Title: What is the gamma gamma resonance at 750 GeV?

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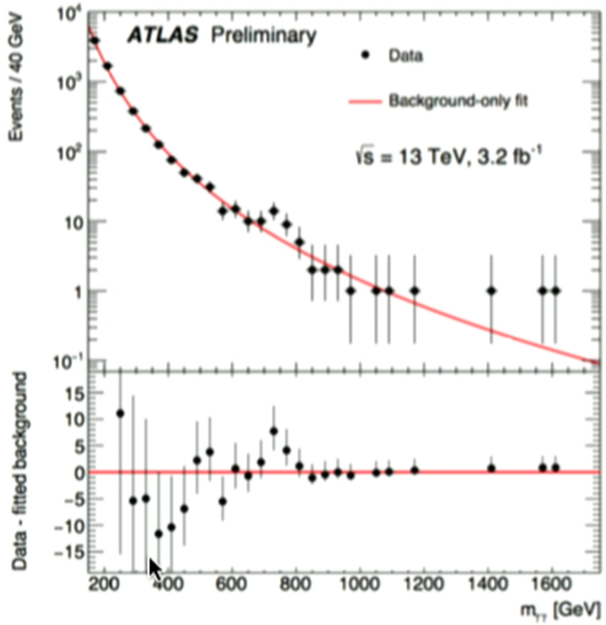
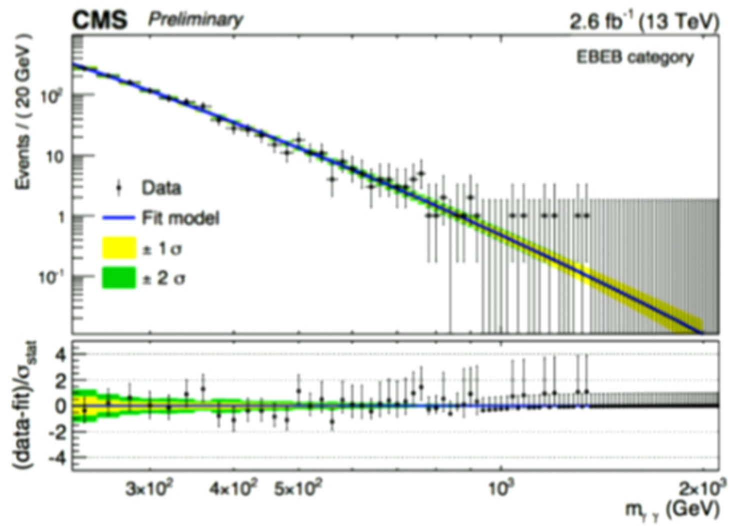
Abstract: <p>I will discuss the recent LHC excess in the di-photon distribution at an invariant mass of 750 GeV. Various explanations in terms of weakly coupled and strongly coupled physics will be presented. Possible connection with Dark Matter will also be discussed.</p>


What is the gamma gamma resonance at 750 GeV?
Michele Redi
INFN
Based on: 1512.04933, 1602.07297, 1603.07719
Perimeter, 29 March 2016

FACTS





ATLAS $3.9\,\sigma$ @ $750\,\mathrm{GeV}$ $\Gamma \sim 45\,\mathrm{GeV}$

CMS $2.6\,\sigma$ @ $760\,\mathrm{GeV}$ $\Gamma \sim 0$

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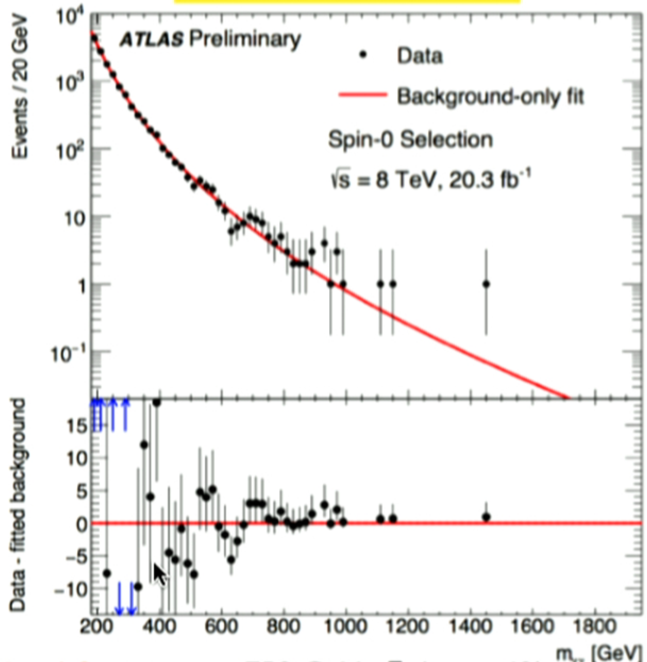
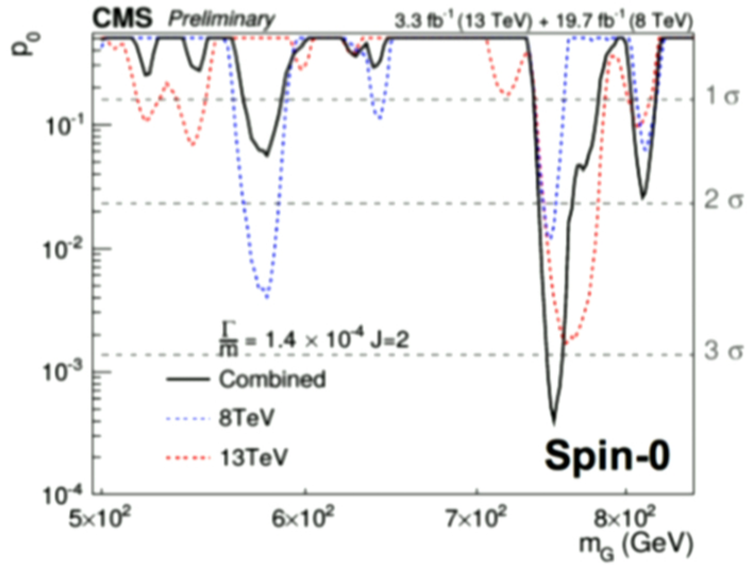
Even better after Moriond?

