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Probing light Higgs boson with 96 GeV in di-photon channel

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Outline

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   - YUKAWA couplings
   - Alignment limit

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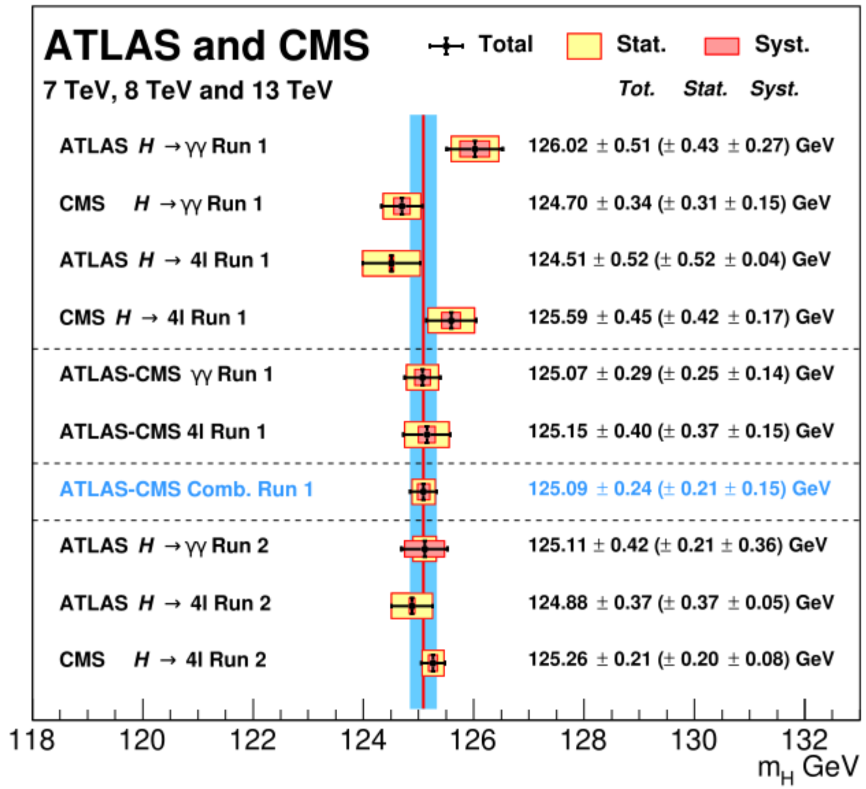
INTRODUCTION

- ✩ Higgs properties measurements at run 1 and run 2 are in a good agreement with the SM
- ✩ Perhaps other scalars are not yet discovered
- ✩ Two Higgs Doublet Model (2HDM)
  - ✩ Minimal extension to the SM
  - ✩ Rich collider phenomenology
  - ✩ LHC benchmark mode
    - ✩ Benchmarks for light/heavy charged Higgs
    - ✩ Benchmarks for light/heavy neutral Higgses

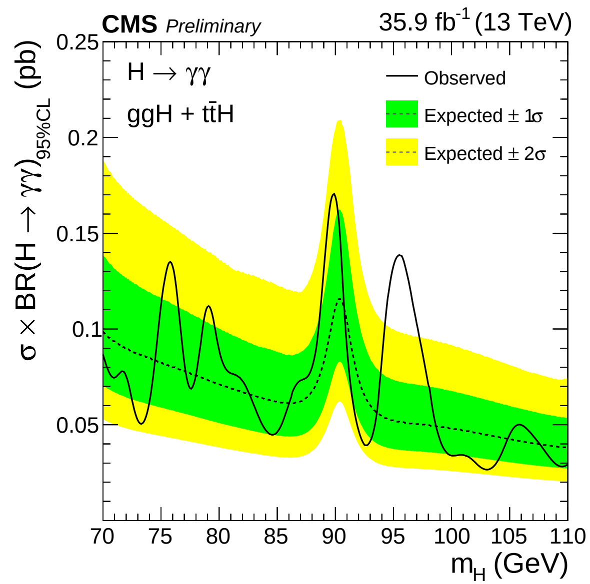


C. Patrignani et al., Particle Physics Group, Chin. Phys. C, 40 100001

MOTIVATION

✩ **CMS reported a $\sim 3\sigma$ local excess at $\sim$ 96 GeV**

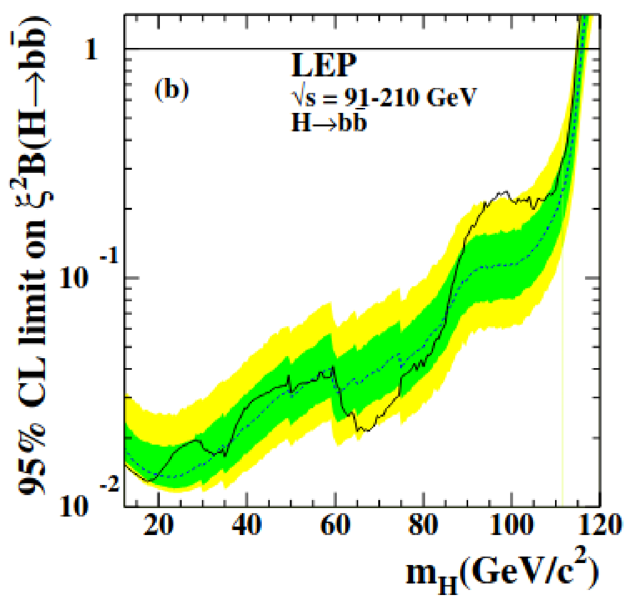
$$\mu^{\gamma\gamma}_{CMS} = \frac{\sigma(gg\to h)}{\sigma_{SM}(gg\to h)} \times \frac{\mathcal{BR}(h\to\gamma\gamma)}{\mathcal{BR}_{SM}(h\to\gamma\gamma)} = |c_{htt}|^2 \times \frac{\mathcal{BR}(h\to\gamma\gamma)}{\mathcal{BR}_{SM}(h\to\gamma\gamma)} = 0.6 \pm 0.2.$$



