Diphoton Excess at 750 GeV in leptophobic U(1)′ model inspired by E_6 GUT

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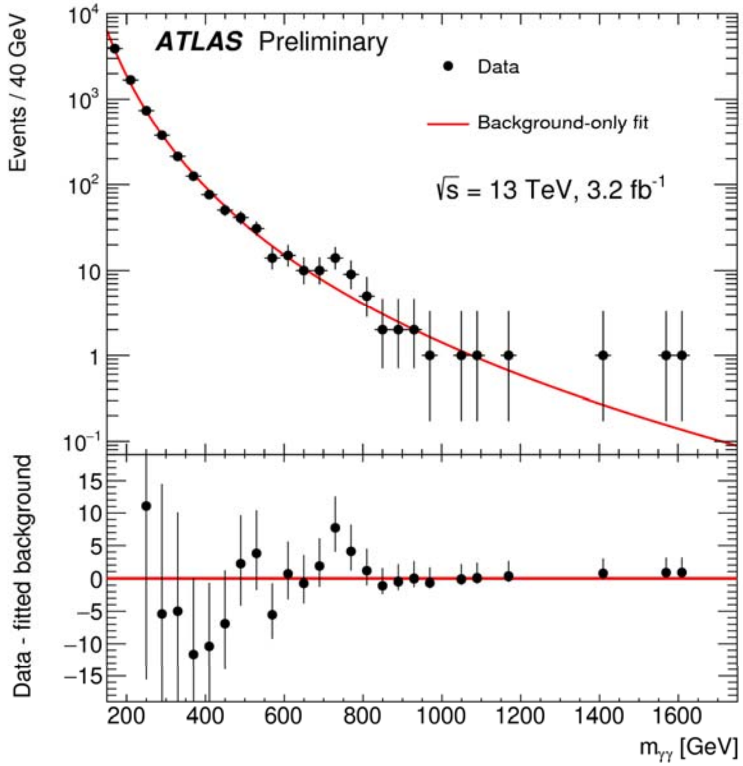
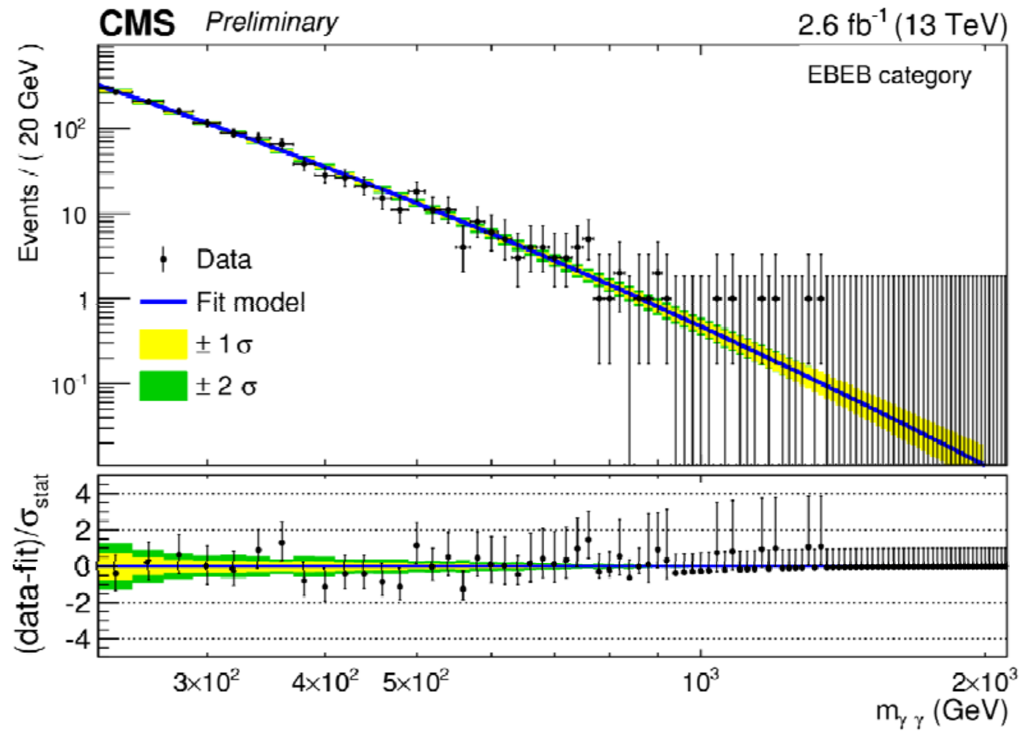
Diphoton excess Run-II



