Scotogenic $U(1)_{L_\mu - L_\tau}$ origin of $(g-2)_\mu$, W-mass anomaly, and 95 GeV excess

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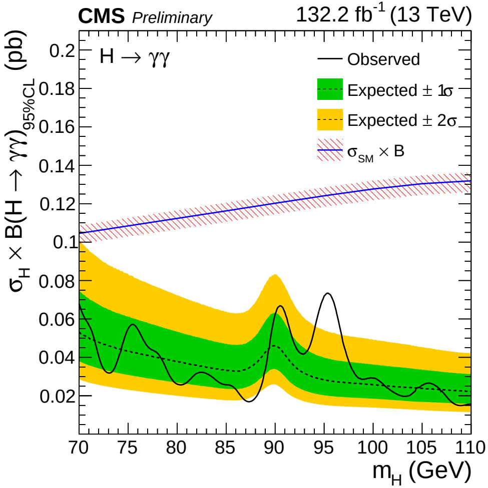
95 GeV Excess

CMS result on low mass Higgs search in $pp \to \phi \to \gamma\gamma$



CMS-PAS-HIG-20-002

95 GeV Excess

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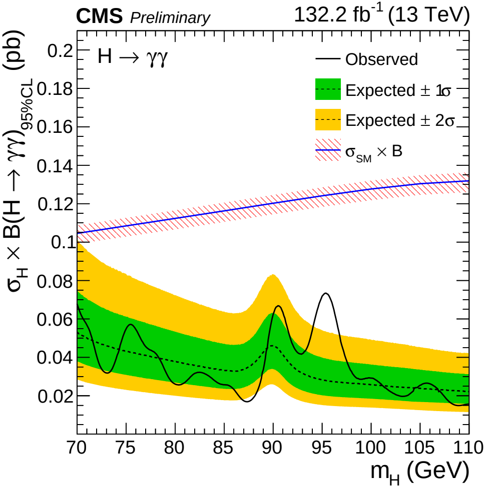

$$\mu_{\gamma\gamma} = \frac{\sigma(gg \to H_{95})}{\sigma_{SM}(gg \to H_{95})} \times \frac{\text{BR}(H_{95} \to \gamma\gamma)}{\text{BR}_{SM}(H_{95} \to \gamma\gamma)}$$

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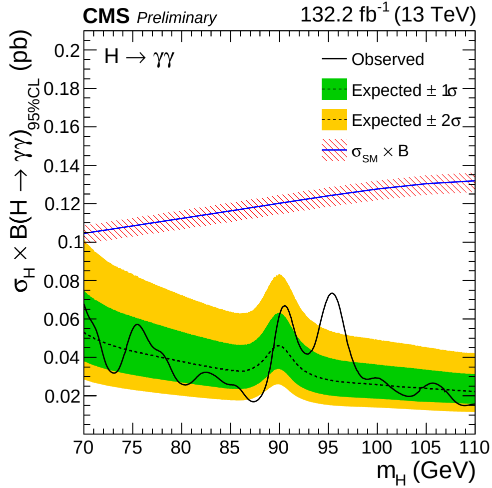

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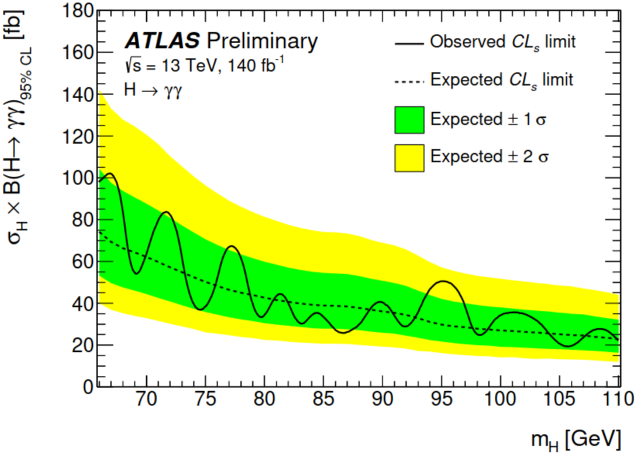
$$\mu_{\gamma\gamma}^{CMS} = 0.33^{+0.19}_{-0.12} \quad (2.9\ \sigma)$$

