S(750) and FCCee

Fitting the $\gamma\gamma$ peak:
1) Widths
2) Models
3) Theories
4) What next?

Alessandro Strumia
talk at the 10th FCC-ee physics workshop
CERN, February 5, 2016

European Commission
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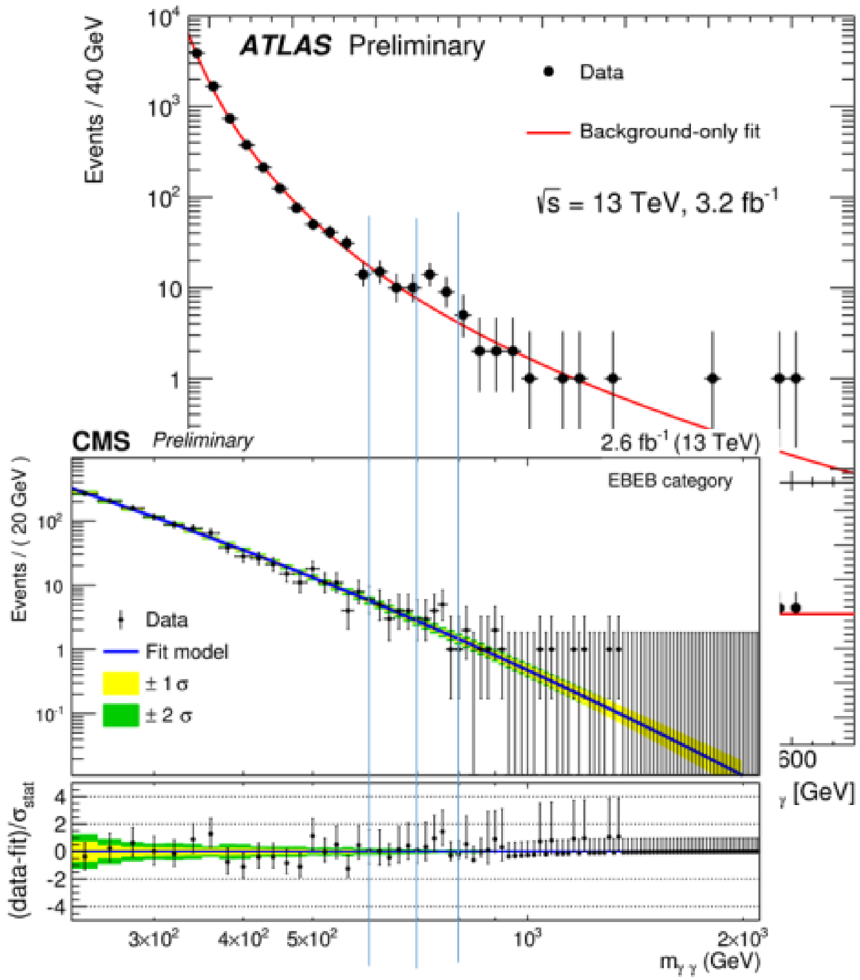
The data



Flatland plus a $\gamma\gamma$ peak around 750 GeV

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

Theorethically clean

Experimentally simple

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

CMS prefers narrow width.

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

Full energy distribution? Angular distribution? Full events?

Needless to say

Maybe a fluke.
Gold does not come to you spontaneously.

The Gold Rush

INSPIRES list

Date	papers
16 Dec	10
19 Dec	46
25 Dec	101
1 Jan	137
1 Feb	212
1 Apr	?

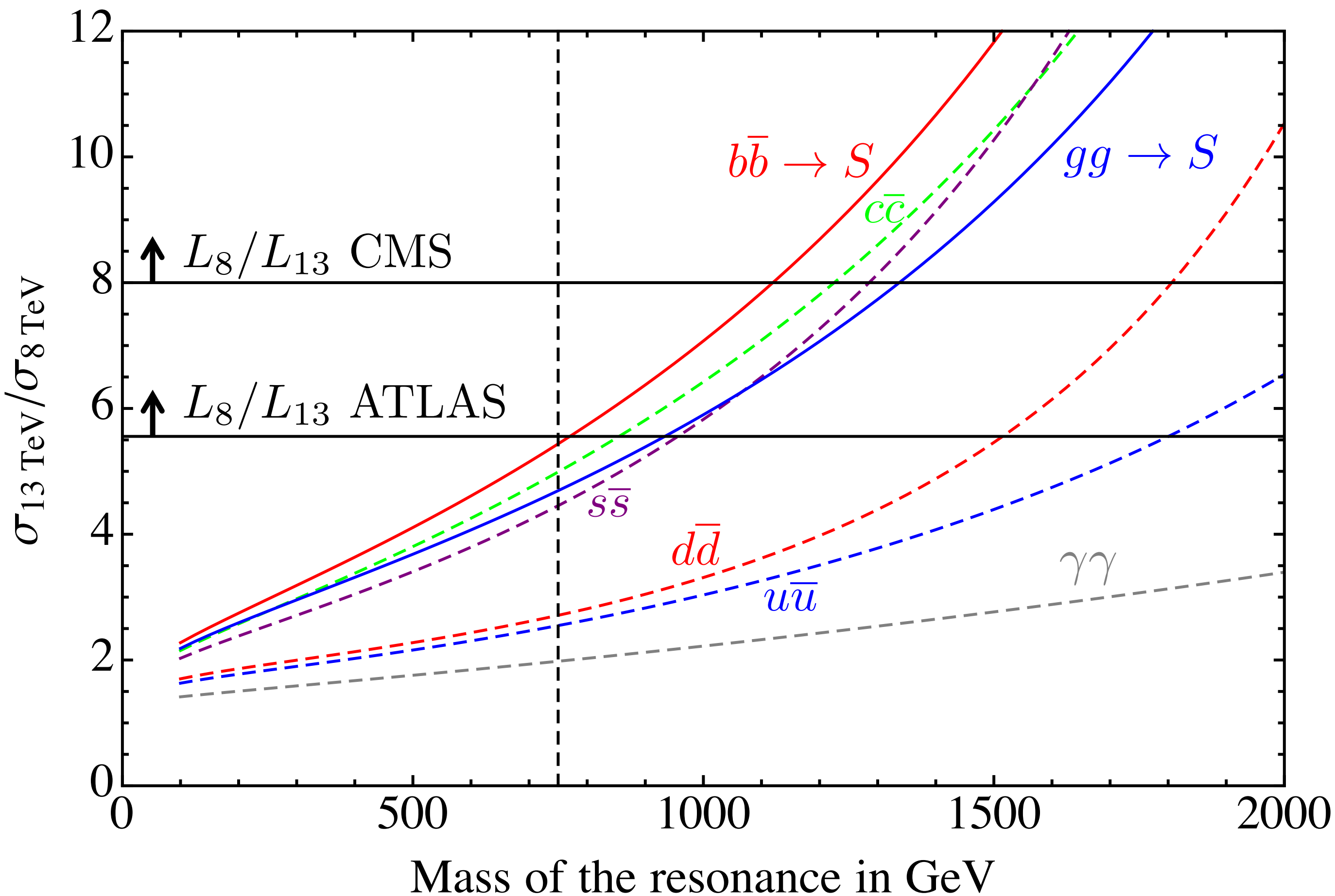
All that is gold does not glitter

physics = experiment + i theory

It's time to present a review of the new boson.

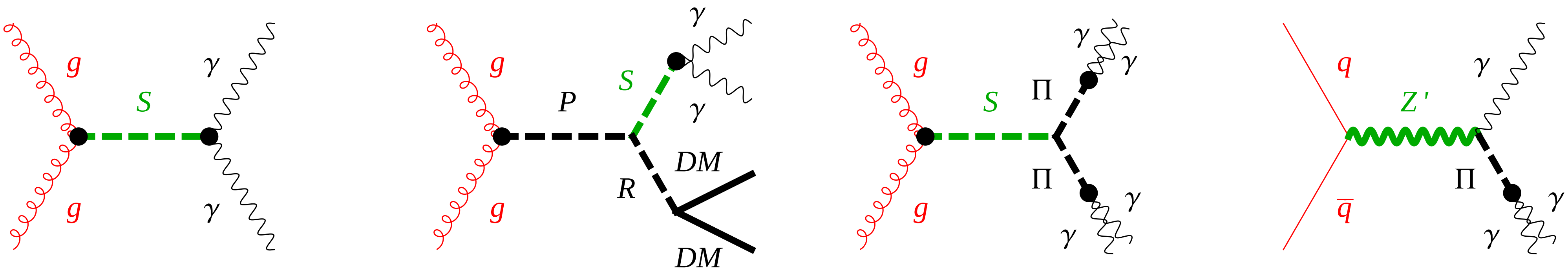
A new boson at 750 GeV?