Phys.Lett.B 793 (2019) 320

✩ **LEP reported a $\sim 2\sigma$ local excess at $\sim$ 98 GeV**

$$\mu^{bb}_{LEP} = \frac{\sigma(e^+e^-\to Zh)}{\sigma_{SM}(e^+e^-\to Zh)} \times \frac{\mathcal{BR}(h\to b\bar{b})}{\mathcal{BR}_{SM}(h\to b\bar{b})} = |c_{hZZ}|^2 \times \frac{\mathcal{BR}(h\to b\bar{b})}{\mathcal{BR}_{SM}(h\to b\bar{b})} = 0.117 \pm 0.057.$$



Phys.Lett.B 565 61-75,2003

2HDM PARAMETRIZATION

- The most general scalar potential of the 2HDM :

$$
\begin{aligned}
V(\Phi_1\Phi_2) = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left[m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\
& + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
& + \left\{\frac{\lambda_5}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\lambda_6\left(\Phi_1^\dagger\Phi_1\right) + \lambda_7\left(\phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}
\end{aligned}
$$

with :

$$
\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ + i\varphi_{1,2}^+ \\ \frac{1}{\sqrt{2}}\left(v_{1,2} + \rho_{1,2} + i\eta_{1,2}\right) \end{pmatrix}
$$

- Adopting the $\mathcal{CP}$-conserving, the 10 independent parameters ($m_{11}^2,\ m_{22}^2,\ m_{12}^2,\ \lambda_{1,\ldots,7}$) are assumed to be real.
- After EWSB $\rightarrow$ 7 free parameters:
  - 4 Scalar physical states: $m_h,\ m_H,\ m_A,\ m_{H^\pm}$.
  - 2 mixing angels α, β, and m_{12}^2, (with $\tan\beta = \frac{v_2}{v_1}$ and $v^2 = v_1^2 + v_2^2 = (246\ \text{GeV})^2$).

YUKAWA COUPLINGS

- Tree-level FCNCs allowed $\Longrightarrow$ both doublets can couple to leptons and quarks.
- The associated model is called **2HDM type-III.**
- The Yukawa Lagrangian in terms of physical scalar masses:

$$
\begin{aligned}
-\mathcal{L}_Y^{III} &= \sum_{f=u,d,\ell} \frac{m_j^f}{v}\left[(\xi_h^f)_{ij}\bar{f}_{Li}f_{Rj}h + (\xi_H^f)_{ij}\bar{f}_{Li}f_{Rj}H - i(\xi_A^f)_{ij}\bar{f}_{Li}f_{Rj}A\right] \\
&+ \frac{\sqrt{2}}{v}\sum_{k=1}^{3}\bar{u}_i\left[\left(m_i^u(\xi_A^{u*})_{ki}V_{kj}P_L + V_{ik}(\xi_A^d)_{kj}m_j^d P_R\right)\right] d_j H^+ \\
&+ \frac{\sqrt{2}}{v}\bar{\nu}_i(\xi_A^\ell)_{ij}m_j^\ell P_R \ell_j H^+ + h.c.\,,
\end{aligned}
$$

- To get naturally small **FCNCs**, one can use the ansatz formulated by: $\tilde{Y}_{ij} \propto \sqrt{m_i m_j}/v\,\chi_{ij}$

ϕ	$(\xi_\phi^u)_{ij}$	$(\xi_\phi^d)_{ij}$	$(\xi_\phi^\ell)_{ij}$
h	$\frac{c_\alpha}{s_\beta}\delta_{ij} - \frac{c_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
H	$\frac{s_\alpha}{s_\beta}\delta_{ij} + \frac{s_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
A	$\frac{1}{t_\beta}\delta_{ij} - \frac{1}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$

ALIGNMENT LIMIT

- In the Higgs-basis the alignment limit is most clearly exhibited :

$$H_1 = \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \Longrightarrow \langle H_1^0 \rangle = v/\sqrt{2},\ \langle H_2^0 \rangle = 0.$$

  with $\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i. \end{pmatrix}$

- The 2 physical Higgs states h et H are as follows:

$$\begin{aligned} H &= (\sqrt{2}\mathrm{Re}H_1^0 - v)\cos(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \sin(\beta-\alpha) \\ h &= (\sqrt{2}\mathrm{Re}H_1^0 - v)\sin(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \cos(\beta-\alpha) \end{aligned}$$

- $\cos(\beta-\alpha) \to 0$, $h \equiv H_{SM}$. (Standard hierarchy) [J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 92 (2015) no.7, 075004].

- $\sin(\beta-\alpha) \to 0$, $H \equiv H_{SM}$. (Inverted hierarchy) [J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 93 (2016) no.3, 035027].

