A discussion on the 750 GeV diphoton anomaly

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Outline

- BSM at the beginning of Run 2
- Diphoton anomaly phenomenological aspects
- Weakly coupled extensions
- Strongly coupled extensions
- Conclusions

New Physics

- SM is very successful in describing physics up to the EW scale
- SM is not a complete theory (neutrino masses, dark matter, baryon asymmetry)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields}).$$

- Big question is Λ?

- Unfortunately, no unique indication from observed BSM physics

  1. Neutrino masses, from Dirac neutrino to GUT see-saw

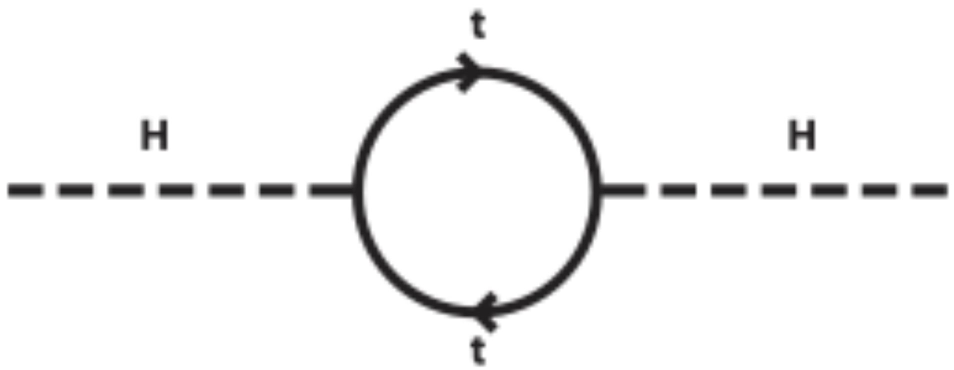
  2. Dark Matter, from axions to Wimpzillas

  3. Baryon asymmetry, from EW baryogenesis to GUT baryogenesis

- However we have a theoretical guideline….

New Physics

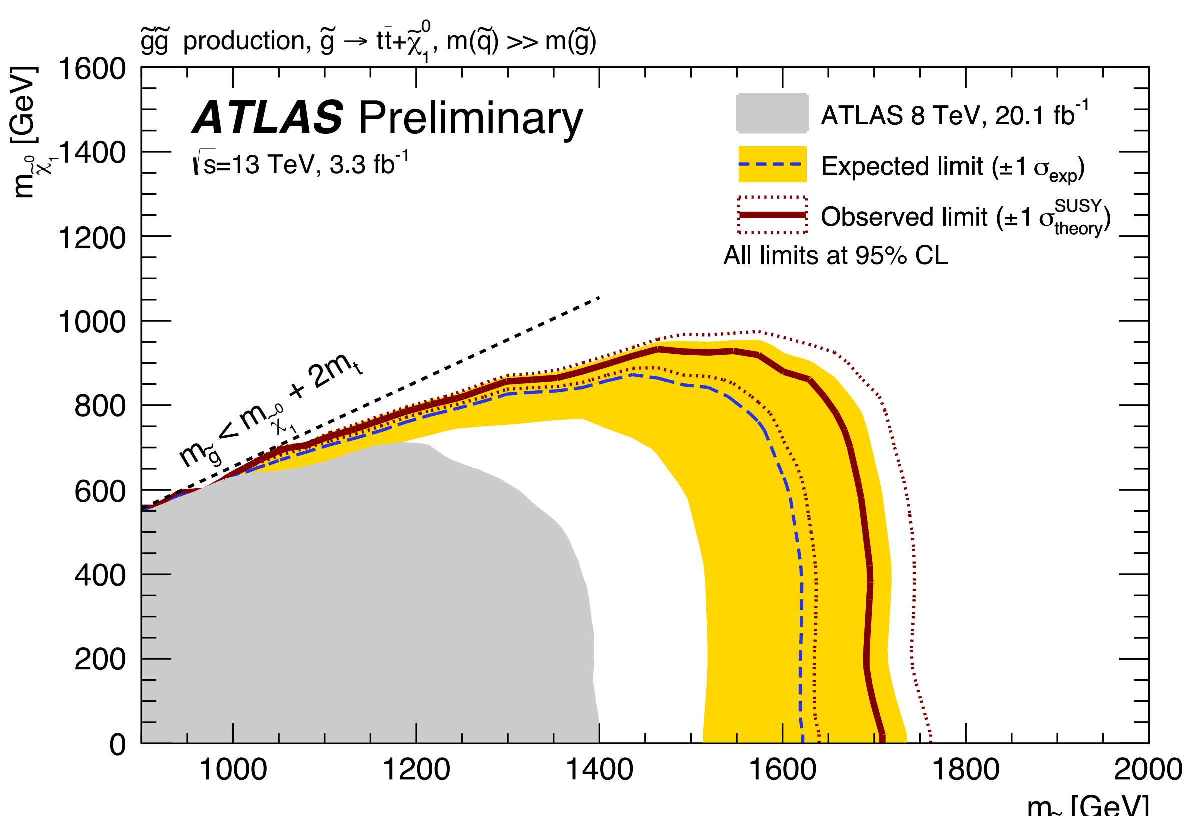
- Upper bound from naturalness of the Higgs mass $\Lambda < 1\ \text{TeV}$

