

ABOUT THE 95 GEV EXCESSES IN THE UN2HDM

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7th Red LHC Workshop

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Ongoing work done in collaboration with: **Juan A. Aguilar Saavedra, Henrique B. Câmara**
and **Filipe R. Joaquim**



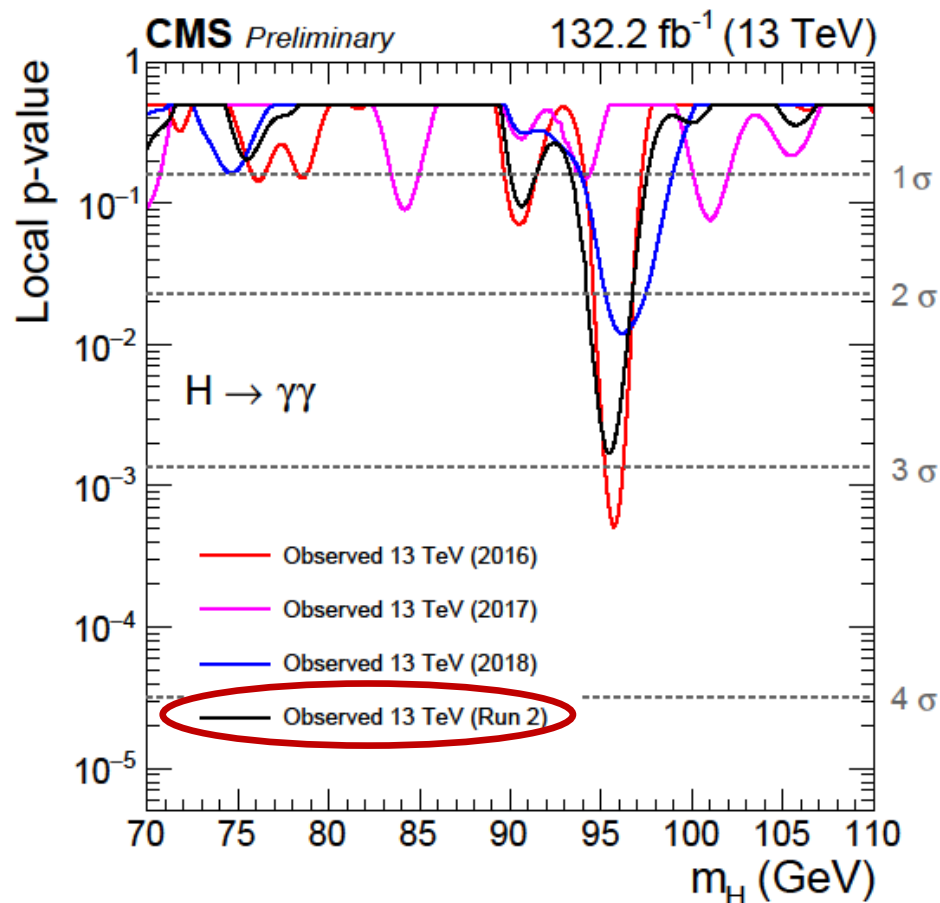
MOTIVATION

- Several theoretical frameworks beyond the Standard Model (SM) feature extended Higgs sectors;
- A recent CMS result based on the full Run 2 dataset **unconfirmed an excess of diphoton events** reducing the local significance to 2.9σ at a mass around 95 GeV.

Signal strength:

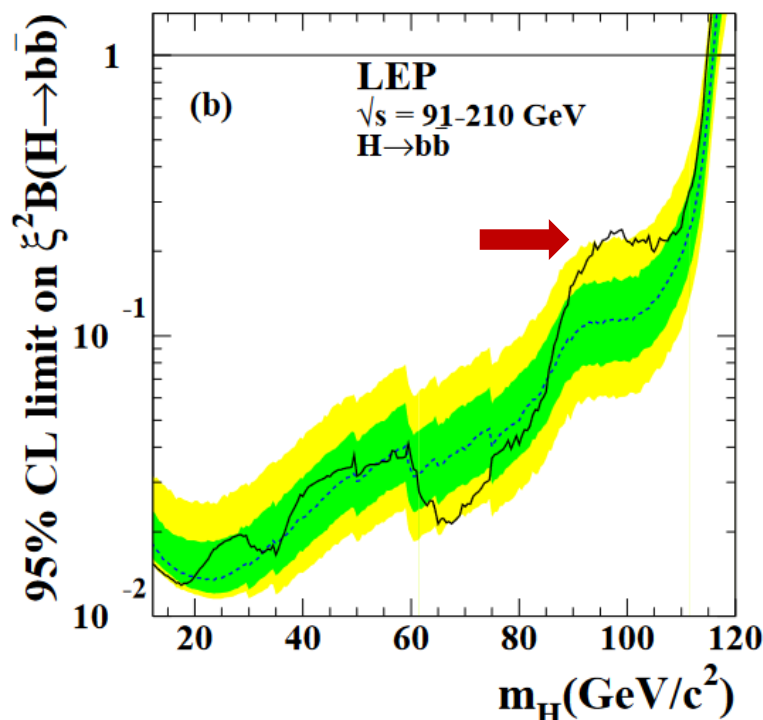
$$\mu_{\gamma\gamma} = \frac{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)_{\text{SM}}} = 0.33^{+0.19}_{-0.12}$$

