Universität Hamburg
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Masters Colloquium: Presentation | SARA CHOPRA

Sum rules for the Extended Higgs Models:

A comparative analysis of 2HDM, GM and the Septet model

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Extended Higgs Models (BSM models):

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INTRODUCTION AND MOTIVATION

Rho - Parameter

- ρ parameter is an important experimental parameter which preserves the custodial symmetry at tree level and for Standard Model ρ = 1.
- We preserve this quantity in our models through Hypercharge and Isospin combinations.

Sum Rules in BSM

- To ensure good high energy behaviour exists in our tree level vector boson calculations and to ensure perturbative unitary is conserved, we obtain sum rules for our BSM models.

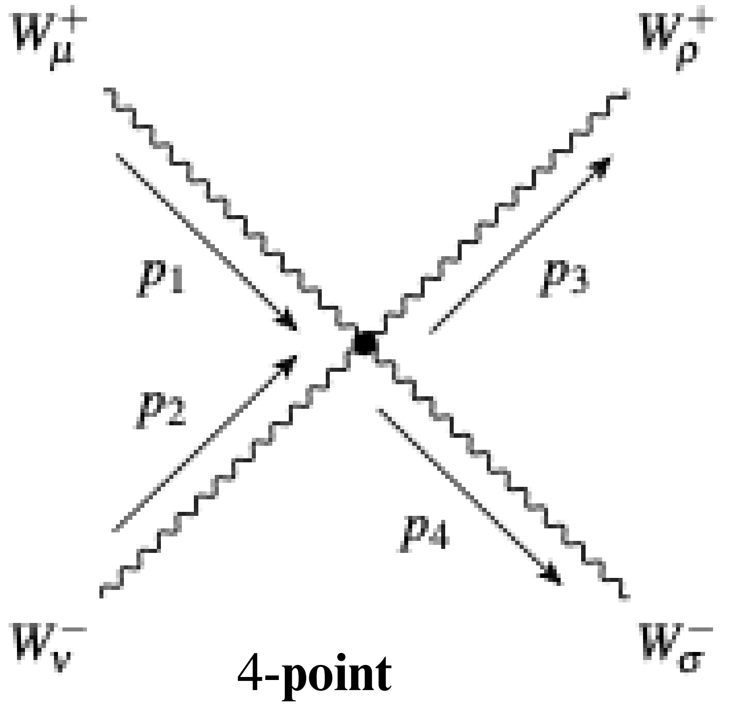
INTRODUCTION AND MOTIVATION

Sum Rules in BSM

High Energy Vector Boson Scattering [1]

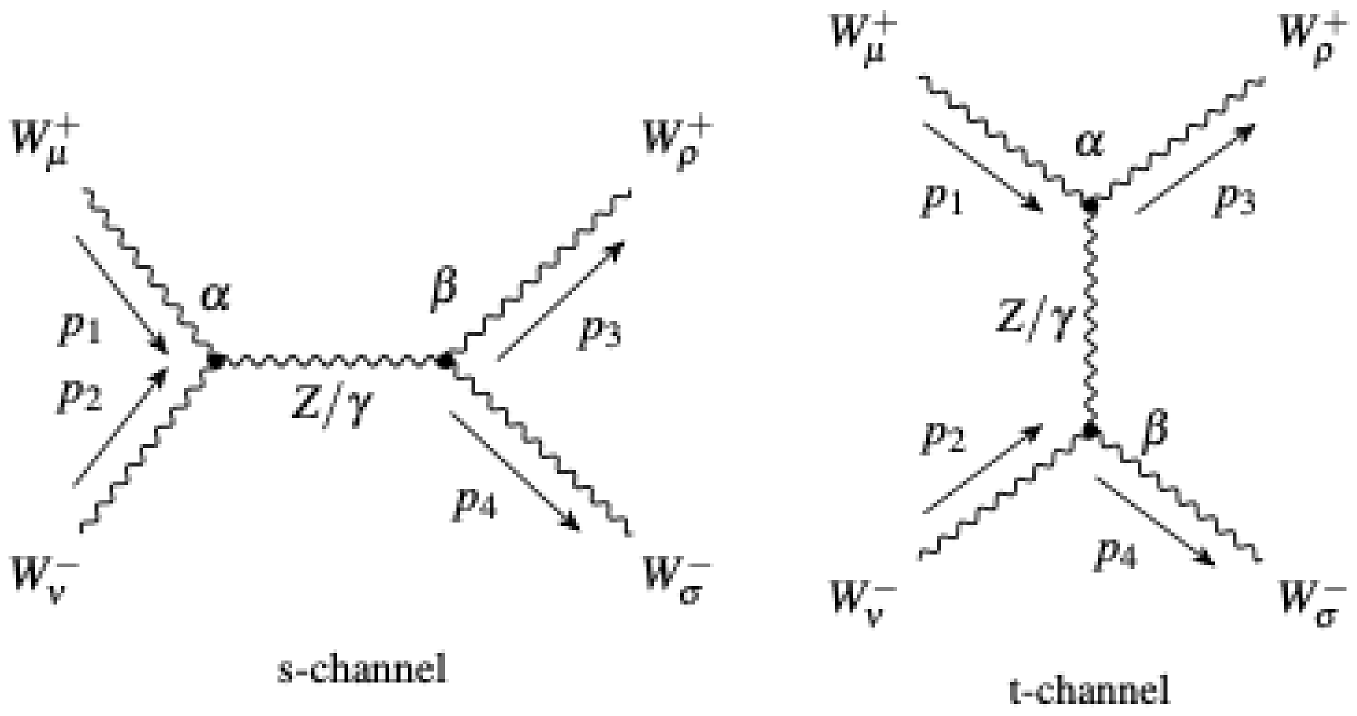
Eg. $W^+W^- \xrightarrow{h^0/H^0/H^{++}} W^+W^-$

Figure: Standard Model Feynman Diagrams



E^4 dependence

$$i\mathcal{M} \approx ig^2 \frac{E^4}{M_W^4}\left[.. + \mathcal{O}\left(E^2\right)\right]$$

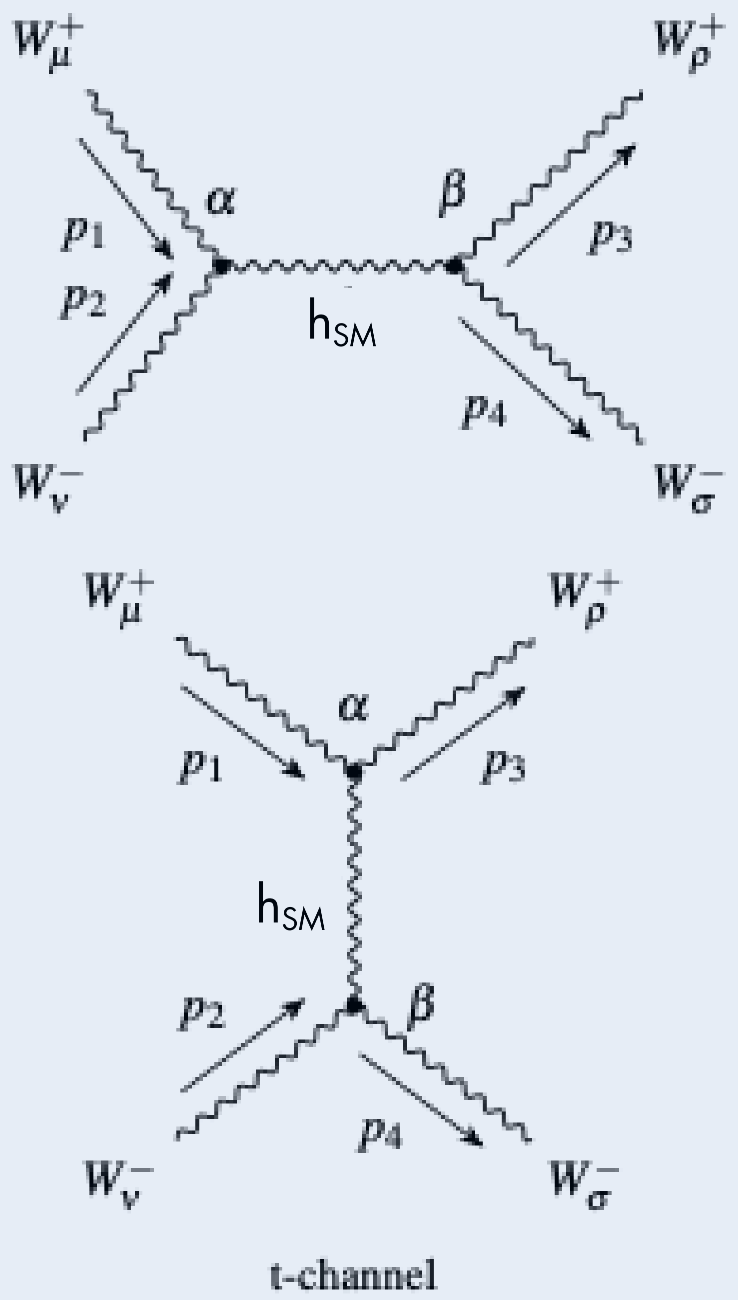


$$i\mathcal{M} = \frac{ig^2}{4M_{W^2}}\left(s+t+\mathcal{O}\left(M_W^2\right)\right)$$

$$i\mathcal{M} \approx \frac{i}{v^2}(s+t)$$

E^4 cancels out but E^2 remains

SM: h_{SM} = 125 Gev



$$i\mathcal{M} = -\frac{i}{v^2}\left(\frac{s^2}{s-m_h^2}+\frac{t^2}{t-m_h^2}+..\right)$$

$$i\mathcal{M} = -\frac{i}{v^2}\left(s+t+2m_h^2\right)$$

E^2 cancels due to Higgs

THEORETICAL AND ANALYTIC COMPUTATIONS

SEPTET MODEL

Imp: All models - 2HDM, GM, Septet have **ρ = 1**

SEPTET MODEL

1 Higgs Doublet (ϕ) & 1 Septet (X) [Z]

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$X = \begin{pmatrix} \chi^{+5} \\ \chi^{+4} \\ \chi^{+3} \\ \chi^{+2} \\ \chi_1^{+1} \\ \chi^0 \\ \chi_2^{-1} \end{pmatrix}$$

note: $(\chi_1^{+1})^* \neq (\chi_2^{-1})$

Using Rotation matrix, ***R***, we obtain physical Higgs fields

GAUGE FIELDS:

Higher charged states	$\chi^{\pm5}, \chi^{\pm4}, \chi^{\pm3}, \chi^{\pm\pm}$
Singly charged states	$\phi^{\pm}, \chi_1^{\pm}, \chi_2^{\pm}$
CP-even states:	$\phi^{0,r}, \chi^{0,r}$
CP-odd states:	$\phi^{0,i}, \chi^{0,i}$

PHYSICAL FIELDS:

Higher charged states	$H^{\pm\pm}, H^{\pm3}$ $H^{\pm4}$ $H^{\pm5}$
Singly charged States	G^+, H_1^+, H_2^+
Intermediate States	H_v^+ (vector boson) H_f^+ (fermion)
CP-even states:	h^0, H^0
CP-odd states:	G^0, A^0

$$\phi^0 = \frac{v_\phi + \phi^{0,r} + i\phi^{0,i}}{\sqrt{2}},$$

$$\chi^0 = \frac{v_\chi + \chi^{0,r} + i\chi^{0,i}}{\sqrt{2}}.$$

neutral state decompsition

attain vevs as

$$\boxed{v_\phi^2 + 16 v_\chi^2 = v^2 \approx (246\ \text{GeV})^2}$$

SEPTET MODEL

Hyper Charges:

$Y_\phi = 1/2$,

$Y_\chi = 2$,

T^3(Isospin) = 3

$Q = T^3 + Y$

Rotation Matrices, R

[2]

CP-even	CP-odd & Charged	Singly charged
$R_\alpha = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$	$R_7 = \begin{pmatrix} c_7 & -s_7 \\ s_7 & c_7 \end{pmatrix}$	$R_\gamma = \begin{pmatrix} c_\gamma & -s_\gamma \\ s_\gamma & c_\gamma \end{pmatrix}$

$$c_7 \equiv \cos\theta_7 = \frac{v_\phi}{v},$$

$$s_7 \equiv \sin\theta_7 = \frac{4v_\chi}{v}.$$

$$M_W^2 = \frac{g^2(v_\phi^2 + 16v_\chi^2)}{4}$$

SEPTET MODEL

$$g_{h^0VV} = g_{h_{SM}VV} \cdot \kappa_{VV}^{h^0}$$

Interaction	Effective Coupling
$\kappa_{WW}^{h^0} = \kappa_{ZZ}^{h^0}$	$c_7 c_\alpha - 4 s_7 s_\alpha \equiv \kappa_{VV}^{h^0}$
$\kappa_{WW}^{H^0} = \kappa_{ZZ}^{H^0}$	$c_7 s_\alpha + 4 s_7 c_\alpha \equiv \kappa_{VV}^{H^0}$
$\kappa_{WZ}^{H_v^+}$	$-\sqrt{15} s_7$
$\kappa_{WW}^{H^{++}}$	$\sqrt{15} s_7$
$\kappa_{WZ}^{H_1^+}$	$\sqrt{15} s_7 s_\gamma$
$\kappa_{WZ}^{H_2^+}$	$-\sqrt{15} s_7 c_\gamma$

Table: Septet Model: Effective coupling

$$g_{h^0VV}^2 + g_{H^0VV}^2 = g_{h_{SM}VV}^2$$

$$\Rightarrow \quad (\kappa_{VV}^{h^0})^2 + (\kappa_{VV}^{H^0})^2 = (\kappa_{VV}^{h_{SM}})^2 = 1$$

SEPTET CONTRIBUTIONS TO WW → WW :

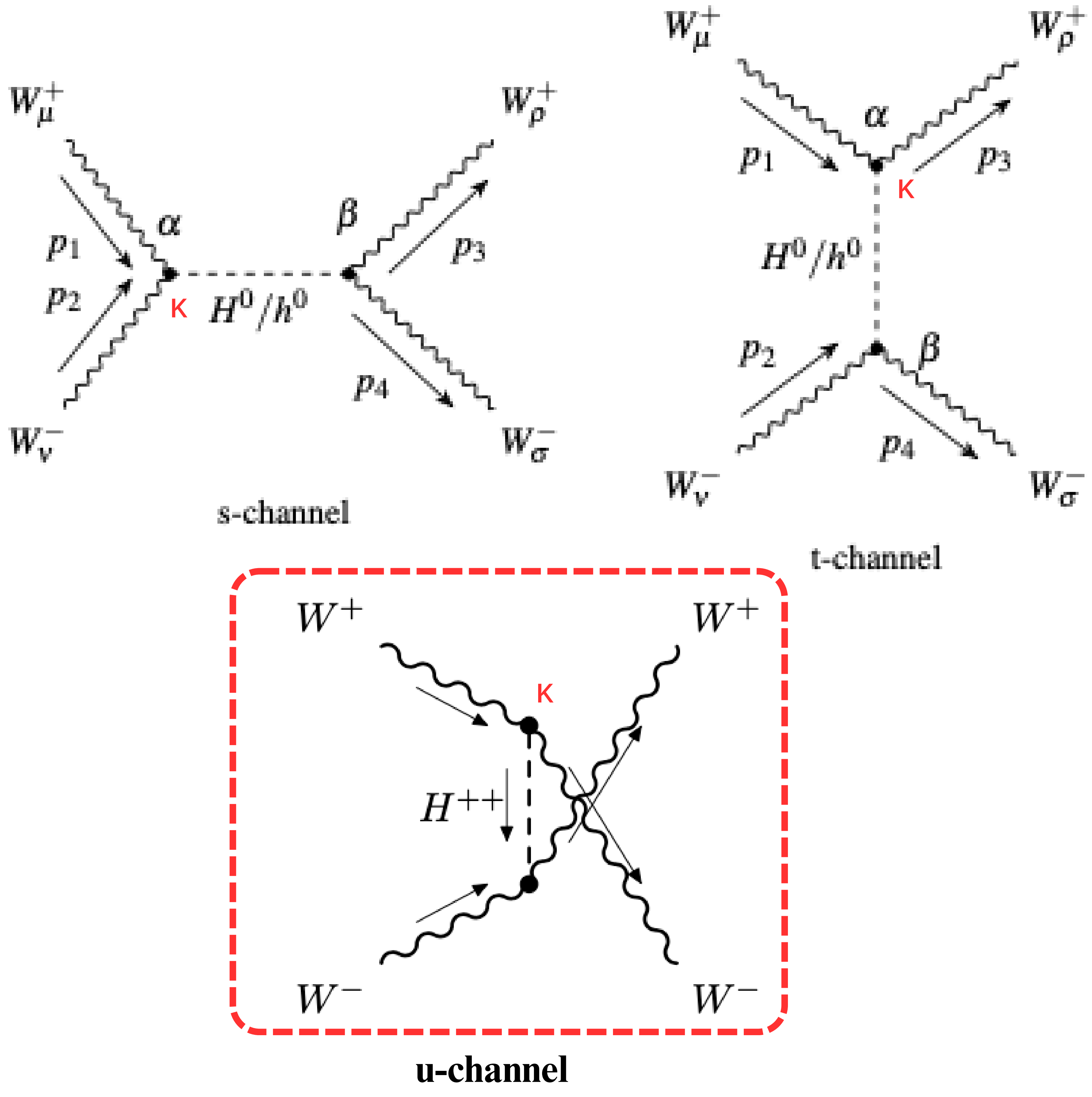


Figure: Septet Model: Feynman Diagrams

[2]

SEPTET MODEL

High Energy Vector Boson Scattering

1. $W^+W^- \xrightarrow{h^0/H^0/H^{++}} W^+W^-$
2. $W^\pm Z \xrightarrow{h^0/H^0/H^{+}} W^\pm Z$

Matrix Element and 1st Sum Rule:

$$\mathcal{M} \simeq -\frac{1}{v^2}\left[\left(\left(\kappa_{WW}^{h^0}\right)^2 + \left(\kappa_{WW}^{H^0}\right)^2\right)(s+t) + \left(\kappa_{WW}^{H^{++}}\right)^2 u \right.$$

$$s + t \simeq -u$$

$$\left. +2\left(\kappa_{WW}^{h^0}\right)^2 m_{h^0}^2 + 2\left(\kappa_{WW}^{H^0}\right)^2 m_{H^0}^2 + \left(\kappa_{WW}^{H^{++}}\right)^2 m_{H^{++}}^2\right].$$

1st Sum Rule:

$$\boxed{\left(\kappa_{WW}^{h^0}\right)^2 + \left(\kappa_{WW}^{H^0}\right)^2 - \left(\kappa_{WW}^{H^{++}}\right)^2 = 1.}$$

Theoretical Check: SUCCESS!!