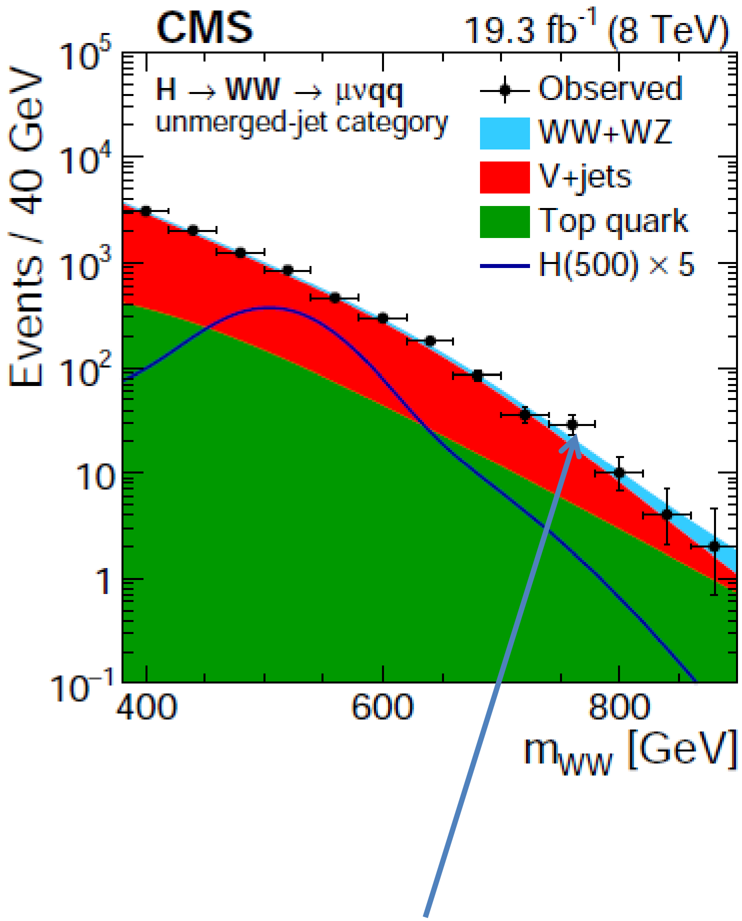


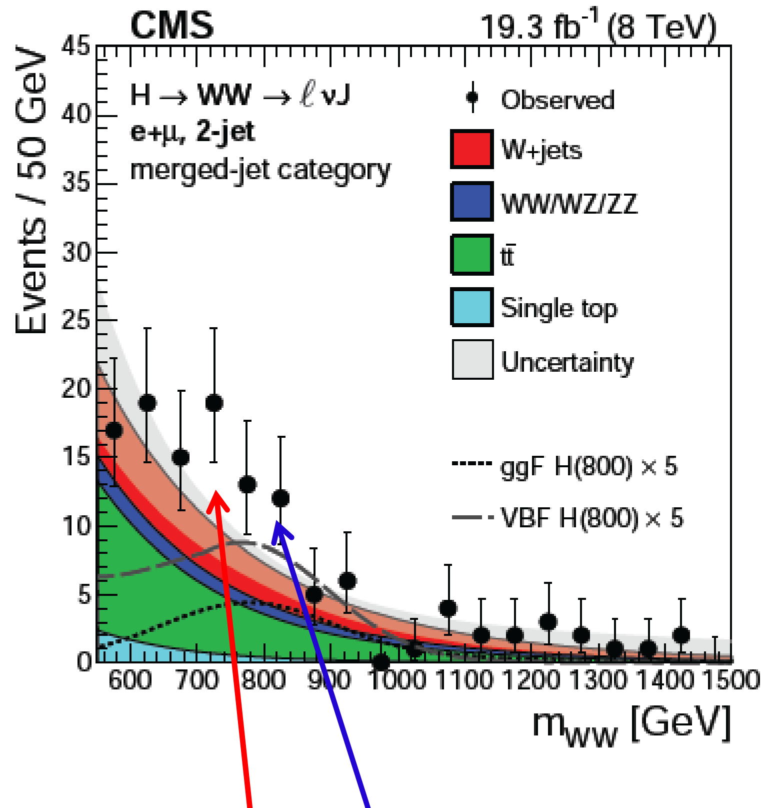
ATLAS: local 3.6σ (global 2.0σ)

$\sigma(pp\to\gamma\gamma)$ ~ 6 fb with Γ~45 GeV

CMS: local 2.6σ for narrow width
<2σ for wide width
(global <1.2σ)

CMS Run-I





small excess at 750 GeV

local excess of 2.1σ

local excess of 2.6σ

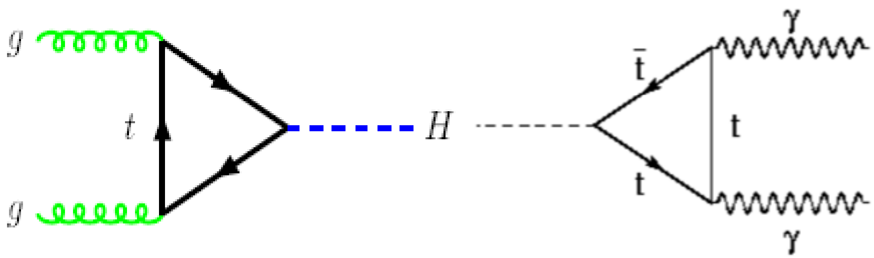
But, there is no excess in the 0+1 jet category

Run-I constraints

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

Franceschini et al., arXiv:1512.04933

SM-like spin-0 resonance



$$\sigma(gg \to H \to \gamma\gamma) \sim \frac{C_{gg}}{s m_H \Gamma_{\text{tot}}} \Gamma[H \to gg]\Gamma[H \to \gamma\gamma]$$

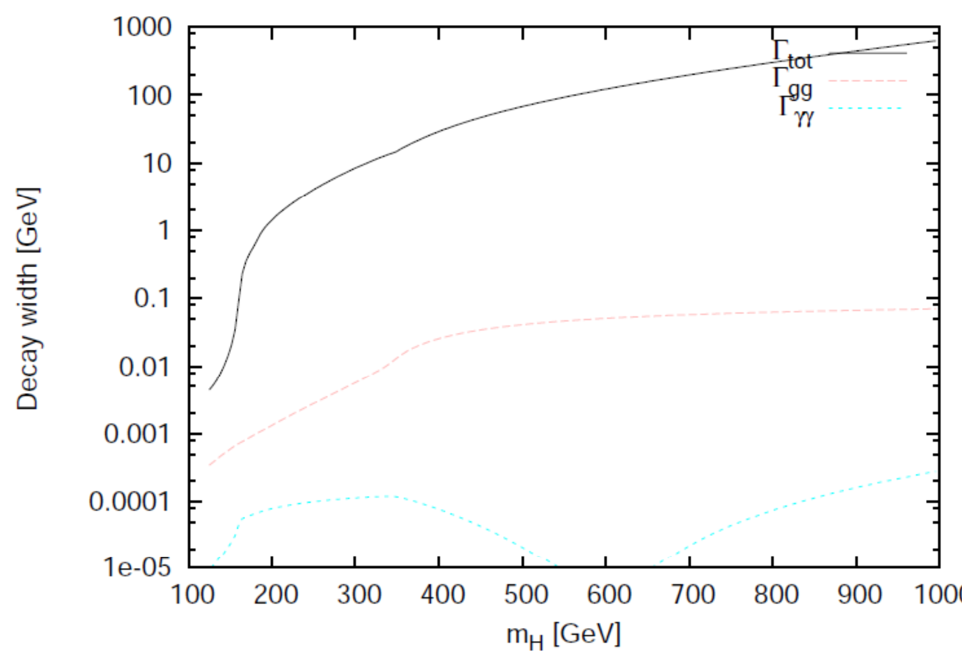
$$C_{gg} = \frac{\pi^2}{8} \int_\tau^1 \frac{dx}{x} g\left(x, m_\Phi^2\right) g\left(\frac{\tau}{x}, m_\Phi^2\right)$$

Diphoton excess requires

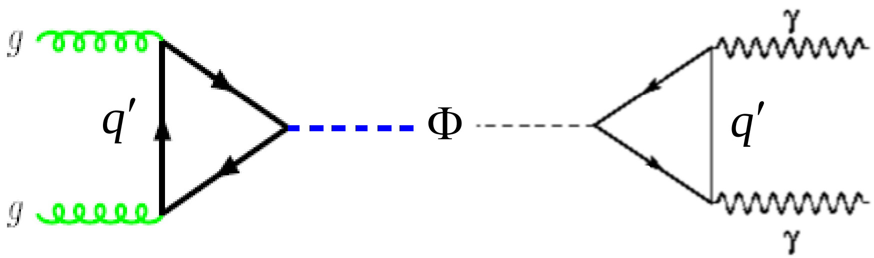
$$\Gamma[H \to gg]\Gamma[H \to \gamma\gamma] \sim 10^{-2}\,\text{GeV}^2$$

