# Mounting evidence for a 95 GeV Higgs boson

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in collaboration with Sven Heinemeyer and Georg Weiglein

[2203.13180]

2HDM group meeting

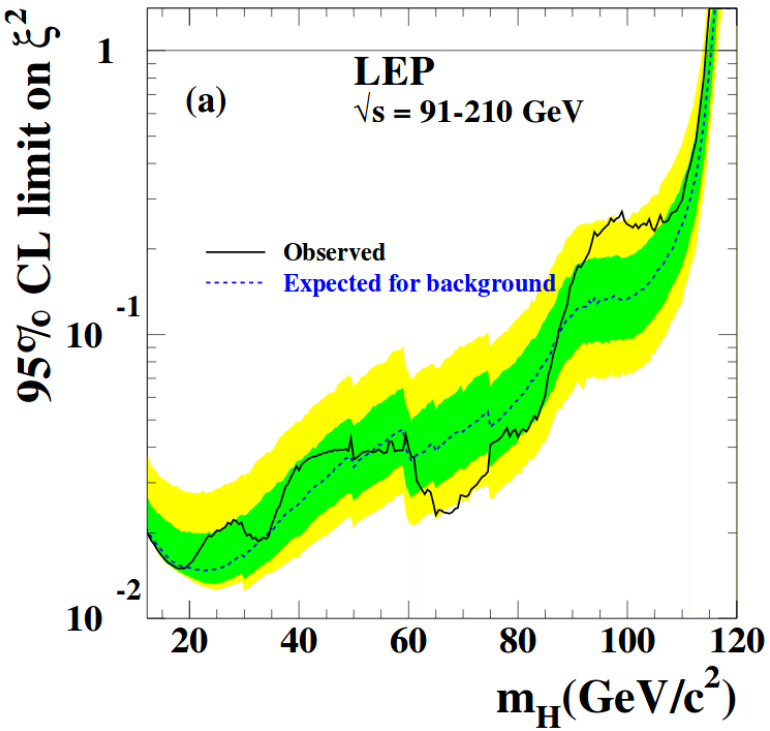
April 7 2021


CLUSTER OF EXCELLENCE

QUANTUM UNIVERSE

# Previously on the 95 GeV excesses

# "The 95GeV excesses"

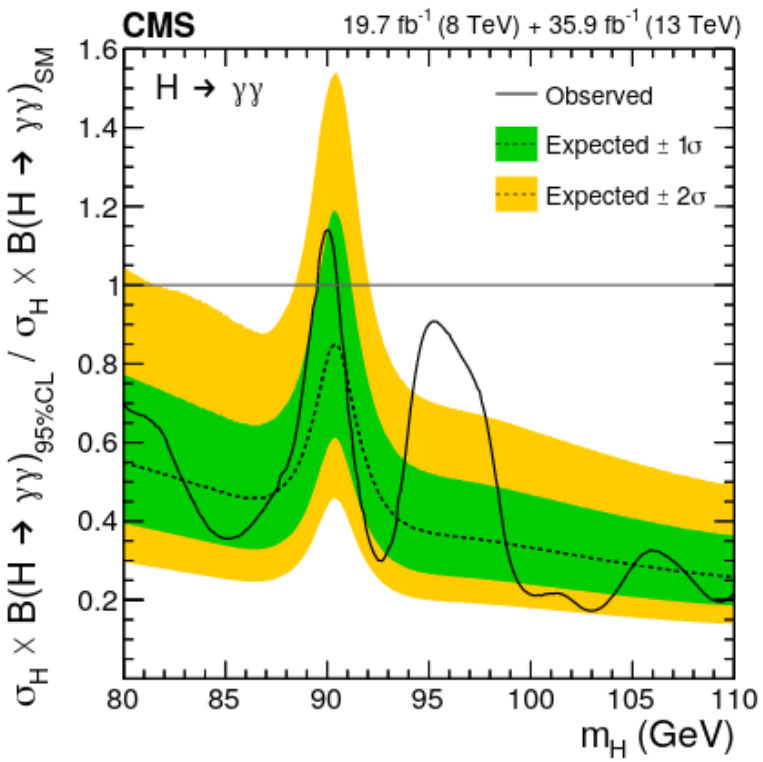



[LEP: hep-ex/0306033]

$\sim 2\sigma$ 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]

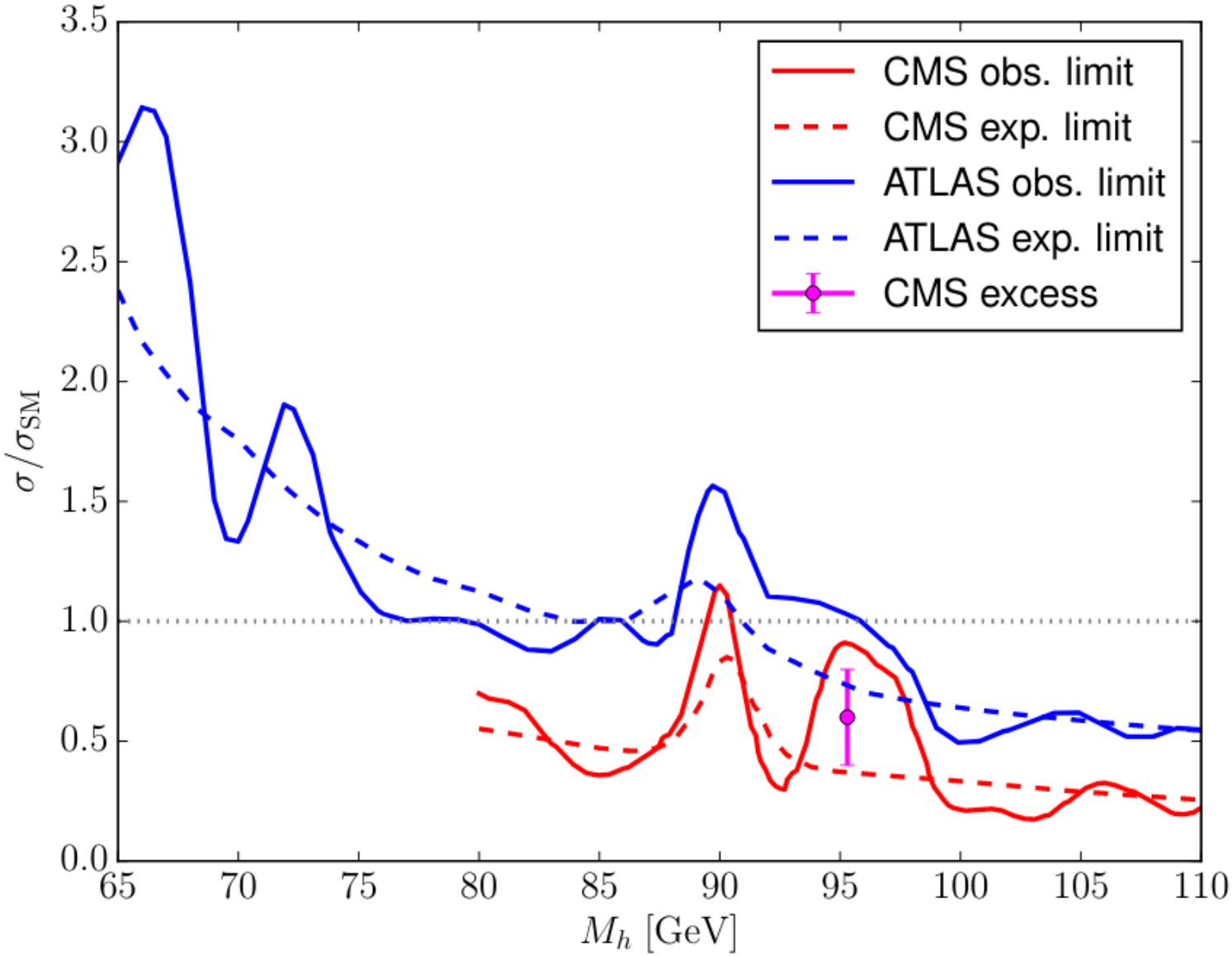
Run I/II data: Local excess of $\sim 3\sigma$