CMS-PAS-HIG-20-002

95 GeV Excess

ATLAS result on low mass Higgs search in $pp \to \phi \to \gamma\gamma$



https://indico.cern.ch/event/1281604/

95 GeV Excess

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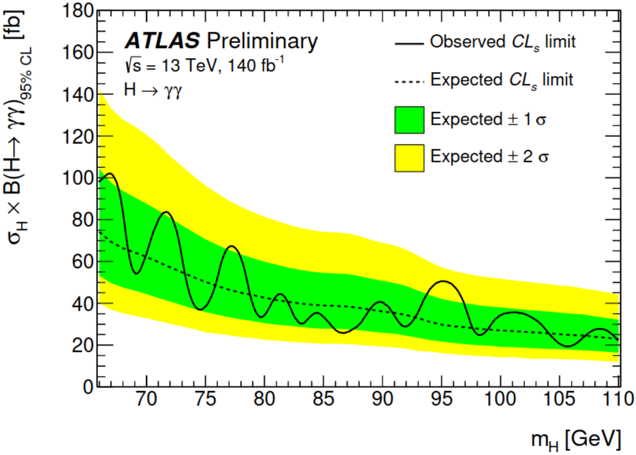

$$\mu_{\gamma\gamma}^{ATLAS} = 0.18 \pm 0.10 \quad (1.7\,\sigma)$$

https://indico.cern.ch/event/1281604/

Anomalaous magnetic moment of muon

$$\vec{\mu}_\mu = g_\mu \left(\frac{q}{2m}\right)\vec{S} \,, \qquad a_\mu = \frac{(g_\mu - 2)}{2}$$

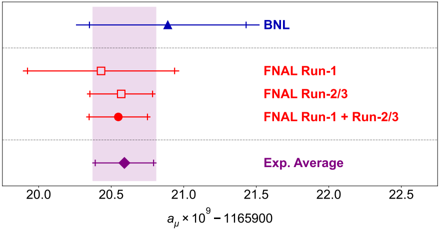

Figure: Experimental value of a_μ

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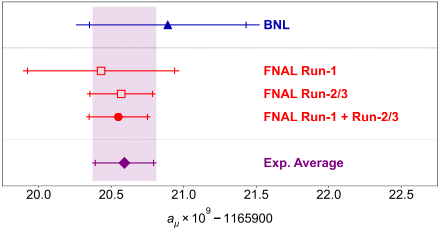

Figure: Experimental value of a_μ

$a_\mu^{SM} = 116591810(43) \times 10^{-11}$

$a_\mu^{exp} = 116592059(22) \times 10^{-11}$

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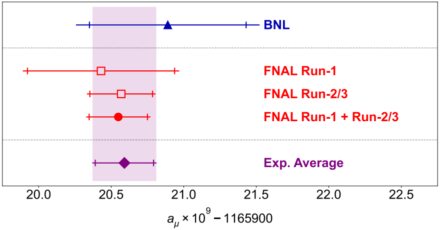


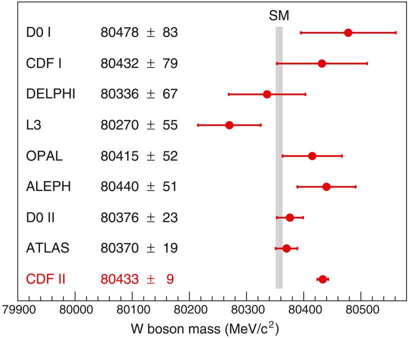
Figure: Experimental value of a_μ

$$a_\mu^{SM} = 116591810(43) \times 10^{-11} \qquad a_\mu^{exp} = 116592059(22) \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 249(48) \times 10^{-11}\ (5.1\,\sigma)$$

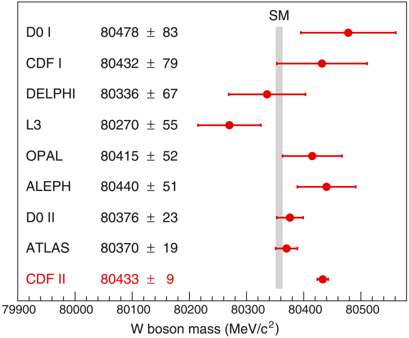
2308.06230

CDF-II W-mass anomaly



$M_W(\mathrm{SM}) = 80357 \pm 6$ MeV $\qquad$ $M_W(\mathrm{CDF}) = 80433.5 \pm 9.4$ MeV

CDF-II W-mass anomaly



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7σ away from the SM prediction