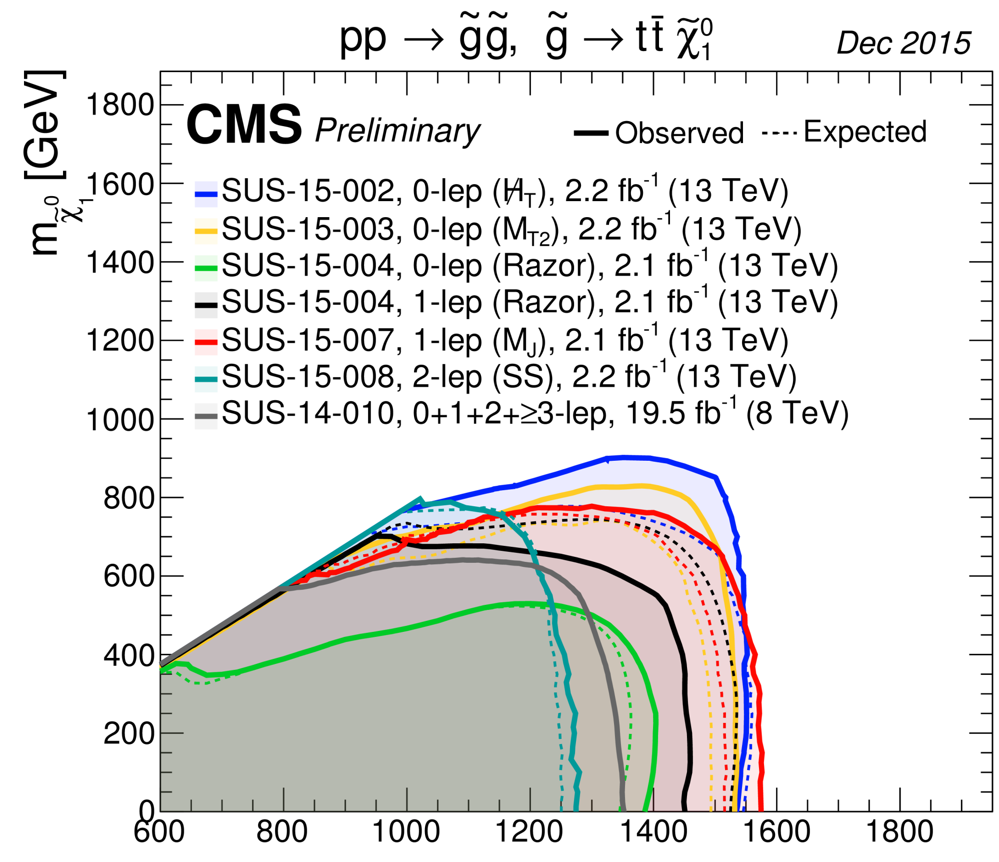


$$m_H^2 = m_{\text{tree}}^2 + \delta m_H^2$$

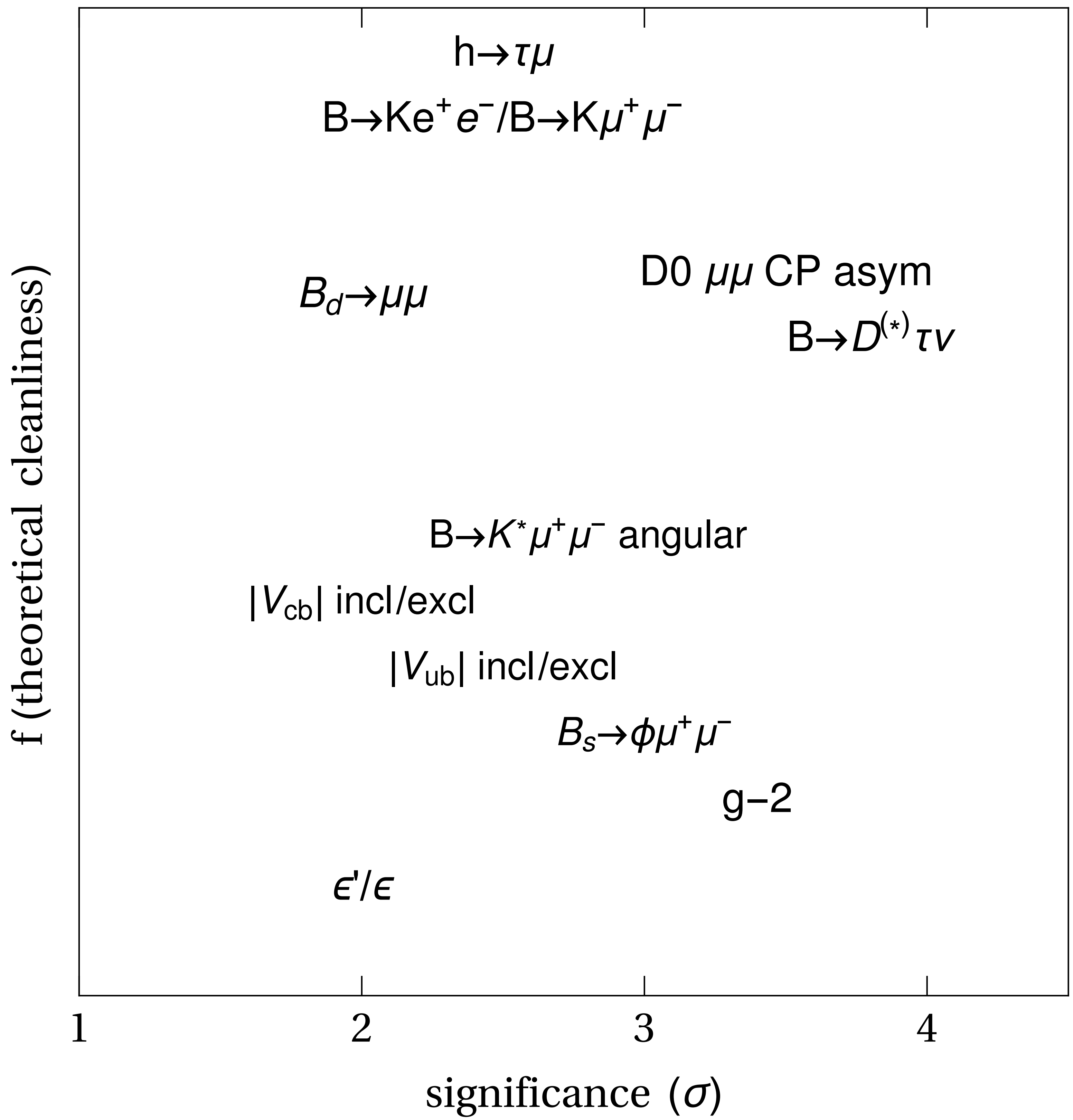
$$\delta m_H^2 = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 \approx (0.3\,\Lambda)^2$$

- Main frameworks to solve this problem: composite Higgs and Supersymmetry
- Prediction: new colored states (the lighter the better)
- Instead….





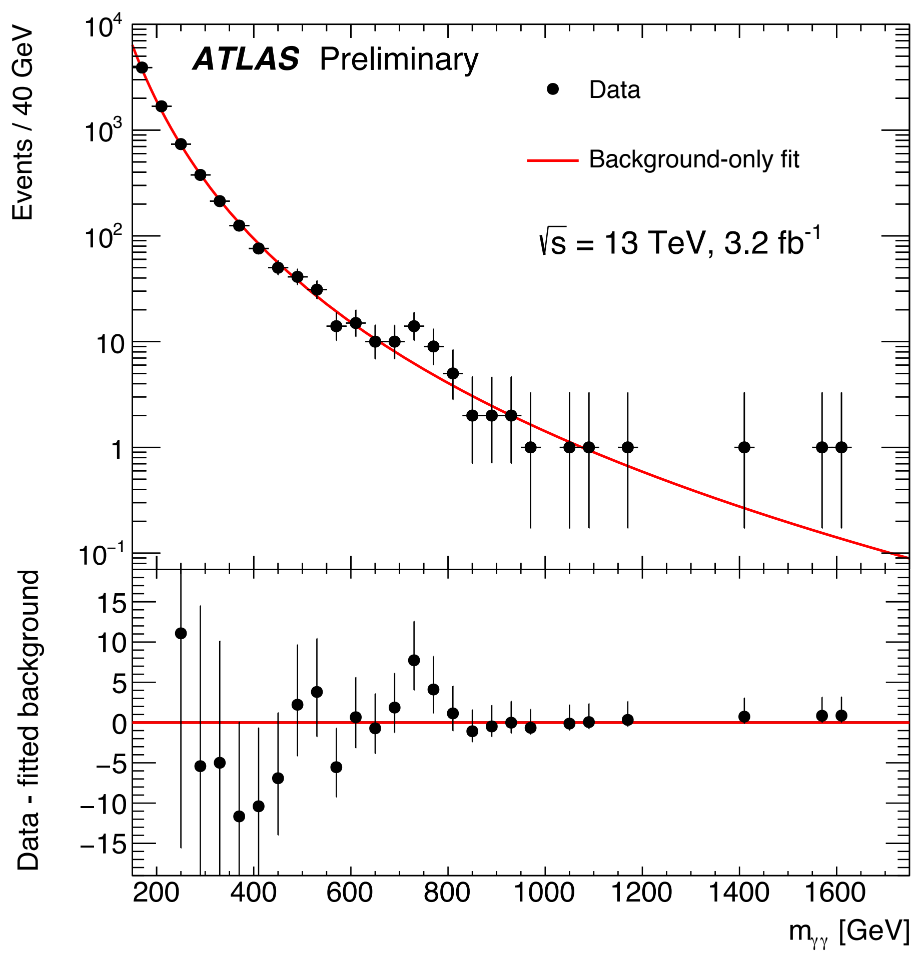
Flavour Anomalies



Z. Ligeti,
Moriond QCD 2016

Diphoton anomaly

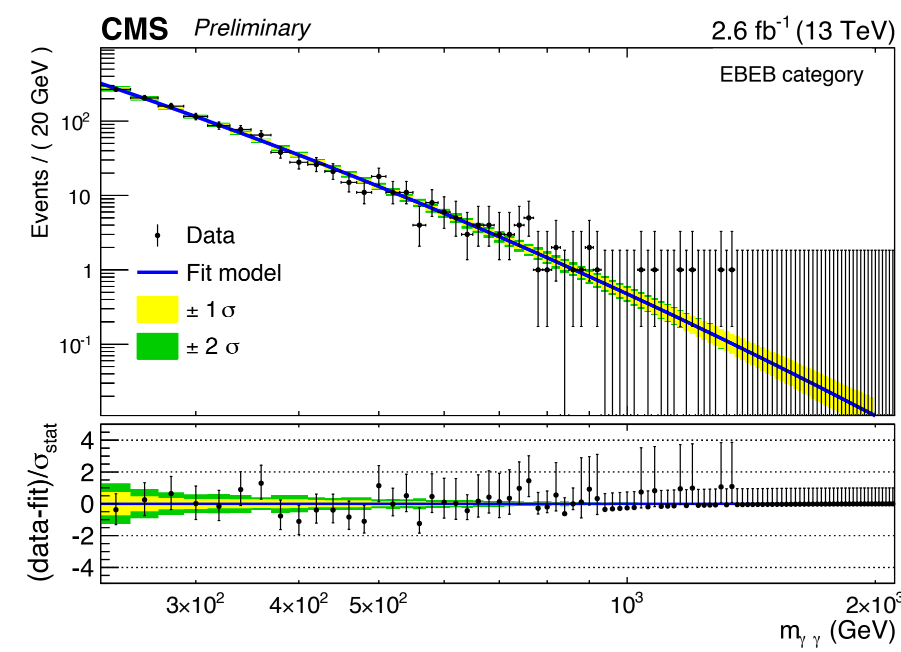
[ATLAS-CONF-2015-081]



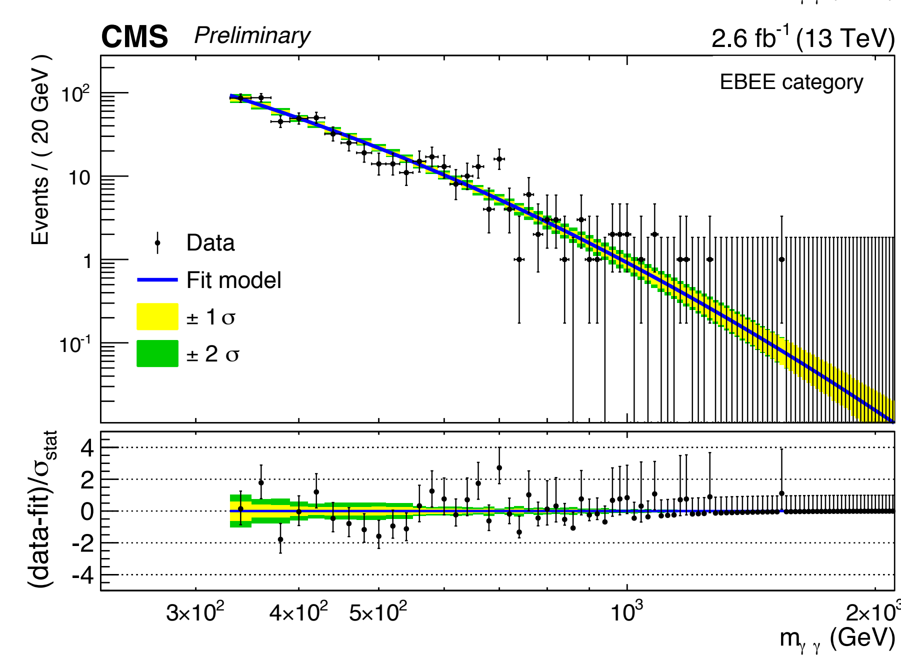
Bin[GeV]	650	690	730	770	810	850
N_{events}	10	10	14	9	5	2
$N_{\text{background}}$	11.0	8.2	6.3	5.0	3.9	3.1

[1512.05777]

[CMS-EXO-15-004]