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

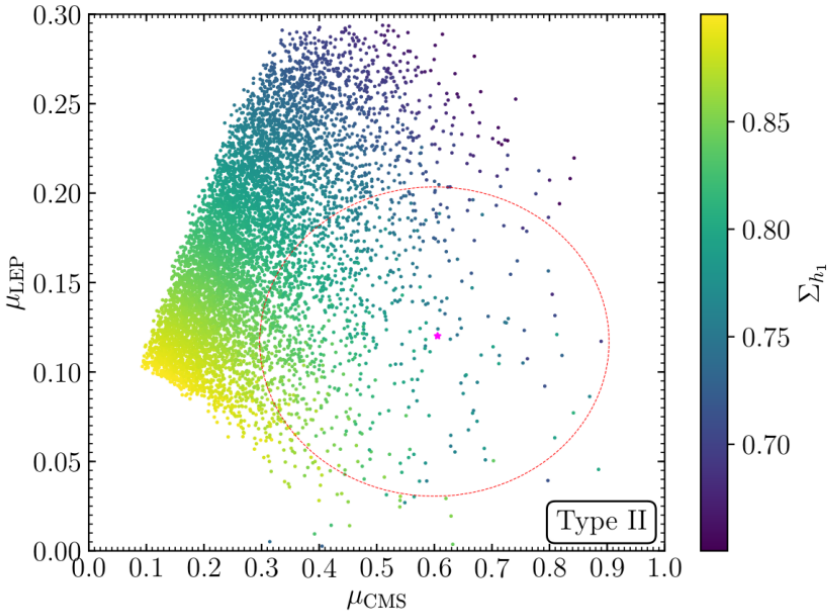
see [T.B, M. Chakraborti, S. Heinemeyer: 2003.05422] for a list models

# What ATLAS had to say so far

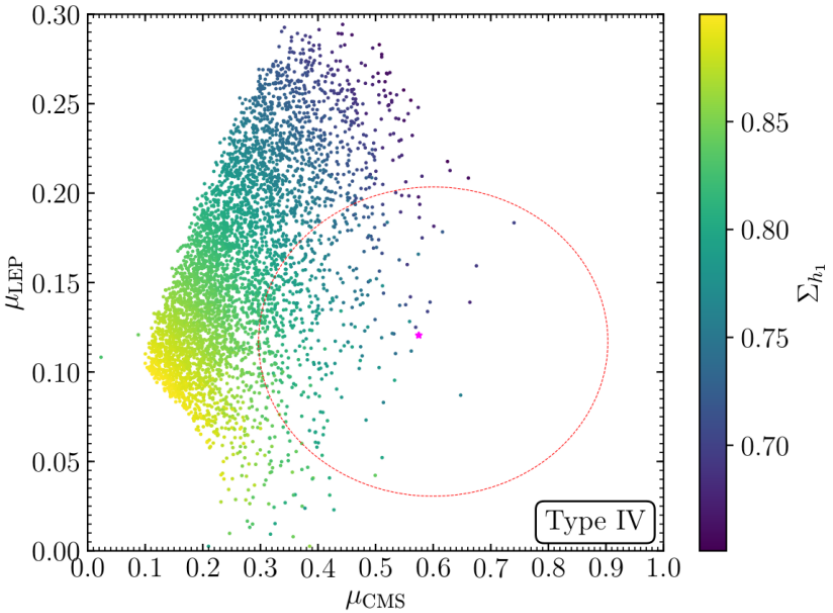



[1812.05864]

# N2HDM interpretations




(a) Type II




(b) Type IV (flipped)

[1903.11661]

## TLDR: N2HDM Type II and Type IV work

See also [2109.01128] for interpretation in combination with a 400 GeV pseudoscalar

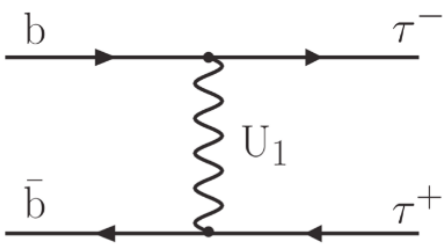
# Why am I talking about it again?

