Light Diphoton Resonances

Chris Meyer

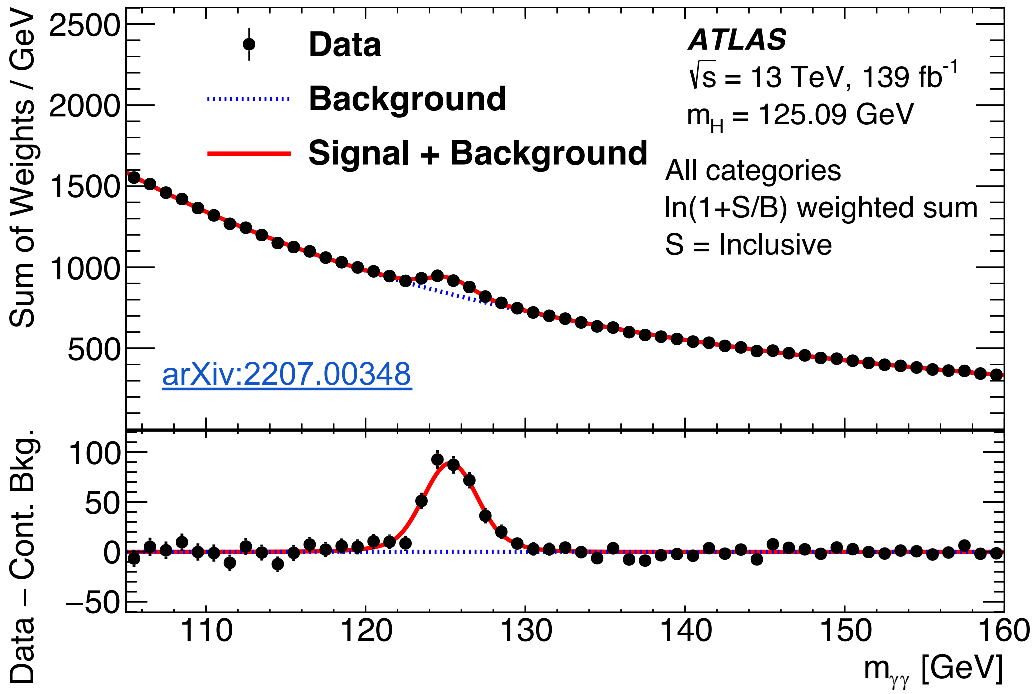
on behalf of the

ATLAS EXPERIMENT

U.S. DEPARTMENT OF ENERGY | Office of Science

DIS23 MICHIGAN STATE UNIVERSITY

We found the Higgs! Seems like just yesterday…



BUT is it the only one?

Does history repeat itself?

Once upon a time…

- There was one electron
  - Thomson, 1897

…but later!

1936 → discovery of muon

Does history repeat itself?

Once upon a time…

- There was one electron
  - Thomson, 1897
- There was one gauge boson
  - Photon → Einstein, 1905

…but later!

1936 → discovery of muon

1983 → discovery of W/Z

Does history repeat itself?

Once upon a time…

- There was one electron
    - Thomson, 1897
- There was one gauge boson
    - Photon → Einstein, 1905
- Simple hypothesis…

…but later!

1936 → discovery of muon

1983 → discovery of W/Z

…Nature more creative!

Does history repeat itself?

Once upon a time…

- There was one electron
  - Thomson, 1897
- There was one gauge boson
  - Photon → Einstein, 1905

…but later!

1936 → discovery of muon

1983 → discovery of W/Z

We've only found **one Higgs boson** so far...

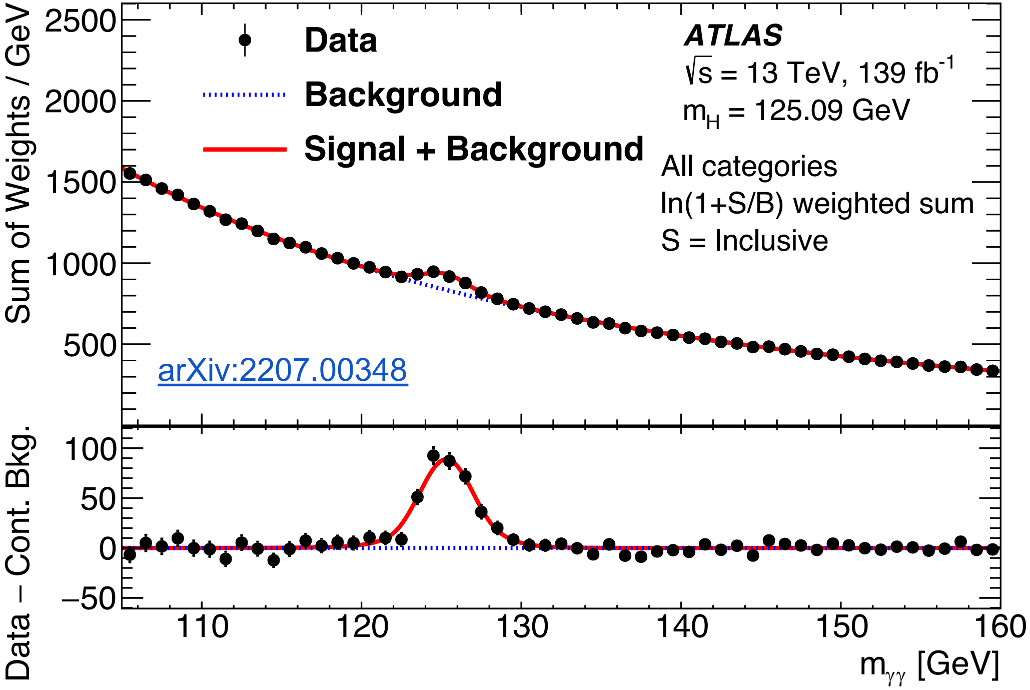
...**why not more?** Supersymmetry and other theories include them!

→ handy for solving hierarchy problem, etc.

To be a bit more concrete

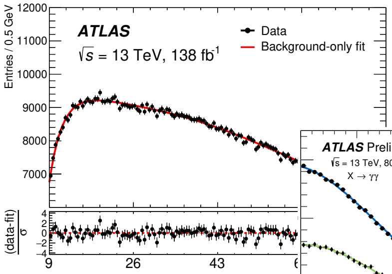
- Laundry list of popular extensions to the Higgs sector:
  - SUSY w/ 2 Higgs doublet
  - Vector-like fermions w/ 2 Higgs doublet
  - Composite Higgs
  - Heavy QCD axion
  - R-axion in SUSY-breaking models
- Aim to explain one or more open questions:
  - Hierarchy problem
  - Axion → mediator of dark-matter freeze out, trigger of baryogenesis

What we’ve found



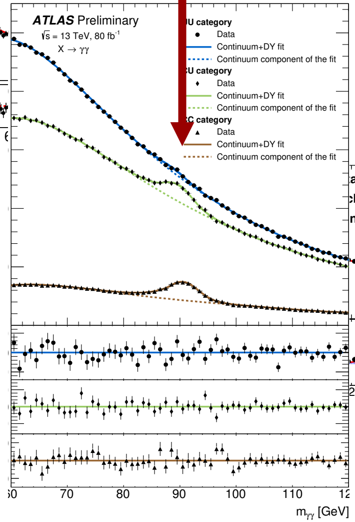
BUT is it the only one?