SPIN-0 ANALYSIS



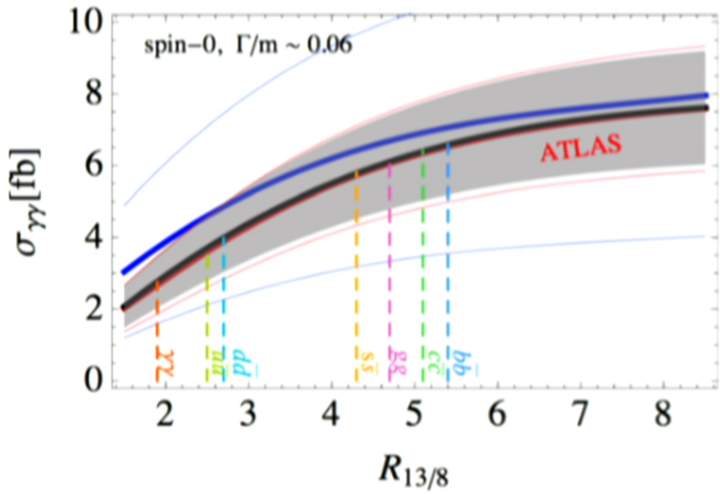
- $1.9\ \sigma$ at m_X = 750 GeV , Γ_X/m_X = 6%
- Compatibility with 13 TeV scalar
  - ✓ gg (scaling: 4.7) → compatibility: $1.2\ \sigma$
  - ✓ qq (scaling: 2.7) → compatibility: $2.1\ \sigma$



$$2.6\,\sigma \to 3.4\,\sigma$$

ATLAS run2:

S-channel resonance:



$$\sigma(pp \to \gamma\gamma) = 3 - 10\,\mathrm{fb}$$

Kamenik, Safdi, Soreq, Zupan '16

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

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

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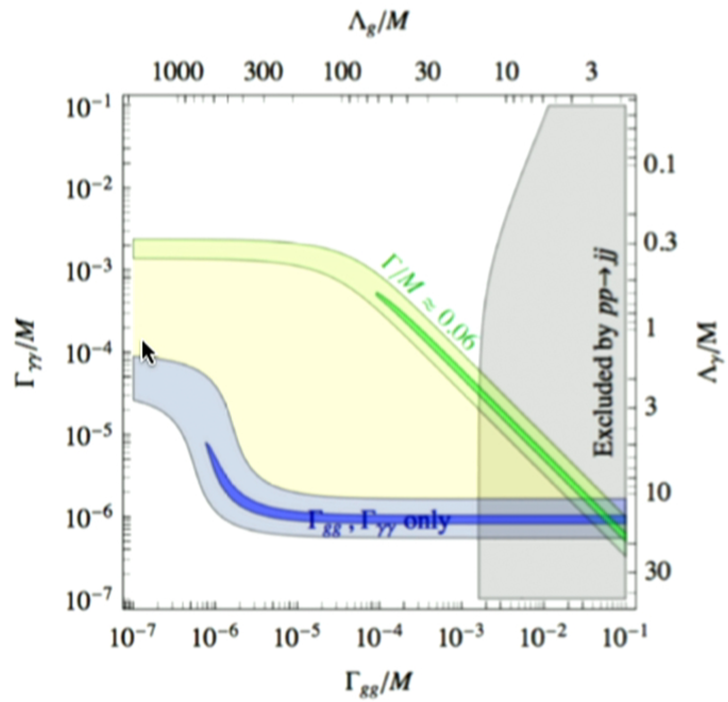
Assume:

$$\sigma(pp \to \gamma\gamma) \approx 8\text{fb} \qquad @\,13\text{TeV} \qquad (\Gamma_{TOT} \approx 45\,\text{GeV})$$

gluon production: $$\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M} \approx 10^{-6}\,\frac{\Gamma}{M} \approx 5\times 10^{-8}$$



small width:

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

45 GeV width:

$$\frac{\Gamma(S \to \gamma\gamma)}{M} > 10^{-4}$$ **BIG!**

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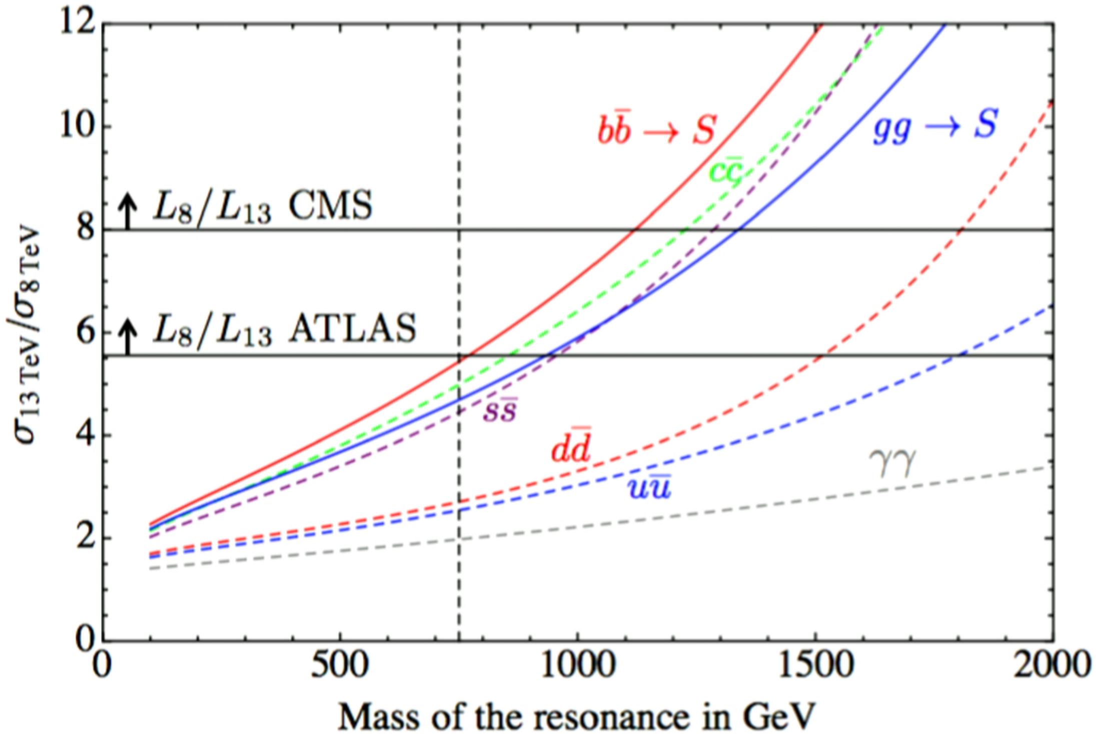
LHC13 vs. LHC8:



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

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

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

Significant constraints in all channels:

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	[7, 8]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[9]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[10]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[11]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[12]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[13]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[14]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[15, 16]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[17]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[18]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[19]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[6]	$< 1300\ (r/5)$

If width dominated by gluons:

$$\Gamma < 2\,\text{GeV}$$

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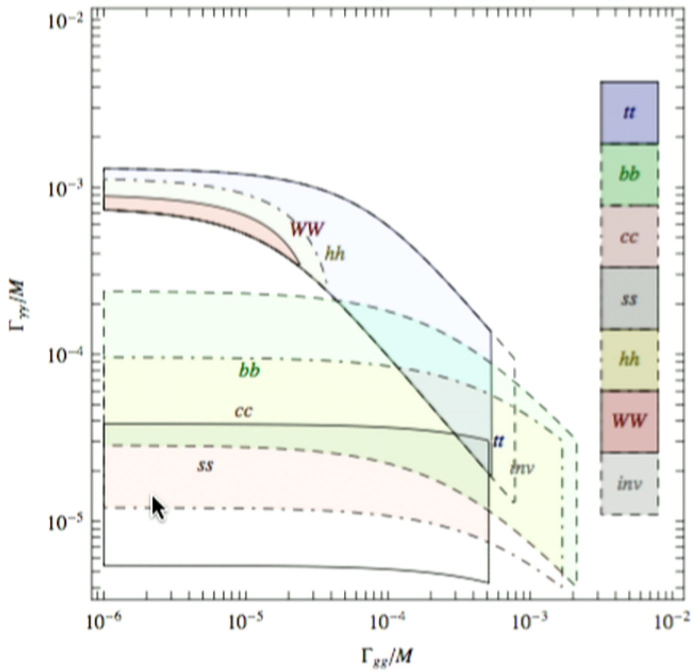
$$\Gamma = 45\,\mathrm{GeV}$$

