Constraining electroweak breaking from exotic scalars using LHC diboson searches

Heather Logan
Carleton University

Particle Physics Group seminar
Université de Montréal, February 16, 2016

H.E.L. & V. Rentala, 1502.01275; M.J. Harris & H.E.L., in progress

K. Hartling, K. Kumar, & H.E.L., 1404.2640, 1410.5538, 1412.7387

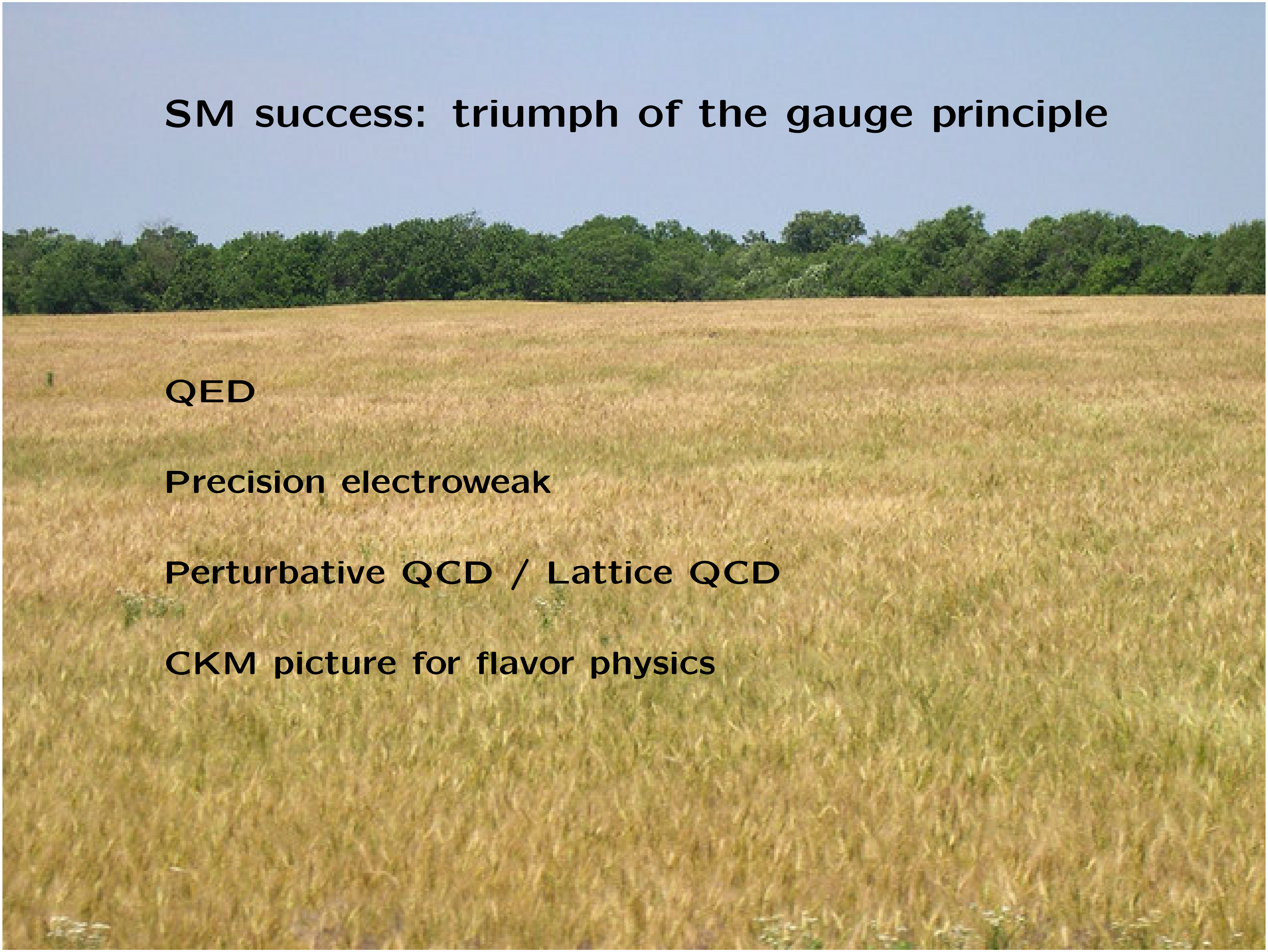
Outline

Introduction & motivation

The models

Phenomenology & LHC search prospects

Summary & outlook



SM success: triumph of the gauge principle

QED

Precision electroweak

Perturbative QCD / Lattice QCD

CKM picture for flavor physics

SM challenge: mystery of the vacuum

Origin of W, Z masses

Origin of quark & lepton masses, mixing, CP violation

Origin of neutrino masses, mixing

Dark energy / Inflation

Hierarchy

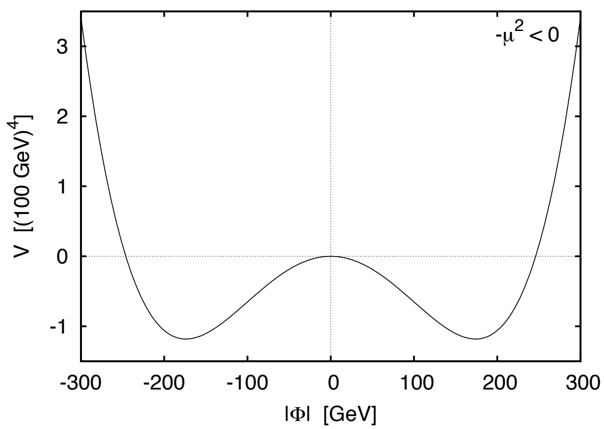
The Standard Model: EWSB from a scalar SU(2)$_L$ doublet

A one-line theory:

$$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu \Phi|^2 - [-\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2] - [y_f \bar{f}_R \Phi^\dagger F_L + \text{h.c.}]$$

Most general, renormalizable, gauge-invariant theory involving a single spin-zero (scalar) field with isospin 1/2, hypercharge 1.

$-\mu^2$ term: vacuum condensate! EW symmetry spontaneously broken; Goldstone bosons gauged away, 1 physical particle h.



$$\Phi = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}$$

Mass and vacuum expectation value of h are fixed by minimizing the Higgs potential:

$$v^2 = \mu^2/\lambda \qquad\qquad M_h^2 = 2\lambda v^2 = 2\mu^2$$

The Standard Model: EWSB from a scalar SU(2)$_L$ doublet

SM Higgs couplings to SM particles are <u>fixed</u> by the mass-generation mechanism.

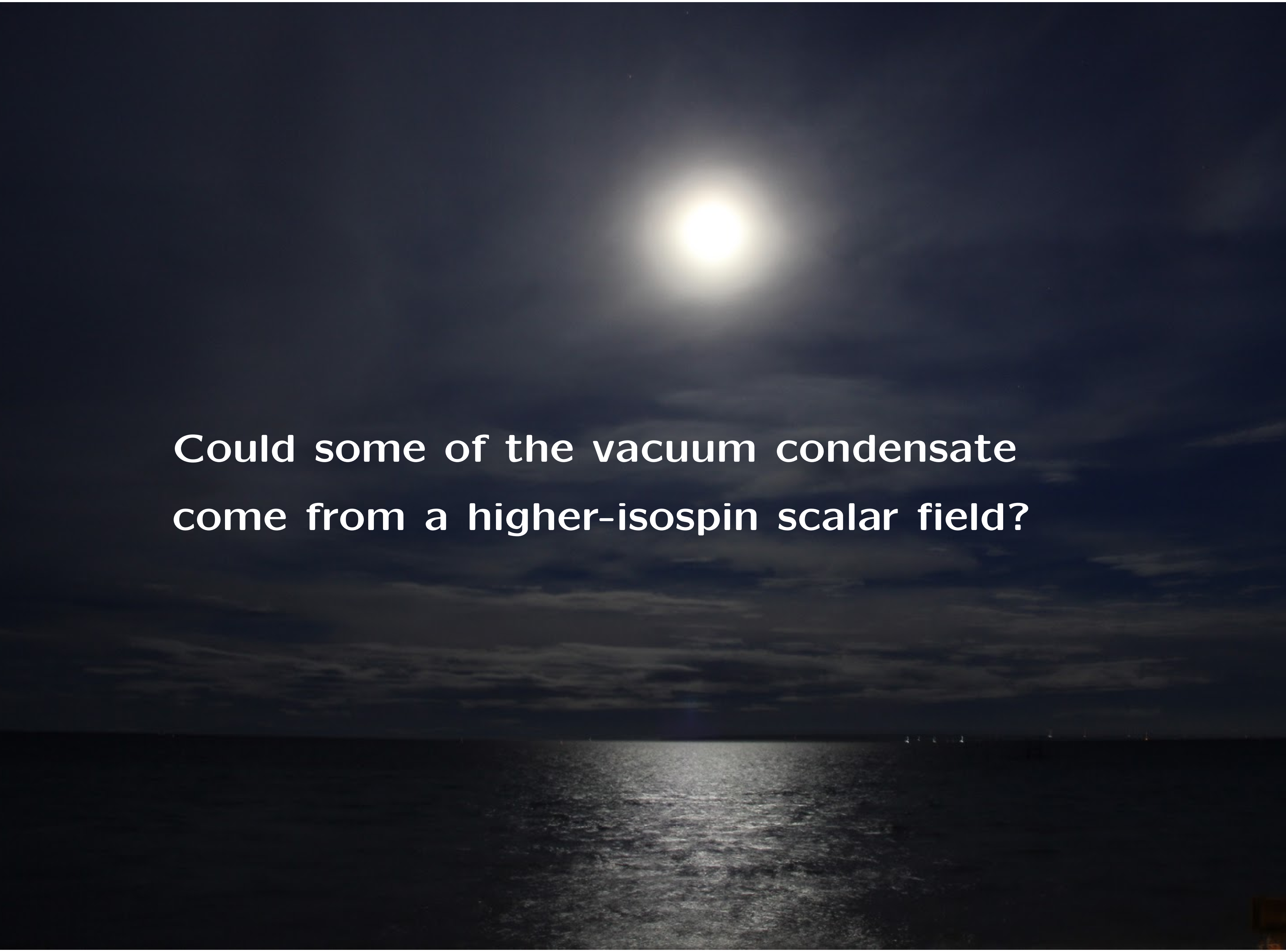
W and Z: $g_Z \equiv g/\cos\theta_W = \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu \Phi|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i(g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

$$\mathcal{L} = -y_f \bar{f}_R \Phi^\dagger F_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f: \; i m_f/v$$

Gluon pairs and photon pairs:
induced at 1-loop by fermions, W-boson.