EBEB
Barrel-Barrel



EBEE
Barrel-Endcaps

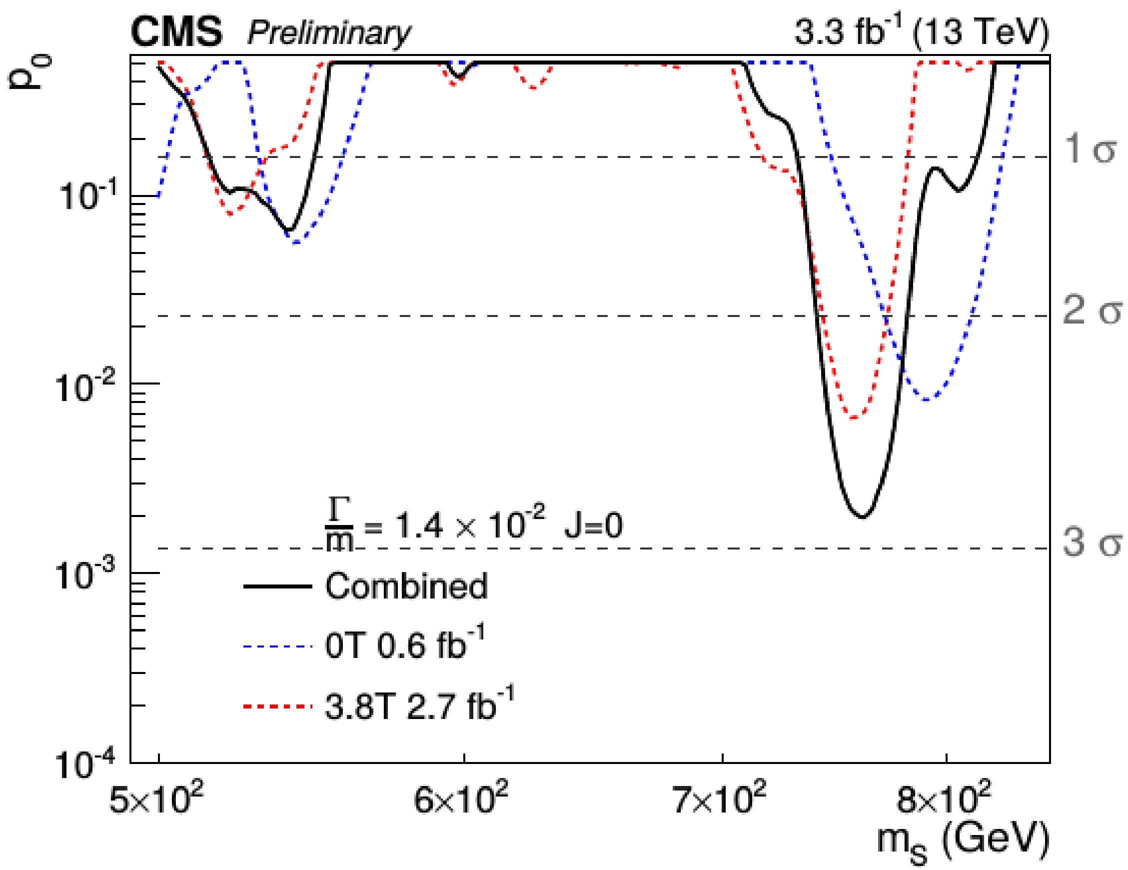
- ATLAS: local significance of 3.9σ
- ATLAS: best fit is obtained for $\alpha = \Gamma/M = 6\%$
- CMS: local significance of 2.6σ (narrow width)

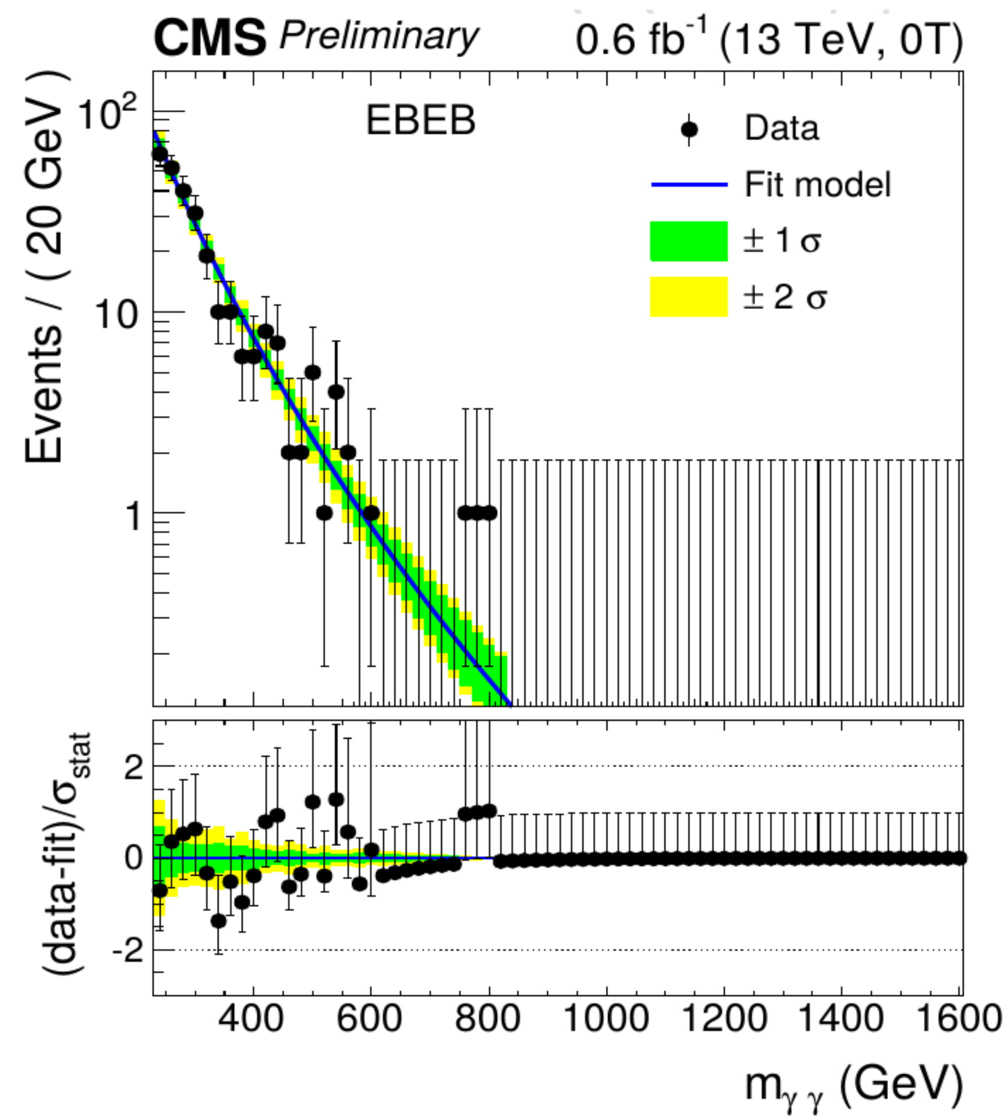
Bin[GeV]	700	720	740	760	780	800
N_{events} (EBEB)	3	3	4	5	1	1
$N_{\text{background}}$ (EBEB)	2.7	2.5	2.1	1.9	1.6	1.5
N_{events} (EBEE)	16	4	1	6	2	3
$N_{\text{background}}$ (EBEE)	5.2	4.6	4.0	3.5	3.1	2.8

[1512.05777]

After Moriond EW 2016

- ATLAS: spin 2 analysis + re-analysis of Run 1
- CMS: improved detector calibration + analyzed dataset recorded a 0T



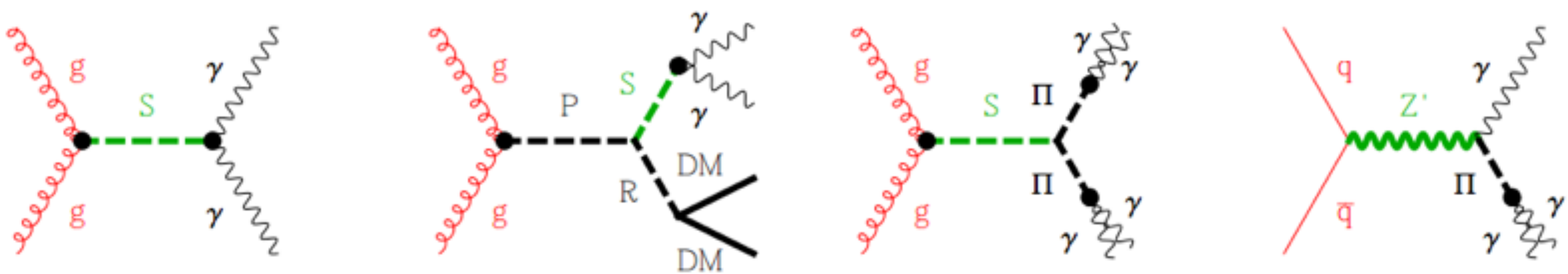


- Local significance: 2.9σ
- Combining with Run 1 data: 3.4σ
- Preference for a narrow width

Warning

- We need more data, most likely just a statistical fluctuation
- However… more than 250 pre-prints on the arXiv
- I will try to give a (biased,partial and simplified) summary on possible interpretations of the anomaly in terms of New Physics, my apologies for the missing references/works/ideas

