Explaining 95 GeV Anomalies in Type – 1 2HDM

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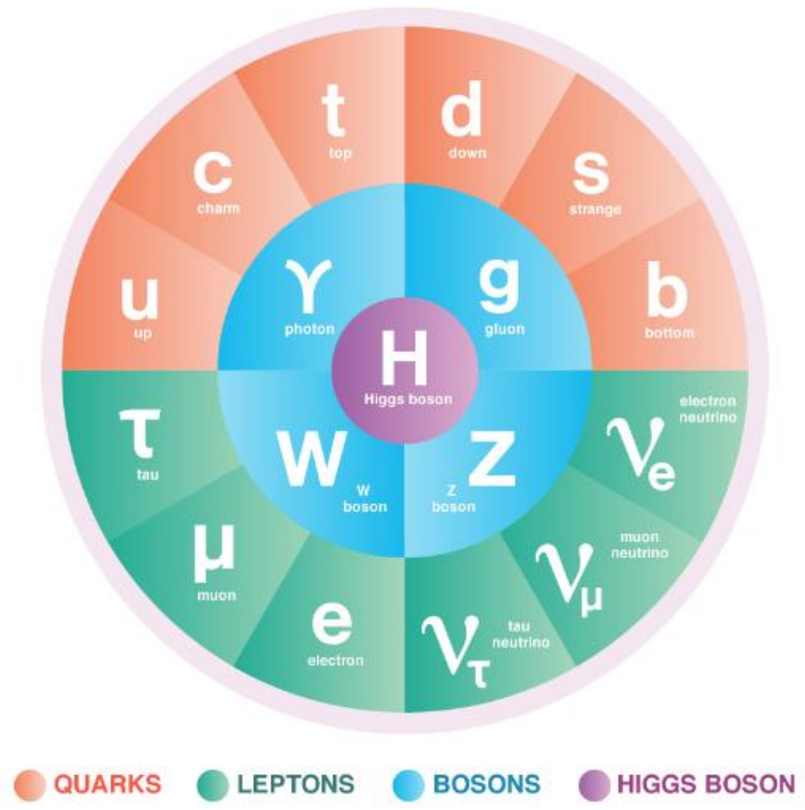
Standard Model Of Particle Physics



Source : https://www.energy.gov/science/doe-explainsthe-standard-model-particle-physics

Beyond Standard Model

Present experimental uncertainties leave room for a BSM interpretation of the detected Higgs boson.

Could there by hints for an additional Higgs boson in the currently existing searches ?

Experimental Results

- Di-photon channel – CMS / ATLAS
- Di-tau channel – CMS
- Bottom quark pair – LEP

Explaining the Anomalies

Explaining the Anomalies

Signal Strength is defined as,

$$\mu(\Phi_{95})_X = \frac{\sigma(\Phi_{95}) \times \mathrm{BR}(\Phi_{95} \to X)}{\sigma^{\mathrm{SM}}(\Phi_{95}) \times \mathrm{BR}^{\mathrm{SM}}(\Phi_{95} \to X)},$$

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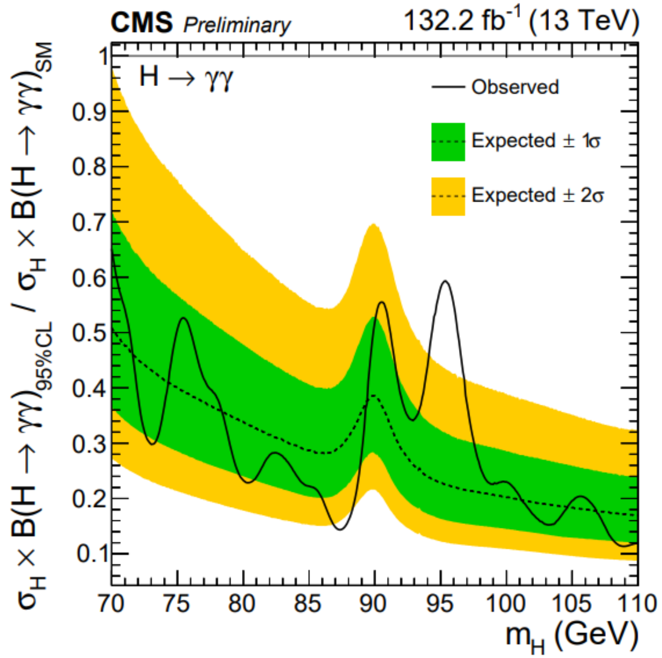
$$\mu(\Phi_{95})_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$$



