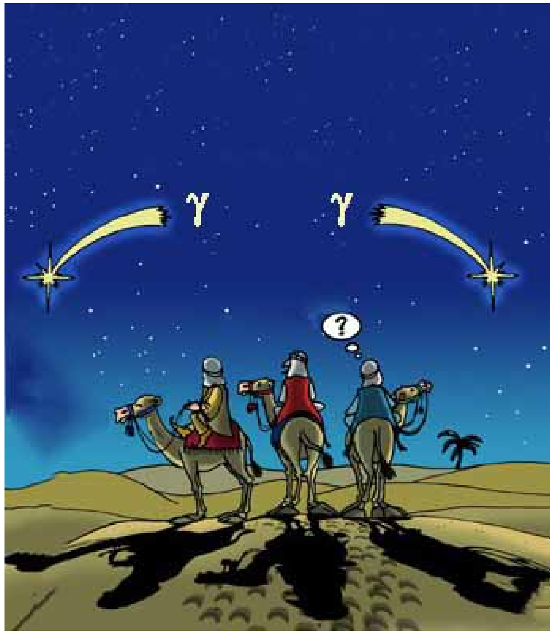
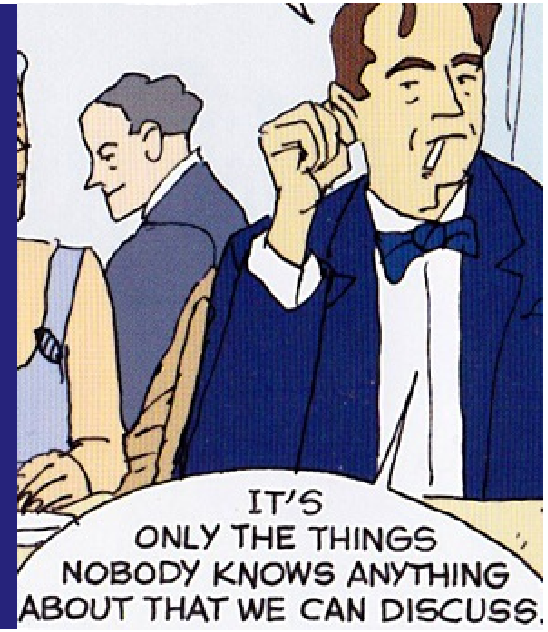
The $\gamma\gamma$ resonance at 750 GeV



Fitting the $\gamma\gamma$ peak:

1) Widths
2) Models
3) Theories
4) What next?



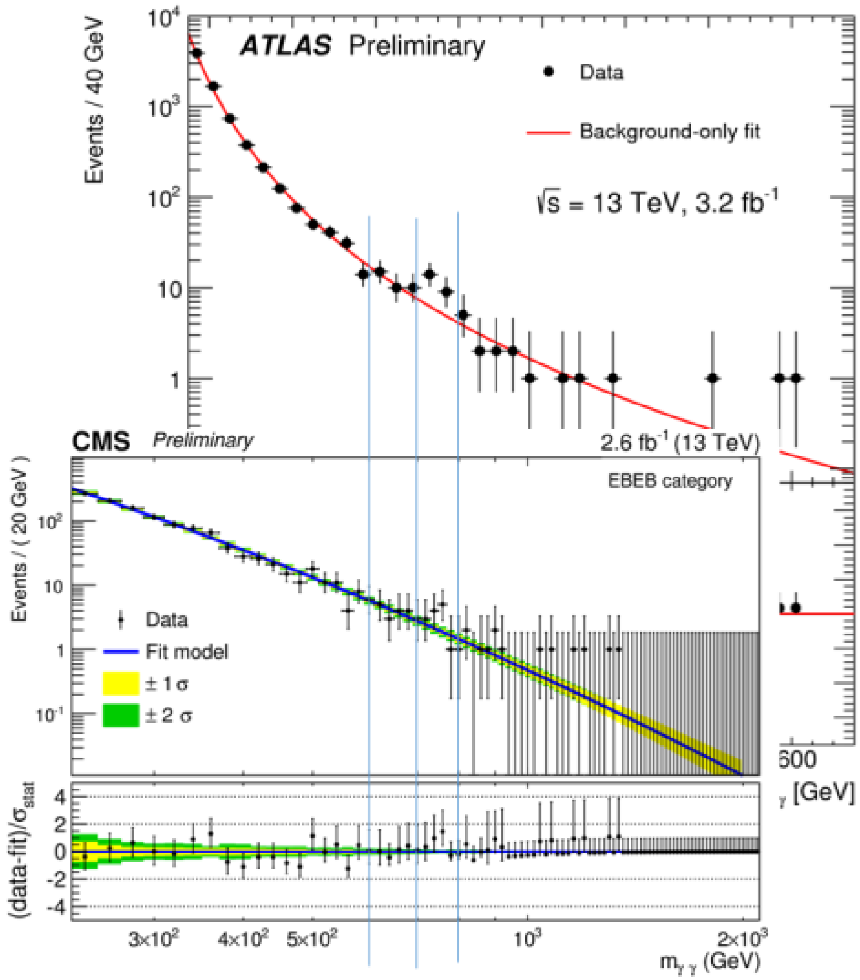
Alessandro Strumia, talk at RENCONTRES DE MORIOND 750 since 1966, March 17, 2016

European Commission

Horizon 2020
European Union funding
for Research & Innovation

erc European Research Council

First LHC data at 13 TeV



$\gamma\gamma$ peak around 750 GeV over flatland

$\sigma(pp \to \gamma\gamma)$	CMS	ATLAS
8 TeV	(0.5 ± 0.6) fb	(0.4 ± 0.8) fb
13 TeV	(6 ± 3) fb	(10 ± 3) fb

Theoretically clean.
Experimentally simple.

ATLAS prefers large width $\Gamma/M \sim 0.06$.
CMS prefers narrow width.

$\gamma\gamma$ not accompanied by hard extras.

Needless to say

Maybe the main discovery in 30 years.
Maybe the main statistical fluctuation.

Physics = experiment + i theory

The Gold Rush: [INSPIRES][list]

Date	papers
16 Dec	10
25 Dec	101
1 Jan	137
1 Feb	212
1 Mar	263
1 Apr	?

Sociological problem:
gold doesn't come spontaneously.

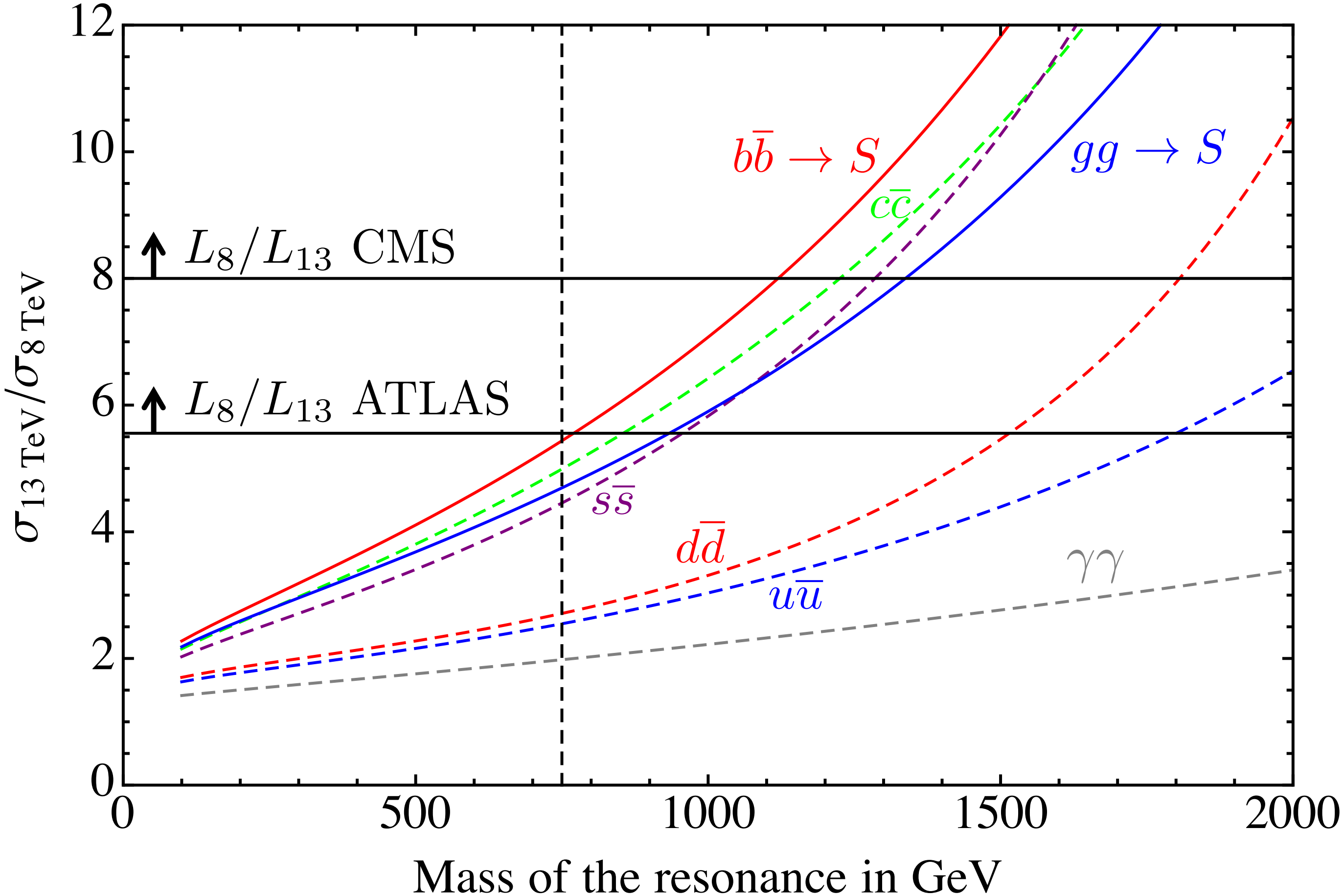
Time to review the confusion

8 TeV vs 13 TeV

The background $q\bar{q} \to \gamma\gamma$ at 750 GeV grows by 2.3.

