Next-to-Leading Order Unitarity Fits in the (Extended) Georgi-Machacek Model

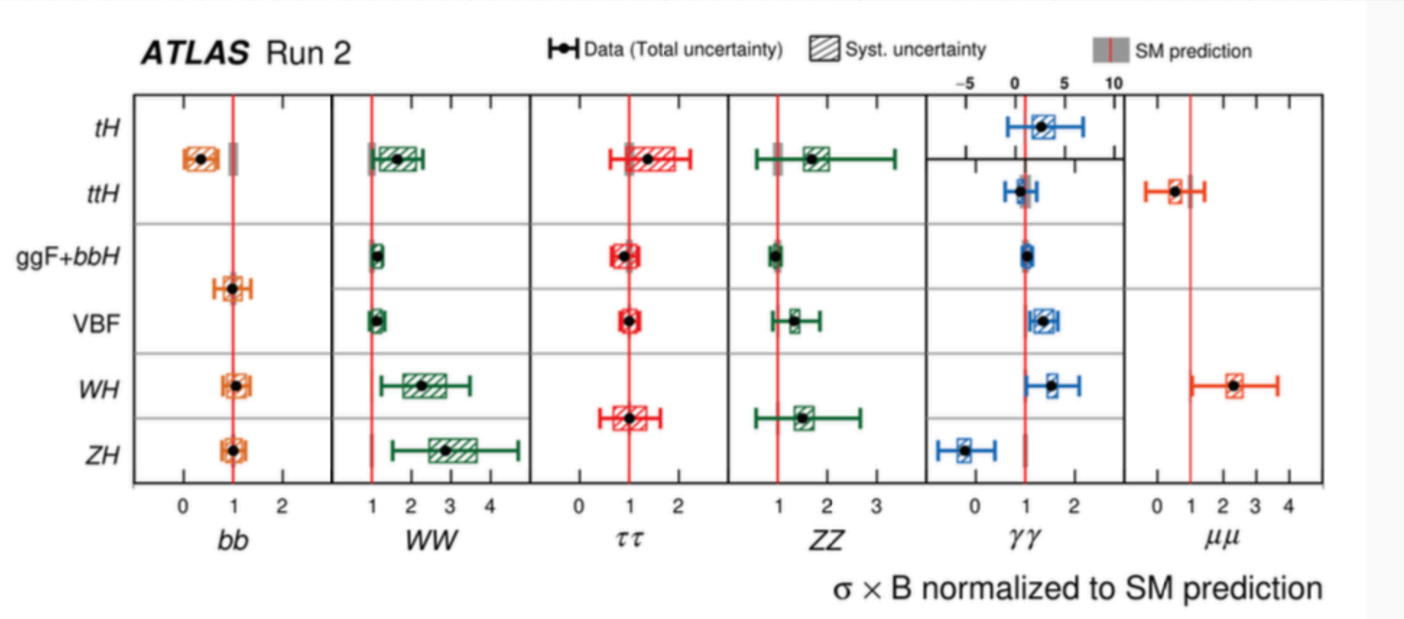
based on
[arXiv: 2111.14195] with A. Kundu and P. B. Pal
[arxiv: 2404.18996] with D. Chowdhury and S. Samanta

Poulami Mondal
IIT Kanpur, India

Higgs Hunting Workshop, Orsay/Paris
September 25, 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

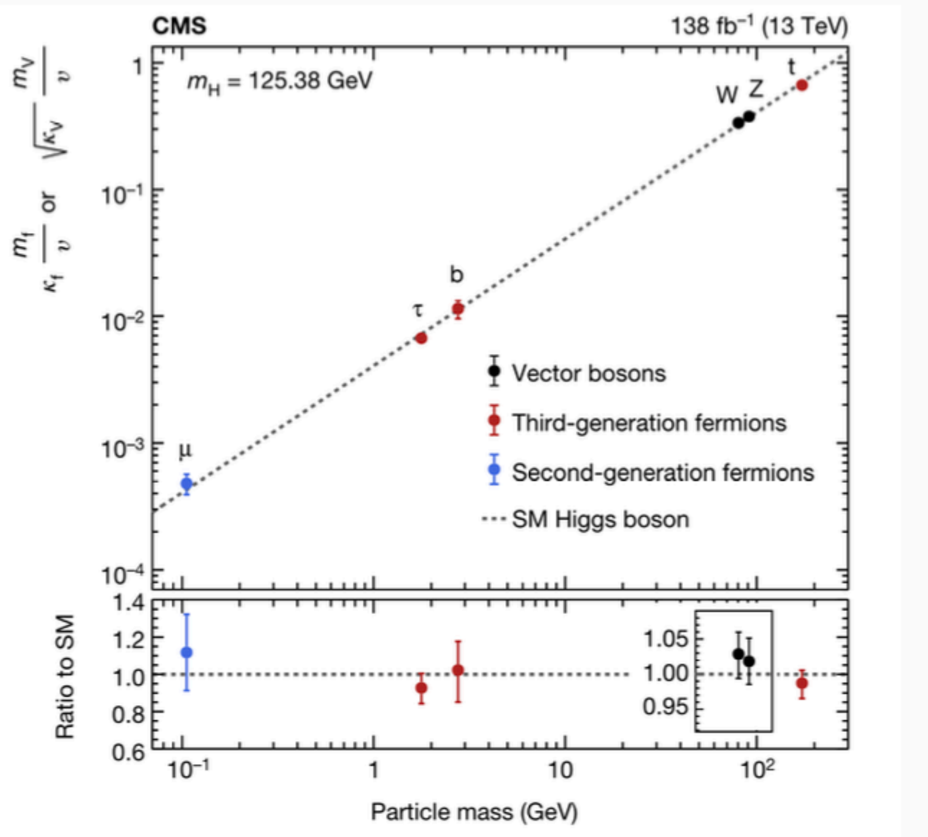
Search for BSM @ forefront of particle physics research

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 (CS)

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

Custodial Symmetry

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

Y=1/2 **Y=1** **Y=0**

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

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

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

EW symmetry breaking

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)

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

Katy Hartling,[*] Kunal Kumar,[†] and Heather E. Logan[‡]

Ottawa-Carleton Institute for Physics, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

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

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

Ting-Kuo Chen,[1,*] Cheng-Wei Chiang,[1,2,†] Cheng-Tse Huang,[1,‡] and Bo-Qiang Lu[3,§]

[1]*Department of Physics, National Taiwan University, Taipei, Taiwan 10617, Republic of China*
[2]*Physics Division, National Center for Theoretical Sciences, Taipei, Taiwan 10617, Republic of China*
[3]*School of Science, Huzhou University, Huzhou, Zhejiang 313000, People's Republic of China*

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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

Katy Hartling,[*] Kunal Kumar,[†] and Heather E. Logan[‡]

Ottawa-Carleton Institute for Physics, Carleton University, 1125 Colonel By Drive, Ottawa, Ontario K1S 5B6, Canada