Run 1 compatible with Run 2 if S is produced as gg, $b\bar{b}$, $c\bar{c}$, $s\bar{s}$.
The SM background $q\bar{q} \to \gamma\gamma$ at 750 GeV grows only by 2.3



A more complicated kinematics?

Compatibility between runs 1, 2 improved if S decays from a heavier particle.



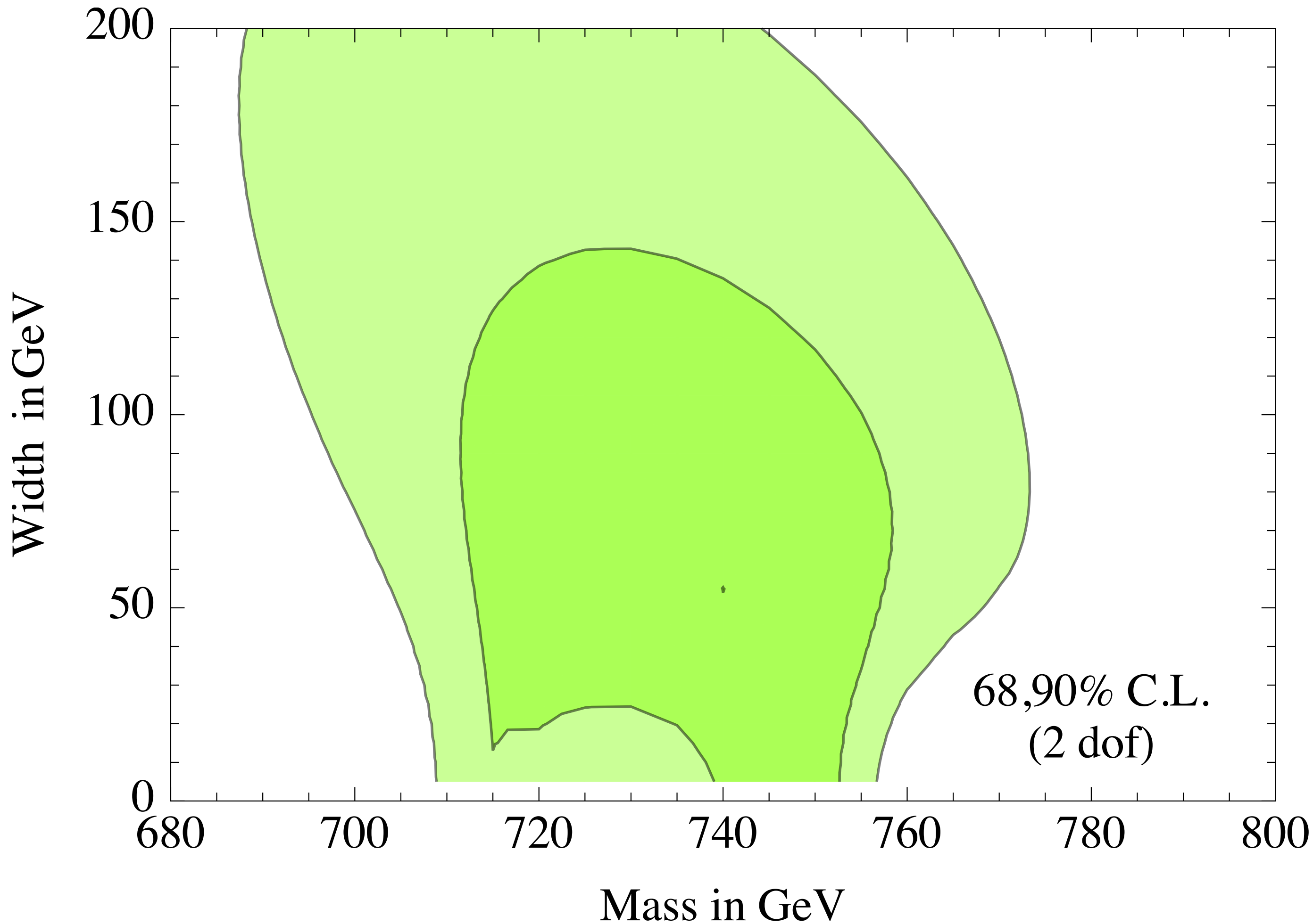
Tuning $M_P \approx M_S + M_R$ needed to avoid $\not{p}_T$. S virtuality can fake S width.

Or large $S \to \Pi\Pi$ with $\Pi \to \gamma\gamma$, collimated and seen as a single γ if $M_\Pi \ll M_S$.

Or many collimated γ. Or not a peak. Or two nearby narrow resonances.

Widths

M and Γ from data



Apology: public ATLAS data only

Cross section

It can be computed in terms of (narrow) widths:

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

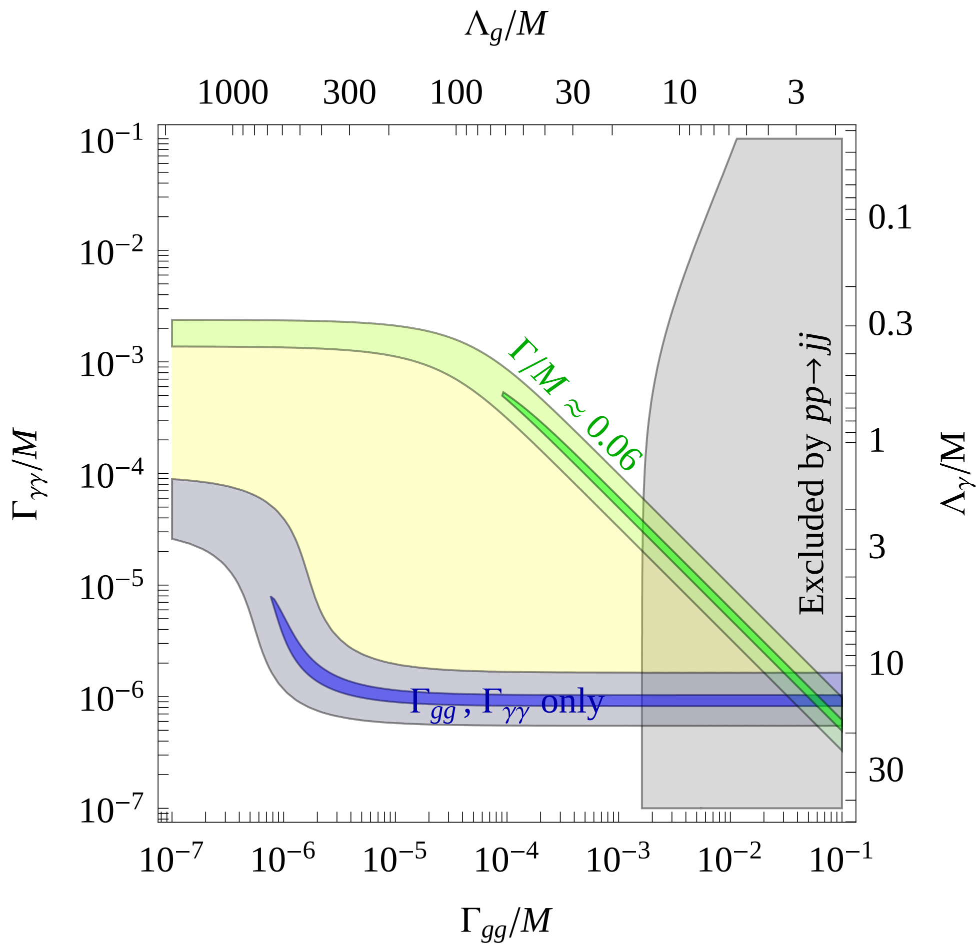
Parton $\wp$ luminiosities:

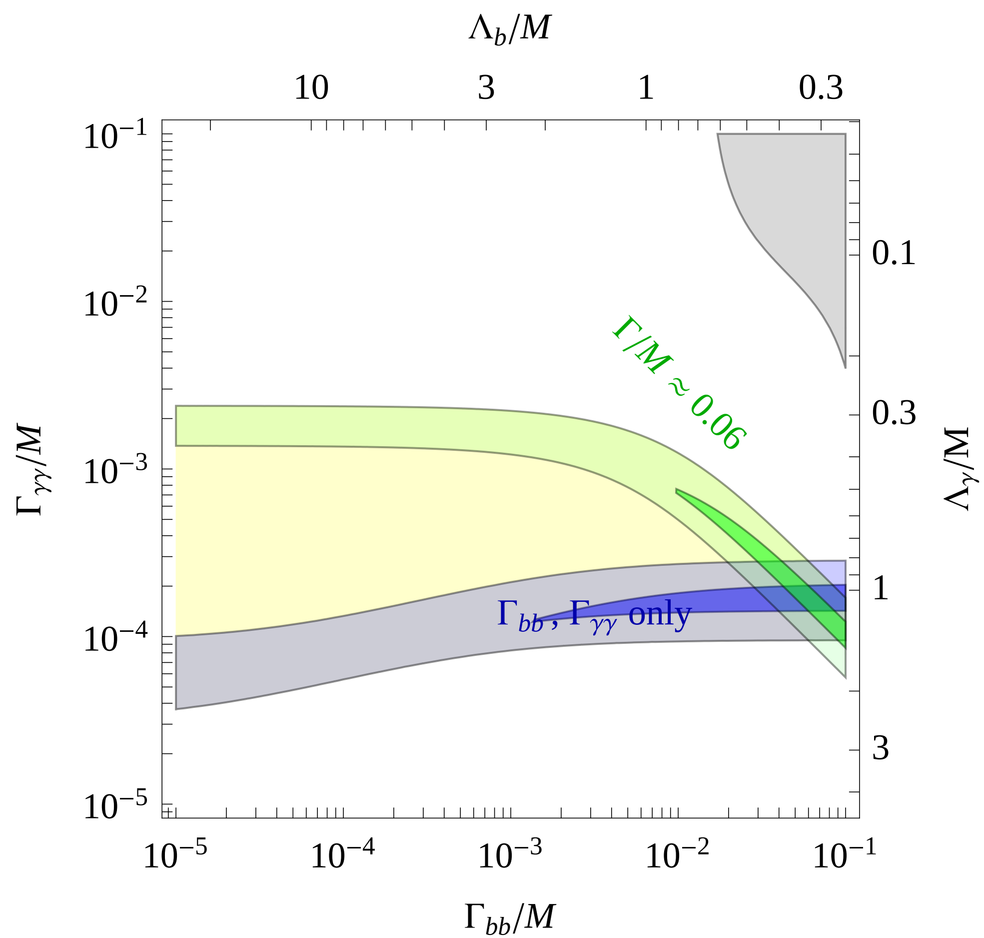
$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}	$C_{\gamma\gamma}$
8 TeV	1.07	2.7	7.2	89	158	174	54
13 TeV	15.3	36	83	627	1054	2137	11

(Partonic $\gamma\gamma \to S \to \gamma\gamma$ would be minimal but run1/run2 compatibility is poor).

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

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





$S \leftrightarrow \gamma\gamma, gg, ?$

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

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 $(r/5)$

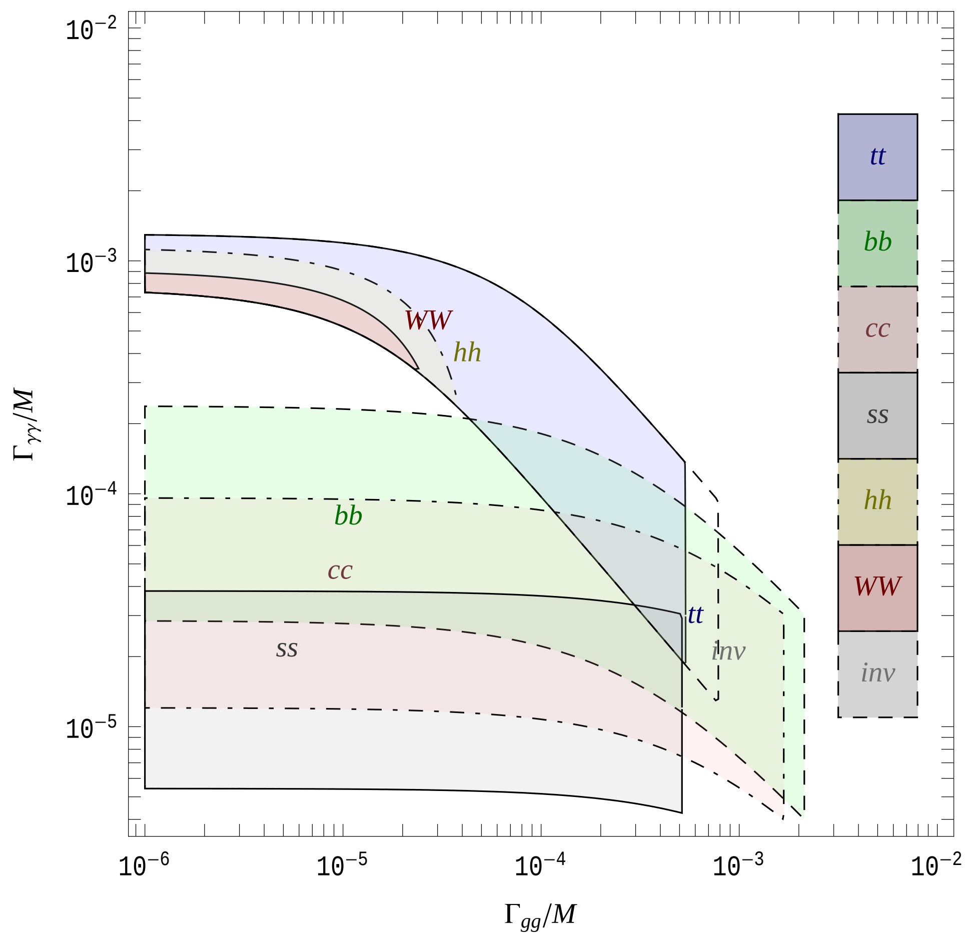
Here $r = \sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}$. Using run 2 data only would be safer. Run 2 jj?

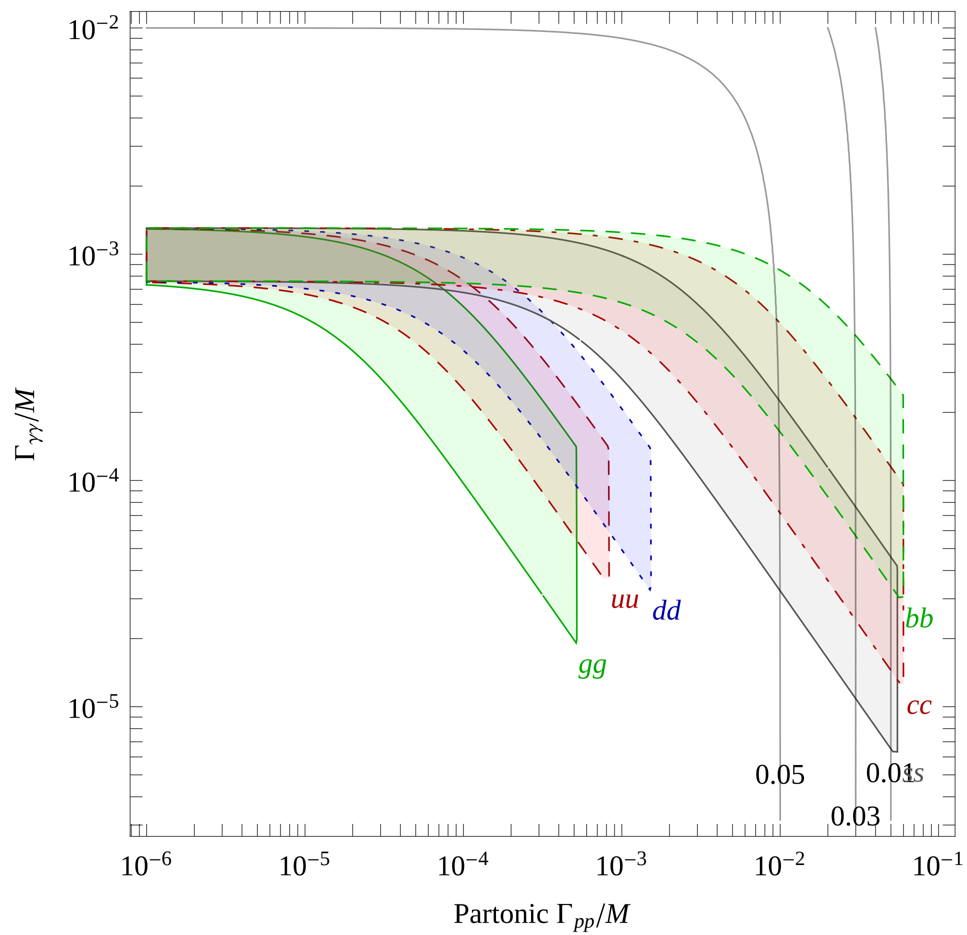
Even invisible modes are constrained

Global fits

Regions that fit the rate, the width $\Gamma/M \sim 0.06$ and that satisfy all bounds:

$S \leftrightarrow gg, \gamma\gamma, X$ $\qquad$ $S \leftrightarrow \wp\wp, \gamma\gamma$, invisible





$\Gamma(S \to \gamma\gamma)/M \gtrsim$ few $\times 10^{-5}$ needed: it's big!

Spin 2?

$S_{\mu\nu}$ coupled to the various components $T^{(p)}_{\mu\nu}$ of the energy-momentum tensor:

$$\mathscr{L}_{\text{eff}} = S^{\mu\nu} \sum_{p=\{\gamma,g,\ell,\dots\}} \frac{T^{(p)}_{\mu\nu}}{\Lambda_p}$$

The width into photons can be large. Angular distributions: not flat.