2nd Sum Rule: $W^\pm Z \longrightarrow W^\pm Z$

$$\boxed{(\kappa_V^h)^2 + (\kappa_V^H)^2 - (\kappa_{WZ}^{H_1^+})^2 - (\kappa_{WZ}^{H_2^+})^2 = 1}$$

[2]

SEPTET MODEL

Mass bound: 1st Sum Rule

$$\boxed{\left(\kappa_{WW}^{h^0}\right)^2 + \left(\kappa_{WW}^{H^0}\right)^2 - \left(\kappa_{WW}^{H^{++}}\right)^2 = 1.}$$

Assuming $\kappa_V^H = 0$

Decoupling limit

$$(\kappa_V^h)^2\big|_{\max} = 1 + (\kappa_{WW}^{H^{++}})^2.$$

Perturbative Unitarity: Mass bounds

$$(\kappa_{WW}^{H^{++}})^2 \leq \frac{8\pi v^2 - 2m_h^2}{m_{H^{++}}^2 + 2m_h^2}.$$

$h^0 \longrightarrow h_{SM}$

Alignment limit

$$s_7^2 \leq \frac{1}{15}\frac{8\pi v^2 - 2m_h^2}{m_{H^{++}}^2 + 2m_h^2}$$

SM: m_h = 125 Gev

[2]

Mass bound: 2nd Sum Rule

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 - (\kappa_{WZ}^{H_1^+})^2 - (\kappa_{WZ}^{H_2^+})^2 = 1 \longrightarrow s_7^2 \leq \frac{1}{15}\frac{8\pi v^2 - m_h^2}{2s_\gamma^2 m_{H_1^+}^2 + 2c_\gamma^2 m_{H_2^+}^2 + m_h^2}$$

SEPTET MODEL

Mass bound obtained using sum rule

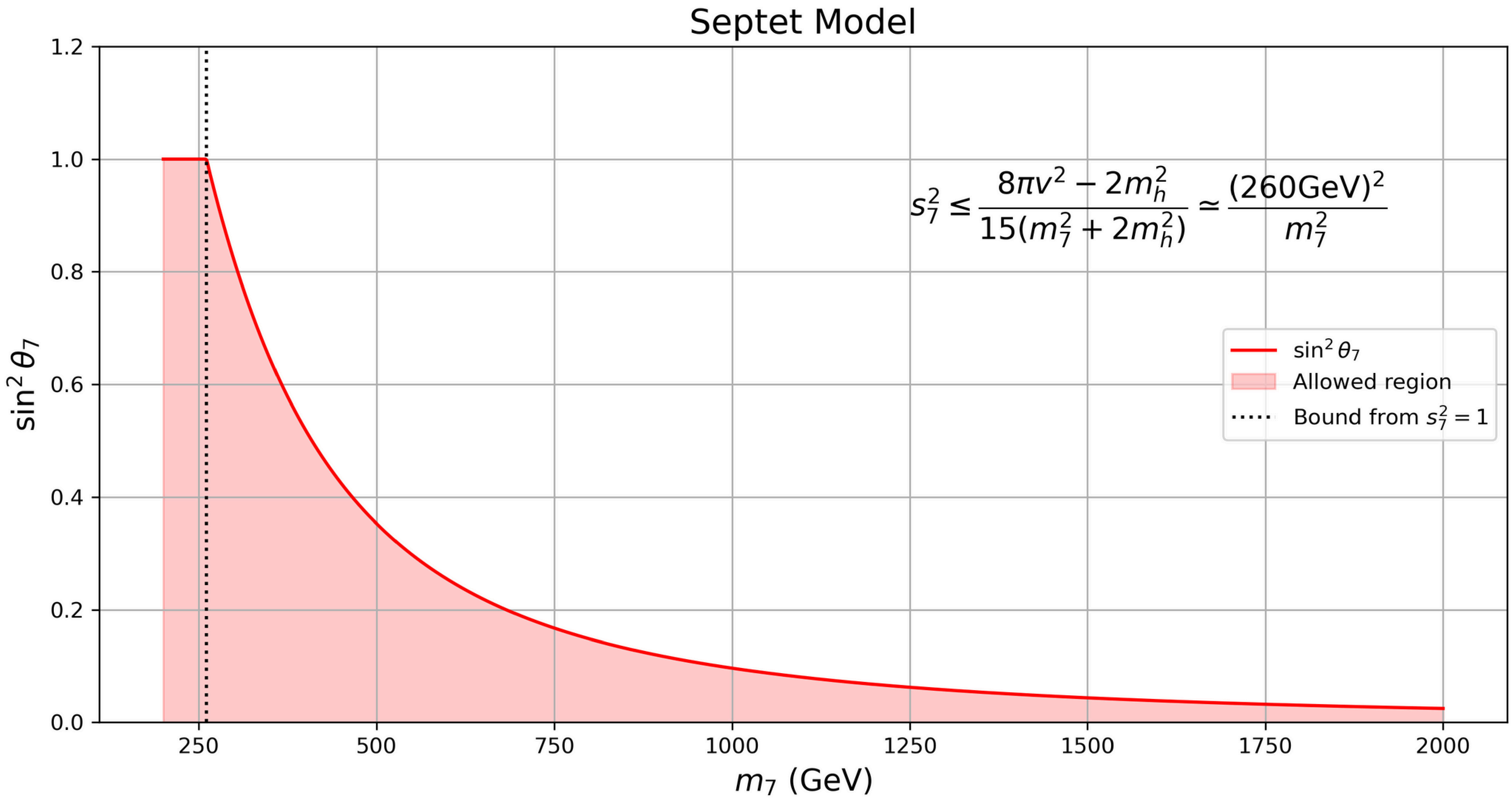


Figure: Septet: The relation sets a bound on s_7 that falls with increasing m_7

THEORETICAL AND ANALYTIC COMPUTATIONS

TWO HIGGS DOUBLET MODEL (THDM)

THE TWO HIGGS DOUBLET MODEL (THDM)

Two Complex SU(2)L Doublets : Φ_i (i = 1,2)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

[5]

Two CP – Conserving Neutral minima

attain vevs as

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

GAUGE FIELDS:

$(i = 1,2)$

Charged states:	$\omega_i^\pm$
CP-even states:	ρ_i
CP-odd states:	η_i

PHYSICAL FIELDS:

Charged states:	$H^\pm$, $G^\pm$
CP-even states:	h^0, H^0
CP-odd states:	G^0, A^0

2HDM Coupling:

$$g_{h^0 W^+ W^-} = g_{H_{SM} W^+ W^-} \cdot \kappa^{h^0}_{W^+ W^-}$$

Coupling	Effective Coupling $\kappa^{h^i}_{VV}$
$\kappa^{h^0}_{W^+W^-}$	$\sin(\beta - \alpha)$
$\kappa^{H^0}_{W^+W^-}$	$\cos(\beta - \alpha)$
$\kappa^{h^0}_{ZZ}$	$\sin(\beta - \alpha)$
$\kappa^{H^0}_{ZZ}$	$\cos(\beta - \alpha)$
$\kappa^{h^0}_{H^+W^-}$	$\cos(\beta - \alpha)$
$\kappa^{H^0}_{H^+W^-}$	$\sin(\beta - \alpha)$
$\kappa^{h^0}_{A^0Z}$	$\cos(\beta - \alpha)$
$\kappa^{H^0}_{A^0Z}$	$\sin(\beta - \alpha)$

Table: 2HDM Model: Effective coupling

THE TWO HIGGS DOUBLET MODEL

High Energy Vector Boson Scattering

1. $W^+W^- \xrightarrow{h^0/H^0} W^+W^-$
2. $Z\,Z \xrightarrow{h^0/H^0} Z\,Z$
3. $W^\pm Z \xrightarrow{h^0/H^0/H^+_5} W^\pm Z$

Matrix Element and Sum Rule

$$i\mathcal{M} = -i\frac{g^2}{4m_W^2}\left[\left(\kappa_{WW}^{h^0}\right)^2\left(\frac{s^2}{s-m_{h^0}^2}+\frac{t^2}{t-m_{h^0}^2}\right)+\left(\kappa_{WW}^{H^0}\right)^2\left(\frac{s^2}{s-m_{h^0}^2}+\frac{t^2}{t-m_{h^0}^2}\right)\right],$$

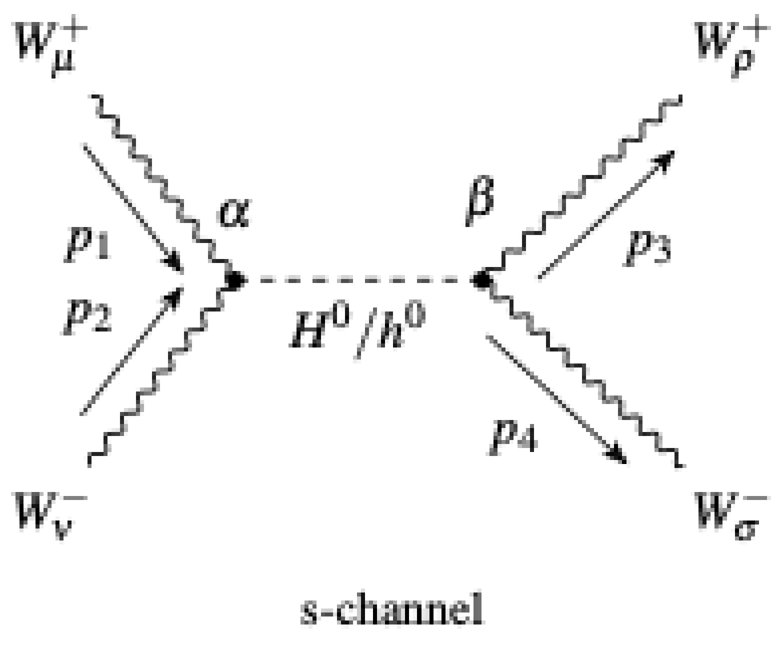
$$i\mathcal{M} \simeq -\frac{i}{v^2}\left[\left(\left(\kappa_{WW}^{h^0}\right)^2+\left(\kappa_{WW}^{H^0}\right)^2\right)(s+t)+2\left(\kappa_{WW}^{h^0}\right)^2 m_{h^0}^2+2\left(\kappa_{WW}^{H^0}\right)^2 m_{H^0}^2+\dots\right].$$

1st Sum Rule:

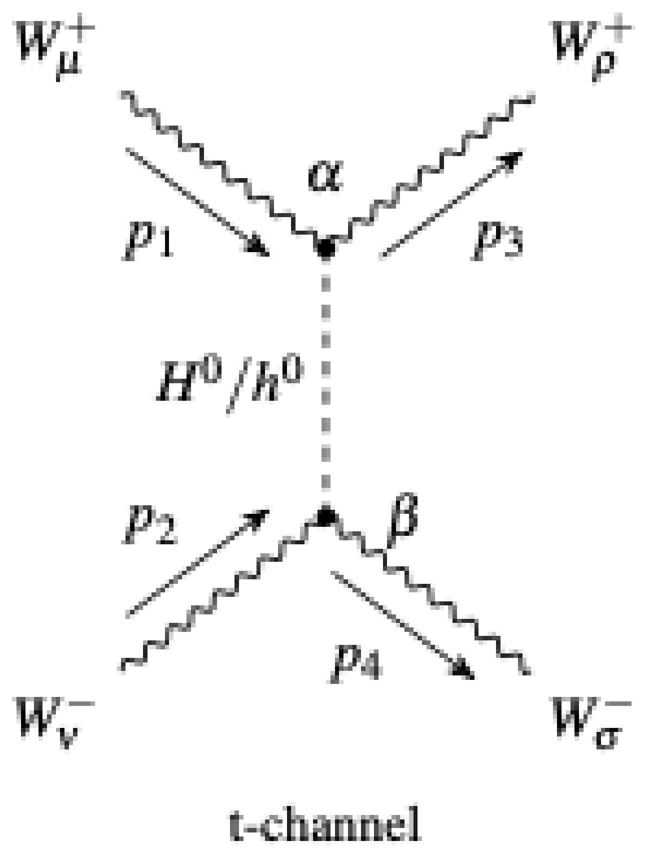
$$\left(\kappa_{WW}^{h^0}\right)^2+\left(\kappa_{WW}^{H^0}\right)^2=1, \quad \text{or}$$

$$\sum_i \left(g_{h_iWW}\right)^2=\left(g_{H_{SM}WW}\right)^2, \quad h_i=h^0,H^0$$

Eg. $W^+W^- \xrightarrow{h^0/H^0} W^+W^-$



s-channel



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SM: h_{SM} = 125 Gev

Theoretical Check:
SUCCESS!!

$$\sin^2(\beta-\alpha)+\cos^2(\beta-\alpha)=1$$

THE TWO HIGGS DOUBLET MODEL

Sum Rules in 2HDM

[5]

1. $W^+W^- \xrightarrow{h^0/H^0} W^+W^-$
2. $Z\,Z \xrightarrow{h^0/H^0} Z\,Z$

$$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 = 1, V = W, Z \text{ or}$$

$$\sum_i g_{h_i VV}^2 = g_{H_{SM} VV}^2, \quad h_i = h^0, H^0$$

3. $W^\pm Z \xrightarrow{h^0/H^0/H^+} W^\pm Z$

$$\left(\kappa_{WW}^{h^0} \kappa_{ZZ}^{h^0}\right) + \left(\kappa_{WW}^{H^0} \kappa_{ZZ}^{h^0}\right) = 1 \quad \text{,or}$$

$$\sum_i g_{h_i WW} g_{h_i ZZ} = g_{H_{SM} WW} g_{H_{SM} ZZ}, \quad h_i = h^0, H^0$$

Mass bounds from Perturbative unitarity

$$\cos^2(\beta - \alpha) \leq \frac{4\pi v^2 - m_h^2}{m_{H^0}^2 - m_h^2} \simeq \left(\frac{880 \text{ GeV}}{m_{H^0}}\right)^2,$$

$$m_{H^0}^2 \lesssim \left(\frac{880 \text{ GeV}}{\kappa_{WW}^{H^0}}\right)^2$$

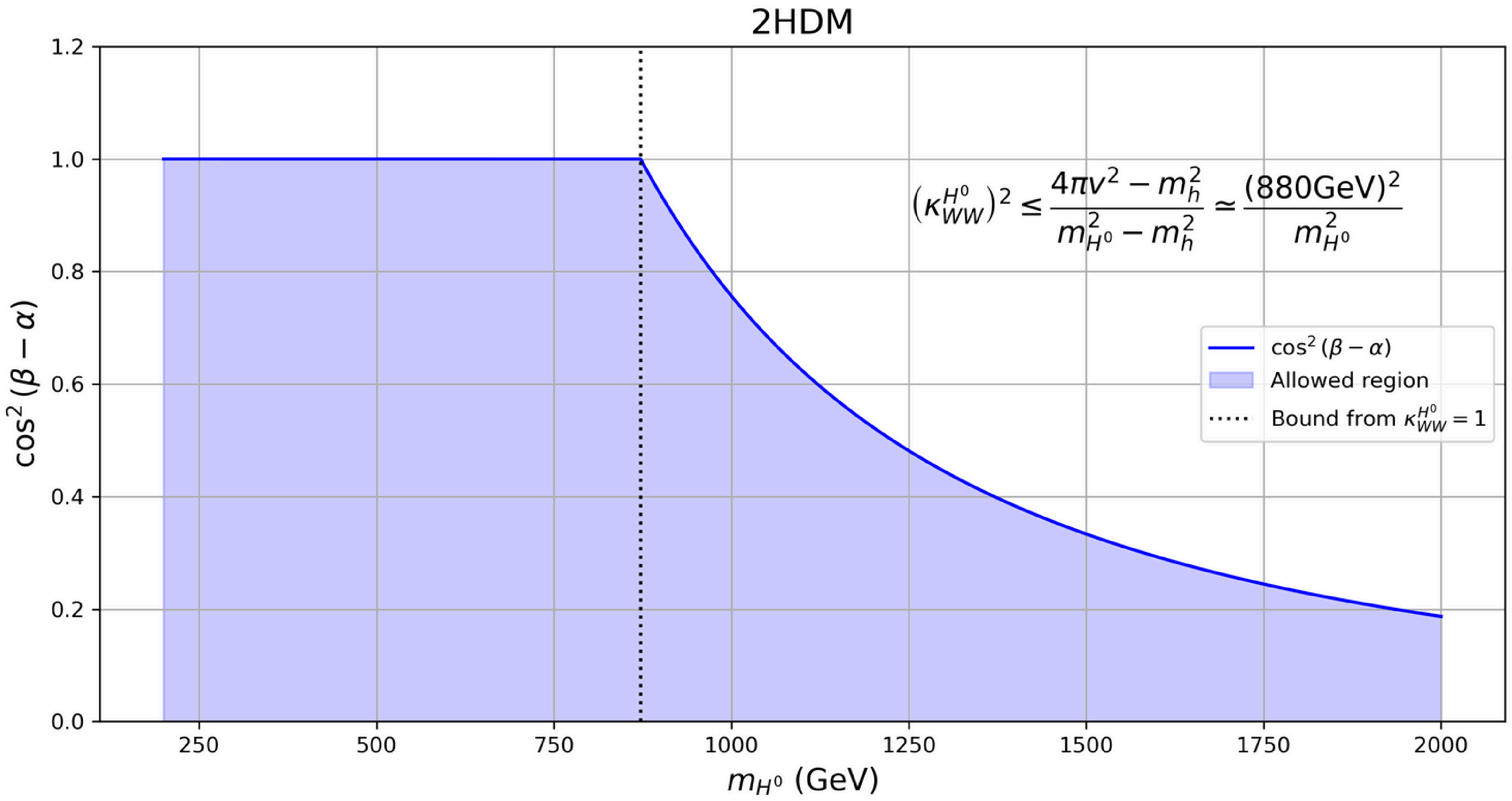


Figure: 2HDM: The relation sets a bound on H^0 coupling that falls with increasing m_{H0}

THEORETICAL AND ANALYTIC COMPUTATIONS

GEORGIE MACHACEK (GM)

GEORGIE MACHACEK (GM)

1 Higgs Doublet (ϕ), 1 Complex Triplet (X) & 1 Real Triplet (ξ) [4]

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$$

Hyper Charges:

$Y_\Phi = 1$

$Y_X = 2$

$Y_\xi = 0$

bi-doublet and bi-triplet under $SU(2)_L \times SU(2)_R$

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}, \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}.$$

attain vevs as

$$v^2 = v_\phi^2 + 8v_\chi^2 = \frac{4M_W^2}{g^2} = (246\ \text{GeV})^2,$$

neutral state decompsition

$$\phi^0 = \frac{v_\phi + \phi^{0,r} + \phi^{0,i}}{\sqrt{2}}$$

$$\chi^0 = v_\chi + \frac{\chi^{0,r} + \chi^{0,i}}{\sqrt{2}}$$

$$\xi^0 = v_\chi + \xi^{0,r}$$

GAUGE FIELDS:

Doubly charged states:	$\chi^{\pm\pm}$
Singly charged states:	$\phi^\pm,\ \xi^\pm,\ \chi^\pm$
CP-even states:	$\phi^{0,r},\ \chi^{0,r},\ \xi^{0,r}$
CP-odd states:	$\phi^{0,i},\ \chi^{0,i}$

PHYSICAL FIELDS:

Custodial Singlet	$h^0,\ H^0$
Custodial Triplet	$H_3^\pm,\ H_3^0$
Custodial Fiveplet	$H_5^{\pm\pm},\ H_5^\pm,\ H_5^0$
Goldstone Bosons	$G^\pm,\ G^0$

GEORGIE MACHACEK (GM)

GM Coupling:

Interaction ($\kappa^{h^i}_{VV}$)	Effective Coupling
$\kappa^{h^0}_{WW}$	$c_H c_\alpha - \frac{\sqrt{8}}{\sqrt{3}} s_H s_\alpha$
$\kappa^{h^0}_{ZZ}$	$c_H c_\alpha - \frac{\sqrt{8}}{\sqrt{3}} s_H s_\alpha$
$\kappa^{H_5^0}_{WW}$	$-\frac{2}{\sqrt{3}} s_H$
$\kappa^{H_5^0}_{ZZ}$	$-\frac{2}{\sqrt{3}} s_H$
$\kappa^{H_5^{++}}_{WW}$	$\sqrt{2} s_H$
$\kappa^{H^0}_{WW}$	$c_H s_\alpha + \frac{\sqrt{8}}{\sqrt{3}} s_H c_\alpha$
$\kappa^{H^0}_{ZZ}$	$c_H s_\alpha + \frac{\sqrt{8}}{\sqrt{3}} s_H c_\alpha$
$\kappa^{H_5^0}_{W^+W^-}$	$-\frac{1}{\sqrt{3}} s_H$
$\kappa^{H_5^+}_{W^\pm Z}$	s_H

