NLO unitarity and stability bounds in extended Higgs sectors

Subrata Samanta (Indian Institute of Technology Kanpur)

BCTP, Bonn, November 2024

Outline

- Perturbative Unitarity at Next-to-Leading Order
- Vaccum Stability
- Models with Higgs Triplets
- Constraints on the Parameter Space

Introductions

- Standard Model (SM) of particle physics is a framework
  $\longrightarrow$ good agreement with the collider data

  Open questions : Neutrino masses , Dark Matter , Baryon asymmetry of the Universe (BAU) , Electroweak Phase Transitions (EWPT)

- SM might be a simplified version of a more complicated model

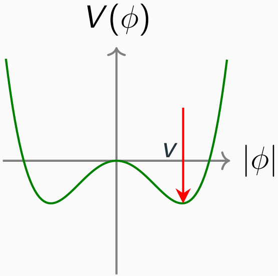
- Do the LHC data preclude the existence of additional multiplets in the scalar sector of the SM ?

Prior to the Higgs Discovery

Standard Model

$$V(\phi) = -\mu'^2|\phi|^2 + \lambda|\phi|^4$$

Higgs mass : $m_h = \sqrt{2\lambda}\, v$



$\mu'^2 > 0, \quad \lambda > 0$

$m_h \rightarrow$ free parameter

This is a potential at tree-level

Theoretical considerations were used to place bound on the Higgs mass

... such as perturbative unitarity bounds

Perturbative Unitarity

- Unitarity of the S-matrix, $S^\dagger S = I$,

$$\left|a_\ell^{2\to 2} - \tfrac{1}{2} i\right|^2 + \sum_{k>2} \left|a_\ell^{2\to k}\right|^2 = \tfrac{1}{4}\,. \qquad (1)$$

$\rightarrow$ a_ℓ's are the ℓ-th partial-wave amplitudes

- For a given $2 \rightarrow 2$ process, the unitarity bounds :

$$\left|a_\ell - \tfrac{1}{2} i\right|^2 \leq \tfrac{1}{4} \qquad (2)$$

- At tree-level, $a_\ell \in \mathbb{R}$, leads to a strong bound, $|\mathrm{Re}(a_\ell)| \leq \frac{1}{2}$.
- Beyond tree-level, $a_\ell \notin \mathbb{R}$, hence above bound gets weaker.

Partial-Wave Amplitudes

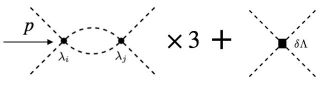
- Let's consider high energy limit to compute scattering amplitudes
  - $SU(2)_L \otimes U(1)_Y$ symmetry is intact at high energies, leads to block diagonal form of scattering matrix.
  - Most dominant contribution comes from $\ell = 0$ partial-wave.
- For a given process, $i \to f$,

$$(a_0)_{i,f}(s) = \frac{1}{16\pi s} \int_{-s}^{0} dt \mathcal{M}_{i\to f}(s,t)\,, \tag{3}$$

$\to \mathcal{M}_{i\to f}$ represents the sum of scattering amplitudes.

$2 \to 2$ **Scattering Amplitudes**

- Let's consider an extended Higgs sector with quartic couplings λ_i ($i = 1, .., j$)
  - In the limit, $s \gg |\lambda_i| v^2 \gg M_W^2$, only 1PI diagrams survive at one-loop.



$$\lambda_i^0 = \lambda_i + \delta\lambda_i \,, \quad \delta\Lambda = \frac{1}{16\pi^2 \epsilon} \beta_\Lambda \tag{4}$$

  - Scattering amplitudes at one-loop,

$$\mathcal{M}_{\rm 1PI}^{2\to 2} = \frac{\lambda_i \lambda_j}{16\pi^2} \left[\frac{1}{\epsilon} + 2 - \ln\left(\frac{-p^2 - i0_+}{\mu^2} \right) \right] \,, \tag{5}$$

