HAVE WE OBSERVED NEW PHYSICS AT THE LHC?

IFAE 2016

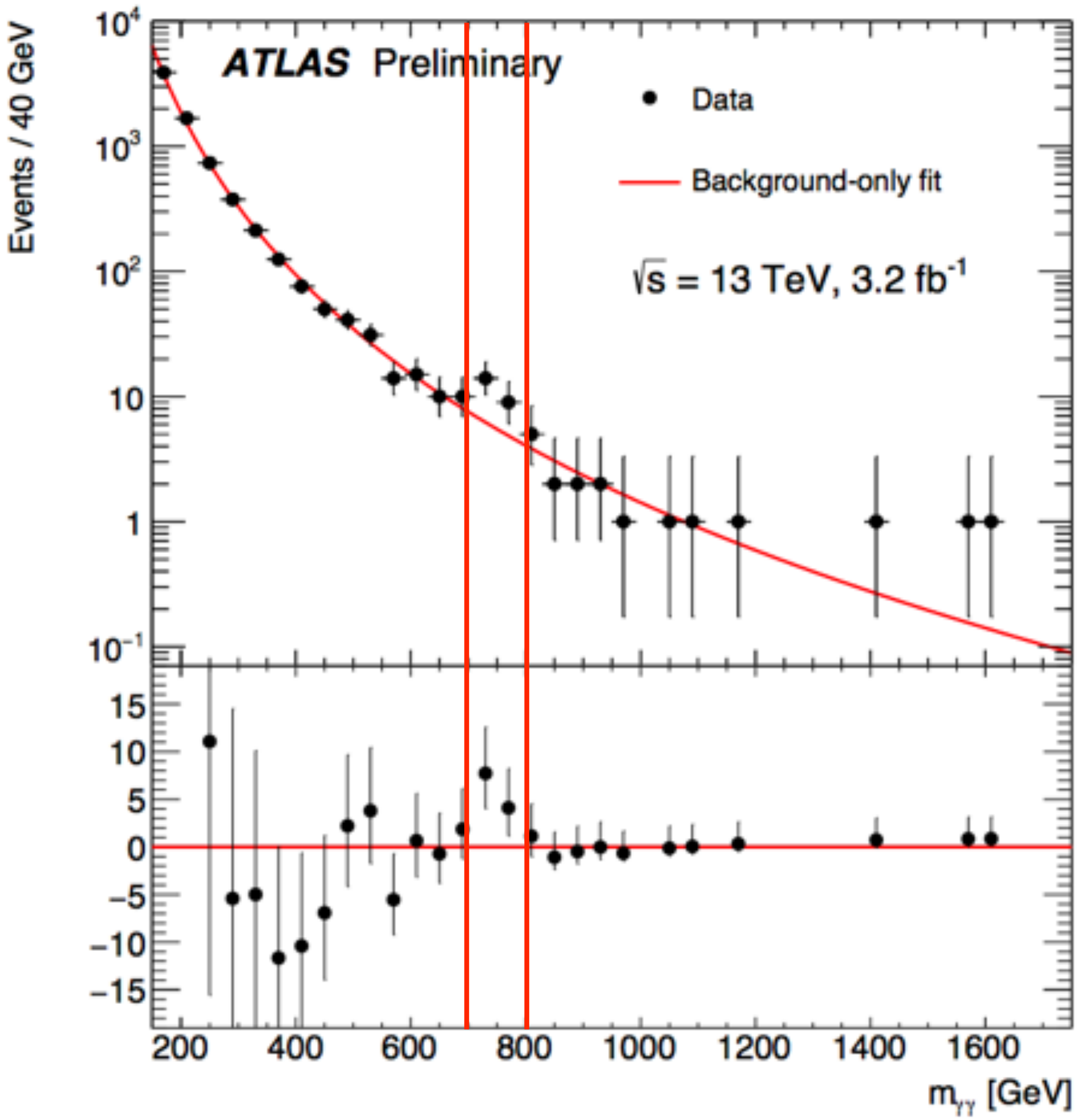
Riccardo Torre

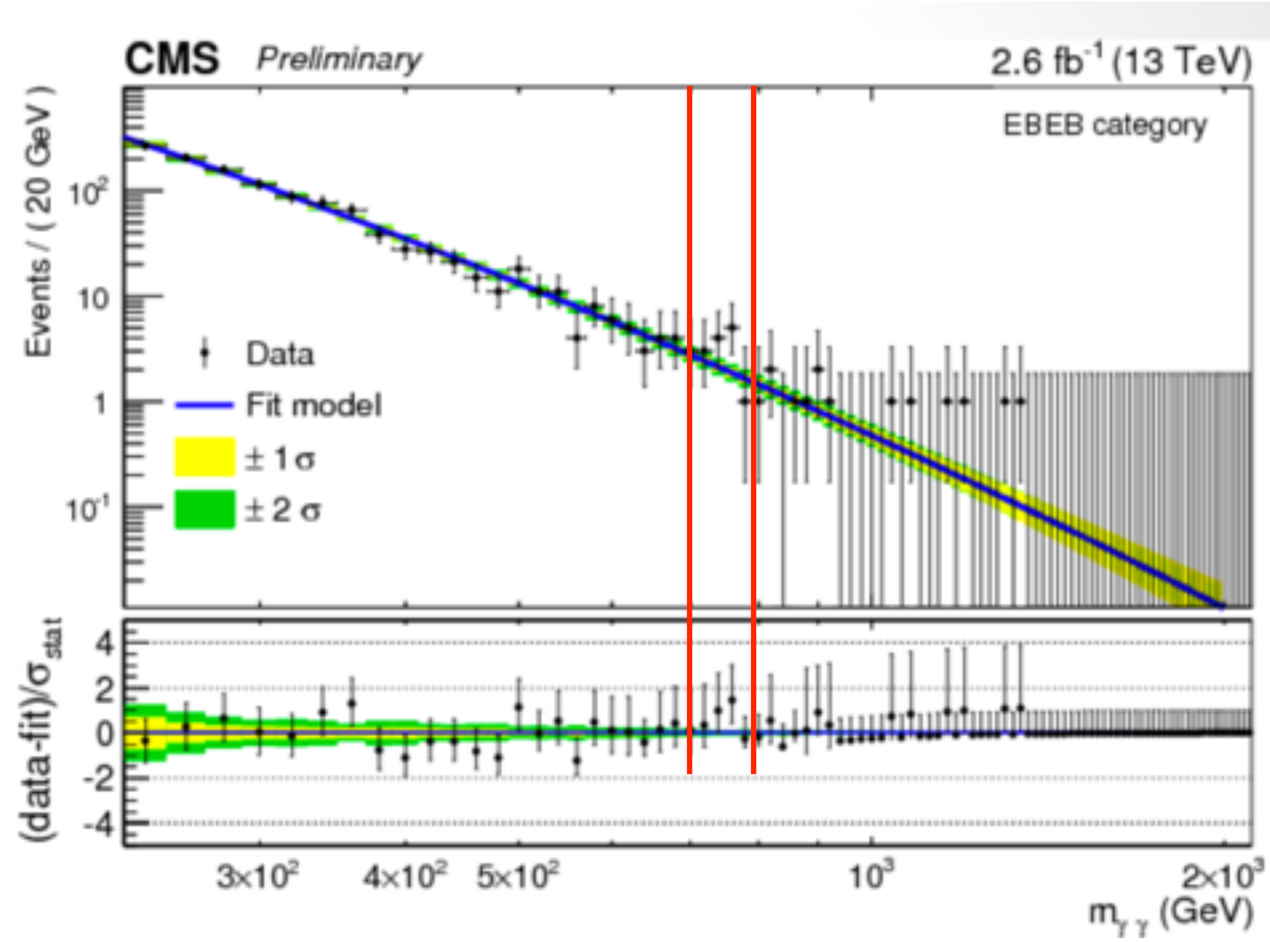
EPFL Lausanne

Genova - 30 March 2016

R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Pomarol, R. Rattazzi, M. Redi, F. Riva, A. Strumia, R. Torre, arXiv:1512.04933,
C. Petersson and R. Torre, arXiv:1512.05333,
R. Franceschini, G. F. Giudice, J. F. Kamenik, M. McCullough, A. Strumia, R. Torre, in progress

WHAT HAS BEEN SEEN?





