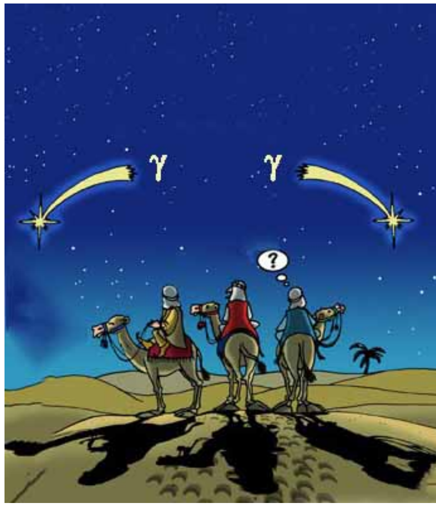
A $\gamma\gamma$ resonance at 750 GeV?



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

Alessandro Strumia, talk at SUSY 2016, July 8, 2016

European Commission

Horizon 2020
European Union funding
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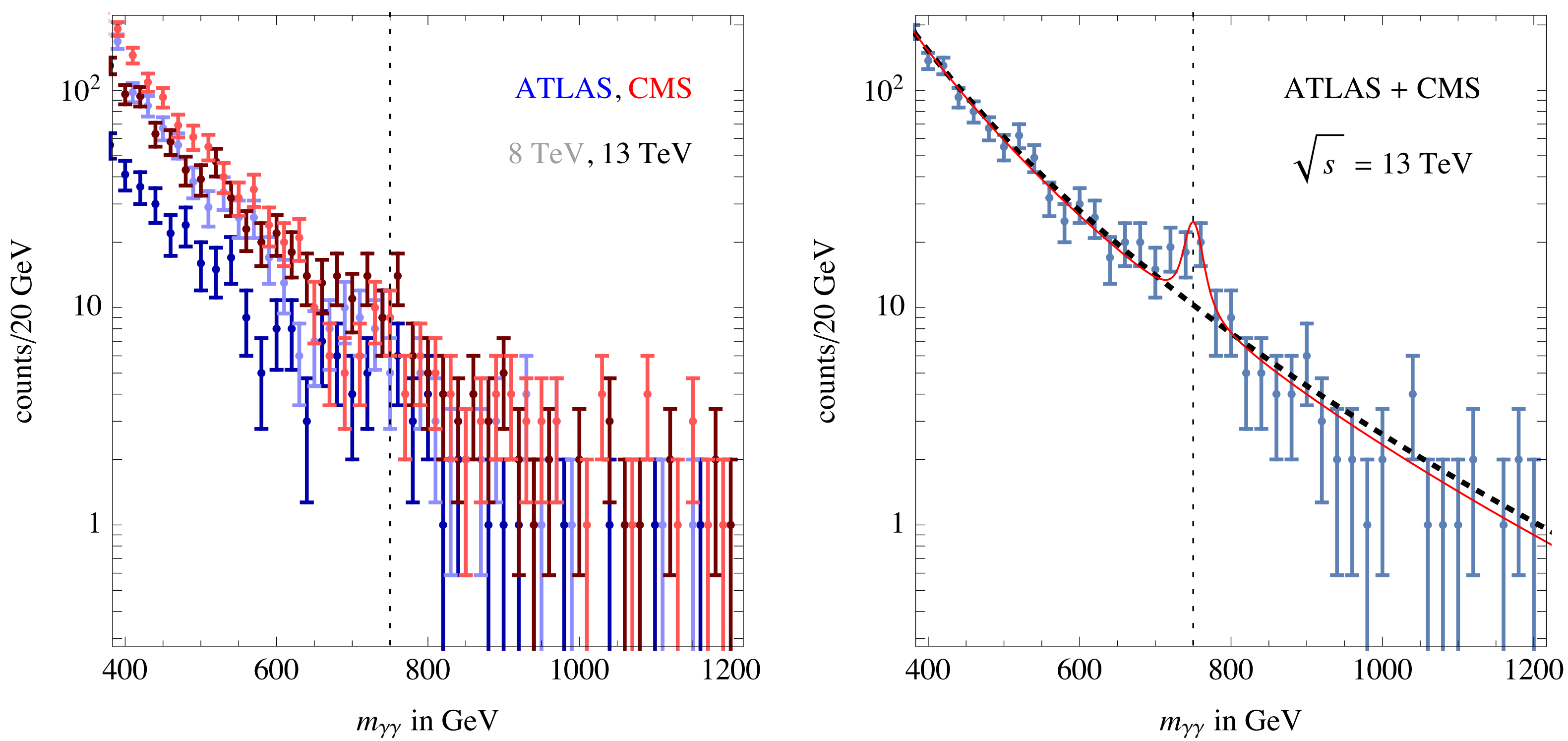
News from the outback of physics

Explores went to Australian inland carrying boats because naturalness predicted great lakes and mountains. They found a lot of nothing. Wandering trough the flatland, a peak or maybe a mirage appeared on the horizon...

First LHC data at 13 TeV

Depressing flatland plus maybe a peak at $m_{\gamma\gamma} \approx 750\,\text{GeV}$



Theoretically clean. Experimentally simple.

Significance	ATLAS	CMS	naive combination
Local	3.9σ	3.4σ	$\approx 4.5\sigma$
Global	$\approx 2.1\sigma$	$\approx 1.6\sigma$	$\sim 3\sigma$

Denote as F, 'digamma' in archaic greek. Later $F = 6 = 750/125$.

Needless to say

Either the main discovery in 30 years
or the main statistical fluctuation.

God plays loaded dices?

Physics = experiment + i theory

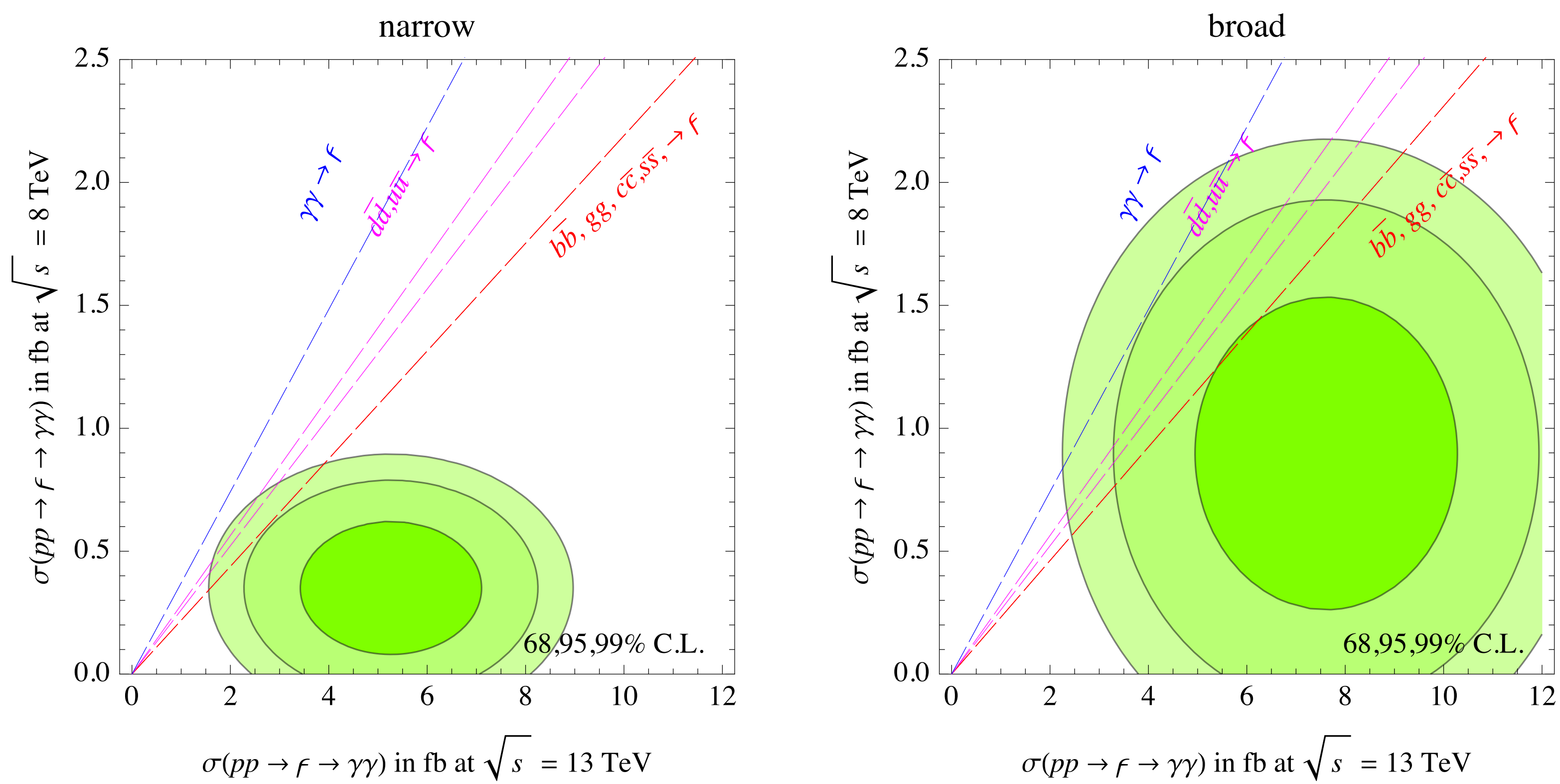
The Gold Rush: [INSPIRES][list]

Date	papers
16 Dec	10
25 Dec	101
1 Jan	137
1 Feb	212
1 Jun	411
1 Aug	?

Rates

Width: narrow or large, $\Gamma/M \sim 0.06$?

