Status of the (extended) Georgi Machacek model in the light of NLO unitarity and the latest LHC data

based on
[arXiv: 2111.14195] with A. Kundu and P. B. Pal
[2404.18996] with D. Chowdhury and S. Samanta

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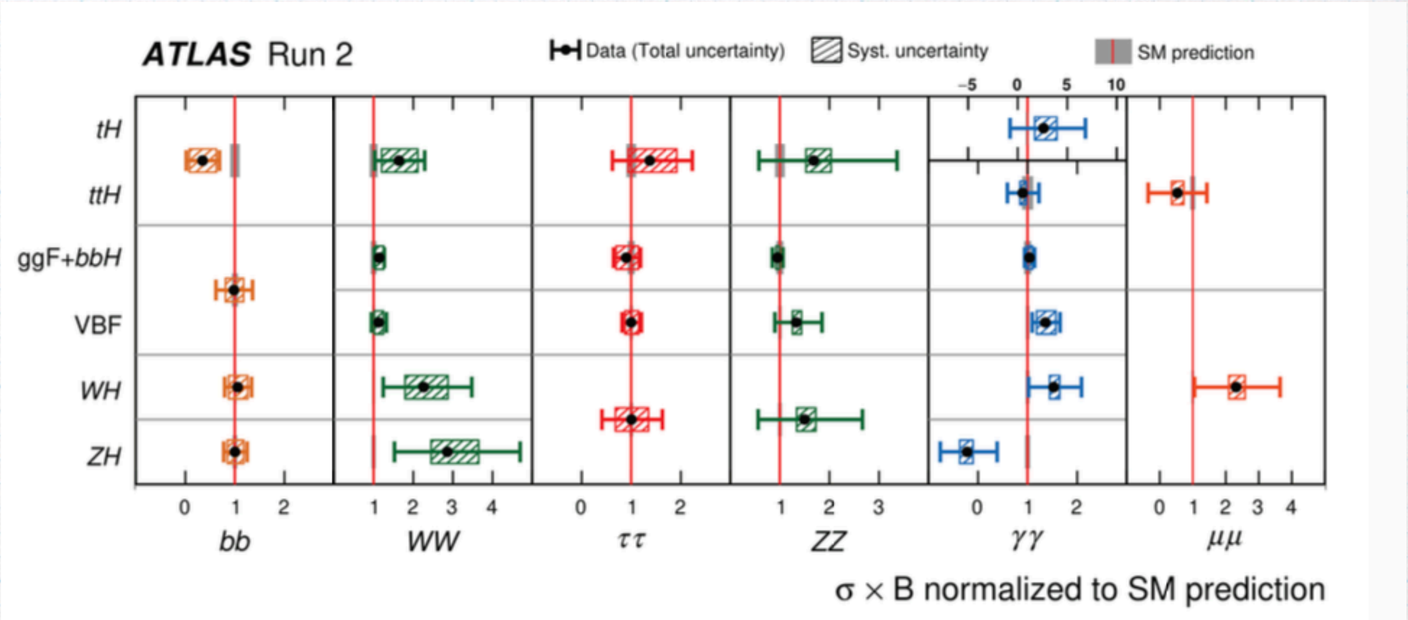
IIT Kanpur

Workshop on Multi-Higgs Models
Lisbon, Portugal
September 3, 2024

Beyond the Standard Model

The Standard Model provides a framework for explaining much of the observed results @ expts.

Major Issues



- Dark Matter
- Massive Neutrinos
- Baryon asymmetry of the Universe (BAU)
- Origin of electroweak (EW) symmetry breaking and the type of EWPT

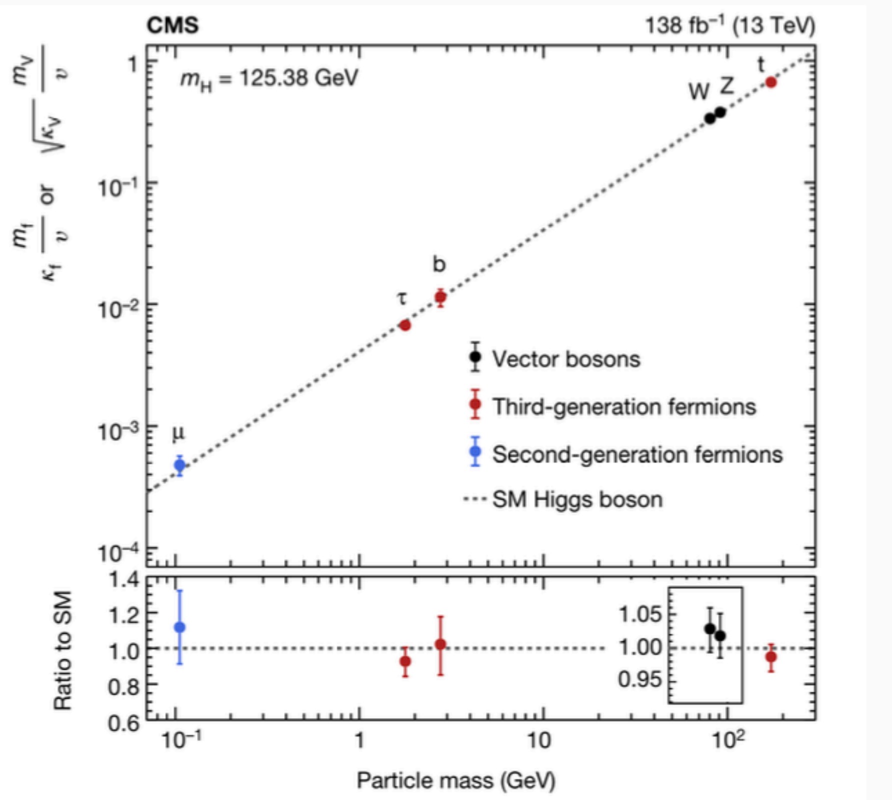
Search for BSM @ forefront of particle physics research

Higgs Triplet Models (HTMs)

- **Data suggests** $\kappa_V > 1$

- **SM + doublets (e.g. 2HDM)** $\rightarrow \kappa_V < 1$

- **SM + triplets** $\rightarrow \kappa_V < 1, \quad \kappa_V > 1$



CMS Collaboration, Nature 607 (2022)

HTMs

- Can explain EWBG, DM puzzle, neutrino oscillation

- **Exciting phenomenological aspects in colliders : LHC, HL-LHC, ILC, Muon collider, FCC etc.**

- **Can be probed in cosmological observatories: LISA, DECIGO, PRIME, Roman Telescope etc.**

HTM with Custodial Symmetry

$$\rho = \frac{m_W^2}{m_Z^2 Cos^2\theta_W} = 1,$$ at tree level

Consequence of **Custodial Symmetry**

$$V = -m_\phi^2(\phi^\dagger\phi) - m_\xi^2(\xi^\dagger\xi) - m_\chi^2(\chi^\dagger\chi) + \mu_1(\chi^\dagger t_a\chi)\xi_a + \mu_2(\phi^\dagger\tau_a\phi)\xi_a$$
$$+ \mu_3\left[(\phi^T\epsilon\tau_a\phi)\tilde{\chi}_a + \text{h.c.}\right] + \lambda_\phi(\phi^\dagger\phi)^2 + \lambda_\xi(\xi^\dagger\xi)^2 + \lambda_\chi(\chi^\dagger\chi)^2$$
$$+ \tilde{\lambda}_\chi|\tilde{\chi}^\dagger\chi|^2 + \lambda_{\phi\xi}(\phi^\dagger\phi)(\xi^\dagger\xi) + \lambda_{\phi\chi}(\phi^\dagger\phi)(\chi^\dagger\chi) + \lambda_{\chi\xi}(\chi^\dagger\chi)(\xi^\dagger\xi)$$
$$+ \kappa_1|\xi^\dagger\chi|^2 + \kappa_2(\phi^\dagger\tau_a\phi)(\chi^\dagger t_a\chi) + \kappa_3\left[(\phi^T\epsilon\tau_a\phi)(\chi^\dagger t_a\xi) + \text{h.c.}\right],$$

After electro-weak symmetry breaking:

$$\langle\phi\rangle = v_\phi, \langle\xi\rangle = v_\xi, \langle\chi\rangle = v_\chi$$

$$\rho = \frac{v_\phi^2 + 4(v_\xi^2 + v_\chi^2)}{v_\phi^2 + 8v_\chi^2}, \qquad \rho = 1 \to v_\chi = v_\xi$$

Georgi Machacek Model

- **In 1985, GM model was first proposed by Georgi and Machacek as a minimal HTM with $\rho = 1$**

$$
\begin{aligned}
V &= \frac{1}{2}m_2^2\,\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{1}{2}m_3^2\,\mathrm{Tr}(X^\dagger X) \\
&\quad - M_1\,\mathrm{Tr}(\Phi^\dagger\tau_a^\dagger\Phi\tau_b)X_{ab} - M_2\,\mathrm{Tr}(X^\dagger t_a^\dagger X t_b)X_{ab} \\
&\quad + \lambda_1(\mathrm{Tr}\,\Phi^\dagger\Phi)^2 + \lambda_2(\mathrm{Tr}\,X^\dagger X)^2 + \lambda_3\,\mathrm{Tr}(X^\dagger X X^\dagger X) \\
&\quad + \lambda_4(\mathrm{Tr}\,\Phi^\dagger\Phi)\,\mathrm{Tr}(X^\dagger X) - \lambda_5\,\mathrm{Tr}(\Phi^\dagger\tau_a^\dagger\Phi\tau_b)\,\mathrm{Tr}(X^\dagger t_a^\dagger X t_b)\,,
\end{aligned}
$$

On the centre stage of BSM searches @collider and cosmological expts.