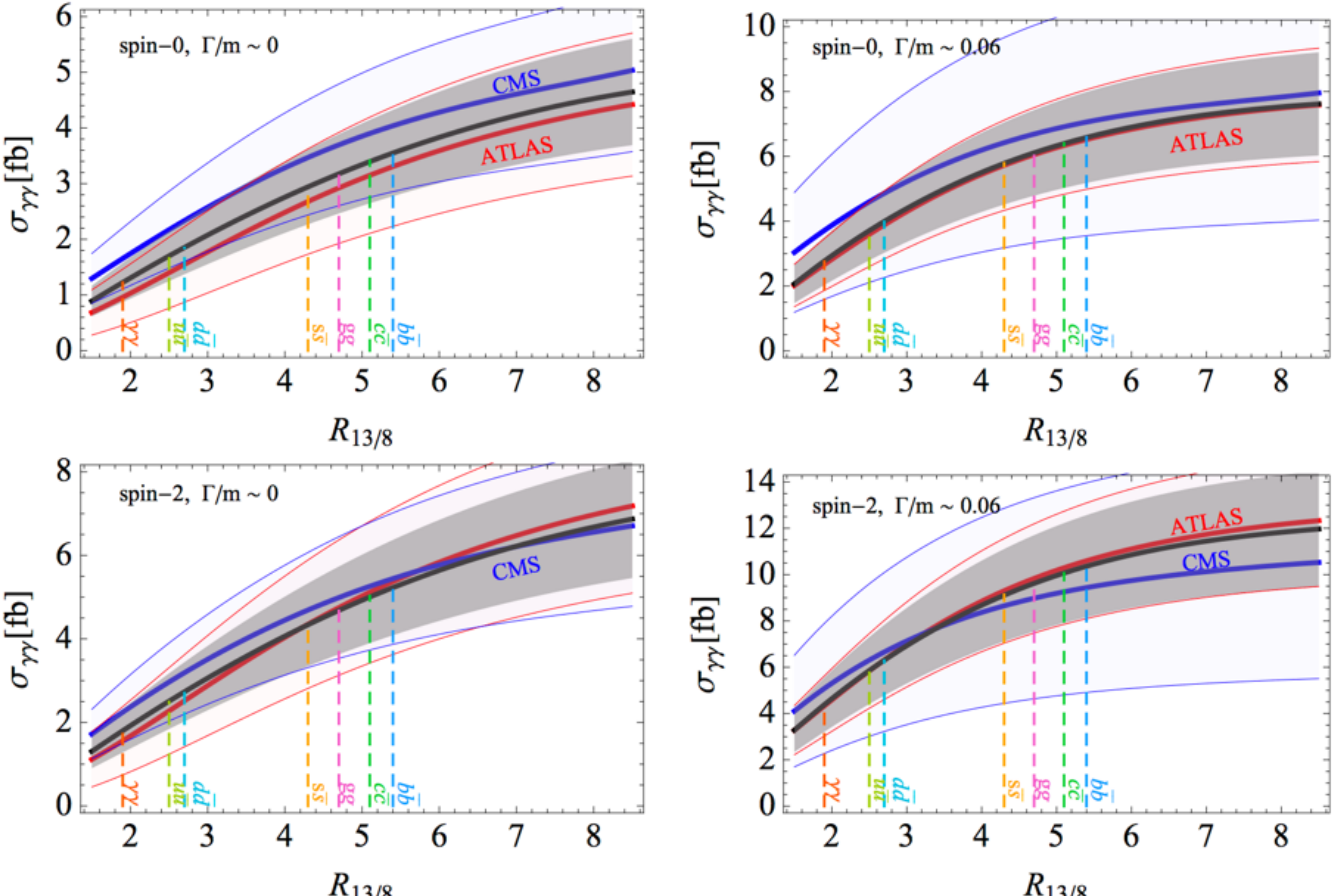
- I will consider only the simplest topology, interesting options have been discussed



- Focus on the s-channel 2 body decay, spin 0 or 2

Combinations

[1603.06566]



- Typical cross section: 1-10 fb

Consistency with LHC 8 TeV

$$\sigma(pp \to \gamma\gamma) \approx \begin{cases} (0.5 \pm 0.6)\,\text{fb} & \text{CMS [2]} \quad \sqrt{s} = 8\,\text{TeV}, \\ (0.4 \pm 0.8)\,\text{fb} & \text{ATLAS [3]} \quad \sqrt{s} = 8\,\text{TeV}, \\ (6 \pm 3)\,\text{fb} & \text{CMS [1]} \quad \sqrt{s} = 13\,\text{TeV}, \\ (10 \pm 3)\,\text{fb} & \text{ATLAS [1]} \quad \sqrt{s} = 13\,\text{TeV}. \end{cases}$$

[1512.04933
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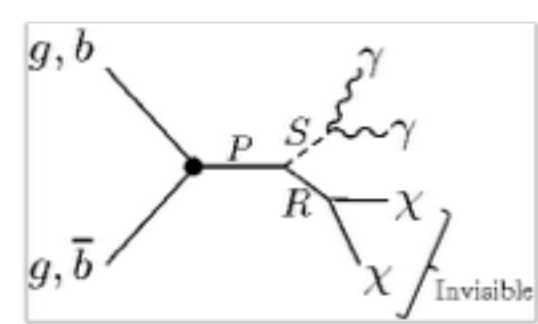
- An enhancement of the cross section is required $r \equiv \sigma_{13\,\text{TeV}} / \sigma_{8\,\text{TeV}}$
- Consistency (at 2σ) with LHC8 requires $r > 3.5$
- Cross section is given by $\sigma(pp \to S \to \gamma\gamma) = \frac{2J+1}{M\Gamma s}\left[\sum_{\wp} C_{\wp\bar{\wp}}\Gamma(S \to \wp\bar{\wp})\right]\Gamma(S \to \gamma\gamma)$
- Gain factor depends only on the type of p.d.f responsible for the production

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

- Focus on two cases: gluon-gluon and bottom-bottom production
- Another option: change topology and kinematics →



[see, 1512.04928,1512.06083,1512.06113,1512.06833, ..., ..., ...]

Production mechanism

[1512.04933
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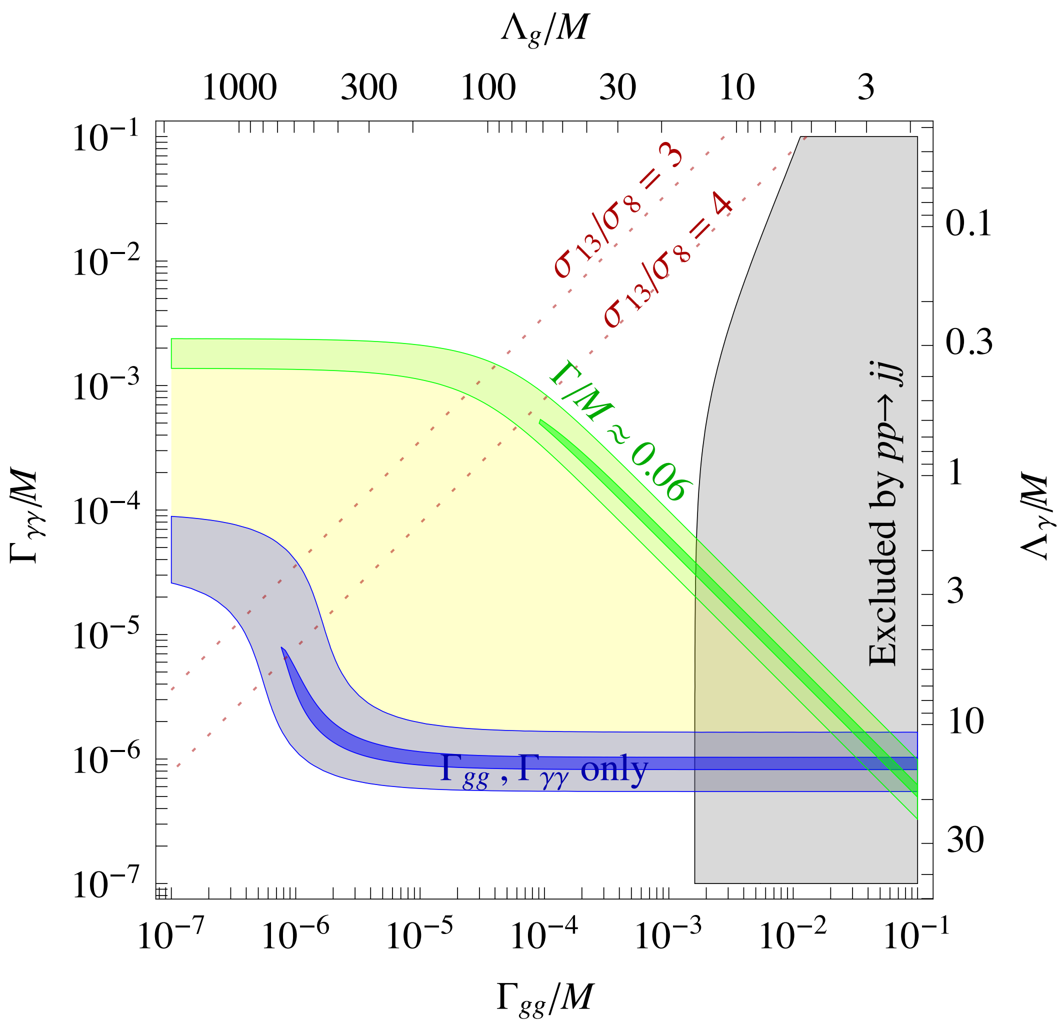

