Mounting evidence for a 95 GeV Higgs boson

Thomas Biekötter

in collaboration with Sven Heinemeyer and Georg Weiglein

[2203.13180,2204.05975]

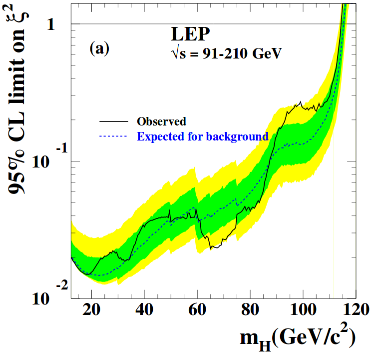
ICHEP 2022 in Bologna

July 8, 2022

DESY.

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

"The 95GeV excesses"

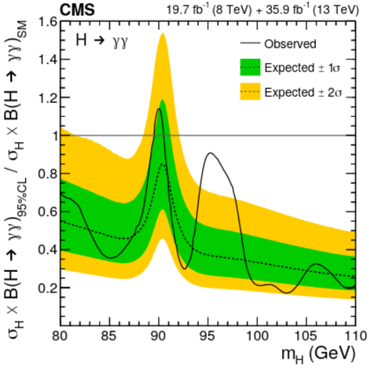


[LEP: hep-ex/0306033]

$\sim 2\sigma$ local excess at 95 - 98GeV

Extracted signal strength:
$\mu_{bb}\left(e^+e^- \to Zh \to Zb\bar{b}\right) = 0.117 \pm 0.057$

[1612.08522]



[CMS: 1811.08459]

Run I/II data: Local excess of $\sim 3\sigma$

Extracted signal strength:
$\mu_{\gamma\gamma}\left(gg \to h \to \gamma\gamma\right) = 0.6 \pm 0.2$

Many model interpretations with common origin of both excesses, including N2HDM and NMSSM

see [T.B, M. Chakraborti, S. Heinemeyer: 2003.05422] for a list models

The Next-to 2 Higgs Doublet Model: N2HDM

$$\text{N2HDM} = \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s)$$
$$= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s)$$

Scalar tree-level potential

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}]$$
$$+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

Symmetries: Z_2: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$ and $\phi_s \to \phi_s$, only softly broken by m_{12}^2
Z_2': $\phi_1 \to \phi_1$, $\phi_2 \to \phi_2$ and $\phi_s \to -\phi_s$, spontaneously broken by v_s

Extension of Z_2 to Yukawa sector $\Rightarrow$ 4 types of the (N)2HDM

EW vacuum:

$$\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix} , \quad \langle\phi_2\rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix} , \quad \langle\phi_S\rangle = v_S/\sqrt{2} \quad \in \mathbb{R}$$

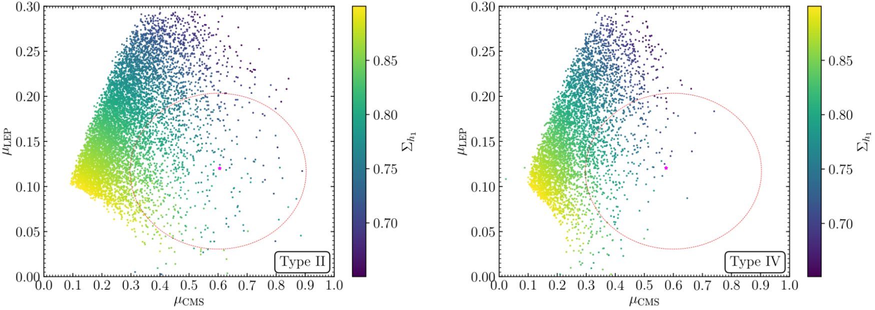
BSM Particles:

CP-even scalars h_1, h_2, h_3, CP-odd scalar A, charged scalars $H^\pm$

N2HDM interpretation

$$\text{N2HDM} = \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s)$$
$$= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s)$$

Σ_{h_1} : Singlet-component of h_1



(a) Type II

(b) Type IV (flipped)