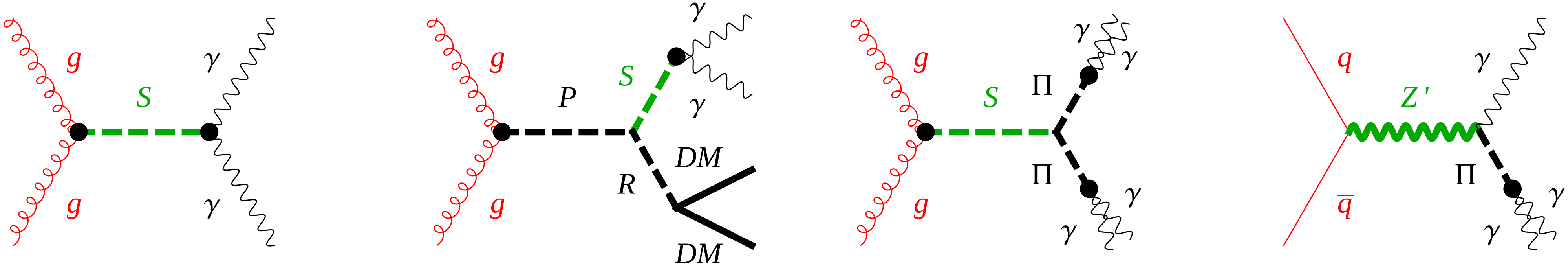
The signal grows by ≈ 5 if produced from gg, $b\bar{b}$, $c\bar{c}$, $s\bar{s}$: ok.

The signal grows by ≈ 2.5 if produced from $\gamma\gamma$, $u\bar{u}$, $d\bar{d}$: disfavored.



Compatibility between 8/13 TeV improved if S decays from a heavier particle.

A more complicated kinematics?



Tuning $M_P \approx M_S + M_R$ needed to avoid $\not{p}_T$. S virtuality can fake S width.

Or large $S \to \Pi\Pi$ with $\Pi \to \gamma\gamma$, collimated and seen as a single γ if $M_\Pi \ll M_S$. Traveling in the detector material, 'photon jets' give more $\gamma \to e^+e^-$.

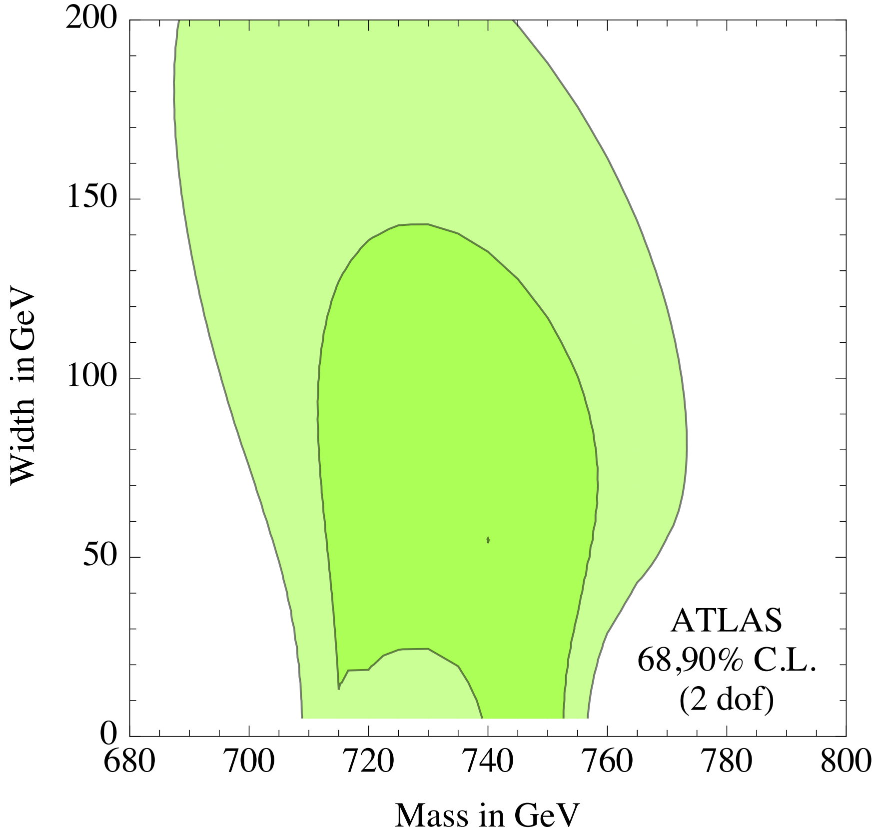
Or two nearby narrow resonances. Or N.

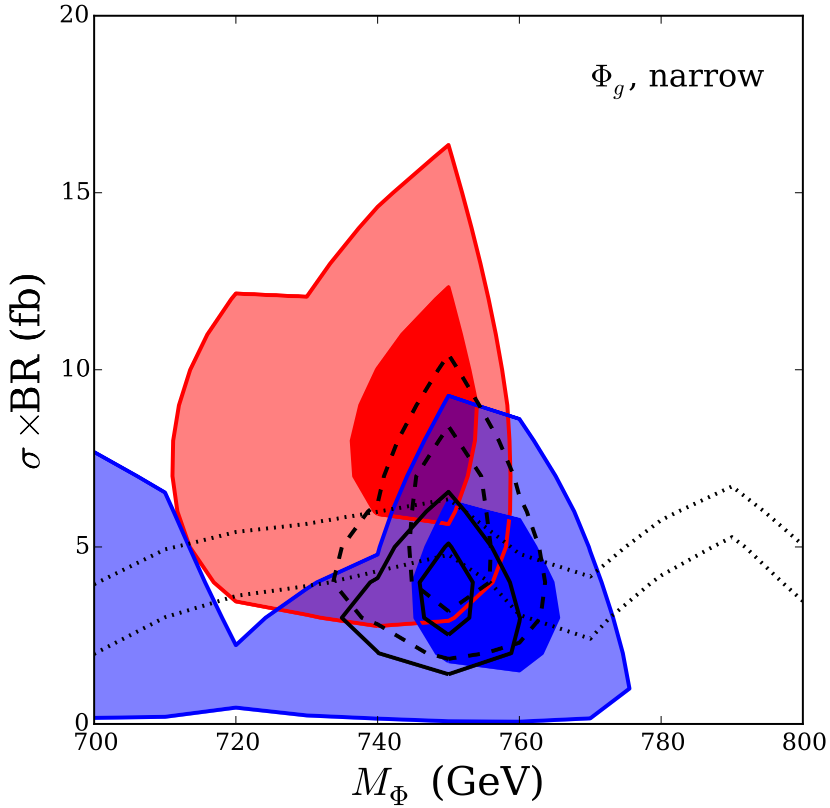
Or a QCD bound state of a new quark with $M \sim 380\,\mathrm{GeV}$ and obscure decays.

Please show the full energy distribution and the events

Widths

M, Γ, σ from data





PARENTAL
ADVISORY
FITS PUBLIC DATA ONLY

Cross section

Can be computed in terms of (narrow) widths:

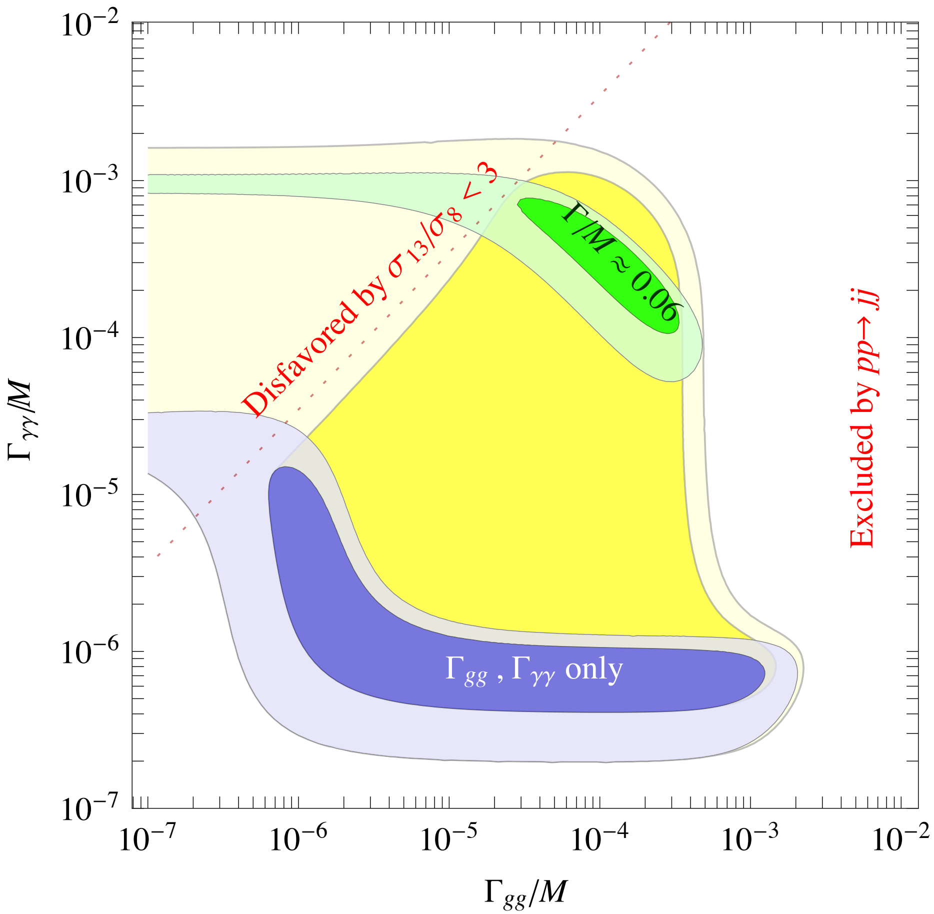
$$\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{s} \left[\sum_{\wp} C_{\wp\bar{\wp}} \frac{\Gamma(S \to \wp\bar{\wp})}{M} \right] \frac{\Gamma(S \to \gamma\gamma)}{\Gamma}$$