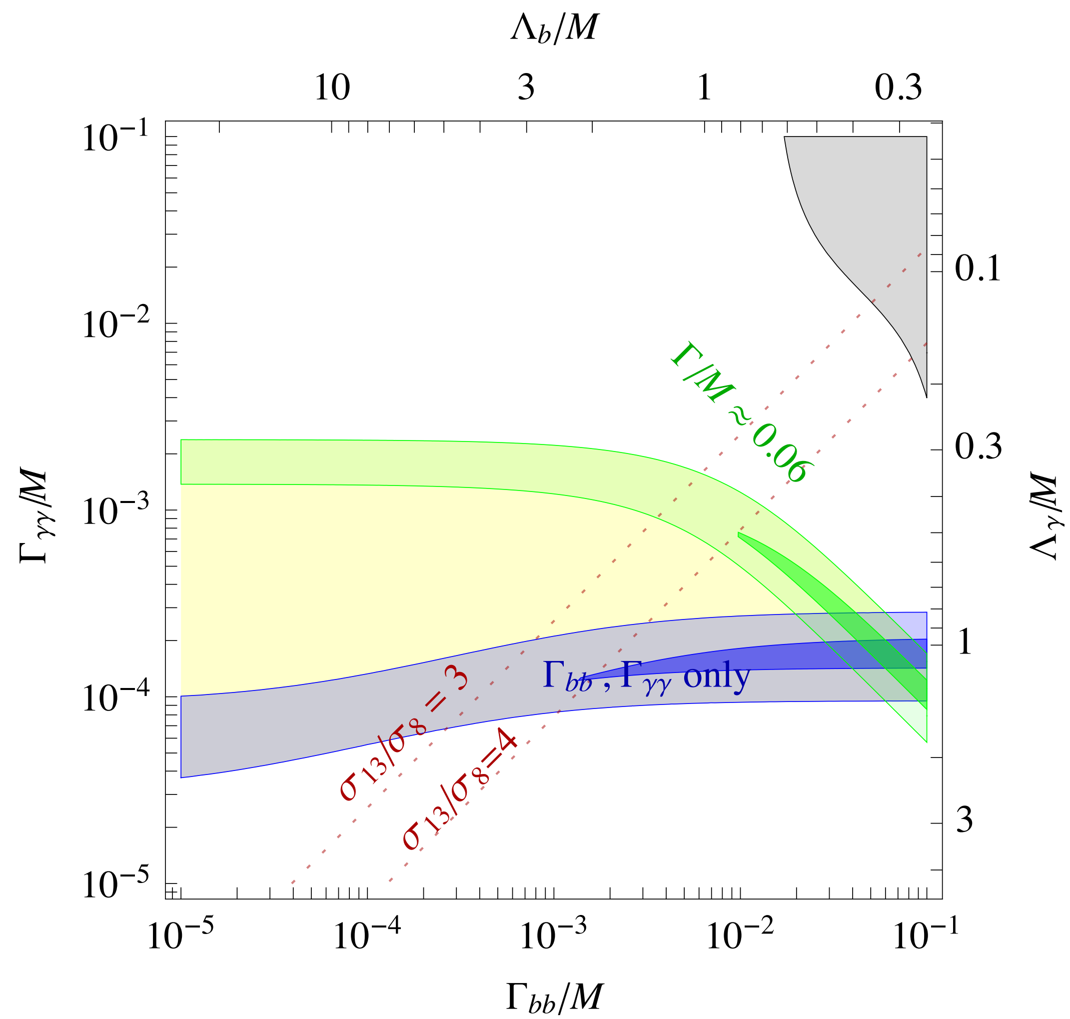

$$\frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{gg}}{M} \approx 1.1\times 10^{-6}\ \frac{\Gamma}{M} \approx 6\times 10^{-8} \qquad \frac{\Gamma_{\gamma\gamma}}{M}\frac{\Gamma_{b\bar b}}{M} \approx 1.9\times 10^{-4}\ \frac{\Gamma}{M} \approx 1.1\times 10^{-5}$$

- Large partial width in diphoton

$\Gamma_{\gamma\gamma}/M \gtrsim 10^{-6}$ narrow width $\qquad$ $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-4}$ large width

- In the gluon-gluon case, total width (if large) is dominated by decays into other channels

Other decay channels

[1512.04933
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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	[8, 9]	$< 0.8\ (r/5)$
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[10]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[11]	$< 6\ (r/5)$
$Z\gamma$	< 11 fb	< 11 fb	[12]	$< 6\ (r/5)$
ZZ	< 12 fb	< 20 fb	[13]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[14]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[15]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[16, 17]	$< 20\ (r/5)$
$t\bar{t}$	< 450 fb	< 600 fb	[18]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[19]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[20]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[7]	$< 1300\ (r/5)$

- Electroweak gauge invariance suggests (forces) the presence of other decay channels accessible at the LHC

operator	$\dfrac{\Gamma(S \to Z\gamma)}{\Gamma(S \to \gamma\gamma)}$	$\dfrac{\Gamma(S \to ZZ)}{\Gamma(S \to \gamma\gamma)}$	$\dfrac{\Gamma(S \to WW)}{\Gamma(S \to \gamma\gamma)}$
WW only	$2/\tan^2\theta_{\text{W}} \approx 7$	$1/\tan^4\theta_{\text{W}} \approx 12$	$2/\sin^4\theta_{\text{W}} \approx 40$
BB only	$2\tan^2\theta_{\text{W}} \approx 0.6$	$\tan^4\theta_{\text{W}} \approx 0.08$	0

$$g_2^2 S\left(\frac{W_{\mu\nu}^2}{2\Lambda_W} + \frac{W_{\mu\nu}\tilde{W}^{\mu\nu}}{2\tilde{\Lambda}_W}\right)$$

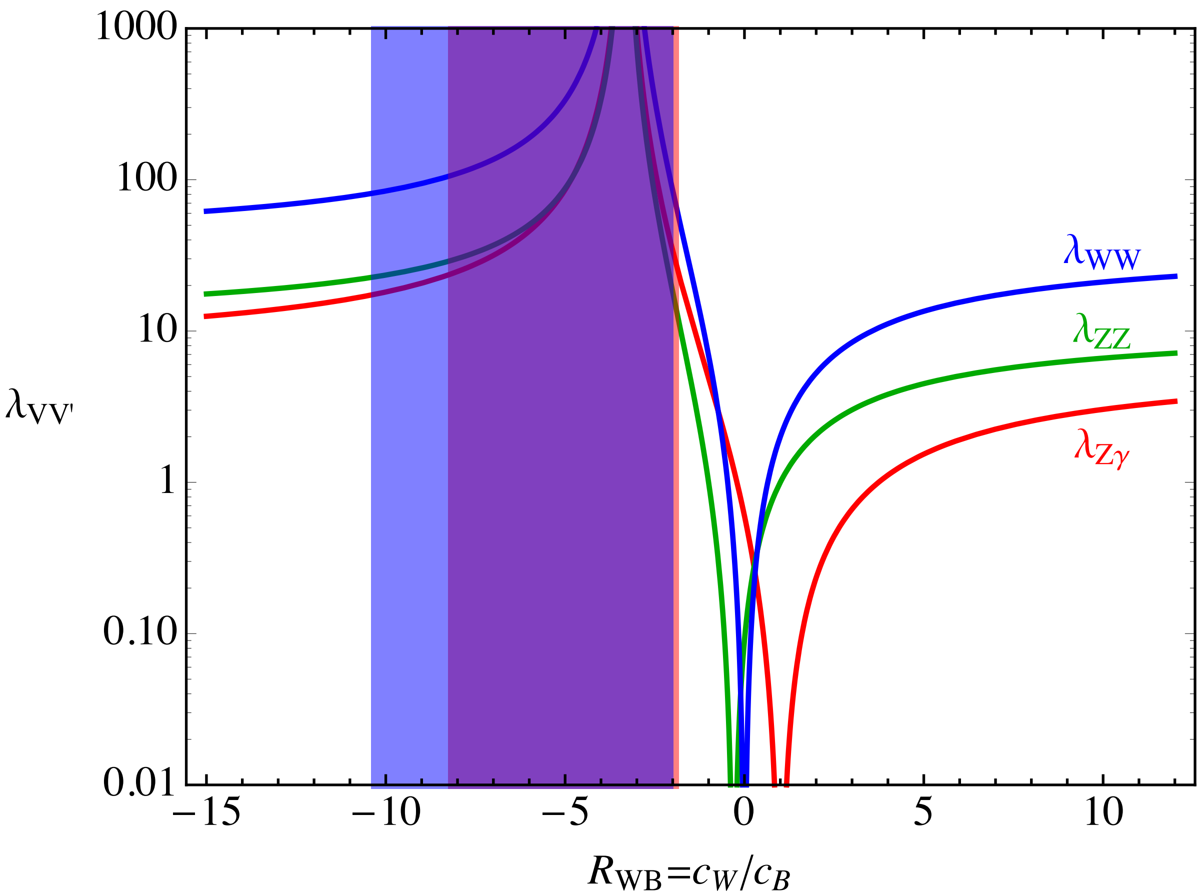
$$g_1^2 S\left(\frac{B_{\mu\nu}^2}{2\Lambda_B} + \frac{B_{\mu\nu}\tilde{B}^{\mu\nu}}{2\tilde{\Lambda}_B}\right)$$