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The minimal model

Gauge Group	Fermion Fields			Scalar Field		
	N_e	N_μ	N_τ	Φ_1	Φ_2	η
$SU(2)_L$	1	1	1	1	1	2
$U(1)_Y$	0	0	0	0	0	$\frac{1}{2}$
$U(1)_{L_\mu - L_\tau}$	0	1	-1	1	2	0
Z_2	-1	-1	-1	$+1$	$+1$	-1

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$$\mathcal{L}_{Fermion} \supseteq \overline{N_e} i\gamma^\mu \partial_\mu N_e + \overline{N_\mu} i\gamma^\mu \mathfrak{D}_\mu N_\mu + \overline{N_\tau} i\gamma^\mu \mathfrak{D}_\mu N_\tau - \frac{M_{ee}}{2}\overline{N_e^C} N_e - M_{\mu\tau}\overline{N_\mu^C} N_\tau - Y_{e\mu}\Phi_1^\dagger \overline{N_e^C} N_\mu - Y_{e\tau}\Phi_1 \overline{N_e^C} N_\tau$$
$$-Y_\mu \Phi_2^\dagger \overline{N_\mu^C} N_\mu - Y_\tau \Phi_2 \overline{N_\tau^C} N_\tau - Y_{De}\overline{L_e}\tilde{\eta} N_e - Y_{D\mu}\overline{L_\mu}\tilde{\eta} N_\mu - Y_{D\tau}\overline{L_\tau}\tilde{\eta} N_\tau - Y_{le}\overline{L_e} H e_R - Y_{l\mu}\overline{L_\mu} H \mu_R$$
$$-Y_{l\tau}\overline{L_\tau} H \tau_R + \text{h.c.} \quad (3)$$

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$$-Y_\mu \Phi_2^\dagger \overline{N_\mu^C} N_\mu - Y_\tau \Phi_2 \overline{N_\tau^C} N_\tau - Y_{De}\overline{L}_e \tilde{\eta} N_e - Y_{D\mu}\overline{L}_\mu \tilde{\eta} N_\mu - Y_{D\tau}\overline{L}_\tau \tilde{\eta} N_\tau - Y_{le}\overline{L}_e H e_R - Y_{l\mu}\overline{L}_\mu H \mu_R$$
$$-Y_{l\tau}\overline{L}_\tau H \tau_R + \text{h.c.}$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}(Z_{\mu\tau})_{\mu\nu} Z_{\mu\tau}^{\mu\nu} - \frac{\epsilon}{2}(Z_{\mu\tau})_{\mu\nu} B^{\mu\nu} \quad (4)$$

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$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4}(Z_{\mu\tau})_{\mu\nu} Z^{\mu\nu}_{\mu\tau} - \frac{\epsilon}{2}(Z_{\mu\tau})_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{L}_{scalar} = |\mathcal{D}_\mu H|^2 + |\mathcal{D}_\mu \eta|^2 + |\mathfrak{D}_\mu \Phi_i|^2 - V(H, \Phi_i, \eta)$$

$$V(H,\Phi_i,\eta) = -\mu_H^2 \left(H^\dagger H\right) + \lambda_H \left(H^\dagger H\right)^2 - \mu_{\Phi_i}^2 (\Phi_i^\dagger \Phi_i) + \lambda_{\Phi_i}(\Phi_i^\dagger \Phi_i)^2 + \lambda_{H\Phi_i}(H^\dagger H)(\Phi_i^\dagger \Phi_i) + m_\eta^2(\eta^\dagger \eta) +$$
$$\lambda_2(\eta^\dagger\eta)^2 + \lambda_3(\eta^\dagger\eta)(H^\dagger H) + \lambda_4(\eta^\dagger H)(H^\dagger \eta) + \frac{\lambda_5}{2}[(H^\dagger\eta)^2 + (\eta^\dagger H)^2] + \lambda_{\eta\Phi_i}(\eta^\dagger\eta)(\Phi_i^\dagger\Phi_i) +$$
$$\lambda_{\Phi_1\Phi_2}(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + [\mu\Phi_1^2\Phi_2^\dagger + \text{h.c.}]$$

Scalar Mixing

The VEV alignments of the scalars are given as,

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}, \Phi_1 = \frac{1}{\sqrt{2}}(\phi_1 + v_1), \Phi_2 = \frac{1}{\sqrt{2}}(\phi_2 + v_2).$$

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$$\begin{pmatrix} h \\ \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{12}s_{13}s_{23} - c_{23}s_{12} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}.$$

where $\cos\theta_{ij} = c_{ij}$ and $\sin\theta_{ij} = s_{ij}$.

