750 GeV diphoton Resonance

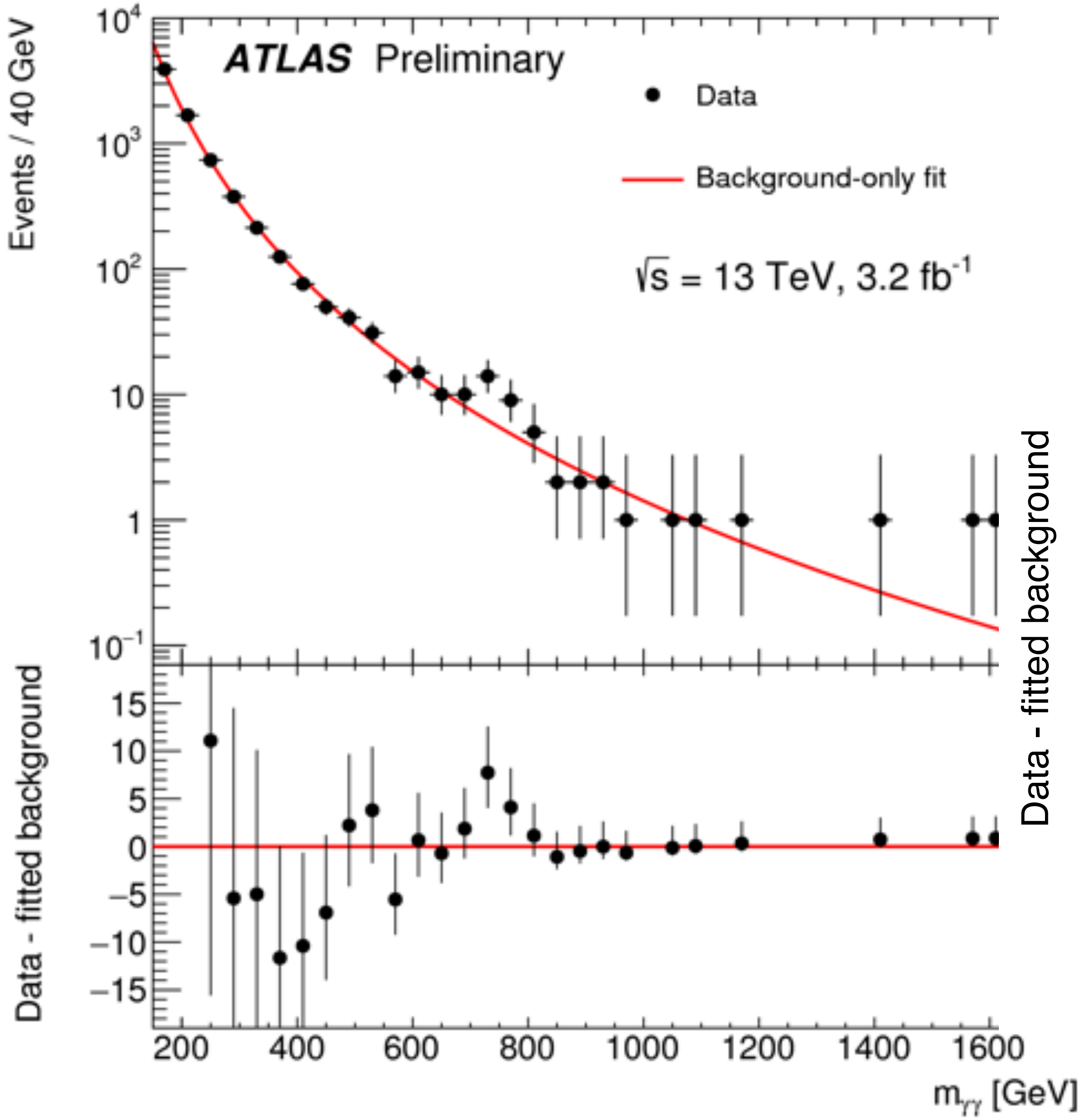
&

Photon-jets

Jung Chang, KC, Chih-Ting Lu 1512.06671, PRD

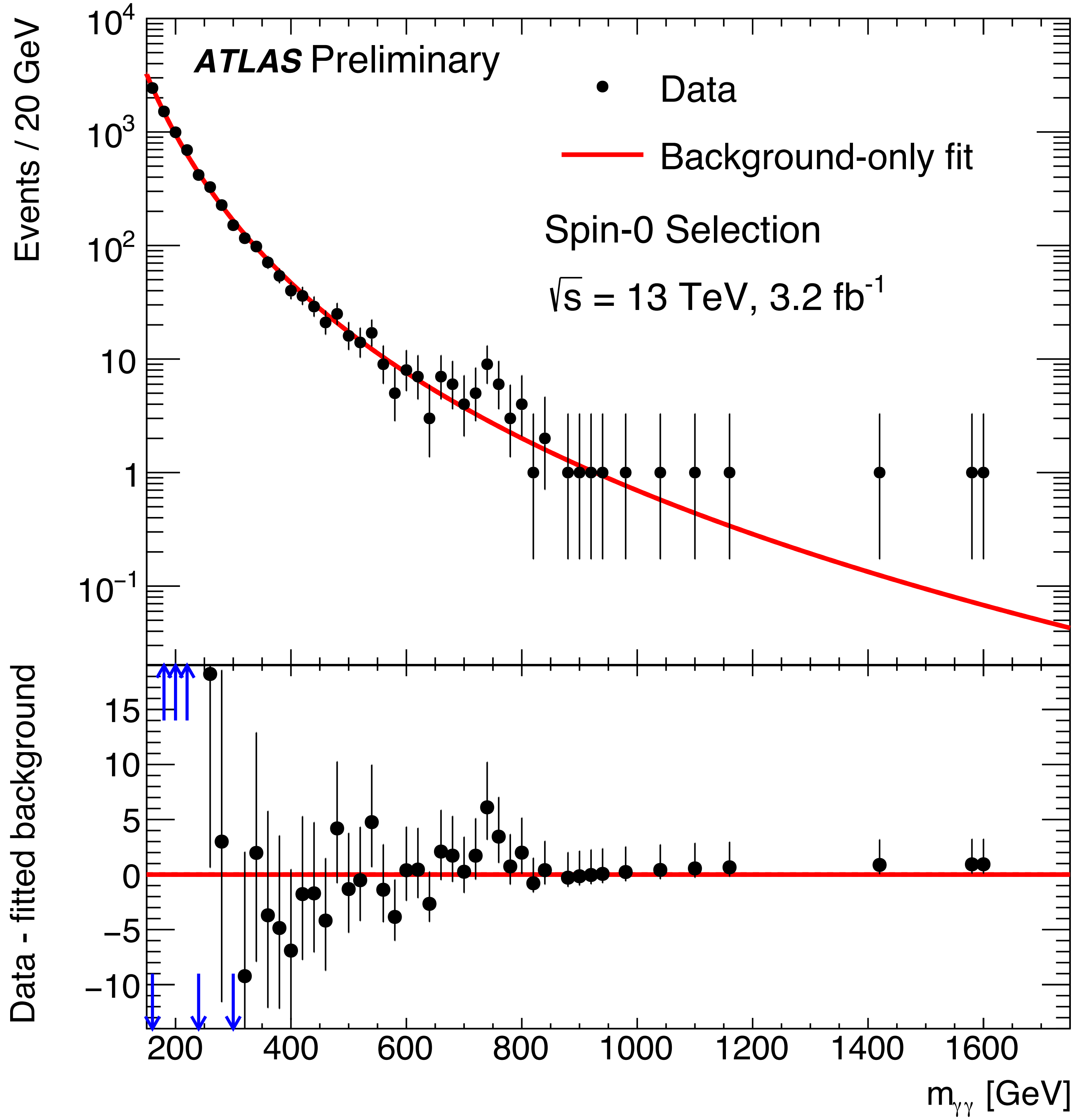
Outlines

1. Present status of the data and update.
2. A difficulty facing many models.
3. Interpretation by photon-jets.