CONSTRAINTS

Theoretical

- ☆ **Unitarity** constraints require a variety of scattering process to be unitary: specifically, the tree-level 2-to-2 body scattering matrix involving scalar-scalar, gauge–gauge and/or scalar-gauge initial and/or final states must have eigenvalues e_i's such that $|e_i| < 8\pi$.
- ☆ **Perturbativity** constraints impose the following condition on the quartic couplings of the scalar potential:$|\lambda_i| < 8\pi$
- ☆ **Vacuum stability** constraints require the potential be bounded from below and positive in any direction of the fields Φ_i, consequently, the parameter space must satisfy the following conditions:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1\lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1\lambda_2}.$$

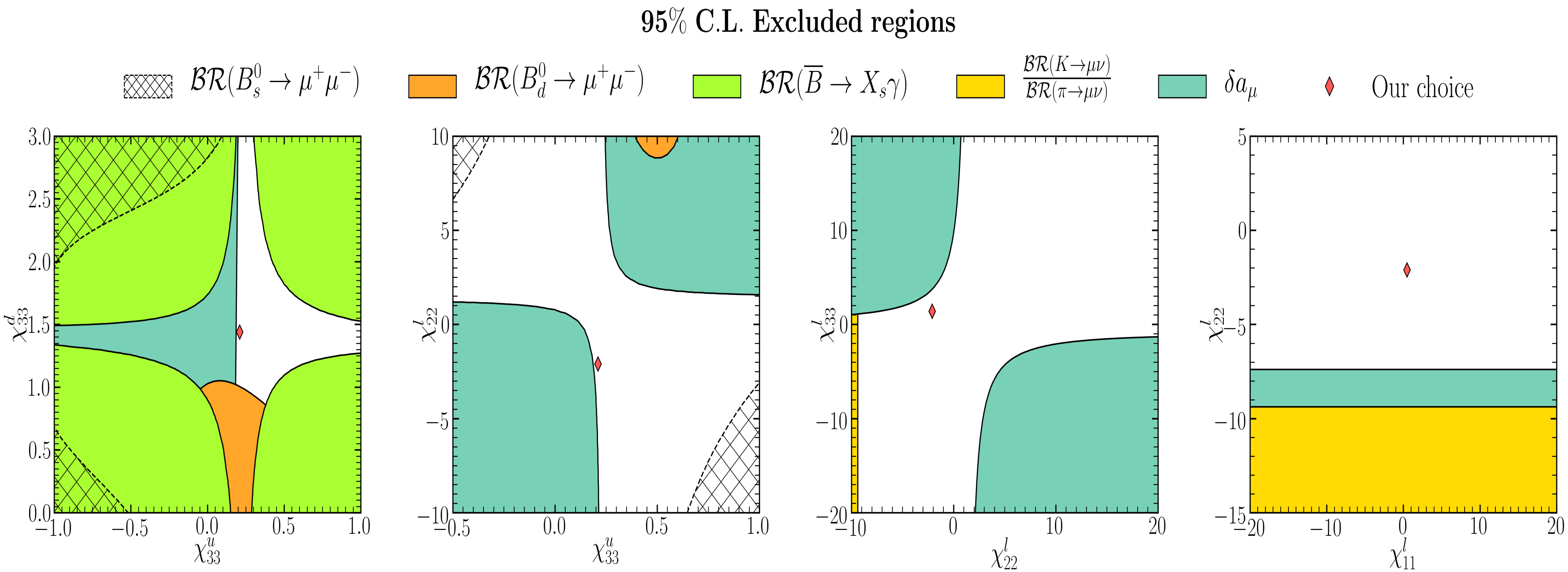
`2HDMC-1.8.0` (D. Eriksson, J. Rathsman and O. Stal [0902.0851])

Experimental

- ☆ **EWPOs**, implemented through the EW oblique parameters S, T, U `2HDMC-1.8.0`.
- ☆ **SM-like Higgs boson discovery**: an agreement between selected points in parameter space and the current measurements of the properties of the discovered Higgs boson at 125 GeV is enforced by means of the publicly available cod `HiggsSignals-2.6.1` [2012.09197] (P. Bechtle et al).
- ☆ **Non-SM-like Higgs boson exclusions**: to check the parameter space points against the exclusion limits from null Higgs boson searches at LEP, Tevatron and, in particular, the LHC, we apply the public code `HiggsBounds-5.10.1` [2006.06007] (P. Bechtle et al).
- ☆ **B-physics observables** are tested against data by resorting to the public code `SuperIso_v4.1` (F. Mahmoudi [0808.3144]), (mainly $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$, $\frac{\mathcal{BR}(K\to\mu\nu)}{\mathcal{BR}(\pi\to\mu\nu)}$).
- ☆ **Anomalous magnetic moment of the muon δa_μ**.