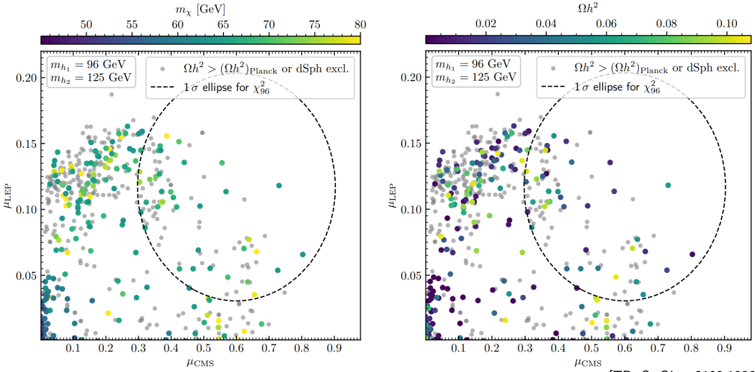
[TB, M. Chakraborti, S. Heinemeyer, 1903.11661]

A singlet-like scalar (h_1) at 95GeV that mixes with h_{125} can accommodate the excesses

See also [2109.01128] for interpretation in combination with a 400 GeV pseudoscalar that accommodates a local 3.5σ excess in $pp \to t\bar{t}$

S2HDM = SM(ϕ_1) + Second Higgs Doublet(ϕ_2) + Complex Scalar Singlet(ϕ_s) + U(1)
= 2HDM(ϕ_1, ϕ_2) + Complex Scalar Singlet(ϕ_s) + U(1)

ϕ_S → Two new states: h_1 at 96 GeV and DM candidate χ



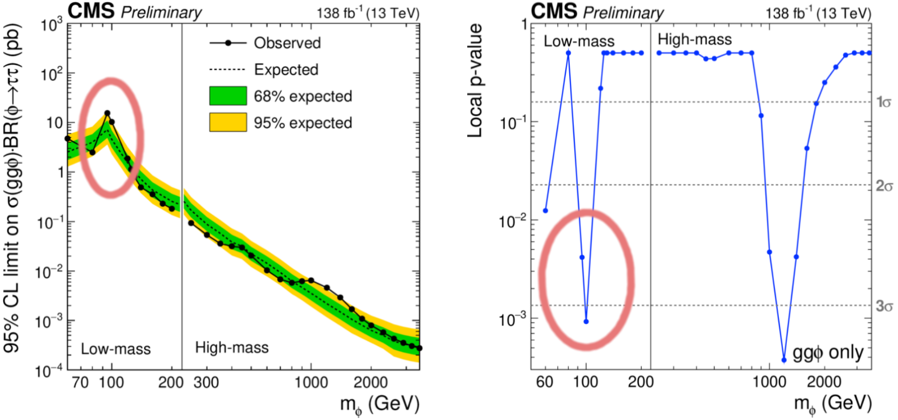
[TB, O. Olea, 2108.10864]

✓ Relic abundance ✓ Galactic-center excess ✓ AMS $\bar{p}$ excess ✓CMS excess ✓LEP excess

A softly broken global U(1) makes χ a pseudo-Nambu-Goldstone DM candidate
→ vanishing DM direct-detection scattering cross sections at tree-level

Recent news from CMS

Searches for additional Higgs bosons in $\tau^+\tau^-$ final states



[CMS-HIG-21-001]

Local 3.1(2.6)σ excess at 100(95) GeV

$$\mu_{\tau\tau}^{\rm exp} = \frac{\sigma^{\rm exp}(gg \to \phi \to \tau^+\tau^-)}{\sigma^{\rm SM}(gg \to H \to \tau^+\tau^-)} = 1.2 \pm 0.5$$

N2HDM: Can we accommodate also the new excess in $\tau^+\tau^-$?

1. $\tau^+\tau^-$ excess in combination with $\gamma\gamma$ excess
2. $\tau^+\tau^-$ excess in combination with $\gamma\gamma$ and $b\bar{b}$ excesses
3. And what about M_W?

Strategie: Random scan to minimize χ^2 in order to find valid points that accommodate the excesses