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- CMS – Full dataset 13 TeV - $2.9\ \sigma\ at\ 95.4\ GeV$

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- ATLAS – Full dataset 13 TeV - $1.7\ \sigma\ at\ 95.4\ GeV$

$$\mu(\Phi_{95})_{\gamma\gamma} = 0.18 \pm 0.1$$

Di-photon Excess

$$\mu_{\gamma\gamma}^{\mathrm{exp}} = \mu_{\gamma\gamma}^{\mathrm{ATLAS+CMS}} = 0.24^{+0.09}_{-0.08},$$

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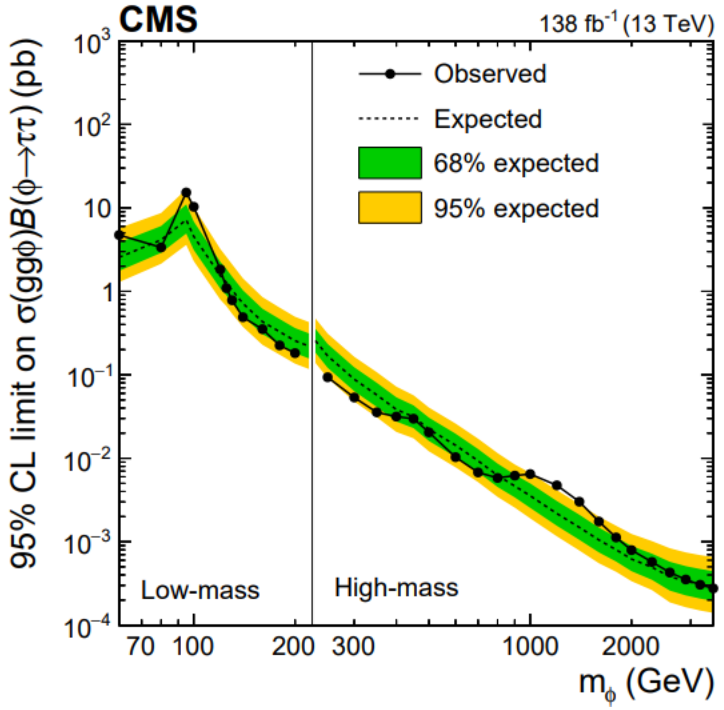
- Higgs bosons expected to have coupling with fermions that increases with fermion mass
- CMS – 13 TeV Run 2 dataset. – most pronounced excess at 100 GeV with local and global significance as $3.1\ \sigma\ and\ 2.7\ \sigma$
- At around 95 GeV - $2.6\ \sigma\ and\ 2.3\ \sigma$

$$\mu(\Phi_{95})_{\tau\tau} = 1.23^{+0.61}_{-0.49}$$



LEP excess

- Maximum Centre of Mass energy – 209 GeV
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- Higgstrahlung

$$e^+e^- \to Z\Phi_{95} \to Zb\bar{b}$$

- $2.3\ \sigma\ at\ 98\ GeV$
- 95 GeV

$$\mu(\Phi_{95})_{bb} = 0.117^{+0.057}_{-0.057}$$

Summary

Channel	Signal Rate	Local (global) significance
$gg \to \Phi_{95} \to \gamma\gamma$	$\mu(\Phi_{95})_{\gamma\gamma} = 0.33^{+0.19}_{-0.12}$	$2.9(1.3)\sigma$
$gg \to \Phi_{95} \to \tau^+\tau^-$	$\mu(\Phi_{95})_{\tau\tau} = 1.23^{+0.61}_{-0.49}$	$2.6(2.3)\sigma$
$e^+e^- \to Z\Phi_{95} \to Zb\bar{b}$	$\mu(\Phi_{95})_{bb} = 0.117^{+0.057}_{-0.057}$	$2.3(< 1)\sigma$

2HDM – Type 1

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$$V(\phi_1,\phi_2) = m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 - m_{12}^2\left[\phi_1^\dagger\phi_2 + \phi_2^\dagger\phi_1\right] + \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \left[\frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + h.c.\right] + \{\left[\lambda_6(\phi_1^\dagger\phi_1) + \lambda_7(\phi_2^\dagger\phi_2)\right](\phi_1^\dagger\phi_2) + h.c.\}.$$

