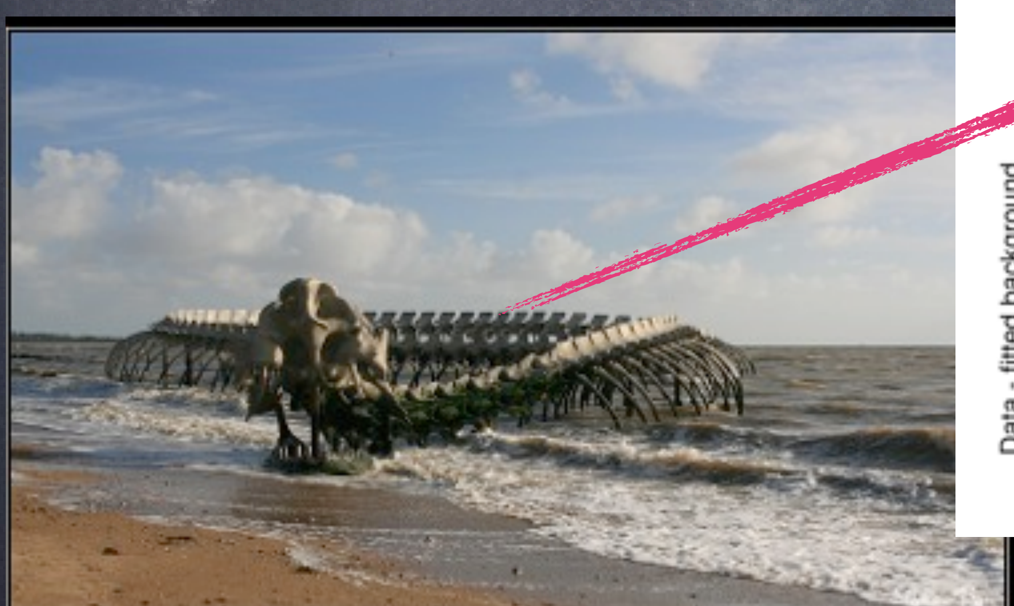
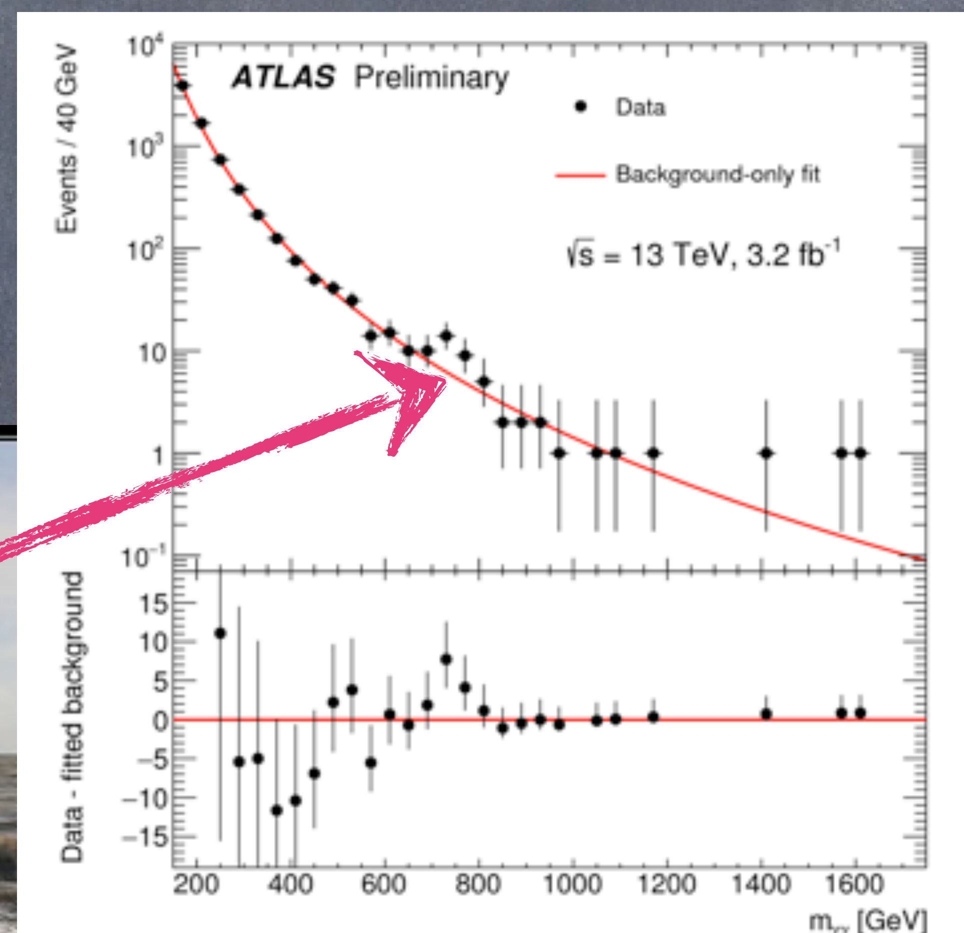
Adam Falkowski