$$\Gamma_{\text{tot}} \sim 246\ \text{GeV}$$

$$\sigma(gg \to H \to \gamma\gamma) \le 10^{-4}\,\text{fb}$$



Spin-0 with vector-like q's



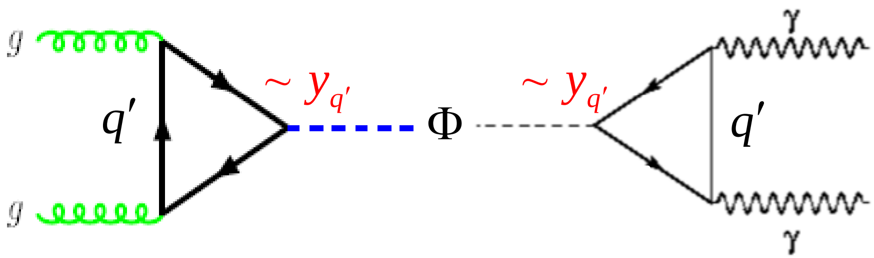
$$\Gamma[\Phi \to gg] = \frac{\alpha_s^2 m_\Phi^3}{128\pi^3 v_\Phi^2}\left|\sum_{q'} A_{1/2}^H(\tau_{q'})\right|^2 \qquad \Gamma[\Phi \to \gamma\gamma] = \frac{\alpha^2 m_\Phi^3}{256\pi^3 v_\Phi^2}\left|\sum_{q'} N_c Q_{q'}^2 A_{1/2}^H(\tau_{q'})\right|^2$$

$$\sigma(gg \to \Phi \to \gamma\gamma) \sim \frac{C_{gg}}{s m_\Phi \Gamma_{\text{tot}}}\Gamma[\Phi \to gg]\Gamma[\Phi \to \gamma\gamma] \propto n_{q'}^4$$

In order to enhance the cross section, we need

$$n_{q'} \uparrow$$

Spin-0 with vector-like q's



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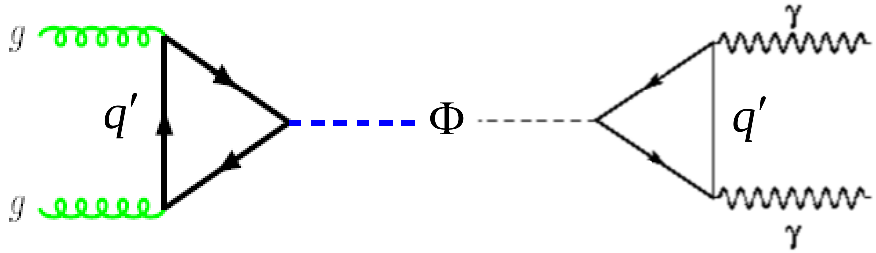
$$\sigma(gg \to \Phi \to \gamma\gamma) \sim \frac{C_{gg}}{s m_\Phi \Gamma_{\text{tot}}}\Gamma[\Phi \to gg]\Gamma[\Phi \to \gamma\gamma] \ \propto \ n_{q'}^4,\ y_{q'}^4$$

In order to enhance the cross section, we need

$$n_{q'} \uparrow,\ y_{q'} \uparrow$$

Spin-0 with vector-like q's



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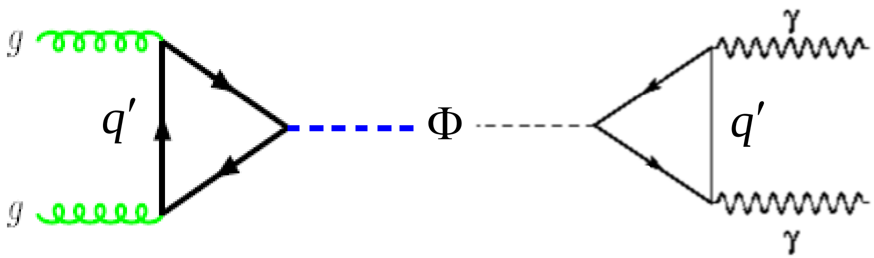
$$\sigma(gg \to \Phi \to \gamma\gamma) \sim \frac{C_{gg}}{s m_\Phi \Gamma_{\text{tot}}} \Gamma[\Phi \to gg]\Gamma[\Phi \to \gamma\gamma] \propto n_{q'}^4,\ y_{q'}^4,\ v_\Phi^{-4}$$

In order to enhance the cross section, we need

$$n_{q'} \uparrow,\ y_{q'} \uparrow,\ v_\Phi \downarrow$$

Spin-0 with vector-like q's



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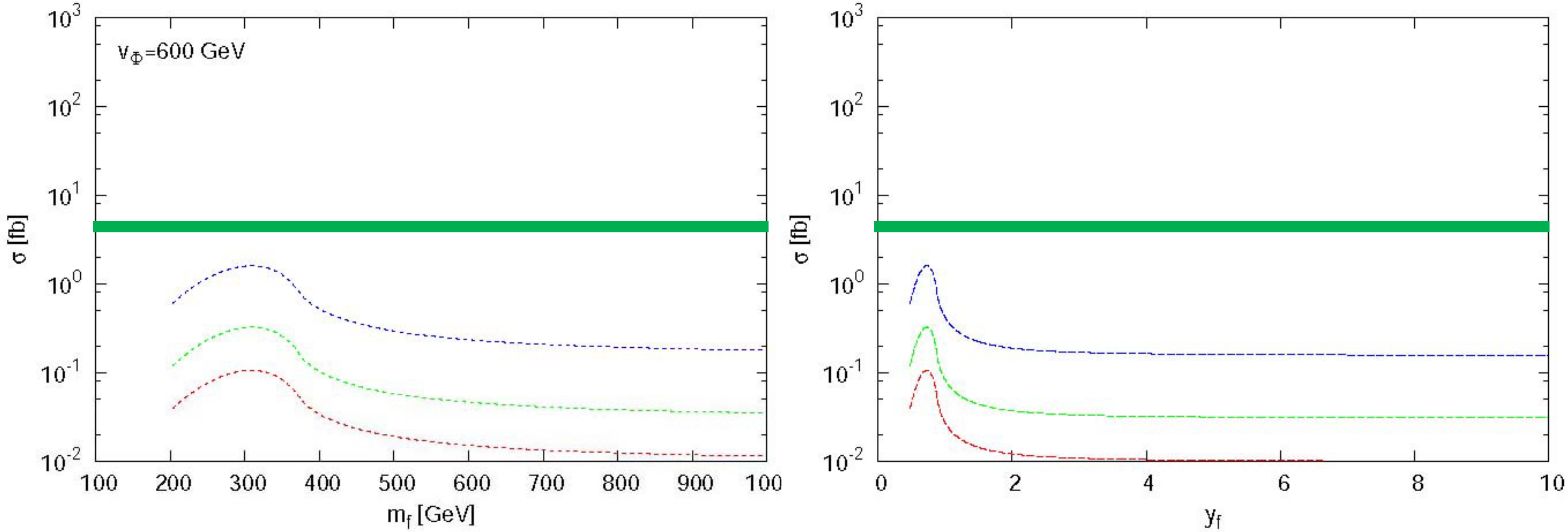
$$\sigma(gg \to \Phi \to \gamma\gamma) \sim \frac{C_{gg}}{s m_\Phi \Gamma_{\text{tot}}} \Gamma[\Phi \to gg]\Gamma[\Phi \to \gamma\gamma] \propto n_{q'}^4,\ y_{q'}^4,\ v_\Phi^{-4},\ Q_{q'}^4$$