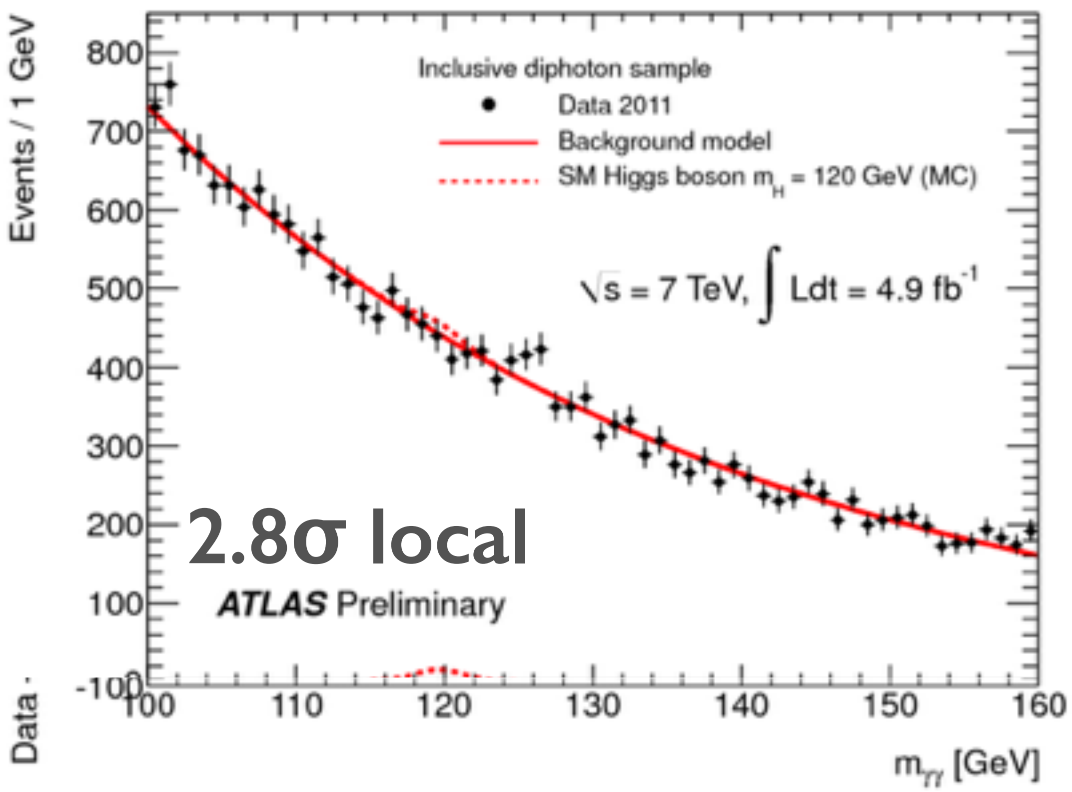
PROS

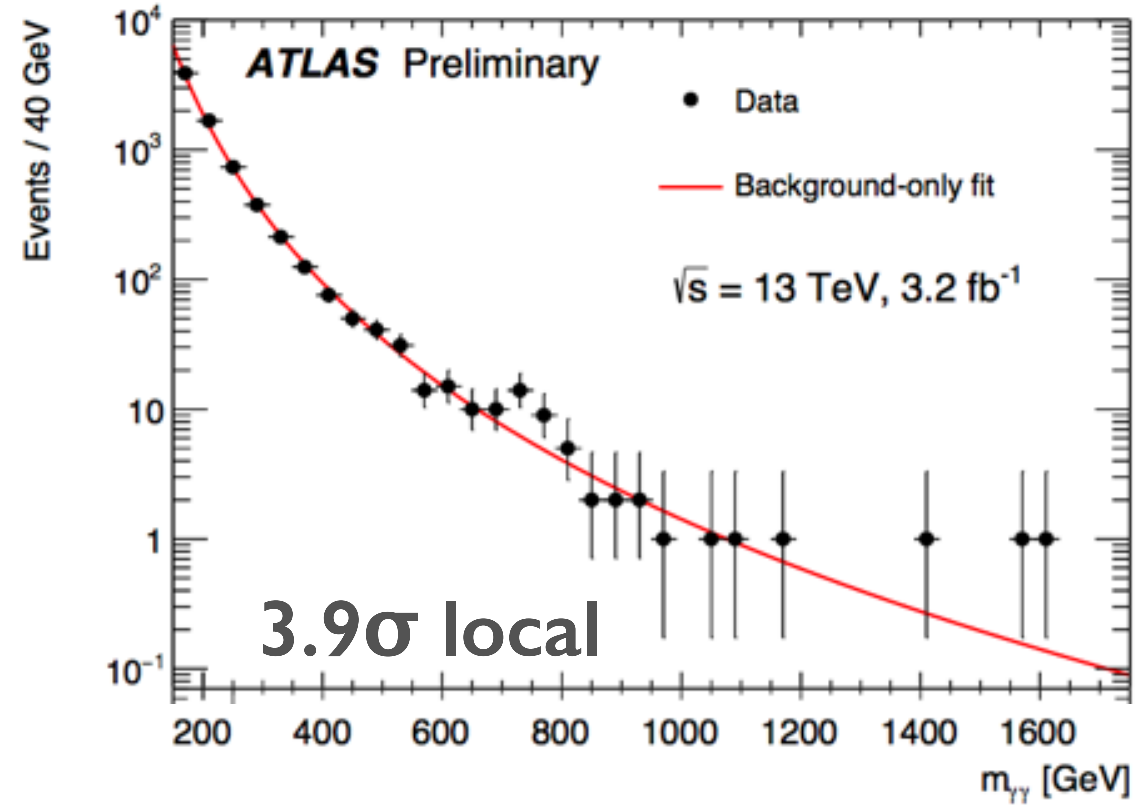
- One of the simplest channels at collider
- Lot of experience from the Higgs

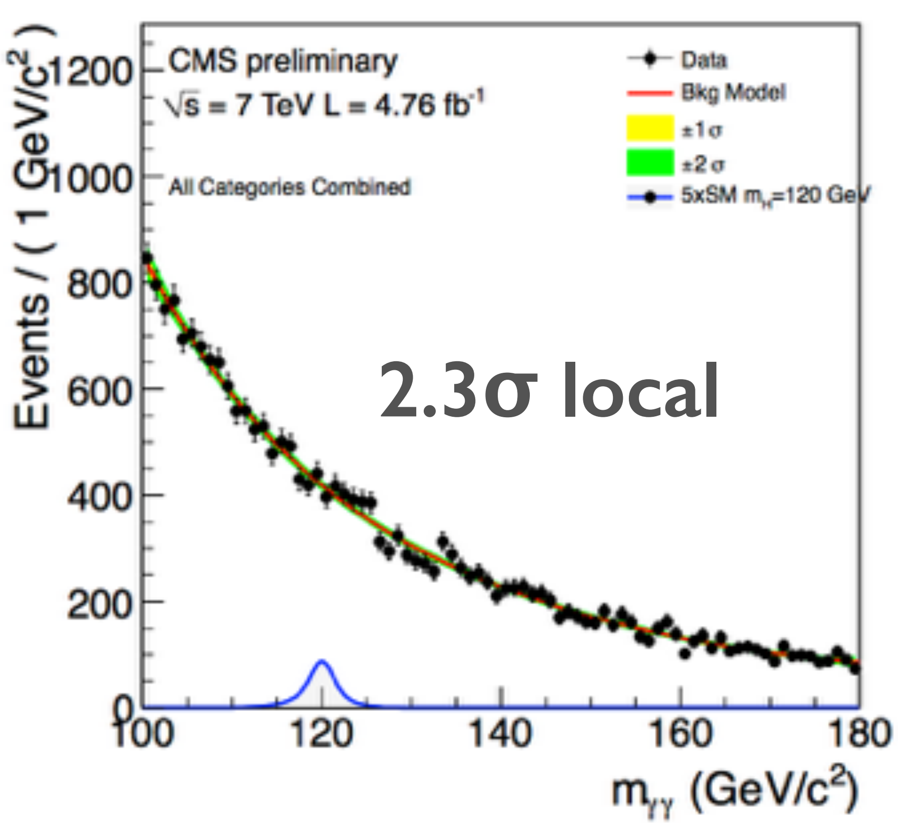
CONS

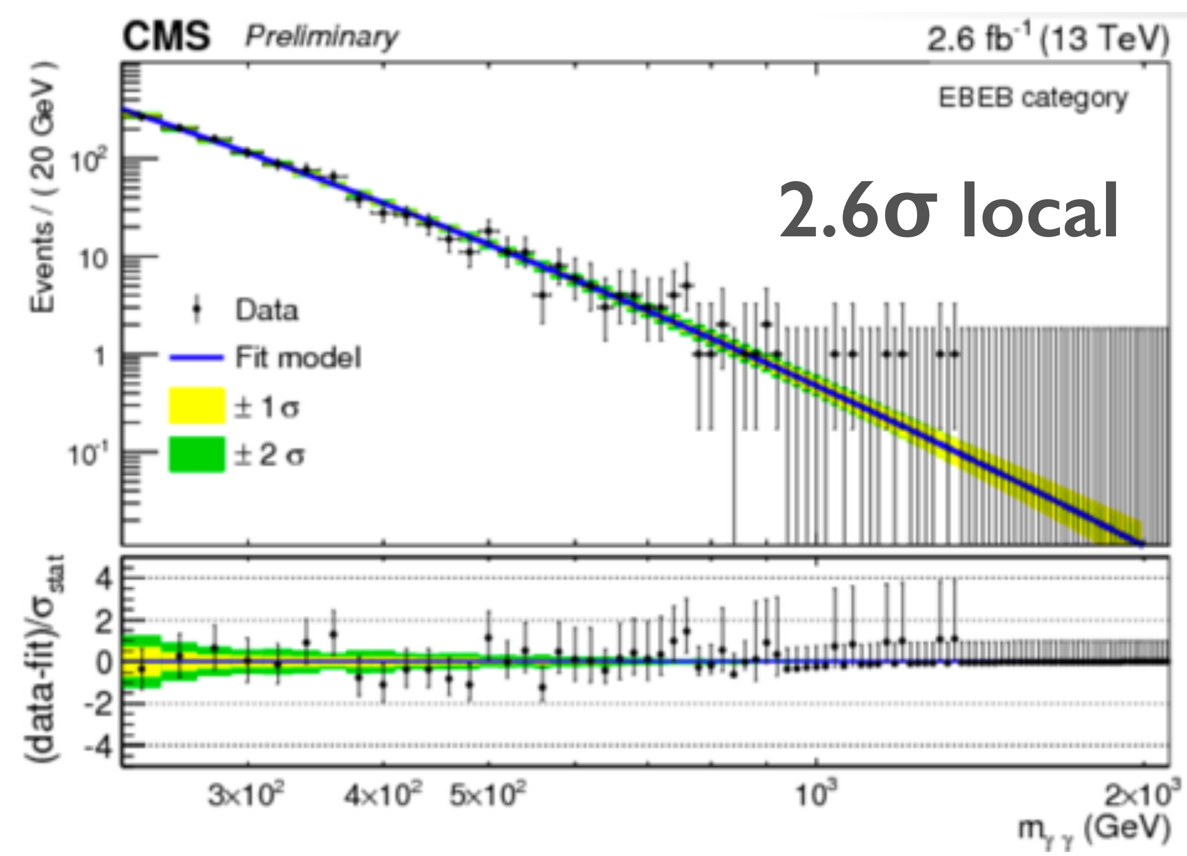
- Limited statistics (could well be a fluctuation)
- Little (public) information about the events (additional jets, met etc.)