2HDM – Type 1

$$V(\phi_1, \phi_2) = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 + \frac{\lambda_1}{2}(\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger \phi_2)^2$$
$$+ \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \{\frac{\lambda_5}{2}(\phi_1^\dagger \phi_2)^2 + h.c.\}.$$

$$\phi_1 \to \phi_1,\ \phi_2 \to -\phi_2.$$

2HDM – Type 1

$$\lambda_1 = \frac{c_\alpha^2 m_H^2 + s_\alpha^2 m_h^2}{v^2 c_\beta^2},$$

$$\lambda_2 = \frac{c_\alpha^2 m_h^2 + s_\alpha^2 m_H^2}{v^2 s_\beta^2},$$

$$\lambda_3 = \frac{(m_H^2 - m_h^2) s_\alpha c_\alpha - (\lambda_4 + \lambda_5) v^2 c_\beta s_\beta}{v^2 c_\beta s_\beta},$$

$$\lambda_4 = \frac{m_A^2 - 2 m_{H^\pm}^2}{v^2},$$

$$\lambda_5 = -\frac{m_A^2}{v^2}.$$

2HDM – Type 1

$$-\mathcal{L}_{Yukawa} = +\sum_{f=u,d,\ell}\left[m_f f\bar{f} + \left(\frac{m_f}{v}\kappa_h^f \bar{f}fh + \frac{m_f}{v}\kappa_H^f \bar{f}fH - i\frac{m_f}{v}\kappa_A^f \bar{f}\gamma_5 fA\right)\right]$$

$$+\frac{\sqrt{2}}{v}\bar{u}\left(m_u V\kappa_{H^+}^u P_L + V m_d \kappa_{H^+P_R}^d\right) dH^+ + \frac{\sqrt{2}m_\ell \kappa_{H^+}^\ell}{v}\bar{\nu}_L \ell_R H^+ + h.c.$$

Couplings

- HVV $\longrightarrow$ $\cos(\alpha - \beta)$

- hVV $\longrightarrow$ $\sin(\alpha - \beta)$

Constraints

- Constraints
  - Theoretical
    - Stability
    - Perturbativity
    - Unitarity
  - Experimental
    - Direct Search Constraints
    - Chi Square Fit – SM Like Higgs Boson
    - EW Precision
  - Flavor Constraints
    - $b \to s\gamma$
    - $B^+ \to \tau^+\nu_\tau$
    - $D_s \to \tau\nu_\tau$
    - $B \to \mu^+\mu^-$

Solutions

- Overlapping Solution

- Single Solution

Chi – Square Fit

$$\chi^2_{\gamma\gamma,\tau^+\tau^-,b\bar{b}} = \frac{(\mu_{\gamma\gamma,\tau^+\tau^-,b\bar{b}}(\phi) - \mu^{\exp}_{\gamma\gamma,\tau^+\tau^-,b\bar{b}})^2}{(\Delta\mu^{\exp}_{\gamma\gamma,\tau^+\tau^-,b\bar{b}})^2}.$$

$$\chi^2_{\gamma\gamma,\tau^+\tau^-,b\bar{b}} = \chi^2_{\gamma\gamma} + \chi^2{}_{\tau^+\tau^-} + \chi^2_{b\bar{b}}.$$