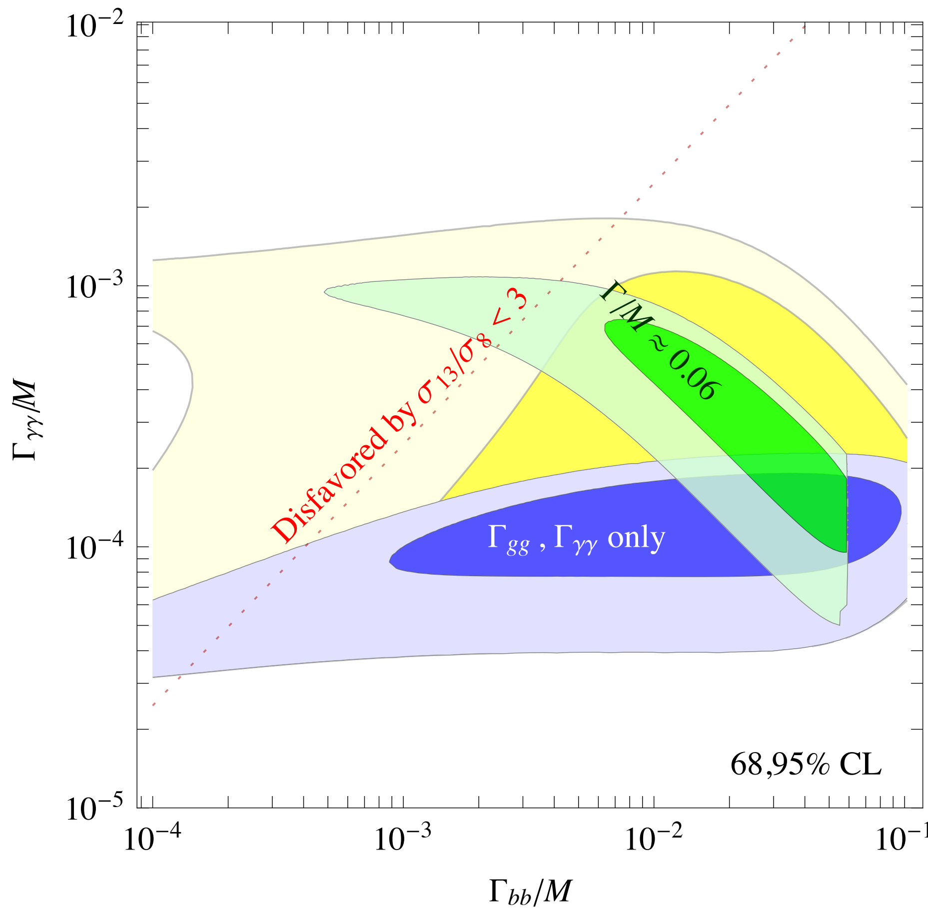
The parton $\wp$ luminosities are:

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

Extreme cases: gg and $b\bar{b}$

$$\mathscr{L}_{\text{scalar}} = S\left[g_3^2\frac{G_{\mu\nu}^2}{2\Lambda_g} + e^2\frac{F_{\mu\nu}^2}{2\Lambda_\gamma} + \frac{HQ_3D_3}{\Lambda_b}\right] \quad \text{or} \quad \mathscr{L}_{\text{scalar}}^{\text{pseudo}} = S\left[g_3^2\frac{G_{\mu\nu}\tilde{G}_{\mu\nu}}{2\tilde{\Lambda}_g} + e^2\frac{F_{\mu\nu}\tilde{F}_{\mu\nu}}{2\tilde{\Lambda}_\gamma} + \frac{HQ_3 i\gamma_5 D_3}{\tilde{\Lambda}_b}\right]$$





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

Bounds on other decay modes

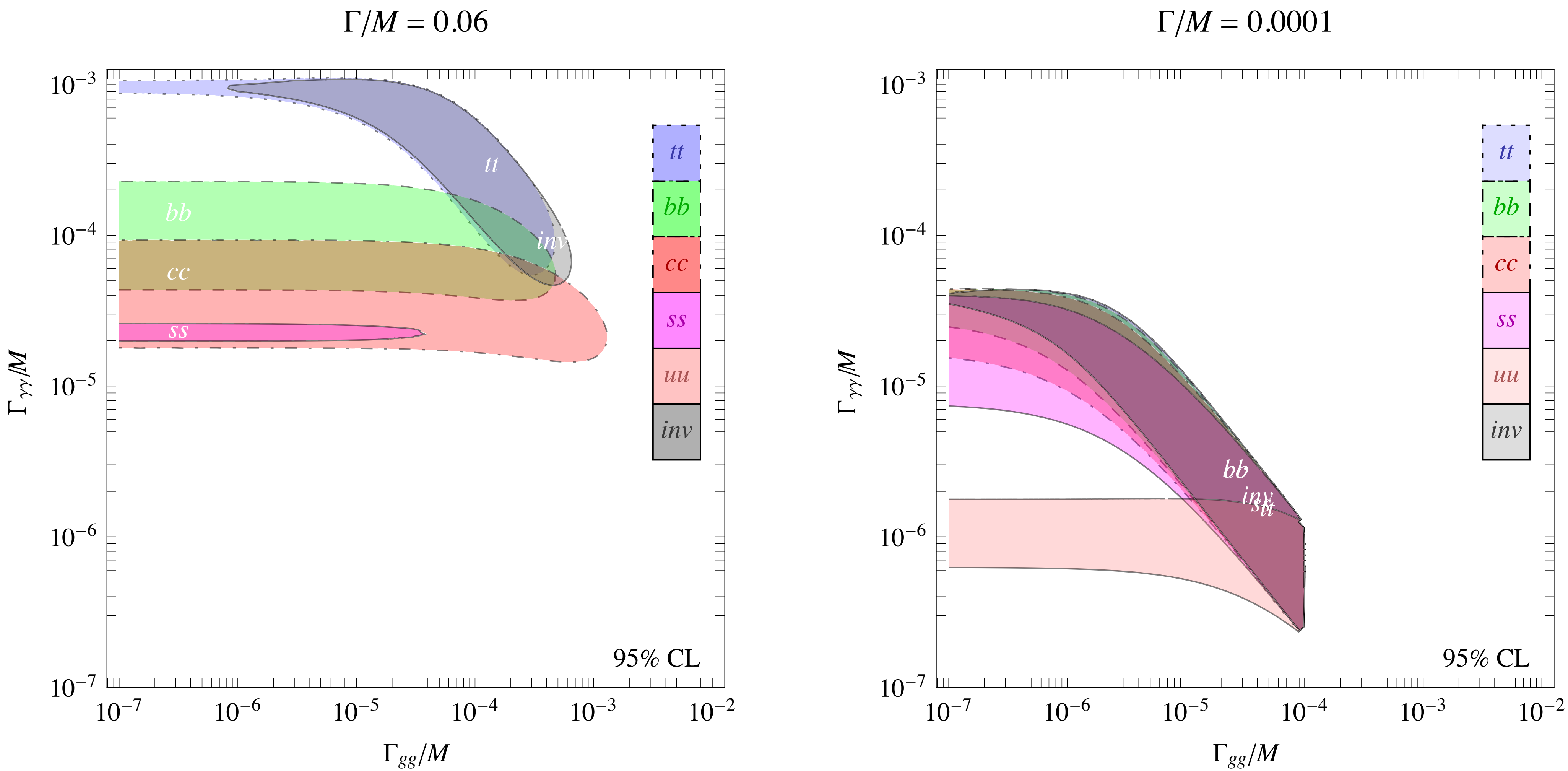
final state f	σ at $\sqrt{s} = 8\,$TeV observed	expected	implied bound on $\Gamma(S \to f)/\Gamma(S \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 12 fb	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	$< 300\ (r/5)$
invisible	< 0.8 pb	-	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1\,$pb	$\lesssim 1\,$pb	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	$< 1300\ (r/5)$

Here $r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$. Using run 2 data only would be safer. Run 2 jj?

Even invisible modes are constrained

Global fits, $S \leftrightarrow gg, \gamma\gamma, X$

Regions that fit $\sigma(pp \to \gamma\gamma)_{8,13}$, the width Γ and that satisfy all bounds:



Large width needs $\Gamma(S \to \gamma\gamma)/M \gtrsim 10^{-5}$: it's big!

$\mathbf{SU(2)}_L$ invariance

implies $S \to Z\gamma, ZZ$ nearby. Consider S as a scalar singlet:

$$\mathscr{L}_{\text{eff}} = S\left[g_3^2\frac{G^2_{\mu\nu}}{2\Lambda_g} + g_2^2\frac{W^2_{\mu\nu}}{2\Lambda_W} + g_1^2\frac{B^2_{\mu\nu}}{2\Lambda_B} + \left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi} + \text{h.c.}\right) + \frac{|D_\mu H|^2}{\Lambda_H}\right]$$

so

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

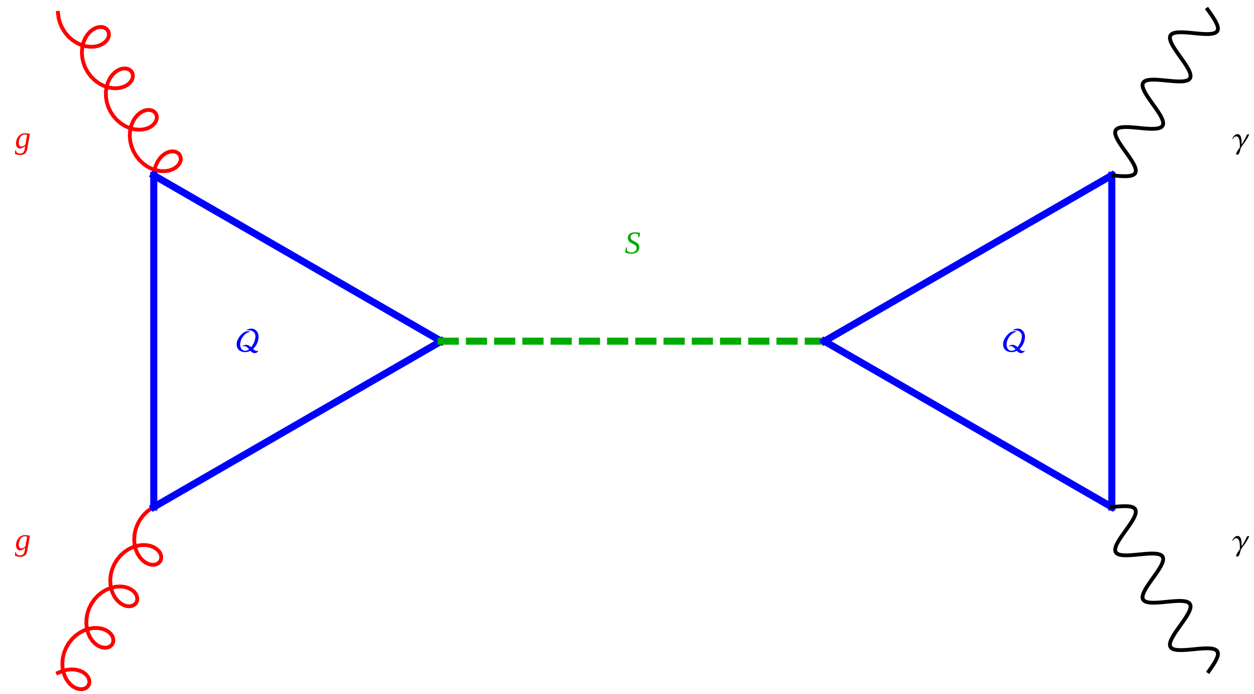
Bounds satisfied for $-0.3 < \Lambda_B/\Lambda_W < 2.5$

