95 GeV excess within the scotogenic scenario

[based on 2306.03735 with A. Vicente and P. Escribano]

Víctor Martín Lozano victor.lozano@ific.uv.es

Funded by the European Union

GENERALITAT VALENCIANA
Conselleria d'Educació, Universitats i Ocupació

IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

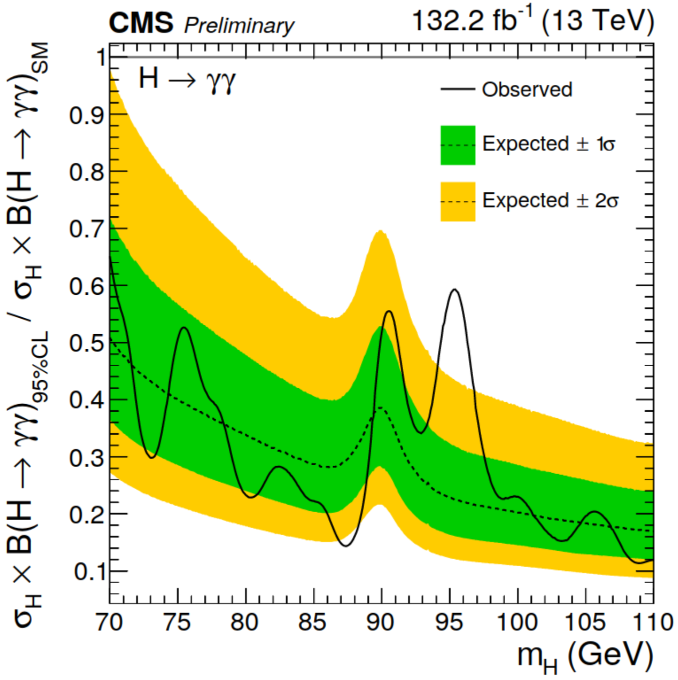
CSIC Consejo Superior de Investigaciones Científicas

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

ASTROPARTICLES Astroparticles and High Energy Physics Group

Plan de Recuperación, Transformación y Resiliencia

The 95 GeV excess.

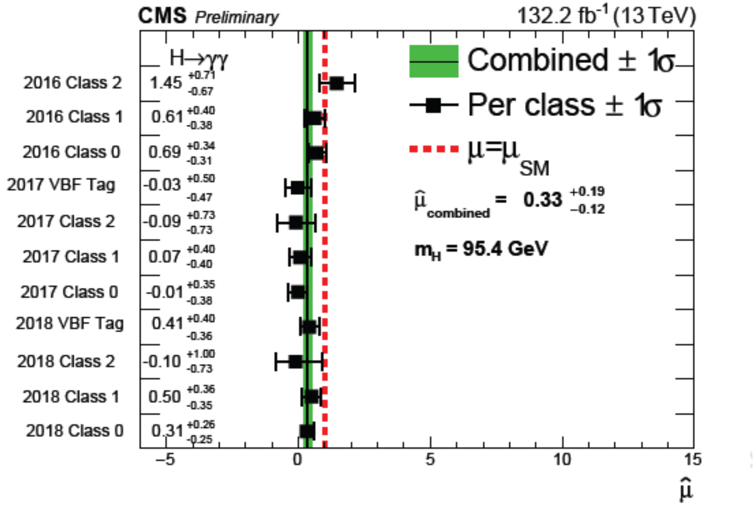


[CMS-PAS-HIG-20-002.]

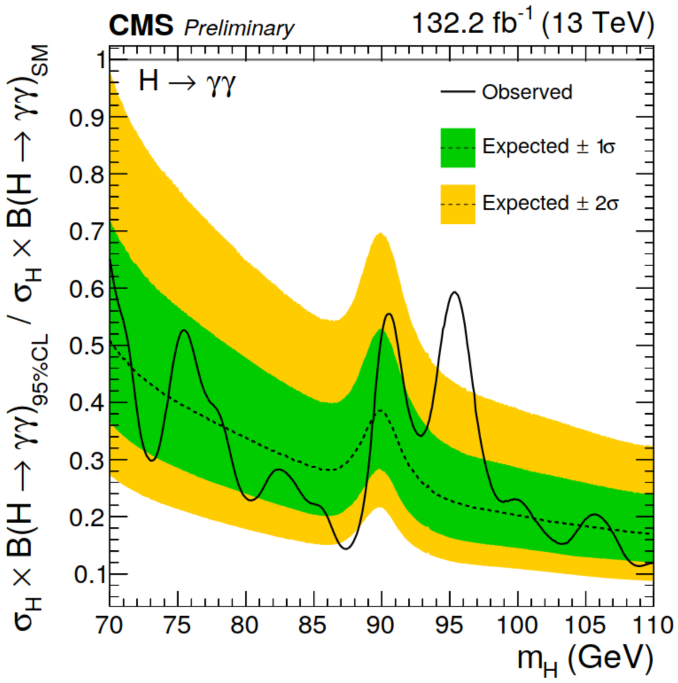
- Run II data:

  $\sim 2.9\sigma$ local significance

  with signal strength:



The 95 GeV excess.