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where $\cos\theta_{ij} = c_{ij}$ and $\sin\theta_{ij} = s_{ij}$.

$$M_{Z_{\mu\tau}} = g_{\mu\tau}\sqrt{v_1^2 + 4v_2^2}.$$

Fermion Mixing

$$\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix} = \begin{pmatrix} \cos\beta_{12} & \frac{\sin\beta_{12}}{\sqrt{2}} & \frac{\sin\beta_{12}}{\sqrt{2}} \\ -\sin\beta_{12} & \frac{\cos\beta_{12}}{\sqrt{2}} & \frac{\cos\beta_{12}}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} . \begin{pmatrix} N_e \\ N_\mu \\ N_\tau \end{pmatrix}$$

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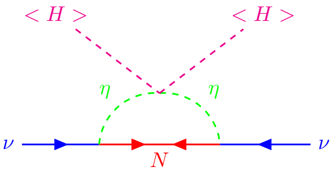
The mixing angle is given by,

$$\beta_{13} = 0; \ \beta_{23} = \frac{\pi}{4}; \ \tan(2\beta_{12}) = \frac{2\sqrt{2} Y_{e\mu} v_1}{M_{ee} - Y_\mu v_2 - M_{\mu\tau}}$$

Neutrino mass



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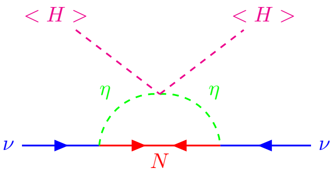

$$Y_D = \begin{pmatrix} Y_{De} & 0 & 0 \\ 0 & Y_{D\mu} & 0 \\ 0 & 0 & Y_{D\tau} \end{pmatrix}, \; M_R = \begin{pmatrix} M_{ee} & Y_{e\mu}v_1 & Y_{e\tau}v_1 \\ Y_{e\mu}v_1 & Y_{\mu}v_2 & M_{\mu\tau} \\ Y_{e\tau}v_1 & M_{\mu\tau} & Y_{\tau}v_2 \end{pmatrix}$$

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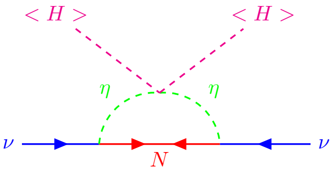

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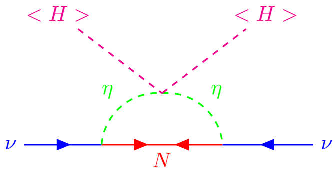
$$(M_\nu)_{\alpha\beta} = \sum_k \frac{Y_{\alpha k} Y_{k\beta} M_k}{32\pi^2} \left[L_k(M^2_{\eta_R}) - L_k(M^2_{\eta_I}) \right]$$

Neutrino mass



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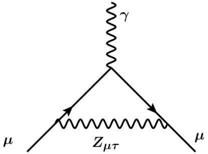
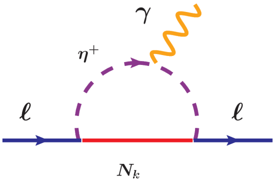
$$Y_{\alpha k} \;=\; \left(U D_\nu^{1/2} R^\dagger \Lambda^{1/2} \right)_{\alpha k}$$

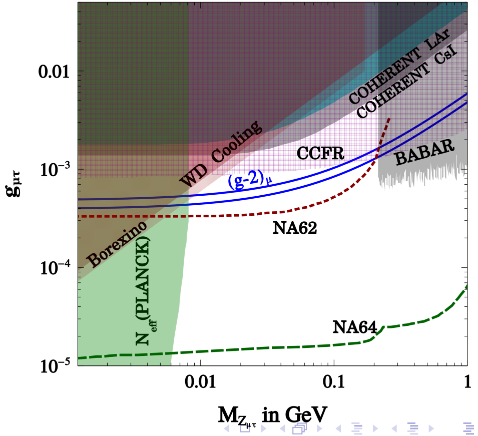
$$\Lambda_k = \frac{2\pi^2}{\lambda_5} \zeta_k \frac{2M_k}{v^2}, \quad \zeta_k = \left(\frac{M_k^2}{8(M^2_{\eta_R} - M^2_{\eta_I})} \left[L_k(M^2_{\eta_R}) - L_k(M^2_{\eta_I}) \right] \right)^{-1}, \quad L_k(m^2) = \frac{m^2}{m^2 - M_k^2} \ln \frac{m^2}{M_k^2}$$

