Enhanced hVV couplings in the Georgi-Machacek model and beyond

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H.E.L. & V. Rentala, 1502.01275

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

Outline

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Outlook

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

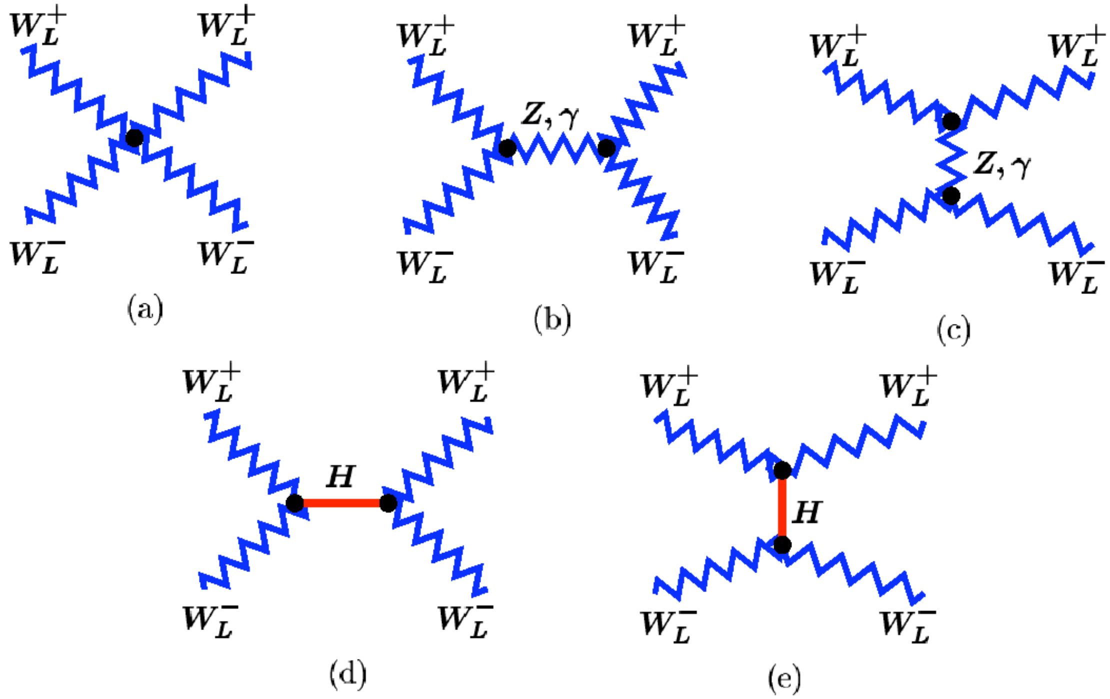
$$\kappa^2 = \frac{1}{1 - \text{BR}_{\text{new}}} \qquad\qquad \text{BR}_{\text{new}} \equiv \frac{\Gamma_{\text{new}}}{\kappa^2 \Gamma_{\text{tot}}^{\text{SM}} + \Gamma_{\text{new}}}$$

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.

First interesting feature: $WW \to WW$ unitarization



Graphic: S. Chivukula

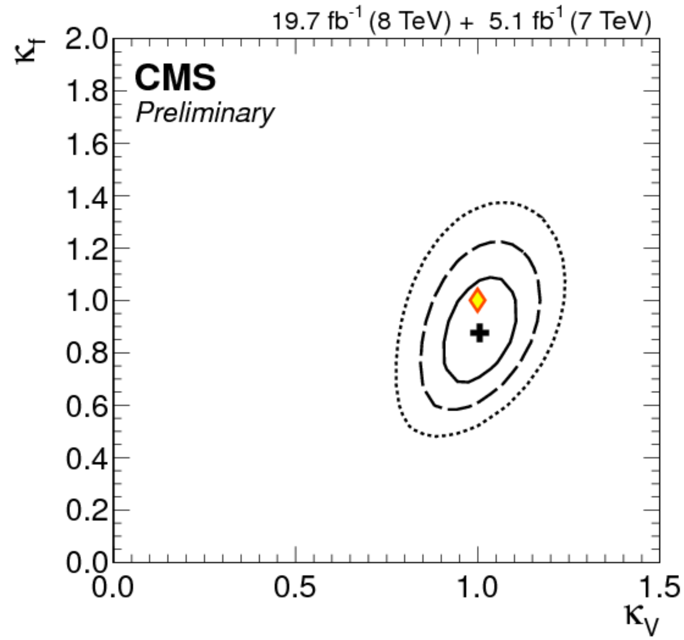
SM: Higgs exchange cancels remaining E^2/v^2 term in amplitude.