In order to enhance the cross section, we need

$$n_{q'} \uparrow,\ y_{q'} \uparrow,\ v_\Phi \downarrow,\ Q_{q'} \uparrow$$

Spin-0 with vector-like q's



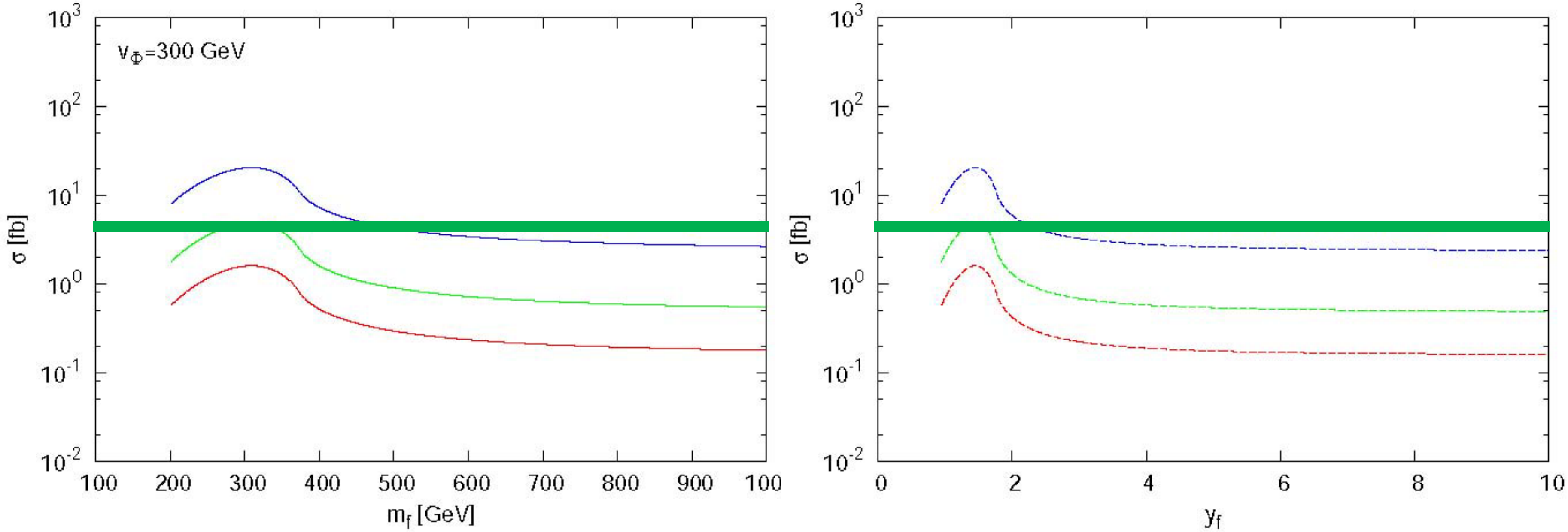
$v_\Phi = 600$ GeV

$n_{q'} = 3, \quad Q_{q'} = -\frac{1}{3}$

$n_{q'} = 3, \quad Q_{q'} = \frac{2}{3}$

$n_{q'} = 6, \quad Q_{q'} = -\frac{1}{3}$ or $\frac{2}{3}$

Spin-0 with vector-like q's



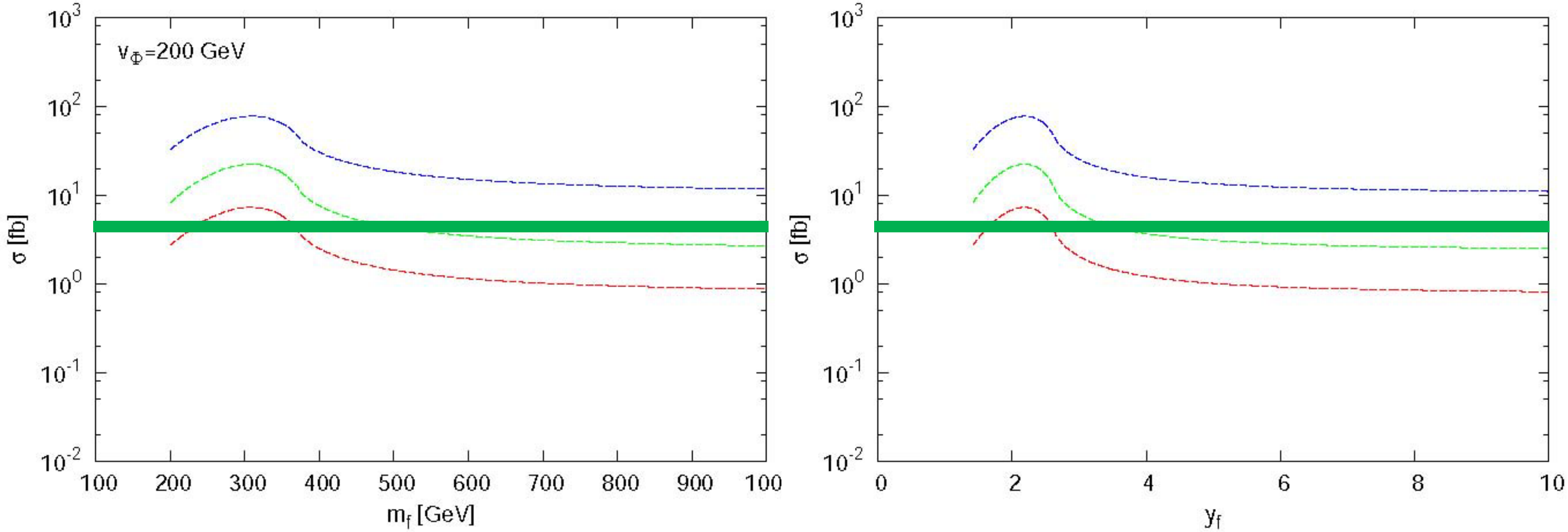
$$v_{\Phi} = 300 \text{ GeV}$$

$$n_{q'} = 3, \quad Q_{q'} = -\frac{1}{3}$$

$$n_{q'} = 3, \quad Q_{q'} = \frac{2}{3}$$

$$n_{q'} = 6, \quad Q_{q'} = -\frac{1}{3} \text{ or } \frac{2}{3}$$

Spin-0 with vector-like q's



$v_\Phi = 200$ GeV

$n_{q'} = 3, \quad Q_{q'} = -\frac{1}{3}$

$n_{q'} = 3, \quad Q_{q'} = \frac{2}{3}$

$n_{q'} = 6, \quad Q_{q'} = -\frac{1}{3} \text{ or } \frac{2}{3}$

The model

• Type-II two Higgs doublet model where Z_2 symmetry is replaced by U(1) gauge symmetry

• contains extra vector-like fermions, but chiral under new U(1)

• scalar: two doublet+one singlet

• mixing of doublets and singlet is suppressed by SM-like Higgs boson data

• the extra singlet may be the candidate for the diphoton excess

• no tree-level coupling to SM particles, but decays to non-SM particles may enhance the total decay width

