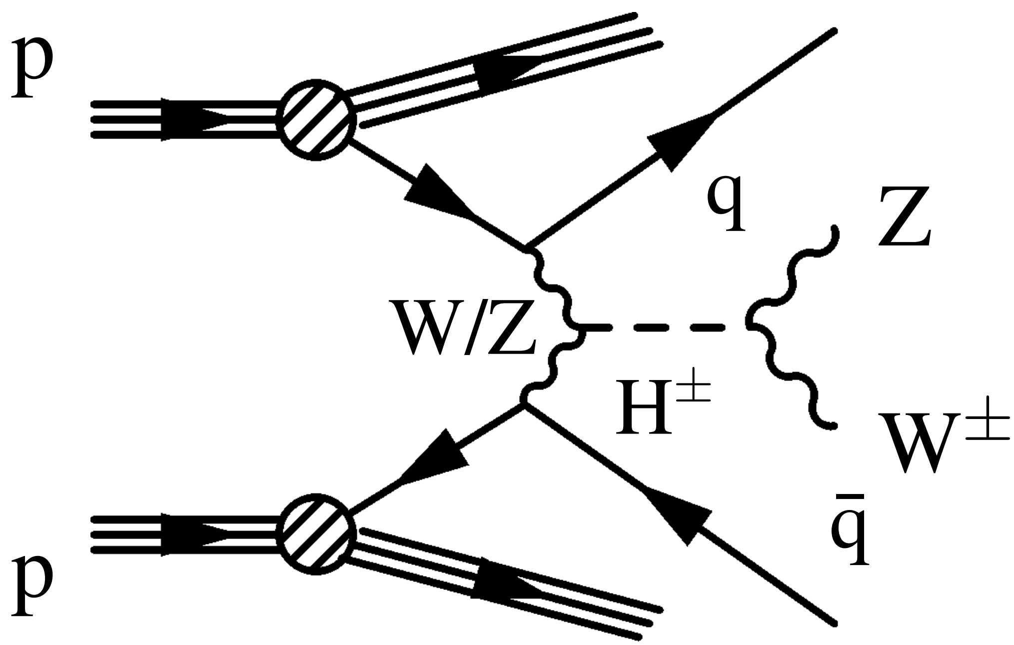
Larger than sextets $\rightarrow$ too many large multiplets, violates perturbativity!

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

Explicit LHC searches up to now:

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

VBF $\rightarrow H_5^{\pm} \rightarrow W^\pm Z \rightarrow$ ATLAS + CMS 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

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

"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 $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ $\longleftarrow \bigstar$

- 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:

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

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

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

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

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

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

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

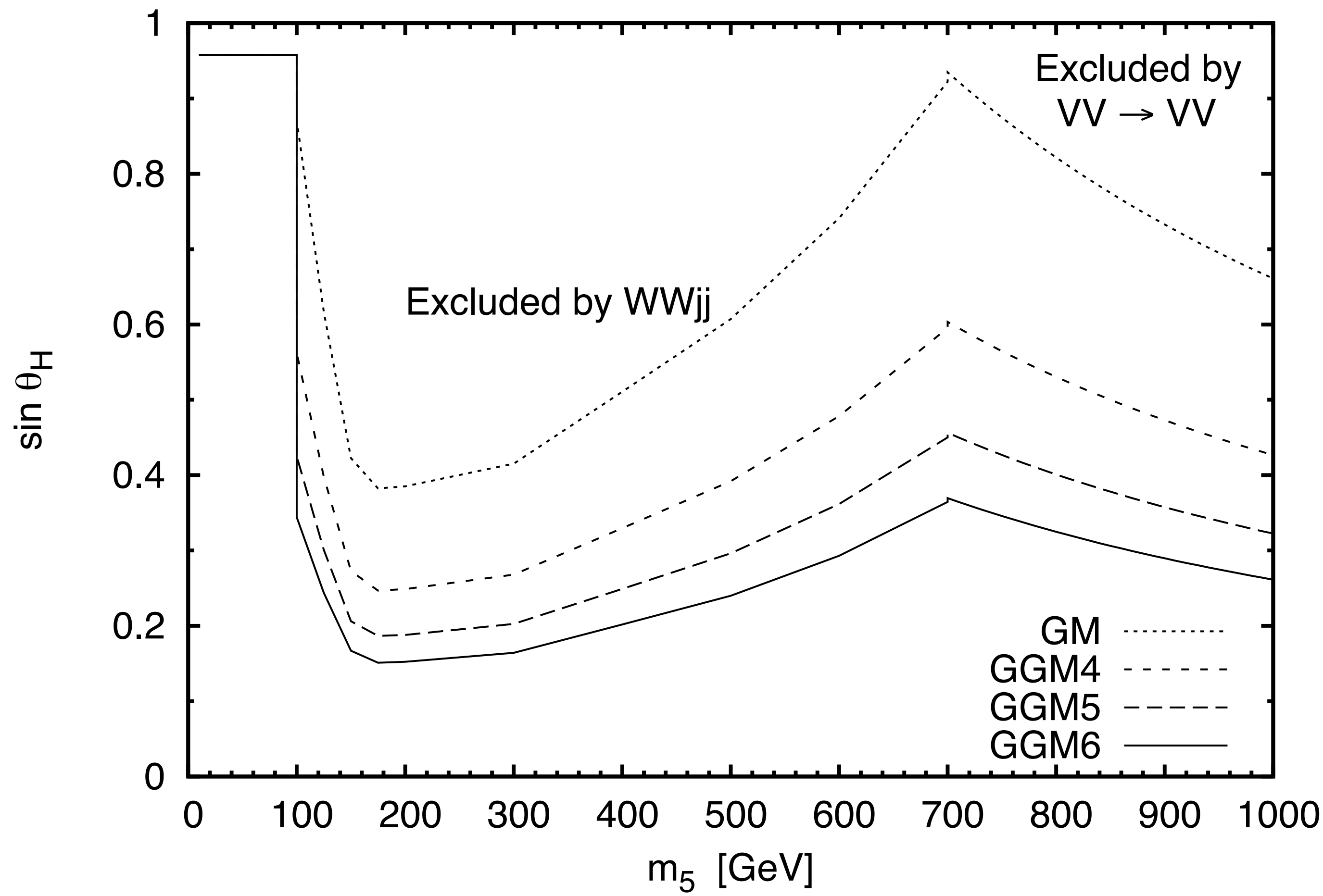
$$\text{GGM6}: \quad g_5 = \sqrt{64/5}s_H$$

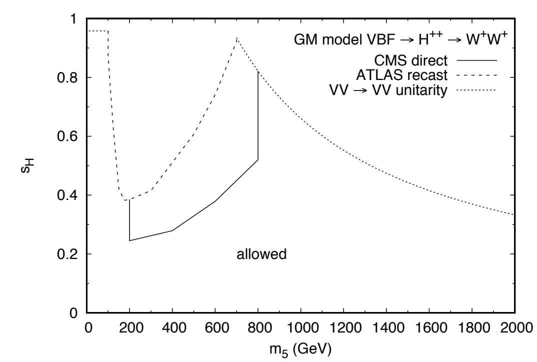
s_H^2 = fraction of M_W^2, M_Z^2 from exotic scalars

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

(plot needs updating: CMS Run 1 direct search not shown)