Could some of the vacuum condensate
come from a higher-isospin scalar field?

Part of vacuum condensate from a higher-isospin scalar field?

Fermion masses can arise only from SU(2)$_L$ doublet(s)

$$\mathcal{L} = -y_f \bar{f}_R \Phi^\dagger F_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(\phi^{0,r} + v_\phi)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v_\phi/\sqrt{2} \qquad \phi^{0,r}\bar{f}f : \; i y_f/\sqrt{2} = i m_f/v_\phi$$

F_L is doublet, f_R is singlet, need Φ doublet for gauge invariance

Top quark Yukawa perturbativity $\Rightarrow$ lower bound on doublet vev: define $\cos\theta_H \equiv v_\phi/v_{\rm SM}$, then $\tan\theta_H < 10/3$ (or $\cos\theta_H > 0.287$)

Scalar couplings to fermions come from their doublet content

$$\Phi = \begin{pmatrix} \phi^+ \\ (v_\phi + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix}$$

With other scalar fields in play, Goldstone bosons are linear combinations of different fields.

Part of vacuum condensate from a higher-isospin scalar field?

W and Z masses arise from anything carrying $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

$$M_W^2 = \frac{g^2}{4} \sum_k 2 \left[T_k(T_k+1) - \frac{Y_k^2}{4} \right] v_k^2 = \frac{g^2}{4} v_{\mathrm{SM}}^2$$

$$M_Z^2 = \frac{g^2}{4\cos^2\theta_W} \sum_k Y_k^2 v_k^2 = \frac{g^2}{4\cos^2\theta_W} v_{\mathrm{SM}}^2$$

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

Used $Q = 0$ for component carrying the vev to simplify expressions

Top Yukawa perturbativity $\rightarrow (v_\phi / v_{\mathrm{SM}})^2 > (0.287)^2 = 0.082$
$\Rightarrow$ At least 8.2% of $M_{W,Z}^2$ comes from doublet.

Lots of room for higher-isospin scalar contributions!

Can we constrain this exotic possibility?

Problem with higher-isospin scalar multiplets

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

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

($Q = T^3 + Y/2$, 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: $\rho = 1.000\,40 \pm 0.000\,24$

We can still have higher-isospin scalars with non-negligible vevs;
only two approaches using symmetry: (could also tune ρ by hand, but icky)

1) 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 1985; Chanowitz & Golden 1985

2) $\rho = 1$ "by accident" for $(T, Y) = (\frac{1}{2}, 1)$ doublet; $(3, 4)$ septet

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

Larger solutions forbidden by perturbative unitarity of weak charges.

Both have theoretical "issues":

1) Global SU(2)$_L\times$SU(2)$_R$ is broken by gauging hypercharge.

Gunion, Vega & Wudka 1991

Special relations among param's of *full* gauge-invariant scalar potential can only hold at one energy scale: violated by running due to hypercharge. Garcia-Pepin, Gori, Quiros, Vega, Vega-Morales, Yu 2014

Need the UV completion to be nearby!

2) Can't give the septet a vev through spontaneous breaking without generating a physical massless Goldstone boson.

Have to couple it to the SM doublet through a dimension-7 $X\Phi^*\Phi^5$ term Hisano & Tsumura 2013

Need the UV completion to be nearby!

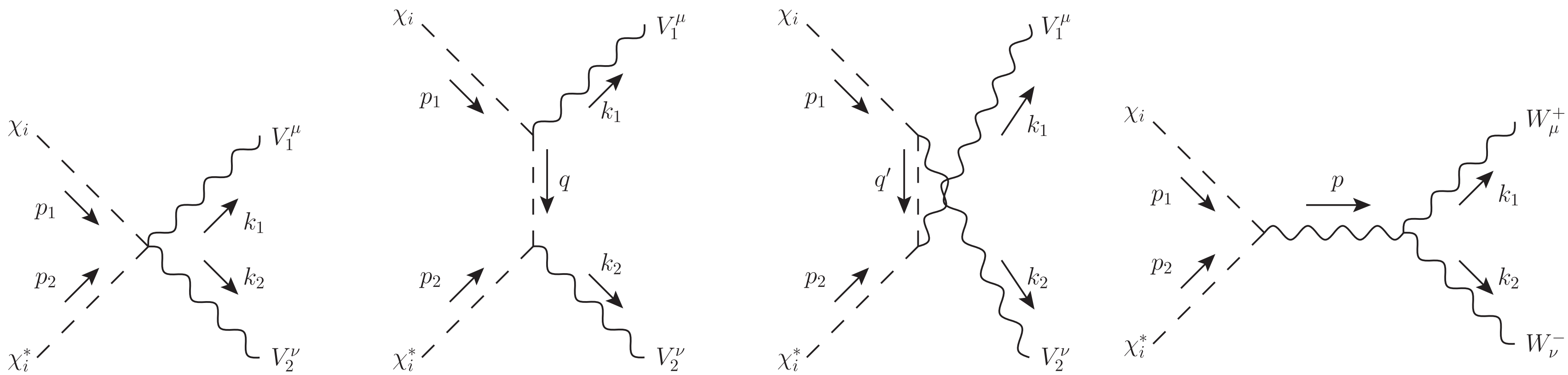
Need UV completion to solve the hierarchy problem anyway!

How large can the isospin be?

Hally, HEL, & Pilkington 1202.5073

Consider $2 \to 2$ scattering amplitudes for $\phi\phi \to V_T V_T$:
transverse SU(2)$_L$ gauge bosons

- no growth with E^2; amplitude depends on weak charges & number of ϕ's



How large can the isospin be?

Hally, HEL, & Pilkington 1202.5073

Consider $2 \to 2$ scattering amplitudes for $V_T V_T \to \phi\phi$: *transverse* $\mathrm{SU}(2)_L$ gauge bosons

- no growth with E^2; amplitude depends on weak charges & number of ϕ's

General result for complex scalar multiplet with $n = 2T + 1$:

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

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

Unitarity: require largest eigenvalue a_0^{max} satisfies $|\mathrm{Re}\, a_0| < 1/2$:

- 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 is present

(generally required in $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$-symmetric models)

Essentially a requirement that the weak charges not be too large.

The models

1) Models with global SU(2)$_L\times$SU(2)$_R$ symmetry:

   a) Georgi-Machacek model

   b) Generalizations to higher isospin

2) Model with a scalar septet

All these models share a key common feature:

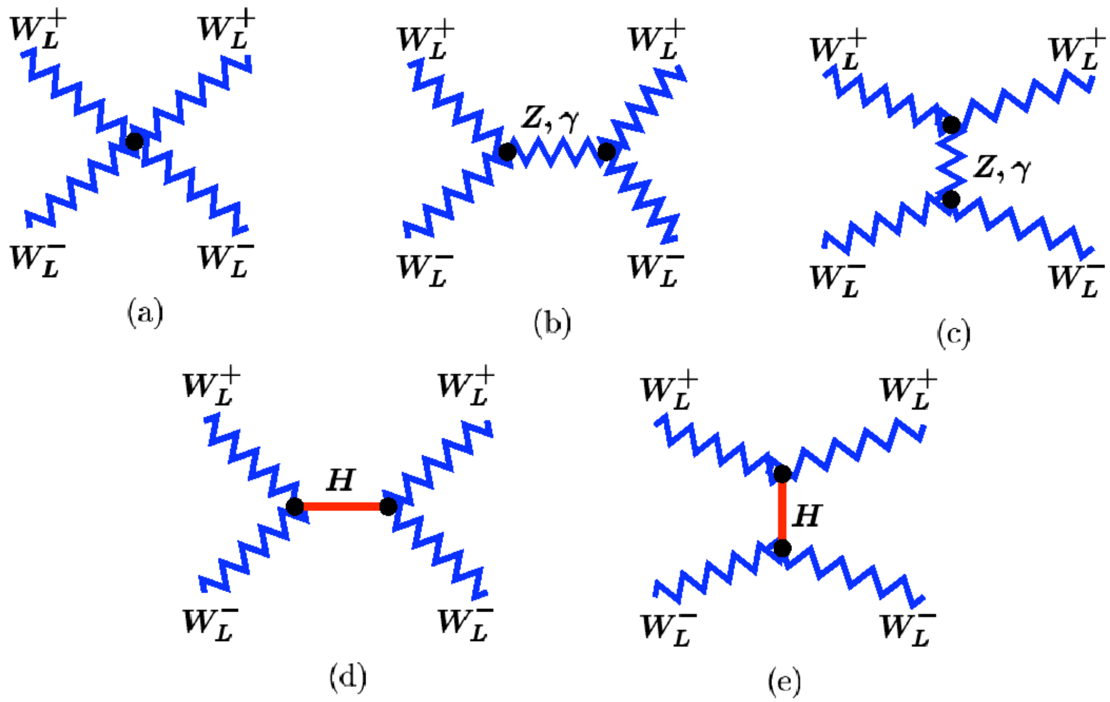
$H^{\pm\pm} \leftrightarrow W^\pm W^\pm$ and $H^\pm \leftrightarrow W^\pm Z$

with couplings controlled by vev of higher-isospin scalar(s)

Generic experimental probe is diboson resonance search in VBF.

Theoretical origin of common feature:

Unitarization of $WW \to WW$, $WW \to ZZ$ scattering amplitudes



Graphic: S. Chivukula

- SM: Higgs exchange cancels E^2/v^2 term in amplitude.
- 2HDM/SM+singlet: cancellation $\to$ sum rule $(\kappa_V^h)^2+(\kappa_V^H)^2 = 1$
- Higher-isospin scalars: $(\kappa_V^h)^2 + (\kappa_V^H)^2 > 1$, need $H^{\pm\pm}$ and $H^{\pm}$ in new u-channel diagrams: couplings inter-related

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

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!