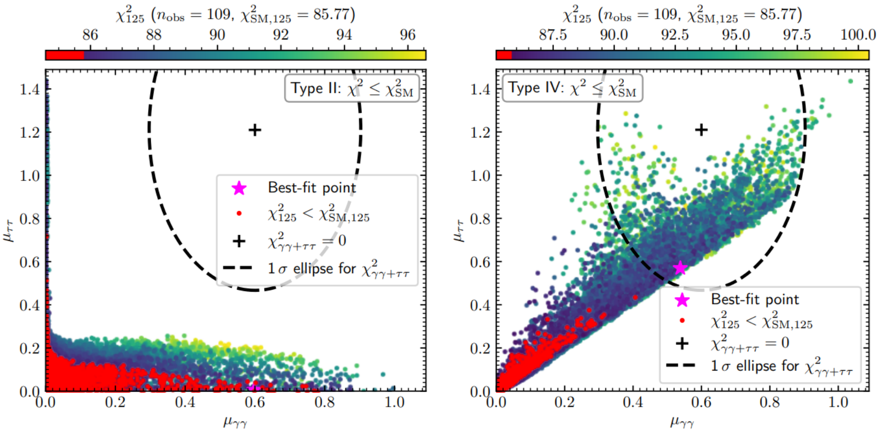
$$\chi^2 = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau}(+\chi^2_{bb}) + \chi^2_{125} \;, \quad \chi^2_{\gamma\gamma,\tau\tau,bb} = \frac{(\mu_{\gamma\gamma,\tau\tau,bb} - \mu^{\exp}_{\gamma\gamma,\tau\tau,bb})^2}{(\Delta\mu^{\exp}_{\gamma\gamma,\tau\tau,bb})^2}$$

Constraints: Collider searches, measurements of $h_{125} \to \chi^2_{125}$, flavour phyiscs, vacuum stability, tree-level perturbative unitarity, electroweak precision observables

For M_W-Tevatron:

$$\chi^2_{M_W^{\rm CDF-new}} = \frac{(M_W^{\rm N2HDM} - M_W^{\rm CDF-new})^2}{(\Delta M_W^{\rm CDF-new})^2} \leq 4 \;, \quad M_W^{\rm N2HDM} = M_W^{\rm N2HDM}(S,T,U)$$

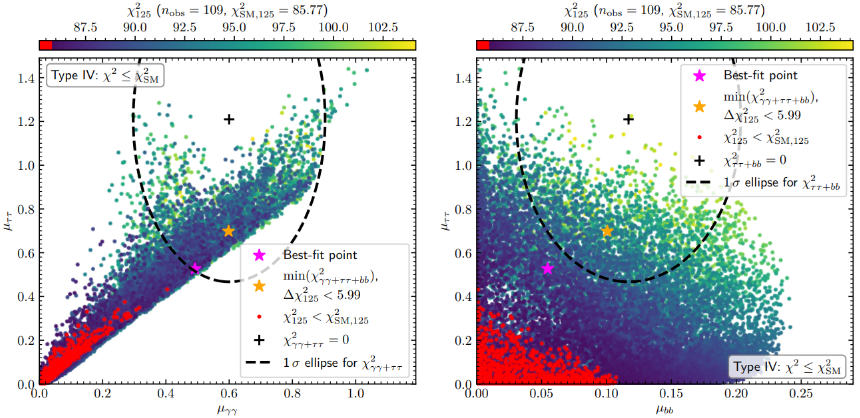
N2HDM interpretation: $\tau^+\tau^-$ and $\gamma\gamma$



[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

Type II does not work, but type IV does!

N2HDM interpretation: $\tau^+\tau^-$ and $\gamma\gamma$ and $b\bar{b}$

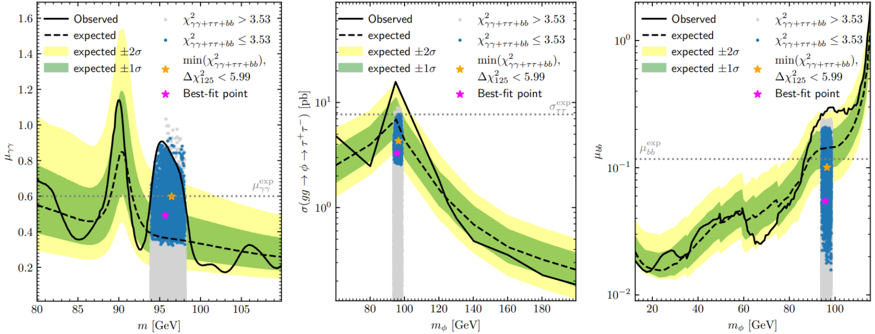


[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

N2HDM Type IV can accommodate the excesses in all three decay modes

N2HDM interpretation: $\tau^+\tau^-$ and $\gamma\gamma$ and $b\bar{b}$

$gg \to h_{95} \to \gamma\gamma$ | $gg \to h_{95} \to \tau^+\tau^-$ | $e^+e^- \to Z(h_{95}) \to (b\bar{b})$