2HDM/SM+singlet: cancellation $\Rightarrow$ sum rule $(\kappa_V^h)^2 + (\kappa_V^H)^2 = 1$.

$\kappa_V^h > 1$: need doubly-charged scalar exchanged in u-channel!
Implies presence of larger isospin representation(s).

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

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

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; a_0 depends on weak charges & multiplicity of ϕ's

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

$$a_{0,c}^{\text{max,SU(2)}}(T) = \frac{g^2}{16\pi} \frac{(n^2-1)\sqrt{n}}{2\sqrt{3}}$$

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

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 multiple large multiplets are present

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

Problem with isospin ≥ 1: the ρ parameter

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

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

($Q = T^3 + Y/2$, 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: $\rho = 1.00040 \pm 0.00024$

Two approaches:

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

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

Larger solutions forbidden by perturbative unitarity of weak charges!

2) 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

Both have theoretical "issues":

1) 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!

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

Gunion, Vega & Wudka 1991

Special relations among params 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!

This talk: focus on (2): Georgi-Machacek model and its generalizations to higher isospin

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 $VV \to VV$

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: construct in parallel to original GM model

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

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

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

Couplings:

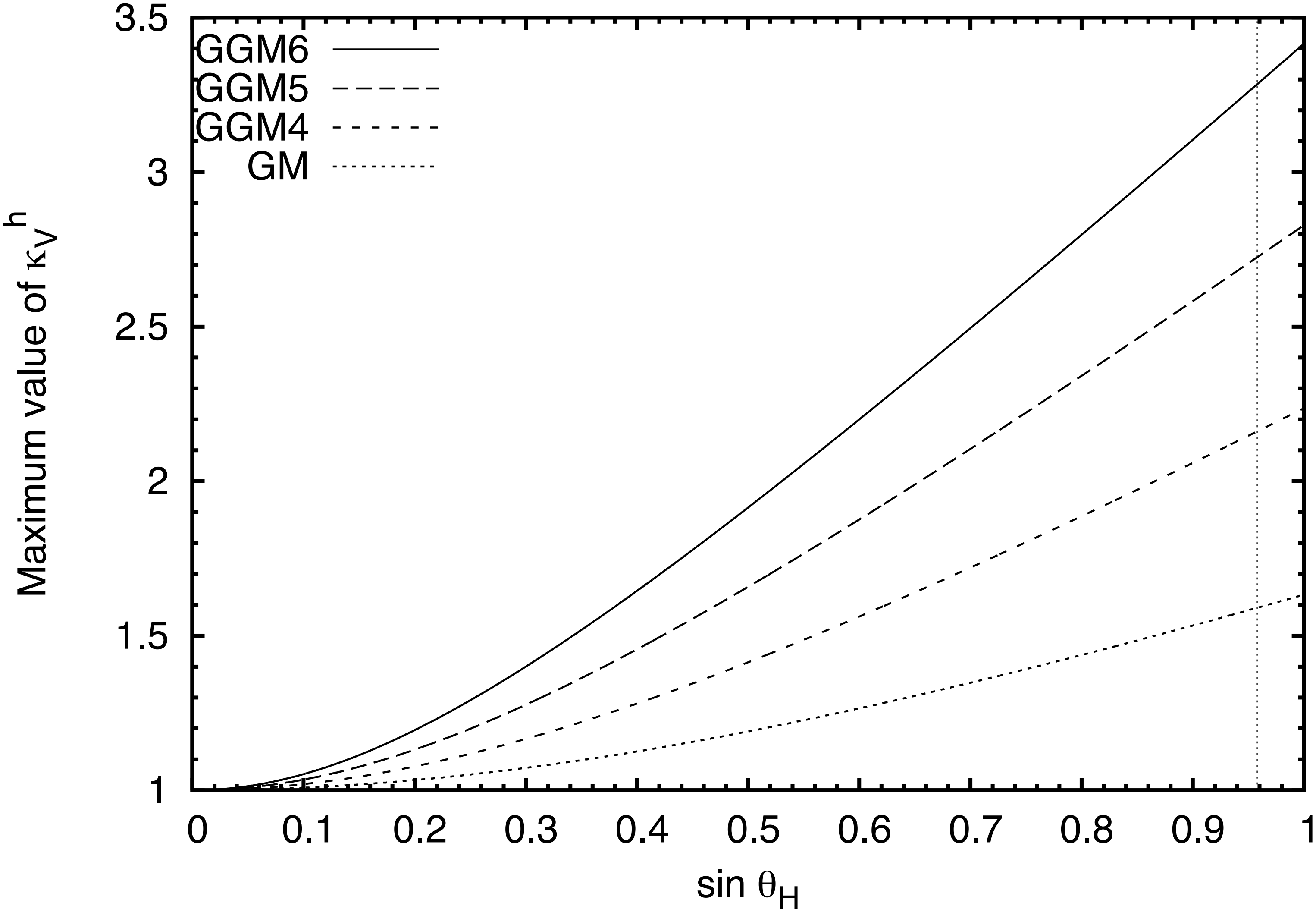
$$\kappa_V^h = c_\alpha c_H - \sqrt{A} s_\alpha s_H \qquad \kappa_f^h = c_\alpha / c_H$$
$$\kappa_V^H = s_\alpha c_H + \sqrt{A} c_\alpha s_H \qquad \kappa_f^H = s_\alpha / c_H$$