LPT Orsay

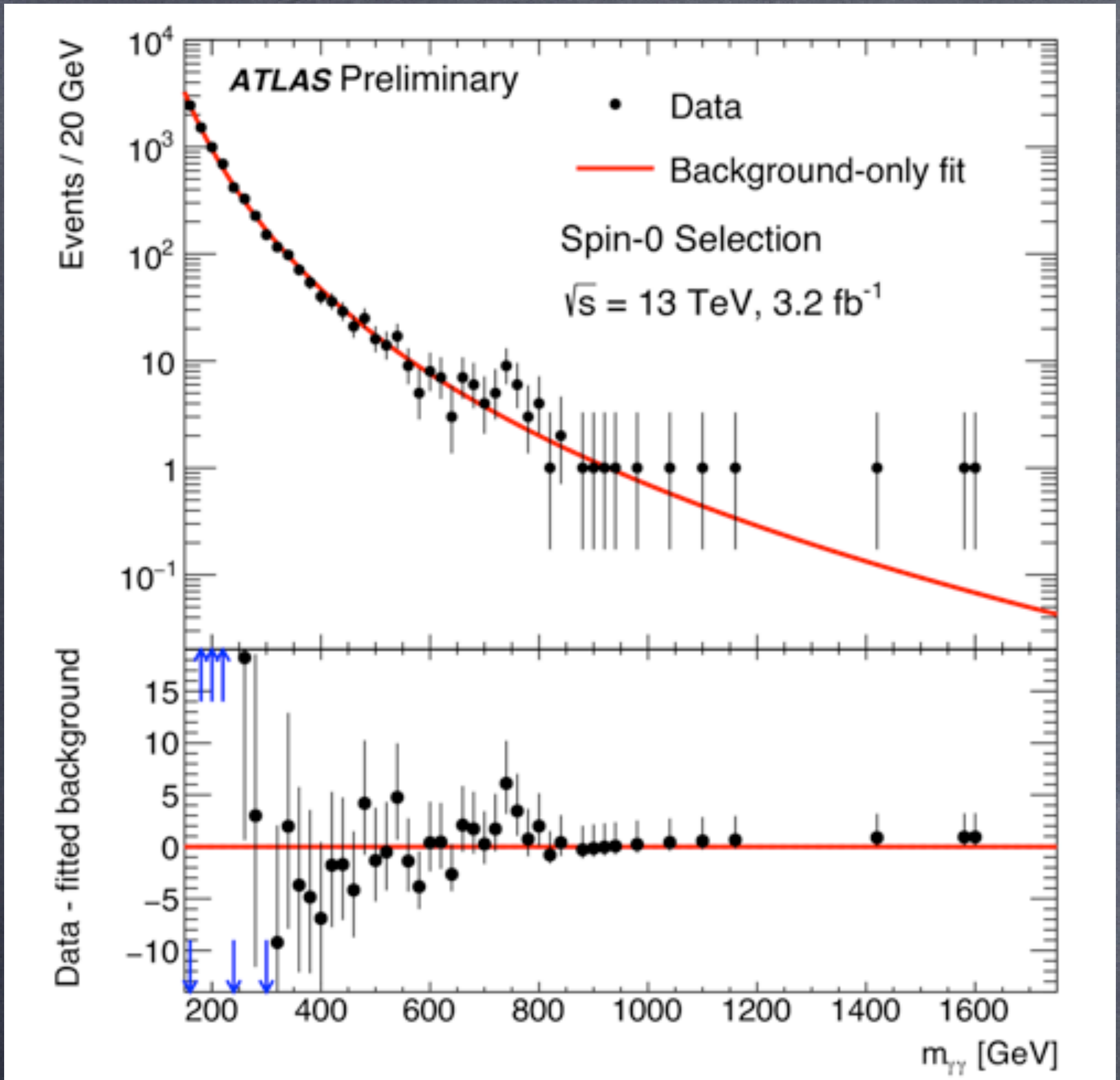
X(750) model review

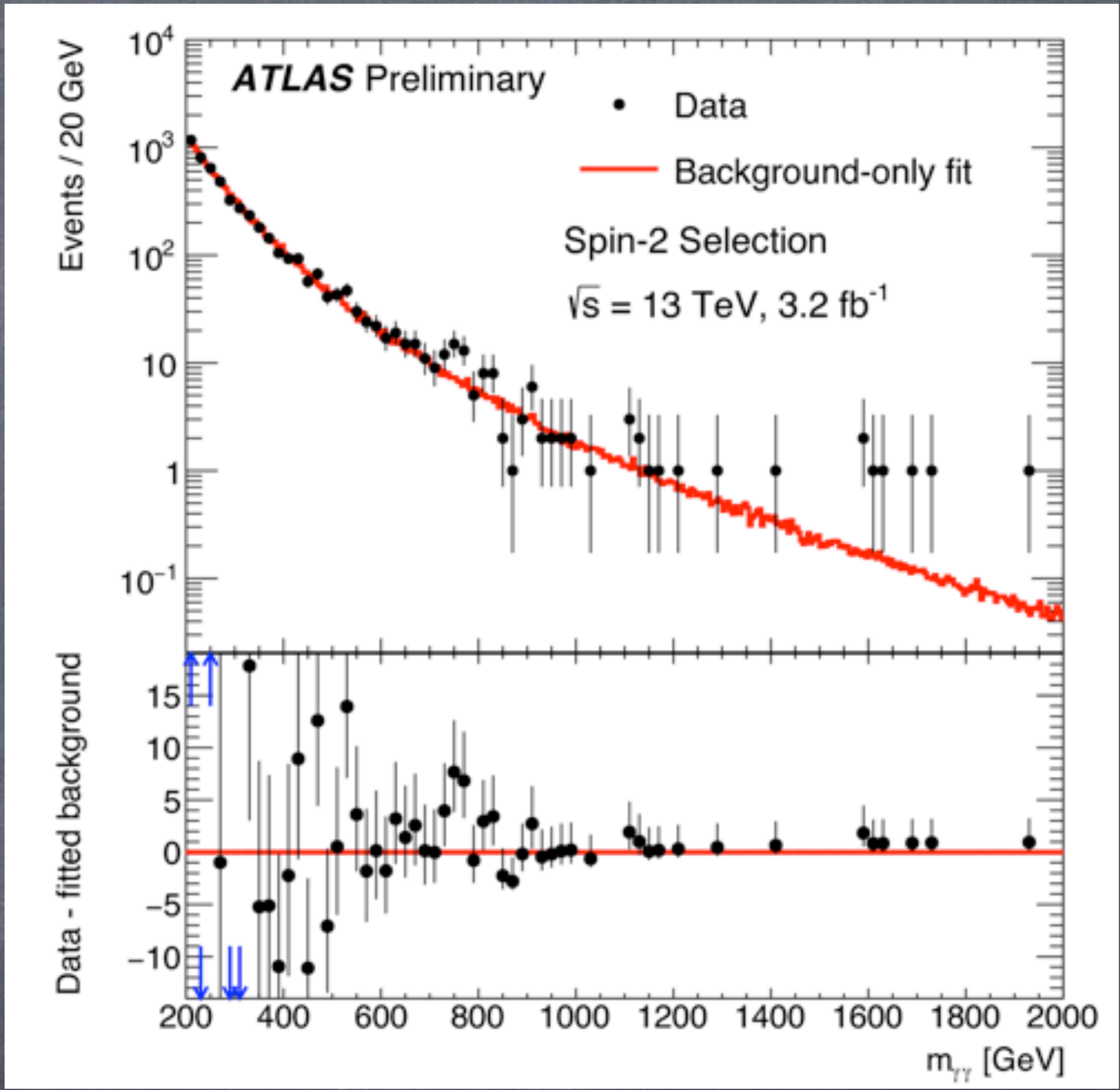




Nantes, 24 May, 2016

ATLAS Run-2 Data - Spectrum





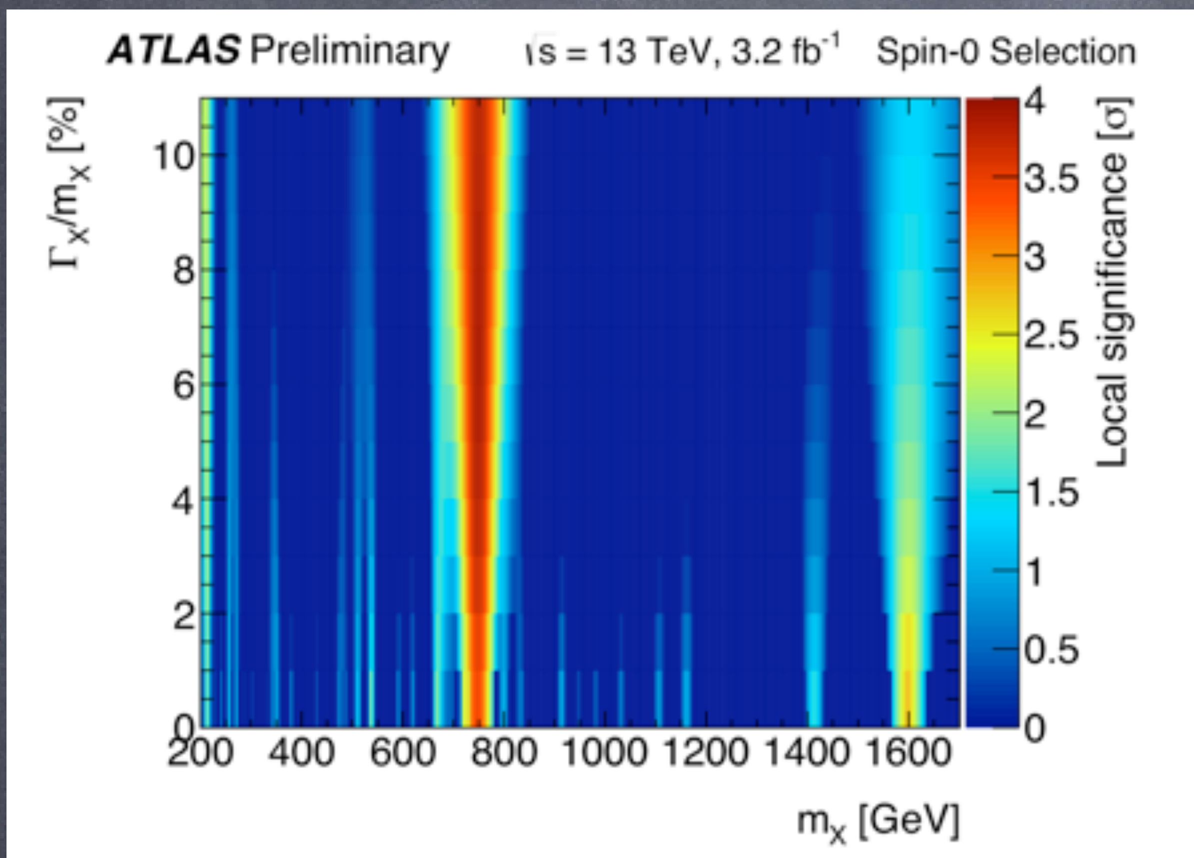
$$p_{T,\gamma_1} > 0.4\, m_{\gamma\gamma} \quad (300\ \text{GeV})$$
$$p_{T,\gamma_2} > 0.3\, m_{\gamma\gamma} \quad (225\ \text{GeV})$$

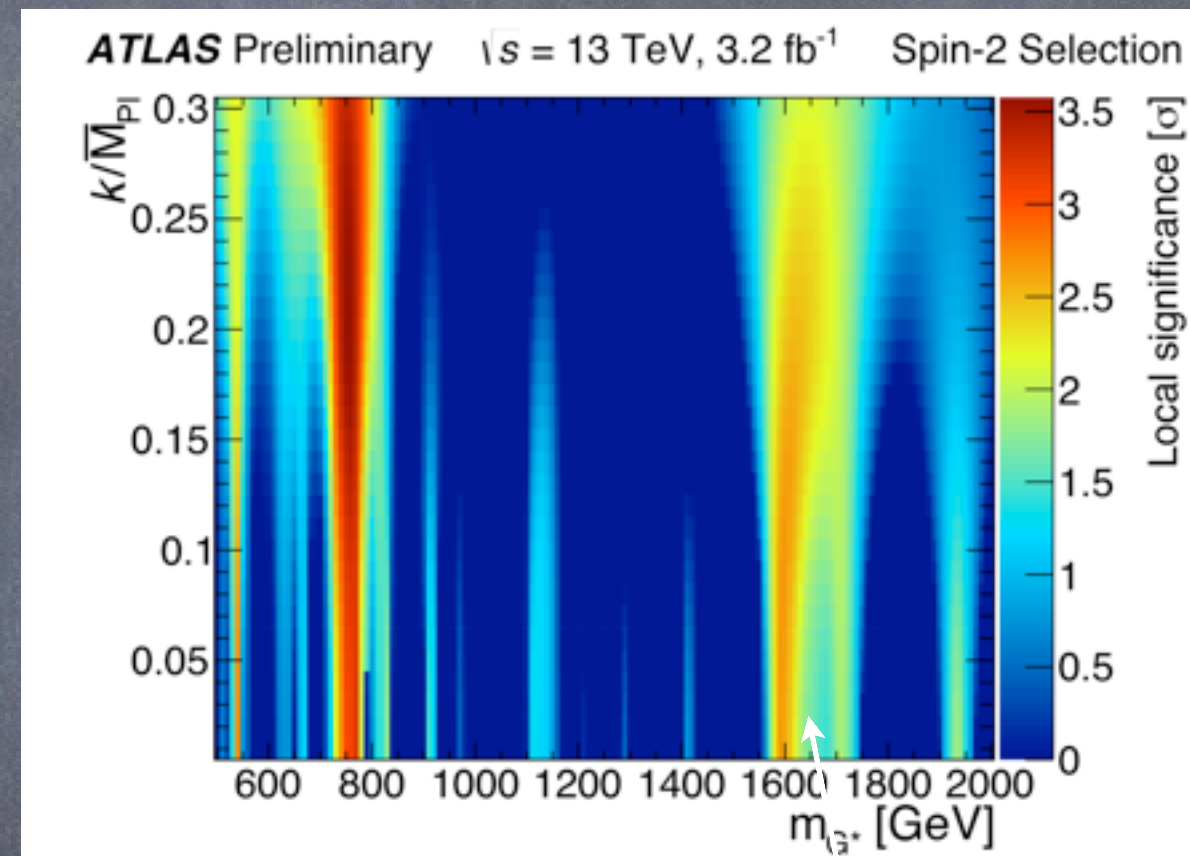
15 events in 40 GeV window around 750 GeV, roughly 10 above bg

$$p_{T,\gamma} > 55\ \text{GeV}$$

40 events in 60 GeV window around 750 GeV, roughly 19 above bg

ATLAS Run-2 Data - Significance





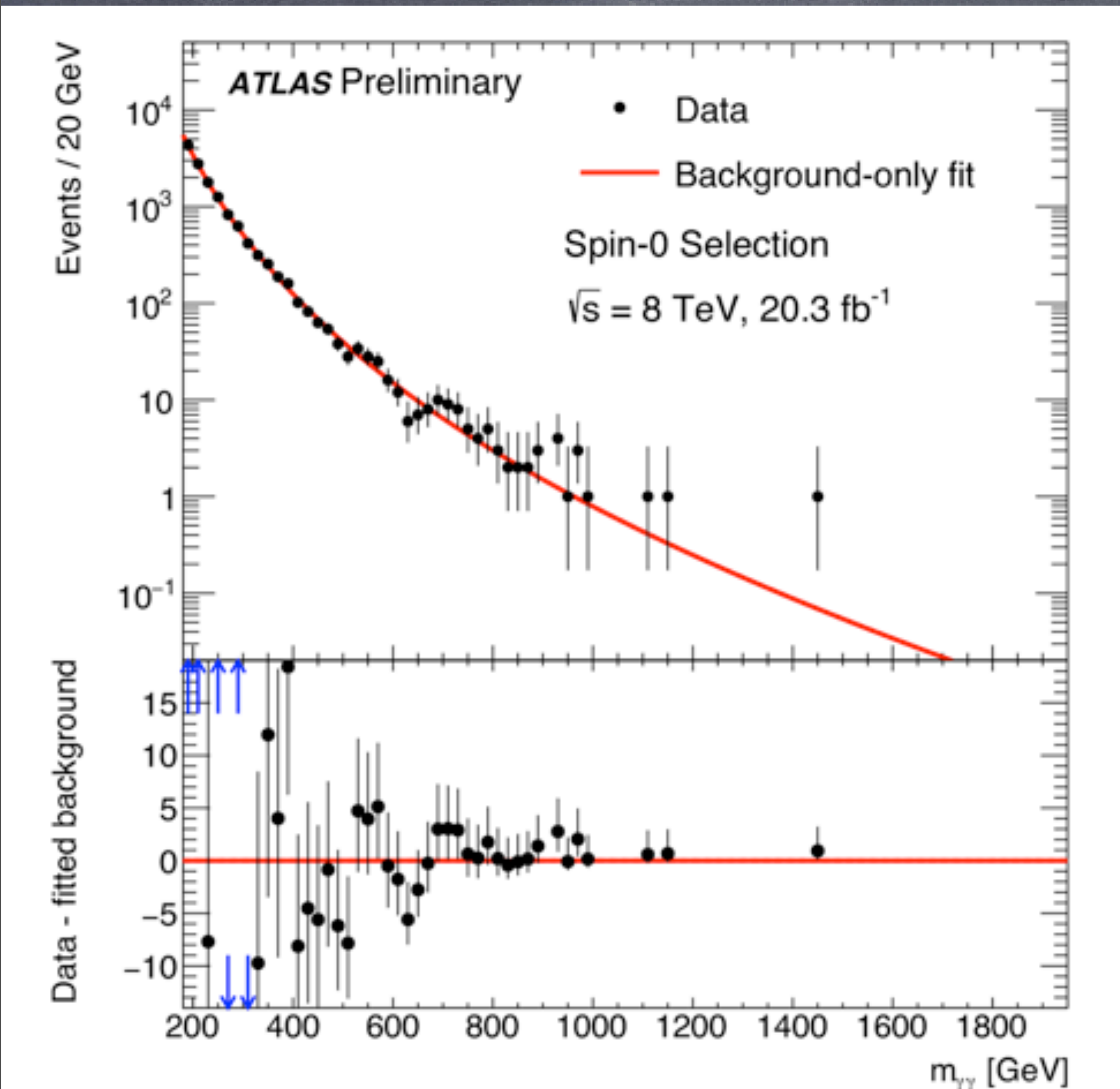
At 750 GeV
3.9σ excess for Γ=45 GeV
3.6σ excess for Γ=0