Decays



INV, tt, bb: $\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-4}$

WW, hh: $\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-3}$

weakest bound: $\frac{\Gamma_{\gamma\gamma}}{M} > 6.8 \times 10^{-6}\sqrt{\frac{\Gamma}{45\,\mathrm{GeV}}}$

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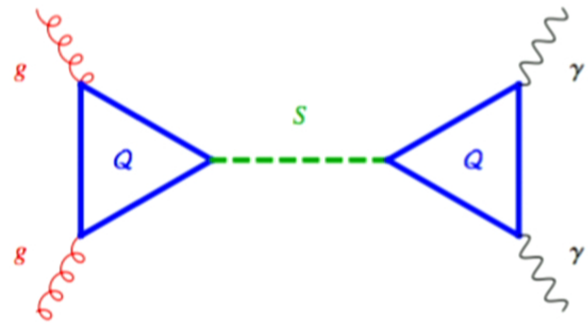
INTERPRETATION

Likely a **spin-0** resonance coupled to photons and gluons.



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

$$\Gamma(S\to\gamma\gamma) = \pi\alpha^2 M\left(\frac{M^2}{\Lambda_\gamma^2} + \frac{M^2}{\tilde{\Lambda}_\gamma^2}\right) \qquad \Gamma(S\to gg) = 8\pi\alpha_3^2 M\left(\frac{M^2}{\Lambda_g^2} + \frac{M^2}{\tilde{\Lambda}_g^2}\right)$$

$$\frac{M}{\Lambda_\gamma}\frac{M}{\Lambda_g} \approx 0.037\sqrt{\frac{\Gamma}{45\,\mathrm{GeV}}}$$

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SU(2)xU(1) invariant lagrangian:

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g}+\frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right)+g_2^2 S\left(\frac{W_{\mu\nu}^2}{2\Lambda_W}+\frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W}\right)+g_1^2 S\left(\frac{B_{\mu\nu}^2}{2\Lambda_B}+\frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B}\right)+$$
$$+S\left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi}+\text{h.c.}\right)+S\frac{|D_\mu H|^2}{\Lambda_H}+\frac{M^2}{2}\left(S+\frac{\Lambda_S}{M^2}(|H|^2-v^2)\right)^2 ,$$

Coupling to electro-weak gauge bosons:

operator	$\frac{\Gamma(S\to Z\gamma)}{\Gamma(S\to\gamma\gamma)}$	$\frac{\Gamma(S\to ZZ)}{\Gamma(S\to\gamma\gamma)}$	$\frac{\Gamma(S\to WW)}{\Gamma(S\to\gamma\gamma)}$
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

S must couple to hypercharge:

$$-0.25 < \Lambda_B/\Lambda_W\ ,\ \tilde{\Lambda}_B/\tilde{\Lambda}_W < 2.4$$

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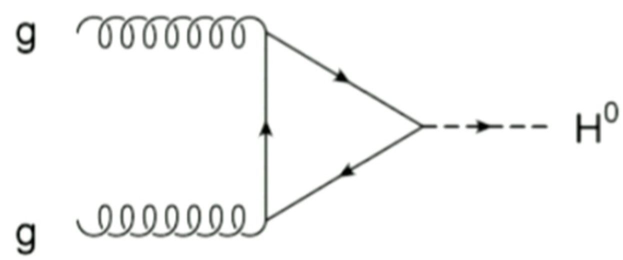
A coupling to gluons and photons requires new particles with color and electric charge.

- Weak coupling:

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



- $2M_f > M$

$$\frac{\Gamma(S\to gg)}{M} \approx 7.2\times 10^{-5}\left|\sum_f I_{r_f} y_f \frac{M}{2M_f}\right|^2 \qquad \frac{\Gamma(S\to\gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f}\right|^2$$

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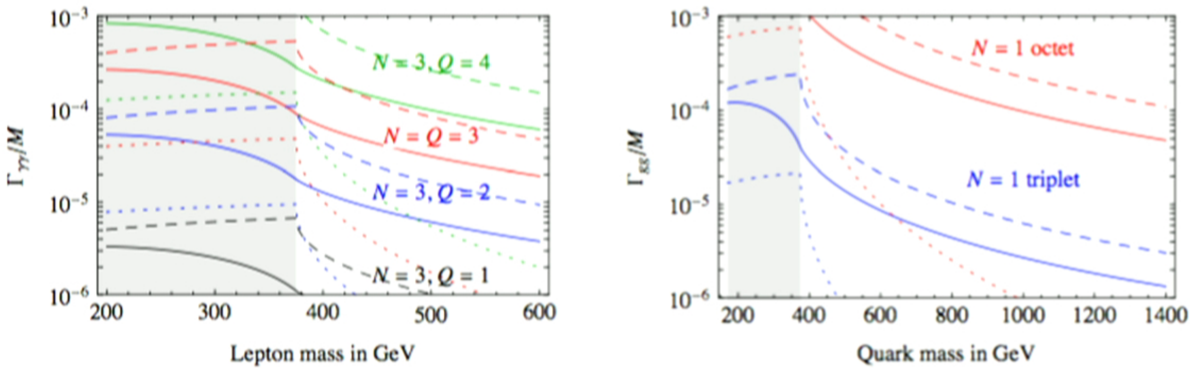
Easy to reproduce signal:

Scalar (continuous), pseudo–scalar (dashed) and cubic coupling $y, y_5 = 1, A = M$



Total width suggests tree level decays

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

The width into photons is challenging:

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

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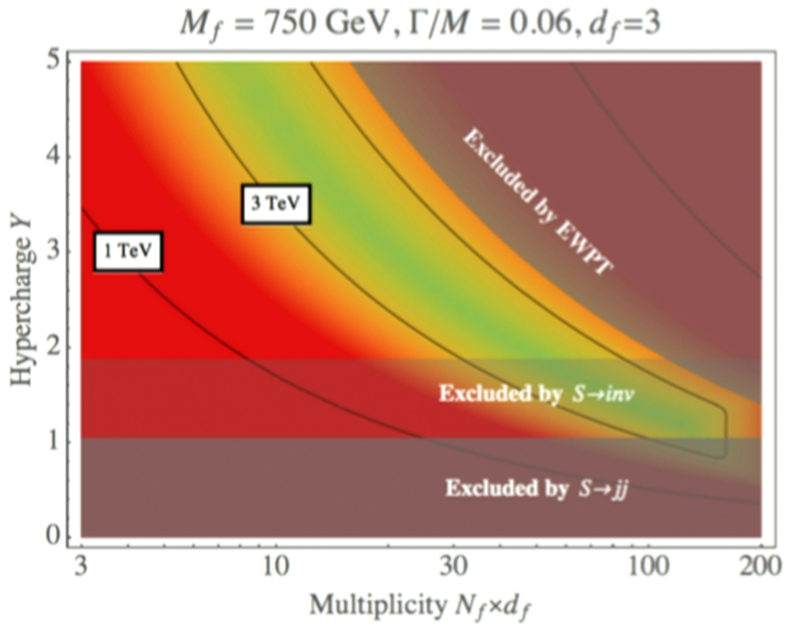
A large width implies either large multiplicities, large charges or large couplings. In all cases one obtains Landau poles:



Theories are strongly coupled at the TeV scale.
Alternatively the width is reproduced by multiple states.