Type-II 2HDM with U(1)

$$V_y = y_{ij}^U \overline{Q}_{Li} \tilde{H}_1 U_{Rj} + y_{ij}^D \overline{Q}_{Li} H_2 D_{Rj} + y_{ij}^E \overline{L}_i H_2 E_{Rj} + y_{ij}^N \overline{L}_i \tilde{H}_1 N_{Rj}$$

u_R	d_R	Q_L	l	E_R	ν_R	H_1	H_2
1	0	0	0	0	1	1	0

chiral fermions	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_H$	Z_2
u_{Ri}	3	1	2/3	1	+
ν_{Ri}	1	1	0	1	+
U_{Li}	3	1	2/3	1	−
U_{Ri}	3	1	2/3	0	−
N_{Li}	1	1	0	1	−
N_{Ri}	1	1	0	0	−
H_1	1	2	1/2	1	+
Φ	1	1	0	1	+
X	1	1	0	1	−

SM particles, ν_R

extra quarks

extra singlet fermions

Type-II 2HDM with U(1)

- type-II 2HDM with U(1) inspired by the E_6 GUT

$$E_6 \to SO(10)\times U(1)_\psi \to SU(5)\times U(1)_\chi \times U(1)_\psi .$$

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Q^i	3	2	$1/6$	$-1/3$	1	-1	-2
U_R^i	3	1	$2/3$	$2/3$	-1	1	2
D_R^i	3	1	$-1/3$	$-1/3$	-1	-3	-1
L_i	1	2	$-1/2$	0	1	3	1
E_R^i	1	1	-1	0	-1	1	2
N_R^i	1	1	0	1	-1	5	5
H_1	1	2	$1/2$	0	2	2	-1
H_2	1	2	$1/2$	1	-2	2	4

$$Q_\eta = \frac{3}{4}Q_\chi - \frac{5}{4}Q_\psi$$

$$Q_b = \frac{1}{5}(Q_\eta + 2Q_Y)$$ ⟹ leptophobic

Only one U(1) symmetry remains at low energy while the other symmetry is spontaneously broken at the high energy scale.

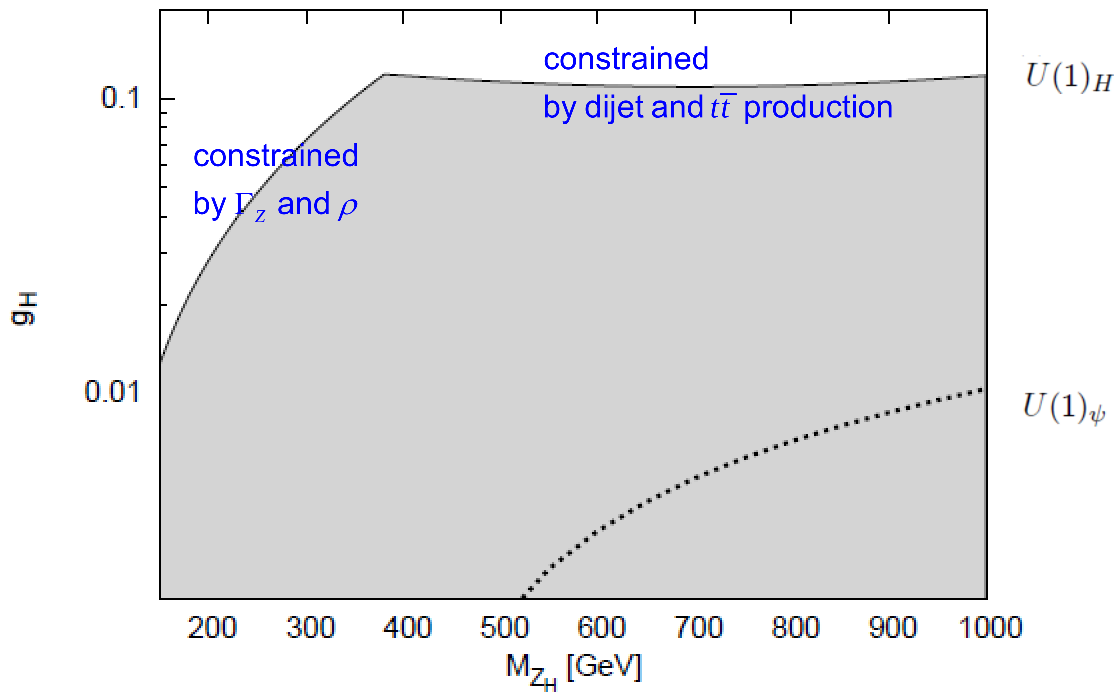
Z-Z_H mixing

- tree-level mixing

$$M^2 = \begin{pmatrix} \hat{M}_Z^2 & \Delta M_{ZZ_H}^2 \\ \Delta M_{ZZ_H}^2 & \hat{M}_{Z_H}^2 \end{pmatrix}$$

$$\Delta M_{ZZ_H}^2 = -\frac{\hat{M}_Z}{v} g_H \sum_{i=1}^{2} q_{H_i} v_i^2$$

$$\tan 2\xi = \frac{2\Delta M_{ZZ_H}^2}{\hat{M}_{Z_H}^2 - \hat{M}_Z^2}$$



Type-II 2HDM with U(1)

Extra fermions (required by anomaly-free conditions)

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
D_L^i	3	1	$-1/3$	$2/3$	-2	2	4
D_R^i	3	1	$-1/3$	$-1/3$	2	2	-1
$\tilde{H}_L^i$	1	2	$-1/2$	0	-2	-2	1
$\tilde{H}_R^i$	1	2	$-1/2$	-1	2	-2	-4
N_L^i	1	1	0	-1	4	0	-5

extra quarks

extra leptons

extra singlet fermions

The SM fermions and extra chiral fermions can be embedded into three-family 27 representations of the E6 group.

Singlet scalar required for $U(1)_H$ breaking and masses for extra fermions

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_b$	$U(1)_\psi$	$U(1)_\chi$	$U(1)_\eta$
Φ	1	1	0	1	-4	0	5

Higgs Potential

$$V_{\rm scalar} = \tilde{m}_1^2 H_1^\dagger H_1 + \tilde{m}_2^2 H_2^\dagger H_2 + \frac{\lambda_1}{2}\left(H_1^\dagger H_1\right)^2 + \frac{\lambda_2}{2}\left(H_2^\dagger H_2\right)^2 + \lambda_3 H_1^\dagger H_1 H_2^\dagger H_2 + \lambda_4 H_1^\dagger H_2 H_2^\dagger H_1 + V_\Phi,$$

no λ_5 terms!

$$V_\Phi = \tilde{m}_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda_\Phi}{2}(\Phi^\dagger\Phi)^2 - \left(\mu_\Phi H_1^\dagger H_2 \Phi + \text{h.c.}\right) + \tilde{\lambda}_1 H_1^\dagger H_1 \Phi^\dagger\Phi + \tilde{\lambda}_2 H_2^\dagger H_2 \Phi^\dagger\Phi$$