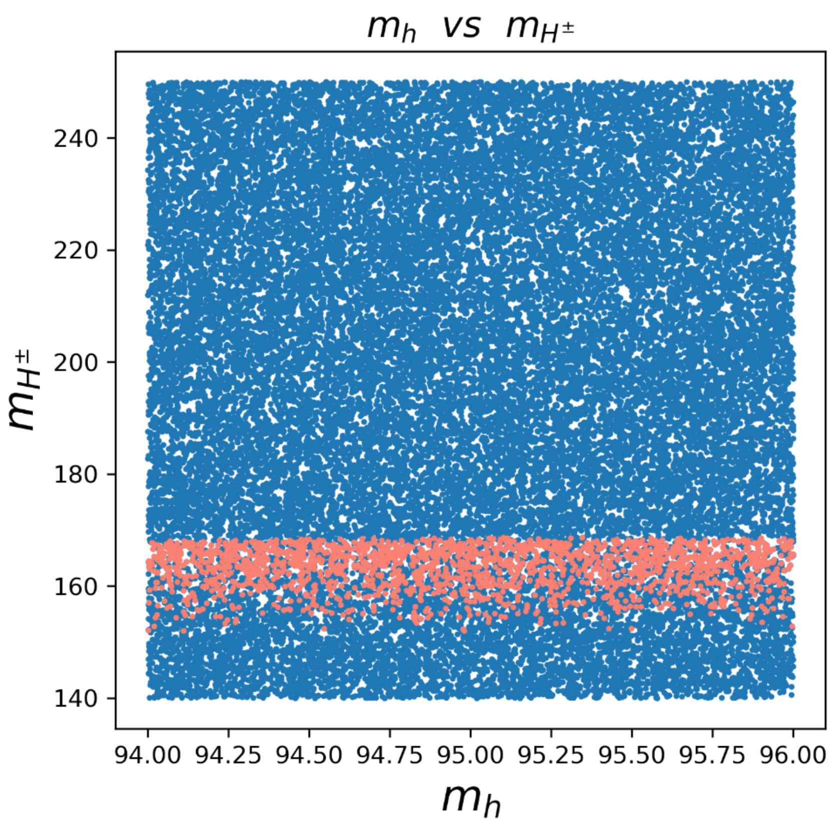
Overlapping Solution

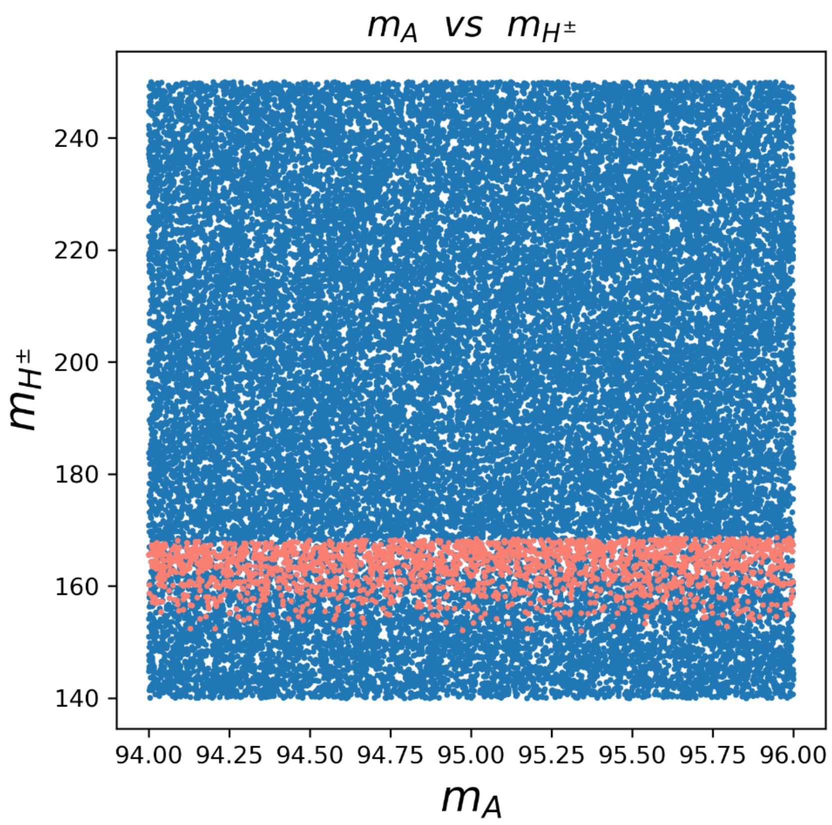
$$\mu_{\tau^+\tau^-}(h + A) = \mu_{\tau^+\tau^-}(h) + \mu_{\tau^+\tau^-}(A), \quad \mu_{\gamma\gamma}(h + A) = \mu_{\gamma\gamma}(h) + \mu_{\gamma\gamma}(A), \quad \mu_{b\bar{b}}(h).$$

Overlapping Solution

Parameter	Scan Range
m_H	125 GeV
m_h	94 GeV – 96 GeV
m_A	94 GeV – 96 GeV
$m_{H^\pm}$	140 GeV – 250 GeV
$\tan\beta$	0.5 – 100
$\sin(\beta-\alpha)$	-0.60 – 0.60