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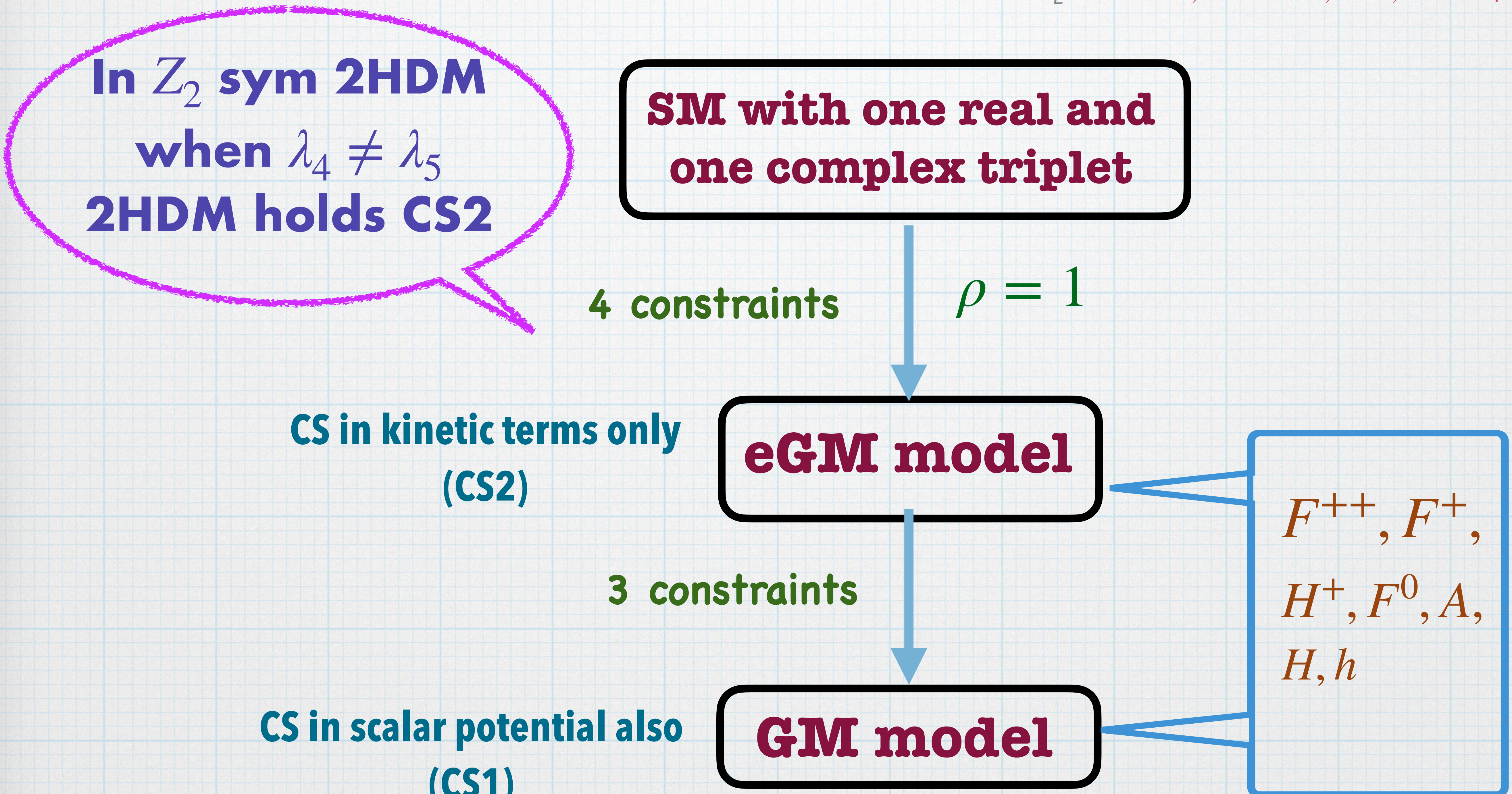
Testing the custodial symmetry in the Higgs sector of the Georgi-Machacek model

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]



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?**

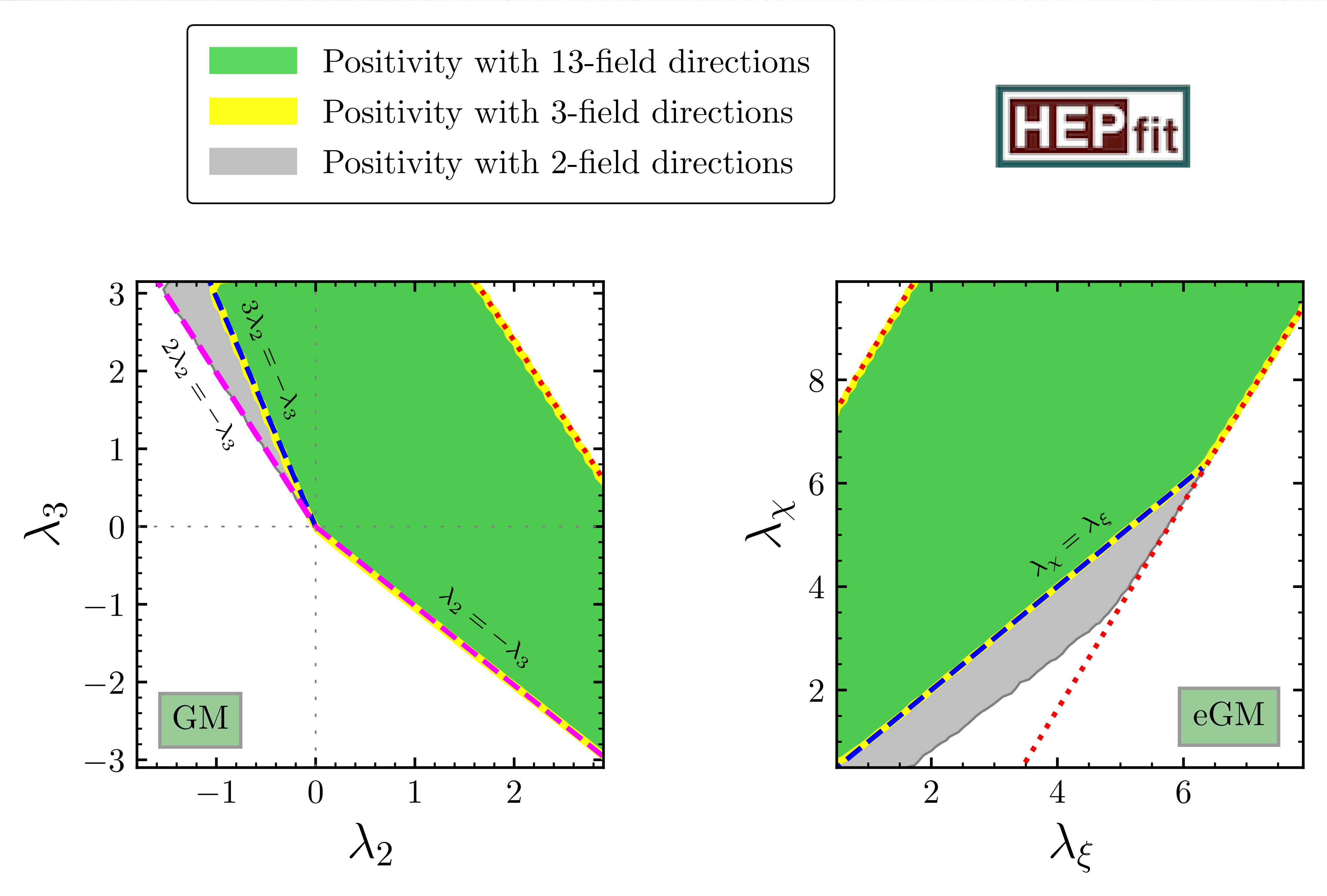
Ans: More statistically robust than expt data with errors