This is **not the only hint for a 95 GeV Higgs boson!**

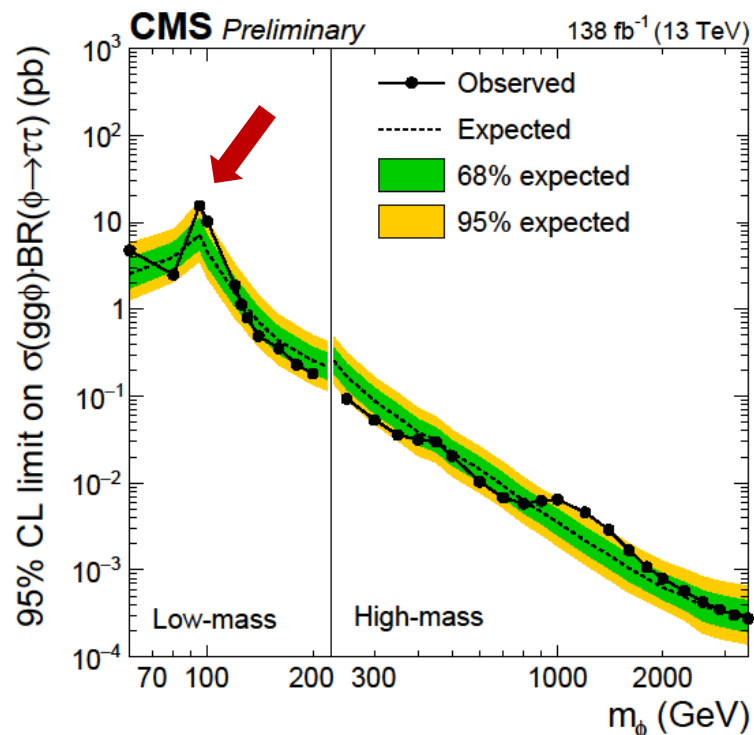


CMS Collaboration; CMS-PAS-HIG-20-002

MOTIVATION



[LEP Working Group for Higgs boson searches];
 Phys. Lett. B 565 (2003) 61



[CMS Collaboration]; CMS-PAS-HIG-21-001

- An excess of $H \rightarrow b\bar{b}$ events with 2.3σ local significance was found in LEP;

$$\mu_{bb} = 0.117 \pm 0.057$$

- Another excess of 3.1σ was discovered by CMS in the channel $H \rightarrow \tau^- \tau^+$.

$$\mu_{\tau\tau} = 1.2 \pm 0.5$$

YUKAWA TYPES IN TWO HIGGS DOUBLET MODELS

Type-I : Same Higgs doublet couples to all fermions

$$\mathcal{L}_Y = -y_u \bar{q}_L \tilde{\Phi}_2 u_R - y_d \bar{q}_L \Phi_2 d_R - y_e \bar{\ell}_L \Phi_2 e_R + \text{h.c.}$$

Type-II : One Higgs doublet couples to down-type quarks and leptons while the other couples to up-type quarks

$$\mathcal{L}_Y = -y_u \bar{q}_L \tilde{\Phi}_2 u_R - y_d \bar{q}_L \Phi_1 d_R - y_e \bar{\ell}_L \Phi_1 e_R + \text{h.c.}$$

Type-III/Lepton specific : One Higgs doublet couples to quarks the other to leptons

$$\mathcal{L}_Y = -y_u \bar{q}_L \tilde{\Phi}_1 u_R - y_d \bar{q}_L \Phi_1 d_R - y_e \bar{\ell}_L \Phi_2 e_R + \text{h.c.}$$

Type-IV/Flipped : One Higgs doublet couples to up-type quarks and leptons while the other couples to down-type quarks