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

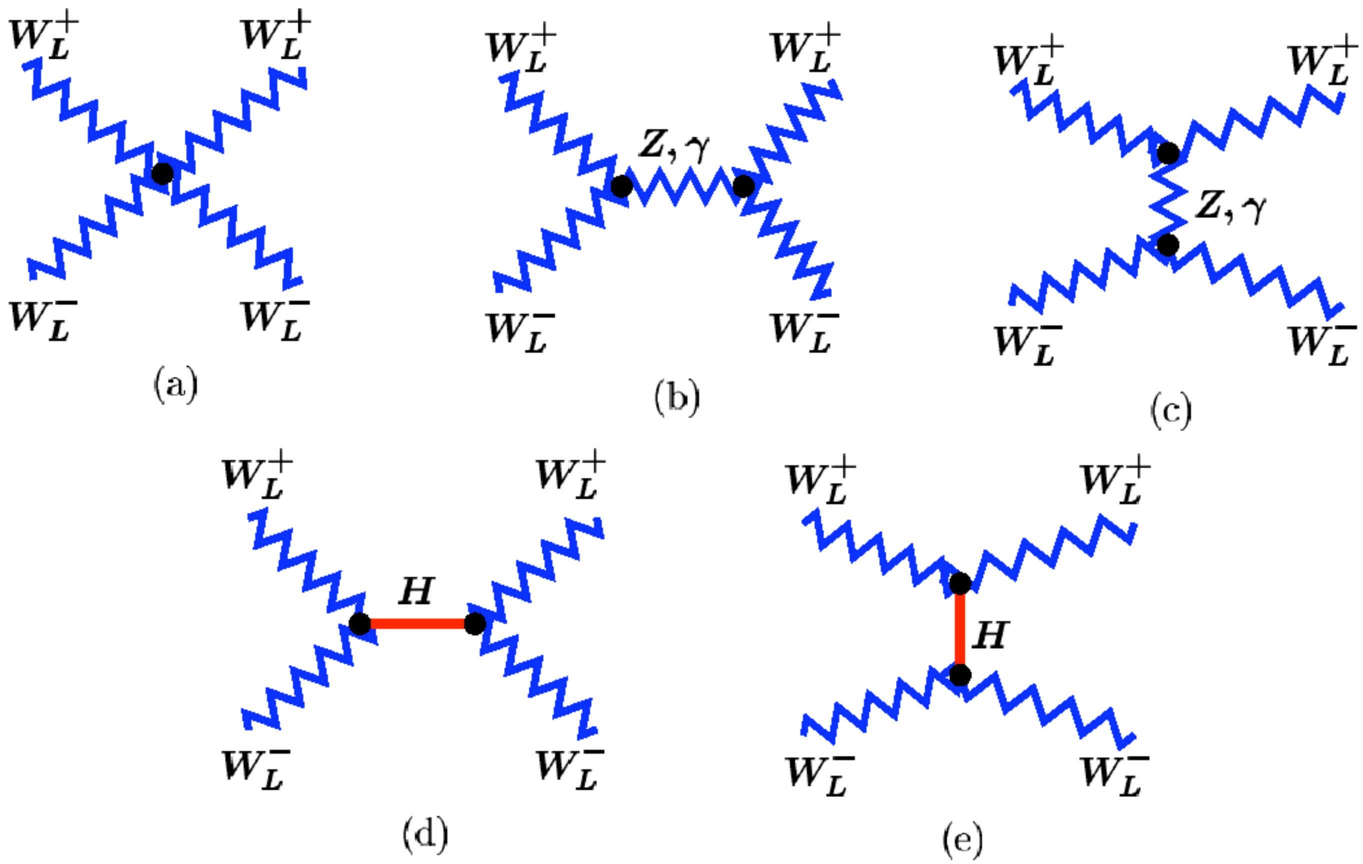
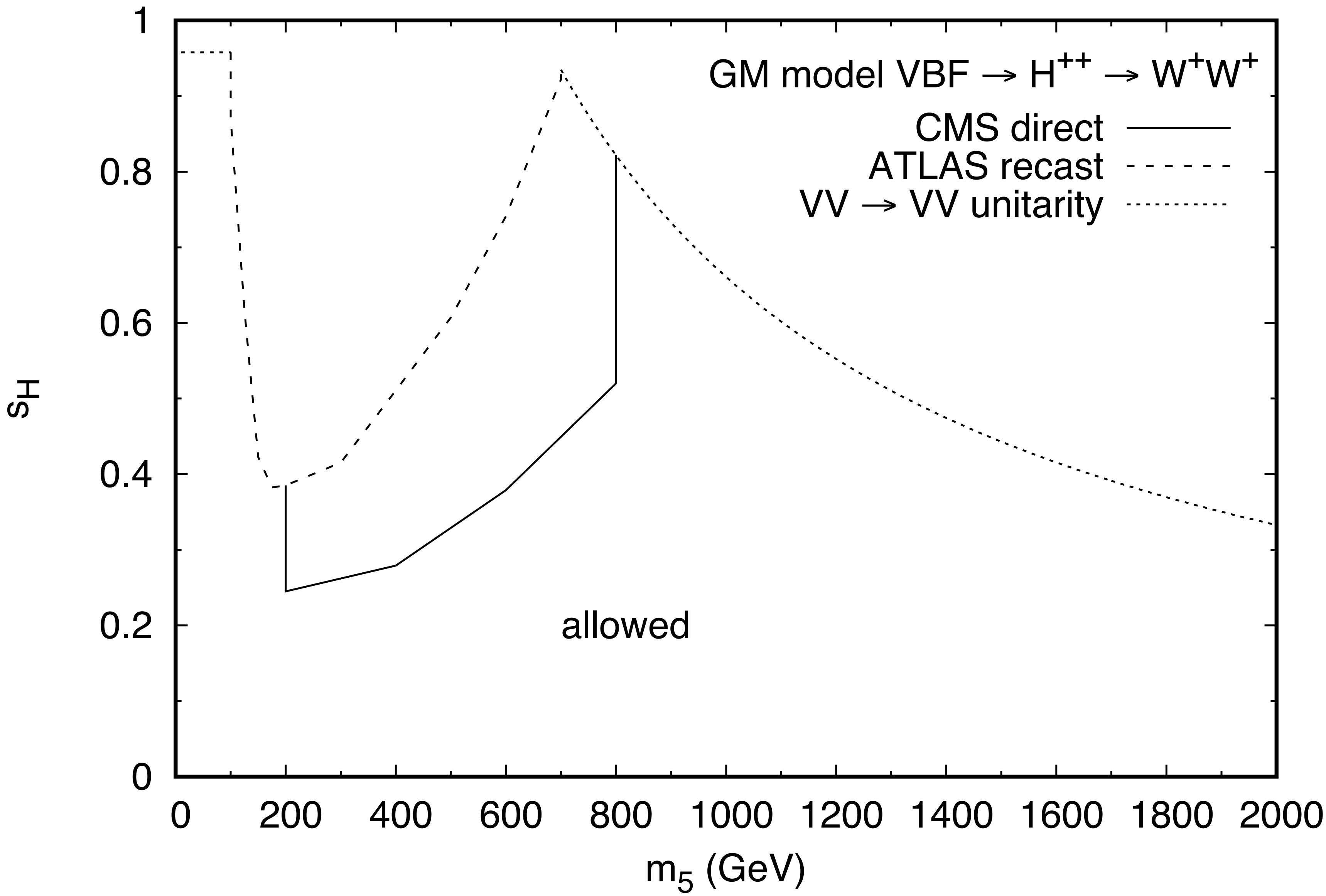