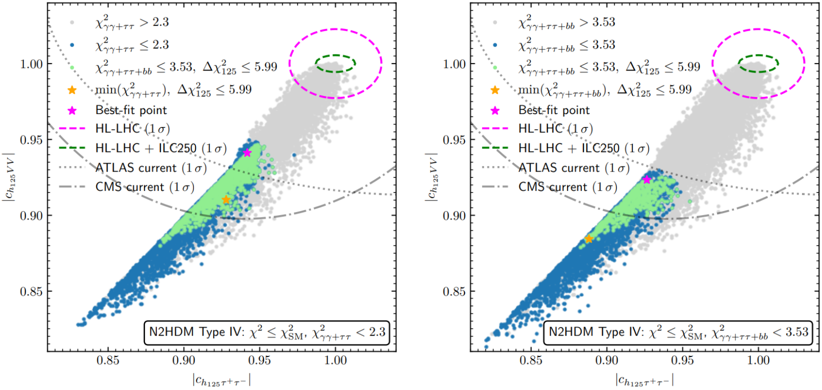


[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

Blue points = Describe the excesses within 1σ confidence level: $\chi^2_{\gamma\gamma+\tau\tau+bb} \le 3.53$

N2HDM interpretation: $\tau^+\tau^-$ and $\gamma\gamma$ and $b\bar{b}$

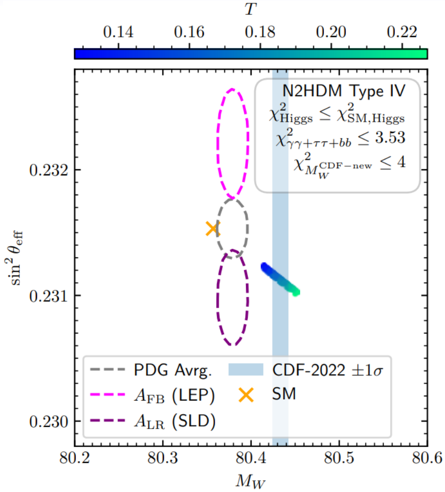
Can be probed indirectly via h_{125}:



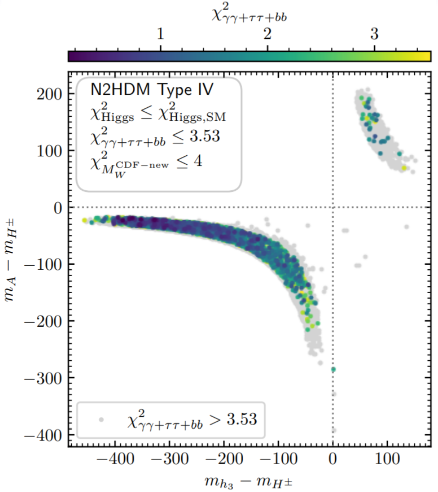
[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

HL-LHC precision sufficient to exclude the scenario

Tevatron and M_W in the N2HDM



Preference for value of effective weak mixing angle as extracted from $A_{\rm LR}$ measured at SLD



Preferred region with mass hierarchy for heavy Higgs bosons: $m_{h_3} < m_A \approx m_{H^\pm}$

[TB, S. Heinemeyer, G. Weiglein, 2204.05975]

Conclusions

Three local excesses ($3\sigma + 3\sigma + 2\sigma$) at the same mass
$\rightarrow$ two different production modes (ggF and Higgsstrahlung)
$\rightarrow$ three different decay modes ($\gamma\gamma$, $\tau\tau$, bb)

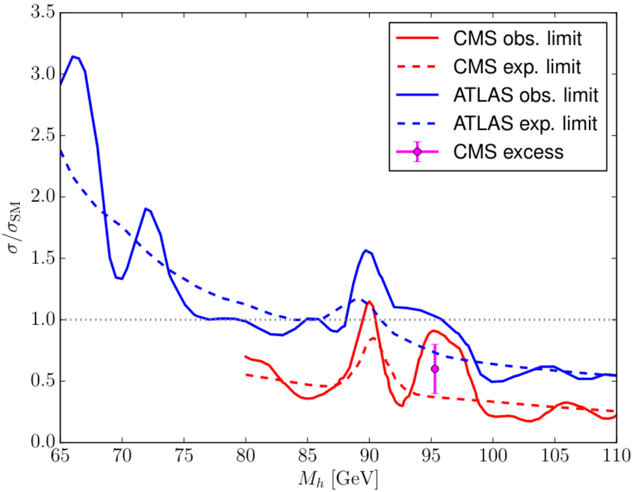
Can be described economically in the N2HDM
$\rightarrow$ valid DM candidate if N2HDM $\rightarrow$ S2HDM (galactic-center excess)
$\rightarrow$ Can simultaneously accommodate M_W Tevatron measurement