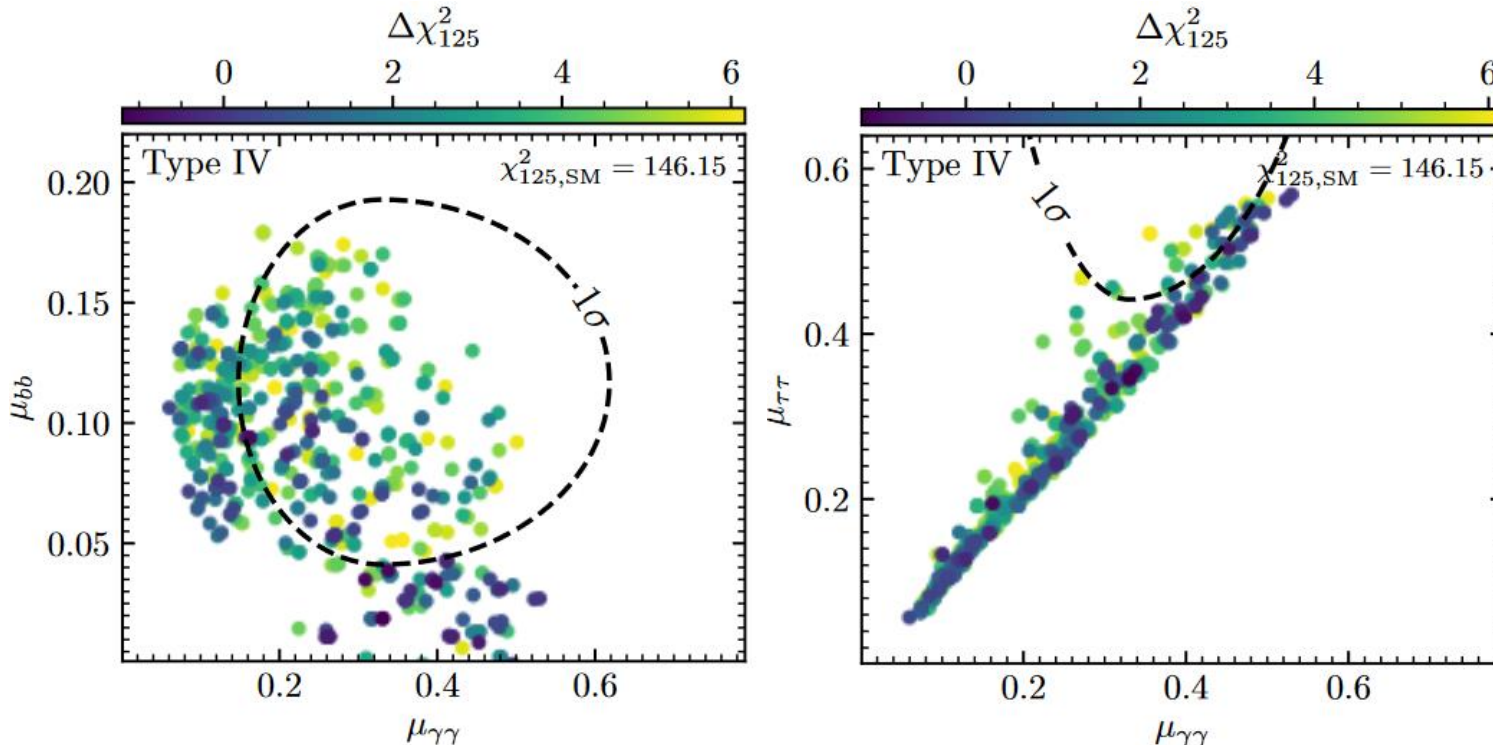
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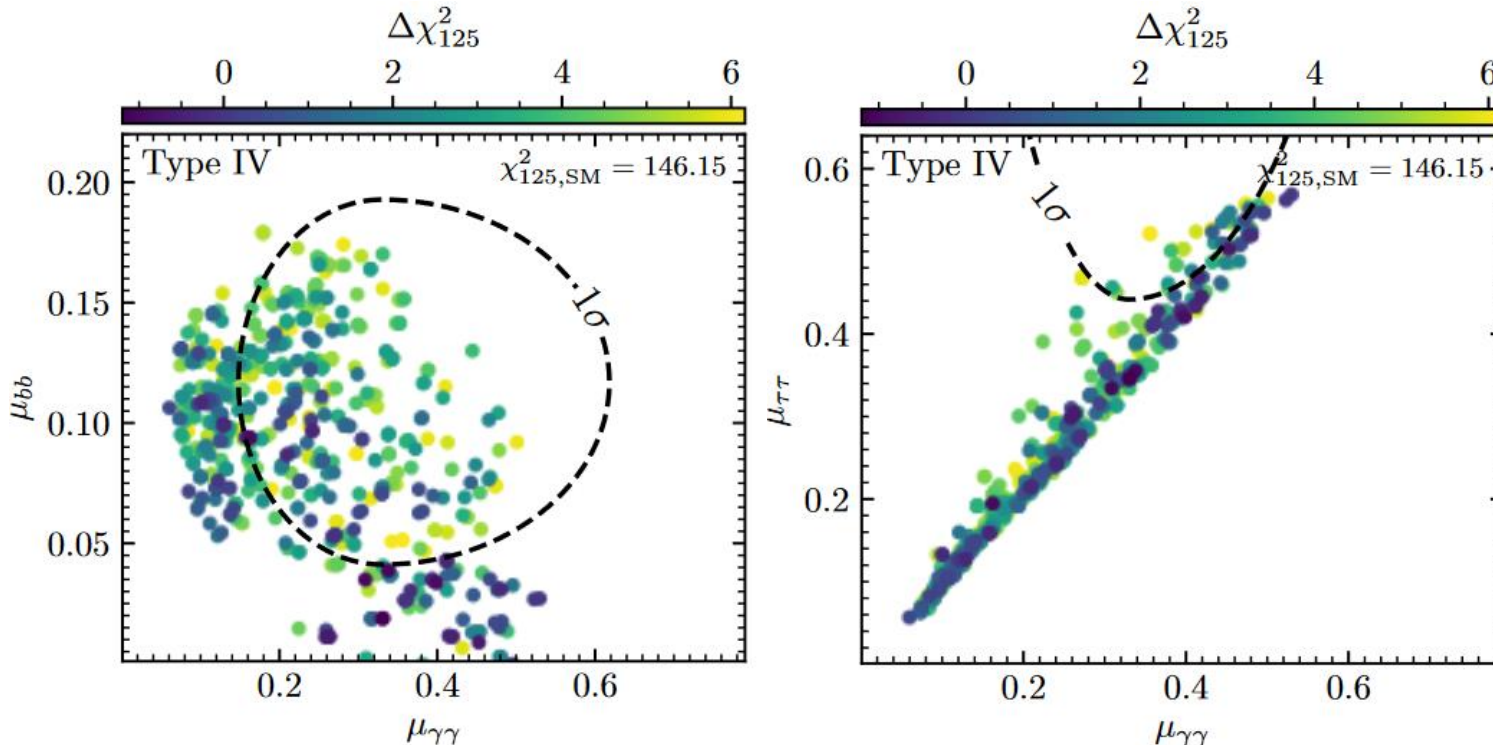
- Extensions of the SM Higgs sector with a doublet and a real (N2HDM) or complex (S2HDM) singlet;
- When considering a **Type-IV**, these theories can explain the three observed excesses at a mass close to 95 GeV (Type-II has been also explored, but with less success).



T. Biekötter, S. Heinemeyer and G. Weiglein; arXiv [hep-ph]: 2303.12018

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**What about
 bb vs $\tau\tau$??**

T. Biekötter, S. Heinemeyer and G. Weiglein; arXiv [hep-ph]: 2303.12018

- **The diphoton excess is diminishing ...
It may well disappear ...**
- **Can we account for the bb and $\tau\tau$ excesses in such case?**
- **Can we account for an excess in just one channel?**
- **...**

WHAT ABOUT THE UN2HDM?

- Its scalar sector has the same structure as the S2HDM but extends the Standard Model (SM) gauge symmetry with an **additional U(1) group**:

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)'_{Y'} \rightarrow$$

New massive gauge boson
 Z'

