Planck 2019

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The Minimal Simple Composite Higgs Model

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DESY, IB & HU

Based on arXiv: 1904.02560 [hep-ph], w/ L. Da Rold

The main idea behind CHM

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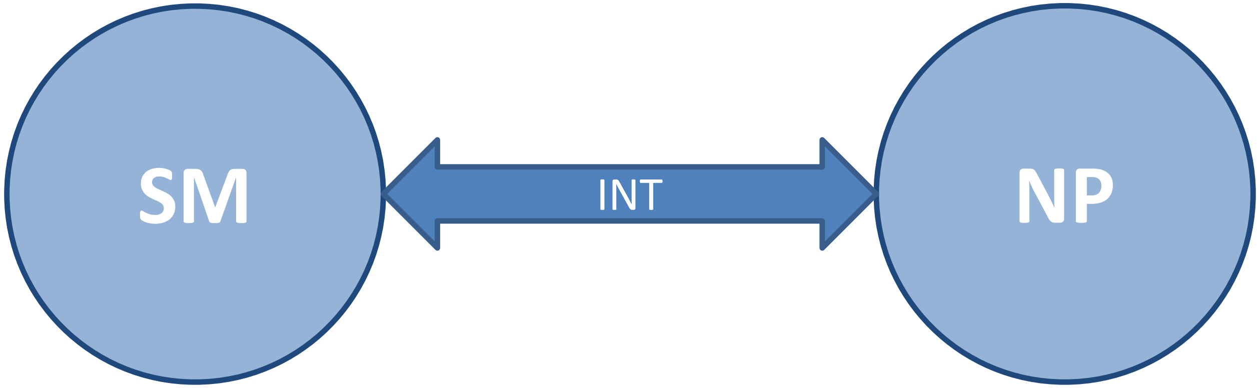
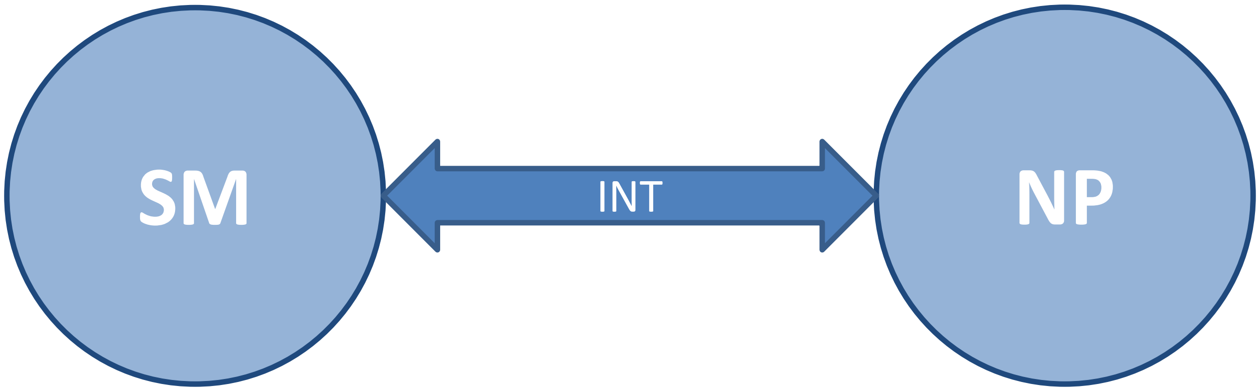


$$G \xrightarrow[\text{SSB}]{} H$$

The main idea behind CHM



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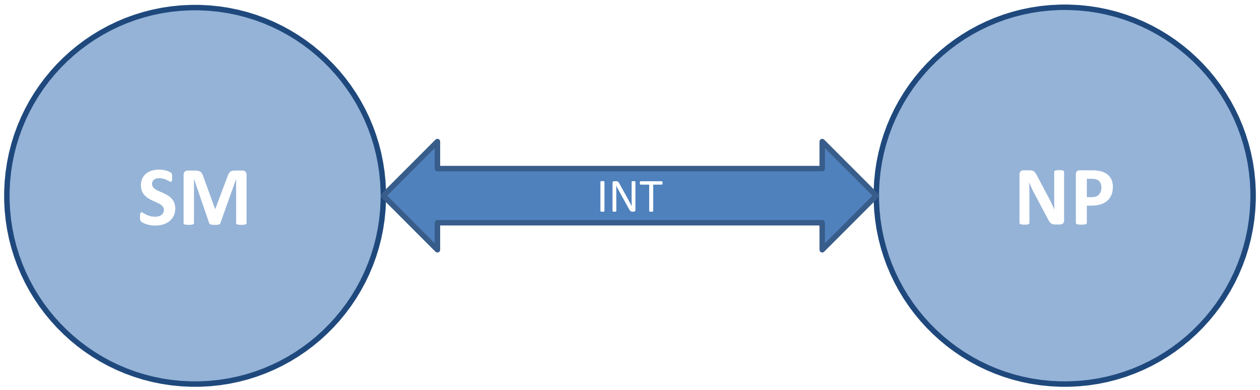
Why a non-minimal CHM?

The main idea behind CHM



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Why a non-minimal CHM?

- **LHC results constrain severely the MCHM.**

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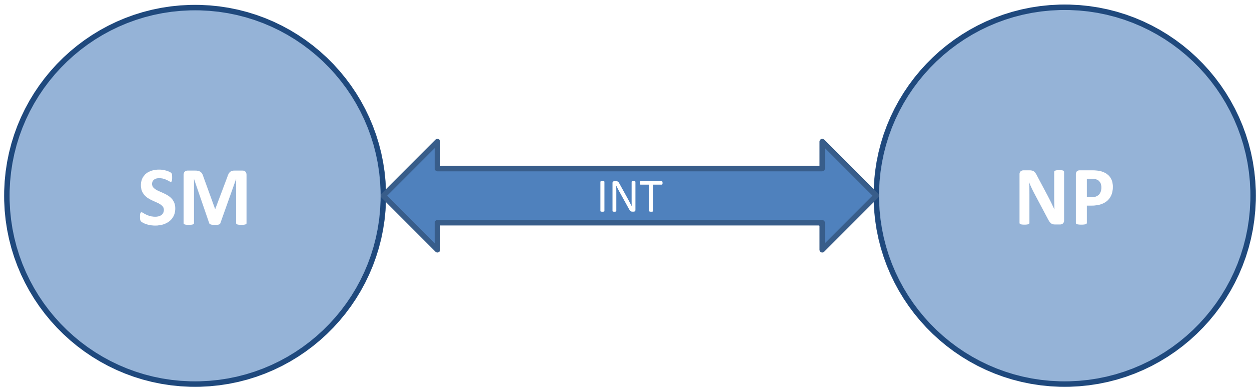

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- Non-minimal CHMs satisfy the bounds better.

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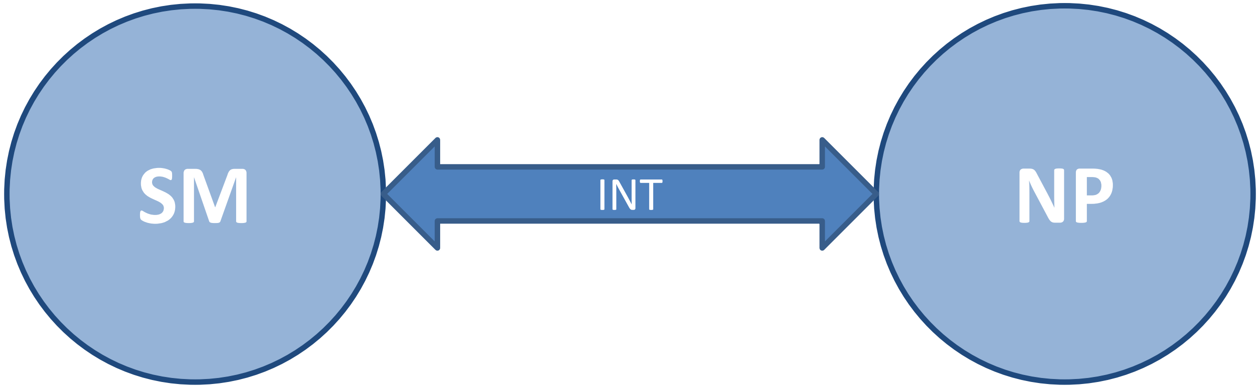

$$G \xrightarrow[\text{SSB}]{} H$$

Why a non-minimal CHM?

- LHC results constrain severely the MCHM
- Non-minimal CHMs satisfy the bounds better
- Different and rich phenomenology, less explored.

Minimal CHM

$$\mathbf{SO}(5)\times\mathbf{U}(1)_X/\mathbf{SO}(4)\times\mathbf{U}(1)_X$$

Agashe et al (hep-ph/0412089)

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Next to MCHM

$$\mathbf{SO}(6)\times\mathbf{U}(1)_X/\mathbf{SO}(5)\times\mathbf{U}(1)_X$$

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SO(7) CHM

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Chala et al (1605.08663), Balkin et al (1707.07685, 1809.09106)

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Nevertheless...

$$\mathbf{SO}(7) \supset \mathbf{SO}(6) \supset \mathbf{SO}(4) \times \mathbf{U}(1)$$

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$$\mathbf{SO}(7)/\mathbf{SO}(6)$$

The Minimal <u>Simple</u> CHM

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$$\Downarrow$$

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The Minimal <u>Simple</u> CHM

- ✓ Simple Lie groups

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The Minimal <u>Simple</u> CHM

- ✓ Simple Lie groups
- ✓ Higgs doublet

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The Minimal Simple CHM

- ✓ Simple Lie groups
- ✓ Higgs doublet
- ✓ Custodial Symmetry

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$$\mathbf{SO}(7) / \mathbf{SO}(6)$$

The Minimal <u>Simple</u> CHM

- ✓ Simple Lie groups
- ✓ Higgs doublet
- ✓ Custodial Symmetry
- ✓ Unifies EW group

What are the pNGBs there like?

