

# What is the gamma gamma resonance at 750 GeV?

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Based on: 1512.04933,  
1602.07297, 1603.07719

LHCP, Lund, 16 June 2016

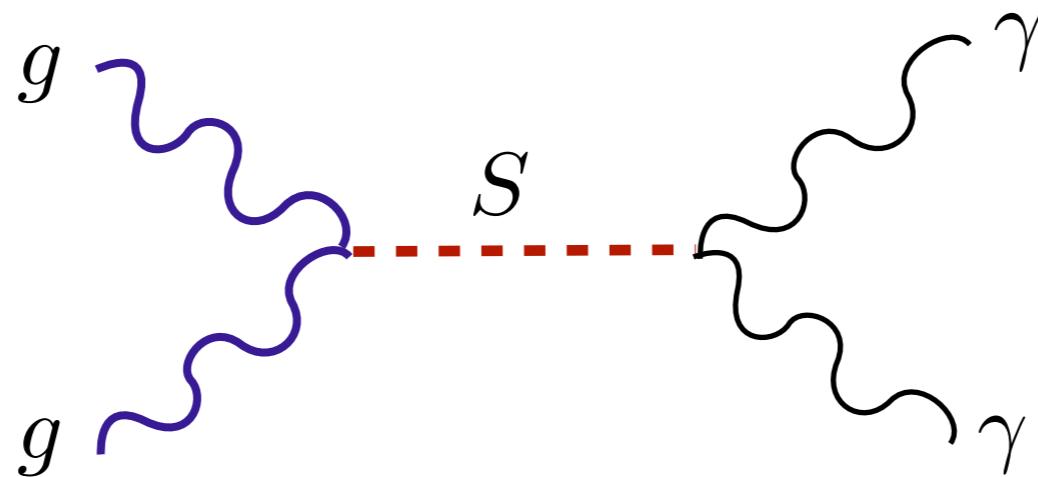
$S(750)$

$I(J^P) = 0(0^?)$

$\sigma(pp \rightarrow S) \times \text{Br}(S \rightarrow \gamma\gamma) \approx 5 \text{ fb}$  @ 13TeV

$m_S \approx 750 \text{ GeV}$   $\Gamma(S) < 100 \text{ GeV}$

I will focus on a resonance produced in the s-channel:



Cross-section in the narrow width approximation is:

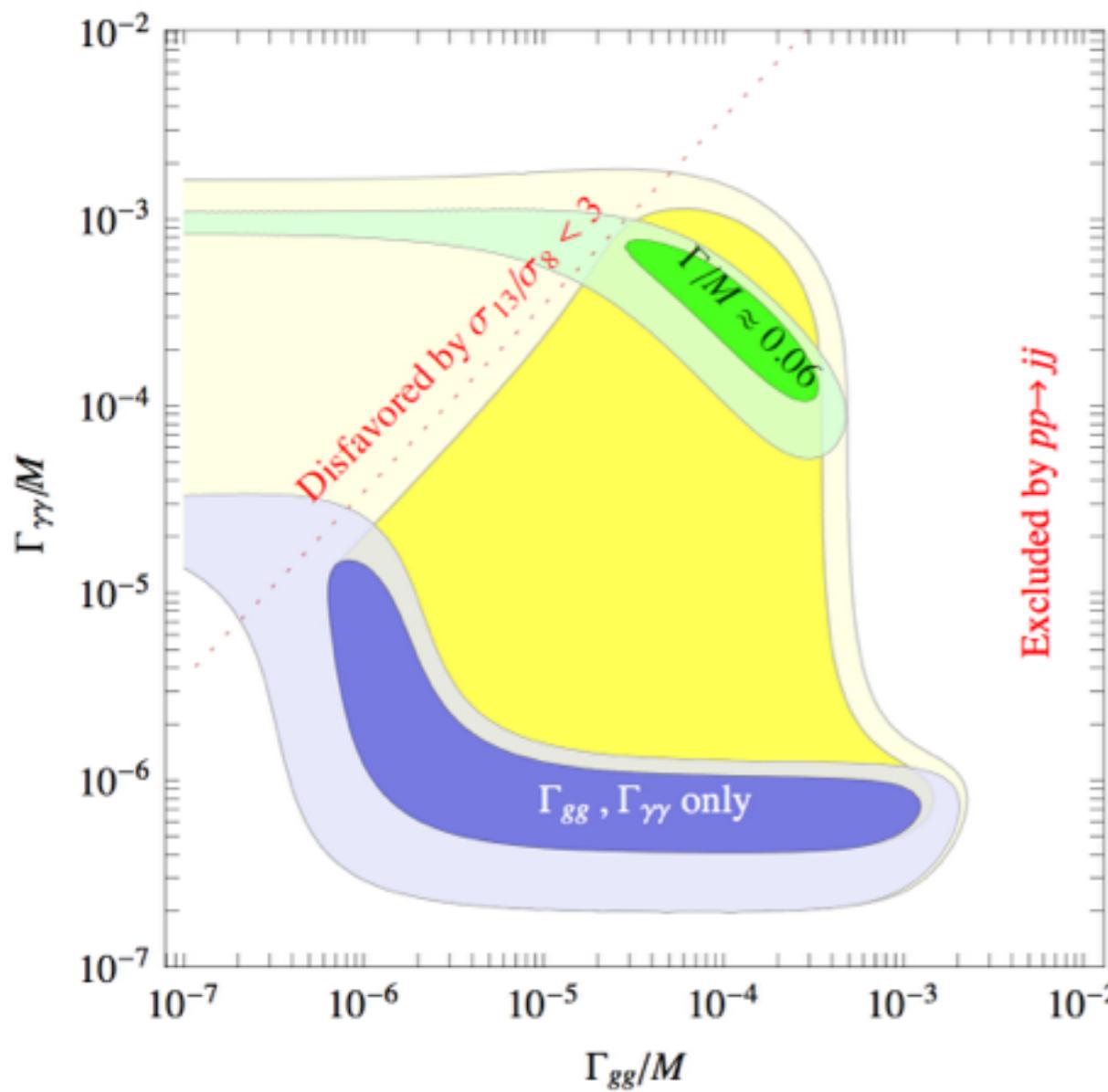
$$\sigma(pp \rightarrow S \rightarrow \gamma\gamma) = \frac{2J+1}{Ms} \left[ \sum_{\wp} C_{\wp\bar{\wp}} \Gamma(S \rightarrow \wp\bar{\wp}) \right] \frac{\Gamma(S \rightarrow \gamma\gamma)}{\Gamma}$$

parton luminosities:

$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	$C_{gg}$	$C_{\gamma\gamma}$
8TeV	1.07	2.7	7.2	89	158	174	11
13TeV	15.3	36	83	627	1054	2137	54

# gluon production:

$$\frac{\Gamma_{\gamma\gamma}}{M} \approx 10^{-6} \times \frac{\Gamma}{\Gamma_{gg}}$$



gluon dominated width:

$$\frac{\Gamma(S \rightarrow \gamma\gamma)}{M} \approx 10^{-6}$$

45 GeV width:

$$\frac{\Gamma(S \rightarrow \gamma\gamma)}{M} > 10^{-4} \quad \text{BIG!}$$

Constraints in all channels from LHC8:

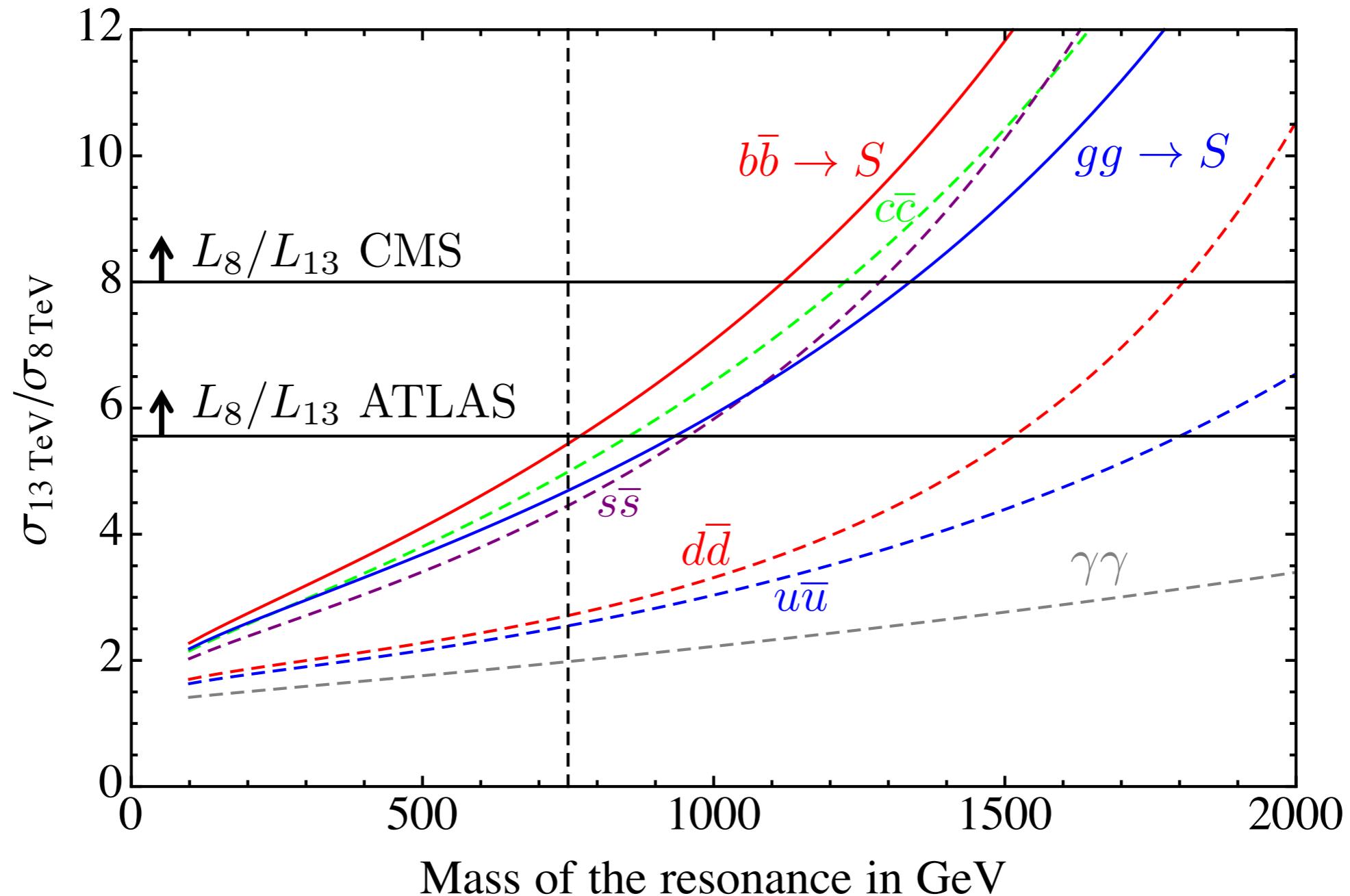
$$r = \frac{\sigma_{13 \text{ TeV}}}{\sigma_{8 \text{ TeV}}}$$