One-loop corrections to S-matrix

- For a given process, $i \to f$, arXiv: 1512.04567, 1702.08511

$$(a_0)_{i,f}(s) = -\frac{1}{16\pi} b_0 + \frac{1}{256\pi^3}\left(b_1^R + i b_1^I\right), \qquad (6)$$

or,

$$256\pi^3 (\mathbf{a_0^{Q,Y}})_{\mathrm{NLO}} = -16\pi^2 \mathbf{b_0} + (i\pi - 1)\mathbf{b_0}\cdot\mathbf{b_0} + 3\beta_{\mathbf{b_0}}\,.$$

  - $\mathbf{b_0}$ is the tree-level S-matrix and $\beta_{\mathbf{b_0}}$ represents the matrix involving beta functions.
  - For example, if $b_0 = a\lambda_i + b\lambda_j$, then $\beta_{b_0} = a\beta_{\lambda_i} + b\beta_{\lambda_j}$, $\forall a, b \in \mathbb{R}$.

Vaccum Stability

- Potential with bi-quadratic form,

$$V_{2.0}^{(4)} = \lambda_\chi|\chi^0|^4 + \lambda_{\chi\xi}|\chi^0|^2(\xi^0)^2 + \lambda_\xi(\xi^0)^4 \quad (7)$$

$$V_{2.0}^{(4)} > 0 \implies \lambda_\chi > 0 \wedge \lambda_\xi > 0 \wedge \lambda_{\chi\xi} + 2\sqrt{\lambda_\chi\lambda_\xi} > 0$$

- Potential with non bi-quadratic form,

$$V_{3.0}^{(4)} = \lambda_\phi|\phi^0|^4 + \lambda_\xi(\xi^0)^4 + \lambda_\chi|\chi^0|^4 + \lambda_{\phi\xi}|\phi^0|^2(\xi^0)^2 + \lambda_{\chi\xi}|\chi^0|^2(\xi^0)^2 + \left(\lambda_{\phi\chi} + \frac{\kappa_2}{2}\right)|\phi^0|^2|\chi^0|^2 + \frac{\kappa_3}{\sqrt{2}}\left[(\phi^0)^2\xi^0\chi^{0*} + \text{h.c.}\right] \quad (8)$$

$\rightarrow$ Introduce a dimensionless gauge-invariant parameter,

$$\zeta = \frac{1}{2}\frac{\left[(\phi^0)^2\xi^0\chi^{0*} + \text{h.c.}\right]}{|\phi^0|^2\sqrt{|\chi^0|^2(\xi^0)^2}}, \quad \text{with} \quad \zeta \in [-1, 1]$$

Positivity conditions will depend on the parameter ζ.

Theoretical Bounds in Weakly Interacting Theories

- Standard Model : Prior to the Higgs discovery

LO unitarity : $\lambda \leq \frac{8\pi}{3}$ [Lee, Quigg, Thacker '77]

NLO unitarity : $\lambda \leq 2 - 2.5$ [Dawson, Eillenbrock '89; Durand, Johnson, Lopez'92]

No revised limit @2-loop [Durand, Maher, Riesselmann, 92]

} Weakly interacting SM Higgs scenario

Positivity conditions : $\lambda > 0$

- Two-Higgs Doublet Model : arXiv: 1512.04567, 1609.01290

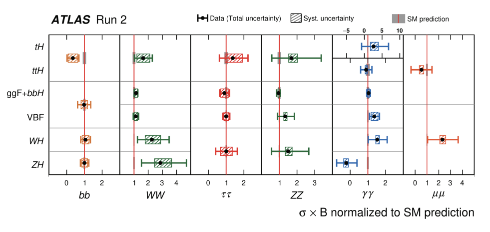
In principle, unitarity can hold up to $\lambda(s) \approx 15$