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: $A = 4T(T+1)/3$

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

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



Vertical line: y_t perturbativity $\to \tan\theta_H < 10/3$ HEL & Rentala, 1502.01275

Phenomenology II: entirely the same as original GM model

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:

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

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

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

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

Vector-phobic: no $H_3 V V$ couplings

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

Phenomenology III: again in parallel to original GM model

Custodial-fiveplet comes only from X: no couplings to fermions.

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

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

g_5 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)

Constraints I & II:

Focus on constraining $(H_5^{++}, H_5^{+}, H_5^{0})$: sum rule guarantees

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

(1) Direct-search constraint on VBF $H_5^{++} \to W^+W^+$ from recasting ATLAS W^+W^+jj cross-section measurement.

Chiang, Kanemura & Yagyu, 1407.5053

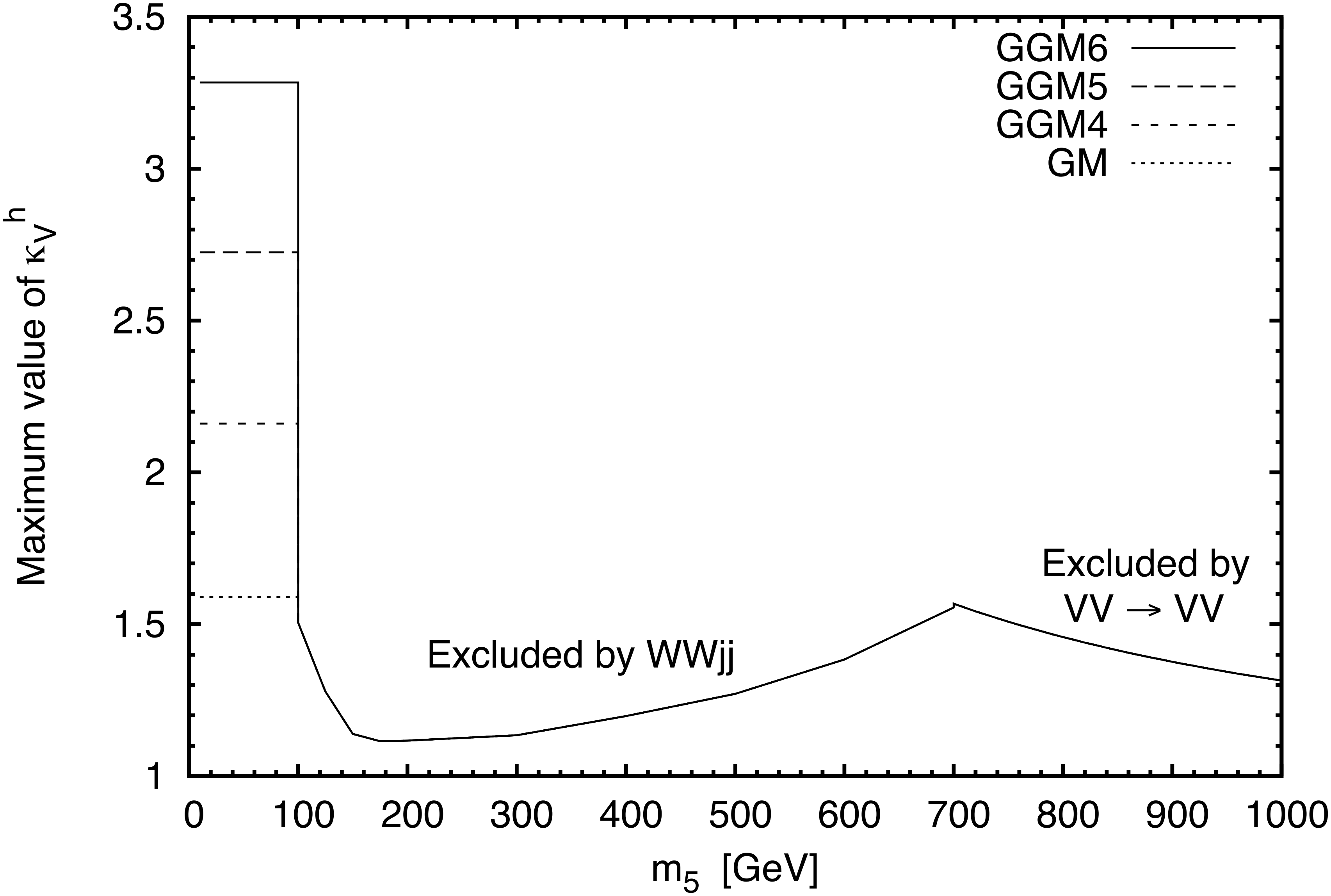
(2) Perturbative unitarity bound from finite part of $VV \leftrightarrow VV$.

