Extended scalar sectors with Higgs triplets

Heather Logan
Carleton University
Ottawa, Canada

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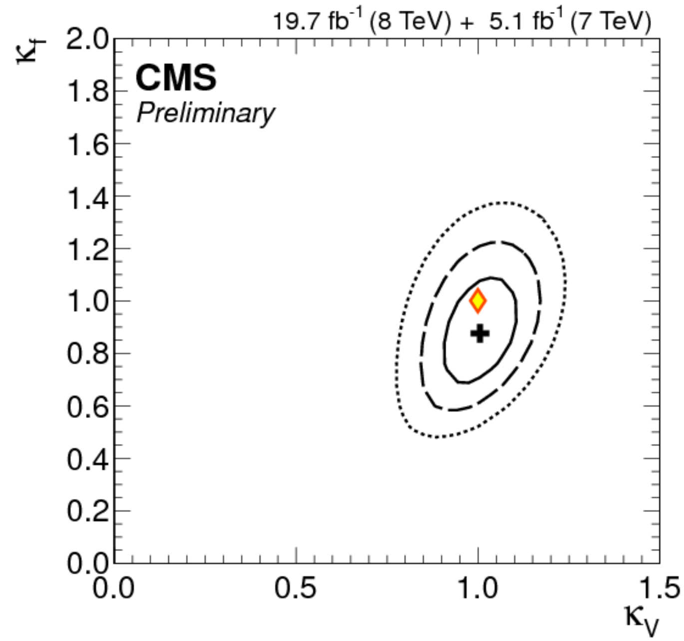
Motivation for isospin ≥ 1



hWW coupling always suppressed in models with doublets/singlets:

- SM: $2i\frac{M_W^2}{v}g_{\mu\nu}$ ($v \simeq 246$ GeV)

- 2HDM: $2i\frac{M_W^2}{v}g_{\mu\nu}\sin(\beta-\alpha)$

- SM + singlet: $2i\frac{M_W^2}{v}g_{\mu\nu}\cos\alpha$ ($h = \phi\cos\alpha - s\sin\alpha$)

hWW coup can be enhanced in models with triplets (or larger):

- SM + some multiplet X: $2i\frac{M_W^2}{v}g_{\mu\nu}\cdot\frac{v_X}{v}2\left[T(T+1)-\frac{Y^2}{4}\right]$

$(Q = T^3 + Y/2)$

- scalar with isospin ≥ 1
- must have a non-negligible vev
- must mix into the observed Higgs h

Problem with isospin ≥ 1: the ρ parameter

$\rho \equiv$ ratio of strengths of charged and neutral weak currents

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = \frac{\sum_k 2[T_k(T_k+1) - Y_k^2/4]v_k^2}{\sum_k Y_k^2 v_k^2}$$

($Q = T^3 + Y/2$, vevs defined as $\langle \phi_k^0 \rangle = v_k/\sqrt{2}$ for complex reps and $\langle \phi_k^0 \rangle = v_k$ for real reps)

PDG 2014: $\rho = 1.00040 \pm 0.00024$

SM + real triplet ξ $(Y=0)$: $\rho > 1$
SM + complex triplet χ $(Y=2)$: $\rho < 1$

1) Small triplet vev, $v_\chi <$ few GeV: Higgs Triplet Model ν mass

2) Combine two triplets: $\langle \chi^0 \rangle = v_\chi$, $\langle \xi^0 \rangle = v_\xi$; doublet $\langle \phi^0 \rangle = v_\phi/\sqrt{2}$

$$\rho = \frac{v_\phi^2 + 4v_\xi^2 + 4v_\chi^2}{v_\phi^2 + 8v_\chi^2} = 1 \text{ when } v_\xi = v_\chi$$

Symmetry point of view: Georgi & Machacek 1985; Chanowitz & Golden 1985
Impose global SU(2)$_L\times$SU(2)$_R$ symmetry on scalar sector
$\Longrightarrow$ breaks to custodial SU(2) upon EWSB; $\rho = 1$ at tree level

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs bidoublet + two isospin-triplets in a bitriplet:

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

Physical spectrum: Custodial symmetry fixes almost everything!