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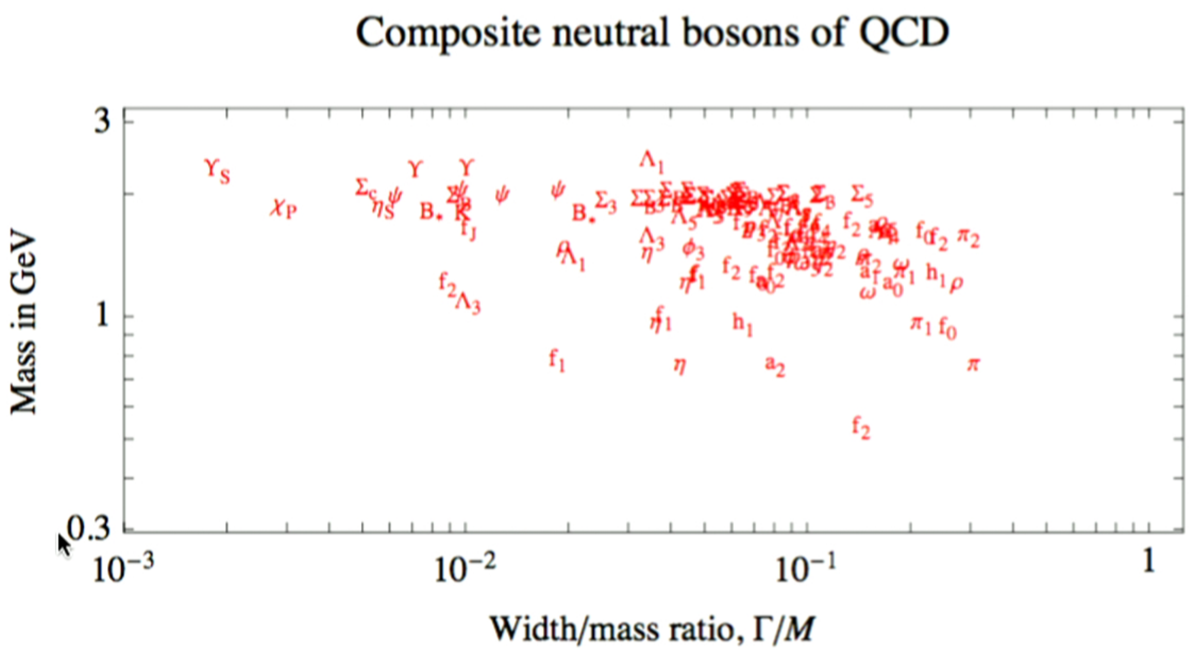
- **Strong coupling:**



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

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

- S could be part of an extended Higgs sector where the Higgs is composite. For example it could be a PGB in models with partial compositeness

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

Unbroken group must contain SM group

Ex: $$\frac{SU(11)}{SO(11)}$$

- S belongs to a sector that does not break electro-weak symmetry and the Higgs is elementary.
Simple gauge theory realisations. Di-photon could be a new pion or a bound state of vectorial fermions.

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- Composite Higgs Models:

If S is CP even (a dilaton or a composite scalar):

$$\mathcal{L}_{eff} = -\frac{1}{16\pi^2}\frac{S}{f}\left[b_G\, g_3^2 G_{\mu\nu}G^{\mu\nu} + b_W\, g_2^2 W_{\mu\nu}W^{\mu\nu} + b_B\, g_1^2 B_{\mu\nu}B^{\mu\nu}\right]$$
$$+ c_H \frac{S}{f}|D_\mu H|^2 + c_S m_h^2 \frac{S}{f}|H|^2 + c_f y_f \frac{S}{f} H \bar{f}_L f_R + \text{h.c.}$$

$$b_{G,W,B} \sim N \qquad\qquad c_f \sim 1$$

For PGBs coupling to gauge bosons is suppressed by symmetry breaking SM couplings.

Width can be reproduced with decays to SM fields:

$$\begin{cases} c_t \approx 3.5\left(\frac{f}{M}\right)\sqrt{\frac{\Gamma}{45\,\text{GeV}}} & \text{for } \Gamma \approx \Gamma(S \to \bar{t}t) \\ c_H \approx 2.5\left(\frac{f}{M}\right)\sqrt{\frac{\Gamma}{45\,\text{GeV}}} & \text{for } \Gamma \approx \Gamma(S \to W^+W^-, ZZ, hh) \end{cases}$$

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A large width implies:

$$b_B + b_W \gtrsim \begin{cases} 80\,(f/M)\,\sqrt{\Gamma/45\,\text{GeV}} & \text{for } \Gamma \approx \Gamma(S \to \bar{t}t) \\ 285\,(f/M)\,\sqrt{\Gamma/45\,\text{GeV}} & \text{for } \Gamma \approx \Gamma(S \to W^+W^-, ZZ, hh) \end{cases}$$

$$b_G \lesssim \begin{cases} 2.8\,(f/M) & \text{for } \Gamma \approx \Gamma(S \to \bar{t}t) \\ 0.8\,(f/M) & \text{for } \Gamma \approx \Gamma(S \to W^+W^-, ZZ, hh) \end{cases}$$

PGB CP odd case:

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

$$b_{G,W,B} \to c_{G,W,B}$$

Coupling to gauge bosons determined by anomalies.
It only depends on the pattern of symmetry breaking.