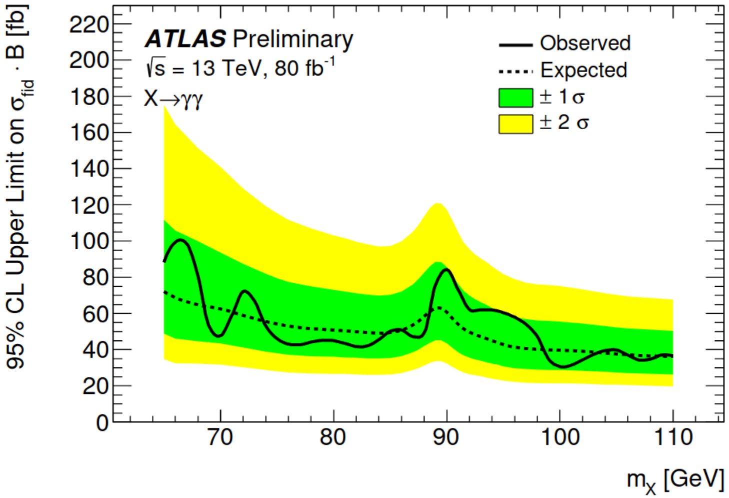


[CMS-PAS-HIG-20-002.]

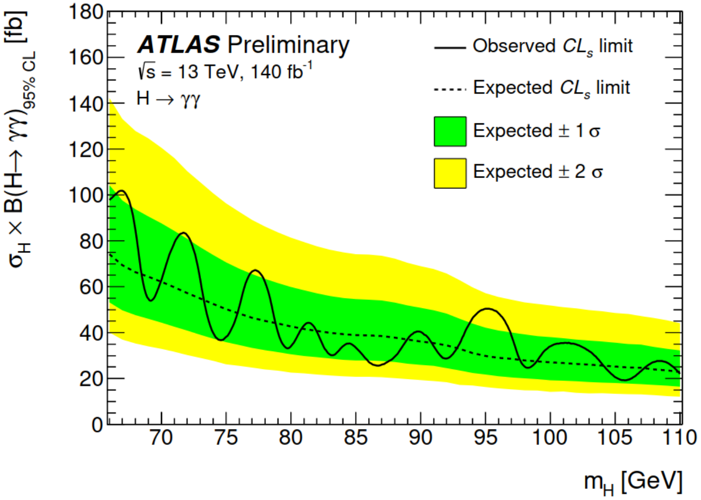
- Run II data:
  $\sim 2.9\sigma$ local significance
  with signal strength:

$$\mu_{\gamma\gamma}^{\rm CMS} = \frac{\sigma^{\rm CMS}(gg \to h_{95} \to \gamma\gamma)}{\sigma^{\rm SM}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

The 95 GeV excess.



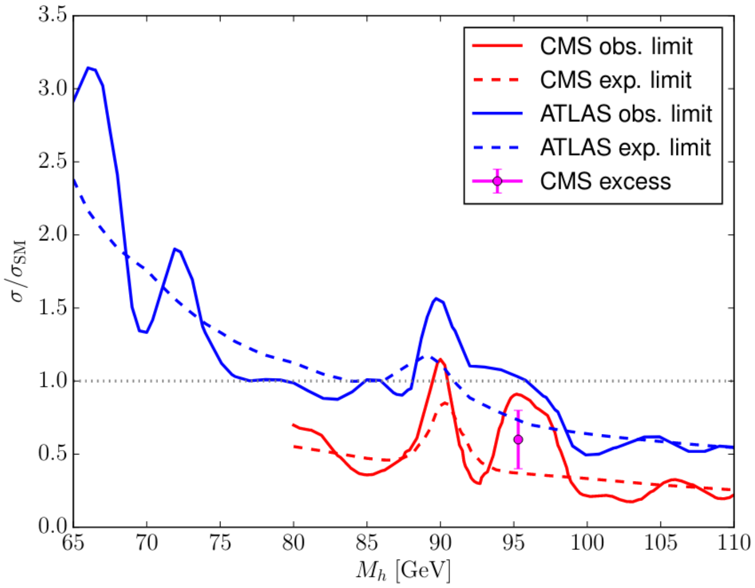
[ATLAS-CONF-2018-025]



[ATLAS-CONF-2023-035]

ATLAS shows a milder excess at the same mass range

The 95 GeV excess.

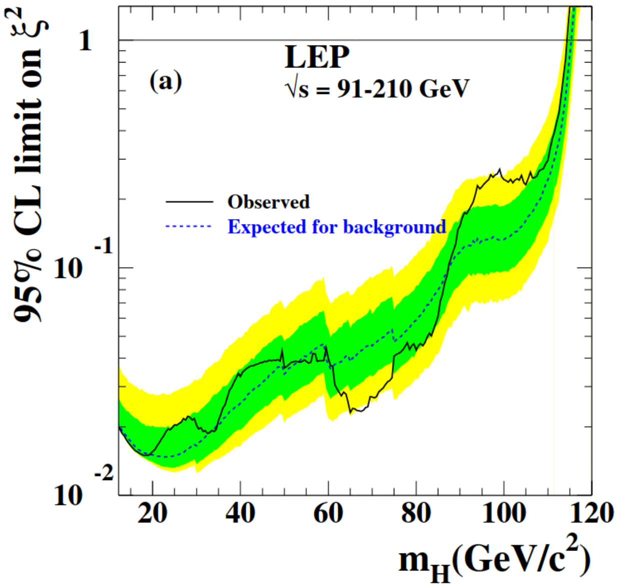


[S. Heinemeyer, T. Stefaniak 1812.05864]

However, the mild excess from ATLAS is in agreement with the stronger excess from CMS.