$\rightarrow (\kappa^{h^0}_{VV})$

$\rightarrow (\kappa^{H^0}_{VV})$

Table: GM Model: Effective coupling

[1]

High Energy Vector Boson Scattering

1. $W^+W^- \xrightarrow{h^0/H^0/H^0_5/H_5^{++}} W^+W^-$
2. $W^\pm Z \xrightarrow{h^0/H^0/H^+_5} W^\pm Z$

GM CONTRIBUTIONS:

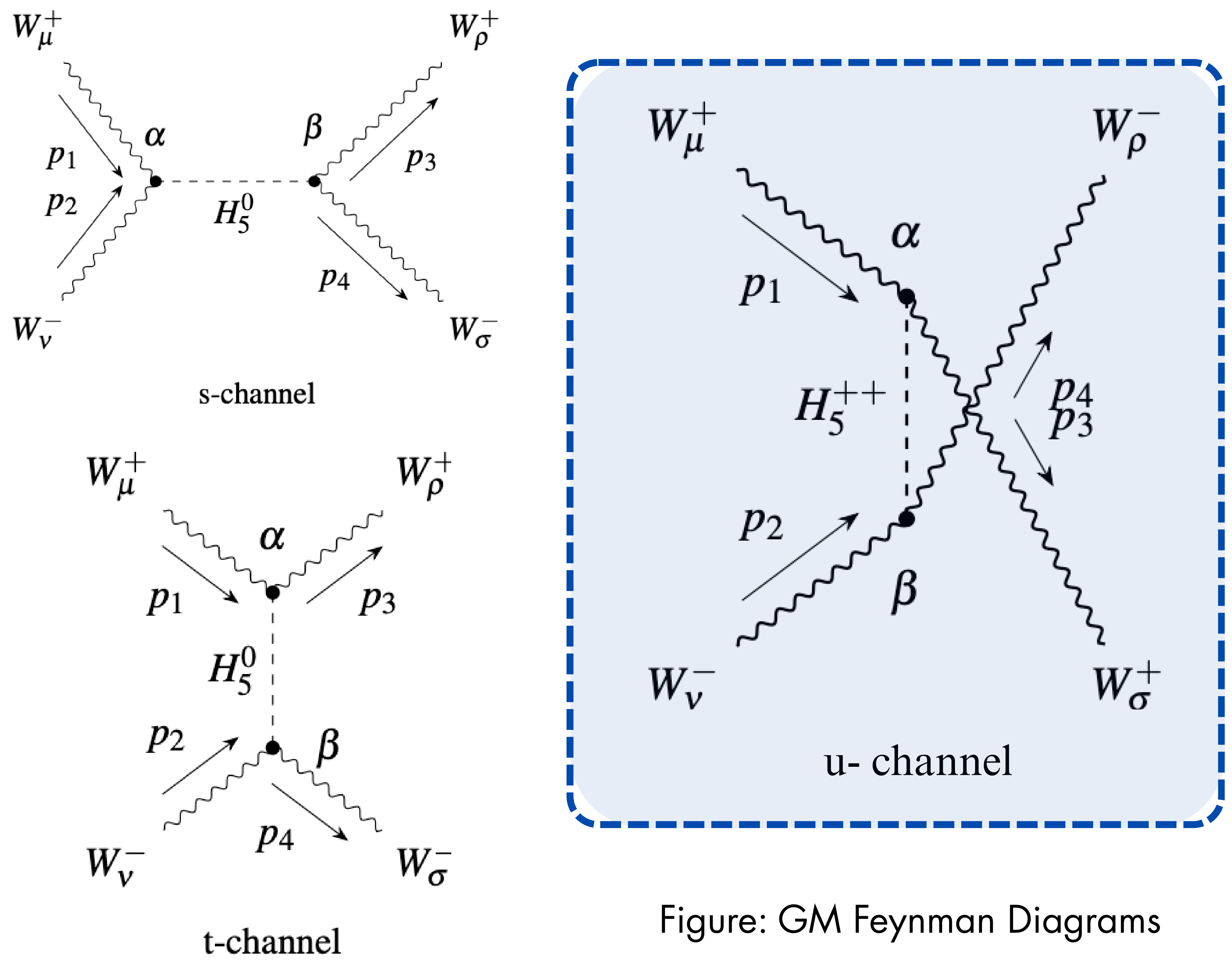
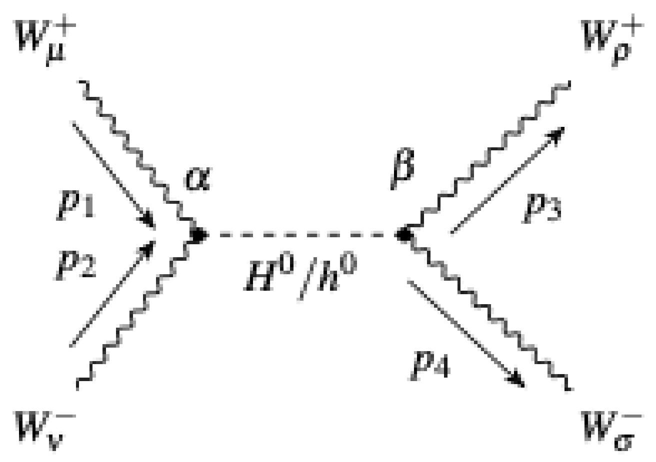


Figure: GM Feynman Diagrams

GEORGIE MACHACEK (GM)

SM: h_{SM} = 125 Gev

Eg. $W^+W^- \xrightarrow{h^0/H^0/H^0_5/H_5^{++}} W^+W^-$



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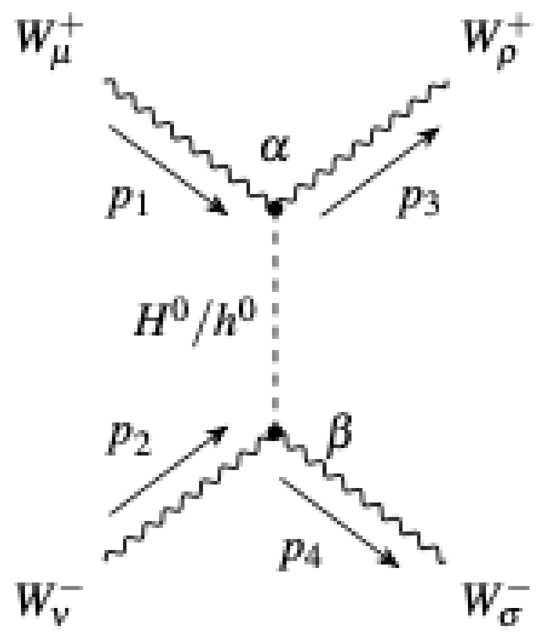

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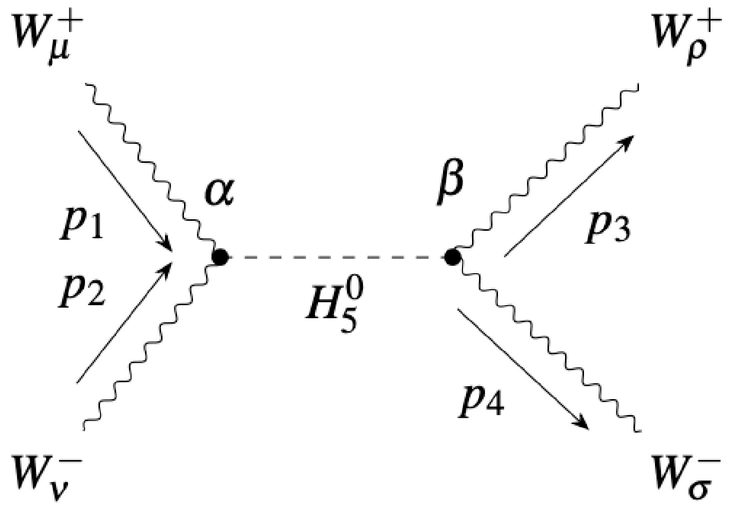

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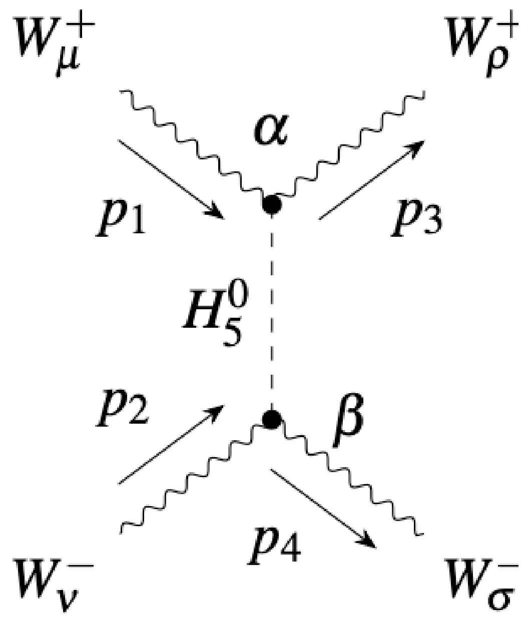

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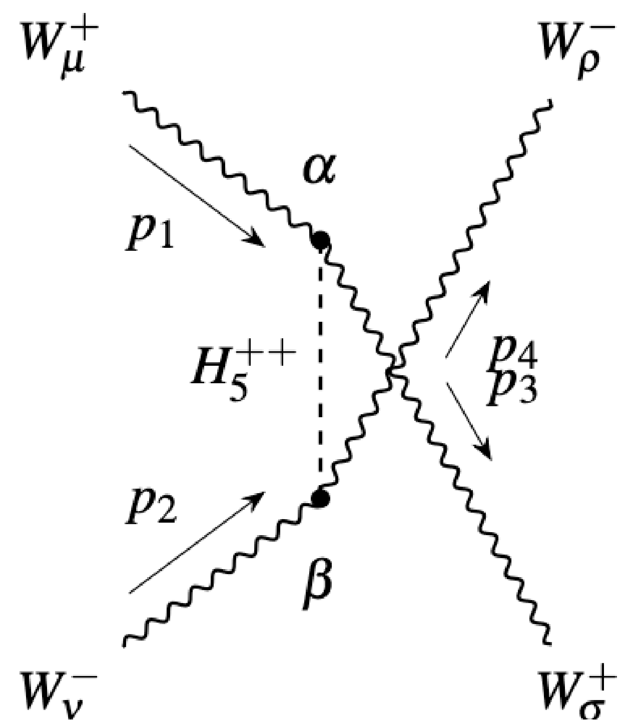


u- channel

Matrix Element and Sum Rule:

$$\mathcal{M} = -\frac{1}{v^2}\left[\left(\left(\kappa_{WW}^{h^0}\right)^2 + \left(\kappa_{WW}^{H^0}\right)^2 + \left(\kappa_{WW}^{H_5^0}\right)^2 - \left(\kappa_{WW}^{H_5^{++}}\right)^2\right)(s+t) + 2\left(\kappa_{WW}^{h^0}\right)^2 m_{h^0}^2 + 2\left(\kappa_{WW}^{H^0}\right)^2 m_{H^0}^2 + 2\left(\kappa_{WW}^{H_5^0}\right)^2 m_5^2 + \left(\kappa_{WW}^{H_5^{++}}\right)^2 m_5^2\right].$$

1 st Sum Rule:

$$\left(\kappa_{WW}^{h^0}\right)^2 + \left(\kappa_{WW}^{H^0}\right)^2 + \left(\kappa_{WW}^{H_5^0}\right)^2 - \left(\kappa_{WW}^{H_5^{++}}\right)^2 = 1, \quad \text{or}$$

$$\sum_i g^2_{h_i W^+W^-} - g_{h^{--}W^+W^+} g_{h^{++}W^-W^-} = g^2_{H_{SM}WW},$$

$$c_H^2 + \frac{8}{3}s_H^2 + \frac{1}{3}s_H^2 - 2s_H^2 = c_H^2 + s_H^2 = 1,$$

Theoretical Check: SUCCESS!!

GEORGIE MACHACEK (GM)

Sum Rules in GM

1. W⁺W⁻ —— h⁰/H⁰/H^0_5/H_5^{++} → W⁺W⁻

$$\left(\kappa_{WW}^{h^0}\right)^2+\left(\kappa_{WW}^{H^0}\right)^2+\left(\kappa_{WW}^{H_5^0}\right)^2-\left(\kappa_{WW}^{H_5^{++}}\right)^2=1$$

Mass bound :

$$s_H^2 \leq \frac{3}{2}\cdot\frac{8\pi v^2-2m_h^2}{4m_5^2+5m_h^2} \simeq \left(\frac{734\text{ GeV}}{m_5}\right)^2$$

2. W$^\pm$Z —— h⁰/H⁰/H^0_5/H^+_5 → W$^\pm$ Z

$$\left(\kappa_{VV}^{h^0}\right)^2+\left(\kappa_{VV}^{H^0}\right)^2+\left(\kappa_{WW}^{H_5^0}\kappa_{ZZ}^{H_5^0}\right)-\left(\kappa_{WZ}^{H_5^+}\right)^2=1$$

Mass bound :

$$s_H^2 \leq \frac{3}{5\sqrt{2}}\frac{(16\pi v^2-m_{h^0}^2)}{(m_{h^0}^2-m_5^2)} \approx \left(\frac{(800\text{ GeV})^2}{m_5^2}\right).$$

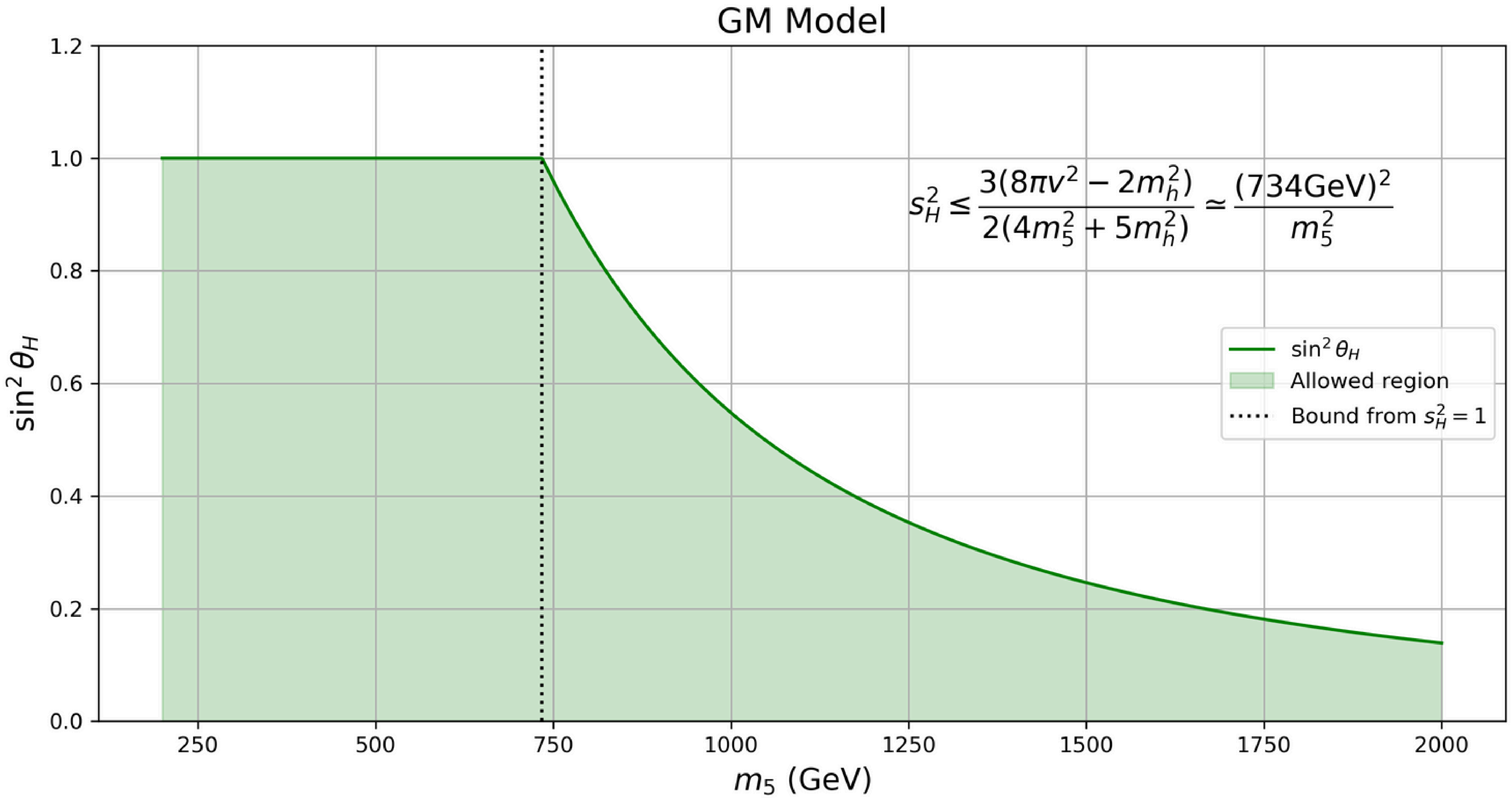


Figure: GM: mass bound sets upper bound on s_H that falls with increasing m_5

COMPARATIVE ANALYSIS

COMPARATIVE ANALYSIS

Feature	2HDM	GM Model	Septet Model
Field content and SU(2) representation	$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \ \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$	$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \ \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \ \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}$	$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \ X = \begin{pmatrix} \chi^{+5} \\ \chi^{+4} \\ \chi^{+3} \\ \chi^{+2} \\ \chi_1^{+1} \\ \chi^0 \\ \chi_2^{-1} \end{pmatrix}$
Higgs couplings to Gauge Bosons	$\kappa_{VV}^{h^0} = \sin(\beta - \alpha)$ $\kappa_{VV}^{H^0} = \cos(\beta - \alpha)$	$\kappa_{VV}^{h^0} = c_{\theta_H} c_\alpha - \sqrt{\frac{8}{3}} c_{\theta_H} s_\alpha$ $\kappa_{VV}^{H^0} = c_{\theta_H} s_\alpha + \sqrt{\frac{8}{3}} c_{\theta_H} c_\alpha$ $\kappa_{VV}^{H_5^{++}} = \sqrt{2} s_{\theta_H}$	$\kappa_{VV}^{h^0} = c_7 c_\alpha - 4 s_7 s_\alpha$ $\kappa_{VV}^{H^0} = c_7 s_\alpha + 4 s_7 c_\alpha$ $\kappa_{VV}^{H^{++}} = \sqrt{15} s_7$
VEV Structure	$v^2 = v_1^2 + v_2^2$	$v^2 = v_\phi^2 + 8 v_\chi^2$	$v^2 = v_\phi^2 + 16 v_\chi^2$
$\tan(\beta, \theta_H, \theta_7)$ relation (VEV)	$\tan\beta = \frac{v_2}{v_1}$	$\tan\theta_H = \frac{2\sqrt{2} v_\chi}{v_\phi}$	$\tan\theta_7 = \frac{4 v_\chi}{v_\phi}$
Coupling Sum Rules	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 = 1$	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 + \left(\kappa_{VV}^{H_5^0}\right)^2 - \left(\kappa_{VV}^{H_5^{++}}\right)^2 = 1$	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 - \left(\kappa_{VV}^{H^{++}}\right)^2 = 1$
Mass Bounds	$\cos^2(\beta - \alpha) \le \left(\frac{880 \text{ GeV}}{m_{H^0}}\right)^2$	$s_H^2 \le \left(\frac{734 \text{ GeV}}{m_5}\right)^2$	$s_7^2 \le \left(\frac{260 \text{ GeV}}{m_{H^{++}}}\right)^2$