Overlapping Solution





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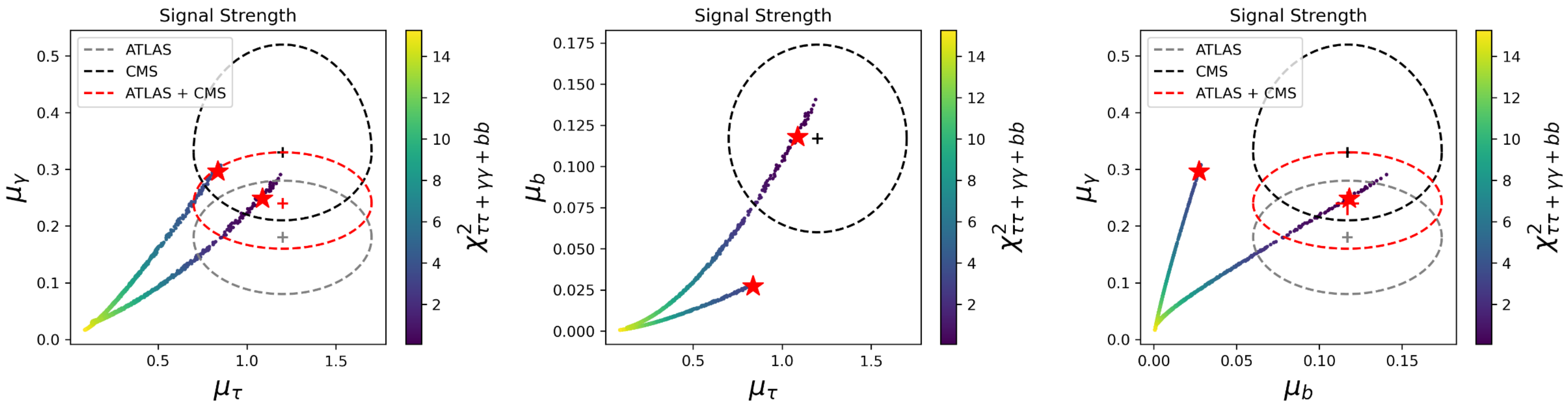

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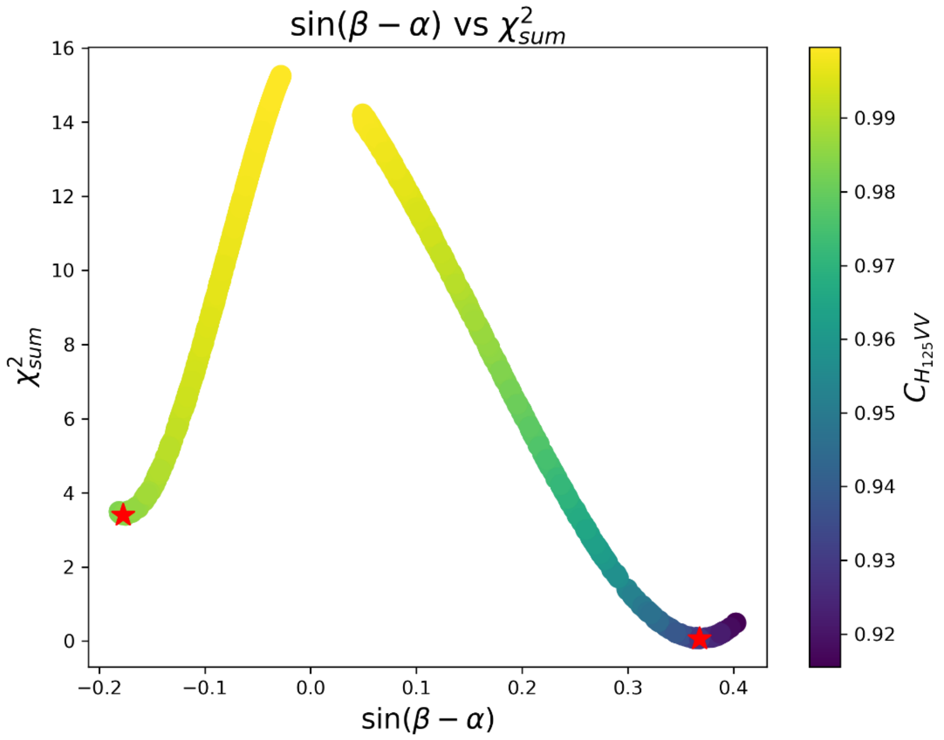