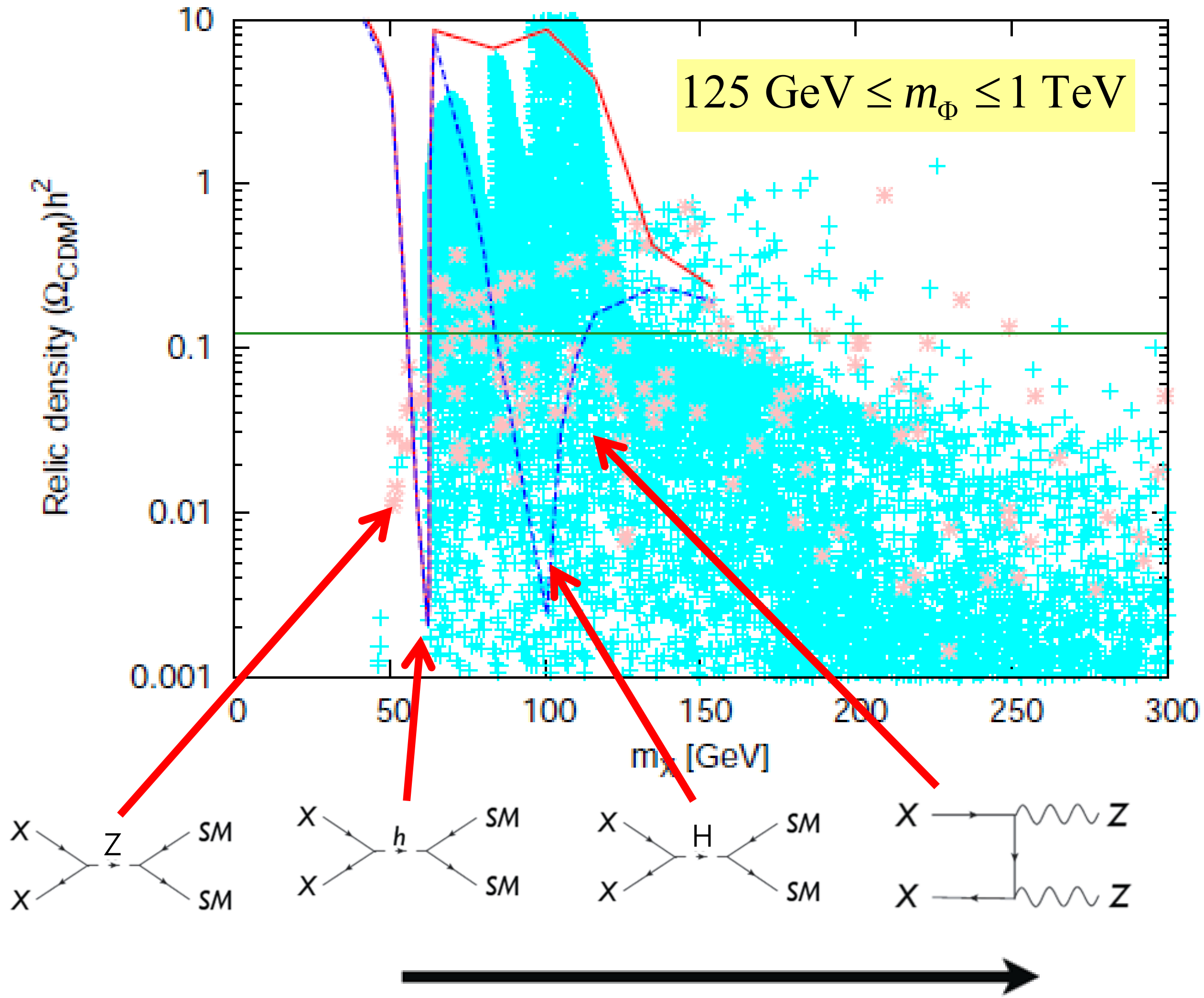
$$H_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i\chi_i) \end{pmatrix} \qquad \Phi = \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi + i\chi_\Phi)$$

three CP-even scalars mix with each other

$$\tilde{\mathcal{M}}^2 = \begin{pmatrix} \tilde{\mathcal{M}}_{11}^2 & \tilde{\mathcal{M}}_{12}^2 & \tilde{\mathcal{M}}_{1\Phi}^2 \\ \tilde{\mathcal{M}}_{12}^2 & \tilde{\mathcal{M}}_{22}^2 & \tilde{\mathcal{M}}_{2\Phi}^2 \\ \tilde{\mathcal{M}}_{1\Phi}^2 & \tilde{\mathcal{M}}_{2\Phi}^2 & \tilde{\mathcal{M}}_{\Phi\Phi}^2 \end{pmatrix} \Rightarrow \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha_h & -\sin\alpha_h \\ \sin\alpha_h & \cos\alpha_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

h_Φ does not mix with h1 and h2 by $\tilde{M}_{1\Phi}^2 = \tilde{M}_{2\Phi}^2 = 0$

Relic density



very large Yukawa couplings required

with the bounds on
EWPOs
$b \to s\gamma$
$B \to \tau\nu$
extra scalar search
extra fermion search

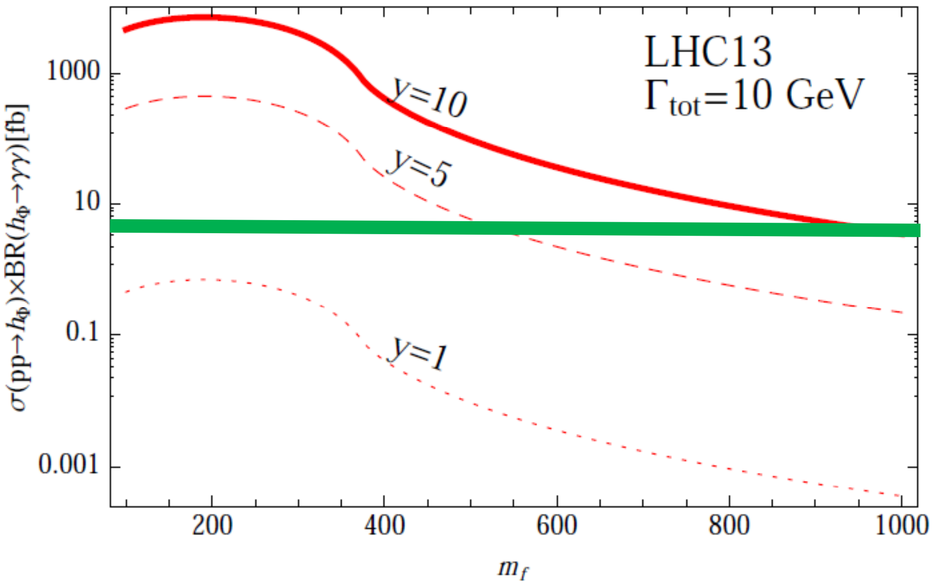
$pp \to l_{ex} l_{ex} \to ll + \text{missing}$