- SM: $m_{h_{\rm SM}}^2 < 16\pi v^2/5$ Lee, Quigg & Thacker 1977
- Custodial-symmetric models:

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

- Combine with sum rule: HEL & Rentala, 1502.01275

$$(\kappa_V^h)^2 < 1 + \frac{(16\pi v^2 - 5m_h^2)}{(4m_5^2 + 5m_h^2)}$$



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

HEL & Rentala, 1502.01275

Constraints III:

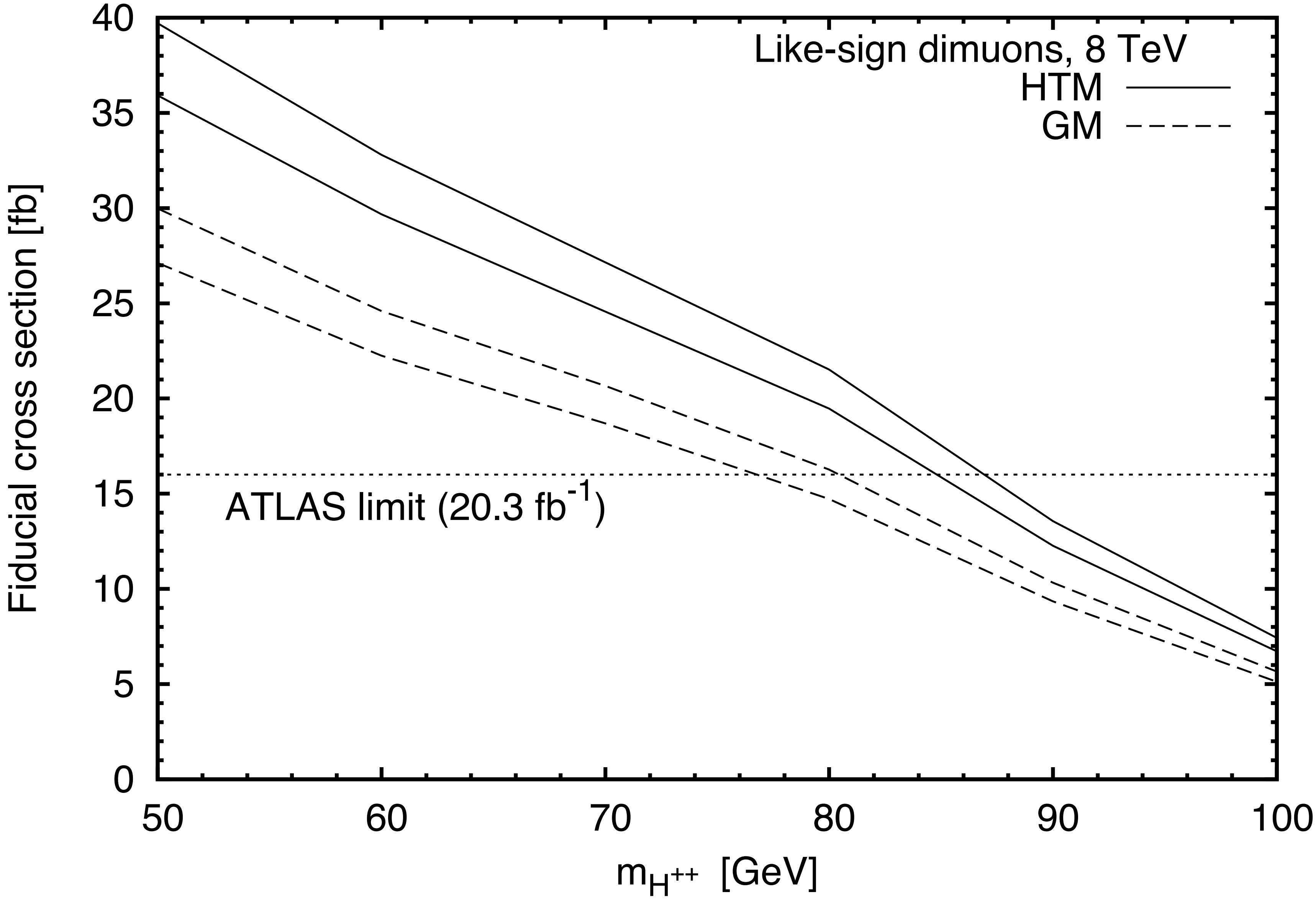
(3) Direct-search constraint on $H^{\pm\pm}H^{\mp\mp} + H^{\pm\pm}H^{\mp}$ in Higgs Triplet Model from recasting ATLAS like-sign dimuons meas.