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT

Submitted to: Phys. Lett. B.

CERN-EP-2024-189
July 16, 2024

Combination of searches for singly and doubly charged Higgs bosons produced via vector-boson fusion in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

PHYSICAL REVIEW D **91,** 015013 (2015)

Indirect constraints on the Georgi-Machacek model and implications for Higgs boson couplings

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(Received 4 November 2014; published 15 January 2015)

PHYSICAL REVIEW D **106,** 055019 (2022)

Updated constraints on the Georgi-Machacek model and its electroweak phase transition and associated gravitational waves

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Electroweak phase transition and Higgs phenomenology in the Georgi-Machacek model

Ruiyu Zhou,[a] Wei Cheng,[a] Xin Deng,[a] Ligong Bian[a,b,1] and Yongcheng Wu[c]

PHYSICAL REVIEW D **90,** 015007 (2014)

The decoupling limit in the Georgi-Machacek model

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Testing the custodial symmetry in the Higgs sector of the Georgi-Machacek model

Cheng-Wei Chiang[a,b,c] and Kei Yagyu[a]

Extended Georgi Machacek (eGM) Model

- **Minimal two triplet extension of SM with $\rho = 1$ gives rise to eGM model, not the conventional GM model.** [A. Kundu, P. B. Pal, PM, 2111.14195]

16 parameters — **SM with one real and one complex triplet**

$\rho = 1$

$$m_\chi^2 = 2m_\xi^2\,, \quad \mu_2 = \sqrt{2}\mu_3\,, \quad \lambda_{\chi\xi} = 2\lambda_\chi - 4\lambda_\xi\,, \quad \kappa_2 = 4\lambda_{\phi\xi} - 2\lambda_{\phi\chi} + \sqrt{2}\kappa_3\,.$$

12 parameters — **eGM model**

$$\kappa_2 = \sqrt{2}\kappa_3\,, \quad \kappa_1 = 2\tilde{\lambda}_\chi = 4\lambda_\xi - \lambda_{\chi\xi}\,.$$

9 parameters — **GM model**

$SU(2)_L \times SU(2)_R$

$F^{++}, F^{+}, H^{+}, F^{0}, A, H, h$

eGM	λ_ϕ	λ_ξ	λ_χ	$\tilde{\lambda}_\chi$	$\lambda_{\phi\xi}$	$\lambda_{\phi\chi}$	κ_1	κ_3
GM	$4\lambda_1$	$\lambda_2 + \lambda_3$	$4\lambda_2 + 2\lambda_3$	$2\lambda_3$	$2\lambda_4$	$4\lambda_4$	$4\lambda_3$	$\sqrt{2}\lambda_5$

GM model	vs.	eGM model

GM model	eGM model
• Scalar multiplets mass degenerate	• Scalar multiplets non mass degenerate ↓ new decay modes open up ↓ search for new physics @ colliders
• Divergent contribution to ρ parameter @ one-loop	• All the counter-terms are present in the Lagrangian
• Only H^+ couples to fermions.	• Both H^+ and F^+ couple to fermions ↓ Much richer flavour physics phenomenology

Theory Constraints on the parameter space

* **Why theory bounds are important?**

  Ans: More statistically robust than expt data with errors

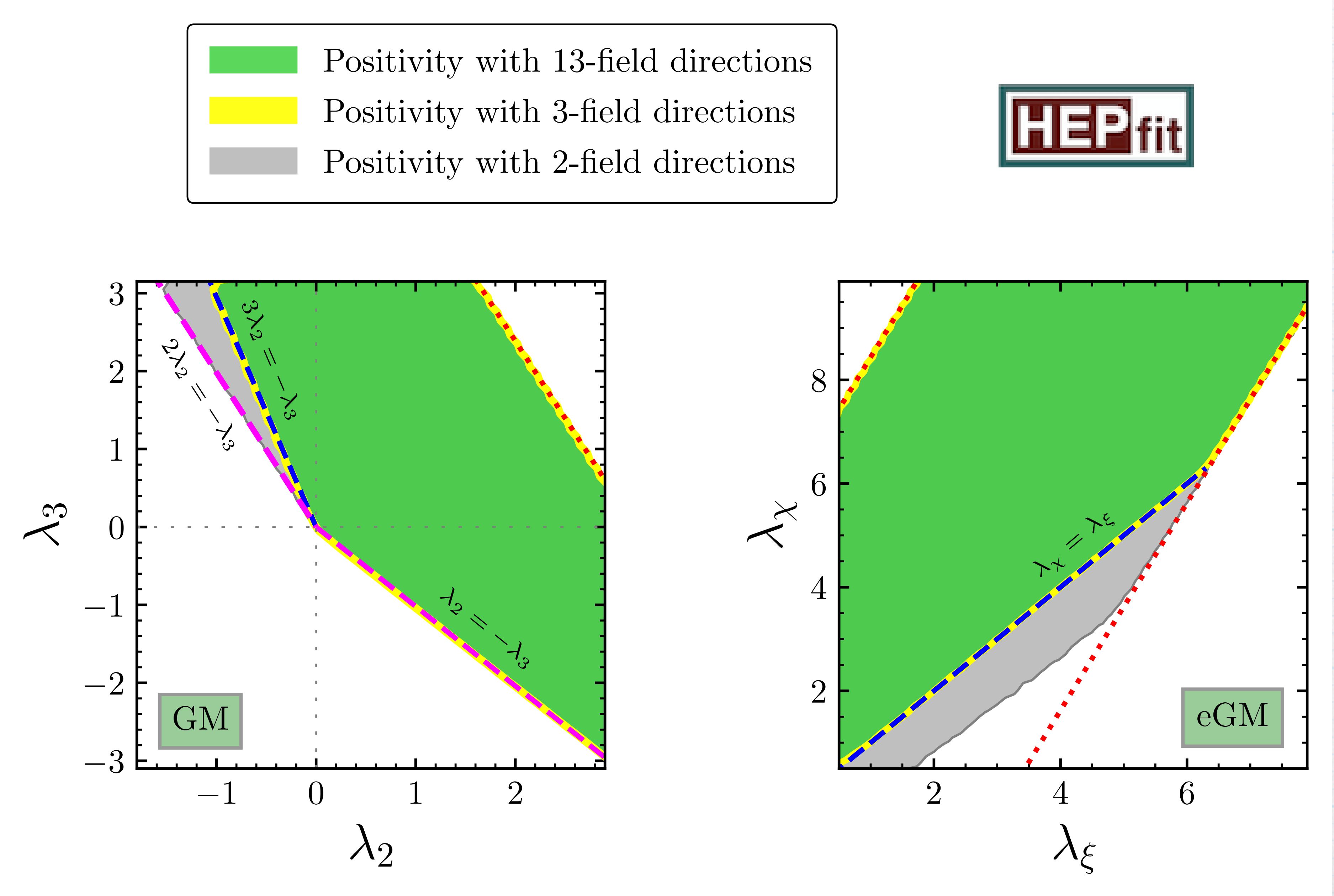
Theory Constraints

- Higgs potential must be bounded from below
- Yukawa and quartic couplings need to be in perturbative regime
- Eigenvalues of the S matrix of 2×2 scattering should satisfy NLO unitarity bounds
- NLO corrections to the LO eigenvalues should be smaller in magnitude.