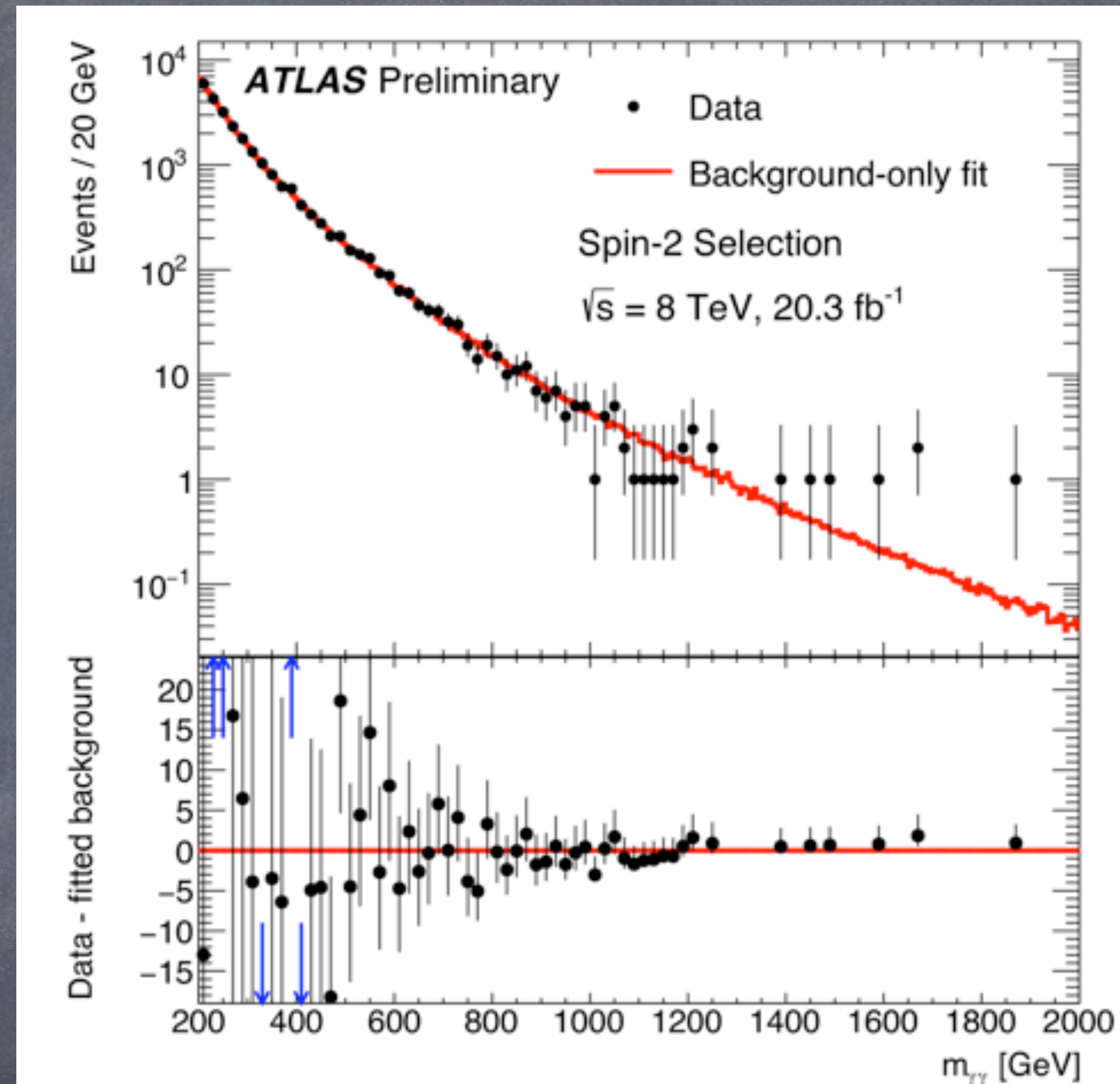
At 750 GeV
3.6σ excess for
Γ=48 GeV

2nd KK mode
also visible ;)

ATLAS-CONF-2016-018

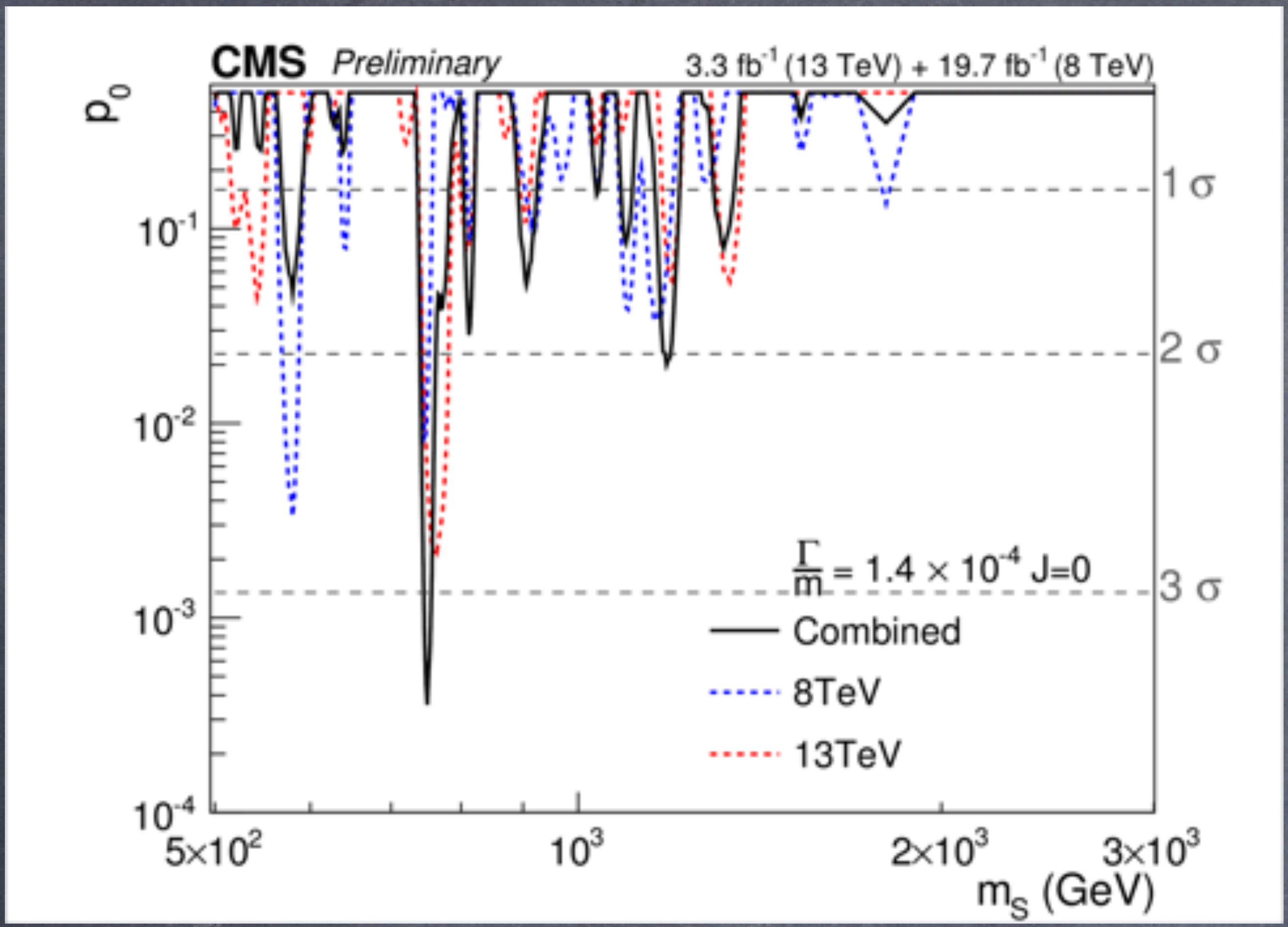
ATLAS Run-1 Data - Spectrum

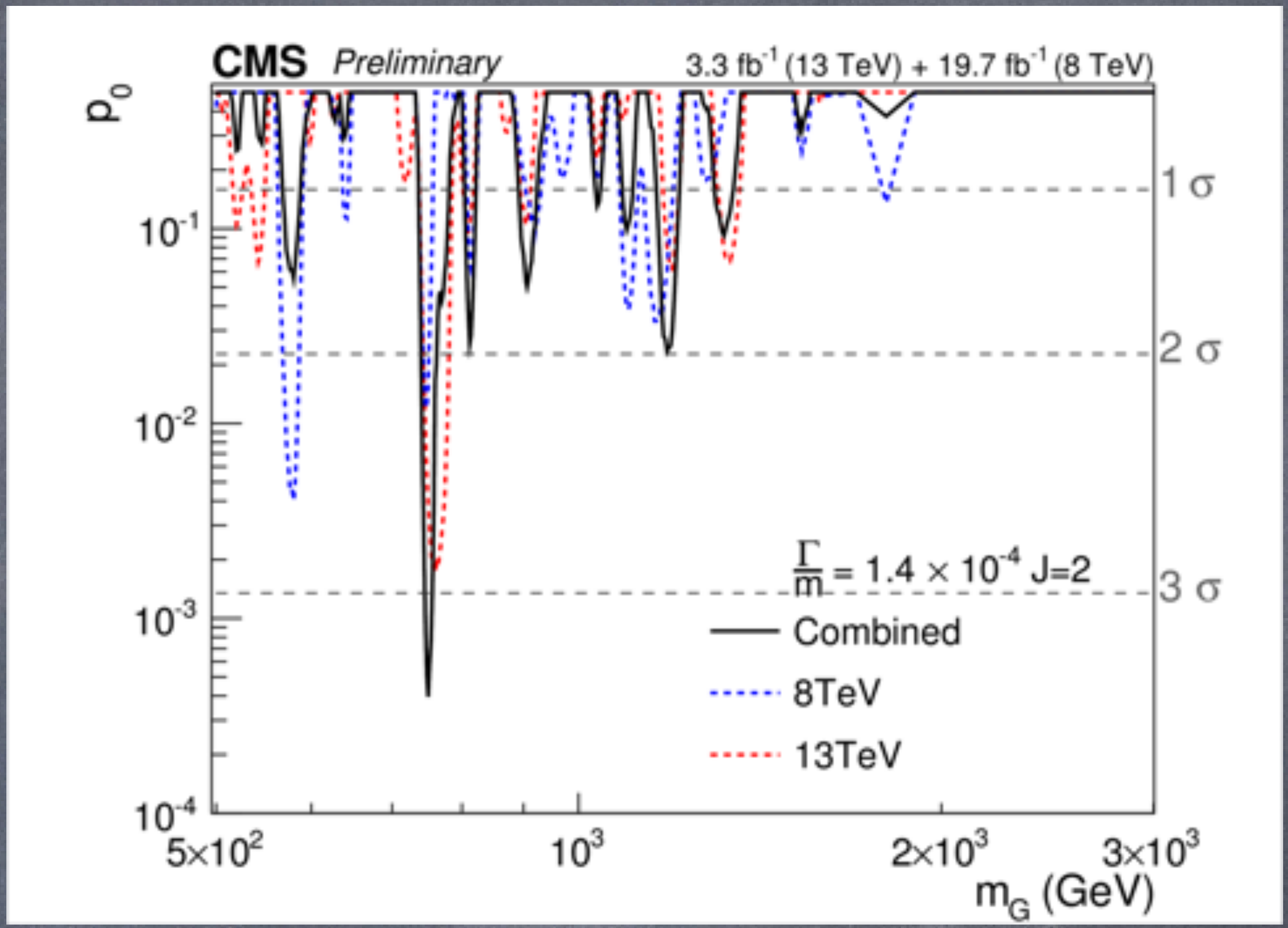




For spin-0 analysis, 1.9σ excess at 750 GeV in run-1. Decent compatibility (at 1.2 σ) between run-2 and run-1 diphoton bumps assuming gluon-fusion production. Much worse compatibility (at 2.7 σ) for spin-2 analysis.