Kanemura, Kikuchi, Yagyu & Yokoya, 1412.7603

Adapt to generalized GM models using

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

Take advantage of mass degeneracy of all H_5 states.



$\Rightarrow$ $m_5 \gtrsim 76$ GeV, no g_5 dependence

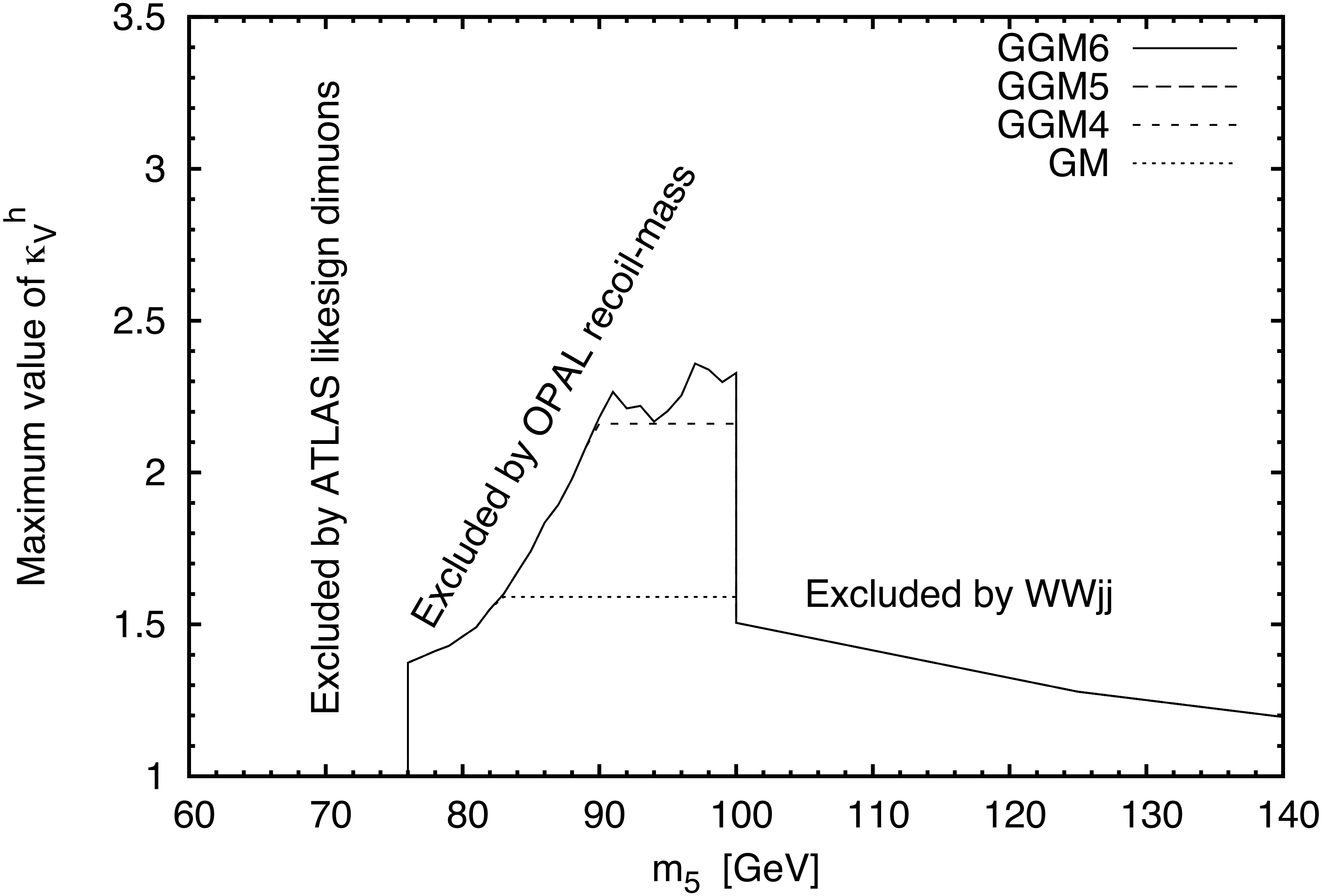
HEL & Rentala, 1502.01275

Constraints IV:

(4) OPAL search for $Z + S^0$ production independent of S^0 decay modes: used recoil-mass method!