Randall-Sundrum graviton disfavored: it predicts a common Λ such that

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

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

Spin 0: SU(2)$_L$ singlet or doublet?

S as a doublet: coupling to $\gamma\gamma$ and gg suppressed by $v/M \sim 0.2$.

S as a singlet: coupling to SM fermions suppressed by $v/M \sim 0.2$:

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

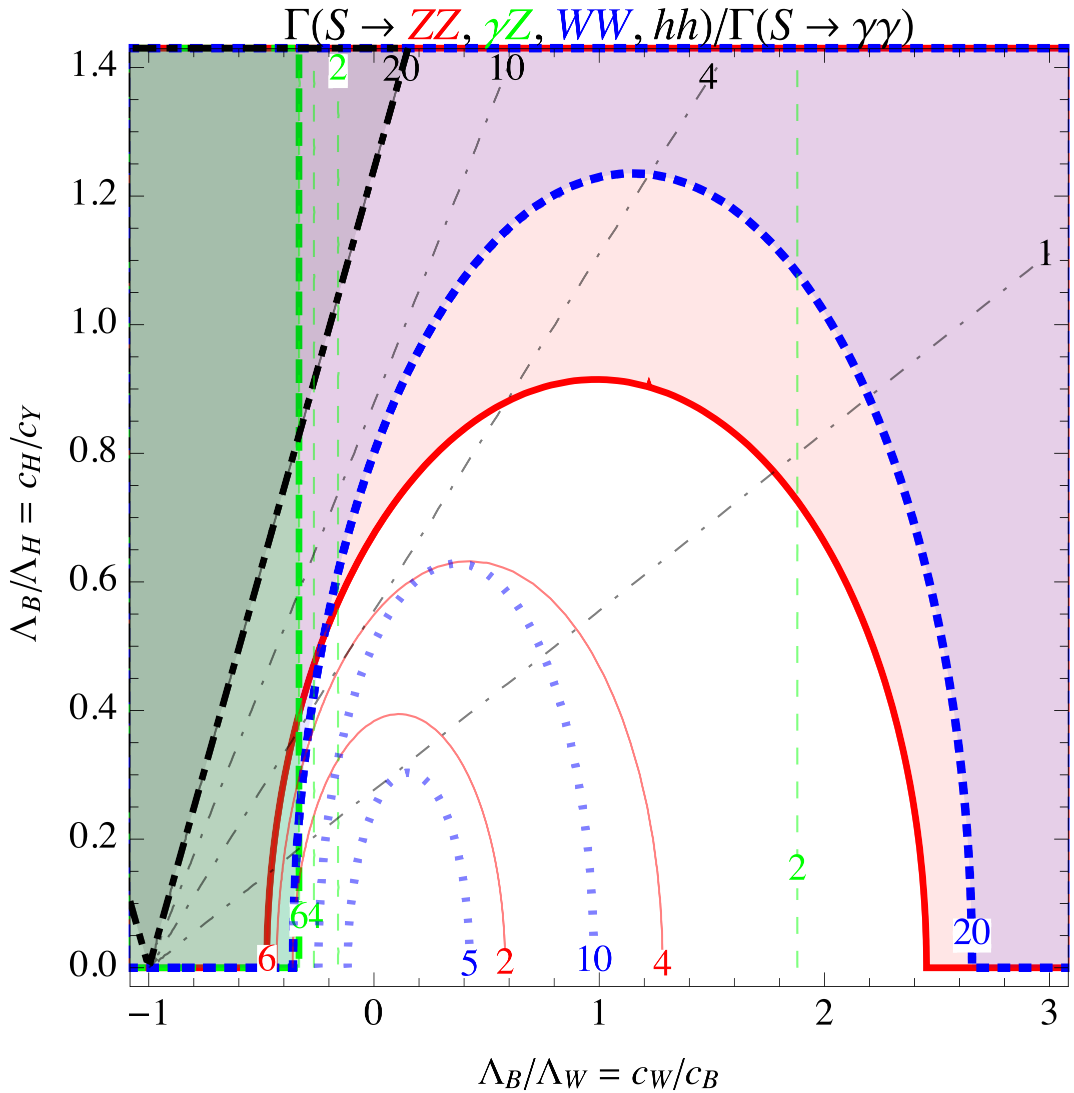
SU(2)-invariance implies $S \to Z\gamma, ZZ, WW$ nearby

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	$2/\tan^2\theta_{\rm W} \approx 7$	$1/\tan^4\theta_{\rm W} \approx 12$	$2/\sin^4\theta_{\rm W} \approx 40$
BB only	$2\tan^2\theta_{\rm W} \approx 0.6$	$\tan^4\theta_{\rm W} \approx 0.08$	0

Bounds satisfied for $-0.2 < \Lambda_B/\Lambda_{\rm W} < 2.5$

Future

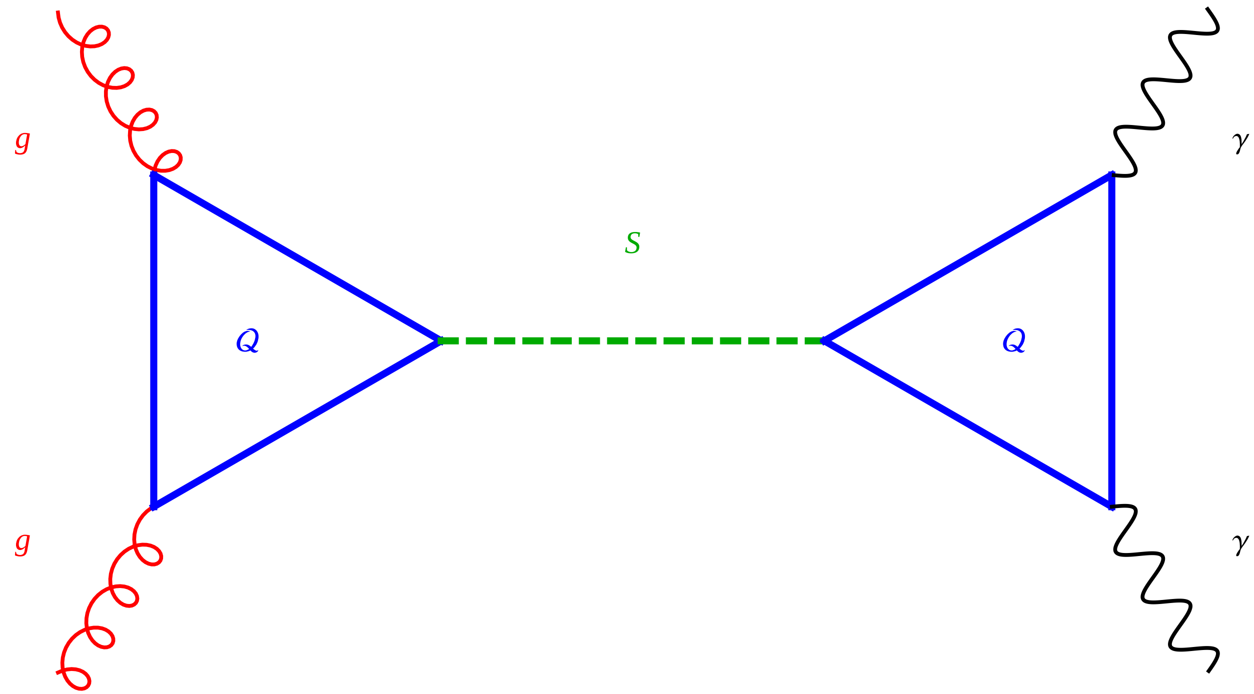
Measuring the EW widths will over-constrain the operators



and maybe discover coupling to h

Models

Volksmodell (the everybody's model)