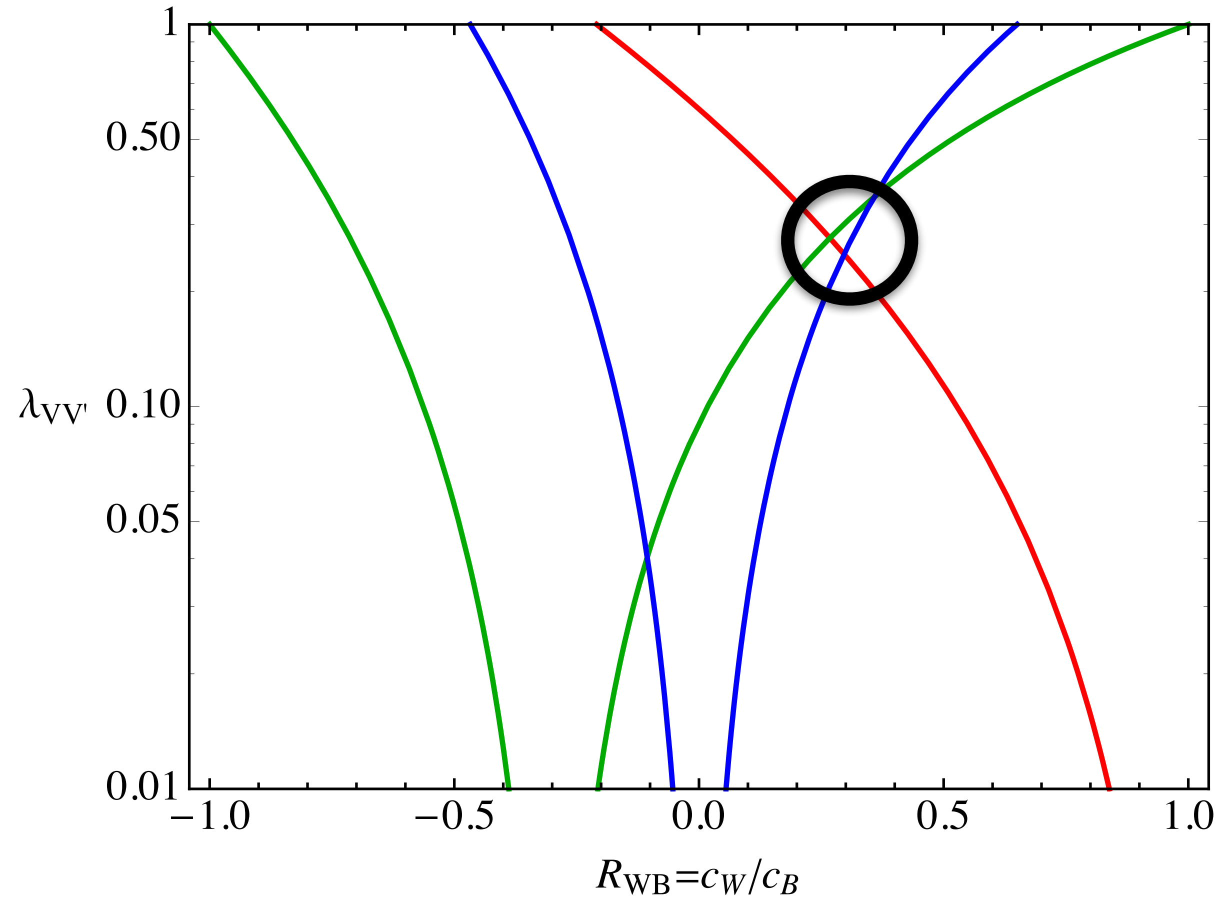
$$-0.3 < \Lambda_B/\Lambda_W, \tilde{\Lambda}_B/\tilde{\Lambda}_W < 2.4$$

- An interesting possibility: S decays into a dark sector

Decays into EW gauge bosons

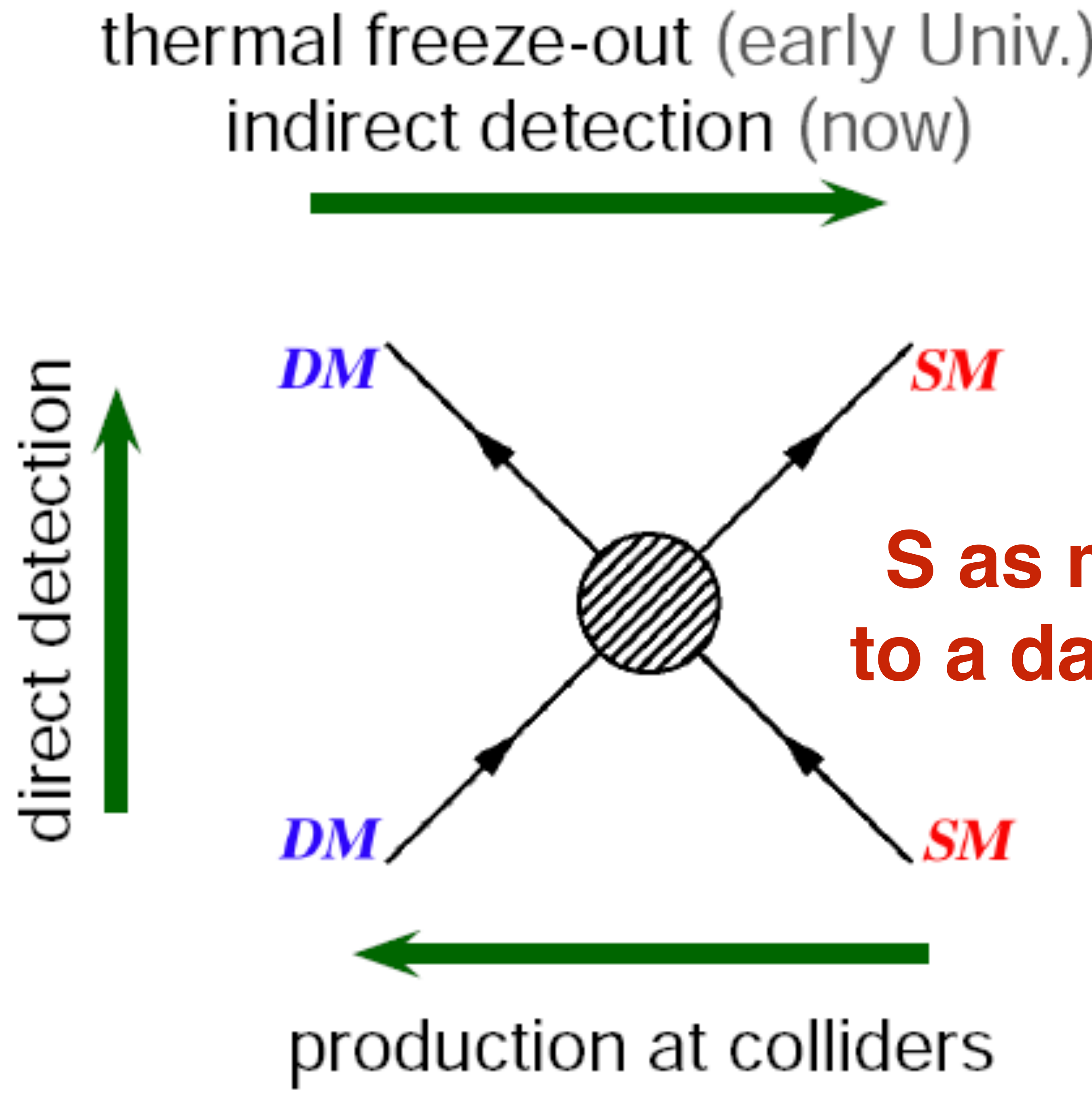
[A discussion with David Marzocca (ETH)]





- In general we expect to see other decays at the LHC
- There is an evil region where Br are all small, more quantitative studies are needed to compare with the LHC

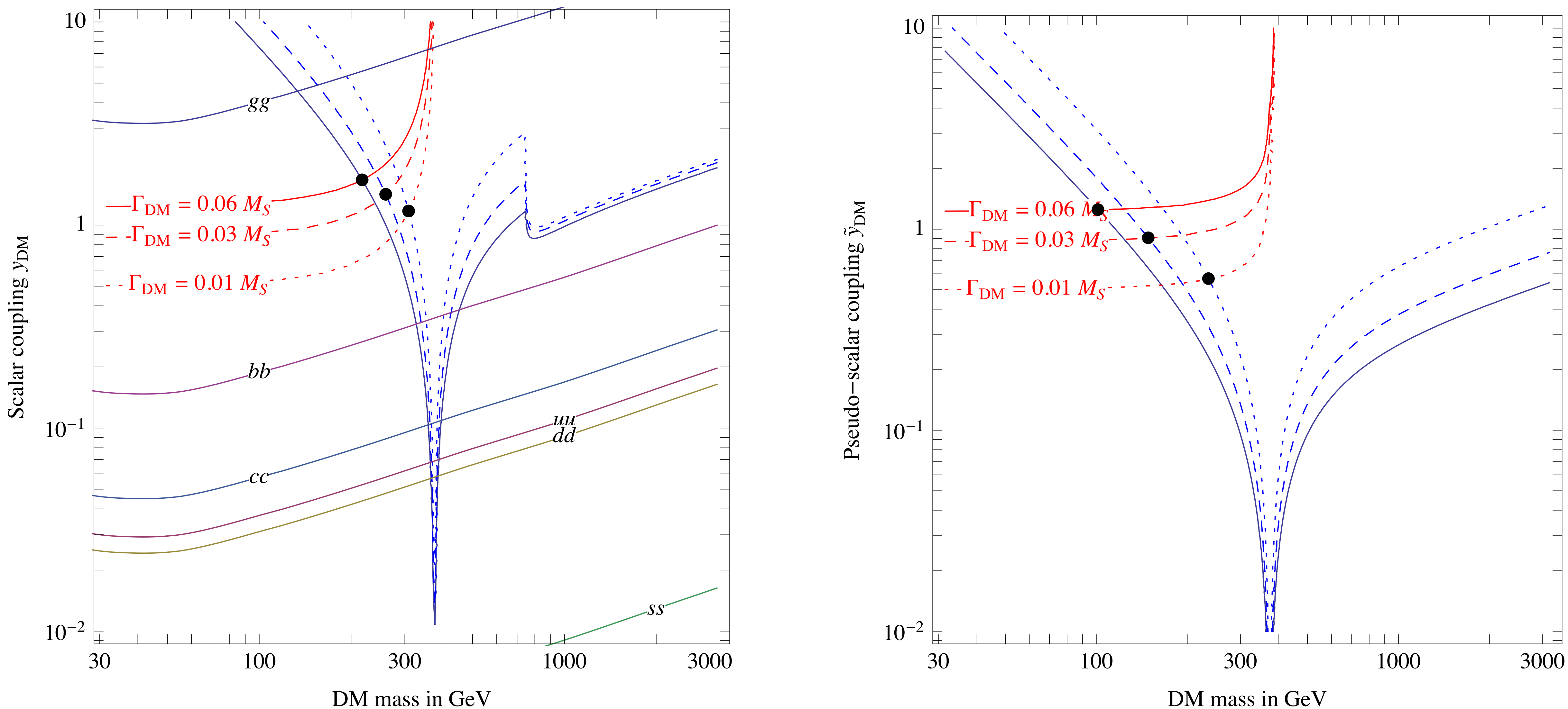
A Dark Matter connection



S as mediator to a dark sector

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

1) The connection with Ω_{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.