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



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

Unitarity Constraints

Prior to Higgs discovery : unitarity bound @ tree level **@ 1-loop**

Lee, Quigg, Thacker '77 $\lambda \leq \frac{8\pi}{3}$

$\lambda \leq 2 - 2.5$

Dawson, Eillenbrock '89; Durand, Johnson, Lopez'92

2 loop calculation shows no revised limit

Durand, Maher, Riesselmann, 92

Weakly interacting Higgs scenario

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

Goldstone boson equivalence theorem

$$\mathcal{M}(W_L^\pm, Z_L, h, ...) \ = \ (iC)^k \mathcal{M}(w^\pm, z, h, ...) \, .$$

unitarity in eGM/GM

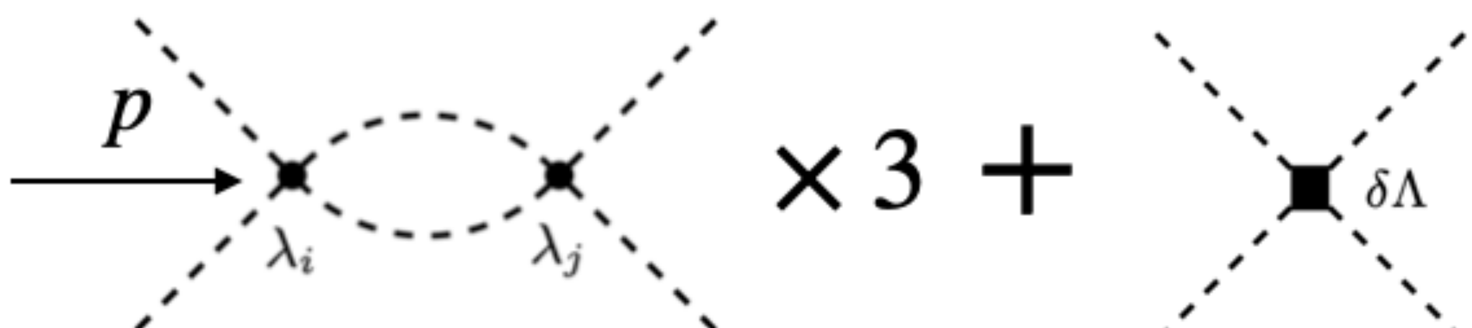
Tree-level unitarity

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

19 eigenvalues are independent → eGM

9 eigenvalues are independent → GM

NLO unitarity

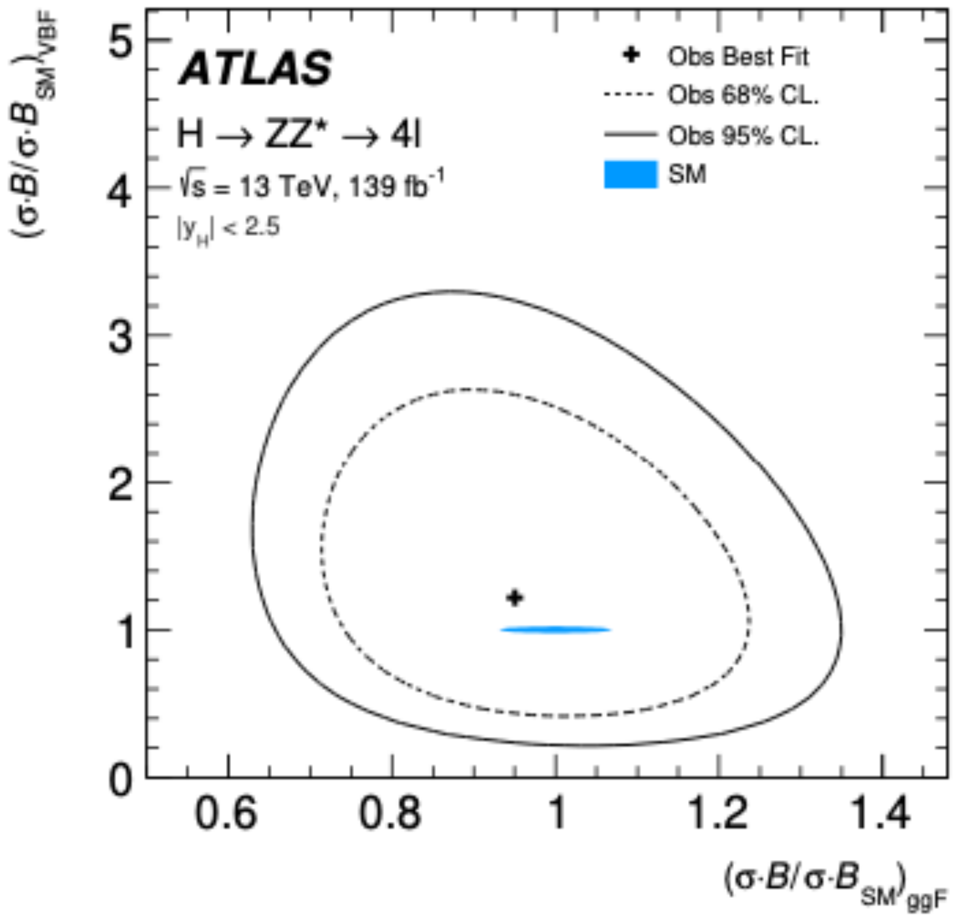


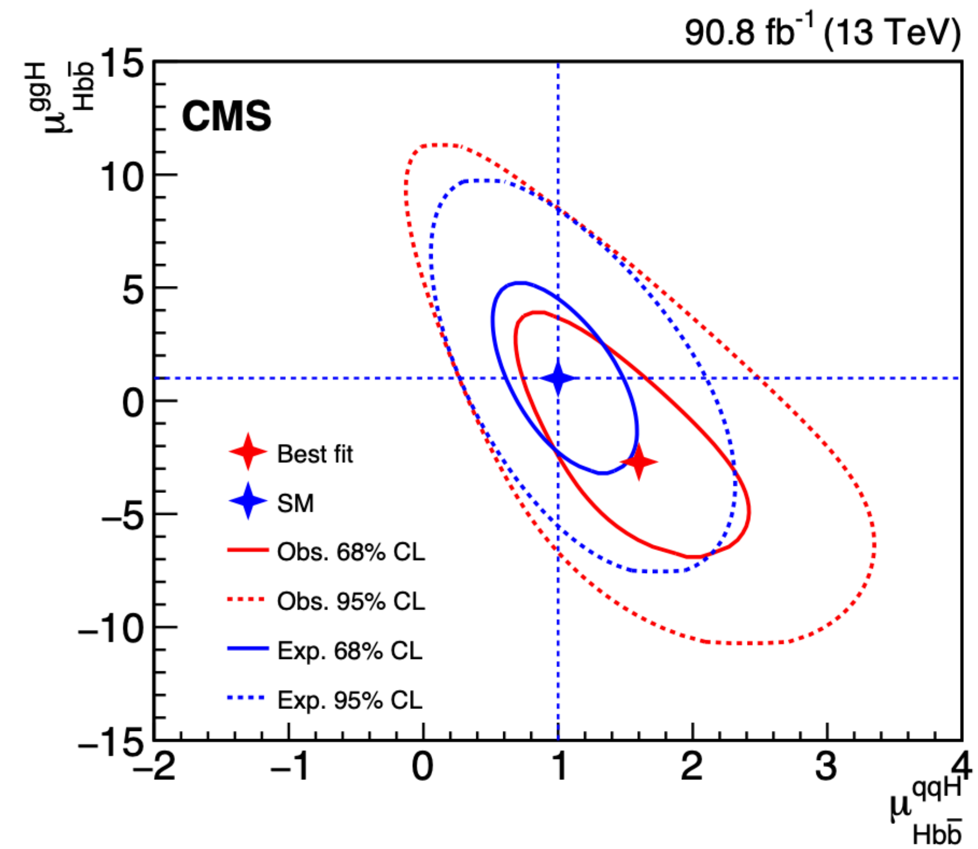
[Grinstein, Murphy, Uttayarat '15;
Cacchio, Chowdhury, Murphy, Eberhardt'16]