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$\mathrm{SO}(6)$ $\quad (\mathrm{SU}(2)_L, \mathrm{SU}(2)_R)_X$

$$\mathbf{6} \sim (\mathbf{2}, \mathbf{2})_0 + (\mathbf{1}, \mathbf{1})_{\pm 1/\sqrt{2}}$$

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$$\underset{\mathrm{SO}(6)}{\mathbf{6}} \sim \overset{(\mathrm{SU}(2)_L, \mathrm{SU}(2)_R)_X}{(\mathbf{2},\mathbf{2})_0 + (\mathbf{1},\mathbf{1})_{\pm 1/\sqrt{2}}}$$

$$(\mathbf{2},\mathbf{2})_0 \downarrow \text{Higgs boson} \qquad (\mathbf{1},\mathbf{1})_{\pm 1/\sqrt{2}} \downarrow \chi \text{ boson}$$

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$\downarrow$ Higgs boson

$\downarrow$ χ boson

EW embedding

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$(\mathbf{2},\mathbf{2})_0$ → Higgs boson

$(\mathbf{1},\mathbf{1})_{\pm 1/\sqrt{2}}$ → χ boson

EW embedding

$$Y = T_R^3 + \frac{2\sqrt{2}}{3} X$$

$$Q = T_L^3 + Y$$

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$(\mathbf{2},\mathbf{2})_0 \to$ Higgs boson

$(\mathbf{1},\mathbf{1})_{\pm 1/\sqrt{2}} \to$ χ boson

EW embedding

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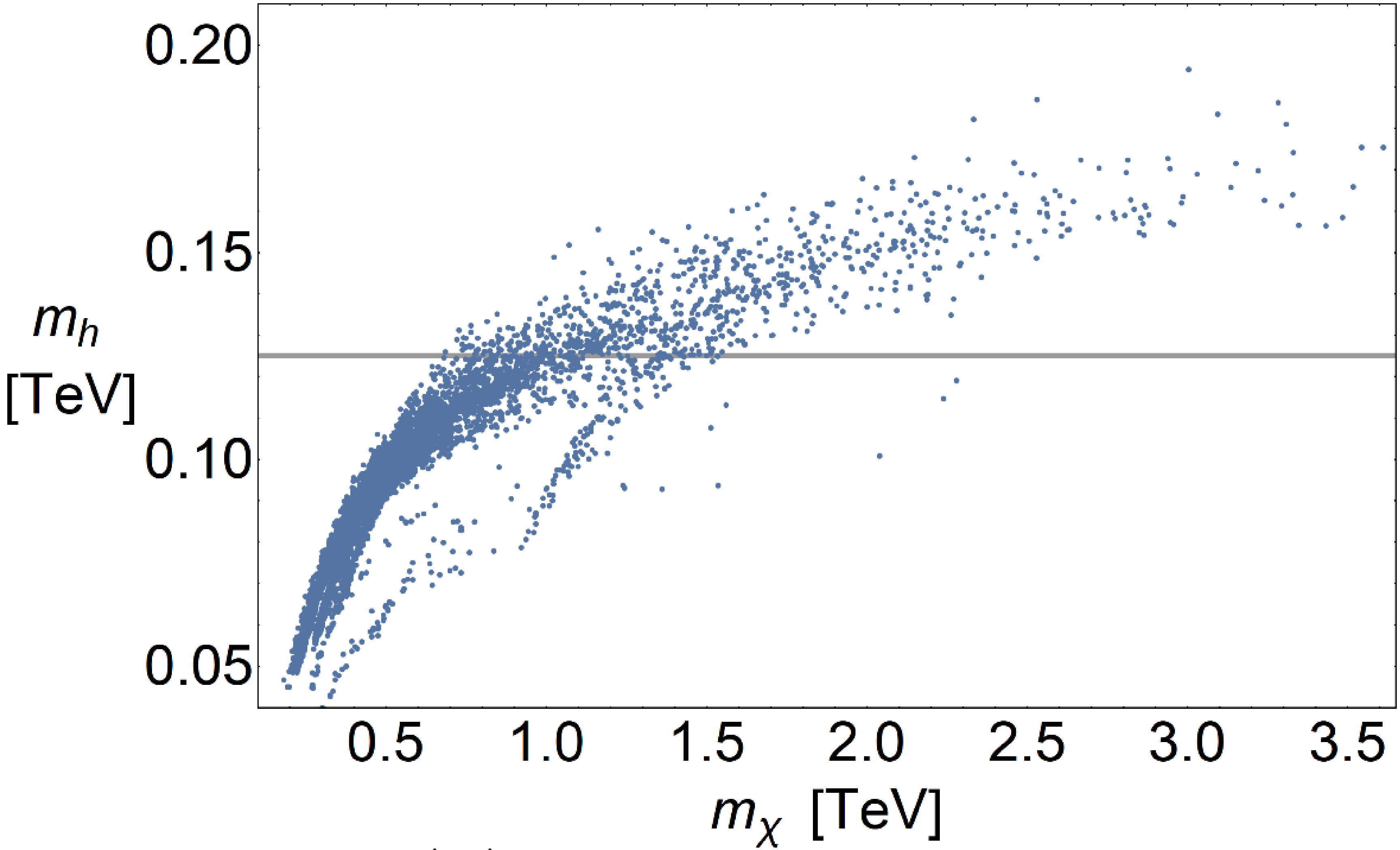
$$Q = T_L^3 + Y$$

$$\left.\begin{array}{l} \textbf{H: } \mathbf{2}_{\frac{1}{2}} \\ \boldsymbol{\chi}\textbf{: } \mathbf{1}_{\frac{2}{3}} \end{array}\right\} SU(2)_L \times U(1)_Y$$

Parameter space scan



$\langle \chi \rangle = 0 \qquad \langle h \rangle > 0$

Resonances

Vector bosons

$|Q| = 0, 1/3, 2/3,$
$1, 5/3$

Dirac fermions

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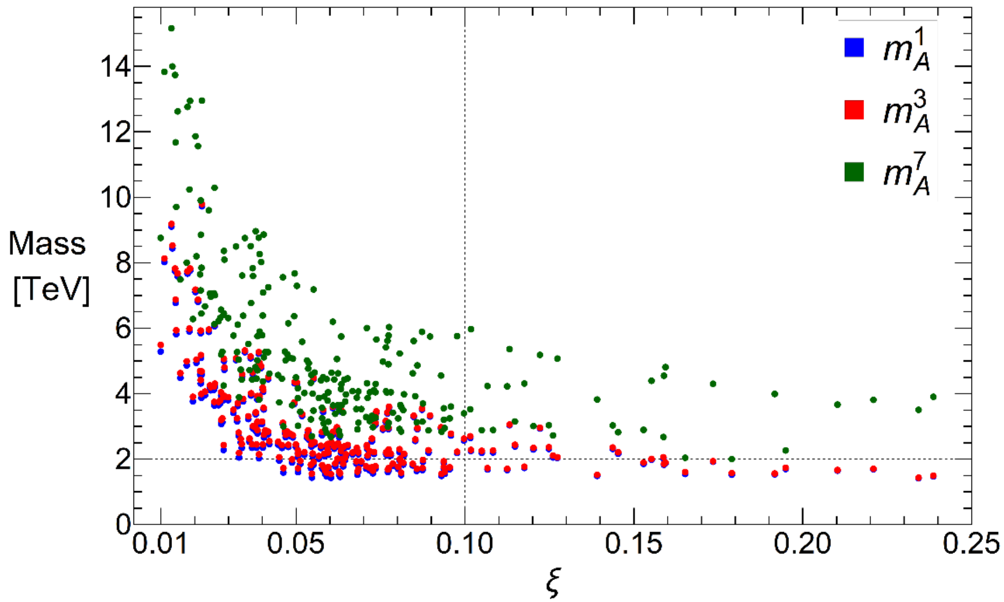
$1, 5/3$