final state $f$	$\sigma$ at $\sqrt{s} = 8 \text{ TeV}$			implied bound on $\Gamma(S \rightarrow f)/\Gamma(S \rightarrow \gamma\gamma)_{\text{obs}}$
	observed	expected	ref.	
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	[8, 9]	< 1.6 ( $r/5$ )
$e^+e^-$ , $\mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	< 1.2 ( $r/5$ )
$\tau^+\tau^-$	< 12 fb	< 15 fb	[11]	< 12 ( $r/5$ )
$Z\gamma$	< 11 fb	< 11 fb	[12]	< 12 ( $r/5$ )
$ZZ$	< 12 fb	< 20 fb	[13]	< 12 ( $r/5$ )
$Zh$	< 19 fb	< 28 fb	[14]	< 20 ( $r/5$ )
$hh$	< 39 fb	< 42 fb	[15]	< 40 ( $r/5$ )
$W^+W^-$	< 40 fb	< 70 fb	[16, 17]	< 40 ( $r/5$ )
$t\bar{t}$	< 450 fb	< 600 fb	[18]	< 600 ( $r/5$ )
invisible	< 0.8 pb	-	[19]	< 800 ( $r/5$ )
$b\bar{b}$	$\lesssim 1 \text{ pb}$	$\lesssim 1 \text{ pb}$	[20]	< 1000 ( $r/5$ )
$jj$	$\lesssim 2.5 \text{ pb}$	-	[7]	< 2600 ( $r/5$ )

If width dominated by gluons:

$$\Gamma < \text{GeV}$$

## LHC13 vs. LHC8:

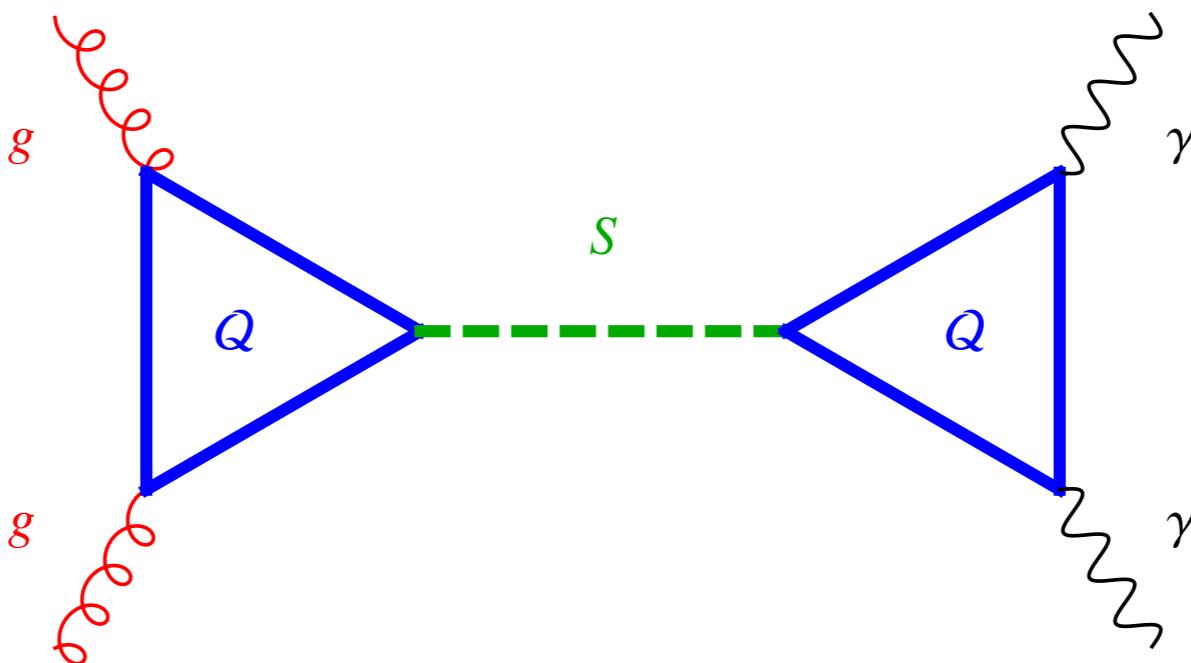


$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	$r_{g g}$	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9

Poor compatibility run1/run2 for u, d, gamma.

# INTERPRETATION

Likely a spin-0 singlet coupled to photons and gluons.



$$\mathcal{L}_{eff} = g_3^2 S \left( \frac{G_{\mu\nu}^2}{2\Lambda_g} + \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g} \right) + e^2 S \left( \frac{F_{\mu\nu}^2}{2\Lambda_\gamma} + \frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\tilde{\Lambda}_\gamma} \right)$$

$$\Gamma(S \rightarrow \gamma\gamma) = \pi\alpha^2 M \left( \frac{M^2}{\Lambda_\gamma^2} + \frac{M^2}{\tilde{\Lambda}_\gamma^2} \right)$$

$$\Gamma(S \rightarrow gg) = 8\pi\alpha_3^2 M \left( \frac{M^2}{\Lambda_g^2} + \frac{M^2}{\tilde{\Lambda}_g^2} \right)$$

$SU(2) \times U(1)$  invariant lagrangian. CP even scalar:

$$\mathcal{L}_{SU(2) \times U(1)} = S \left[ g_3^2 \frac{G_{\mu\nu}^2}{2\Lambda_g} + g_2^2 \frac{W_{\mu\nu}^2}{2\Lambda_W} + g_1^2 \frac{B_{\mu\nu}^2}{2\Lambda_B} + \left( \frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi} + \text{h.c.} \right) + \frac{|D_\mu H|^2}{\Lambda_H} \right] + \dots$$

Coupling to electro-weak gauge bosons is predicted:

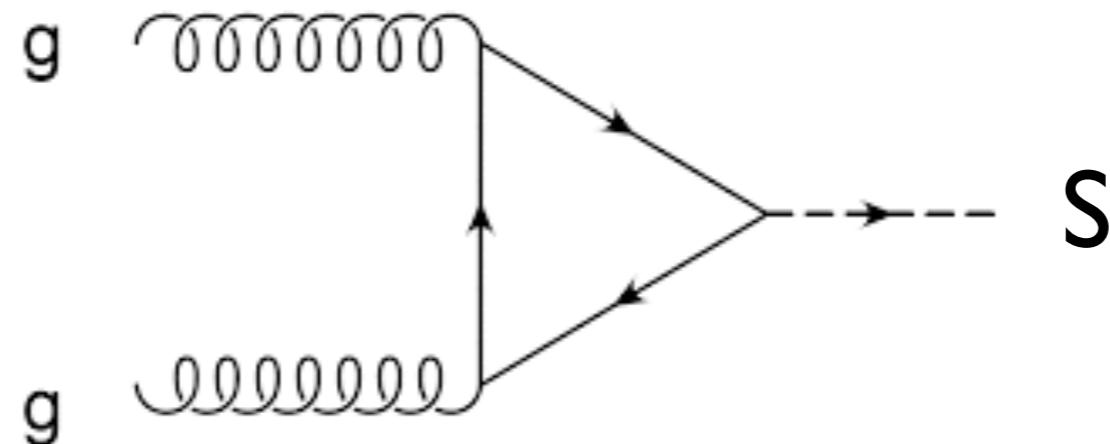
operator	$\frac{\Gamma(S \rightarrow Z\gamma)}{\Gamma(S \rightarrow \gamma\gamma)}$	$\frac{\Gamma(S \rightarrow ZZ)}{\Gamma(S \rightarrow \gamma\gamma)}$	$\frac{\Gamma(S \rightarrow WW)}{\Gamma(S \rightarrow \gamma\gamma)}$
$WW$ only	$2/\tan^2 \theta_W \approx 7$	$1/\tan^4 \theta_W \approx 12$	$2/\sin^4 \theta_W \approx 40$
$BB$ only	$2 \tan^2 \theta_W \approx 0.6$	$\tan^4 \theta_W \approx 0.08$	0

Observable at LHC!

A coupling to gluons and photons requires new particles with color and electric charge.

- Elementary di-photon:

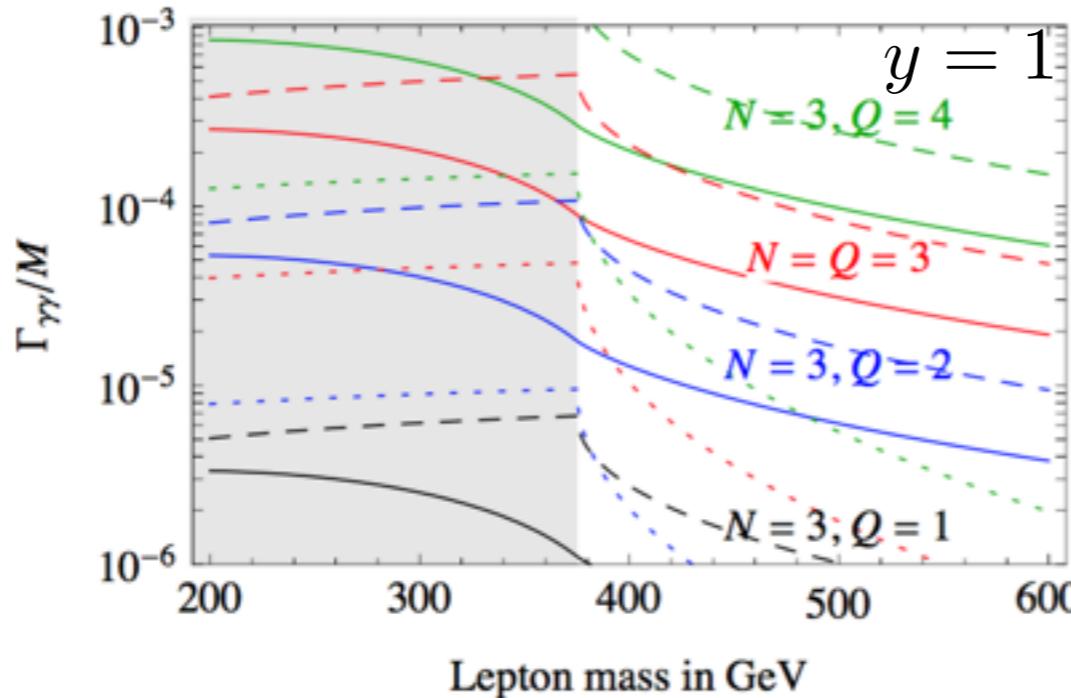
$$S \bar{Q}_f (y_f + i y_{5f} \gamma_5) Q_f$$