The 95 GeV excess.

(the origin)



[LEP collab. hep-ex/0306033]

All this comes from an excess of $\sim 2\sigma$ significance at LEP in the same range of masses.

$$\mu_{bb}^{\rm LEP} = \frac{\sigma^{\rm LEP}(e^+e^- \to Z\,h_{95} \to Z\,b\bar{b})}{\sigma^{\rm SM}(e^+e^- \to Z\,H \to Z\,b\bar{b})} = 0.117 \pm 0.057$$

There are also hints in other channels:

$$\mu_{\tau\tau}^{\rm CMS} = 1.2 \pm 0.5$$ [CMS 2208.02717]

(No results from ATLAS so far)

The 95 GeV excess.

(the ambulance)

J. Cao, X. Guo, Y. He, P. Wu, and Y. Zhang, "Diphoton signal of the light Higgs boson in natural NMSSM," Phys. Rev. D **95** no. 11, (2017) 116001, arXiv:1612.08522 [hep-ph].

P. J. Fox and N. Weiner, "Light Signals from a Lighter Higgs," JHEP **08** (2018) 025, arXiv:1710.07649 [hep-ph].

F. Richard, "Search for a light radion at HL-LHC and ILC250," arXiv:1712.06410 [hep-ex].

U. Haisch and A. Malinauskas, "Let there be light from a second light Higgs doublet," JHEP **03** (2018) 135, arXiv:1712.06599 [hep-ph].

T. Biekötter, S. Heinemeyer, and C. Muñoz, "Precise prediction for the Higgs-boson masses in the $\mu\nu$ SSM," Eur. Phys. J. C **78** no. 6, (2018) 504, arXiv:1712.07475 [hep-ph].

A. Mariotti, D. Redigolo, F. Sala, and K. Tobioka, "New LHC bound on low-mass diphoton resonances," Phys. Lett. B **783** (2018) 13–18, arXiv:1710.01743 [hep-ph].

A. Crivellin, J. Heeck, and D. Müller, "Large $h \to bs$ in generic two-Higgs-doublet models," Phys. Rev. D **97** no. 3, (2018) 035008, arXiv:1710.04663 [hep-ph].

F. Domingo, S. Heinemeyer, S. Paßehr, and G. Weiglein, "Decays of the neutral Higgs bosons into SM fermions and gauge bosons in the $\mathcal{CP}$-violating NMSSM," Eur. Phys. J. C **78** no. 11, (2018) 942, arXiv:1807.06322 [hep-ph].

D. Liu, J. Liu, C. E. M. Wagner, and X.-P. Wang, "A Light Higgs at the LHC and the B-Anomalies," JHEP **06** (2018) 150, arXiv:1805.01476 [hep-ph].

S. Heinemeyer and T. Stefaniak, "A Higgs Boson at 96 GeV?!" PoS **CHARGED2018** (2019) 016, arXiv:1812.05864 [hep-ph].

S. Heinemeyer, "A Higgs boson below 125 GeV?!" Int. J. Mod. Phys. A **33** no. 31, (2018) 1844006.

J. M. Cline and T. Toma, "Pseudo-Goldstone dark matter confronts cosmic ray and collider anomalies," Phys. Rev. D **100** no. 3, (2019) 035023, arXiv:1906.02175 [hep-ph].

T. Biekötter, M. Chakraborti, and S. Heinemeyer, "A 96 GeV Higgs boson in the N2HDM," Eur. Phys. J. C **80** no. 1, (2020) 2, arXiv:1903.11661 [hep-ph].

J. Cao, X. Jia, Y. Yue, H. Zhou, and P. Zhu, "96 GeV diphoton excess in seesaw extensions of the natural NMSSM," Phys. Rev. D **101** no. 5, (2020) 055008, arXiv:1908.07206 [hep-ph].

C. Bonilla, A. E. Cárcamo Hernández, S. Kovalenko, H. Lee, R. Pasechnik, and I. Schmidt, "Fermion mass hierarchy in an extended left-right symmetric model," arXiv:2305.11967 [hep-ph].

D. Azevedo, T. Biekötter, and P. M. Ferreira, "2HDM interpretations of the CMS diphoton excess at 95 GeV," arXiv:2305.19716 [hep-ph].

J. A. Aguilar-Saavedra and F. R. Joaquim, "Multiphoton signals of a (96 GeV?) stealth boson," Eur. Phys. J. C **80** no. 5, (2020) 403, arXiv:2002.07697 [hep-ph].

T. Biekötter and M. O. Olea-Romacho, "Reconciling Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM using a genetic algorithm," JHEP **10** (2021) 215, arXiv:2108.10864 [hep-ph].