Resonances

Vector bosons

|Q|= 0, 1/3, 2/3,
1, 5/3



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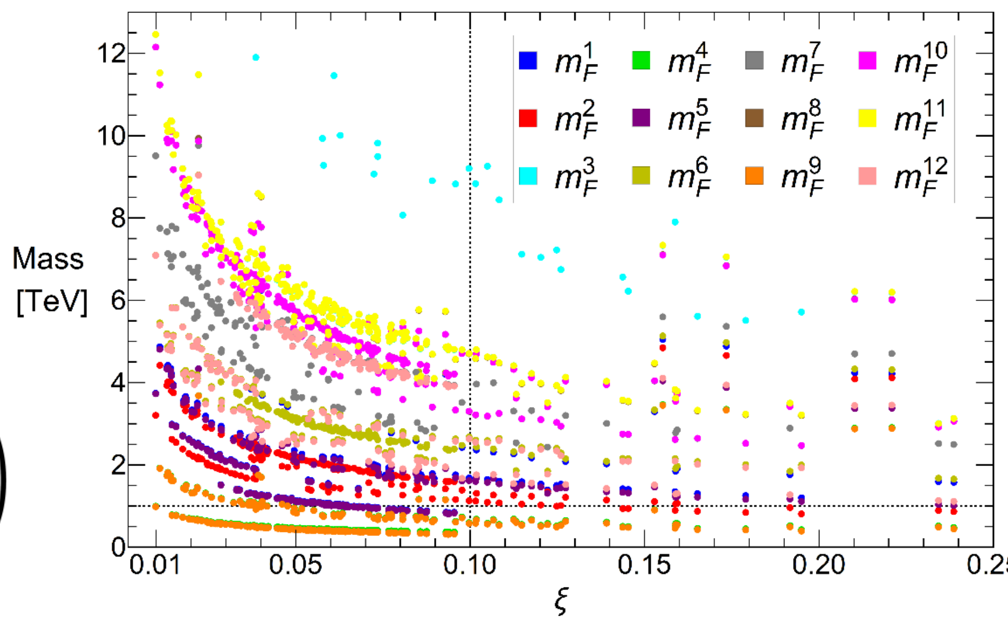
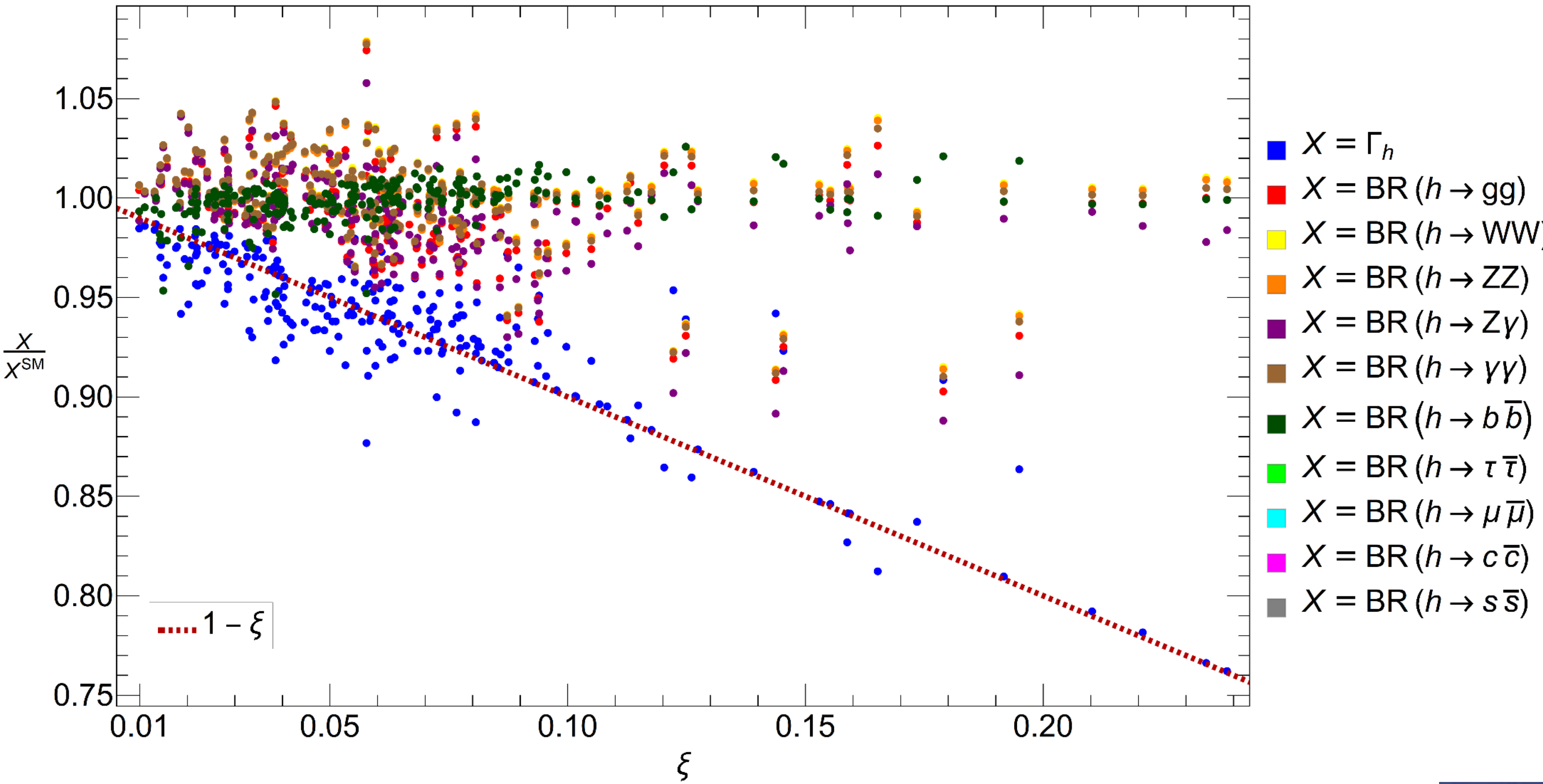


$$\xi = \left(\frac{v}{f}\right)^2 = \sin^2\left(\frac{\langle h \rangle}{f}\right)$$

Decay width and BRs



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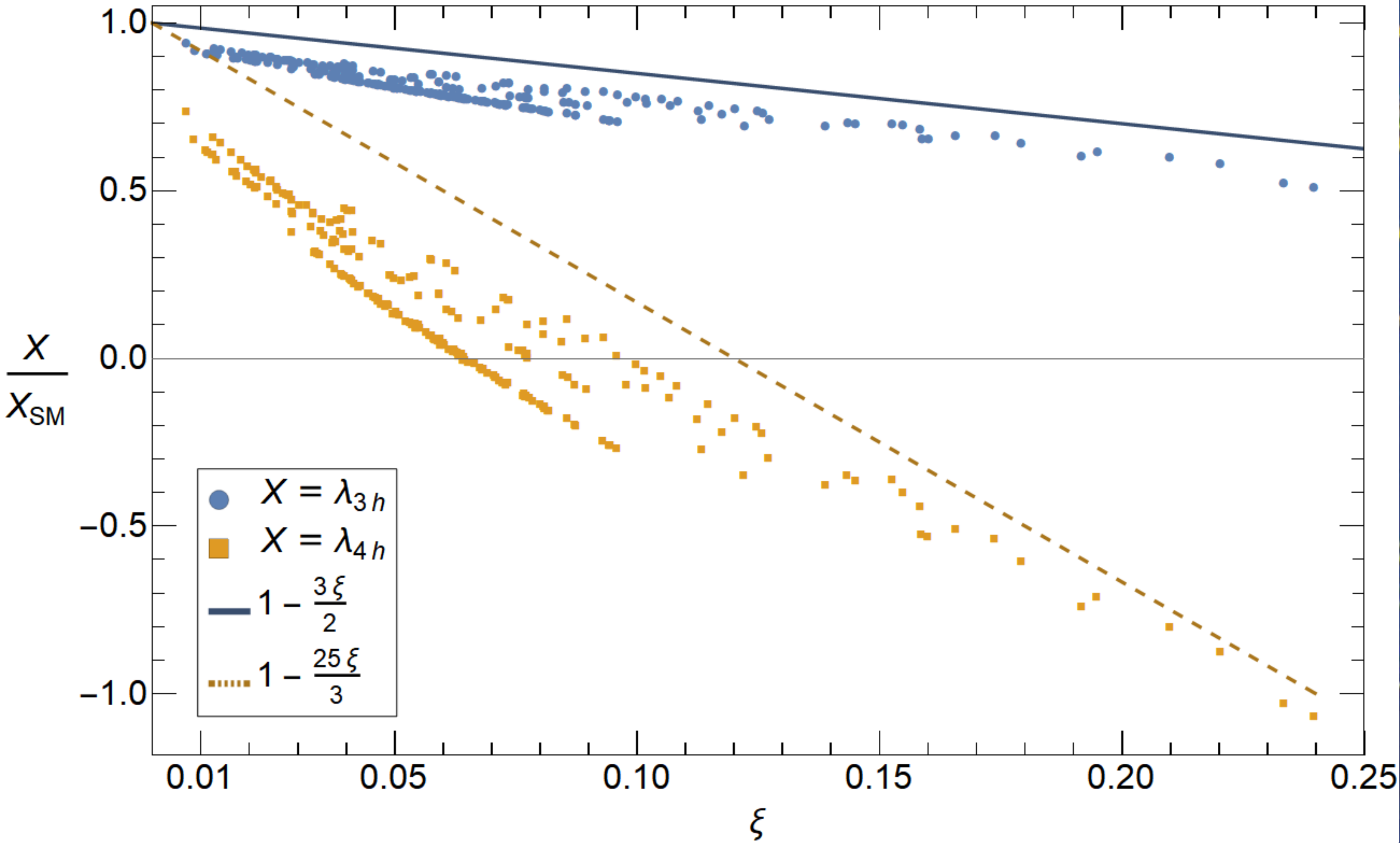
Higgs self-couplings



Exotic stable particle

Exotic stable particle

$$\chi$$

$|Q| = 2/3$

Exotic stable particle

χ

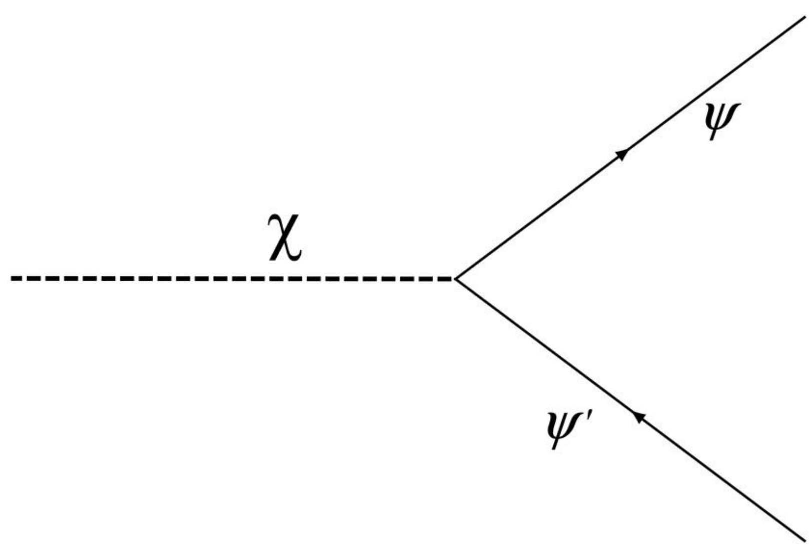
$|Q| = 2/3$

ψ

$|Q| = 0$

Quorn

De Luca et al (1801.01135)
Gross et al (1811.08418)



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Conclusions

1. We built a new CHM based on the minimal coset of simple Lie groups that gives the Higgs with the right charges.
2. This model is phenomenologically viable.
3. New particles with exotic charges appear.
4. Suppression in Higgs couplings, decay and production amplitudes of order 5-10%.
5. Stronger suppression in Higgs self couplings.
6. There is an exotic stable particle, which might be a DM candidate.

