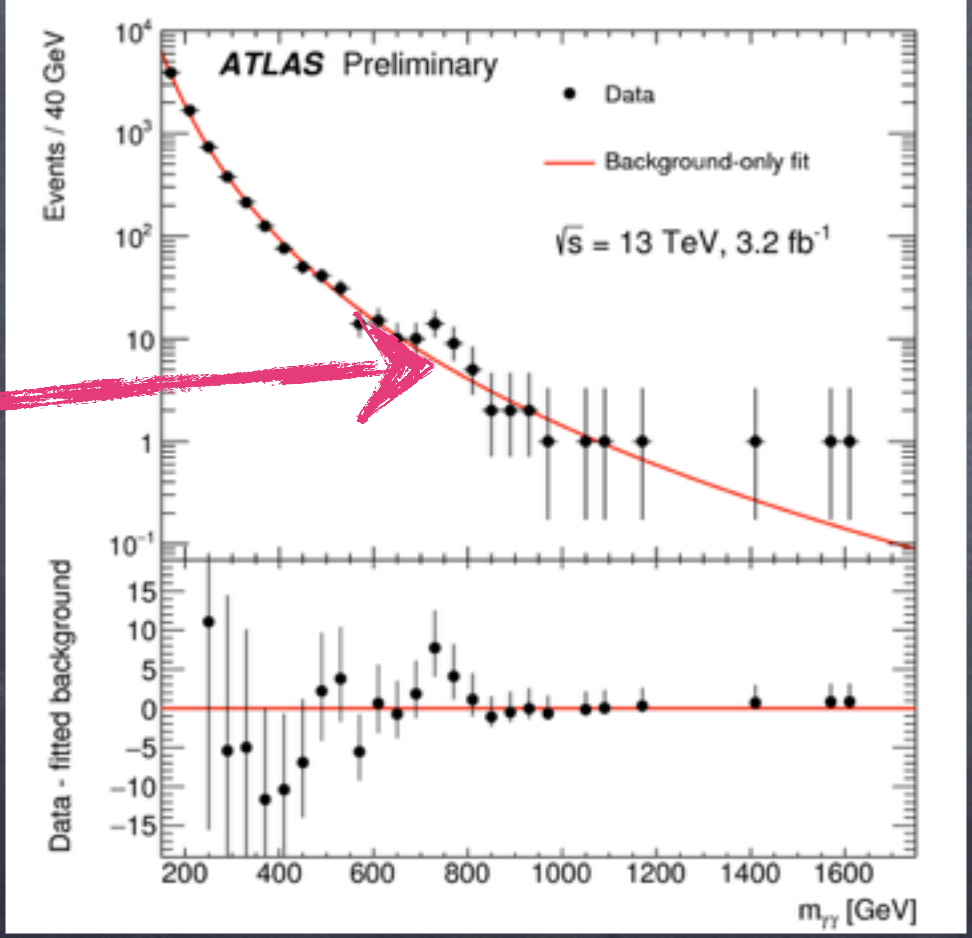
Adam Falkowski

Phenomenology of the 750 GeV resonance

Cet obscur objet du désir

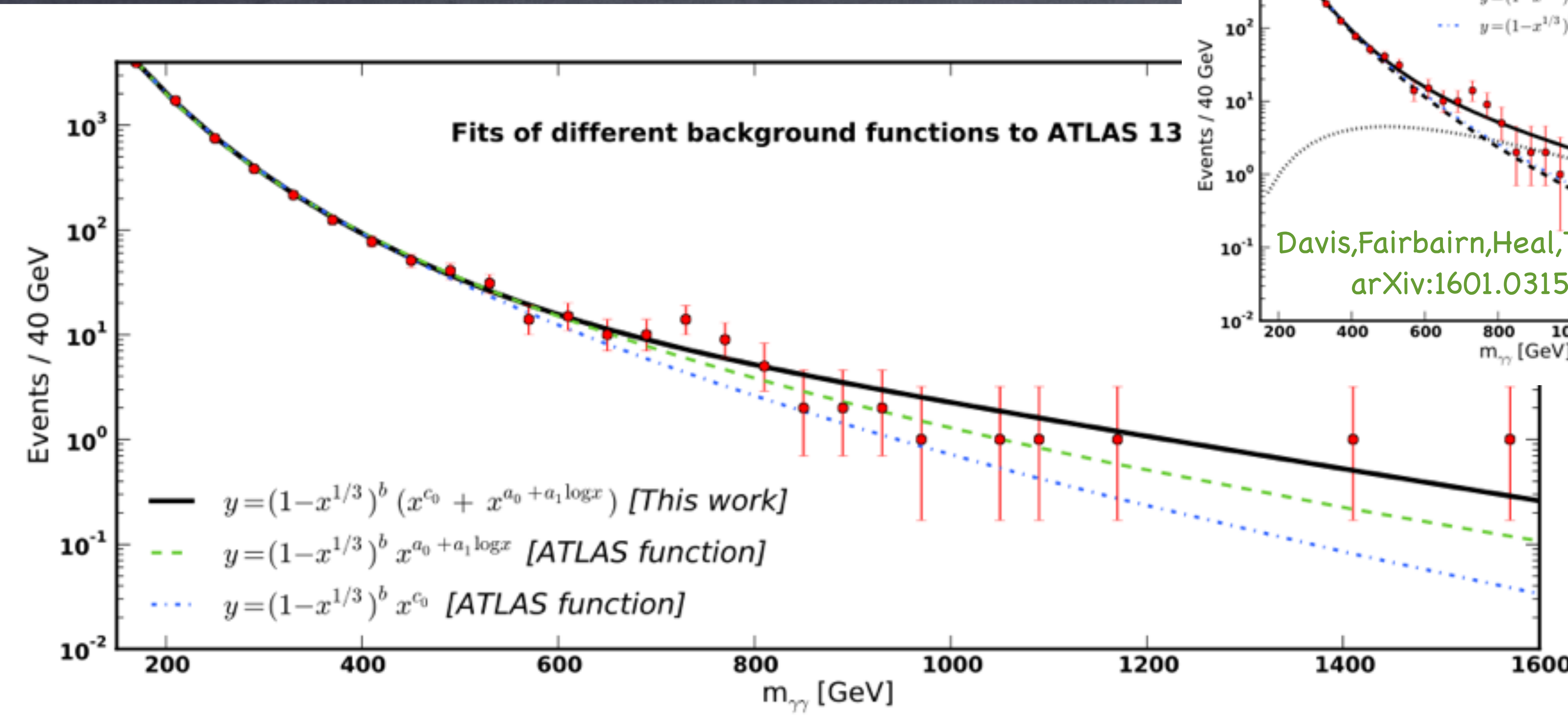


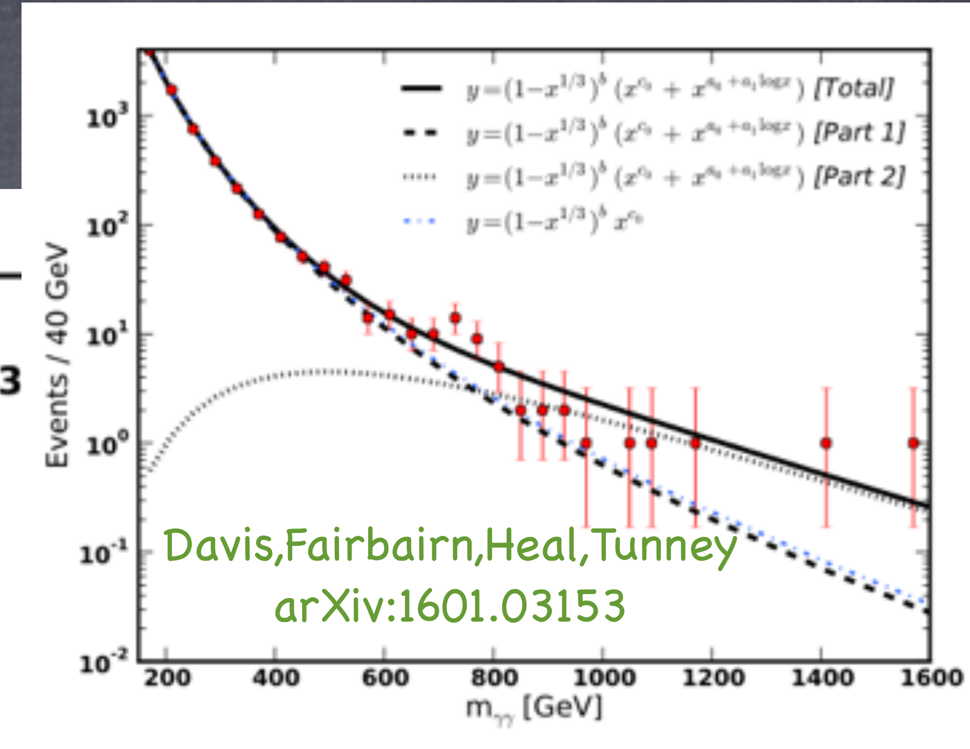
LLR Palaiseau, 15 February 2016

Plan

- How is it produced and how it decays
- What are its parameters
- In which models can it fit
- A bigger picture?

Is it even true?



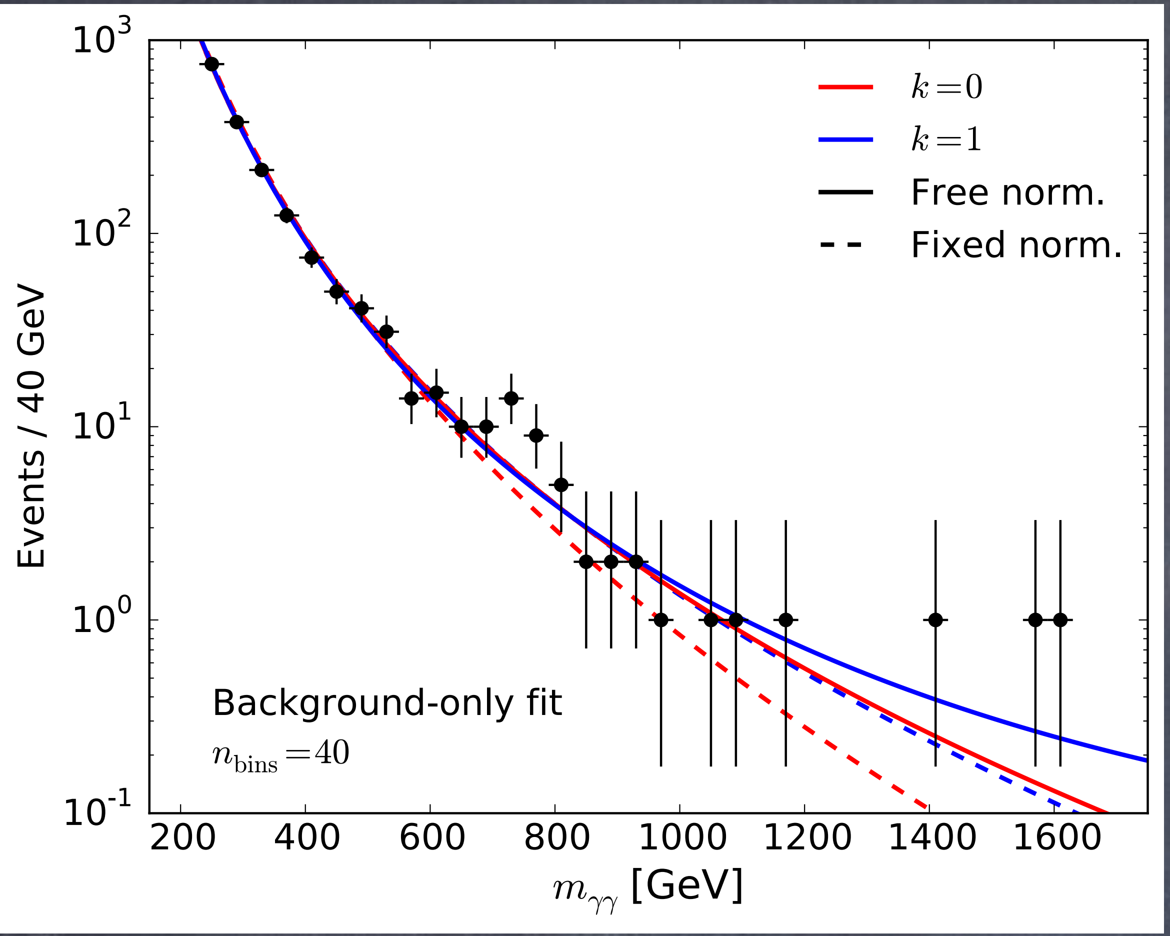


- Claim that another function fits background better than ATLAS fit, and when it's used, significance drops to 2 sigma
- However their analysis has several grave errors: empty bins at the tail are ignored, and normalization is not treated as a free parameter unlike in ATLAS
- Fixing these errors, one recovers ATLAS results and significance of 750 GeV excess

Kavanagh, 1601.07330

Is it even true?