$\sigma(pp \to \mathcal{F} \to \gamma\gamma)$	$\sqrt{s} = 8$ TeV		$\sqrt{s} = 13$ TeV	
	narrow	broad	narrow	broad
CMS	0.63 ± 0.31 fb	0.99 ± 1.05 fb	4.8 ± 2.1 fb	7.7 ± 4.8 fb
ATLAS	0.21 ± 0.22 fb	0.88 ± 0.46 fb	5.5 ± 1.5 fb	7.6 ± 1.9 fb

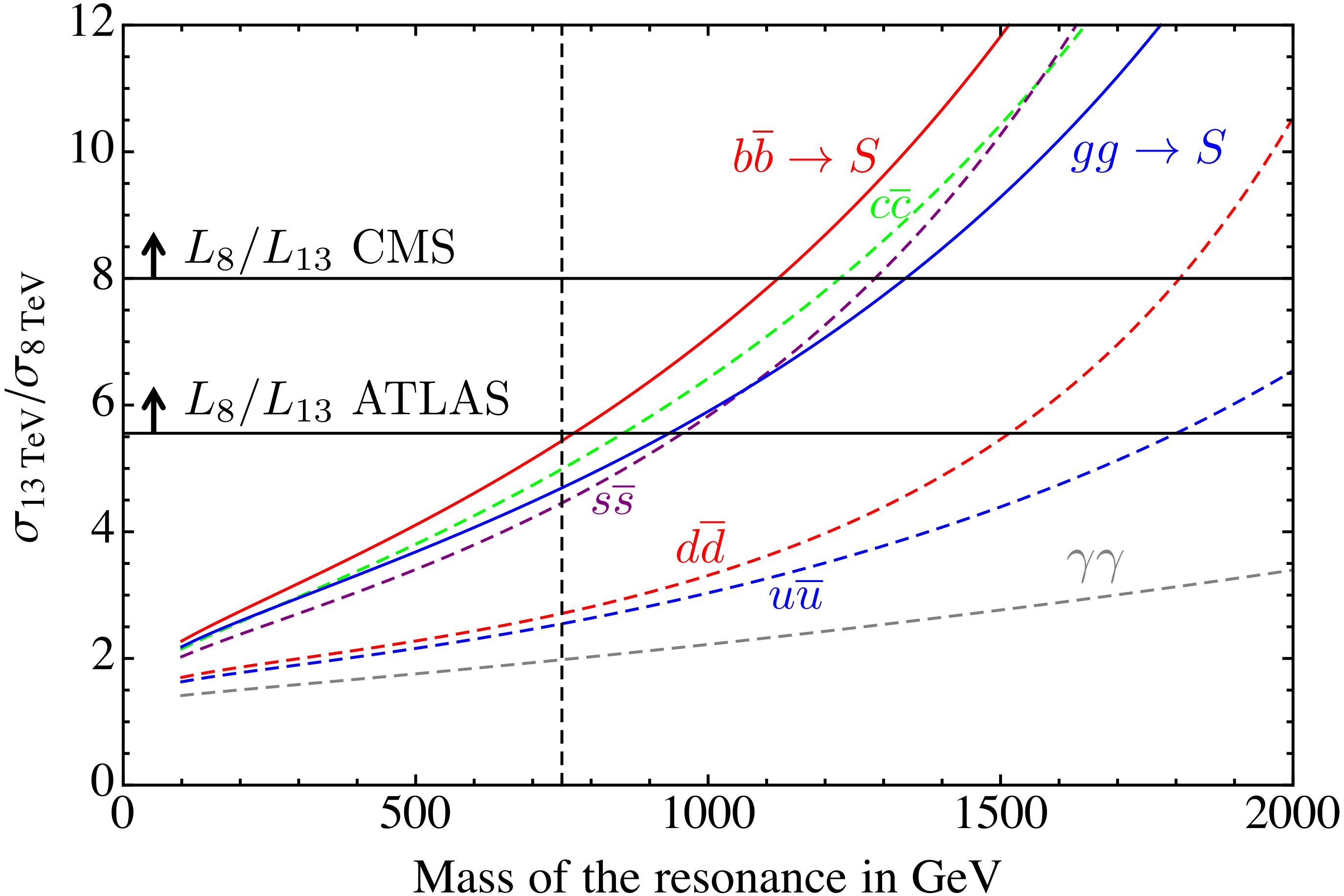


8 TeV vs 13 TeV

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

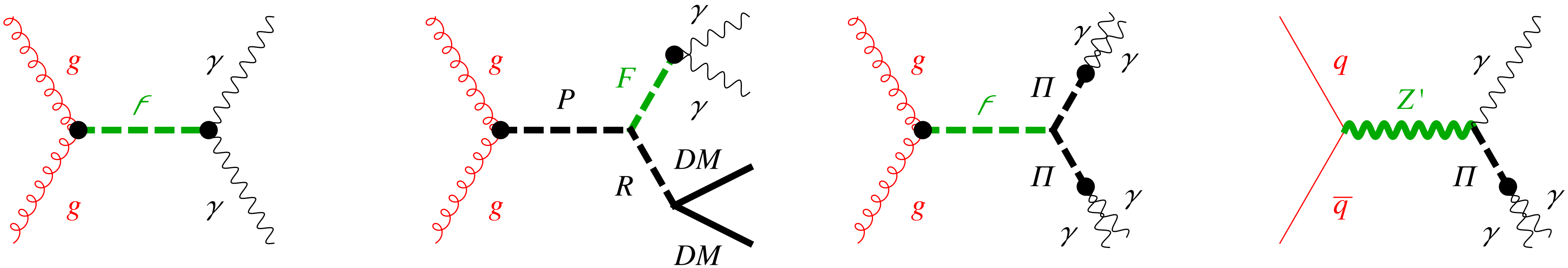
The signal grows by ≈ 5 if produced from gg, $b\bar{b}$, $c\bar{c}$, $s\bar{s}$: ok.

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 F decays from a heavier particle.

A more complicated kinematics?



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

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

Or two nearby narrow resonances.

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

Widths

Cross section

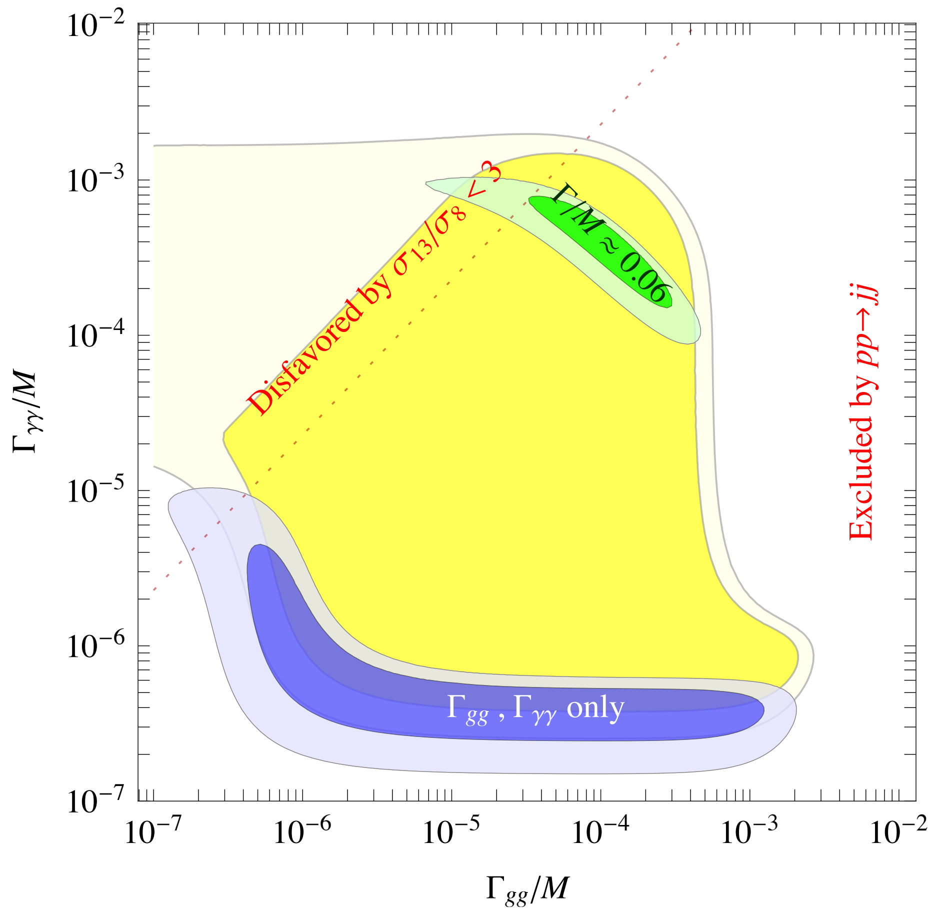
Can be computed in terms of (narrow) widths:

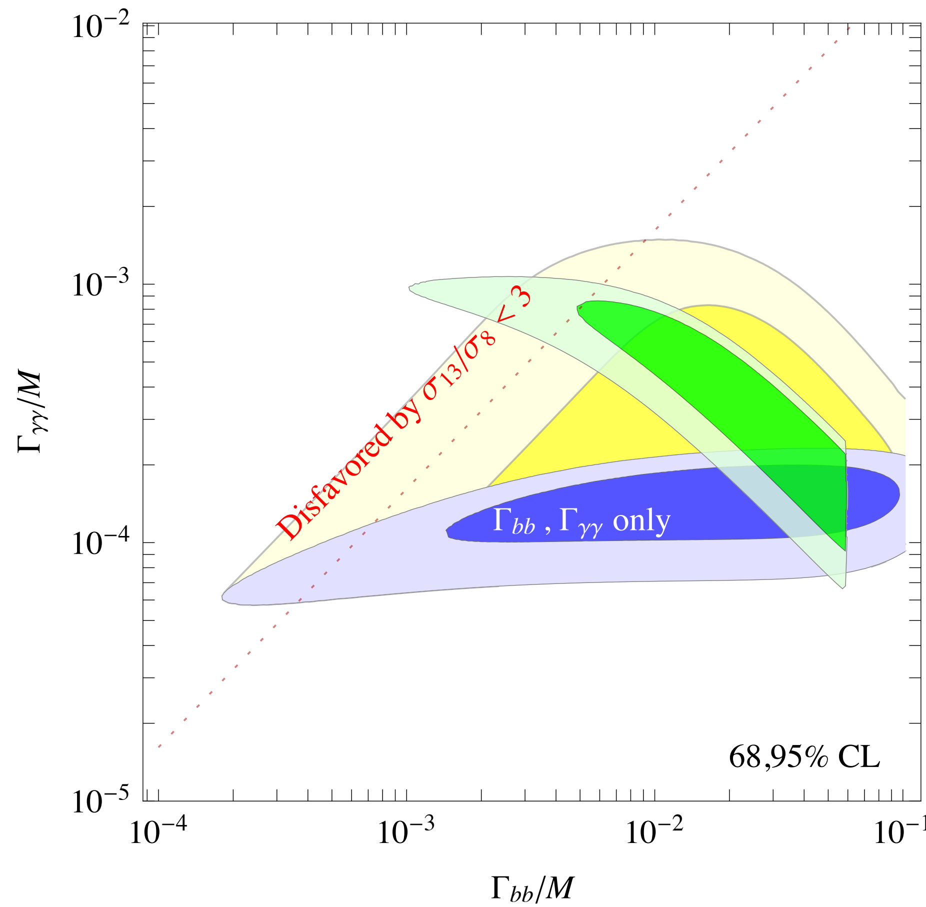
$$\sigma(pp \to F \to \gamma\gamma) = \frac{2J+1}{s}\left[\sum_{\wp} C_{\wp\bar{\wp}} \frac{\Gamma(F \to \wp\bar{\wp})}{M}\right]\frac{\Gamma(F \to \gamma\gamma)}{\Gamma}$$