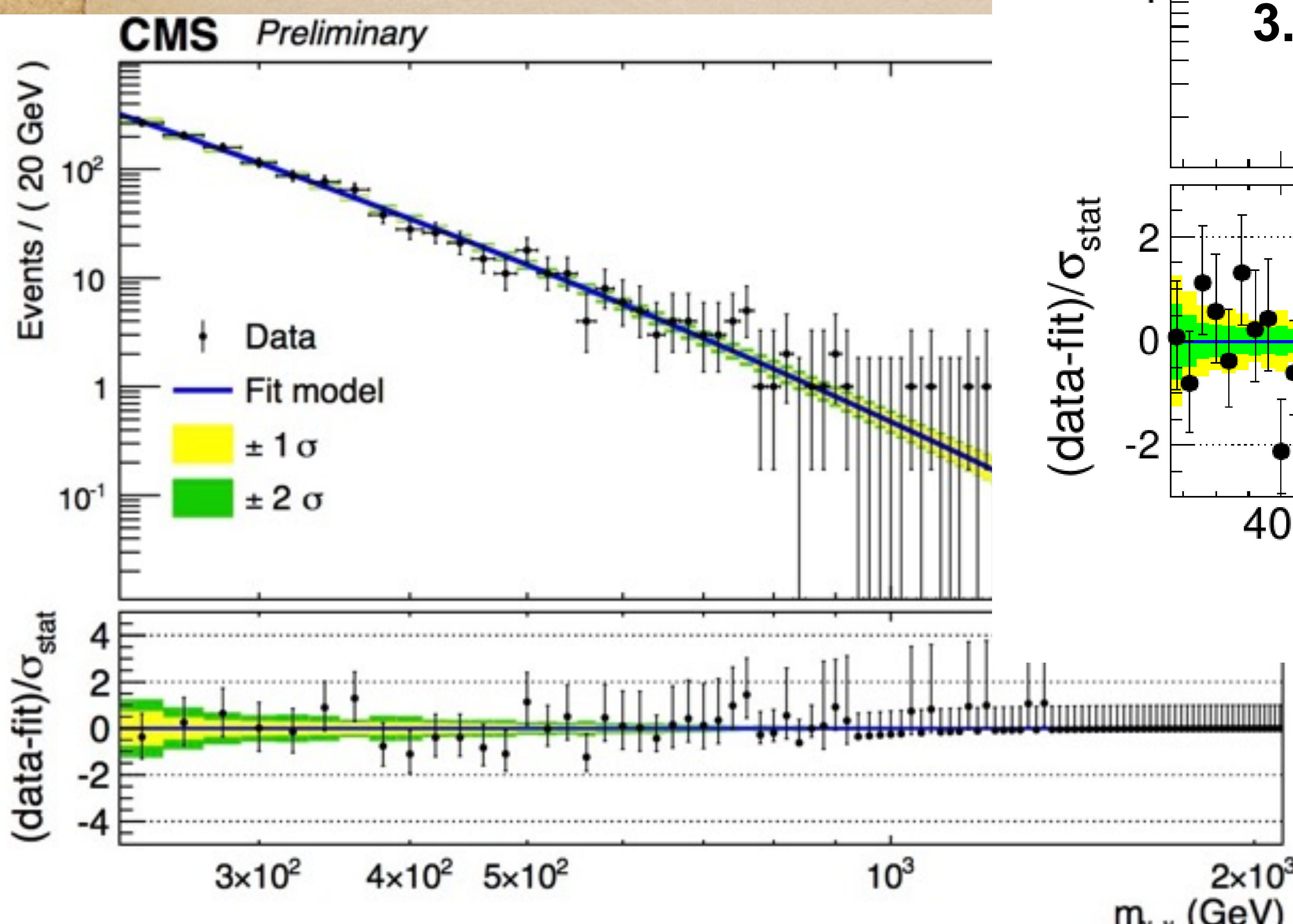


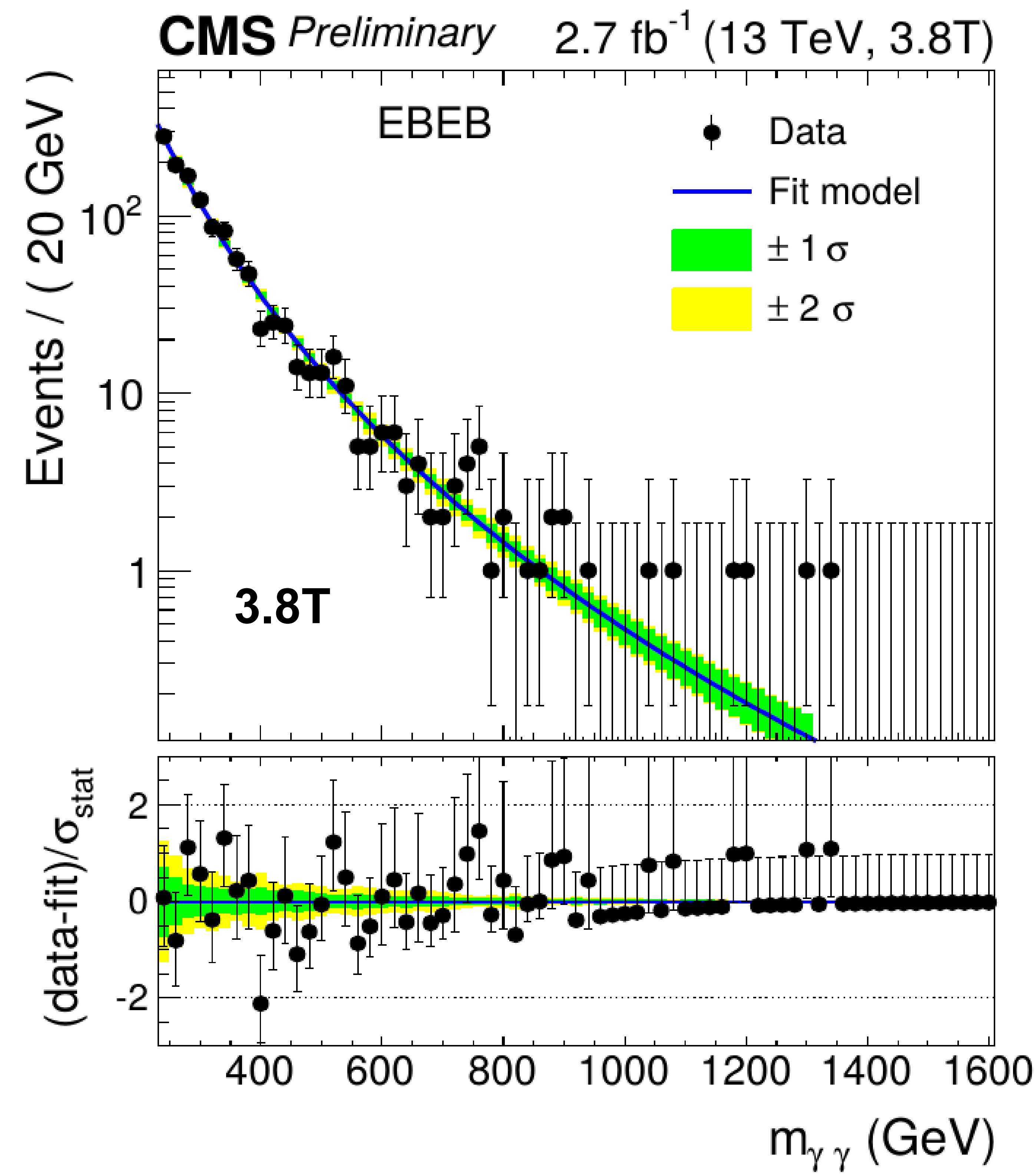
SPIN-0 ANALYSIS

background-only fit

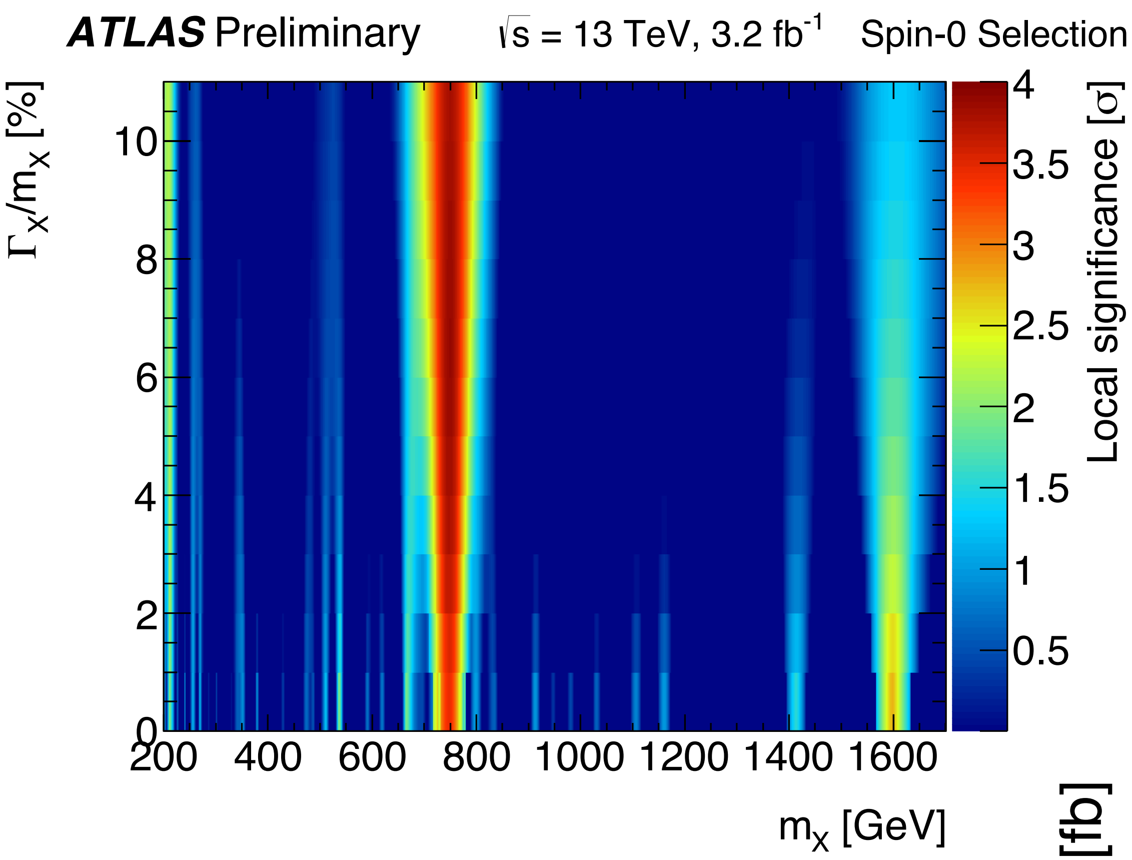


2878 events ($m_{\gamma\gamma}$ > 200 GeV)

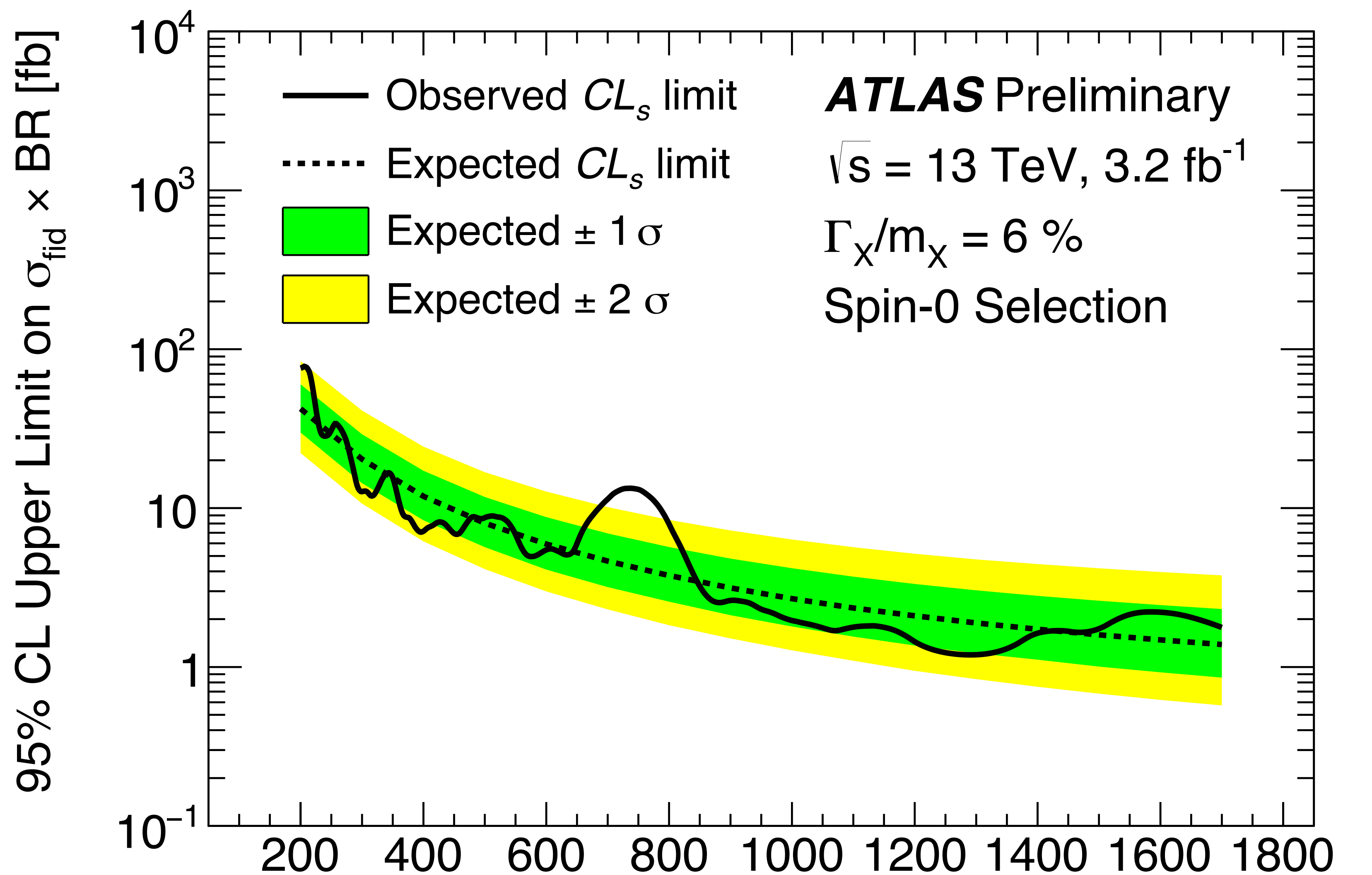

CMS Preliminary
Events / (20 GeV)