Thank you!

Any question?

APPENDIX

SO(7) irreps decomposed…

…into SO(6)

$$\mathbf{7} \sim \mathbf{6} + \mathbf{1} \qquad \mathbf{21} \sim \mathbf{15} + \mathbf{6} \qquad \mathbf{35} \sim \mathbf{15} + \mathbf{10} + \overline{\mathbf{10}}$$

…into SU(2)xSU(2)xU(1)

$$\mathbf{10} \sim (\mathbf{2},\mathbf{2})_0 + (\mathbf{3},\mathbf{1})_{1/\sqrt{2}} + (\mathbf{1},\mathbf{3})_{-1/\sqrt{2}}$$

$$\mathbf{15} \sim (\mathbf{2},\mathbf{2})_{\pm 1/\sqrt{2}} + (\mathbf{3},\mathbf{1})_0 + (\mathbf{1},\mathbf{3})_0 + (\mathbf{1},\mathbf{1})_0$$

$$\begin{aligned} \mathbf{21}_{SO(7)} = &(\mathbf{3},\mathbf{1})_{\mathbf{0}} \oplus (\mathbf{1},\mathbf{3})_{\mathbf{0}} \oplus (\mathbf{1},\mathbf{1})_{\mathbf{0}} \oplus (\mathbf{2},\mathbf{2})_{\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}} \\ &\oplus (\mathbf{2},\mathbf{2})_{-\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}} \oplus (\mathbf{2},\mathbf{2})_{\mathbf{0}} \oplus (\mathbf{1},\mathbf{1})_{\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}} \oplus (\mathbf{1},\mathbf{1})_{-\frac{\mathbf{1}}{\sqrt{\mathbf{2}}}} \end{aligned}$$

SM fermions embedding and Partial compositeness

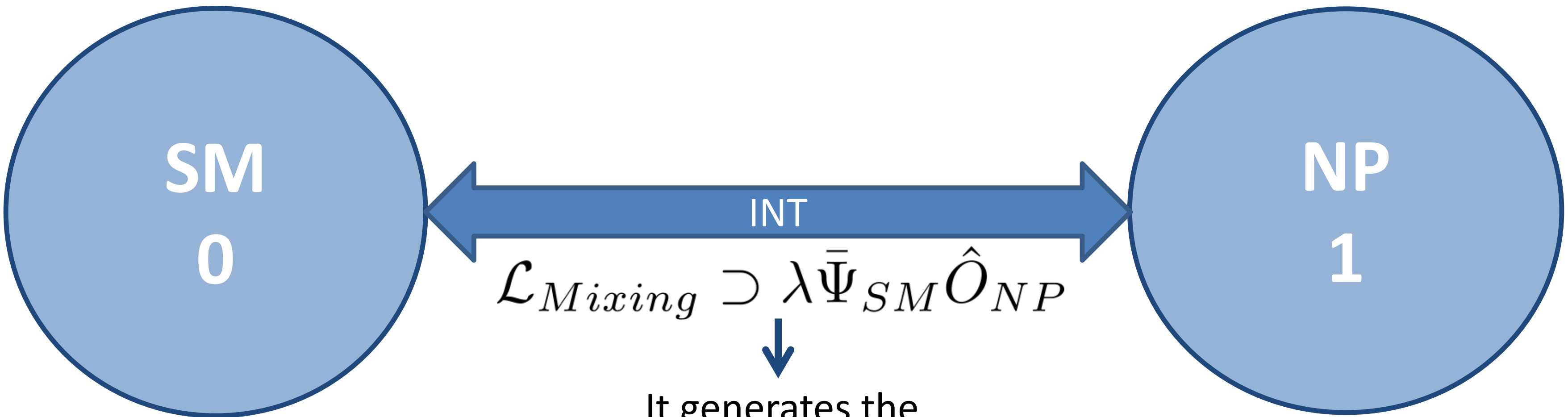
Field	T^3_R	$SO(4)\times U(1)_X$	SO(6)	SO(7)
q	-1/2	$(\mathbf{2},\mathbf{2})_{1/\sqrt{2}}$	$\mathbf{15}$	$\mathbf{21}$
u	0	$(\mathbf{1},\mathbf{3})_{1/\sqrt{2}}$	$\overline{\mathbf{10}}$	$\mathbf{35}$
d	-1	$(\mathbf{1},\mathbf{3})_{1/\sqrt{2}}$	$\overline{\mathbf{10}}$	$\mathbf{35}$
ℓ	-1/2	$(\mathbf{2},\mathbf{2})_0$	$\mathbf{6}$	$\mathbf{7}$
e	-1	$(\mathbf{1},\mathbf{3})_0$	$\mathbf{15}$	$\mathbf{21}$

$$ME_\psi = \cos(\theta_\psi)\,\psi + \sin(\theta_\psi)\,C_\psi$$

$$y_\psi \sim y_{\hat{\Psi}_\mathbf{r}} \sin(\theta_\psi)\sin(\theta_{\hat{\psi}}) \qquad m_\psi \sim y_\psi v$$

$$\tan(\theta_\psi) = \frac{f_0 \lambda_\psi}{m_\Psi}$$

2-site model



$$\mathcal{L}_{Mixing} \supset \lambda \bar{\Psi}_{SM} \hat{O}_{NP}$$

It generates the potential for the NGB. Partial compositeness for all the fermions.

Elementary sector. Copy of the SM without the Higgs.

$$SO(7) \xrightarrow{\text{SSB}} SO(6)$$

$$\xi = \left(\frac{v}{f}\right)^2 = \sin^2\left(\frac{\langle h \rangle}{f}\right)$$

A

Site 1, mixing and pNGBs

$$\mathcal{L}_1 = -\frac{1}{4g_1^2} F^a_{\mu\nu} F^{a,\mu\nu} + \frac{f_1^2}{4} d^{\hat a}_\mu d^{\hat a,\mu} + \bar Q(\not{D} - m_Q) Q + \bar U(\not{D} - m_U) U + \bar D(\not{D} - m_D) D$$
$$+ \bar L(\not{D} - m_L) L + \bar E(\not{D} - m_E) E + f_1 y_U [(\bar Q_L U_1)_{\mathbf{15}} (U_1^\dagger U_R)_{\mathbf{15}}]_{\mathbf{1}}$$
$$+ f_1 y_D [(\bar Q_L U_1)_{\mathbf{15}} (U_1^\dagger D_R)_{\mathbf{15}}]_{\mathbf{1}} + f_1 y_E [(\bar L_L U_1)_{\mathbf{6}} (U_1^\dagger E_R)_{\mathbf{6}}]_{\mathbf{1}} + \text{h.c.}$$

$$\mathcal{L}_{\text{mix}} = \frac{f_0^2}{4} |D_\mu \Omega|^2 + f_0 \sum_i \lambda_i \bar\psi_i \Omega \Psi_i + \text{h.c.}$$

$$\psi_i = q, u, d, \ell, e \ , \qquad \Psi_i = Q, U, D, L, E \ ,$$

$$\Gamma_1^2 = \sum_{\hat a} (\Pi_1^{\hat a})^2 \qquad U_1^\dagger D_\mu U_1 = i e^a_\mu T^a + i d^{\hat a}_\mu T^{\hat a}$$

$$\Omega = e^{i\sqrt{2}\Pi_0/f_0} \quad U_1 = e^{i\sqrt{2}\Pi_1/f_1} \ , \qquad \Pi_1 = \Pi_1^{\hat a} T^{\hat a}$$

$$U_1 = I + i\frac{\sin(\Gamma_1/f_1)}{\Gamma_1}\Pi_1 + 2\frac{\cos(\Gamma_1/f_1) - 1}{\Gamma_1^2}\Pi_1^2$$

Physical pNGBs and EW bosons identification

$$U = e^{i\sqrt{2}\Pi/f}\,, \qquad \Pi = \Pi^{\hat{a}} T^{\hat{a}}\,, \qquad \frac{1}{f^2} = \frac{1}{f_0^2} + \frac{1}{f_1^2}$$

$$\frac{1}{g^2} = \frac{1}{g_0^2} + \frac{1}{g_1^2} \qquad \frac{1}{g'^2} = \frac{17}{9}\left(\frac{1}{g_0'^2} + \frac{1}{g_1^2}\right)$$

$$W_\mu^i = \cos(\varphi)\, w_\mu^i + \sin(\varphi)\, A_\mu^{L,i}$$

$$B_\mu = \cos(\omega)\, b_\mu + \sin(\omega)\left[\cos(\theta_Y)\, A_\mu^{R,3} + \sin(\theta_Y)\, A_\mu^X\right]$$

$$\tan(\varphi) = \frac{g_0}{g_1} \qquad \tan(\omega) = \frac{g_0'}{g_1} \qquad \tan(\theta_Y) = \alpha = \frac{2\sqrt{2}}{3}$$

$$D_\mu \Omega = \partial_\mu \Omega - i A_\mu^{0,A} T^A \Omega + i A_\mu^{1,A} \Omega T^A$$