Numerical results

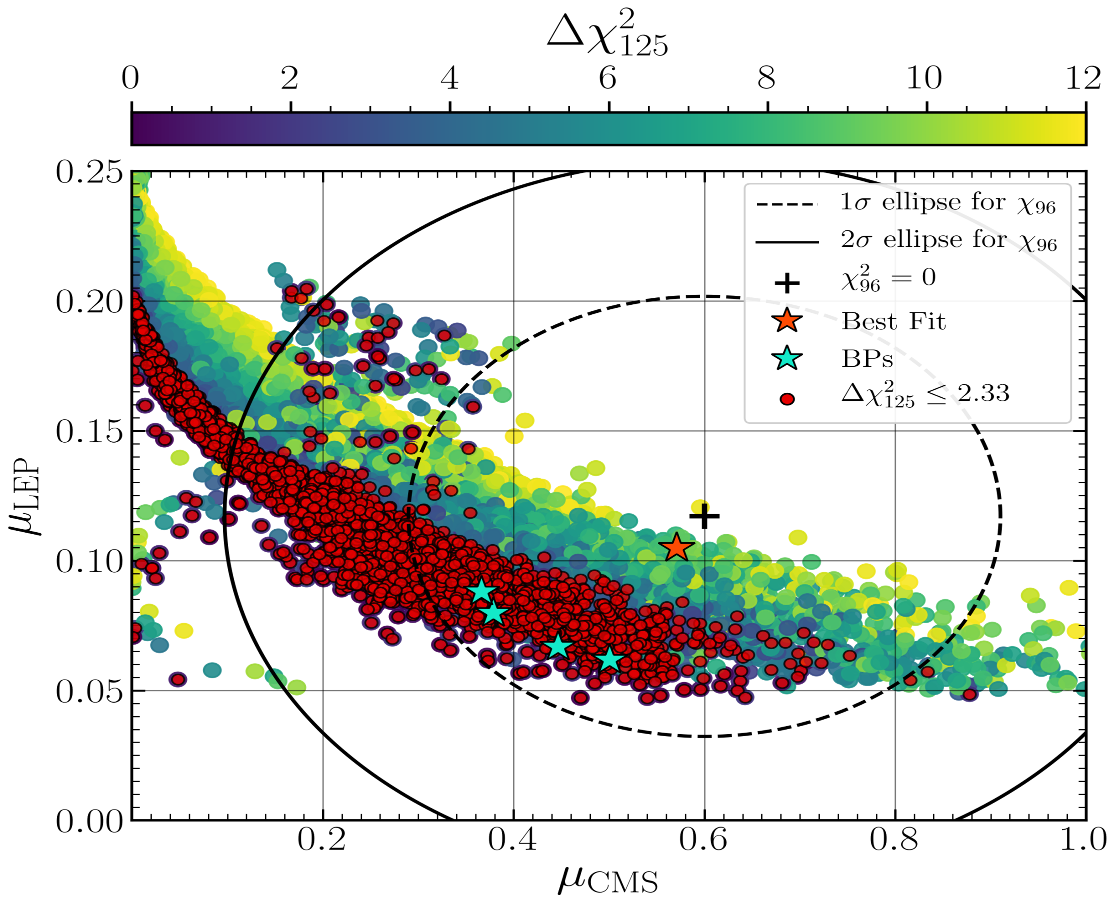
✭ The free parameters $\chi_{ij}^{u,d,l}$ are tested at the current constraints from B-physics observables.



$$\chi^u = \begin{pmatrix} 0.187 & 0 & 0 \\ 0 & 0.254 & 0 \\ 0 & 0 & 0.210 \end{pmatrix}, \chi^d = \begin{pmatrix} -0.553 & 0 & 0 \\ 0 & 2.863 & 0 \\ 0 & 0 & 1.440 \end{pmatrix}, \chi^l = \begin{pmatrix} 0.484 & 0 & 0 \\ 0 & -2.101 & 0 \\ 0 & 0 & 1.400 \end{pmatrix}$$

2HDM TYPE-III INTERPRETATION

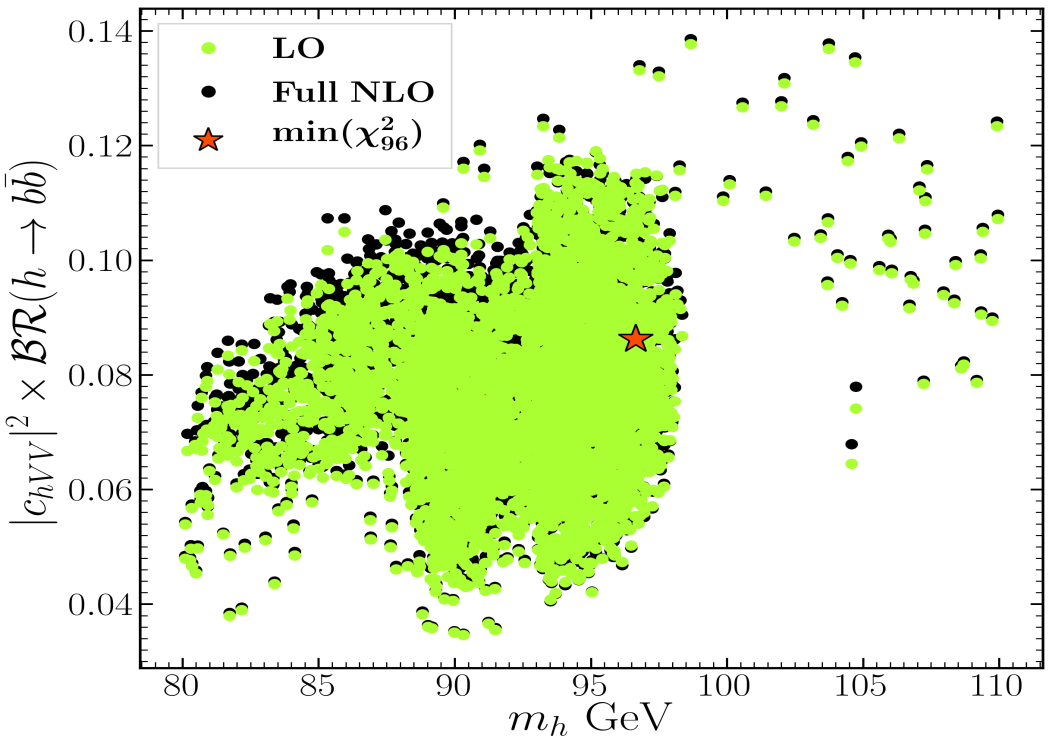
☆ Fitting to the excess: $\chi^2_{96} = \left(\frac{\mu^{bb}_{LEP} - 0.117}{0.057}\right)^2 + \left(\frac{\mu^{\gamma\gamma}_{CMS} - 0.6}{0.2}\right)^2 .$