Models

VolksModell (the everybody's model)

The Sgg and $S\gamma\gamma$ operators can be generated if S couples to charged particles

$$S\bar{\mathcal{Q}}_f(y_f + i\, y_{5f}\gamma_5)\mathcal{Q}_f + S A_s \tilde{\mathcal{Q}}_s^* \tilde{\mathcal{Q}}_s$$



Extra fermions $\mathcal{Q}$ or scalars $\tilde{\mathcal{Q}}$ needed

SM loop excluded: the tree level decay would be too large e.g. $\dfrac{\Gamma_{t\bar{t}}}{\Gamma_{\gamma\gamma}} \approx 10^5$.

Can loops give the needed widths?

At one loop

$$\frac{\Gamma(S\to gg)}{M} \approx 7.2\times 10^{-5}\left|\sum_f I_{r_f} y_f \frac{M}{2M_f} + \sum_s I_{r_s}\frac{A_s M}{16 M_s^2}\right|^2$$

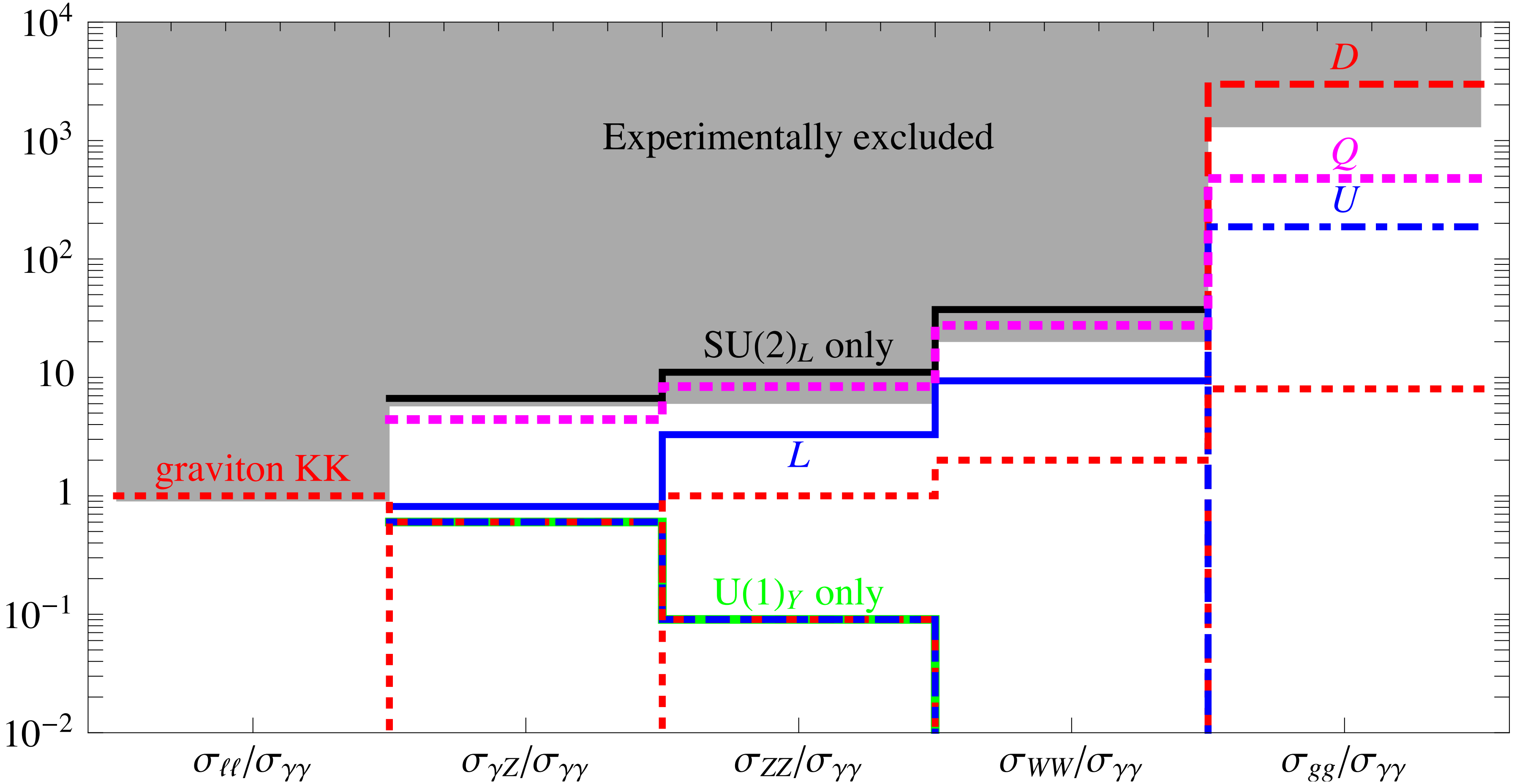
$$\frac{\Gamma(S\to \gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2\frac{A_s M}{16 M_s^2}\right|^2$$

- Loop decays cannot make a large total width $\Gamma/M \sim 0.06$ which is typical of a $1\to 2$ *tree level* decay with coupling $y\sim 1$.

- If Γ is large, data want $\Gamma(S\to\gamma\gamma) \gtrsim 10^{-4} M$, which again seems too large?

- If Γ is small, data want $\Gamma(S\to\gamma\gamma) \gtrsim 10^{-6} M$, which can be done. E.g. a H', with S and P splitted by $\Delta M = \lambda v^2/M = \lambda\times 40$ GeV (< 6 GeV in MSSM)