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 $b\bar{b}$





$F \leftrightarrow \gamma\gamma + gg + ?$

$F \leftrightarrow \gamma\gamma + b\bar{b} + ?$

Bounds on other decay modes

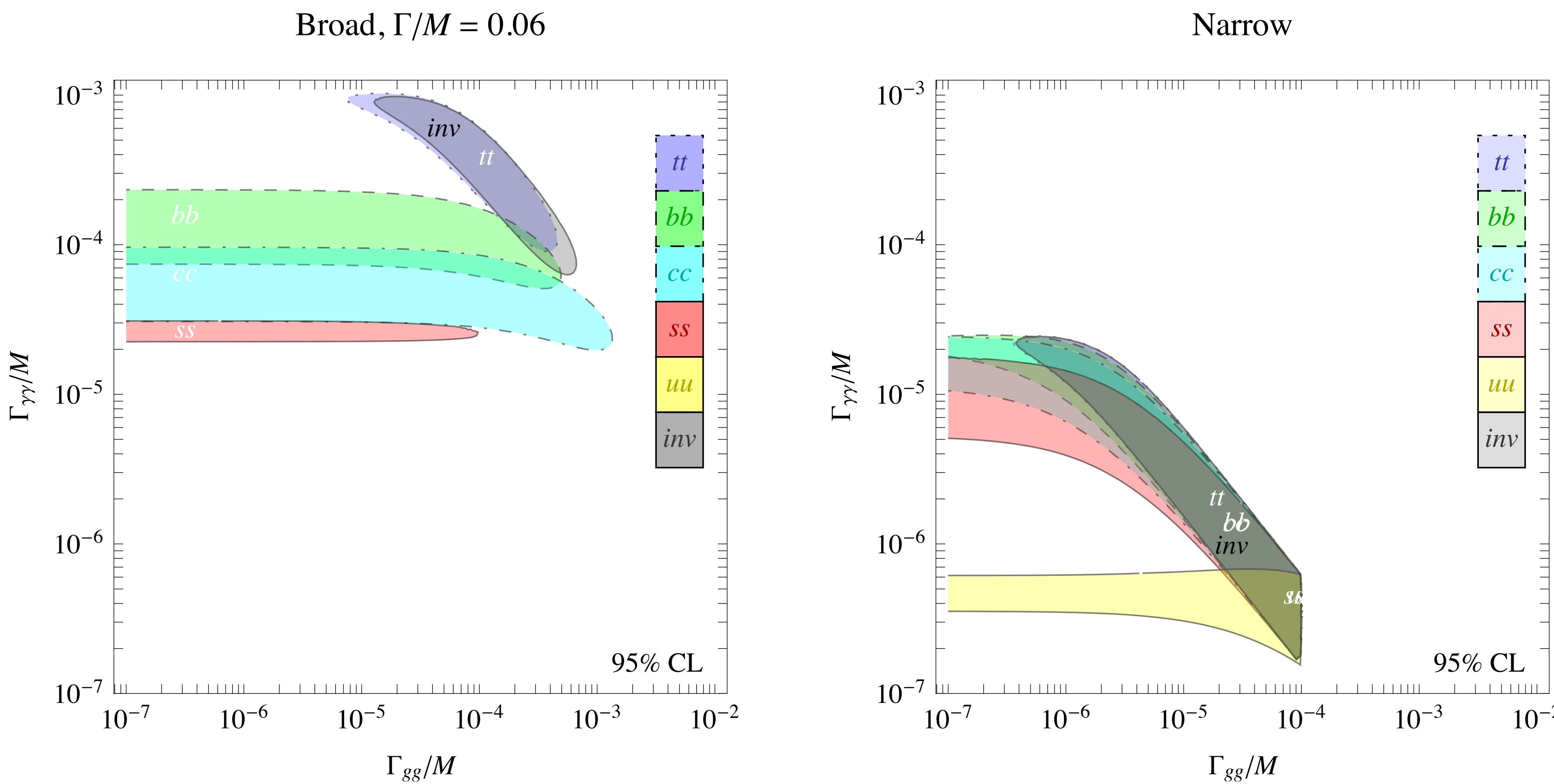
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	implied bound on $\Gamma(F \to f)/\Gamma(F \to \gamma\gamma)_{\text{obs}}$
$\gamma\gamma$	< 1.5 fb	< 1.1 fb	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 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.

Even invisible modes are constrained

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

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



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

Effective theory

Valid if extra particles that mediate operators are much heavier than $\frac{1}{2}750\,\text{GeV}$.

If $\mathcal{F}$ is a CP-even scalar singlet:

$$\mathscr{L}_{\text{eff}}^{\text{dim}\le 5} = \mathcal{F}\left[g_3^2\frac{G_{\mu\nu}^2}{2\Lambda_{gg}} + g_2^2\frac{W_{\mu\nu}^2}{2\Lambda_{WW}} + g_1^2\frac{B_{\mu\nu}^2}{2\Lambda_{BB}} + \left(\frac{H\bar{\psi}_L\psi_R}{\Lambda_\psi} + \text{h.c.}\right) + \right. \\ \left. -\kappa_{\mathcal{F}H}M_{\mathcal{F}}(|H|^2 - v^2) + \frac{|D_\mu H|^2}{\Lambda_H} - \kappa_{\mathcal{F}}M_{\mathcal{F}}\mathcal{F}^2 + \frac{(\partial_\mu\mathcal{F})^2}{2\Lambda_{\mathcal{F}}}\right]$$

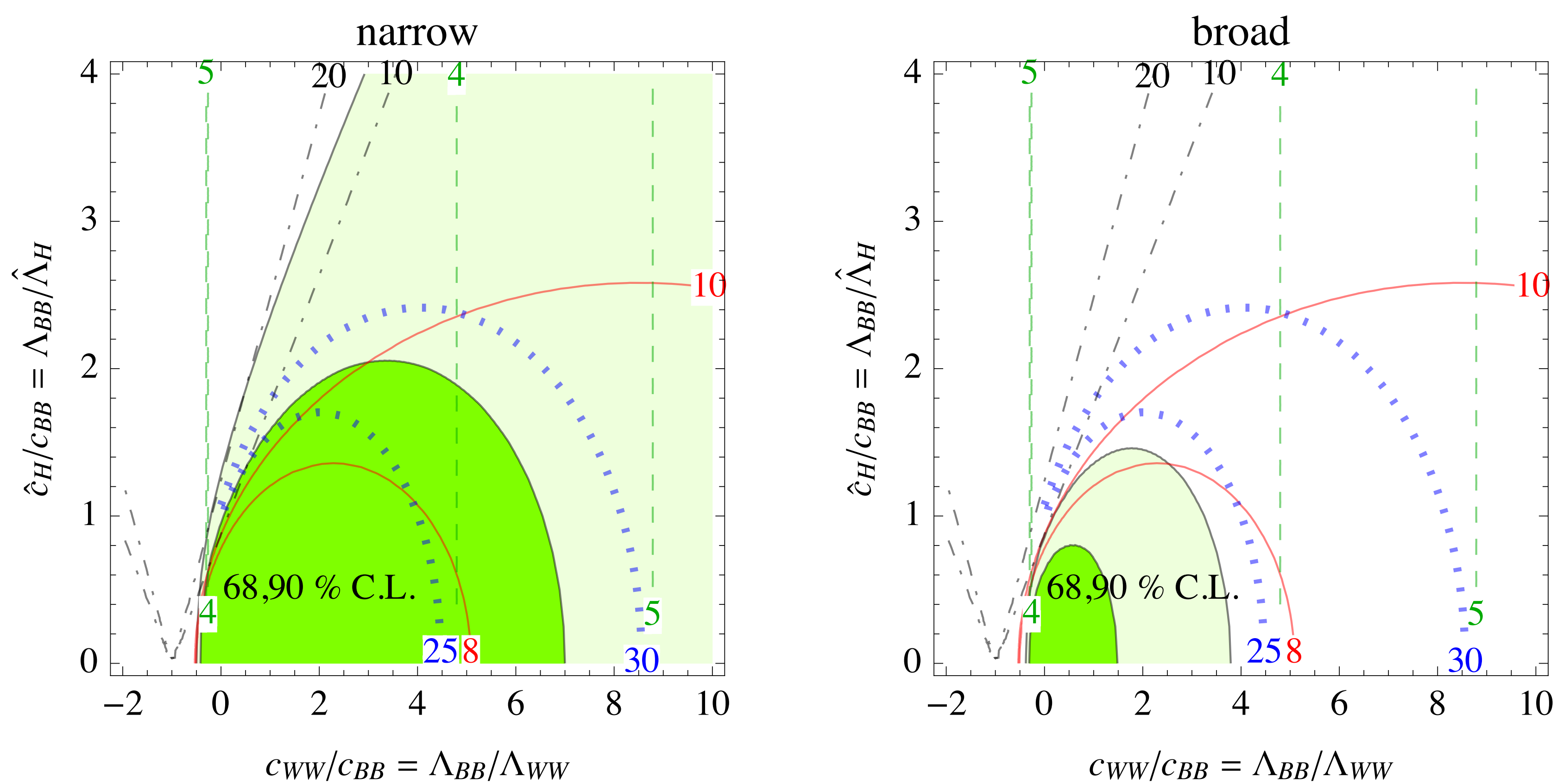
If $\mathcal{F}$ is a CP-odd scalar singlet:

$$\mathscr{L}_{\text{eff}}^{\text{dim}\le 5} = \mathcal{F}\left[g_3^2\frac{G_{\mu\nu}\tilde{G}_{\mu\nu}}{2\tilde{\Lambda}_{gg}} + g_2^2\frac{W_{\mu\nu}\tilde{W}_{\mu\nu}}{2\tilde{\Lambda}_{WW}} + g_1^2\frac{B_{\mu\nu}\tilde{B}_{\mu\nu}}{2\tilde{\Lambda}_{BB}} + \left(\frac{H\bar{\psi}_L i\gamma_5\psi_R}{\tilde{\Lambda}_\psi} + \text{h.c.}\right)\right]$$