$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \to \mathrm{SU}(2)_{\mathrm{custodial}}$:

Bidoublet: $2 \times 2 \to 1 + 3$

Bitriplet: $3 \times 3 \to 1 + 3 + 5$

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

- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstones m_3

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5

Phenomenology I:

Vevs: $\langle\Phi\rangle = \frac{v_\phi}{\sqrt{2}} I_{2\times 2}$, $\langle X\rangle = v_\chi I_{3\times 3}$ $\Rightarrow$ $c_H = \frac{v_\phi}{v}$, $s_H = \frac{2\sqrt{2} v_\chi}{v}$

Two custodial-singlet states are mixtures of $\phi^{0,r}$ and custodial singlet from X, mixing angle α:

$$h = c_\alpha \phi^{0,r} - s_\alpha H_1'^0, \qquad H = s_\alpha \phi^{0,r} + c_\alpha H_1'^0$$

Couplings:

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

$$\kappa_V^H = s_\alpha c_H + \sqrt{8/3} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

- plus $\Delta\kappa_\gamma$, $\Delta\kappa_{Z\gamma}$ due to $H_3^\pm$, $H_5^\pm$, $H_5^{\pm\pm}$ in the loop.
- Higgs-to-Higgs decays $H \to hh$ possible.

Things to note:

- Usual 2HDM ϕVV coupling sum rule is violated:

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1 + \frac{5}{3} s_H^2$$

- Mixed $\phi VV \times \phi f f$ coupling sum rule is same as in 2HDM:

$$\kappa_V^h \kappa_f^h + \kappa_V^H \kappa_f^H = 1$$

Phenomenology II:

Two custodial triplets are mixtures of $(\phi^+, \phi^{0,i})$ and custodial triplet from X:

$$G^{0,\pm} = c_H \Phi_3^{0,\pm} + s_H H_3'^{0,\pm} \qquad H_3^{0,\pm} = -s_H \Phi_3^{0,\pm} + c_H H_3'^{0,\pm}$$

Couplings to fermions are completely analogous to Type-I 2HDM:

$$H_3^0 \bar{u} u : \quad \frac{m_u}{v} \tan\theta_H \gamma_5, \qquad H_3^0 \bar{d} d : \quad -\frac{m_d}{v} \tan\theta_H \gamma_5,$$

$$H_3^+ \bar{u} d : \quad -i\frac{\sqrt{2}}{v} V_{ud} \tan\theta_H \left(m_u P_L - m_d P_R\right),$$

$$H_3^+ \bar{\nu} \ell : \quad i\frac{\sqrt{2}}{v} \tan\theta_H m_\ell P_R.$$

$Z H_3^+ H_3^-$ coupling also same as in 2HDM: constraints from $b \to s\gamma$, $B_s \to \mu\mu$, R_b, etc. translate directly.

Vector-phobic: no $H_3 VV$ couplings

To do: better understand mapping onto 2HDM in order to translate LHC constraints.

Phenomenology III:

Custodial fiveplet comes only from X: fermiophobic! no gluon fusion

$H_5 VV$ couplings are nonzero: production in VBF; $W\phi/Z\phi$

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

$g_5 \equiv \sqrt{2} s_H$ fixed by $VV \to VV$ unitarization sum rule:

$$
(\kappa_V^h)^2 + (\kappa_V^H)^2 - \frac{5}{6}(g_5)^2 = 1
$$

Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

Higgs-to-Higgs decays not yet investigated (that I know of).

Proposed strategy: Georgi-Machacek model

1) "2HDM-like" sector

- Expt signatures of h^0, H^0, (H_3^+, H_3^0, H_3^-) are (largely?) the same as in the Type-I 2HDM.
- Combination of different channels to constrain parameter space will be somewhat different.

$\rightarrow$ Develop mapping of existing 2HDM Type-I searches/constraints onto GM model, + strategy to present results.

2) Custodial fiveplet sector

- Expt signatures of $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ are novel: e.g., VBF $\rightarrow H_5^+ \rightarrow W^+Z$.