Upper bound on $H_5^0 ZZ$ coupling $\propto g_5$ as function of m_5.

Take advantage of mass degeneracy of all H_5 states and custodial-symmetry relationship among couplings.



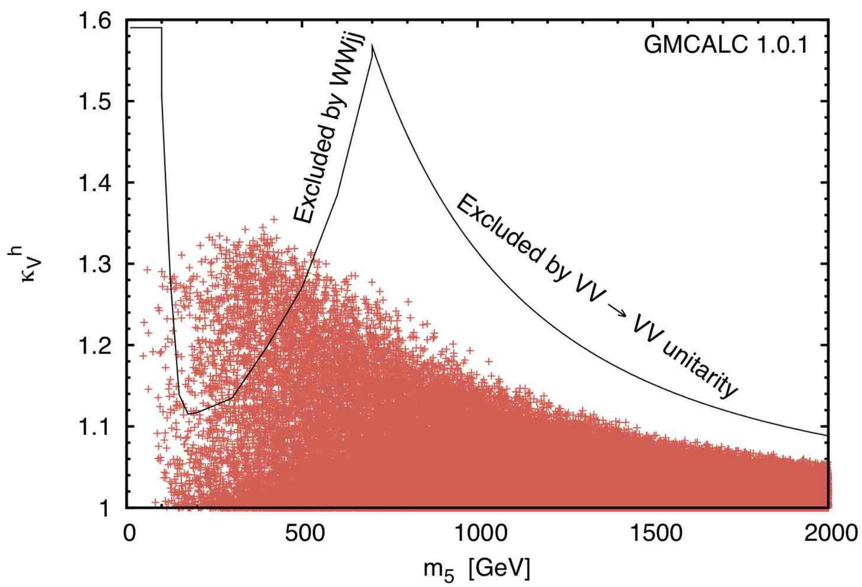
$\Rightarrow \ \kappa_V^h \lesssim 2.36$ for all m_5! HEL & Rentala, 1502.01275

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

Outlook

⋆ 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?

⋆ 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)

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

BACKUP

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

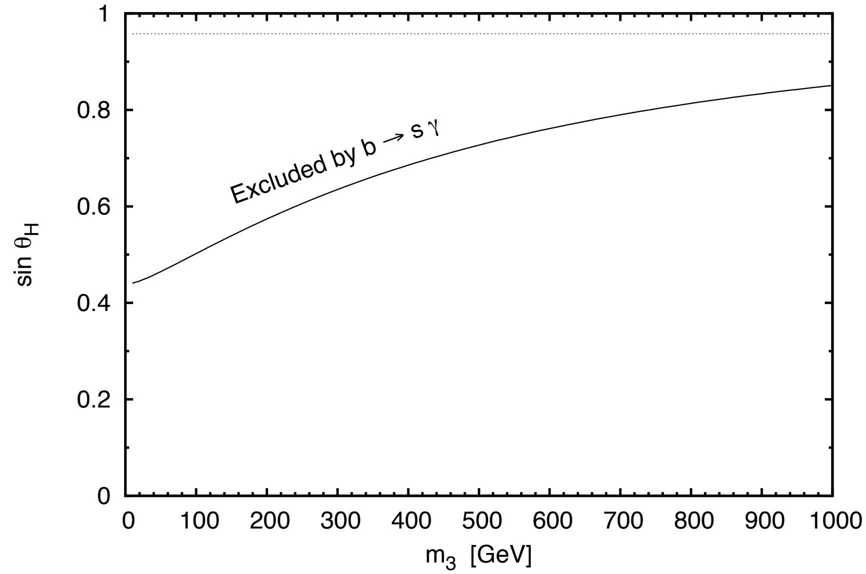
Dimension-3 terms usually omitted by imposing Z_2 sym. on X.