Good particles in the loop: L, E, U

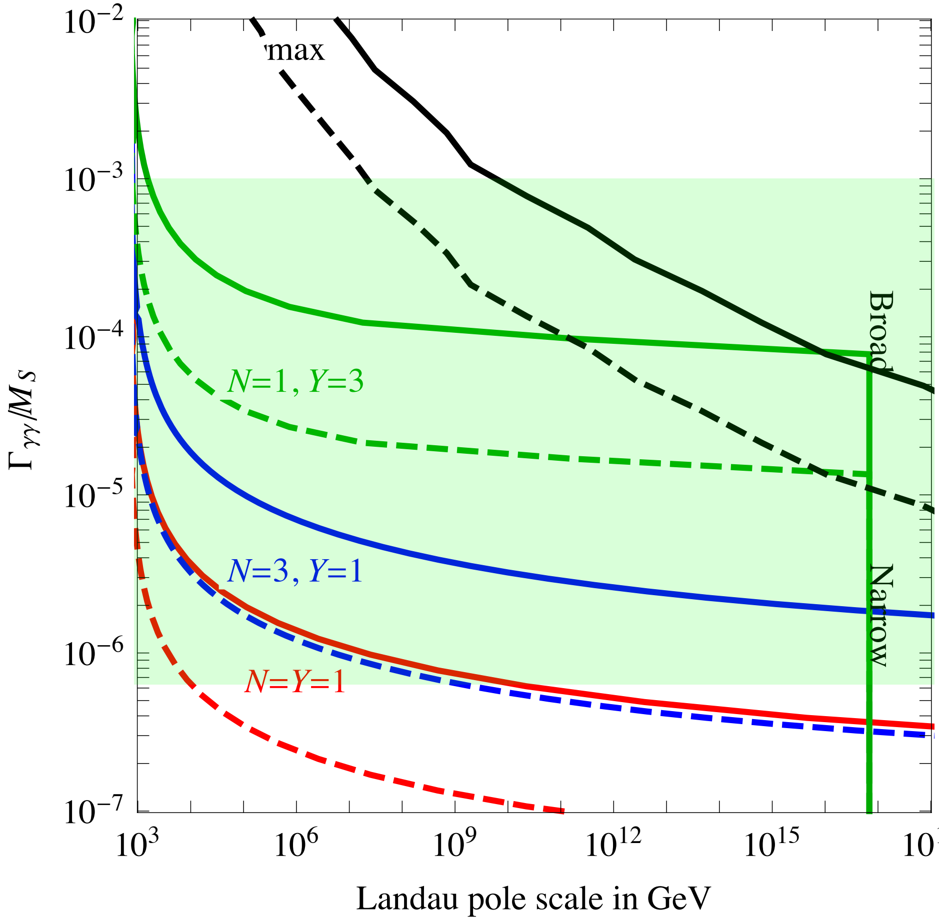


Large width ⇒ non-perturbativity

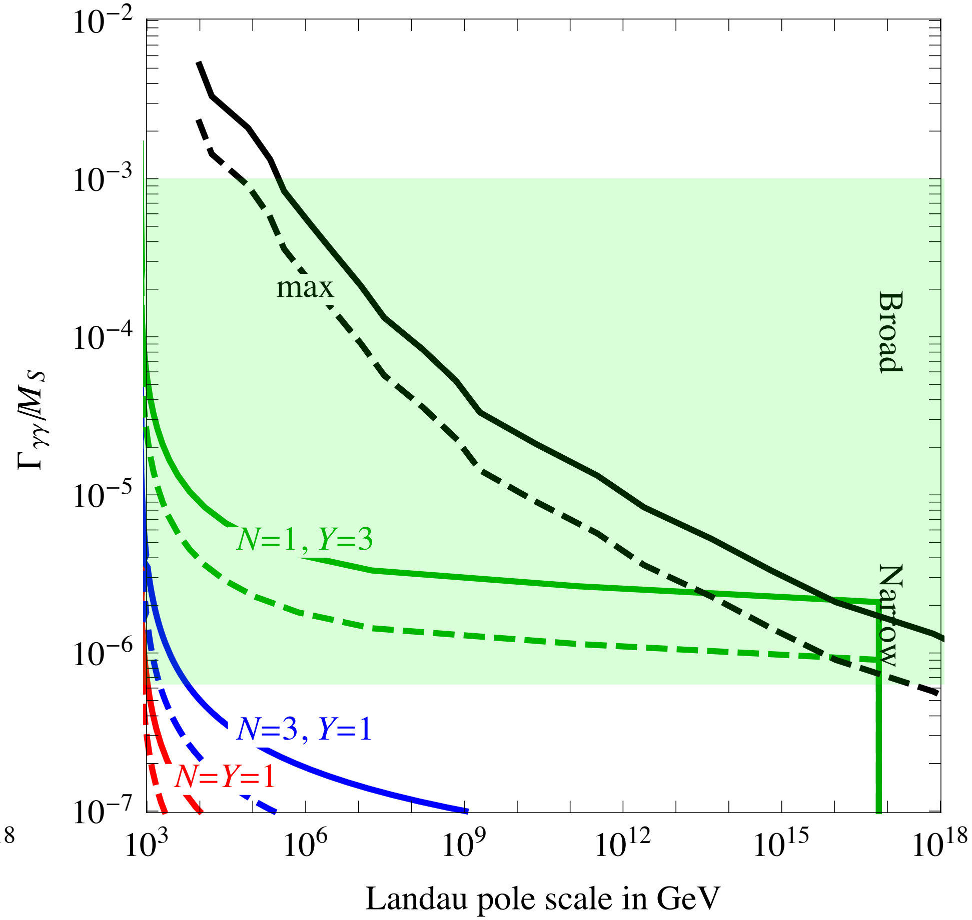
Enhance $\Gamma(S \to \gamma\gamma)$ with: a) many fermions; b) big Yukawa y; c) big charge.

In any case: nearby Landau poles for g_3 or e or y:

$\Gamma(S \to \gamma\gamma)$ from a fermion loop, $M_\psi = 375$ GeV



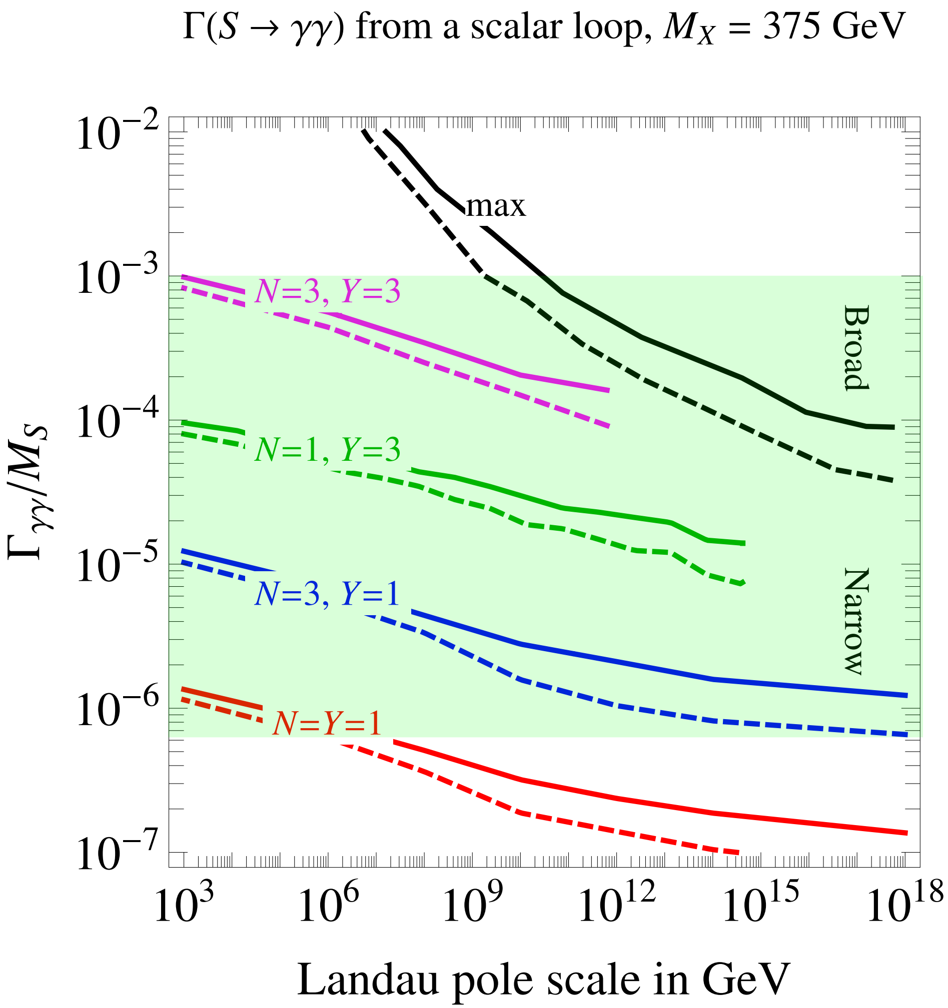
$\Gamma(S \to \gamma\gamma)$ from a fermion loop, $M_\psi = 1$ TeV

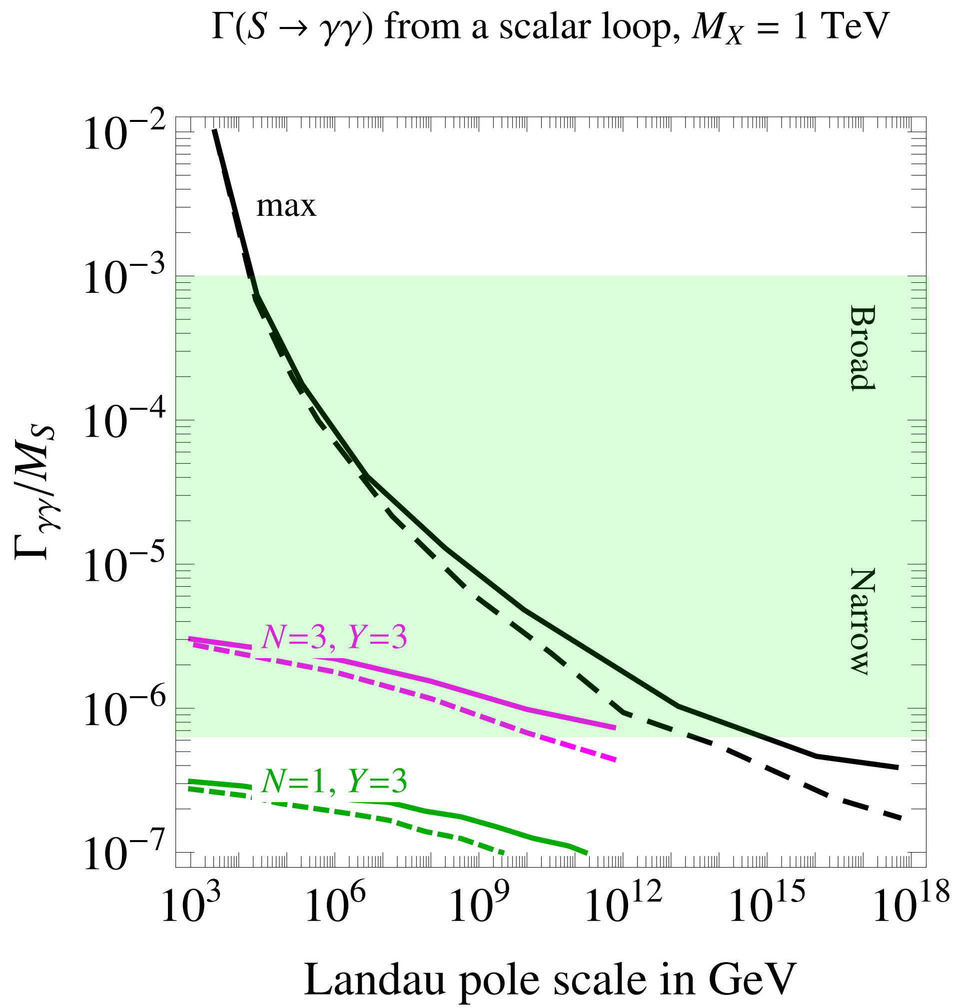


Much larger y and $\Gamma_{\gamma\gamma}$ if gauged SU(N) with IR fixed point. Then $pp \to SS$.

Similar results with extra scalars

A large cubic does not give Landau poles, but it is limited by vacuum decay.