Bounded From Below (BFB)

Make sure that the scalar potential must be bounded from in any direction of the field scape

$$V^{(4)} = \lambda_\phi(\phi^\dagger\phi)^2 + \lambda_\xi(\xi^\dagger\xi)^2 + \lambda_\chi(\chi^\dagger\chi)^2 + \tilde{\lambda}_\chi|\tilde{\chi}^\dagger\chi|^2 + \lambda_{\phi\xi}(\phi^\dagger\phi)(\xi^\dagger\xi) + \lambda_{\phi\chi}(\phi^\dagger\phi)(\chi^\dagger\chi)$$
$$+ \lambda_{\chi\xi}(\chi^\dagger\chi)(\xi^\dagger\xi) + \kappa_1|\xi^\dagger\chi|^2 + \kappa_2(\phi^\dagger\tau_a\phi)(\chi^\dagger t_a\chi) + \kappa_3\Big[(\phi^T\epsilon\tau_a\phi)(\chi^\dagger t_a\xi) + \text{h.c.}\Big] > 0\,.$$



3 and all 13 non-vanishing field directions generating large overlapping parameter space

Unitarity Constraints

Prior to Higgs discovery :

unitarity bound @ tree level: $\lambda \leq \frac{8\pi}{3}$ **@ 1-loop** $\lambda \leq 2 - 2.5$

Lee, Quigg, Thacker '77 *Dawson, Eillenbrock '89; Durand, Johnson, Lopez'92*

2 loop calculation shows no revised limit *Durand, Maher, Riesselmann, 92*

Weakly interacting Higgs scenario

S matrix unitary : $SS^\dagger = 1$ **Partial wave amplitudes:**

$$\left| a_\ell^{2\to 2} - \frac{1}{2} i \right|^2 + \sum_{k>2} \left| a_\ell^{2\to k} \right|^2 = \frac{1}{4} .$$

$s \gg |\lambda_i| v^2,\ s \gg |\mu_i| v,$ → **We neglect** $a_l^{2\to k>2}$ **and set** $l = 0$

$$|\mathrm{Re}(a_\ell)| \ \leq 1/2.$$

$$(a_0)_{i,f}(s) = \frac{1}{16\pi s} \int_{-s}^{0} dt \mathcal{M}_{i\to f}(s,t) \,,$$

Unitarity in eGM/GM

- **Goldstone boson equivalence theorem**

$$\mathcal{M}(W_L^{\pm}, Z_L, h, ...) \;=\; (iC)^k \mathcal{M}(w^{\pm}, z, h, ...)\,. \qquad \sqrt{s} \;\gg\; M_W$$

Q \ Y	0			1/2		1		3/2	2
0	$\phi^{0*}\phi^0$ $\phi^+\phi^-$	$\frac{\xi^0\xi^0}{\sqrt{2}}$ $\xi^+\xi^-$	$\chi^{0*}\chi^0$ $\chi^+\chi^-$ $\chi^{++}\chi^{--}$	$\phi^0\xi^0$ $\phi^+\xi^-$	$\phi^{0*}\chi^0$ $\chi^+\phi^-$	$\frac{\phi^0\phi^0}{\sqrt{2}}$	$\chi^0\xi^0$ $\chi^+\xi^-$	$\phi^0\chi^0$	$\frac{\chi^0\chi^0}{\sqrt{2}}$
1	$\phi^{0*}\phi^+$	$\xi^0\xi^+$	$\chi^{0*}\chi^+$ $\chi^-\chi^{++}$	$\phi^0\xi^+$ $\phi^+\xi^0$	$\phi^{0*}\chi^+$ $\chi^{++}\phi^-$	$\phi^0\phi^+$ $\chi^0\xi^+$	$\xi^0\chi^+$ $\chi^{++}\xi^-$	$\phi^0\chi^+$ $\phi^+\chi^0$	$\chi^+\chi^0$
2		$\frac{\xi^+\xi^+}{\sqrt{2}}$	$\chi^{0*}\chi^{++}$	$\phi^+\xi^+$	$\phi^{0*}\chi^{++}$	$\frac{\phi^+\phi^+}{\sqrt{2}}$	$\xi^+\chi^+$ $\xi^0\chi^{++}$	$\phi^+\chi^+$ $\phi^0\chi^{++}$	$\chi^0\chi^{++}$ $\frac{\chi^+\chi^+}{\sqrt{2}}$
3	✗			✗			$\xi^+\chi^{++}$	$\phi^+\chi^{++}$	$\chi^+\chi^{++}$
4	✗			✗		✗		✗	$\frac{\chi^{++}\chi^{++}}{\sqrt{2}}$

Block diagonal form @ tree-level

Does not hold beyond tree-level due to hypercharge interactions

Tree-level Unitarity

$$-16\pi a_{0;1} = 2\lambda_{\chi\xi} + \kappa_1 \,,$$

$$-16\pi a_{0;2}^{\pm} = \lambda_\chi - 2\tilde{\lambda}_\chi + \lambda_\phi \pm \sqrt{\kappa_2^2 + \left(-\lambda_\chi + 2\tilde{\lambda}_\chi + \lambda_\phi\right)^2} \,, \qquad -16\pi a_{0;3} = \lambda_{\phi\chi} + \frac{\kappa_2}{2} \,,$$

$$-16\pi a_{0;4}^{\pm} = 4\lambda_\xi + \lambda_\chi + 2\tilde{\lambda}_\chi \pm \sqrt{2\kappa_1^2 + \left(-4\lambda_\xi + \lambda_\chi + 2\tilde{\lambda}_\chi\right)^2} \,, \qquad -16\pi a_{0;5} = 2\lambda_{\chi\xi} + 4\kappa_1 \,,$$

$$-16\pi a_{0;6}^{\pm} = \lambda_{\phi\xi} + \frac{\lambda_{\phi\chi}}{2} - \frac{\kappa_2}{4} \pm \sqrt{\kappa_3^2 + \left(\frac{\kappa_2}{4} + \lambda_{\phi\xi} - \frac{\lambda_{\phi\chi}}{2}\right)^2} \,, \qquad -16\pi a_{0;7} = 2\lambda_\chi \,,$$

$$-16\pi a_{0;8}^{\pm} = \lambda_{\phi\xi} + \frac{\lambda_{\phi\chi}}{2} + \frac{\kappa_2}{2} \pm \sqrt{4\kappa_3^2 + \left(\frac{\kappa_2}{2} - \lambda_{\phi\xi} + \frac{\lambda_{\phi\chi}}{2}\right)^2} \,, \qquad -16\pi a_{0;9} = \lambda_{\phi\chi} - \kappa_2 \,,$$

$$-16\pi a_{0;10}^{\pm} = \lambda_{\chi\xi} + \lambda_\phi - \frac{\kappa_1}{2} \pm \sqrt{2\kappa_3^2 + \left(\frac{\kappa_1}{2} - \lambda_{\chi\xi} + \lambda_\phi\right)^2} \,, \qquad -16\pi a_{0;11} = 2\lambda_\chi + 6\tilde{\lambda}_\chi \,,$$

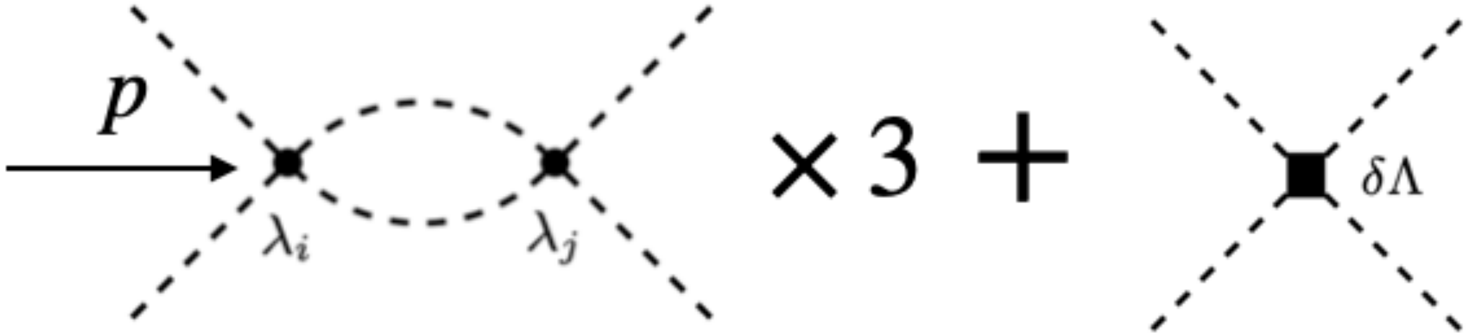
and $-16\pi a_{0;i}$ $(i = 12, 13, 14)$ being the eigenvalues of the following matrix,

$$\begin{bmatrix} 20\lambda_\xi & 2\sqrt{3}\lambda_{\phi\xi} & \sqrt{2}\left(\kappa_1 + 3\lambda_{\chi\xi}\right) \\ 2\sqrt{3}\lambda_{\phi\xi} & 6\lambda_\phi & \sqrt{6}\lambda_{\phi\chi} \\ \sqrt{2}\left(\kappa_1 + 3\lambda_{\chi\xi}\right) & \sqrt{6}\lambda_{\phi\chi} & 8\lambda_\chi + 4\tilde{\lambda}_\chi \end{bmatrix} .$$

16,15,11,3,1 unique tree level eigenvalues for the Block $Q = 0,1,2,3,4$

19 eigenvalues are independent

NLO unitarity



[Grinstein, Murphy, Uttayarat '15;
Cacchio, Chowdhury, Murphy, Eberhardt'16]