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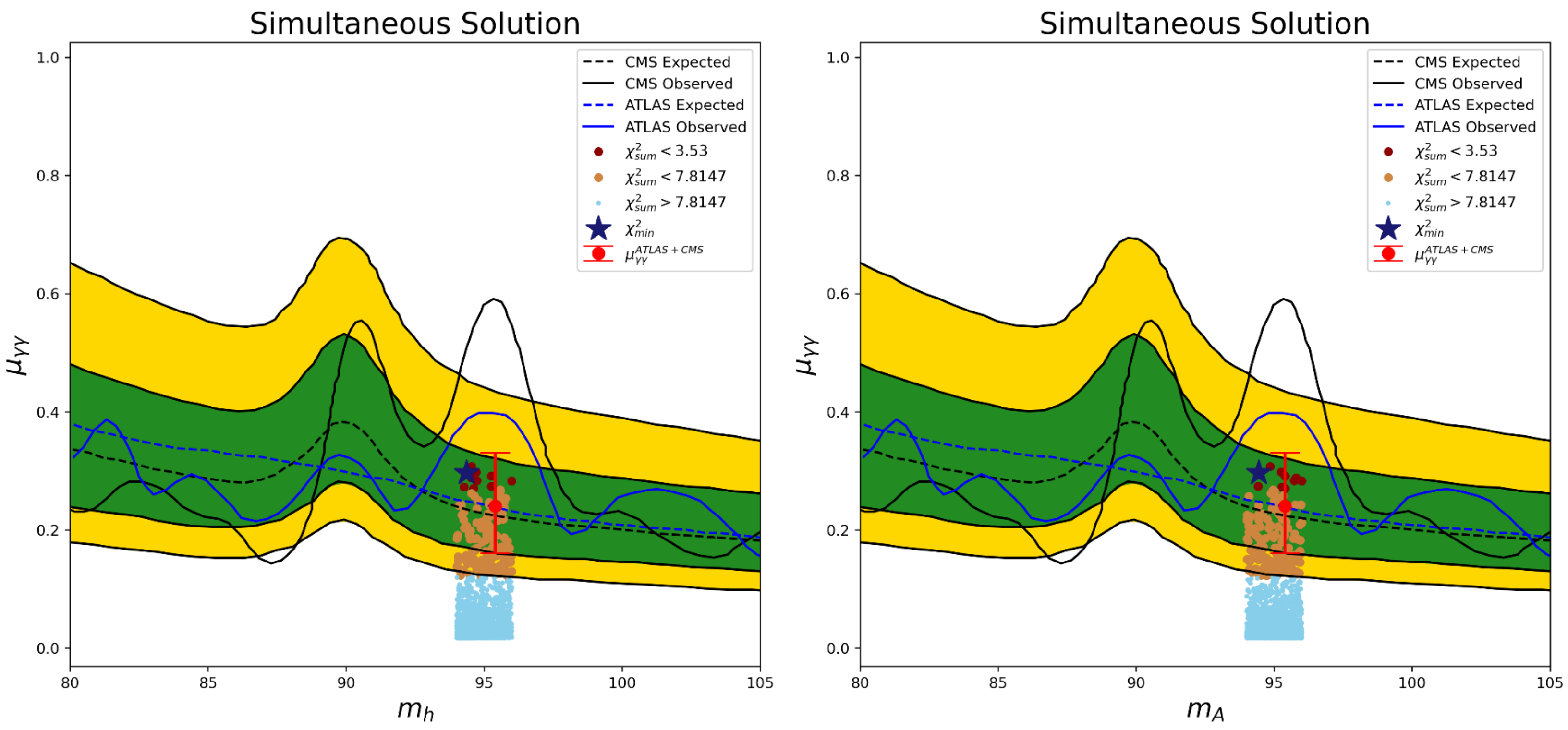