T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, and G. Weiglein, "Possible indications for new Higgs bosons in the reach of the LHC: N2HDM and NMSSM interpretations," Eur. Phys. J. C **82** no. 2, (2022) 178, arXiv:2109.01128 [hep-ph].

S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, and S. Paasch, "Phenomenology of a 96 GeV Higgs boson in the 2HDM with an additional singlet," Phys. Rev. D **106** no. 7, (2022) 075003, arXiv:2112.11958 [hep-ph].

T. Biekötter, S. Heinemeyer, and G. Weiglein, "Mounting evidence for a 95 GeV Higgs boson," JHEP **08** (2022) 201, arXiv:2203.13180 [hep-ph].

T. Biekötter, S. Heinemeyer, and G. Weiglein, "Excesses in the low-mass Higgs-boson search and the W-boson mass measurement," arXiv:2204.05975 [hep-ph].

S. Iguro, T. Kitahara, and Y. Omura, "Scrutinizing the 95–100 GeV di-tau excess in the top associated process," Eur. Phys. J. C **82** no. 11, (2022) 1053, arXiv:2205.03187 [hep-ph].

S. Iguro, T. Kitahara, Y. Omura, and H. Zhang, "Chasing the two-Higgs doublet model in the di-Higgs boson production," Phys. Rev. D **107** no. 7, (2023) 075017, arXiv:2211.00011 [hep-ph].

S. Banik, A. Crivellin, S. Iguro, and T. Kitahara, "Asymmetric Di-Higgs Signals of the N2HDM-$U(1)$," arXiv:2303.11351 [hep-ph].

G. Coloretti, A. Crivellin, S. Bhattacharya, and B. Mellado, "Searching for Low-Mass Resonances Decaying into W Bosons," arXiv:2302.07276 [hep-ph].

T. Biekötter, S. Heinemeyer, and G. Weiglein, "The CMS di-photon excess at 95 GeV in view of the LHC Run 2 results," arXiv:2303.12018 [hep-ph].

The Scotogenic model.

σκότος = darkness

-γενής = that produces or generates

	gen	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
η	1	**2**	1/2	−
N	3	**1**	0	−

[Ma, hep-ph/0601225]

← One inert doublet

← Singlet fermion

(Dark Matter candidates due to the $\mathbb{Z}_2$ symmetry)

$$\mathcal{L}_N = \overline{N_i}\partial\!\!\!/ N_i - \frac{M_{R_i}}{2}\overline{N_i^c}N_i + y_{i\alpha}\eta\overline{N_i}\ell_\alpha + \text{h.c.}$$

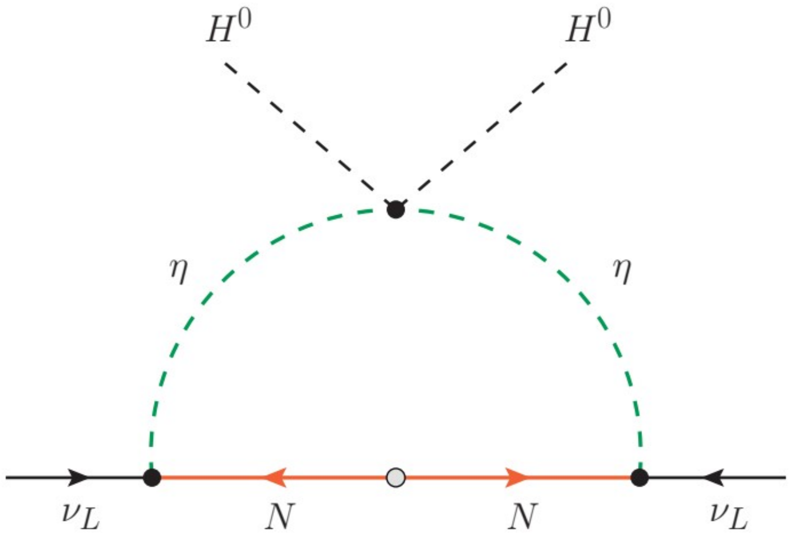
$$\mathcal{V} = m_H^2 H^\dagger H + m_\eta^2 \eta^\dagger\eta + \frac{\lambda_1}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_2}{2}\left(\eta^\dagger\eta\right)^2 + \lambda_3\left(H^\dagger H\right)\left(\eta^\dagger\eta\right) + \lambda_4\left(H^\dagger\eta\right)\left(\eta^\dagger H\right) + \frac{\lambda_5}{2}\left[\left(H^\dagger\eta\right)^2 + \left(\eta^\dagger H\right)^2\right]$$

The Scotogenic model.