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

Ratios in electro-weak gauge bosons predicted:

$$\frac{\Gamma_{\gamma Z}}{\Gamma_{\gamma\gamma}} \approx \frac{2(-c_W \cot\theta_W + c_B \tan\theta_W)^2}{c_\gamma^2}, \quad \frac{\Gamma_{ZZ}}{\Gamma_{\gamma\gamma}} \approx \frac{(c_W \cot\theta_W^2 + c_B \tan\theta_W^2)^2}{c_\gamma^2},$$

$$\frac{\Gamma_{WW}}{\Gamma_{\gamma\gamma}} \approx 2\frac{c_W^2}{c_\gamma^2 \sin^4\theta_W}, \quad \frac{\Gamma_{gg}}{\Gamma_{\gamma\gamma}} \approx \frac{8\alpha_3^2}{\alpha^2}\frac{c_G^2}{c_\gamma^2} \approx 1300\,\frac{c_G^2}{c_\gamma^2}.$$

di-jets: $c_G < c_\gamma$

If no other decays exist:

$$\frac{\Gamma_{\gamma\gamma}}{M} \approx 10^{-6} \longrightarrow \frac{M}{f} \approx \frac{6}{c_\gamma}$$

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Extra decay channels:

$$\frac{\Gamma_{gg}}{M} = 1.3 \times 10^{-3}\, \frac{c_G}{c_\gamma} \sqrt{\frac{\Gamma_{tot}}{\mathrm{GeV}}} \qquad \frac{\Gamma_{\gamma\gamma}}{M} = 10^{-6}\, \frac{c_\gamma}{c_G} \sqrt{\frac{\Gamma_{tot}}{\mathrm{GeV}}}$$

$$f \approx 130\,\mathrm{GeV}\, \sqrt{c_\gamma c_G} \left(\frac{\mathrm{GeV}}{\Gamma_{tot}}\right)^{\frac{1}{4}}$$

$$\frac{\Gamma_{\gamma\gamma}}{M} > 10^{-4} \longrightarrow \frac{M}{f} > \frac{50}{c_\gamma}$$

1) Composite Higgs: **M=f, N=10**. The strong dynamics is heavier and weakly coupled. Landau poles.

$$g_* \sim 3$$

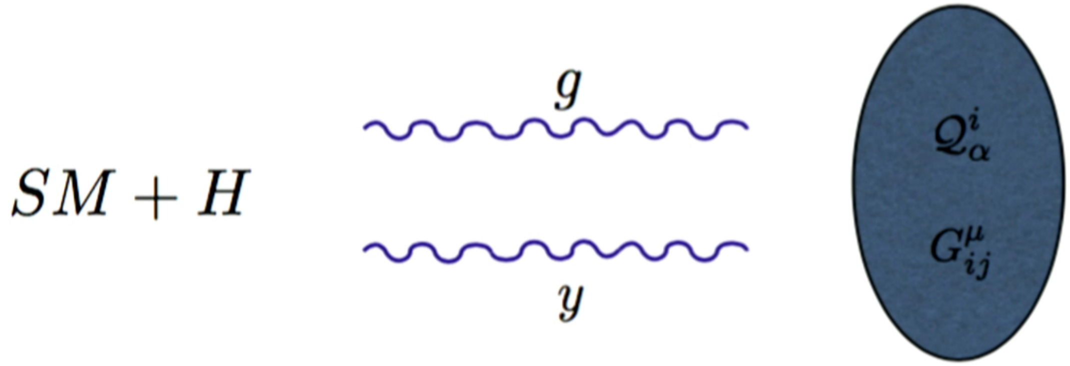
2) Elementary Higgs: **M =4 pi f, N=3**. Automatic for eta'. Strong dynamics nearby but hidden by strong coupling.

$$g_{eff} \sim \frac{g_{SM}^2}{g_*} \sim \frac{g_{SM}^2}{4\pi}$$

- Vector-like gauge theories:

Kilic, Okui, Sundrum '09

Antipin, MR, Strumia, Vigiani '15



New confining gauge theory with fermions vectorial under SM

SM including Higgs couples to the new sector with renormalizable couplings:

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\Psi}_i(i\not{D} - m_i)\Psi_i - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm TC}} + \frac{\theta_{\rm TC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + [H\bar{\Psi}_i(y^L_{ij}P_L + y^R_{ij}P_R)\Psi_j + \text{h.c.}]$$

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- **Models**

SU(N) gauge theory with NF flavors.
Techni-quarks are vectorial with respect to SM.

Fermions	SM	$SU(n)_{\rm TC}$
Ψ_L	$\sum_i r_i$	n
Ψ_R	$\sum_i \bar{r}_i$	$\bar{n}$

$$\sum_i d[r_i] = N_F$$

$$\langle \bar{\Psi}^i \Psi^j \rangle \sim 4\pi f^3 \delta^{ij} \qquad \Lambda_{TC} \sim \frac{4\pi}{\sqrt{N_{\rm TC}}} f$$

Vacuum does not break electro-weak symmetry.

NGB:

$$\frac{SU(N_F) \times SU(N_F)}{SU(N_F)} \qquad \text{Adj}_{SU(N_F)} + 1 = \sum_{i=1}^{K} r_i \times \sum_{i=1}^{K} r_i$$

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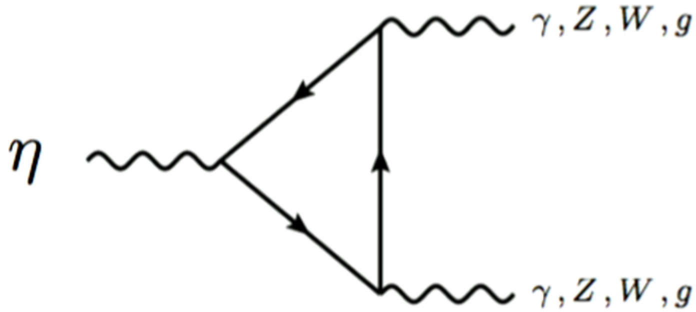
Singlets NGB are di-photon candidates. Two species:

$$\eta' \sim Q_1\bar{Q}_1 + Q_2\bar{Q}_2 \qquad \eta \sim \sqrt{\frac{d_2}{d_1}}Q_1\bar{Q}_1 - \sqrt{\frac{d_1}{d_2}}Q_2\bar{Q}_2$$

$$m^2_{\eta'} \sim \frac{N_F}{N_{\rm TC}}\Lambda^2_{\rm TC} \qquad m^2_\eta \sim m_Q\Lambda_{\rm TC}$$



$$c_i\,\delta^{AB} = 2N_{\rm TC}\,{\rm Tr}\,(T_\eta T^A T^B)$$

$$c_f \sim 0$$

$\theta-$ angle induces CP violating interactions allowing decay into two pions if kinematically allowed.