Zoom out a bit…



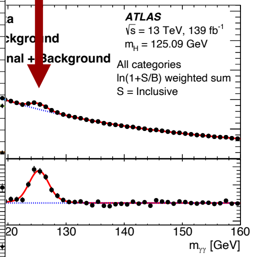
arXiv:2211.04172

Z Boson

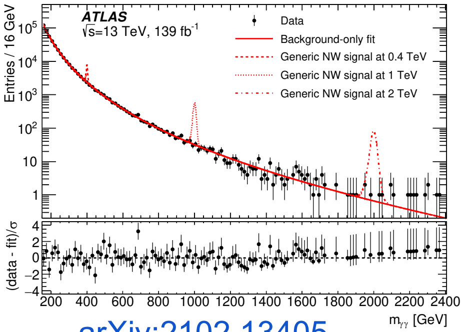


ATLAS-CONF-2018-025

Higgs Boson



arXiv:2207.00348



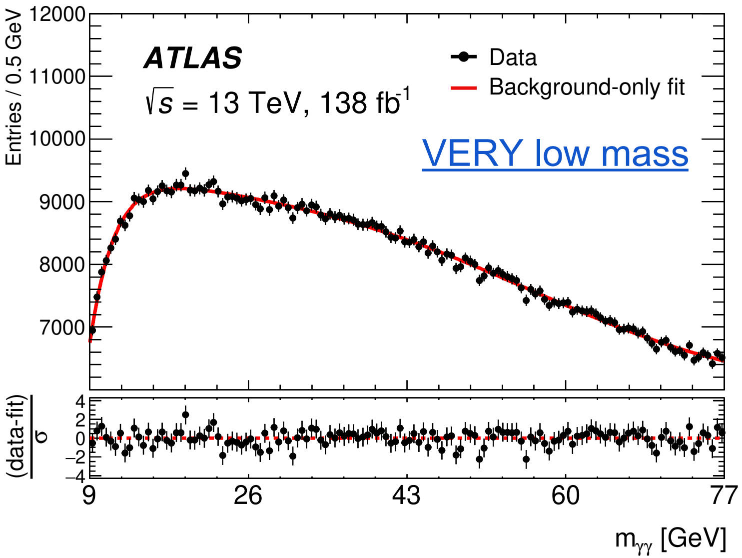
arXiv:2102.13405

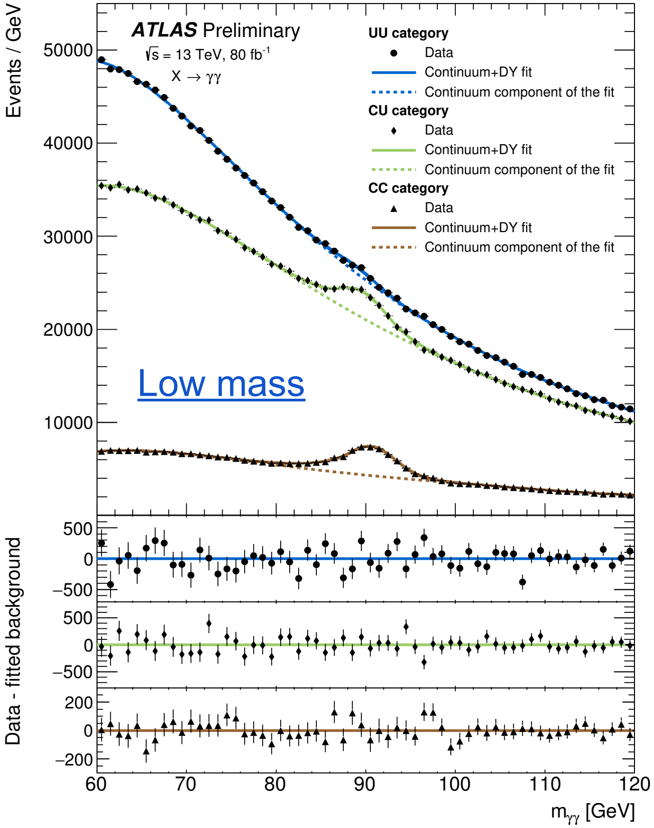
"low" mass

$m_{\gamma\gamma}$ [GeV]