CMS Run-2 and Run-1 Data





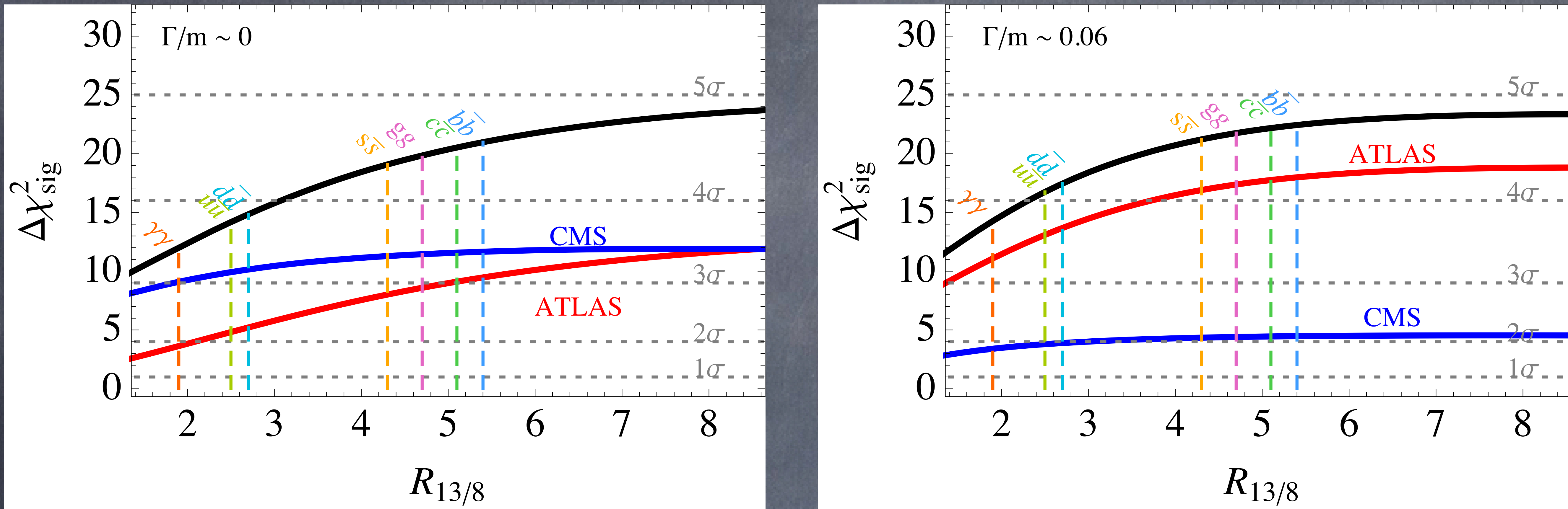
- 2.9σ excess at 760 GeV in run-2 data. Adding B=0 data slightly increased significance
- Very good compatibility of ATLAS and CMS diphoton bumps at 750 GeV
- Very good compatibility between CMS run-2 and run-1 data, this time independently of the spin hypothesis. 3.4σ excess at 750 GeV in combined run-1 and run-2 data

Main questions

- Production process?
- Narrow or wide?
- Other decays channels?
- Spin 0 or Spin 2 (or higher)?
- Parity even or parity odd?
- Singlet or multiplet?
- One particle or a part of a larger sector?
- Meaning of life and universe?

Post Moriond fits

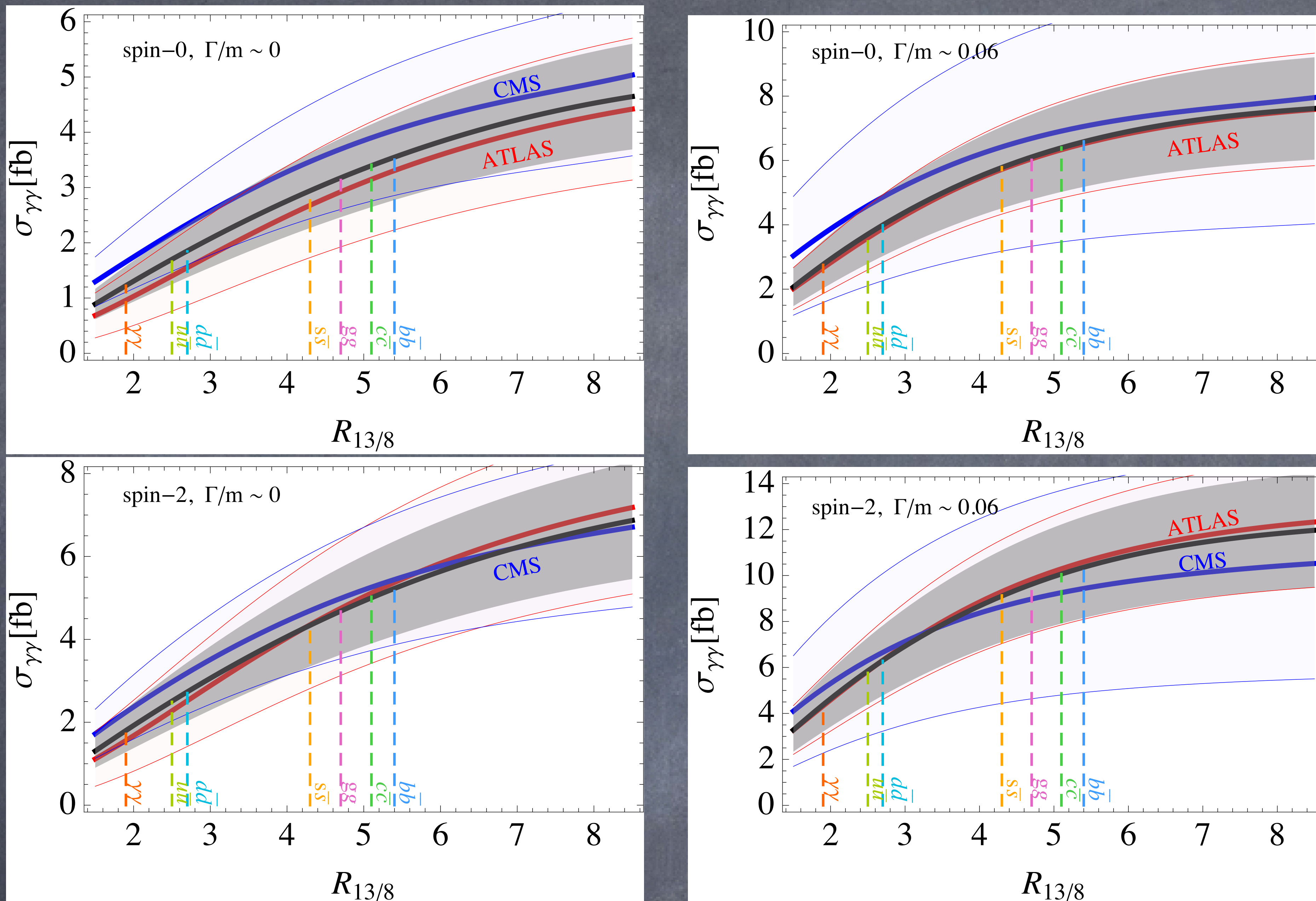
Kamenik et al
1603.06566



- The larger the ratio of 13 to 8 TeV cross sections, the more significant is the combined ATLAS+CMS signal
- Preference for large width is significant for ATLAS alone, but marginal in combined data
- At this point it's no longer "ATLAS diphoton excess", it's "LHC diphoton excess"