Name	Mass	$\lvert Q_{em}\rvert$	Multiplicity
m_A^1	$\frac{f_0 g_1}{\sqrt{2}}$	$\{0, 1/3, 2/3, 1, 5/3\}$	$\{1, 2, 4, 2, 2\}$
m_A^2	$f_0\sqrt{\frac{{g'_0}^2+g_1^2}{2}+\epsilon}$	0	1
m_A^3	$f_0\sqrt{\frac{g_0^2+g_1^2}{2}+\eta}$	1	2
m_A^4	$f_0\sqrt{\frac{g_0^2+g_1^2}{2}+\Delta}$	0	1
m_A^5	$g_1\sqrt{\frac{f_0^2+f_1^2}{2}}$	$\{2/3, 0\}$	$\{2, 1\}$
m_A^6	$g_1\sqrt{\frac{f_0^2+f_1^2}{2}+\delta}$	1	2
m_A^7	$g_1\sqrt{\frac{f_0^2+f_1^2}{2}+\alpha}$	0	1

Fermion resonances spectrum

Name	Q_{em}	Number of Dirac fermions
m_F^1	$\{0, \pm 1, -2/3\}$	$\{2, 2, 1\}$
m_F^2	$\{0, \pm 1/3, 2/3, -2/3, \pm 1, \pm 5/3\}$	$\{4, 4, 1, 2, 4, 4\}$
m_F^3	$2/3$	1
m_F^4	$2/3$	1
m_F^5	$2/3$	1
m_F^6	$2/3$	1
m_F^7	$2/3$	1
m_F^8	$2/3$	1
m_F^9	$\{0, 1/3, -2/3, \pm 1, \pm 5/3\}$	$\{3, 1, 2, 4, 2\}$
m_F^{10}	$\{0, 1/3, -2/3, \pm 1, \pm 5/3\}$	$\{3, 1, 2, 4, 2\}$
m_F^{11}	$-\frac{1}{3}$	1
m_F^{12}	$-\frac{1}{3}$	1

Effective theory

$$\mathcal{L}_{\rm eff} \supset \frac{f^2}{4} d^{\hat{a}}_\mu d^{\hat{a},\mu} + \sum_{\mathbf{r}=\mathbf{6},\mathbf{15}} \Pi_{\mathbf{r}}(p^2)(U^\dagger a_\mu)_{\mathbf{r}}(U^\dagger a^\mu)_{\mathbf{r}} + \sum_{i=q,u,d,\ell,e} \sum_{\mathbf{r}} \Pi^i_{\mathbf{r}}(p^2)\overline{(U^\dagger \psi_i)}_{\mathbf{r}} \not{p}\, (U^\dagger \psi_i)_{\mathbf{r}}$$
$$+ \sum_{i=u,d} \sum_{\mathbf{r}} M^i_{\mathbf{r}}(p^2)\overline{(U^\dagger \psi_q)}_{\mathbf{r}}(U^\dagger \psi_i)_{\mathbf{r}} + \sum_{\mathbf{r}} M^e_{\mathbf{r}}(p^2)\overline{(U^\dagger \psi_\ell)}_{\mathbf{r}}(U^\dagger \psi_e)_{\mathbf{r}} \,.$$

$$\mathcal{L}_{\rm eff} \supset \frac{1}{2}[Z_w + \Pi_w(p^2)] w^i_\mu w^{\mu i} + \frac{1}{2}[Z_b + \Pi_b(p^2)] b_\mu b^\mu + \Pi_{ib}(p^2) w^i_\mu b^\mu$$
$$+ \bar{q}_L \not{p}\, (Z_q + \Pi_q) q_L + \sum [\bar{\psi}_R \not{p}\, (Z_\psi + \Pi_\psi)\psi_R + \bar{q}_L M_{q\psi}\psi_R + \text{h.c.}]$$

CW potential

$$V = \int \frac{d^4p}{(2\pi)^4} \left(-2N_c \ln\left[\frac{\det[\mathcal{A}_\mathcal{F}]}{\det[\mathcal{A}_\mathcal{F}|_0]}\right] + \frac{3}{2}\ln\left[\frac{\det[\mathcal{A}_\mathcal{B}]}{\det[\mathcal{A}_\mathcal{B}|_0]}\right]\right)$$

$$V = m_H^2 H^2 + m_\chi^2 \chi^2 + \lambda_H H^4 + \lambda_{H\chi} H^2 \chi^2 + \lambda_\chi \chi^4 + \mathcal{O}(\phi^6)$$

Parameter space scan

$$f_{0,1} \sim 1 \text{ TeV} \quad m_{U,Q} \in (0.5, 10) \text{ TeV}$$

$$\theta_{q,u} \in (0.4, \pi/2) \quad y_U \in (0.1, 3) \quad g_1 \in (1, 6)$$

$$g = 0.65 \quad g' = 0.35 \quad \langle\chi\rangle = 0 \quad 0 < \xi < 1$$

Benchmark points criteria

$$v = 246 \text{ GeV} \quad f_0 g_1 > 2 \text{ TeV} \quad 100 \text{ GeV} < m_H < 145 \text{ GeV}$$

$$140 \text{ GeV} < m_t < 175 \text{ GeV} \quad \xi < 0.25$$

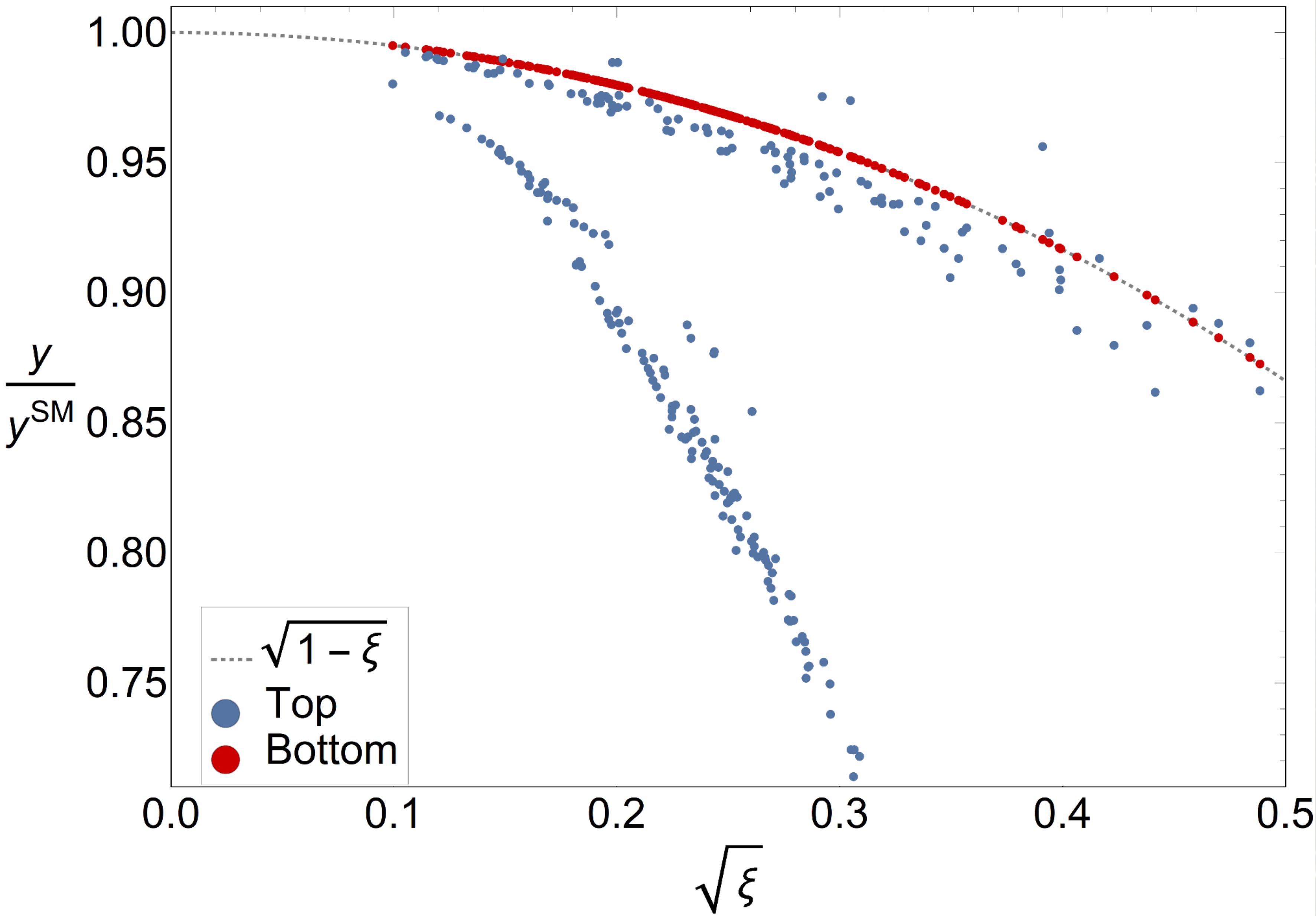
Point for systematic scan

$$f_0 = 1.47 \text{ TeV} \quad f_1 = 2.34 \text{ TeV} \quad m_U = 2.44 \text{ TeV}$$