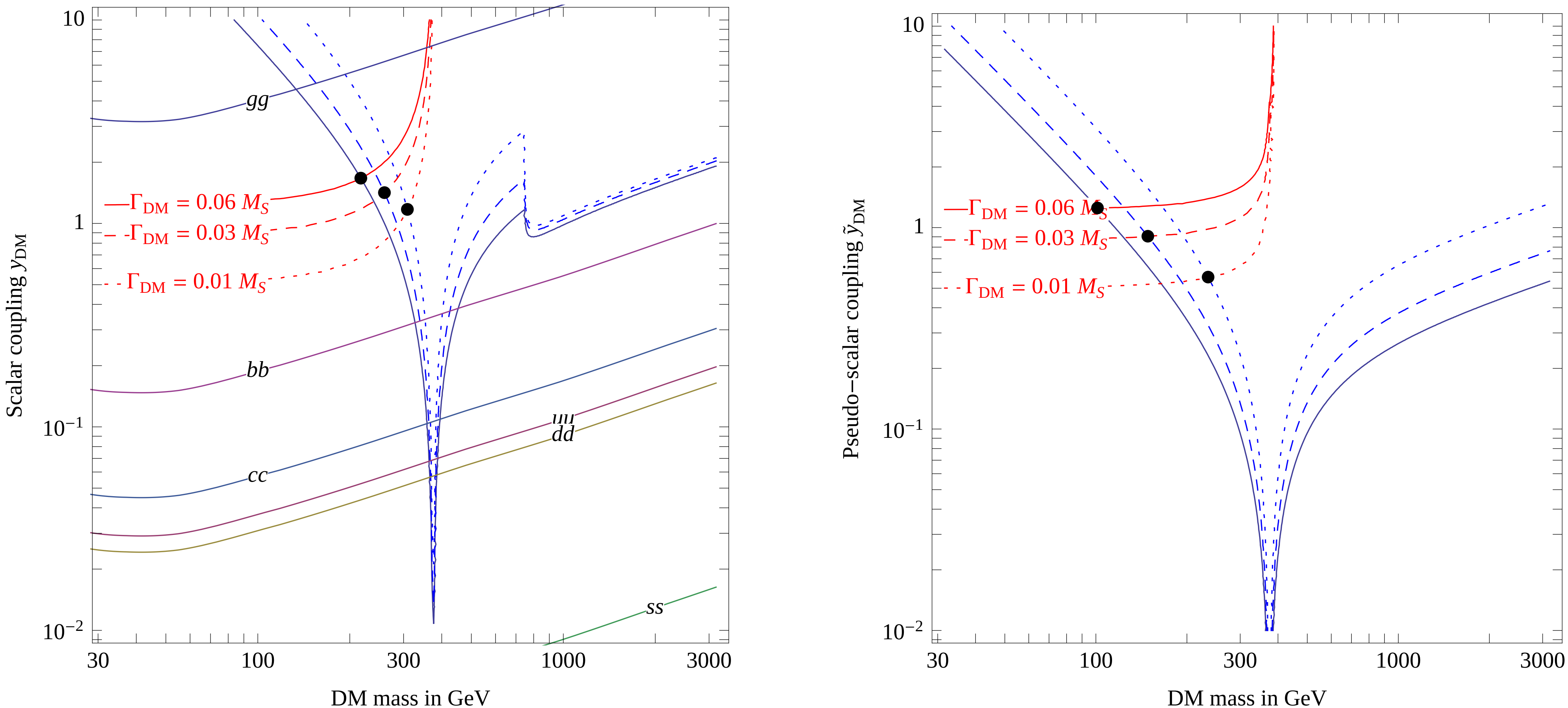




$\Gamma_{\gamma\gamma}$ can be much larger if gauged SU(N) with IR fixed point

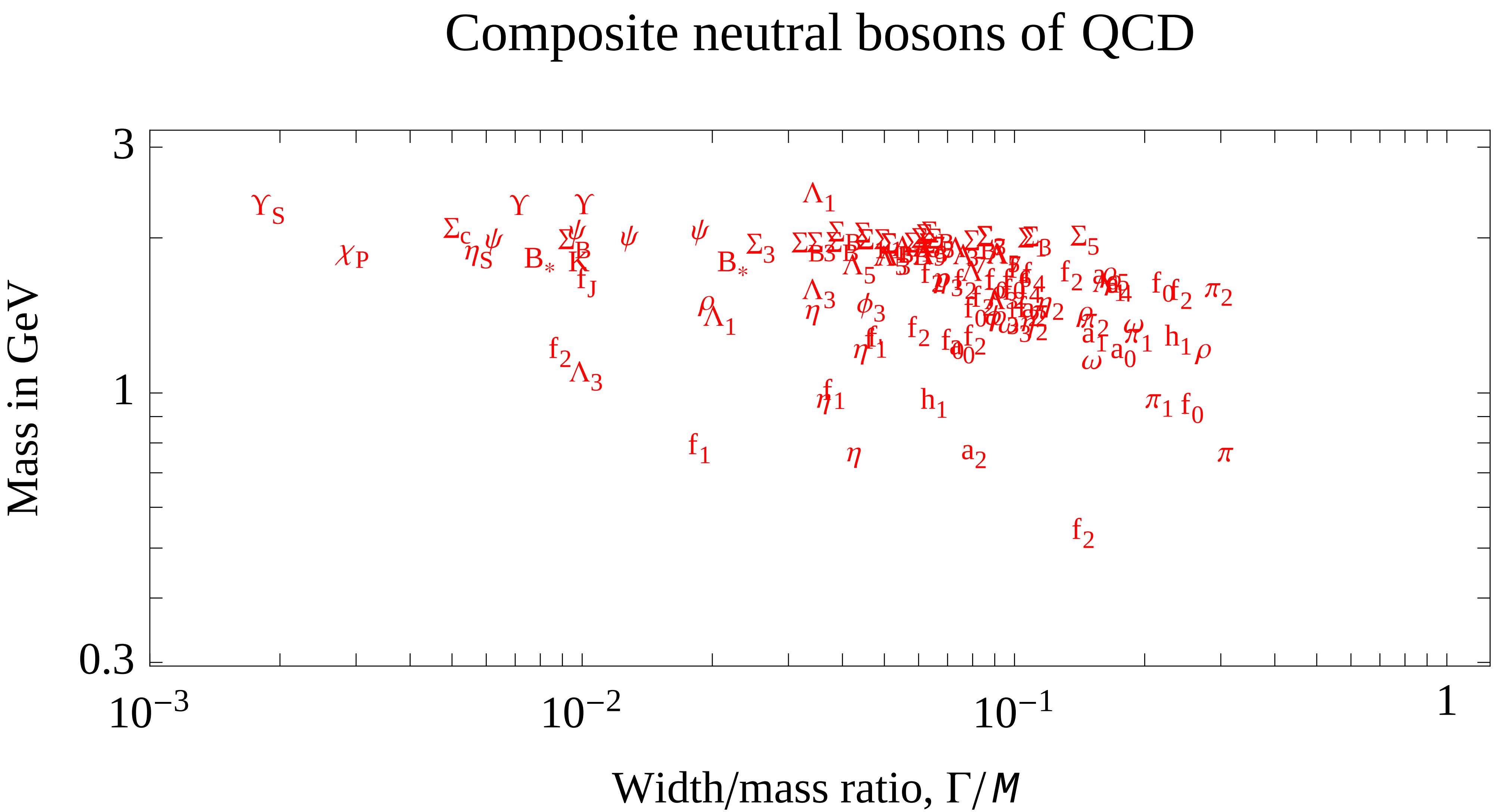
Extra $\mathcal{Q}$ = Dark Matter?

1) The connection with $\Omega_{\rm DM}$ is interesting on its own;
2) if $\Gamma/M \sim 0.06$ allows to hide many particles that enhance $S \to \gamma\gamma$;
3) if $\Gamma/M \sim 0.06$ allows to get tree level $S \to$ DM DM decays.



Direct detection bounds are (weak) irrelevant if S is a scalar (pseudo-scalar).

$\Gamma/M \sim 0.06$ is typical of QCD resonances



Strongly coupled models

Larger width natural. S could be:

1) a pseudo-scalar TCη or η';
2) a scalar mildly light being a (dirty) dilaton;
3) TC-charmonium resonances.

Main options:

Technicolor: SU(2)$_L$ broken by strong dynamics. Bonus/malus:

+ Simple UV-complete fundamental theories. E.g. extra fermions $\mathcal{Q}$ *chiral* under SU(2)$_L$ and charged under extra SU($N_{\rm TC}$) strong at $\Lambda_{\rm TC} \sim M_h$.
+ TCη' is a perfect 750 GeV candidate.
− All the rest is a problem: flavor, precision data, h: dead?

Francesco Sannino does not agree

Technidreams, partially composite H and S. Bonus/malus:

− Never born: postulates $\mathscr{L}_{\rm eff}$ that avoid problems, no fundamental theory.

If you think that this sentence is too strong, please show a strong dynamics that realises partial compositeness

+ Allows large width trough $S \to t\bar{t}$.
+ 750 GeV compatible with usual (fine-tuned) naturalness.

Composite S, elementary H and SM. Bonus/malus:

+ No problems, simple UV-complete fundamental theories. E.g. extra particles $\mathcal{Q}$ *non-chiral* under SM and extra strong SU($N_{\rm TC}$).
+ Dark Matter could be a stable TCπ, and S could decay into it.
+ 750 GeV could source $M_h \sim {\rm loop} \times \Lambda_{\rm TC}$ in modified naturalness?

A composite model

Over-ambitious model: extra SU($N_{\rm TC}$) with $\mathcal{Q} = N_1 \oplus N_2 \oplus U$ and $\theta_{\rm TC}$.

$$\text{TC}\pi = \underbrace{(8,1)_0}_{\chi \sim U\bar{U}} \oplus \underbrace{2 \times [(\bar{3},1)_{-2/3} + (3,1)_{2/3}]}_{\phi_i \sim U\bar{N}_i,\ \phi_i^*} \oplus \underbrace{4 \times (1,1)_0}_{\Pi \sim N_1\bar{N}_2,\ \Pi^*,\ \eta_{1,2}}$$

Pseudo-scalars η with couplings to $G\tilde{G}, W\tilde{W}, B\tilde{B}$ predicted by anomalies:
$\eta_2 \sim N_1\bar{N}_1 - N_2\bar{N}_2$, $\eta_1 \sim N_i\bar{N}_i - \frac{3}{2}U\bar{U}$, $\eta' \sim \mathcal{Q}\bar{\mathcal{Q}}$ up to mixings $\propto m_{N_1} - m_{N_2}$.

TCπ masses in terms of $B_0 \sim \Lambda_{\rm TC}$ for TC$\mathcal{Q}$ masses $\Lambda_{\rm TC} \sim m_U > \frac{7}{2} m_{N_{1,2}}$

$$\begin{array}{rll} \text{DM}: & m_\Pi^2 = B_0(m_{N_1} + m_{N_2}), & \\ 750\text{ GeV } S: & m_{\eta_1}^2 \approx \frac{4}{5} B_0 m_U & m_{\eta'} \sim \Lambda_{\rm TC} \qquad m_{\eta_2} \lesssim m_\Pi \\ \text{Extra colored}: & m_\chi^2 = 2B_0 m_U + \Delta_\chi & m_{\phi_i}^2 = B_0(m_U + m_{N_i}) + \Delta_\phi, \end{array}$$

S can $\not{C}$P decay to DM, $\Gamma(\eta_1 \to \Pi\Pi^*) \sim$ GeV $\times\, \theta_{\rm TC}^2 < 45$ GeV.
DM abundance, direct detection: ok. Lightest TCbaryon $N_{1,2}^{N_{\rm TC}}$ can be DM$'$.

Predictive! Look for extra resonances

Theories


Ferrari 125


Ferrari 750
MONZA SCAGLIETTI 1955
MILLE MIGLIA 2014

The Big Picture

'Who ordered that?' 20th particle, 2nd massive parameter?
Naturalness? Will it kill anthropics? Too joung to tell what it will become.