"high" mass

Focus on the lower side

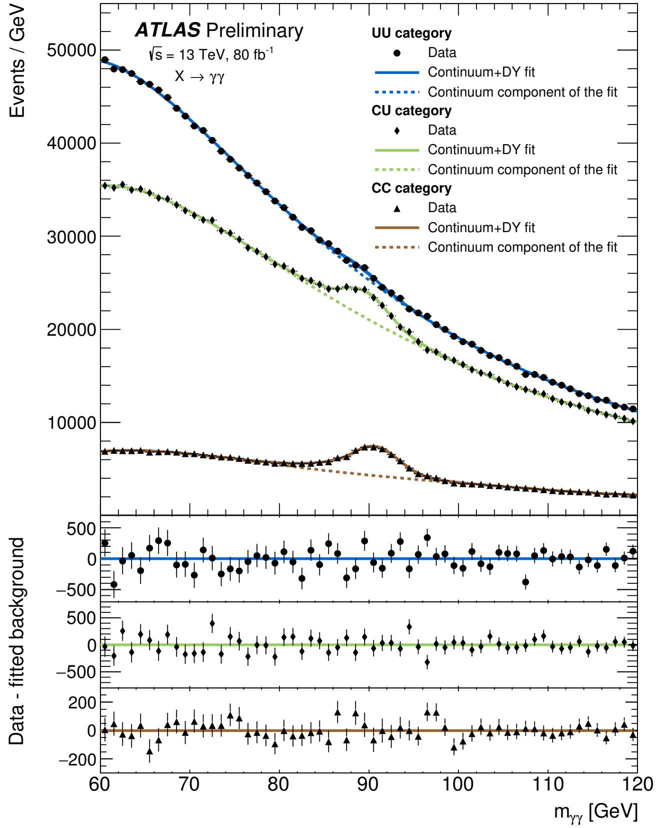




- Diphoton mass spectra
- Low-mass bump → new physics

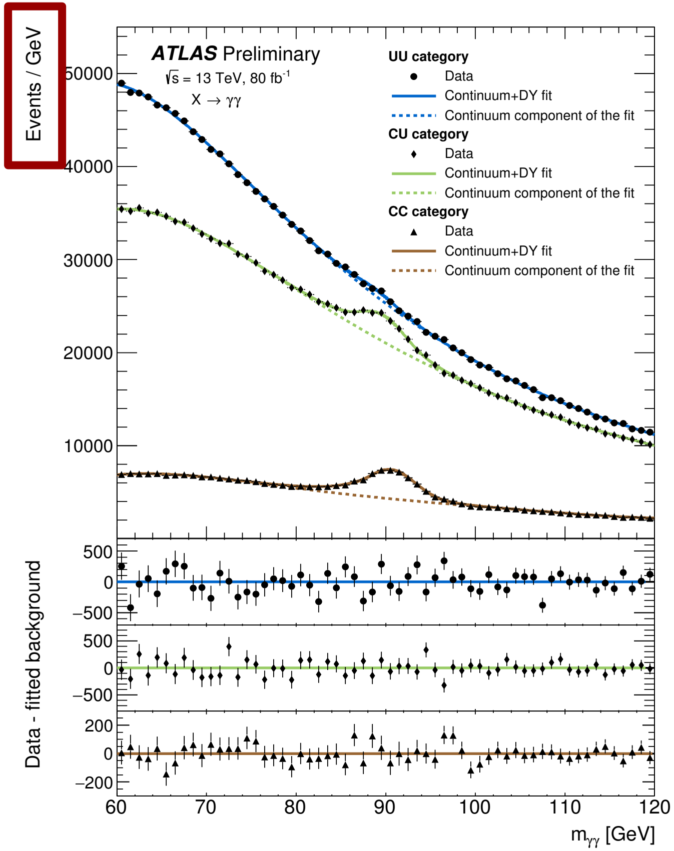
Talk outline

1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results



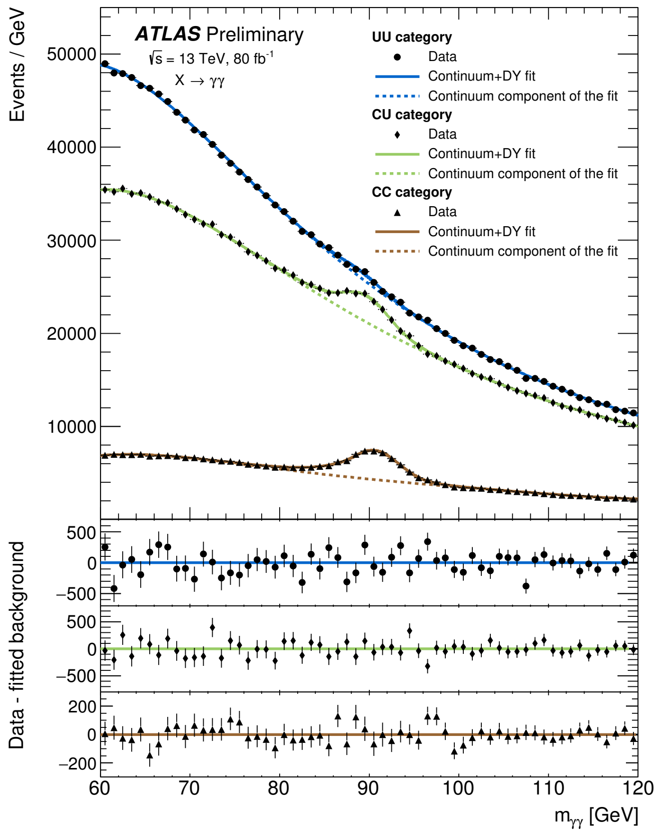
Talk outline

1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results



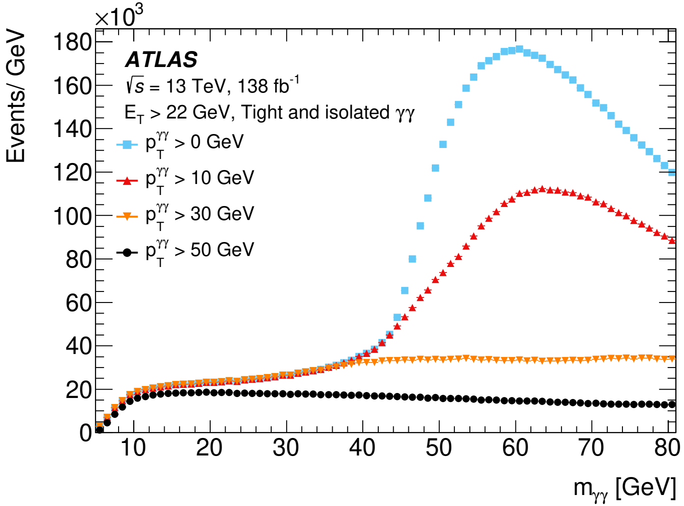
Event selection

	Very Low Mass	Low Mass
Energy	$22\ \mathrm{GeV} < E_T$	
Identification	“Tight”	
Isolation	$E_{calo} < 0.065\ E_T$, $E_{track} < 0.05\ E_T$	
Boost	$50\ \mathrm{GeV} < p_{T,\gamma\gamma}$	



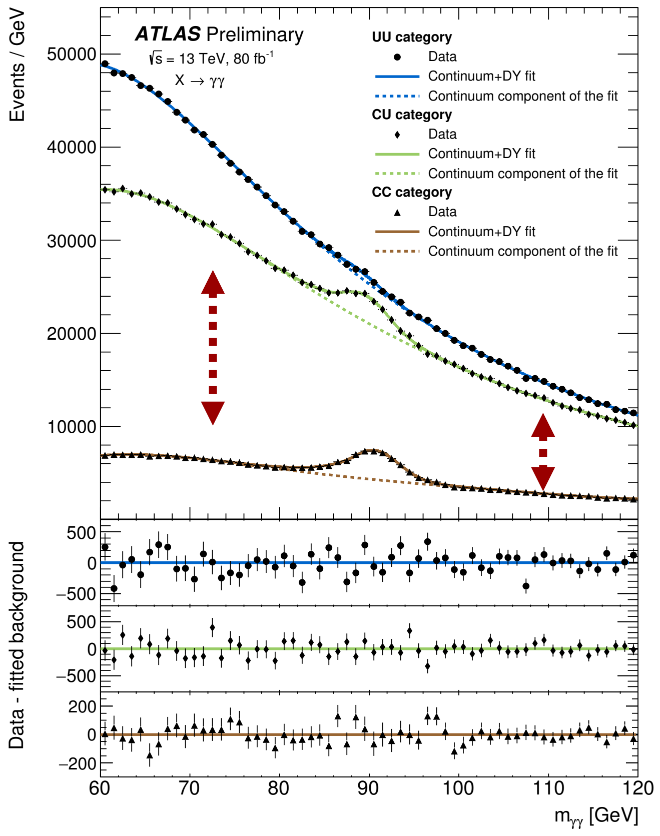
Event selection

	Very Low Mass	Low Mass
Energy	$22\ \text{GeV} < E_T$	
Identification	"Tight"	
Isolation	$E_{calo} < 0.065\ E_T$, $E_{track} < 0.05\ E_T$	
Boost	$50\ \text{GeV} < p_{T,\gamma\gamma}$	