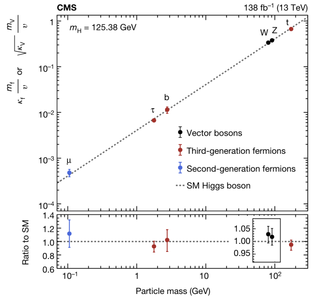
$$R_1 = \frac{\left|a_0^{\mathrm{NLO}}\right|}{\left|a_0^{\mathrm{LO}} + a_0^{\mathrm{NLO}}\right|}, \quad R_1' = \frac{\left|a_0^{\mathrm{NLO}}\right|}{\left|a_0^{\mathrm{LO}}\right|},$$

$R_1 = 1$, *or* $R_1' = 1$, perturbativity is violated when $\lambda(s) \sim 4.3$

Positivity conditions : $\lambda_1 > 0$, $\lambda_2 > 0$, $\lambda_3 + \sqrt{\lambda_1 \lambda_2} > 0$, ...

LHC era



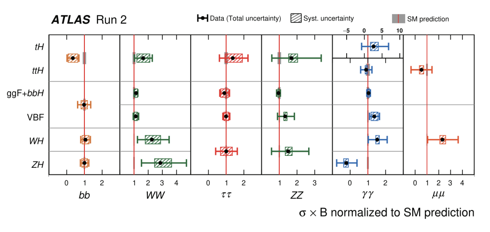


ATLAS Collaboration, Nature 607 (2022)

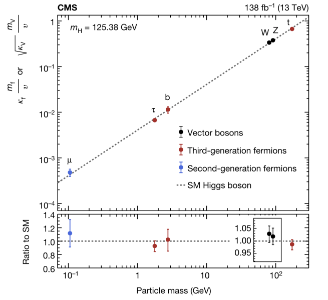
CMS Collaboration, Nature 607 (2022)

$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i \times B^f)_{\rm SM}}, \qquad \kappa_f = \frac{g_{hff}}{g_{hff}^{\rm SM}}, \quad \kappa_V = \frac{g_{hVV}}{g_{hVV}^{\rm SM}}$$

LHC era



ATLAS Collaboration, Nature 607 (2022)



CMS Collaboration, Nature 607 (2022)

$$\mu_i^f = \frac{\sigma_i \times B^f}{(\sigma_i \times B^f)_{\mathrm{SM}}}, \qquad \kappa_f = \frac{g_{hff}}{g_{hff}^{\mathrm{SM}}}, \quad \kappa_V = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}}$$

Any deviation from unity suggesting that the SM needs to be extended

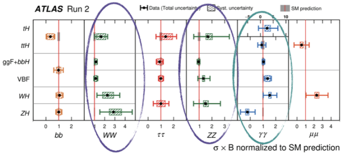
Models with Higgs Triplets

- Both ATLAS and CMS suggest an enhanced rate of WW and ZZ relative to the SM

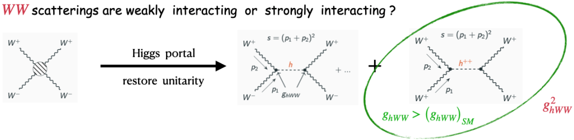
The questions we ask is :

If WW and ZZ rates are enhanced,
how far beyond the SM one must to describe them?

Additional charged Higgs ?



Recap : WW scatterings are weakly interacting or strongly interacting ?



$$g^2_{hWW} - g^2_{h^{++}WW} = (g^2_{hWW})_{SM}$$

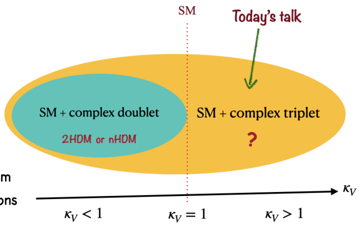
✔ Additional doubly charged Higgs boson plays an important role to restore unitarity at high energies

Search for BSM @ forefront of particle physics research

Models with Higgs Triplets

- Model with triplet extended Higgs sector
  can explain an enhanced rate of WW and ZZ