Table: Comparative analysis of 2HDM, GM and Septet Models

PHENOMENOLOGICAL APPLICATIONS FOR BSM

EXPERIMENTAL LIMITS ON BSM MODELS

Experimental limits: A portrait of the Higgs boson by the CMS experiment ten years after the discovery (arxiv:2207.00043)

Framework	Definition
Coupling Modifier (κ)	$\kappa_V^2 = \frac{\sigma^{\mathrm{BSM}}}{\sigma^{\mathrm{SM}}}$

Experimental Value
CMS Global Fit: $\kappa_V = 1.02 \pm 0.08$ $\Rightarrow \kappa_V \in [0.86, 1.18]$ (2σ)

[3]

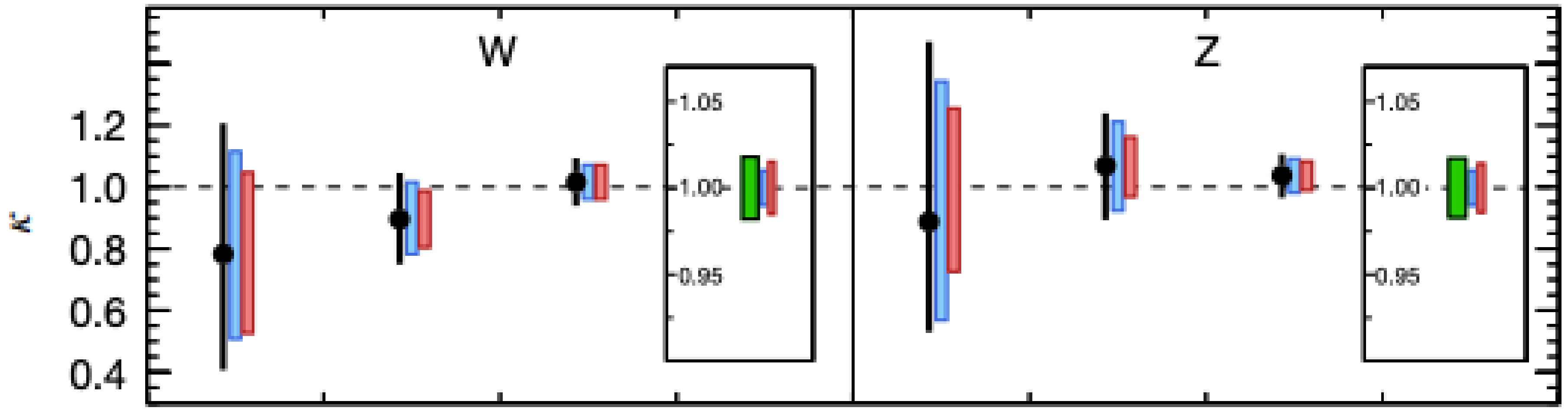
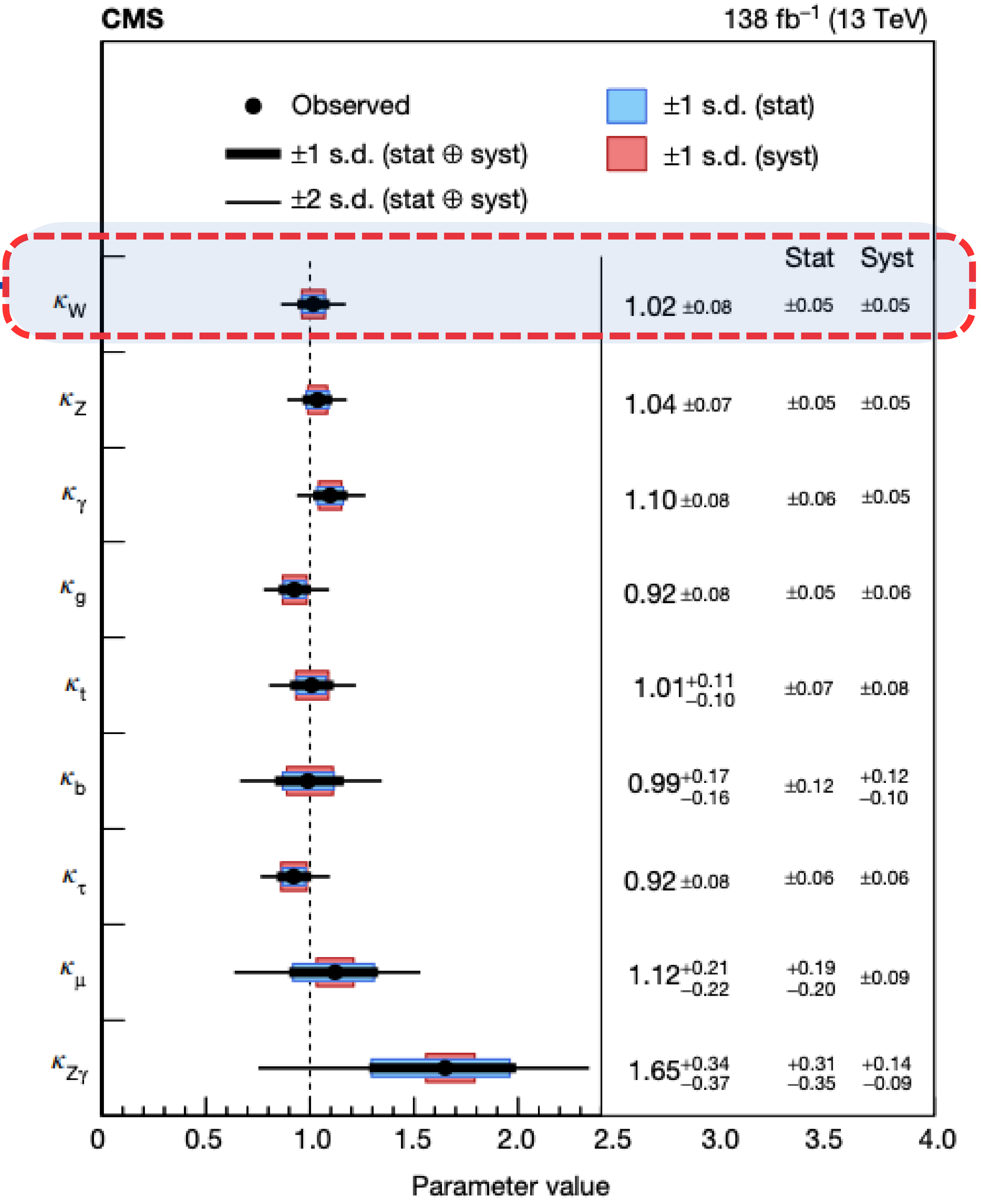
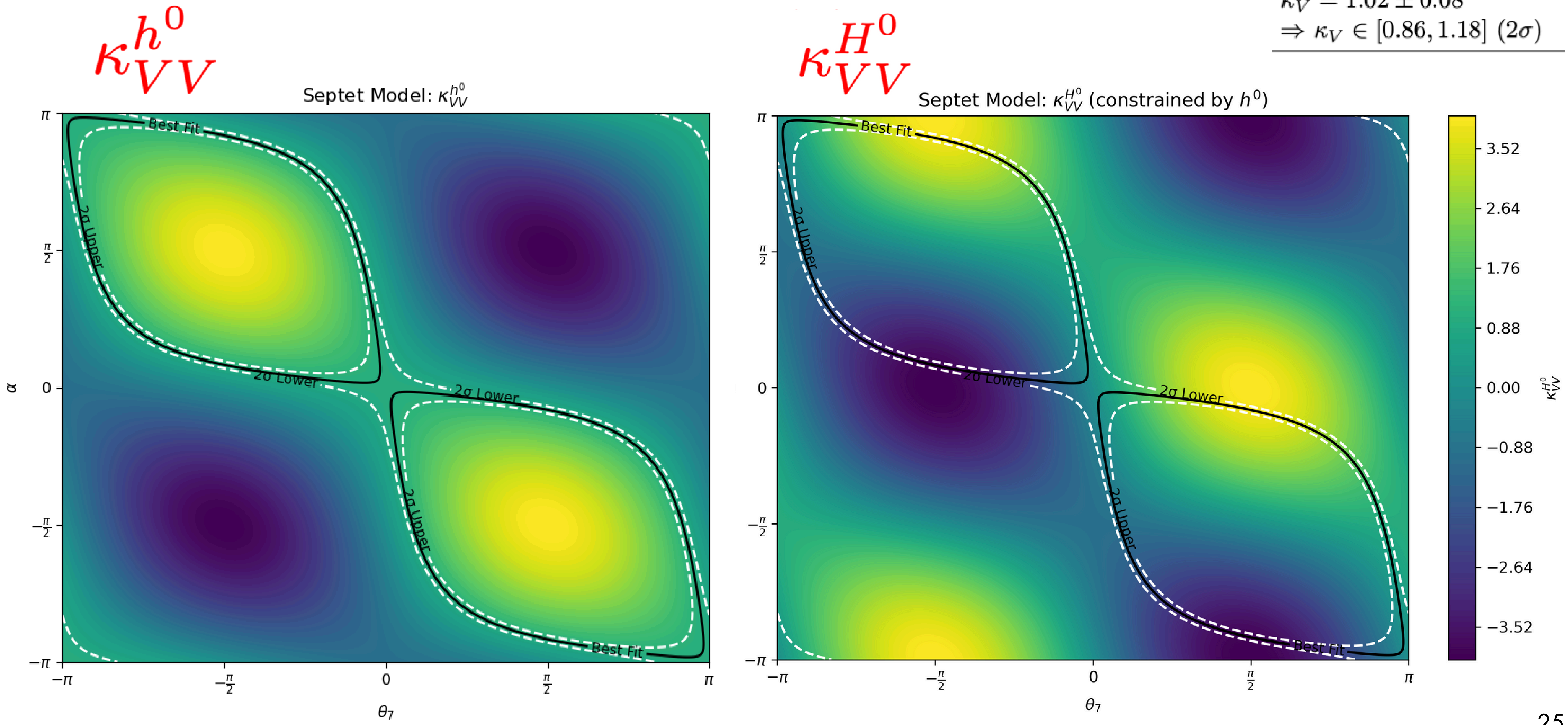


Figure: Coupling Modifier measurements



EXPERIMENTAL LIMITS ON BSM MODELS

CMS Global Fit:
$\kappa_V = 1.02 \pm 0.08$
$\Rightarrow \kappa_V \in [0.86, 1.18]\ (2\sigma)$



SEPTET MODEL

Figure: Heatmap for K^{h0}_{VV} and K^{H0}_{VV} with coupling strength limits

EXPERIMENTAL LIMITS ON BSM MODELS

$\kappa_{VV}^{H^{++}}$

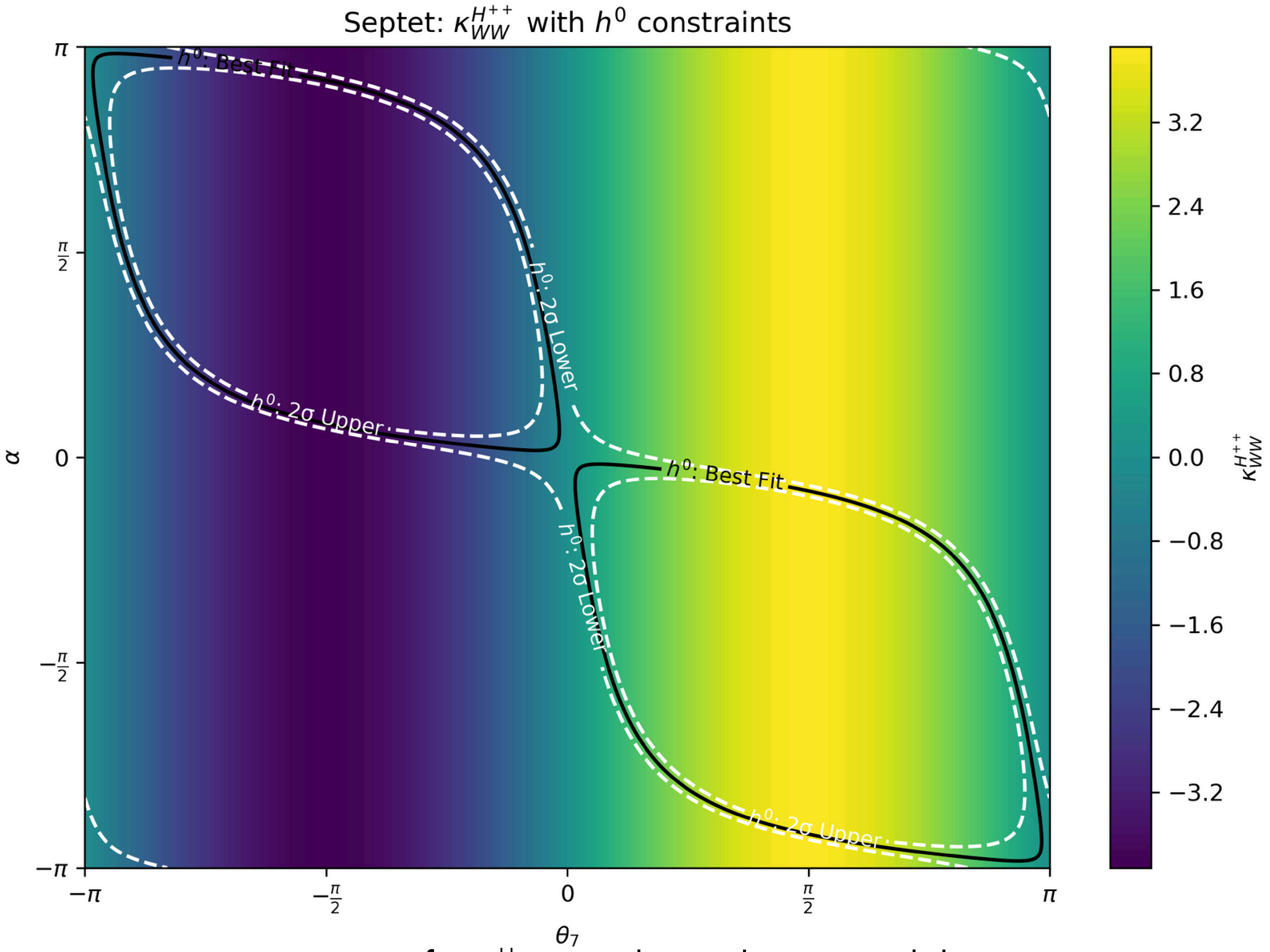
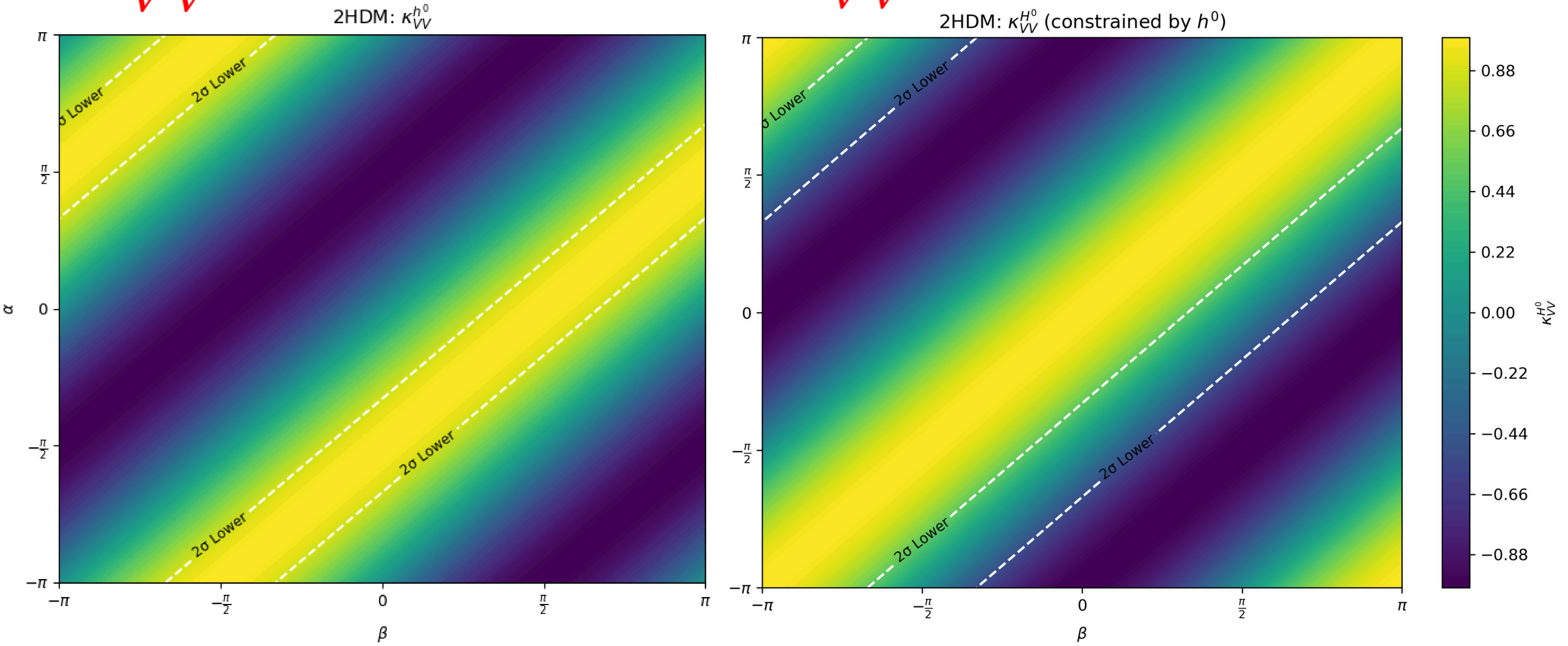