- $2M_f > M$

$$\frac{\Gamma(S \rightarrow \gamma\gamma)}{M} \approx 5.4 \times 10^{-8} \left| \sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} \right|^2 + (y_f \rightarrow 3y_{5f}/2)$$

Easy to reproduce signal:



A large width suggests tree level decays

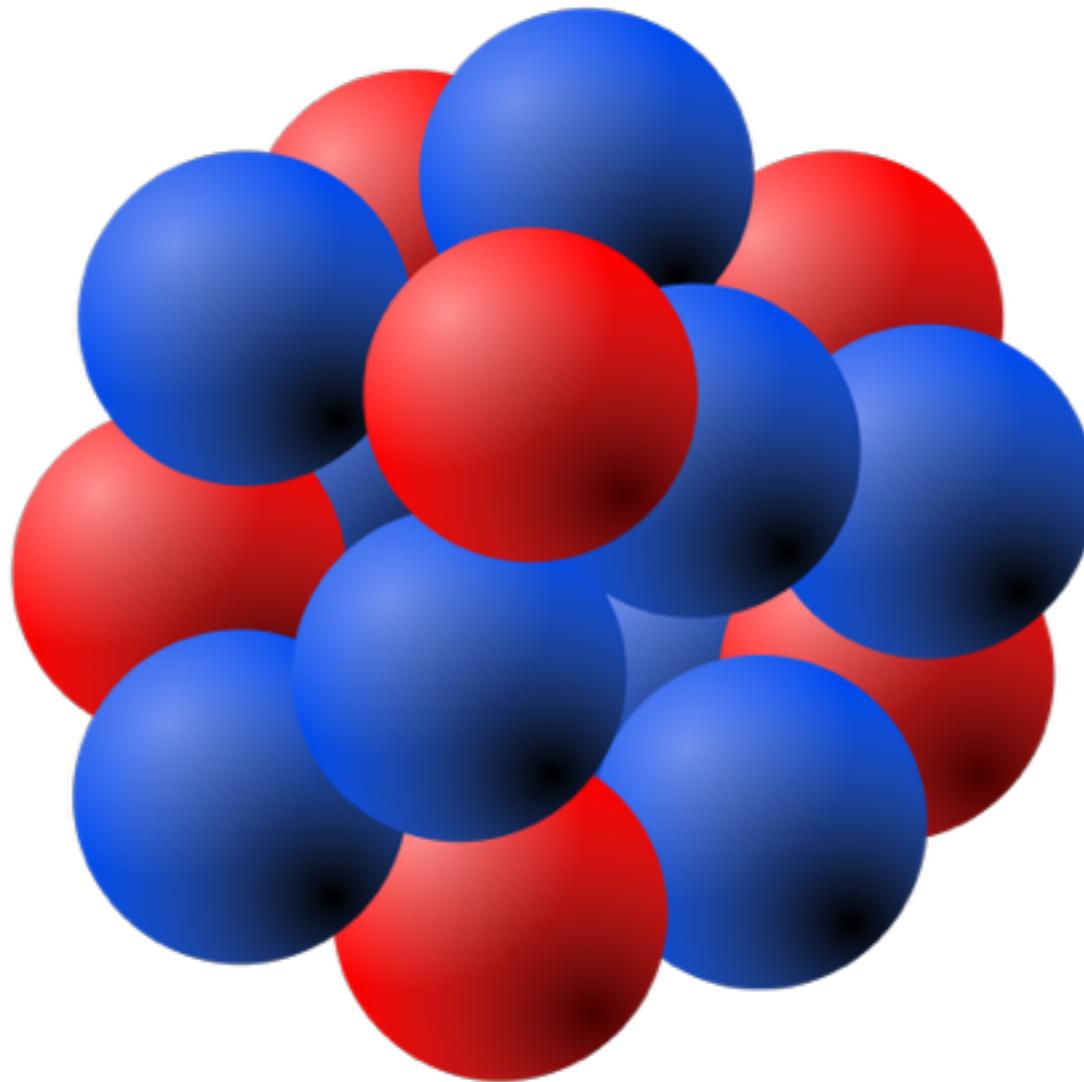
$$\frac{\Gamma_{\text{tree}}}{M} \sim \frac{y^2}{8\pi} \longrightarrow y \sim 1$$

The width into photons is challenging:

$$\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-4} \longrightarrow \sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} > 50$$

In all cases one finds Landau poles close to TeV.

- Composite di-photon:



In QCD:

$$\frac{\Gamma(\eta \rightarrow \gamma\gamma)}{M} \sim 10^{-6}$$

$$\frac{\Gamma(\eta_c \rightarrow \gamma\gamma)}{M} \sim 2 \times 10^{-6}$$

- $S$  could be part of a sector where the Higgs is composite. For example it could be a Nambu-Goldstone boson as the Higgs:

$$m_S \sim m_h \times \frac{f}{v} \quad f \sim \text{TeV}$$

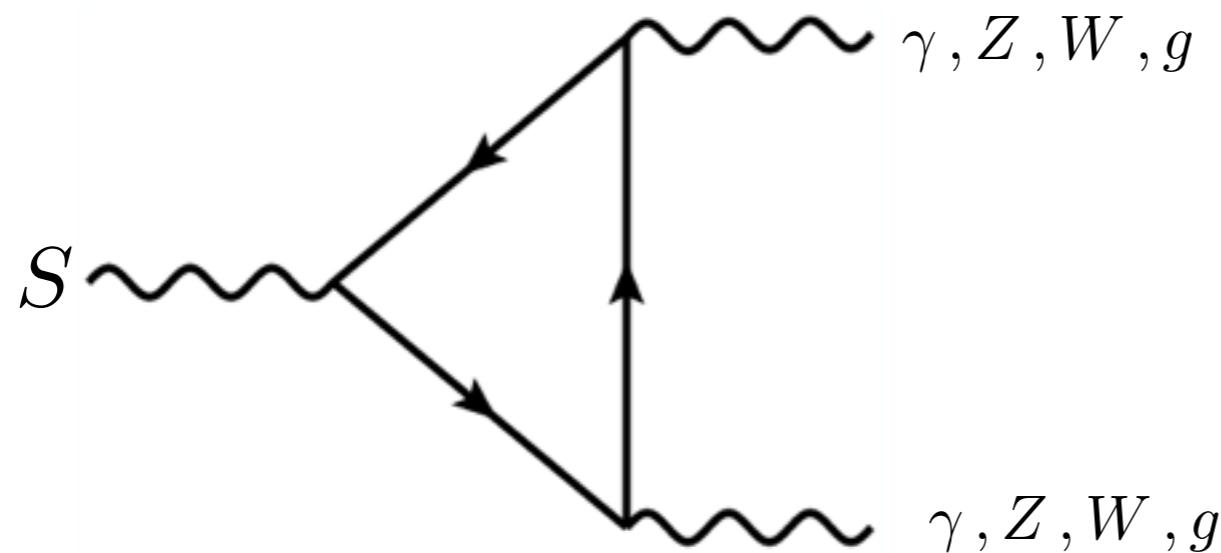
Other possibilities are CP even resonances such us a the dilaton.

- $S$  is composite and the Higgs is elementary. Simple gauge theory realisations. The di-photon could be a heavy pion or a bound state of vectorial fermions.

# Di-photon resonance as a Nambu-Goldstone Boson:

$$\mathcal{L}_{NGB} \supset -\frac{1}{16\pi^2} \frac{S}{f} \left[ g_1^2 c_B B_{\mu\nu} \tilde{B}^{\mu\nu} + g_2^2 c_W W_{\mu\nu}^a \tilde{W}_a^{\mu\nu} + g_3^2 c_G G_{\mu\nu}^a \tilde{G}_a^{\mu\nu} \right] + i c_f y_f \frac{S}{f} H \bar{f}_L f_R + h.c.$$