figure: S. Chivukula

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

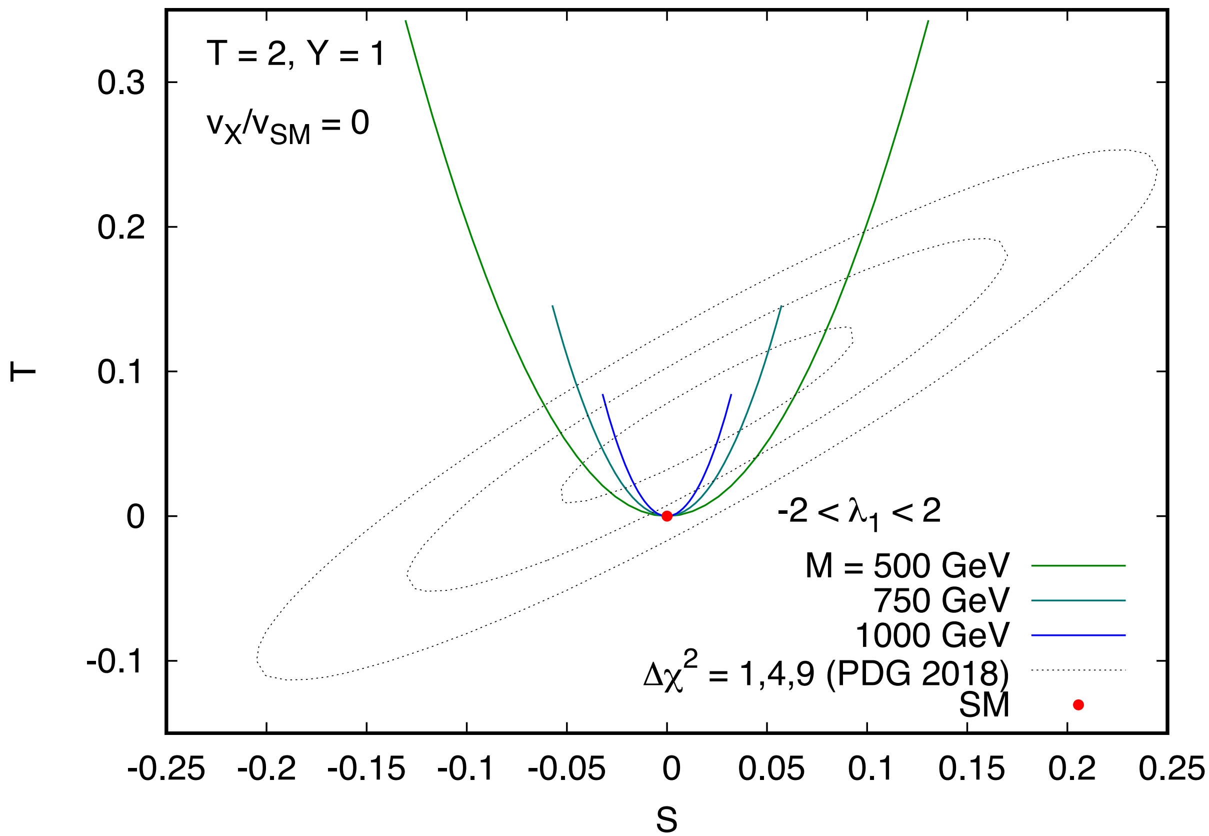
- $H^{++} = \chi^{+2}$: analogue of H_5^{++}
- ϕ^+, χ^{+1}, $(\chi^{-1})^*$ mix: no purely fermiophobic analogue of H_5^+
- Only 2 CP-even neutral scalars (h^0, H^0): no analogue of H_5^0

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

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

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

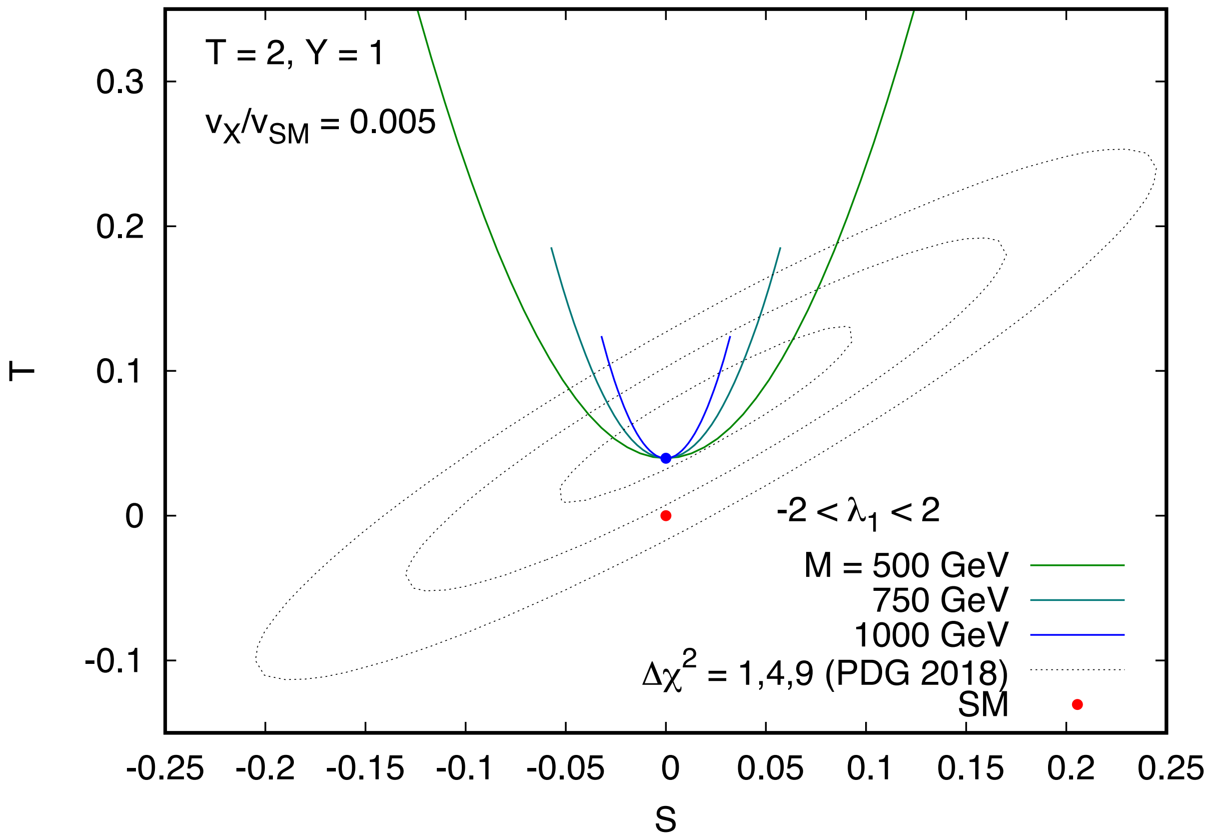
Take advantage of correlation between S and T to try to ease the constraint.