σκότος = darkness

-γενής = that produces or generates

(but also that is produced or generated by)



It generates neutrino masses at 1-loop level due to the dark particles in the loop.

$$m_\nu = \frac{\lambda_5 v^2}{32\pi^2}\, y^T\, M_R^{-1} f_{\text{loop}}\, y$$

The Scotogenic model.

$$\mathcal{L} \supset y_{na\alpha} \, \overline{N}_n \widetilde{\eta}_a^\dagger \ell_L^\alpha - \kappa_{nm} \, S \, \overline{N^c}_n N_m - \frac{1}{2} \left(M_N\right)_{nn} \overline{N^c}_n N_n + \text{h.c.}$$

Field	Generations	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
ℓ_L	3	1	2	-1/2	+
e_R	3	1	1	-1	+
N	n_N	1	1	0	-
H	1	1	2	1/2	+
η	n_η	1	2	1/2	-
S	1	1	1	0	+

n_η generations of inert doublets

n_N generations of Singlet fermions

$$\mathcal{V}_H = m_H^2 \, H^\dagger H + \frac{1}{2}\lambda_1 \left(H^\dagger H\right)^2 ,$$

$$\mathcal{V}_\eta = \left(m_\eta^2\right)_{aa} \eta_a^\dagger \eta_a + \frac{1}{2}\lambda_2^{abcd} \left(\eta_a^\dagger \eta_b\right)\left(\eta_c^\dagger \eta_d\right) , \quad \mathcal{V}_S = \frac{1}{2} m_S^2 \, S^2 + \frac{1}{3}\mu_S \, S^3 + \frac{1}{4}\lambda_S \, S^4 ,$$

$$\mathcal{V}_{\text{mix}} = \lambda_3^{ab} \left(H^\dagger H\right)\left(\eta_a^\dagger \eta_b\right) + \lambda_4^{ab} \left(H^\dagger \eta_a\right)\left(\eta_b^\dagger H\right) + \frac{1}{2}\left[\lambda_5^{ab} \left(H^\dagger \eta_a\right)\left(H^\dagger \eta_b\right) + \text{h.c.}\right]$$
$$+ \mu_H \, H^\dagger H S + \frac{1}{2}\lambda_{HS} \, H^\dagger H S^2 + \mu_\eta^{ab} \, \eta_a^\dagger \eta_b \, S + \frac{1}{2}\lambda_{\eta S}^{ab} \, \eta_a^\dagger \eta_b \, S^2 .$$

Interpretation of the 95 GeV.

$$\langle H^0 \rangle = \frac{v}{\sqrt{2}}\,, \quad \langle \eta_a^0 \rangle = 0\,, \quad \langle S \rangle = v_S$$

$$\mathcal{M}^2_{\mathcal{H}} = \begin{pmatrix} v_S\,(\mu_S + 2\lambda_S v_S) - \frac{\mu_H v^2}{2 v_S} & \mu_H v + \lambda_{HS}\, v\, v_S \\ \mu_H v + \lambda_{HS}\, v\, v_S & \lambda_1 v^2 \end{pmatrix}$$

$$V_{\mathcal{H}}\, \mathcal{M}^2_{\mathcal{H}}\, V^T_{\mathcal{H}} = \widehat{\mathcal{M}}^2_{\mathcal{H}} = \text{diag}\left(m^2_{h_1}, m^2_{h_2}\right)$$

$$V_{\mathcal{H}} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}$$

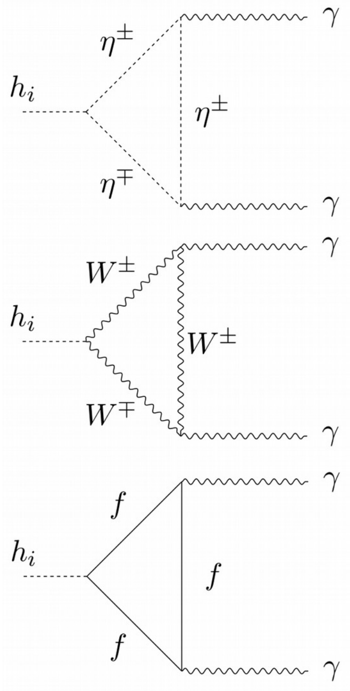
After EWSB takes place both H and S acquire a VEV and the physical states are an admixture of them.

After diagonalizing the mass matrix we can identify two states:

$$h_1 \equiv h_{95}\,, \quad h_2 \equiv h_{125}\,.$$

Interpretation of the 95 GeV.

$$h_1 \equiv h_{95}\,, \quad h_2 \equiv h_{125}\,.$$



Due to the presence of the inert doublets there is an additional channel for the $\gamma\gamma$ decay.

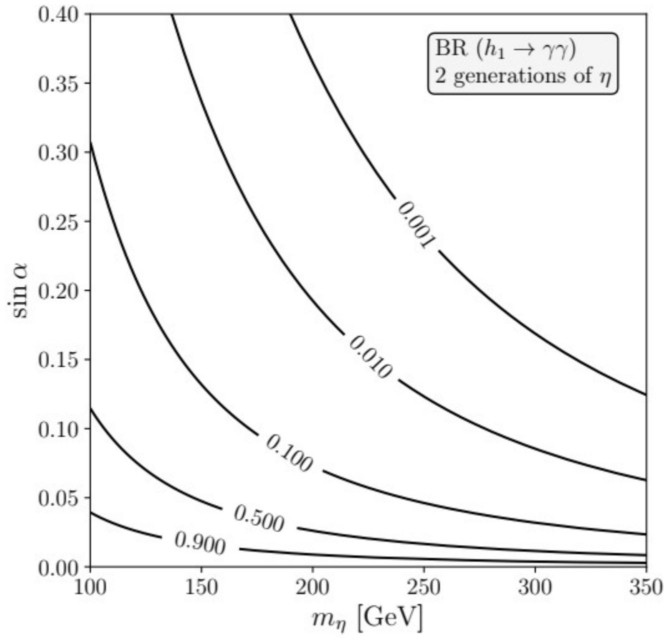
$$\Gamma(h_i \to \gamma\gamma) = \frac{G_F \alpha^2 m_{h_i}^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c Q_f^2 g_{h_i ff}\, A_{1/2}(\tau_f) + g_{h_i WW}\, A_1(\tau_W) + \sum_a \frac{v}{2m_{\eta_a}^2} g_{h_i \eta\eta}^{aa}\, A_0(\tau_\eta) \right|^2$$