Decays to SM gauge bosons analogous to  $\pi_0 \rightarrow \gamma\gamma$

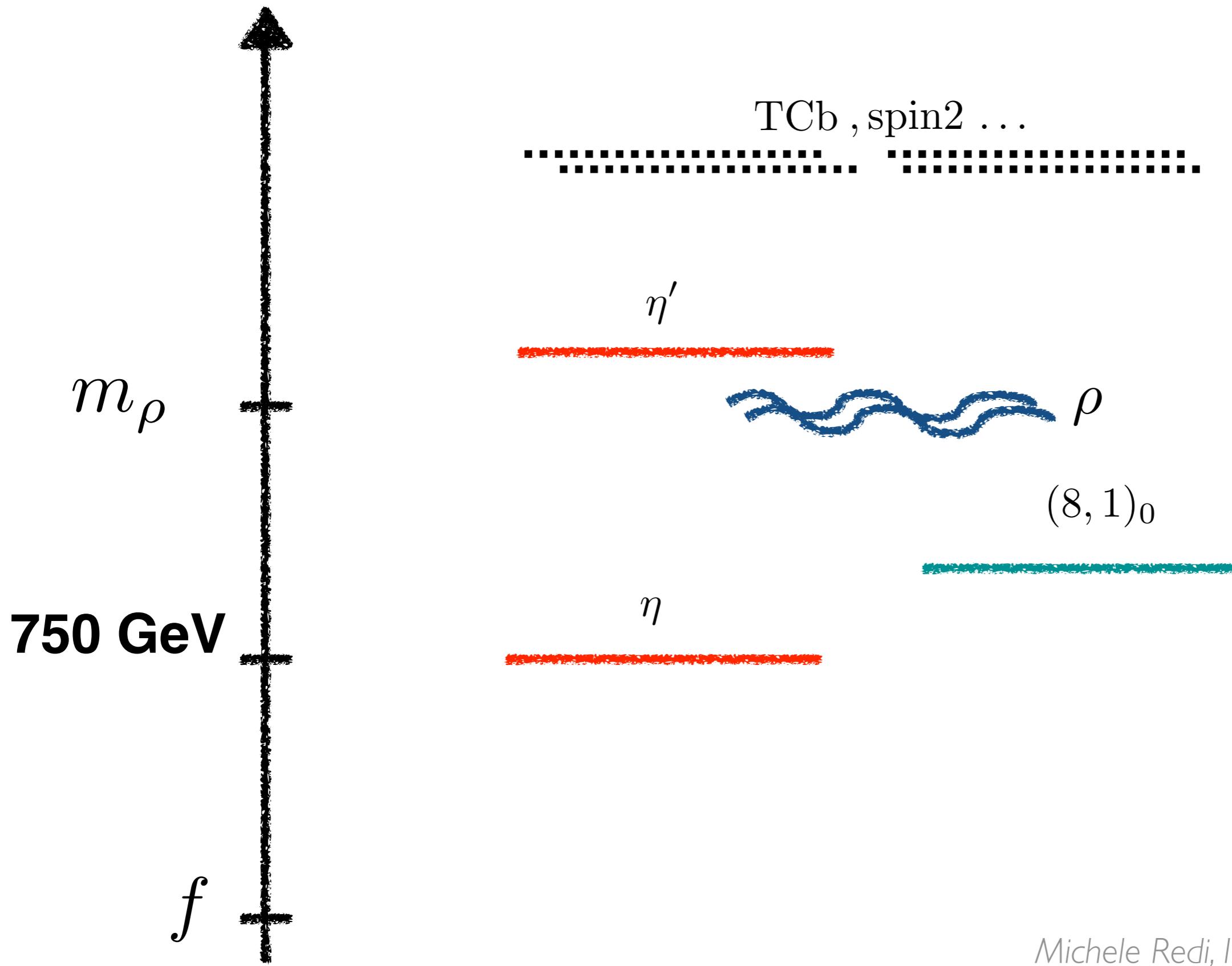


$$c_i \delta^{AB} = 2N \text{Tr}[T_\eta T^A T^B]$$

$$c_f \sim 0$$

Besides the scalar singlet other spin-0 (NGB) and heavier spin-1 resonances with SM quantum numbers are predicted within the reach of LHC.

# Pion-like di-photon



$\mathcal{Q}$	$N_{\text{TF}}$	$\frac{c_B^\eta}{N_{\text{TC}}}$	$\frac{c_W^\eta}{N_{\text{TC}}}$	$\frac{c_G^\eta}{N_{\text{TC}}}$	$\frac{\Gamma_{\gamma Z}^\eta}{\Gamma_{\gamma\gamma}^\eta}$	$\frac{\Gamma_{ZZ}^\eta}{\Gamma_{\gamma\gamma}^\eta}$	$\frac{\Gamma_{GG}^\eta}{\Gamma_{\gamma\gamma}^\eta}$	$\frac{f(\text{GeV})}{N_{\text{TC}}}$	$\frac{c_B^{\eta'}}{N_{\text{TC}}}$	$\frac{c_W^{\eta'}}{N_{\text{TC}}}$	$\frac{c_G^{\eta'}}{N_{\text{TC}}}$	$\frac{\Gamma_{\gamma Z}^{\eta'}}{\Gamma_{\gamma\gamma}^{\eta'}}$	$\frac{\Gamma_{ZZ}^{\eta'}}{\Gamma_{\gamma\gamma}^{\eta'}}$	$\frac{\Gamma_{GG}^{\eta'}}{\Gamma_{\gamma\gamma}^{\eta'}}$	$\frac{f(\text{GeV})}{N_{\text{TC}}}$
$D \oplus L$	5	$\frac{1}{6}\sqrt{\frac{5}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{5}}$	$-\frac{1}{\sqrt{15}}$	1.8	4.7	240	96	$\frac{1}{3}\sqrt{\frac{5}{2}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.23	1.9	180	-
$D \oplus U$	6	$\frac{1}{\sqrt{3}}$	0	0	0.57	0.082	0	-	$\frac{5}{3\sqrt{3}}$	0	$\frac{1}{\sqrt{3}}$	0.57	0.082	470	150
$D \oplus E$	4	$\frac{4}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	46	170	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	180	-
$D \oplus Q$	9	$-\frac{1}{6}$	$\frac{1}{2}$	0	17	22	0	-	$\frac{1}{3\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	2.9	6.1	740	150
$D \oplus T$	6	$\frac{8}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	0.43	2.4	15	430	$\frac{10}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	0.23	1.9	12	-
$L \oplus U$	5	$\frac{7}{6\sqrt{15}}$	$-\frac{1}{2}\sqrt{\frac{3}{5}}$	$\frac{1}{\sqrt{15}}$	200	180	12000	-	$\frac{11}{3\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.0027	0.83	60	230
$L \oplus Q$	8	$-\frac{2}{3\sqrt{3}}$	0	$\frac{1}{2\sqrt{3}}$	0.57	0.082	740	61	$\frac{1}{3}$	1	$\frac{1}{2}$	2.9	6.1	180	210
$L \oplus S$	8	$\frac{7}{12\sqrt{3}}$	$-\frac{\sqrt{3}}{4}$	$\frac{5}{4\sqrt{3}}$	200	180	74000	-	$\frac{19}{12}$	$\frac{1}{4}$	$\frac{5}{4}$	0.095	0.47	610	290
$U \oplus E$	4	$\frac{5}{3\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	120	110	$\frac{7}{3\sqrt{2}}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	60	260
$U \oplus Q$	9	$-\frac{5}{6}$	$\frac{1}{2}$	0	32	17	0	-	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	0.79	3.0	330	220
$U \oplus V$	6	$-\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	83	82	740	-	$\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	1.5	4.1	29	310
$U \oplus N$	4	$-\frac{2}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.57	0.082	180	87	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.57	0.082	180	-
$E \oplus Q$	7	$-\frac{5}{6}\sqrt{\frac{7}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{7}}$	$\frac{1}{\sqrt{21}}$	3.6	0.52	70	150	$\frac{1}{3}\sqrt{\frac{7}{2}}$	$\frac{3}{\sqrt{14}}$	$\sqrt{\frac{2}{7}}$	1.2	3.7	180	-
$E \oplus S$	7	$-\frac{10}{3\sqrt{21}}$	0	$\frac{5}{2\sqrt{21}}$	0.57	0.082	740	120	$\frac{11}{3}\sqrt{\frac{2}{7}}$	0	$5\sqrt{14}$	0.57	0.082	610	310
$S \oplus V$	9	$-\frac{8}{9}$	$\frac{4}{3}$	$-\frac{5}{6}$	83	82	4600	-	$\frac{8\sqrt{2}}{9}$	$\frac{2\sqrt{2}}{3}$	$\frac{5}{3\sqrt{2}}$	0.43	2.4	380	350
$S \oplus N$	7	$-\frac{8}{3\sqrt{21}}$	0	$-\frac{5}{2\sqrt{21}}$	0.57	0.082	1200	93	$\frac{8}{3}\sqrt{\frac{2}{7}}$	0	$\frac{5}{\sqrt{14}}$	0.57	0.082	1200	230
$N \oplus Q$	7	$\frac{1}{6\sqrt{21}}$	$\frac{1}{2}\sqrt{\frac{3}{7}}$	$\frac{1}{\sqrt{21}}$	4.9	8.5	470	58	$\frac{1}{3\sqrt{14}}$	$\frac{3}{\sqrt{14}}$	$\sqrt{\frac{2}{7}}$	4.9	8.5	470	140

Gauge theory models fully predictive.

## Ex: D+L

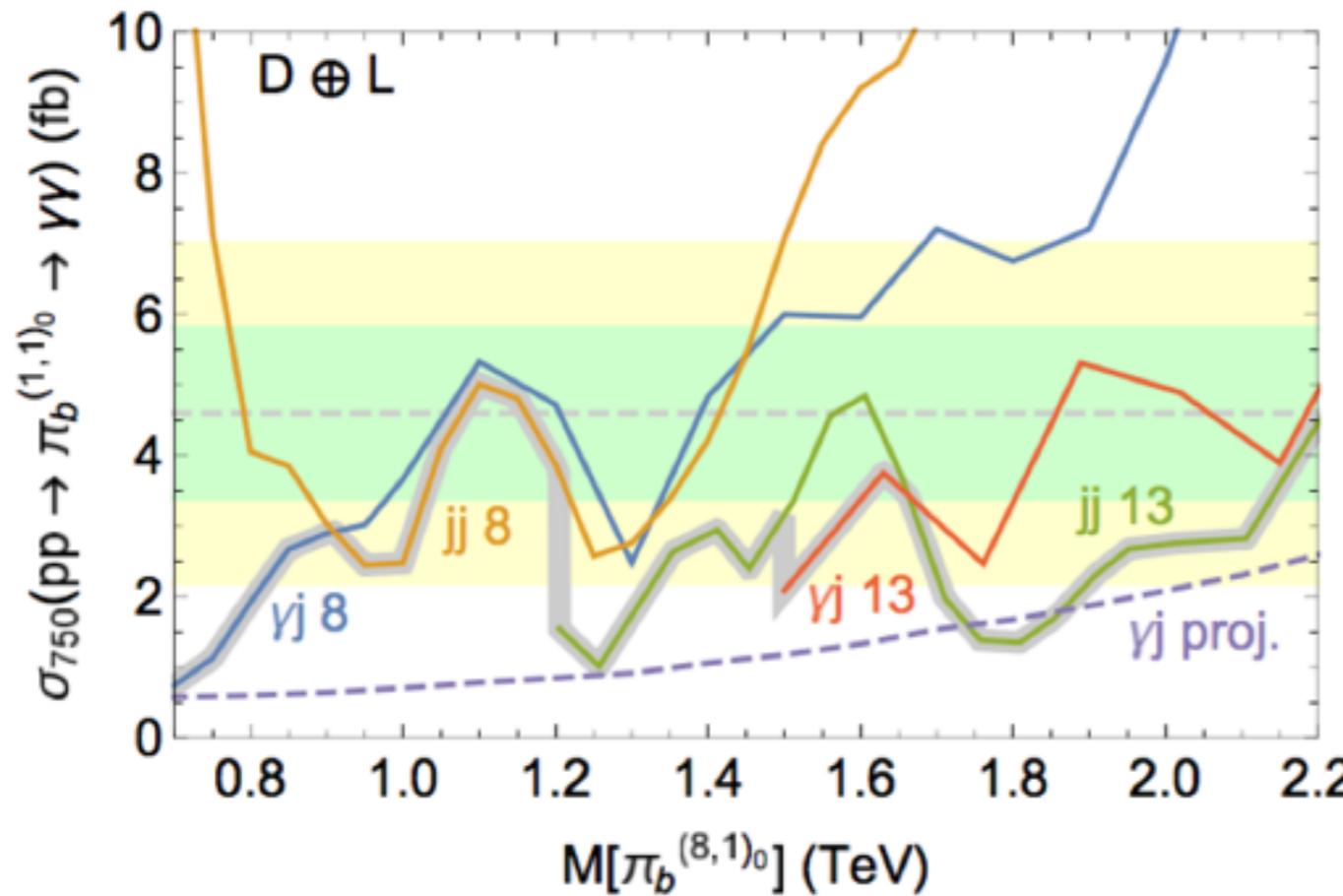
$$GB = 2 \times (1, 1)_0 + (1, 3)_0 + (8, 1)_0 + (3, 2)_{\frac{1}{6}} + (\bar{3}, 2)_{-\frac{1}{6}}$$