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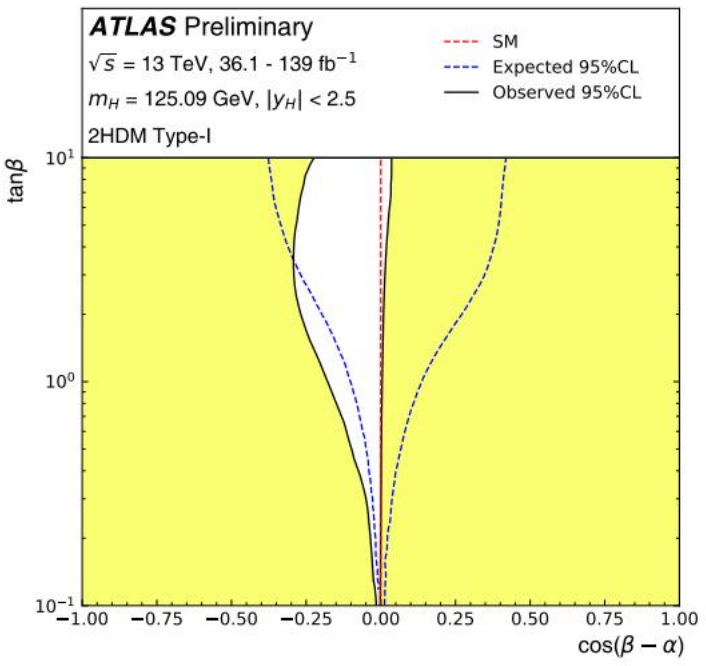

Overlapping Solution

m_H	m_h	m_A	$m_{H^\pm}$	$\tan\beta$	$\sin(\beta-\alpha)$	$\mu_{\tau^+\tau^-}(h+A)$	$\mu_{\gamma\gamma}(h+A)$	$\mu_{b\bar{b}}(h)$	$\chi^2_{\tau^+\tau^-+\gamma\gamma+b\bar{b}}$
125.0	94.36	94.44	166.63	2.33	-0.17	0.836	0.296	0.027	3.402

Single Solution

Parameter	Scan Range
m_H	125 GeV
m_h	94 GeV – 96 GeV
m_A	90 GeV – 250 GeV
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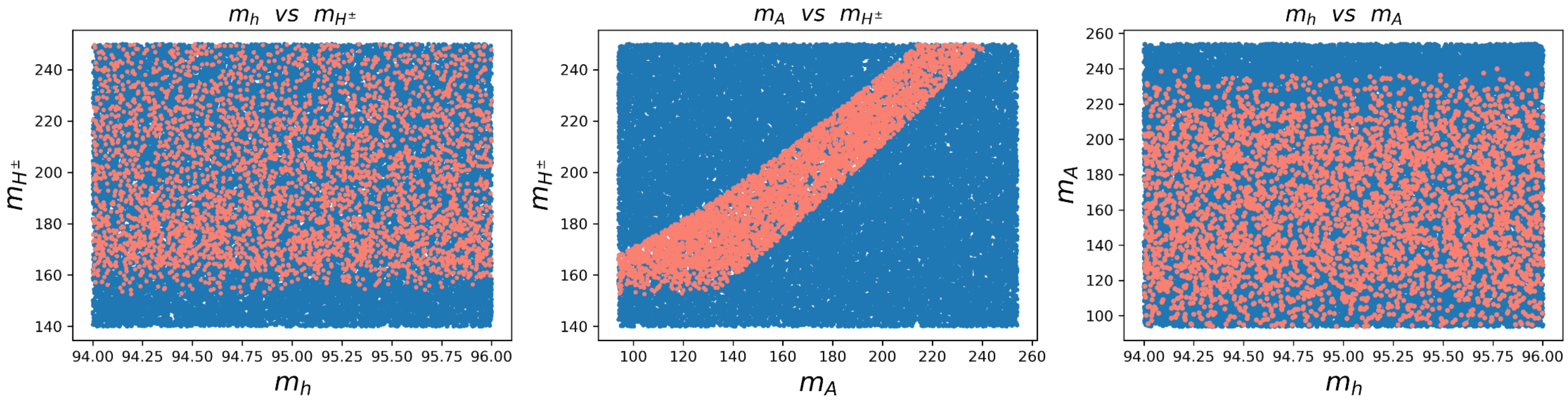