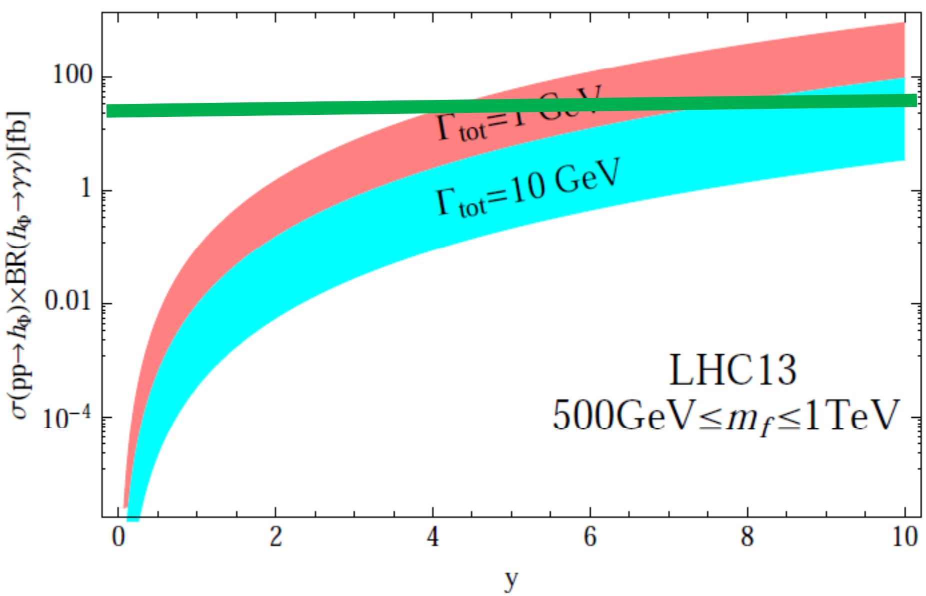
$m_{l_{ex}}, m_{q_{ex}} \gtrsim 1\text{TeV}$

(red line)
$500\ \text{GeV} \le m_{H,A,H^+} \le 1\ \text{TeV}$
$y'_n = 1$

(blue line)
$m_{H,A} = 200\ \text{GeV},\ m_{H^+} = 360\ \text{GeV}$
$y'_n = 1$

Diphoton excess





$y \approx 5 - 10$ for $m_f > 400$ GeV

Fermionic dark matter

- the Yukawa interactions which respect all the U(1)′ symmetries

$$V^{\rm ex} = y_{ij}^{D}\overline{D_R^j}\Phi D_L^i + y_{ij}^{H}\overline{\widetilde{H}_R^j}\Phi \widetilde{H}_L^i + y_{IJ}^{N}\overline{N_L^c}H_1^\dagger i\sigma_2 \widetilde{H}_L^i + y_{IJ}^{\prime N}\overline{\widetilde{H}_R^i}H_2 N_L^j + H.c.$$

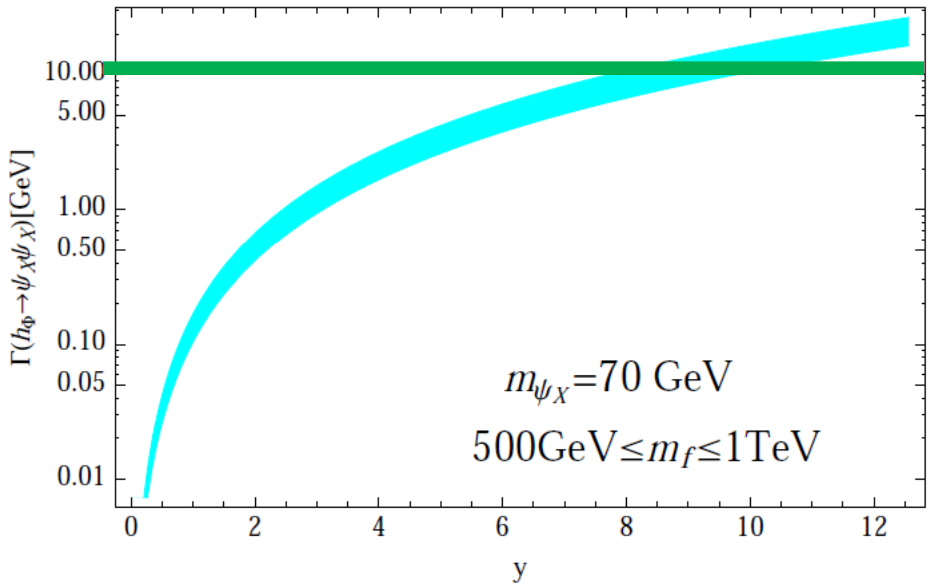
Charged fermions get masses from nonzero ⟨Φ⟩ while neutral fermions from ⟨Φ⟩ and $\langle H_{1,2}\rangle$.

Mixing of extra neutral fermions

$$\mathcal{L}_\nu = -\frac{1}{2}\left(\overline{\widetilde{\nu}_L^c}\ \overline{\widetilde{\nu}_R}\ \overline{n_L^c}\right)\begin{pmatrix} 0 & m_{\widetilde{e}} & m_M \\ m_{\widetilde{e}} & 0 & m_D \\ m_M & m_D & 0 \end{pmatrix}\begin{pmatrix} \widetilde{\nu}_L \\ \widetilde{\nu}_R^c \\ n_L \end{pmatrix} + h.c.$$

$$= -\frac{1}{2}\left(\overline{N_1}\ \overline{N_2}\ \overline{N_3}\right)\begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}.$$

⟹ The lightest one is CDM.



Scalar dark matter

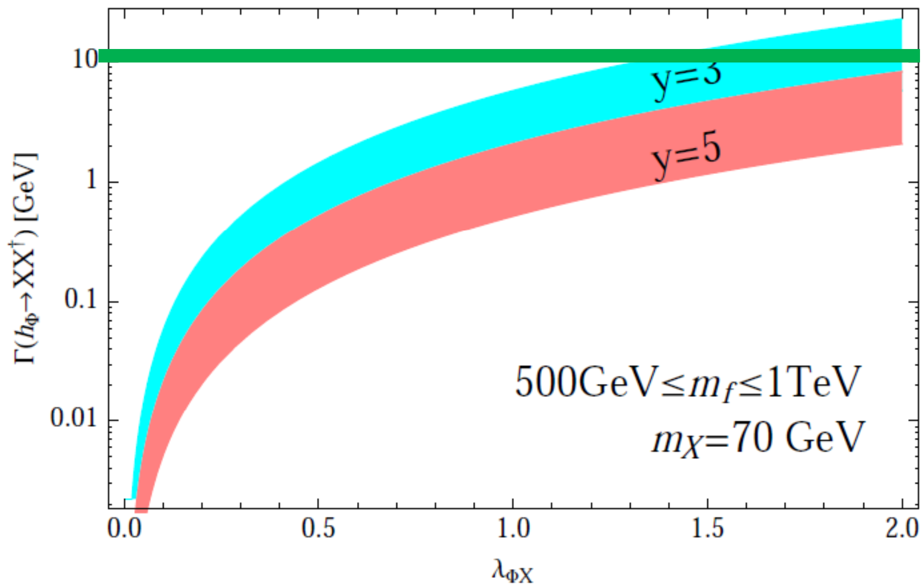
- introduce new Z_2-odd scalar X with quantum number (1,1,0,-1)

$$\mathcal{L}_X = D_\mu X^\dagger D^\mu X - (m_{X0}^2 + \lambda_{H_1X} H_1^\dagger H_1 + \lambda_{H_2X} H_2^\dagger H_2) X^\dagger X - \lambda_X (X^\dagger X)^2$$
$$- \left(\lambda''_{\Phi X} (\Phi^\dagger X)^2 + H.c.\right) - \lambda_{\Phi X} \Phi^\dagger \Phi X^\dagger X - \lambda'_{\Phi X} |\Phi^\dagger X|^2$$
$$- \left(y_{dX}^D \overline{d_R} D_L X + y_{LX}^{\tilde{H}} \overline{L} \widetilde{H}_R X^\dagger + H.c.\right)$$