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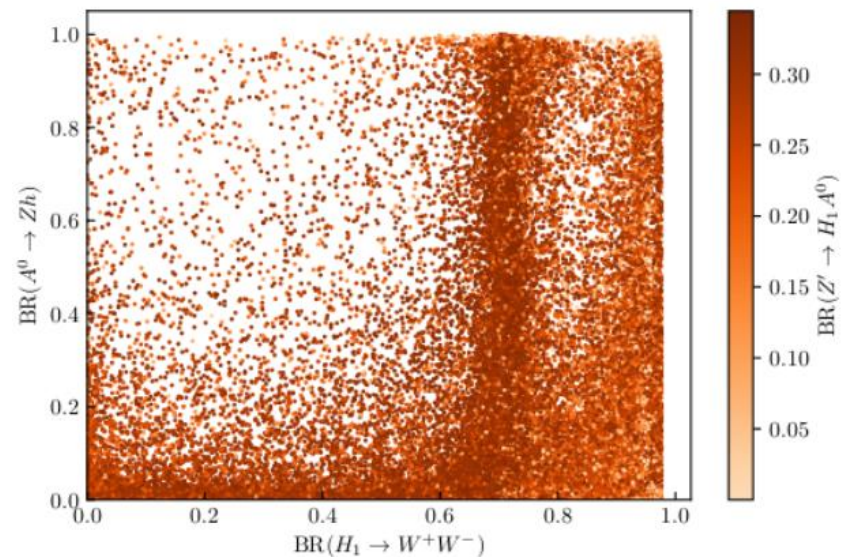
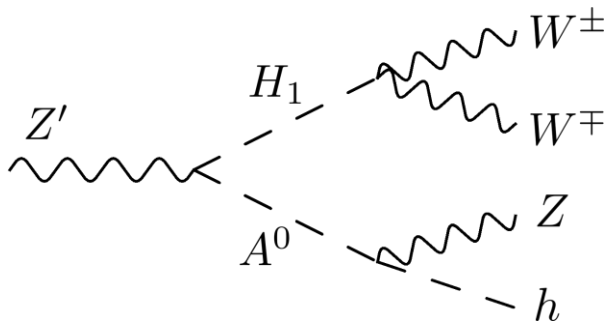
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J. A. Aguilar Saavedra, F. R. Joaquim and J. F. Seabra; Eur.Phys.J.C 82 (2022) 11, 1080

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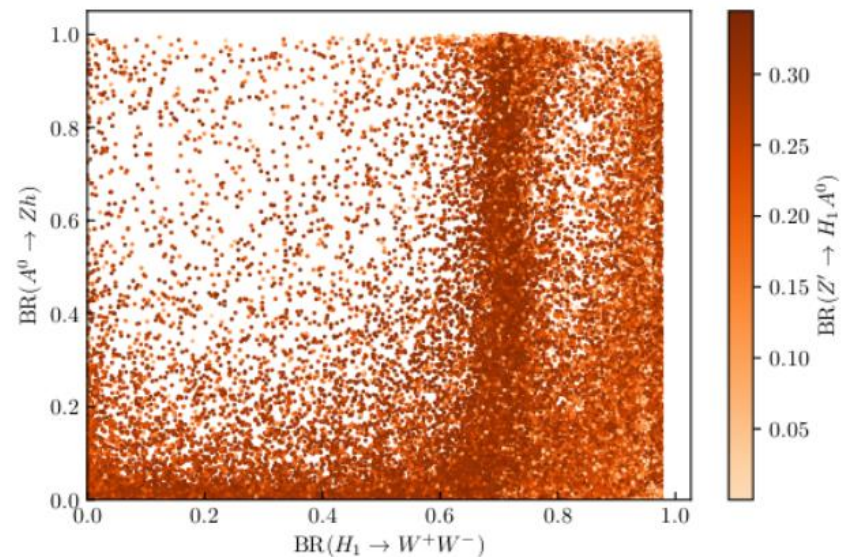
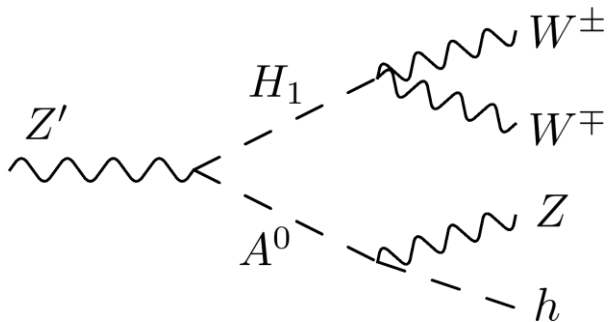
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Can it also accommodate the 95 GeV Higgs boson?

MORE ABOUT THE UN2HDM

SM fermions	Y	Y'
$(u\ d)_L$	$1/6$	$\neq 0$
u_R	$2/3$	$\neq 0$
d_R	$-1/3$	$\neq 0$
$(\nu\ l)_L$	$-1/2$	0
l_R	-1	0

Scalars	Y	Y'
Φ_1	$1/2$	$\neq 0$
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χ	0	$\neq 0$

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- SM quarks get $U(1)'$ hypercharge, meaning that **extra matter** is required for **cancelling anomalies**.

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- **Dark matter candidate**, if the lightest VLL is neutral;

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- Dark matter candidate**, if the lightest VLL is neutral;

**Simplest scenarios to cancel anomalies are obtained when
all quark fields couple to the same Higgs doublet.**

MORE ABOUT THE UN2HDM

SM fermions	Y	Y'
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Scalars	Y	Y'
Φ_1	$1/2$	$9Y'_q$
Φ_2	$1/2$	0
χ	0	$9Y'_q$

VLLs	Y	Y'
$(N_1 \ E_1)_{R(L)}$	$-1/2$	$(-)9Y'_q/2$
$N_{2L(R)}$	0	$(-)9Y'_q/2$
$E_{2L(R)}$	1	$(-)9Y'_q/2$

Type-I Yukawa sector:

$$\begin{aligned}
 \mathcal{L}_Y = & -y_u \bar{q}_L \tilde{\Phi}_2 u_R \\
 & - y_d \bar{q}_L \Phi_2 d_R \\
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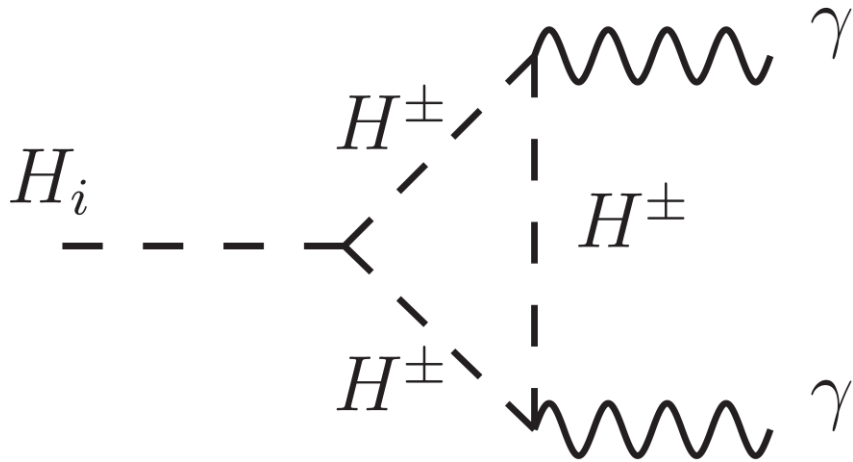
Vector-like leptons	Y	Y'
N_{iL}	0	0
N_{iR}	0	Y'_q
E_{iL}	-1	0
E_{iR}	-1	$-Y'_q$
$i = 1, 2, 3$		