If broad, new strong dynamics: theory can be predictive.

If narrow, just add weakly coupled extra scalar and extra charged states.

SUSY: S could be H, A, $\tilde{\nu}$, NMSSM, sgoldstinos + sparticles in the loop...

Extra dimensional radion or graviton.

String models often have extra states.

Unification could give extra light multiplets.

Extended gauge group can imply extra chiral fermions, need extra scalars:

G	extra ψ	diphoton	diboson
$\mathrm{SU}(3)_L \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_c$	L, D	yes	no
$\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$	L, D	yes	yes
$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_c$	–	ad hoc	yes

What next?

Significant progress soon

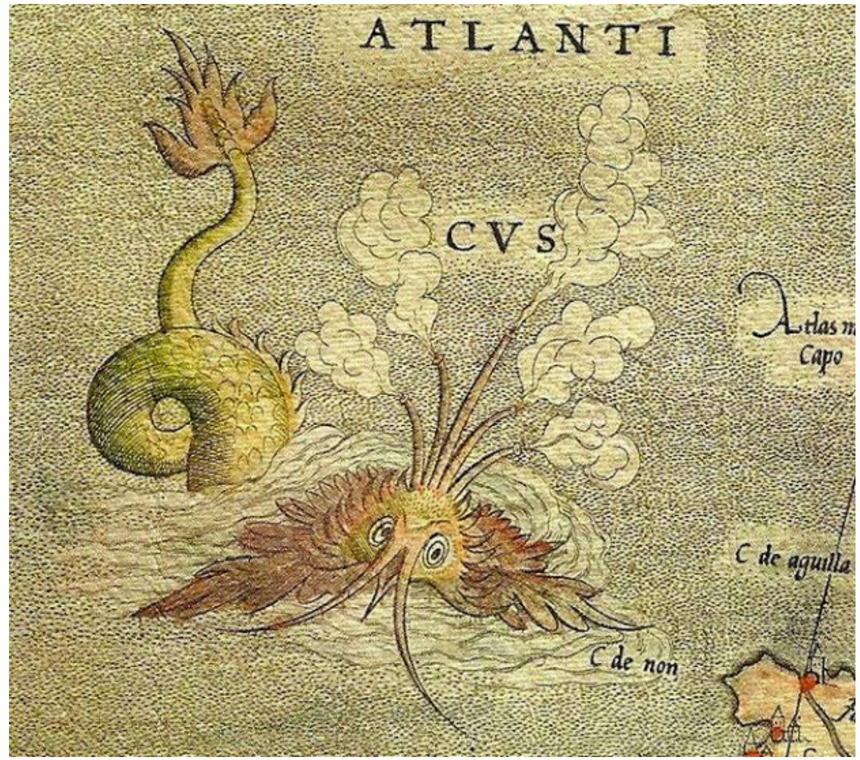
Warnings

A 750 GeV $\gamma\gamma$ peak reminds the 125 GeV $\gamma\gamma$ peak. But $H \neq S$:
(circumnavigating Elba island) $\neq$ (going beyond Hercules pillars)

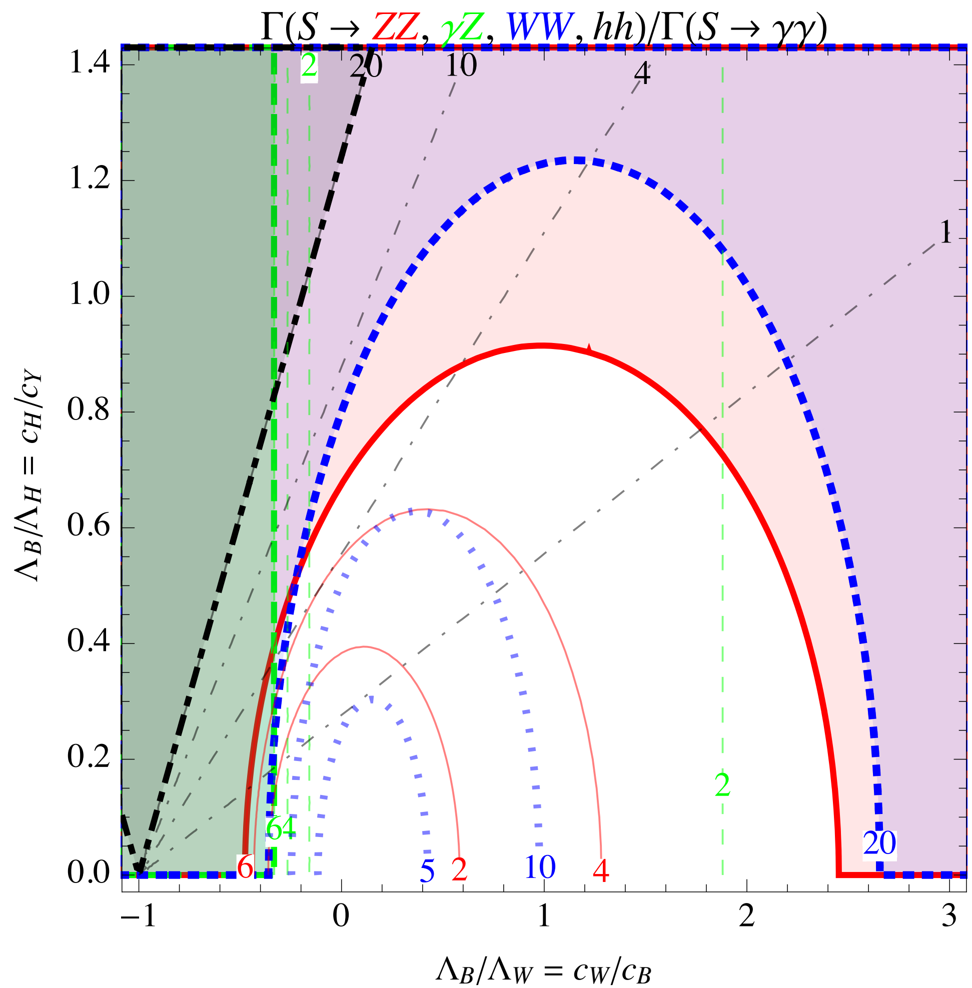
H: SM NNNLO predictions $\Rightarrow$ neural network analyses of issues 'with the same potential for surprises as Brasil-Tonga'.

S: deep sea, all issues open $\Rightarrow$ I will focus on VolksModel@LHC just not to get lost in a plethora of possibilities. But

VM $\neq$ SM.



More decay channels



1. $S \to ZZ, \gamma Z$: a must implied by $S \to \gamma\gamma$.
2. $S \to W^+W^-$ (or correlations of 1) would tell that $SU(2)_L$ is involved.
3. $S \to hh$ (or correlations of 1,2) would tell that H is involved.
4. $S \to t\bar{t}, b\bar{b}, \ldots$ DM, ? would point to different directions.

Confirm spin 0 or exclude spin 2,3...

(The speaker is biased, and data too...)

Randall-Sundrum graviton could fit with $\Lambda \sim 60\,\text{TeV}$ predicting $\Gamma/M \sim 10^{-5}$.

But the graviton is already disfavoured because it predicts

$$\sigma(pp \to e^+e^- + \mu^+\mu^-) = \sigma(pp \to \gamma\gamma)$$

and no peaks seen in leptons, $\sigma(pp \to \ell^+\ell^-) < 5\,\text{fb}$ (ATLAS) and $\lesssim 3\,\text{fb}$ (CMS).

Spin 2 can be resurrected by assuming that it couples more to γ than to ℓ.
But this would give bad $1/M_S^4$ terms: only the universal $T_{\mu\nu}$ is conserved.
The zombie could even be CP-odd: discriminate with $\Delta\eta_\gamma$ and $50\,\text{fb}^{-1}$.

Which initial state?

$S\gamma\gamma$ is already disfavoured by σ_{13}/σ_8.

Sgg gives more jets than $Sq\bar{q}$, test measuring the transverse momentum of S:

$$\frac{\sigma(20\,\text{GeV} < p_T^S < 40\,\text{GeV})}{\sigma(p_T^S < 20\,\text{GeV})} = \begin{cases} 1.4 & gg \\ 0.6 & q\bar{q} \\ \sim 1.1 & b\bar{b} \end{cases}$$

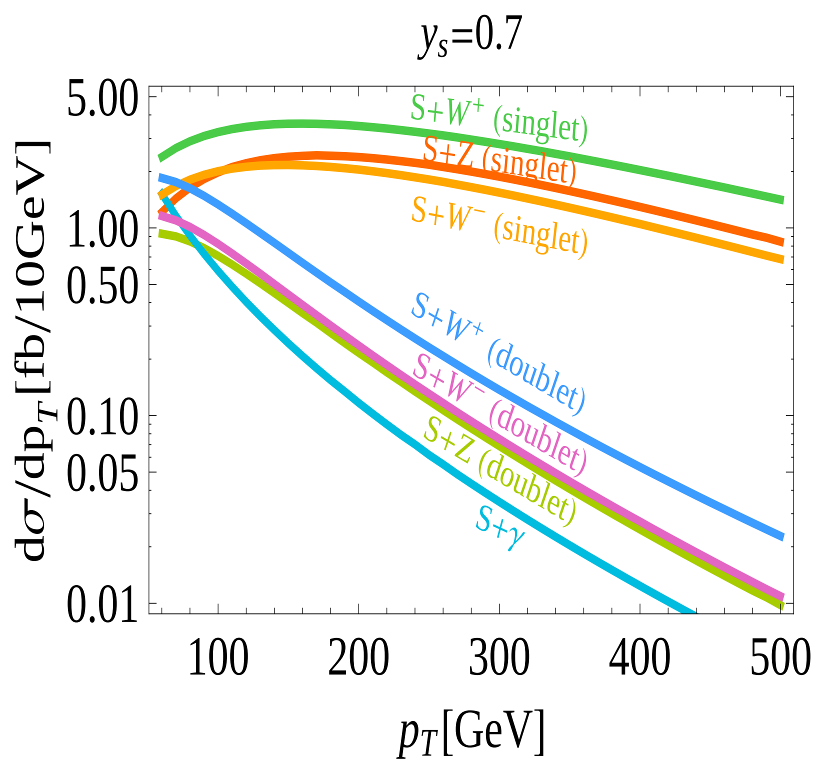
$Sb\bar{b}$ gives extra b jets.