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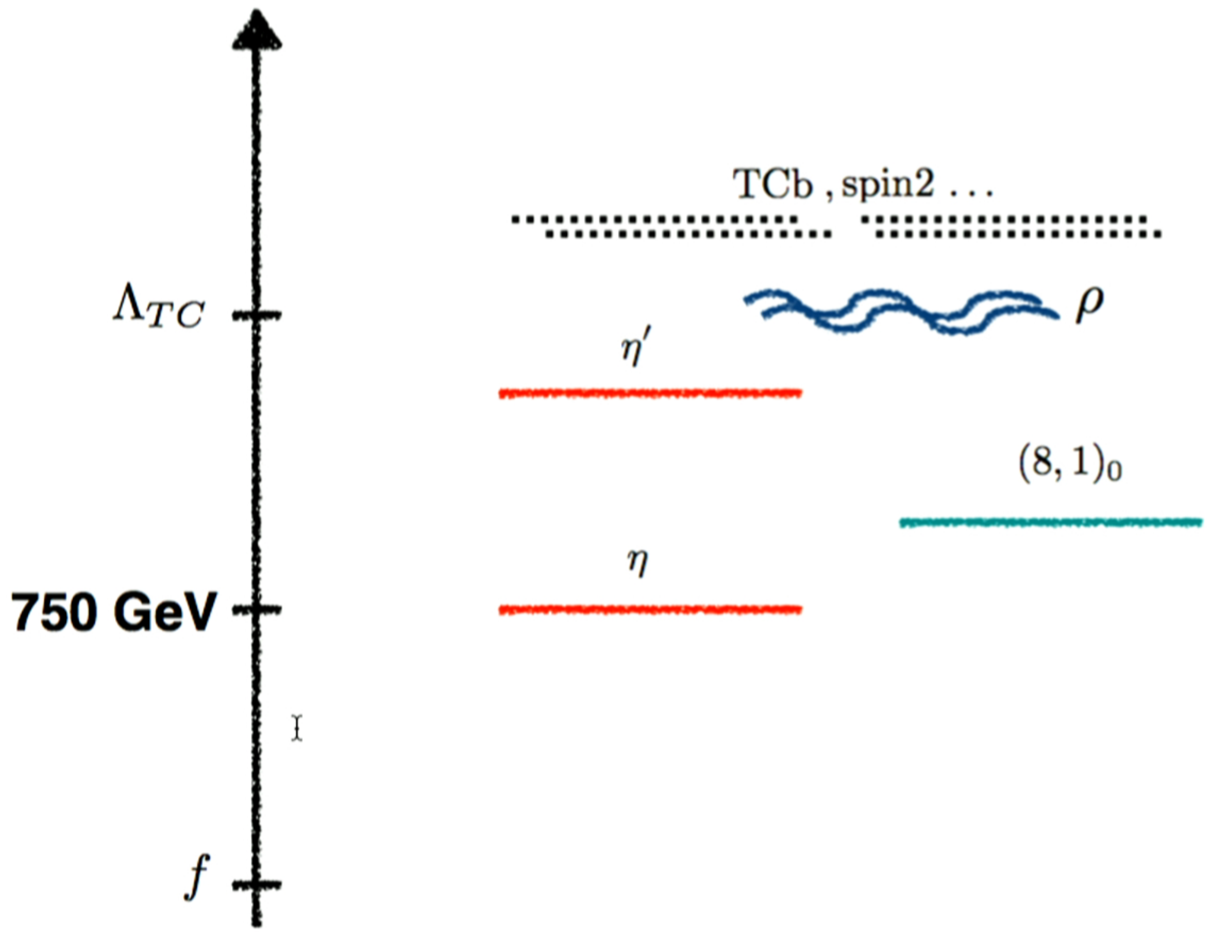
Di-photon system



MR, Strumia, Tesi, Vigiani '16

Q	N_{TF}	$\frac{c_B^\eta}{N_{TC}}$	$\frac{c_W^\eta}{N_{TC}}$	$\frac{c_G^\eta}{N_{TC}}$	$\frac{\Gamma^\eta_{\gamma Z}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{\Gamma^\eta_{ZZ}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{\Gamma^\eta_{GG}}{\Gamma^\eta_{\gamma\gamma}}$	$\frac{f(\text{GeV})}{N_{TC}}$	$\frac{c_B^{\eta'}}{N_{TC}}$	$\frac{c_W^{\eta'}}{N_{TC}}$	$\frac{c_G^{\eta'}}{N_{TC}}$	$\frac{\Gamma^{\eta'}_{\gamma Z}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{\Gamma^{\eta'}_{ZZ}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{\Gamma^{\eta'}_{GG}}{\Gamma^{\eta'}_{\gamma\gamma}}$	$\frac{f(\text{GeV})}{N_{TC}}$
$D \oplus L$	5	$\frac{1}{6}\sqrt{\frac{5}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{5}}$	$-\frac{1}{\sqrt{15}}$	1.8	4.6	240	78	$\frac{1}{3}\sqrt{\frac{5}{2}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.22	1.9	180	110
$D \oplus U$	6	$\frac{1}{\sqrt{3}}$	0	0	0.58	0.083	0	-	$\frac{5}{3\sqrt{3}}$	0	$\frac{1}{\sqrt{3}}$	0.58	0.083	470	125
$D \oplus E$	4	$\frac{4}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.58	0.083	46	142	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.58	0.083	180	123
$D \oplus Q$	9	$-\frac{1}{6}$	$\frac{1}{2}$	0	17	21	0	-	$\frac{1}{3\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	2.9	6.0	740	123
$D \oplus T$	6	$\frac{8}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	0.42	2.3	15	350	$\frac{10}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	0.22	1.9	12	400
$L \oplus U$	5	$\frac{7}{6\sqrt{15}}$	$-\frac{1}{2}\sqrt{\frac{3}{5}}$	$\frac{1}{\sqrt{15}}$	200	180	12000	-	$\frac{11}{3\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	$\frac{1}{\sqrt{10}}$	0.0032	0.82	60	192
$L \oplus Q$	8	$-\frac{2}{3\sqrt{3}}$	0	$\frac{1}{2\sqrt{3}}$	0.58	0.083	740	50	$\frac{1}{3}$	1	$\frac{1}{2}$	2.9	6.0	180	173
$L \oplus S$	8	$\frac{7}{12\sqrt{3}}$	$-\frac{\sqrt{3}}{4}$	$\frac{5}{4\sqrt{3}}$	200	180	74000	-	$\frac{19}{12}$	$\frac{1}{4}$	$\frac{5}{4}$	0.097	0.47	610	238
$U \oplus E$	4	$\frac{5}{3\sqrt{6}}$	0	$-\frac{1}{2\sqrt{6}}$	0.58	0.083	120	88	$\frac{7}{3\sqrt{2}}$	0	$\frac{1}{2\sqrt{2}}$	0.58	0.083	60	215
$U \oplus Q$	9	$-\frac{5}{6}$	$\frac{1}{2}$	0	32	16	0	-	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{\sqrt{2}}$	0.78	3.0	330	184
$U \oplus V$	6	$-\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$-\frac{1}{2\sqrt{3}}$	83	80	740	-	$\frac{4}{3\sqrt{3}}$	$\frac{2}{\sqrt{3}}$	$\frac{1}{2\sqrt{3}}$	1.5	4.1	29	50
$U \oplus N$	4	$-\frac{2}{3}\sqrt{\frac{2}{3}}$	0	$-\frac{1}{2\sqrt{6}}$	0.58	0.083	180	71	$\frac{2\sqrt{2}}{3}$	0	$\frac{1}{2\sqrt{2}}$	0.58	0.083	180	123
$E \oplus Q$	7	$-\frac{5}{6}\sqrt{\frac{7}{3}}$	$\frac{1}{2}\sqrt{\frac{3}{7}}$	$\frac{1}{\sqrt{21}}$	3.6	0.51	70	123	$\frac{1}{3}\sqrt{\frac{7}{2}}$	$\frac{3}{\sqrt{14}}$	$\sqrt{\frac{2}{7}}$	1.2	3.7	180	185
$E \oplus S$	7	$-\frac{10}{3\sqrt{21}}$	0	$\frac{5}{2\sqrt{21}}$	0.58	0.083	740	95	$\frac{11}{3}\sqrt{\frac{2}{7}}$	0	$5\sqrt{14}$	0.58	0.083	610	255
$S \oplus V$	9	$-\frac{8}{9}$	$\frac{4}{3}$	$-\frac{5}{6}$	83	80	4600	-	$\frac{8\sqrt{2}}{9}$	$\frac{2\sqrt{2}}{3}$	$\frac{5}{3\sqrt{2}}$	0.42	2.3	380	58
$S \oplus N$	7	$-\frac{8}{3\sqrt{21}}$	0	$-\frac{5}{2\sqrt{21}}$	0.58	0.083	1200	76	$\frac{8}{3}\sqrt{\frac{2}{7}}$	0	$\frac{5}{\sqrt{14}}$	0.58	0.083	1200	185