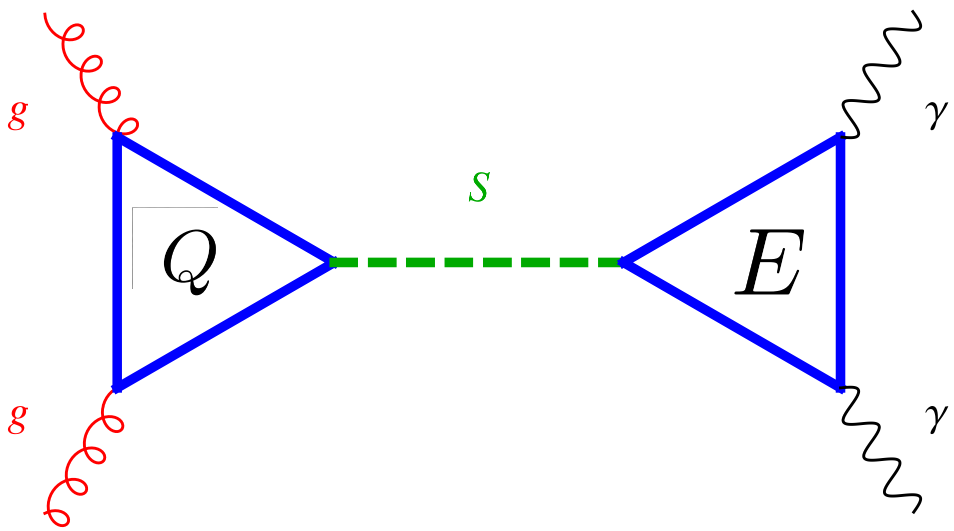


Direct detection bounds are (weak) irrelevant if S is a scalar (pseudo-scalar).

[Slides from A. Strumia, Moriond EW 2016]

Weakly coupled models

- Let's focus on the gg production mechanism, a simple renormalizable picture is given by SM extensions with vector-like fermions



- A simple toy model

Goertz, Kamenik,Katz, MN 1512.08500
same mechanism in O(100) papers

$$S \sim (\mathbf{1},\mathbf{1},0)$$
$$Q \sim (\mathbf{3},\mathbf{1},0) \quad \times N_Q$$
$$E \sim (\mathbf{1},\mathbf{1},Y) \quad \times N_E$$

$$\mathcal{L} \supset i y_q S \overline{Q}\gamma^5 Q + i y_e S \overline{E}\gamma^5 E$$

- A large diphoton rate is required

$$\Gamma(S\to\gamma\gamma) = M\frac{\alpha^2}{16\pi^3}Y^4 N_E^2 y_e^2 \tau_E |\mathcal{P}(\tau_E)|^2$$
$$\tau_E = 4M_E^2/M^2$$

$M_E \to 400$ GeV

$$\frac{\Gamma(S\to\gamma\gamma)}{M} = 1.1\cdot 10^{-7}\, Y^4 y_e^2 N_E^2$$

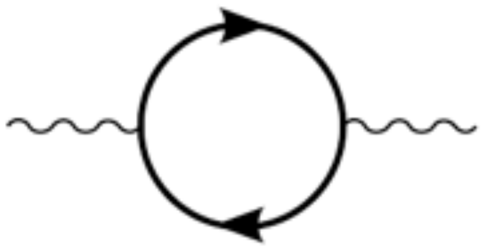
- Narrow Width $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-6}$ → $Y^4 y_e^2 N_e^2 \gtrsim 10$

$Y^4 y_e^2 N_e^2 \approx 1.5$ for a top-like state

- Large Width $\Gamma_{\gamma\gamma}/M \gtrsim 10^{-4}$ → $Y^4 y_e^2 N_e^2 \gtrsim 10^3$ ⚠

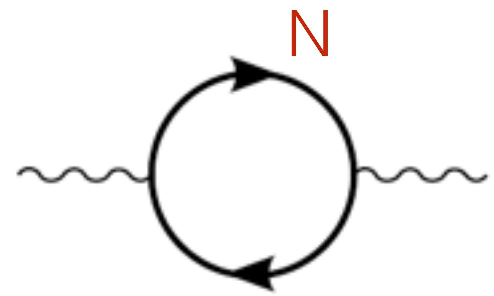
Calculability in perturbative models

- How large can the couplings and/or the number of states be?



naively $\frac{y^2}{16\pi^2} < 1$

$y < 4\pi$



less naively $\frac{Ny^2}{16\pi^2} < 1$

$y < 4\pi/\sqrt{N}$

- Other possible issues

1) Landau pole can be very close to the TeV scale

2) Beta function changes very rapidly compared with the coupling itself

$$\mu \frac{d}{d\mu} y = \beta_y \qquad \mathcal{A} = y + \beta_y \log\left(\frac{\mu}{E}\right)$$

Possible criterion $\left|\frac{\beta_y}{y}\right| < 1$

[1512.07624, 1512.08307, 1512.07889, 1512.08500, 1602.01460, …., …., ….,]

3) Vacuum stability, new interactions (and new scalars) can modify the scalar potential

4) Unitary implications from 2 —> 2 scatterings of mediators

[with L. Di Luzio and J. Kamenik, tomorrow?]

- Strong constraints, a large width makes the interpretation of this anomaly in terms of weakly coupled models very challenging

The Usual Suspects

- Most economical attempt at the renormalizable level: 2 Higgs Doublet Model

see also
1512.04921
1512.05332
1512.05623
1512.06587
1512.07497
1512.07616
1512.08508
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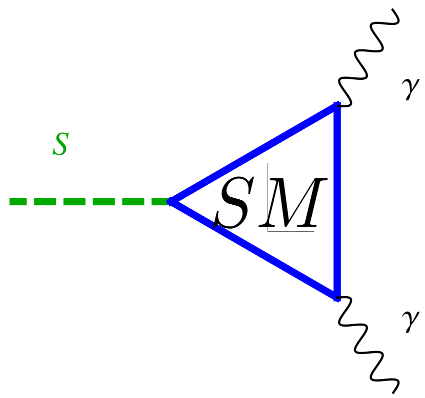

- Production: directly trough quarks at the tree level
- Decay into photons: trough loops of SM particles
- TREE level decays are available, for example

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{t\bar{t}}} \simeq \frac{2\alpha^2 m_t^2}{27\pi^2 M^2}\left[\pi^2 + 4\log^2(M/m_t)\right]^2 \simeq 10^{-5}$$ ✗

Excluded by direct searches

- Requires other mediators in the loop as in the previous case (but now with more constraints: Higgs, EWPT, flavour, …)

- MSSM: is a special 2HDM + other states (in particular stops and higgsinos)

c.f.
1512.04921
1512.05332
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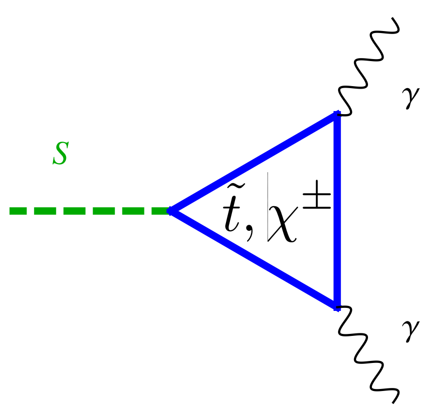