(g-2) of Muon

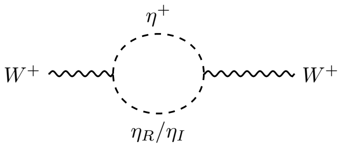
$$\Delta a_\mu = \frac{\alpha_{\mu\tau}}{2\pi}\int_0^1 dx \frac{2m_\mu^2 x^2(1-x)}{x^2 m_\mu^2 + (1-x)M_{Z_{\mu\tau}}^2} \quad ; \quad \alpha_{\mu\tau} = g_{\mu\tau}^2/(4\pi)$$







W-mass anomaly



$$T = \frac{\Theta(m^2_{\eta^+}, m^2_{\eta_R}) + \Theta(m^2_{\eta^+}, m^2_{\eta_I}) - \Theta(m^2_{\eta_R}, m^2_{\eta_I})}{16\pi^2 \alpha_{\rm em}(M_Z) v^2} \; ; \; \Theta(x,y) \equiv \frac{1}{2}(x+y) - \frac{xy}{x-y} \ln\left(\frac{x}{y}\right)$$

$$S = \frac{1}{12\pi} \log\left[\frac{M^2_{\eta_R} + M^2_{\eta_I}}{2M^2_{\eta^+}}\right].$$

$$M_W \simeq M_W^{SM}\left[1 - \frac{\alpha_{\rm em}(M_Z)(S - 2\cos^2\theta_W T)}{4(\cos^2\theta_W - \sin^2\theta_W)}\right].$$

95 GeV Excess in Scotogenic $U(1)_{L_\mu - L_\tau}$ model

$$H_1 \equiv H_{\rm SM},\ H_2 \equiv H_{95},\ H_3 \equiv H_{\rm heavy}.$$

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$$\mu_{\gamma\gamma} = \sin^2\theta_{12}\cos^2\theta_{13}\ \frac{{\rm BR}(H_{95} \to \gamma\gamma)}{{\rm BR}_{\rm SM}(H_{95} \to \gamma\gamma)}.$$

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The diphoton decay width of Z_2-even scalars is given by,

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

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Coupling between the neutral scalars and the inert doublet is given by,

$$\begin{aligned}
C_{H_1\eta\eta} &= c_{12}c_{13}\lambda_3 v + (-c_{23}s_{12} - c_{12}s_{13}s_{23})\lambda_{\eta\Phi_1}v_1 + (-c_{12}c_{23}s_{13} + s_{12}s_{23})\lambda_{\eta\Phi_2}v_2\,,\\
C_{H_2\eta\eta} &= s_{12}c_{13}\lambda_3 v + (c_{23}c_{12} - s_{12}s_{13}s_{23})\lambda_{\eta\Phi_1}v_1 + (-s_{12}c_{23}s_{13} + c_{12}s_{23})\lambda_{\eta\Phi_2}v_2\,,\\
C_{H_3\eta\eta} &= s_{13}\lambda_3 v + c_{13}s_{23}\lambda_{\eta\Phi_1}v_1 + c_{13}c_{23}\lambda_{\eta\Phi_2}v_2.
\end{aligned}$$

Range of parameter for scan

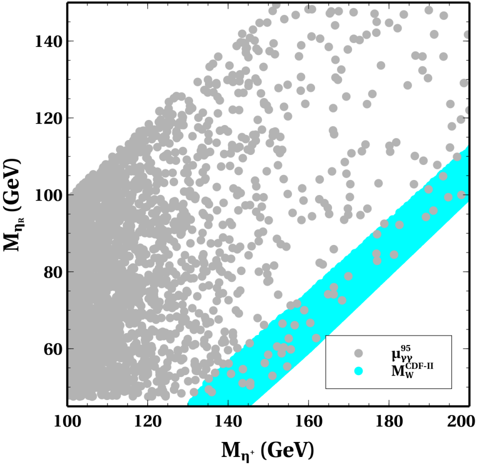
The range in which the free parameters are randomly varied for the numerical analysis.