Godfrey & Moats 1003.3033

$\rightarrow$ New theory deliverables: cross sections, decay BRs/widths.

Internal note LHCHXSWG-INT-2015-002: xsecs & widths for VBF $H_5^+ \rightarrow WZ$

Propose to focus on deliverables for YR4:

- Final or almost-final results for mid-July general meeting
- Complete draft by Oct 1, arXiv submission December 2015

Existing tools

VBF@NNLO: Cross sections for VBF production of h^0, H^0, H_5^0, $H_5^{\pm}$, $H_5^{\pm\pm}$ at NNLO in QCD.

P. Bolzoni, F. Maltoni, S.-O. Moch, & M. Zaro, 1003.4451, 1109.3717

http://vbf-nnlo.phys.ucl.ac.be/vbf.html

GMCALC: Spectrum calculator; checks theoretical & indirect expt constraints ($b \to s\gamma$, etc). Generates param_card.dat.

K. Hartling, K. Kumar & H.E. Logan, 1412.7387

http://people.physics.carleton.ca/~logan/gmcalc/

FeynRules implementation: LO for MG5 K. Kumar

http://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel

NLO QCD version for MG5_aMC@NLO being developed. C. Degrand

Twiki page at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGGM

(linked from WG3)

Discussion

- requests from experimentalists for deliverables

- issues needing more discussion

  will schedule dedicated meeting(s)

- any interest in the Higgs Triplet Model?

  pure-triplet states are pair produced

BACKUP

Contents of internal note LHCHXSWG-INT-2015-002

1) LO, NLO, NNLO total cross sections for VBF $\rightarrow H_5^+$
- for a benchmark value of s_H (xsec scales with s_H^2)
- $\sqrt{s} = 8$ TeV: $m_5 = 200 \ldots 600$ GeV in steps of 20 GeV + $m_5 = 650 \ldots 1000$ GeV in steps of 50 GeV
- $\sqrt{s} = 13$ TeV: $m_5 = 200 \ldots 600$ GeV in steps of 20 GeV + $m_5 = 650 \ldots 2000$ GeV in steps of 50 GeV

2) LO decay width for $H_5^+ \rightarrow W^+ Z$
- for a benchmark value of s_H (width scales with s_H^2)
- $m_5 = 200 \ldots 600$ GeV in steps of 20 GeV + $m_5 = 650 \ldots 2000$ GeV in steps of 50 GeV

3) Some suggestions (and rationales) for benchmark choices of s_H and BR($H_5^+ \rightarrow W^+ Z$)

Motivation for isospin ≥ 1

Enhancement of (all) the h couplings is also interesting because it can hide a non-SM contribution to the Higgs BRs.

LHC measures rates in particular final states:

$$\text{Rate} = \frac{\sigma_{\text{SM}}\Gamma_{\text{SM}}}{\Gamma_{\text{SM}}^{\text{tot}}} \to \frac{\kappa^2\sigma_{\text{SM}} \cdot \kappa^2\Gamma_{\text{SM}}}{\kappa^2\Gamma_{\text{SM}}^{\text{tot}} + \Gamma_{\text{new}}}$$

Rates are identical to SM Higgs predictions if

$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}}$$

Constraint on Γ^{tot} (equivalently on κ) from off-shell $gg\ (\to h^*) \to ZZ$ assumes no new resonances in s-channel: a light H can cancel effect of modified h couplings. 1412.7577

GM is a concrete model in which this can be studied further.

Physical spectrum: Custodial symmetry fixes almost everything!

Bidoublet: $2 \times 2 \to 3 + 1$ Bitriplet: $3 \times 3 \to 5 + 3 + 1$

Custodial 5-plet $(H_5^{++}, H_5^{+}, H_5^0, H_5^-, H_5^{--})$, common mass m_5

$H_5^{++} = \chi^{++}$, $H_5^+ = (\chi^+ - \xi^+)/\sqrt{2}$, $H_5^0 = \sqrt{2/3}\,\xi^0 - \sqrt{1/3}\,\chi^{0,r}$ (fermiophobic)