A BAYESIAN COMPARISON (DEC 2011 VS DEC 2015)





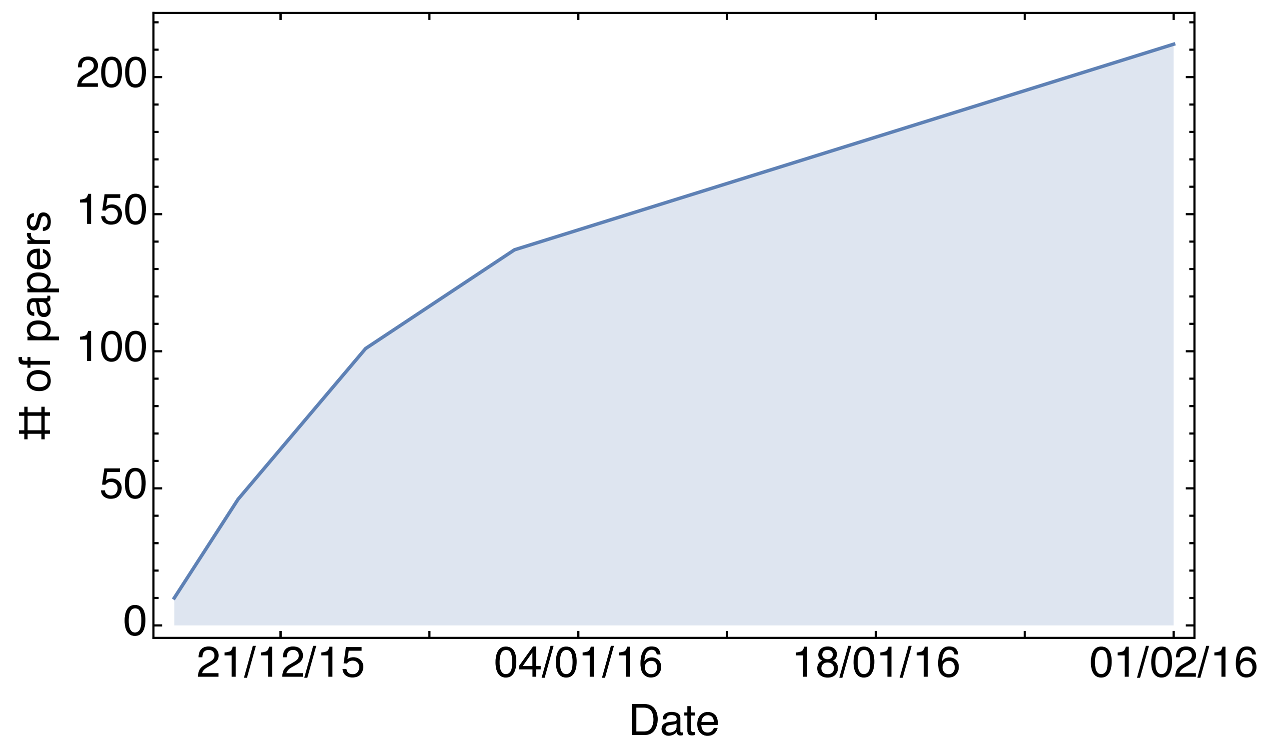




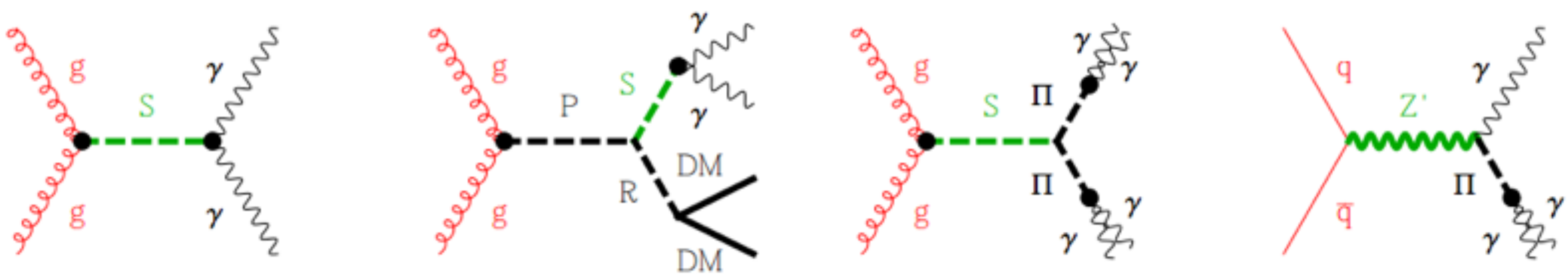
cfr. resolution, width, peak position vs resolution, width, peak position

THE THEORISTS REACTION

Even with this little information, the theory community could speculate a lot

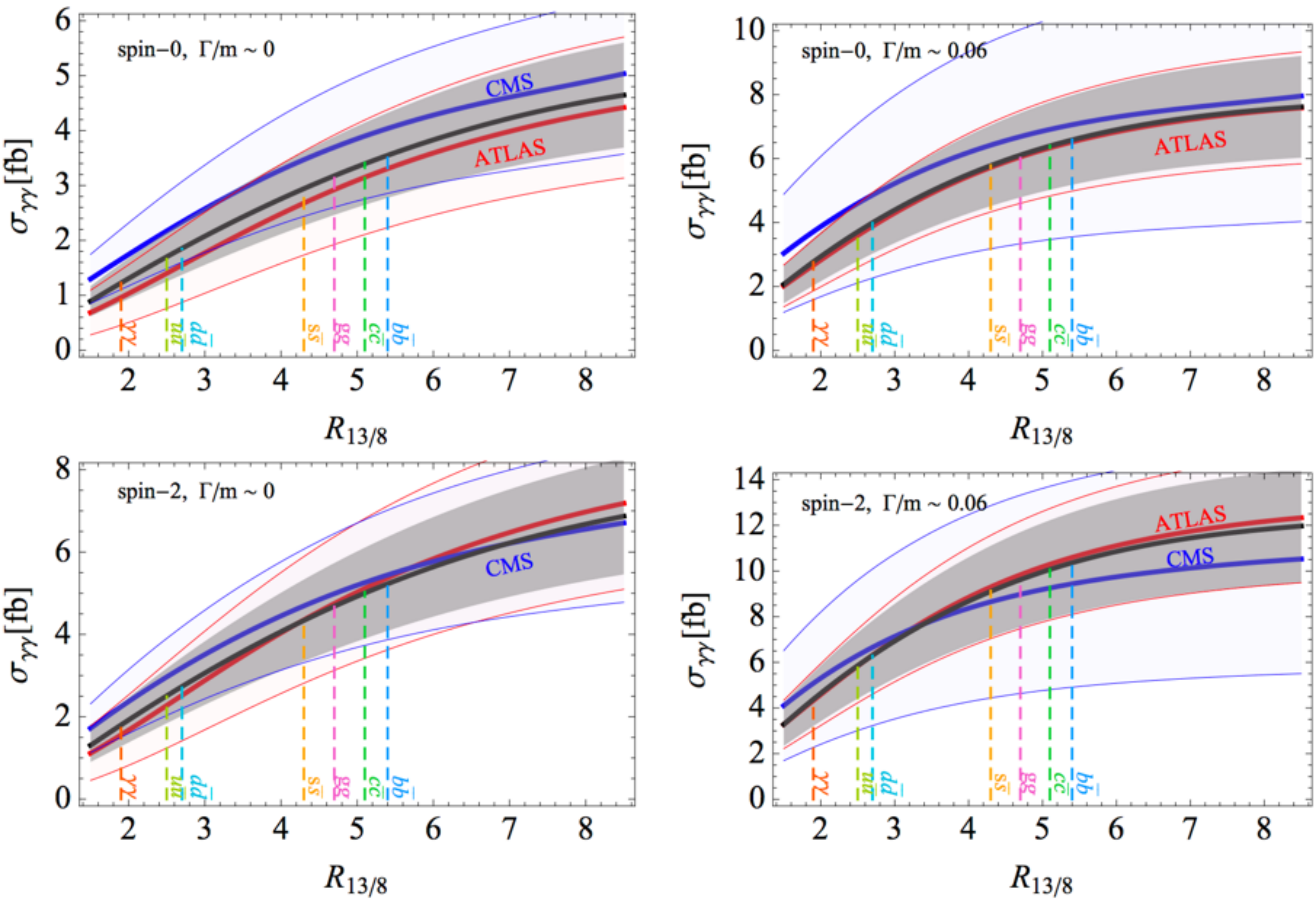


Many different explanations



- Spin 0 or 2 due to Landau-Yang
- For narrow resonance very simple (trivial) theory explanations
- For large width harder to explain (non-perturbative couplings, nearby resonances, etc.)