Figure: Heatmap for $K^{H^{++}}_{VV}$ with coupling strength limits

SEPTET MODEL

EXPERIMENTAL LIMITS ON BSM MODELS

$\kappa^{h^0}_{VV}$ $\kappa^{H^0}_{VV}$

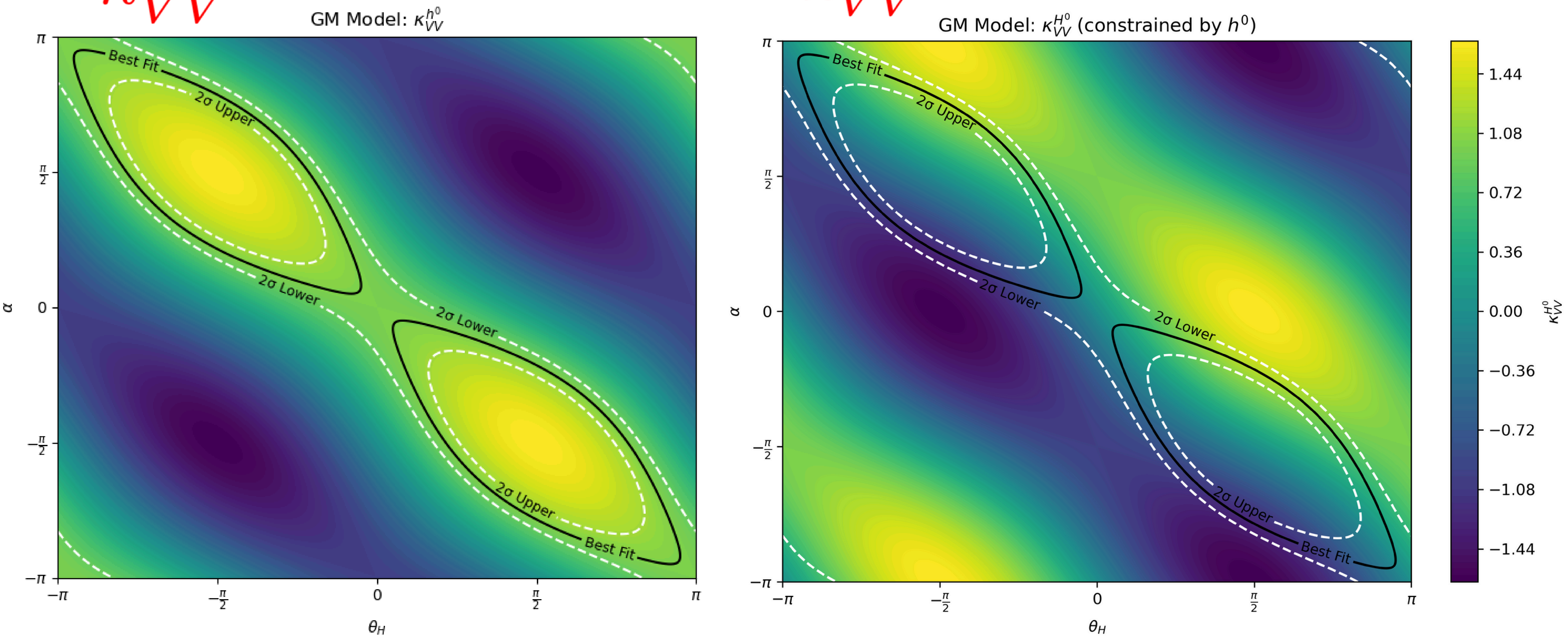


2HDM

Figure: Heatmap for K^{h0}_{VV} and K^{H0}_{VV} with coupling strength limits

EXPERIMENTAL LIMITS ON BSM MODELS

$\kappa^{h^0}_{VV}$ $\kappa^{H^0}_{VV}$



GM MODEL

Figure: Heatmap for K^{h0}_{VV} and K^{H0}_{VV} with coupling strength limits

EXPERIMENTAL LIMITS ON BSM MODELS

$\kappa_{VV}^{H^{++}}$

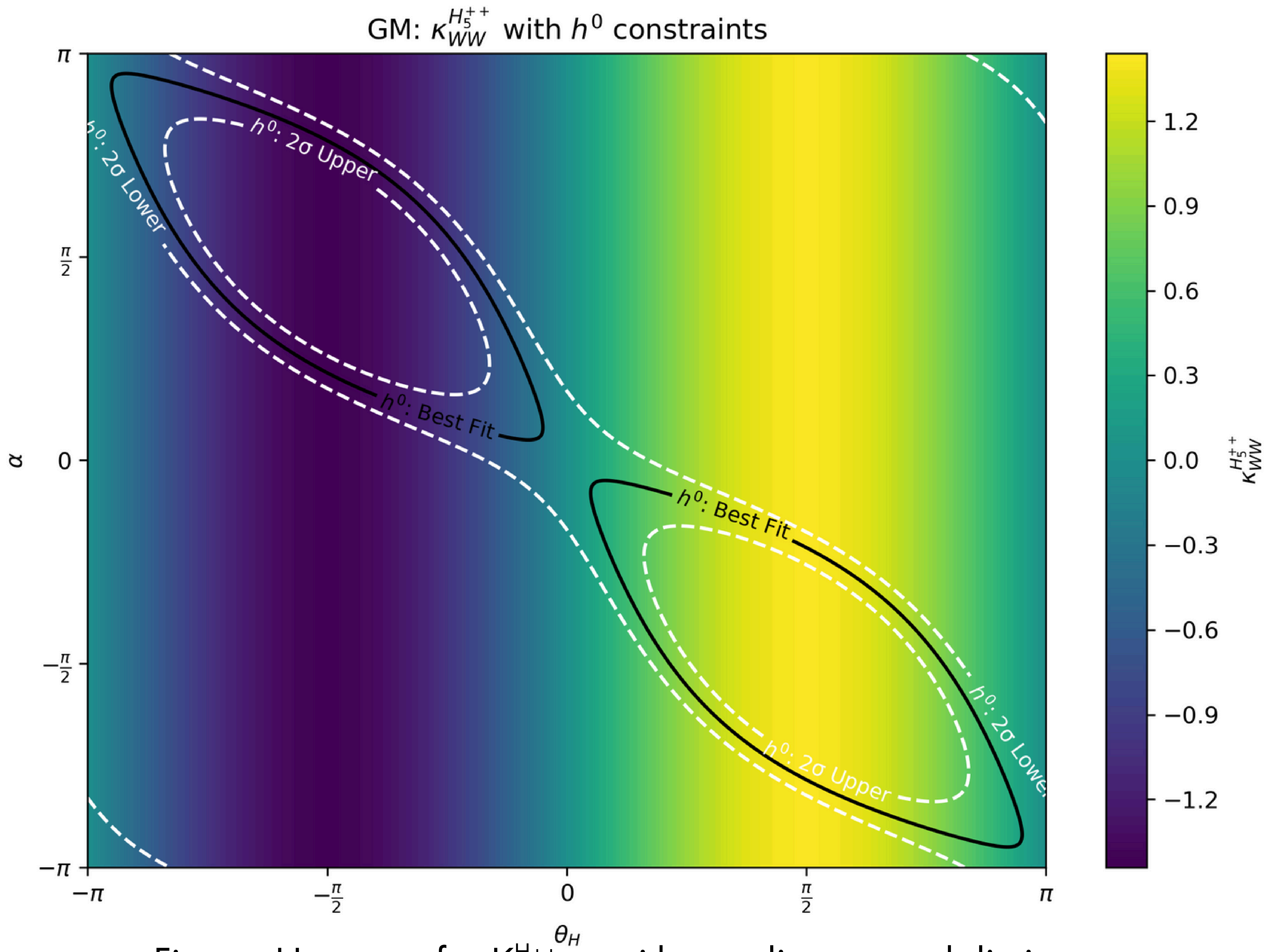


Figure: Heatmap for K^{H++}_{VV} with coupling strength limits

GM MODEL

HIGGSTOOLS FRAMEWORK AND ANALYSIS STRATEGY

HIGGSTOOLS: WORKING AND ANALYSIS STATERGY

HiggsTools [10]

- **HiggsPredictions**

Entry point: HiggsPredictions handles model predictions for BSM particles.

1. Provide effective coupling input
2. Provide total width, production cross sections and branching ratios

- **HiggsBounds**

1. Evaluating bounds from direct searches for scalar particles
2. Obtain obsRatio and expRatio
3. Obtain allowed and excluded points

- **HiggsSignals**

Check compatibility of the model with the LHC rate measurements of the Higgs boson at 125 GeV

Model	Scan range for $\kappa_V^{H^0}$
2HDM	$[-0.51,\ 0.50]$
GM	$[-1.39,\ 1.39]$
Septet	$[-3.91,\ 3.91]$

Table: Model-wise ranges for the effective coupling, $\kappa_V^{H^0}$, which we use as our input parameters

HiggsBounds Result Sample

[ALLOWED] obsRatio 0.749, expRatio: 0.359 for ["H0"] with LHC13 [vbfH,H]>[ZZ] from 1804.01939 (CMS 35.9fb^{-1}, M=(130, 3000), Gam/M=(0, 0.3))

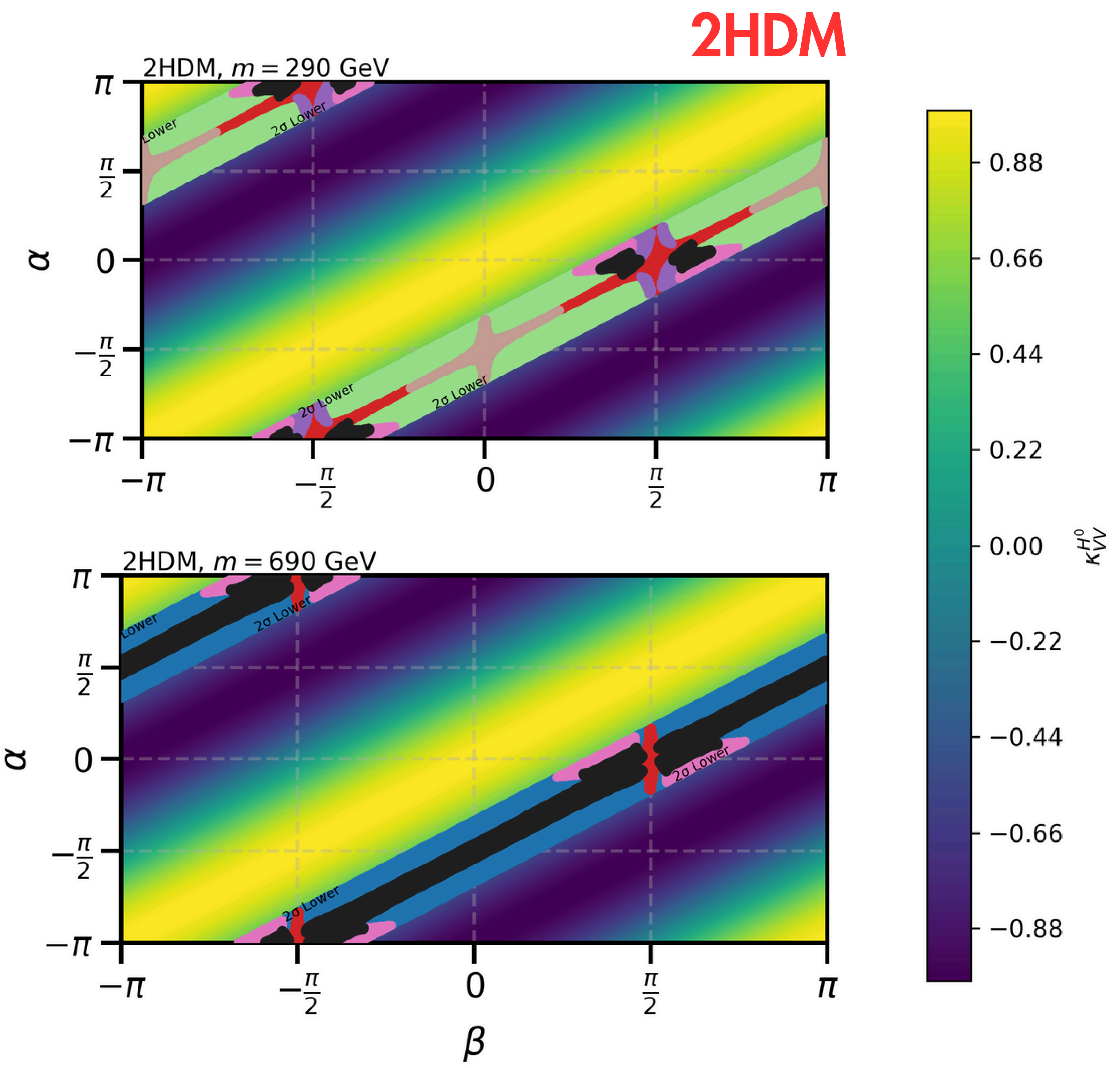
$$\text{expRatio} \equiv \frac{(\sigma \times \text{BR})_{\text{theory}}}{(\sigma \times \text{BR})^{95\%}_{\text{exp}}}$$

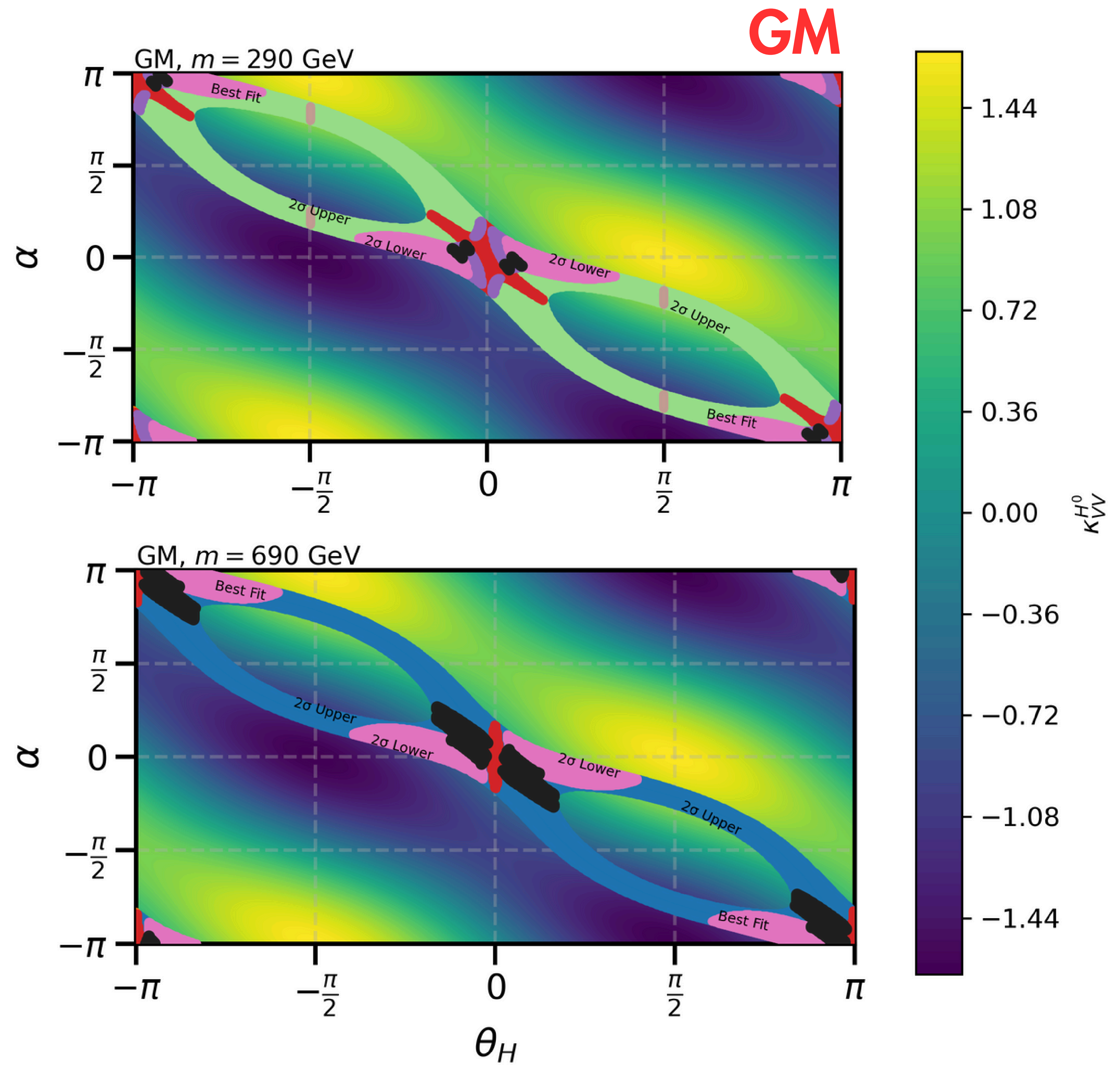
Largest expRatio gives us the Most Sensitive Channel

$$\text{obsRatio} \equiv \frac{(\sigma \times \text{BR})_{\text{theory}}}{(\sigma \times \text{BR})^{95\%}_{\text{obs}}}$$

Exclusion Limit: points with obsRatio>1are excluded

HIGGSTOOLS: EXCLUSION BOUNDS (BY CHANNEL)





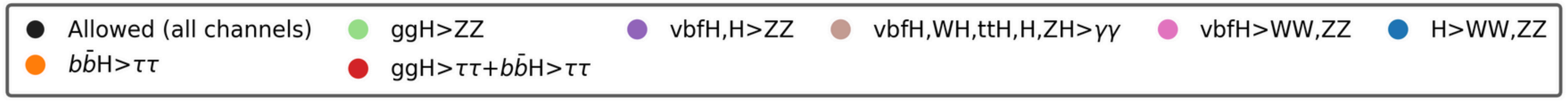
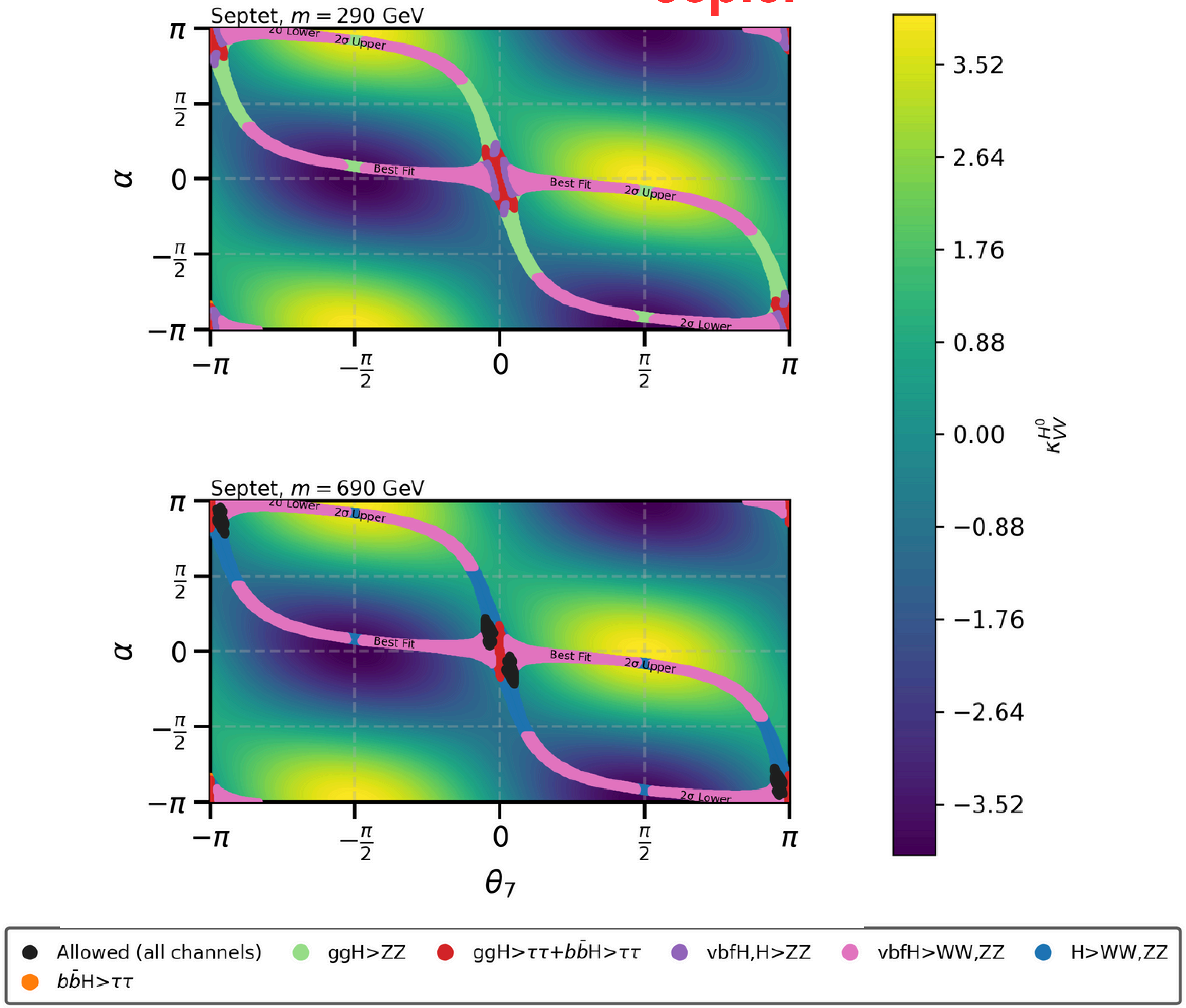


Figure: Model-wise mass panel overlays in the (β , α$\kappa_V^{H^0}$lane, with effective coupling heatmaps the background and the color-coded regions are most-sensitive exclusion channel from the HiggsBounds result.