$SU(2)_L$ invariance implies $\Gamma_{\rm extra} > 0.3\Gamma_{\gamma\gamma}$

operator	$\Gamma(F \to Z\gamma)/\Gamma(F \to \gamma\gamma)$	$\Gamma(F \to ZZ)/\Gamma(F \to \gamma\gamma)$	$\Gamma(F \to WW)/\Gamma(F \to \gamma\gamma)$
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

Isocurves of $\Gamma(F \to ZZ, \gamma Z, WW, hh)/\Gamma(F \to \gamma\gamma)$

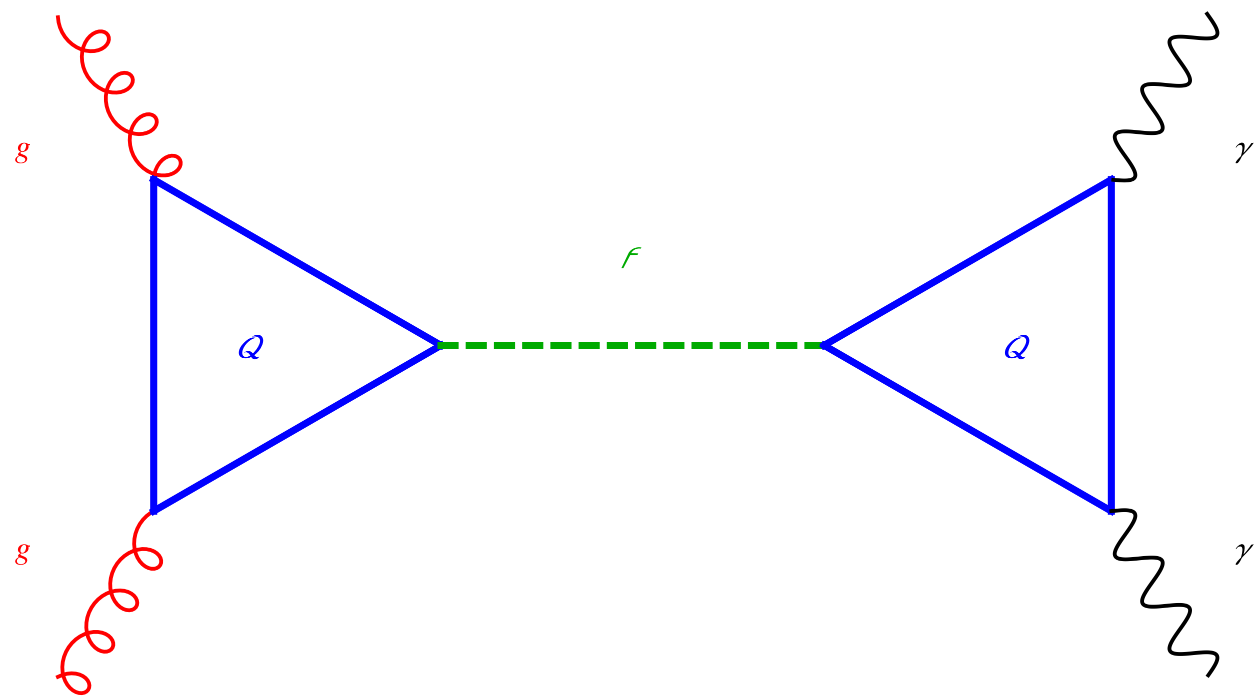


Models

VolksModell (the everybody's model)

The $\mathcal{F}gg$ and $\mathcal{F}\gamma\gamma$ operators can be generated if $\mathcal{F}$ couples to charged particles

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



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

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

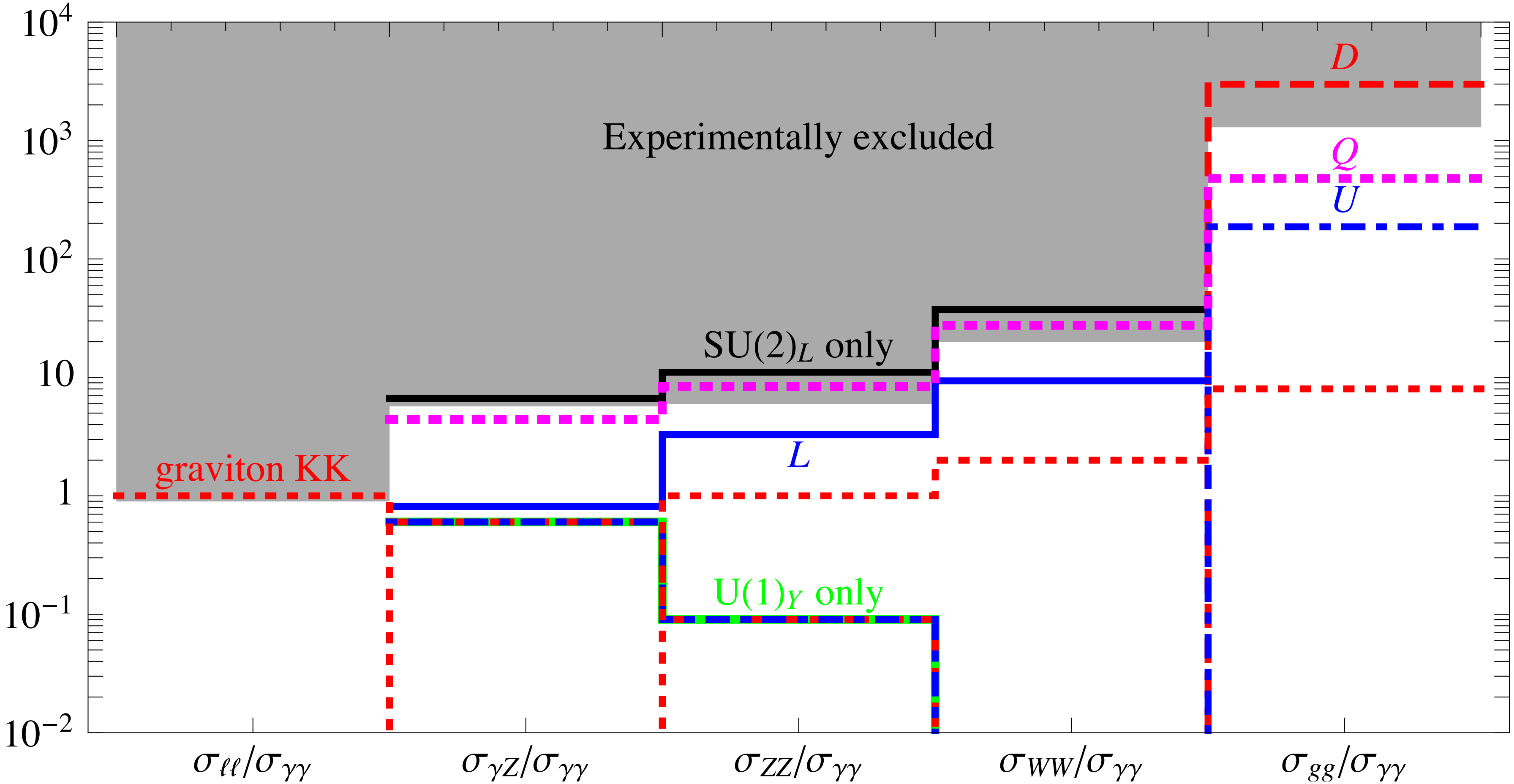
$$\frac{\Gamma(F \to \gamma\gamma)}{M} \approx 5.4 \times 10^{-8} \left| \sum_f d_{r_f} Q_f^2 y_f \frac{M}{2M_f} + \sum_s d_{r_s} Q_s^2 \frac{A_s M}{16 M_s^2} \right|^2$$

- 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 $\Gamma(F \to \gamma\gamma) \gtrsim 10^{-4} M$, which again seems too large?

- If Γ is small, data want $\Gamma(F \to \gamma\gamma) \gtrsim 10^{-6} M$, 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)