CROSS SECTION BEST FITS

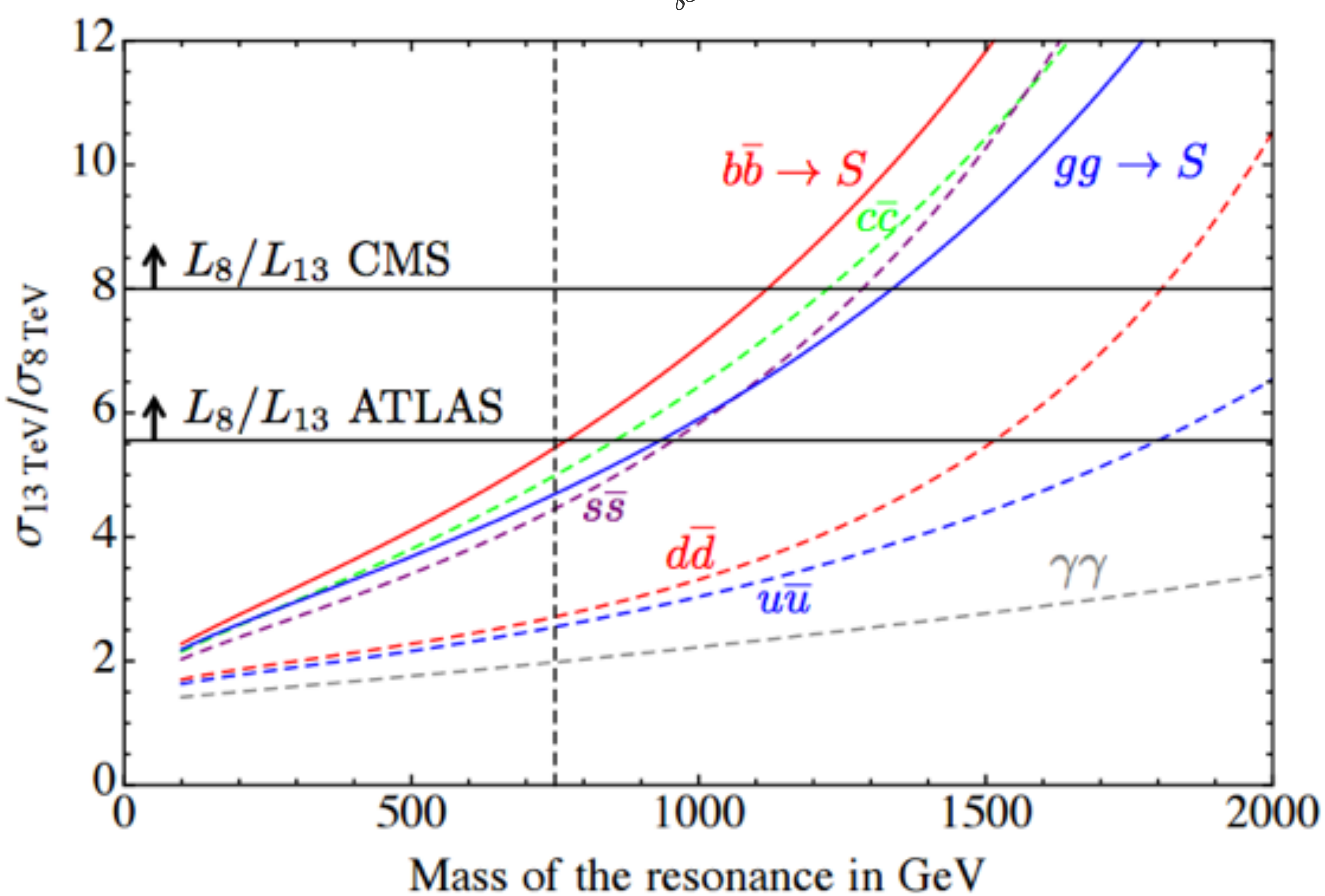


Kamenik, Safdi, Soreq, Zupan, 1603.06566 [hep-ph]

COMPATIBILITY RUN-I/RUN-II

$$\sigma(pp\to\gamma\gamma)\approx\begin{cases}(0.5\pm0.6)\,\text{fb} & \text{CMS [2]} & \sqrt{s}=8\,\text{TeV},\\ (0.4\pm0.8)\,\text{fb} & \text{ATLAS [3]} & \sqrt{s}=8\,\text{TeV},\\ (6\pm3)\,\text{fb} & \text{CMS [1]} & \sqrt{s}=13\,\text{TeV},\\ (10\pm3)\,\text{fb} & \text{ATLAS [1]} & \sqrt{s}=13\,\text{TeV},\end{cases}$$

$$\sigma(pp\to S\to\gamma\gamma)=\frac{2J+1}{M\Gamma s}\left[\sum_{\wp}C_{\wp\bar{\wp}}\Gamma(S\to\wp\bar{\wp})\right]\Gamma(S\to\gamma\gamma)\qquad J=0,2$$

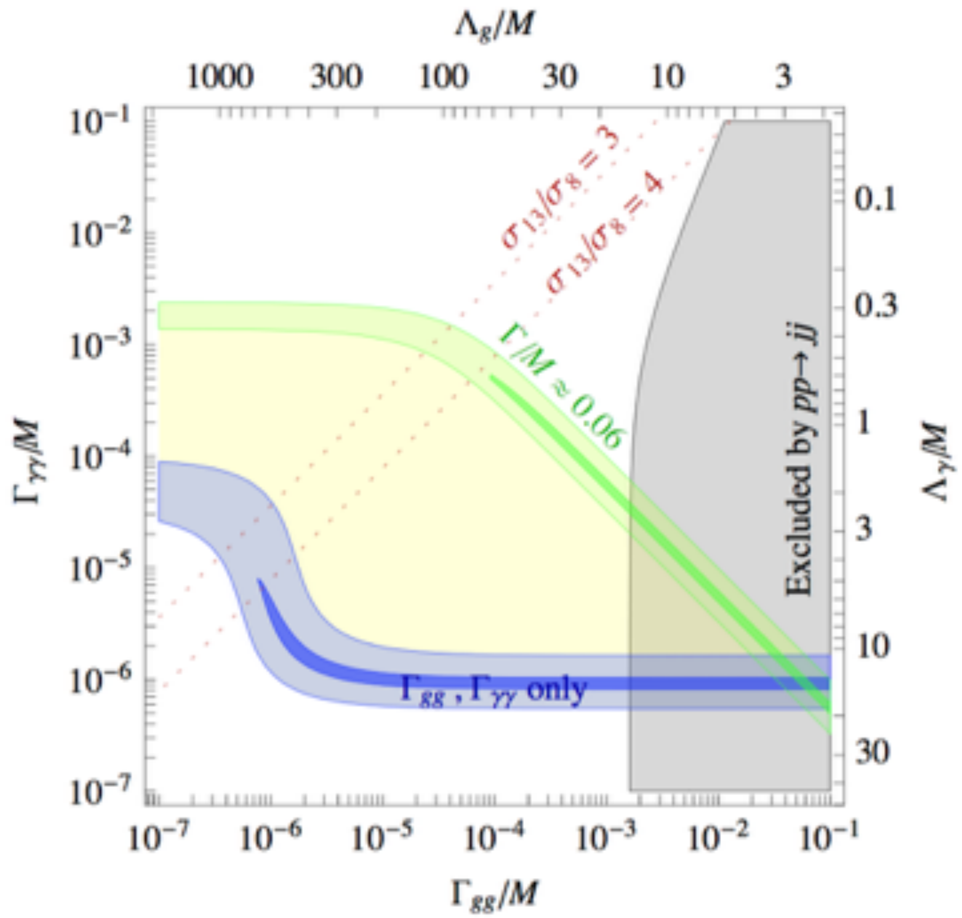


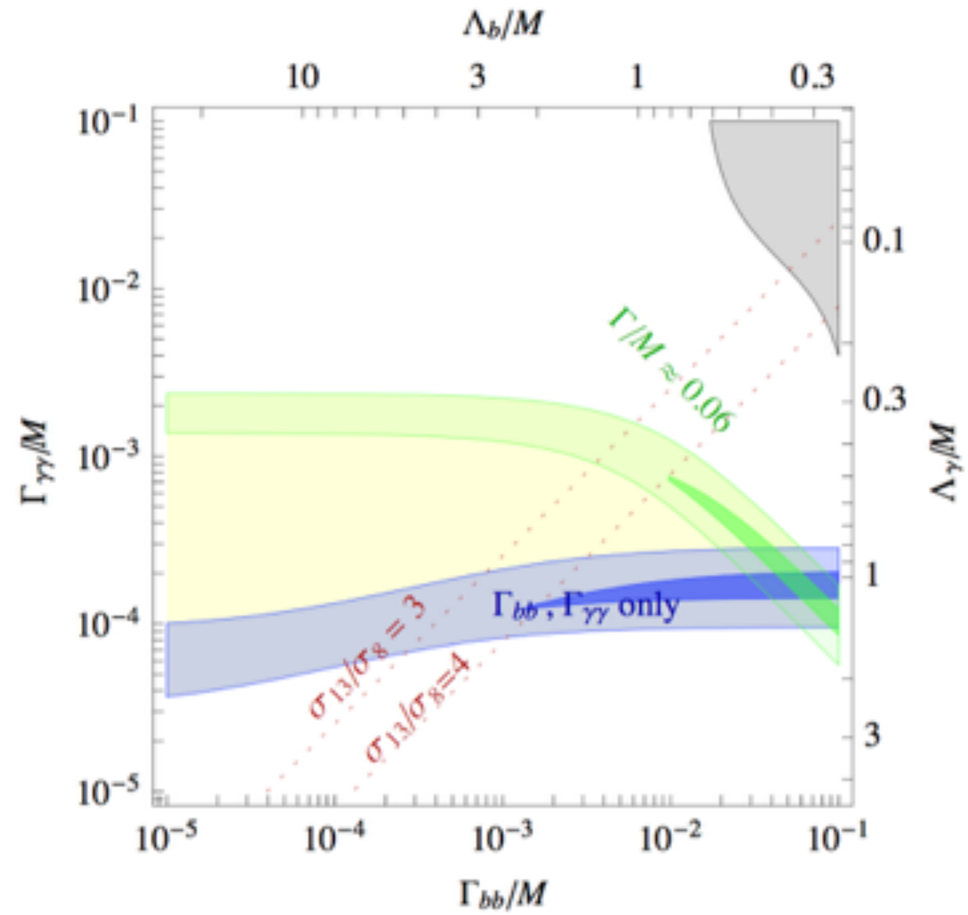
$\sqrt{s}$	$C_{b\bar{b}}$	$C_{c\bar{c}}$	$C_{s\bar{s}}$	$C_{d\bar{d}}$	$C_{u\bar{u}}$	C_{gg}	$C_{\gamma\gamma}$
8 TeV	1.07	2.7	7.2	89	158	174	11
13 TeV	15.3	36	83	627	1054	2137	54