Kavanagh, 1601.07330



Background function	NWA	Free-width
Fixed normalisation		
$k = 0$	4.2σ	4.9σ
$k = 1$	3.4σ	3.7σ
$k = 2$	3.4σ	3.7σ
Free normalisation		
$k = 0^\dagger$	3.4σ	3.6σ
$k = 1$	3.5σ	3.8σ
$k = 2$	3.4σ	3.6σ
ATLAS reported	3.6σ	3.9σ

- Correct theory level analysis roughly reproduces ATLAS results concerning diphoton background and signal significance

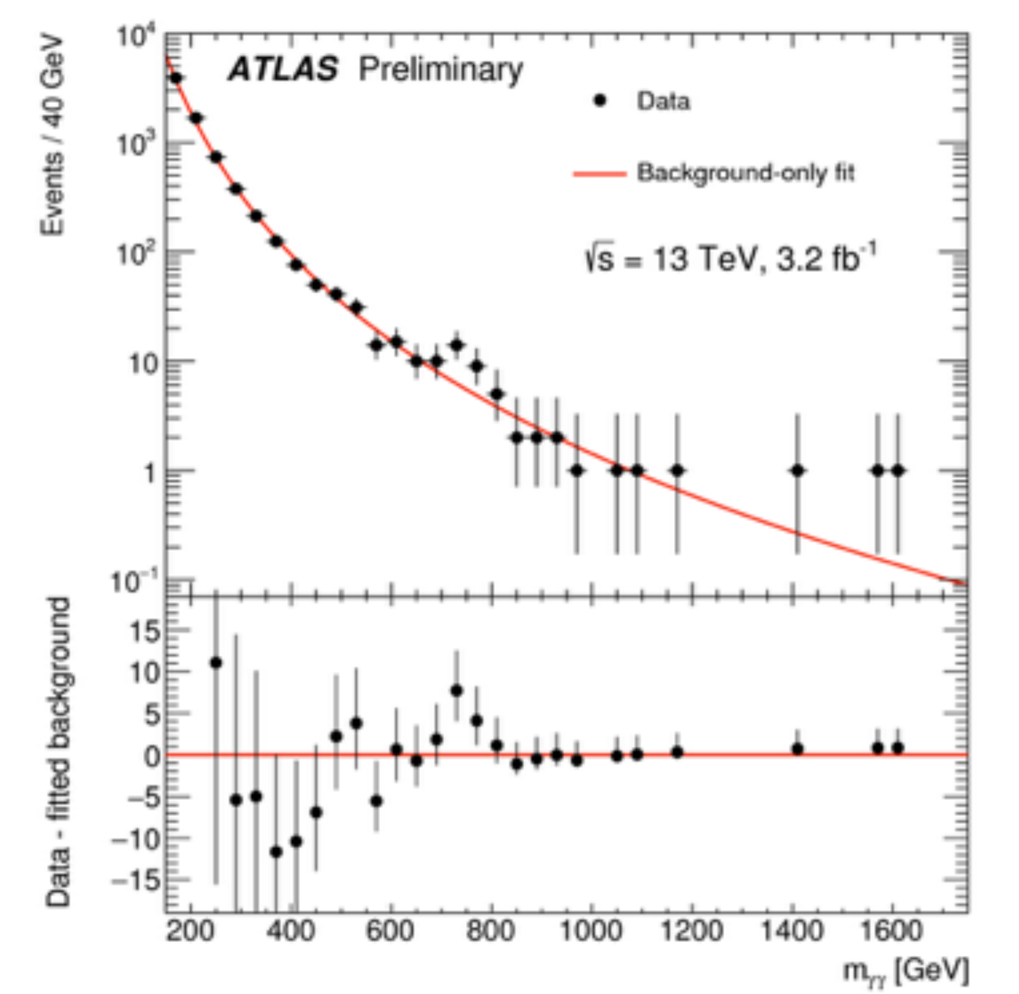
Run-2 Data

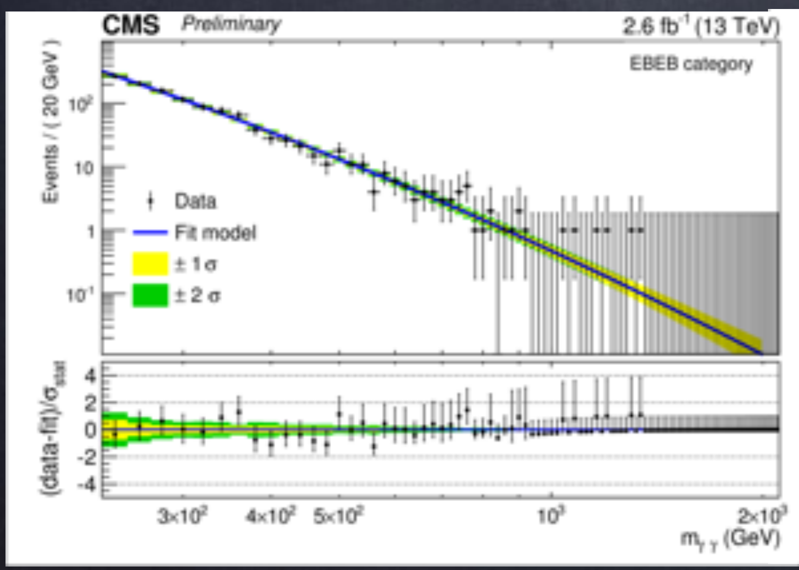
ATLAS 13 TeV

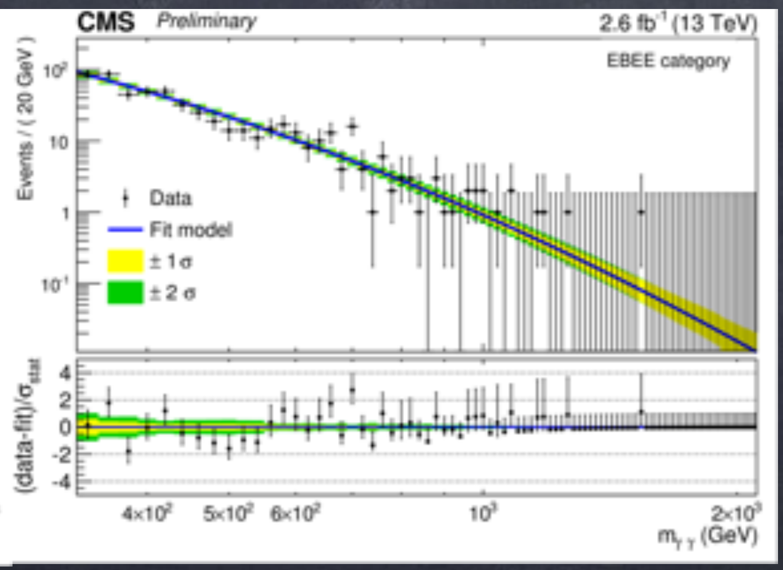
Bin[GeV]	650	690	730	770	810	850
N_{events}	10	10	14	9	5	2
$N_{\text{background}}$	11.0	8.2	6.3	5.0	3.9	3.1

CMS 13 TeV

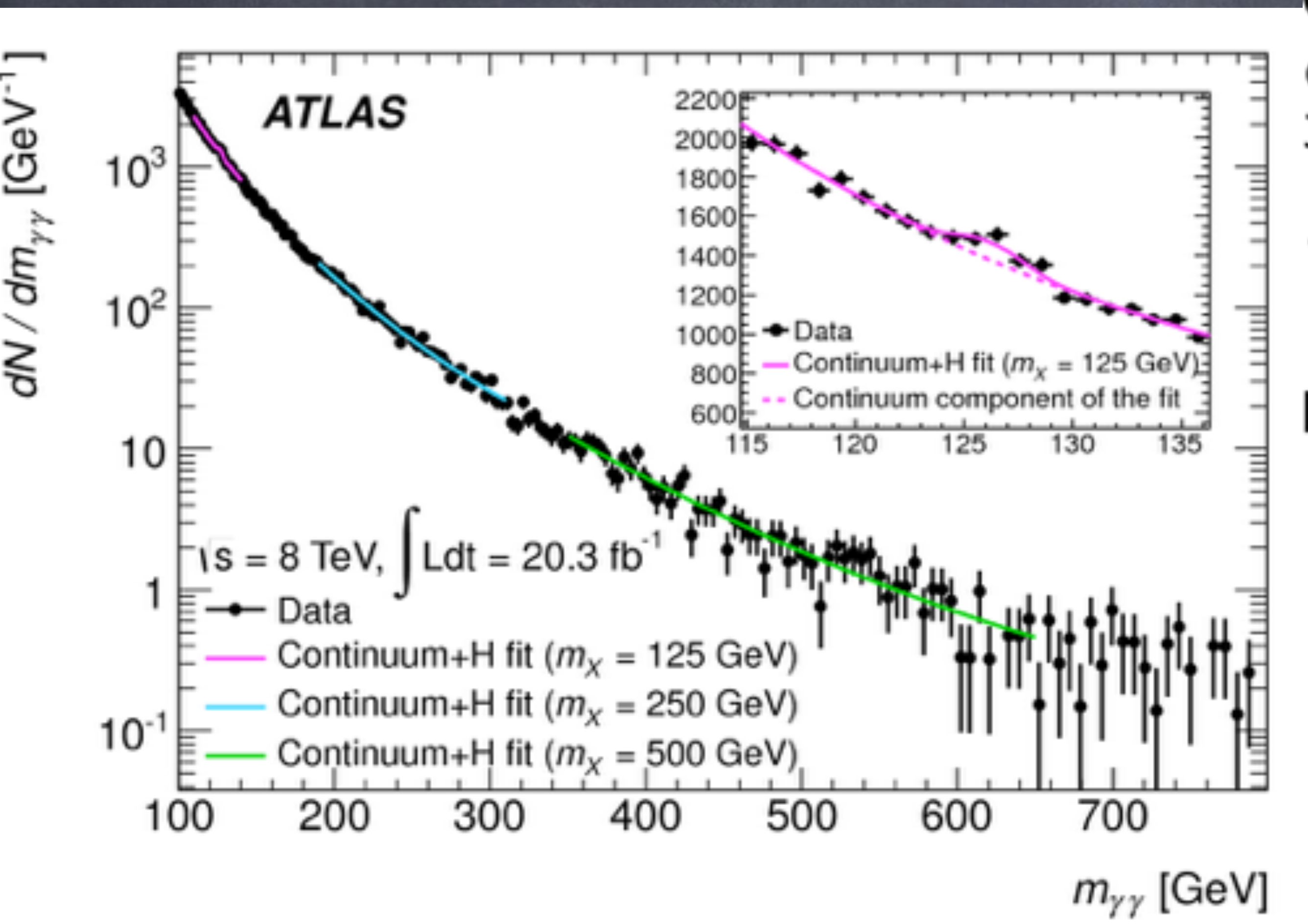
Bin[GeV]	700	720	740	760	780	800
N_{events} (EBEB)	3	3	4	5	1	1
$N_{\text{background}}$ (EBEB)	2.7	2.5	2.1	1.9	1.6	1.5
N_{events} (EBEE)	16	4	1	6	2	3
$N_{\text{background}}$ (EBEE)	5.2	4.6	4.0	3.5	3.1	2.8