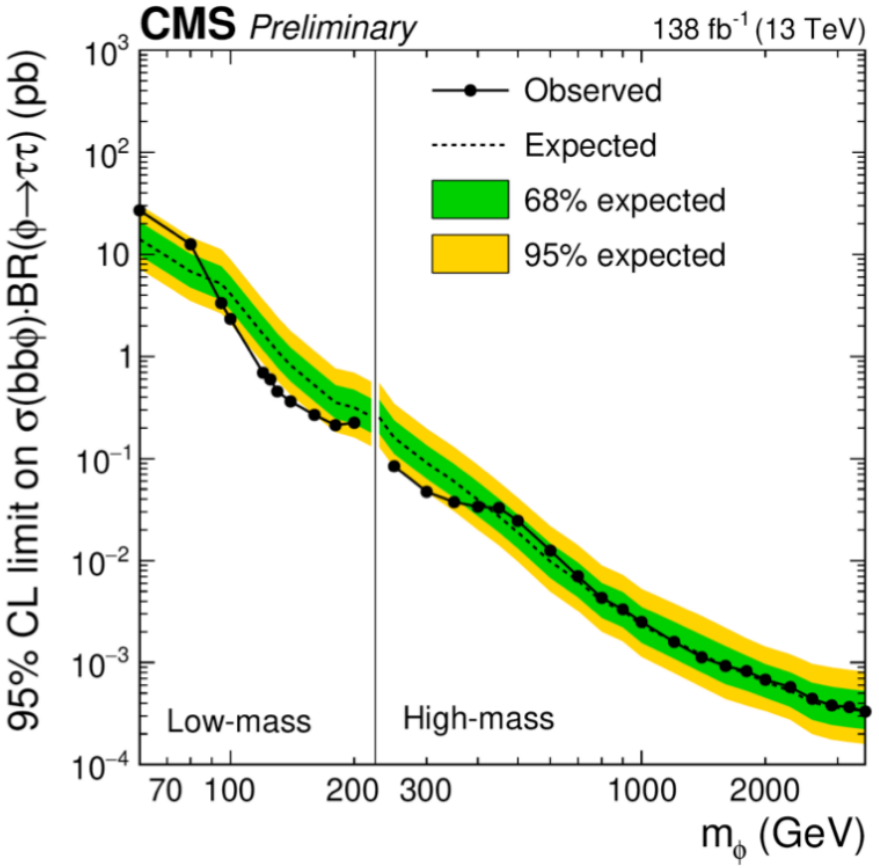
# CMS: Searches for additional Higgs bosons in $\tau^+\tau^-$ final states

Both production channels exploited, bbH and ggH, using all Run 2 CMS data, in a wide range of masses (60-3500 GeV), extending a lot both at low and high mass

Local excess seen in two mass regions in the ggH channel, the one at 100 GeV particularly interesting due to the previous 95 GeV excess in $\gamma\gamma$ (however no excess in bbH channel as expected for high $tan\beta$)

Data interpreted in terms of MSSM Higgs limits, but also for vector-like leptoquarks in the t-channel




[CMS-HIG-21-001] (Alexei Raspereza et al.)

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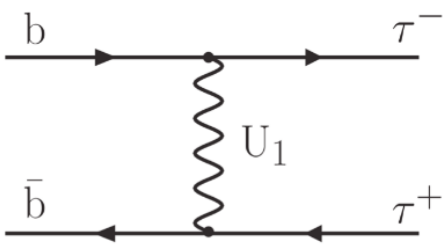


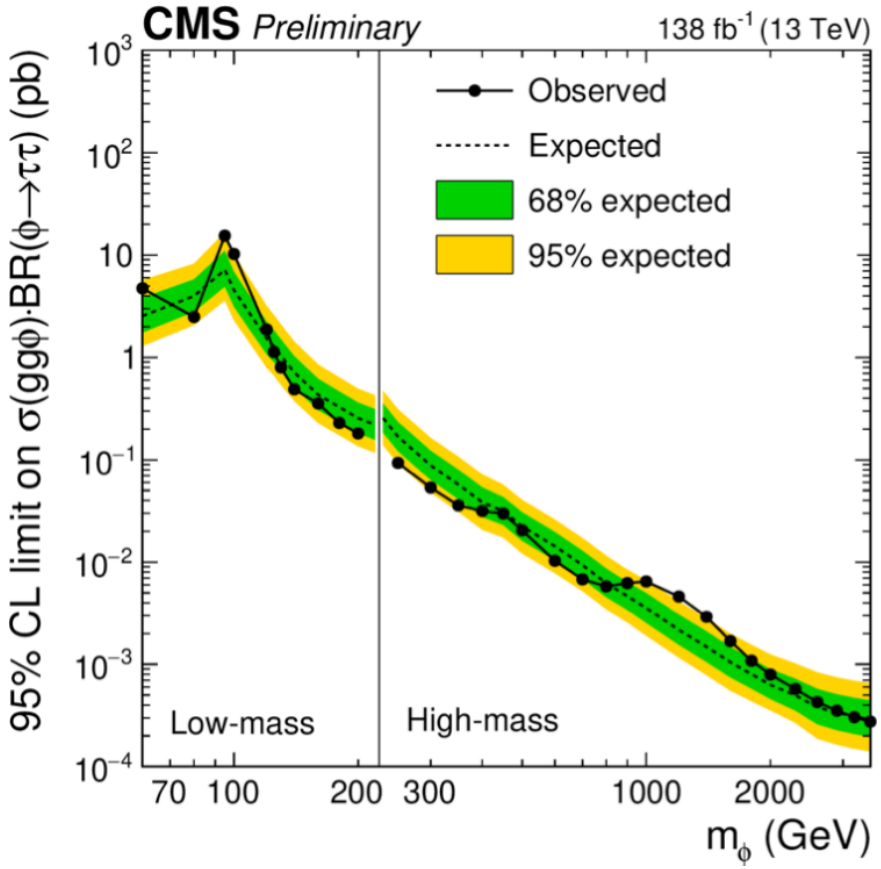


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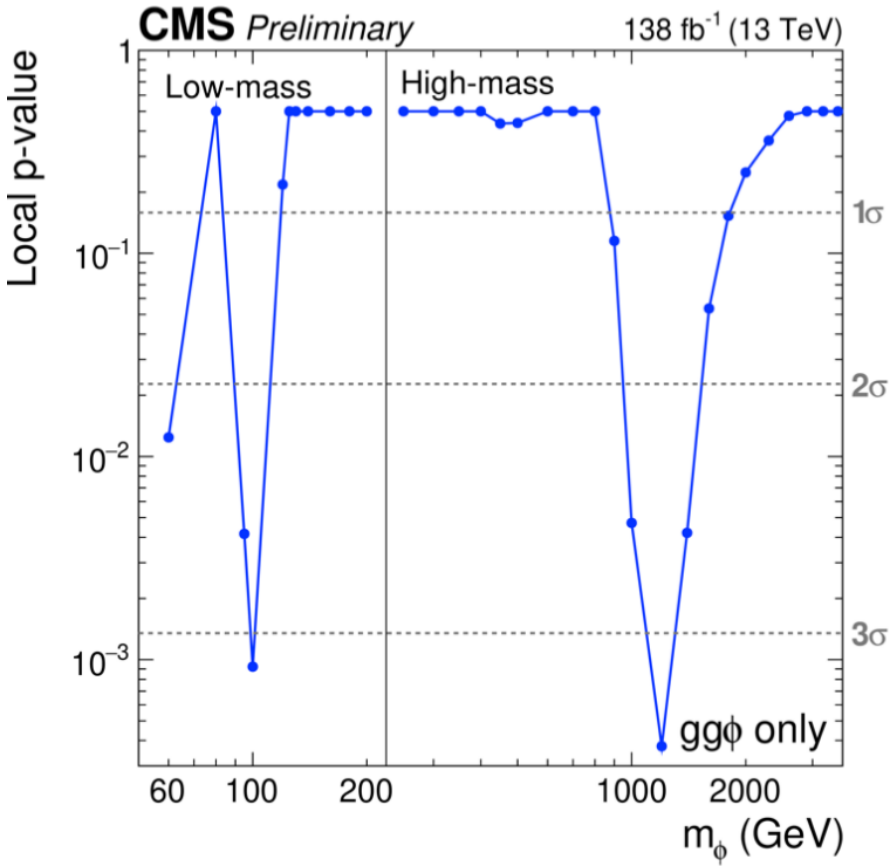