Talk outline

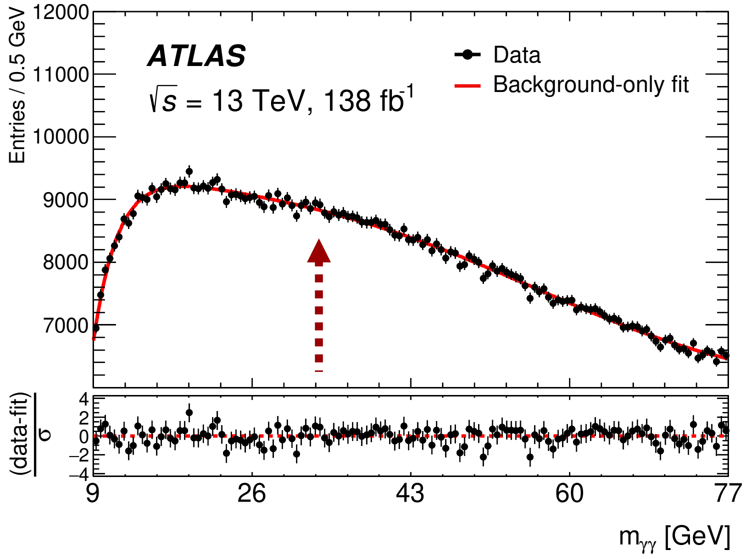
1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results

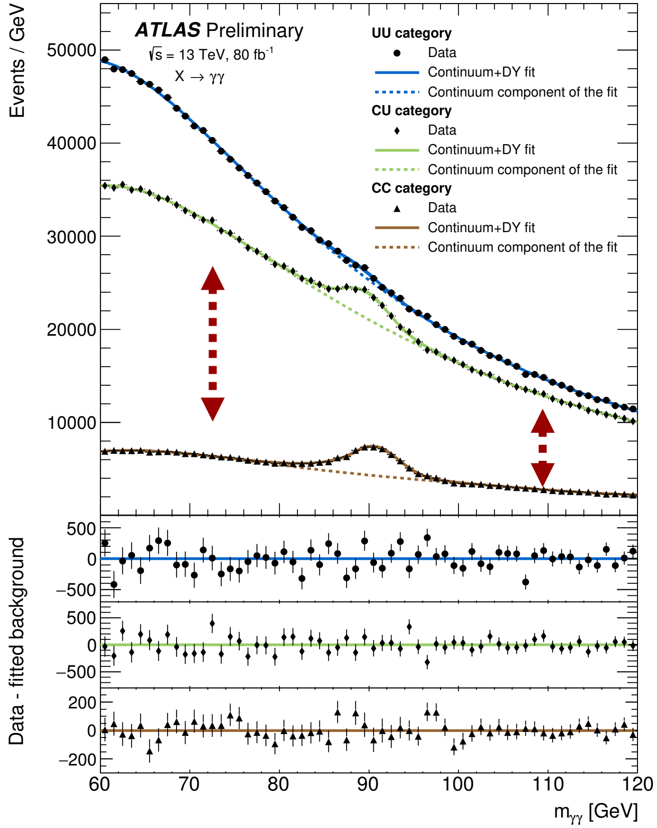


Talk outline

1. Event Selection

2. Continuum background (γγ, γj, jj)





Background model → analytic function

- Very low mass:

Turn-on region / **Smoothly falling region**

$$\left[1-(1-f_0)\,e^{-\frac{m_{\gamma\gamma}}{\tau_{TO}}}\right] \times \underbrace{\left(1-\left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}}_{\text{Power-law}} \underbrace{\left(1+\frac{e^{\frac{m_{\gamma\gamma}-\delta_{\text{tail}}}{\tau_{\text{tail}}}}}{1+e^{-\frac{m_{\gamma\gamma}-\delta_{\text{thresh}}}{\tau_{\text{thresh}}}}}\right)}_{\text{Activation function}}$$

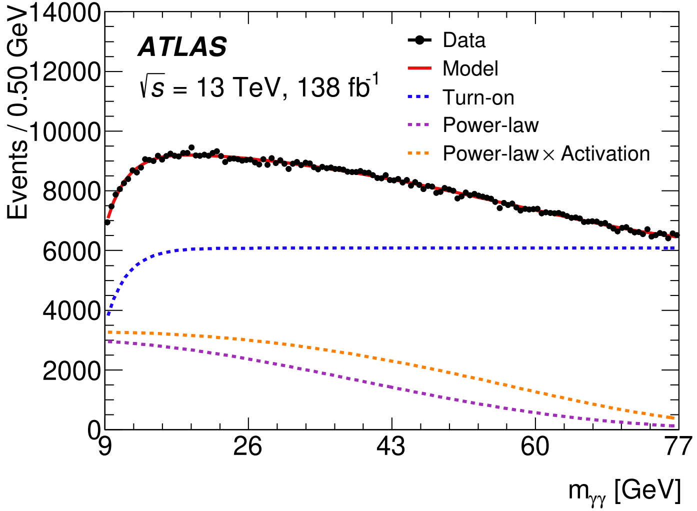
- Low mass:
  - UU/CU → Landau + exponential
  - CC → Fifth-order Bernstein polynomial

Background model → analytic function

- Very low mass:

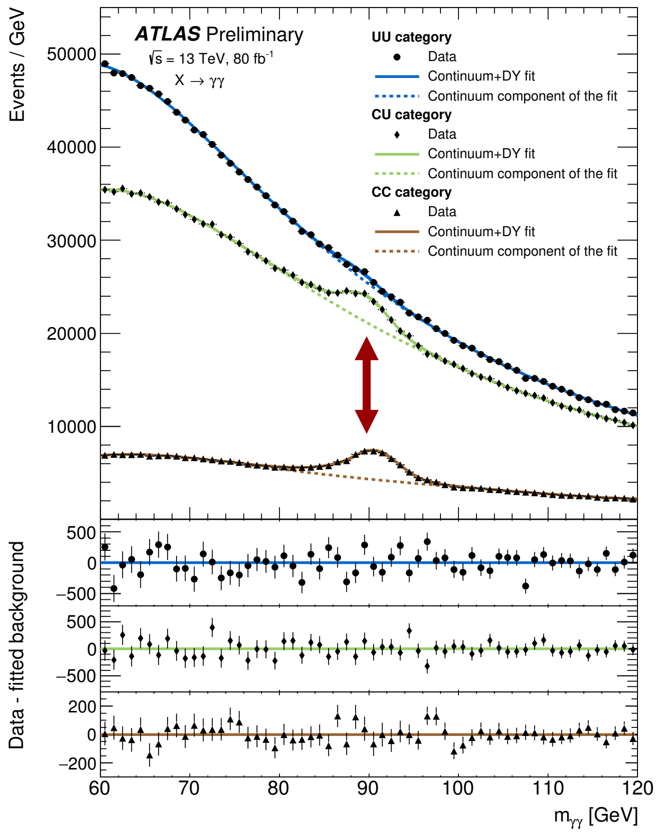
Turn-on region **Smoothly falling region**

$$\left[1-(1-f_0)\,e^{-\frac{m_{\gamma\gamma}}{\tau_{TO}}}\right] \times \underbrace{\left(1-\left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}}_{\text{Power-law}} \underbrace{\left(1+\frac{e^{\frac{m_{\gamma\gamma}-\delta_{\text{tail}}}{\tau_{\text{tail}}}}}{1+e^{-\frac{m_{\gamma\gamma}-\delta_{\text{thresh}}}{\tau_{\text{thresh}}}}}\right)}_{\text{Activation function}}$$