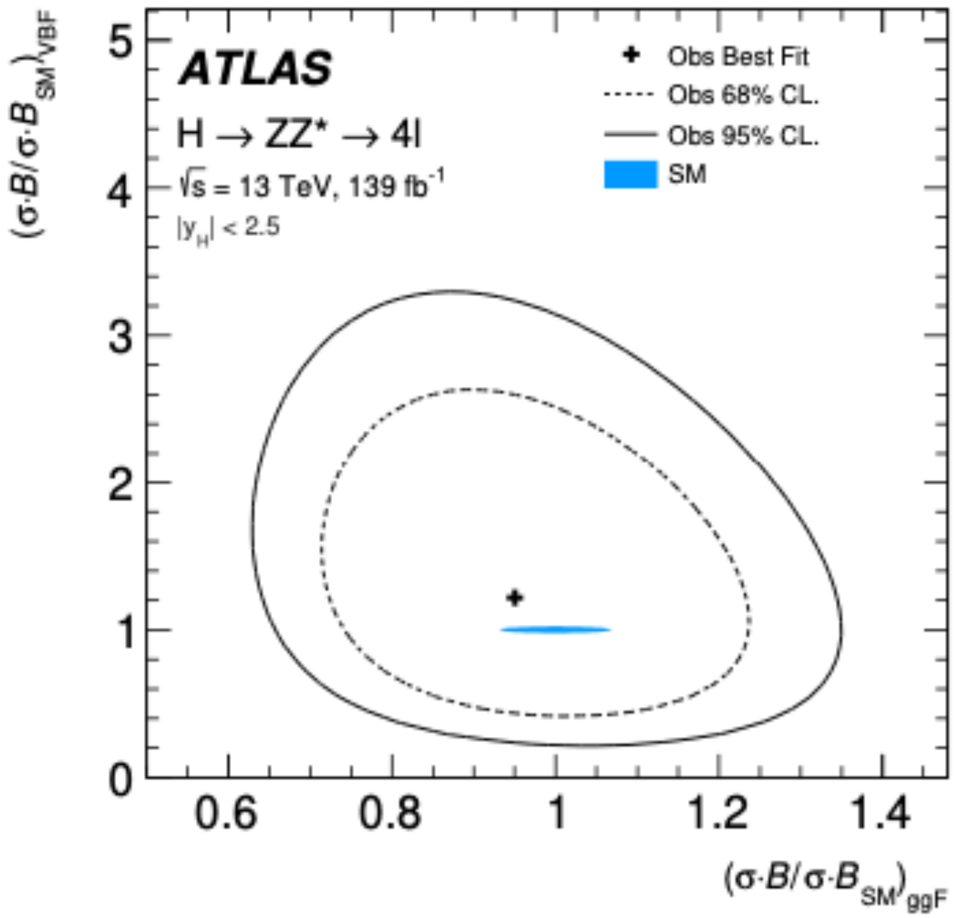
$$R_1 = \frac{\left|a_0^{\mathrm{NLO}}\right|}{\left|a_0^{\mathrm{LO}} + a_0^{\mathrm{NLO}}\right|}\,, \qquad R_1' = \frac{\left|a_0^{\mathrm{NLO}}\right|}{\left|a_0^{\mathrm{LO}}\right|}\,,$$

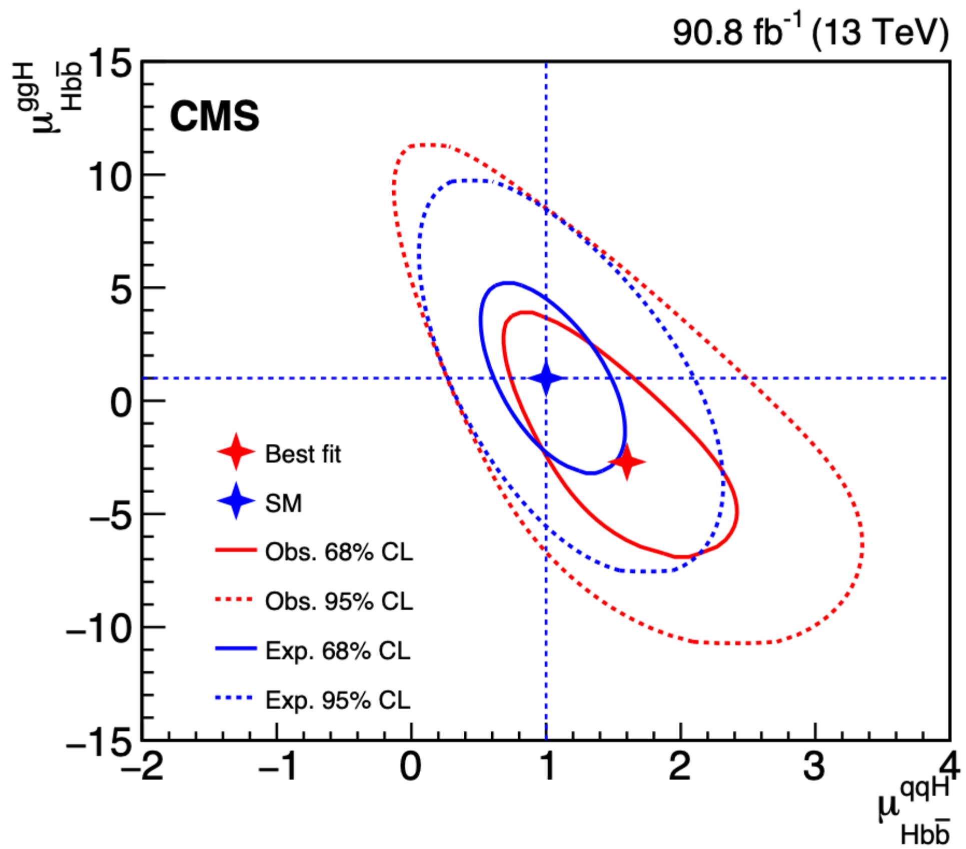
Perturbative expansion is not valid at NLO when $R_1 = 1$ or $R_1' = 1$

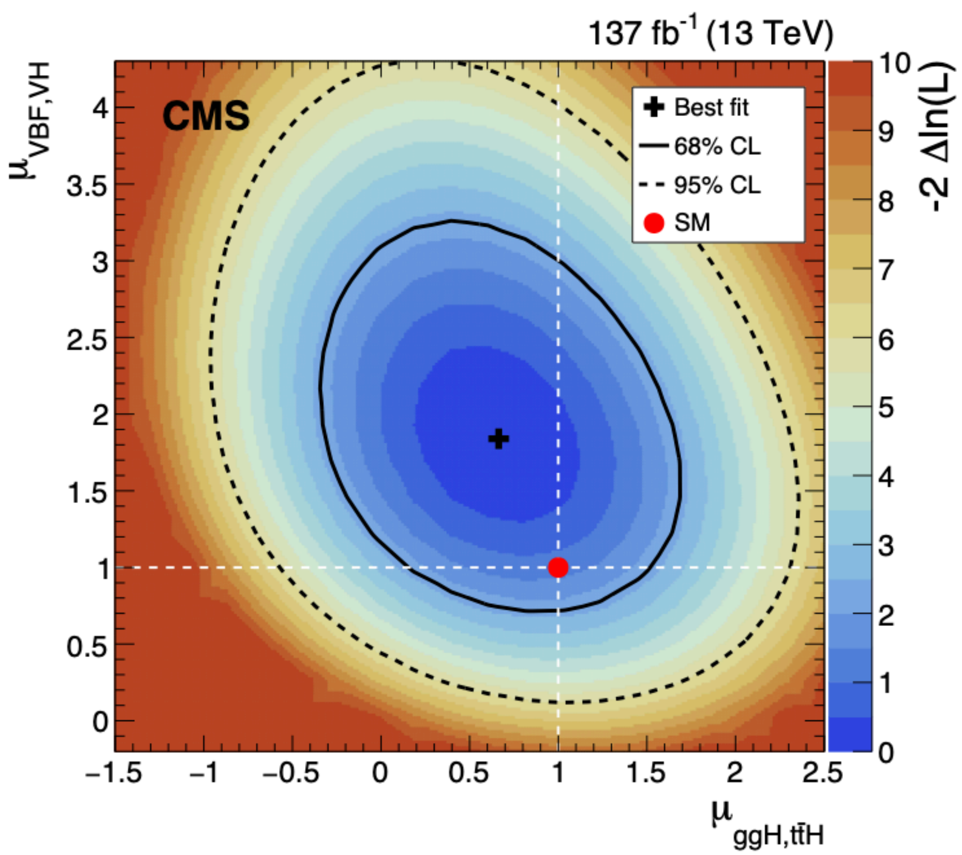
For a given Q and Y, S matrix element @ 1-loop