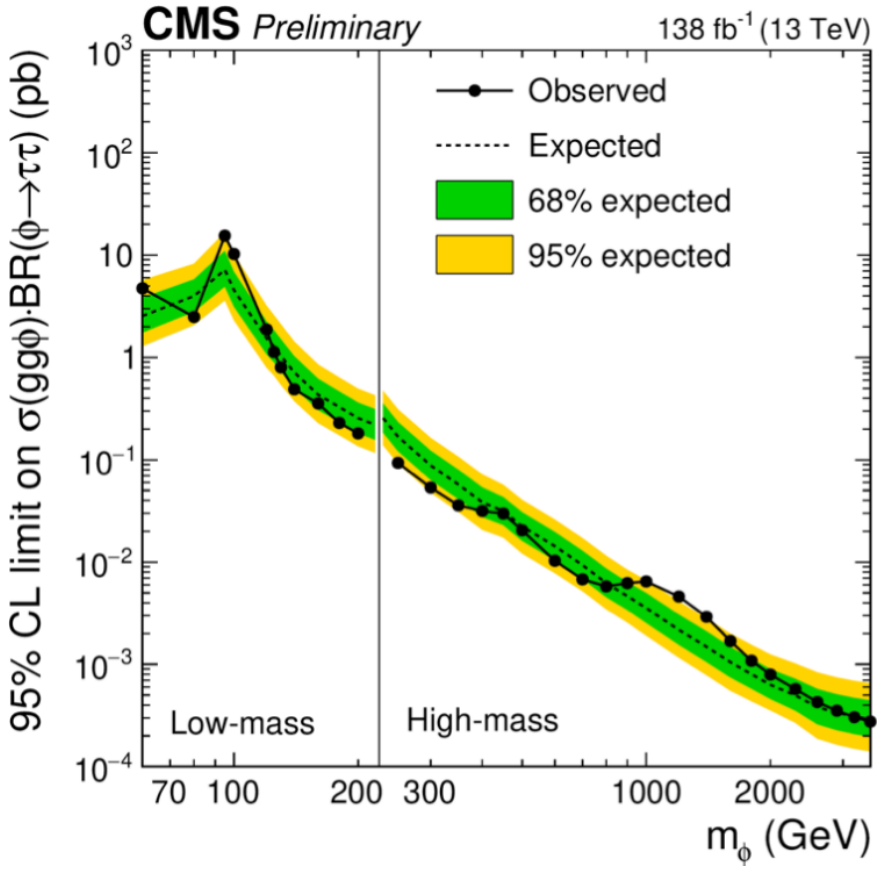


[CMS-HIG-21-001] (Alexei Raspereza et al.)

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

# The Next-to 2 Higgs Doublet Model: N2HDM

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

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## Higgs sector

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

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 $v_s$

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

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

| Type | $u$-quarks | $d$-quarks | leptons |
|---|---|---|---|
| I | $\phi_2$ | $\phi_2$ | $\phi_2$ |
| II (Susy-like) | $\phi_2$ | $\phi_1$ | $\phi_1$ |
| III (lepton-specific) | $\phi_2$ | $\phi_2$ | $\phi_1$ |
| IV (flipped) | $\phi_2$ | $\phi_1$ | $\phi_2$ |

# The broken phase

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

## Electroweak symmetry breaking

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

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

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

Coupling to SM fermions:

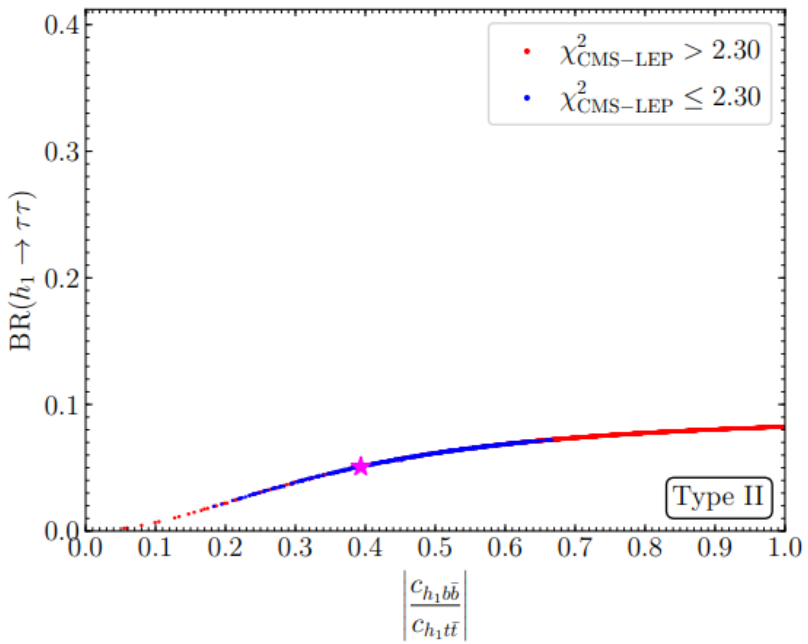
$$-\mathcal{L}_{\text{Yuk}} = \sum_{i=1}^{2} \frac{\sqrt{2} m_f}{v} c_{h_i f \bar{f}} \overline{\Psi}_f \Psi_f h_i$$