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

- Two custodial singlets mix $\to h^0,\ H^0$
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ + Goldstones
- Custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$ unitarizes $VV \to VV$

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!

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

- Two custodial singlets mix $\to h^0$, H^0 m_h, m_H $\leftarrow$ (very similar
- Two custodial triplets mix $\to (H_3^+, H_3^0, H_3^-)$ m_3 $\leftarrow$ to 2HDM)
- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 $\leftarrow$ new!

Generalized Georgi-Machacek models

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

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

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

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

Biquartet: $4 \times 4 \to 7 + 5 + 3 + 1$

Bipentet: $5 \times 5 \to 9 + 7 + 5 + 3 + 1$

Bisextet: $6 \times 6 \to 11 + 9 + 7 + 5 + 3 + 1$

Larger bi-n-plets forbidden by perturbative unitarity 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 $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ unitarizes $VV \to VV$

- Additional states

Phenomenology I: custodial singlets h^0, H^0

Vevs: $\langle \Phi \rangle = (v_\phi/\sqrt{2}) I_{2\times 2}$, $\langle X_n \rangle = v_n I_{n\times n} \Longrightarrow$ define $c_H = v_\phi / v$

Recall $c_H^2 =$ fraction of $M_{W,Z}^2$ coming from doublet vev

Two custodial-singlet states are mixtures of $\phi^{0,r}$ and custodial singlet from higher-isospin scalars:

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

Couplings to W^+W^-/ZZ and $\bar{f}f$:

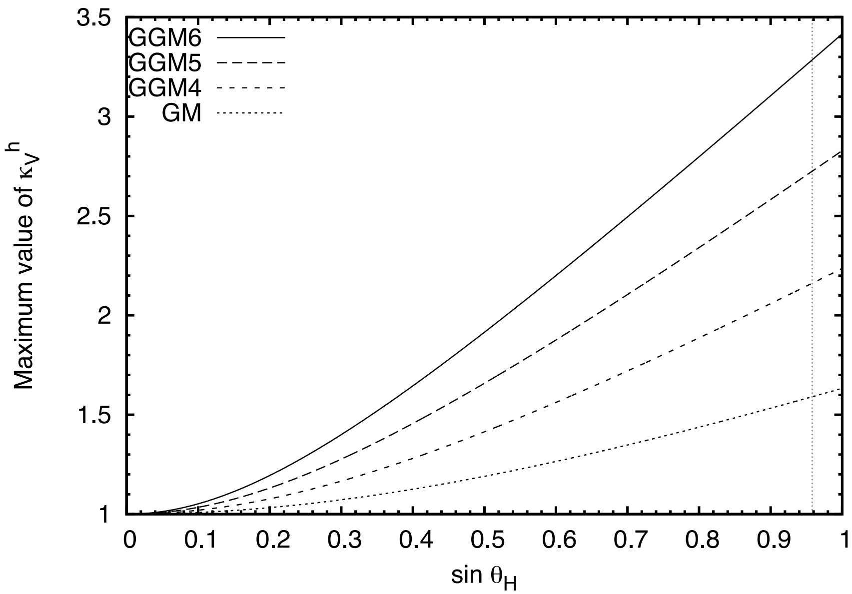
$$\kappa_V^h = c_\alpha c_H - \sqrt{A} s_\alpha s_H \qquad \kappa_f^h = c_\alpha / c_H$$
$$\kappa_V^H = s_\alpha c_H + \sqrt{A} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

Note that $\kappa_V^h \leq \left[1 + (A-1)s_H^2\right]^{1/2}$, saturated when $\kappa_V^H = 0$.
$\sqrt{A}$ factor comes from the generators: $A = 4T(T+1)/3$

$A_{\text{GM}} = 8/3, \quad A_{\text{GGM4}} = 15/3, \quad A_{\text{GGM5}} = 24/3, \quad A_{\text{GGM6}} = 35/3$

(Septet model: $A_7 = 16$)

Large enhancements of κ_V^h possible for large s_H (up to about 3.3):



Vertical line:

y_t perturbativity $\rightarrow \tan\theta_H < 10/3$

HEL & Rentala, 1502.01275

Impossible to have $\kappa_V^h, \kappa_f^h = 1$ without $s_H \rightarrow 0$:

High-precision measurements of Higgs couplings will constrain higher-isospin vacuum condensate.

$$\kappa_V^h = c_\alpha c_H - \sqrt{A} s_\alpha s_H \qquad \kappa_f^h = c_\alpha / c_H$$
$$\kappa_V^H = s_\alpha c_H + \sqrt{A} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

Phenomenology II: custodial triplet H_3^+, H_3^0, H_3^-

Couplings to fermions are the same as $H^\pm, A^0$ in Type-I 2HDM:

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

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

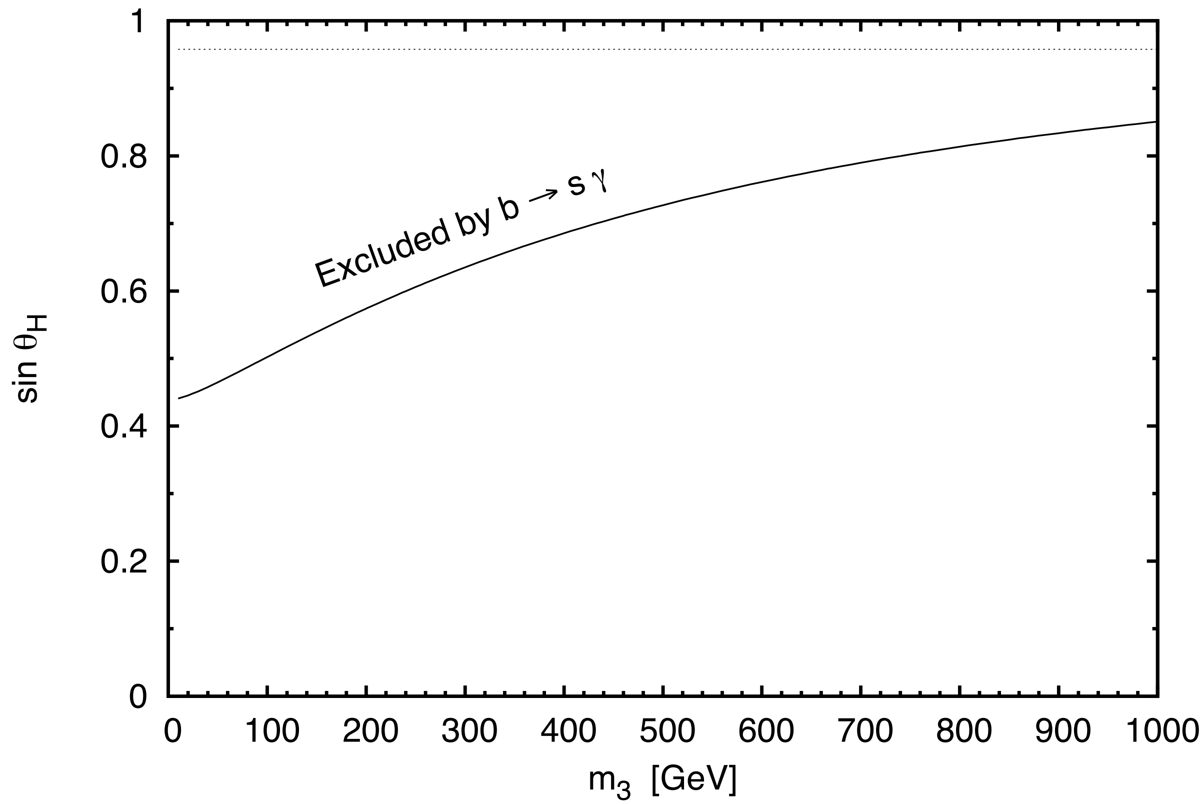
$$H_3^+ \bar\nu \ell: \quad i\frac{\sqrt{2}}{v} \tan\theta_H m_\ell P_R.$$

$Z H_3^+ H_3^-$ also the 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 at tree level.

Constraint from $b \to s\gamma$

H_3^+ in the loop: measurement constrains m_3 and $\sin\theta_H$
- Holds for all generalizations of Georgi-Machacek model
- Also constrains septet model, but not identical



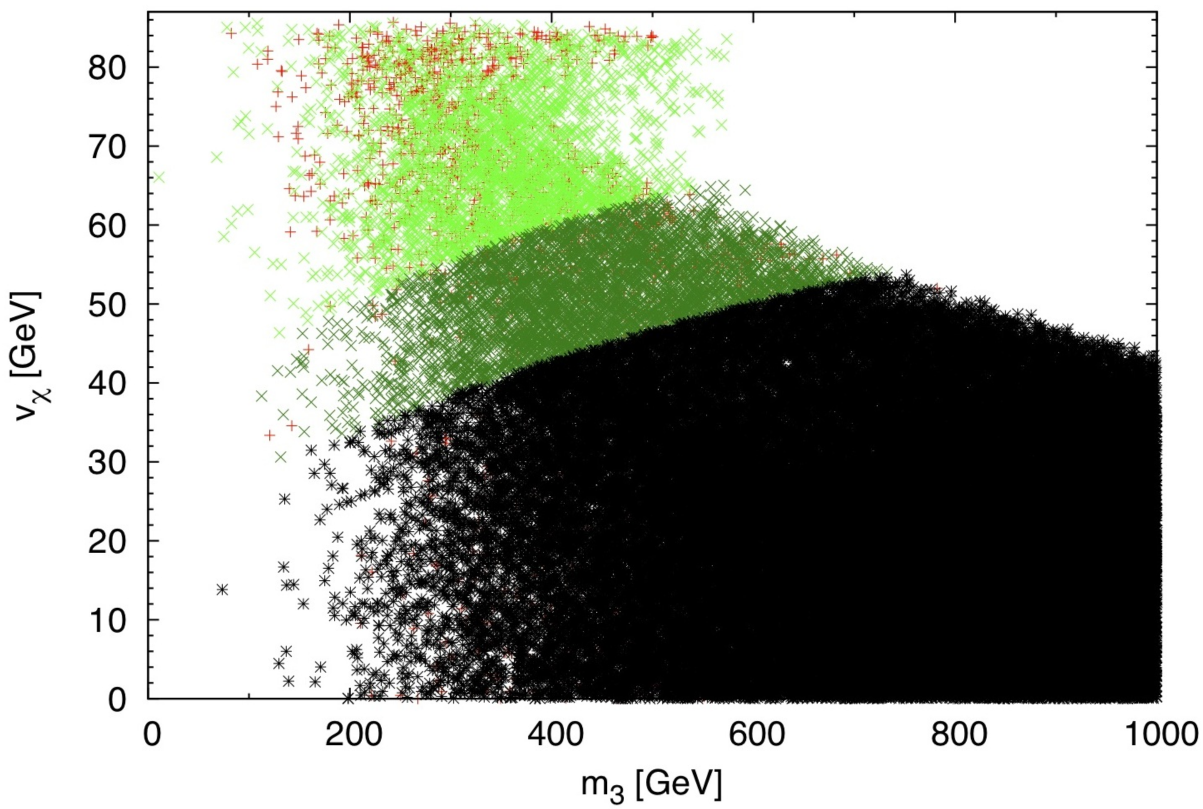
Hartling, Kumar & HEL, 1410.5538

Constraint from $b \to s\gamma$ in original Georgi-Machacek model:

Apply to original Georgi-Machacek model: $s_H^2 < 0.56$

Can constrain because high s_H at high m_3 is theoretically inaccessible.