Parameter	Scanned range
M_{η_R} (GeV)	45,150
$M_{\eta^+} - M_{\eta_R}$ (GeV)	1,100
λ_3	$1, 4\pi$
λ_5	$10^{-8}, 10^{-2}$
$\lambda_{\eta\Phi_1}$	$0.01, 4\pi$
$\lambda_{\eta\Phi_2}$	$0.01, 4\pi$
$\sin\theta_{12}$	$0.1, 0.7$
$\sin\theta_{23}$	$0.1, 0.7$
$\sin\theta_{13}$	$0.001, 0.1$
$\sin\beta_{12}$	$10^{-4}, 0.7$
v_1 (GeV)	$20, 60$
m_{H_3} (GeV)	$200, 500$

We also impose the LEP limits on the doublet scalar as $M_{\eta_R} + M_{\eta_I} > M_Z$ and a conservative limit on the charged scalar $M_{\eta^+} > 100$ GeV

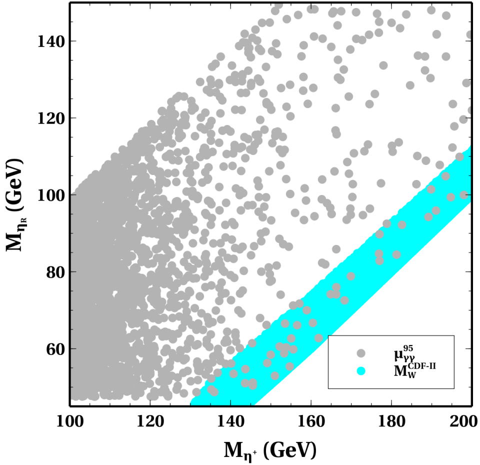
One generation of η

Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess in the plane of $M_{\eta_R} - M_{\eta^+}$ with one generation of η.



One generation of η

Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess in the plane of $M_{\eta_R} - M_{\eta^+}$ with one generation of η.

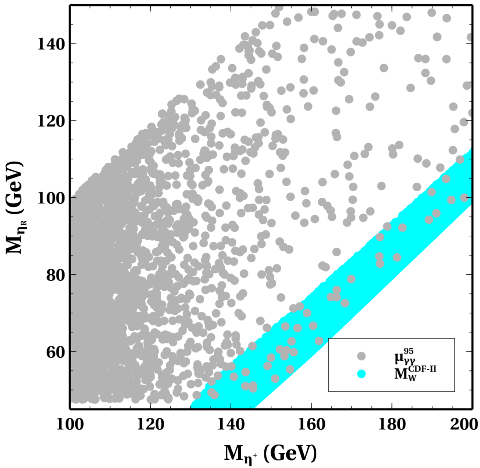


$H_i \to \eta_{R/I}, \eta_{R,I}$

$H_i \to N_1, N_1;\ Z_{\mu\tau}, Z_{\mu\tau}$

One generation of η

Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess in the plane of $M_{\eta_R} - M_{\eta^+}$ with one generation of η.



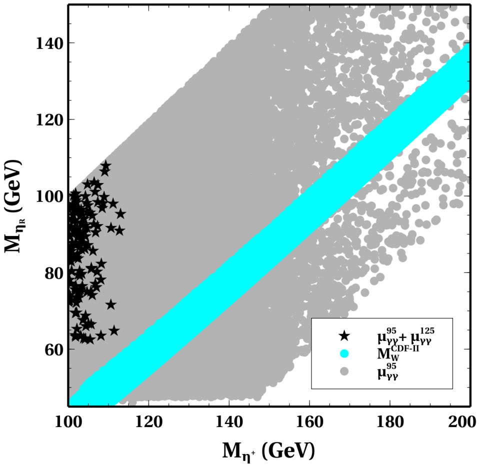
$H_i \to \eta_{R/I}, \eta_{R,I}$

$H_i \to N_1, N_1;\ Z_{\mu\tau}, Z_{\mu\tau}$

$M_{\eta^+} - M_{\eta_R} \in [80, 100]$ GeV

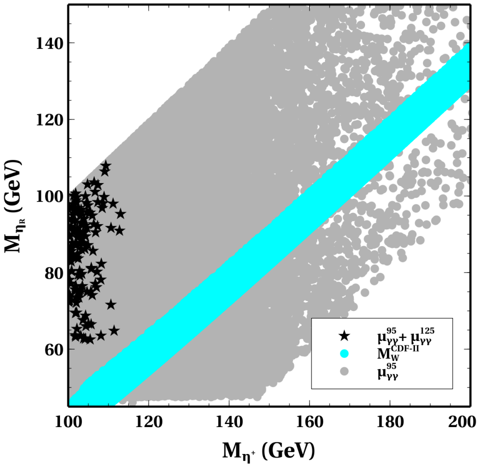
Two generation of η

Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess in the plane of $M_{\eta_R} - M_{\eta^+}$ with two generations of η