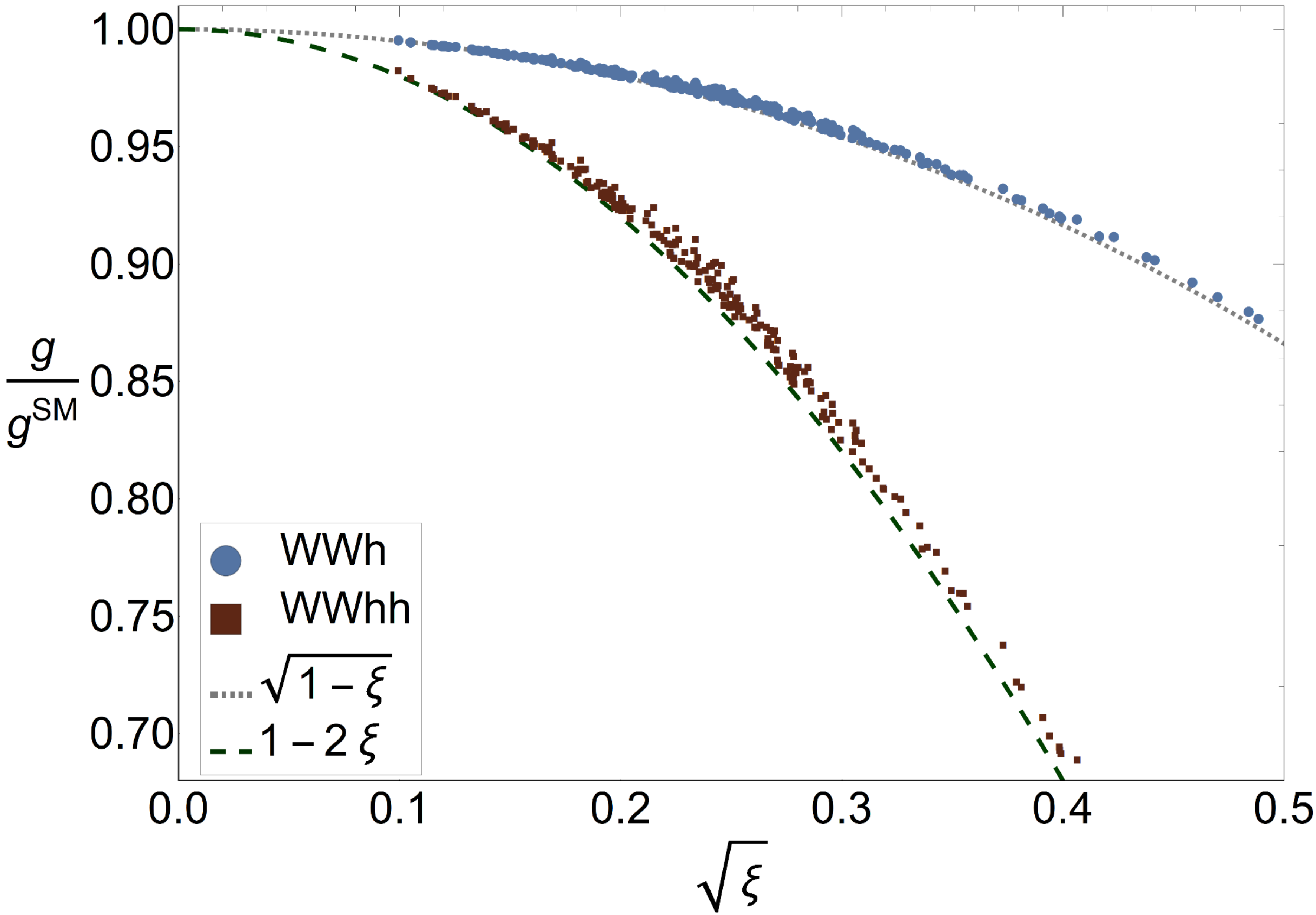
$$m_Q = 1.26 \text{ TeV} \quad \theta_u = 0.79 \quad \theta_q = 1.37$$

$$g_1 = 1.95 \quad y_U = 2.52$$

Yukawa couplings



Higgs- EW vector bosons couplings



Corrections w.r.t. the SM couplings

$$\frac{y_\psi^{(0)}}{m_\psi^{(0)}} \simeq \frac{F_\psi(\xi)}{\sqrt{\xi} f}\left[1+\mathcal{O}\left(\xi\frac{\lambda_{\psi_L}^2 f^2}{m_\Psi^2}, \xi\frac{\lambda_{\psi_R}^2 f^2}{m_\Psi^2}\right)\right]$$

$$F_u = F_d = F_e = \sqrt{1-\xi}$$

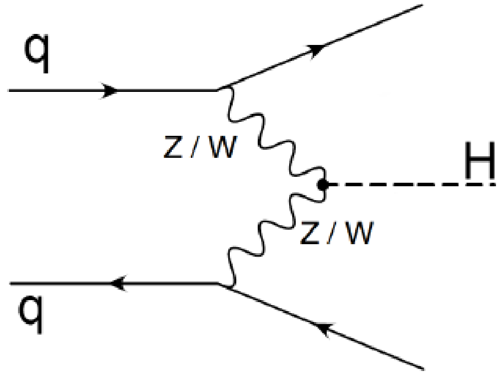
$$\frac{y_d}{m_d} \simeq \frac{F_d}{\sqrt{\xi} f}\left[1-\xi\frac{f_1^2\, y_D^2}{4}\frac{\sin^2(\theta_d)}{m_Q^2}+\mathcal{O}\left(\sin^4(\theta_{q,d})\right)\right]$$

$$\frac{y_u}{m_u} \simeq \frac{F_u}{\sqrt{\xi} f}\left[1+\xi\frac{f_1^2\, y_U^2}{4}\left(\frac{\sin^2(\theta_q)}{m_U^2}-\frac{\sin^2(\theta_u)}{m_Q^2}\right)+\mathcal{O}\left(\sin^4(\theta_{q,u})\right)\right]$$

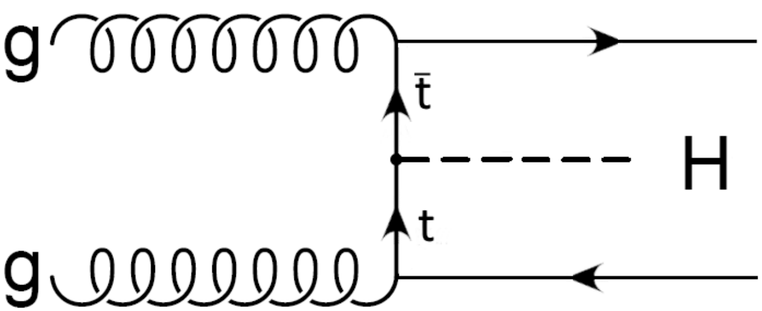
$$\frac{g_{WWh}}{g_{WWh}^{\rm SM}} \simeq \sqrt{1-\xi}\left\{1+\xi\frac{3}{4}\frac{g_0^2}{(g_0^2+g_1^2)^2}\frac{f^4}{f_0^4 f_1^2}\left[f_1^2 g_1^2+f_0^2\left(g_0^2+2g_1^2\right)\right]\right\}$$

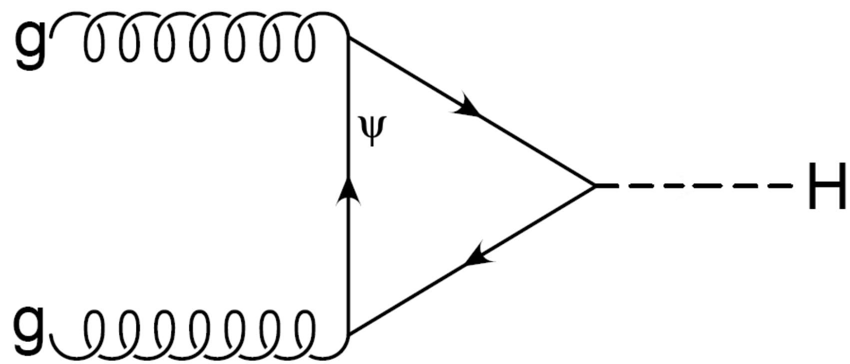
$$\frac{g_{WWhh}}{g_{WWhh}^{\rm SM}} \simeq 1-2\xi+\xi(3-4\xi)\frac{g_0^2}{g_0^2+g_1^2}\frac{g_1^2 f_1^2+f^2}{f_0^2+f_1^2}$$