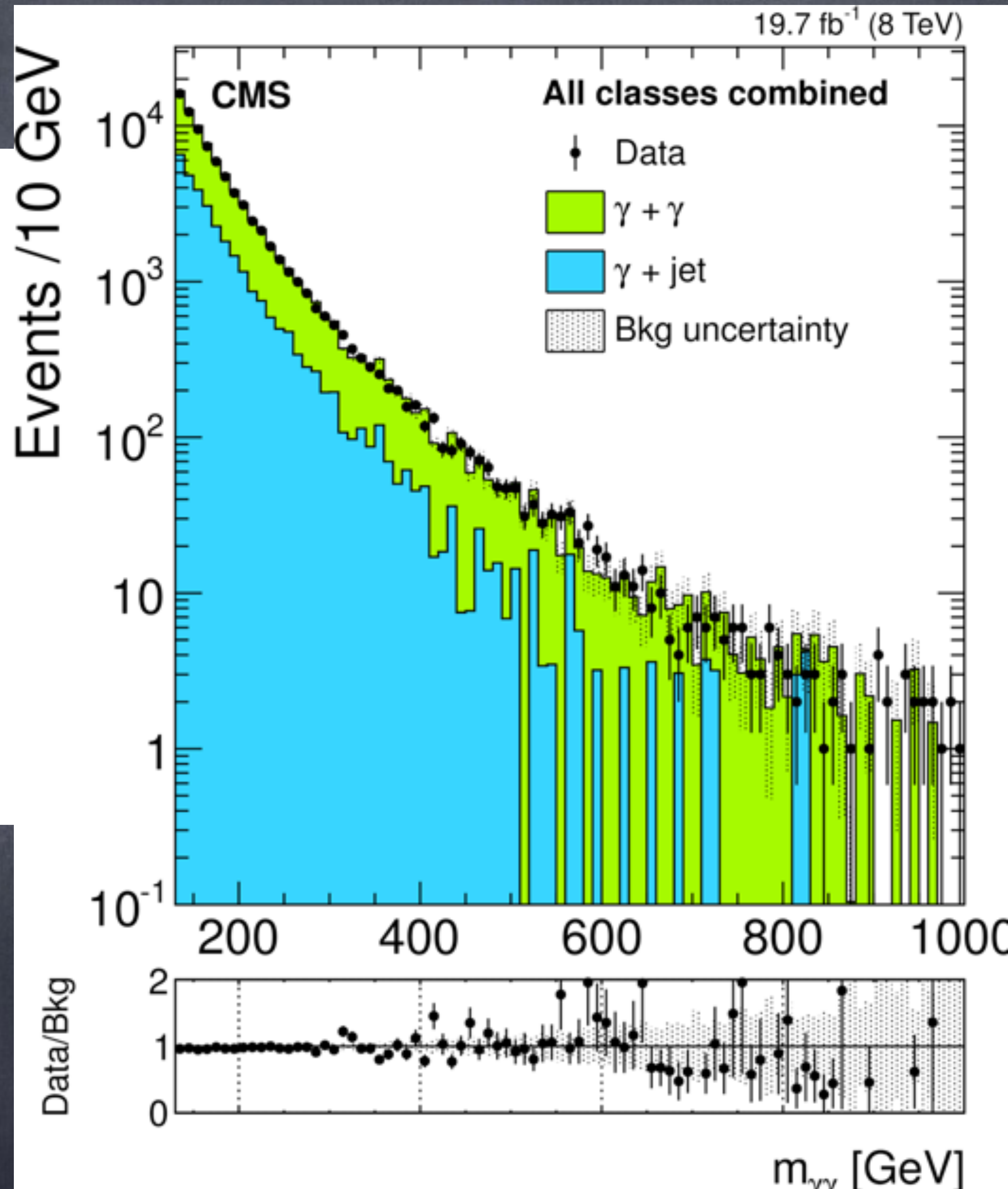






Run-1 Data





No significant excess in ATLAS or CMS

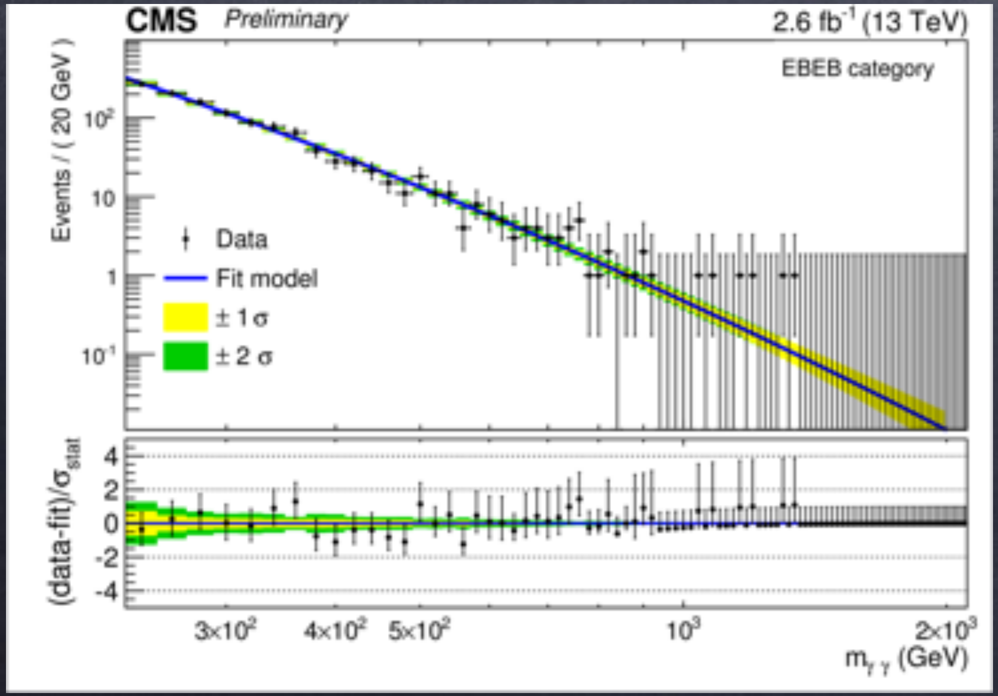
Production processes

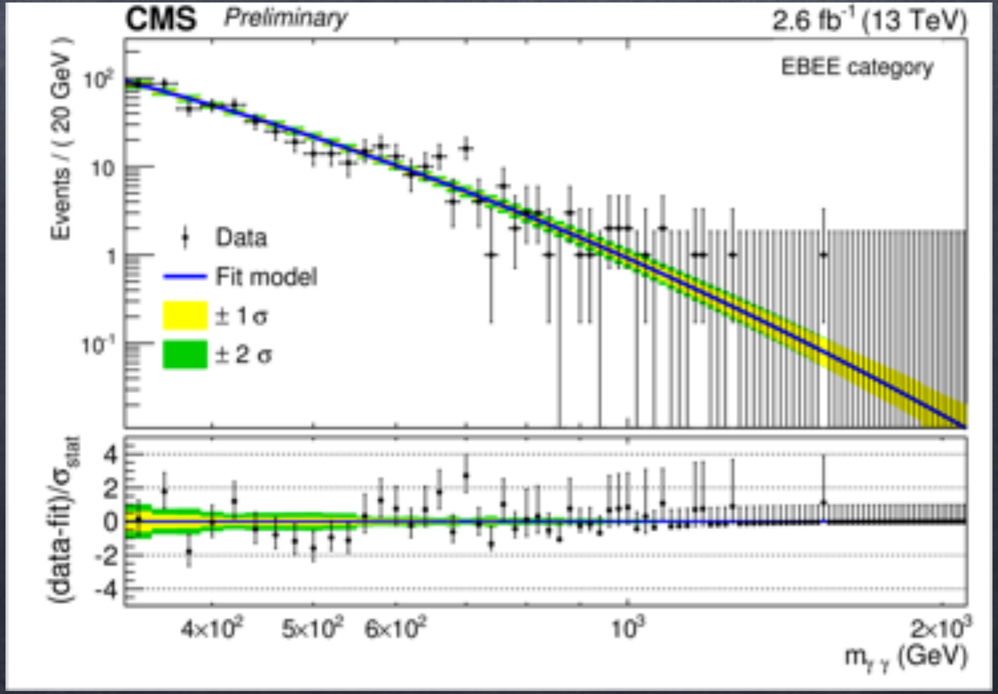
To include in these considerations:

CERN-TH et al.
1512.04933

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

- Compatibility between 13 TeV and 8 TeV LHC data
- Angular distributions
- Additional activity in diphoton events

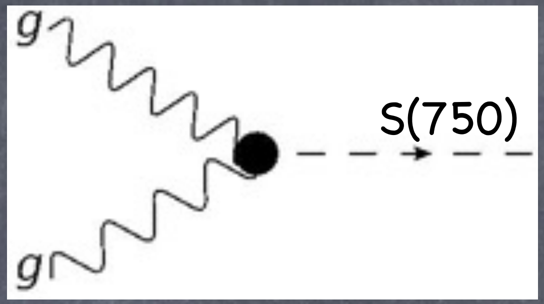




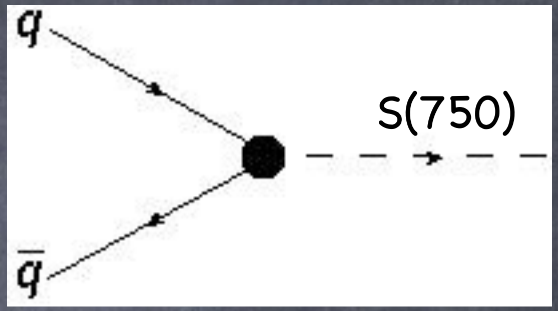
Direct production processes

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

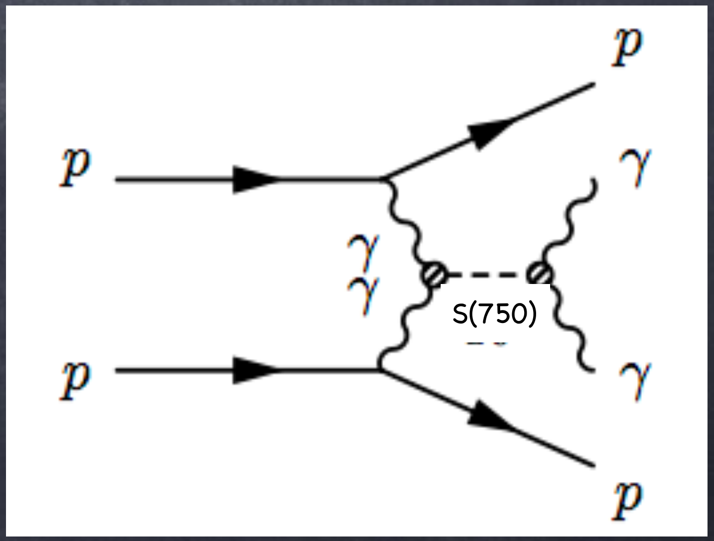
- Gluon fusion is theoretically preferred



- Production dominated by light quark-antiquark collisions leads to serious tension between 8 and 13 TeV data.
- Production dominated by heavy quark-antiquark collisions is just as good as gluon fusion from compatibility point of view, however model building is more challenging



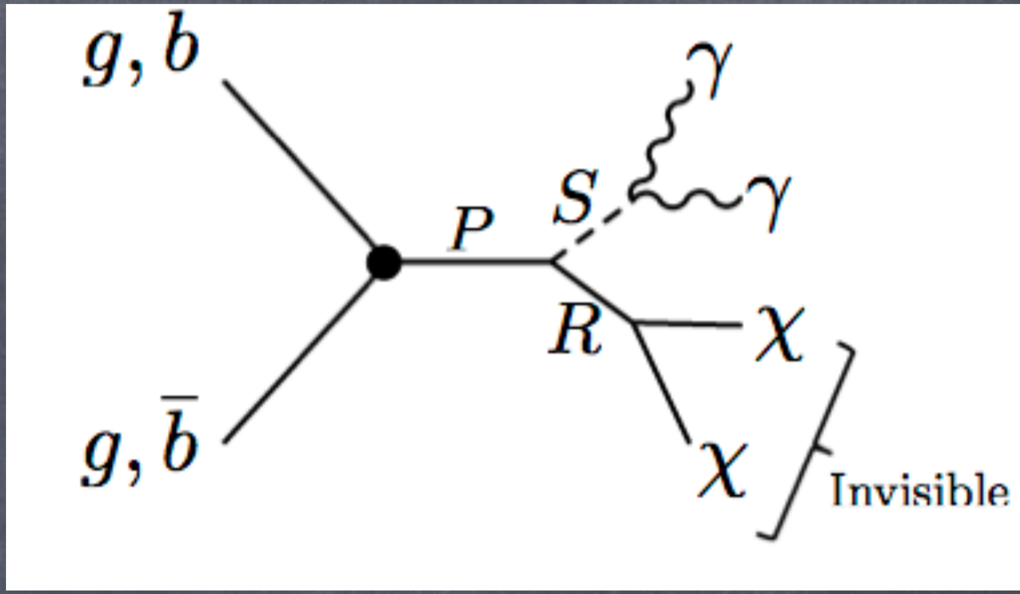
- Production via photon fusion is present in any model, however if it's dominant there is again tension between 8 and 13 TeV data
- One or many closely packed resonances near 750 GeV may be present



see e.g. Csaki et al 1601.00638

Associated production processes

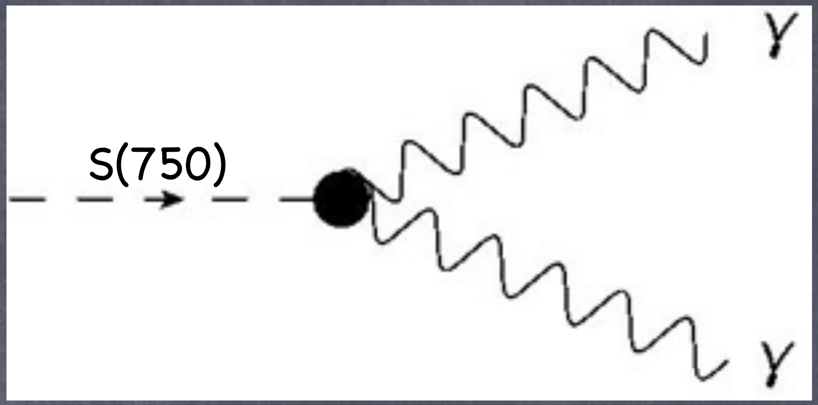
- In general, all associated production processes predict additional activity in diphoton events, however problem can be avoided by fine tuning the model
- On the plus side, tension between 8 and 13 TeV data can be diminished
- On the minus side, required cross section more difficult to achieve from theory point of view



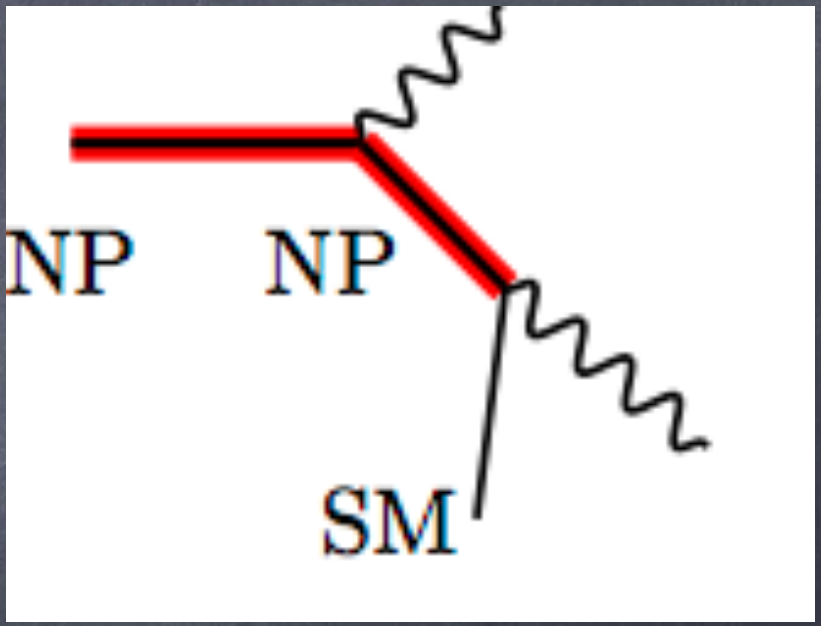
CERN-TH et al.
1512.04933

Decay process

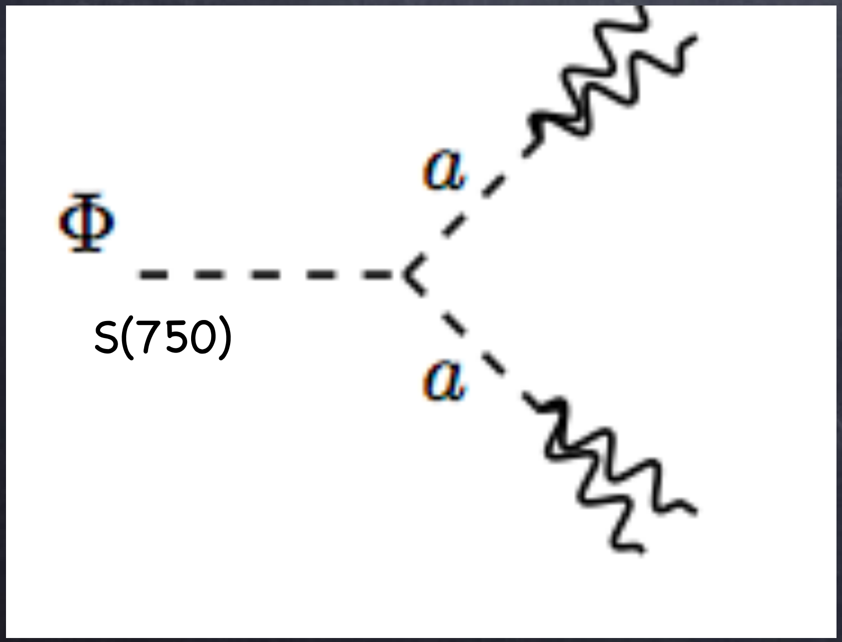
- Direct decay into 2 photons is of course the most plausible option

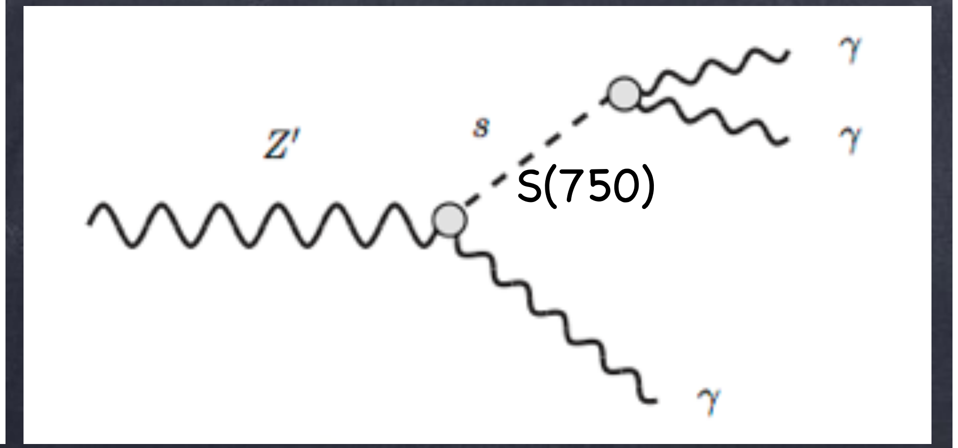


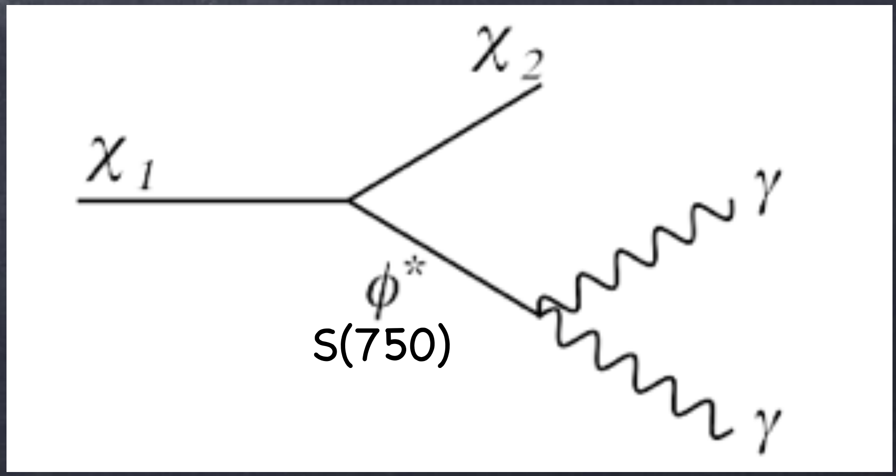
- Multi-body decay states are also possible as long as additional particles are, for kinematic reasons, soft or aligned with the photons