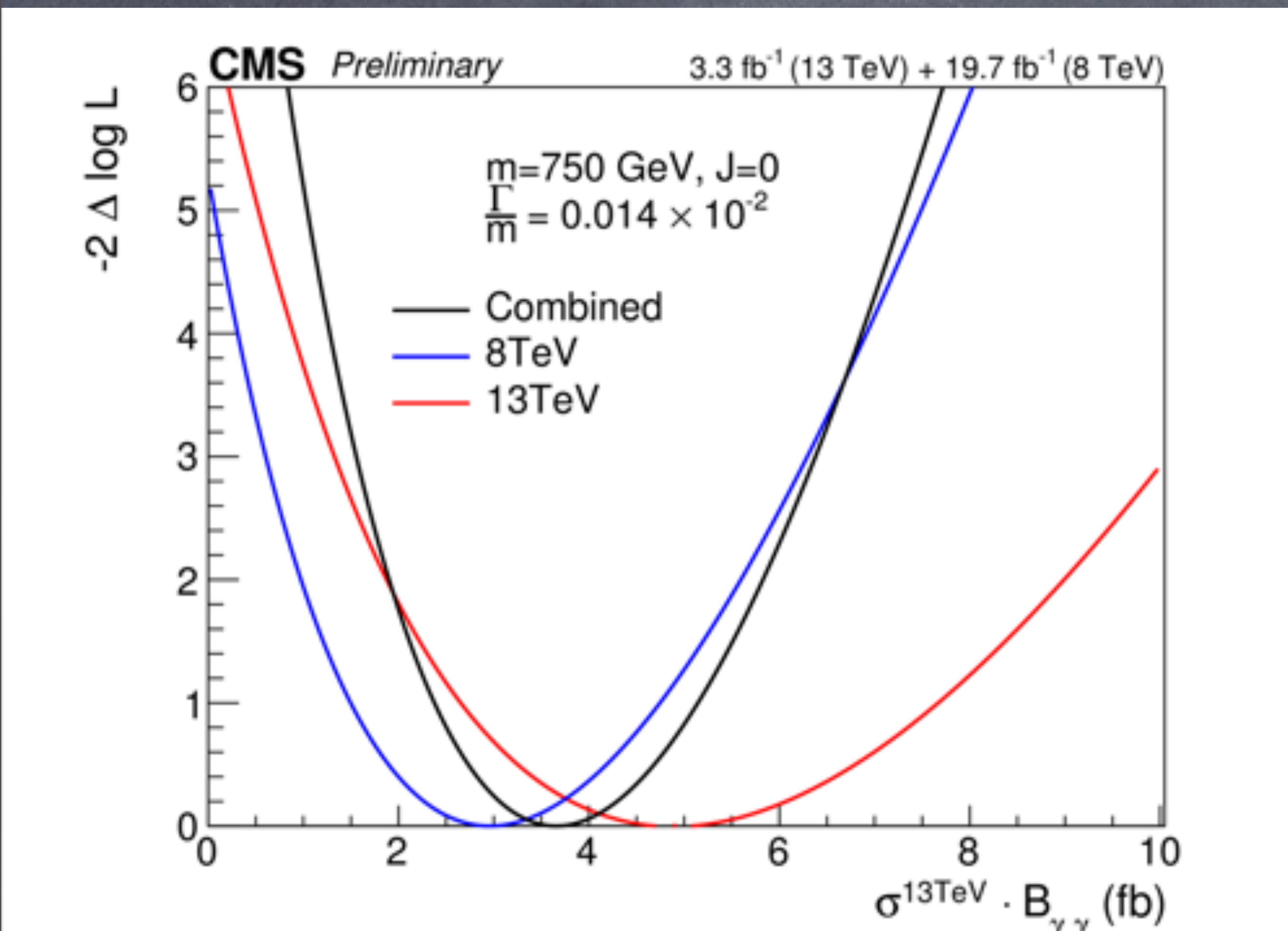
Best fit cross section

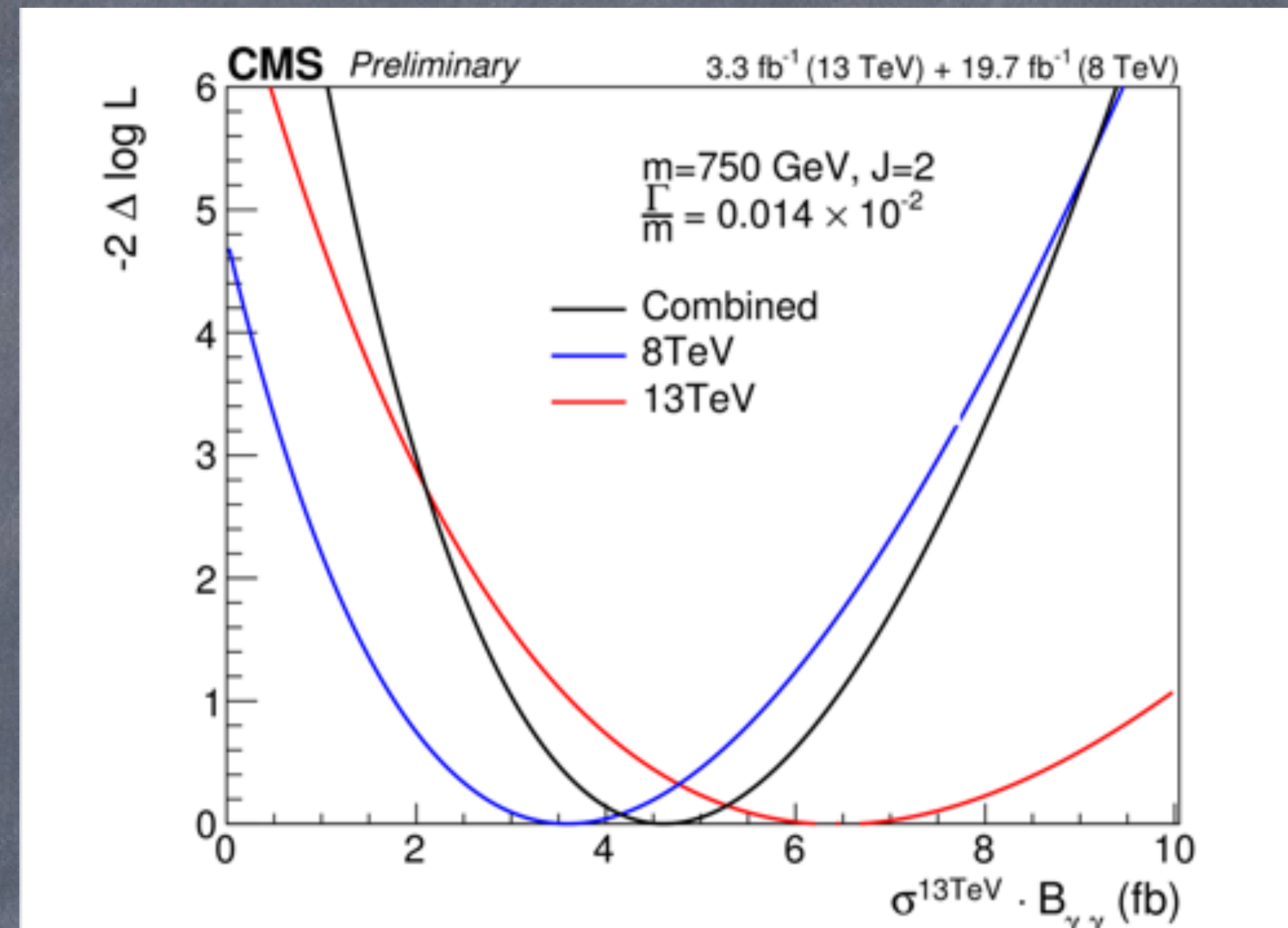
Kamenik et al
1603.06566



- Combining run-1 and run-2 data, best fit cross section for narrow scalar resonance produced in gluon fusion is around $\sigma(pp\to S)\ Br(S\to\gamma\gamma) \approx 3$ fb
- Slightly larger cross sections needed for large width and/or larger spin

What is the mass and cross section?



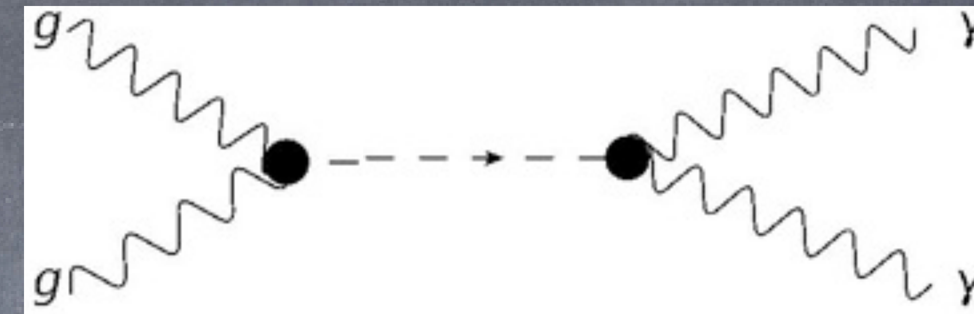


CMS xsec fits in good agreement with theorist fits

Everyone's model

AA,Slone,Volansky
1512.05777

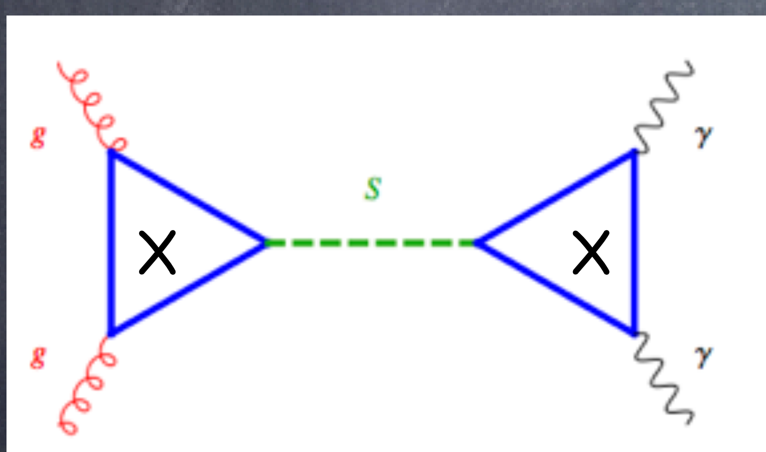
Scalar field S coupled to photons and gluons via effective non-renormalizable interactions



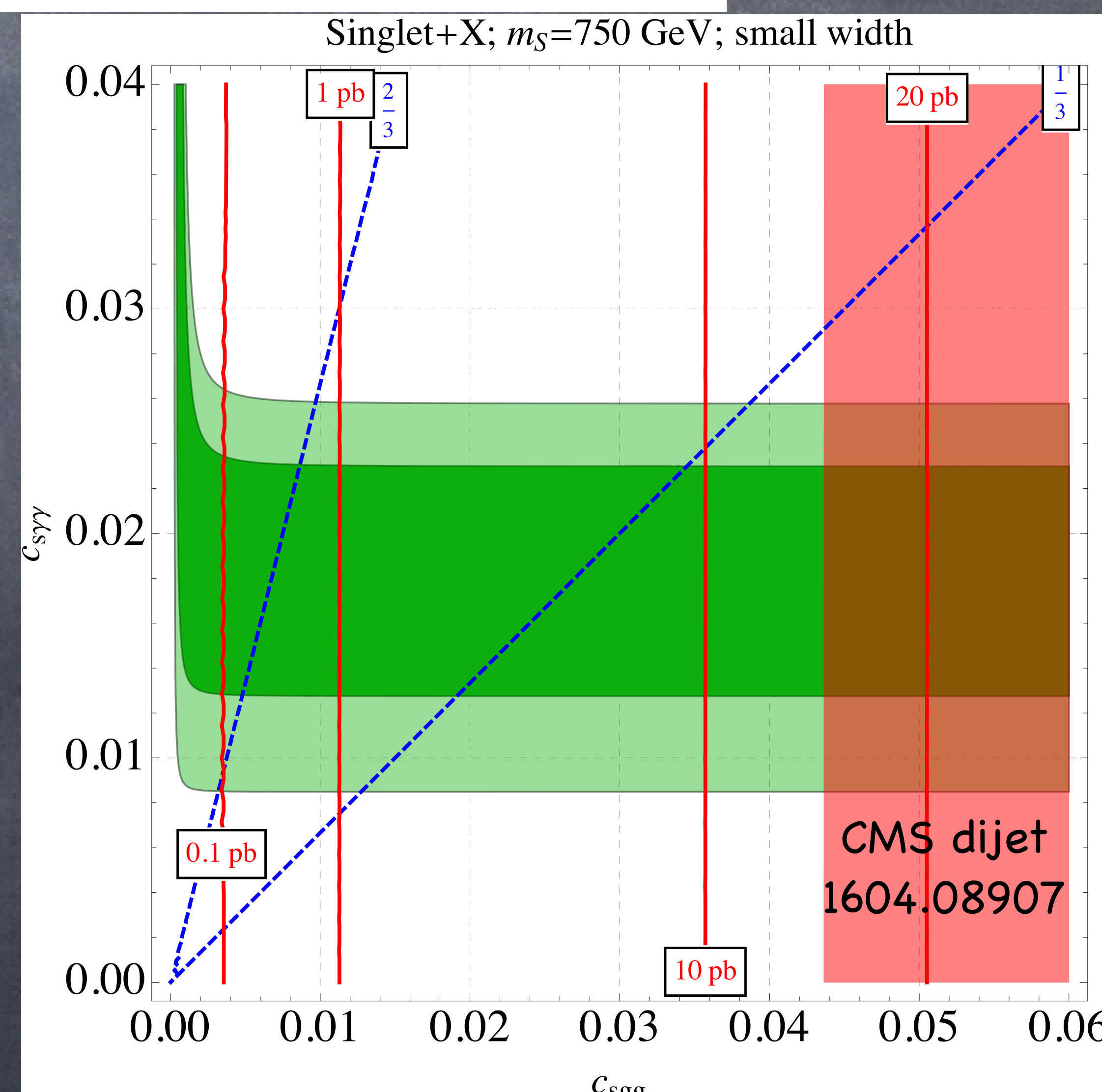
$$\mathcal{L}_{S,\mathrm{eff}} = \frac{S}{4v}\left(c_{sgg} g_s^2 G^a_{\mu\nu} G^a_{\mu\nu} + c_{sww} g_L^2 W^i_{\mu\nu} W^i_{\mu\nu} + c_{sbb} g_Y^2 B_{\mu\nu} B_{\mu\nu}\right)$$

$$c_{s\gamma\gamma} = c_{sww} + c_{sbb}$$

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



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



What else it decays to?