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

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

More particles needed

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

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

At one loop

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

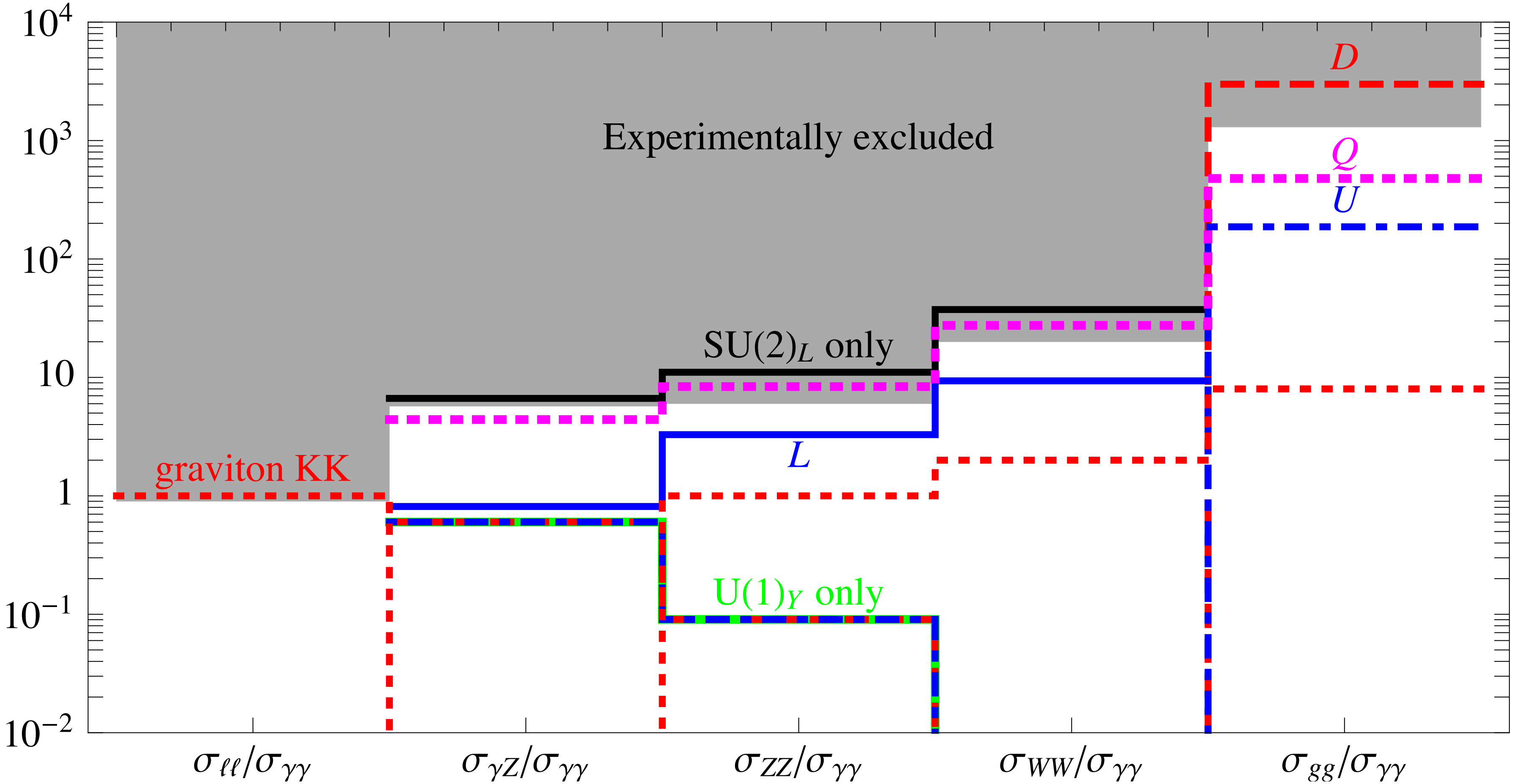
$$\frac{\Gamma(S\to \gamma\gamma)}{M} \approx 5.4\times 10^{-8}\left|\sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2\frac{A_s M}{16 M_s^2}\right|^2,$$

- Such loop processes cannot make $\Gamma/M \sim 0.06$.
  The large width is typical of a $1\to 2$ tree level decay with coupling $y\sim 1$.

- 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)