Custodial triplet (H_3^+, H_3^0, H_3^-), common mass m_3

$H_3^+ = -\sin\theta_H \phi^+ + \cos\theta_H (\chi^+ + \xi^+)/\sqrt{2}$, $H_3^0 = -\sin\theta_H \phi^{0,i} + \cos\theta_H \chi^{0,i}$; $\tan\theta_H = 2\sqrt{2} v_\chi / v_\phi$

(orthogonal triplet is the Goldstones) (gauge-phobic)

Two custodial singlets h^0, H^0, masses m_h, m_H, mixing angle α

$$h^0 = \cos\alpha\,\phi^{0,r} - \sin\alpha(\sqrt{1/3}\,\xi^0 + \sqrt{2/3}\,\chi^{0,r})$$
$$H^0 = \sin\alpha\,\phi^{0,r} + \cos\alpha(\sqrt{1/3}\,\xi^0 + \sqrt{2/3}\,\chi^{0,r})$$

Most general scalar potential:

Aoki & Kanemura, 0712.4053

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

Hartling, Kumar & HEL, 1404.2640

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

9 parameters, 2 fixed by G_F and m_h.
Free params are m_H, m_3, m_5, s_H, α, plus 2 triple-scalar coups.

$s_H \equiv \sin\theta_H = 2\sqrt{2}v_\chi/v$

(Two free parameters can be eliminated by imposing Z_2 symmetry $X \to -X$. Removes M_1 and M_2; can express everything in terms of m_H, m_3, m_5, s_H, α. Price to pay is upper bound on all scalar masses $m_H, m_3, m_5 \lesssim 700$ GeV.)

Aoki & Kanemura, 0712.4053

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9 parameters, 2 fixed by G_F and m_h.
Free params are m_H, m_3, m_5, s_H, α plus 2 triple-scalar coups.

$(UXU^\dagger)_{ab}$ is the matrix X in the Cartesian basis of SU(2), found using

$$U = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}$$

Theory constraints

Perturbative unitarity: impose $|\mathrm{Re}\, a_0| < 1/2$ on eigenvalues of coupled-channel matrix of $2 \to 2$ scalar scattering processes. Constrain ranges of λ_{1-5}.

Aoki & Kanemura, 0712.4053

Bounded-from-belowness of the scalar potential: consider all combinations of fields nonzero. Further constraints on λ_{1-5}.

Hartling, Kumar & HEL, 1404.2640

Absence of deeper custodial SU(2)-breaking minima: numerical check that desired minimum is the deepest (1-dim scan over finite parameter range). Constraints involve all 9 parameters.

Hartling, Kumar & HEL, 1404.2640

(we do not consider situations in which the desired vacuum is metastable)

Indirect constraints: R_b, $b \to s\gamma$, etc.

R_b: known a long time in GM model; same form as Type-I 2HDM

HEL & Haber, hep-ph/9909335; Chiang & Yagyu, 0902.4665; Type-I: Grant, hep-ph/9410267

B_s–$\bar{B}_s$ mixing: adapted from Type-I 2HDM

Mahmoudi & Stal, 0907.1791

$B_s \to \mu^+\mu^-$: adapted from new calculation for Aligned 2HDM

Li, Lu & Pich, 1404.5865

$b \to s\gamma$: adapted from Type-I 2HDM, using SuperIso

Barger, Hewett & Phillips, PRD41, 3421 (1990); SuperIso v3.3 (Mahmoudi)

Strongest constraint is from $b \to s\gamma$: implemented in GMCALC using BR grid generated by SuperIso v3.3.

Calculation of $B_s \to \mu^+\mu^-$ also implemented in GMCALC: will become more constraining with additional LHC data.

Indirect constraints: S parameter

We also implement the S-parameter constraint, marginalizing over the T-parameter.

Rationale:

T-parameter is (notoriously) divergent at 1-loop in GM model; to cancel the divergence one must introduce a global-SU(2)$_R$–violating counterterm. Gunion, Vega & Wudka, PRD43, 2322 (1991)

Introduces a small tree-level breaking of custodial SU(2)
$\rightarrow$ small tree-level contribution to ρ parameter
$\rightarrow$ use to cancel a finite piece of the 1-loop contribution to T.