  - Doubly charged Higgs boson comes
    from $SU(2)_L$ triplet through EWSB mechanism



Triplet or higher multiplets leave an imprint on the EWSB mechanism
that can be detected via SM-like Higgs couplings to the vector bosons

- ✅ It can also explain neutrino oscillation , EWBG , Dark-Matter puzzle
- ✅ It offers a much richer prospect for collider experiments

Can be probed in particle colliders and in cosmological observatories

Models with Higgs Triplets

- Custodial Symmetry : $M_W^2 = M_Z^2 \cos^2\theta_W$

  Rho-parameter, $\rho = \dfrac{M_W^2}{M_Z^2 \cos^2\theta_W}$

  At tree-level, $\rho = 1$

- Triplet extended Higgs sector with Custodial Symmetry :

  SM doublet $\phi\ (T = 1/2,\ Y = 1/2)$ + Real triplet $\xi\ (T = 1,\ Y = 0)$ + Complex triplet $\chi\ (T = 1,\ Y = 1)$

  $\langle\phi\rangle = v_\phi,\ \langle\xi\rangle = v_\xi,\ \langle\chi\rangle = v_\chi$ → $\rho = 1$ in tree-level if $v_\chi = v_\xi$

  * Georgi-Machacek (GM) model :

    Equality of triplet VEVs is preserved by the Higgs potential [Georgi, Machacek '85; Chanowitz, Golden '85]

    Interactions among the Higgs fields maintained $SU(2)_L \times SU(2)_R$ symmetry

  * extended Georgi-Machacek (eGM) model :

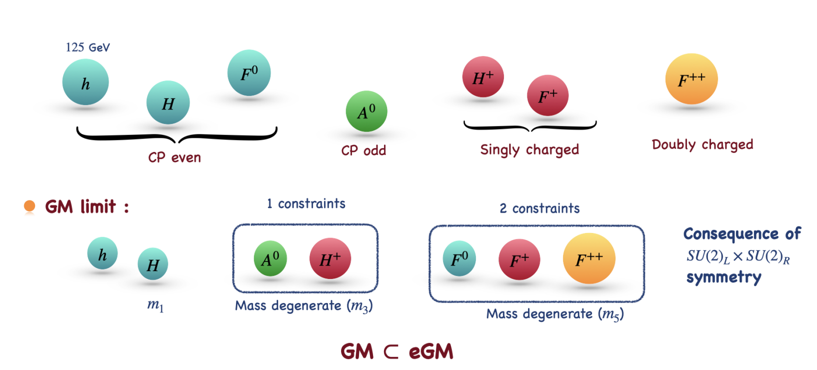
    Equality of triplet VEVs is obtained by tuning the potential parameters @ tree-level [Kundu, Mondal, Pal '21]

    Higgs interactions does not maintained $SU(2)_L \times SU(2)_R$ symmetry

    ...Similar interactions were considered in 2HDM with softly broken Z_2 symmetry

GM and eGM models are classified based on their symmetry, with identical field contents

Models with Higgs Triplets



In eGM model, both H^+ and F^+ couple to fermions

$\rightarrow$ Much richer flavor physics phenomenology

Theoretical Constraints

- Positivity of the Higgs potential

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

- Yukawa and quartic couplings of the theory need to be in perturbative regime

$y_i < \sqrt{4\pi}$ and $\lambda_i < 4\pi$

- Quartic couplings should satisfy the unitarity conditions @ one-loop

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

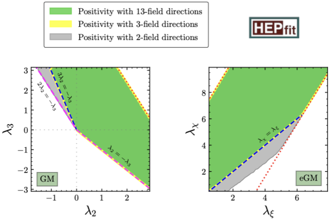
- NLO corrections to the LO amplitudes should be smaller in magnitude

$$|a_\ell^{NLO}| < |a_\ell^{LO}|$$

Positivity Conditions

It is not possible to recast the necessary and sufficient positivity conditions into a fully analytical, compact form