CERN et al. 1604.06446

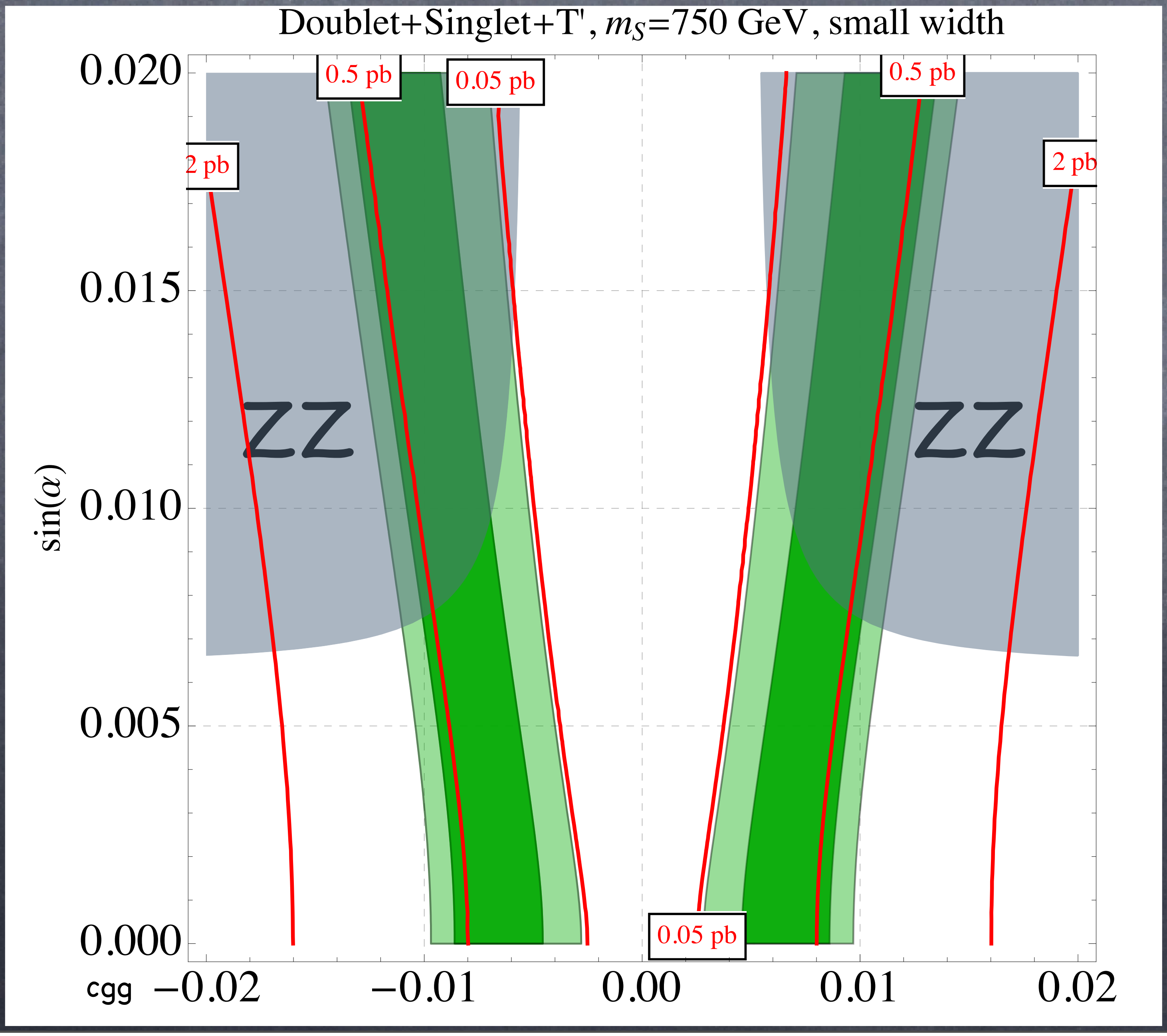
final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\text{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[78]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[3]	< 60 fb	< 67 fb	[79]
$Z\gamma$	< 11 fb	< 11 fb	[3]	< 28 fb	< 40 fb	[80]
ZZ	< 12 fb	< 20 fb	[3]	< 200 fb	< 220 fb	[81]
Zh	< 19 fb	< 28 fb	[3]	< 116 fb	< 116 fb	[82]
hh	< 39 fb	< 42 fb	[3]	< 120 fb	< 110 fb	[83]
W^+W^-	< 40 fb	< 70 fb	[3]	< 300 fb	< 300 fb	[84]
$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

- On general grounds (SU(2)xU(1) gauge symmetry) we expect decays to ZZ and Zγ and maybe also WW. Other decay modes possible but more model dependent
- Current constraints allow cross section in other channels to be larger than diphoton one. Strongest constraints on dilepton cross section, comparable to diphoton one.
- Still, constraints non-trivial such that it's difficult to pump up X(750) GeV width by decays to SM particles. Exotic but not invisible decays needed.

How much mixing with Higgs?

AA,Slone,Volansky
1512.05777

- 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 $\sin\alpha \sim m_h^2/m_S^2 \sim 1/30$
- For 750 GeV resonance, mixing angle strongly constrained by non-observation of WW and ZZ resonances



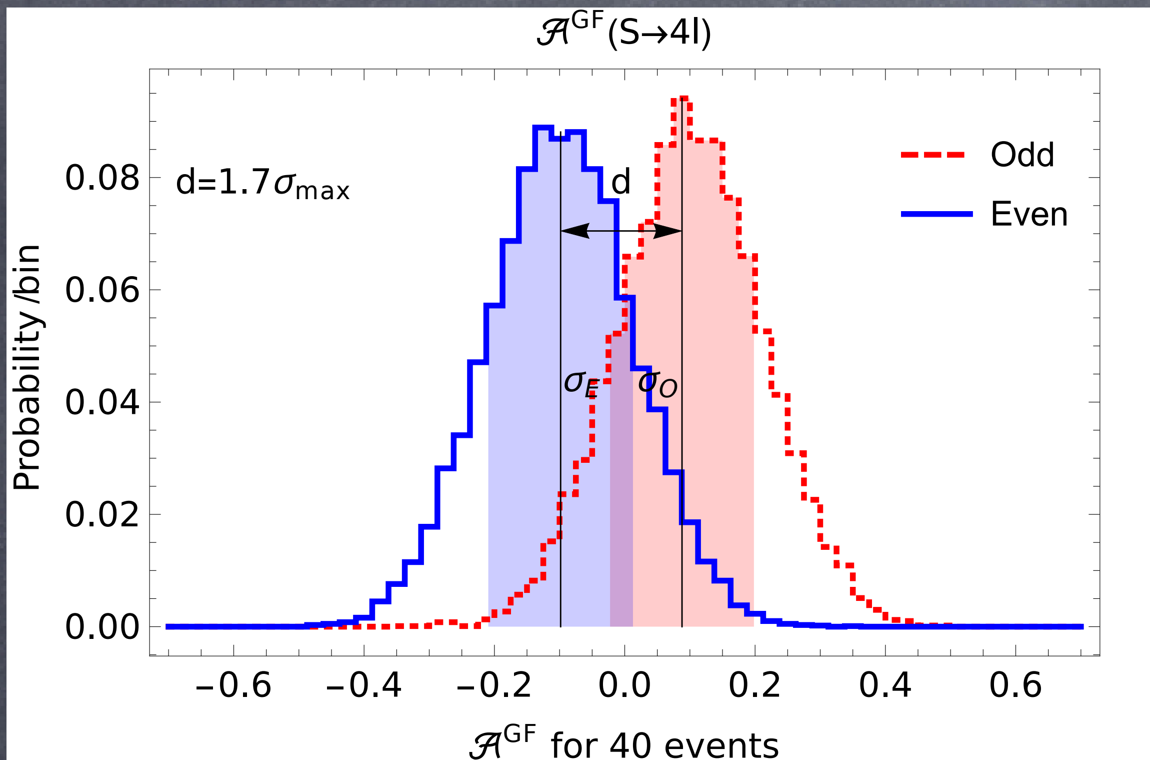
Parity and Spin studies

- Topic received (disproportionally) large attention in context of LHC Higgs studies
- It is much more interesting for 750 GeV case, as no preferred hypothesis a priori
- Good theoretical motivation for pseudo-scalars (e.g. pions of new technicolor-like sector coupled to photons via anomalies), as well as experimental one (mixing with Higgs suppressed)
- For spin ≥ 2 weaker theoretical motivation (basically that it'd be cool), and experimental one (currently based on rumors only)

Parity determination

Chala et al.
1604.02029

$$\mathcal{L}_{P,\mathrm{eff}} = \frac{P}{4v}\left(\tilde{c}_{pgg} g_s^2 G^a_{\mu\nu}\tilde{G}^a_{\mu\nu} + \tilde{c}_{pww} g_L^2 W^i_{\mu\nu}\tilde{W}^i_{\mu\nu} + \tilde{c}_{pbb} g_Y^2 B_{\mu\nu}\tilde{B}_{\mu\nu}\right)$$



$$\mathcal{A}^{\mathrm{GF}} = \frac{N(\theta^{\mathrm{GF}} > \pi/4) - N(\theta^{\mathrm{GF}} < \pi/4)}{N(\theta^{\mathrm{GF}} > \pi/4) + N(\theta^{\mathrm{GF}} < \pi/4)},$$

where

$$\theta^{\mathrm{GF}} = \begin{cases} \theta & \text{if} \quad \theta < \pi/2 \\ \pi - \theta & \text{if} \quad \theta > \pi/2 \end{cases},$$