Data
Fit model
± 1 σ
± 2 σ
(data-fit)/σstat
3×10²
4×10²
5×10²
10³
2×10³
mγ γ (GeV)

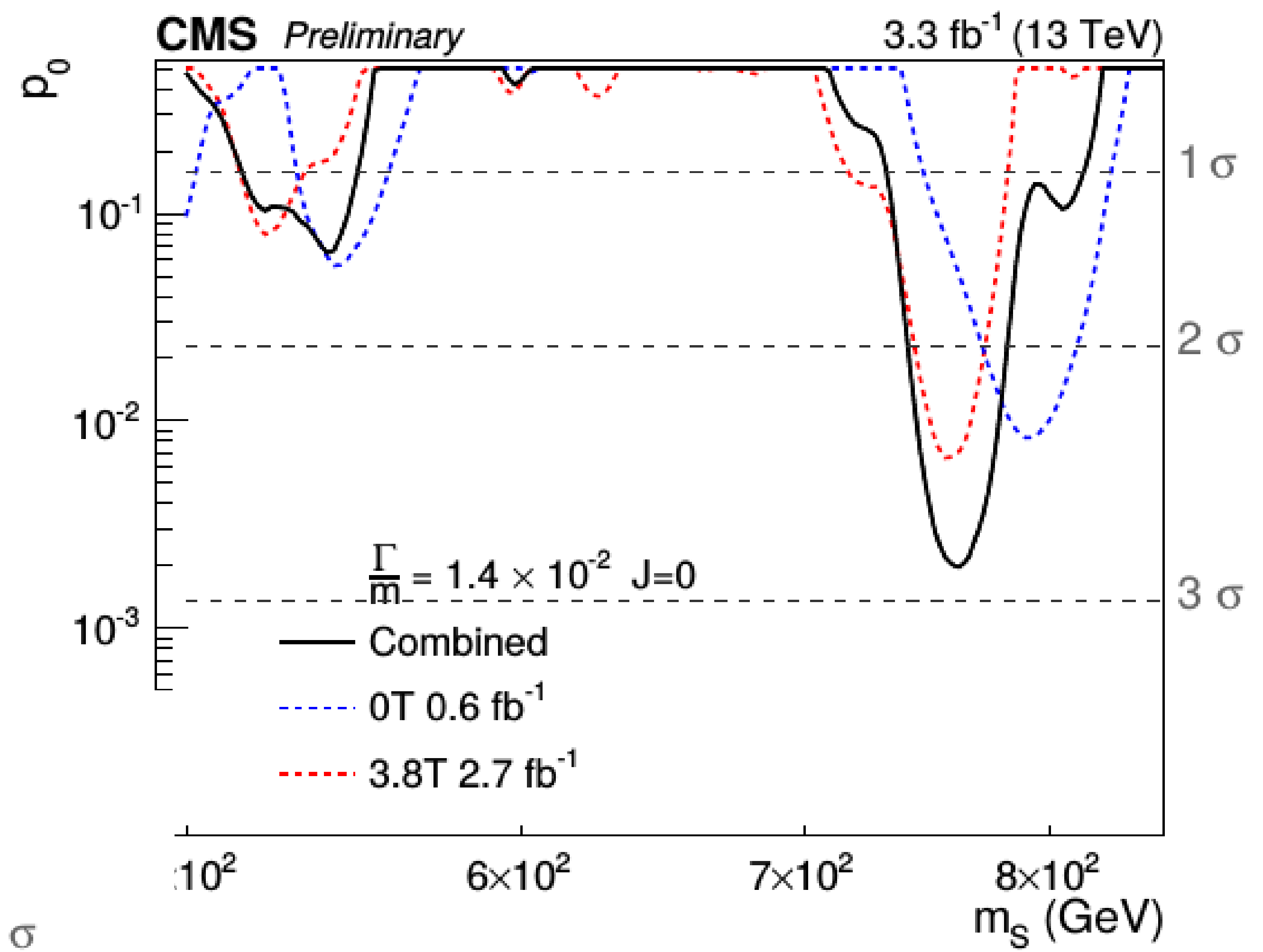

CMS Preliminary
2.7 fb⁻¹ (13 TeV, 3.8T)
EBEB
Data
Fit model
± 1 σ
± 2 σ
3.8T
Events / (20 GeV)
(data-fit)/σstat
400
600
800
1000
1200
1400
1600
mγ γ (GeV)