☆ 2HDM type-III is able to fit both excesses simultaneously.

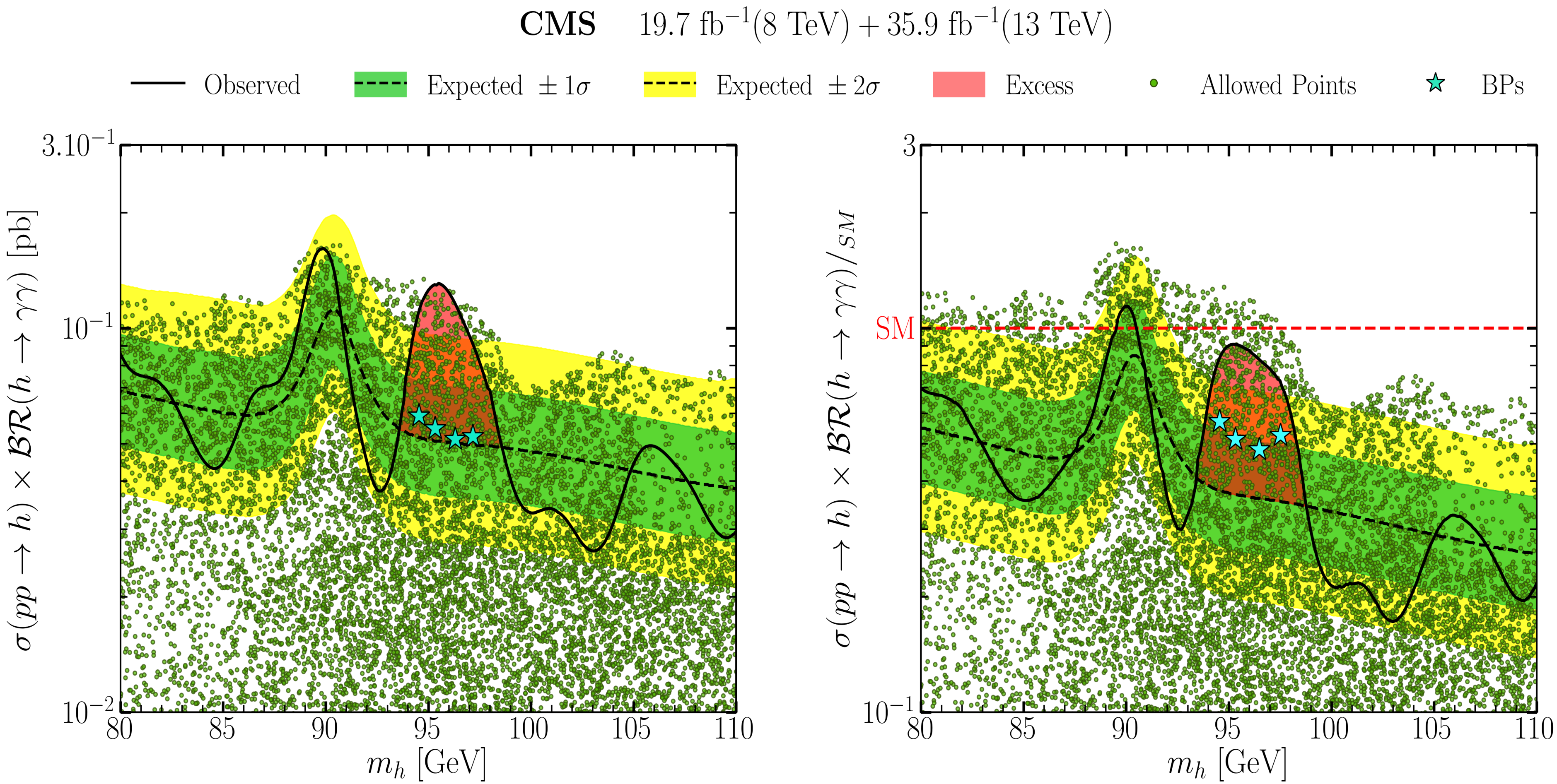
N2HDM can also fit both excesses, see Thomas's talk [T. Biekötter, S. Heinemeyer, Georg Weiglein: 2203.13180]
For more details see [2109.01128, 1903.11661]