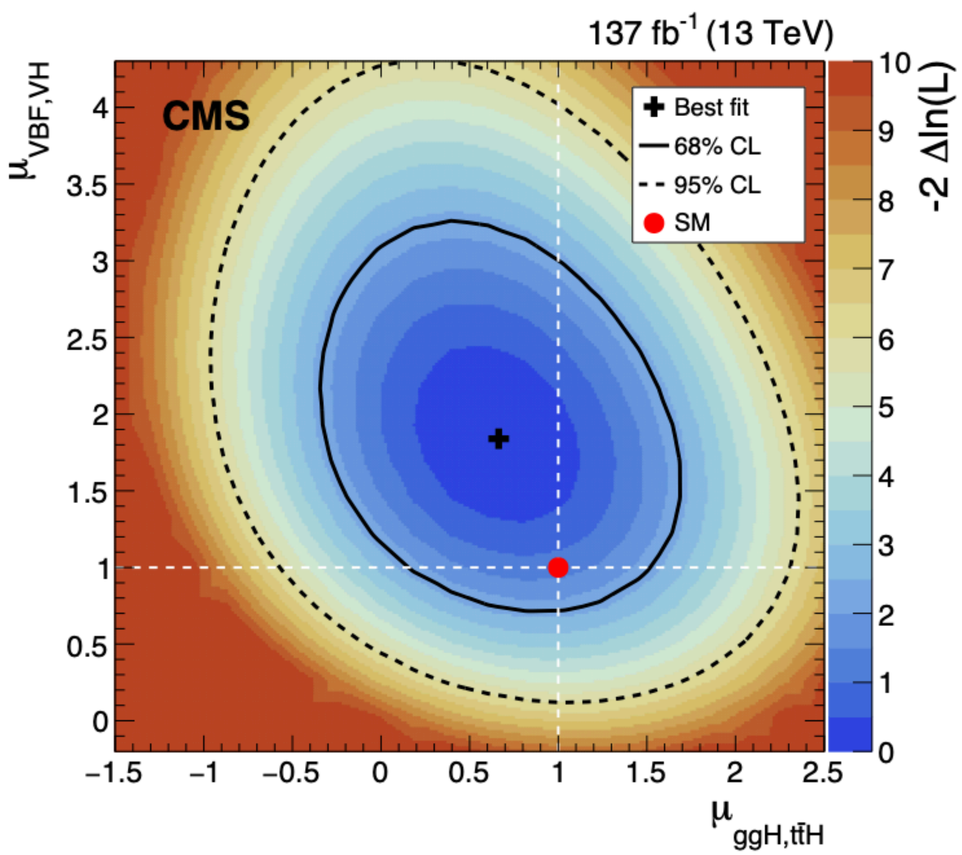
$$R_1 = \frac{\left|a_0^{\rm NLO}\right|}{\left|a_0^{\rm LO} + a_0^{\rm NLO}\right|}\,, \qquad R_1' = \frac{\left|a_0^{\rm NLO}\right|}{\left|a_0^{\rm LO}\right|}\,,$$

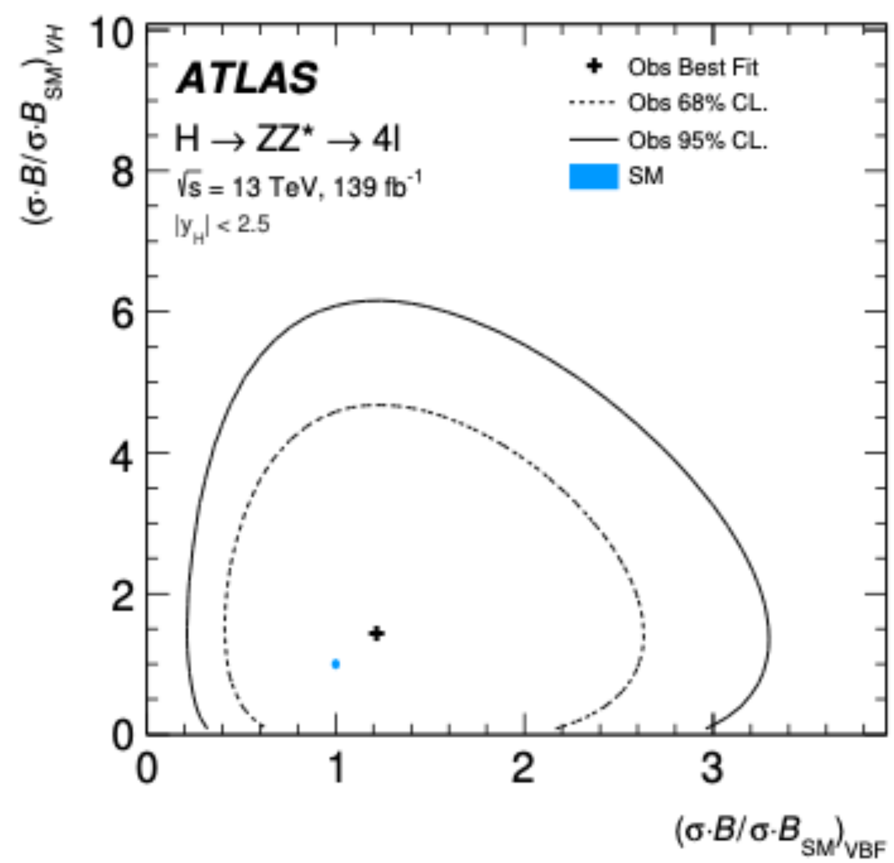
Perturbative expansion is not valid at NLO when $R_1 = 1$ or $R_1' = 1$