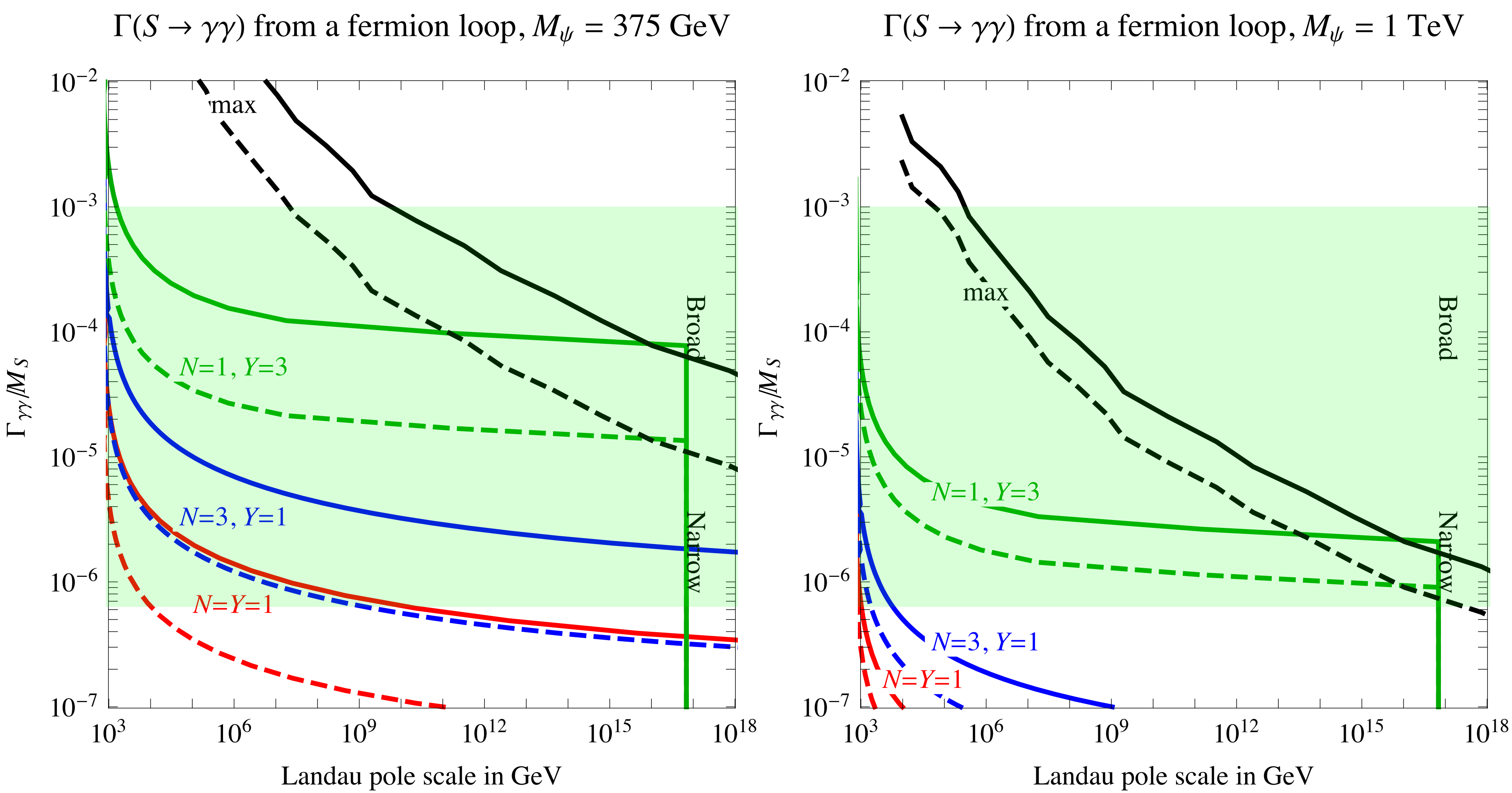
Good particles in the loop: L, E, U



Large width ⇒ non-perturbativity

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

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

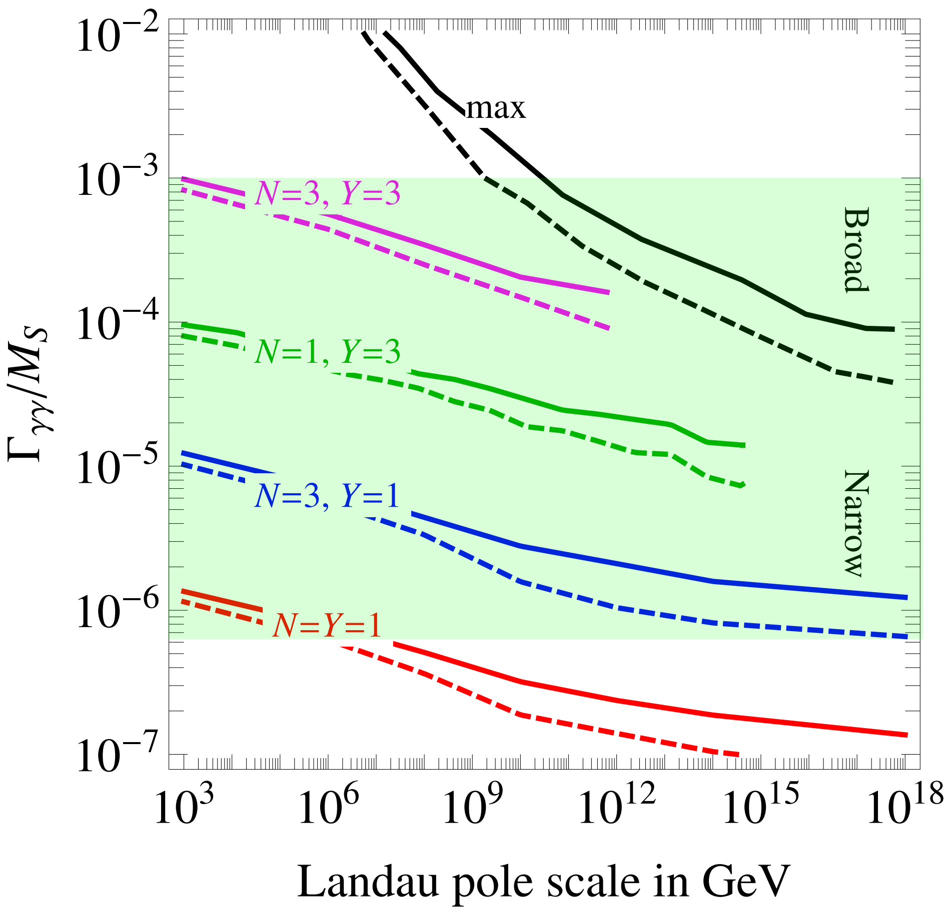


Much larger y and $\Gamma_{\gamma\gamma}$ if gauged SU(N) with IR fixed point. Then $pp \to FF$.

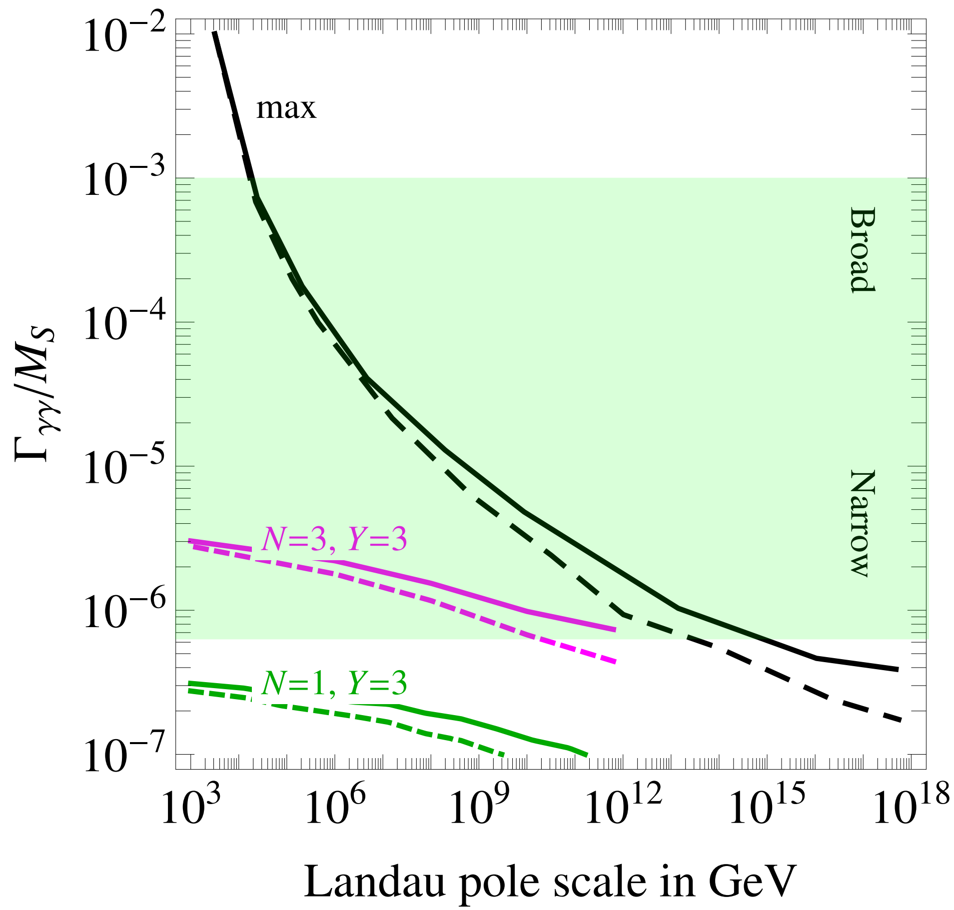
Similar results with extra scalars

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

$\Gamma(S \to \gamma\gamma)$ from a scalar loop, $M_X = 375$ GeV



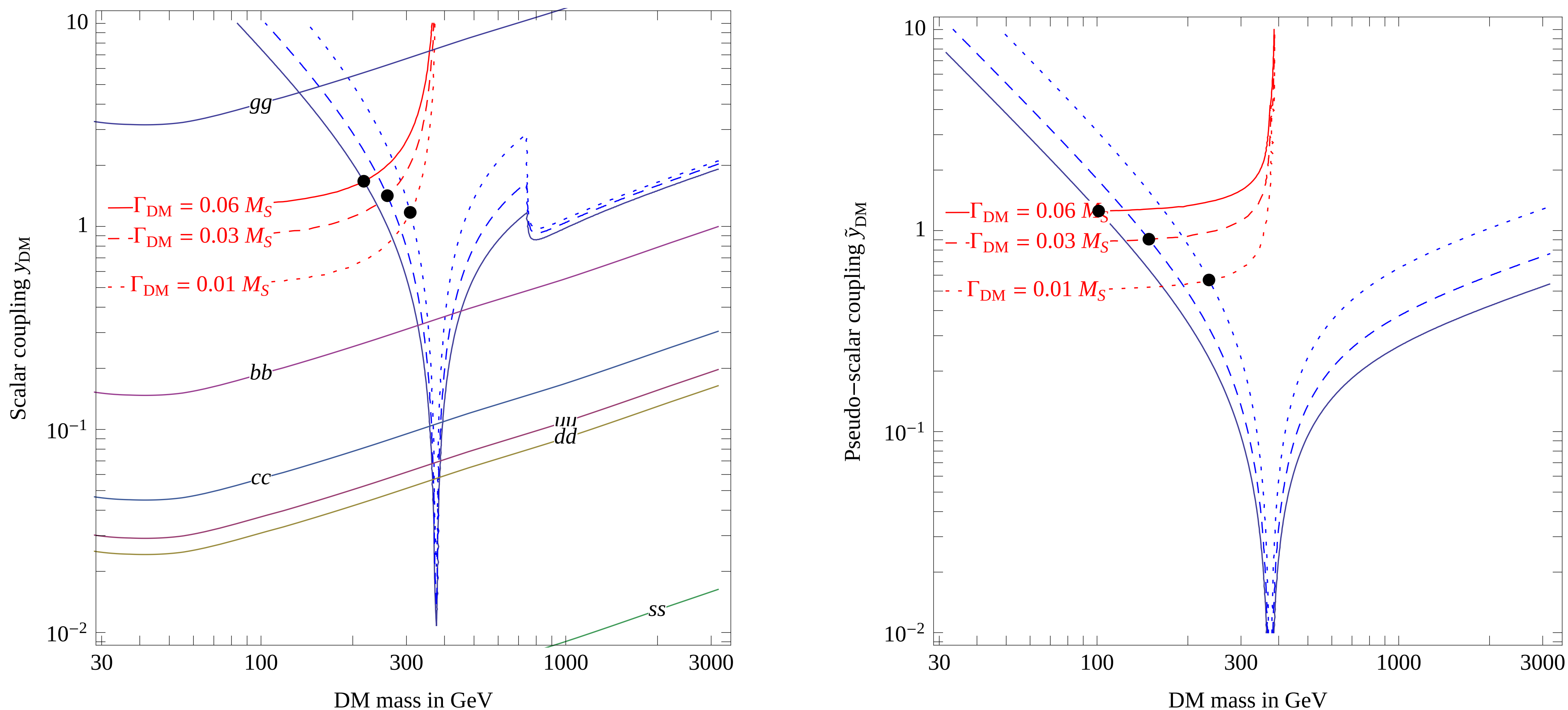
$\Gamma(S \to \gamma\gamma)$ from a scalar loop, $M_X = 1$ TeV