HIGGSTOOLS: EXCLUSION LIMITS (BY CHANNEL)

Septet



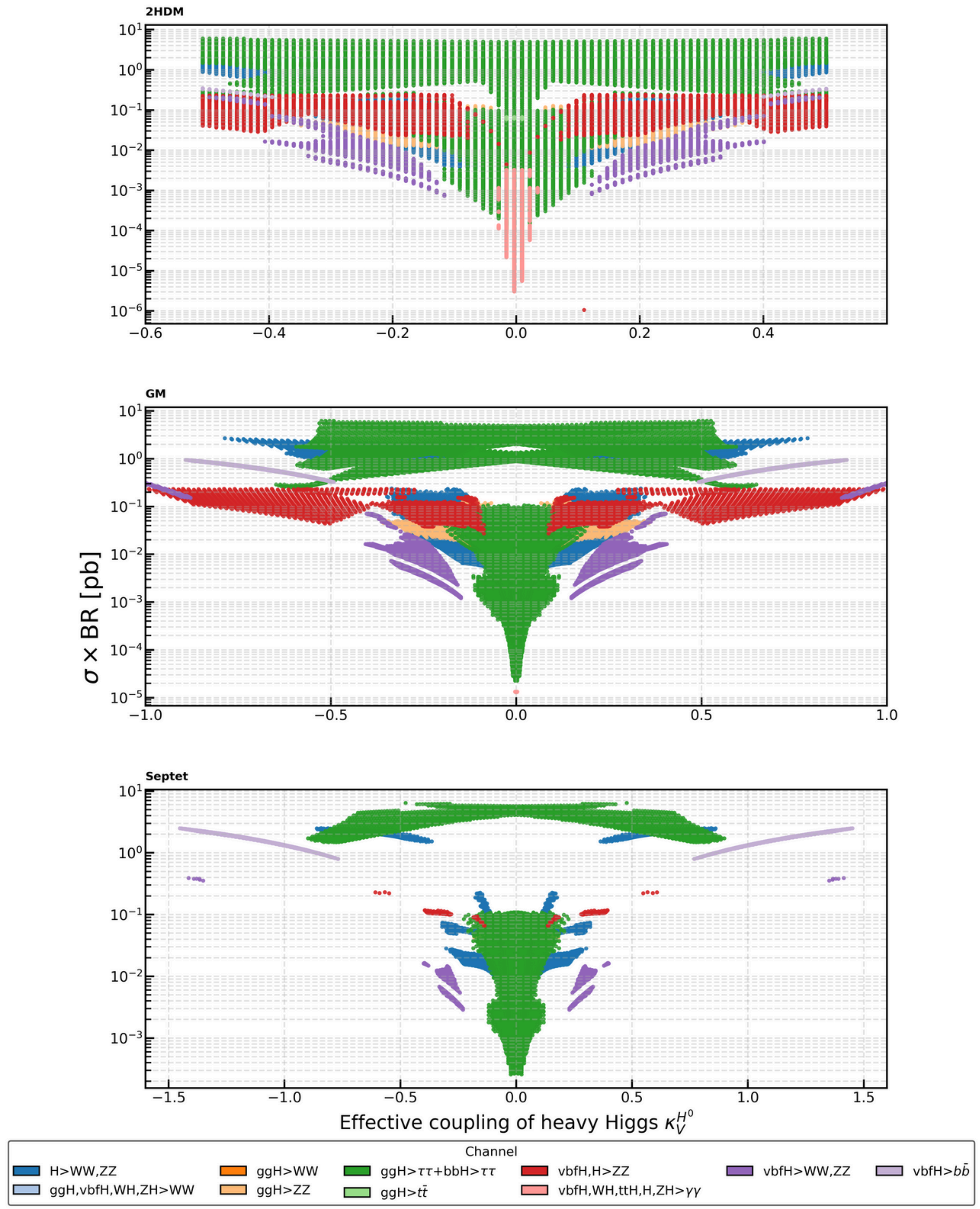
Important Exclusion Channels

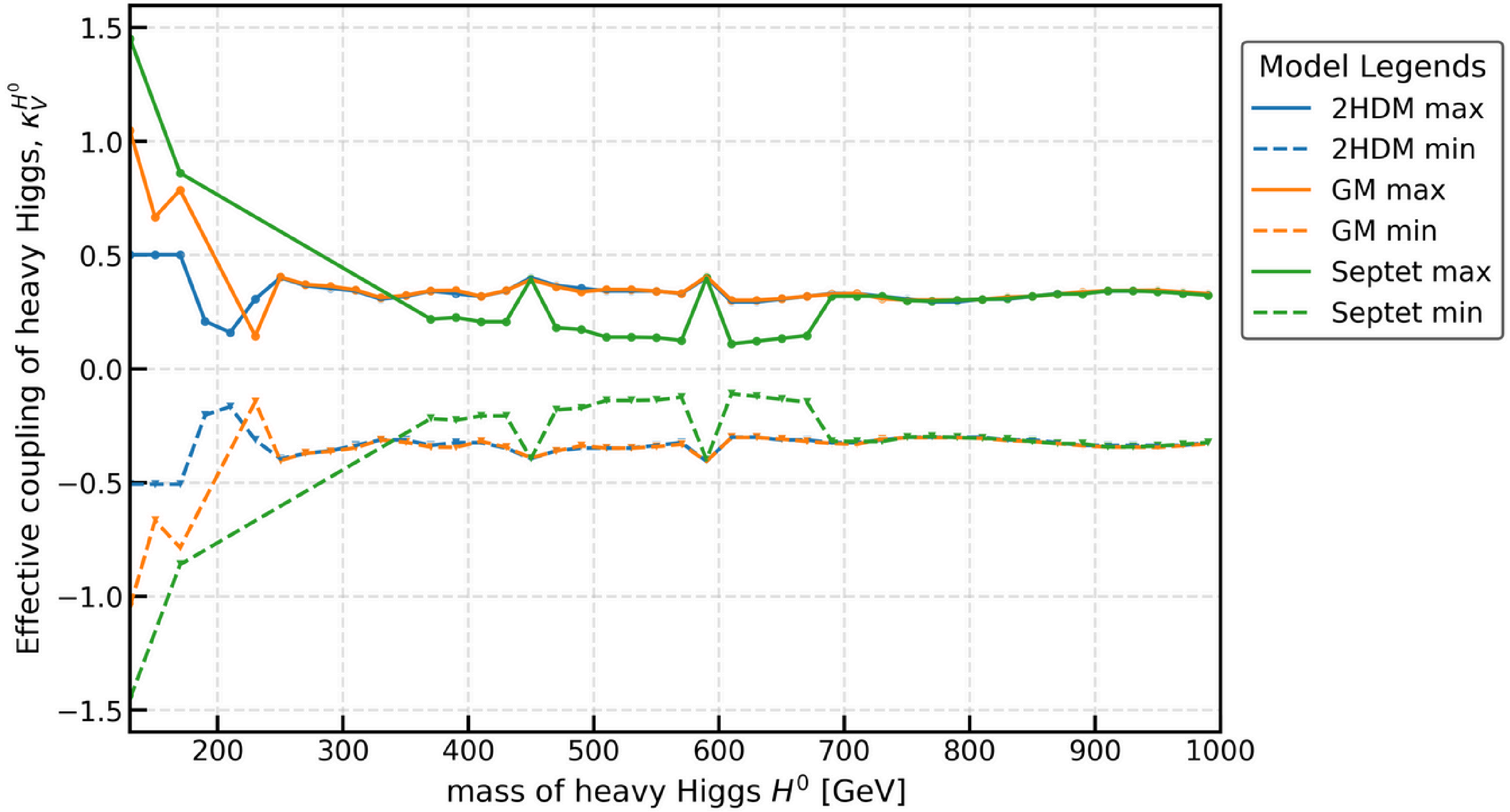
1. 2HDM:
Lower Mass: dominant exclusion **ggH>ZZ** channel
Higher Mass: H>WW,ZZ & **vbfH>WW,ZZ**

2. GM:
Lower Mass: dominant exclusion **ggH>ZZ** channel
Higher Mass: H>WW,ZZ & vbfH>WW,ZZ

3. Septet: Dominant exclusion channel for all mass ranges **vbfH>WW,ZZ**

HIGGSTOOLS: EFFECTIVE COUPLING RANGES





Model	Scan range for $\kappa_V^{H^0}$	Updated range from allowed points
2HDM	$[-0.51,\ 0.50]$	$\approx [-0.5,\ 0.5]$
GM	$[-1.39,\ 1.39]$	$\approx [-1,\ 1]$
Septet	$[-3.91,\ 3.91]$	$\approx [-1.49,\ 1.49]$

Table: Model-wise ranges for the effective coupling, $\kappa_V^{H^0}$ input parameters and resulting allowed range.

HIGGSTOOLS: CHANNEL-WISE $\sigma \times \mathrm{BR}$ (ALLOWED POINTS)

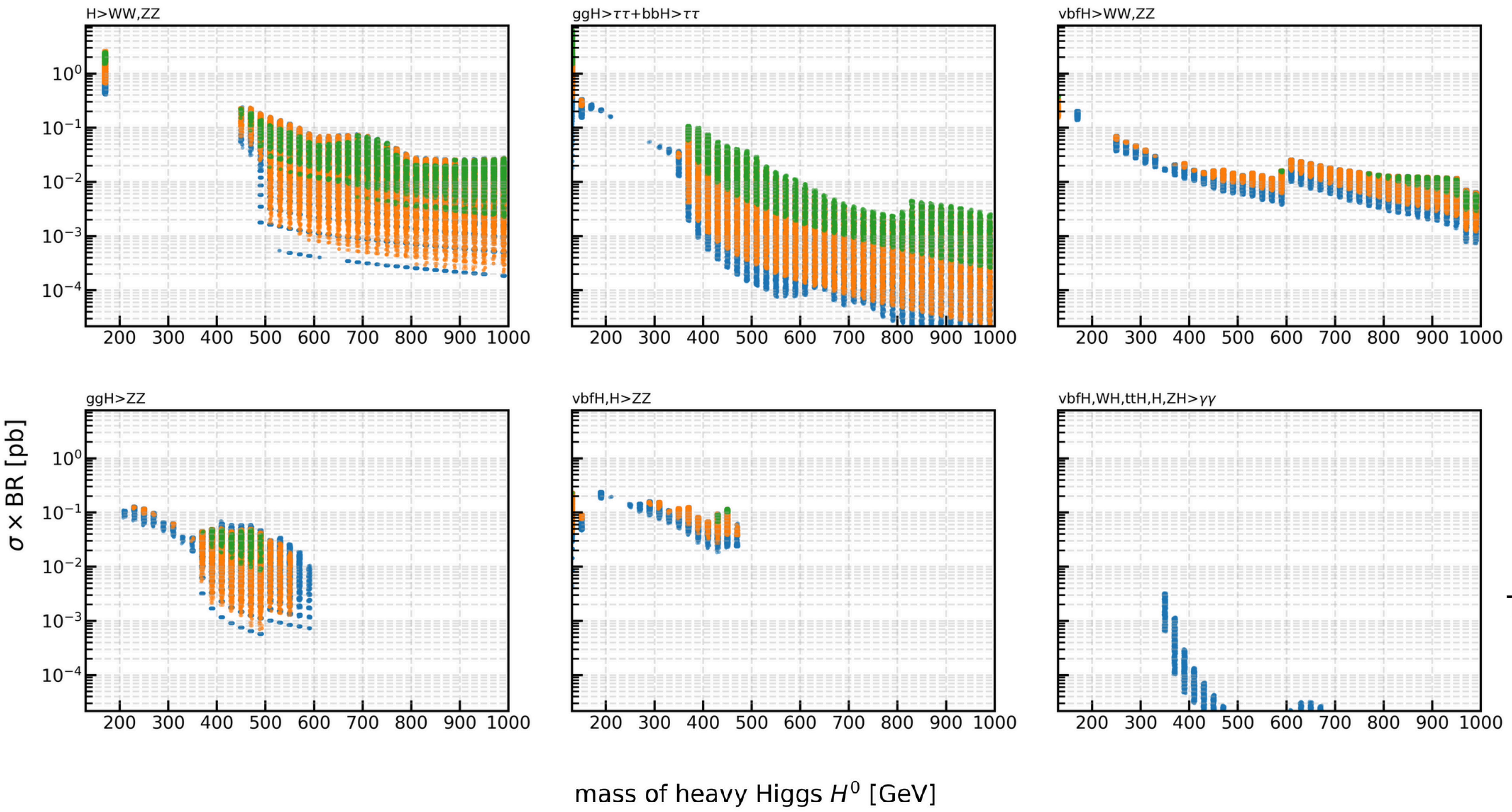


Figure: Channel-wise panels with allowed points coloured by model for the most sensitive channels with broad mass coverage

Channel	$(\sigma \times \mathrm{BR})$ range [pb]
VBF $\to WW, ZZ$	$[1.4\times10^{-3}$–$2.7\times10^{-2}]$
ggF $\to ZZ$	$[5.8\times10^{-4}$–$0.1\times10^{-1}]$
$\tau\tau$ (ggF+bbH)	$[1\times10^{-6}$–$6.40]$
VBF $\to ZZ$	$[3\times10^{-3}$–$7\times10^{-2}]$
`vbfH,H`$\to ZZ$	$[2\times10^{-2}$–$0.2]$
Diphoton	$[2.5\times10^{-5}$–$6.7\times10^{-4}]$
VBF $\to b\bar{b}$	$[0.2$–$2.49]$
$H \to WW, ZZ$	$[1\times10^{-6}$–$7\times10^{-2}]$

Table: Channel-wise (σ × BR) ranges for the HB-selected analysis for the allowed points

SUMMARY AND FUTURE PLAN FOR THESIS

SUMMARY OF THE THESIS

Summary: Comparative Analysis of 2HDM, GM, Septet Model

Model	Coupling Expressions	Sum Rule	Mass Bound Constraint
Septet	$\kappa_{VV}^{h^0} = \cos\theta_7 \cos\alpha - 4\sin\theta_7 \sin\alpha$ $\kappa_{VV}^{H^0} = \cos\theta_7 \sin\alpha + 4\sin\theta_7 \cos\alpha$ $\kappa_{VV}^{H^{++}} = \sqrt{15}\sin\theta_7$	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 - \left(\kappa_{VV}^{H^{++}}\right)^2 = 1$	$\sin^2\theta_7 \lesssim \frac{(260\,\mathrm{GeV})^2}{m_{H^{++}}^2}$
GM	$\kappa_{VV}^{h^0} = \cos\theta_H \cos\alpha - \sqrt{\frac{8}{3}}\sin\theta_H \sin\alpha$ $\kappa_{VV}^{H^0} = \cos\theta_H \sin\alpha + \sqrt{\frac{8}{3}}\sin\theta_H \cos\alpha$ $\kappa_{VV}^{H_5^{++}} = \sqrt{2}\sin\theta_H$	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 + \left(\kappa_{VV}^{H_5^0}\right)^2 - \left(\kappa_{VV}^{H_5^{++}}\right) = 1$	$\sin^2\theta_H \lesssim \frac{(734\,\mathrm{GeV})^2}{m_5^2}$
2HDM	$\kappa_{VV}^{h^0} = \sin(\beta-\alpha)$ $\kappa_{VV}^{H^0} = \cos(\beta-\alpha)$	$\left(\kappa_{VV}^{h^0}\right)^2 + \left(\kappa_{VV}^{H^0}\right)^2 = 1$	$\cos^2(\beta-\alpha) \lesssim \frac{(880\,\mathrm{GeV})^2}{m_{H^0}^2}$

SUMMARY OF THE THESIS

Summary: HiggsTools Analysis

Important Exclusion Channels

1. 2HDM:
Lower Mass: dominant exclusion **ggH>ZZ** channel
Higher Mass: H>WW,ZZ & **vbfH>WW,ZZ**

2. GM:
Lower Mass: dominant exclusion **ggH>ZZ** channel
Higher Mass: H>WW,ZZ & vbfH>WW,ZZ

3. Septet: Dominant exclusion channel for all mass ranges **vbfH>WW,ZZ**

Channel	$(\sigma \times \mathrm{BR})$ range [pb]
$\mathrm{VBF} \to WW, ZZ$	$[1.4\times10^{-3}$–$2.7\times10^{-2}]$
$\mathrm{ggF} \to ZZ$	$[5.8\times10^{-4}$–$0.1\times10^{-1}]$
$\tau\tau$ (ggF+bbH)	$[1\times10^{-6}$–$6.40]$
$\mathrm{VBF} \to ZZ$	$[3\times10^{-3}$–$7\times10^{-2}]$
`vbfH,H`$\to ZZ$	$[2\times10^{-2}$–$0.2]$
Diphoton	$[2.5\times10^{-5}$–$6.7\times10^{-4}]$
$\mathrm{VBF} \to b\bar{b}$	$[0.2$–$2.49]$
$H \to WW, ZZ$	$[1\times10^{-6}$–$7\times10^{-2}]$

Allowed Points Analysis:
$\sigma \times \mathrm{BR}$
Ranges

Model	Scan range for $\kappa_V^{H^0}$	Updated range from allowed points
2HDM	$[-0.51,\ 0.50]$	$\approx [-0.5,\ 0.5]$
GM	$[-1.39,\ 1.39]$	$\approx [-1,\ 1]$
Septet	$[-3.91,\ 3.91]$	$\approx [-1.49,\ 1.49]$

FUTURE PROSPECTS

(i) Heavier mass reach (up to 3 TeV).
In our current analysis with HiggsTools, we obtain results upto 1 TeV, but some search channels have cross section limits upto 3 TeV.

(ii) Incorporation of Run–3 datasets in HiggsTools: Integrating future collider data including HL-LHC.