Ensure that boundedness of the potential in any directions of field space



Numerically, 3-field direction BFB conditions (neither necessary nor sufficient) are a very good approximation of all 13-field direction BFB conditions

[Moultaka, Peyranère '21, D. Chowdhury, P. Mondal, S.S. 2404.18996]

These 3-field direction BFB conditions are faster numerically

Perturbative Unitarity

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	✗	✗	✗	✗	$\frac{\chi^{++}\chi^{++}}{\sqrt{2}}$

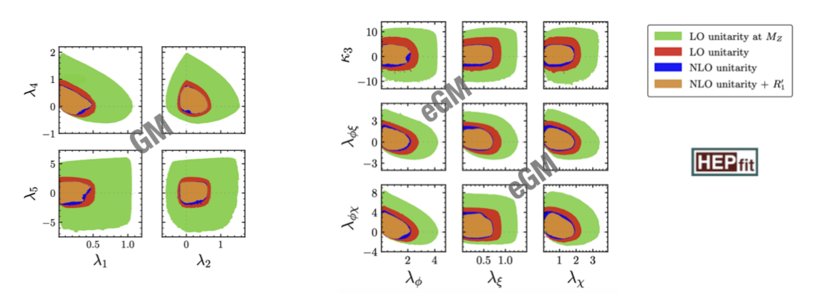
Two-particle basis states broken down by their total charge Q and total hypercharge Y.

$\rightarrow$ 16, 15, 11, 3, 1 unique tree-level eigenvalues for the blocks with $Q = 0, 1, 2, 3, 4$, respectively. Out of these, total 19 eigenvalues are appeared to be independent.

Perturbative Unitarity

NLO unitarity :

$$256\pi^3(\mathbf{a_0^{Q,Y}})_{\text{NLO}} = -16\pi^2\mathbf{b_0} + (i\pi - 1)\mathbf{b_0}\cdot\mathbf{b_0} + 3\beta_{\mathbf{b_0}}\,.$$



NLO unitarity significantly refine the parameter space

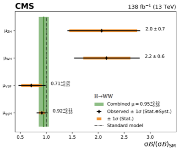
arXiv: 2404.18996

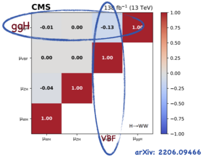
Higgs Signal strengths

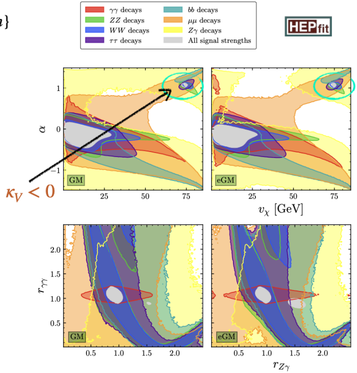
$$\mu_i^f = \frac{\sigma B\,(i \to h \to f)}{\sigma B_{SM}\,(i \to h \to f)}$$

$i \in \{ggF, bbh, VBF, Wh, Zh, tth, th\}$

$f \in \{ZZ, WW, \gamma\gamma, Z\gamma, \mu\mu, bb, \tau\tau\}$





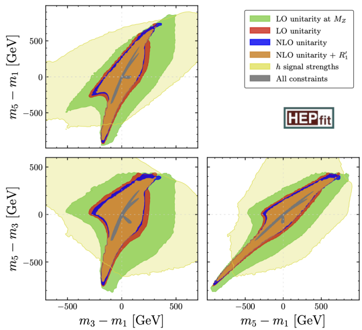


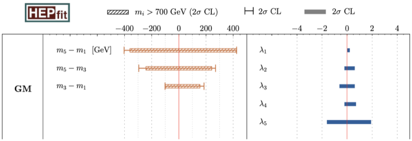
Latest Run 2 LHC data put a stringent bound on triplet VEV , $v_\chi < 32$ GeV