$\Gamma_{\gamma\gamma}$ 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 $\mathcal{F} \to \gamma\gamma$;
3) if $\Gamma/M \sim 0.06$ allows to get tree level $\mathcal{F} \to$ DM DM decays.



Direct detection bounds are (weak) irrelevant if $\mathcal{F}$ is a scalar (pseudo-scalar).

A resonance?

A heavy quark or squark with mass $M_{\mathcal{Q}} \approx \frac{1}{2}750\,\mathrm{GeV}$?
$\Lambda_{\rm QCD} \lesssim M_{\mathcal{Q}}$: only a small fraction of $pp \to \mathcal{Q}\bar{\mathcal{Q}}$ manifests as a peak, extra distortions, need poorly detectable $\Gamma_{\mathcal{Q}} \lesssim \Gamma_{\mathcal{Q}\bar{\mathcal{Q}}}$ and favourable QCD factors.

Add extra strong force with $\Lambda_{\rm TC} \lesssim M_{\mathcal{Q}}$ to get TC-charmonium resonances:

$$M_n = 2M_{\mathcal{Q}}\left(1 - \frac{\alpha_{\rm eff}^2}{8n^2}\right), \qquad \frac{\Gamma(\mathcal{F}_1 \to \gamma\gamma)}{M_{\mathcal{F}}} = \frac{q^4 N}{4}\alpha_{\rm em}^2 \alpha_{\rm eff}^3 = 10^{-6} N q^4 \left(\frac{\alpha_{\rm eff}}{0.4}\right)^3$$

But $3 \otimes \bar{3} = 1 \oplus 8$: predicts coloured octets close to 750 GeV.

Focus on models where the $\mathcal{F}$ singlet is lighter than the other unseen states:

1) pseudo-Goldstone of a chiral symmetry: pseudo-scalar TCη;
2) rough pseudo-Goldstone of scale invariance: scalar dilaton.

Strongly coupled models

3 main options:

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

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

Technidreams, composite H and F. Bonus/malus:

− Postulates $\mathscr{L}_{\mathrm{eff}}$ that avoid problems, fundamental theory with TCscalars.
+ Allows large width trough $F \to t\bar{t}$.
+ 750 GeV compatible with usual (fine-tuned) naturalness.

Composite F, 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 $\mathrm{SU}(N_{\mathrm{TC}})$.
+ Dark Matter could be a stable $\mathrm{TC}\pi$, and F could decay into it.
+ 750 GeV could source $M_h \sim \mathrm{loop} \times \Lambda_{\mathrm{TC}}$ in modified naturalness?

F as TCη

$$\frac{\Gamma(F\to\gamma\gamma)}{M_F} = \frac{\alpha_{\text{em}}^2}{64\pi^3}\frac{\kappa_{\gamma\gamma}^2 M_F^2}{f_{\text{TC}}^2} = 10^{-6}(\kappa_{\gamma\gamma}\frac{120\text{ GeV}}{f_{\text{TC}}})^2.$$

$$\frac{1}{\Lambda_{VV'}} = \frac{\kappa_{VV'}}{8\pi^2 f_{\text{TC}}}, \qquad \kappa_{VV'} = N\,\text{Tr}\,(T_F T^V T^{V'})$$

Sample model: extra SU(N_{TC}) with $\mathcal{Q} = N_1 \oplus N_2 \oplus U$.

$$\text{TC}\pi = \underbrace{(8,1)_0}_{\chi\sim U\bar U} \oplus \underbrace{2\times[(\bar 3,1)_{-2/3} + (3,1)_{2/3}]}_{\phi_i\sim U\bar N_i,\ \phi_i^*} \oplus \underbrace{4\times(1,1)_0}_{\Pi\sim N_1\bar N_2,\ \Pi^*,\ \eta_{1,2}}$$

$\eta_2 \sim N_1\bar N_1 - N_2\bar N_2$, $\eta_1 \sim N_i\bar N_i - \frac{3}{2}U\bar U$, $\eta' \sim \mathcal{Q}\bar{\mathcal{Q}}$ up to mixings $\propto m_{N_1} - m_{N_2}$.

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

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

$\Gamma(\eta_1 \to \Pi\Pi^*) \sim$ GeV $\times\,\theta_{\text{TC}}^2$. Predictive! Look for extra resonances

$\mathcal{F}$ as dilaton

aka "the Higgs of the Higgs": all masses M arise from $\langle \mathcal{F} \rangle$.

Signature: $\mathcal{F}$ couples to everybody as $M/\langle \mathcal{F} \rangle$.

$\mathcal{F} \to \gamma\gamma$ if extra heavy charged particles get mass as $M = y\langle \mathcal{F} \rangle$, y cancels out

$$\mathscr{L}_{\rm eff} = \sum_{i,\mathcal{Q}} \Delta b_i^{\wp} \frac{\alpha_i}{8\pi} (F^i_{\mu\nu})^2 \ln \frac{M_{\mathcal{Q}}(\mathcal{F})}{M_{\mathcal{Q}}} \qquad \frac{\Gamma(\mathcal{F} \to \gamma\gamma)}{M_{\mathcal{F}}} = 10^{-6} (\Delta b_{\rm em} \frac{120\,\text{GeV}}{\langle \mathcal{F} \rangle})^2$$

Strongly coupled models where $g_{\rm TC}$ 'walks' non-perturbative around 750 GeV, $\mathcal{F}$ can be the composite TCσ. RS radion in models with AdS dual.

Weakly coupled models where $\mathcal{F}$ is a fundamental scalar and its quartic runs negative around 750 GeV generating $M_{\mathcal{F}}, M_h, M_W, \ldots$ a la Coleman-Weinberg.

Theories


Ferrari 125


Ferrari 750
MONZA SCAGLIETTI 1955
MILLE MIGLIA 2014

The Big Picture

'Who ordered that?' Naturalness?

$F \to \gamma\gamma$ needs extra charged states, why are they light?

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

Unification could give extra light multiplets, **extra dimensions**, **strings**...

Scale invariance would keep extra states light.

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

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

What next?