$\eta :$

$$\Gamma \approx 130 \text{ MeV}$$

$$\frac{f}{N} \sim 100 \text{ GeV}$$

Color octet pion decays into gluons or gluon+photon:



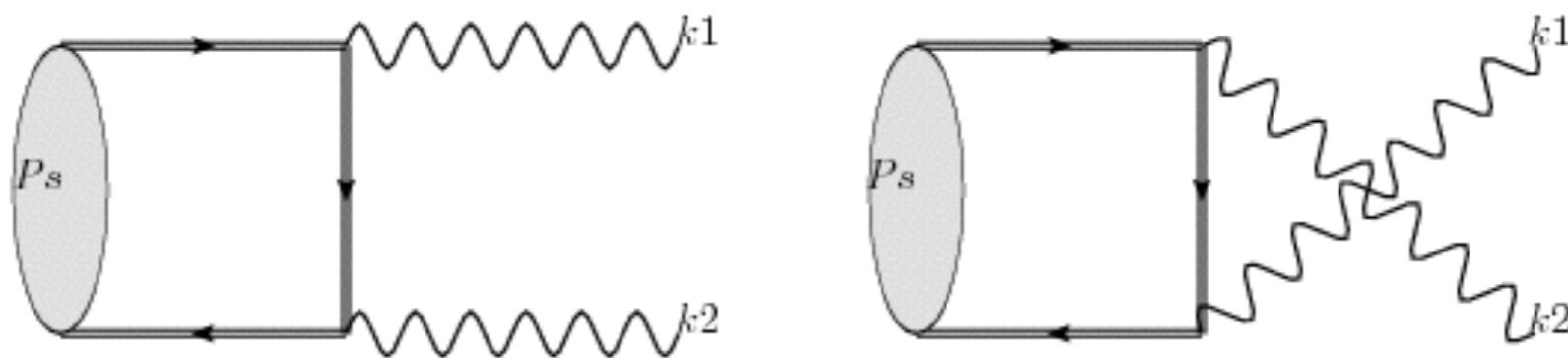
Bai, Barger, Berger '16

Squark-like pion is long lived. Triplet pion can be lighter.

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# Q-onium

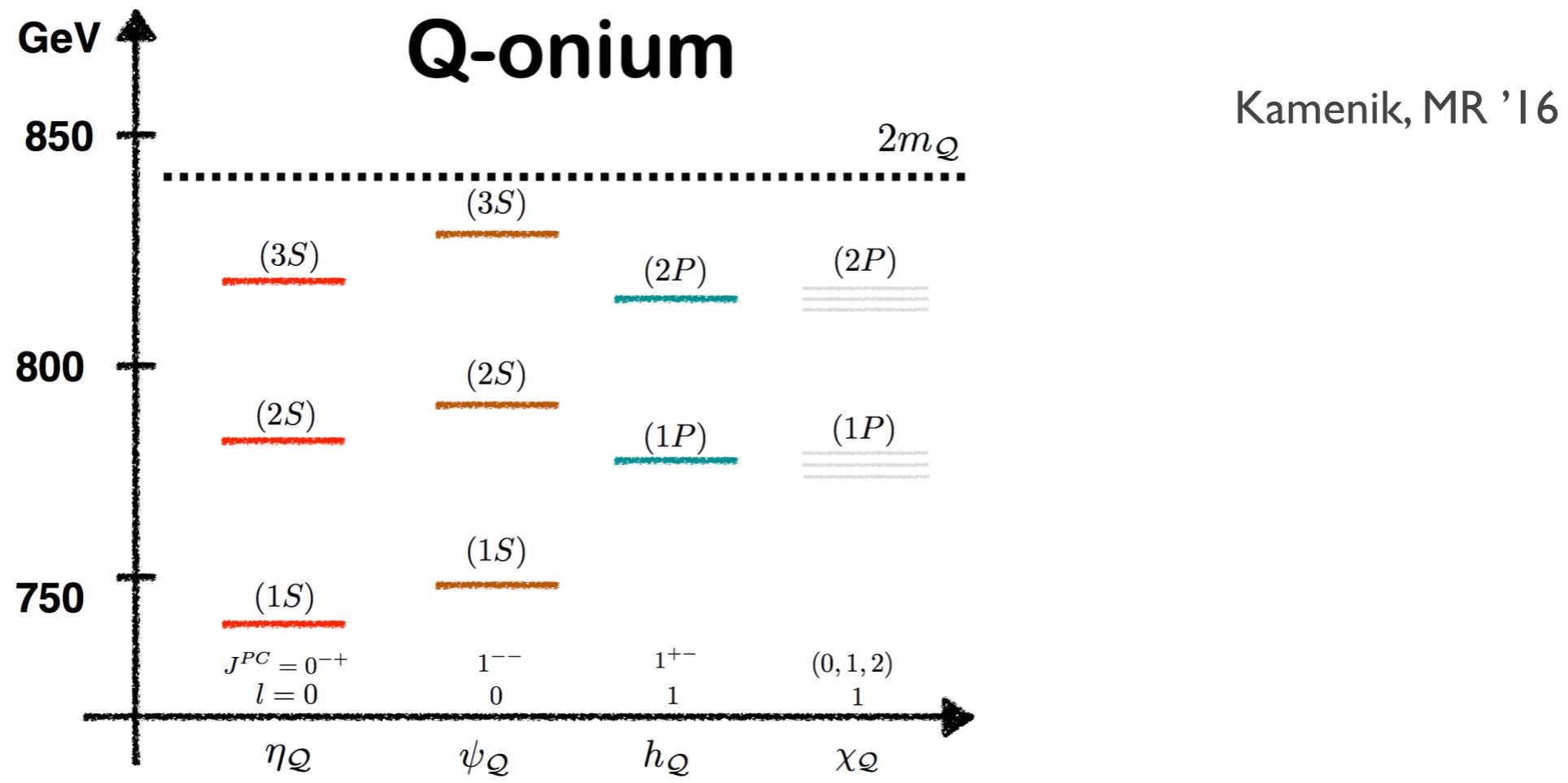
The resonance could be a non-relativistic bound state of new fermions with SM charges similar to charmonium.



$$\frac{\Gamma(\eta_Q^1 \rightarrow \gamma\gamma)}{M} = 12N\alpha^2 Q^4 \frac{|R(0)|^2}{M^3} \quad m_{\eta_Q} \sim 2m_Q$$

A QCD bound state would require a large charge.

A new gauge interaction could form the bound state



Almost degenerate color octet spin-0 resonances and spin-1 resonances analogous to J/PSI predicted:

- spin-0: gluon production

$$\eta_Q^1$$

$$\eta_Q^8$$

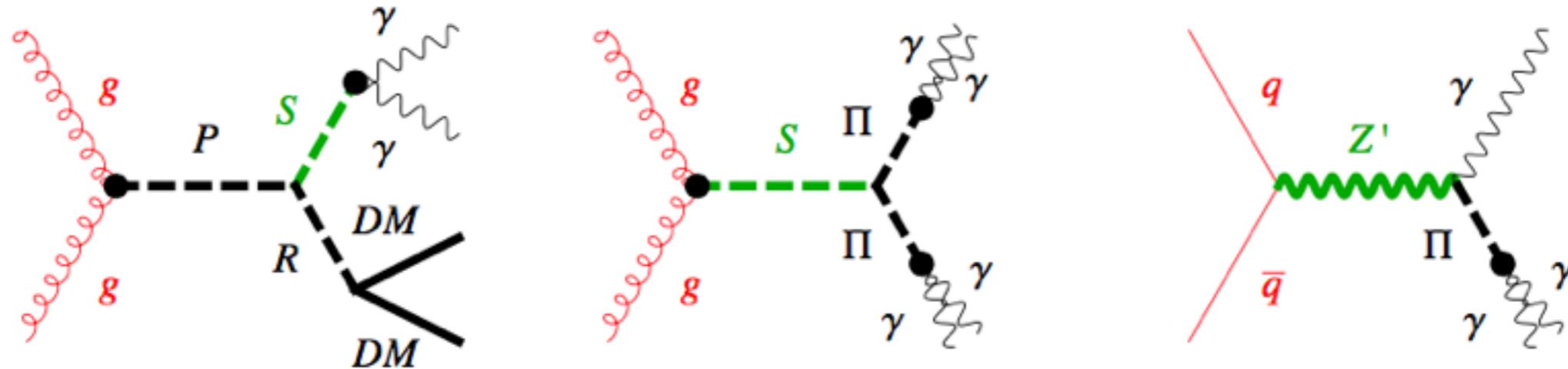
- spin-1: quark production

$$\psi_Q^1$$

$$\psi_Q^8$$

# Other models:

- More complicated kinematics:



- spin-2: Kaluza-Klein gravitons. Theoretically challenging.
- SUSY: heavy Higgs, singlet in NMSSM, sgoldstino... Vector-like fermions typically required.
- Different production/non trivial SM representations.  
Difficult to generate the signal.