- Most interesting alternative possibility is cascade decay into 4 photons via light

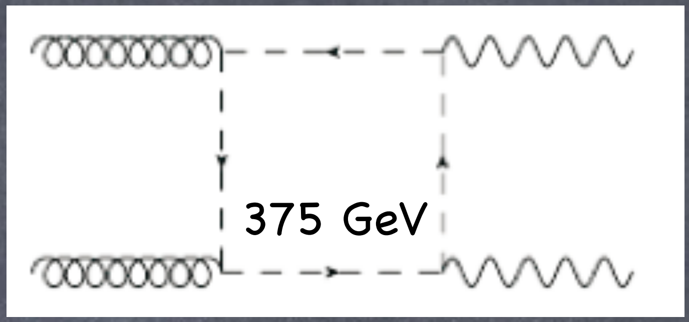






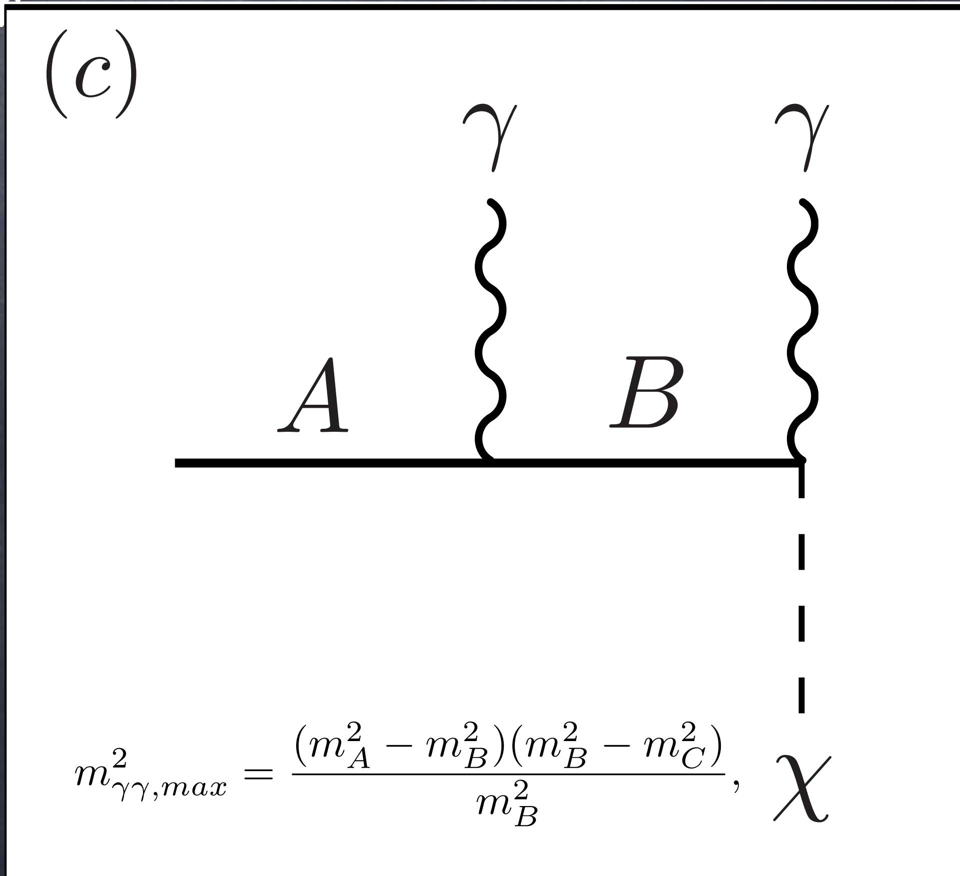
Bump without a resonance?

- Few proposal in the literature to realize a bump at 750 GeV without a new particle at 750 GeV (but with another mass)



- 1512.08221 argues that the bump can be reproduced with 375 GeV particle coupled to gluon and photons, thanks to kinematic properties of the 1-loop gg→$\gamma\gamma$ diagram

- 1512.04928 argues the bump could me a kinematic edge in a cascade decay from heavier resonance into 2 photons and one additional particle

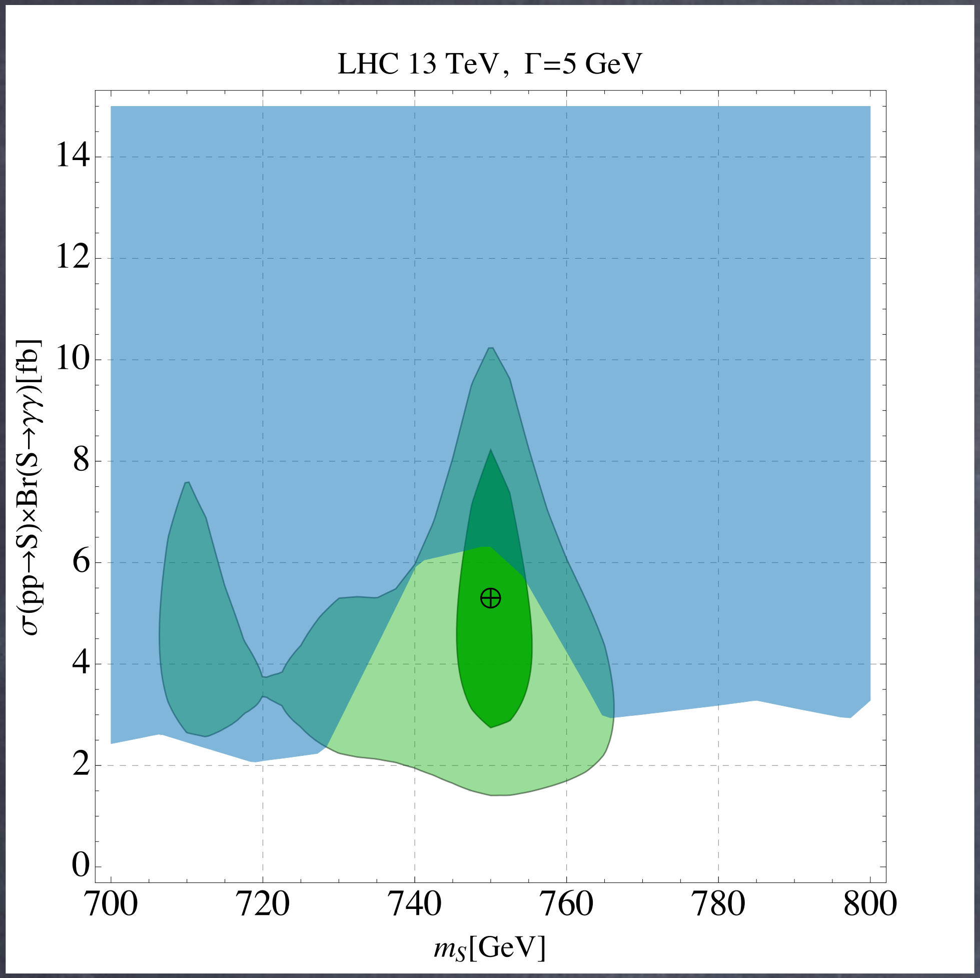


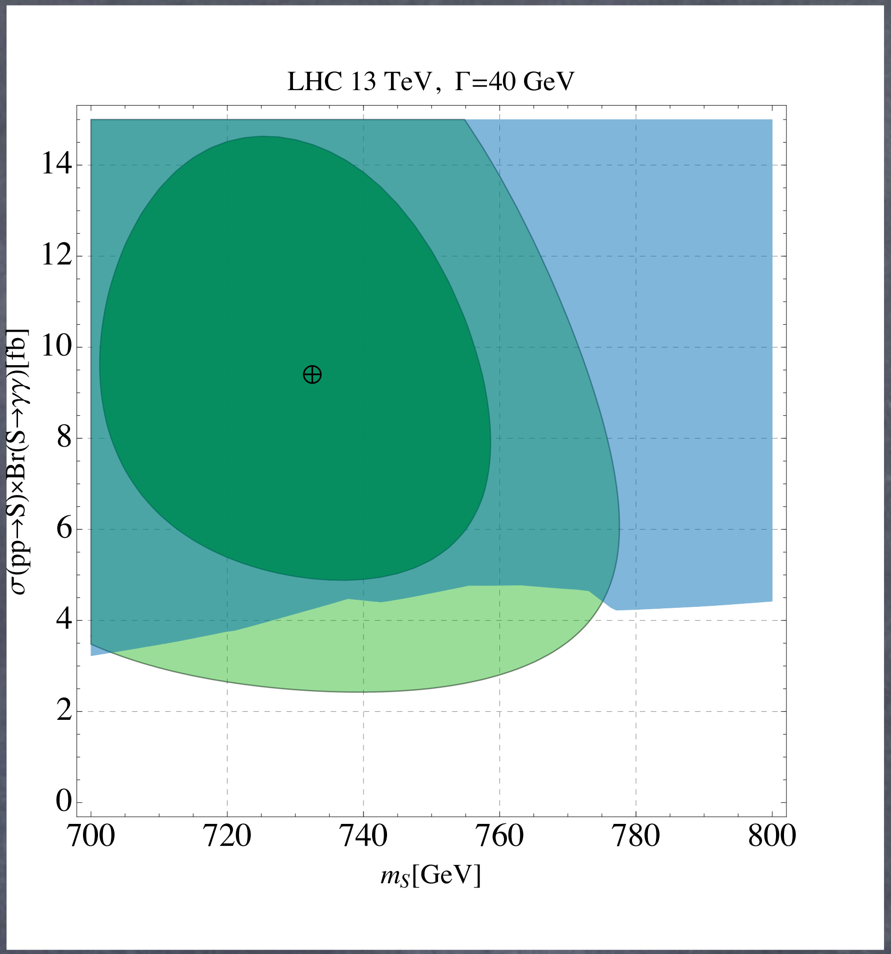
$$m^2_{\gamma\gamma,max} = \frac{(m_A^2 - m_B^2)(m_B^2 - m_C^2)}{m_B^2},$$

Model-independent analysis

What is the mass and cross section?