and

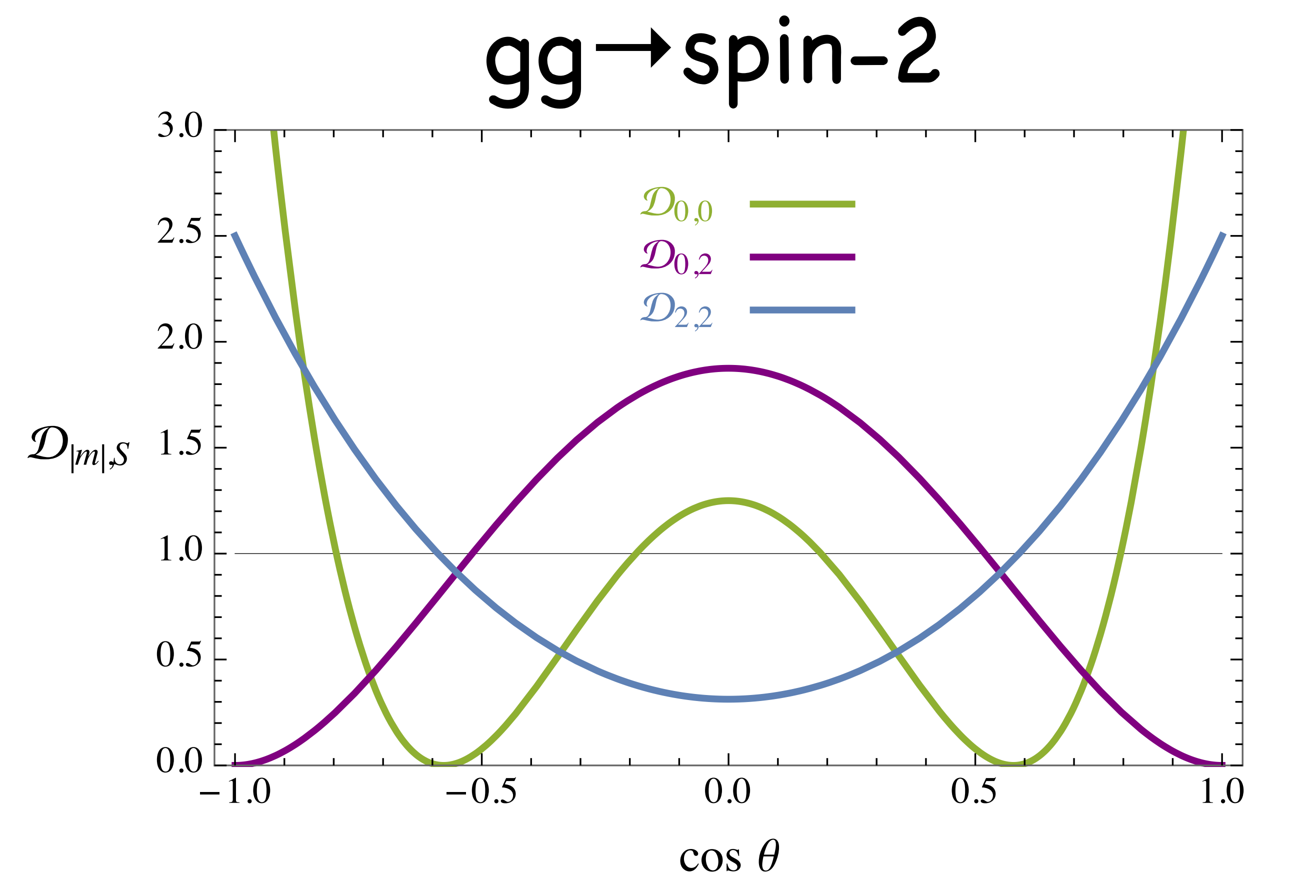
$$\theta = \arccos\left\{\frac{(p_1 \times p_2)\cdot(p_3 \times p_4)}{|p_1 \times p_2||p_3 \times p_4|}\right\},$$

- Assuming spin 0, usual methods of parity determination inherited from Higgs study apply for 750 GeV
- One example: angle between decay planes of two Z bosons in X -> ZZ -> 4l decays

Spin Discrimination

Panico,Vecchi,Wulzer
1603.04248

$\mathbf{J=0}$	$\mathcal{D}^{(0)}_{0,0} = 1$
$\mathbf{J=2}$	$\mathcal{D}^{(2)}_{\lvert m\rvert,S} = \begin{bmatrix} \frac{5}{4}(3c^2-1)^2 & \frac{15}{8}s^4 \\ \frac{15}{2}s^2c^2 & \frac{5}{4}s^2(1+c^2) \\ \frac{15}{8}s^4 & \frac{5}{16}(1+6c^2+c^4) \end{bmatrix}$
$\mathbf{J=3}$	$\mathcal{D}^{(3)}_{\lvert m\rvert,S} = \begin{bmatrix} \frac{7}{4}c^2(3-5c^2)^2 & \frac{105}{8}s^4c^2 \\ \frac{21}{16}s^2(5c^2-1)^2 & \frac{35}{32}s^2(1-2c^2+9c^4) \\ \frac{105}{8}s^4c^2 & \frac{7}{16}(4-15c^2+10c^4+9c^6) \end{bmatrix}$



- Spin-0 is trivial, spin-1 is impossible
- For spin-2 4 different distributions possible, with forward and/or central enhancement
- For KK graviton-like coupling to matter resonance produced in m=2 and decaying to S=2 diphoton state, leading to D2,2 distribution with forward enhancement

Phenomenological model for spin-2 resonance

Kinetic terms (unique ghost free form)

$$\mathcal{L}_{\rm FP} = \frac{1}{2}(\partial_\rho X_{\mu\nu})^2 - \frac{1}{2}(\partial_\rho X)^2 - (\partial_\rho X_{\mu\rho})^2 + \partial_\mu X \partial_\rho X_{\mu\rho} - \frac{m_X^2}{2}(X_{\mu\nu})^2 + \frac{m_X^2}{2} X^2$$

Interactions with matter: for each particle, coupling to its energy-momentum tensor
Since latter is dimension-4, spin-2 has dimension-5 non-renormalizable couplings

$$\begin{aligned}\mathcal{L}_{\rm int} \supset & \frac{c_v}{v} X_{\mu\nu} \left(\frac{\eta_{\mu\nu}}{4} V_{\rho\sigma} V_{\rho\sigma} - V_{\mu\rho} V_{\nu\rho}\right), \\ & - \frac{i c_\chi}{4v} X_{\mu\nu} \left[\bar\chi(\bar\sigma_\mu \partial_\nu + \bar\sigma_\nu \partial_\mu)\chi - (\partial_\mu \bar\chi \bar\sigma_\nu + \partial_\nu \bar\chi \bar\sigma_\mu)\chi - 2\eta_{\mu\nu}\left(\bar\chi \bar\sigma_\rho \partial_\rho \chi - \partial_\rho \bar\chi \bar\sigma_\rho \chi\right)\right] \\ & + \frac{c_H}{v} X_{\mu\nu} \left(\partial_\mu H^\dagger \partial_\nu H + \partial_\nu H^\dagger \partial_\mu H - \eta_{\mu\nu} \partial_\rho H^\dagger \partial_\rho H + \eta_{\mu\nu} m_H^2 H^\dagger H + \eta_{\mu\nu} \lambda |H|^4\right)\end{aligned}$$

For ordinary massless graviton these couplings are universal
and suppressed by the Planck scale

$$c_H = c_V = c_\chi = \frac{v}{M_P} \approx 10^{-16},$$

But in general massive graviton couplings don't have to be universal,
and we know calculable examples

Spin-2: decay widths

see e.g. Lee,Park,Sanz 1306.4107

- No chiral suppression for decays to fermions (unlike for scalars)
- For ZZ and WW, decays depends also on coupling to the Higgs field (because it contains longitudinal components of W and Z)
- For Zγ, decays occur only when coupling to WW and BB field strength is non-universal

$$c_{\gamma\gamma} = s_\theta^2 c_W + c_\theta^2 c_B,\ c_{ZZ} = c_\theta^2 c_W + s_\theta^2 c_B,$$
$$c_{Z\gamma} = c_\theta s_\theta (c_W - c_B),$$

$$r_i \equiv m_i^2/m_X^2$$

$$\begin{aligned}
\Gamma(X \to hh) &= \frac{c_H^2 m_X^3}{960\pi v^2}(1-4r_h)^{5/2}, \\
\Gamma(X \to f\bar{f}) &= \frac{m_X^3}{320\pi v^2}(1-4r_f)^{3/2}\Big[\\
&\quad (c_{f_L}^2 + c_{f_R}^2)\left(1 - \frac{2r_f}{3}\right) + c_{f_L}c_{f_R}\frac{20r_f}{3}\Big], \\
\Gamma(X \to ZZ) &= \frac{m_X^3}{80\pi v^2}\sqrt{1-4r_Z}\Big[c_{ZZ}^2 + \frac{c_H^2}{12} \\
&\quad + \frac{r_Z}{3}(3c_H^2 + 20c_H c_{ZZ} - 9c_{ZZ}^2) \\
&\quad + \frac{2r_Z^2}{3}(7c_H^2 - 10c_H c_{ZZ} + 9c_{ZZ}^2)\Big], \\
\Gamma(X \to Z\gamma) &= \frac{c_{Z\gamma}^2 m_X^3}{40\pi v^2}(1-r_Z)^3\left(1 + \frac{r_Z}{2} + \frac{r_Z^2}{6}\right), \\
\Gamma(X \to \gamma\gamma) &= \frac{c_{\gamma\gamma}^2}{8c_G^2}\Gamma(X \to GG) = \frac{c_{\gamma\gamma}^2 m_X^3}{80\pi v^2},
\end{aligned}$$

Parameters for spin-2 resonance

$$\sigma(pp \to X)_{E_{\rm LHC}} = \frac{\pi m_X^2}{v^2 E_{\rm LHC}^2}\left[\frac{1}{16} k_{GGX} c_G^2 L_{GG}\left(\frac{m_X^2}{E_{\rm LHC}^2}\right) + \frac{1}{24}\sum_q k_{qqX}(c_{q_L}^2 + c_{q_R}^2) L_{q\bar{q}}\left(\frac{m_X^2}{E_{\rm LHC}^2}\right)\right]$$

Assuming gluon fusion production:

$$c_G \approx 3.1 \times 10^{-3}\sqrt{\frac{4.4\times 10^{-2}}{\mathrm{Br}(X\to\gamma\gamma)}}$$

$\mathrm{Br}(X\to\gamma\gamma)$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	2×10^{-7}
c_g	0.0015	0.0049	0.015	0.049	1

For reasonable branching fractions to photons, scale suppressing spin-2 interactions with gluons should be in 1-100 TeV range

Thus, spin-2 explanations of diphoton anomaly are necessary effective theories with low cut-off

RS realization of spin-2

Giddings,Zhang
1602.02793

Predictions:

f	$\mathrm{Br}(X \to f)$ [%]	$\frac{\mathrm{Br}(X\to f)}{\mathrm{Br}(X\to\gamma\gamma)}$
$\gamma\gamma$	4.3	1
ZZ	4.0	0.9
WW	8.4	1.9
$\mu\mu$	2.2	0.5
jj	67	15.5
tt	5.8	1.3
bb	5.5	1.5
hh	0.4	0.08

$$m_n \approx 3.8 k a_L \begin{cases} 1 & \text{750 GeV} \\ 1.8 & \text{1.4 TeV} \\ 2.7 & \text{2 TeV} \\ \dots \end{cases}$$

final state f	σ at $\sqrt{s} = 8\,\mathrm{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\mathrm{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[78]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[3]	< 60 fb	< 67 fb	[79]
$Z\gamma$	< 11 fb	< 11 fb	[3]	< 28 fb	< 40 fb	[80]
ZZ	< 12 fb	< 20 fb	[3]	< 200 fb	< 220 fb	[81]
Zh	< 19 fb	< 28 fb	[3]	< 116 fb	< 116 fb	[82]
hh	< 39 fb	< 42 fb	[3]	< 120 fb	< 110 fb	[83]
W^+W^-	< 40 fb	< 70 fb	[3]	< 300 fb	< 300 fb	[84]
$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