(iii) Systematic study of doubly charged Higgs bosons. Using the same analysis, one can provide the required production rates and branching ratios for H^{++}. Important from GM and Septet models

THANK YOU

APPENIDX: MOTIVATION

Rho - Parameter

$$\rho_{SM} = \frac{M_W^2}{M_Z^2 \cos(\theta_w)^2} = 1$$

$$\rho_{exp} = 1.00040 \pm 0.00024$$

Model	Hypercharge (Y)	Isospin (I)
2HDM	$Y = 1/2$	$I = 1/2$
GM	$Y_D = 1/2$ $Y_{RT} = 0$ $Y_{CT} = 1$	$I_D = 1/2$ $I_T = 1$
Septet	$Y = 2$	$I = 3$

$Y_D =$ For Doublet, $Y_{RT} =$ For Real triplet, $Y_{CT} =$ For Complex Triplet,

$I_D =$ For Doublet, $I_T =$ For Triplets

Hypercharge (Y_i)
& Isospin (I_i)

[5]

$$\rho = \frac{\sum_{i=1}^{n} v_i [4I_i(I_i+1) - Y_i^2]}{\sum_{i=1}^{n} 2Y_i^2 v_i}$$

Imp: All models - 2HDM, GM, Septet have **ρ = 1**

APPENDIX: SEPTET MODEL

The Electroweak Lagrangian for Septet :

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) + (\mathcal{D}_\mu X)^\dagger (\mathcal{D}^\mu X),$$

Replacement Rules and physical fields

$$h^0 = \cos\alpha\,\phi^{0,r} - \sin\alpha\,\chi^{0,r},$$
$$H^0 = \sin\alpha\,\phi^{0,r} + \cos\alpha\,\chi^{0,r}.$$

$$G^0 = \cos\theta_7\,\phi^{0,i} + \sin\theta_7\,\chi^{0,i},$$
$$A^0 = -\sin\theta_7\,\phi^{0,i} + \cos\theta_7\,\chi^{0,i},$$

$$H^{++} \equiv \chi^{+2}, \quad \chi^{+3}, \quad \chi^{+4}, \quad \chi^{+5},$$

Covariant Derivative

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}(W_\mu^+ T^+ + W_\mu^- T^-) - \frac{ie}{s_W c_W} Z_\mu (T^3 - s_W^2 Q) - ieA_\mu Q.$$

$$G^+ = \cos\theta_7\,\phi^+ + \sin\theta_7 \left(\sqrt{\frac{5}{8}}\chi^{+1} - \sqrt{\frac{3}{8}}(\chi^{-1})^*\right),$$

$$H_f^+ = -\sin\theta_7\,\phi^+ + \cos\theta_7 \left(\sqrt{\frac{5}{8}}\chi^{+1} - \sqrt{\frac{3}{8}}(\chi^{-1})^*\right),$$

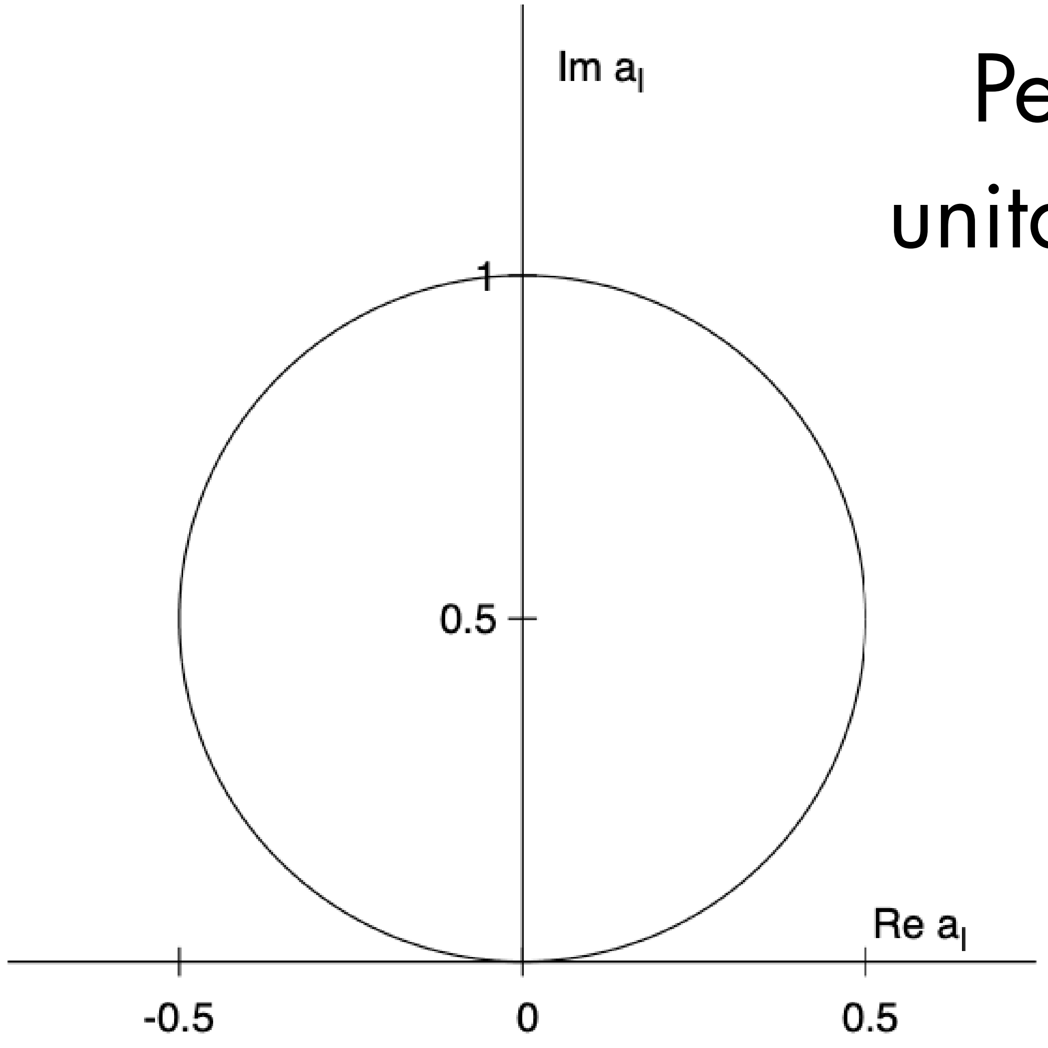
$$H_V^+ = \sqrt{\frac{3}{8}}\chi^{+1} + \sqrt{\frac{5}{8}}(\chi^{-1})^*.$$

$$H_1^+ = \cos\gamma\,H_f^+ - \sin\gamma\,H_V^+,$$
$$H_2^+ = \sin\gamma\,H_f^+ + \cos\gamma\,H_V^+;$$

APPENDIX: PERTURBATIVE UNITARITY

Unitarity Conservation with Higgs

$$\mathscr{M} = 16\pi \sum_{l=0}^{\infty} (2l+1)\, a_l(|\vec{p}|)\, P_l \cos\theta,$$



Perturbative unitarity bounds

$$|a_l| \le 1; \quad |Re(a_l)| \le \frac{1}{2}; \quad 0 \le |Im(a_l)| \le 1.$$

Mass Bound calculation:

$$(\kappa_V^h)^2 + (\kappa_V^H)^2 - (\kappa_{WW}^{H^{++}})^2 = 1,$$

$$\kappa_{WW}^{H} = 0$$

$$(\kappa_V^h)^2\big|_{\max} = 1 + (\kappa_{WW}^{H^{++}})^2.$$

$$2(\kappa_V^h)^2 m_h^2 + 2(\kappa_V^H)^2 m_H^2 + (\kappa_{WW}^{H^{++}})^2 m_{H^{++}}^2 \le 8\pi v^2.$$

$$(\kappa_{WW}^{H^{++}})^2 \le \frac{8\pi v^2 - 2m_h^2}{m_{H^{++}}^2 + 2m_h^2}.$$

APPENDIX: 2HDM (1)

Two Complex SU(2)L Doublets : Φ_i (i = 1,2)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}.$$

parametrization

$$\Phi_1 = \begin{pmatrix} \omega_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix},$$

$$\Phi_2 = \begin{pmatrix} \omega_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix},$$

$$\tan\beta = \frac{v_2}{v_1},$$

$$\tan 2\alpha = \frac{2\left(m_{12}^2 - \lambda_{345} v^2 s_\beta c_\beta\right)}{m_{12}^2\left(c_\beta - s_\beta\right) - v^2\left(\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2\right)},$$

CP-even mixing angle

$$R_\alpha = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

CP-odd & Charged mixing angle

$$R_\beta = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix}$$

$$\rho_1 = H^0\cos\alpha - h^0\sin\alpha,$$
$$\rho_2 = H^0\sin\alpha + h^0\cos\alpha,$$
$$\eta_1 = G^0\cos\beta - A^0\sin\beta,$$
$$\eta_2 = G^0\sin\beta + A^0\cos\beta,$$
$$\omega_1^\pm = G^\pm\cos\beta - H^\pm\sin\beta,$$
$$\omega_2^\pm = G^\pm\sin\beta + H^\pm\cos\beta.$$

Replacement Rules and physical fields

where $c_\alpha = \cos\alpha, s_\alpha = \sin\alpha$

$c_\beta = \cos\beta, s_\beta = \sin\beta.$

The Electroweak Lagrangian for 2HDM :

$$\mathscr{L} = \left(D_\mu\Phi_1\right)^\dagger\left(D_\mu\Phi_1\right) + \left(D_\mu\Phi_2\right)^\dagger\left(D_\mu\Phi_2\right).$$

Covariant Derivative $D_\mu = \partial_\mu - ig\frac{\sigma_a}{2}W_\mu^a - ig'\frac{Y}{2}B_\mu$

$$M_W^2 = \frac{1}{4}g^2v^2,$$
$$M_Z^2 = \frac{1}{4}(g^2+g'^2)v^2,$$
$$M_\gamma^2 = 0.$$

2HDM Potential

$$\begin{aligned} V_{2HDM}(\Phi_1,\Phi_2) = {} & m_{11}^2\left(\Phi_1^\dagger\Phi_1\right) + m_{22}^2\left(\Phi_2^\dagger\Phi_2\right) - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) \\ & + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) \\ & + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \frac{\lambda_5}{2}\left(\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right) \end{aligned}$$

APPENDIX: 2HDM

Mass Matrices from Potential

$$\frac{\partial V_{2HDM}}{\partial \Phi_1}\Big|_{\langle\Phi_1\rangle,\langle\Phi_2\rangle} = 0, \quad \frac{\partial V_{2HDM}}{\partial \Phi_2}\Big|_{\langle\Phi_1\rangle,\langle\Phi_2\rangle} = 0,$$

$$V|_{bilinear} = \frac{1}{2}\begin{pmatrix}\rho_1 & \rho_2\end{pmatrix} M_\rho^2 \begin{pmatrix}\rho_1 \\ \rho_2\end{pmatrix} + \frac{1}{2}\begin{pmatrix}\eta_1 & \eta_2\end{pmatrix} M_\eta^2 \begin{pmatrix}\eta_1 \\ \eta_2\end{pmatrix} + \frac{1}{2}\begin{pmatrix}\omega_1^+ & \omega_2^+\end{pmatrix} M_\omega^2 \begin{pmatrix}\omega_1^- \\ \omega_2^-\end{pmatrix}.$$

CP-even mixing angle $R_\alpha = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$ **CP-odd & Charged mixing angle** $R_\beta = \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix}$

Mass matrix (non-diagonal) for CP-Even Higgs(Scalar) [2]:

$$\begin{aligned} M^2_{\rho_{11}} &= \frac{\lambda_1 v_1^3 + m_{12}^2 v_2}{v_1} \\ M^2_{\rho_{22}} &= \frac{\lambda_2 v_2^3 + m_{12}^2 v_1}{v_2} \\ M^2_{\rho_{12}} &= (\lambda_3+\lambda_4+\lambda_5)v_1 v_2 - m_{12}^2 \end{aligned} \quad \longleftrightarrow \quad M_\rho^2 = \begin{pmatrix} M^2_{\rho_{11}} & M^2_{\rho_{12}} \\ M^2_{\rho_{12}} & M^2_{\rho_{22}} \end{pmatrix},$$

where $c_\alpha = \cos\alpha, s_\alpha = \sin\alpha, c_\beta = \cos\beta, s_\beta = \sin\beta$.

Mass matrix (non-diagonal) for CP-Odd Higgs (Pseudoscalar):

$$\begin{aligned} M^2_{\eta_{11}} &= \left(-\lambda_5 v_1 v_2 + m_{12}^2\right)\frac{v_2}{v_1} \\ M^2_{\eta_{22}} &= \left(-\lambda_5 v_1 v_2 + m_{12}^2\right)\frac{v_1}{v_2} \\ M^2_{\eta_{12}} &= \lambda_5 v_1 v_2 - m_{12}^2 \end{aligned} \quad \longleftrightarrow \quad M_\eta^2 = \begin{pmatrix} M^2_{\eta_{11}} & M^2_{\eta_{12}} \\ M^2_{\rho_{12}} & M^2_{\rho_{22}} \end{pmatrix},$$

Mass matrix (non-diagonal) for Charged Higgs:

$$\begin{aligned} M^2_{\omega_{11}} &= \left(2m_{12}^2 - (\lambda_4+\lambda_5)v_1 v_2\right)\frac{v_2}{2v_1} \\ M^2_{\omega_{22}} &= \left(2m_{12}^2 - (\lambda_4+\lambda_5)v_1 v_2\right)\frac{v_1}{2v_2} \\ M^2_{\omega_{12}} &= \frac{1}{2}(\lambda_4+\lambda_5)v_1 v_2 - m_{12}^2 \end{aligned} \quad \longleftrightarrow \quad M_\omega^2 = \begin{pmatrix} M^2_{\omega_{11}} & M^2_{\omega_{12}} \\ M^2_{\omega_{12}} & M^2_{\omega_{22}} \end{pmatrix}.$$

APPENDIX: GM(1)

REPLACEMENT RULES:

$\sin\Theta_H = \sqrt{8}v_\chi/v$ and $\cos\Theta_H = v_\phi/v$,

CP - even neutral states:	$h^0 = \cos\alpha\phi^r - \sin\alpha\left(\frac{1}{\sqrt{3}}\xi^r + \sqrt{\frac{2}{3}}\chi^r\right)$ $H^0 = \sin\alpha\phi^r + \cos\alpha\left(\frac{1}{\sqrt{3}}\xi^r + \sqrt{\frac{2}{3}}\chi^r\right)$ $H_5^0 = \sqrt{\frac{2}{3}}\xi^r - \frac{1}{\sqrt{3}}\chi^r.$
CP -odd neutral states	$G^0 = \cos\Theta_H\phi^i - \sin\Theta_H\chi^i,$ $H_3^0 = -\sin\Theta_H\phi^i + \cos\Theta_H\chi^i.$
Singly charged states:	$G^+ = \cos\Theta_H\phi^+ + \sin\Theta_H\frac{(\chi^+ + \xi^+)}{\sqrt{2}},$ $H_3^+ = -\sin\Theta_H\phi^+ + \cos\Theta_H\frac{(\chi^+ + \xi^+)}{\sqrt{2}},$ $H_5^+ = \frac{(\chi^+ - \xi^+)}{\sqrt{2}}.$
Doubly charged states:	$H_5^{++} = \chi^{++}$

The Electroweak Lagrangian for GM :

$$\mathscr{L} = (D^\mu\phi)^\dagger(D_\mu\phi) + (D^\mu\chi)^\dagger(D_\mu\chi) + \frac{1}{2}(D^\mu\xi)^\dagger(D_\mu\xi) - V_{GM}(\Phi,\Delta),$$

This custodial symmetry prevents mixing between states that transform in different representations of SU(2)c.

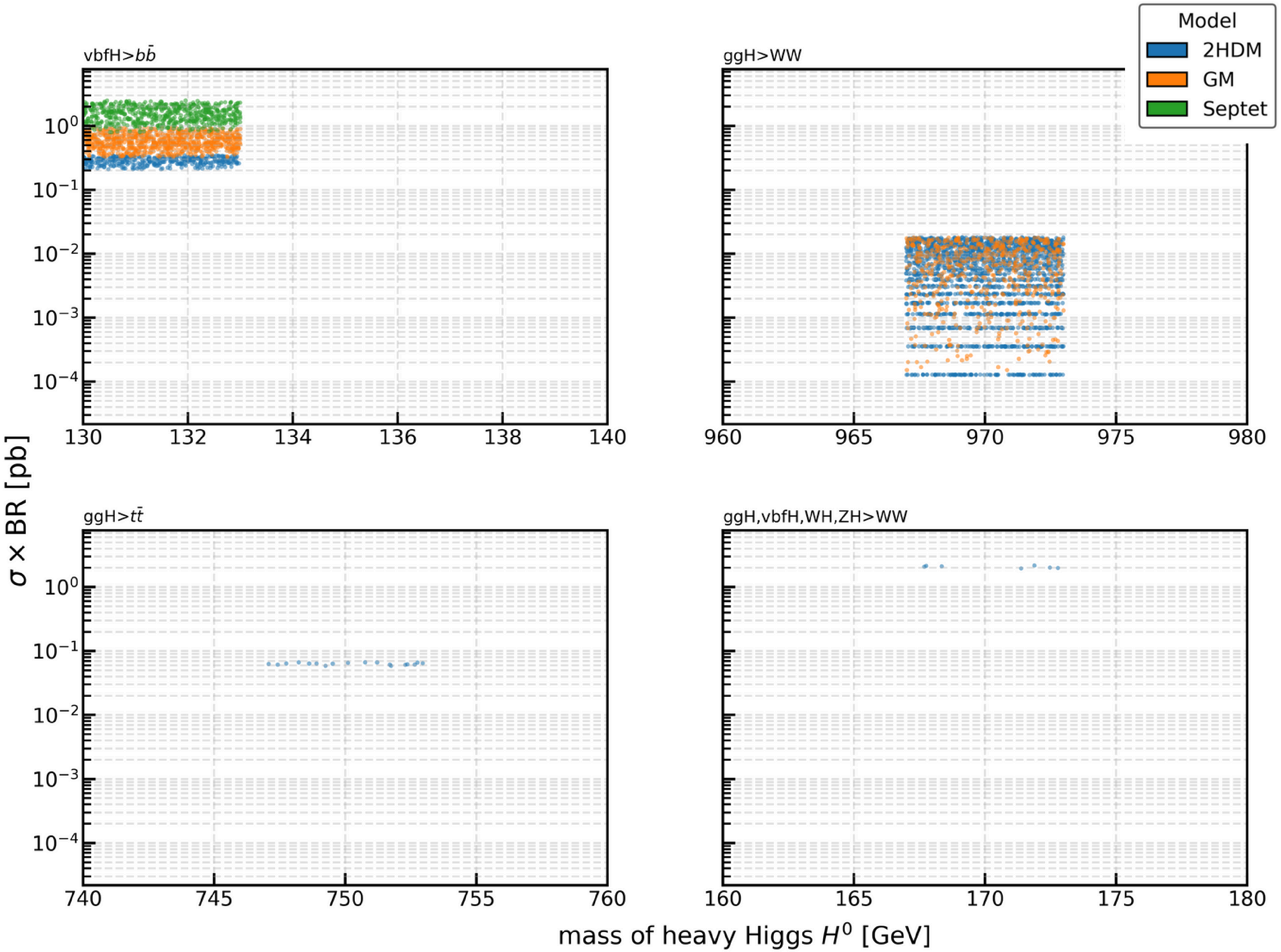
$$\langle\Phi\rangle = \begin{pmatrix} v_\phi/\sqrt{2} & 0 \\ 0 & v_\phi/\sqrt{2} \end{pmatrix}$$

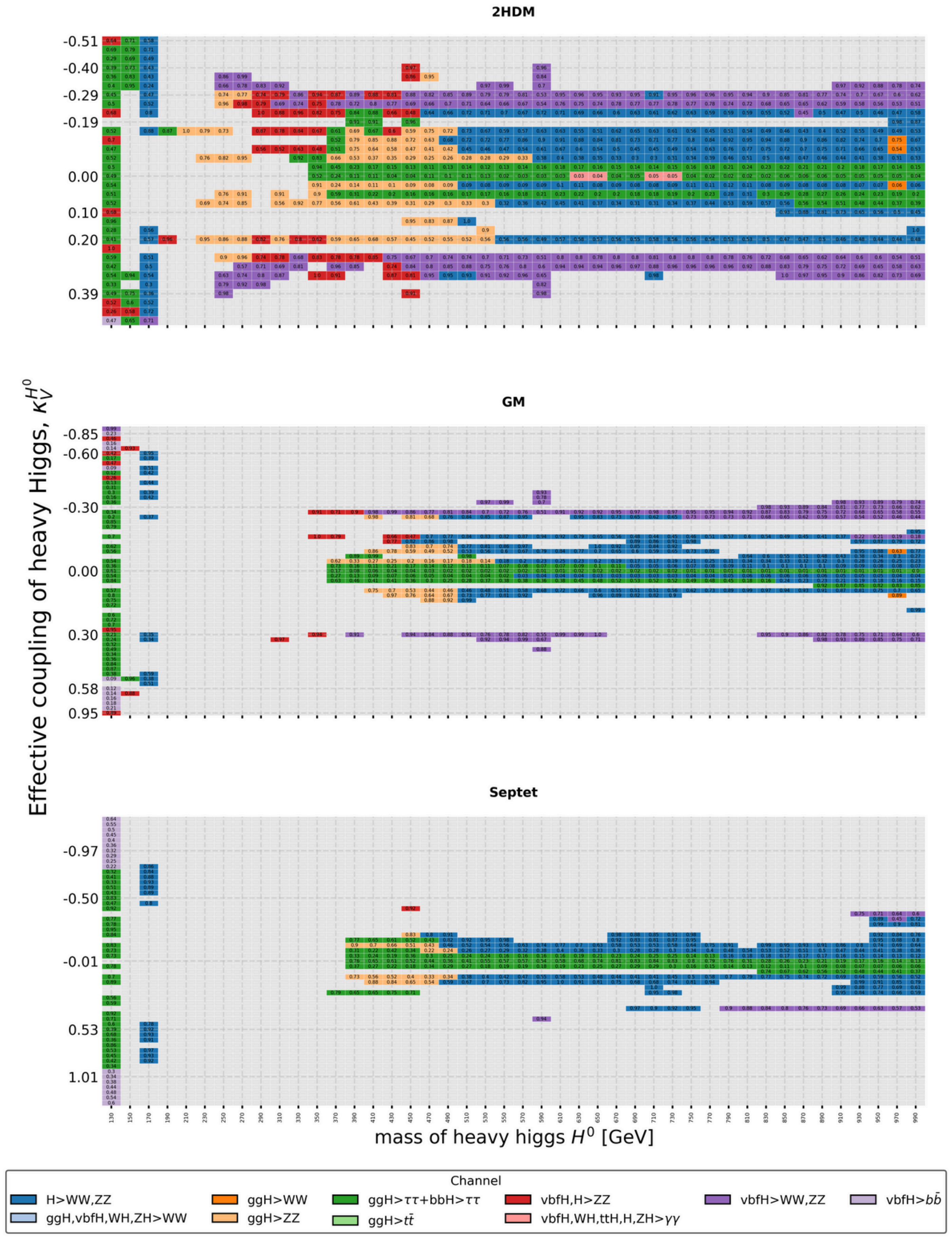
H_3^+ does not mix with H_5^+

H_3^+	H_5^+
Couples to fermions but not vector boson Degenerate mass: m_3	Couples to vector boson but not fermions Degenerate mass: m_5