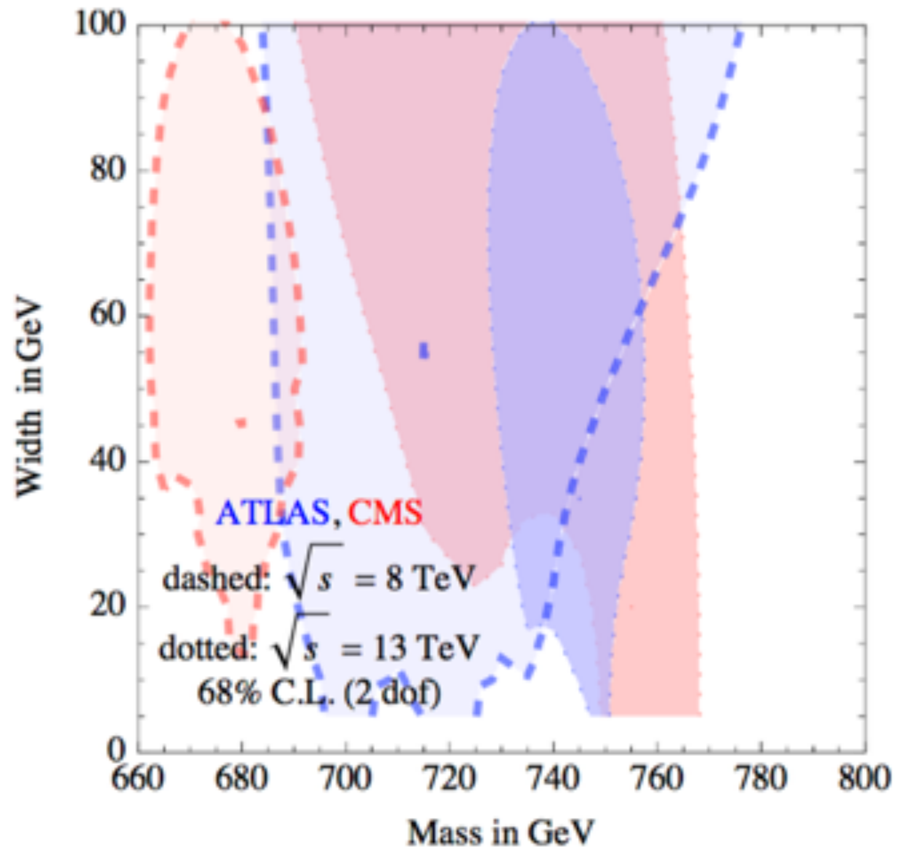
$$r=\sigma_{13\,\text{TeV}}/\sigma_{8\,\text{TeV}}=[C_{gg}/s]_{13\,\text{TeV}}/[C_{gg}/s]_{8\,\text{TeV}}$$

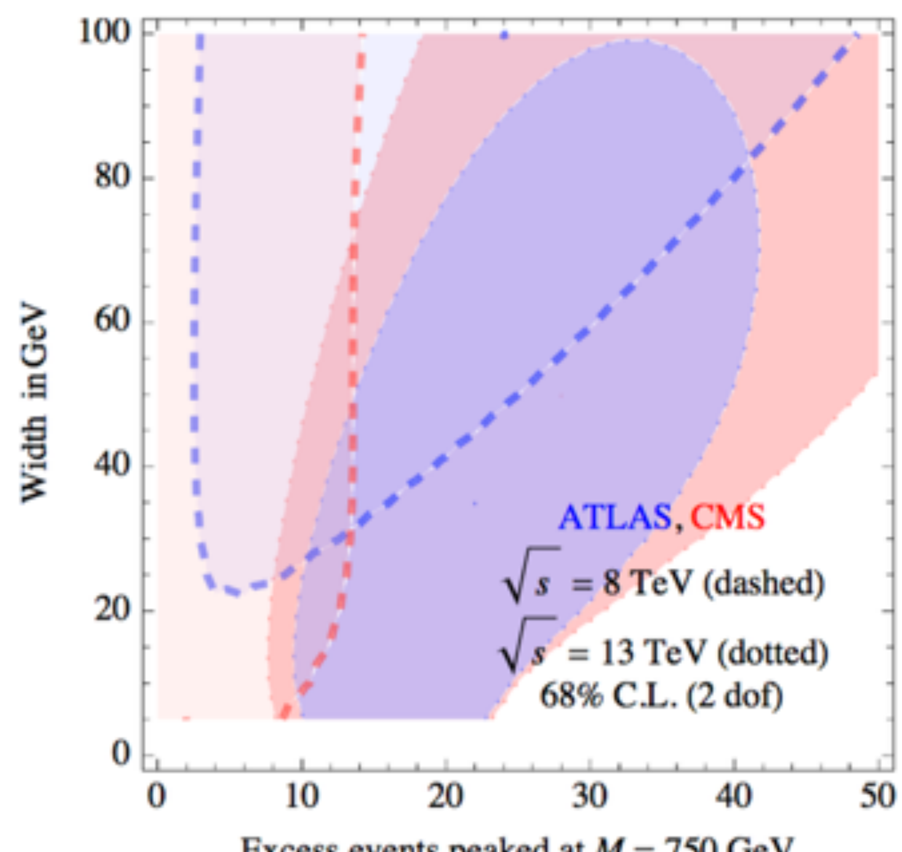
$r_{b\bar{b}}$	$r_{c\bar{c}}$	$r_{s\bar{s}}$	$r_{d\bar{d}}$	$r_{u\bar{u}}$	r_{gg}	$r_{\gamma\gamma}$
5.4	5.1	4.3	2.7	2.5	4.7	1.9

GENERAL ANALYSIS (E.G. SPIN 0)









SUMMARY OF CONSTRAINTS

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]	$< 1300\ (r/5)$

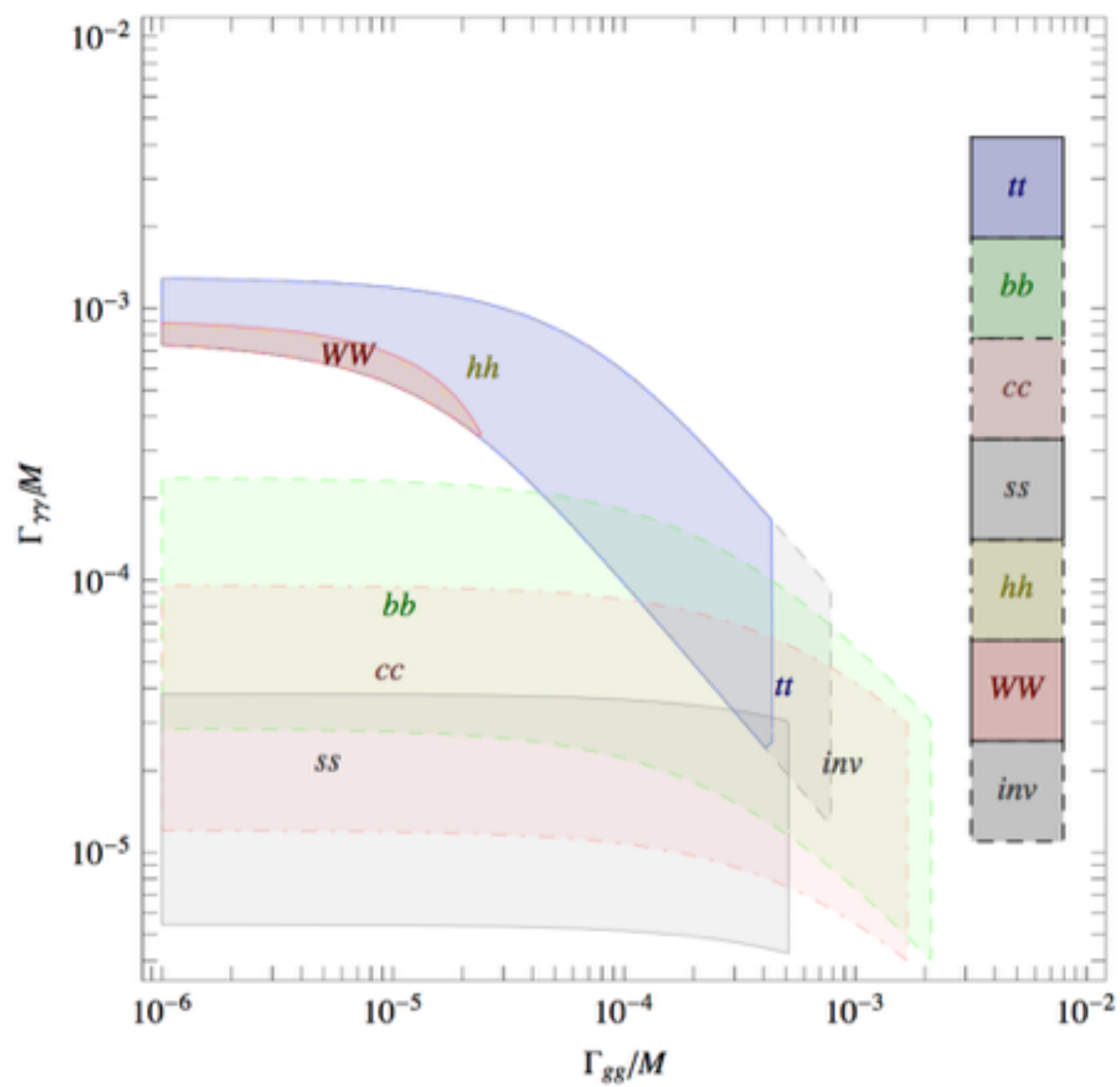
- Constraints in red very strong, these channels cannot account for sizeable width
- Constraints in green less strong, they can possibly account for a sizeable width