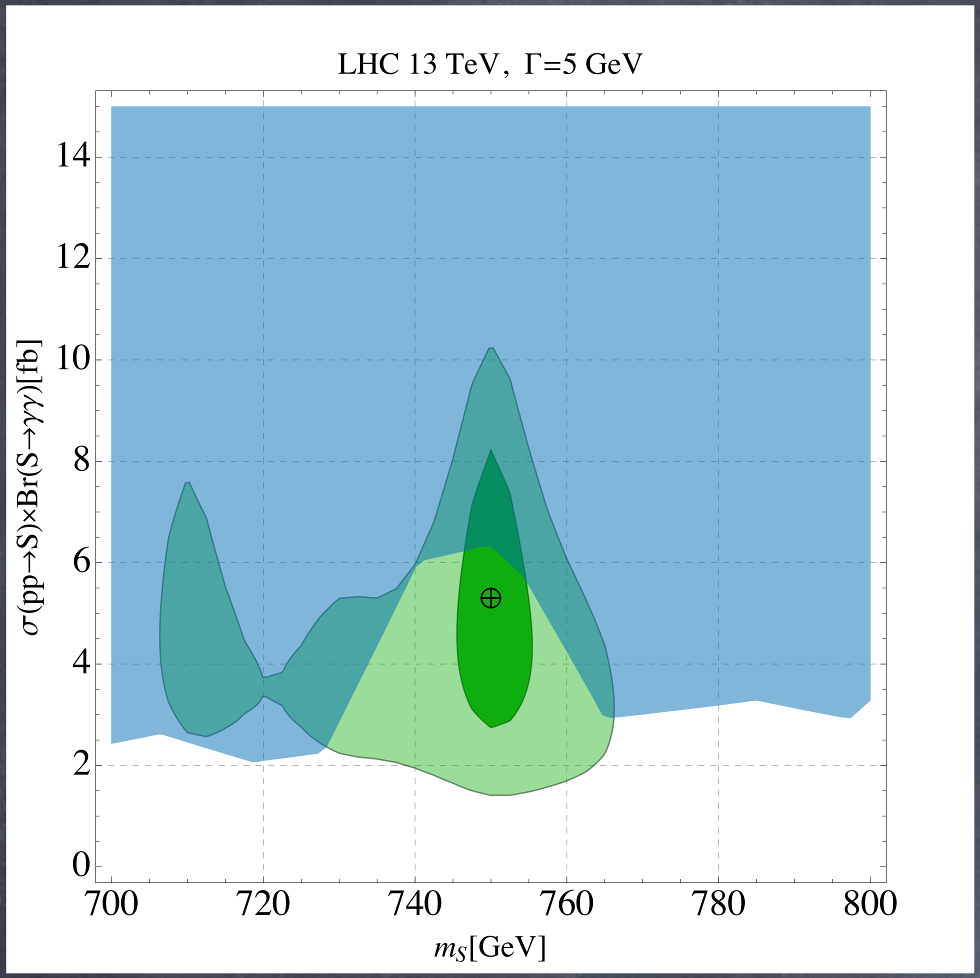
AA,Slone,Volansky
1512.05777

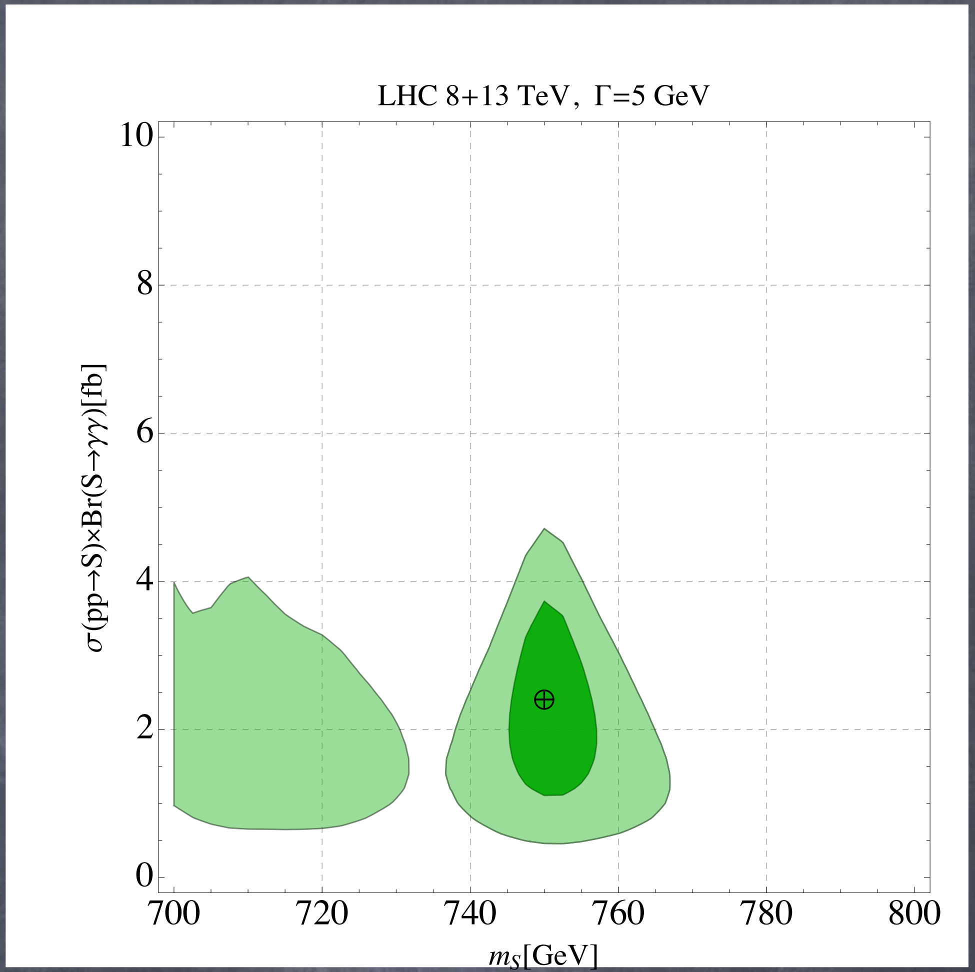




- ATLAS+CMS run-2 data can be well fit with narrow scalar resonance of mass around 750 GeV and $\sigma(pp\to S)Br(S\to\gamma\gamma)\approx$ 5fb
- This is not excluded by run-1 constraints, thanks to a small excess in run-1 CMS diphoton resonance search near 750 GeV
- For a wide resonance the required cross section is twice as large, and any mass between 700 and 750 will do. However tension with CMS run-1 limits is then large

What is the mass and cross section?

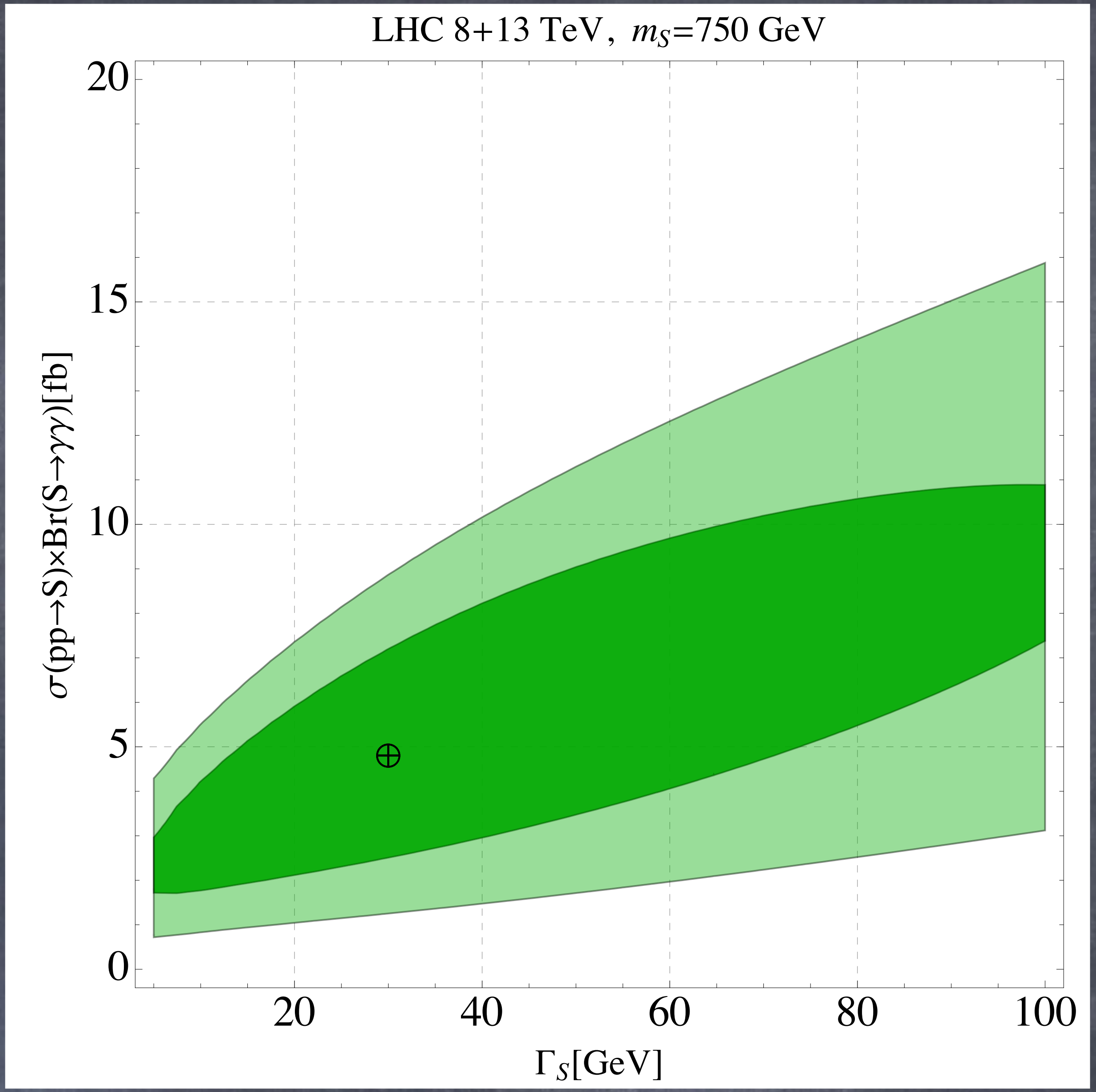




- Combining run-1 and run-2 data, best fit cross section for narrow resonance goes down to $\sigma(pp\to S)$ $Br(S\to\gamma\gamma) \approx 2.5$ fb

- However, combined significance remains around 3 sigma ($\Delta\chi$^2 ≈ 11 between best fit and no signal hypothesis)

What is the width?

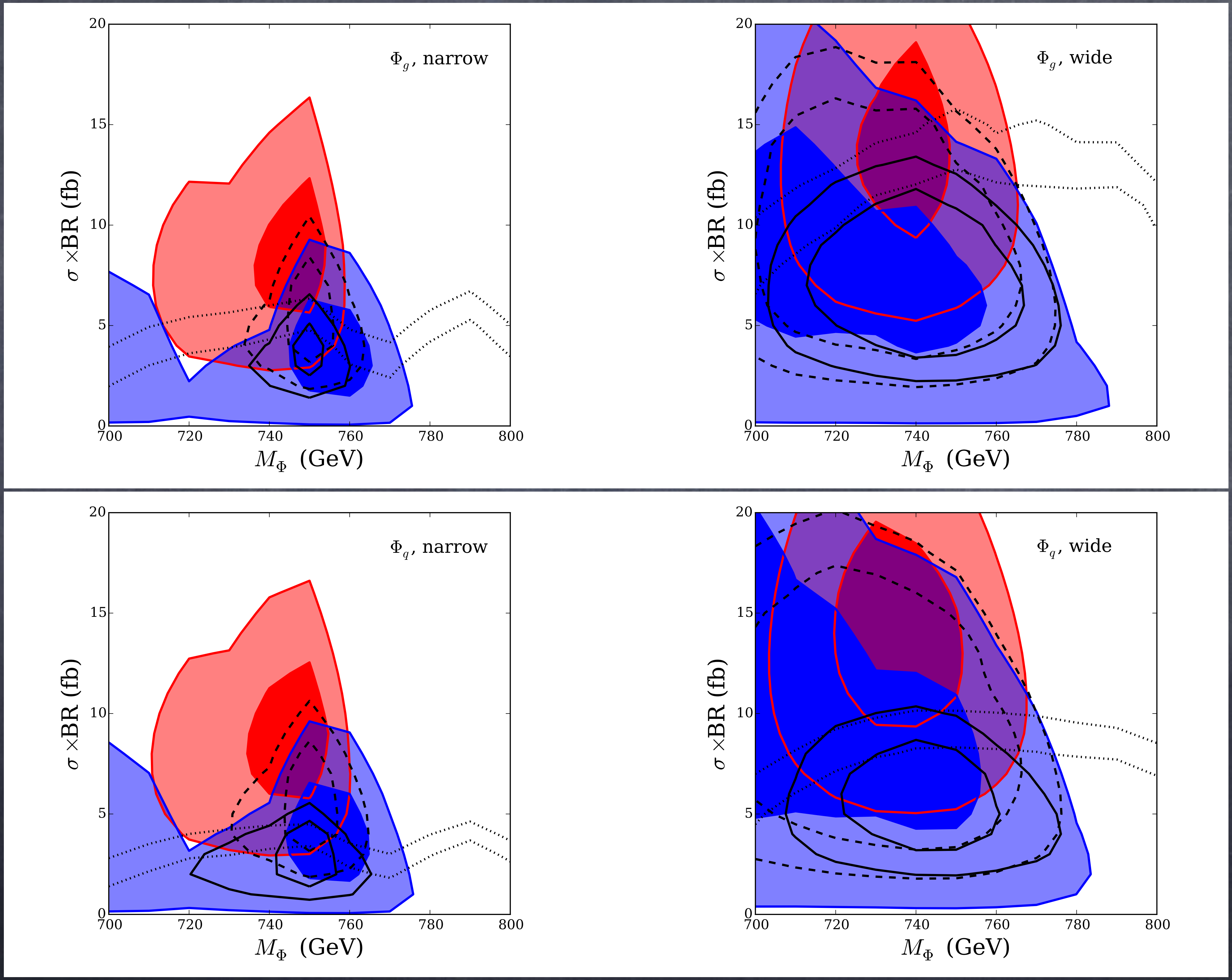


- In combined data, small but not statistically significant preference for a large width
- Large width more difficult theoretically and requires larger diphoton cross section

What is the mass and cross section?

More careful analysis by Buckley 1601.04751

spin-0

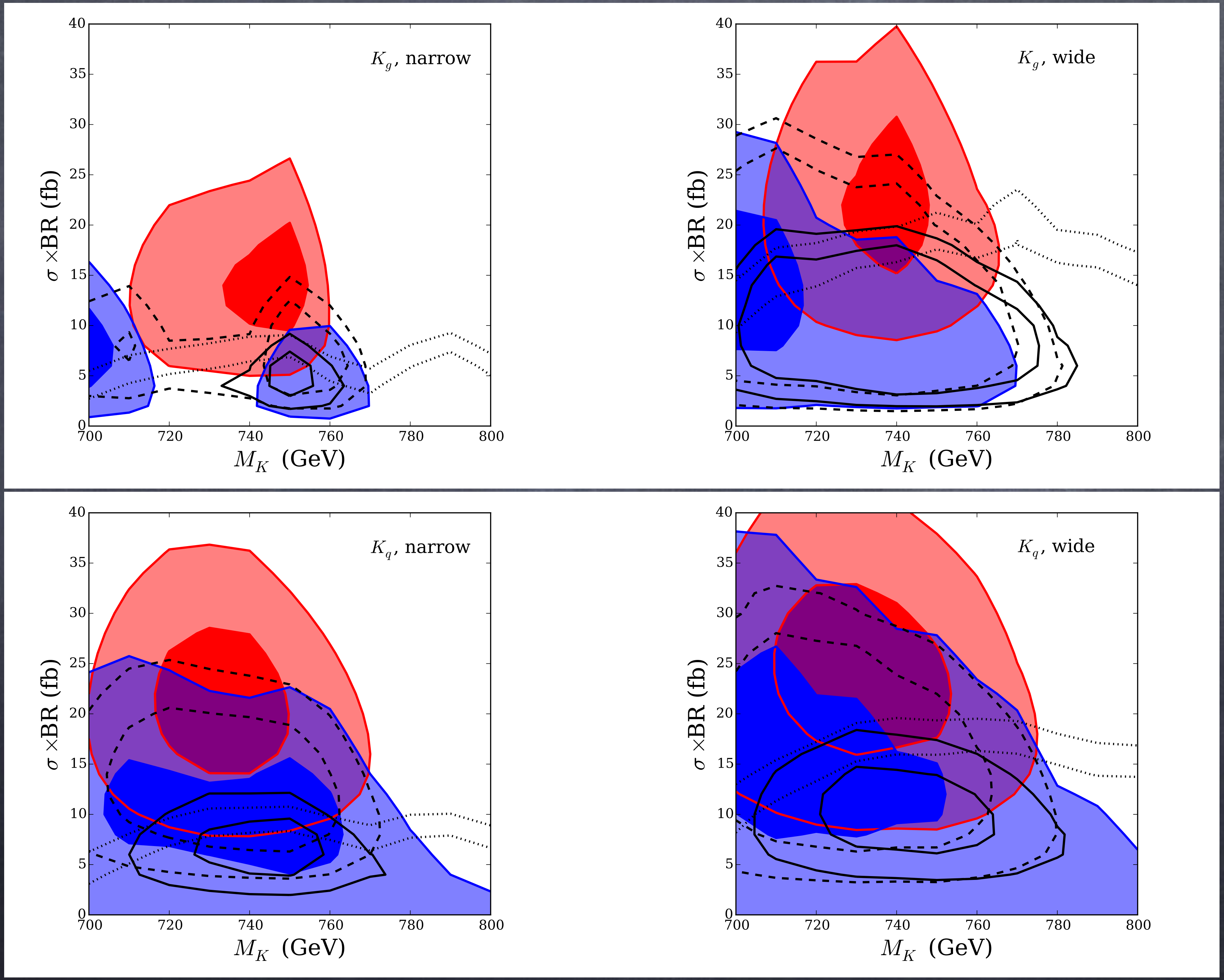


3.5σ combined signal, with 4fb best fit cross section

What is the mass and cross section?