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

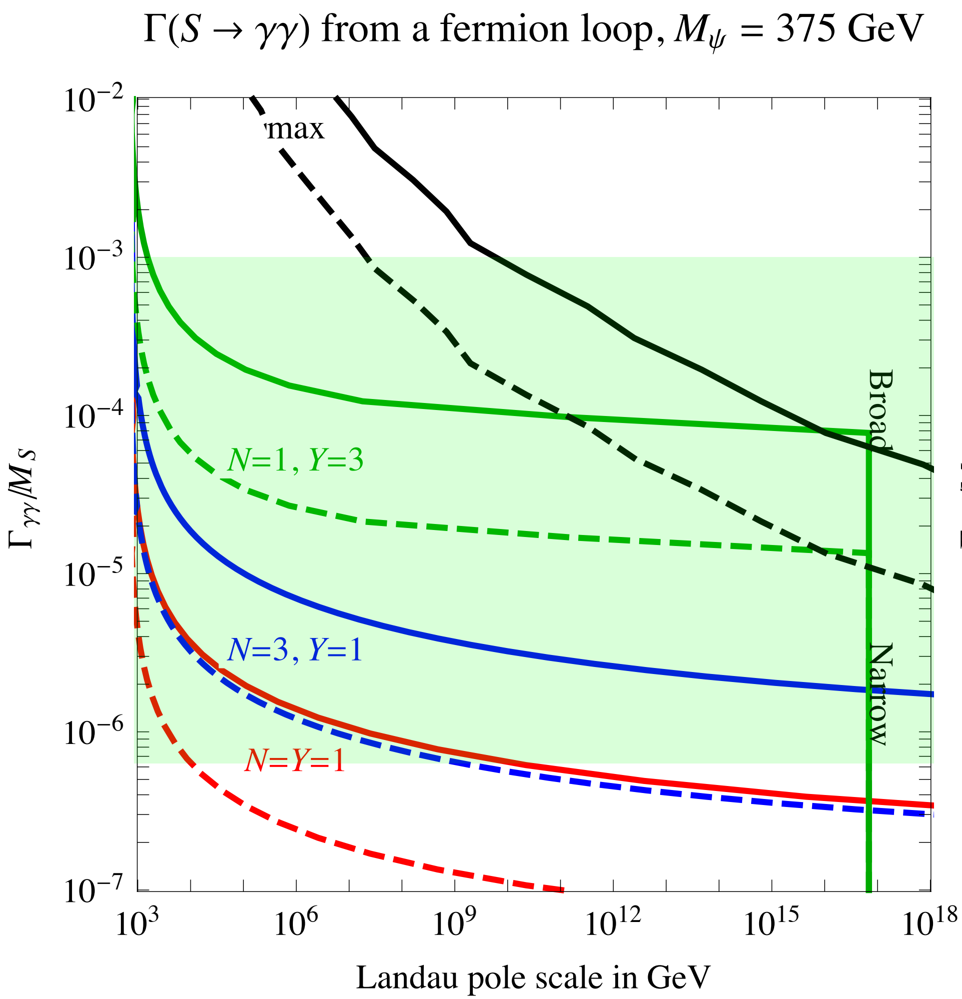
Good particles in the loop: L, E, U

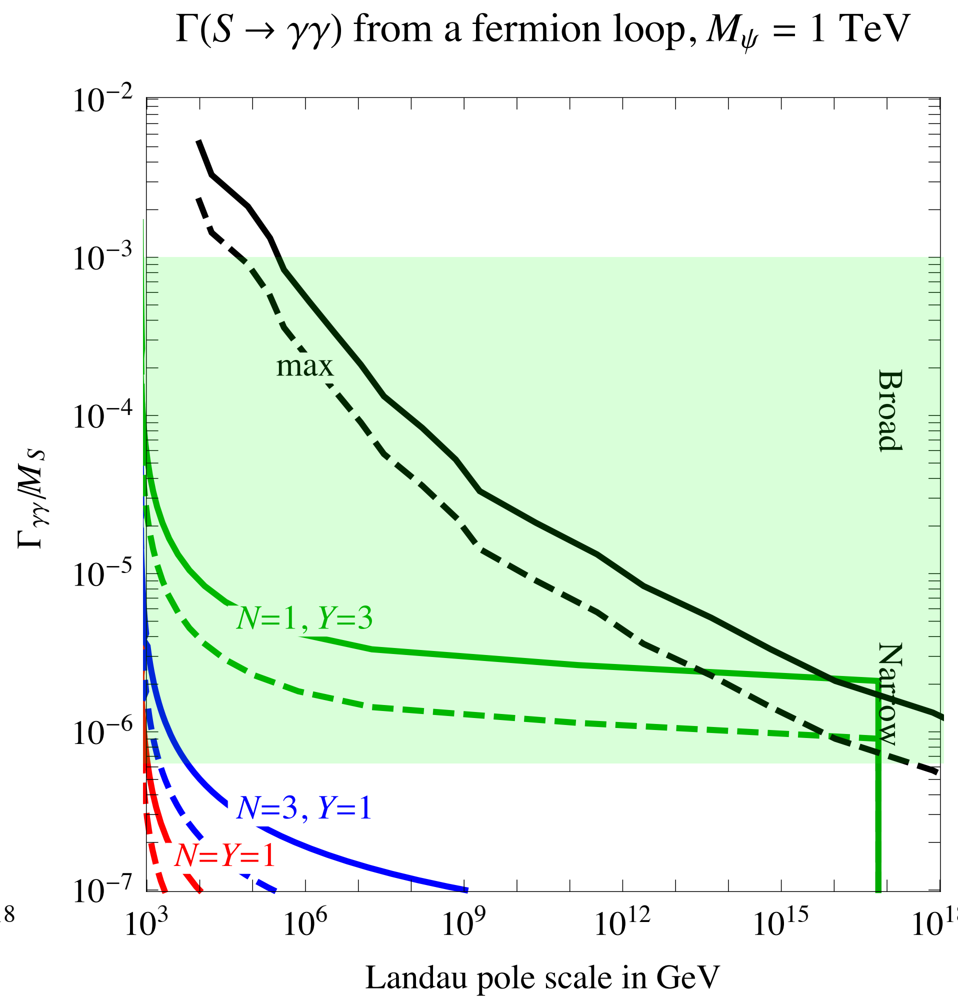


Large width ⇒ non-perturbativity

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

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

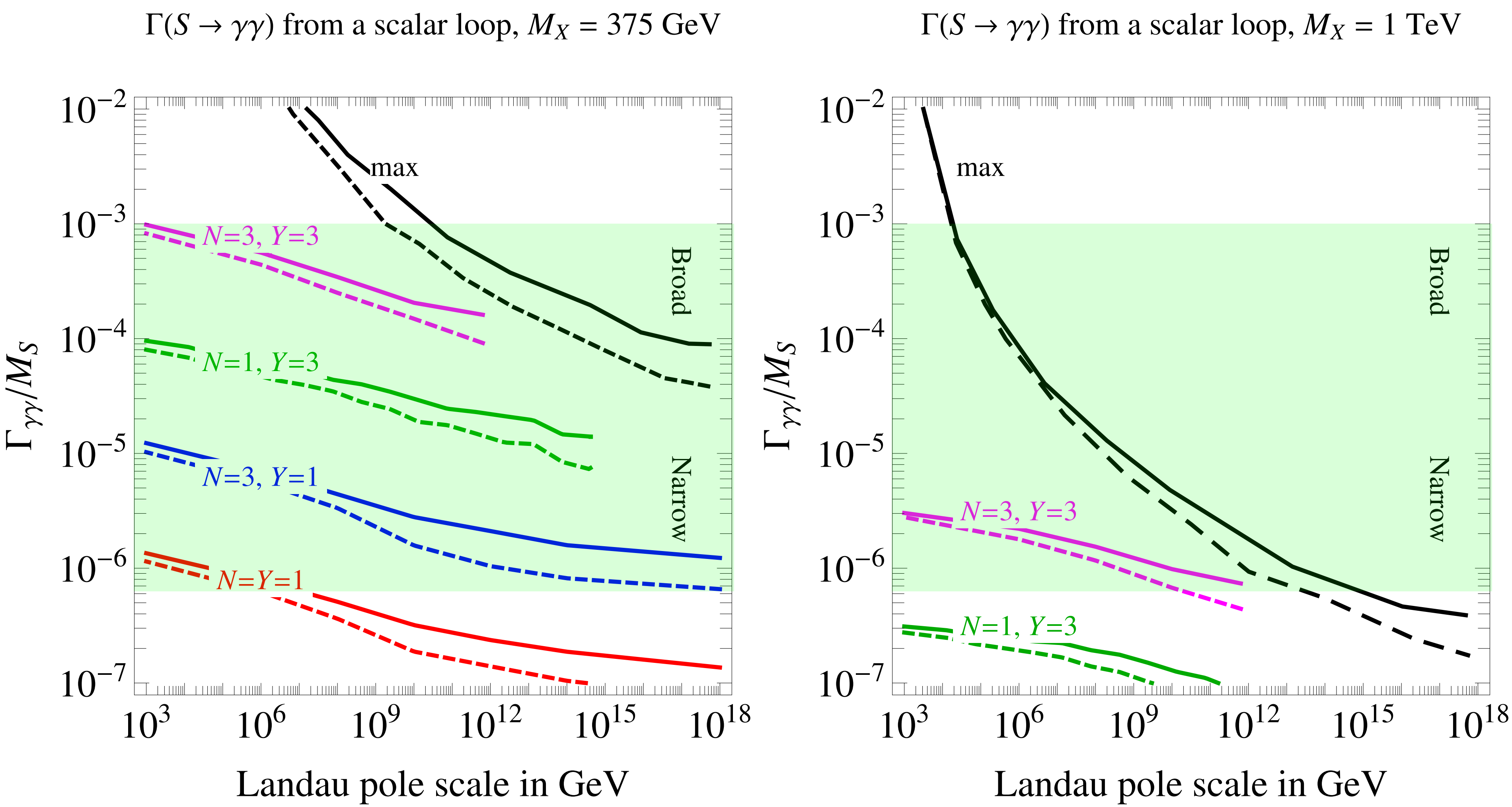




Much larger y and $\Gamma_{\gamma\gamma}$ if gauged SU(N) with IR fixed point. Then $pp \to SS$.

Similar results with extra scalars

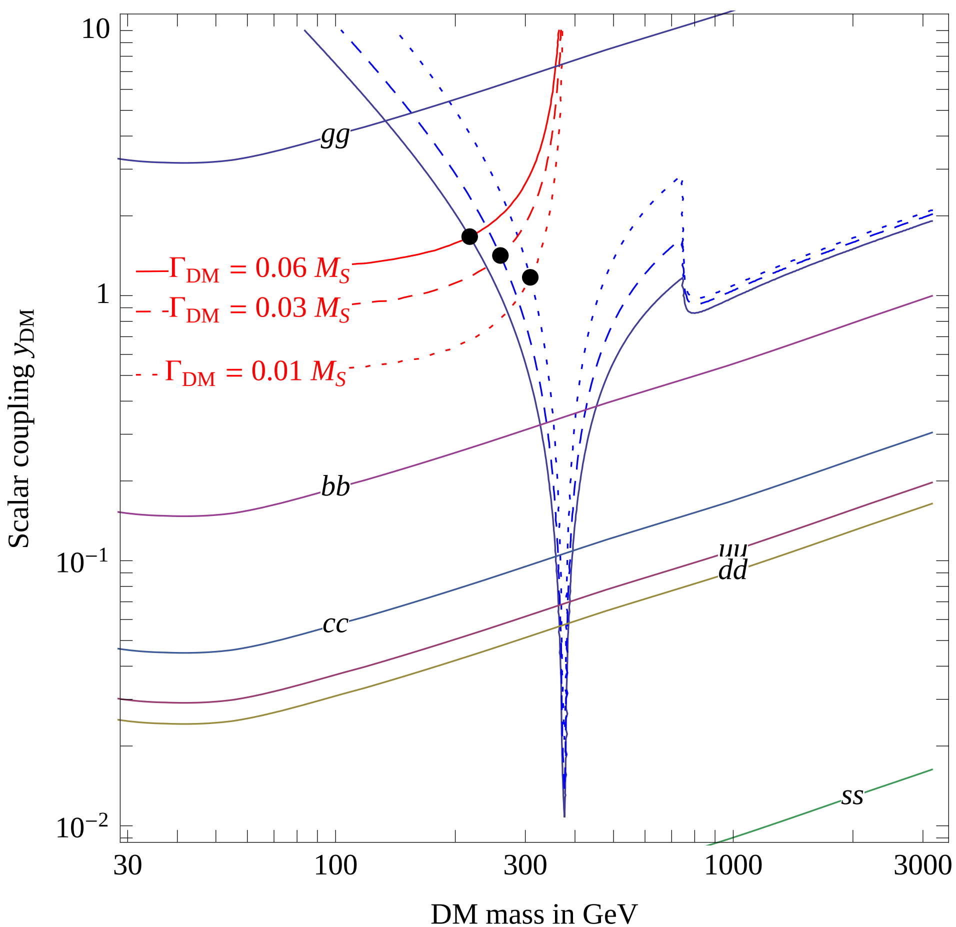
A large cubic does not give Landau poles, but it is limited by vacuum decay.