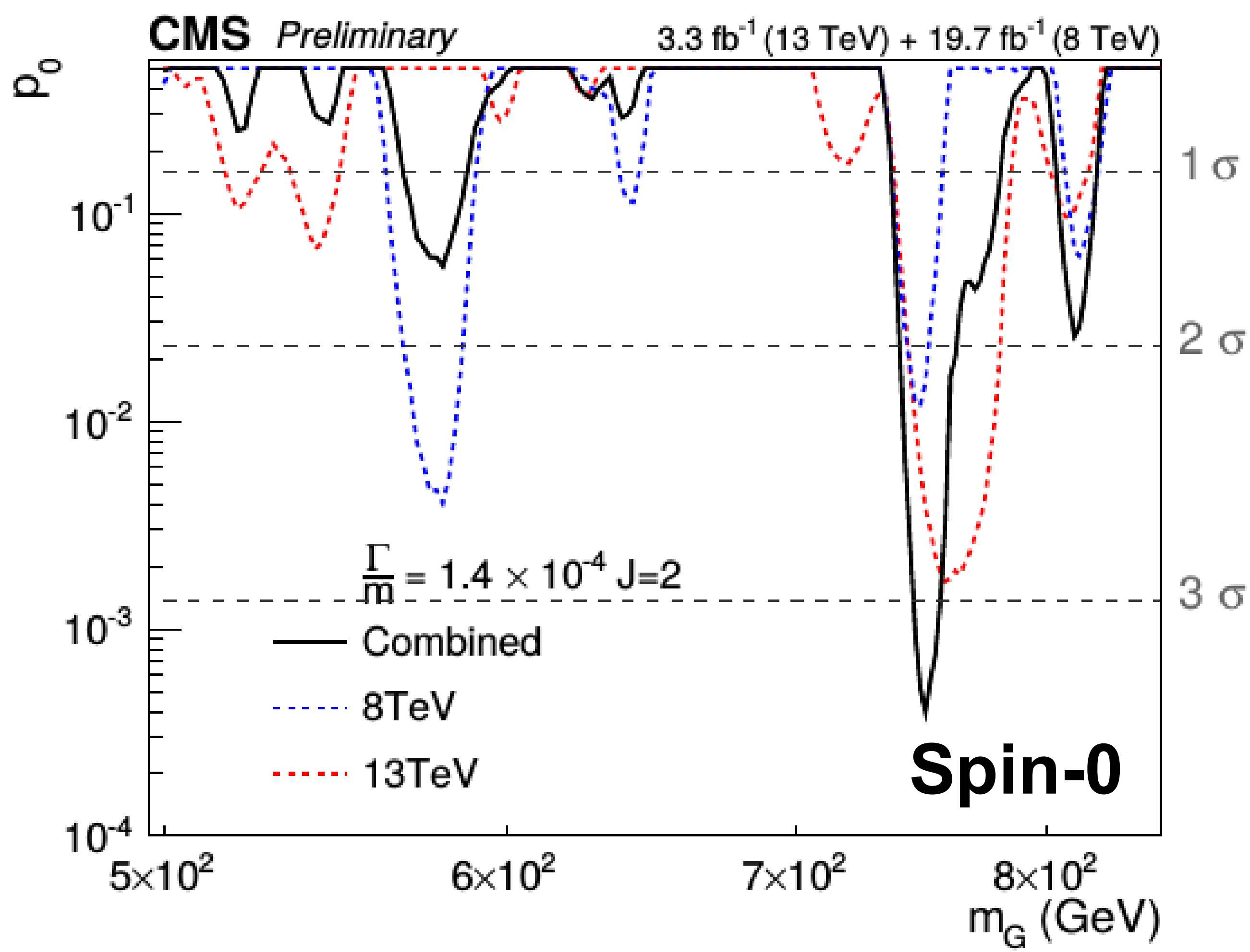
SPIN-0 ANALYSIS



- Largest deviation from B-only hypothe
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

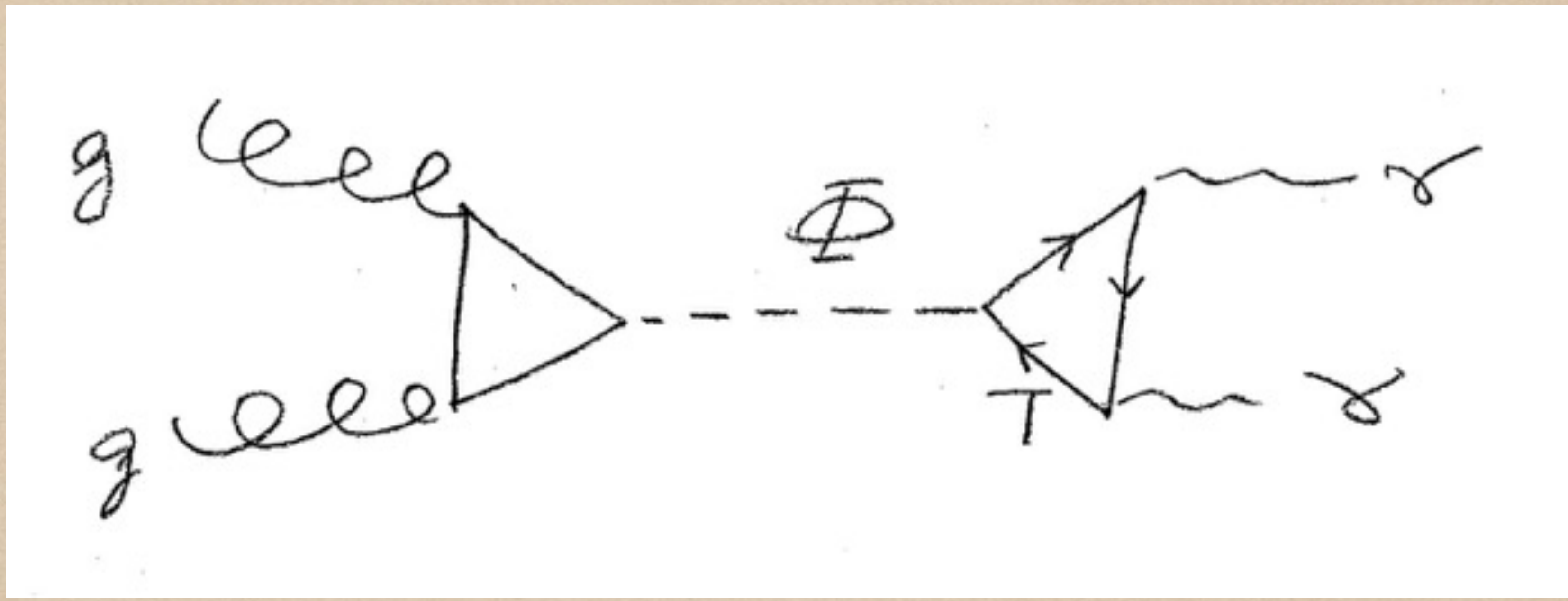



CMS Preliminary
3.3 fb-1 (13 TeV)
p0
10-1
10-2
10-3
1 σ
2 σ
3 σ
Γ/m = 1.4 × 10-2 J=0
Combined
0T 0.6 fb-1
3.8T 2.7 fb-1
6×10²
7×10²
8×10²
mS (GeV)