More careful analysis by Buckley 1601.04751

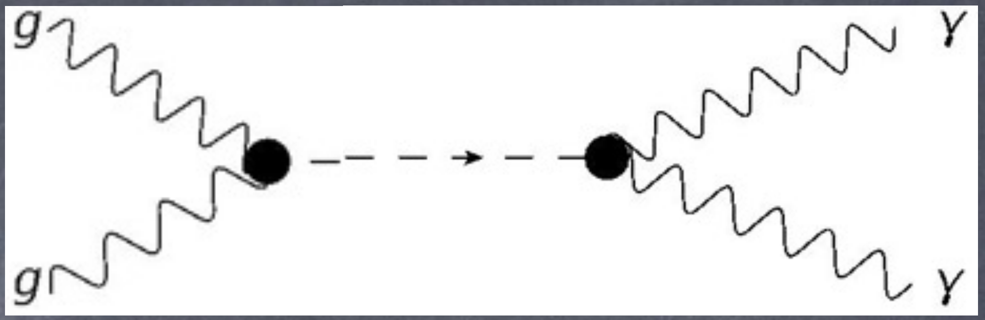
spin-2



Everyone`s model

Simplest effective model

Scalar field S coupled to photons and gluons via effective non-renormalizable interactions



$$\mathcal{L}_{S,\text{eff}} = \frac{e^2}{4v} c_{s\gamma\gamma} S A_{\mu\nu} A_{\mu\nu} + \frac{g_s^2}{4v} c_{sgg} S G^a_{\mu\nu} G^a_{\mu\nu},$$

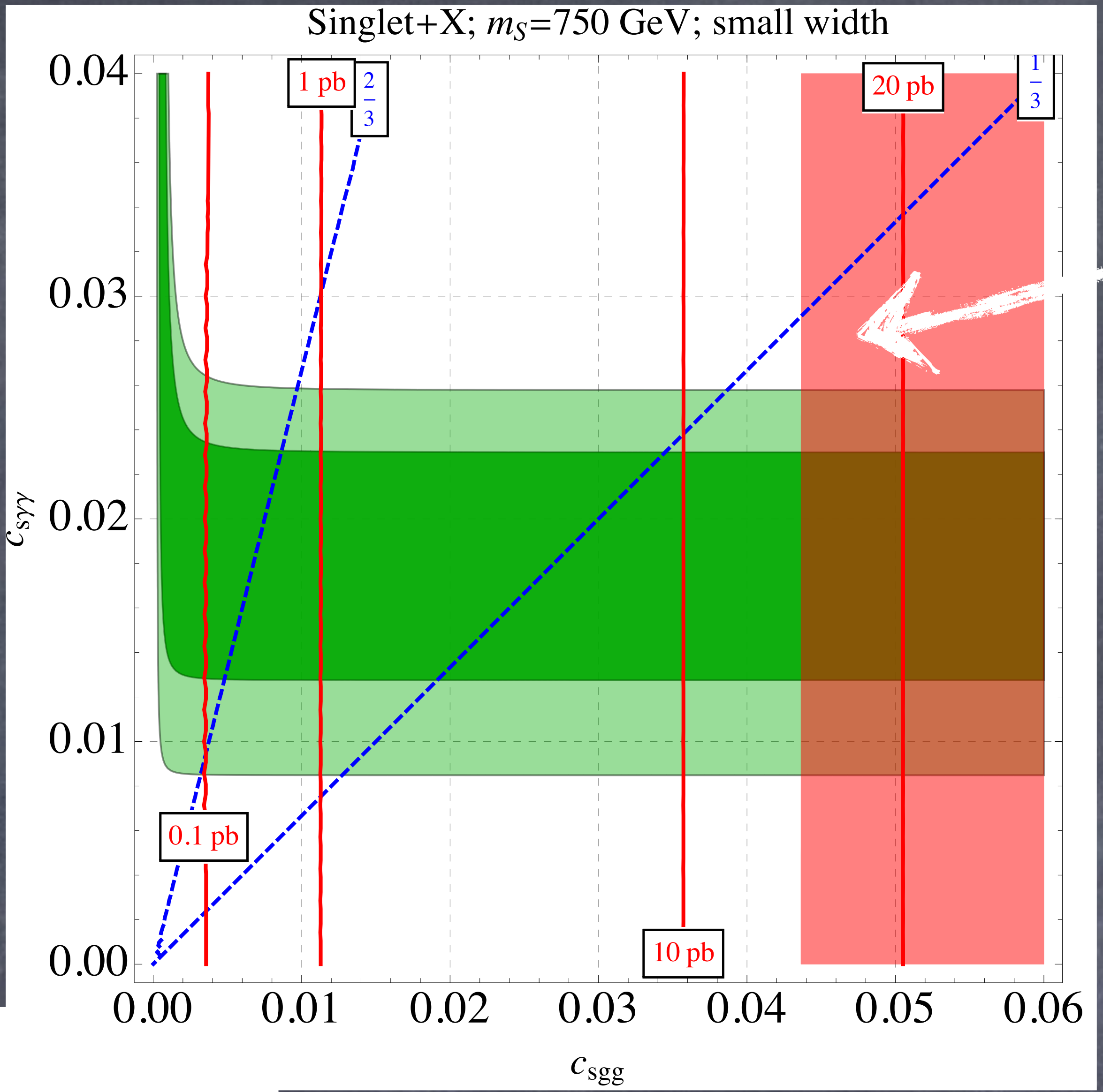
Production

$$\sigma(pp \to S) = k \frac{\pi c_{sgg}^2 g_s^4 m_S^2}{64 v^2 E_{\text{LHC}}^2} L_{gg} \left(\frac{m_S^2}{E_{\text{LHC}}^2} \right),$$

Decay

$$\Gamma(S \to \gamma\gamma) = c_{s\gamma\gamma}^2 \frac{e^4 m_S^3}{64 \pi v^2}, \qquad \Gamma(S \to gg) = c_{sgg}^2 \frac{g_s^4 m_S^3}{8 \pi v^2}.$$

Parameter space

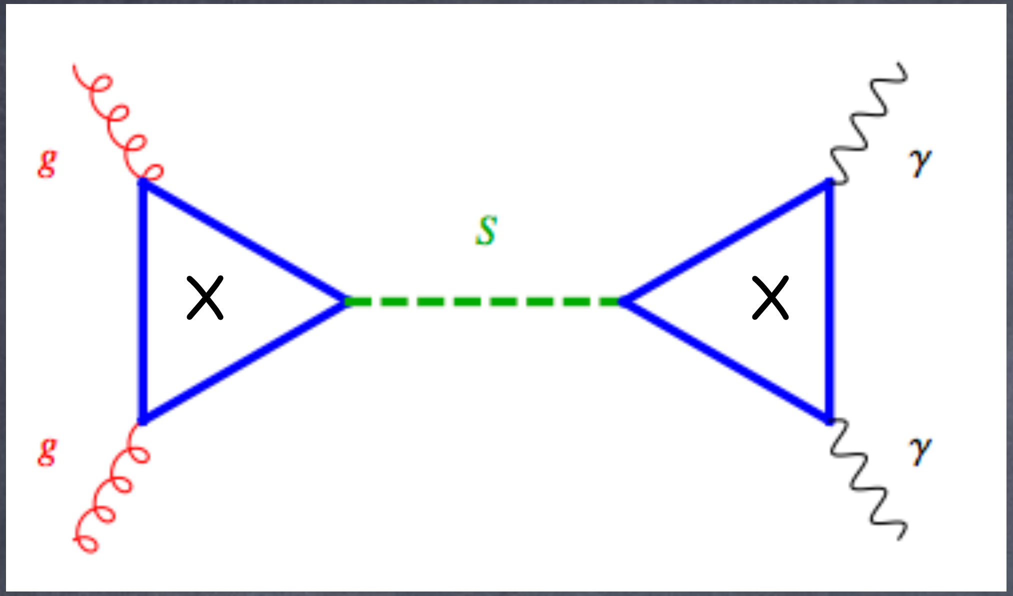


CMS-PAS-EXO-14-005
run-1 dijet search
with scouting data

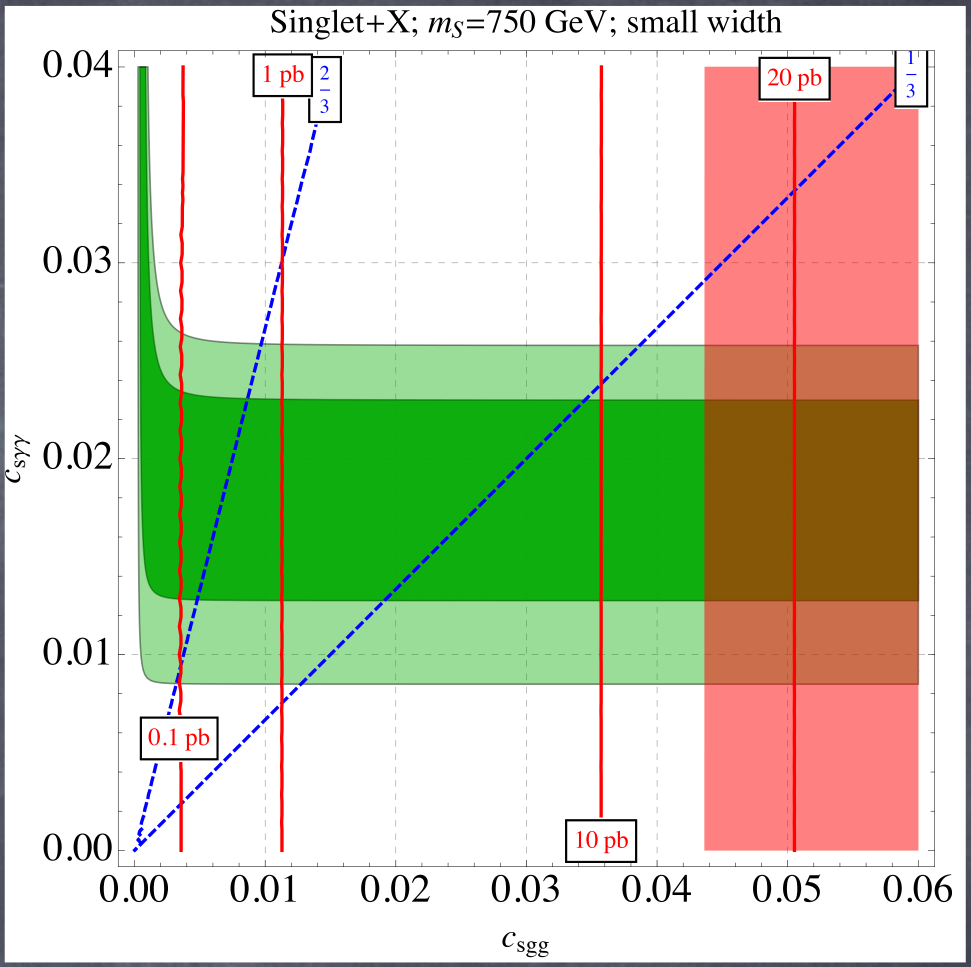
$$\mathcal{L}_{S,\text{eff}} = \frac{e^2}{4v} c_{s\gamma\gamma} S A_{\mu\nu} A_{\mu\nu} + \frac{g_s^2}{4v} c_{sgg} S G^a_{\mu\nu} G^a_{\mu\nu},$$

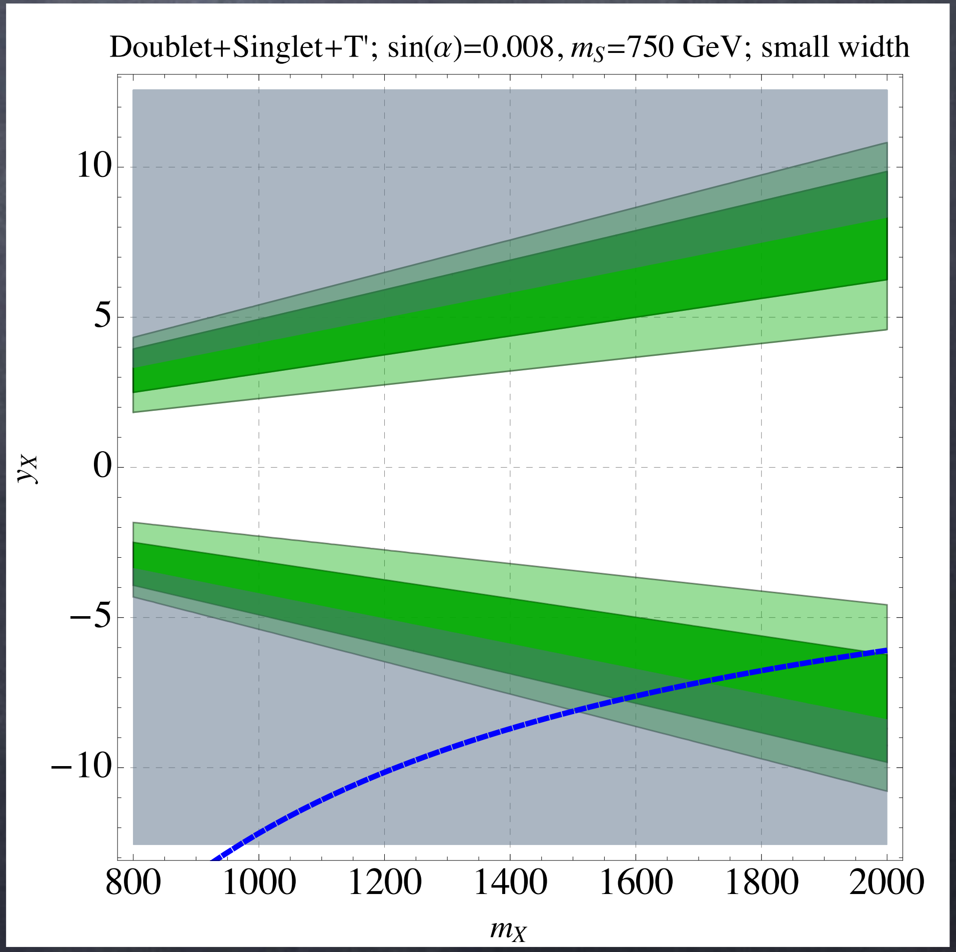
- One prediction of the simplest model: there must be an accompanying dijet resonance signal
- Dijet resonance can be observable in portion of parameter space, but it can also be buried forever under SM background