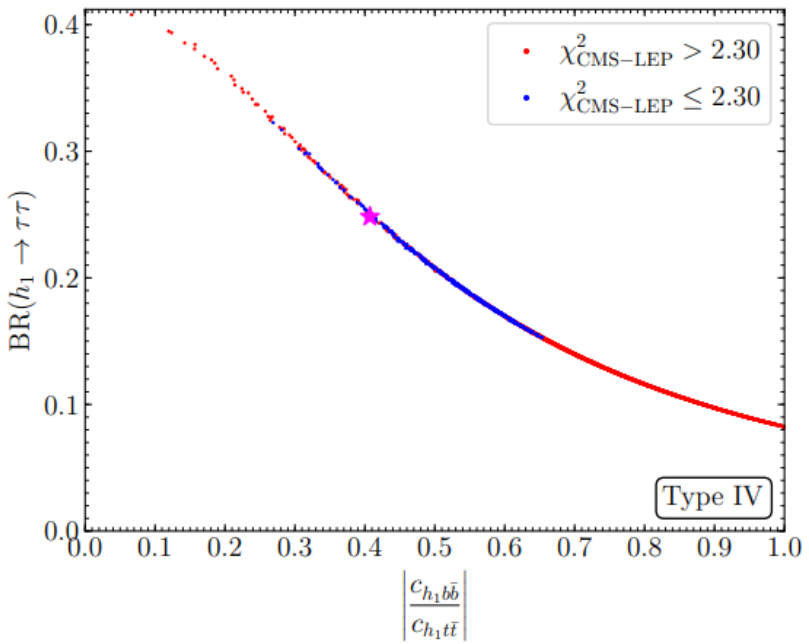
$$t_\beta = \frac{v_2}{v_1}$$

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

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

From the previous paper:



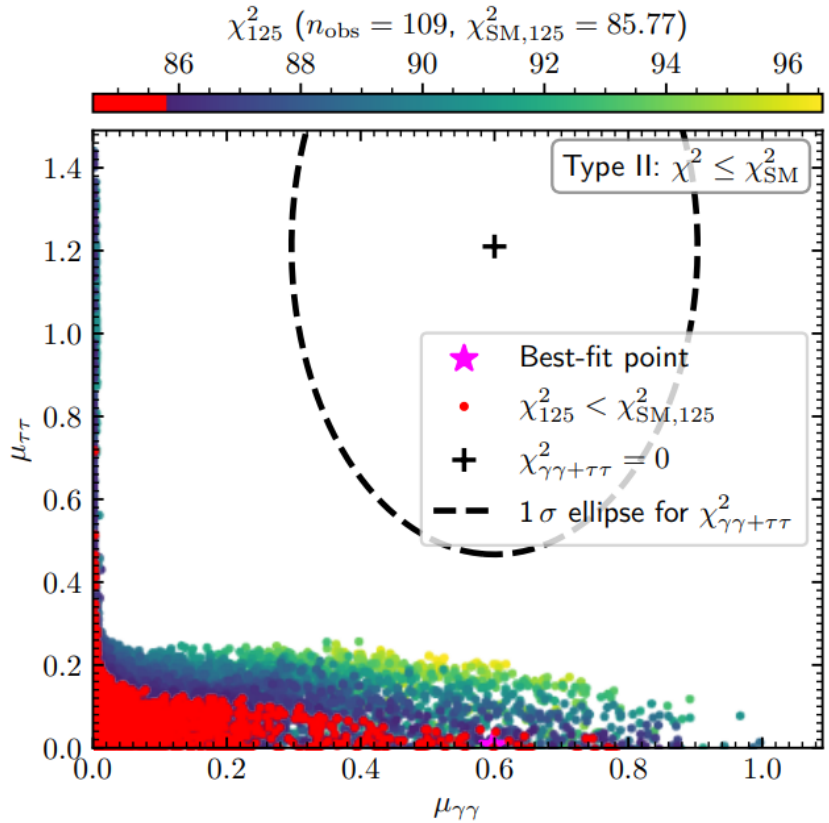



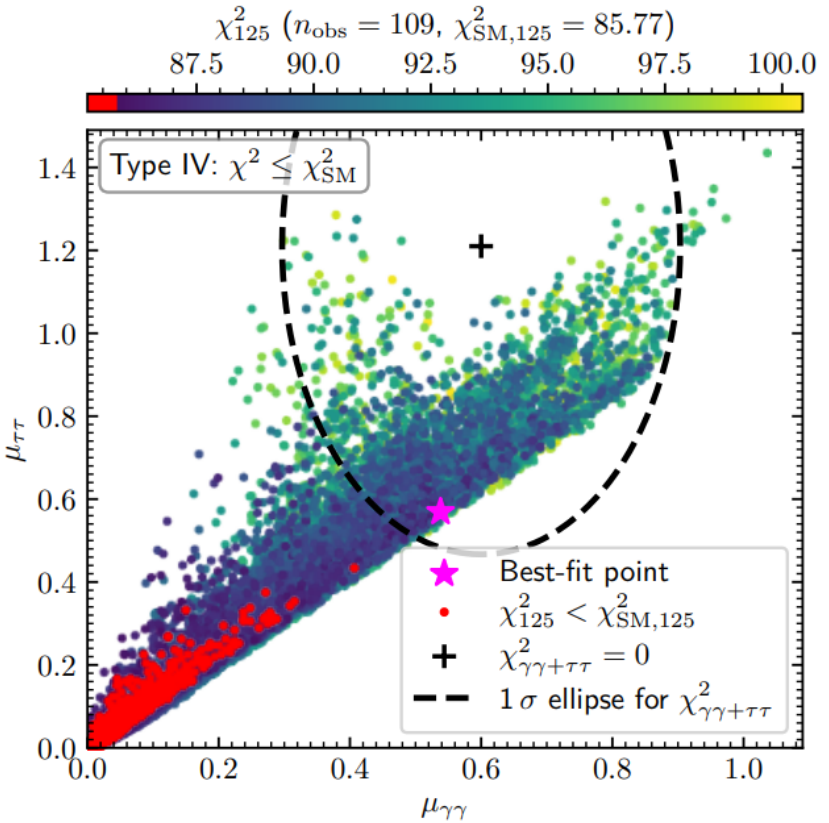

[1903.11661]

TLDR: Type II is probably not going to work, but maybe type IV?

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

So we went and tried it out:



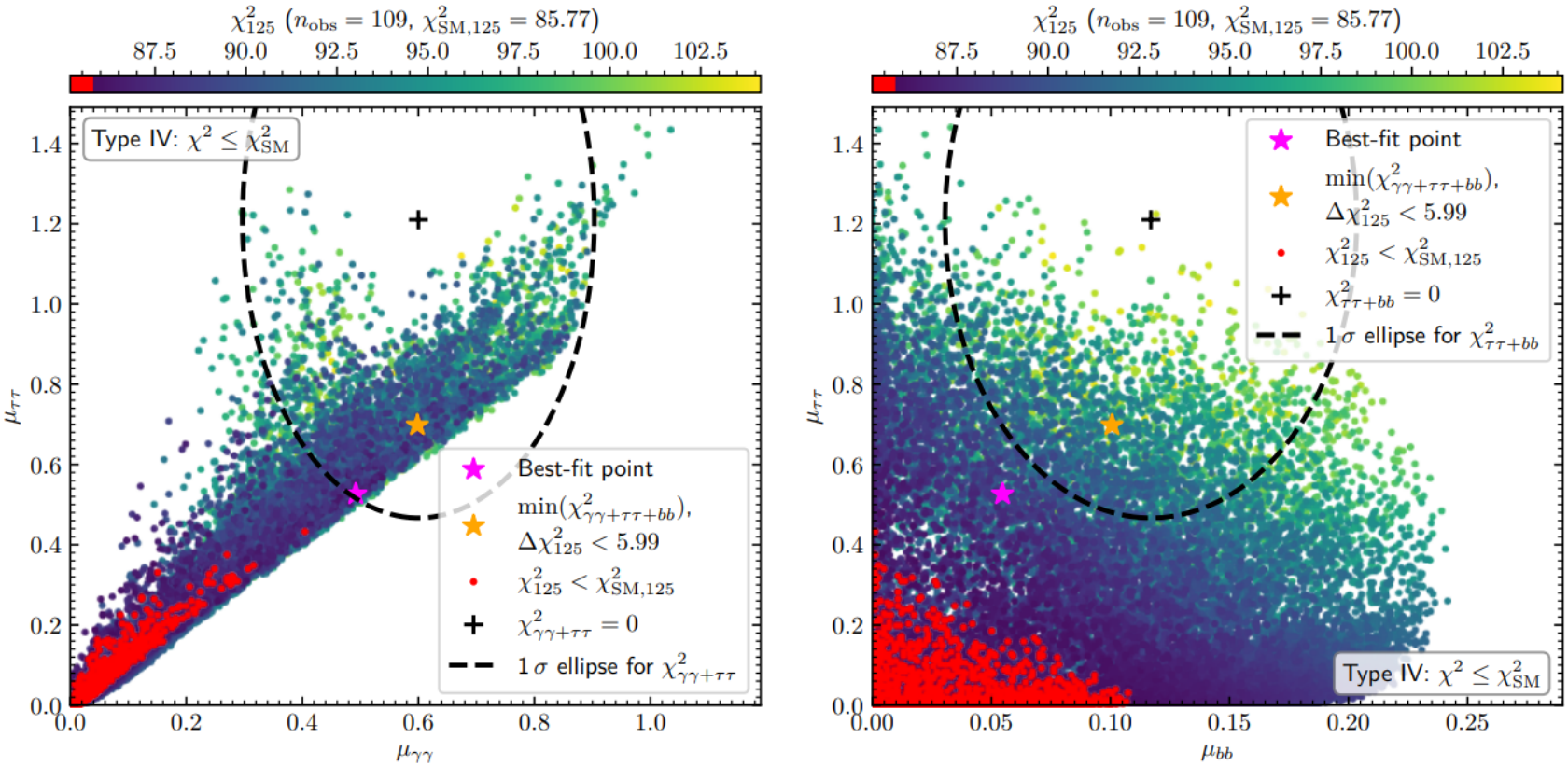

[2203.13180]

TLDR: Type II doesn't work, but type IV does!

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

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

Can we additionally explain the LEP excess?

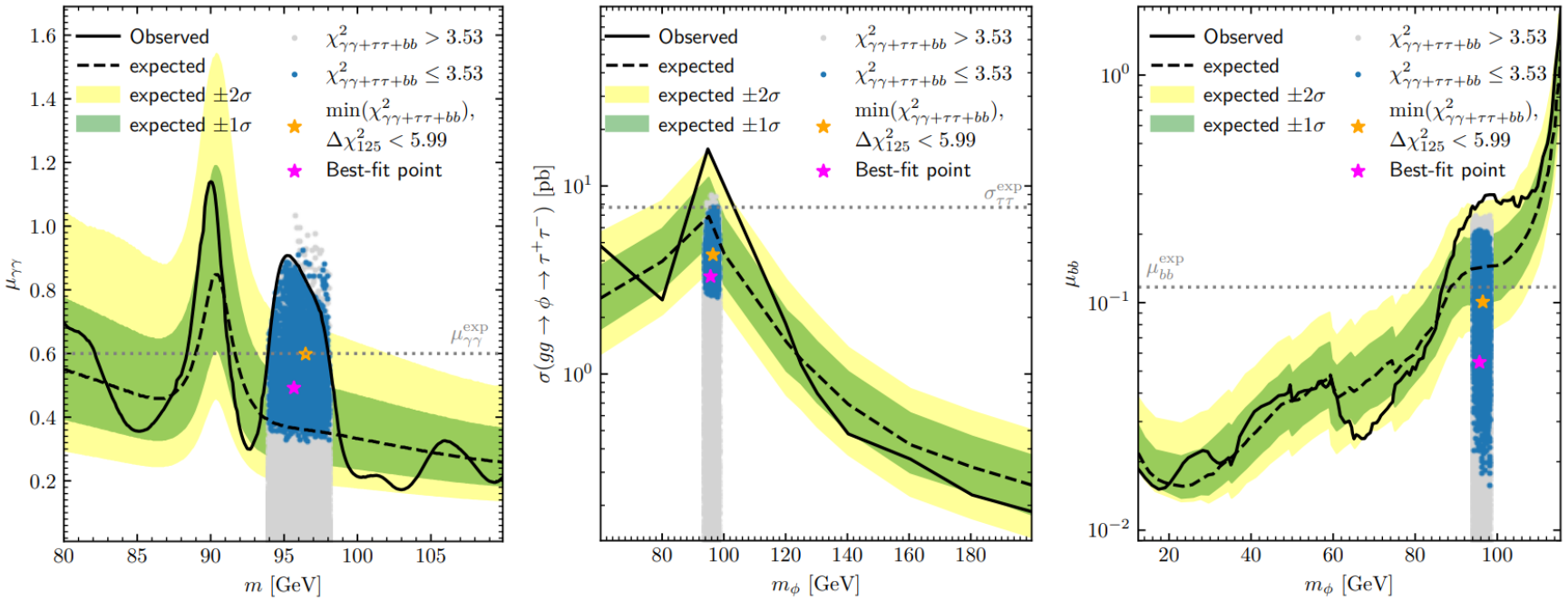



[2203.13180]

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

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

Many good (blue) points![1]




[2203.13180]