CONSTRAINTS VS WIDTH (E.G. SPIN 0)

Requiring to satisfy the rate, the total width $\Gamma/M \sim 0.06$ and all constraints

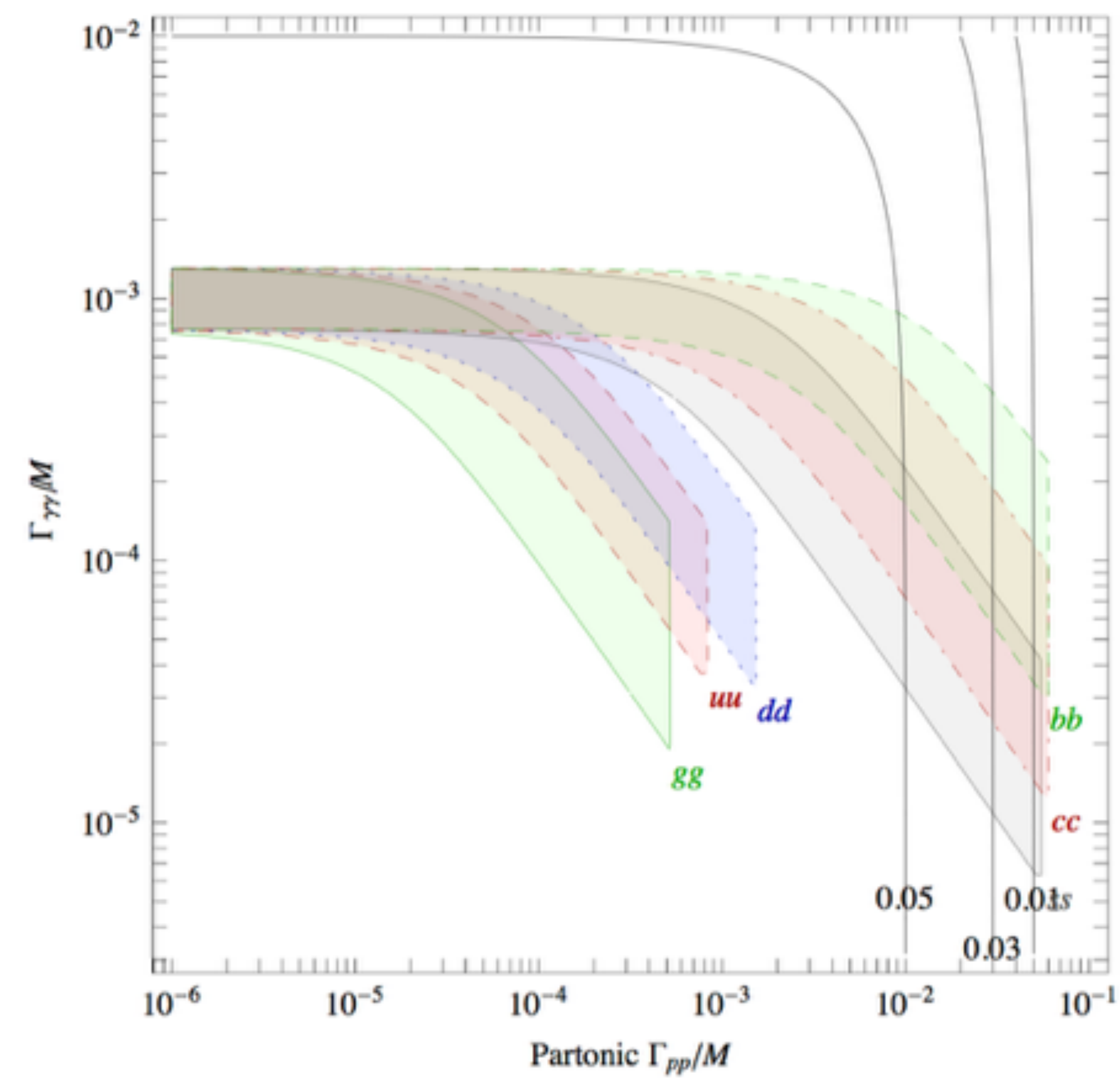
Assuming

$S \to gg, \gamma\gamma, X$



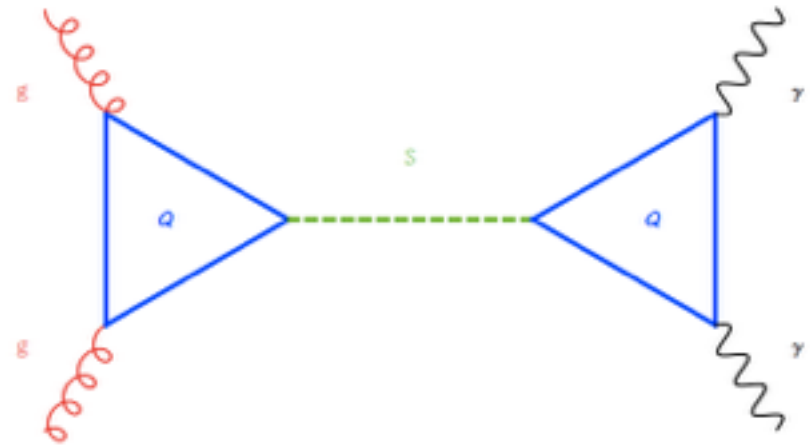
Assuming

$S \to p_i p_i, \gamma\gamma, \text{inv}$



Generally requires $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-5}$, which, as we will see, is a large value

WEAKLY COUPLED MODELS (SMALL WIDTH)