HL-LHC h_{125} measurements have potential to exclude all of this
CMS/ATLAS $\gamma\gamma$ low-mass searches with Full Run II eagerly awaited

Thanks!

ATLAS searches below 125 GeV ($80 fb^{-1}$)

[ATLAS-CONF-2018-025]



[S. Heinemeyer, T. Stefaniak, 1812.05864]

The broken phase

Assuming CP conservation: 3 CP-even, 1 CP-odd, 1 charged Higgs bosons

Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} , \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} , \quad \Phi_S = v_S + \rho_S$$

CP-even scalar sector: Mixing from gauge eigenstate to mass eigenstate basis

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix} , \quad R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}$$

Convention: $m_{h_1} < m_{h_2} < m_{h_3}, -\frac{\pi}{2} \leq \alpha_i \leq \frac{\pi}{2}$

Coupling to SM fermions:

$$-\mathcal{L}_{\rm Yuk} = \sum_{i=1}^{2} \frac{\sqrt{2} m_f}{v} c_{h_i f\bar{f}} \overline{\Psi}_f \Psi_f h_i$$

$$t_\beta = \frac{v_2}{v_1}$$

	$c_{h_i b\bar{b}}$	$c_{h_i t\bar{t}}$	$c_{h_i \tau\bar{\tau}}$
type I	R_{i2}/s_β	R_{i2}/s_β	R_{i2}/s_β
type II	R_{i1}/c_β	R_{i2}/s_β	R_{i1}/c_β
lepton-specific	R_{i2}/s_β	R_{i2}/s_β	R_{i1}/c_β
flipped	R_{i1}/c_β	R_{i2}/s_β	R_{i2}/s_β

S2HDM: Singlet-extended 2 Higgs doublet model

ϕ_1, ϕ_2: SU(2) doublets, ϕ_S: SM singlet, charged under global U(1)

Scalar potential:

$$V = \mu_{11}^2 \left(\phi_1^\dagger \phi_1\right) + \mu_{22}^2 \left(\phi_2^\dagger \phi_2\right) - \mu_{12}^2 \left(\left(\phi_1^\dagger \phi_2\right) + \left(\phi_2^\dagger \phi_1\right)\right) + \frac{1}{2}\mu_S^2 \left|\phi_S\right|^2 - \frac{1}{4}\mu_\chi^2 \left(\phi_S^2 + (\phi_S^*)^2\right)$$
$$+ \frac{1}{2}\lambda_1 \left(\phi_1^\dagger \phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 + \lambda_3 \left(\phi_1^\dagger \phi_1\right)\left(\phi_2^\dagger \phi_2\right) + \lambda_4 \left(\phi_1^\dagger \phi_2\right)\left(\phi_2^\dagger \phi_1\right)$$
$$+ \frac{1}{2}\lambda_5 \left(\left(\phi_1^\dagger \phi_2\right)^2 + \left(\phi_2^\dagger \phi_1\right)^2\right) + \frac{1}{2}\lambda_6 \left(|\phi_S|^2\right)^2 + \lambda_7 \left(\phi_1^\dagger \phi_1\right)|\phi_S|^2 + \lambda_8 \left(\phi_2^\dagger \phi_2\right)|\phi_S|^2$$

EW vacuum: $\langle\phi_1\rangle = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}$, $\langle\phi_2\rangle = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}$, $\langle\phi_S\rangle = v_S/\sqrt{2} \quad \in \mathbb{R}$

BSM particles:

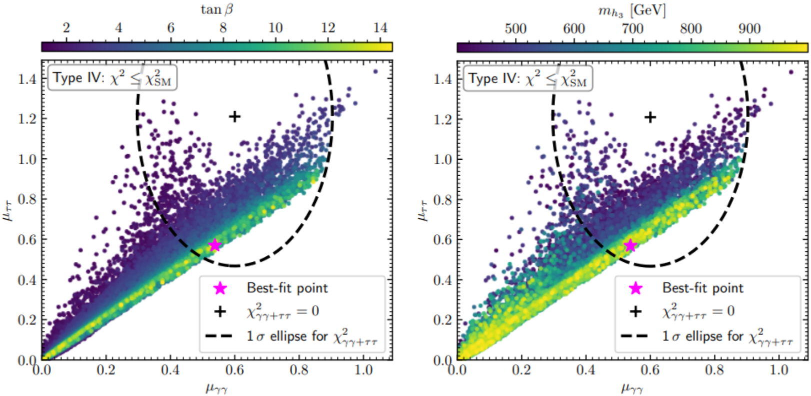
- $h_{1,2,3}$: CP-even Higgs bosons
- $H^\pm$: Charged Higgs bosons
- A: CP-odd Higgs boson
- χ: pNG DM

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R(\alpha_1, \alpha_2, \alpha_3) \cdot \begin{pmatrix} \mathrm{Re}(\phi_1^0) \\ \mathrm{Re}(\phi_2^0) \\ \mathrm{Re}(\phi_S^0) \end{pmatrix}$$

Free parameters (Yukawa type II):

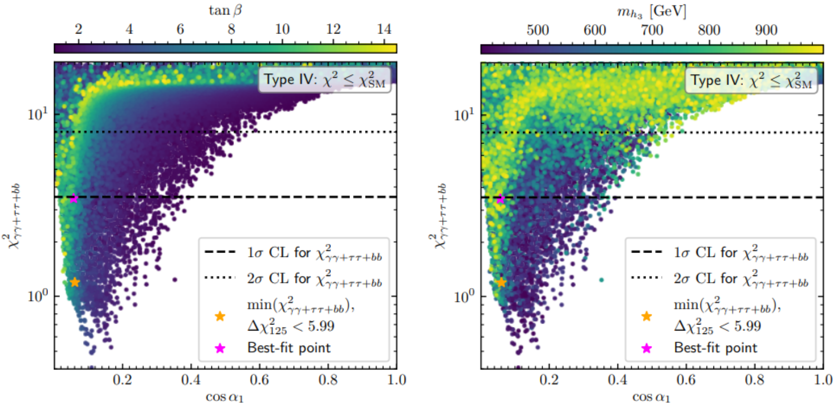
$$m_{h_{1,2,3}}\ , \quad m_A\ , \quad m_{H^\pm}\ , \quad m_\chi\ , \quad \alpha_{1,2,3}\ , \quad \tan\beta\ , \quad M = \sqrt{\mu_{12}^2/\left(s_\beta c_\beta\right)}\ , \quad v_S$$

Favoured parameter space



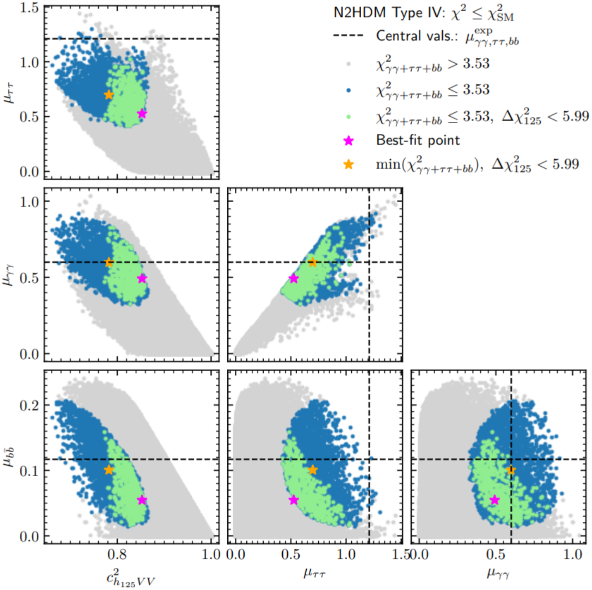
[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

Favoured parameter space



[TB, S. Heinemeyer, G. Weiglein, 2203.13180]

Correlations of $\mu_{\gamma\gamma}$, $\mu_{\tau\tau}$, μ_{bb} and $c^2_{h_{125}VV}$



[TB, S. Heinemeyer, G. Weiglein, 2203.13180]