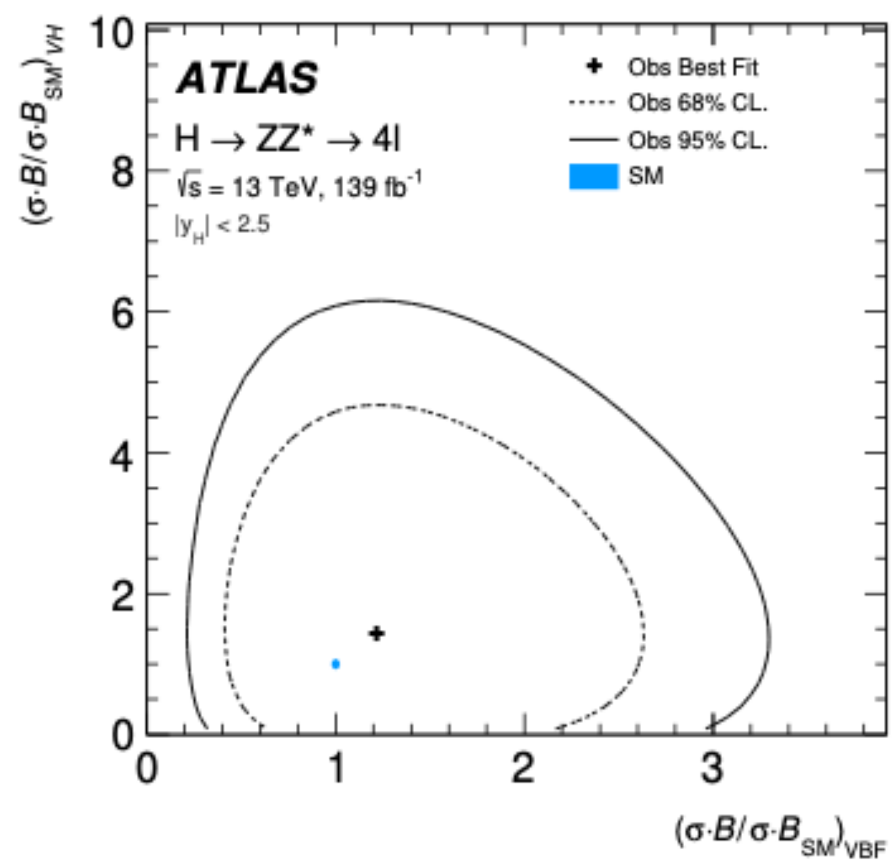
$$256\pi^3 \mathbf{a_0} = -16\pi^2 \mathbf{b_0} + (i\pi - 1)\mathbf{b_0}\cdot\mathbf{b_0} + 3\beta_{\mathbf{b_0}}\,,$$

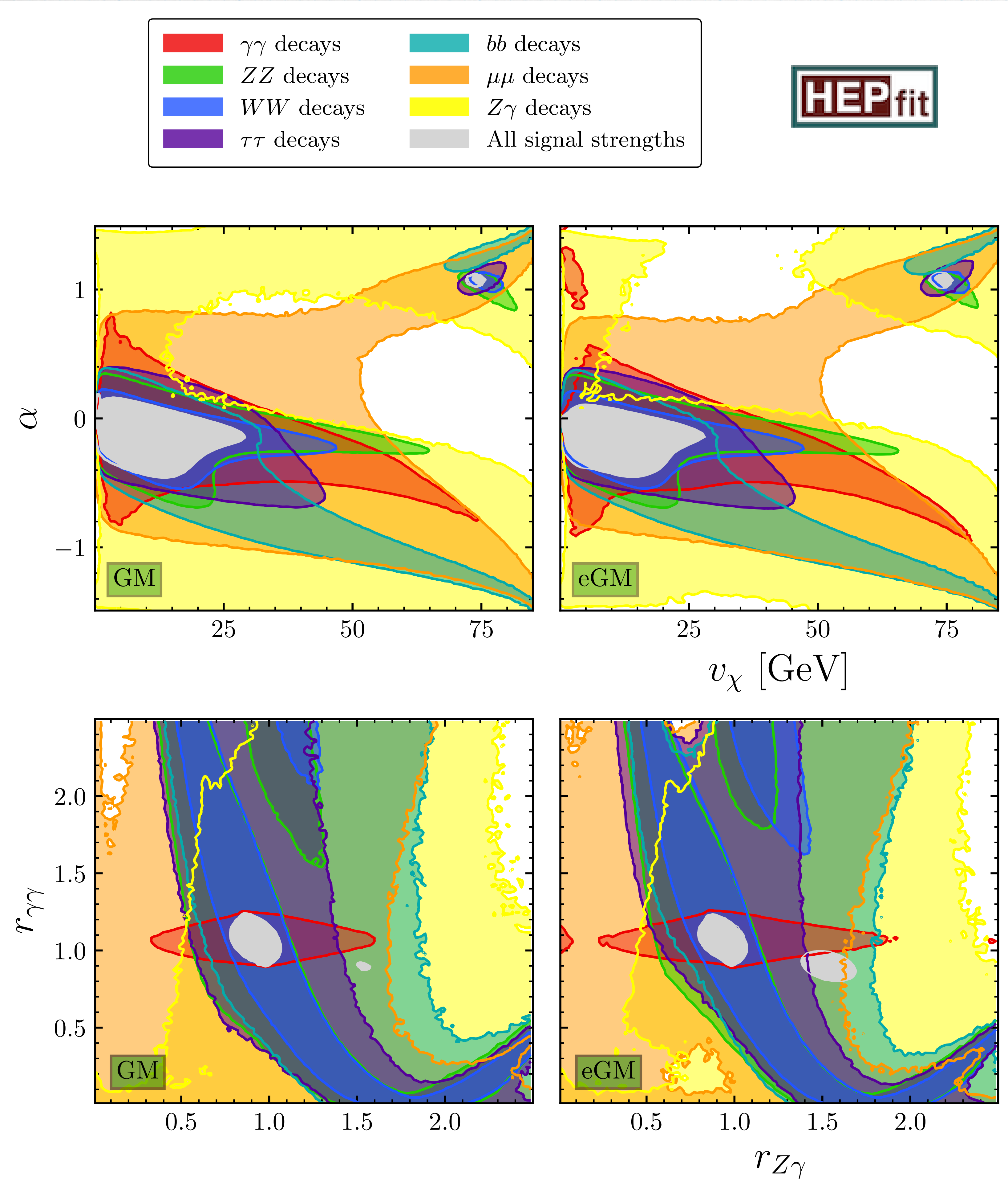
Higgs Signal Strength (Run 2)











Results from the combined fit:

$-0.47 < \alpha < 0.2$ @ $95.4\,\%$ **CL**

$v_\chi < 30$ **GeV**

Decoupling limit

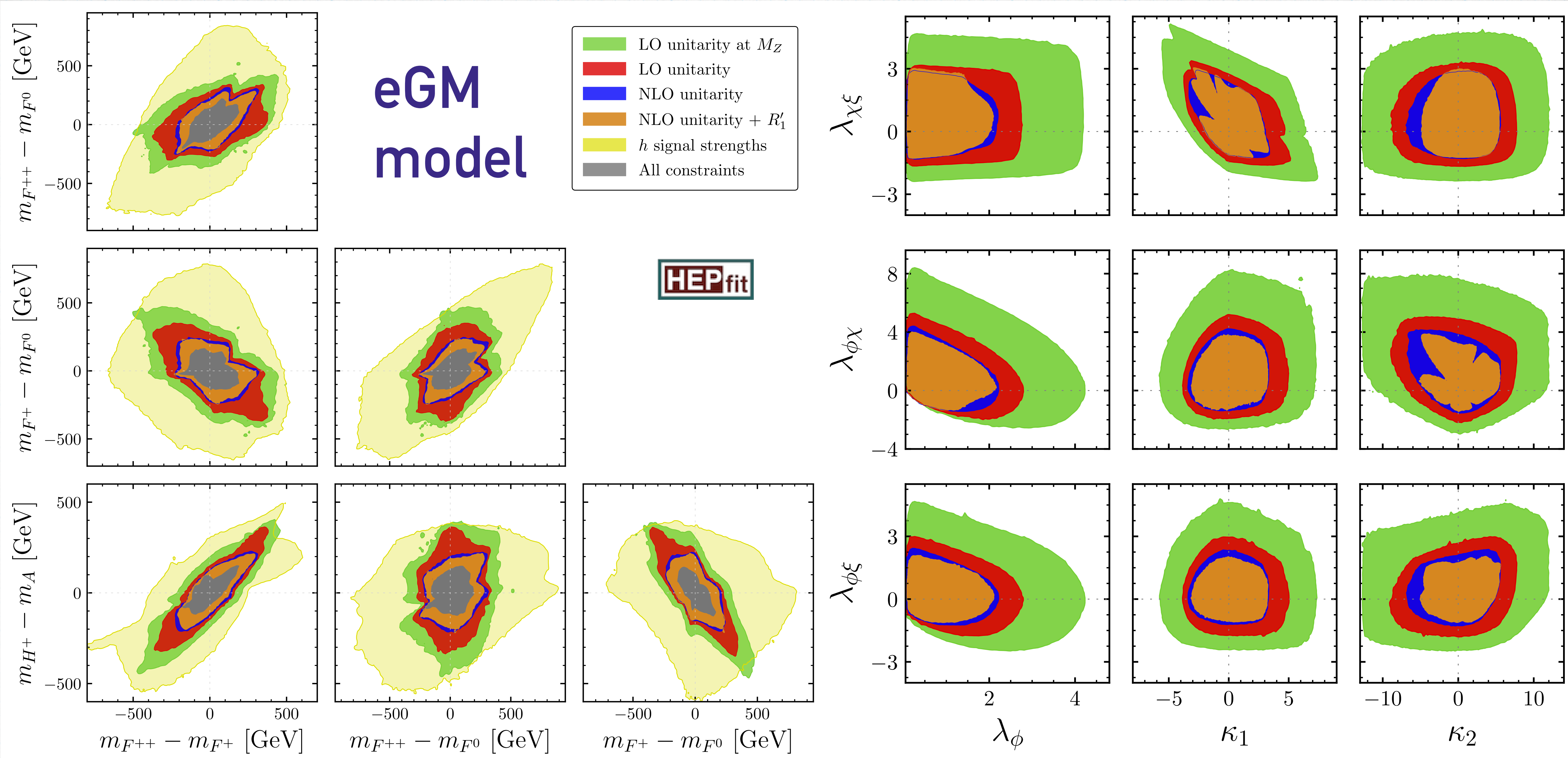
$\alpha = v_\chi = 0$

all additional Higgs become heavy

$\kappa_V \to 1$

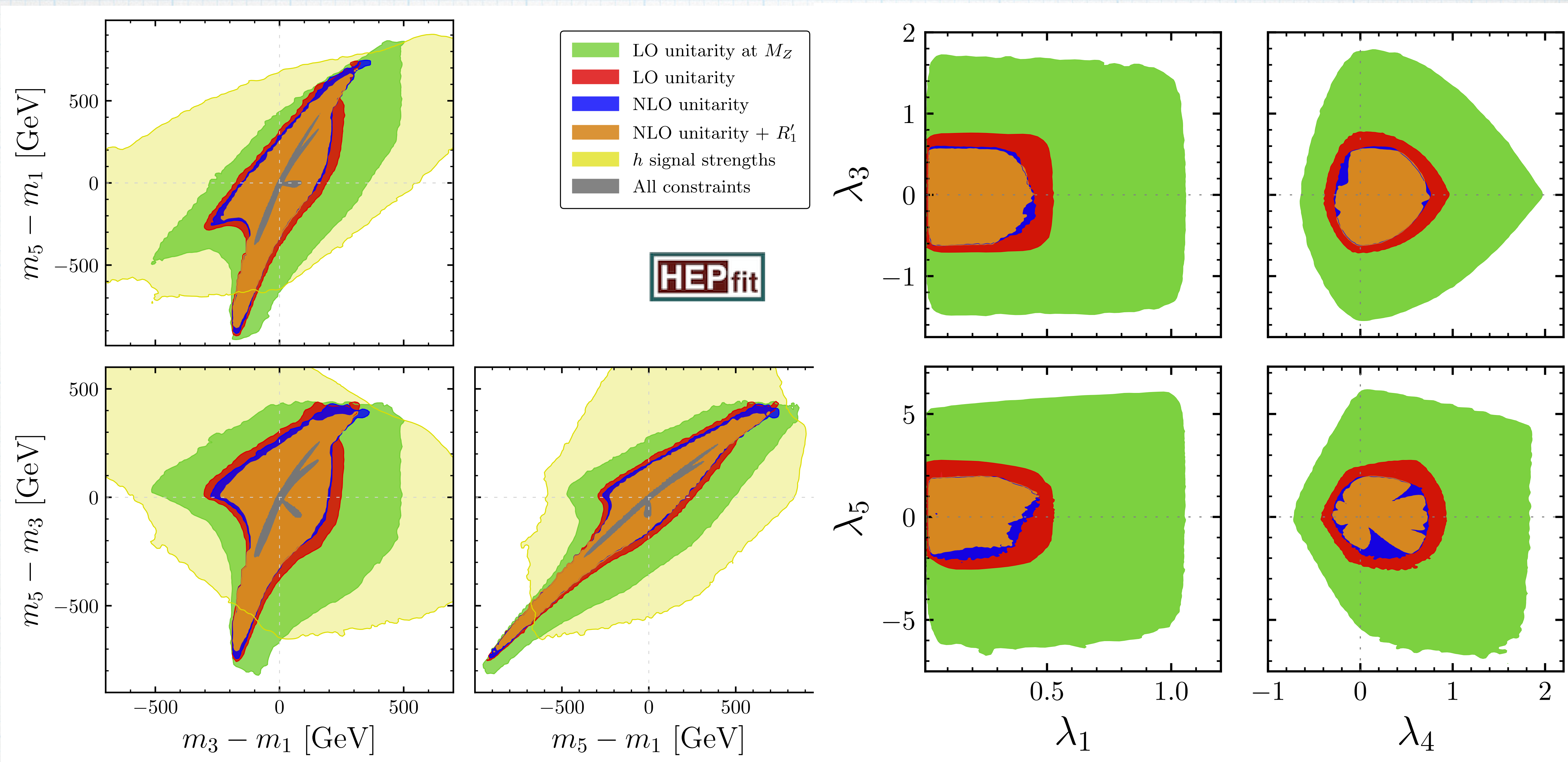
Higgs signal strength data strongly disfavours

$\kappa_V > 1.05$ @ $95.4\,\%$ **CL**



- Maximum Mass difference within same multiplet in eGM model is < 210 GeV

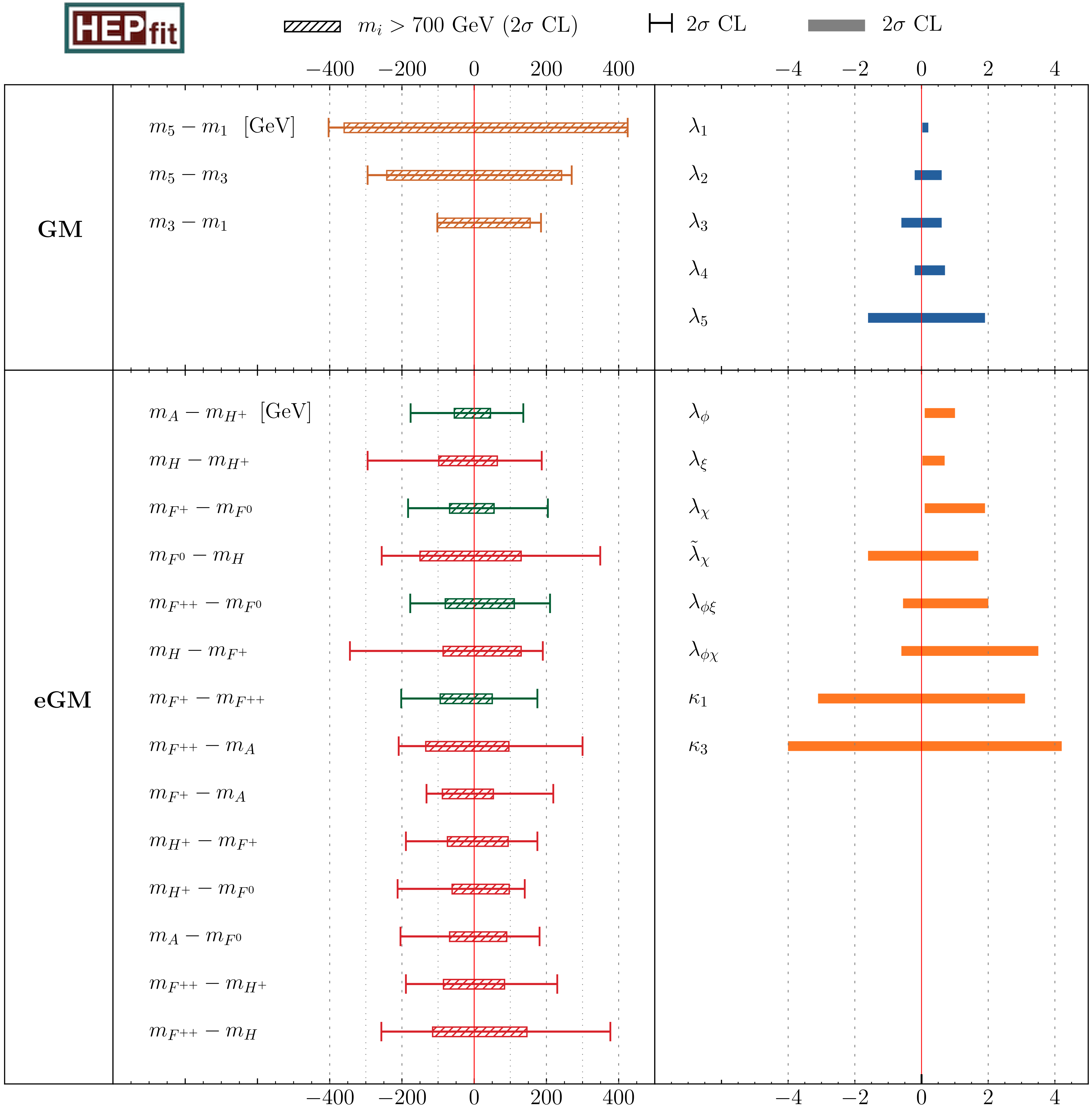
Status of GM model



The maximum mass splitting for heavy Higgs boson masses > 700 GeV is 400 GeV for GM model

which is reduced ~ 100 GeV from the literature

Allowed mass differences and quartic couplings



Summary

- Minimal two triplet extension of SM with $\rho = 1$ gives **eGM model**
- Quartic couplings in GM and eGM model gets strongly constrained by **NLO unitarity**
- Mixing angles and vevs get constrained from the latest **LHC Higgs signal strength data**
- Updated theory constraints (NLO unitarity, BFB) **alone** exclude a large part of the parameter space

Thank You!