- Original RS model with the SM on the IR brane provides a self-consistent explanation of the 750 excess (up to providing mechanism for stabilizing radion)
- Very predictive model with no free parameters after fitting observations so far
- Tension with run-1 and run-2 dilepton resonance searches

Challenge for RS bulk

- In standard version of RS bulk, lightest gauge KK modes are a factor of 1.5 lighter than lightest graviton KK mode
- In present context this would mean gauge KK modes at 500 GeV
- Solutions: hide the light gauge modes, OR make graviton KK modes lighter by the use of gravity brane kinetic terms, OR both

AA,Kamenik
1603.06980

Hewett,Rizzo
1603.08250

Carmona
1603.08913

Dillon,Sanz
1603.09550

Benchmark points

AA,Kamenik
1603.06980

Parameters

$$a_L = 10^{-15}, \quad r_L = 10/k$$

	MIN	MED	MAX
$r_0[1/\mathrm{k}]$	100	120	1700
$M_*[\mathrm{GeV}]$	4.1×10^{17}	3.9×10^{17}	1.6×10^{17}
α_{t_R}	∞	0	-0.3
$\alpha_{Q_L^3}$	∞	0	0
α_H	∞	0	-0.1
$-c_G$	2.3×10^{-3}	2.5×10^{-3}	9.6×10^{-3}
$\sigma(pp \to X)[\mathrm{pb}]$	0.06	0.08	1.1
$\sigma(pp \to X \to \gamma\gamma)[\mathrm{fb}]$	5.3	5.3	5.4
$\Gamma_X[\mathrm{GeV}]$	2×10^{-3}	3×10^{-3}	0.5

Remaining fermions localized at UV brane

Branching fractions

	IR	MIN	MED	MAX	GMAX
$\gamma\gamma$	4.3	8.5	7.0	0.5	2.3
ZZ	4.8	7.9	7.8	2.9	12
WW	9.5	16	15	5.6	21
$Z\gamma$	0	0	0	0	1.1
hh	0.3	0	0.4	1.4	6.9
tt	5.1	0	8.3	85	56
bb	6.4	0	5.2	0.4	0.04
jj	66	68	61	4.5	0.5
$e^+e^- + \mu^+\mu^-$	4.3	0	0	0	0

Output

$$m_{X_1} = 750\ GeV, \qquad m_{X_2} \approx 6\ TeV, \qquad m_{V_1} \approx 2.9\ TeV$$

- Other KK modes than 750 GeV spin-2 can be heavy enough to avoid detection
- Dilepton branching fraction is practically zero
- If Higgs and top localized toward IR, so as to solve hierarchy problem, large branching fraction to ttbar, hh, ZZ, and WW predicted

Bigger picture?

Dirac Gaugino:
Benakli et al
1605.05313

Goldstino:
Torre,Petersson,
1512.05333

NMSSM+cascade decays
Ellwanger,Hugonie
1602.03344

SUSY

just MSMM:
Djouadi et al,
1605. 01040

X-tra dimensions

KK Graviton:
Giddings,Zhang
1602.02793

Radion:
Ahmed et al
1512.05771

Composite

Dilaton:
CERN-th et al
1512.04933

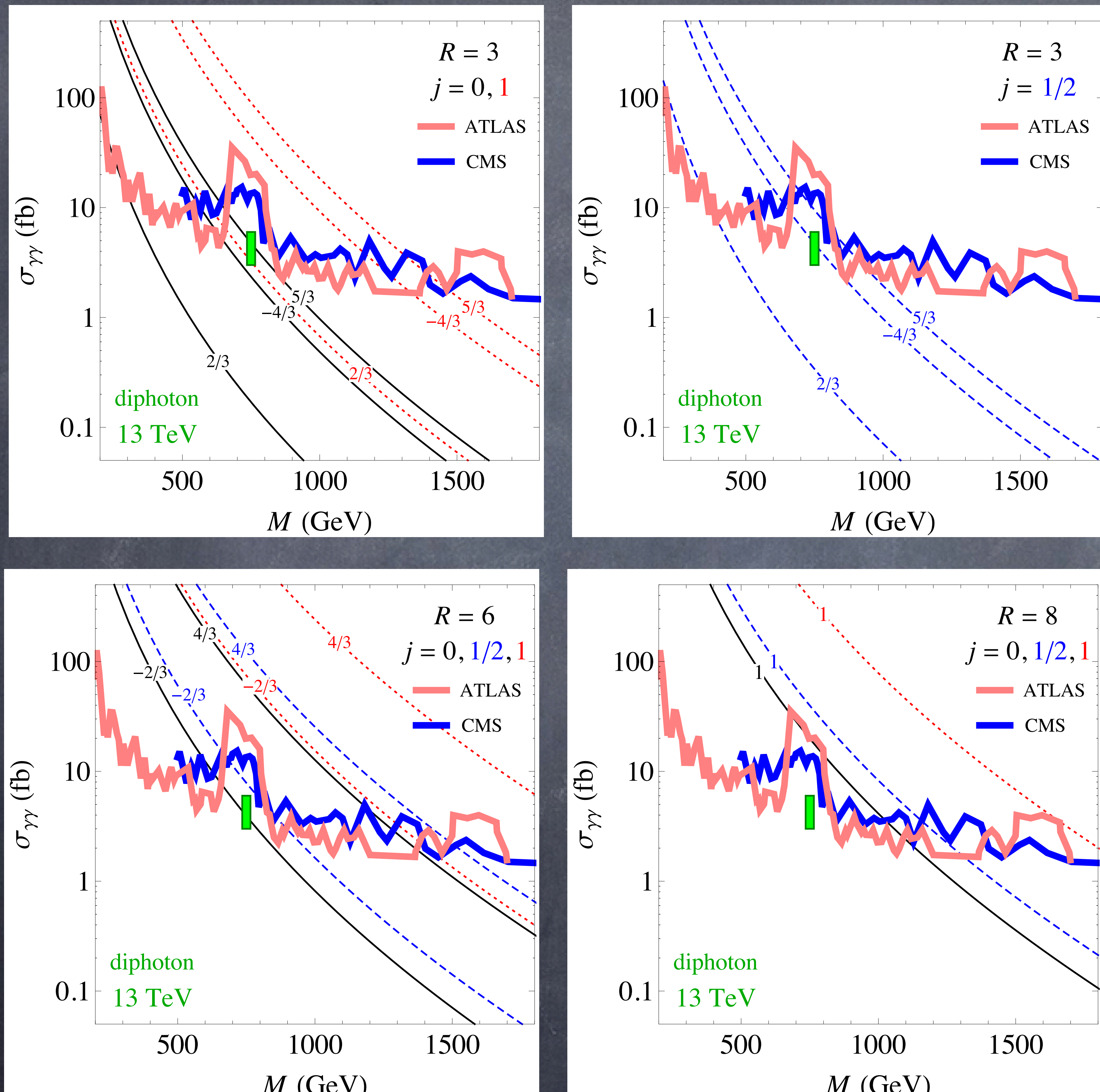
Hidden pion:
Harigaya,Nomura
1602.01092

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
- This strongly interacting sector may well have something to do with solving the hierarchy problem, as e.g. in little Higgs, composite Higgs, or Randall-Sundrum-type models.

Counterexample: just so?

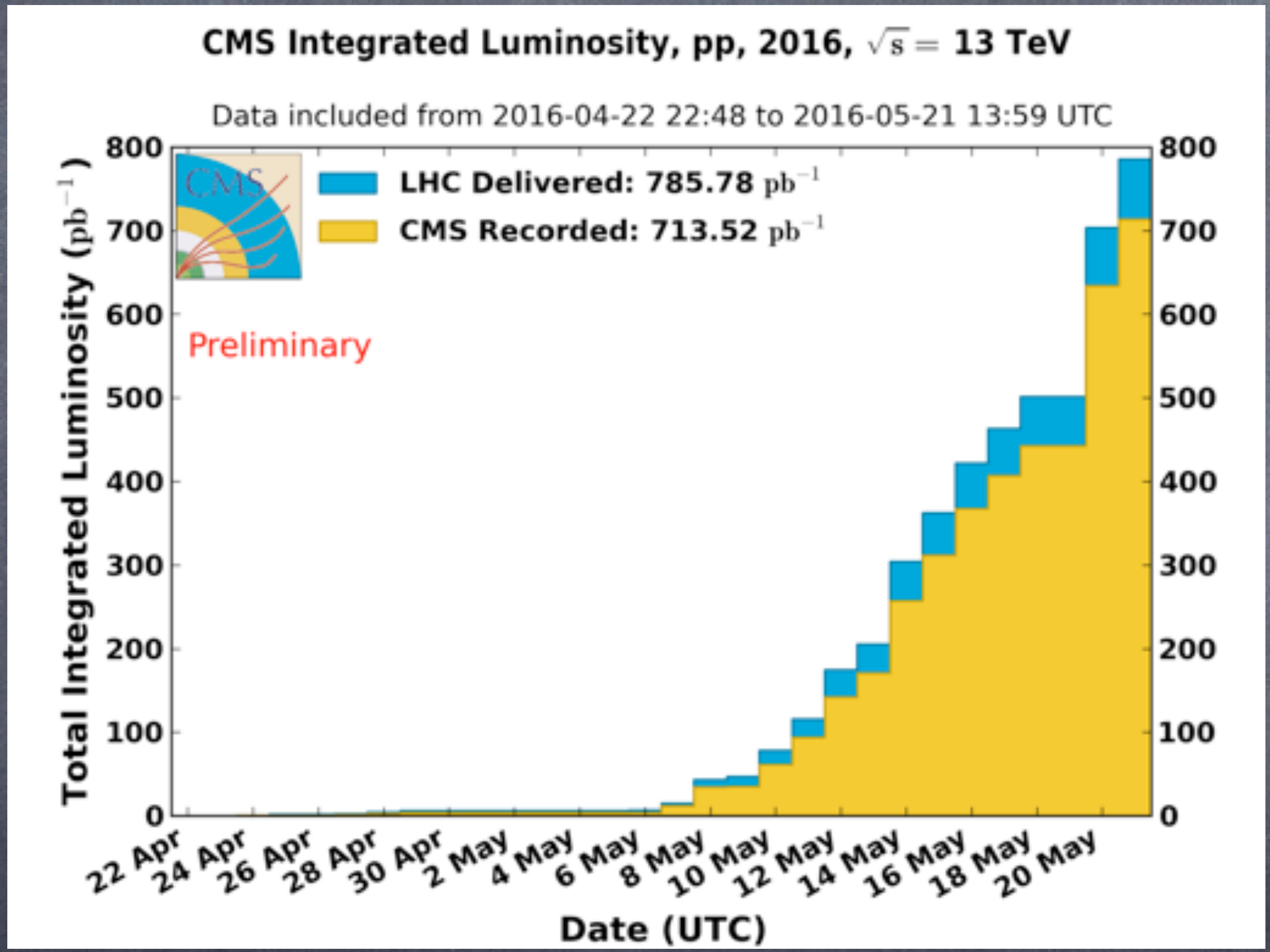
Kats,Strassler
1602.08819



E.g., a bound state of charge -4/3 quarks can explain excess without new extended sector

Take away

- 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



Already O(1-5) 750 GeV diphoton events in 2016 data

;) Have you looked yet? ;)