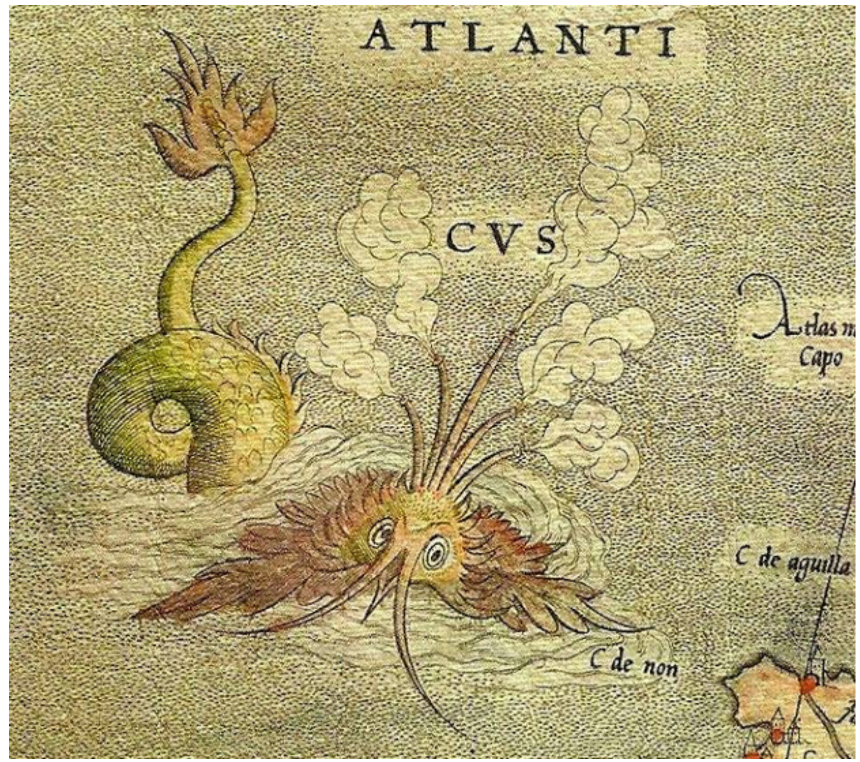
Warnings

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

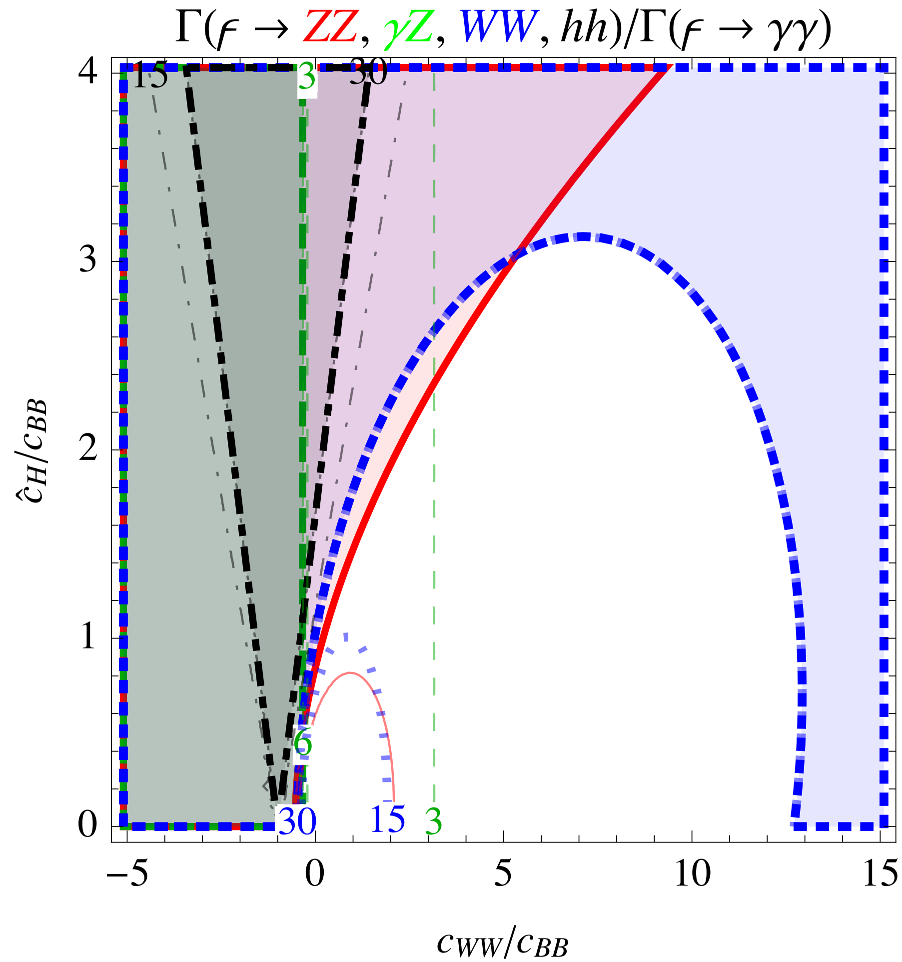
H: SM NNNLO predictions $\Rightarrow$ neural network analyses of issues 'with the same potential for surprises as Brasil-Tonga'.

F: 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. $F \to ZZ, \gamma Z$: a must implied by $F \to \gamma\gamma$.
2. $F \to W^+W^-$ (or correlations of 1) would tell that SU(2)$_L$ is involved.
3. $F \to hh$ (or correlations of 1,2) would tell that H is involved.
4. $F \to t\bar{t}, b\bar{b}, \ldots$ 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 $1/M_F^4$ terms: only the universal $T_{\mu\nu}$ is conserved.
The zombie could even be CP-odd: discriminate with $\Delta\eta_\gamma$ and $50\,\text{fb}^{-1}$.
Or look at extra resonances.

Which initial state?

1) $\mathcal{F}\gamma\gamma$ and $\mathcal{F}q\bar{q}$ already disfavoured by σ_{13}/σ_8.
2) $\wp \to \mathcal{F}$ implies $\mathcal{F} \to \wp$.
3) $\mathcal{F}q\bar{q}H$ implies a large $\Gamma(\mathcal{F} \to q\bar{q}H) \sim 1\% \times \Gamma(\mathcal{F} \to q\bar{q})$ where $H = \{h, Z, W^\pm\}$.
4) Distributions of $p_{T\mathcal{F}}$ and $\eta_\mathcal{F}$
5) $\mathcal{F}j$, $\mathcal{F}b$, $\mathcal{F}V$

	$\mathcal{F}$ couples to					
$\sqrt{s} = 13\,\text{TeV}$	$b\bar{b}$	$c\bar{c}$	$s\bar{s}$	$u\bar{u}$	$d\bar{d}$	GG
$\sigma_{\mathcal{F}j}/\sigma_\mathcal{F}$	9.2%	7.6%	6.8%	6.7%	6.2%	27.%
$\sigma_{\mathcal{F}b}/\sigma_\mathcal{F}$	6.2%	0	0	0	0	0.32%
$\sigma_{\mathcal{F}jj}/\sigma_\mathcal{F}$	1.4%	1.0%	0.95%	1.2%	1.0%	4.7%
$\sigma_{\mathcal{F}jb}/\sigma_\mathcal{F}$	1.2%	0.18%	0.19%	0.34%	0.31%	0.096%
$\sigma_{\mathcal{F}bb}/\sigma_\mathcal{F}$	0.31%	0.17%	0.18%	0.34%	0.31%	0.024%
$\sigma_{\mathcal{F}\gamma}/\sigma_\mathcal{F}$	0.37%	1.5%	0.38%	1.6%	0.41%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}Z}/\sigma_\mathcal{F}$	1.1%	1.1%	1.3%	2.0%	1.9%	$3\ 10^{-6}$
$\sigma_{\mathcal{F}W+}/\sigma_\mathcal{F}$	$5\ 10^{-5}$	1.7%	2.4%	2.6%	4.1%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}W-}/\sigma_\mathcal{F}$	$3\ 10^{-5}$	2.3%	1.2%	1.0%	1.7%	$\ll 10^{-6}$
$\sigma_{\mathcal{F}h}/\sigma_\mathcal{F}$	1.0%	1.1%	1.2%	1.9%	1.8%	$1\ 10^{-6}$

Singlet or doublet or...?

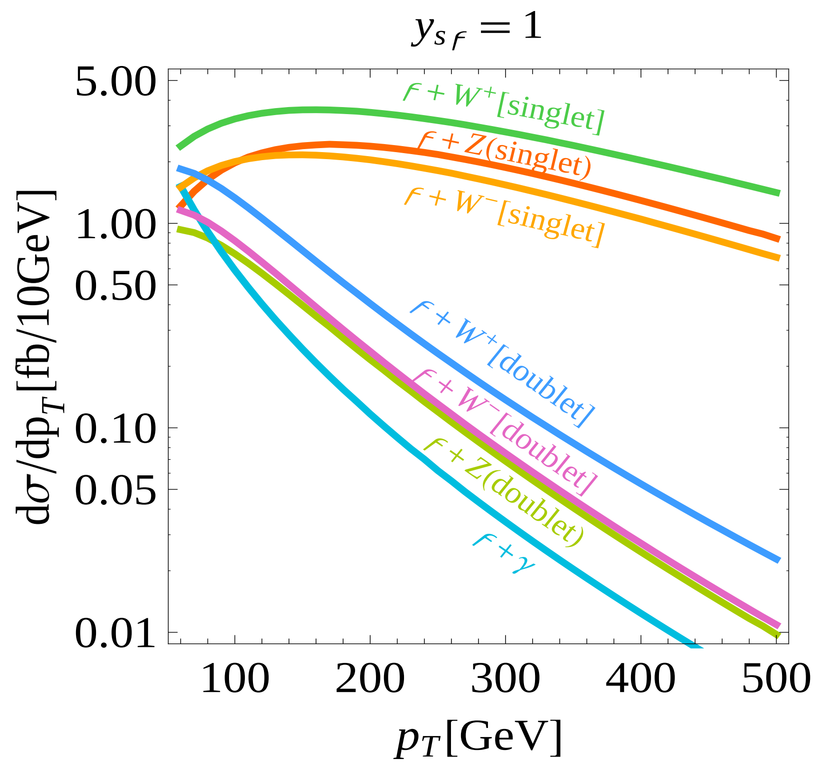
1) Extra component of multiplets must be around 750 GeV.

2) From the production mode: normally

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

3) $p_{T\mathcal{F}}$ in associated production tells the dimension of the operator, testing abnormalities:

- ◦ singlet coupled to $q\bar{q}$ gives hard $q\bar{q} \to \mathcal{F} V_L$
- ◦ doublet coupled to gg gives hard $gg \to \mathcal{F} V_L V_L$



Scalar or pseudo-scalar?

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

Technique	Problems
measure $\digamma \to \gamma^*\gamma^* \to 4\ell$	$\Gamma_{4\ell}/\Gamma_{\gamma\gamma} \approx 10^{-3}$
measure $\digamma \to \gamma\gamma \to 4\ell$ in matter	Small e^+e^- angle
measure $pp \to \digamma jj$	$\sigma_{\digamma jj}/\sigma_{\digamma} = 0.04$
Even if $\digamma \to hh$	$\digamma hh$ exists?
Odd if $\digamma \to hZ$	$\digamma hZ$ exists??
measure $\digamma \to ZZ \to 4\ell$	$\digamma ZZ$ exists*?
measure $pp \to Z \to \digamma Z$	$\digamma ZZ$ exists*?
measure $\digamma \to Z\gamma^{(*)} \to 4\ell$	$\digamma Z\gamma$ exists?

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

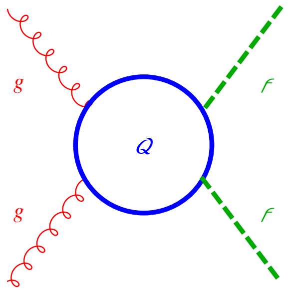
$\digamma$ couplings?

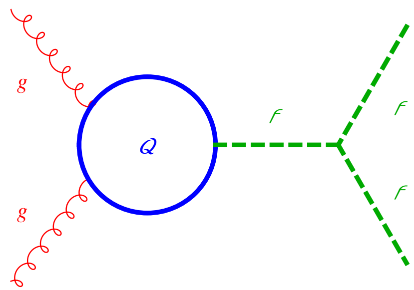
1) From Γ if large enough,
2) one could even see interference with SM background.
3) SU(2)$_L$ relates different widths allowing to identify operators.
4) $\digamma \to$ DM DM from $\not{E}_T$ as usual.
5) $pp \to \digamma j, \digamma V \ldots$ probe the energy dependence of the couplings.
6) $pp \to \digamma\digamma$ would imply large $\digamma^3$ or $\digamma \mathcal{Q}\mathcal{Q}$.