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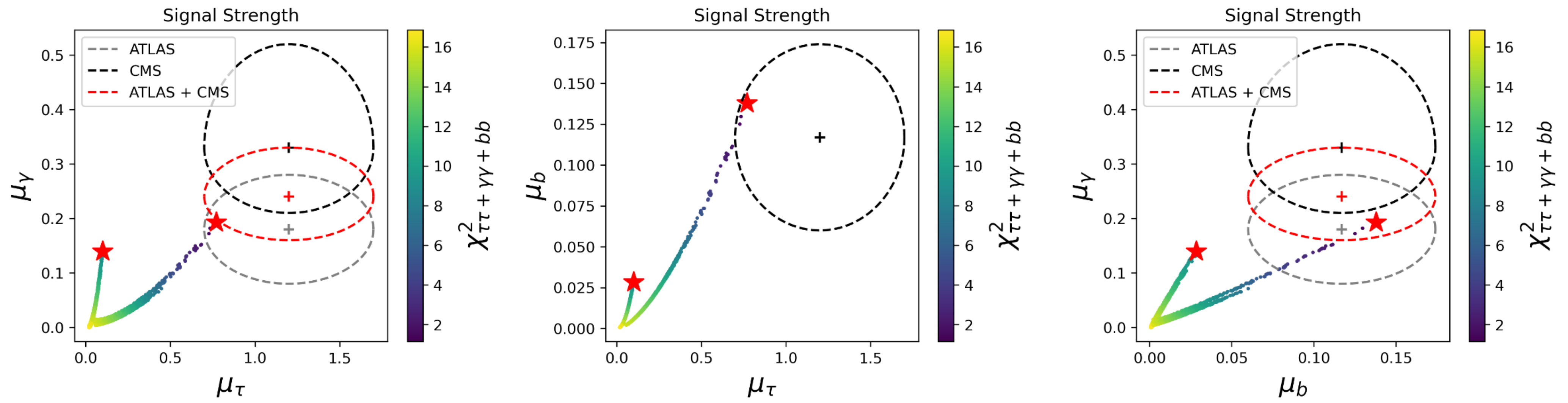

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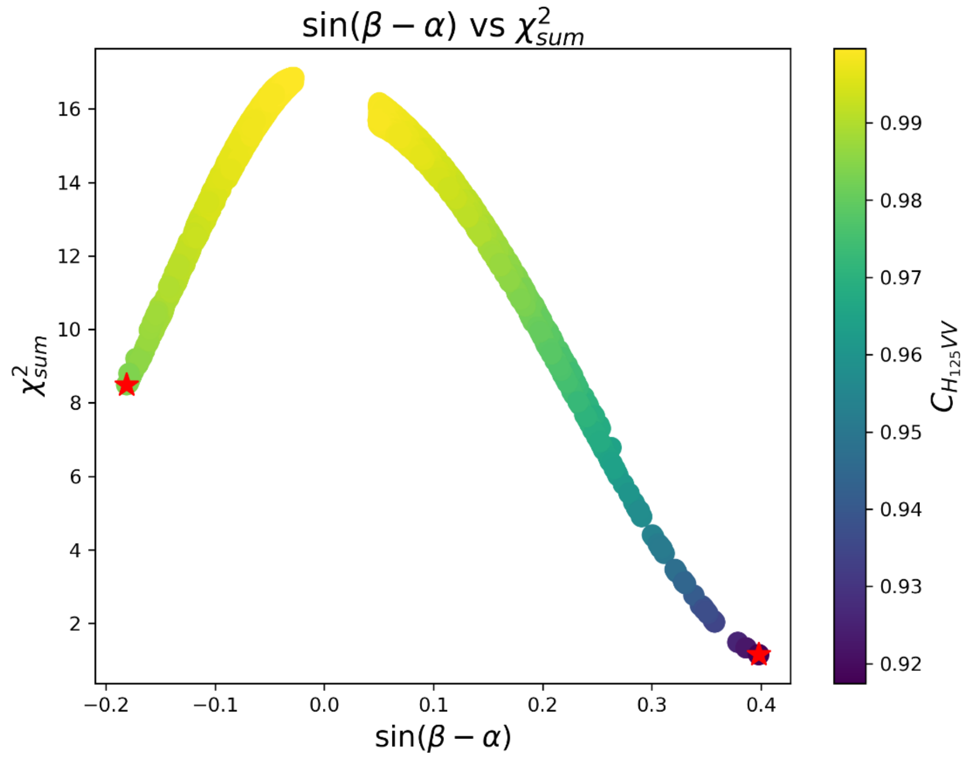

Conclusion

In the Type – I , 2 Higgs Doublet Model

- There exist a possible explanation of 95 GeV anomaly for the case of the overlapping solution at 1σ.

- There does not exist a possible explanation for the single solution.

- The above conclusions remain true even if add a softly symmetry breaking term to the potential.

Thank you