Scalars	Y	Y'
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Φ_2	$1/2$	0
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**Type-III/Lepton specific
Yukawa sector:**

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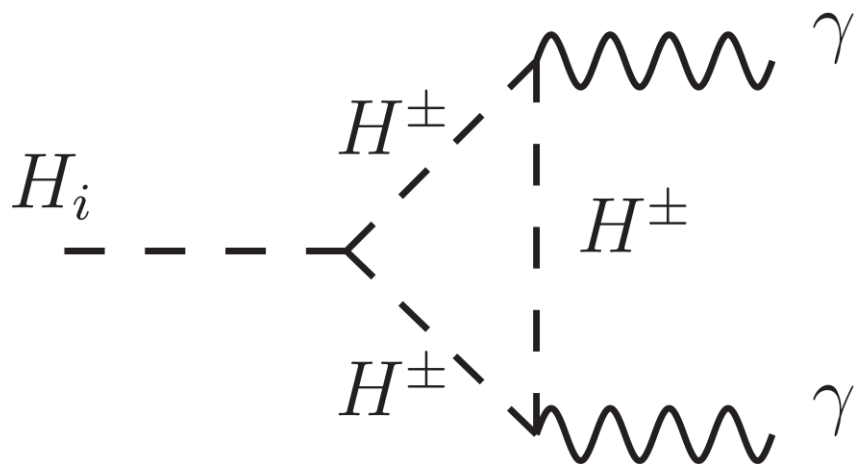
Charged Higgs



Existing in models with two Higgs doublets e.g. 2HDM, N2HDM, S2HDM ...

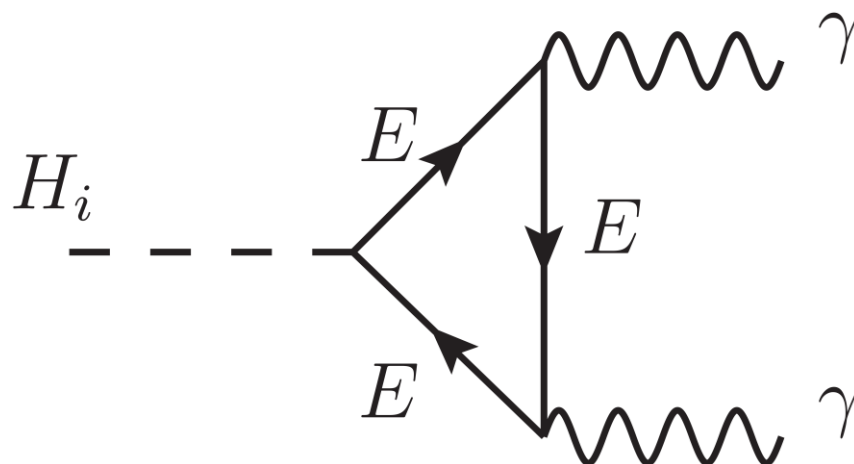
NEW HIGGS TO DIPHOTON CONTRIBUTIONS

Charged Higgs



Existing in models with two Higgs doublets e.g. 2HDM, N2HDM, S2HDM ...