Strongly disfavour $|\kappa_V| > 1.05$ @ 95.4% CL

arXiv: 2404.18996

Combined global fits





More restrictive parameter space from improved theoretical constraints

Maximum mass splitting reduced ~ 100 GeV from the literature

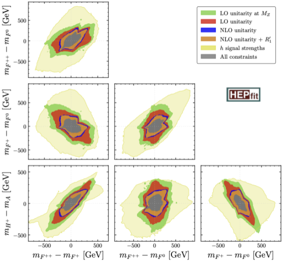
Quartic couplings can't exceed 1.9 @ one-loop

... while about 3.0 @ tree-level

[arXiv: 1807.10660]

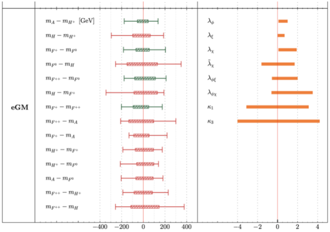
arXiv: 2404.18996

Combined global fits



D. Chowdhury, P. Mondal, S.S. 2404.18996

@ 95.4% CL limit on mass differences and quartic couplings



Maximum mass splitting within custodial multiplets

~ 210 GeV @ 95.4% CL

➡ Flavor or electroweak precision data could be used to constrain the model further. *(Work in progress ...)*

arXiv: 2404.18996

Thank You !

Questions?

Backup slides

Higgs potential with triplets

SM Higgs doublet (ϕ, $Y = 1/2$) + real triplet (ξ, $Y = 0$) + complex triplet (χ, $Y = 1$)

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

A. Kundu, P. Mondal, P.B. Pal, PRD 105 (2022)

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

$$\rho = \frac{v_\phi^2 + 4\left(v_\xi^2 + v_\chi^2\right)}{v_\phi^2 + 8v_\chi^2} \quad \Rightarrow \quad \rho = 1 \quad \text{requires} \quad \boxed{v_\chi = v_\xi}$$

Collider Phenomenology

- Yukawa sector :

  Only the doublet couples to fermions

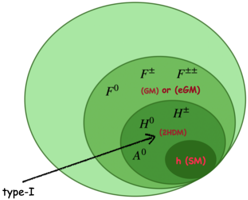
  triplet VEV (v_χ) : $v_\phi^2 + 8v_\chi^2 = v^2$ and $\tan\beta = \dfrac{v_\phi}{2\sqrt{2}v_\chi}$

  $v_\chi \downarrow$ $\tan\beta \uparrow$

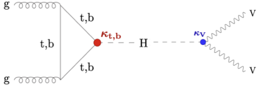
  ……Similar phenomenology as in type-I 2HDM

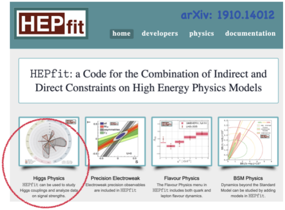
Additional features :

The addition of a singly charged scalar (F^+) coupled to fermions,
along with the presence of a doubly charged scalar,
makes these models highly interesting for collider studies.



Higgs Signal Strengths : *HEPfit Implementation*





http://hepfit.roma1.infn.it

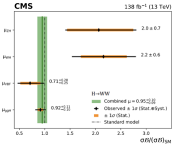
$$\mu_i^f = \frac{\sigma B\,(i \to H \to f)}{\sigma B_{SM}\,(i \to H \to f)}$$

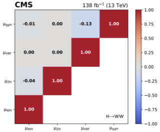
$i \in \{ggF, bbh, VBF, Wh, Zh, tth, th\}$

$f \in \{ZZ, WW, \gamma\gamma, Z\gamma, \mu\mu, bb, \tau\tau\}$

- Make all possible observables μ_i^f for different production and decay modes
- Fit to the ALTAS and CMS data on (correlated) observables μ_i^f for a BSM model
- Present the results on the (new) observables from the combined fit

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





arXiv: 2206.09466

Higgs Signal Strengths : LHC data

ATLAS Run 2

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

CMS Run 2

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