$\Rightarrow$ at least 44% of $M_{W,Z}^2$ is due to doublet vev (Model-dependent bound)



Hartling, Kumar & HEL, 1410.5538 (Light green points excluded by $b \to s\gamma$)

Phenomenology III: custodial fiveplet $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

Custodial-fiveplet comes only from higher-isospin scalars: no couplings to fermions!

$H_5 VV$ couplings are nonzero: very different from 2HDM!

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

Coupling strength depends on the isospins of the scalars involved:

$$
g_5^{\rm GM} = \sqrt{2} s_H, \quad g_5^{\rm GGM4} = \sqrt{\frac{24}{5}} s_H, \quad g_5^{\rm GGM5} = \sqrt{\frac{42}{5}} s_H, \quad g_5^{\rm GGM6} = \frac{8}{\sqrt{5}} s_H
$$

Direct probe of higher-isospin vacuum condensate!

Phenomenology III: custodial fiveplet $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

Custodial-fiveplet comes only from higher-isospin scalars:
no couplings to fermions!

H_5VV couplings are nonzero: very different from 2HDM!

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

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

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

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

But g_5 is also fixed by $VV \to VV$ unitarization sum rule:

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

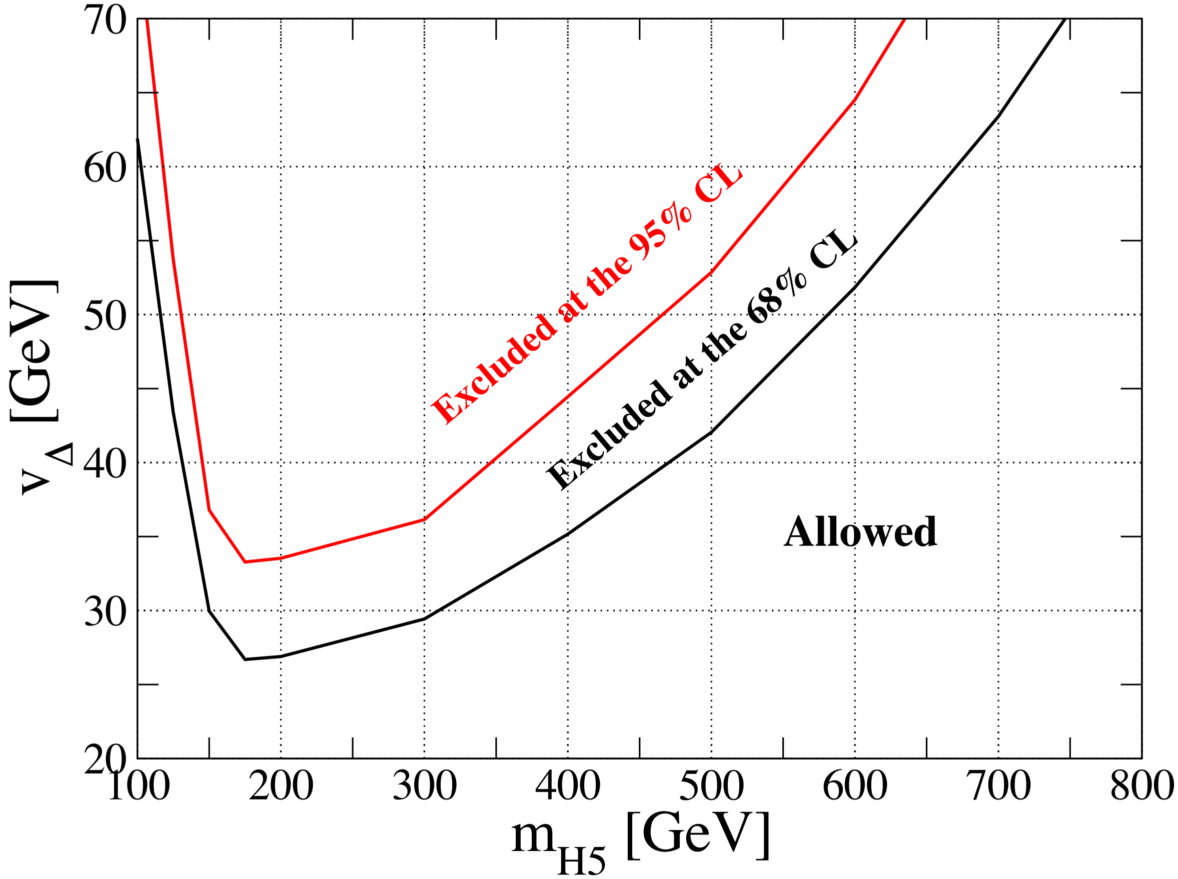
Falkowski, Rychkov & Urbano, 1202.1532 (see also Higgs Hunter's Guide)

(relies on custodial symmetry in scalar sector; same in *all* GGM models)

Constraint from VBF $H_5^{\pm\pm} \to W^\pm W^\pm \to$ same-sign dileptons

Theorist recasting of ATLAS $W^\pm W^\pm jj$ cross-section measurement ATLAS, 1405.6241

$\Rightarrow$ put limit on VBF $\to H_5^{\pm\pm}$ cross section, directly constrain g_5



$g_5 = \sqrt{2} s_H$ in GM model

$v_\Delta \equiv v_\chi = s_H v_{\mathrm{SM}}/\sqrt{8}$

Chiang, Kanemura & Yagyu, 1407.5053

What about higher H_5 masses?

Perturbative unitarity of finite part of $VV \to VV \Rightarrow$ upper bound on H_5 mass as function of s_H, just like SM Higgs mass bound!

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

- SU(2)$_L\times$SU(2)$_R$-symmetric models:

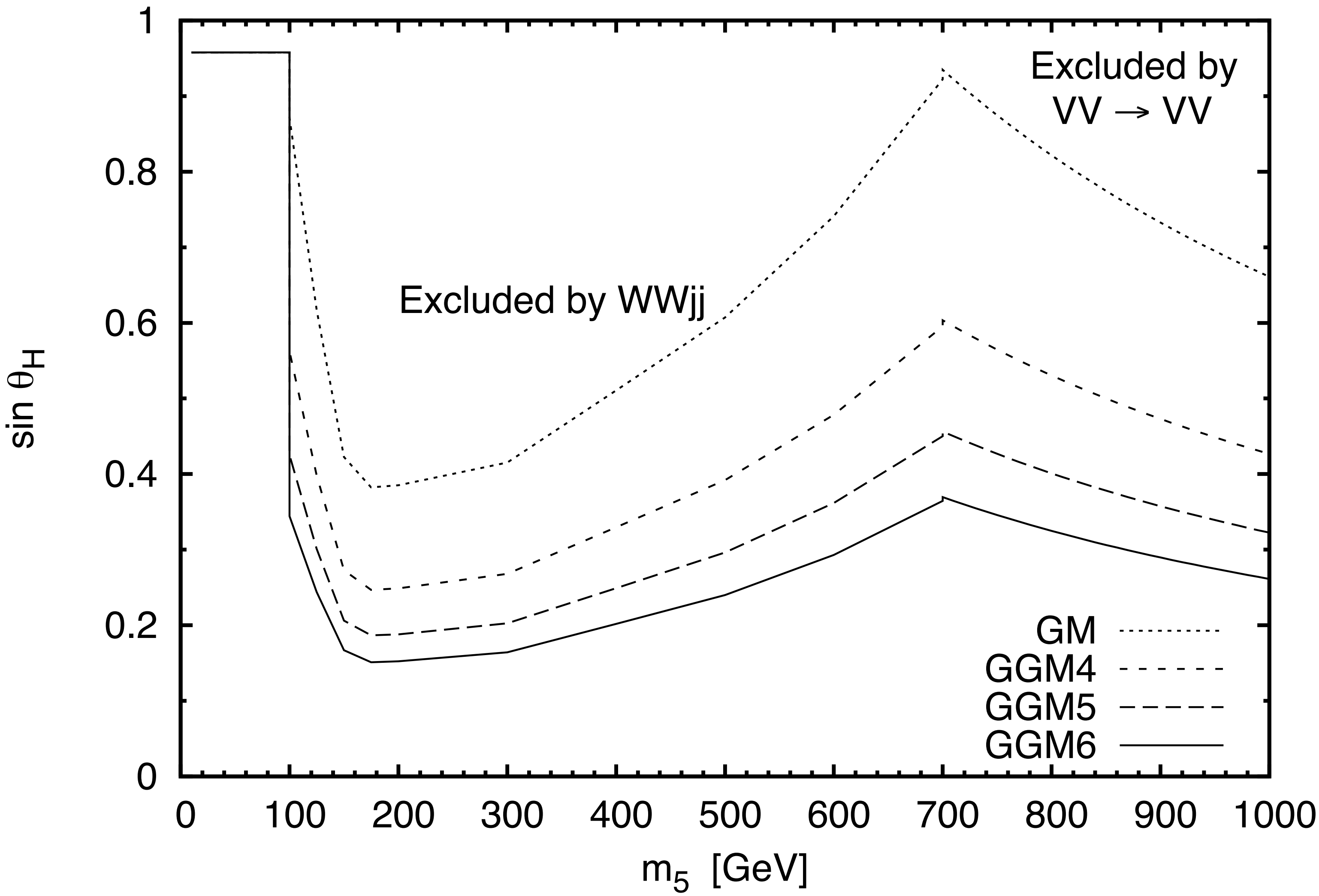
$$\left[(\kappa_V^h)^2 m_h^2 + (\kappa_V^H)^2 m_H^2 + \frac{2}{3} g_5^2 m_5^2\right] < \frac{16\pi v_{\text{SM}}^2}{5}$$