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

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

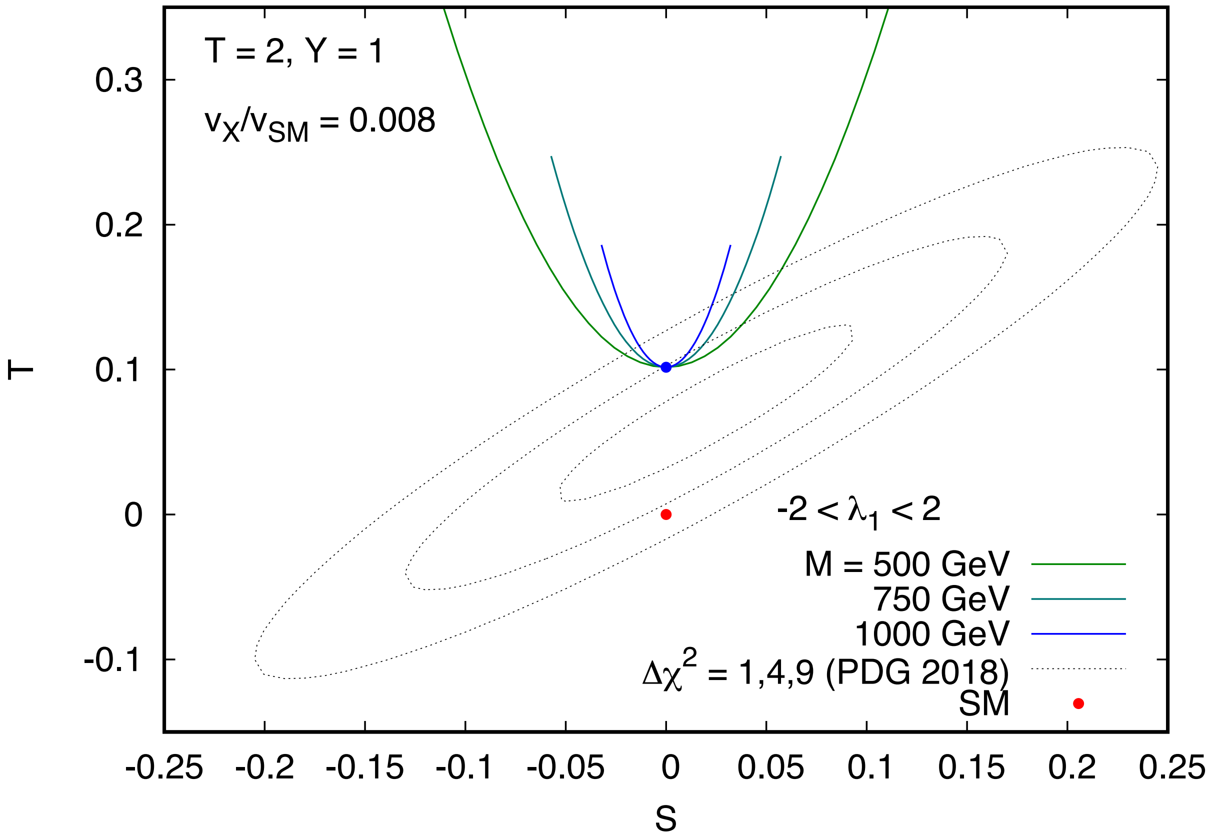
Take advantage of correlation between S and T to try to ease the constraint.