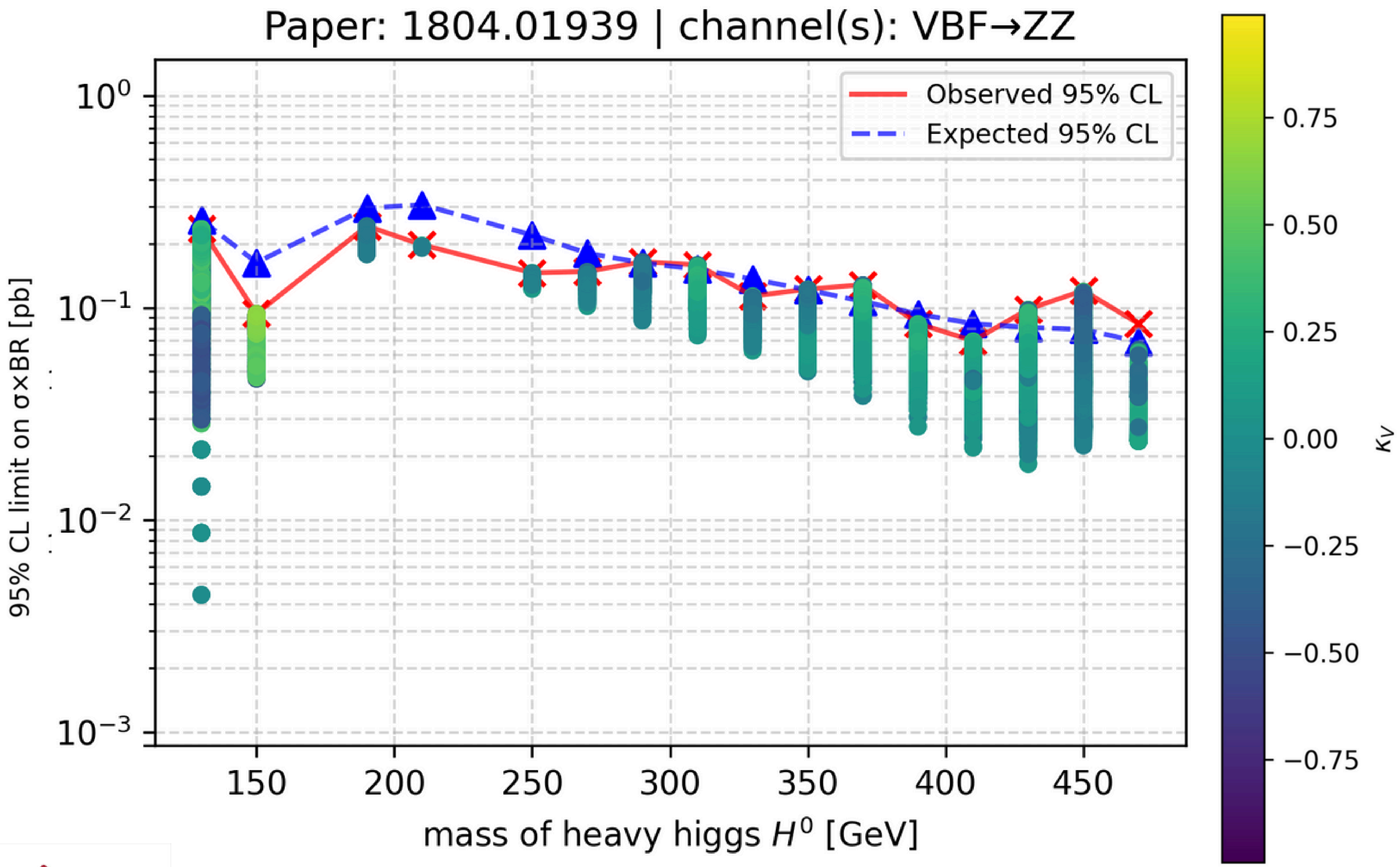
$$\langle X\rangle = \begin{pmatrix} v_\chi & 0 & 0 \\ 0 & v_\chi & 0 \\ 0 & 0 & v_\chi \end{pmatrix}$$

APPENDIX: HIGGSTOOLS PLOTS

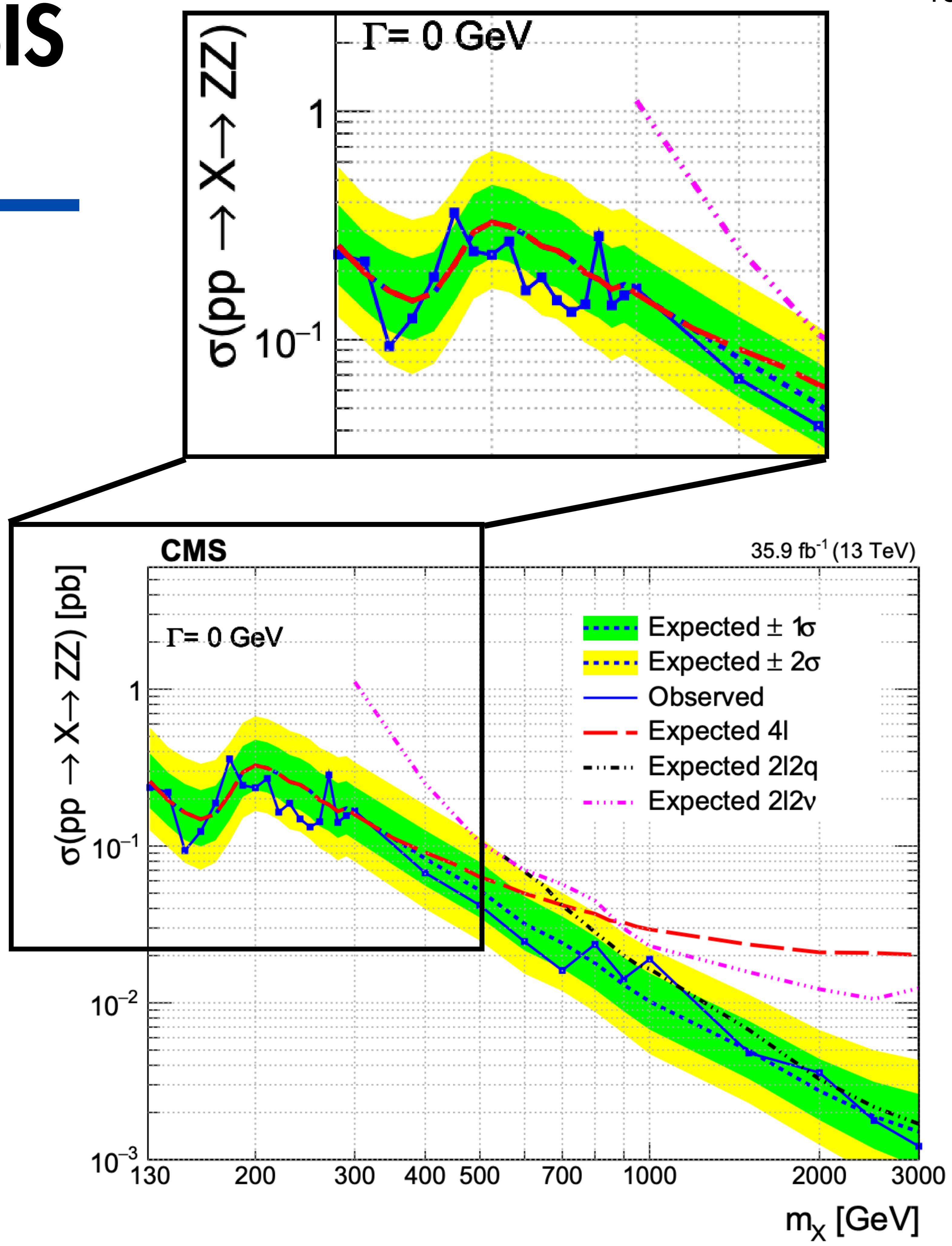


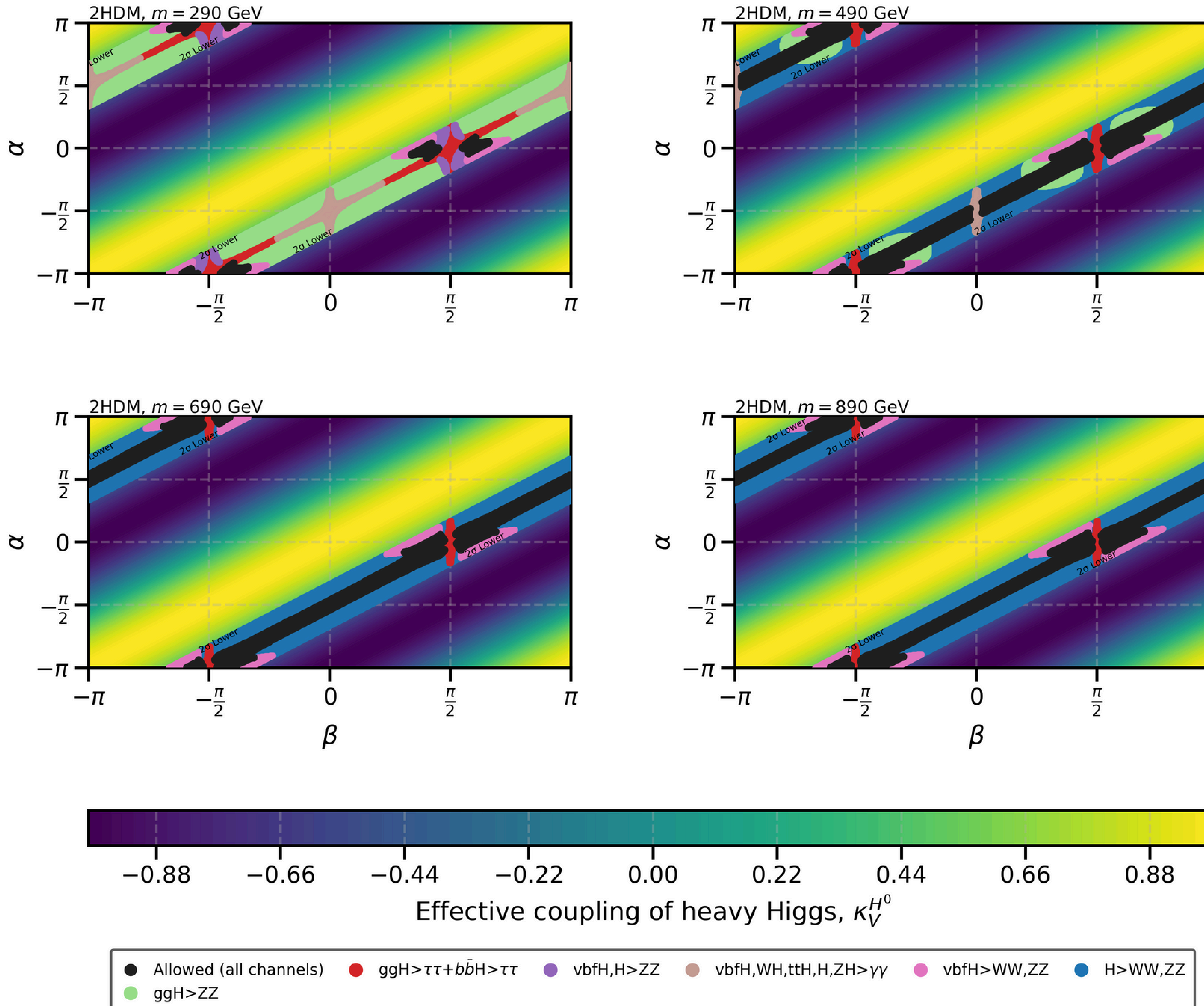


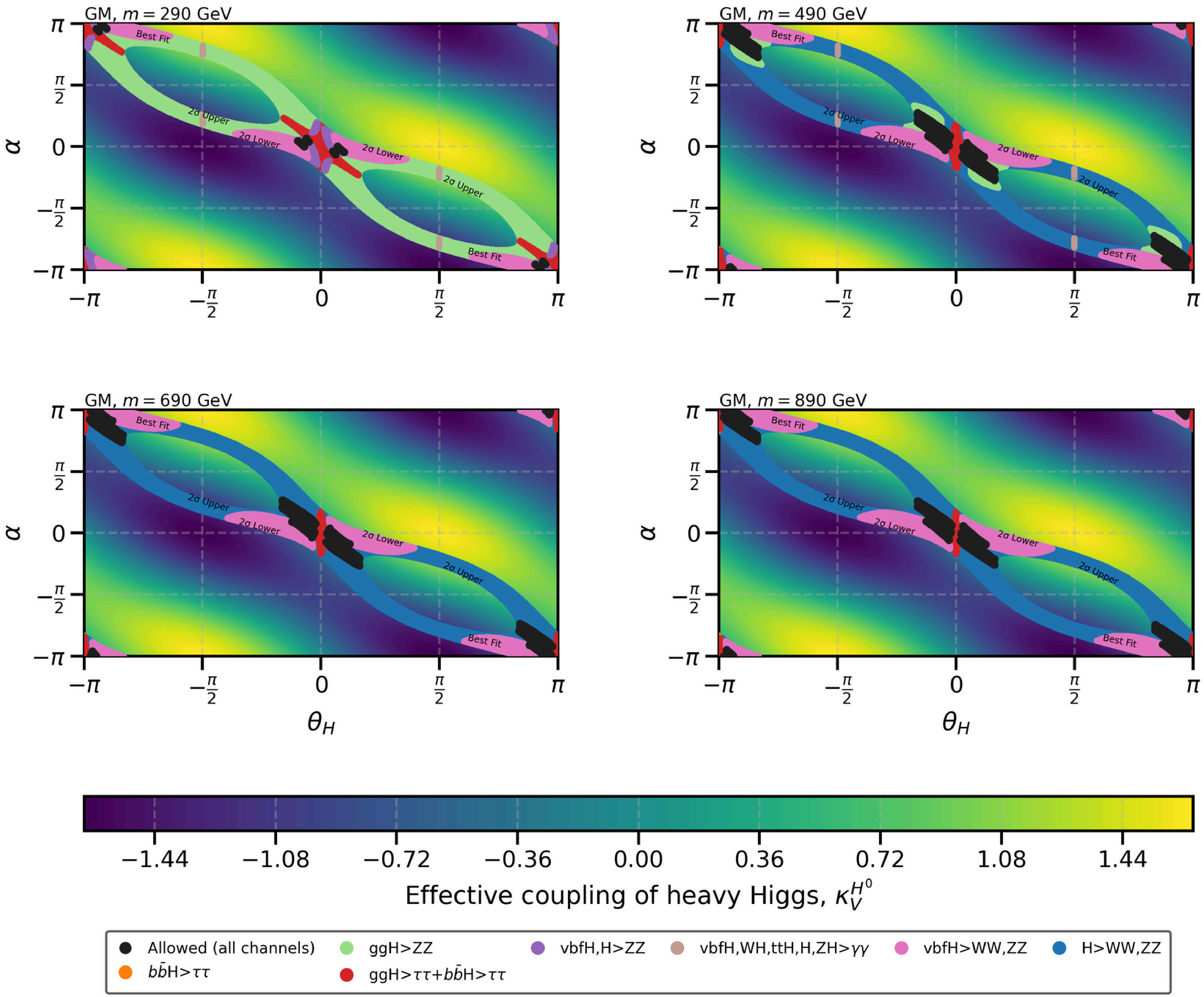
HIGGSTOOLS: SAMPLE FOR ANALYSIS EXPLANATION



Comparison plot for CMS, vbfH → ZZ limits (35.9 fb−1)




2HDM, $m = 290$ GeV
2HDM, $m = 490$ GeV
2HDM, $m = 690$ GeV
2HDM, $m = 890$ GeV
α
β
$-\pi$ $-\frac{\pi}{2}$ 0 $\frac{\pi}{2}$ π
2σ Lower
−0.88 −0.66 −0.44 −0.22 0.00 0.22 0.44 0.66 0.88
Effective coupling of heavy Higgs, $\kappa_V^{H^0}$
Allowed (all channels)
ggH>ττ+$b\bar{b}$H>ττ
vbfH,H>ZZ
vbfH,WH,ttH,H,ZH>γγ
vbfH>WW,ZZ
H>WW,ZZ
ggH>ZZ


GM, $m = 290$ GeV
GM, $m = 490$ GeV
GM, $m = 690$ GeV
GM, $m = 890$ GeV
Best Fit
2σ Upper
2σ Lower
α
θ_H
$-\pi$
$-\frac{\pi}{2}$
0
$\frac{\pi}{2}$
π
−1.44
−1.08
−0.72
−0.36
0.00
0.36
0.72
1.08
1.44
Effective coupling of heavy Higgs, $\kappa_V^{H^0}$
Allowed (all channels)
$b\bar{b}$H>ττ
ggH>ZZ
ggH>ττ+$b\bar{b}$H>ττ
vbfH,H>ZZ
vbfH,WH,ttH,H,ZH>γγ
vbfH>WW,ZZ
H>WW,ZZ

Bibliography and References

[1]Lectures on perturbative unitarity and decoupling in Higgs physics: Heather E. Logan (arXiv:2207.01064v2)

[2]Constraining the scalar septet model through vector boson scattering Mary-Jean Harris and Heather E. Logan (arXiv:1703.03832v2)

[3]A portrait of the Higgs boson by the CMS experiment ten years after the discovery: The CMS Collaboration.

[4]A 95 GeV Higgs Boson in the Georgi-Machacek Model (arXiv:2312.13239v2)

[5]Theory and phenomenology of two-Higgs-doublet models G. C. Branco (arxiv:1106.0034v3)

[6]HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals Henning Bahl (arXiv:2210.09332v2)

[7]The Higgs boson mixes with an SU(2) septet representation Junji Hisano (arxiv:1301.6455v1)

[8]DESY pdf : HiggsTools: A Toolbox for BSM Scalar Phenomenology

[9] HiggsTools documentation

[10] HiggsTools: BSM scalar phenomenology with new versions of HiggsBounds and HiggsSignals