Each model predicts NGB and spin-1 resonances with SM quantum numbers that will be visible at LHC.

Ex: D+L

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

$$m_\eta'^2 \approx \frac{1}{N} g_*^2 f^2 \,, \qquad m_\eta^2 \approx (\frac{3}{5} m_L + \frac{2}{5} m_D) g_* f \,, \qquad m_{(1,3)_0} \approx m_L\, g_* f + \Delta_2$$

$$m_{(8,1)_0} \approx m_D\, g_* f + \Delta_3 \,, \qquad m_{(3,2)_{\frac{1}{6}}} \approx (\frac{m_L + m_D}{2})\, g_* f + \Delta_2 + \Delta_3$$

η :

$$\frac{\Gamma_{gg}}{M} = 2.7 \times 10^{-4} \sqrt{\frac{\Gamma}{0.2\,\mathrm{GeV}}} \qquad \frac{\Gamma_{\gamma\gamma}}{M} = 10^{-6} \sqrt{\frac{\Gamma}{0.2\,\mathrm{GeV}}}$$

$$f \sim 80\,\mathrm{GeV} \left(\frac{0.2\,\mathrm{GeV}}{\Gamma}\right)^{\frac{1}{4}} \times N_{\mathrm{TC}}$$

Color octet scalars decay into gluons through anomalies. Squark-like pion is long lived. Triplet pion could be lighter. Very rich phenomenology.

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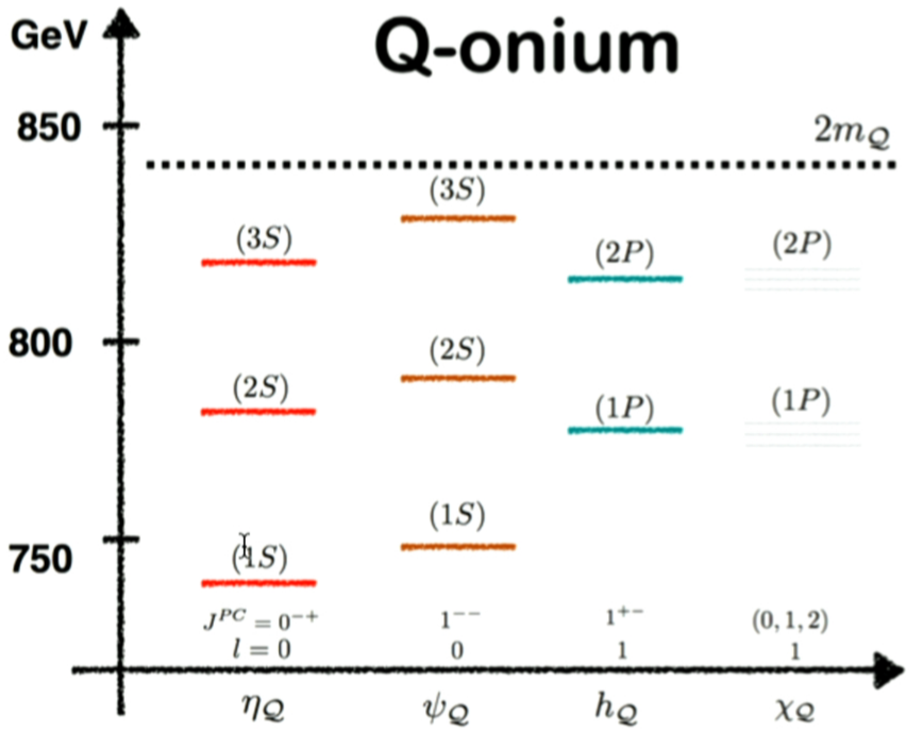
- Q-onium

Kamenik, MR '16

If the fermions are above confinement scale dynamics is similar to charm and bottom in QCD.



$m_{\eta_Q} \sim 2m_Q$

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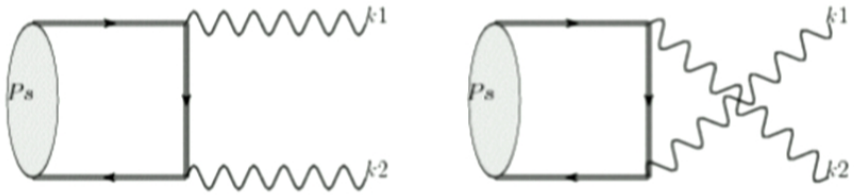
Decay into photons is a tree level process



$$\frac{\Gamma(\eta_Q^1 \to \gamma\gamma)}{M} = 12 N_{\mathrm{TC}} \alpha^2 Q^4 \frac{|R(0)|^2}{M^3}$$

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

- **spin-0:** gluon production η_Q^1 η_Q^8
- **spin-1:** quark production ψ_Q^1 ψ_Q^8

Di-photon can also decay into glueballs or light pions

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Rates in all channels predicted:

	σ_U [fb]	σ_X [fb]	σ_Y [fb]	σ[fb] @ LHC8
$pp \to \eta^1 \to gg$	200(920)	12(58)	44(200)	<2500
$pp \to \eta^8 \to gg$	500(2300)	34(160)	110(520)	<2500
$pp \to \psi^1 \to e\bar{e}$	0.3(0.9)	0.1(0.2)	0.1(0.3)	<1.2
$pp \to \psi^8 \to jj$	600(1600)	40(110)	130(360)	<2500
$pp \to \psi^8 \to t\bar{t}$	120(320)	8(22)	25(65)	<600

$U = (3,1)_{\frac{2}{3}}$

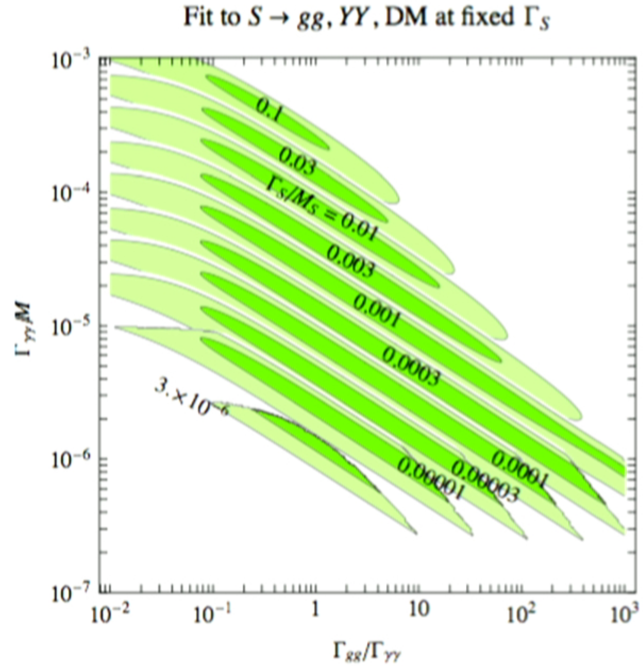
$X = (3,1)_{\frac{4}{3}}$

$Y = (3,2)_{\frac{5}{6}}$

Large width could be reproduced by the production of excited states. Splitting 6% is natural.