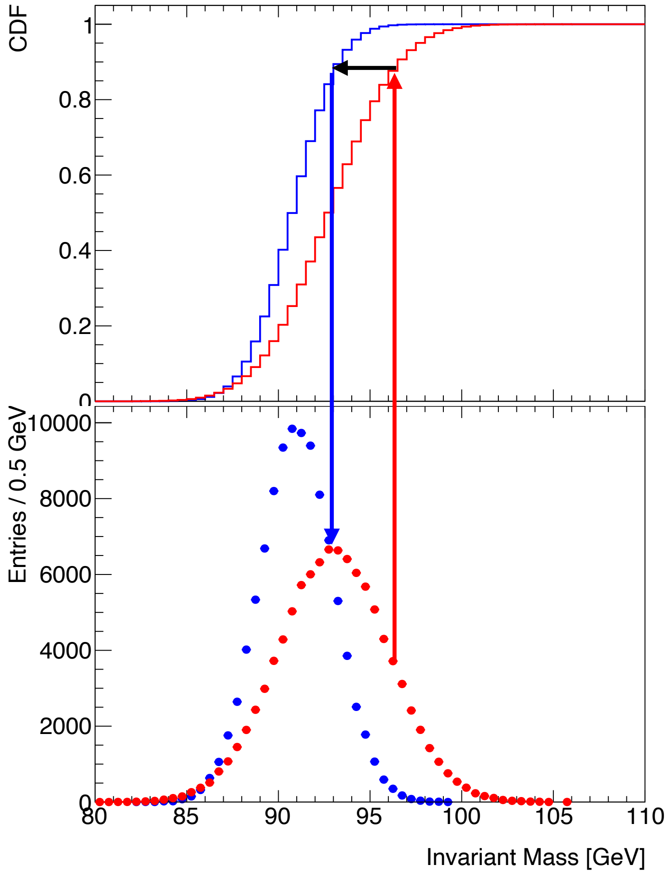
Talk outline

1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results



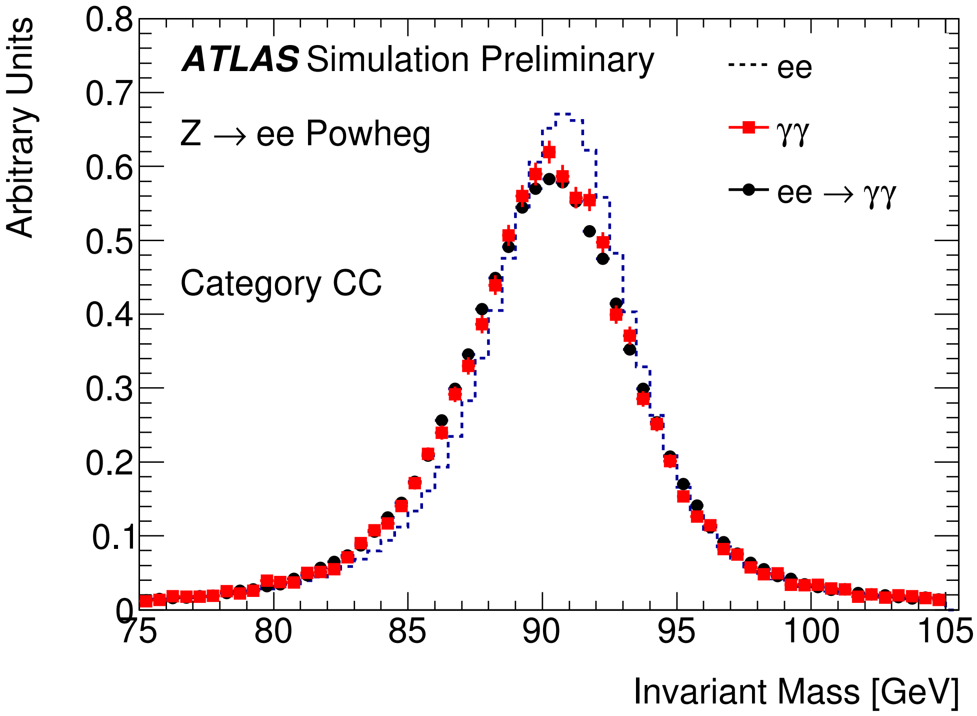
Z→ee background

- Derive Smirnov transform of ee → yy in **MC**
  - Map **cumulative distribution functions**



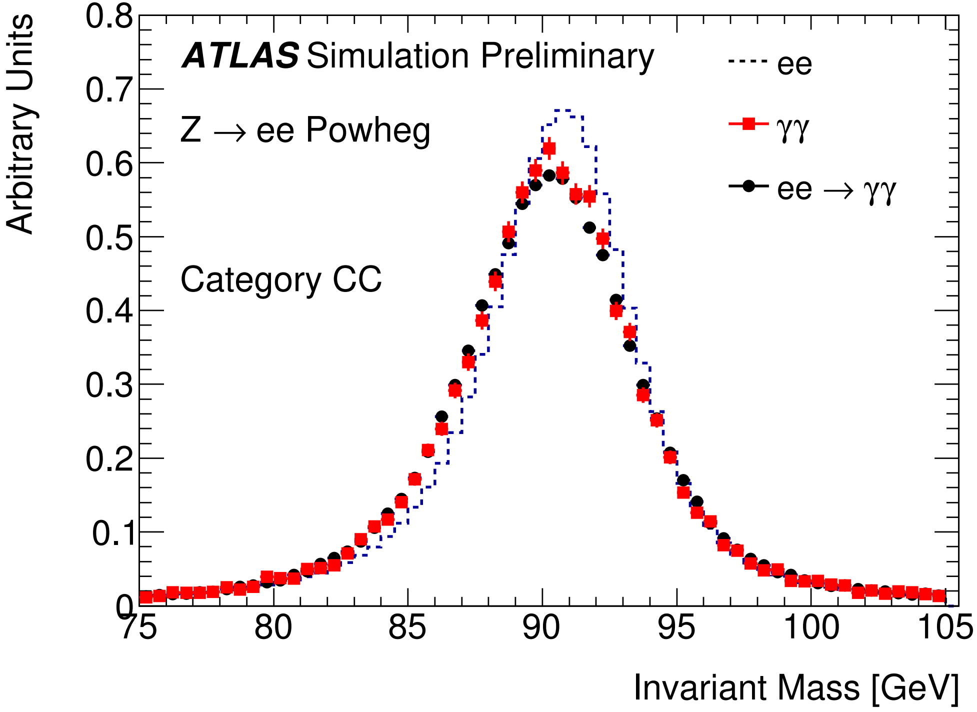
Z→ee background

- Derive Smirnov transform of ee → yy in **MC**
  - Map **cumulative distribution functions**