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

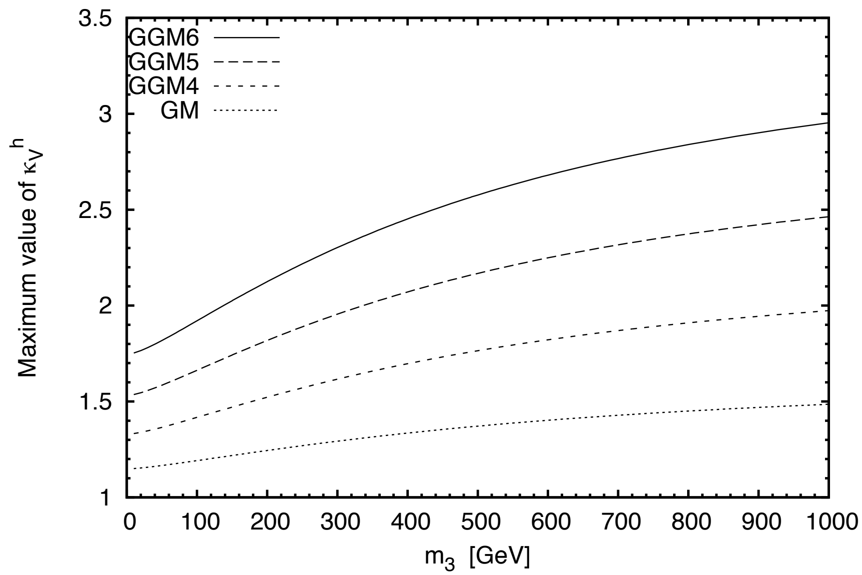
$(UXU^\dagger)_{ab}$ is just the matrix X in the Cartesian basis of SU(2), found using