CMS Preliminary
3.3 fb-1 (13 TeV) + 19.7 fb-1 (8 TeV)
p0
10-1
10-2
10-3
10-4
1 σ
2 σ
3 σ
Γ/m = 1.4 × 10-4 J=2
Combined
8TeV
13TeV
Spin-0
5×10²
6×10²
7×10²
8×10²
mG (GeV)

$$\text{ATLAS}: M_X = 750\ \text{GeV}, \quad \sigma_{\text{fit}}(pp \to X \to \gamma\gamma) \approx 10 \pm 3\,\text{fb}; (95\%\ \text{CL}), \quad \Gamma_X \approx 45\,\text{GeV}$$

$$\text{CMS}: M_X = 760\,\text{GeV}, \quad \sigma_{\text{fit}}(pp \to X \to \gamma\gamma) \approx 9 \pm 7\,\text{fb}; (95\%\ \text{CL})$$



$\sigma_{SM}(pp \to H_{SM}(750\,\mathrm{GeV})$ ≈ 800 fb

B(H ->gg) ≈ 10^-6

Adding Singlet Fields as well as vector-like fermions

Models adding Singlet Higgses

Singlet Scalar Resonances and the Diphoton Excess

Samuel D. McDermott, Patrick Meade, and Harikrishnan Ramani
C. N. Yang Institute for Theoretical Physics, Stony Brook, NY 11794
(Dated: December 17, 2015)

Phenomenology of a 750 GeV Singlet

Adam Falkowski[a] Oren Slone[b] Tomer Volansky[b]

The Minimal Scalar-Stealth Top Interpretation of the Diphoton Excess

Wei Chao[a],* Ran Huo[b],† and Jiang-Hao Yu[a]‡

LHC 750 GeV diphoton resonance explained as a heavy scalar in top-seesaw model

Archil Kobakhidze[1], Fei Wang[2], Lei Wu[1], Jin Min Yang[3], and Mengchao Zhang[3]

Higgs singlet as a diphoton resonance in a vector-like quark model

R. Benbrik *,[1,2] Chuan-Hung Chen †,[3] and Takaaki Nomura ‡[4]

Rays of light from the LHC

Simon Knapen,[1,2,*] Tom Melia,[1,2,†] Michele Papucci,[1,2,‡] and Kathryn M. Zurek[1,2,§]

A hidden confining world on the 750 GeV diphoton excess

Ligong Bian,[1,*] Ning Chen,[2,†] Da Liu,[1,‡] and Jing Shu[1,3,§]

On the Interpretation of a Possible ~ 750 GeV Particle Decaying into $\gamma\gamma$

John Ellis[1,2], Sebastian A. R. Ellis[3], Jérémie Quevillon[1], Verónica Sanz[4] and Tevong You[5]

A 750 GeV Dark Pion: Cousin of a Dark G-parity-odd WIMP

Yang Bai, **Joshua Berger** and **Ran Lu**

Diphoton decay for a 750 GeV scalar boson in an $U(1)'$ model

R. Martinez,* F. Ochoa,† C.F. Sierra ‡

A Higgcision study on the 750 GeV Di-photon Resonance and 125 GeV SM Higgs boson with the Higgs–Singlet Mixing

Kingman Cheung[1,2,3], P. Ko[4], Jae Sik Lee[5], Jubin Park[5], and Po-Yan Tseng[1]

Adding Singlet Fields as well as vector-like fermions

Additional vector-like quarks running in the gg vertex can increase the production x-sec.

sigma(gg->H2) =sin^2 A *sigma(SM) + Delta

$$\Gamma(H_2) = \sin^2\alpha\,\Gamma_{\rm SM}(H_2) + \Delta\Gamma^{H_2}_{\rm vis} + \Delta\Gamma^{H_2}_{\rm inv}$$

Need many copies of VLQs or very large charge

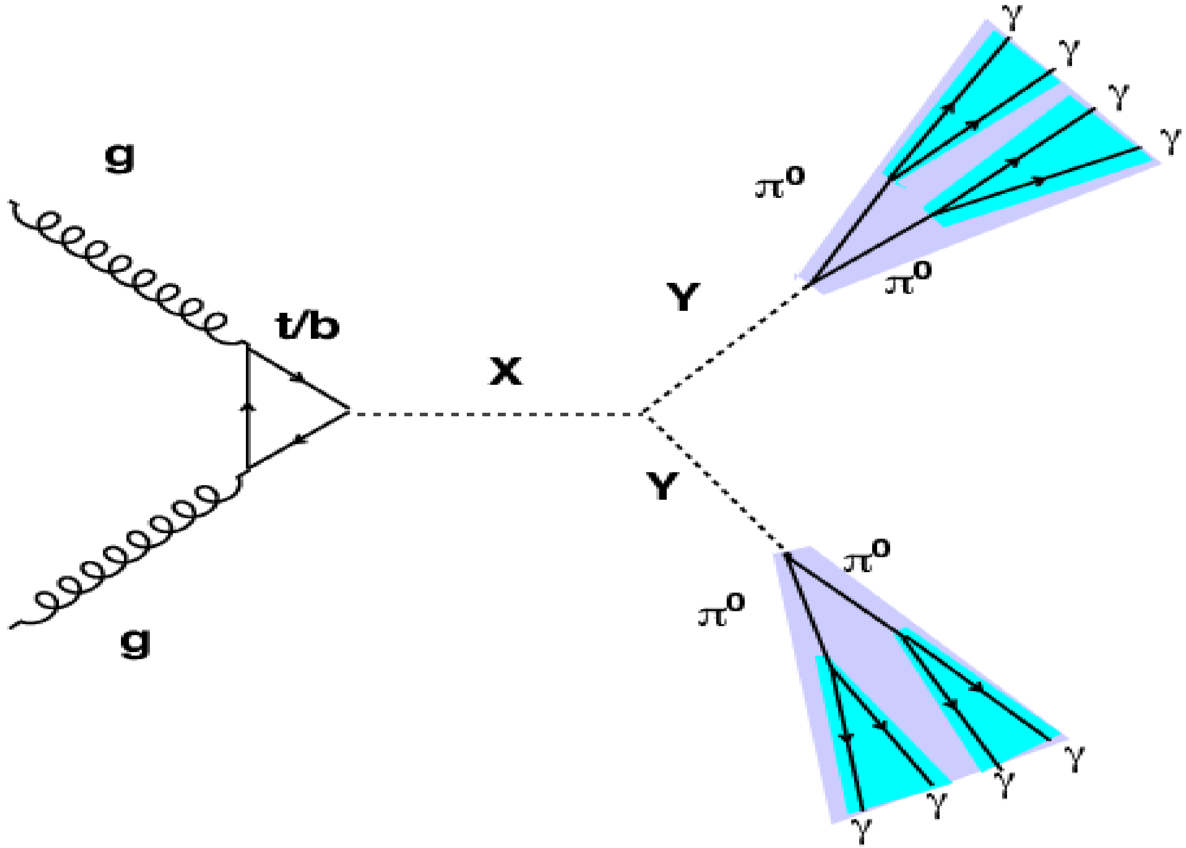
Related to Dark Matter

ATLAS preferred a wide width O(40) GeV. One possibility is let the 750 GeV Resonance decay into invisible particles, like DM.

Motivations of photon-jets

- A photon-jet is an object consisting of a cluster of collinear photons, perhaps from the decay of a fast moving light particle.
- A photon-jet can arise from cascade decays of heavy particles – 750 resonance.
- The spin of the heavy resonance that decays directly into $\gamma\gamma$ can only be 0 or 2. But for photon-jets it can be spin-1.

Picture of Interpretation



Scenario

- The X boson is 750 GeV resonance.
- X then decays into a pair of Y of order 1 GeV or below:

$$pp \to X \to YY$$

- Decay of Y into $\mu^+\mu^-$, $\pi\pi$, e^+e^- (negligible).

$$pp \to X \to YY \to (\pi^0\pi^0)\,(\pi^0\pi^0) \to (4\gamma)\,(4\gamma)$$

- Each set of 4γ appears in a very narrow cone

$$\Delta R \sim \frac{2M_Y}{p_T} \simeq \frac{2}{375} = 0.005$$

Photon selection of ATLAS

- Photon candidates are reconstructed from clusters of energy deposited in the ECAL.
- Only photon candidates with $|\eta| < 2.37$ are considered, also excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and end-cap calorimeters.
- Isolation cuts are applied to reject jet background.
- The measurement of the photon energy is based on the energy collected in calorimeter cells in an area of size $\Delta\eta \times \Delta\phi$ of 0.075×0.175 in the barrel and 0.125×0.125 in the end-caps.

- Selection cuts for photons are different for spin-0 and spin-2 scenarios. The following I will show the spin-0.
- For spin-0, $E_{T_1} > 0.4 m_{\gamma\gamma}$, $E_{T_2} > 0.3 m_{\gamma\gamma}$, also isolation cuts.
- The selected samples consist of events from diphoton production, photon-jet with one jet misidentified as photon, and dijet production with both jets misidentified as photons. Drell-Yan of $e^- e^+$ misidentified as photons is negligible.
- Purity of diphoton larger than $93^{+3}_{-8}\%$ under the selection cuts.