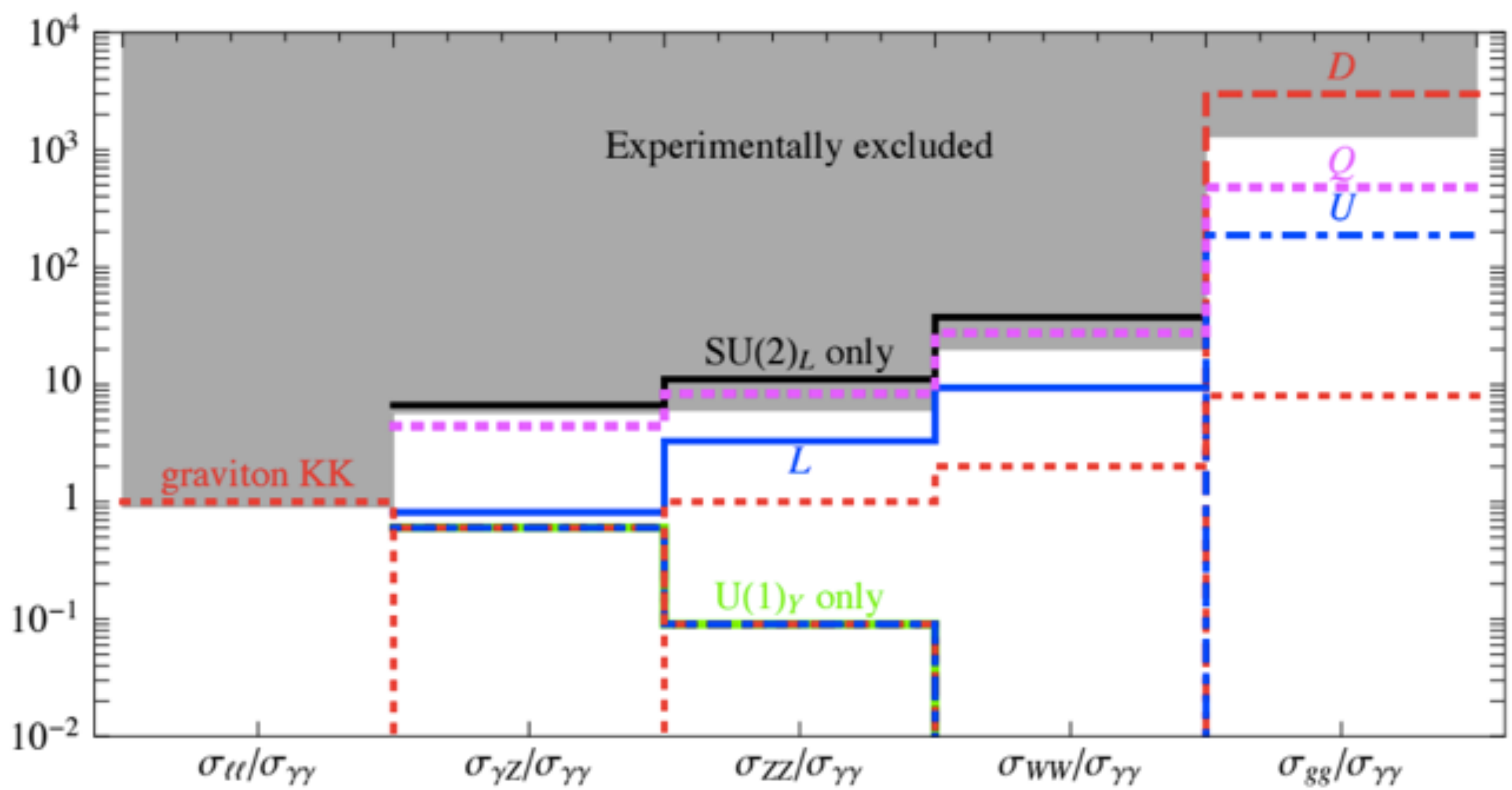


$$S\bar{Q}_f(y_f + i\,y_{5f}\gamma_5)Q_f + S A_s \tilde{Q}_s^* \tilde{Q}_s.$$

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

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

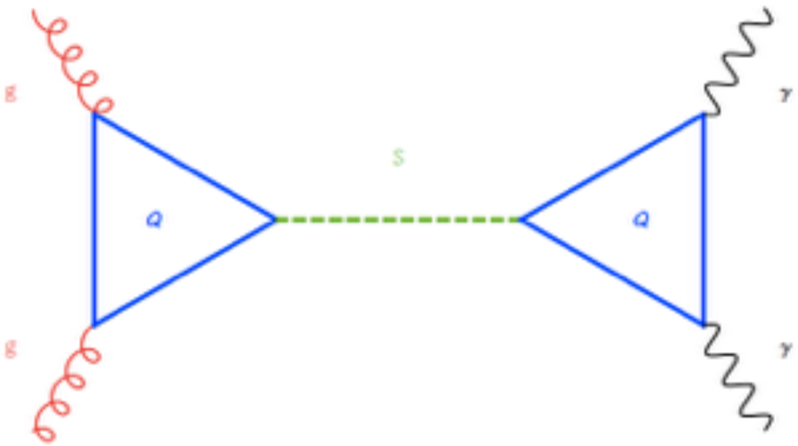
For a small width prefer $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-6}$ which seems feasible with not too large multiplicities, charges, couplings and not too light masses



L, E, U
good candidates

Note:
Cannot work with SM particles in the loop since $\Gamma_{t\bar{t}}/\Gamma_{\gamma\gamma} \approx 10^5$ which is excluded

WEAKLY COUPLED MODELS (SMALL WIDTH)

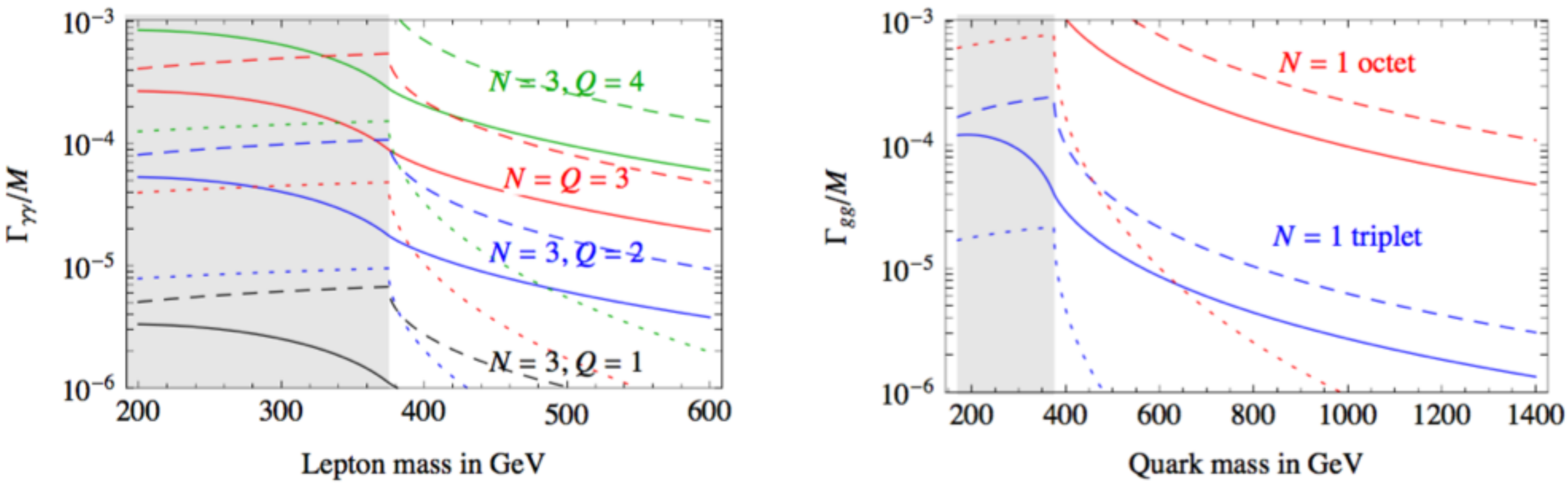


$$S\bar{\mathcal{Q}}_f(y_f + i\,y_{5f}\gamma_5)\mathcal{Q}_f + SA_s\tilde{\mathcal{Q}}_s^*\tilde{\mathcal{Q}}_s.$$

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

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

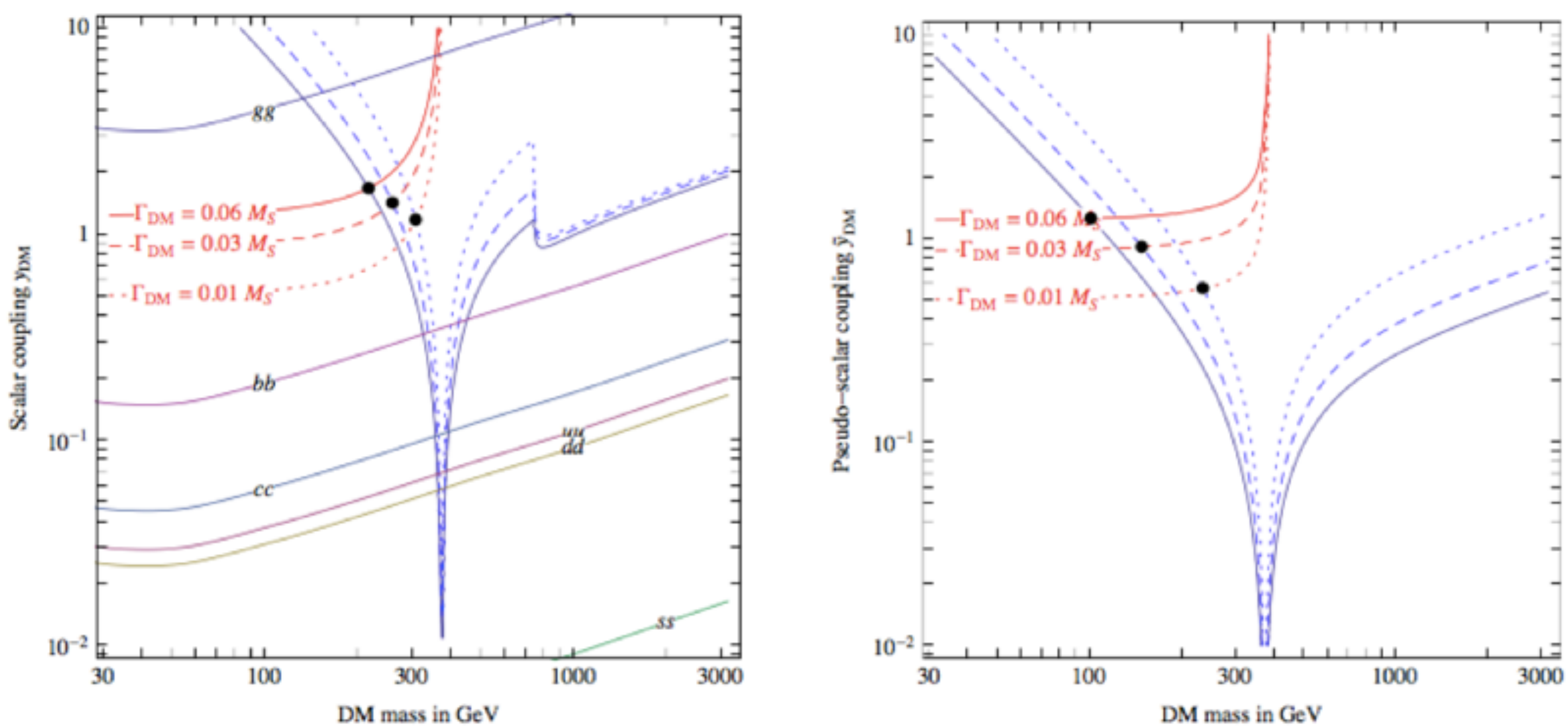
Scalar (continuous), pseudo−scalar (dashed) and cubic coupling $y, y_5 = 1$, $A = M$



A RELATION WITH DM?