This decay will be proportional to the couplings to the doublets:

$$g_{h_1\eta\eta} = \cos\alpha\,(\lambda_{\eta S}\, v_S + \mu_\eta) + \sin\alpha\,\lambda_3\, v\,,$$
$$g_{h_2\eta\eta} = -\sin\alpha\,(\lambda_{\eta S}\, v_S + \mu_\eta) + \cos\alpha\,\lambda_3\, v\,.$$

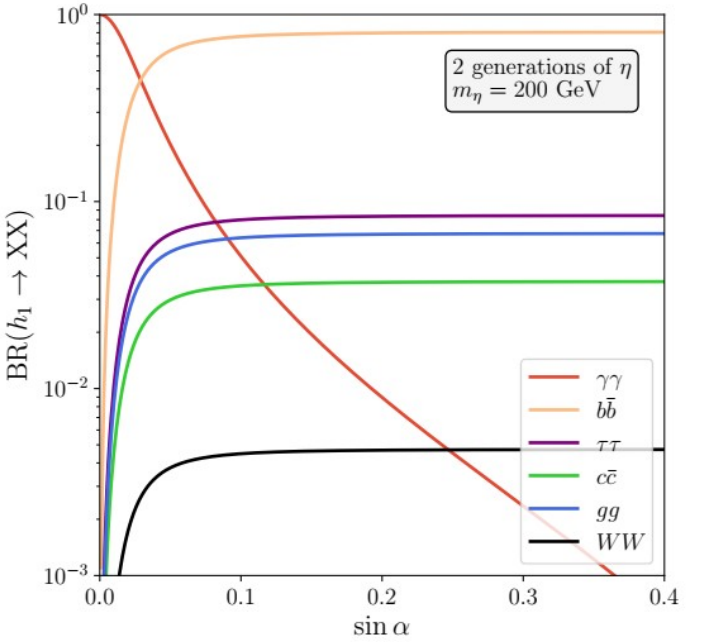
Interpretation of the 95 GeV.

$$h_1 \equiv h_{95}\,, \quad h_2 \equiv h_{125}\,.$$



The lower the mixing the highest th decay rate into $\gamma\gamma$ decay.

$$g_{h_1\eta\eta} = \cos\alpha\,(\lambda_{\eta S}\, v_S + \mu_\eta) + \sin\alpha\,\lambda_3\, v\,,$$
$$g_{h_2\eta\eta} = -\sin\alpha\,(\lambda_{\eta S}\, v_S + \mu_\eta) + \cos\alpha\,\lambda_3\, v\,.$$

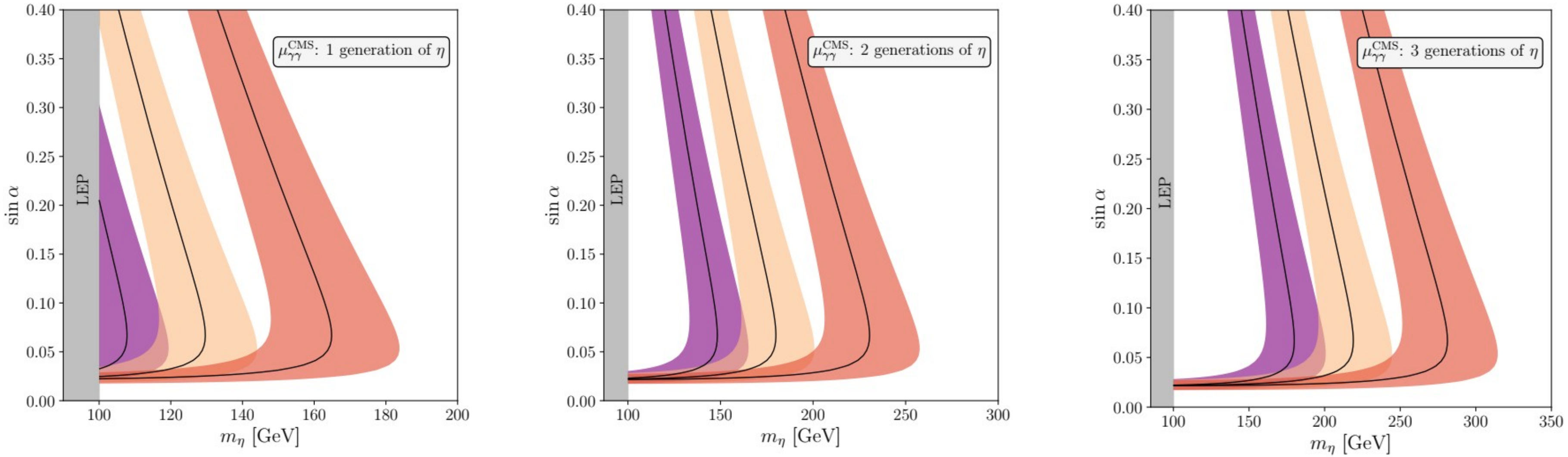


Numerical Results.