2HDM TYPE-III INTERPRETATION



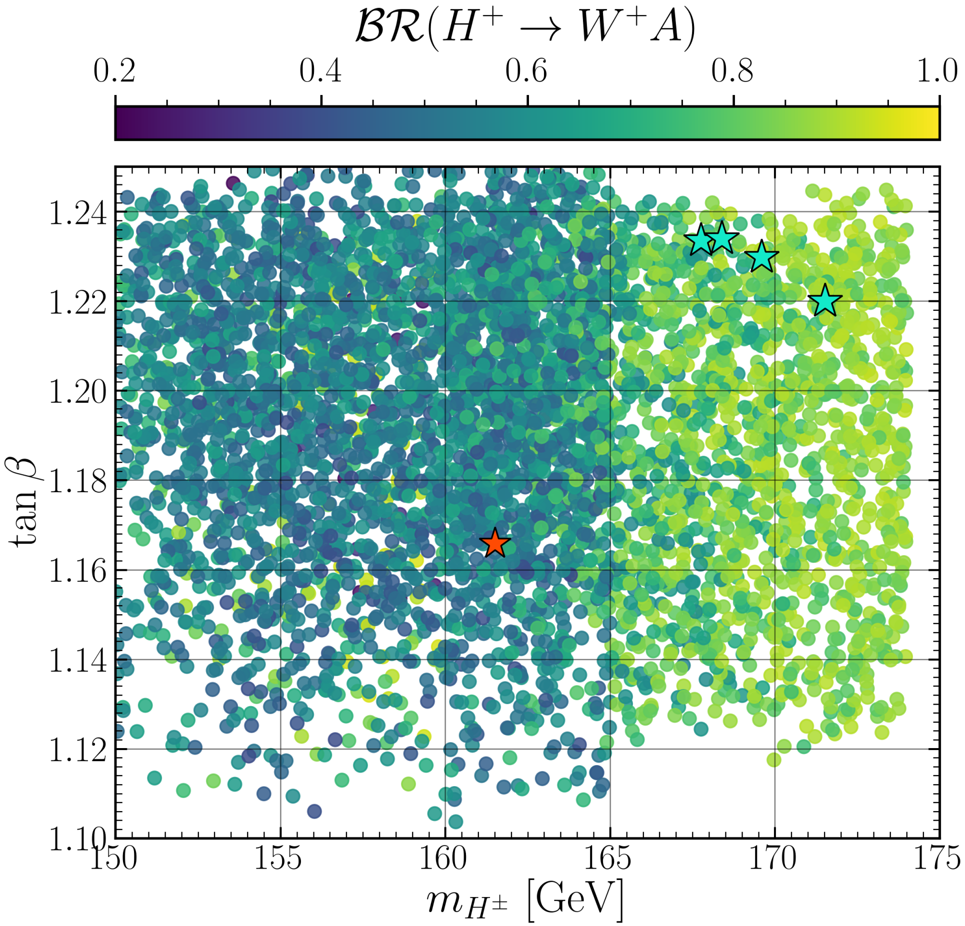
☆ LO and NLO are in pretty accurate agreement nearly for $m_h \geq 90$ GeV.