Combine with $VV \to VV$ unitarization sum rule:

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

Constraint is loosest (most conservative) when $\kappa_V^H \to 0$:

$$g_5^2 < \frac{6}{5}\frac{(16\pi v_{\text{SM}}^2 - 5m_h^2)}{(4m_5^2 + 5m_h^2)} \simeq \frac{24\pi v_{\text{SM}}^2}{5m_5^2}$$



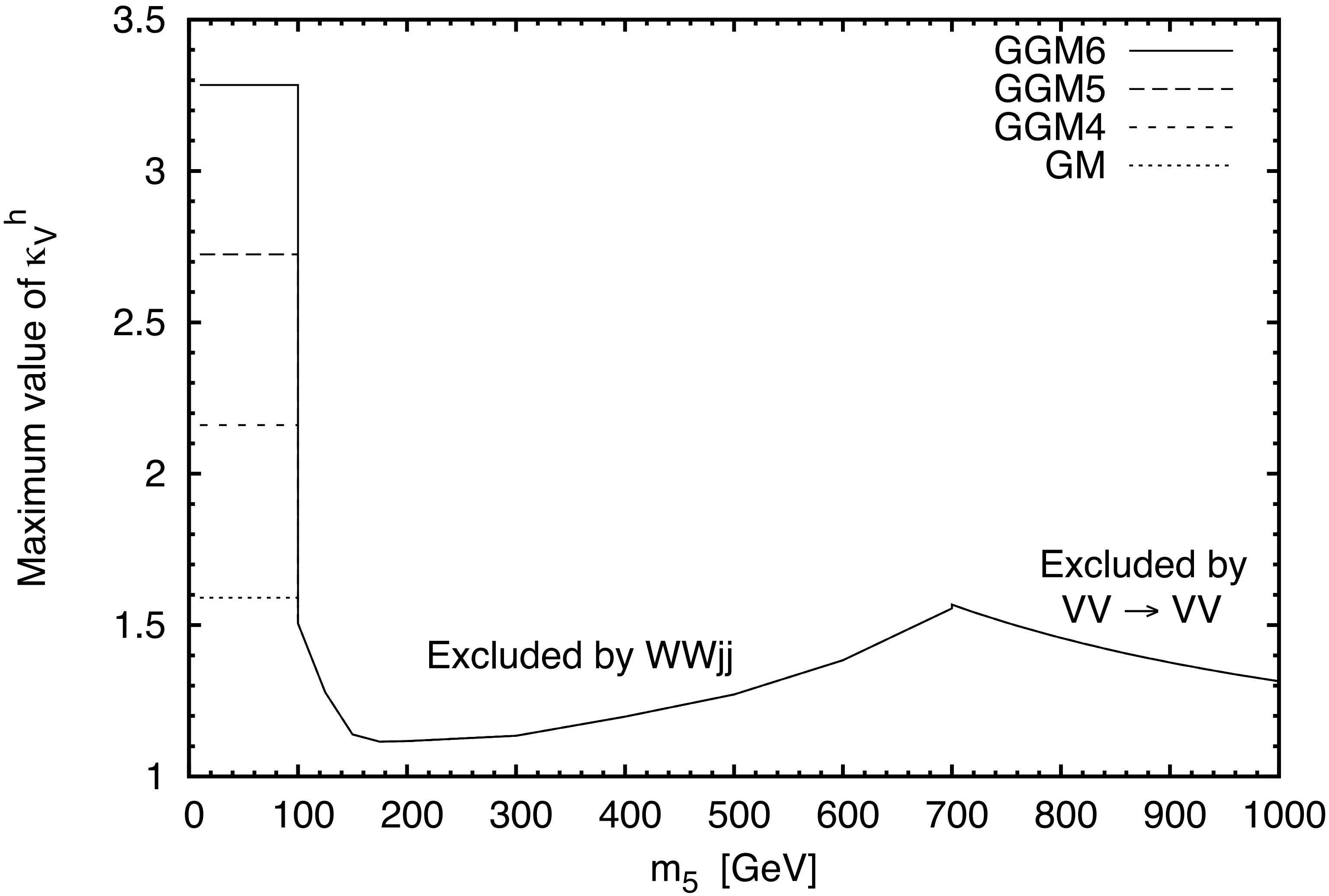
Complementary ranges of m_5!

HEL & Rentala, 1502.01275

$$g_5^{\rm GM} = \sqrt{2} s_H, \quad g_5^{\rm GGM4} = \sqrt{\frac{24}{5}} s_H, \quad g_5^{\rm GGM5} = \sqrt{\frac{42}{5}} s_H, \quad g_5^{\rm GGM6} = \frac{8}{\sqrt{5}} s_H$$

Note: $s_H^2 \equiv$ exotic fraction of $M_{W,Z}^2$ is *least* constrained in original Georgi-Machacek model!

All the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ models are the same when expressed in terms of g_5: use sum rule, $(\kappa_V^h)^2 \leq 1 + 5 g_5^2/6$

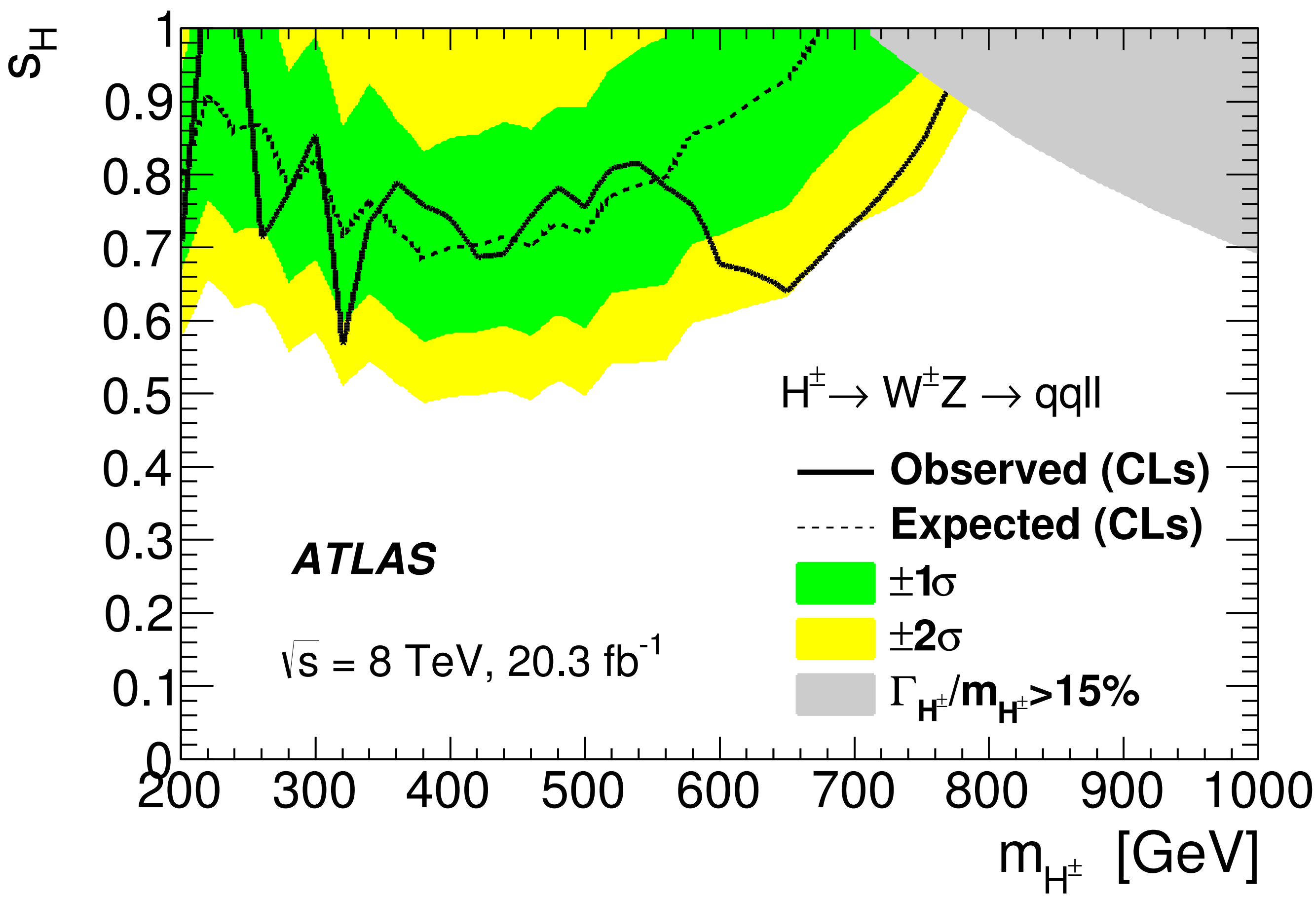


$\Rightarrow \; \kappa_V^h \lesssim 1.57$ for $m_5 > 100$ GeV

HEL & Rentala, 1502.01275

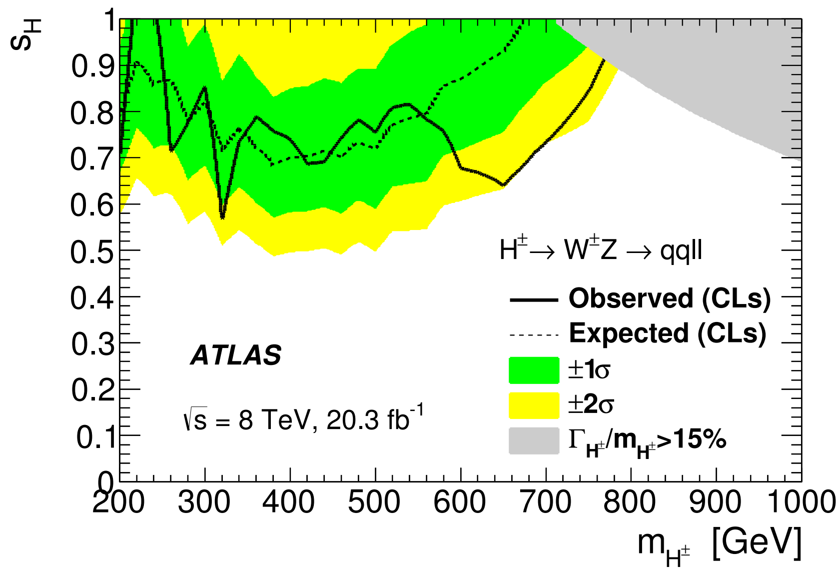
Constraint from VBF $H_5^{\pm} \to W^{\pm}Z \to qq\ell^+\ell^-$