Angular Resolution in the photon-jet

- In Higgs measurement of diphoton, photons of $m_h/2 \sim 65$ GeV is distinguishable from π^0 of the same energy.

$$\Delta R_{\pi^0(65\ \mathrm{GeV})\to\gamma\gamma} \sim \frac{2m_\pi}{65} = 4 \times 10^{-3}$$

- In cascade decay of $X \to YY \to (\pi^0\pi^0)(\pi^0\pi^0)$, the angular separation between two π^0 from each Y

$$\Delta R_{Y\to\pi\pi} \sim \frac{2m_Y}{375} = 5 \times 10^{-3}$$

Each π^0 has energy 187.5 GeV, the separation between 2 photons:

$$\Delta R_{\pi^0\to\gamma\gamma} \sim \frac{2m_\pi}{187.5} = 1.5 \times 10^{-3}$$

- All 4 photons are contained in a cone of 0.005 forming a photon-jet. There are slight substructure inside each photon-jet.
- In principle, the resolution of the EM calorimeter may have capability to differentiate a photon-jet from a single photon.
- Without a dedicated high-photon-resolution analysis, it is very difficult to distinguish a photon-jet from a single photon.
- Further complication can arise from non-prompt decay of Y.

A Hidden-Valley-like model

- The SM Higgs field Φ mixes with two real scalar fields χ_1 and χ_2:

$$\begin{aligned}\mathcal{L} &= \frac{1}{2}\partial_\mu \chi_1 \partial^\mu \chi_1 + \frac{1}{2}\partial_\mu \chi_2 \partial^\mu \chi_2 + \frac{1}{2}\mu_1^2 \chi_1^2 + \frac{1}{2}\mu_2^2 \chi_1^2 + \mu_3^2 \chi_1 \chi_2 \\ &+ (\lambda_1 \chi_1 + \lambda_2 \chi_2)[M(\Phi^\dagger \Phi) + N(\lambda_1 \chi_1 + \lambda_2 \chi_2)^2]\end{aligned}$$

- The SM Higgs field takes on VEV

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \langle \phi \rangle + \phi(x) \end{pmatrix} ,$$

and

$$\mathcal{L}_m = -\frac{1}{2} (\phi \ \chi_1 \ \chi_2) \begin{pmatrix} 2\lambda \langle \phi \rangle^2 & -\lambda_1 M \langle \phi \rangle & -\lambda_2 M \langle \phi \rangle \\ -\lambda_1 M \langle \phi \rangle & -\mu_1^2 & -\mu_3^2 \\ -\lambda_2 M \langle \phi \rangle & -\mu_3^2 & -\mu_2^2 \end{pmatrix} \begin{pmatrix} \phi \\ \chi_1 \\ \chi_2 \end{pmatrix} ,$$

- They mix to form mass eigenstates: h, X, Y through angles $\theta_{1,2,3}$.

- Relevant vertices:

$$\begin{aligned}
\mathcal{L}_{Xhh} &\simeq \frac{1}{2}[2\lambda\langle\phi\rangle cos^2\theta_1 \sin\theta_1 + 6N\lambda_1^3 cos\theta_1 sin^2\theta_1 \\
&\quad +\lambda_1 M(\cos^3\theta_1 - 2\cos\theta_1\sin^2\theta_1)]Xhh \equiv \frac{\mu_{Xhh}}{2}Xhh \\
\mathcal{L}_{XYY} &\simeq \frac{6N}{2}[\lambda_2^3\cos^2\theta_3\sin\theta_3 + \lambda_1^3\cos\theta_3\sin^2\theta_3 + \lambda_1\lambda_2^2(\cos^3\theta_3 - 2\cos\theta_3\sin^2\theta_3) \\
&\quad +\lambda_2\lambda_1^2(\sin^3\theta_3 - 2\cos^2\theta_3\sin\theta_3)]XYY \equiv \frac{\mu_{HS}}{2}XYY \\
\mathcal{L}_{XYh} &\simeq \mathcal{O}(\sin\theta_{1,2,3})
\end{aligned}$$

Decays of X

- Decays into SM particles via mixing are suppressed by the θ_1:

$$\Gamma(X \to W^+W^-) = \sin^2\theta_1 \frac{g^2}{64\pi}\frac{m_X^3}{m_W^2}\sqrt{1-\frac{4m_W^2}{m_X^2}}\left(1-\frac{4m_W^2}{m_X^2}+\frac{12m_W^4}{m_X^4}\right),$$

$$\Gamma(X \to ZZ) = \sin^2\theta_1 \frac{g^2}{128\pi}\frac{m_X^3}{m_Z^2}\sqrt{1-\frac{4m_Z^2}{m_X^2}}\left(1-\frac{4m_Z^2}{m_X^2}+\frac{12m_Z^4}{m_X^4}\right),$$

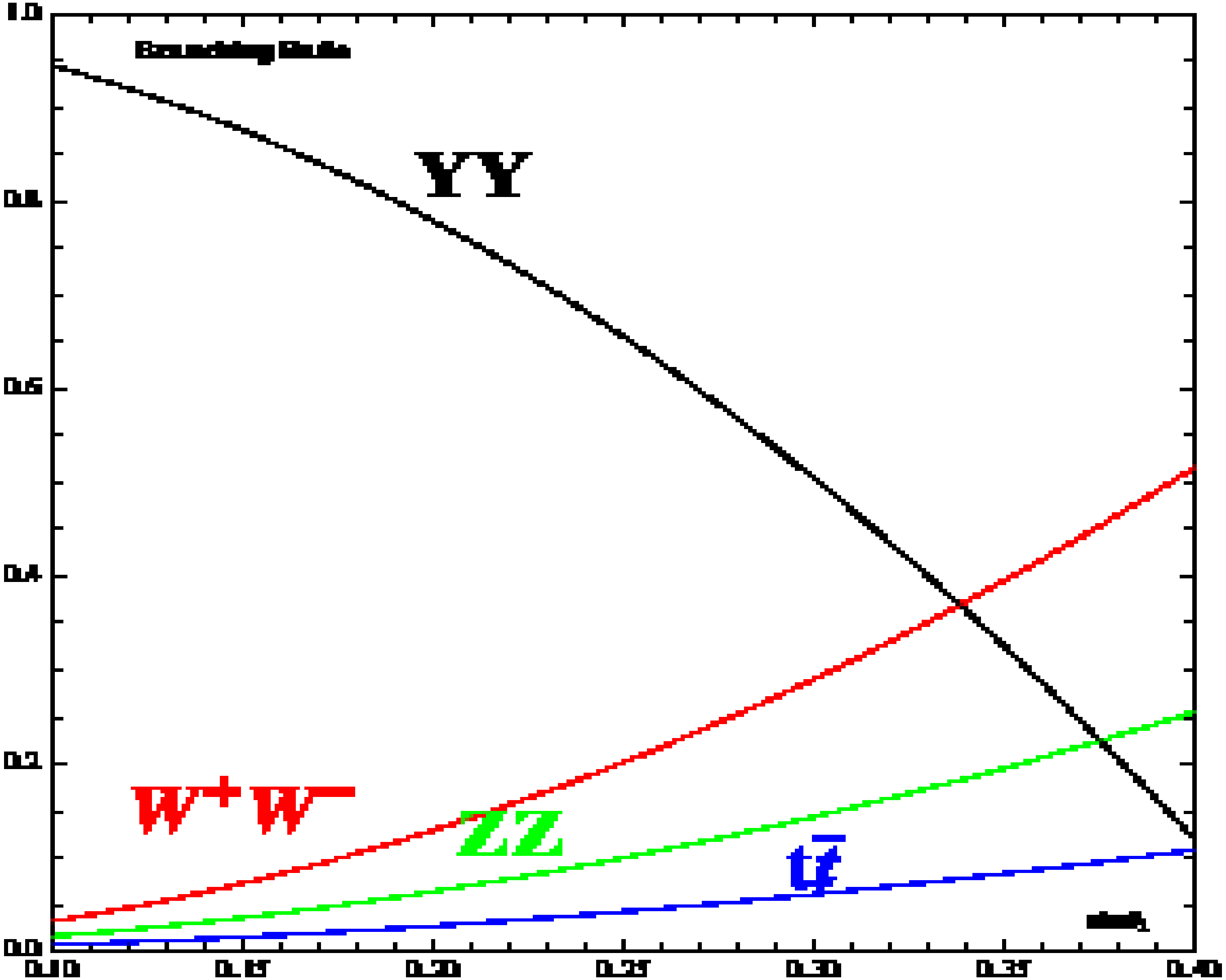
$$\Gamma(X \to t\bar{t}) = \sin^2\theta_1 \frac{N_c g^2 m_t^2}{32\pi m_W^2}\left(1-\frac{4m_t^2}{m_X^2}\right)^{3/2}(1+\triangle_{QCD})$$

- Decays into YY, hh, Yh:

$$\begin{aligned}
\Gamma(X \to YY) &= \frac{\mu_{HS}^2}{32\pi m_X} \times \sqrt{1 - 4\left(\frac{m_Y}{m_X}\right)^2} \\
\Gamma(X \to hh) &= \frac{\mu_{Xhh}^2}{32\pi m_X} \times \sqrt{1 - 4\left(\frac{m_h}{m_X}\right)^2} . \\
\Gamma(X \to Yh) &\ll \Gamma(X \to hh)
\end{aligned}$$

We choose $B(X \to hh) \ll \mathcal{O}(1\%)$ with $|\mu_{Xhh}| \lesssim 190$ GeV, and even smaller for $B(X \to Yh)$.