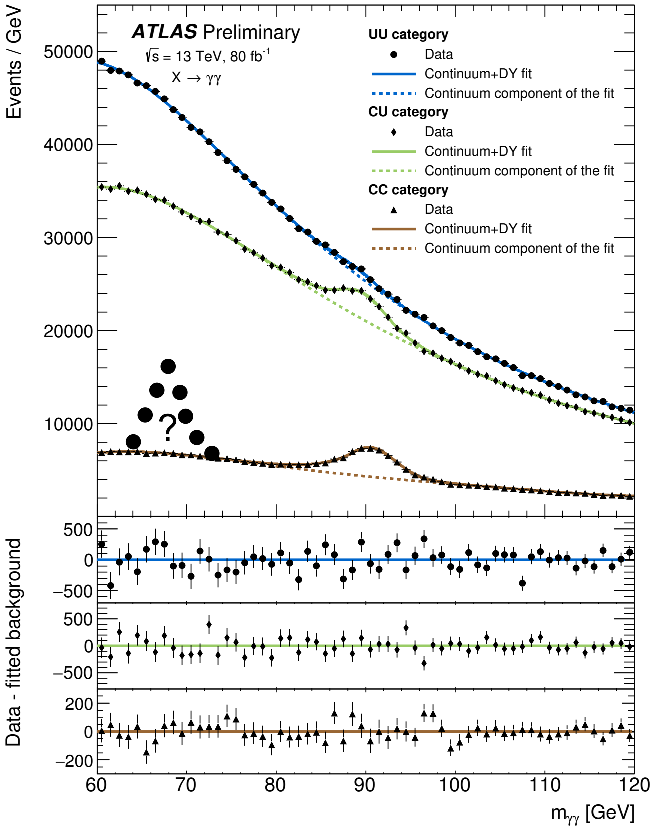
Z→ee background

- Derive Smirnov transform of ee → γγ in **MC**
  - Map **cumulative distribution functions**
- Apply to Z→ee in **data**
- (Mostly) data-driven normalization factor



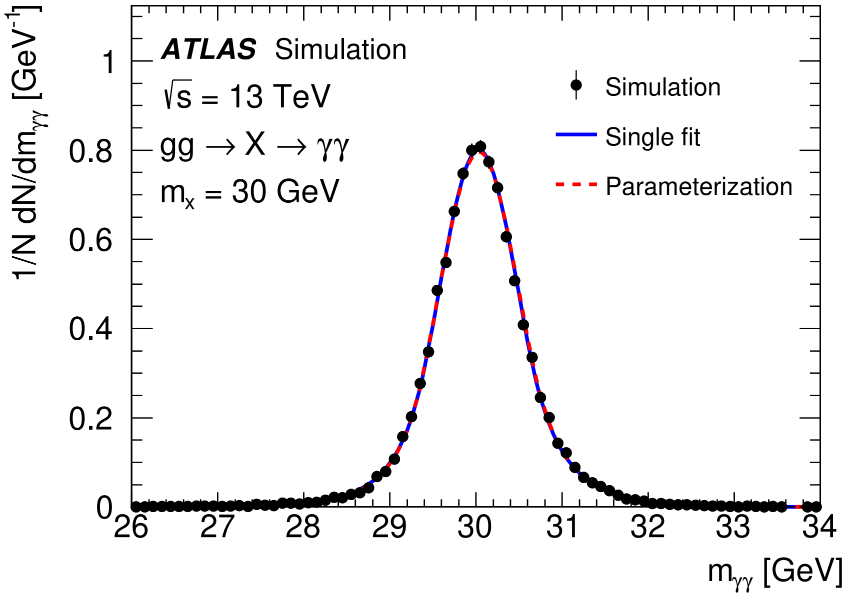
Talk outline

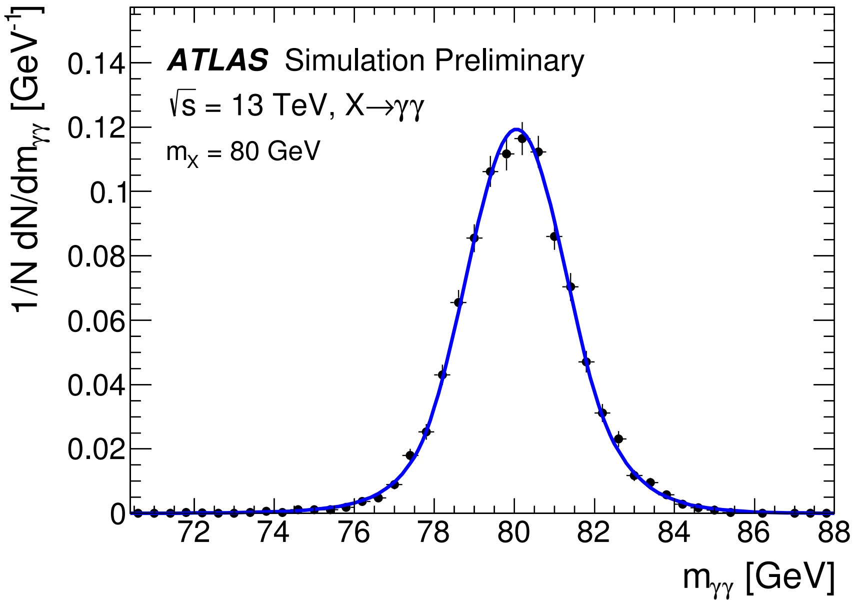
1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results



Signal model

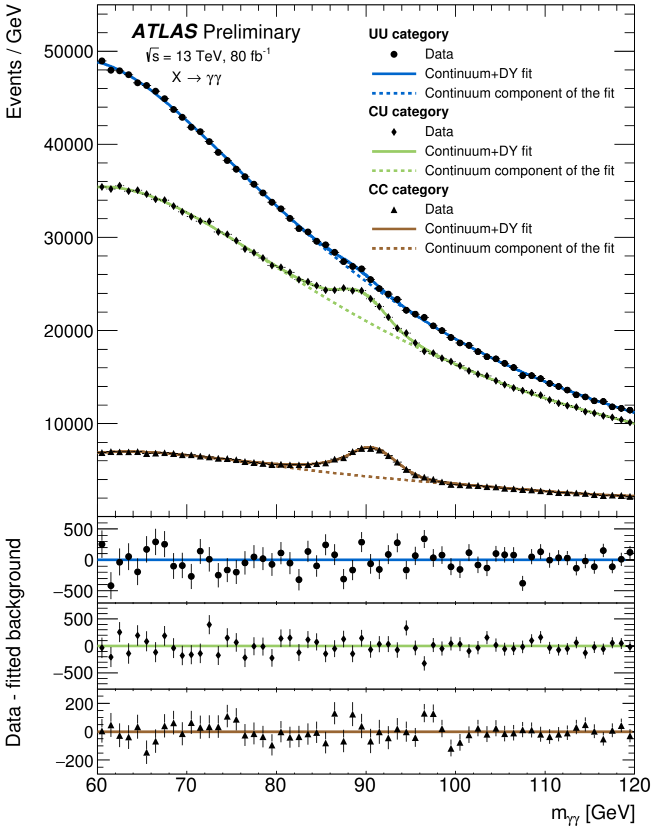
- Model signal with double-sided Crystal Ball function
  - Gaussian core
  - Exponential tails