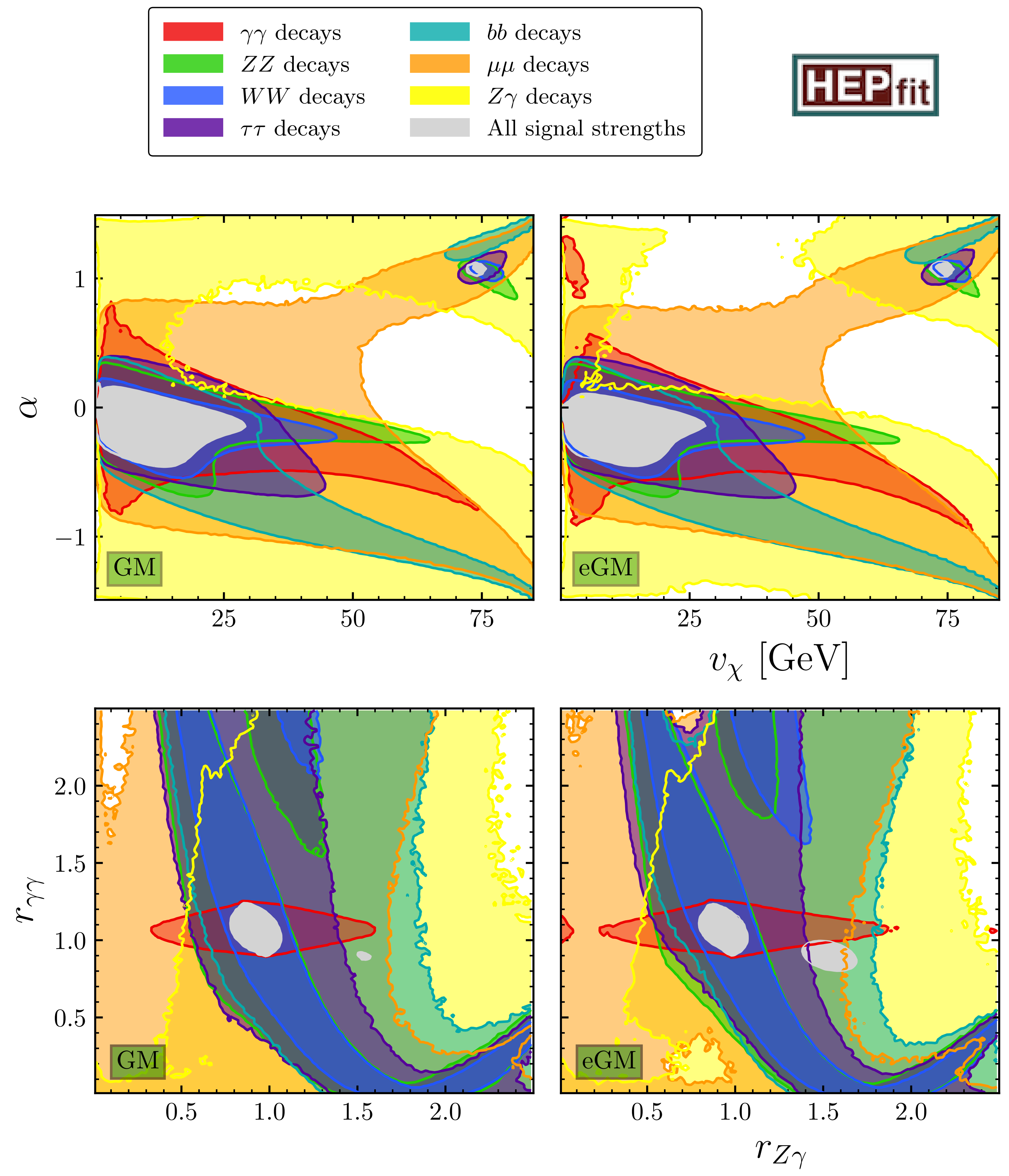
Higgs Signal Strength (Run 2)











Results from the combined fit:

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

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

@ Decoupling limit

$\alpha = v_\chi = 0$

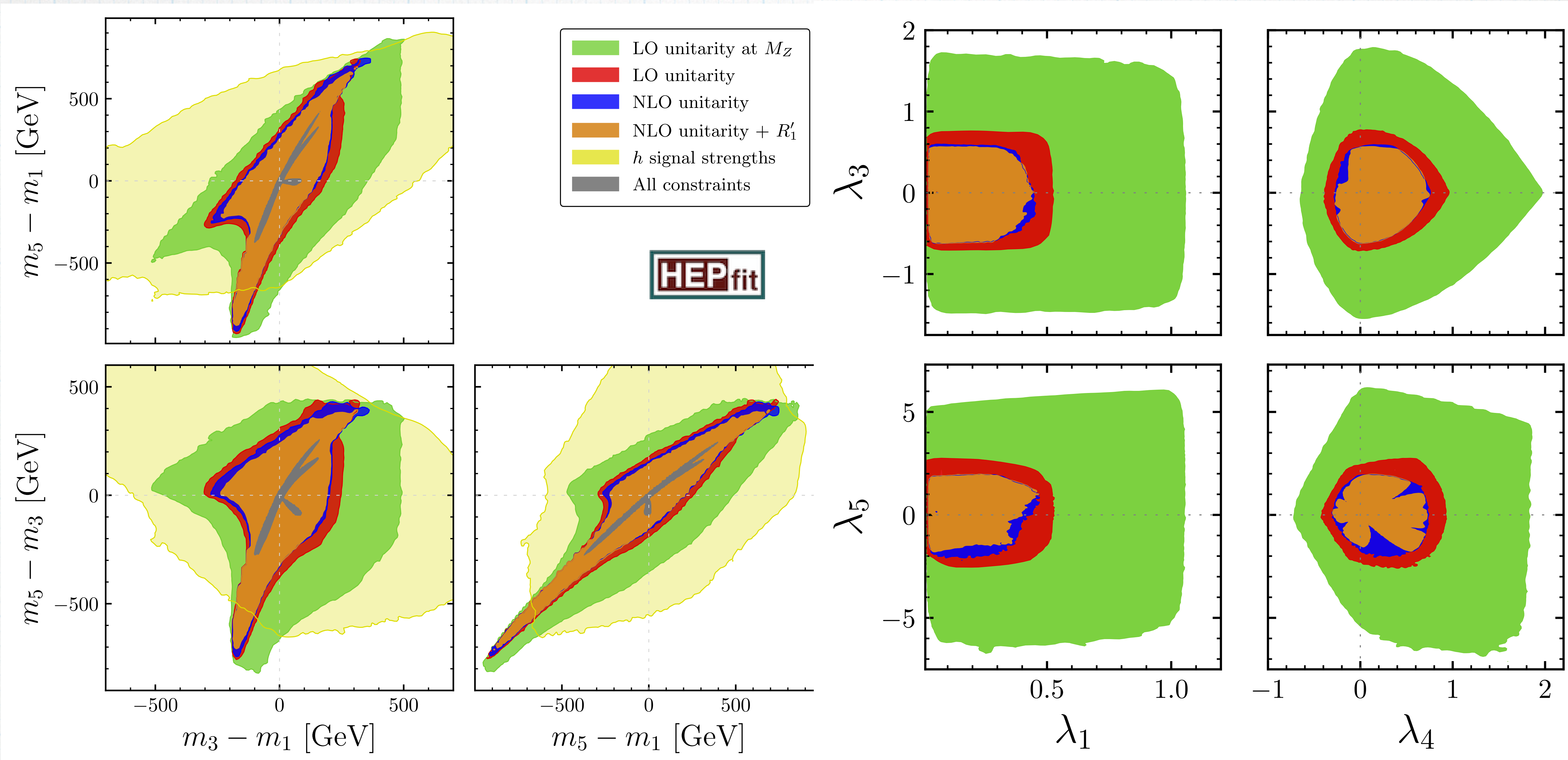
all additional Higgs become heavy

$\kappa_V \to 1$

Higgs signal strength data strongly disfavours

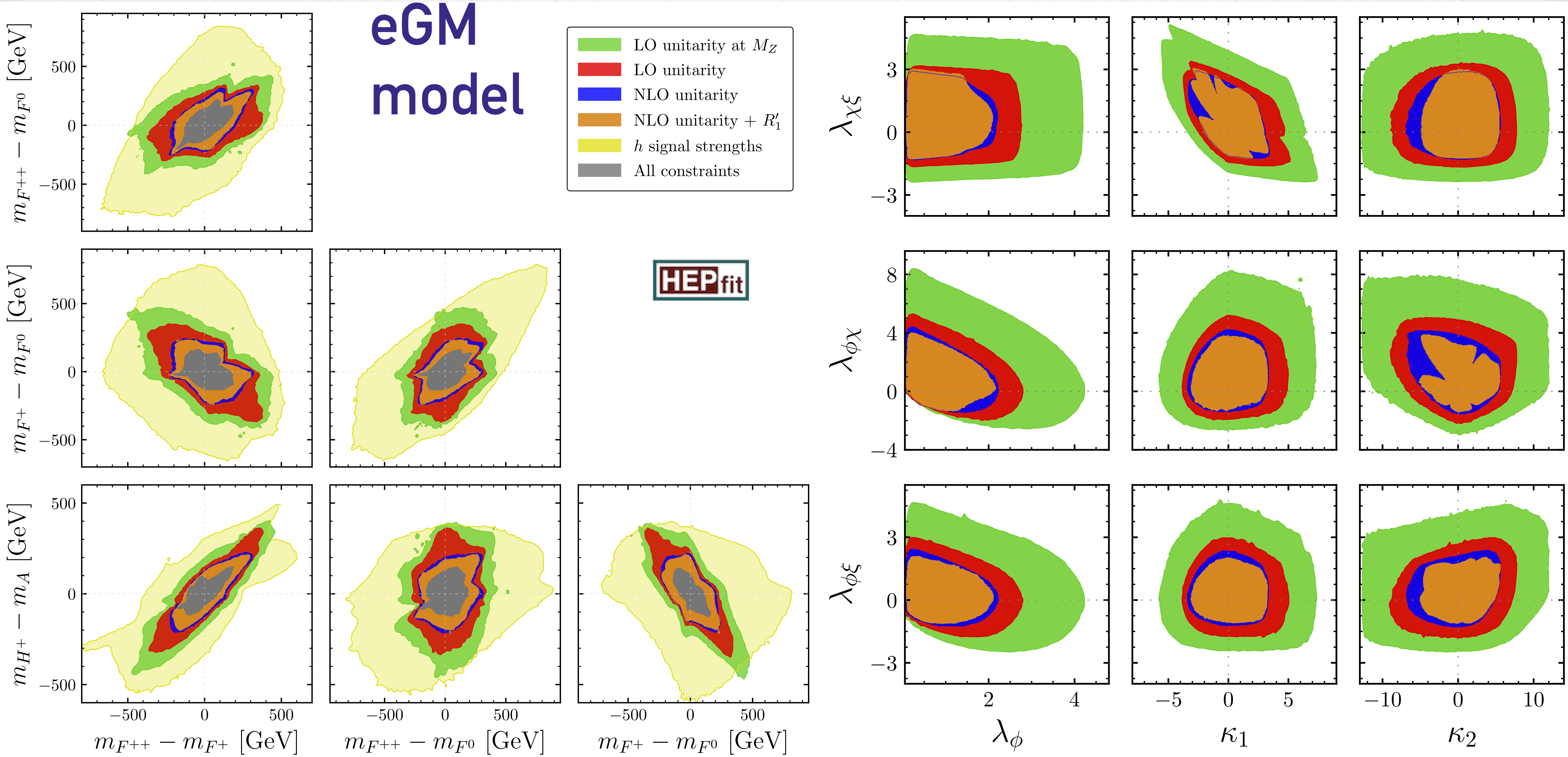
$\kappa_V > 1.05$ **@** 95.4 % **CL**

Status of GM model



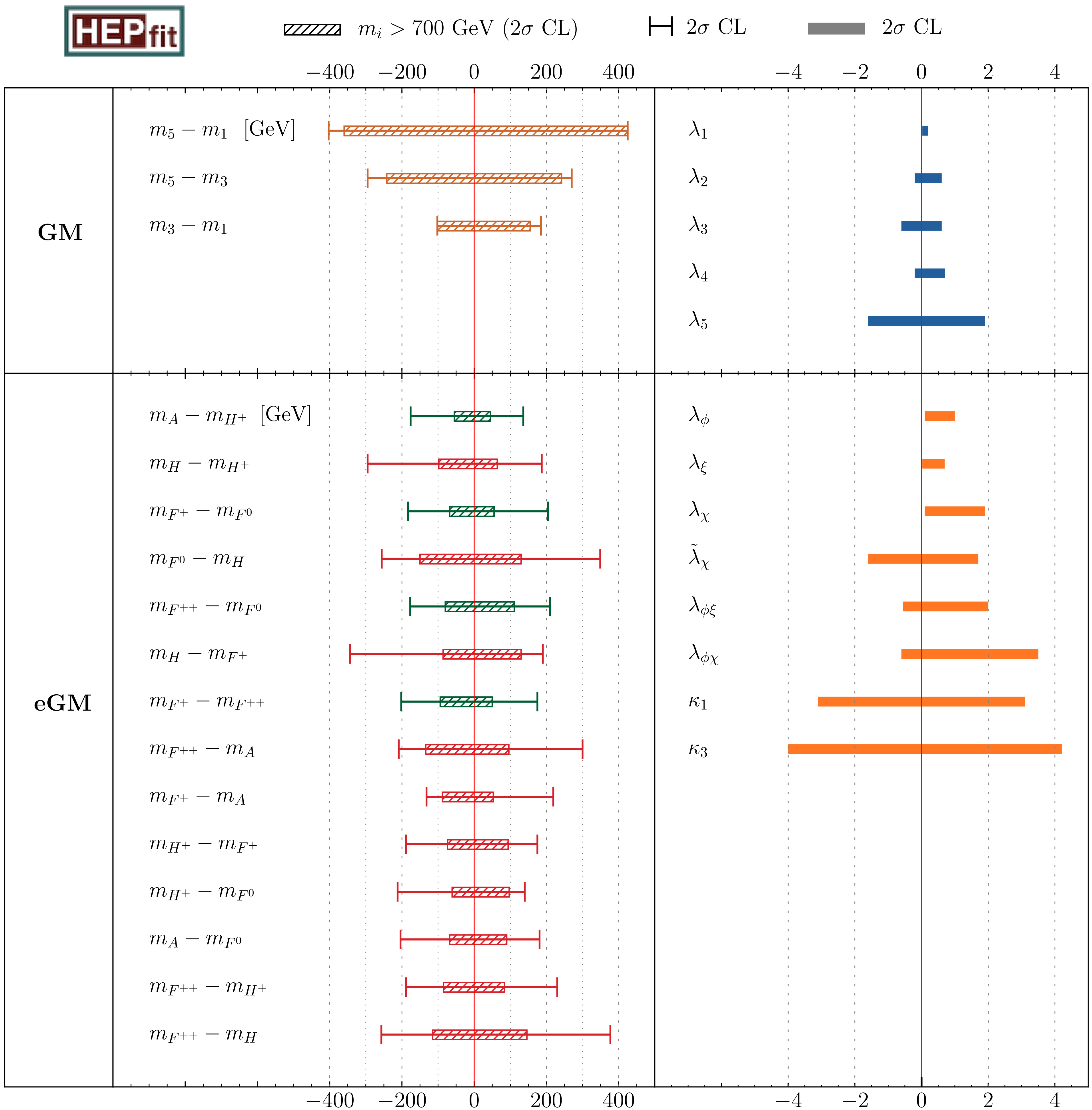
The maximum mass splitting for heavy Higgs boson masses > 700 GeV is 400 GeV for GM model