Vector-like leptons



Specific to the UN2HDM

VLLs are introduced for gauge anomaly cancellation

NUMERICAL PROCEDURE

Scalar masses

$$m_{H_1} \quad 95.4 \text{ GeV}$$

$$m_h \quad 125.09 \text{ GeV}$$

$$m_{H_2} \quad [125.1, 1000] \text{ GeV}$$

$$m_{A^0}, m_{H^\pm} \quad [20, 1000] \text{ GeV}$$

VEV parameter

$$\tan \beta \quad [0, 20]$$

Effective couplings of SM Higgs boson

$$c(hVV)^2 \quad [0.9, 1.0]$$

$$c(ht\bar{t})^2 \quad [0.8, 1.2]$$

CP-even scalars mixing matrix

$$\text{sign}(O_{31}) \quad \{-1, 1\}$$

$$O_{32} \quad [-1, 1]$$

U(1) parameters

$$m_{Z'} \quad 2.2 \text{ TeV}$$

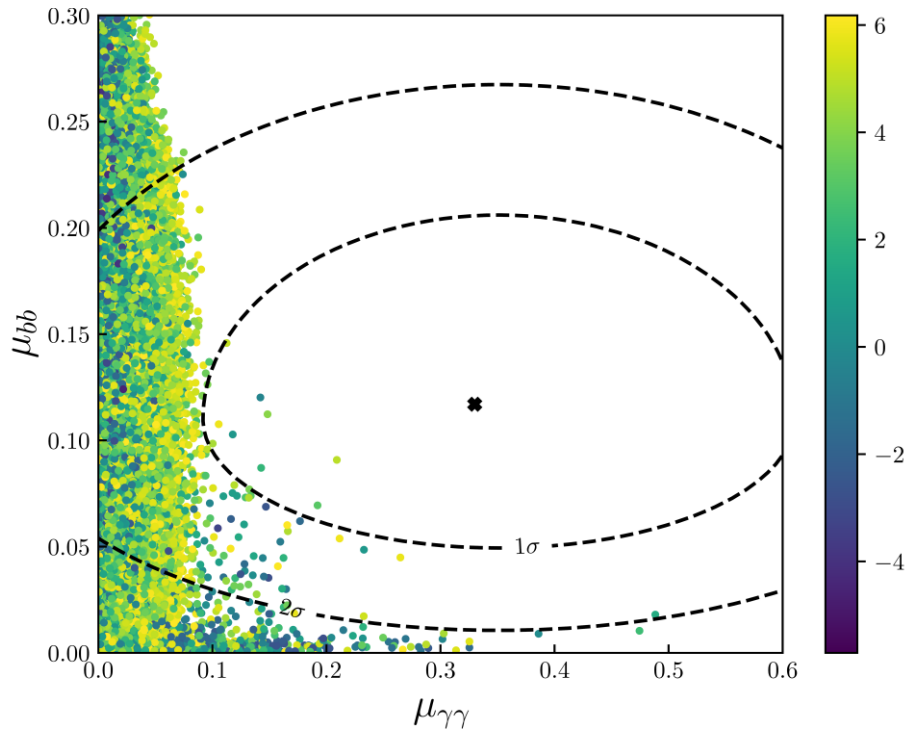
$$g_{Z'} Y'_\chi \quad 0.9$$

$$u \approx 2.2 \text{ TeV}, \quad \tan \theta_Z < 10^{-3}.$$

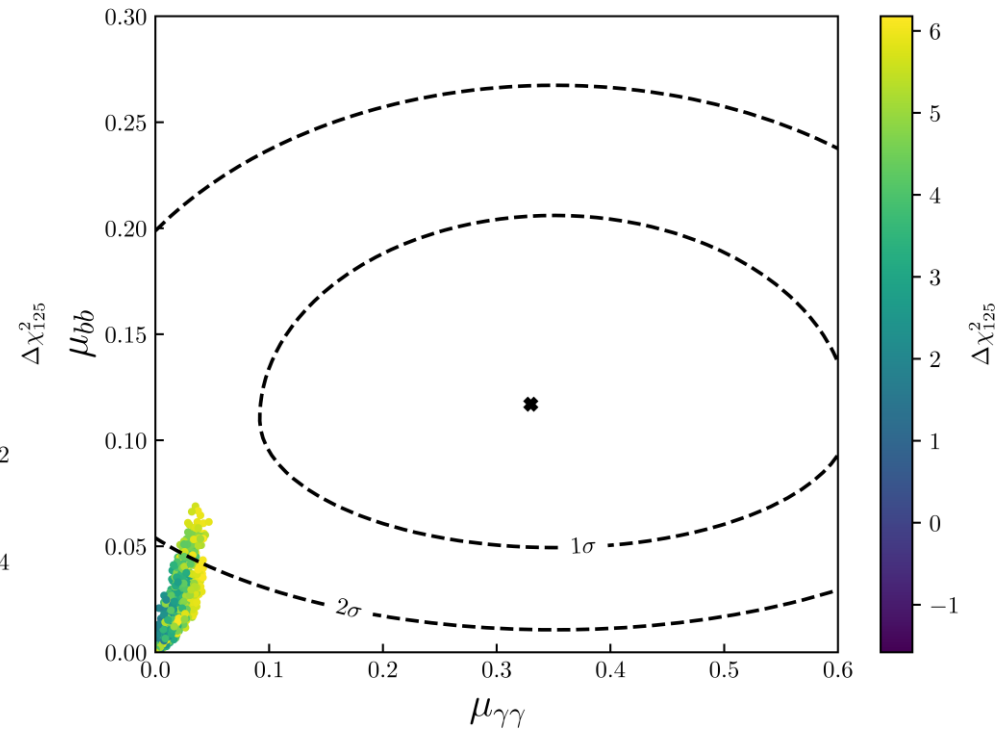
- The constraints taken into account by **ScannerS** are:
 - Theoretical constraints imposed by **perturbative unitarity**, **boundedness from below** and **vacuum stability** conditions (**EVADE**);
 - **Electroweak precision** constraints;
 - **Flavour** constraints;
 - **Higgs searches/measurements (HiggsTools)**.
- The **VLLs** are decoupled and **are not considered in our preliminary analysis** for which we will show our first results.

PRELIMINARY RESULTS: DIPHOTON-DIBOTTOM

Type-I



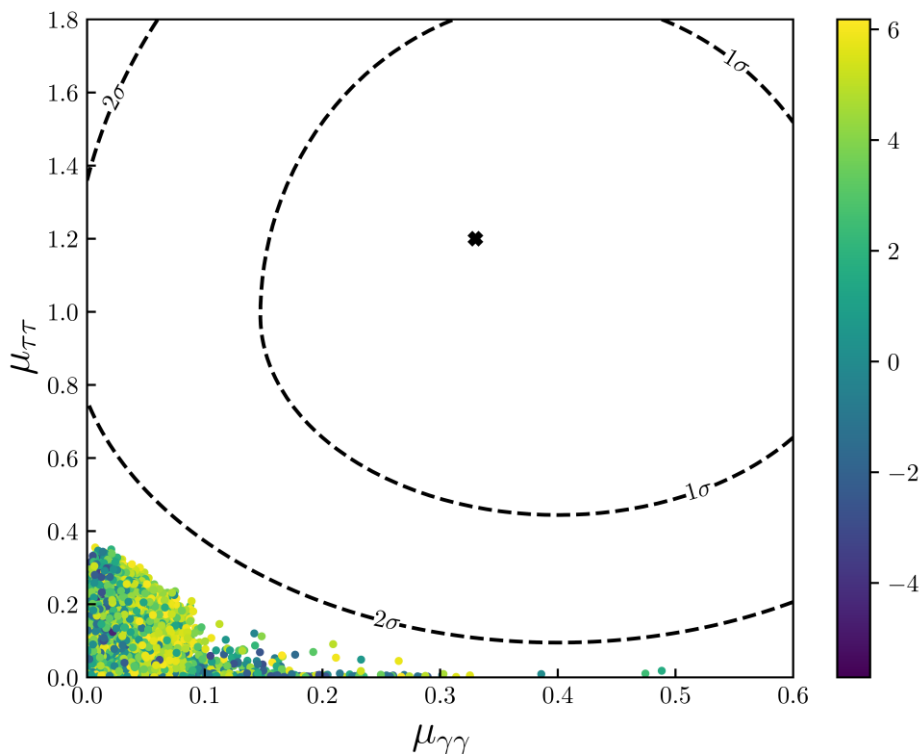
Type-III (Lepton specific)