Two generation of η

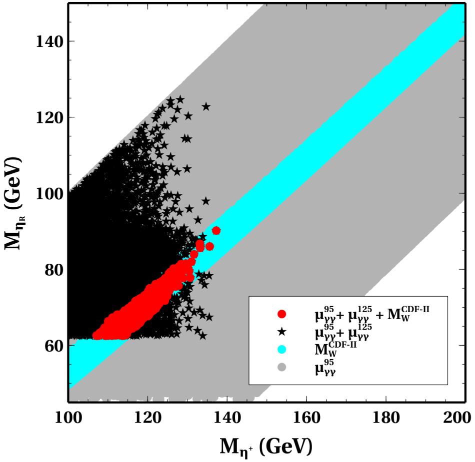
Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess in the plane of $M_{\eta_R} - M_{\eta^+}$ with two generations of η



$M_{\eta^+} - M_{\eta_R} \in [50, 70]$ GeV

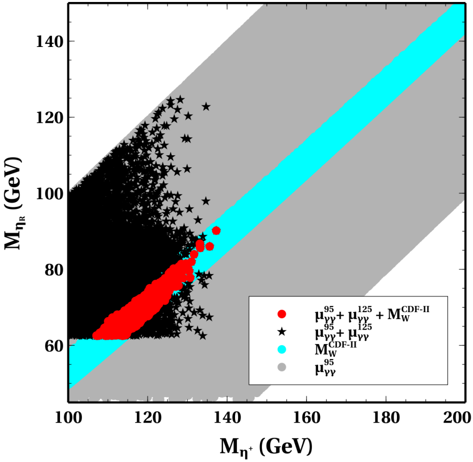
Three generation of η

Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess and SM Higgs signal strength in the plane of $M_{\eta_R} - M_{\eta^+}$ with three generations of η.



Three generation of η

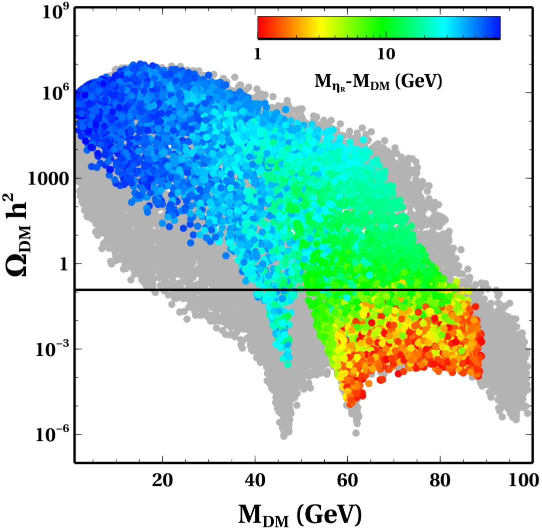
Parameter space satisfying CDF-II W-mass anomaly, 95 GeV excess and SM Higgs signal strength in the plane of $M_{\eta_R} - M_{\eta^+}$ with three generations of η.