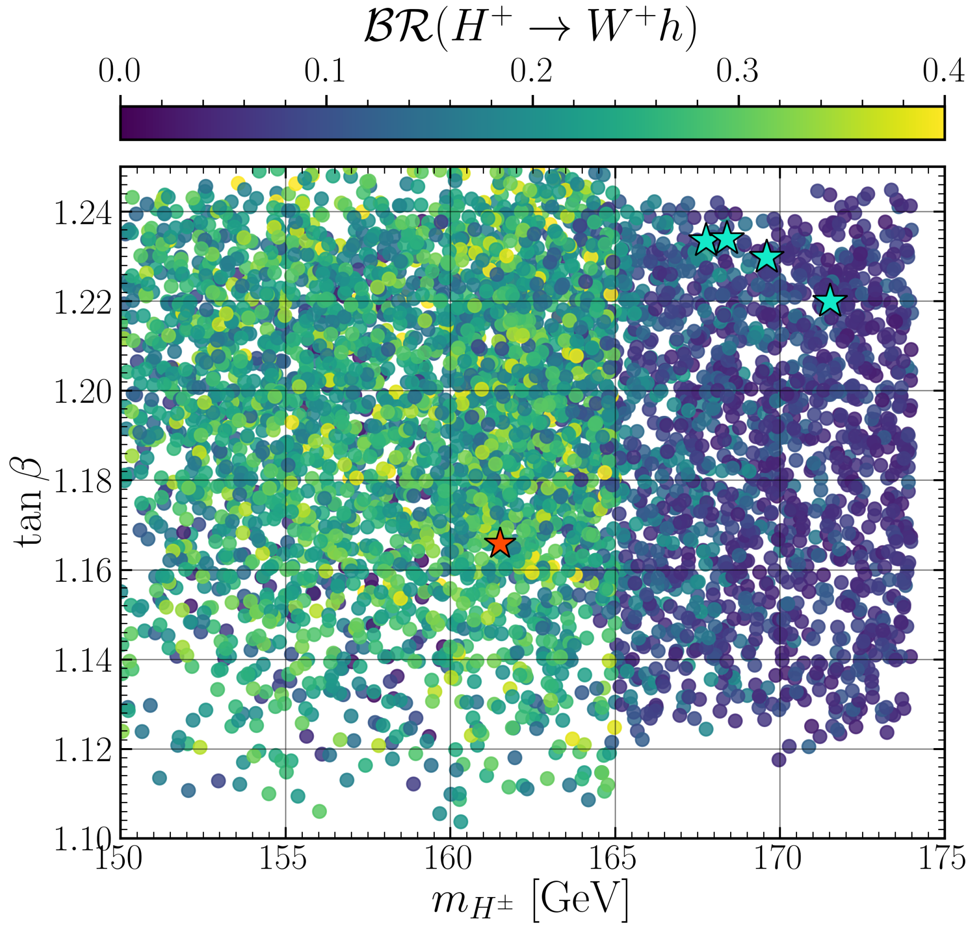
2HDM TYPE-III INTERPRETATION



☆ Many points could contribute to the excess observed by CMS in the $h \to \gamma\gamma$ final state.

2HDM TYPE-III INTERPRETATION





- The charged Higgs decay width is dominated by the decay channel W^+A, for $m_{H^\pm} > 165$ GeV. (within the 1σ ellipse)
- $\mathcal{BR}(H^\pm \to hW^\pm) + \mathcal{BR}(H^\pm \to W^\pm A) \sim 100\%$.

Benchmark Points

Parameters	BP1	BP2	BP3	BP4
(Masses are in GeV)				
m_h	94.55	95.33	96.49	97.52
m_H	125	125	125	125
m_A	87.95	83.36	85.13	82.27
$m_{H^\pm}$	167.76	168.39	169.60	171.52
$\tan\beta$	1.23	1.23	1.22	1.21
$\sin(\beta-\alpha)$	-0.420	-0.423	-0.431	-0.438
λ_6	0	0	0	0
λ_7	0	0	0	0
m_{12}^2	4373.63	4445.61	4557.44	4662.92
Effective coupling $\lvert c_{hXY}\rvert$				
$\lvert c_{hVV}\rvert$	0.427854	0.430945	0.439079	0.446200
$\lvert c_{hb\bar{b}}\rvert$	0.046293	0.048631	0.054028	0.058105
$\lvert c_{ht\bar{t}}\rvert$	0.144724	0.140352	0.131938	0.127975
Effective coupling $\lvert c_{HXY}\rvert$				
$\lvert c_{HVV}\rvert$	0.922878	0.921439	0.917591	0.914149
$\lvert c_{Hb\bar{b}}\rvert$	0.664166	0.663986	0.663746	0.663866
$\lvert c_{Ht\bar{t}}\rvert$	1.167053	1.167399	1.169637	1.173210
$\lvert c_{H\tau\tau}\rvert$	1.068317	1.067894	1.067330	1.067330
Collider signal strength				
μ_{CMS}	0.5	0.446	0.378	0.366
μ_{LEP}	0.061	0.066	0.079	0.087
σ in [pb]				
$\sigma(pp\to h\to\gamma\gamma)$	0.0591	0.0548	0.0513	0.0522
$\sigma(pp\to h\to\gamma\gamma)/SM$	0.5715	0.5135	0.4825	0.5257

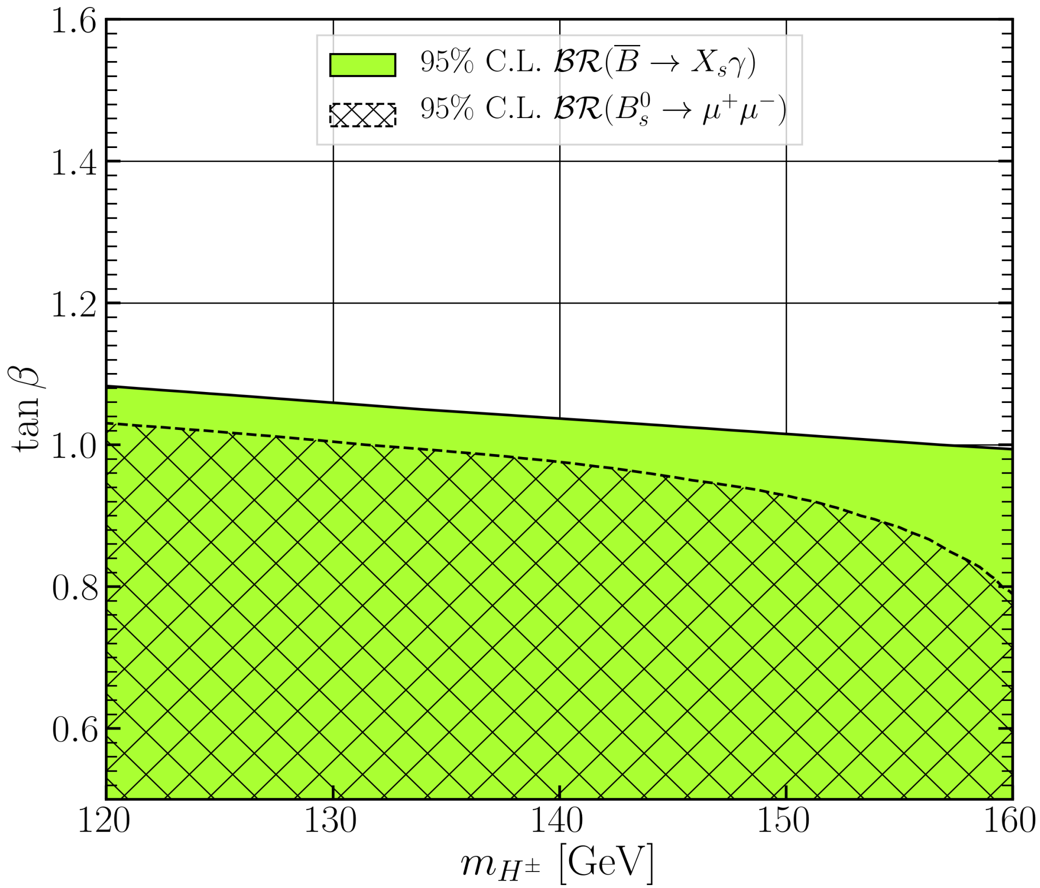
Table: The description of our four BPs.