$$\bar{\lambda}_{\eta S}\, v_S = 500 \text{ GeV}\,,\ \bar{\lambda}_3 = 0.6\,,$$

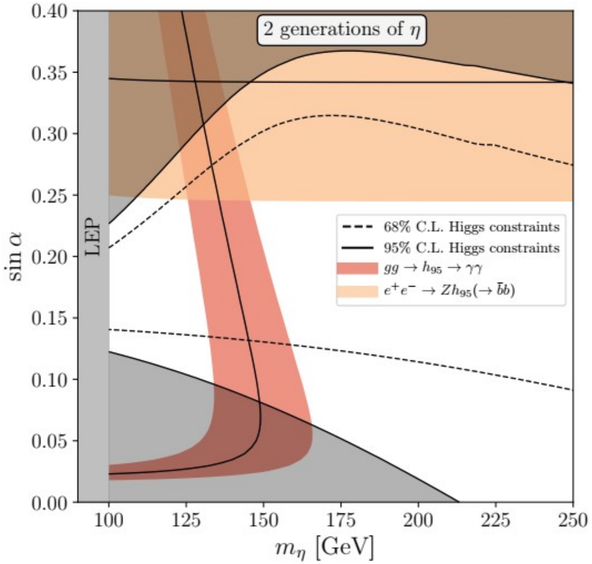
$$\bar{\mu}_\eta = 500 \text{ GeV(purple)},\ 1000 \text{ GeV (yellow)},\ 2000 \text{ GeV (red)}$$

$$\mu_{\gamma\gamma} = \frac{\sigma(gg \to h_1)}{\sigma_{\rm SM}(gg \to H)} \times \frac{\text{BR}(h_1 \to \gamma\gamma)}{\text{BR}_{\rm SM}(H \to \gamma\gamma)} = \sin^2\alpha\, \frac{\text{BR}(h_1 \to \gamma\gamma)}{\text{BR}_{\rm SM}(H \to \gamma\gamma)} \qquad \mu_{\gamma\gamma}^{\rm CMS} = \frac{\sigma^{\rm CMS}(gg \to h_{95} \to \gamma\gamma)}{\sigma^{\rm SM}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

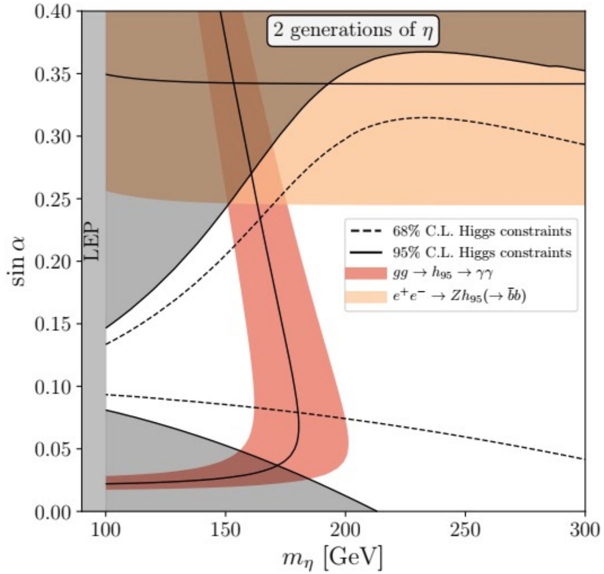


Numerical Results.

$$\bar{\lambda}_{\eta S}\, v_S = 500 \text{ GeV}\,,\ \bar{\lambda}_3 = 0.6\,,$$



$\bar{\mu}_\eta = 500$ GeV



$\bar{\mu}_\eta = 1000$ GeV

$$\mu^{\text{CMS}}_{\gamma\gamma} = \frac{\sigma^{\text{CMS}}(gg \to h_{95} \to \gamma\gamma)}{\sigma^{\text{SM}}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

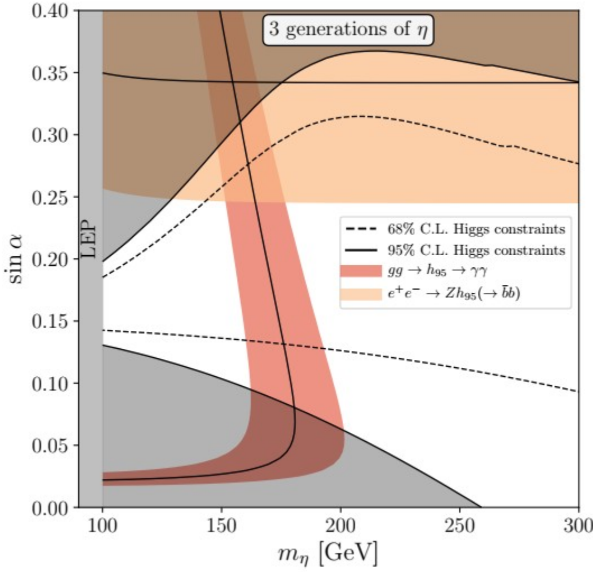
$$\mu^{\text{LEP}}_{bb} = \frac{\sigma^{\text{LEP}}(e^+e^- \to Z\,h_{95} \to Z\,b\bar{b})}{\sigma^{\text{SM}}(e^+e^- \to Z\,H \to Z\,b\bar{b})} = 0.117 \pm 0.057$$