which is reduced ~ 100 GeV from the literature



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

Allowed mass differences and quartic couplings

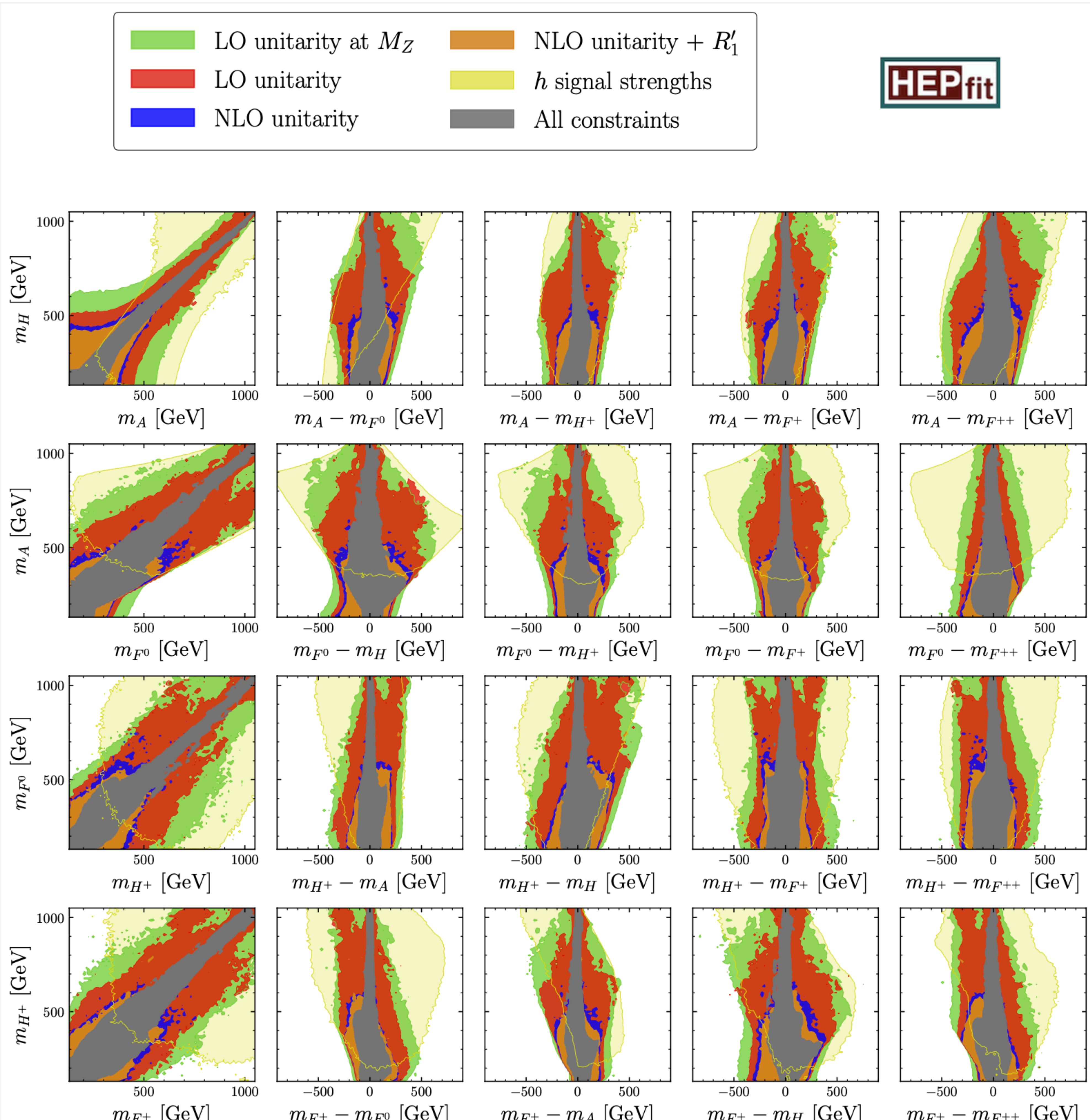


Summary

- 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

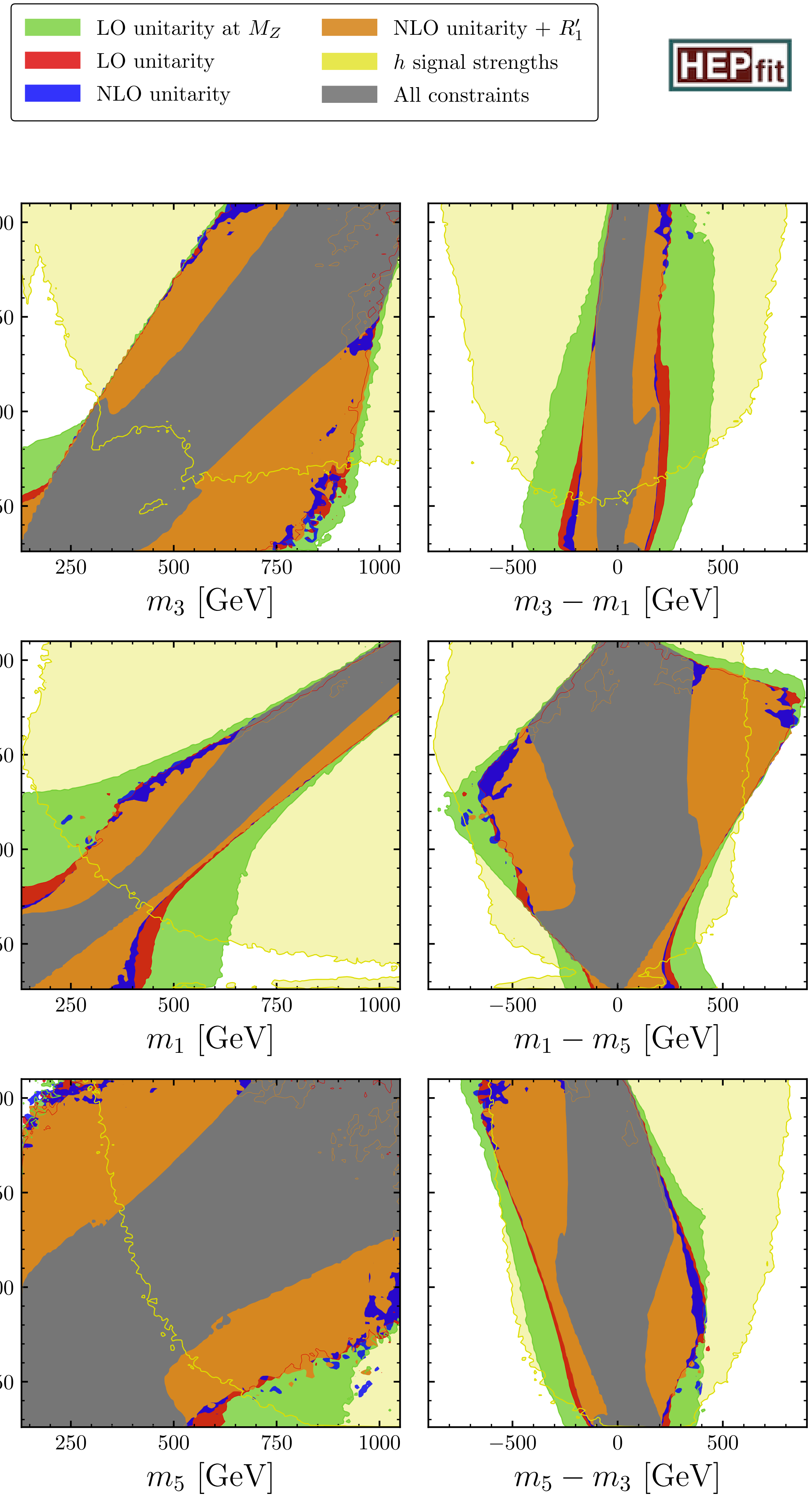
Thank You!