X(750) decay branching rates



Decays of Y

- The mass is of order 1 GeV, the major modes are $\mu^+\mu^-$ and $\pi\pi$, where $\pi\pi = \pi^+\pi^-$, $\pi^0\pi^0$ and $\Gamma(Y \to \pi^+\pi^-) = 2\Gamma(Y \to \pi^0\pi^0)$:

$$\Gamma(Y \to \ell^+\ell^-) = \sin^2\theta_2 \frac{m_\ell^2 m_Y}{8\pi\langle\phi\rangle^2}\left(1 - \frac{4m_\ell^2}{m_Y^2}\right)^{3/2}$$

$$\Gamma(Y \to \pi\pi) = \sin^2\theta_2 \frac{m_Y^3}{216\pi\langle\phi\rangle^2}\left(1 - \frac{4m_\pi^2}{m_Y^2}\right)^{1/2}\left(1 + \frac{11m_\pi^2}{2m_Y^2}\right)^2$$

- Including QCD corrections, $B(Y \to \pi\pi) \simeq 100\%$ while $B(Y \to \mu^+\mu^-) \simeq 0.4\%$.

- For a 1 GeV scalar boson Y with $\sin\theta_2 = 1.6 \times 10^{-2}$, $\Gamma_Y \approx 4.25 \times 10^{-10}$ GeV and so $\tau_Y = \frac{1}{\Gamma_Y} \approx 1.55 \times 10^{-15}(s)$

$$c\gamma\tau_Y \sim (3 \times 10^{11}\ \text{mm/s})(375)(1.55 \times 10^{-15}\ \text{s}) = 0.17\ \text{mm}$$

Almost prompt decay for Y

Constraints on X

- The $X(750)$ mixes with the SM Higgs via θ_1, so it is constrained by the current Higgs boson measurements:

$$\cos\theta_1 > 0.86 \qquad\qquad \text{[KC, Ko, Lee, Tseng 1507.06158]}$$

  which implies $|\sin\theta_1| < 0.51$. We choose $|\sin\theta_1| = 0.3$ for demonstration.

- 8 TeV search limits:

$$\begin{aligned}
&\sigma(pp \to S)_{8\mathrm{TeV}} \times B(S \to ZZ) < 22\ \mathrm{fb}_{(\mathrm{ATLAS})},\ \ 27\ \mathrm{fb}_{(\mathrm{CMS})} \\
&\sigma(pp \to S)_{8\mathrm{TeV}} \times B(S \to W^+W^-) < 38\ \mathrm{fb}_{(\mathrm{ATLAS})},\ \ 220\ \mathrm{fb}_{(\mathrm{CMS})} \\
&\sigma(pp \to S)_{8\mathrm{TeV}} \times B(S \to t\bar{t}) < 0.7\ \mathrm{pb}_{(\mathrm{ATLAS})},\ \ 0.6\ \mathrm{pb}_{(\mathrm{CMS})} \\
&\sigma(pp \to S)_{8\mathrm{TeV}} \times B(S \to hh) < 35\ \mathrm{fb}_{(\mathrm{ATLAS})},\ \ 52\ \mathrm{fb}_{(\mathrm{CMS})} \\
&\sigma(pp \to S)_{8\mathrm{TeV}} \times B(S \to gg) \times \alpha < 1.8\ \mathrm{pb}.
\end{aligned} \tag{1}$$

- Predictions at 8 TeV for $\sin\theta_1 = 0.3$ with

$\sigma_{\rm SM}(pp \to gg \to H_{\rm SM}) \approx 157$ fb:

$$\begin{aligned}
\sigma(pp \to X)_{\rm 8TeV} \times B(X \to ZZ) &= 2.0 \text{ fb} \\
\sigma(pp \to X)_{\rm 8TeV} \times B(X \to W^+W^-) &= 4.1 \text{ fb} \\
\sigma(pp \to X)_{\rm 8TeV} \times B(X \to t\bar{t}) &= 0.38 \text{fb} \\
\sigma(pp \to X)_{\rm 8TeV} \times B(X \to gg) &= 1.76 \times 10^{-3} \text{fb}
\end{aligned}$$

- For $X \to hh$ does not depend on the mixing angle but μ_{Xhh}, we choose $|\mu_{Xhh}| \lesssim 190$ GeV) to obtain

$$B(X \to hh) \ll O(1\%)$$

$B(X \to Yh)$ will be much smaller.

Constraints on Y

- The Y also mixes with the SM Higgs via θ_2, so it is constrained by the current Higgs boson measurements:

$$\cos\theta_2 > 0.86$$

- From B and K meson decays , the strongest is $B \to K\mu^+\mu^-$:

$$\sin^2\theta_2 \times B(Y \to \mu^+\mu^-) < 10^{-6}$$

  implying $\sin\theta_2 < 1.6 \times 10^{-2}$

- Search for rare decays of the Higgs boson

$$h \to aa \to (\gamma\gamma)\,(\gamma\gamma)$$

  by ATLAS but for 10 GeV $< m_a <$ 62 GeV.

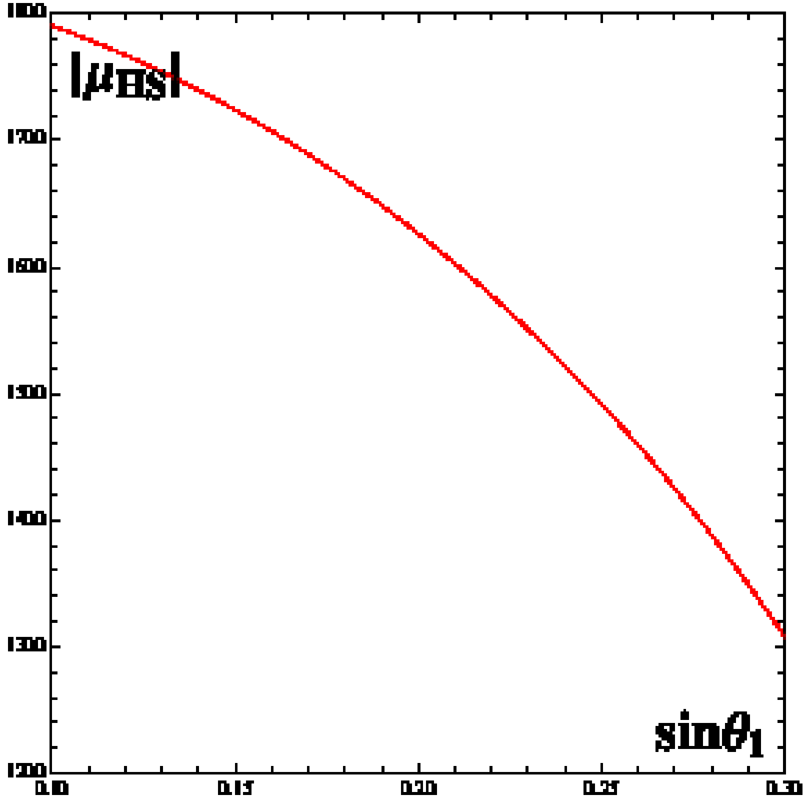
- Yet, another one by ATLAS for $m_a = 100, 200, 400$ MeV such that the photon-jet is indistinguishable from a single photon:

$$B(h \to aa) \times B^2(a \to \gamma\gamma) < 0.01$$

- The mass of Y chosen here is $O(1)$ GeV, such that it is not restrcited and the photon-jet may have a chance to be resolved.