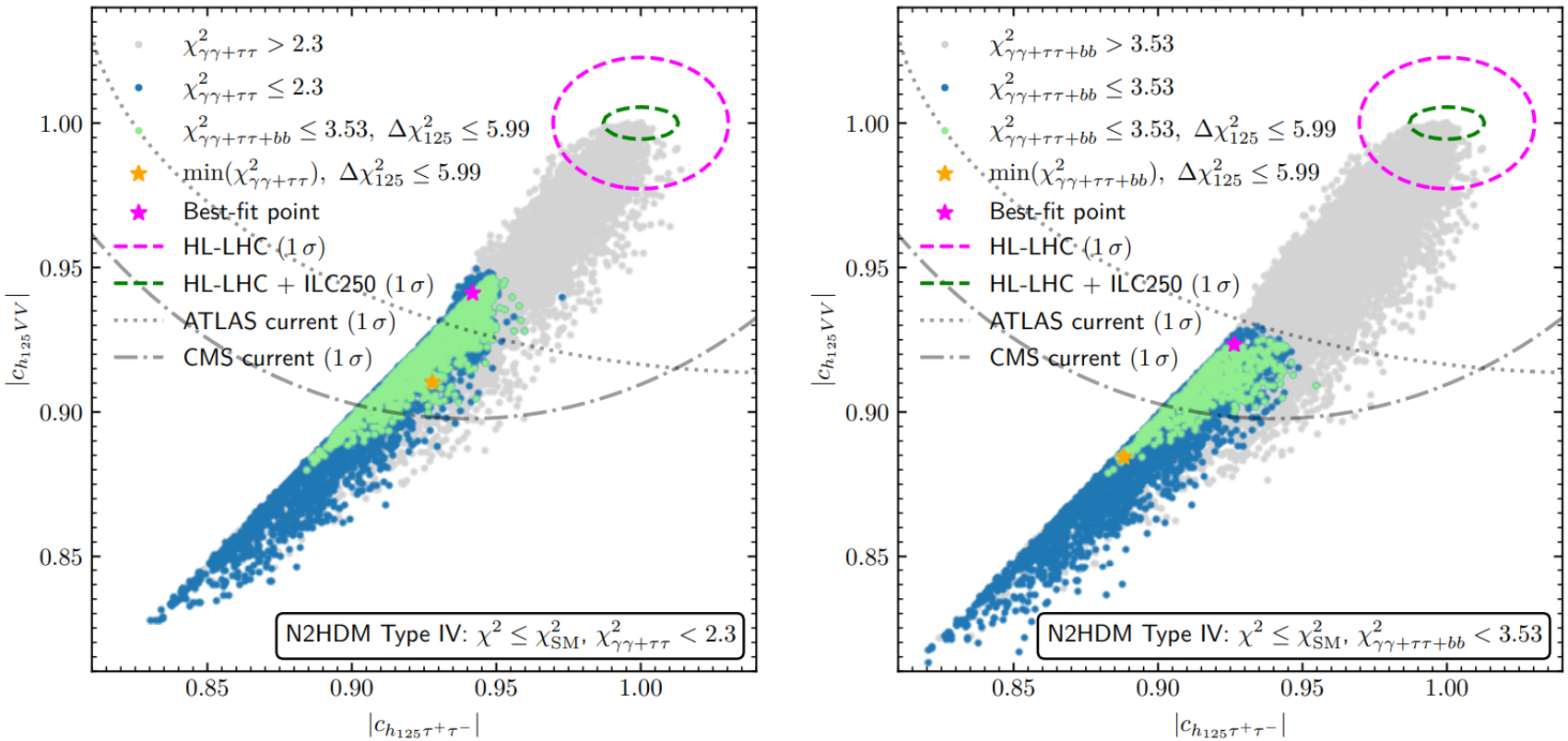
$$\chi^2 = \chi^2_{\gamma\gamma} + \chi^2_{\tau\tau} + \chi^2_{bb} + \chi^2_{125}$$

$\chi^2_{125}$: HiggsSignals

[1] Blue = Describe the excesses within $1\sigma$ confidence level: $\chi^2 \leq 3.53$

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

Can be probed indirectly via $h_{125}$:




[2203.13180]

TLDR: HL-LHC precision sufficient to probe the scenario

# Conclusions

Three local excesses ($3\sigma + 3\sigma + 2\sigma$) at the same mass

$\rightarrow$ two different production modes (ggF and Higgsstrahlung)

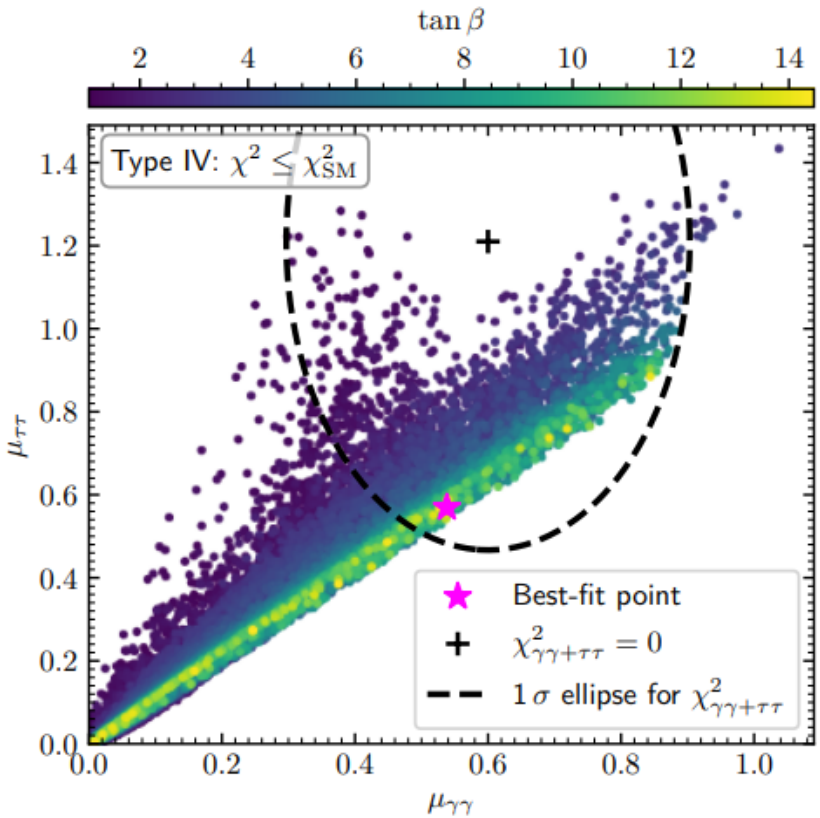
$\rightarrow$ three different decay modes ($\gamma\gamma$, $\tau\tau$, $bb$)