- new Z_2 forbids dangerous terms

$$\Phi^\dagger X \ , H_1^\dagger H_1 \Phi^\dagger X$$

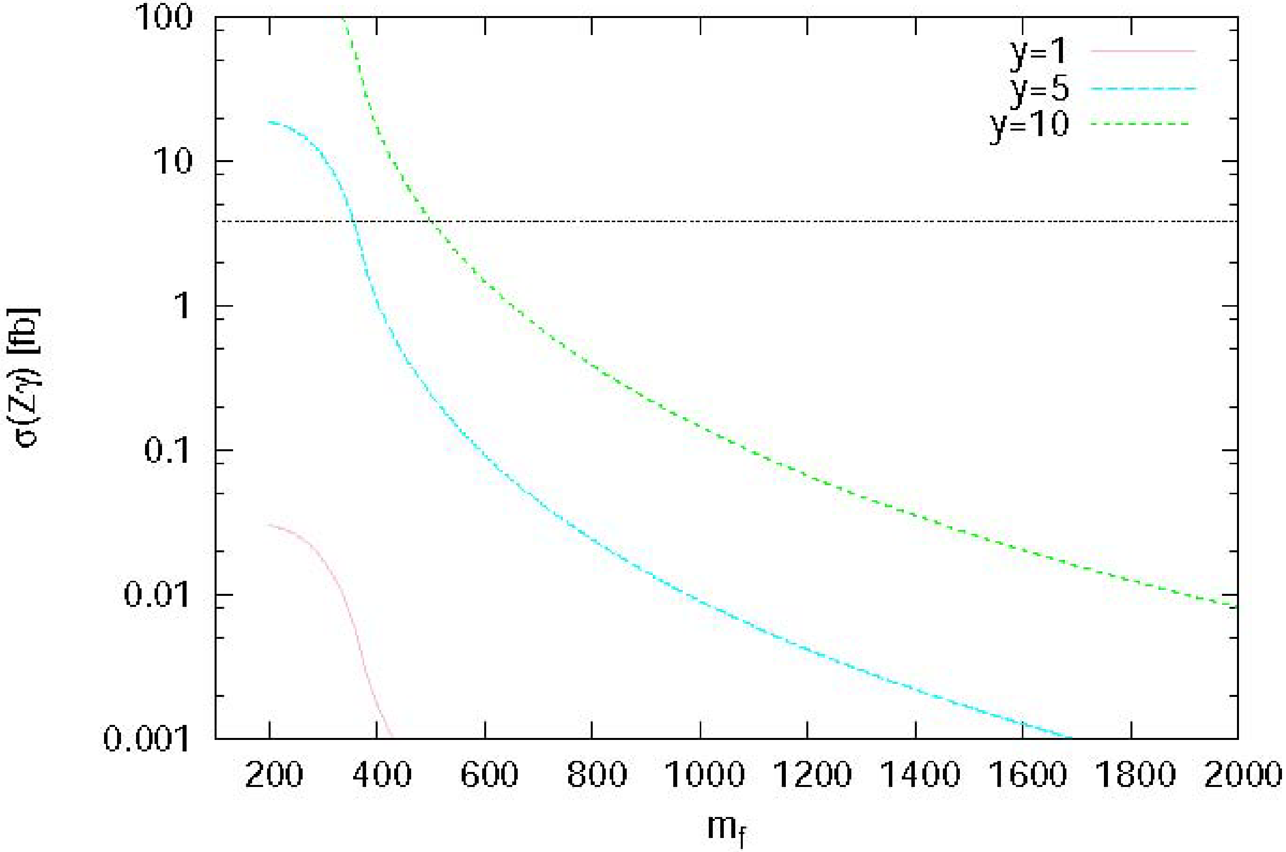
- X could be stable if <X>=0



- might be a dominant decay channel

Zγ production

- The bound at 8 TeV is $\sigma(gg \to h_\Phi \to Z\gamma) \lesssim 3.8 \text{ fb}$



Constraints at 8 TeV

- The bound on the dijet production at 8TeV is about 2 pb

$$\sigma(gg \to h_\Phi \to gg) \lesssim 2 \text{ pb}$$

The mass of exotic quarks must be larger than 400 GeV for y=5 and 600 GeV for y=10

- The bound on the Higgs pair production is about 10 fb

$$\sigma(gg \to h_\Phi \to hh) \lesssim 10 \text{ fb}$$

depends on the model parameters and BR($h_\Phi \to hh$)<0.01

- diboson production

$$\sigma(gg \to h_\Phi \to WW) \lesssim 40 \text{ fb}$$
$$\sigma(gg \to h_\Phi \to ZZ) \lesssim 10 \text{ fb}$$

No tree-level coupling and loop diagrams of SU(2) doublet lepton would be dominant

Constraints at 8 TeV

- The monojet search gives constraints on the invisible decay

$$\sigma(gg \to h_\Phi) \sim 2\text{pb}$$

From the naïve dimensional analysis,

$$\sigma(gg \to h_\Phi g) \sim \frac{\alpha_s}{4\pi} \sigma(gg \to h_\Phi) \sim 0.02\text{pb} < 0.8\text{pb}$$

- $h_\Phi \to$Hh, HH, AA decays are not well constrained

The main decay channel would be the 4b channel

would be one of promising decay channels for large decay width

O(1) Yukawa coupling

• introduce two singlet scalars Φ_1 and Φ_2 which have the same U(1)′ charge

• Yukawa interaction of extra quarks

$$V^{ex} = (y_1 \Phi_1 + y_2 \Phi_2)\overline{D}_R D_L + H.c.$$

• Φ_1 contains the CP-even scalar for 750 GeV excess, but

$$\langle \Phi_1 \rangle = 0, \quad \langle \Phi_2 \rangle = v_\Phi$$

• Φ_1 is decoupled from U(1)′ breaking and y_2 could be a free parameter

Conclusions

- Type-II 2HDM with local U(1) gauge symmetry: leptophobic U(1)′ inspired by E6

- 750 GeV diphoton excess may be possible

- The model will meet more constraints with run-II data

- The model may be improved by adding new scalar