`HiggsTools (Higgs Constraints)`

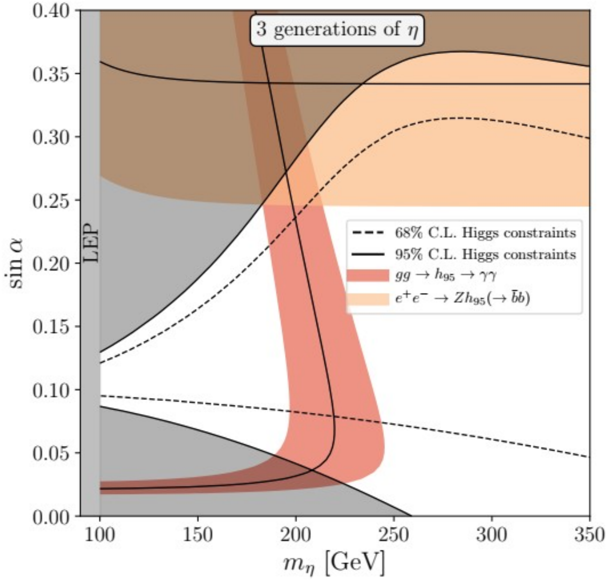
[Bahl, Biekötter, Heinemeyer, Li, Paasch, Weiglein, Wittbrodt, 2210.09332]

Numerical Results.

$$\bar{\lambda}_{\eta S}\, v_S = 500 \text{ GeV}\,, \bar{\lambda}_3 = 0.6\,,$$



$\bar{\mu}_\eta = 500$ GeV



$\bar{\mu}_\eta = 1000$ GeV

$$\mu_{\gamma\gamma}^{\text{CMS}} = \frac{\sigma^{\text{CMS}}(gg \to h_{95} \to \gamma\gamma)}{\sigma^{\text{SM}}(gg \to H \to \gamma\gamma)} = 0.33^{+0.19}_{-0.12}$$

$$\mu_{bb}^{\text{LEP}} = \frac{\sigma^{\text{LEP}}(e^+e^- \to Z\, h_{95} \to Z\, b\bar{b})}{\sigma^{\text{SM}}(e^+e^- \to Z\, H \to Z\, b\bar{b})} = 0.117 \pm 0.057$$

HiggsTools (Higgs Constraints)

[Bahl, Biekötter, Heinemeyer, Li, Paasch, Weiglein, Wittbrodt, 2210.09332]

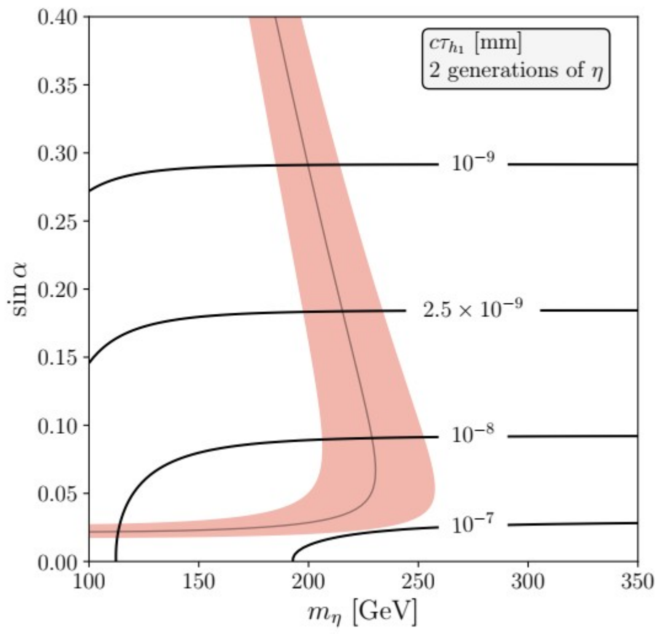
Conclusions.

- There are hints of a possible particle at a mass around ~95.4 GeV
- The scotogenic model is a phenomenologically viable model that predicts dark matter and the small neutrino masses.
- A generalization of the scotogenic model can explain the 95 GeV excess for different values of the parameter space.
- Different number of generations of inert doublets and singlet fermions can accommodate the excess.
- More data will be needed in the low mass region and different channels.

Thank you!

Decay width of the 95 GeV.

$$h_1 \equiv h_{95}\,, \quad h_2 \equiv h_{125}\,.$$



One may ask if the light scalar is long-lived for small values of the mixing angle.

However, for the region where the excess can be explained the lighter scalar decays promptly.