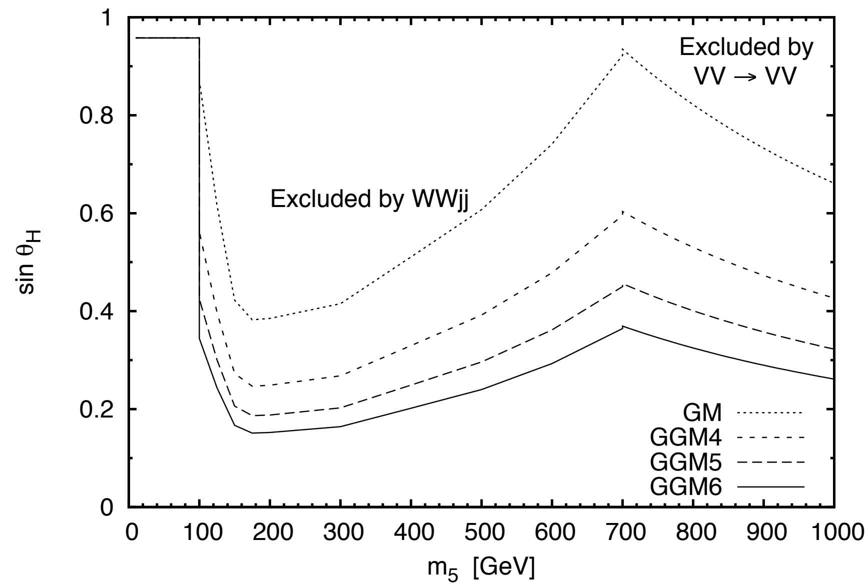
Dedicated ATLAS search for singly-charged resonance in VBF, using Georgi-Machacek model as benchmark



ATLAS 1503.04233

$H_5^\pm \to W^\pm Z$ exclusion not quite as strong as $H_5^{\pm\pm} \to W^\pm W^\pm$, but more data is coming.





ATLAS 1503.04233

HEL & Rentala, 1502.01275,

after Chiang, Kanemura & Yagyu, 1407.5053,

after ATLAS, 1405.6241

Straightforward to translate constraint from GM model to its higher-isospin generalizations.

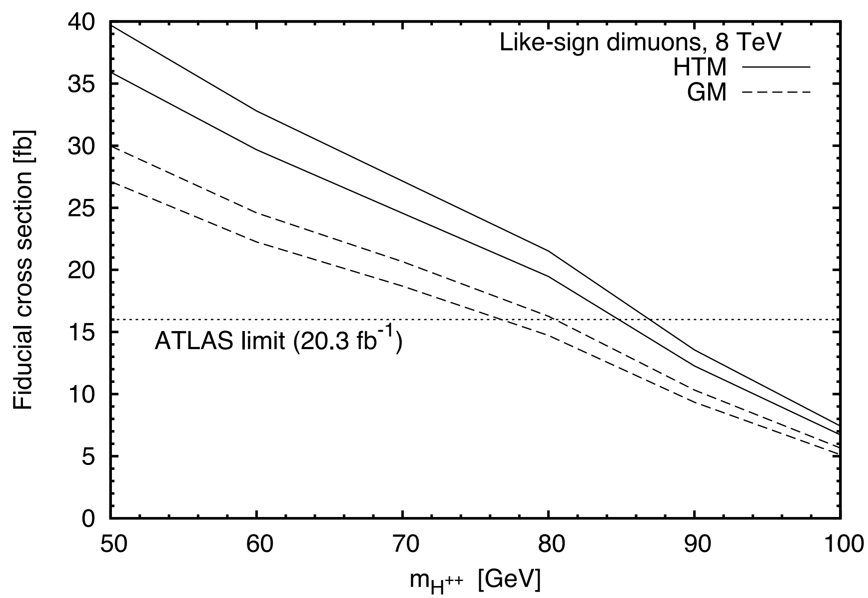
What about lower H_5 masses?

Constraint on $H^{\pm\pm}H^{\mp\mp} + H^{\pm\pm}H^{\mp}$ in Higgs Triplet Model from recasting ATLAS like-sign dimuons search ATLAS, 1412.0237

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Adapt to generalized GM models using

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



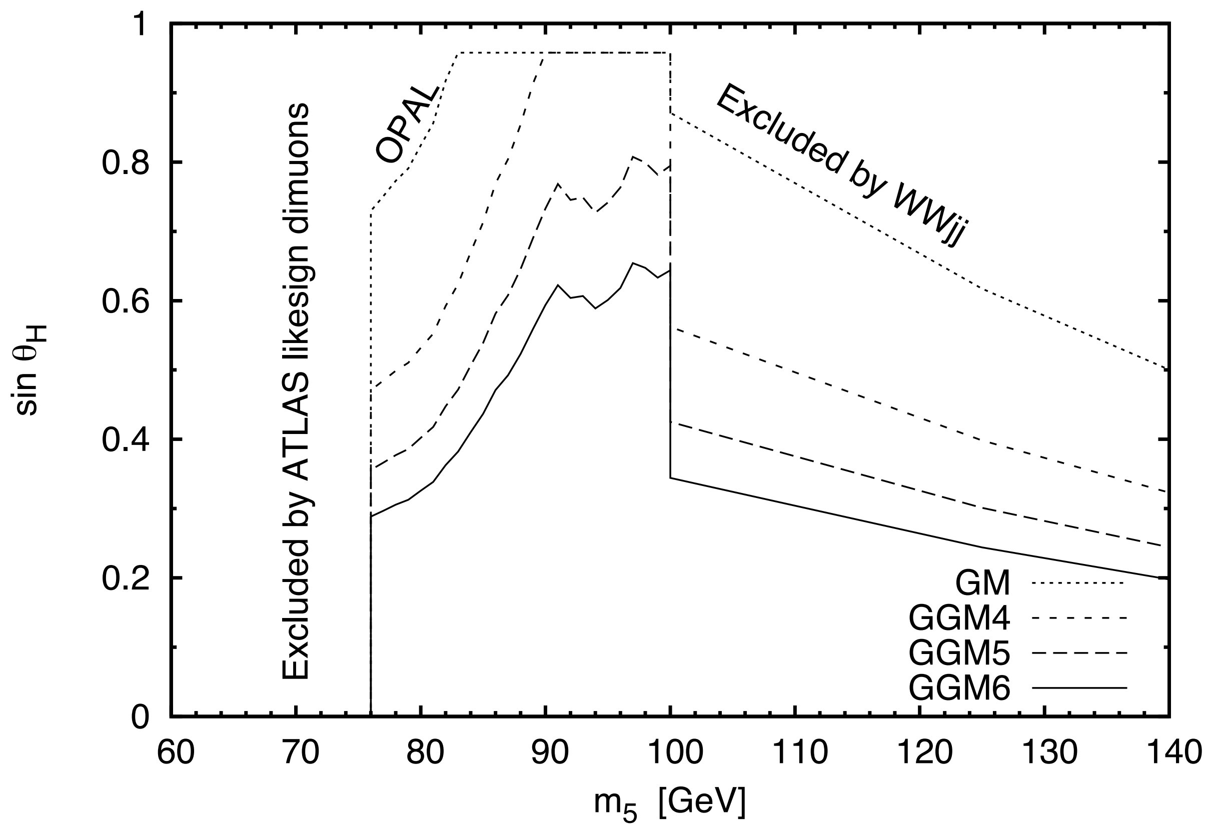
HEL & Rentala, 1502.01275

$\Rightarrow$ $m_5 \gtrsim 76$ GeV, independent of g_5

Takes advantage of mass-degeneracy of H_5^{++} and H_5^{+}

What about lower H_5 masses?

Decay-mode-independent OPAL search for $Z + S^0$ production:
constrain $H_5^0 ZZ$ coupling $\propto g_5$ OPAL, hep-ex/0206022



HEL & Rentala, 1502.01275; used HiggsBounds 4.2.0 for OPAL exclusion contour

Takes advantage of mass degeneracy H_5^0 and H_5^{++}

Septet model (work in progress)

Two CP-even neutral scalars:

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

One CP-odd neutral scalar: ($c_H \equiv v_\phi / v_{\rm SM}$ as usual)

$$A^0 = -s_H \phi^{0,i} + c_H \chi^{0,i}$$

Two charged scalars:
(one fermiophilic and one vectorphilic, but they mix in general)

$$\begin{aligned} H_f^+ &= -s_H \phi^+ + c_H \left(\sqrt{\frac{5}{8}} \chi^{+1} - \sqrt{\frac{3}{3}} (\chi^{-1})^* \right), \\ H_V^+ &= \sqrt{\frac{3}{8}} \chi^{+1} + \sqrt{\frac{5}{8}} (\chi^{-1})^* \end{aligned}$$

A doubly-charged scalar, that couples to W^+W^+:

$$H^{++} = \chi^{+2}$$

Some higher-charged states:

$$\chi^{+3}, \qquad \chi^{+4}, \qquad \chi^{+5}$$

- No H_5^0; would-be H_5^+ mixes with fermiophilic state
- Rely on H^{++} to constrain higher-isospin vacuum condensate

Septet model (work in progress)

$$H^{++}W_\mu^- W_\nu^- : \quad i\frac{2M_W^2}{v_{\rm SM}}(\sqrt{15}s_H)g_{\mu\nu}$$

VBF $H^{\pm\pm} \to W^\pm W^\pm$ is as good as ever!