Origin of effective couplings



$$c_{sgg} = \frac{y_X v}{12\pi^2 m_X}\,, \qquad c_{s\gamma\gamma} = \frac{y_X Q_X^2 v}{2\pi^2 m_X}\,.$$





- Effective couplings generated by integrating out e.g. new vector-like quarks with Yukawa couplings to scalar S
- Because of 1-loop suppression large Yukawa needed. E.g. for QX=2/3, mX=1 TeV we need yX = 3

Origin of effective couplings

In high-energy theory, SU(2)xU(1) invariant operators generated.
This implies correlation between couplings of resonance to EW gauge bosons

e.g. if vector-like quarks have hypercharge but no SU(2) quantum numbers:

$$\mathcal{L}_{S,\text{eff}} \supset \frac{e^2}{4vc_\theta^2} c_{s\gamma\gamma} S B_{\mu\nu} B_{\mu\nu} = \frac{e^2}{4v} c_{s\gamma\gamma} S \left(A_{\mu\nu} A_{\mu\nu} - 2t_\theta A_{\mu\nu} Z_{\mu\nu} + t_\theta^2 Z_{\mu\nu} Z_{\mu\nu} \right),$$

$$\frac{\text{Br}(S \to Z\gamma)}{\text{Br}(S \to \gamma\gamma)} \approx 2t_\theta^2 \approx 0.6$$

$$\frac{\text{Br}(S \to ZZ)}{\text{Br}(S \to \gamma\gamma)} \approx t_\theta^4 \approx 0.1$$

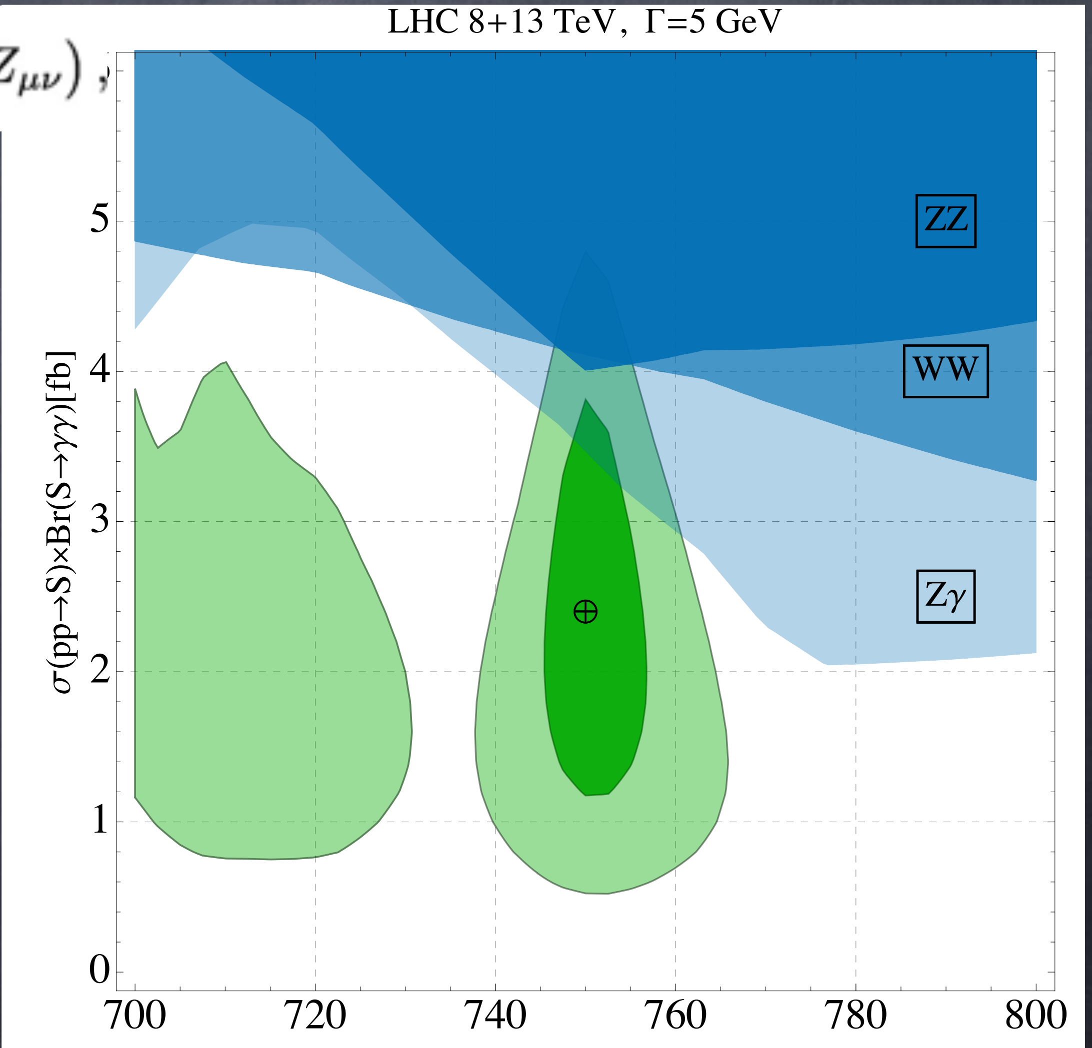
Similarly, if vector-like quarks have no hypercharge but only SU(2) quantum numbers:

$$\mathcal{L}_{S,\text{eff}} \supset \frac{e^2}{4vs_\theta^2} c_{s\gamma\gamma} S W^i_{\mu\nu} W^i_{\mu\nu} = \frac{e^2}{4v} c_{s\gamma\gamma} S \left(A_{\mu\nu} A_{\mu\nu} + 2t_\theta^{-1} A_{\mu\nu} Z_{\mu\nu} + t_\theta^{-2} Z_{\mu\nu} Z_{\mu\nu} \right),$$

$$\frac{\text{Br}(S \to Z\gamma)}{\text{Br}(S \to \gamma\gamma)} \approx 2t_\theta^{-2} \approx 7$$

$$\frac{\text{Br}(S \to ZZ)}{\text{Br}(S \to \gamma\gamma)} \approx t_\theta^{-4} \approx 13$$

$$\frac{\text{Br}(S \to WW)}{\text{Br}(S \to \gamma\gamma)} \approx 2s_\theta^{-4} \approx 40$$



Beyond minimal model

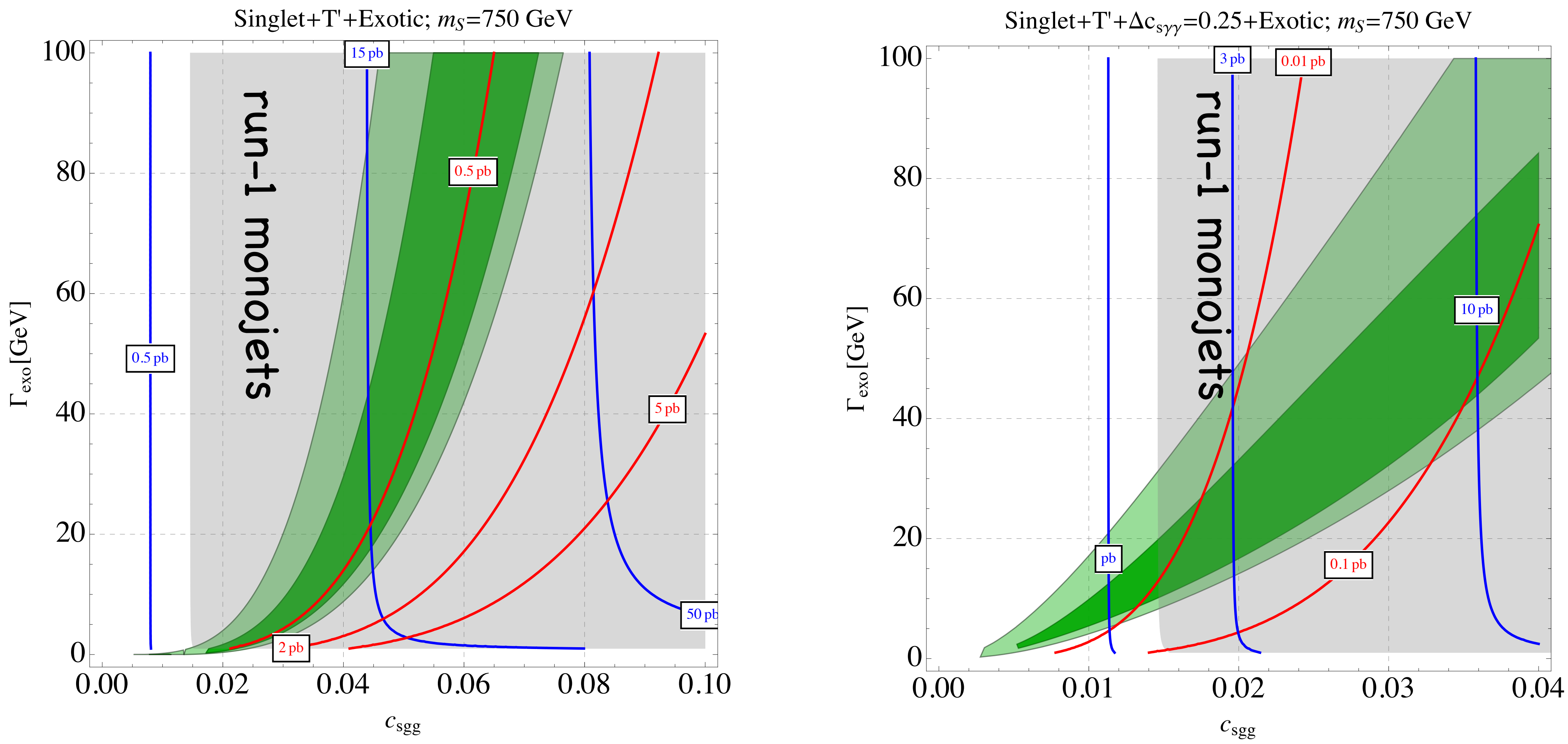
Other channels

CERN-TH et al.
1512.04933

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	[6, 7]	$< 0.8\ (r/5)$
$e^+e^- + \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[8]	$< 0.6\ (r/5)$
$\tau^+\tau^-$	< 12 fb	< 15 fb	[9]	$< 6\ (r/5)$
$Z\gamma$	< 4.0 fb	< 3.4 fb	[10]	$< 2\ (r/5)$
ZZ	< 12 fb	< 20 fb	[11]	$< 6\ (r/5)$
Zh	< 19 fb	< 28 fb	[12]	$< 10\ (r/5)$
hh	< 39 fb	< 42 fb	[13]	$< 20\ (r/5)$
W^+W^-	< 40 fb	< 70 fb	[14, 15]	$< 20\ (r/5)$
$t\bar{t}$	< 550 fb	-	[16]	$< 300\ (r/5)$
invisible	< 0.8 pb	-	[17]	$< 400\ (r/5)$
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[18]	$< 500\ (r/5)$
jj	$\lesssim 2.5$ pb	-	[5]	$< 1300\ (r/5)$

Can it have large invisible width?

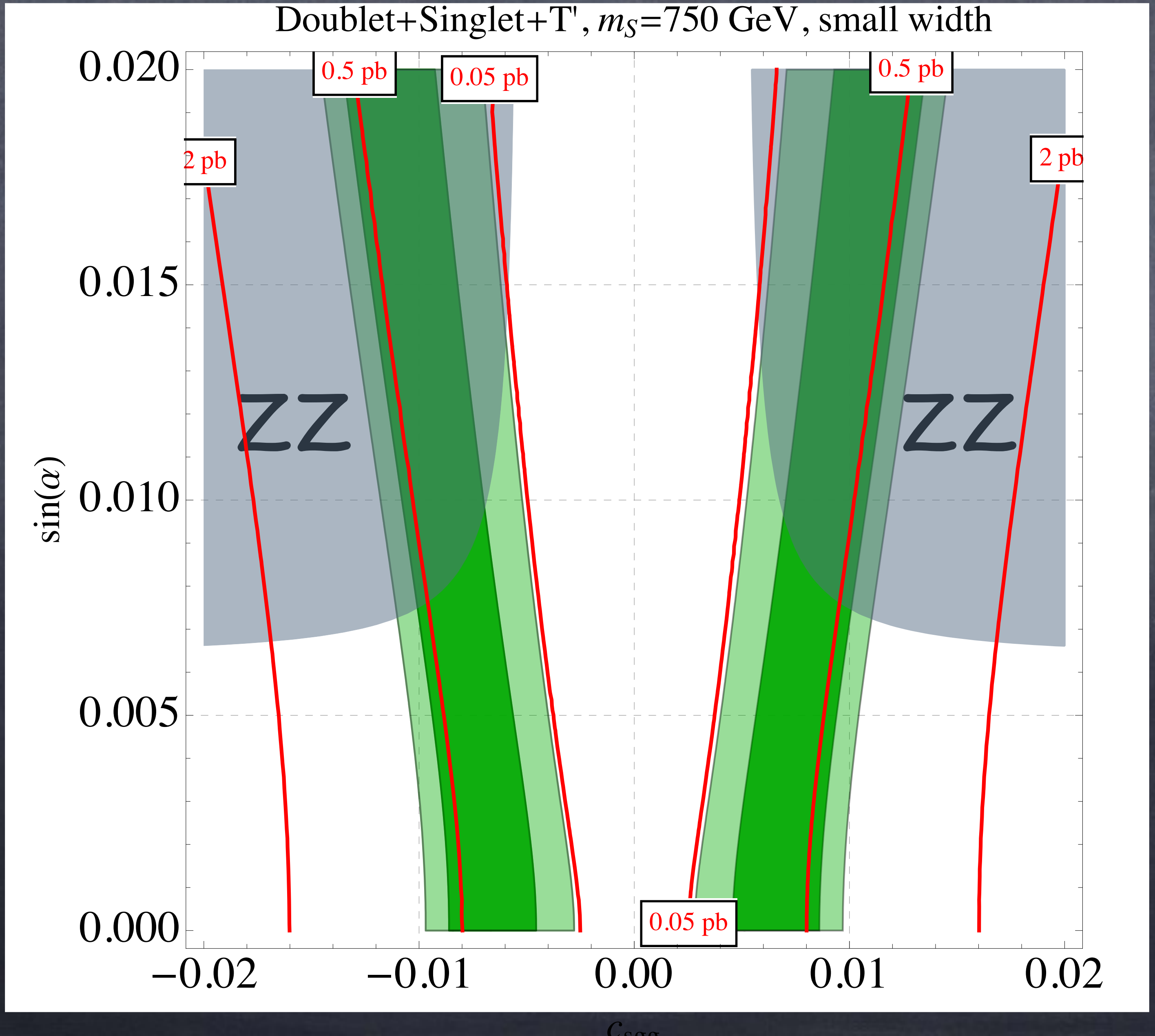
$$\mathcal{L}_{S,\text{eff}} = \frac{e^2}{4v} c_{s\gamma\gamma} S A_{\mu\nu} A_{\mu\nu} + \frac{g_s^2}{4v} c_{sgg} S G^a_{\mu\nu} G^a_{\mu\nu},$$



- Large (10 GeV or more) width difficult to explain by invisible decays due to run-1 monojet bounds
- Loophole if huge contribution to effective coupling to photons present
- Nevertheless, invisible or other exotic (e.g. lepton jets) signals at 750 GeV interesting to search for

How much mixing with Higgs?