Related issue: ***S* is singlet or doublet or...?**
Normally:

- if dominantly coupled to gg it's a singlet;
- if dominantly coupled to $q\bar{q}$ it's a doublet.

Abnormalities can be tested:

- ○ singlet coupled to $q\bar{q}$ gives hard $q\bar{q} \to SV_L$
- ○ doublet coupled to gg gives hard $gg \to SV_LV_L$



Scalar or pseudo-scalar?

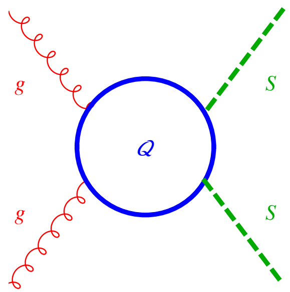
How to measure the CP-parity of S (or discover that CP is violated):

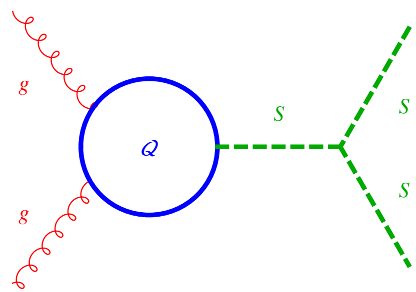
Technique	Problems
measure $S \to \gamma^*\gamma^* \to 4\ell$	$\Gamma_{4\ell}/\Gamma_{\gamma\gamma} \approx 10^{-3}$
measure $S \to \gamma\gamma \to 4\ell$ in matter	Small e^+e^- angle
measure $pp \to Sjj$	$\sigma_{Sjj}/\sigma_S = 0.04$
observe $S \to hh$	Shh exists?
measure $S \to ZZ \to 4\ell$	SZZ exists*?
measure $pp \to Z \to SZ$	SZZ exists*?
measure $S \to Z\gamma^{(*)} \to 4\ell$	$SZ\gamma$ exists?

$$* \quad \sigma(pp \to SZ) = 1.7\,\text{pb}\,\frac{\Gamma_{ZZ}}{M} \pm 0.66\,\text{pb}\,\frac{\sqrt{\Gamma_{ZZ}\Gamma_{\gamma Z}}}{M} + 0.53\,\text{pb}\,\frac{\Gamma_{\gamma Z}}{M}$$

Double S production

Can be sizeable, especially if strong interactions $y \sim 4\pi$. The VM predicts

$\sigma(pp \to SS) \sim$ 

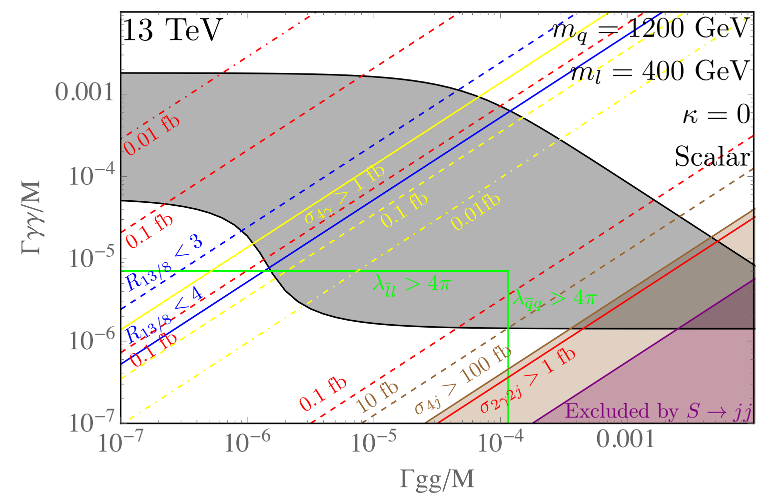


$\sim \left(\frac{yM_S}{4\pi M_{\mathcal{Q}}} + \frac{\kappa}{4\pi M_S}\right)^2 \sigma(pp \to S)$

In the limit $M_{\mathcal{Q}} \gg M_S$ the 'low energy theorem' provides an exact generic result for the Yukawa effect:

$$\mathscr{L}_{\text{eff}} = \frac{\alpha_3 IN}{6\pi} G^2_{\mu\nu} \ln(1 + \frac{S}{f_S}) \qquad \frac{1}{f_S} \equiv \frac{y}{M_{\mathcal{Q}}}$$

Signals: $pp \to SS \to jjjj, jj\gamma\gamma, \gamma\gamma\gamma\gamma$



[to appear, done by collaborators]

Extra fermions or scalars

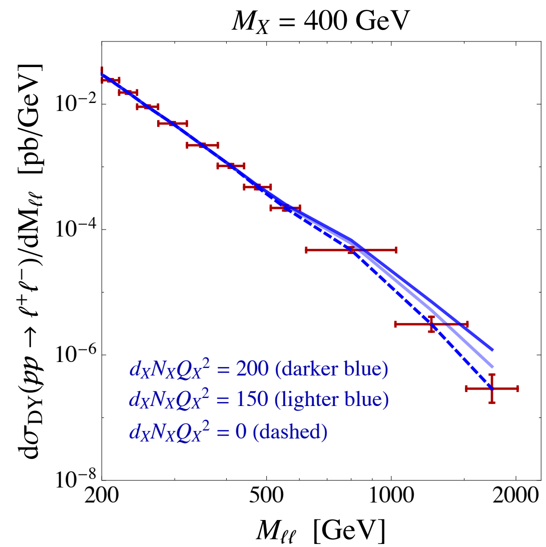
A) Discover $\mathcal{Q}$ at LHC (some anomalies...).

LHC can miss DM multiplets, especially if quasi degenerate (soft tag). Then:

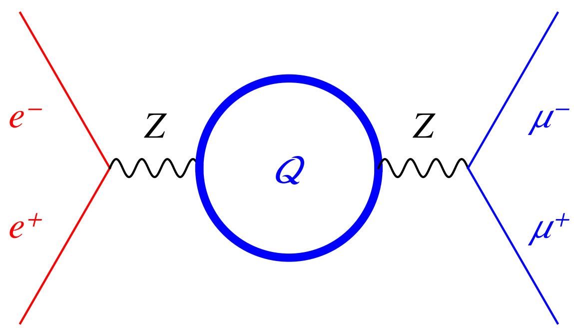
B) High-energy tails of

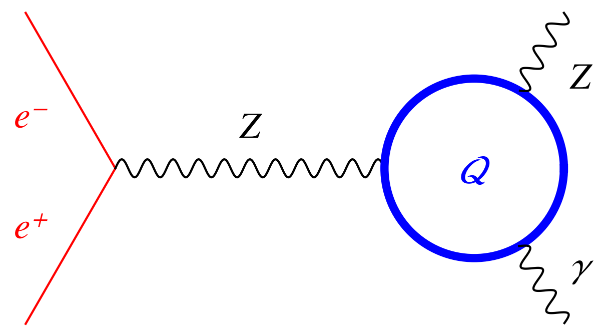
$$\sigma(pp \to \ell^+\ell^-) \propto g^4(\bar{\mu} \sim m_{\ell\ell})$$

sensitive to Δb (BSM running of g_Y, g_2). 8 TeV:



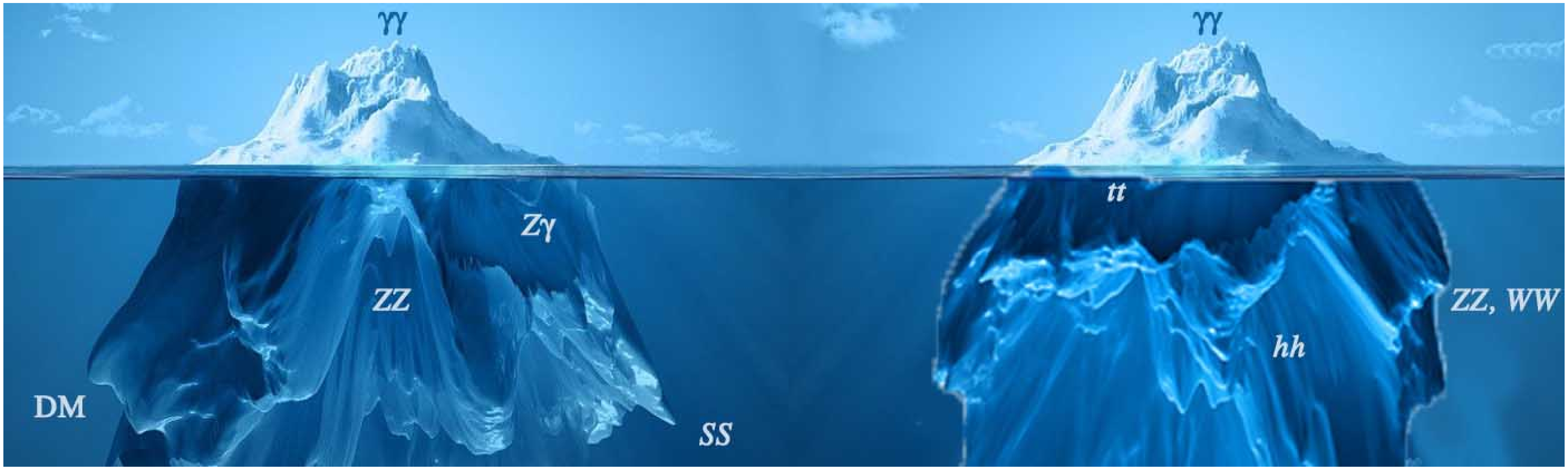
C) e^+e^- collider: even if $\mathcal{Q}$ is too heavy, it could be probed indirectly as W, Y...





Conclusions

- $\gamma\gamma$@750 should be accompanied by $\gamma Z, ZZ$@750 and by new particles.
- A large $\Gamma/M \sim 0.06$ would point to new strong interactions.
- Finding simple reasonable models is (too) easy. A jungle of options:



Narrow or broad? Spin 0 or 2 or...? Singlet or doublet or...? Scalar or pseudo or $\not{C}$P ? Elementary or composite? A cousin of H or not? [...] Real or not?

Today it could be everything, including nothing. In july we will know.

If real, new data (width, $pp \to jS$, $S \to ZZ, \gamma Z$, ...) will kill models, after the massacre the right theory and its fundamental meaning will emerge.