Fitting to the data

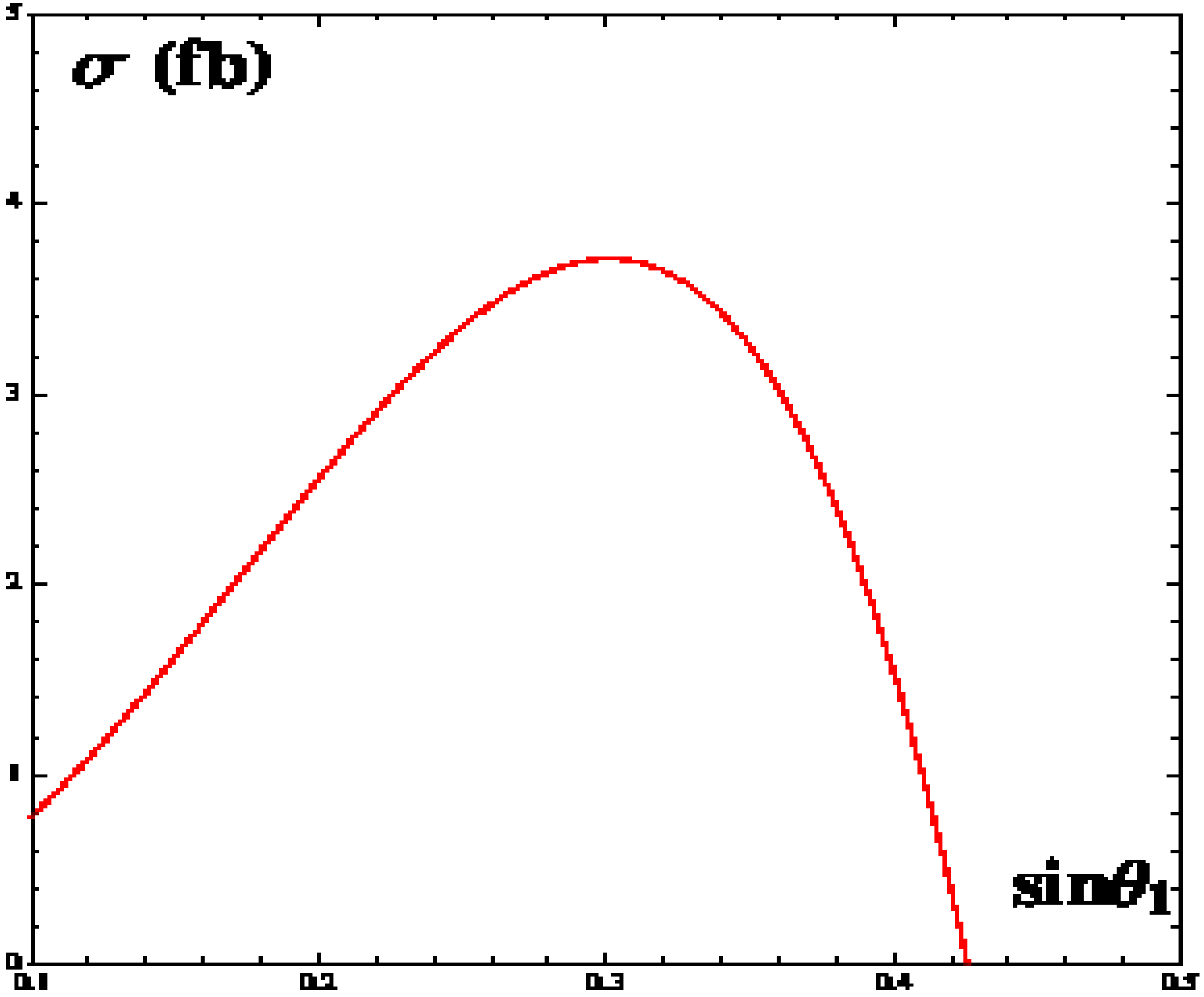
- Width = 45 GeV gives a large coupling for $X \to YY$: $|\mu_{HS}| \gtrsim 1300$ GeV. Contour of fixed $\Gamma_{X(750)} = 45$ GeV:



- Fit to the cross section with $\sin\theta_1 = 0.3$ and $m_Y = 1$ GeV:

$$\sigma\left(pp \to X \to YY \to (\pi^0\pi^0)(\pi^0\pi^0) \to (4\gamma)(4\gamma)\right)$$
$$= \sigma(pp \to X) \times B(X \to YY) \times \left[B(Y \to \pi^0\pi^0)\right]^2 \times \left[B(\pi^0 \to \gamma\gamma)\right]^4$$
$$\approx \left[736 \text{ fb} \times (0.3)^2\right] \times [50.45\%] \times \left[100\% \times \frac{1}{3}\right]^2 \times [100\%]^4$$
$$\approx 3.71 fb$$

	YY	W^+W^-	ZZ	$t\bar{t}$
BR	50.45%	29.07%	14.38%	6.10%
Γ_i (GeV)	22.70	13.08	6.47	2.75

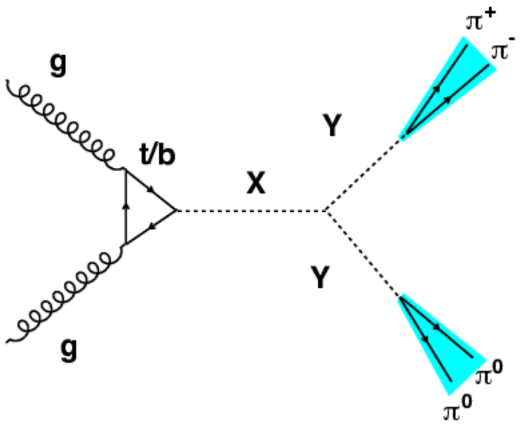

σ (fb)
sinθ1
0
1
2
3
4
5
0.1
0.2
0.3
0.4
0.5

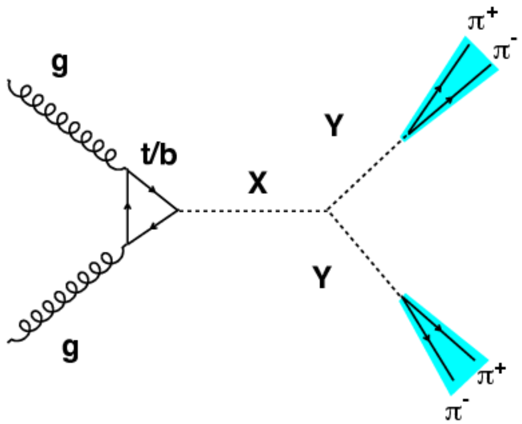
Other possible channels

- Y can also decay into $\pi^+\pi^-$

$$pp \to X \to YY \to (\pi^0\pi^0)(\pi^+\pi^-)$$

$$pp \to X \to YY \to (\pi^+\pi^-)(\pi^+\pi^-)$$

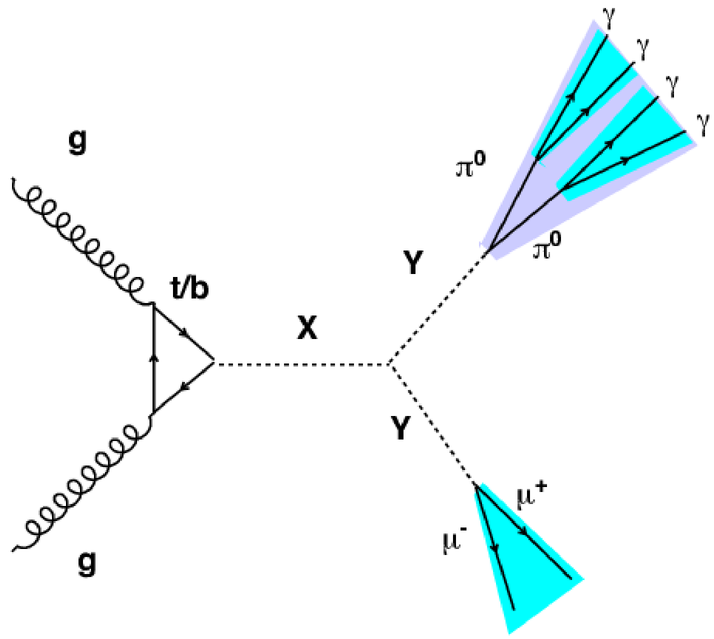




The two pions form a collimated object – pion-jet.

- Y could also decay into $\mu^+\mu^-$:

$$pp \to X \to YY \to (\pi^0\pi^0)(\mu^+\mu^-)$$



The two muons are very collimated, forming a muon-jet.

Outlook

- Other decay modes: $t\bar{t}$, W^+W^-, ZZ, jj.
- Predictions for $Z\gamma$ and ZZ by various models.
- Connection to the 125 Higgs boson.
- Does it related to electroweak symmetry breaking?
- Check the production channels: VBF, associated with W, Z, $t\bar{t}$.