- Connection with DM very appealing
- If the resonance is a portal to DM there are correlated effect on width, relic abundance, (in)direct detection
- A large invisible width can help in saturating the value preferred by ATLAS
- e.g. S is a (pseudo)scalar portal to fermionic DM

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



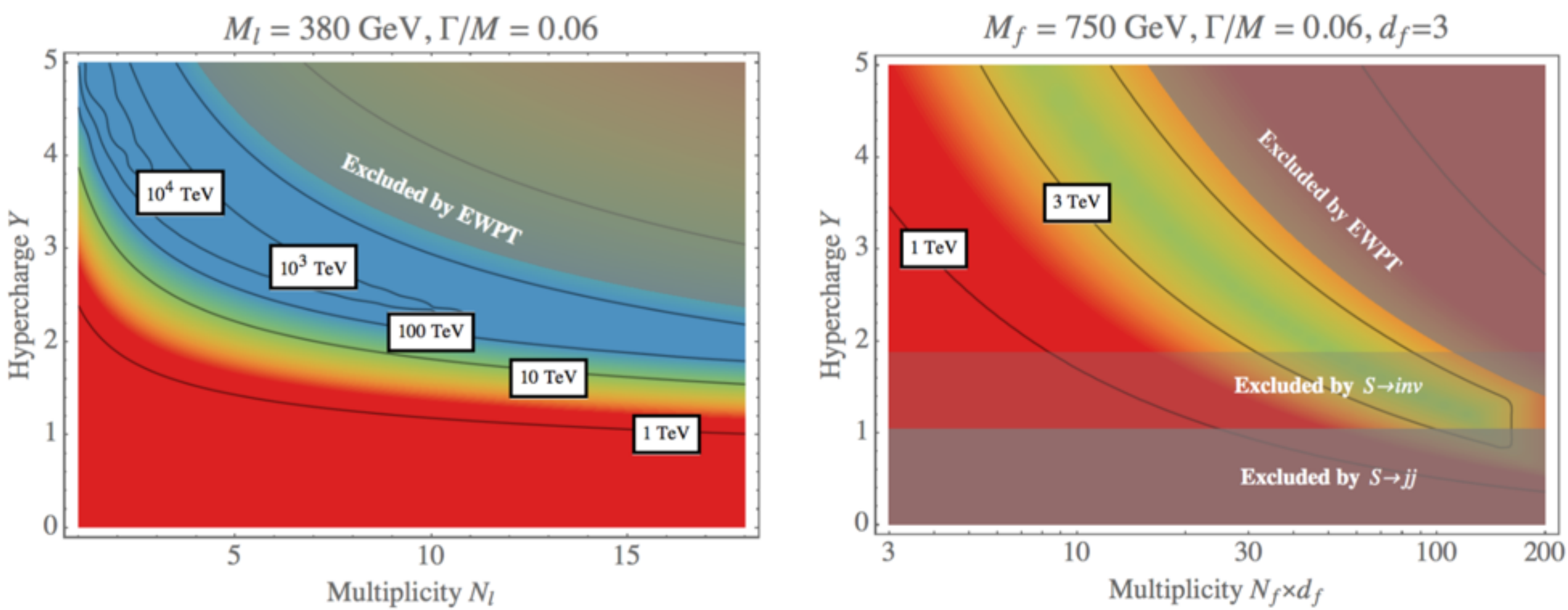
Bounds from direct detection are (weak) irrelevant for S (scalar) pseudoscalar

LARGE WIDTH → STRONG COUPLING

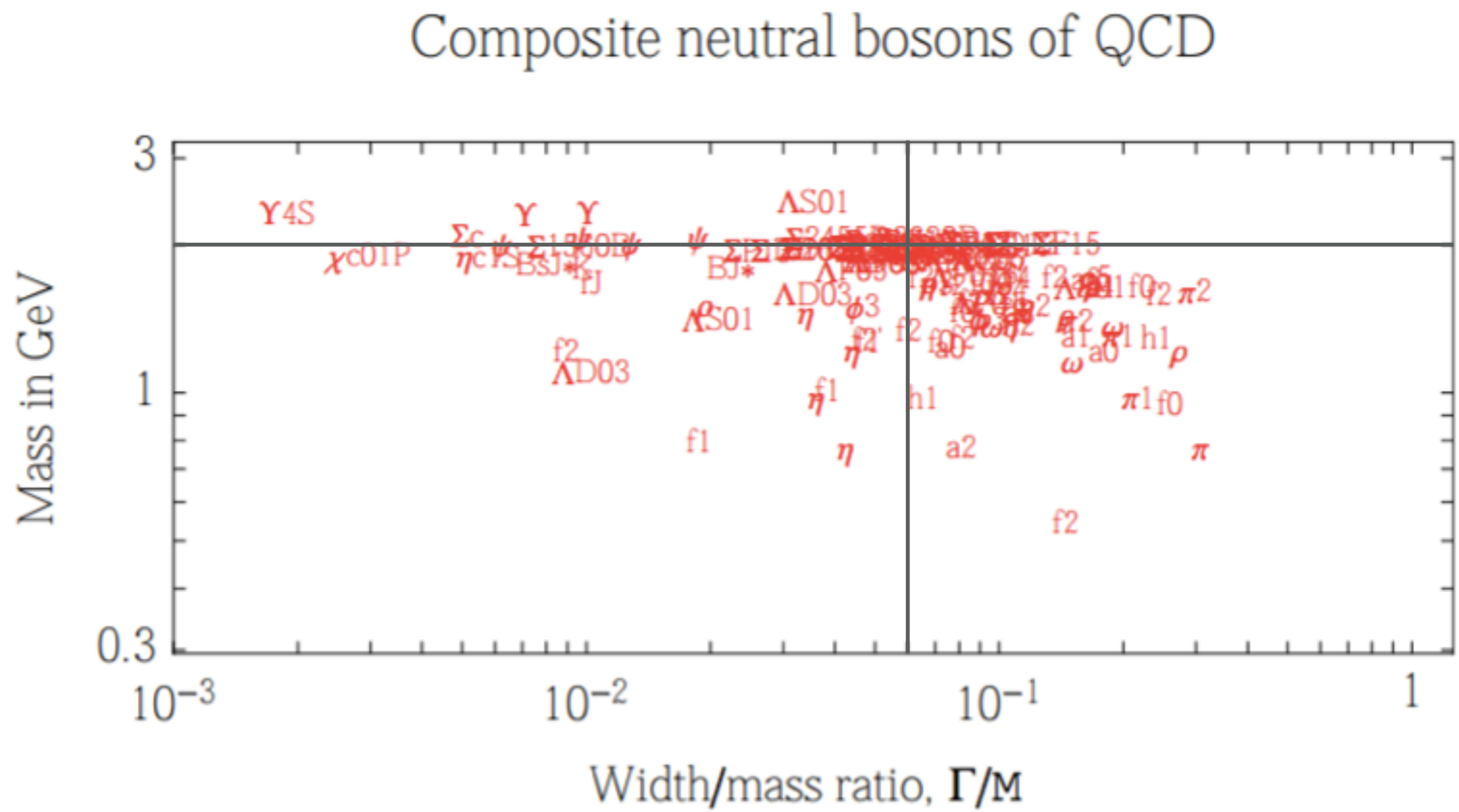
Explaining a large width typically requires large couplings and large number of new particles just above the TeV scale, which points towards strongly coupled models

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

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



STRONGLY COUPLED MODELS



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

However, their mass is typically above the confinement scale Λ, while now bounds on compositeness require the resonance lighter than Λ

In the case of strongly coupled models (like QCD) one needs additional mechanisms to ensure that the resonance can be lighter than Λ

STRONGLY COUPLED MODELS

Explaining a large width typically requires large couplings and large number of new particles just above the TeV scale, which points towards strongly coupled models

- A new scalar that is a PNGB of an extended scalar sector also producing a composite Higgs and is therefore related to electroweak symmetry breaking
  - Pseudo-scalar PNGB coupled through anomalies (Wess-Zumino-Witten terms) or Chern-Simons terms in extra dimensions (e.g. η' in QCD)
  - Scalar PNGB (no WZW term) but coupling typically smaller
  - Dilaton: coupling to Higgs kinetic term (or to tops) can provide the width, but hard to push couplings to photons and gluons
- A new scalar not directly related to the EWSB sector, e.g. in extended confining gauge theories with fermions that are vector-like under the SM
  - QCD-like strong dynamics similar to technicolor: techni-η, techni-pions, techni-quarkonia etc.

The weak feature of strongly coupled models seems to be the difficult in generating a consistent picture of flavour without relying on additional flavour symmetries

MEASURING S PROPERTIES

Is this signal due to a resonance or to more complicated kinematics?

- Look at the events to find more structure
- Look at interference with SM (processes with different structure don't interfere)
- More statistics would allow to exclude two/more nearby resonances
- Distribution of MET very important to distinguish associated production involving DM
- Certainly needs more statistics

Spin

- Look at the angular distribution of the two photons
- Certainly needs more statistics

C-P properties

- If ZZ is observed soon look at 4-lepton distributions (like for the Higgs)
  Here differently from the Higgs this could be CP-even but still coupling only to transverse bosons, which can make things harder!
- The angular distribution of jets in Sjj events can be a good discrimination
- Search in the hh channel, this is a discriminant

Other properties

- Associated productions with W, Z, h and pair production
- Precise measurements of the S properties may require a Future Collider

CONCLUSION

- The hints for an excess of events in the di-photon spectrum both from ATLAS and CMS with the first data at 13 TeV has generated a lot of excitement
- The excess deserves to be taken seriously due to its presence in both experiments in the same region (though with a modest statistical significance) and to the extremely simple and clean final state, not (directly) involving complicated coloured objects
- A very fast reaction of the theoretical community has generated a lot of ideas, however more experimental input is needed (more distributions, additional objects, interpretation in different frameworks)
- The excess could be explained in many different scenarios, both weakly coupled and strongly coupled
- However, if a large width is confirmed this would point either towards weakly coupled models with many almost degenerate narrow resonances (that can be resolved with more statistics) or towards strongly coupled dynamics
- If the signal is confirmed, it should in any case be accompanied by other states which would open up a new era both for experimental and theoretical exploration
- Only new data will tell us if this signal is actually due to new physics, or it is yet another statistical fluctuation

THANK YOU