Talk outline

1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results

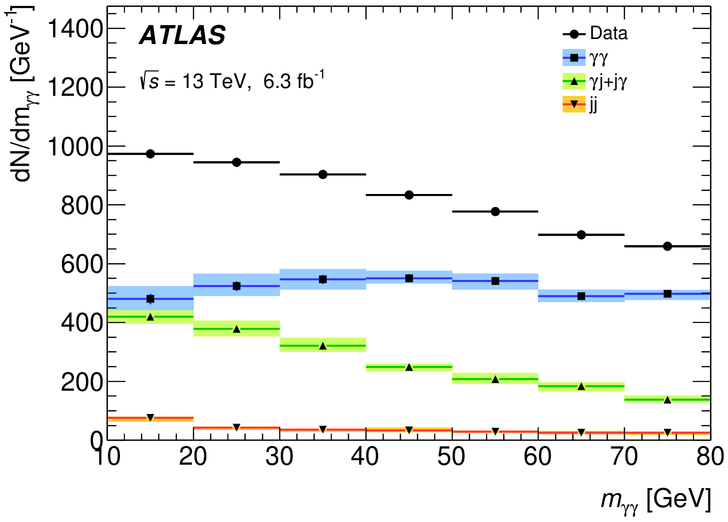


Background uncertainty

- Uncertainty from *spurious signal* method
- Fit **background only** template with **signal+background** model
- A perfect model extracts **zero** signal from background template
  - Caveat: statistical fluctuations of background template…
- Any (spurious) **non-zero signal** extracted is taken as **uncertainty**

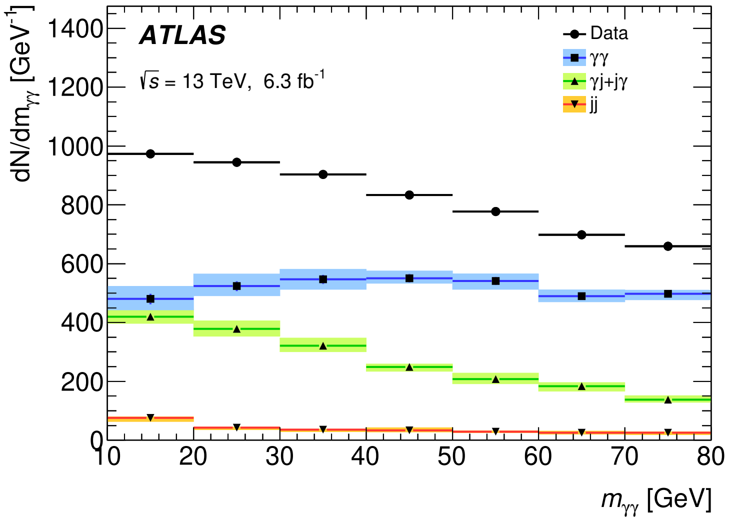
Background template

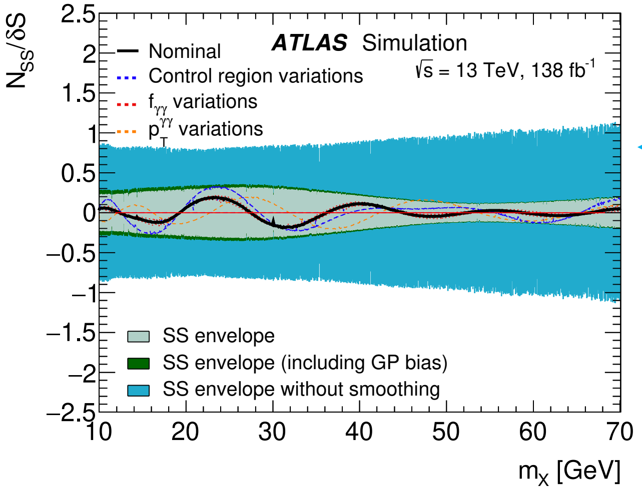
- MC γγ background template
- Add γj and jj based on fraction derived in data control regions



Background template

- MC γγ background template
- Add γj and jj based on fraction derived in data control regions

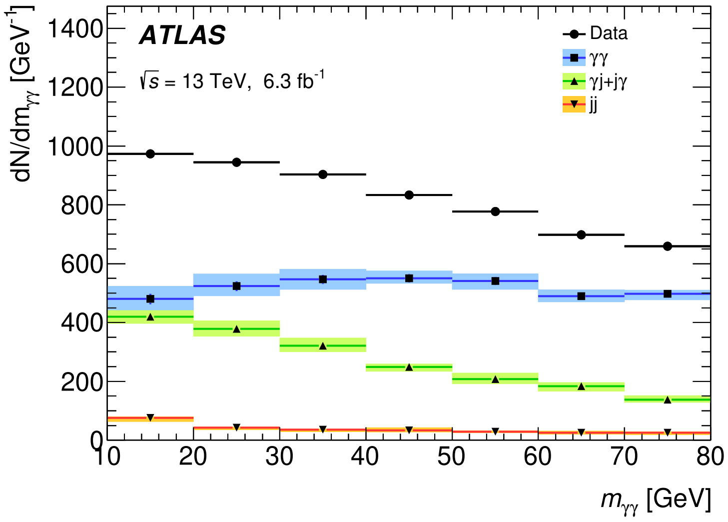


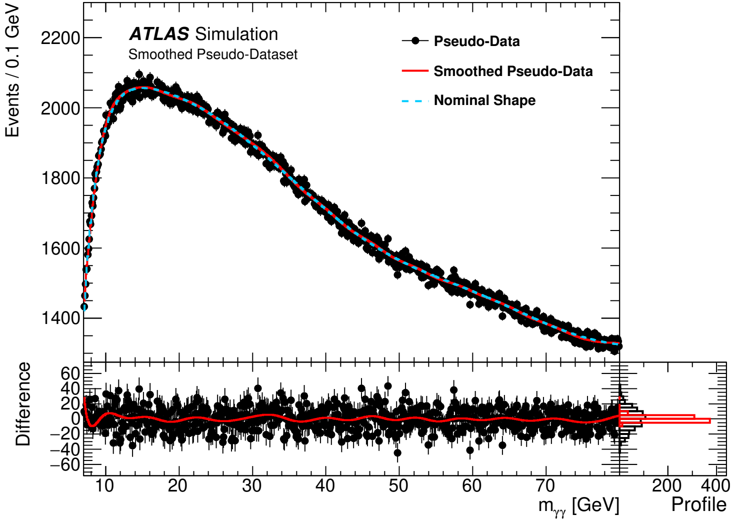


Extracted spurious signal compared with data uncertainty

Background template

- MC γγ background template
- Add γj and jj based on fraction derived in data control regions