Conclusion

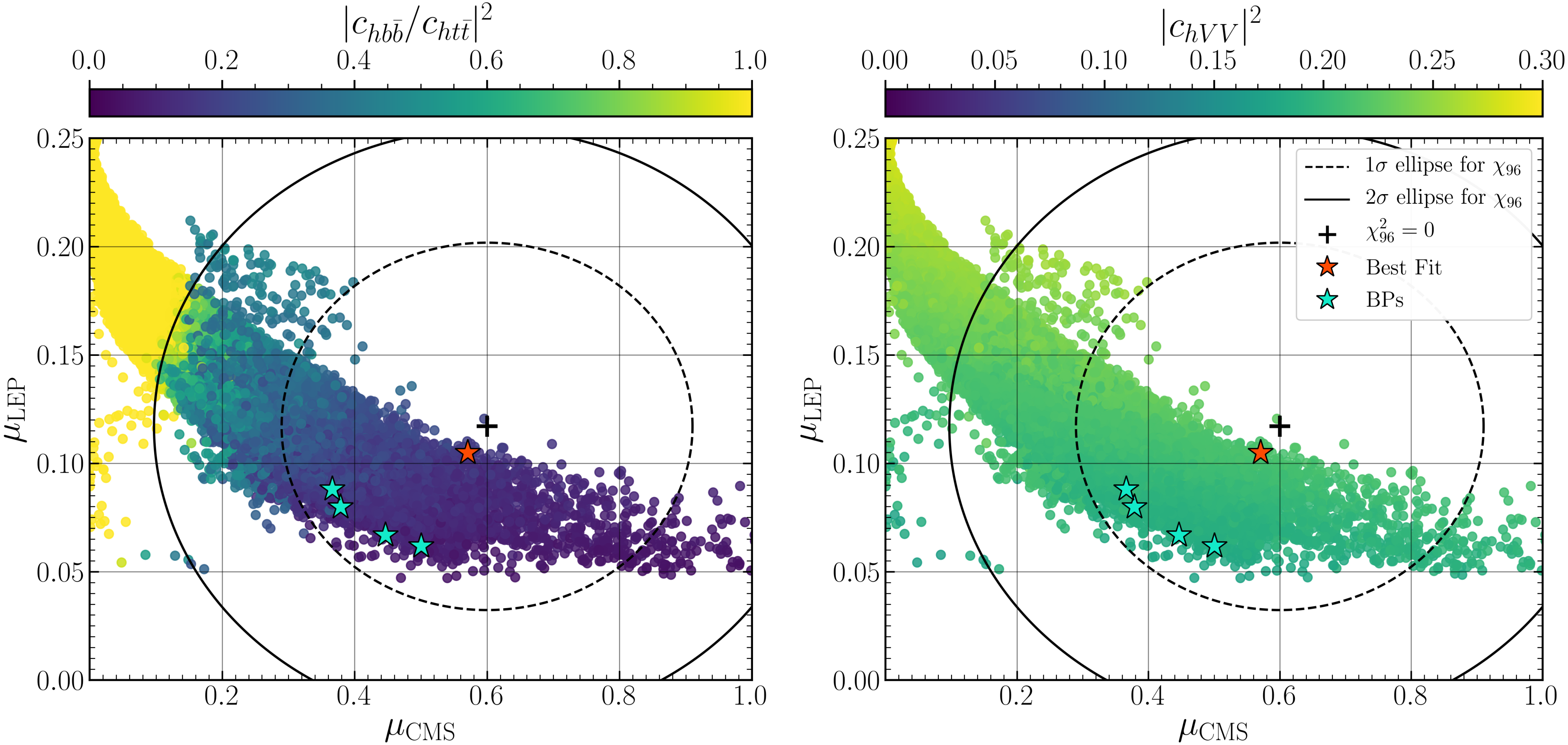
- Under the current existing constraints type III 2HDM can accommodate both excesses.
- Selecting 4 benchmark points for the purpose of encouraging experimental analyses of this scenario at the LHC, chiefly, to both confirm our findings in the $\gamma\gamma$ channel and attempting to extract the hallmark signatures of it, $H^+ \to W^+A$ and/or $H^+ \to W^+h$.

Thank You For Listening!

Back-up



☆ Light charged Higgs boson with mass from around m_H and below m_t is allowed, so long that $\tan\beta > 1.08$.



- Points with higher signal strength μ_{LEP} always have the higher coupling c_{hVV}.
- Points with lower values of $|c_{hb\bar{b}}/c_{ht\bar{t}}|^2$, give a higher μ_{CMS} signal strength.