# DARK MATTER

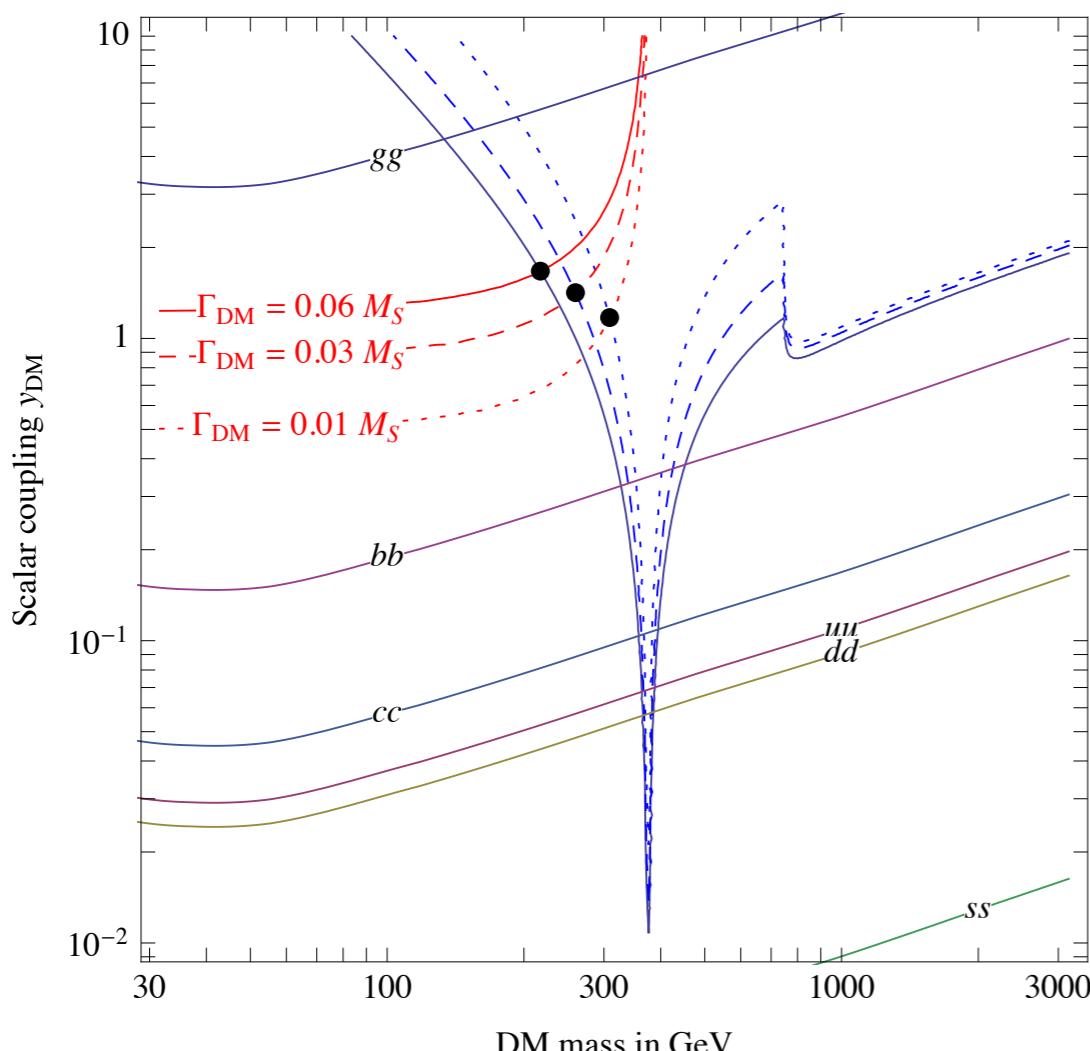
Invisible width could be related to decays into DM.  
Most simply add new fermions neutral under SM:

$$y_{DM} S \bar{\Psi}_{DM} \Psi_{DM}$$

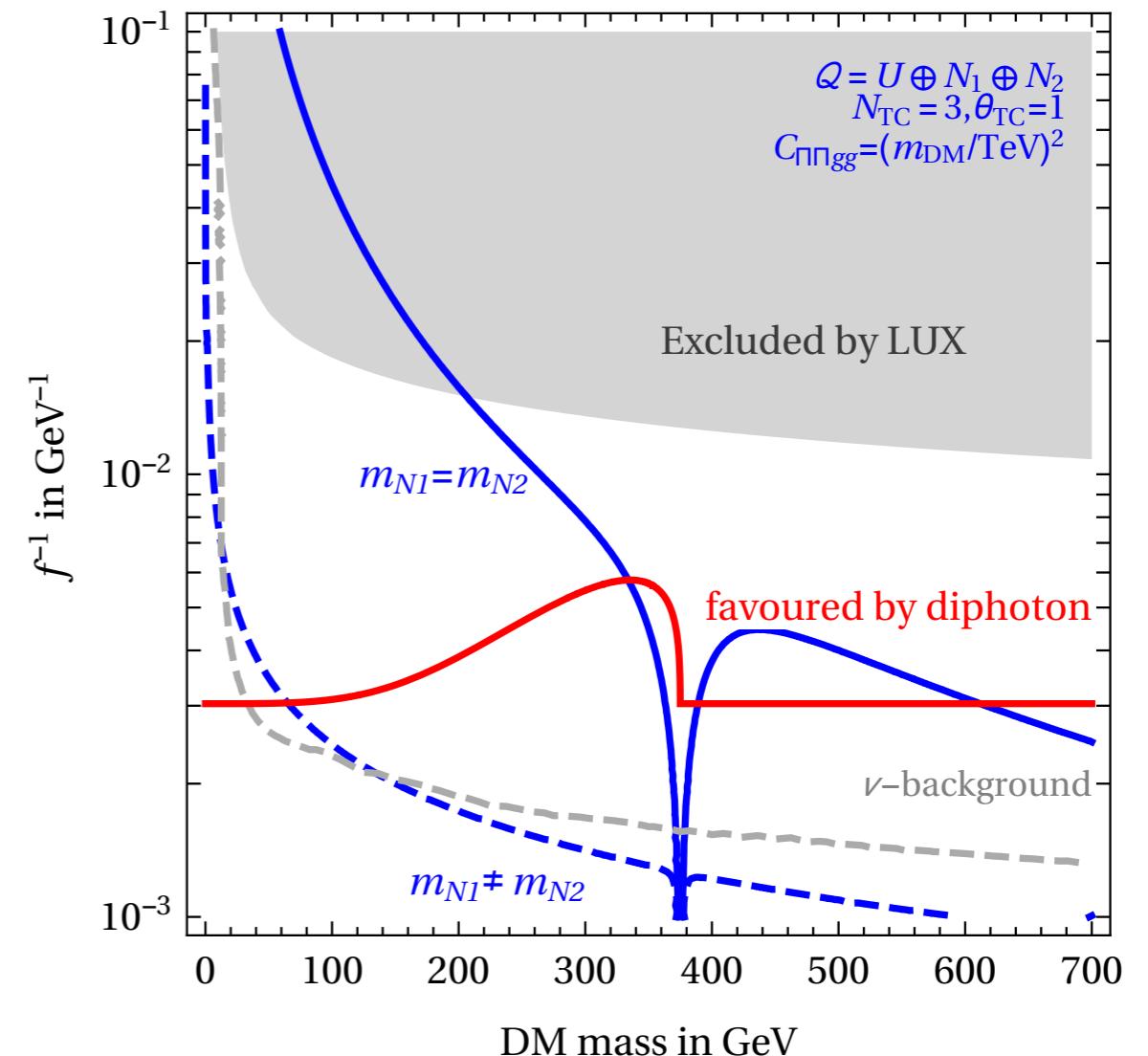
Dark matter candidates:

- elementary di-photon: neutral fermions
- composite di-photon: neutral heavy pions or baryons

Dark matter as a thermal relic can be obtained for masses around 100 GeV compatibly with direct detection bounds.



elementary



composite

# FUTURE

- If the excess is confirmed it will be revolutionary.  
It is the dream nobody in our field anymore had.
- Many models can explain the di-photon excess.  
They predict effects visible in many different channels. Nearly all models prefer a narrow width.  
With more data we might be able to pin down the right theory.
- The di-photon resonance is plausible but very unexpected. Is it elementary or composite? Is it related to EWSB or dark matter?  
Hopefully the fun is just starting...

# LHC reach:

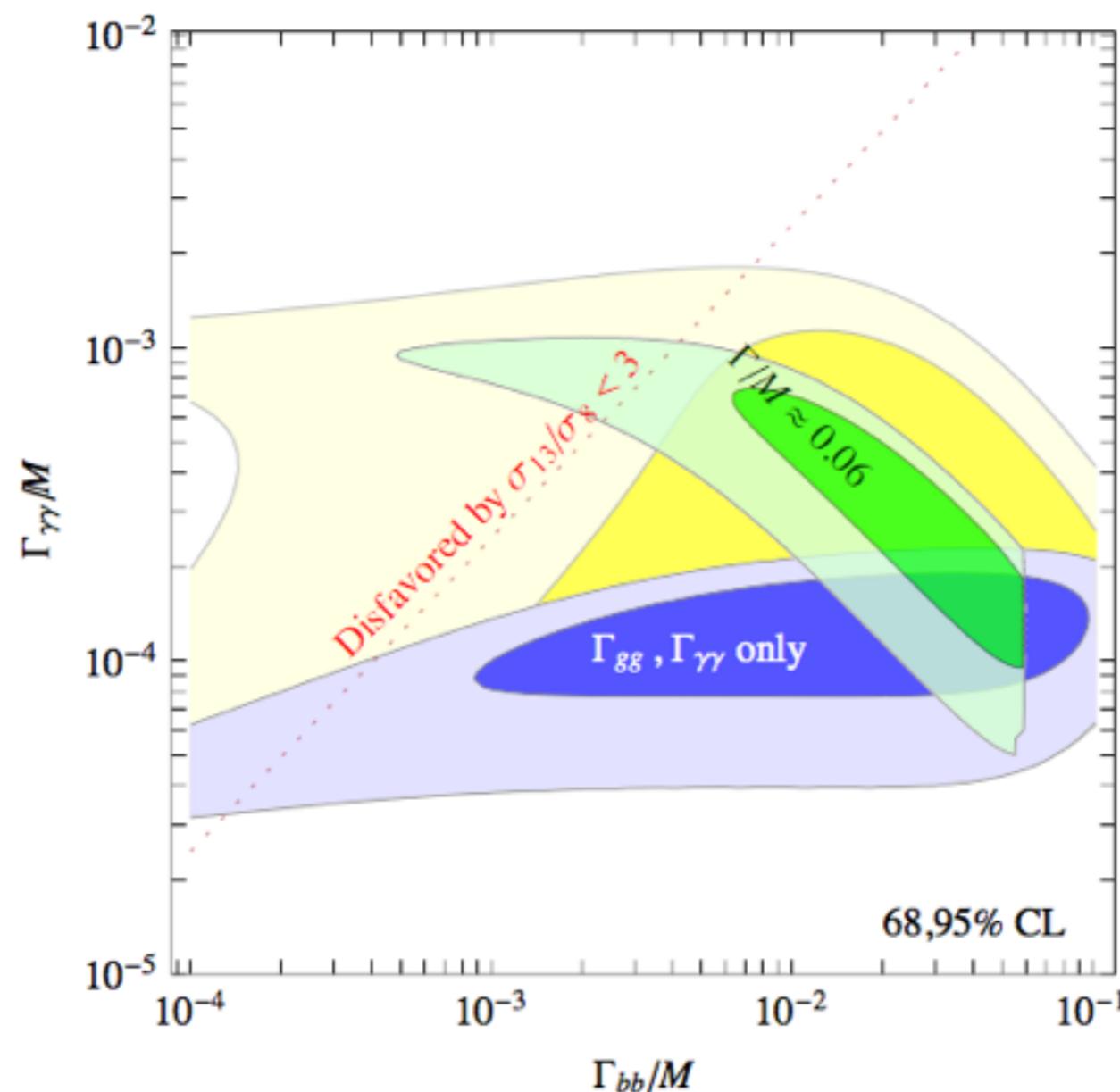
Search	8 TeV limit [fb]	13 TeV limit [fb]	$\mathcal{L} = 3.2 \text{ fb}^{-1}$	13 TeV limit [fb] (expected)		
	(observed)	(observed)		$\mathcal{L} = 30 \text{ fb}^{-1}$	$\mathcal{L} = 300 \text{ fb}^{-1}$	$\mathcal{L} = 3000 \text{ fb}^{-1}$
$Z\gamma$	11 [21]	30 [22]	43	14	4.4	1.4
$ZZ$	12 [23]	180 [24]	82	27	8.5	2.7
$WW$	40 [25]	400 [26]	300	98	31	9.8
$t\bar{t}$	460 [27]	10000 [28]	3267	1067	337	107
MET+ $j$	7.2 (SR7) [29]	61 (IM5) [30] 19 (IM7) [30]	51 15	5	1.5	0.5