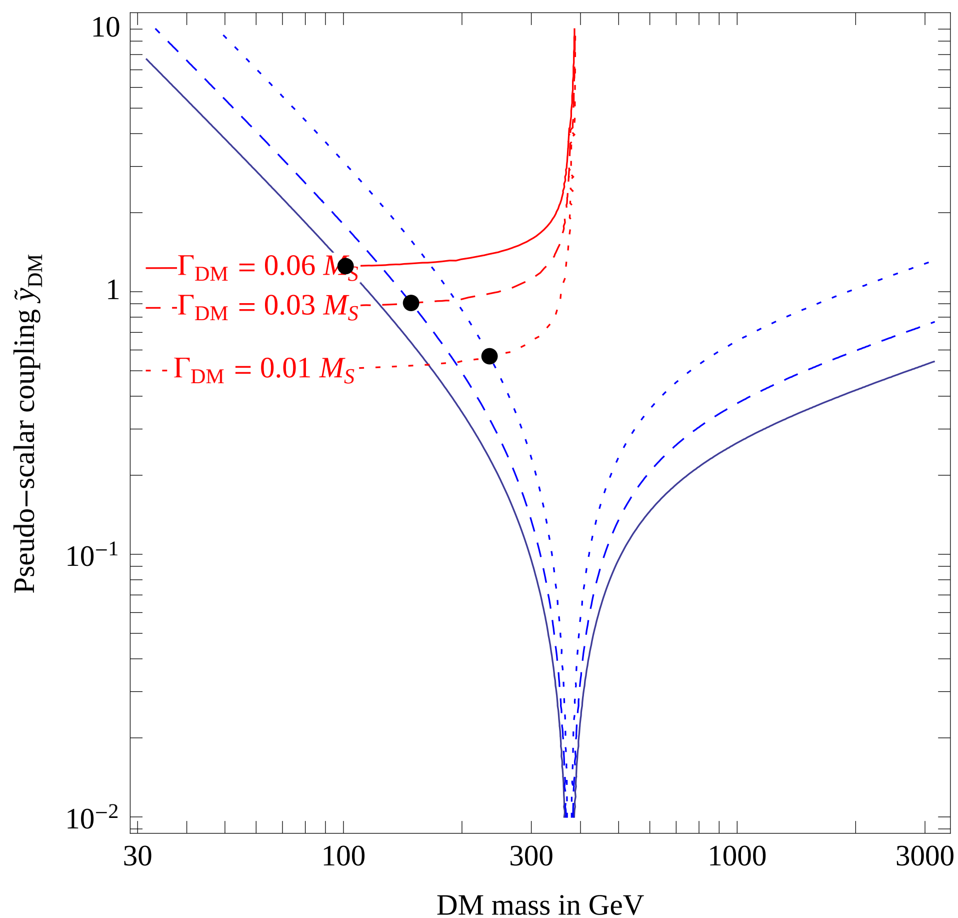


$\Gamma_{\gamma\gamma}$ can be much larger if gauged SU(N) with IR fixed point

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

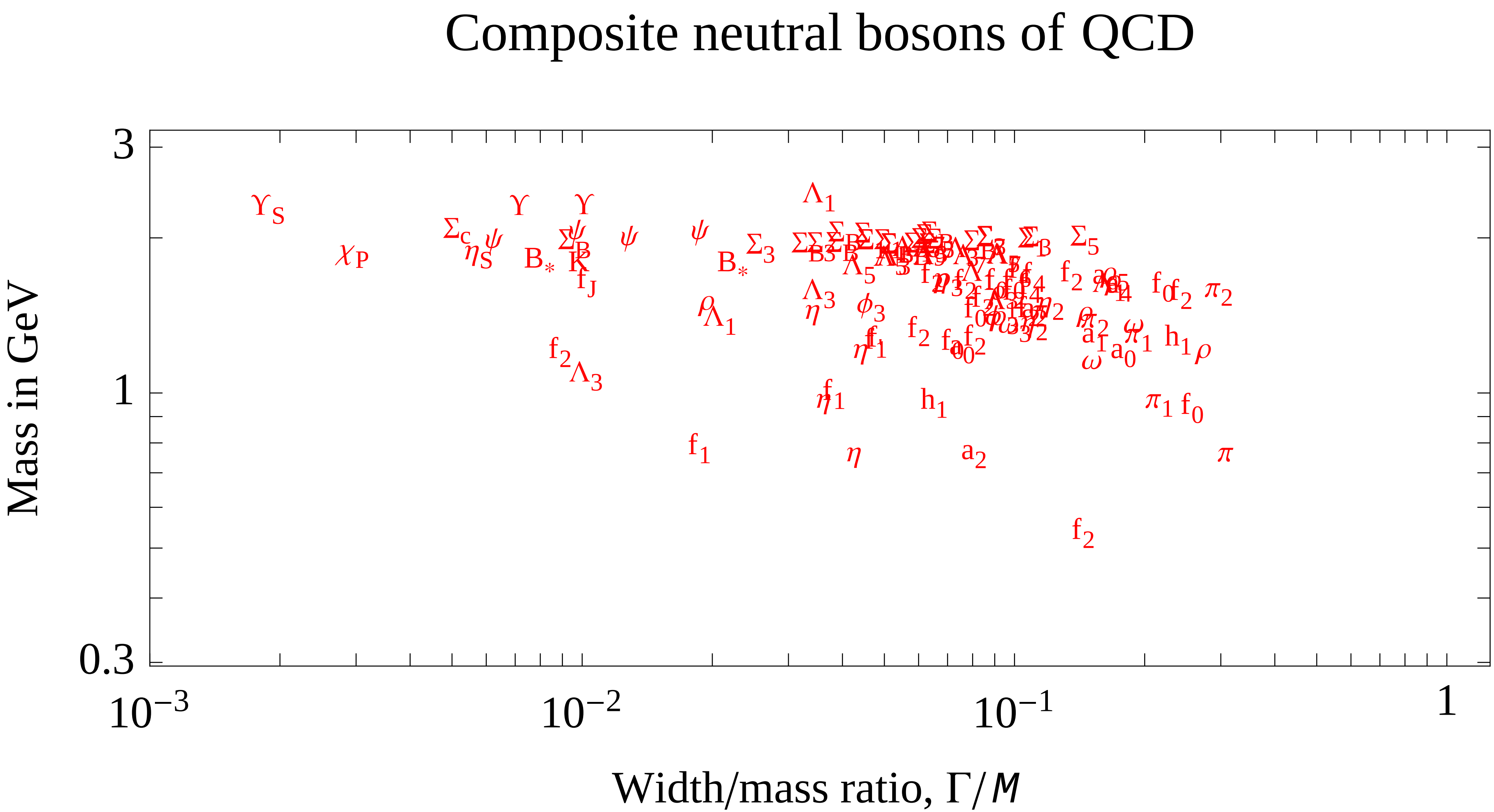
1) The connection with $\Omega_{\rm DM}$ is interesting on its own;
2) as a way to hide many particles, if they are needed to enhance $S \to \gamma\gamma$;
3) as a way to get tree level $S \to$ DM DM decays, if $\Gamma/M \sim 0.06$ is true.





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

Large width natural. Main options:

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

+ Simple UV-complete fundamental theories. E.g. extra fermions $\mathcal{Q}$ chiral under SU(2)$_L$ and charged under extra SU(N) strong at v.
− Dead. RIP.

Composite H and S. Bonus/malus:

− Flavor problems avoided imagining partial compositeness $\mathscr{L}_{\rm eff}$, no theory.
+ 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 flavor problems, simple UV-complete fundamental theories. E.g. extra vectorlike particles $\mathcal{Q}$ charged under SM and under extra strong SU(N).
+ Dark Matter could be a G-stable TCπ. Large width as $S \to$ DM DM?
+ 750 GeV ok with modified naturalness, dynamical generation of v.

S could be:
1) a pseudo-scalar TCη with anomalous coupling to vectors enhanced by N;
2) a scalar, maybe a dirty TC-dilaton;
3) a TC-charmonium.

Theories


Ferrari 125

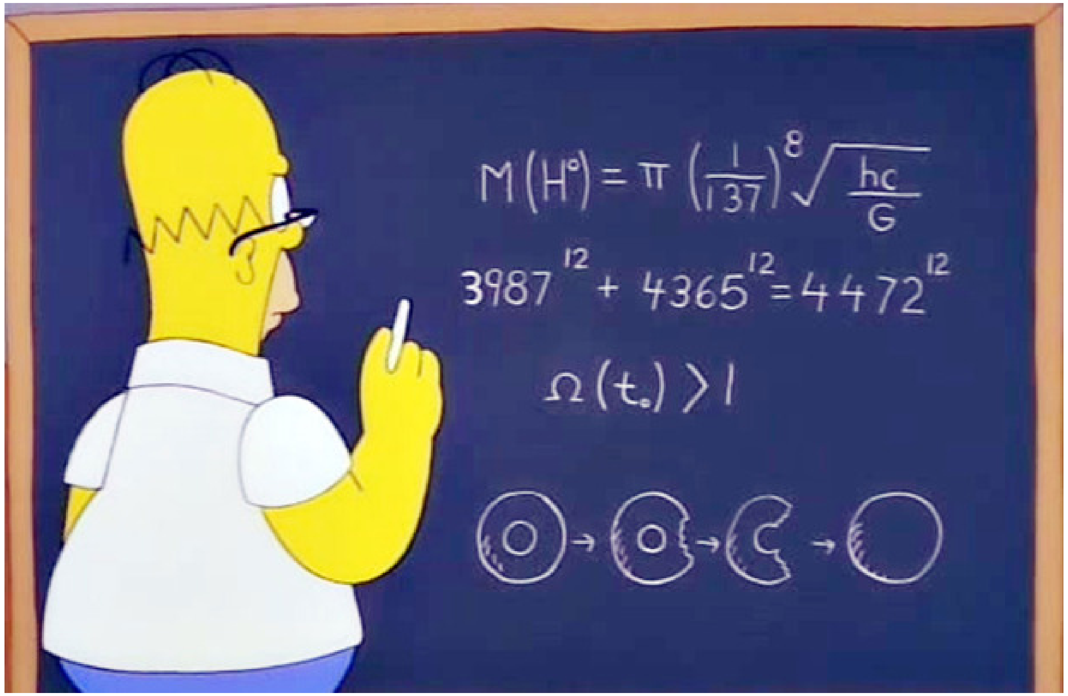

Ferrari 750
MONZA SCAGLIETTI 1955
MILLE MIGLIA 2014
363

The Big Picture

Too early. If narrow, everybody who has a singlet can postdict.