Vector boson fusion

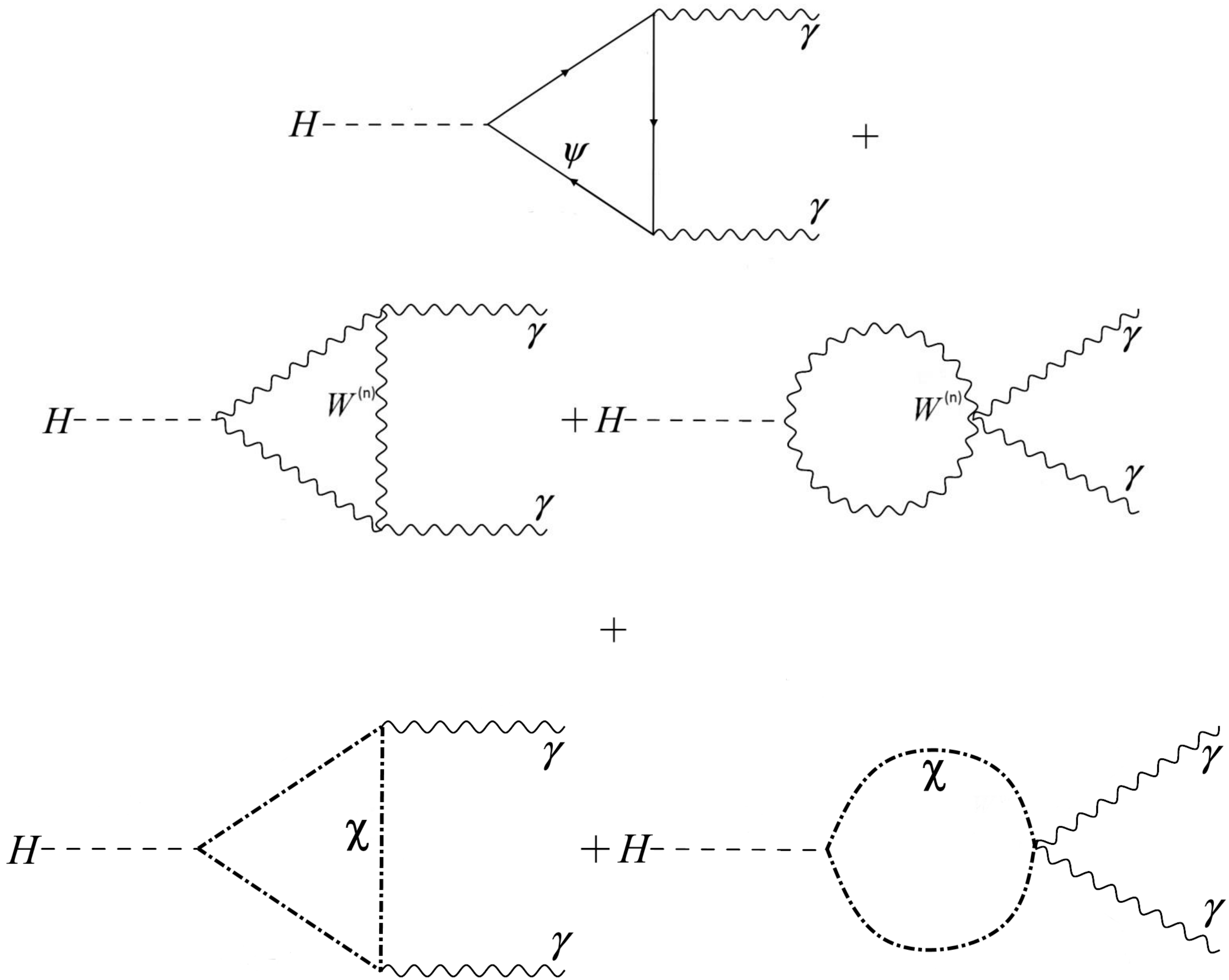


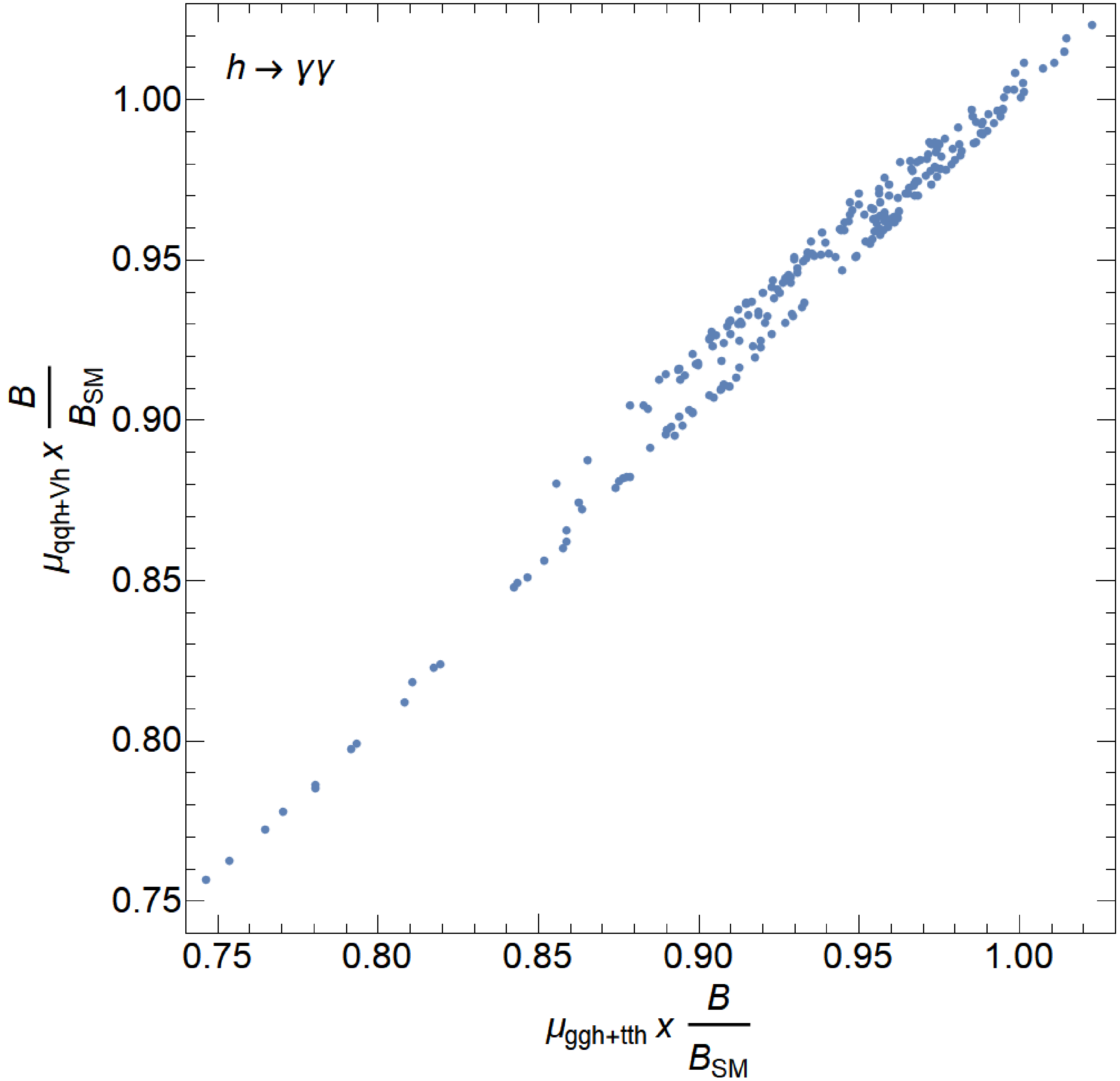
ttH and gluon fusion





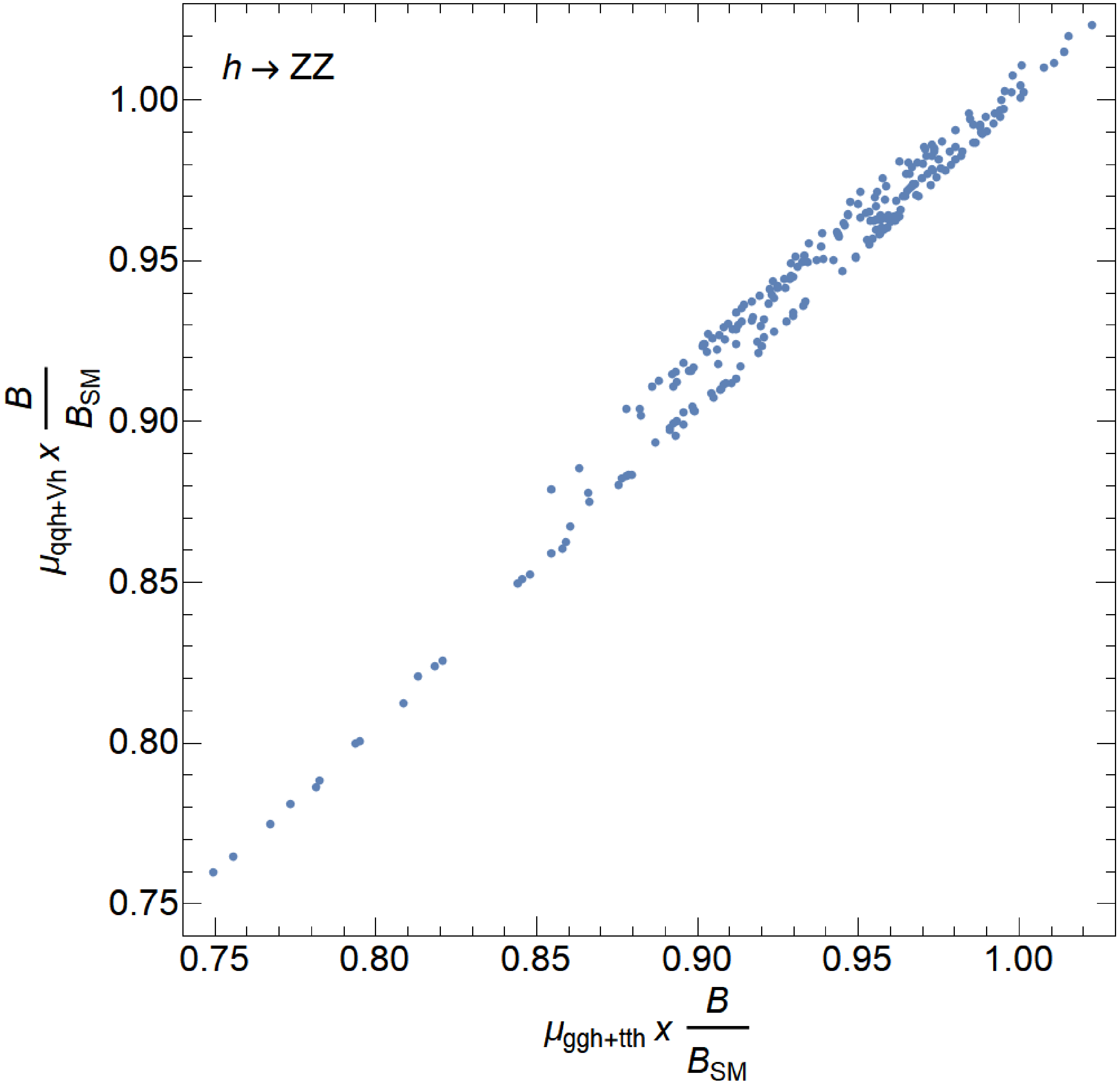
Decay to photons





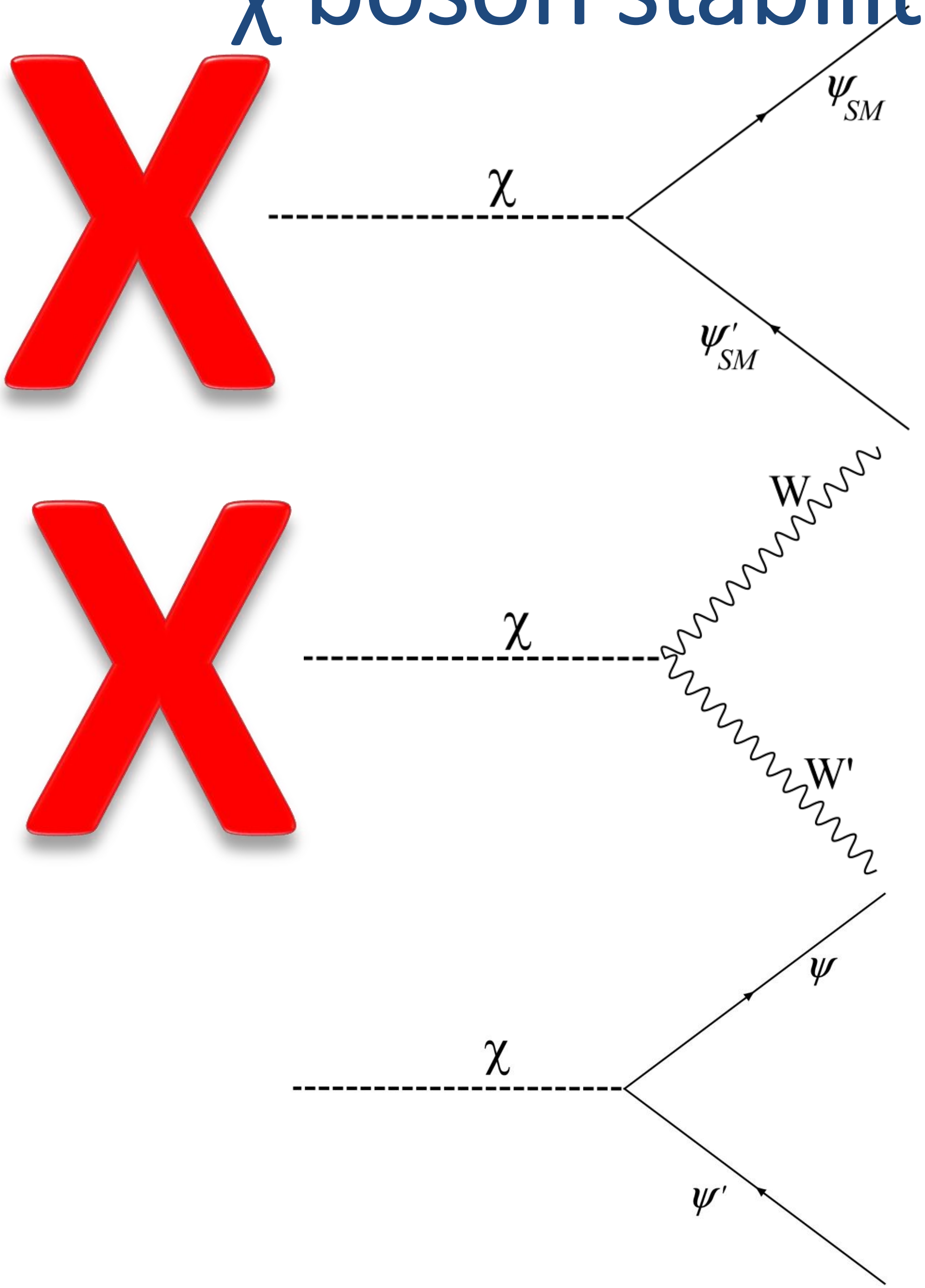
$h \to \gamma\gamma$
1.00
0.95
0.90
0.85
0.80
0.75
0.75
0.80
0.85
0.90
0.95
1.00
$\mu_{\mathrm{qqh+Vh}} \times \frac{B}{B_{\mathrm{SM}}}$
$\mu_{\mathrm{ggh+tth}} \times \frac{B}{B_{\mathrm{SM}}}$

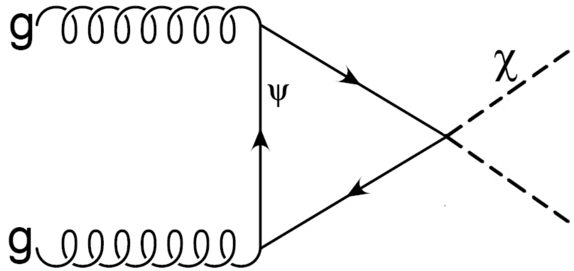
A


h → ZZ
1.00
0.95
0.90
0.85
0.80
0.75
0.75
0.80
0.85
0.90
0.95
1.00
$\mu_{qqh+Vh} \times \frac{B}{B_{SM}}$
$\mu_{ggh+tth} \times \frac{B}{B_{SM}}$

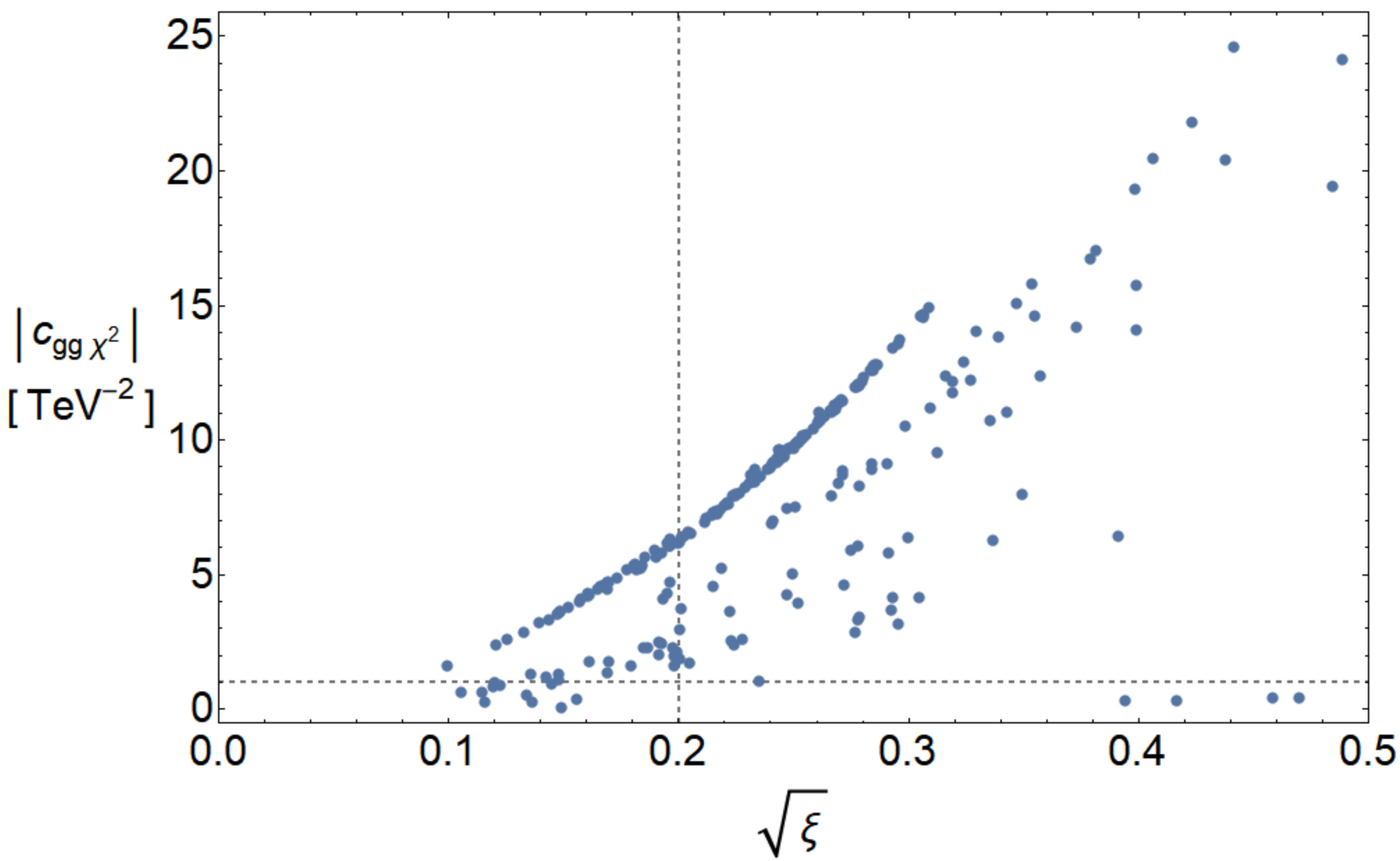

A

χ boson stability





$$c_{gg\chi^2} = \sum_{\psi,n} \frac{y^{(n)}_{\psi\chi^2}}{m^{(n)}_{\psi}} A_{1/2}\left(\frac{Q^2}{(2m^{(n)}_{\psi})^2}\right)$$