$M_{\eta^+} - M_{\eta_R} \in [42, 58]$ GeV

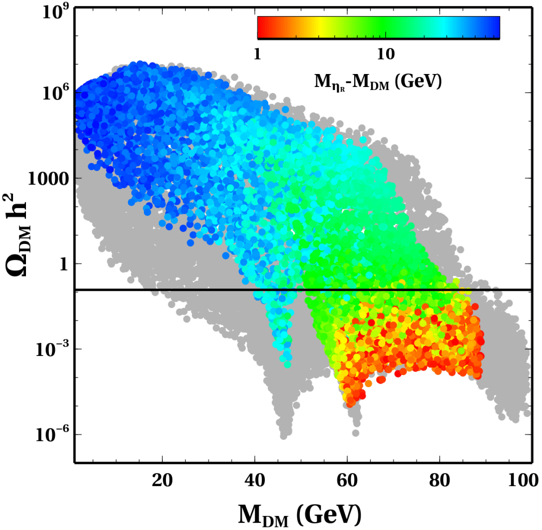
DM phenomenology

DM relic density as a function of DM mass



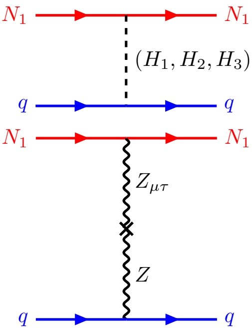
DM phenomenology

DM relic density as a function of DM mass

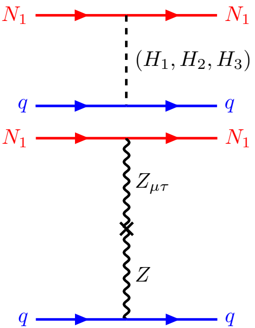


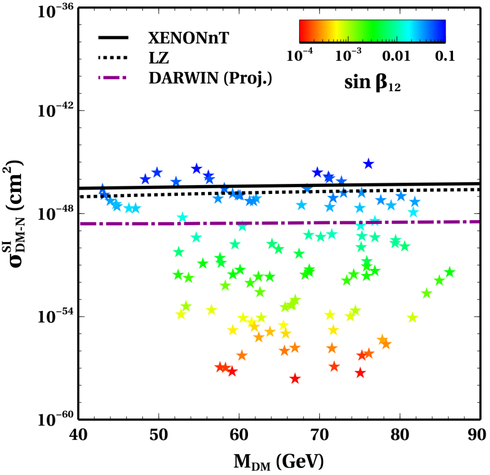
$M_{DM} \in [40, 85]$ GeV.

Direct Detection of DM



Direct Detection of DM





$\sin\beta_{12} < 0.04$, $\sin\beta_{12} \sim 0.01$

Summary

- We have explored the potential to identify a shared connection between the $(g-2)_\mu$ anomaly, the CDF-II W-mass anomaly, and the CMS 95 GeV excess, within the context of the scotogenic $L_\mu - L_\tau$ model.
- The minimal model can effectively accounts for the $(g-2)_\mu$ and CDF-II W-mass anomalies, it falls short in generating the necessary diphoton signal strength for the 95 GeV scalar while being consistent with SM Higgs diphoton signal strength.
- We introduce two extra scalar doublets solely to contribute radiatively to diphoton decay of neutral scalars.
- These new scalar doublets can be motivated from neutrino mass point of view if we have only one right-handed neutrino.
- The DM is constrained in range $\in [40, 85]$ GeV.
- This scotogenic $U(1)_{L_\mu - L_\tau}$ model can explain all these simultaneously.

Thank You

Backup

$$M^2_{\eta_R} = m^2_\eta + \frac{v^2}{2}(\lambda_3 + \lambda_4 + \lambda_5) + \frac{v_1^2}{2}\lambda_{\eta\Phi_1} + \frac{v_2^2}{2}\lambda_{\eta\Phi_2}$$

$$M^2_{\eta_I} = m^2_\eta + \frac{v^2}{2}(\lambda_3 + \lambda_4 - \lambda_5) + \frac{v_1^2}{2}\lambda_{\eta\Phi_1} + \frac{v_2^2}{2}\lambda_{\eta\Phi_2}$$

$$M^2_{\eta^+} = m^2_\eta + \frac{v^2}{2}\lambda_3 + \frac{v_1^2}{2}\lambda_{\eta\Phi_1} + \frac{v_2^2}{2}\lambda_{\eta\Phi_2}$$

Backup

The loop functions involved in the calculation of $\Gamma(h_i \to \gamma\gamma)$ are given by

$$A_0 = -[\tau - f(\tau)]/\tau^2 ,$$
$$A_{1/2} = 2[\tau + (\tau - 1)f(\tau)]/\tau^2 ,$$
$$A_1 = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)]/\tau^2 ,$$

where the function $f(\tau)$ is defined as

$$f(\tau) = \begin{cases} \arcsin^2 \sqrt{\tau} \; ; & \tau \leq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 \; ; & \tau > 1 \end{cases}$$

Backup

LFV

$$\text{Br}(\mu \to e\gamma) = \frac{3(4\pi)^3\alpha}{4G_F^2}(|A^M_{e\mu}|^2 + |A^E_{e\mu}|^2)\text{Br}(\mu \to e\nu_\mu\overline{\nu_e}).$$

$$A^M_{e\mu} = \frac{-1}{(4\pi)^2}\sum_k (Y^*_{ek}Y_{\mu k}I_k^{++} + Y^*_{ek}Y_{\mu k}I_k^{+-})$$

$$A^E_{e\mu} = \frac{-i}{(4\pi)^2}\sum_k (-Y^*_{ek}Y_{\mu k}I_k^{-+} - Y^*_{ek}Y_{\mu k}I_k^{--})$$

$$I_k^{(\pm)_1(\pm)_2} = \int d^3X \frac{x(y + (\pm)_1 z\frac{m_e}{m_\mu} + (\pm)_2\frac{M_k}{m_\mu})}{-xym_\mu^2 - xzm_e^2 + (1-x)M^2_{\eta^+} + xM_k^2}$$