E.g. S could be some SUSY singlet (H, A, $\tilde{\nu}$, NMSSM, sgoldstinos...).

Trinification SU(3)$_L$⊗SU(3)$_R$⊗SU(3)$_c$ predicts extra L, D ($\subset$ 27 of E_6) and can fit diphoton + diboson ($g_R \approx 0.444$). String models often have extra states. Homer Simpson predicted $M = 774\,\text{GeV}$ in 1998



What next?

LHC

Sgg gives more jets than $Sq\bar{q}$. Measure 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 [arXiv:1512.08478].

Scalar/pseudoscalar can be discriminated by
1) observing $S \to hh$,
2) studying $S \to ZZ \to 4\ell$,
3) studying Sjj.

$pp \to SS$ if big coupligs. [...]

Implications for FCCee

1) WOW

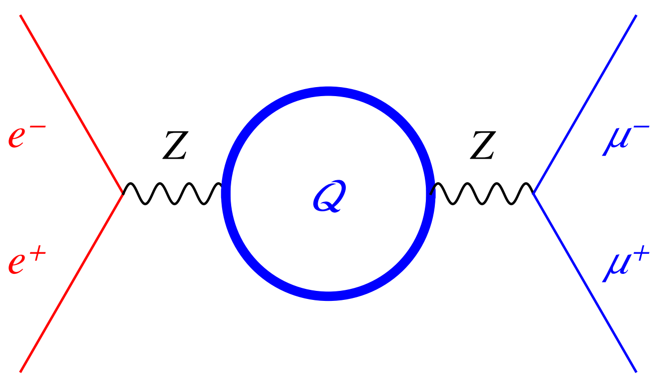
2) New physics at 750 GeV! Is FCCee dis-fed?**

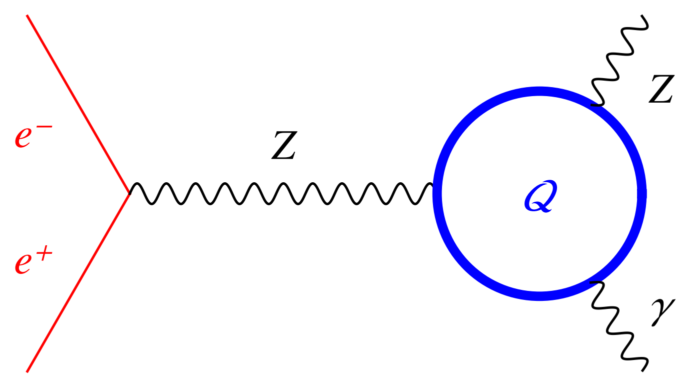
3) Maybe at $\lesssim \frac{1}{2}750\,\text{GeV}$ to give invisible S decays + loop width into $\gamma\gamma$?

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

A) High-energy tails of $pp \to \ell^-\ell^+$, sensitive to Δb (BSM running of g_Y, g_2).

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





Universal new physics

Heavy new physics that affects the SM vector propagators is condensed in:

S, T: affected by new particles coupled to H, FCC sensitivity already studied
W, Y: affected by any new particle with gauge interactions

$W, Y \geq 0$ are cumulative and related to RGE coefficients by

$$Y = \frac{\alpha_Y}{20\pi}\left[\sum_s \frac{\Delta b_Y^{(s)}}{2}\frac{M_{\rm W}^2}{M_s^2} + \sum_f \Delta b_Y^{(f)}\frac{M_{\rm W}^2}{M_f^2}\right] = 1.1\ 10^{-5}\left[\frac{\Delta b_Y^{(s)}}{2} + \Delta b_Y^{(f)}\right](\frac{300\ \text{GeV}}{M})^2$$

and the same for $Y \to W$. For example heavy SUSY particles give:

$$Y = \frac{\alpha_Y}{40\pi}M_{\rm W}^2\left(\frac{1}{m_{\tilde{E}}^2} + \frac{1}{2m_{\tilde{L}}^2} + \frac{1}{3m_{\tilde{D}}^2} + \frac{4}{3m_{\tilde{U}}^2} + \frac{1}{6m_{\tilde{Q}}^2} + \frac{1}{6m_A^2}\right) + \frac{\alpha_Y}{30\pi}\frac{M_{\rm W}^2}{\mu^2} > 0$$

$$W = \frac{\alpha_2}{80\pi}M_{\rm W}^2\left(\frac{1}{m_{\tilde{L}}^2} + \frac{3}{m_{\tilde{Q}}^2} + \frac{1}{3m_A^2}\right) + \frac{\alpha_2}{30\pi}\left(\frac{M_{\rm W}^2}{\mu^2} + \frac{2M_{\rm W}^2}{M_2^2}\right) > 0$$

FCC sensitivity to W, Y

Mostly trough the weak angle from Z couplings, $g_V/g_A \equiv 1 - 4\sin^2\theta_{\rm W}$:

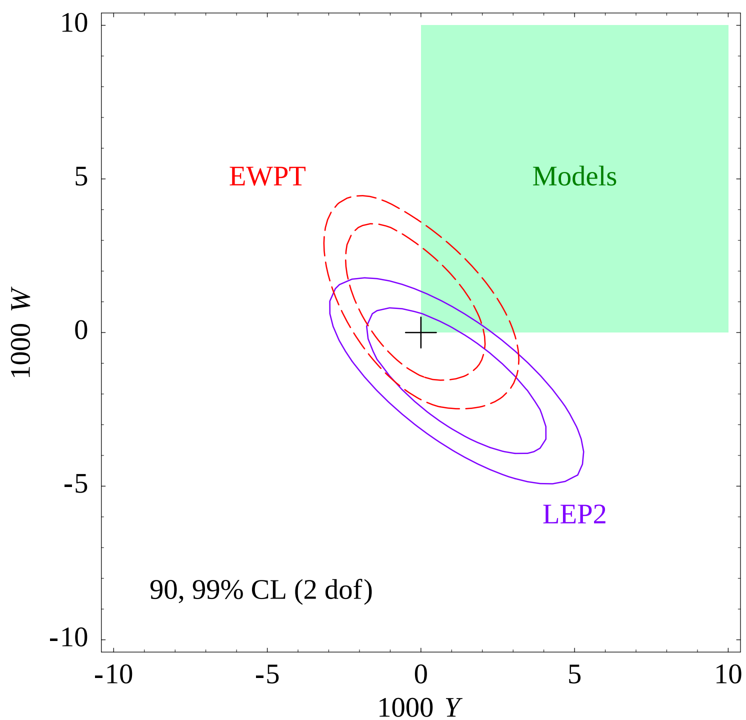
$$\delta \sin^2\theta_{\rm W} = -0.33Y - 0.09W = \pm 10^{-6}|_{\rm exp} \pm 1.8\ 10^{-5}|_{\alpha_{\rm em}}$$

The present $\alpha_{\rm em}$ error might be irreducible. At least Y to $\pm$few $\times\, 10^{-5}$.

Band becomes a long ellipse assuming standard estimates for other observables.

$W < 0.6\ 10^{-4}$ means $m_{\tilde{L}} > 120\,{\rm GeV}$, $\mu > 200\,{\rm GeV}$, $M_2 > 270\,{\rm GeV}$.

LEP1 + LEP2



LEP2 measured W, Y as well as LEP1.
Indeed their effects grow with energy.
At $s \gg M_W^2$

	obs/obs$_{SM}$ − 1
$\sigma(e^+e^- \to \mu^+\mu^-)$	$-(0.67W + 1.33Y)s/M_W^2$
$\sigma(e^+e^- \to q\bar{q})$	$-(1.35W + 0.65Y)s/M_W^2$
A_{FB}^{μ}	$-0.40(W + Y)s/M_W^2$

Can FCCee do the same?
Expected accuracy:

$\sqrt{s}$/ GeV	160	240	350
$\sigma(e^+e^- \to \mu^+\mu^-)$	0.015%	0.025%	0.075%
W, Y	$0.4\ 10^{-4}$	$0.3\ 10^{-4}$	$0.4\ 10^{-4}$

Conclusions

We will know much more, soon.