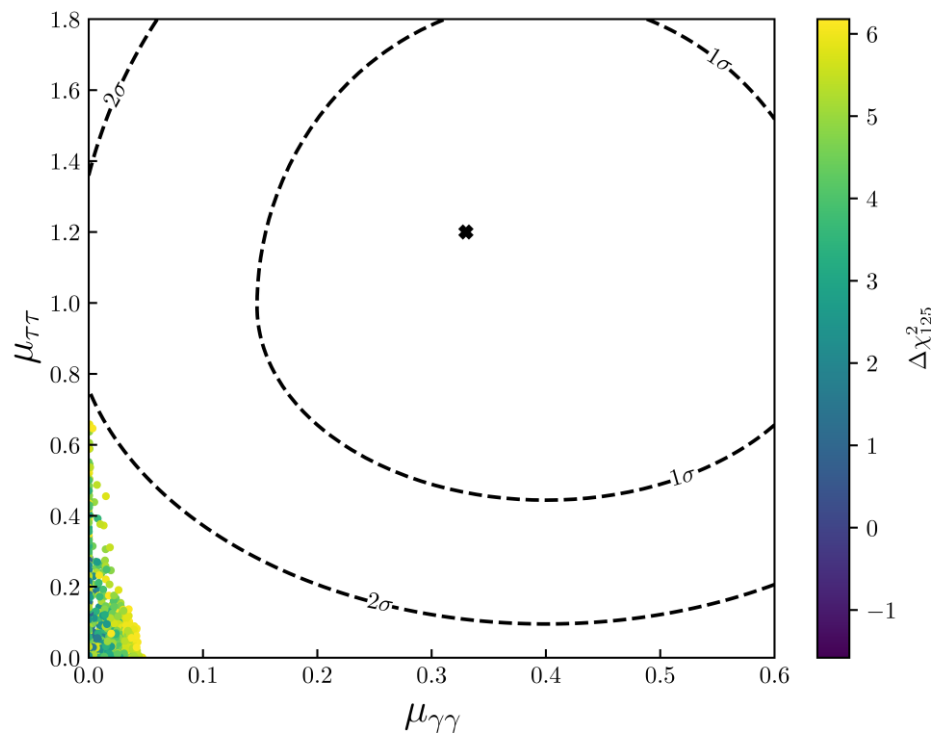
- It is hard to simultaneously account for **diphoton** and **dibottom** excesses **without VLLs**;

PRELIMINARY RESULTS: DIPHOTON-DITAU

Type-I



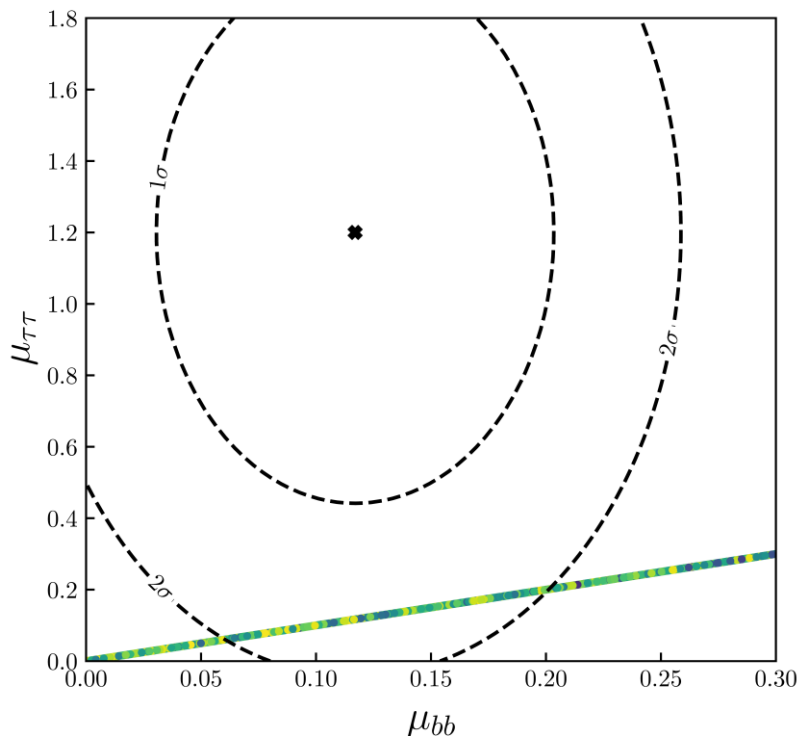
Type-III (Lepton specific)