Double $\mathcal{F}$ production

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

$$\sigma(pp \to \mathcal{F}\mathcal{F}) \sim$$



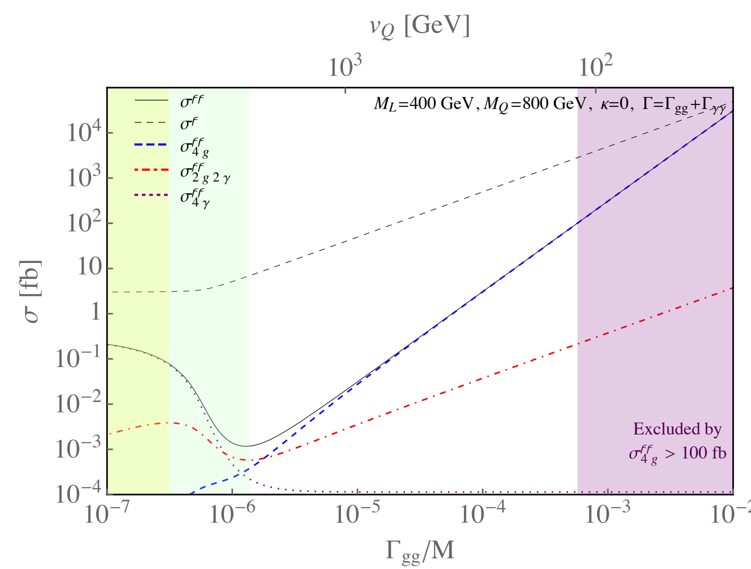


$$\sim \left(\frac{y M_{\mathcal{F}}}{4\pi M_{\mathcal{Q}}} + \frac{\kappa}{4\pi M_{\mathcal{F}}}\right)^2 \sigma(pp \to \mathcal{F})$$

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

$$\mathscr{L}_{\text{eff}} = \frac{\alpha_3 I N}{6\pi} G_{\mu\nu}^2 \ln(1 + \frac{\mathcal{F}}{v_Q}) \qquad \frac{1}{v_Q} \equiv \frac{y}{M_{\mathcal{Q}}}$$

Signals: $pp \to \mathcal{F}\mathcal{F} \to jjjj, jj\gamma\gamma, \gamma\gamma\gamma\gamma$



Extra fermions or scalars

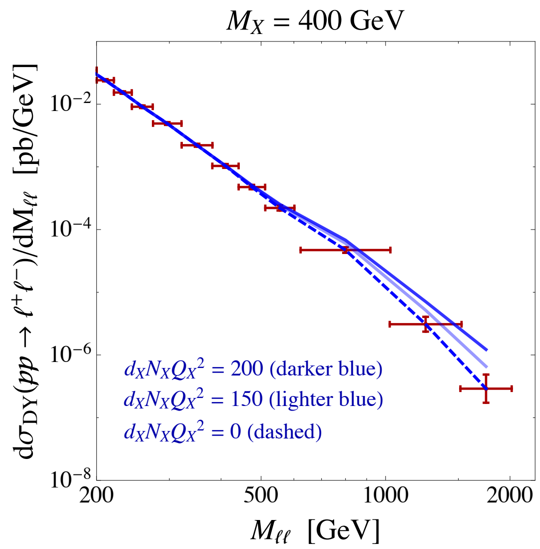
A) Discover $\mathcal{Q}$ at LHC (some anomalies...).

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

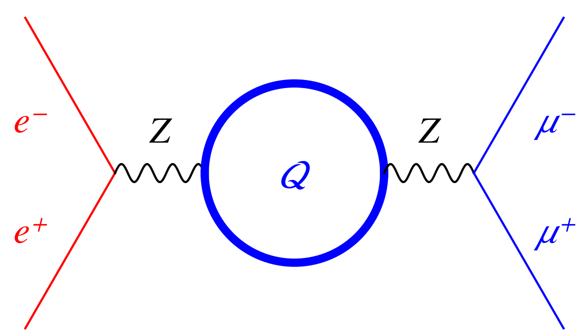
B) High-energy tails of

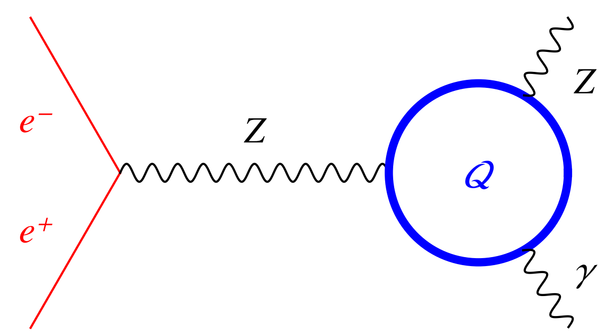
$$\sigma(pp \to \ell^+\ell^-) \propto g^4(\bar{\mu} \sim m_{\ell\ell})$$

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



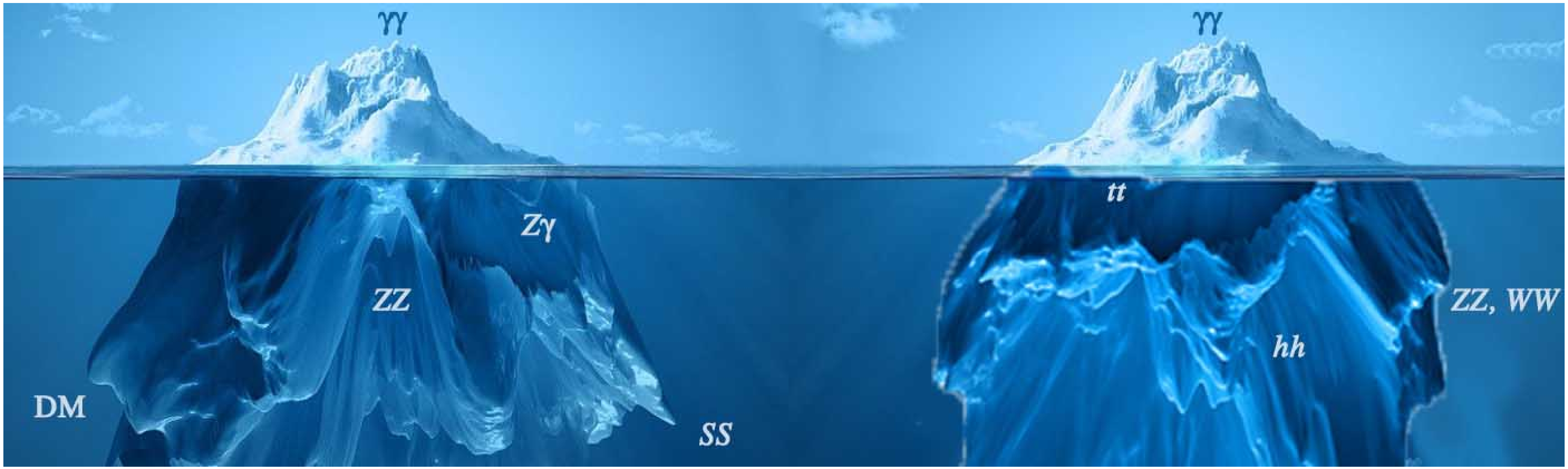
C) e^+e^- collider: even if $\mathcal{Q}$ is too heavy, it could be probed indirectly as W, Y...





Conclusions

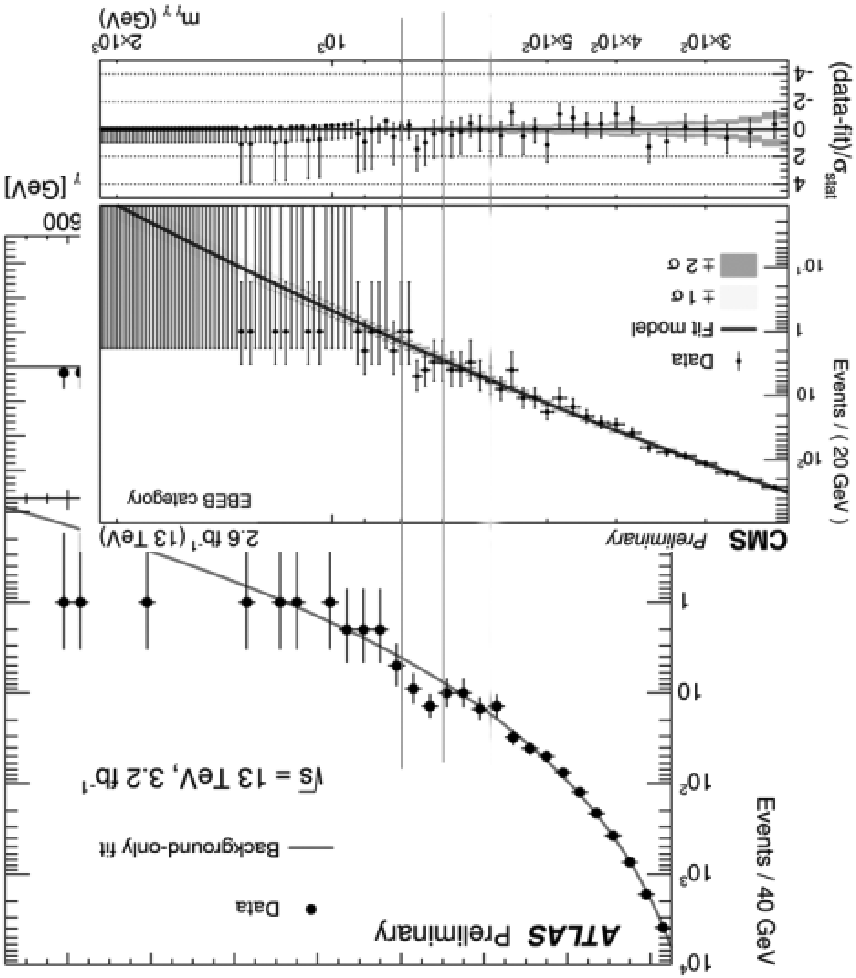
- $\gamma\gamma$@750 should be accompanied by $\gamma Z, ZZ$@750 and by new particles.
- $\Gamma/M \sim 0.06$ difficult to reproduce even with new strong interactions.
- A jungle of reasonable models can reproduce a small width



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?**

Expect $\sigma_{13}(pp \to F \to \gamma\gamma) \approx 3\,\text{fb}$, not more. New data to be shown at ICHEP.

No rumors, a moment of silence



"Any significant (i.e. discovery-like) result has first to be announced in a seminar at CERN".

† DG

no diphoton ⇔ no party

"4 fb^{-1} seen now".

†† CMS@SUSY

"Where the wild roses grow, since, all beauty must die".

† † † ATLAS@SUSY