VBF $H^\pm \to W^\pm Z$ loses its clean interpretation:
$H^+ \to \bar f f$ competes with W^+Z; $m_{H^+} \neq m_{H^{++}}$ in general

No custodial symmetry:

- Unitarity bound on s_H at high $m_{H^{++}}$ is modified
- Sum-rule relationship between $H^{++}W^-W^-$ and hVV couplings is modified

but these still remain useful.

Analysis of LHC constraints on septet-state pair production (trileptons; like-sign dileptons) excludes common masses $\lesssim$ 400 GeV

Alvarado, Lehman & Ostdiek, 1404.3208

Summary & outlook

A higher-isospin component of the vacuum condensate is possible, but it can be constrained experimentally!

Essential signature is $H^{\pm\pm}$, $H^\pm$ (and sometimes H_5^0) coupled to VV: searches in VBF $\to VV$ directly constrain the exotic vev.

Georgi-Machacek model makes a good benchmark:
easy to reinterpret searches in higher-isospin generalizations.

Septet model is best constrained by using $H^{\pm\pm}$, since $H^\pm$ can mix with fermiophilic state.

$VV \to VV$ unitarity constraint means that pushing $H^{\pm\pm}$ heavier forces exotic vev to be smaller.

The least constrained model at high $m_{H^{++}}$ is the original GM model:
exotic fraction of $M_{W,Z}^2 \equiv s_H^2 \lesssim (675 \text{ GeV}/m_5)^2$.

BACKUP

Detail:

SM + real triplet ξ: $\rho > 1$

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

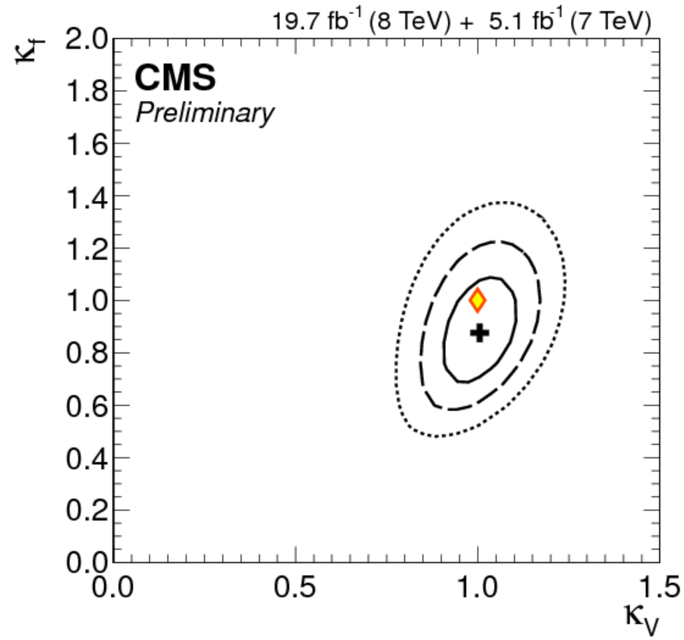
Combine them both: $\langle \chi^0 \rangle = v_\chi$, $\langle \xi^0 \rangle = v_\xi$; doublet $\langle \phi^0 \rangle = v_\phi/\sqrt{2}$

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

To avoid this being fine-tuned, enforce $v_\xi = v_\chi$ using a symmetry.

SU(2)$_L \times$SU(2)$_R$ global symmetry on scalar potential:
- present by accident in SM Higgs sector
- breaks to diagonal subgroup SU(2)$_{\text{custodial}}$ upon EWSB

Implementation of $\kappa_V^h > 1$



hVV 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

Motivation for enhanced hVV couplings

Simultaneous enhancement of all the h couplings can hide a non-SM contribution to the Higgs width.

LHC measures rates in particular final states:

$$\text{Rate}_{ij} = \frac{\sigma_i \Gamma_j}{\Gamma_{\text{tot}}} = \frac{\kappa_i^2 \sigma_i^{\text{SM}} \cdot \kappa_j^2 \Gamma_j^{\text{SM}}}{\sum_k \kappa_k^2 \Gamma_k^{\text{SM}} + \Gamma_{\text{new}}}$$

All rates will be identical to SM Higgs if all $\kappa_i \equiv \kappa \geq 1$ and

$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}} \qquad \text{BR}_{\text{new}} \equiv \frac{\Gamma_{\text{new}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

Coupling enhancement hides presence of new decays!
New decays hide presence of coupling enhancement!

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

Study concrete models in which $\kappa > 1$ to gain insight.

Most general scalar potential:

Aoki & Kanemura, 0712.4053

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

Hartling, Kumar & HEL, 1404.2640

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

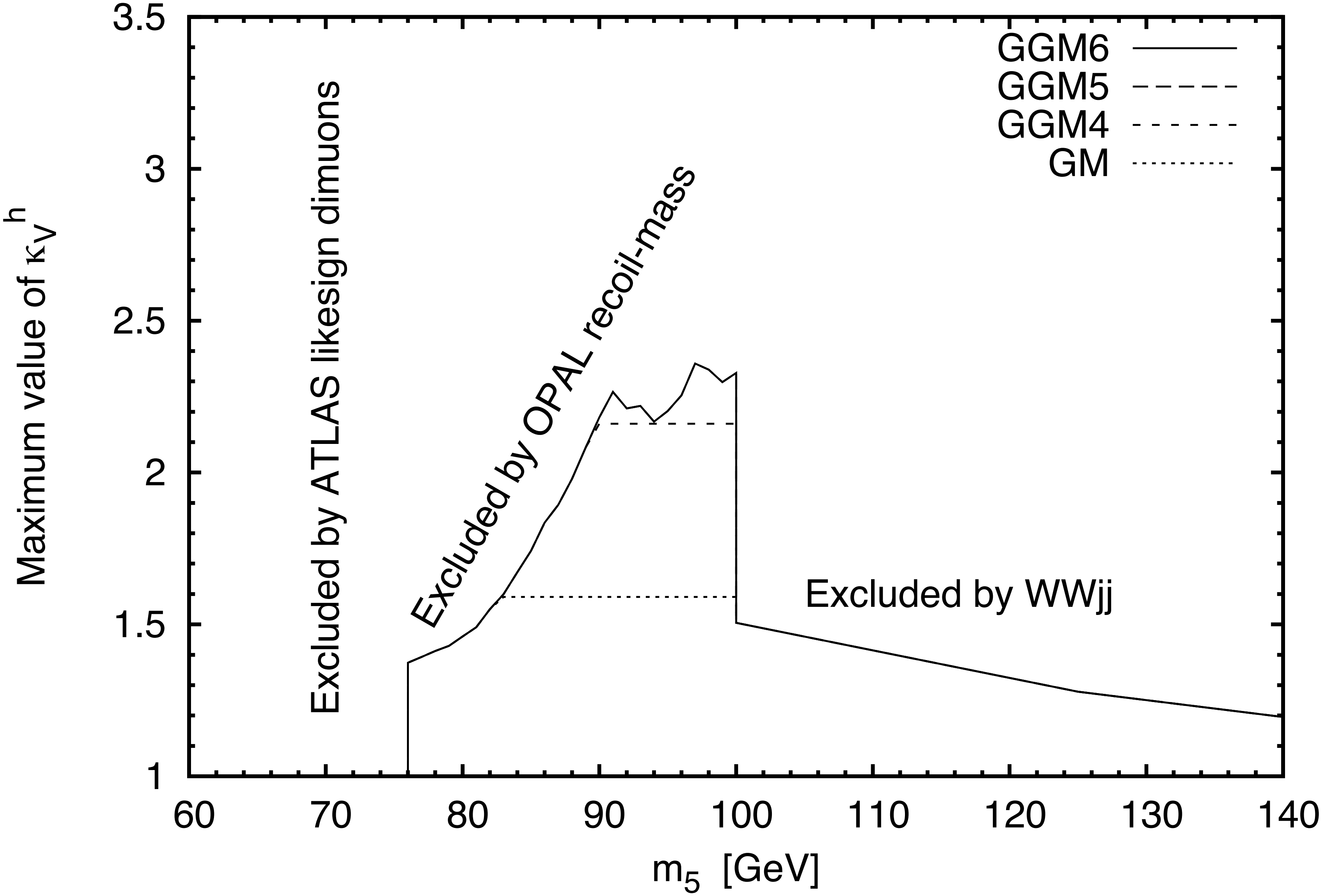
9 parameters, 2 fixed by M_W and m_h $\rightarrow$ free parameters are m_H, m_3, m_5, v_χ, α plus two triple-scalar couplings.

Dimension-3 terms usually omitted by imposing Z_2 sym. on X.

These dim-3 terms are essential for the model to possess a decoupling limit!

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

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



$\Rightarrow \ \kappa_V^h \lesssim 2.36$ for all m_5!

HEL & Rentala, 1502.01275

compare $\kappa_V^h \lesssim 3.3$ in unconstrained GGM6

2 deliverables in YR4 draft:

- A fully-specified benchmark scenario for direct H_5 searches

- Tables of VBF $\to H_5$ cross sections and decay widths

H5plane benchmark scenario:

- benchmark plane varying $m_5 \in [200, 3000]$ GeV and $s_H \in (0, 1)$

  The 2 most relevant parameters for H_5 direct searches are input parameters.

  All other input parameters are specified, including $m_h = 125$ GeV.