Backup Slides

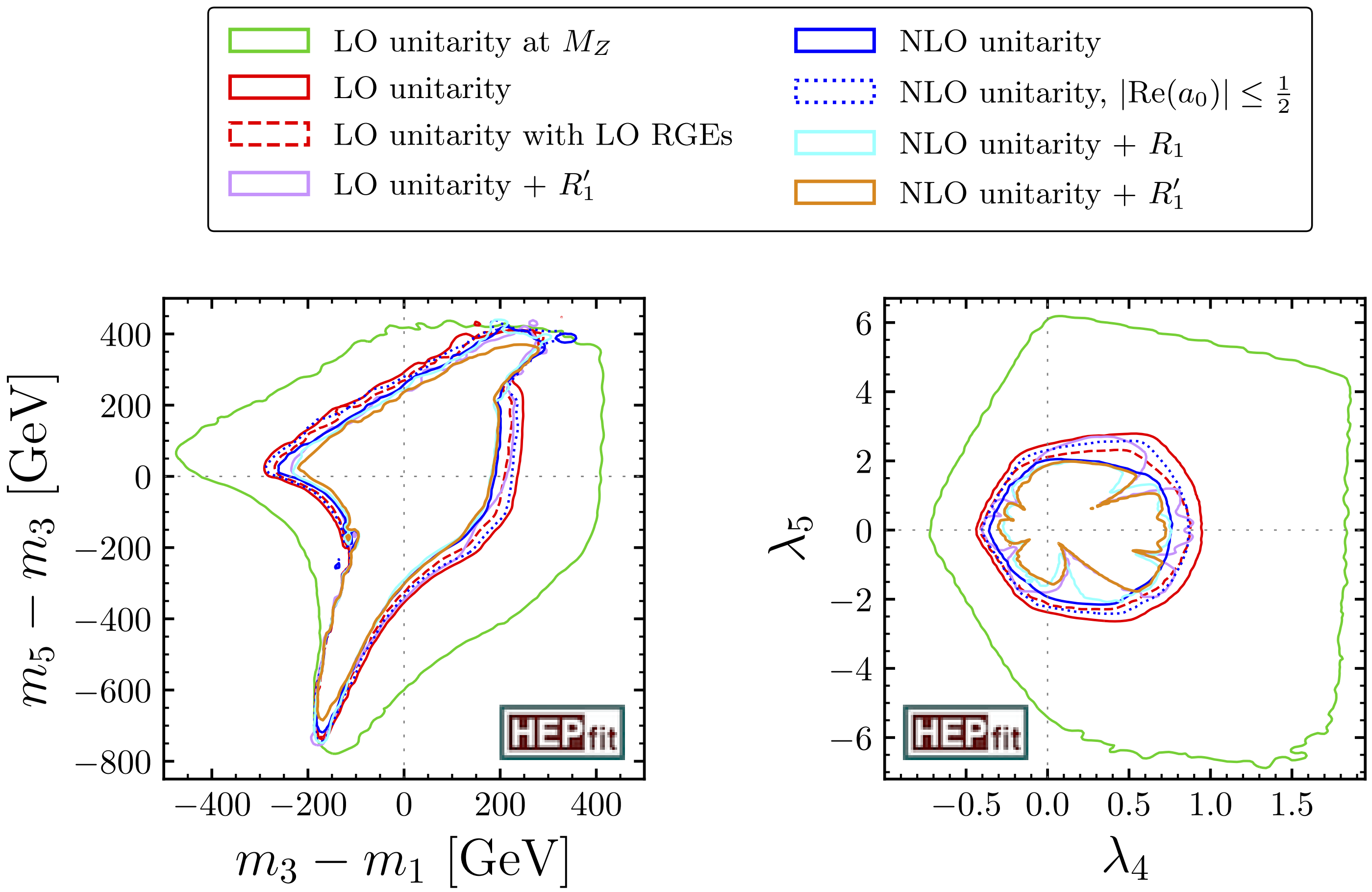


Mass plane of eGM model

GM model



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

Higgs Signal Strength

ATLAS

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

CMS

Signal strength	Value	Correlation matrix				$\mathcal{L}$ [fb^{-1}]	Source
$\mu^{\gamma\gamma}_{\text{ggh,bbh}}$	1.07 ± 0.11					137	[11]
$\mu^{\gamma\gamma}_{\text{VBF}}$	1.04 ± 0.32						
$\mu^{\gamma\gamma}_{\text{Vh}}$	1.34 ± 0.34						
$\mu^{\gamma\gamma}_{\text{tth,th}}$	1.35 ± 0.31						
$\mu^{ZZ}_{\text{ggh,bbh,tth,th}}$	0.95 ± 0.13	1	-0.11			137	[10]
$\mu^{ZZ}_{\text{VBF,Vh}}$	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		
$\mu^{\tau\tau}_{\text{incl.}}$	0.93 ± 0.12					138	[15]
$\mu^{\tau\tau}_{\text{ggh}}$	0.97 ± 0.19						
$\mu^{\tau\tau}_{\text{qqh}}$	0.68 ± 0.23						
$\mu^{\tau\tau}_{\text{Vh}}$	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				
$\mu^{\mu\mu}_{\text{ggh,tth}}$	0.66 ± 0.67	1	-0.24			137	[8]
$\mu^{\mu\mu}_{\text{VBF,Vh}}$	1.85 ± 0.86	-0.24	1				
$\mu^{Z\gamma}_{\text{pp}}$	2.4 ± 0.9					138	[14]

	Signal strength	Value	Correlation matrix					
	$\mu^{\gamma\gamma}_{\text{ggF}}$	1.10 ± 0.23	1	-0.25	0	-0.14	0	
	$\mu^{\gamma\gamma}_{\text{VBF}}$	1.3 ± 0.5	-0.25	1	0	0	0	
	$\mu^{\gamma\gamma}_{\text{Wh}}$	0.5 ± 1.3	0	0	1	-0.64	0	
	$\mu^{\gamma\gamma}_{\text{Zh}}$	0.5 ± 2.8	-0.14	0	-0.64	1	-0.11	
	$\mu^{\gamma\gamma}_{\text{tth}}$	2.2 ± 1.5	0	0	0	-0.11	1	
	μ^{ZZ}_{ggF}	1.13 ± 0.33	1	-0.26				
	μ^{ZZ}_{VBF}	0.1 ± 0.9	-0.26	1				
	μ^{WW}_{ggF}	0.84 ± 0.17	1	-0.16				
	μ^{WW}_{VBF}	1.2 ± 0.4	-0.16	1				
	$\mu^{\tau\tau}_{\text{ggF}}$	1.0 ± 0.6	1	-0.37	0	-0.25	0	-0.21
	$\mu^{\tau\tau}_{\text{VBF}}$	1.3 ± 0.4	-0.37	1	0	0	0	0
	μ^{WW}_{Wh}	1.6 ± 1.1	0	0	1	-0.12	-0.12	0
	$\mu^{\tau\tau}_{\text{Wh}}$	-1.4 ± 1.4	-0.25	0	-0.12	1	0	0
	μ^{WW}_{Zh}	5.9 ± 2.4	0	0	-0.12	0	1	0
	$\mu^{\tau\tau}_{\text{Zh}}$	2.2 ± 2.0	-0.21	0	0	0	0	1
	μ^{WW}_{tth}	5.0 ± 1.8	1	-0.47				
	$\mu^{\tau\tau}_{\text{tth}}$	-1.9 ± 3.5	-0.47	1				
	μ^{bb}_{Wh}	1.0 ± 0.5						
	μ^{bb}_{Zh}	0.4 ± 0.4						
	μ^{bb}_{tth}	1.1 ± 1.0						
	$\mu^{\mu\mu}_{\text{pp}}$	0.1 ± 2.5						

h signal strength from official ATLAS and CMS combination for run 1