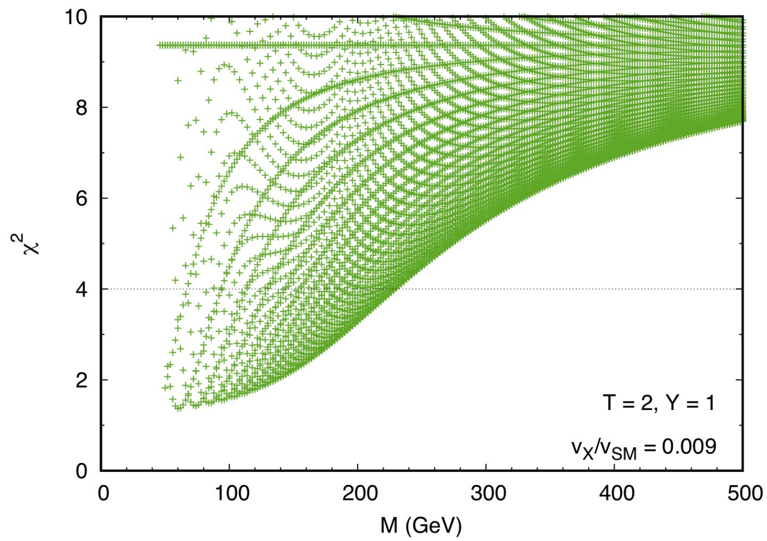
$$S_{\text{loop}} \sim -\frac{\delta m^2}{M^2} \qquad T_{\text{loop}} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\text{loop}} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$

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

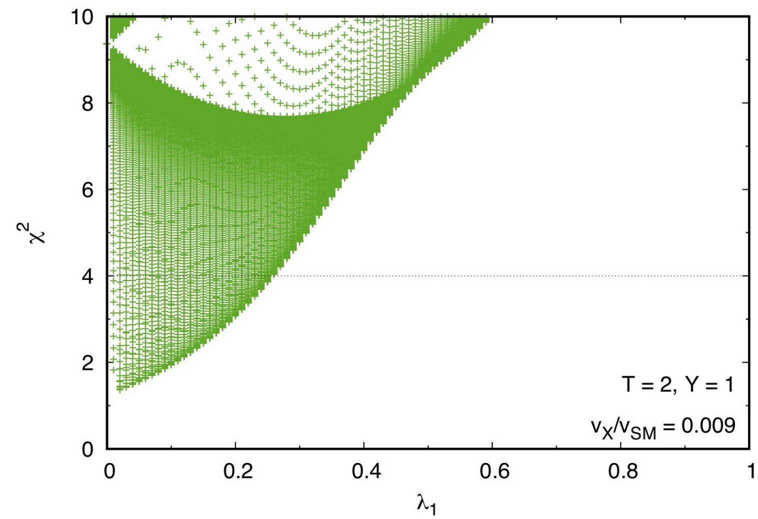
Take advantage of correlation between S and T to try to ease the constraint.