Backovic et al.  
1605.07962

Di-jets challenging to improve.

# b production:

$$\frac{\Gamma_{\gamma\gamma}}{M} \approx 1.5 \times 10^{-4} \frac{\Gamma}{\Gamma_{b\bar{b}}}$$

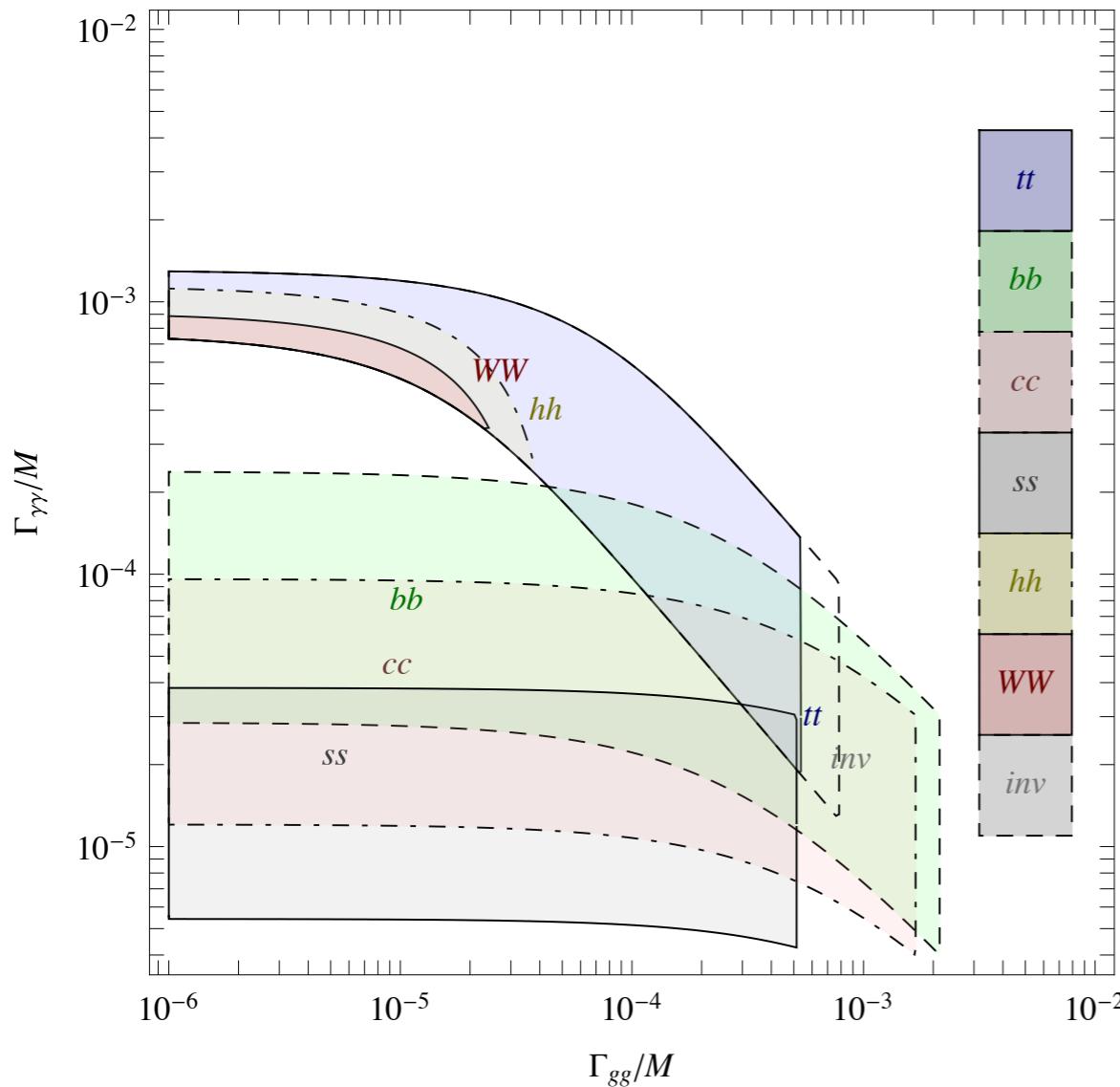


$S \leftrightarrow \gamma\gamma, b\bar{b}, ?$

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$$\Gamma = 45 \text{ GeV}$$

# Decays



**INV, tt, bb:**

$$\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-4}$$

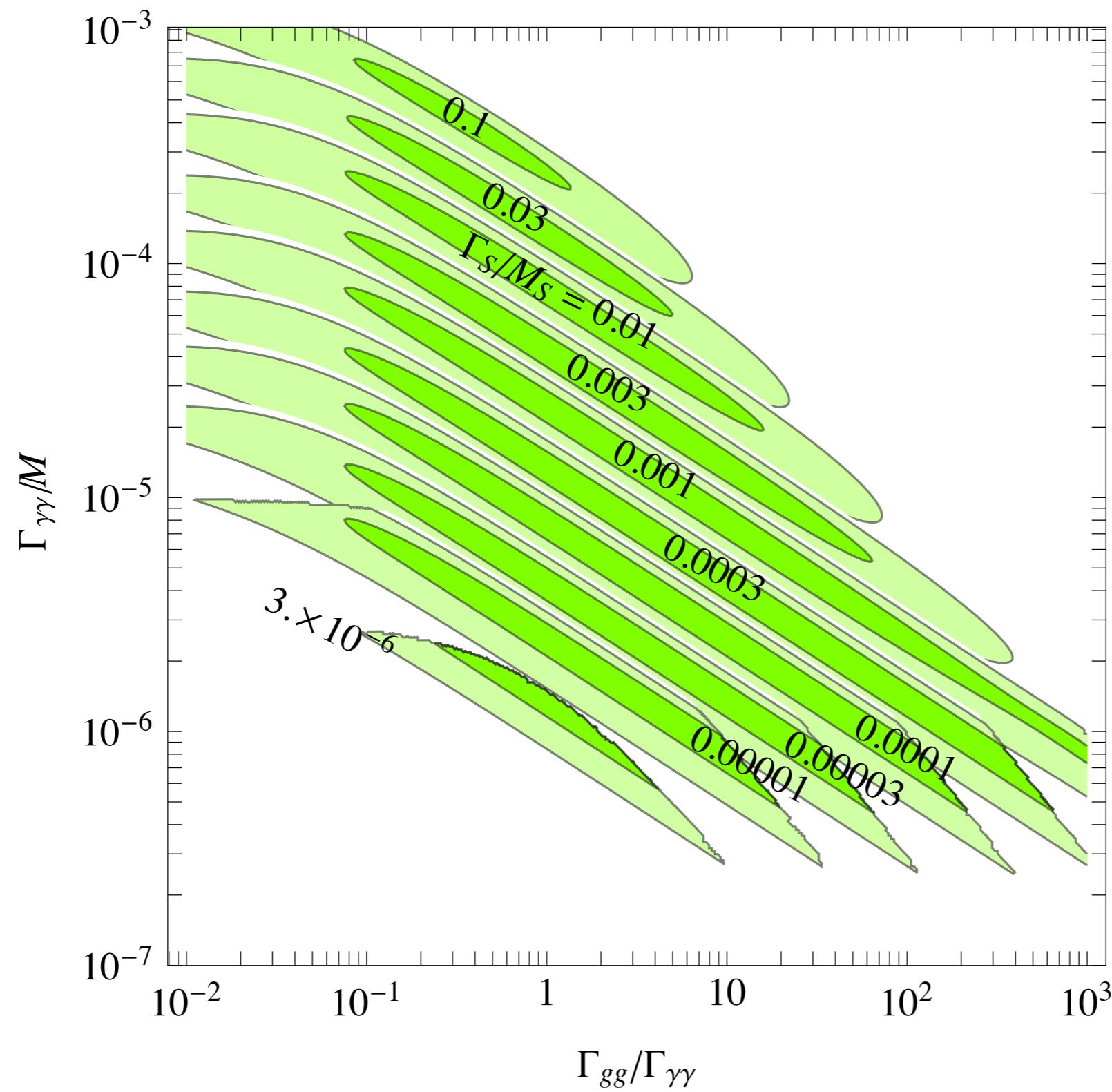
**WW, hh:**

$$\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-3}$$

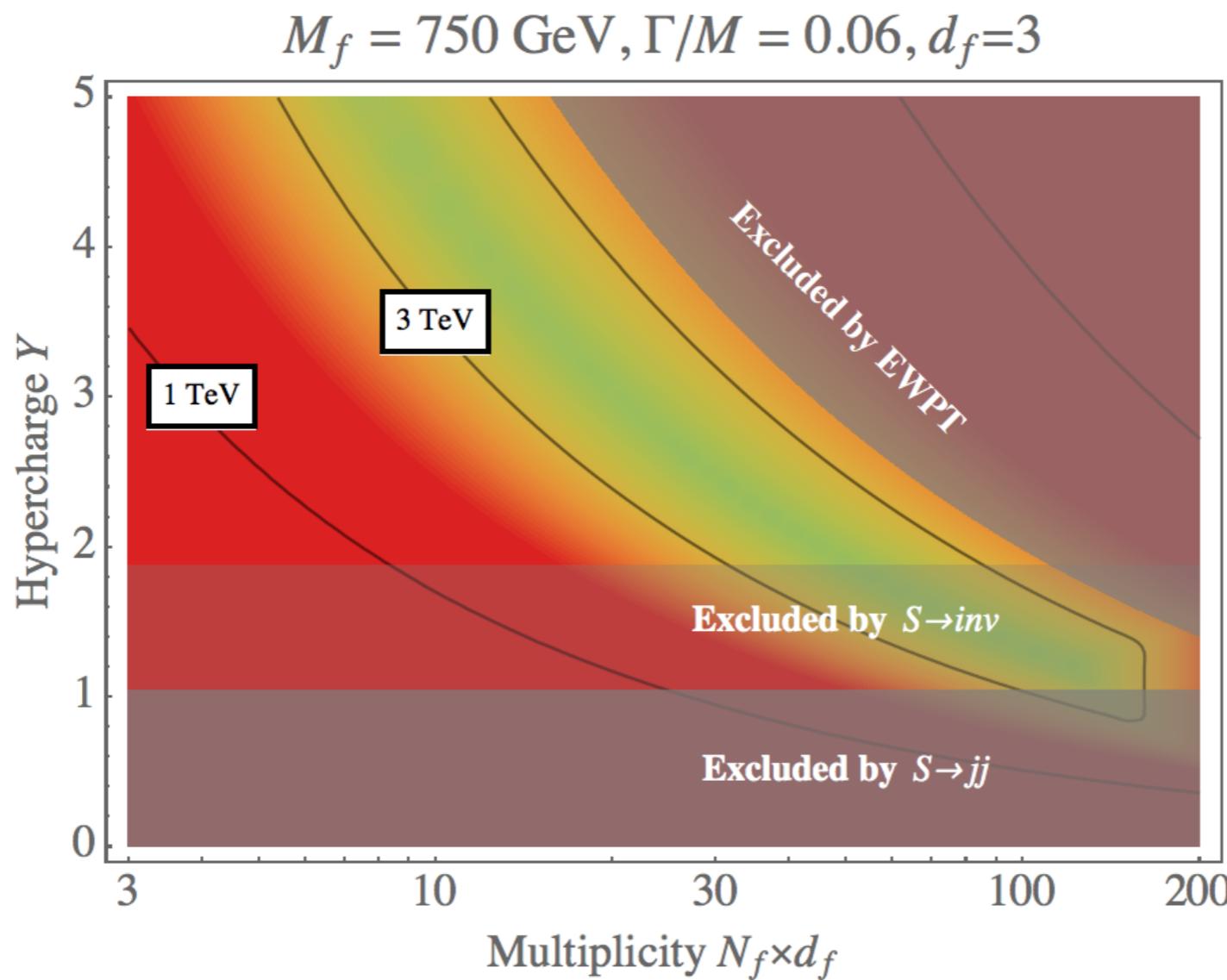
**weakest bound (invisible not applicable):**

$$\frac{\Gamma_{\gamma\gamma}}{M} > 6.8 \times 10^{-6} \sqrt{\frac{\Gamma}{45 \text{ GeV}}}$$

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Fit to  $S \rightarrow gg, YY, \text{DM}$  at fixed  $\Gamma_S$ 

A large width implies either large multiplicities, large charges or large couplings. In all cases one obtains Landau poles at low scales:



Alternatively the width is reproduced by multiple states.

## Di-photon as a Nambu-Goldstone boson:

$$\frac{\Gamma_{\gamma\gamma}}{M} = c_\gamma^2 \frac{\alpha^2}{64\pi^3} \frac{M^2}{f^2} = 3 \times 10^{-8} c_\gamma^2 \frac{M^2}{f^2} \quad \frac{\Gamma_{gg}}{M} = c_G^2 \frac{\alpha_3^2}{8\pi^3} \frac{M^2}{f^2} = 5.6 \times 10^{-5} c_G^2 \frac{M^2}{f^2}$$

## Reproducing excess:

$$f \approx 150 \text{ GeV} \sqrt{c_\gamma c_G} \left( \frac{\text{GeV}}{\Gamma} \right)^{\frac{1}{4}}$$