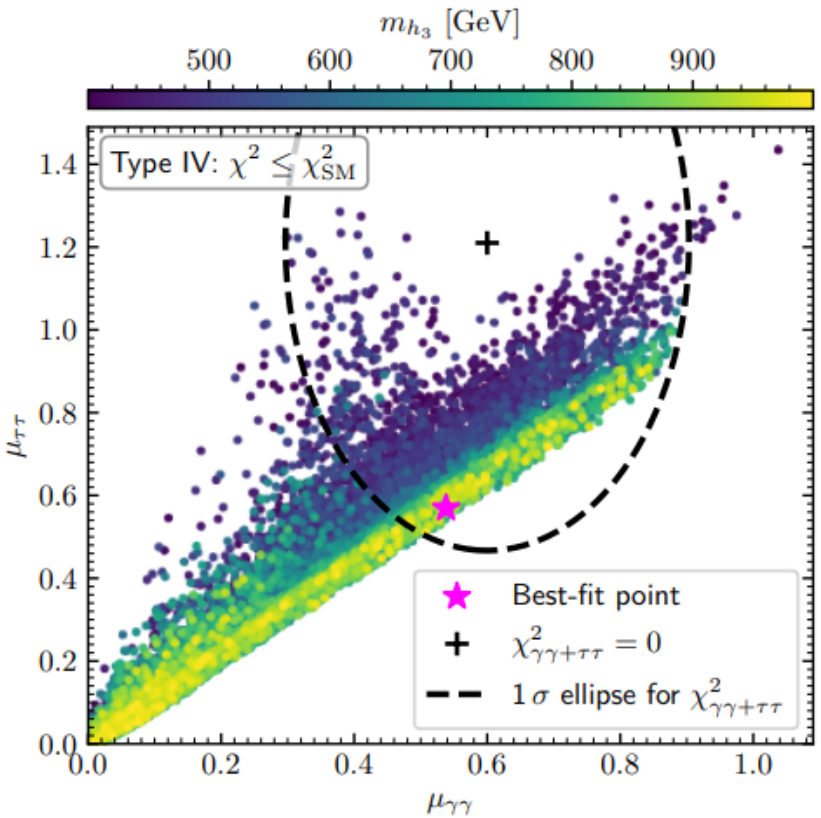
Can be described economically in the N2HDM (no weird stuff)

Personal conlusion: This is interesting

**Thanks!**

# Favoured parameter space



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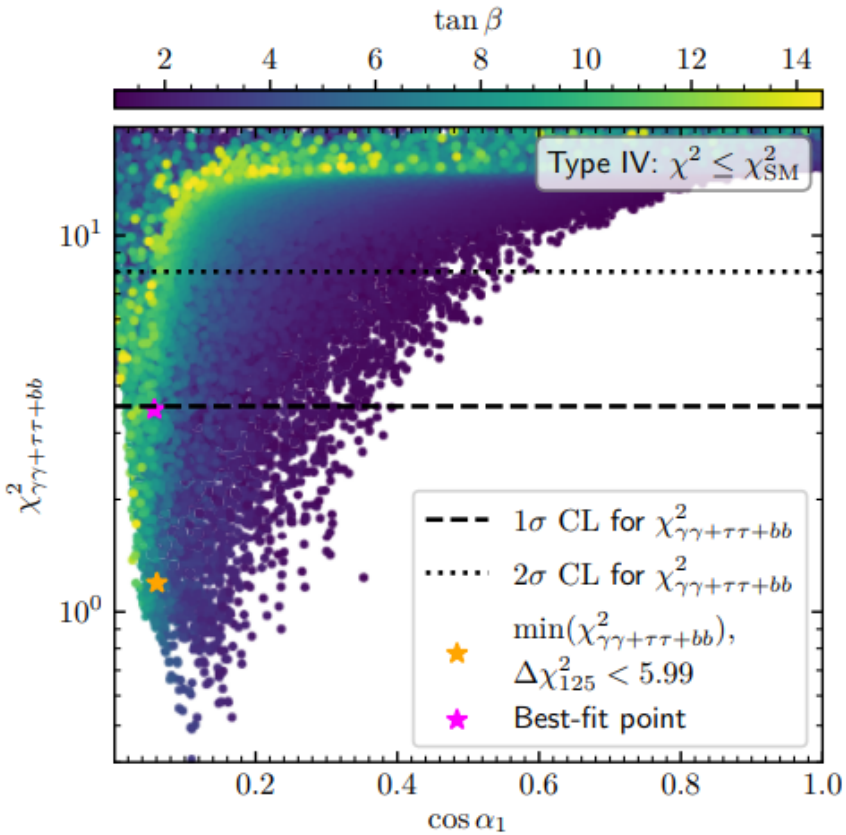


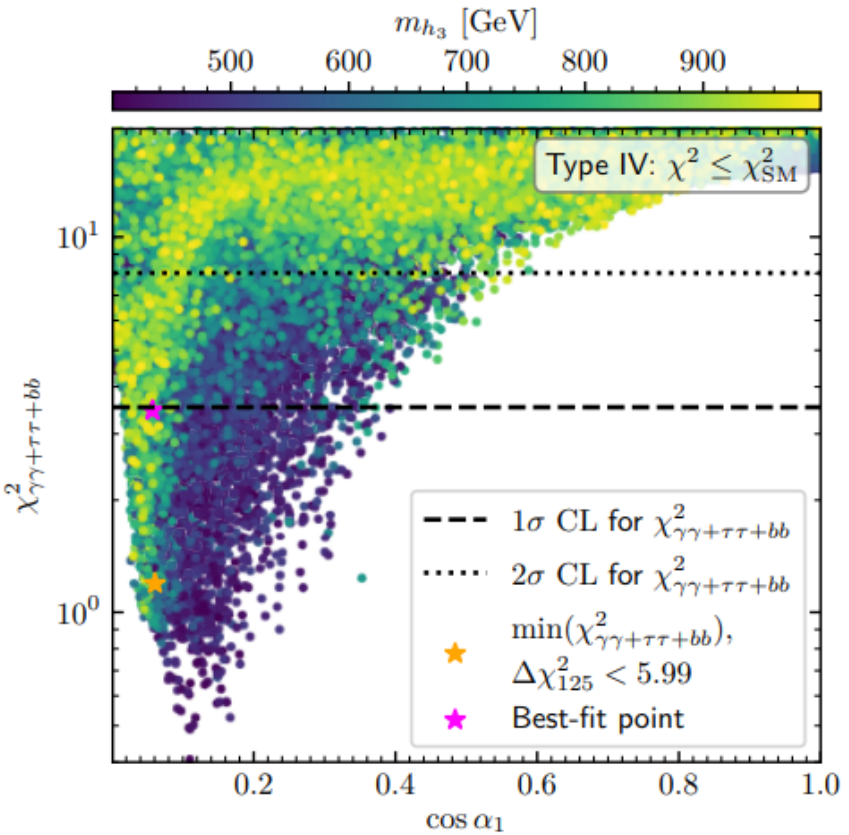

# Correlations of $\mu_{\gamma\gamma}$, $\mu_{\tau\tau}$, $\mu_{bb}$ and $c^2_{h_{125}VV}$