- compatible with spectrum calculator **GMCALC** arXiv:1412.7387

  `INPUTSET = 4`: m_h, m_5, s_H, . . . are specified inputs

- satisfies theoretical constraints as much as possible

  near-largest possible region of m_5–s_H plane theoretically accessible (main challenge)

- Choose $m_3 > m_5$ so that $\mathrm{BR}(H_5 \to VV) = 1$ at tree level

  Higgs-to-Higgs $H_5 \to H_3 V, H_3 H_3$ decays are kinematically forbidden: avoid complications

Specification of H5plane benchmark scenario:

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

9 input parameters $\Rightarrow$ trade $(\mu_2^2, \mu_3^2, \lambda_1, \lambda_5)$ for (G_F, m_5, m_h, s_H)

Fixed parameters	Variable parameters	Dependent parameters
$G_F = 1.1663787 \times 10^{-5}$ GeV^{-2}	$m_5 \in [200, 3000]$ GeV	$\lambda_2 = 0.4(m_5/1000$ GeV$)$
$m_h = 125$ GeV	$s_H \in (0, 1)$	$M_1 = \sqrt{2}s_H(m_5^2 + v^2)/v$
$\lambda_3 = -0.1$		$M_2 = M_1/6$
$\lambda_4 = 0.2$		

Table 6.1: Specification of the H5plane benchmark for the Georgi-Machacek model. These input parameters correspond to `INPUTSET = 4` in GMCALC [252].

VBF $\to H_5$ cross sections (NNLO QCD, LO EW, onshell H_5) and H_5 decay widths (LO) for $H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$

Update of numbers in LHCHXSWG-2015-001 (H. Logan & M. Zaro), already consistent with H5plane benchmark scenario

m_5 [GeV]	$\sigma_1^{\rm NNLO}(H_5^0)$ [fb]	$\sigma_1^{\rm NNLO}(H_5^+)$ [fb]	$\sigma_1^{\rm NNLO}(H_5^-)$ [fb]
200.	$1375.^{+0.35\%}_{-0.20\%} \pm 1.8\% \pm 0.51\%$	$1770.^{+0.30\%}_{-0.18\%} \pm 1.6\% \pm 0.46\%$	$1148.^{+0.36\%}_{-0.21\%} \pm 2.2\% \pm 0.54\%$
210.	$1288.^{+0.33\%}_{-0.19\%} \pm 1.8\% \pm 0.49\%$	$1662.^{+0.28\%}_{-0.17\%} \pm 1.7\% \pm 0.45\%$	$1073.^{+0.34\%}_{-0.21\%} \pm 2.2\% \pm 0.53\%$
220.	$1209.^{+0.30\%}_{-0.18\%} \pm 1.8\% \pm 0.48\%$	$1564.^{+0.26\%}_{-0.17\%} \pm 1.7\% \pm 0.44\%$	$1004.^{+0.32\%}_{-0.20\%} \pm 2.2\% \pm 0.52\%$
230.	$1136.^{+0.28\%}_{-0.17\%} \pm 1.8\% \pm 0.47\%$	$1473.^{+0.25\%}_{-0.16\%} \pm 1.7\% \pm 0.43\%$	$940.9^{+0.31\%}_{-0.19\%} \pm 2.2\% \pm 0.51\%$
240.	$1069.^{+0.26\%}_{-0.17\%} \pm 1.8\% \pm 0.46\%$	$1388.^{+0.25\%}_{-0.15\%} \pm 1.7\% \pm 0.42\%$	$883.0^{+0.29\%}_{-0.18\%} \pm 2.3\% \pm 0.50\%$
250.	$1006.^{+0.27\%}_{-0.16\%} \pm 1.8\% \pm 0.46\%$	$1311.^{+0.25\%}_{-0.14\%} \pm 1.7\% \pm 0.41\%$	$829.6^{+0.27\%}_{-0.17\%} \pm 2.3\% \pm 0.49\%$
260.	$948.9^{+0.27\%}_{-0.15\%} \pm 1.8\% \pm 0.45\%$	$1239.^{+0.25\%}_{-0.14\%} \pm 1.7\% \pm 0.40\%$	$780.4^{+0.27\%}_{-0.17\%} \pm 2.3\% \pm 0.48\%$

m_5 [GeV]	$\sigma_1^{\rm NNLO}(H_5^{++})$ [fb]	$\sigma_1^{\rm NNLO}(H_5^{--})$ [fb]
200.	$2511.^{+0.24\%}_{-0.14\%} \pm 1.9\% \pm 0.40\%$	$1070.^{+0.33\%}_{-0.21\%} \pm 2.9\% \pm 0.54\%$
210.	$2364.^{+0.24\%}_{-0.14\%} \pm 1.9\% \pm 0.39\%$	$997.0^{+0.31\%}_{-0.20\%} \pm 2.9\% \pm 0.53\%$
220.	$2229.^{+0.23\%}_{-0.13\%} \pm 1.9\% \pm 0.38\%$	$930.3^{+0.29\%}_{-0.19\%} \pm 3.0\% \pm 0.52\%$
230.	$2104.^{+0.24\%}_{-0.13\%} \pm 1.9\% \pm 0.37\%$	$869.2^{+0.27\%}_{-0.19\%} \pm 3.0\% \pm 0.51\%$
240.	$1988.^{+0.24\%}_{-0.12\%} \pm 1.9\% \pm 0.35\%$	$813.3^{+0.25\%}_{-0.18\%} \pm 3.0\% \pm 0.51\%$
250.	$1881.^{+0.24\%}_{-0.11\%} \pm 1.9\% \pm 0.34\%$	$762.0^{+0.25\%}_{-0.18\%} \pm 3.1\% \pm 0.50\%$
260.	$1781.^{+0.24\%}_{-0.10\%} \pm 1.9\% \pm 0.33\%$	$714.8^{+0.25\%}_{-0.18\%} \pm 3.1\% \pm 0.49\%$

Uncert on σ from uncalculated NLO EW corrs $\simeq \pm 7\%$

m_5 [GeV]	$\Gamma_1^{\rm tot}(H_5^{\pm\pm})$ [GeV]	$\Gamma_1^{\rm tot}(H_5^{\pm})$ [GeV]	$\Gamma_1^{\rm tot}(H_5^{0})$ [GeV]	BR$(H_5^0 \to W^+W^-)$
200.	1.006	0.8608	0.8008	$0.4187^{+14.\%}_{-14.\%}$
210.	1.275	1.118	1.071	$0.3969^{+15.\%}_{-14.\%}$
220.	1.578	1.410	1.362	$0.3863^{+15.\%}_{-14.\%}$
230.	1.921	1.737	1.686	$0.3799^{+15.\%}_{-14.\%}$
240.	2.307	2.105	2.051	$0.3749^{+15.\%}_{-15.\%}$
250.	2.739	2.516	2.459	$0.3714^{+16.\%}_{-15.\%}$
260.	3.219	2.975	2.912	$0.3685^{+16.\%}_{-15.\%}$

Uncert on Γ from uncalculated NLO EW corrs $\simeq \pm 12\%$

s_H dependence incorporated via $\sigma \equiv s_H^2 \sigma_1$, $\Gamma \equiv s_H^2 \Gamma_1$

Update of numbers in LHCHXSWG-2015-001 (H. Logan & M. Zaro), what's new:

- Used current YR4-recommended electroweak input parameters

$$G_F = 1.1663787 \cdot 10^{-5}\ \mathrm{GeV}^{-2}, \qquad M_W = 80.385\ \mathrm{GeV}, \qquad M_Z = 91.1876\ \mathrm{GeV},$$
$$\Gamma_W = 2.085\ \mathrm{GeV}, \qquad \Gamma_Z = 2.4952\ \mathrm{GeV}.$$

- Used PDF4LHC NNLO parton dist'n fns with $\alpha_s(M_Z) = 0.118$, renorm & factorization scales set to M_W & varied by $[1/2, 2]$

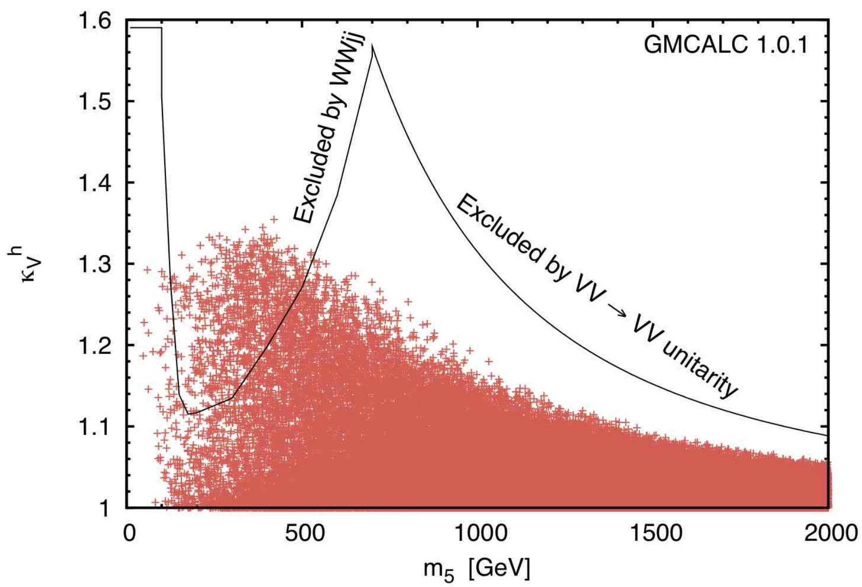
- H_5 decay widths to VV (tree-level) now computed including doubly-offshell effects (GMCALC 1.2.0)

- Used YR4 recommended mass points for m_5: 200–500 GeV in steps of 10 GeV, 500–3000 GeV in steps of 50 GeV

Summary & outlook

$\star$ Custodial symmetry + unitarity sum rules extremely powerful!
- VBF $H_5^\pm \to W^\pm Z$ search coming from ATLAS (Moriond?)
- Weakest constraint: $m_5 \sim$ 76–100 GeV. Offshell/loop decays?

$\star$ High-mass $VV \to VV$ unitarity constraint is not saturated by full theory-constrained model: scan in GM model:



- perturb. unitarity of quartic couplings
- scalar potential bounded from below
- no deeper custodial-violating minima
- $b \to s\gamma$ constraint

Explicit scalar potentials for GGM models now available: full study feasible (but tedious)

$\star$ Sum rules are different in septet model: no H_5^0 state, no custodial symmetry in scalar sector $\Longrightarrow$ under investigation