$$\frac{\Gamma_{\gamma\gamma}}{M} \approx 10^{-6} \quad \xrightarrow{\hspace{1cm}} \quad \frac{M}{f} \approx \frac{6}{c_\gamma}$$

$$\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-4} \quad \xrightarrow{\hspace{1cm}} \quad \frac{M}{f} > \frac{50}{c_\gamma}$$

## Rates in SM gauge bosons predicted from anomalies:

$$\begin{aligned} \frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}} &\approx \frac{2(-c_W \cot \theta_W + c_B \tan \theta_W)^2}{c_\gamma^2}, & \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} &\approx \frac{(c_W \cot \theta_W^2 + c_B \tan \theta_W^2)^2}{c_\gamma^2}, \\ \frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} &\approx 2 \frac{c_W^2}{c_\gamma^2 \sin^4 \theta_W}, & \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}} &\approx \frac{8\alpha_3^2 c_G^2}{\alpha^2 c_\gamma^2} \approx 1300 \frac{c_G^2}{c_\gamma^2}. \end{aligned}$$

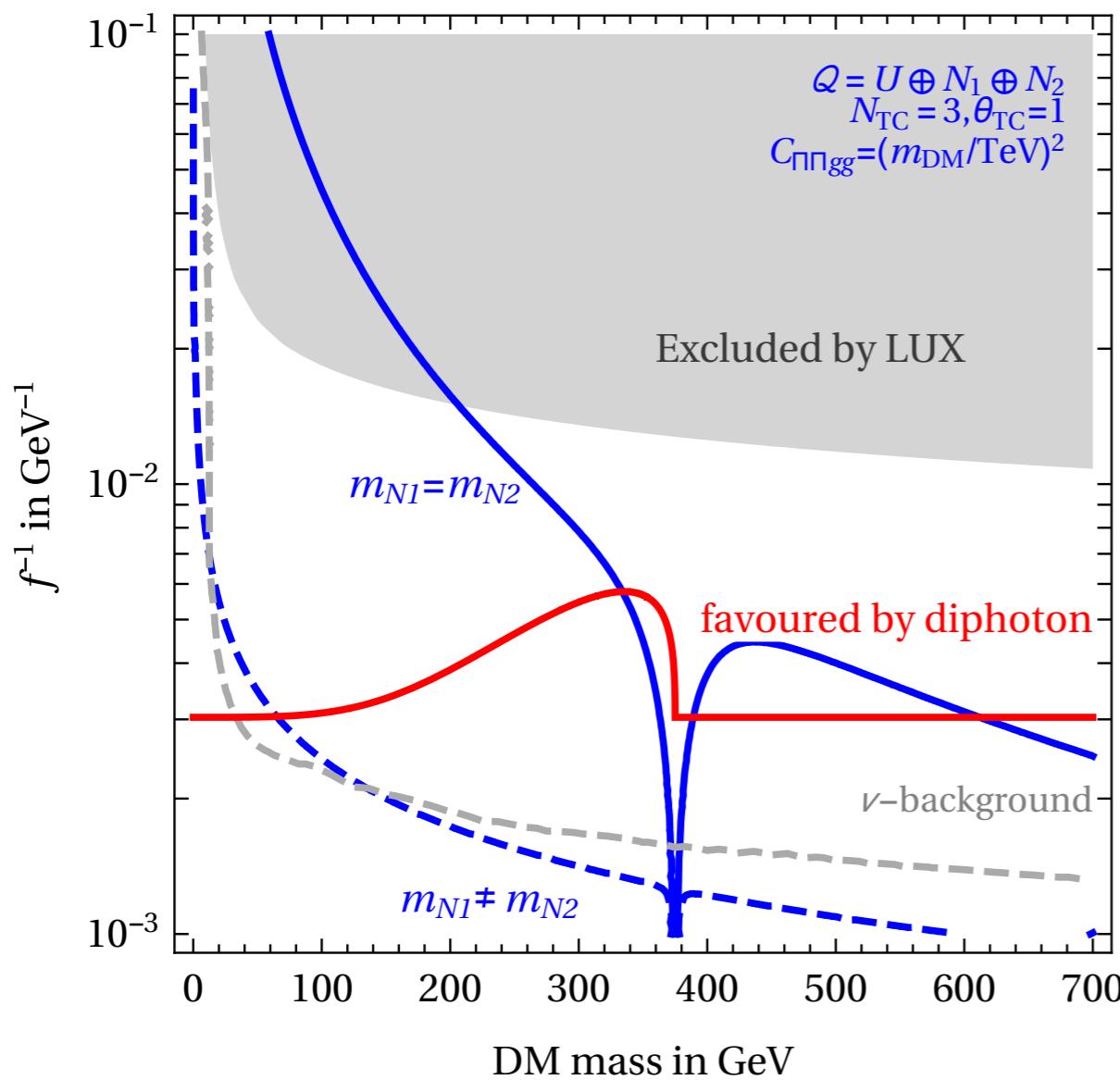
$$Q = U \oplus N_1 \oplus N_2$$

$$24 = \underbrace{(8, 1)_0}_{\chi} \oplus \underbrace{2 \times [(\bar{3}, 1)_{-2/3} + (3, 1)_{2/3}]}_{\phi_{1,2}, \phi_{1,2}^*} \oplus \underbrace{4 \times (1, 1)_0}_{\Pi, \Pi^*, \eta_{1,2}}$$

$$\eta_1 \sim N_1 \bar{N}_1 + N_2 \bar{N}_2 - \frac{2}{3} U \bar{U}$$

$$\eta_2 \sim N_1 \bar{N}_1 - N_2 \bar{N}_2$$

$$\Gamma_{max}(\eta_1 \rightarrow \Pi \Pi^*) \sim \text{GeV} \times \theta_{\text{TC}}^2$$



- $m_1 = m_2$ . Singlets don't mix.  
Relic abundance reproduced through di-photon interactions
- Even for small mixing self-interactions dominate.  
 $m_{\text{DM}} < 100 \text{ GeV}$ .
- Baryonic DM candidates