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

Constraint from $b \to s\gamma$

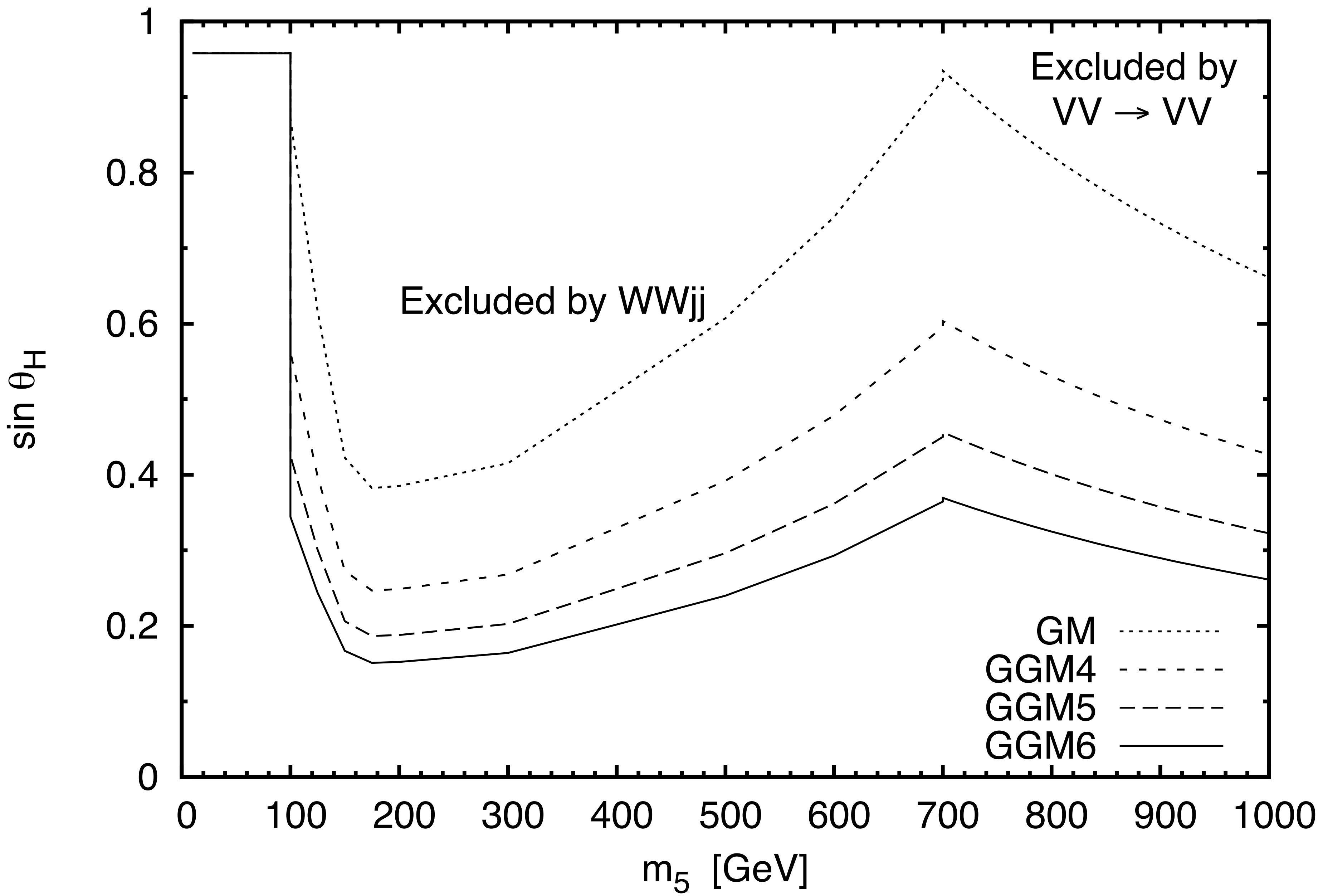


Hartling, Kumar & HEL, 1410.5538

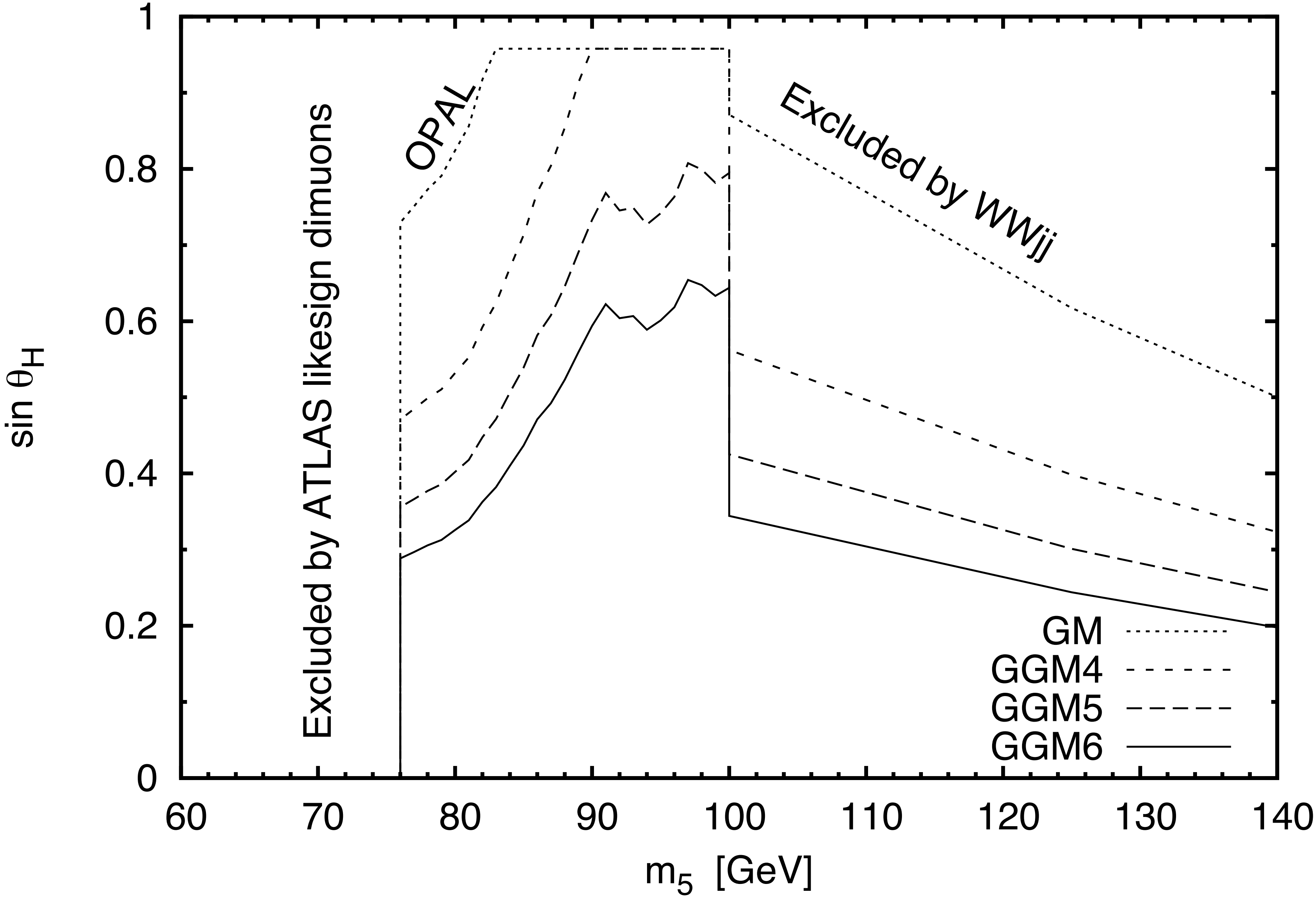


HEL & Rentala, 1502.01275

H_3^+ in the loop: measurement constrains m_3 and $\sin\theta_H$



HEL & Rentala, 1502.01275



HEL & Rentala, 1502.01275