Backup Slides

Higgs Signal Strength

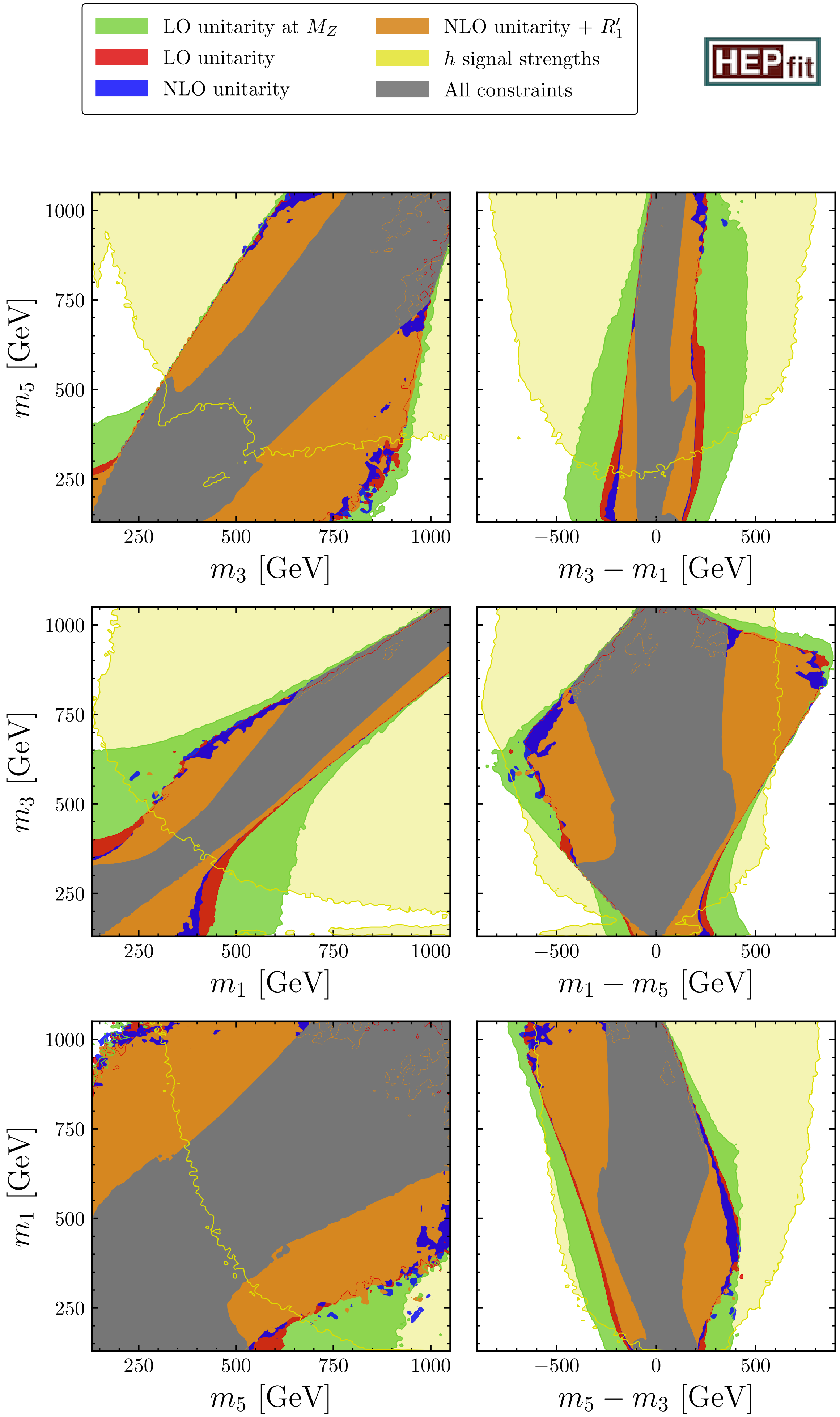
$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\rm SM}} , \quad \text{and} \quad \mu_f = \frac{\mathcal{B}(h \to f)}{\mathcal{B}_{\rm SM}(h \to f)} ,$$

$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i \times B^f)_{\rm SM}}$$

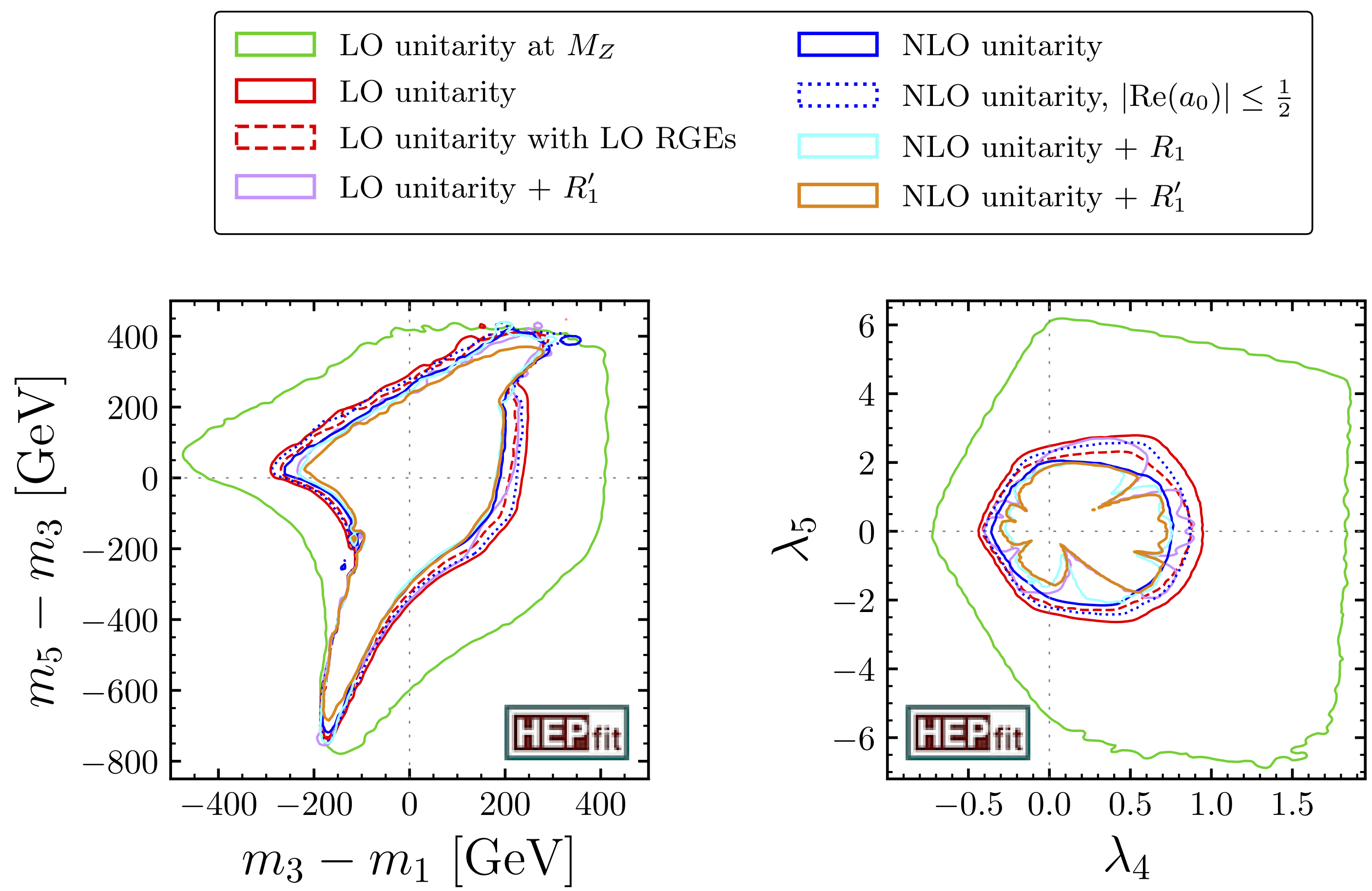
κ framework

$$\kappa_V = c_\alpha c_\beta - \sqrt{\frac{8}{3}} s_\alpha s_\beta , \quad \text{and} \quad \kappa_f = \frac{c_\alpha}{c_\beta} ,$$