- For a singlet scalar, it is natural to mix with the Higgs boson
- Unless some symmetries or fine-tuning prevent it, mixing angle expected to be sinα~mh^2/mS^2
- For 750 GeV resonance, mixing angle strongly constrained by non-observation of WW and ZZ resonances



How much mixing with Higgs?

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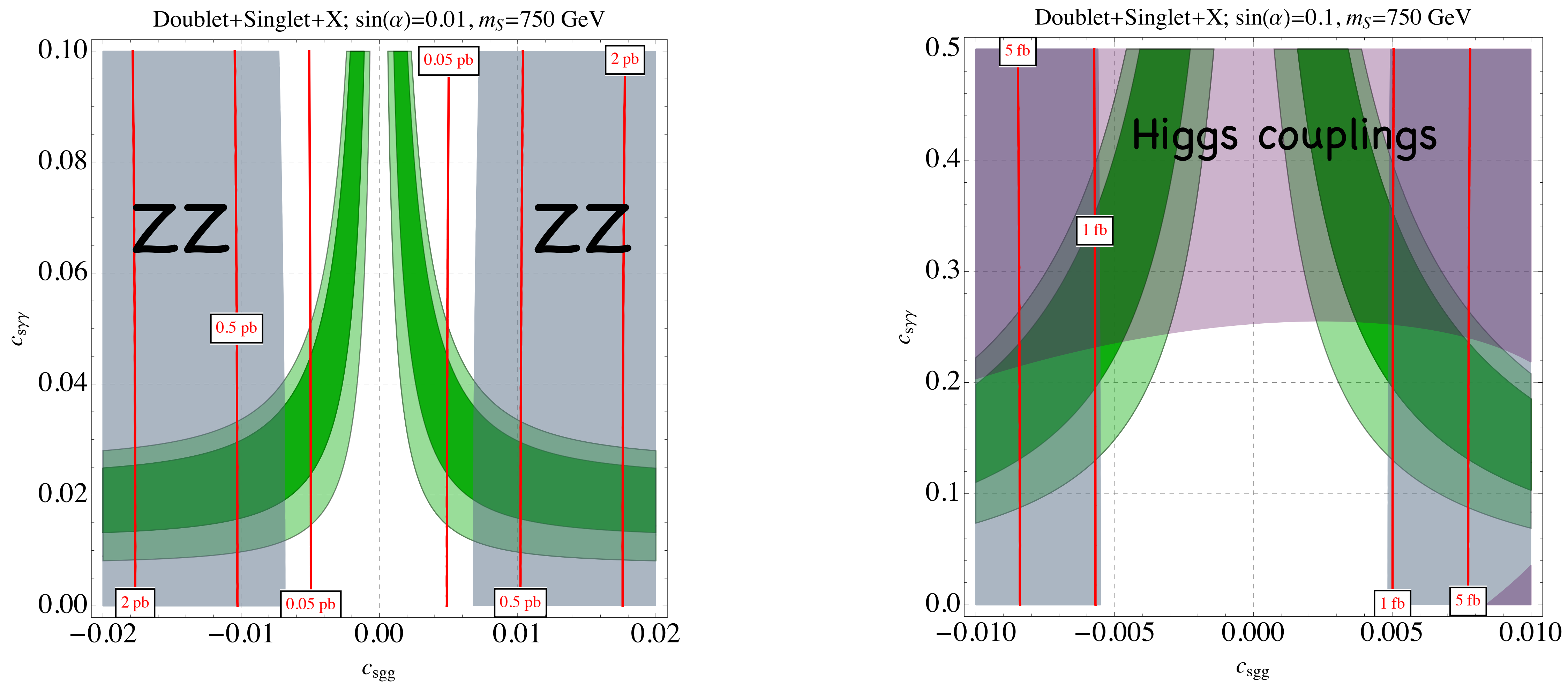
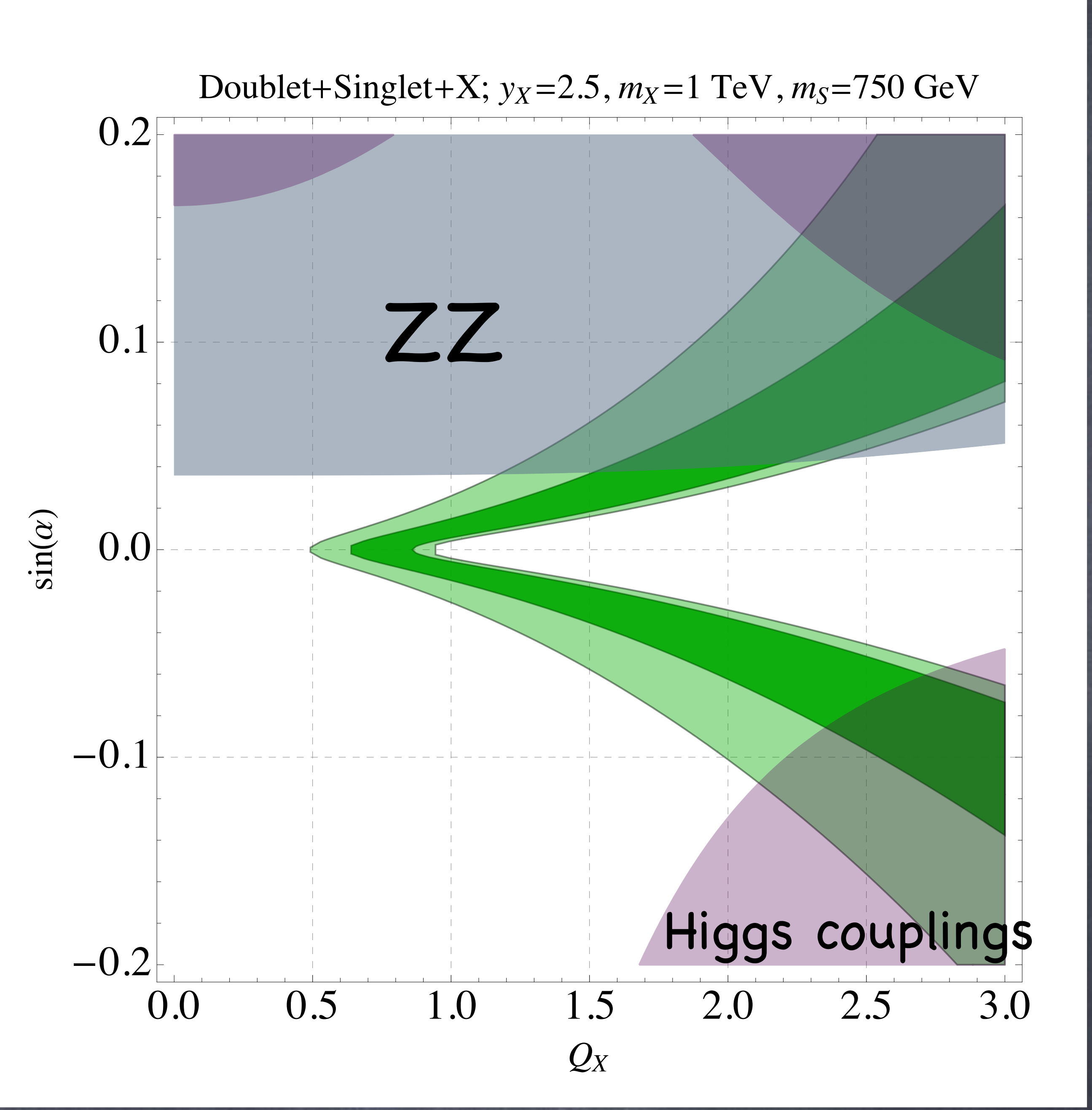


How much mixing with Higgs?

- Large mixing angles excluded by WW and ZZ resonances searches, and by Higgs couplings measurements
- For T′ particle generating effective couplings of 750 GeV particle to gluons and photons, mixing angle needs to be smaller than 0.01
- More generally, mixing angle constrained to be smaller than 0.1



Bigger Picture?

Bigger picture?

- Singlet scalar and vector-like quarks can be trivially embedded in any model, so in the first approximation anything goes

- It is however less trivial to naturally realize a heavy scalar with a large diphoton branching fraction. E.g. SM Higgs with mh=750 GeV would have Br(h→$\gamma\gamma$)~10^-7

- Selected interesting proposals in the literature
  - superpartner of Goldstino from low-scale spontaneous breaking of supersymmetry, see e.g. Torre,Petersson 1512.05333
  - radion in the Randall-Sundrum model, see e.g. Ahmed et al 1512.05771
  - KK graviton in the Randall-Sundrum model, see e.g. Giddings,Zhang 1602.02793
  - 0++ composite state from pure strongly interacting SU(N) sector, see e.g. Craig et al 1512.07733
  - "hidden pion" Goldstone boson of a strongly interacting sector, see e.g. Harigaya,Nomura 1602.01092

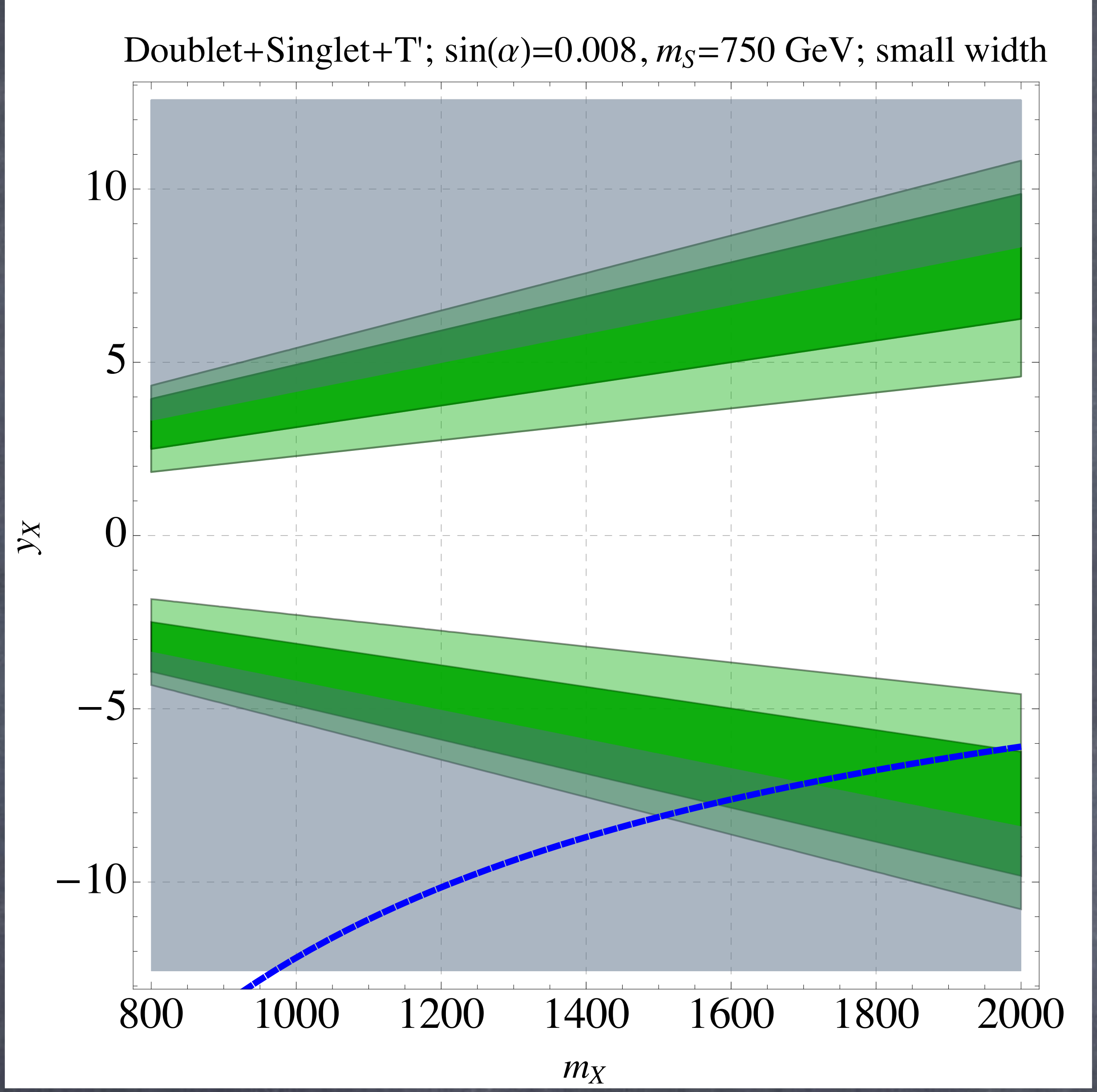
Predictions for RS:

X	$\mathrm{Br}(g_1 \to X)$ [%]	$\frac{\mathrm{Br}(g_1\to X)}{\mathrm{Br}(g_1\to\gamma\gamma)}$
$\gamma\gamma$	4.3	1
ZZ	4.0	0.9
WW	8.3	1.9
$\mu\mu$	2.1	0.5
jj	67	15.5
tt	6.5	1.5
hh	0.4	0.08

Bigger picture?

- In explicit models, large couplings are needed (for example, large Yukawa couplings of resonance to new vector-like fermions)
- Typically, these couplings run away to a Landau pole at a few TeV
- Most natural embedding are into models with new strong interactions, that give rise to a light (pseudo-Goldstone?) composite state
- Can this strongly interacting sector have anything to do with solving the hierarchy problem? (as e.g. in little Higgs, composite Higgs, or Randall-Sundrum-type models)

Can it solve hierarchy problem?



- For T′ particle generating effective couplings of 750 GeV particle to gluons and photons, the same particle may possibly cancel quadratic divergences of from to loop contributions to Higgs mass

Summary

- 750 GeV resonance needs to be confirmed by 2016 LHC data. For the moment, only "what if" speculations
- Several phenomenological models describing ATLAS and CMS observations exist, and they can be embedded in more motivated constructions
- There is some tension between run-2 and run-1 diphoton data, but they can be shrugged off us downward fluke in run-1 and/or upward fluke in run-2
- Resonance searches in other channels (diboson,