Dipole operator

$$\Gamma_{\mathbf{rst}}(p^2)\left[\overline{(U^\dagger\psi_L)}_{\mathbf{r}}(U^\dagger a_{\mu\nu})_{\mathbf{s}}\sigma^{\mu\nu}(U^\dagger\psi_R)_{\mathbf{t}}\right]_{\mathbf{1}}$$

SO(7) generators

$$(T_{ij})_{k\ell} = \frac{i}{\sqrt{2}}(\delta_{ik}\delta_{j\ell} - \delta_{i\ell}\delta_{jk}) \,, \qquad i<j, \;, i = 1,\ldots 6 \;, j = 2,\ldots 7$$

$$T^L_1 = -\frac{1}{\sqrt{2}}(T_{23}+T_{14}) \quad T^L_2 = \frac{1}{\sqrt{2}}(T_{13}-T_{24}) \quad T^L_3 = -\frac{1}{\sqrt{2}}(T_{12}+T_{34})$$

$$T^R_1 = -\frac{1}{\sqrt{2}}(T_{23}-T_{14}) \quad T^R_2 = \frac{1}{\sqrt{2}}(T_{13}+T_{24}) \quad T^R_3 = -\frac{1}{\sqrt{2}}(T_{12}-T_{34})$$

$$X = T_{67} \,.$$

$$\mathbf{7}\otimes\mathbf{21} \sim \mathbf{7}\oplus\mathbf{35}\oplus\mathbf{105}$$