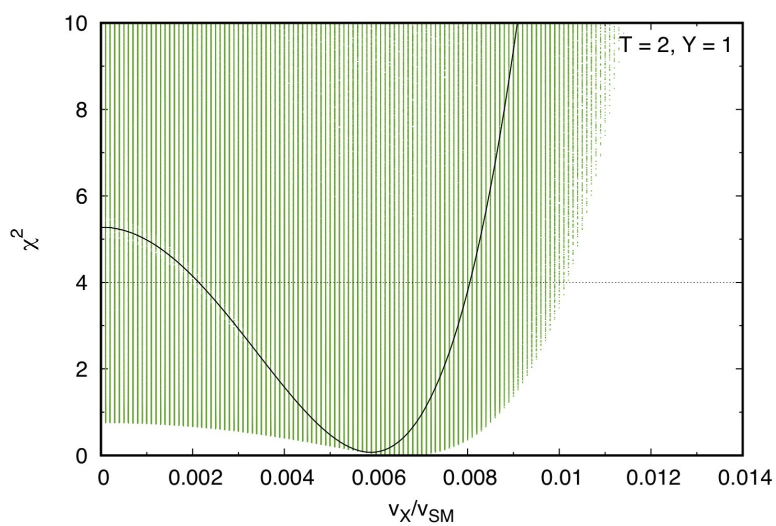
$$S_{\text{loop}} \sim -\frac{\delta m^2}{M^2} \qquad T_{\text{loop}} \sim \frac{(\delta m^2)^2}{M^2 M_Z^2} \qquad U_{\text{loop}} \sim \left(\frac{\delta m^2}{M^2}\right)^2$$



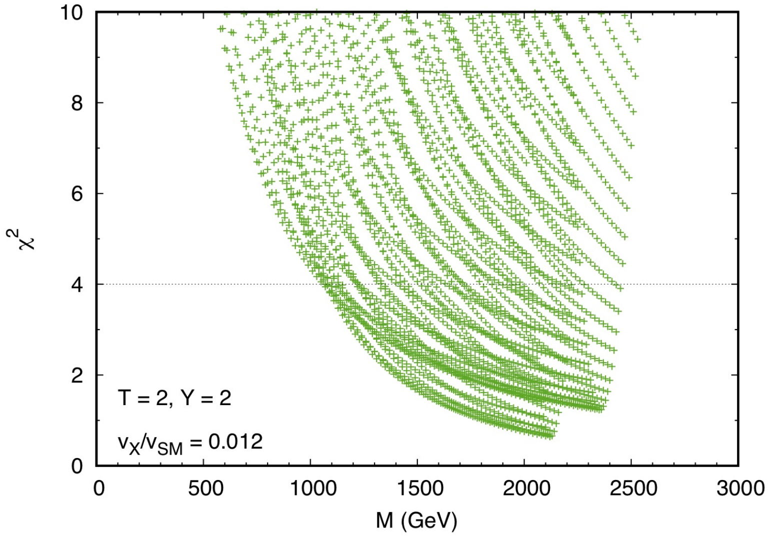
T = 2, Y = 1
v_X/v_{SM} = 0.009
χ^2
M (GeV)



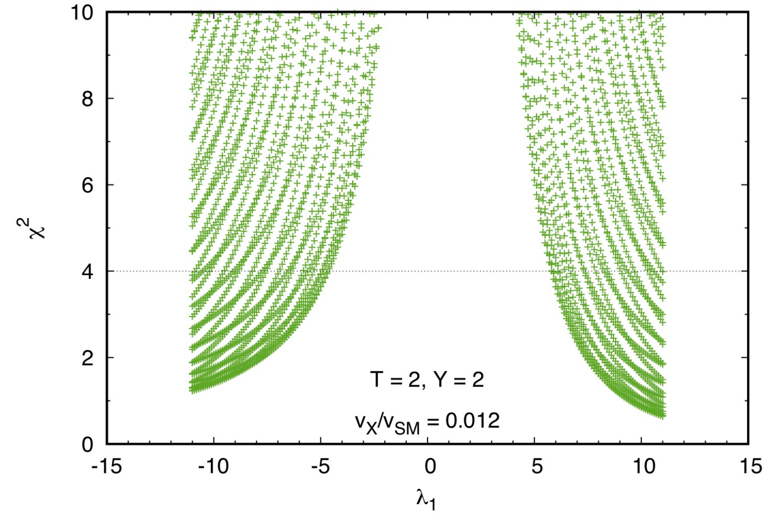
T = 2, Y = 1
v_X/v_{SM} = 0.009
χ^2
λ_1



T = 2, Y = 1
χ^2
v_X/v_{SM}



T = 2, Y = 2
v_X/v_{SM} = 0.012
M (GeV)
χ^2



T = 2, Y = 2
v_X/v_{SM} = 0.012
λ_1
χ^2