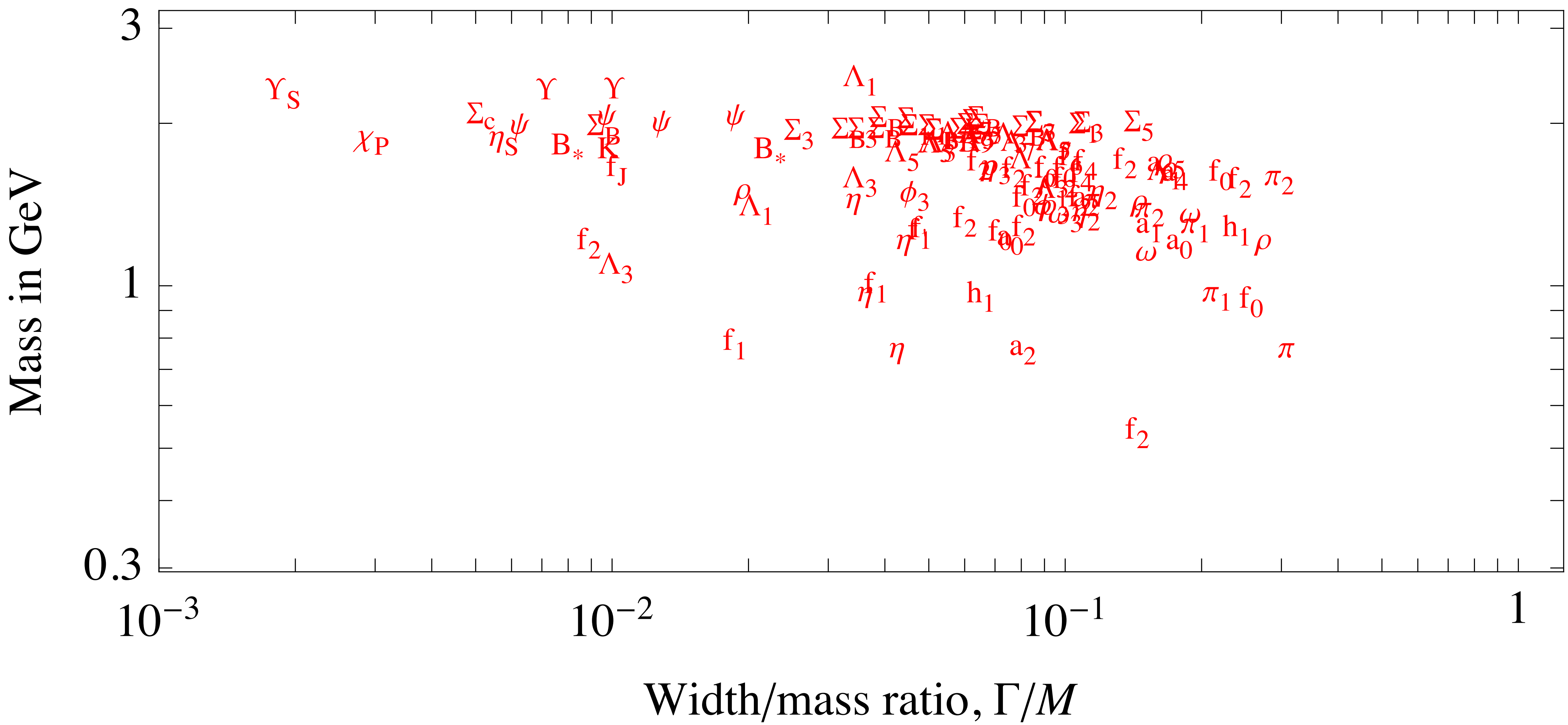
- Enhancement for extreme values of the parameters (large A-terms, low values for soft masses) within the order of magnitude required to fit the diphoton data

- RPV-MSSM has problems too… 1512.07645

- SUSY is not the MSSM, extensions can reproduce the effect

Candidates in strongly coupled models

Composite neutral bosons of QCD



[slides from J. Kamenik,]

Strongly coupled models

- The 750 GeV state is a composite state of a strongly coupled sector
- Simplest idea: vector-like confinement (not direct connection with the EW breaking)

	$G_H = SU(N)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
Ψ_D	$\square$	$\bar{\square}$	$\mathbf{1}$	$1/3$
Ψ_L	$\square$	$\mathbf{1}$	$\square$	$-1/2$
$\bar{\Psi}_D$	$\bar{\square}$	$\square$	$\mathbf{1}$	$-1/3$
$\bar{\Psi}_L$	$\bar{\square}$	$\mathbf{1}$	$\square$	$1/2$

[From 1602.01092,
see also
1512.04850,
1512.04933
1602.07297
]

- SU(N) gauge dynamics similar to QCD
- S is a pseudo-Goldstone boson associated to the breaking of the global symmetry

$$SU(5)_L \times SU(5)_R \to SU(5)_V$$

- Extra colored and charged "pions" are predicted

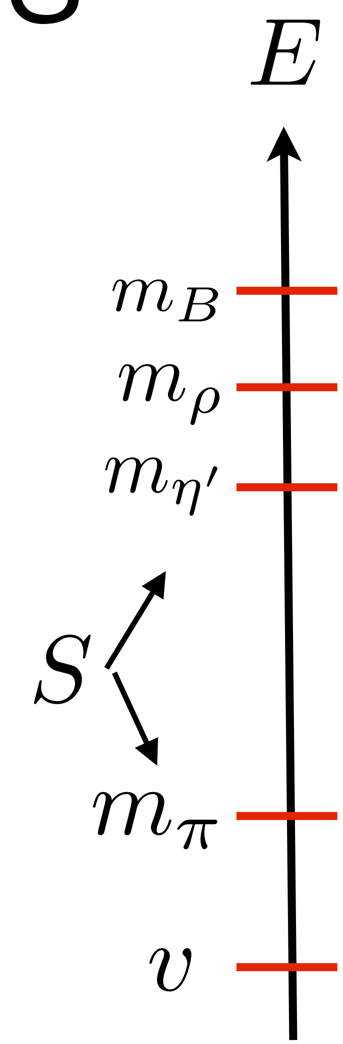
$$\pi \sim (\mathbf{8},\mathbf{1},0) \oplus (\mathbf{3},\mathbf{2},-5/6) \oplus (\bar{\mathbf{3}},\mathbf{2},+5/6) \oplus (\mathbf{1},\mathbf{3},0) \oplus \oplus(\mathbf{1},\mathbf{1},0)$$

- Di-gluon and Di-photon couplings are generated by WZW terms

$$\frac{Ng_3^2}{32\sqrt{15}\pi^2 f}\phi\,\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma} - \frac{3Ng_2^2}{64\sqrt{15}\pi^2 f}\phi\,\epsilon^{\mu\nu\rho\sigma}W^\alpha_{\mu\nu}W^\alpha_{\rho\sigma} - \frac{Ng_1^2}{64\sqrt{15}\pi^2 f}\phi\,\epsilon^{\mu\nu\rho\sigma}B_{\mu\nu}B_{\rho\sigma}$$

- Same as in QCD $\pi^0 \to \gamma\gamma$

Strongly coupled models



- Other phenomenological aspects of this class of theories:

  1) Large coset space contains coloured pseudo-goldstone

  2) $f \gtrsim v$, other strongly coupled resonances accessible at the LHC

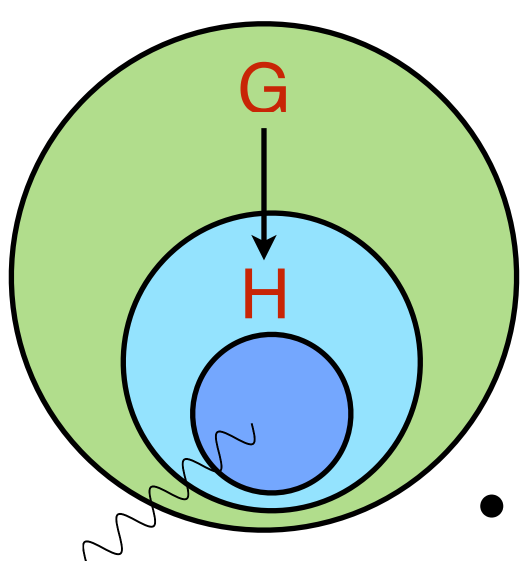
  3) These models are automatically MFV (Minimally Flavour Violating) because of the gauge symmetry

  4) Other options can be explored (for example S is associated with an anomalous current like the eta' in QCD) [in particular see 1602.07297]

  5) Possible dark matter candidate(s) because of extra symmetries

- The bad side: there is no direct link with the EW symmetry breaking. More ambitious idea: Composite Higgs and S from the same strong dynamics

Eg:



- In particular Higgs and S pseudo-NGB
  - Non trivial G/H construction: UV realisation?
  - Flavour through partial compositeness

$$\mathscr{L}_{\rm mix} = \epsilon^i_L \bar{f}^i_L \Psi^i_R + \epsilon^i_R \bar{f}^i_R \Psi^i_L \quad \Rightarrow \quad y^{ij}_{\rm SM} \sim \epsilon^i_L \epsilon^j_R g_*$$

- Large width $S \to \bar{t}t$

[1512.04929, 1512.04933 ,1512.05330,1512.07242,…]

Spin 2

[1602.02793]

- A motived candidate: KK graviton from a warped extra-dimension

$$\mathcal{L} \sim \frac{1}{M_{\rm Planck}} T^{\mu\nu} h^{(0)}_{\mu\nu} + \frac{1}{M_{\rm Planck} e^{-kb}} T^{\mu\nu} \sum h^{(m)}_{\mu\nu}$$

- Massless graviton is Plank suppressed, while the KK modes can have a TeV strength
- Couplings are universal, in particular $\Gamma(h^{(1)}_{\mu\nu} \to \gamma\gamma) = \frac{1}{8}\Gamma(h^{(1)}_{\mu\nu} \to gg)$
- Diphoton anomaly can be reproduced but now we have also another prediction

$$\Gamma(h^{(1)}_{\mu\nu} \to \gamma\gamma) = 2\Gamma(h^{(1)}_{\mu\nu} \to \ell^+\ell^-)$$

- At the moment, absence of peaks in di-leptons in Run 2 data

$$\sigma(pp \to S \to \ell^+\ell^-) < 5 \text{ fb}$$ [ATLAS-CONF-2015-081]

$$\sigma(pp \to S \to \ell^+\ell^-) \lesssim 3 \text{ fb}$$ [CMS-EXO-15-004]

- Another candidate: a resonance from a strongly interacting theory, however difficult to motivate the absence of detection of states with lower spin
- Also, away from the energy-tensor limit, scatterings have very bad UV behaviour

Conclusions

- Experimental situation needs to be clarified, we need more data
- Information on the width is crucial for model building
- We expect to see more decays channels at the LHC, in particular decays into EW gauge bosons
- It is very plausible to have more states at or below the TeV
- Who ordered that? Which is the role of S in connection with other open issues of the SM? (Naturalness problem and origin of the EW scale, DM, flavour, ….)