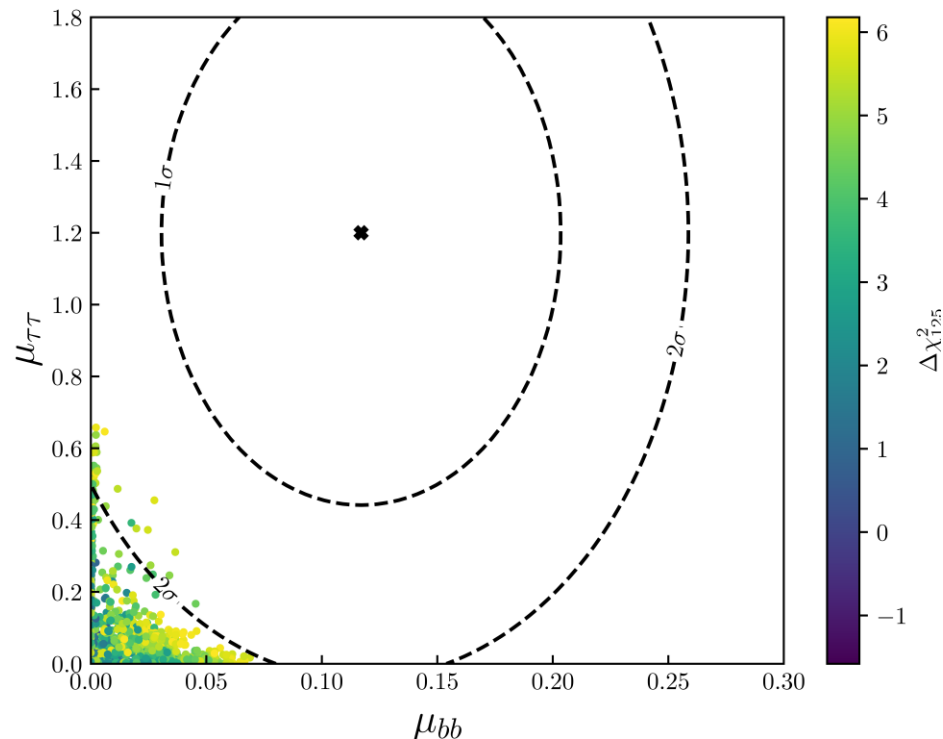
- **Type-III accomodates the ditau excess** at 1σ level and an eventual disappearance of the diphoton excess;
- Neither **Type-I nor Type-III can** explain the (reduced) **diphoton** and **ditau** excesses simultaneously (VLLs could help explaining a larger diphoton excess)

PRELIMINARY RESULTS: DITAU-DIBOTTOM

Type-I



Type-III (Lepton specific)



- **Type-I fails** to explain the **ditau** excess due to neutral Higgs coupling to charged leptons and down-quarks being the same (linear relation)
- **Type-III** accomodates both **ditau** and **dibottom** excesses but only at **2 σ level**

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Thank you!

Backup slides

SCALAR POTENTIAL

$$\begin{aligned}
 V(\Phi_1, \Phi_2, \chi) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{m_0^2}{2} \chi^\dagger \chi \\
 & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\
 & + \frac{\lambda_5}{2} (\chi^\dagger \chi)^2 + \frac{\lambda_6}{2} (\Phi_1^\dagger \Phi_1) (\chi^\dagger \chi) + \frac{\lambda_7}{2} (\Phi_2^\dagger \Phi_2) (\chi^\dagger \chi) + [\mu \chi \Phi_1^\dagger \Phi_2 + \text{h.c.}]
 \end{aligned}$$

Scalar fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \chi = \frac{1}{\sqrt{2}}(u + \rho_3 + i\eta_3).$$

Vacuum expectation values (VEVs)

$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 \end{pmatrix}, \quad \langle \chi \rangle = \frac{1}{\sqrt{2}} u.$$

Rephasing

$$\begin{aligned}
 \Phi_2' &= e^{-i\varphi_2} \Phi_2 \\
 \chi' &= e^{-i\varphi_3} \chi
 \end{aligned}
 \quad \Rightarrow \quad V(\Phi_1, \Phi_2', \chi') = V(\Phi_1, \Phi_2, \chi) \quad \text{if} \quad \mu \rightarrow \mu' = e^{-i(\varphi_2 + \varphi_3)} \mu$$

All VEVs can be assumed as real without loss of generality.

SCALAR POTENTIAL

$$\begin{aligned} V(\Phi_1, \Phi_2, \chi) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + \frac{m_0^2}{2} \chi^\dagger \chi \\ & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) \\ & + \frac{\lambda_5}{2} (\chi^\dagger \chi)^2 + \frac{\lambda_6}{2} (\Phi_1^\dagger \Phi_1) (\chi^\dagger \chi) + \frac{\lambda_7}{2} (\Phi_2^\dagger \Phi_2) (\chi^\dagger \chi) + [\mu \chi \Phi_1^\dagger \Phi_2 + \text{h.c.}] \end{aligned}$$

Minimum conditions

$$0 = m_{11}^2 v_1 + \frac{1}{2} v_1^3 \lambda_1 + \frac{1}{2} v_1 v_2^2 (\lambda_3 + \lambda_4) + \frac{1}{4} u^2 v_1 \lambda_6 + \frac{1}{\sqrt{2}} u v_2 \text{Re}(\mu)$$

$$0 = m_{22}^2 v_2 + \frac{1}{2} v_2^3 \lambda_2 + \frac{1}{2} v_1^2 v_2 (\lambda_3 + \lambda_4) + \frac{1}{4} u^2 v_2 \lambda_7 + \frac{1}{\sqrt{2}} u v_1 \text{Re}(\mu)$$

$$0 = m_0^2 u + u^3 \lambda_5 + \frac{1}{2} u v_1^2 \lambda_6 + \frac{1}{2} u v_2^2 \lambda_7 + \sqrt{2} v_1 v_2 \text{Re}(\mu)$$

$$0 = \text{Im}(\mu),$$

The parameters $\lambda_1, \dots, \lambda_7$ and μ can be written in terms of the **five scalar masses** and the **three mixing angles** of CP-even scalars.

Note:

Henceforth, the VEVs v_1 and v_2 are represented in terms of

$$v = \sqrt{v_1^2 + v_2^2}, \quad \tan \beta = \frac{v_2}{v_1}.$$

PARAMETRISATION BASED ON EFFECTIVE COUPLINGS

$$O = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}^T$$

Input parameters for defining the parametrisation are in **red**:

$$c(ht\bar{t}) = \frac{O_{21}}{s_\beta} \Leftrightarrow O_{21} = c(ht\bar{t})s_\beta$$

$$c(hVV) = O_{11}c_\beta + O_{21}s_\beta \Leftrightarrow O_{11} = \frac{c(hVV) - O_{21}s_\beta}{c_\beta}, \quad (V = W, Z)$$

$$O_{11}^2 + O_{21}^2 + O_{31}^2 = 1 \Leftrightarrow O_{31} = \pm \sqrt{1 - O_{11}^2 - O_{21}^2}$$

$$\theta_1 = \arctan\left(\frac{O_{21}}{O_{11}}\right), \quad \theta_2 = \arcsin(O_{31}), \quad \theta_3 = \arcsin\left(\frac{O_{32}}{c_2}\right)$$