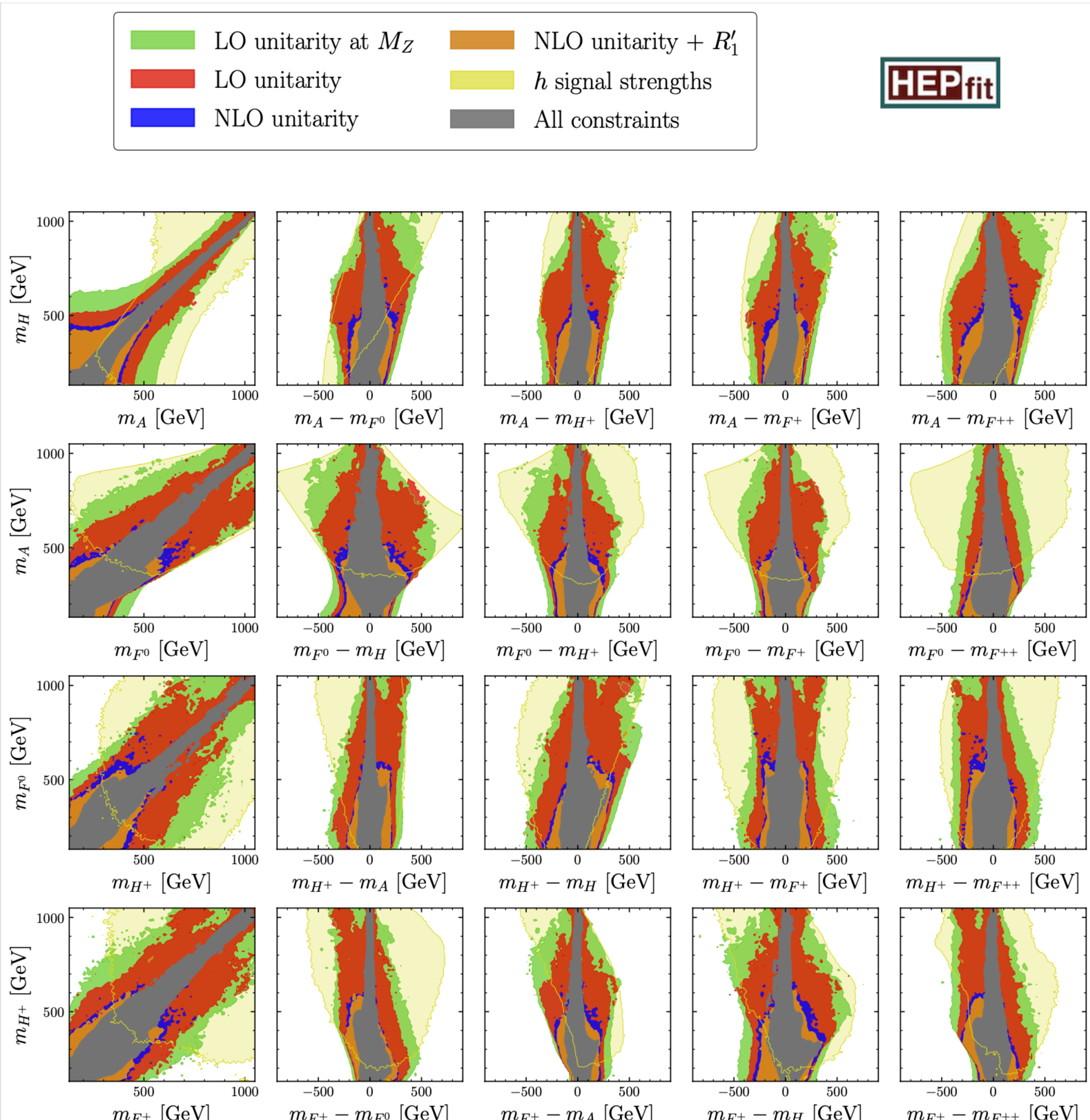
GM model



LO unitarity at M_Z
LO unitarity
NLO unitarity
NLO unitarity + R_1'
h signal strengths
All constraints
HEPfit
m_5 [GeV]
m_3 [GeV]
m_1 [GeV]
$m_3 - m_1$ [GeV]
$m_1 - m_5$ [GeV]
$m_5 - m_3$ [GeV]



LO unitarity at M_Z
LO unitarity
LO unitarity with LO RGEs
LO unitarity + R_1'
NLO unitarity
NLO unitarity, $|\mathrm{Re}(a_0)| \leq \frac{1}{2}$
NLO unitarity + R_1
NLO unitarity + R_1'
$m_5 - m_3$ [GeV]
$m_3 - m_1$ [GeV]
λ_5
λ_4
HEPfit



Mass plane of eGM model

How we impose perturbative unitarity in our work

Energy $< M_Z$

General model with 16 parameters

$\rho \neq 1$

m_Z

eGM model

$\rho = 1$

Run the parameters using β functions

Energy $>> M_Z$

General model with 16 parameters

$\rho \neq 1$

Use Goldstone Boson equivalence theorem

Place unitarity bounds on the quartic couplings at high energy

Constrain the parameter space at m_Z scale

Higgs Signal Strength

ATLAS

Signal strength	Value	Correlation matrix						$\mathcal{L}$ [fb^{-1}]	Source
$\mu^{\gamma\gamma}_{\mathrm{ggF,bbh}}$	1.04 ± 0.10	1	-0.13	0	0	0	0	139	[18]
$\mu^{\gamma\gamma}_{\mathrm{VBF}}$	1.20 ± 0.26	-0.13	1	0	0	0	0		
$\mu^{\gamma\gamma}_{\mathrm{Wh}}$	1.5 ± 0.55	0	0	1	-0.37	0	-0.11		
$\mu^{\gamma\gamma}_{\mathrm{Zh}}$	-0.2 ± 0.55	0	0	-0.37	1	0	0		
$\mu^{\gamma\gamma}_{\mathrm{tth}}$	0.89 ± 0.31	0	0	0	0	1	-0.44		
$\mu^{\gamma\gamma}_{\mathrm{th}}$	3 ± 3.5	0	0	-0.11	0	-0.44	1		
μ^{ZZ}_{ggF}	0.95 ± 0.1	1	-0.22	-0.27	0			139	[4]
μ^{ZZ}_{VBF}	1.19 ± 0.45	-0.22	1	0	0				
μ^{ZZ}_{Vh}	1.43 ± 1.0	-0.27	0	1	-0.18				
μ^{ZZ}_{tth}	1.69 ± 1.45	0	0	-0.18	1				
$\mu^{ZZ}_{\mathrm{incl.}}$	1.0 ± 0.1							139	[4]
$\mu^{WW}_{\mathrm{ggF,bbh}}$	1.15 ± 0.135							139	[17]
μ^{WW}_{VBF}	0.93 ± 0.21								
$\mu^{WW}_{\mathrm{ggF,bbh,VBF}}$	1.09 ± 0.11								
$\mu^{\tau\tau}_{\mathrm{VBF}}$	0.90 ± 0.18	1	-0.24	0	0			139	[13]
$\mu^{\tau\tau}_{\mathrm{ggF,bbh}}$	0.96 ± 0.31	-0.24	1	-0.29	0				
$\mu^{\tau\tau}_{\mathrm{Vh}}$	0.98 ± 0.60	0	-0.29	1	0				
$\mu^{\tau\tau}_{\mathrm{tth,th}}$	1.06 ± 1.18	0	0	0	1				
μ^{bb}_{VBF}	0.95 ± 0.37							126	[9]
μ^{bb}_{Wh}	0.95 ± 0.26							139	[6]
μ^{bb}_{Zh}	1.08 ± 0.24							139	[6]
μ^{bb}_{Vh}	1.02 ± 0.17							139	[6]
$\mu^{bb}_{\mathrm{tth,th}}$	0.35 ± 0.35							139	[12]
$\mu^{\mu\mu}_{\mathrm{pp}}$	1.2 ± 0.6							139	[7]
$\mu^{Z\gamma}_{\mathrm{pp}}$	2.0 ± 0.95							139	[5]

CMS

Signal strength	Value	Correlation matrix				$\mathcal{L}$ [fb^{-1}]	Source
$\mu^{\gamma\gamma}_{\mathrm{ggh,bbh}}$	1.07 ± 0.11					137	[11]
$\mu^{\gamma\gamma}_{\mathrm{VBF}}$	1.04 ± 0.32						
$\mu^{\gamma\gamma}_{\mathrm{Vh}}$	1.34 ± 0.34						
$\mu^{\gamma\gamma}_{\mathrm{tth,th}}$	1.35 ± 0.31						
$\mu^{ZZ}_{\mathrm{ggh,bbh,tth,th}}$	0.95 ± 0.13	1	-0.11			137	[10]
$\mu^{ZZ}_{\mathrm{VBF,Vh}}$	0.82 ± 0.34	-0.11	1				
μ^{WW}_{ggh}	0.92 ± 0.11	1	-0.13	0	0	138	[16]
μ^{WW}_{VBF}	0.71 ± 0.26	-0.13	1	0	0		
μ^{WW}_{Zh}	2.0 ± 0.7	0	0	1	0		
μ^{WW}_{Wh}	2.2 ± 0.6	0	0	0	1		
$\mu^{\tau\tau}_{\mathrm{incl.}}$	0.93 ± 0.12					138	[15]
$\mu^{\tau\tau}_{\mathrm{ggh}}$	0.97 ± 0.19						
$\mu^{\tau\tau}_{\mathrm{qqh}}$	0.68 ± 0.23						
$\mu^{\tau\tau}_{\mathrm{Vh}}$	1.80 ± 0.44						
μ^{bb}_{qqh}	1.59 ± 0.60	1	-0.75			90.8	[19]
μ^{bb}_{ggh}	-2.7 ± 3.89	-0.75	1				
$\mu^{\mu\mu}_{\mathrm{ggh,tth}}$	0.66 ± 0.67	1	-0.24			137	[8]
$\mu^{\mu\mu}_{\mathrm{VBF,Vh}}$	1.85 ± 0.86	-0.24	1				
$\mu^{Z\gamma}_{\mathrm{pp}}$	2.4 ± 0.9					138	[14]