η_X	m_{η_X} [GeV]	$\frac{\Gamma(\eta_X \to \gamma\gamma)}{m_{\eta_X}}$	$\frac{\lvert R(0)\rvert^2}{m_{\eta_X}^3}$
η'	0.958	5×10^{-6}	–
$\eta_c(1S)$	2.983	2×10^{-6}	1.5×10^{-2}
$\eta_c(2S)$	3.639	10^{-6}	6×10^{-3}
$\eta_b(1S)$	9.398	5×10^{-8}	6×10^{-3}
$\eta_b(2S)$	10	2×10^{-8}	2.5×10^{-3}

DARK MATTER



Invisible decays

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

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

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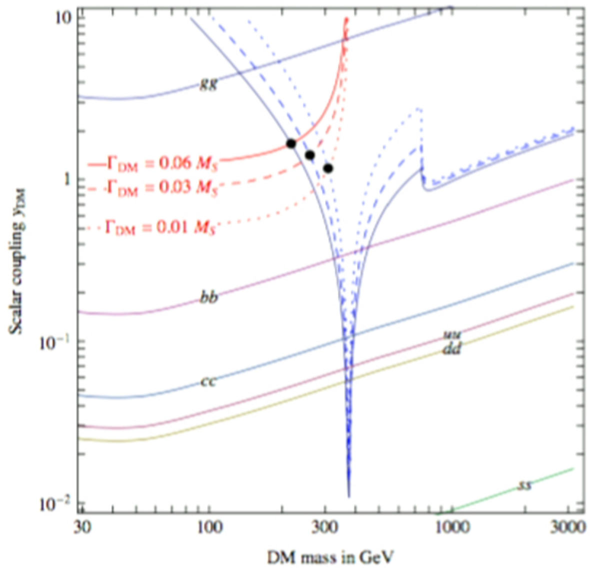
$$y_{DM}\bar{\Psi}_{DM}\Psi_{DM}\left[g_3^2\frac{G_{\mu\nu}G^{\mu\nu}}{2\Lambda_g}+\sum_q y_{Sq}\bar{q}q\right]$$

Thermal relic density mediated by S can be obtained even reproducing the total width.



$$\sigma_{SI}=4\ 10^{-47}\text{cm}^2\,y_{DM}^2\left[-27.\frac{M_S}{\Lambda_g}+0.30\frac{y_{uS}}{y_u}+0.38\frac{y_{dS}}{y_d}+1.5\frac{y_{sS}}{y_s}+\frac{y_{cS}}{y_c}+\frac{y_{bS}}{y_b}+\frac{y_{tS}}{y_t}\right]^2$$

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Accidental DM candidates in gauge theory models:

- Baryon number
- Species number

Lightest baryon and meson with species number stable.
Easiest possibility add singlets. DM candidates:

$$\Pi \sim N_1 \bar{N}_2 \qquad B = \epsilon_{i_1 i_2 \dots i_n} N^{i_1} N^{i_2} \dots N^{i_n}$$

NGB interactions:

$$\mathcal{L}_{\rm DM} = C_{\eta\Pi\Pi} \frac{\eta \Pi^2}{2} + \frac{g_3^2}{16\pi^2} C_{\Pi\Pi gg} \frac{\Pi^2}{f^2} G^a_{\mu\nu} G^{a,\mu\nu} + \frac{1}{f^2} \eta_*^2 (\partial\Pi)^2 + \frac{m^2}{f^2} \eta_*^2 \Pi^2$$

$$C_{\Pi\Pi gg} \sim N_{\rm TC} \frac{m_\Pi^2}{\Lambda_{\rm TC}^2}\,, \qquad C_{\eta\Pi\Pi} \sim \frac{m_\Pi^2}{f} \theta_{\rm TC}$$

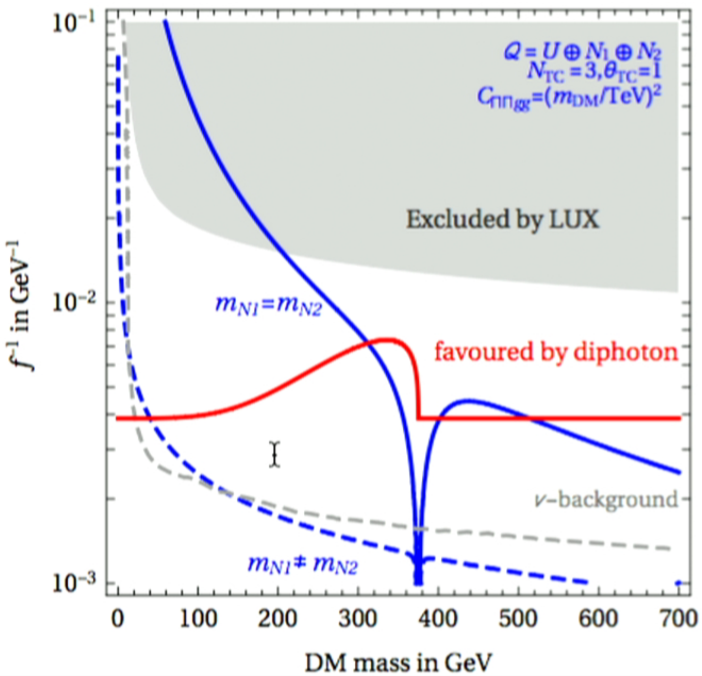
$$\mathcal{Q} = U \oplus N_1 \oplus N_2$$

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

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

$$\Gamma_{max}(\eta_1 \to \Pi\Pi^*) \sim \text{GeV} \times \theta^2_{\rm TC}$$

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



- m1=m2. Singlets don't mix. Relic abundance reproduced through di-photon interactions

- Even for small mixing self-interactions dominate. mDM < 100 GeV.

- Baryon DM candidates

FUTURE

- If excess is confirmed it will be revolutionary. It is the dream nobody in our field anymore had.

- Effects will be visible in many different channels. Invisible decay suggestive of connection with DM.

- Theoretical speculations rely on the width. Is S weakly or strongly coupled? Is it related to EWSB? With more data we might be able to pin down the right theory.

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