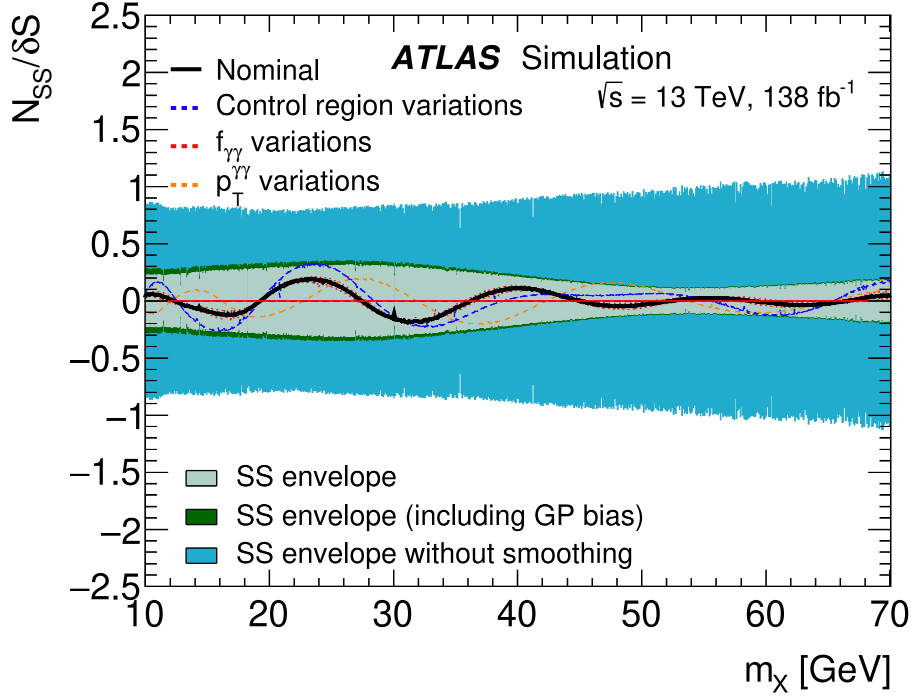




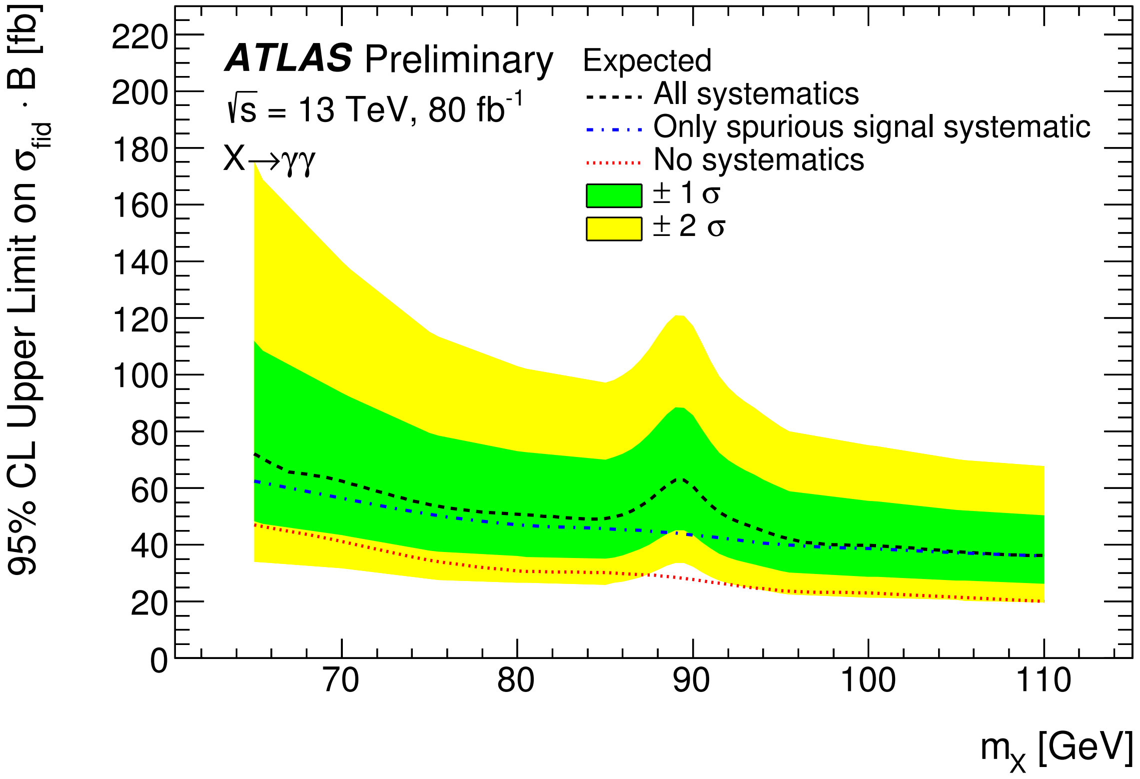
- Smooth with Gaussian Process
  - Currently ONLY **very low mass**
- Reduces spurious signal from statistical fluctuations

Background uncertainty (very low mass)

- Gaussian Process smoothing significantly reduces spurious signal uncertainty due to limited MC events



Room for improvement in low-mass…



Other systematic uncertainties

Very low mass

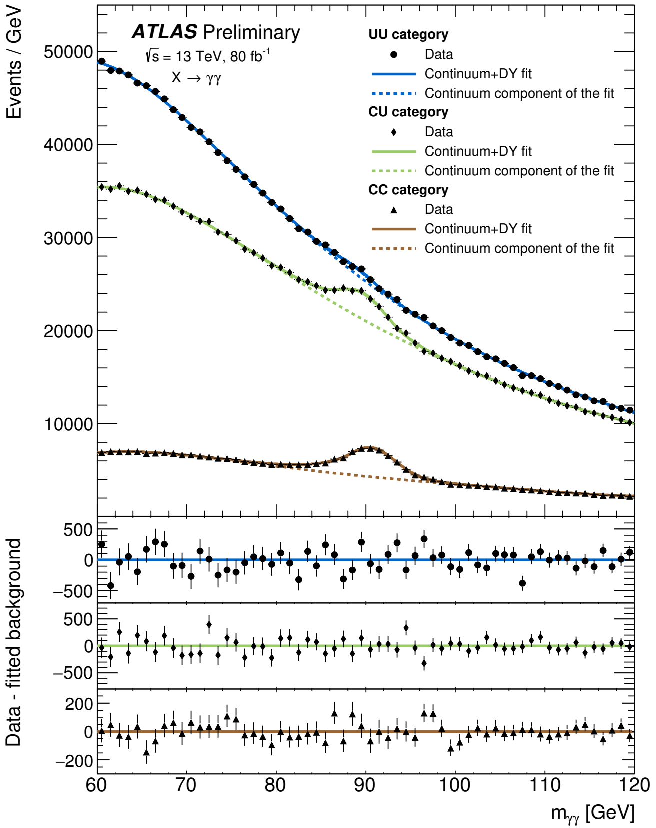
Source	Uncertainty
	On $\sigma_{\text{fid}} \cdot \mathcal{B}(X \to \gamma\gamma)$ [%]
Pile-up modelling	±3.5 (at 10 GeV) to ±2 (beyond 15 GeV), mass dependent
Photon energy resolution	±2.5 to ±2.7, mass dependent
Scale and PDFs uncertainties	±2.5 to ±0.5, mass dependent
Trigger on closely spaced photons	±2 (at 10 GeV) to <0.1 (beyond 35 GeV), mass dependent
Photon identification	±2.0
Isolation efficiency	±2.0
Luminosity (2015–2018)	±1.7
Trigger	±1.0
Signal shape modelling	<1
Photon energy scale	negligible
Background modelling	
Spurious signal (relative to δS)	30–65 events (10%–30%), mass dependent

Low mass

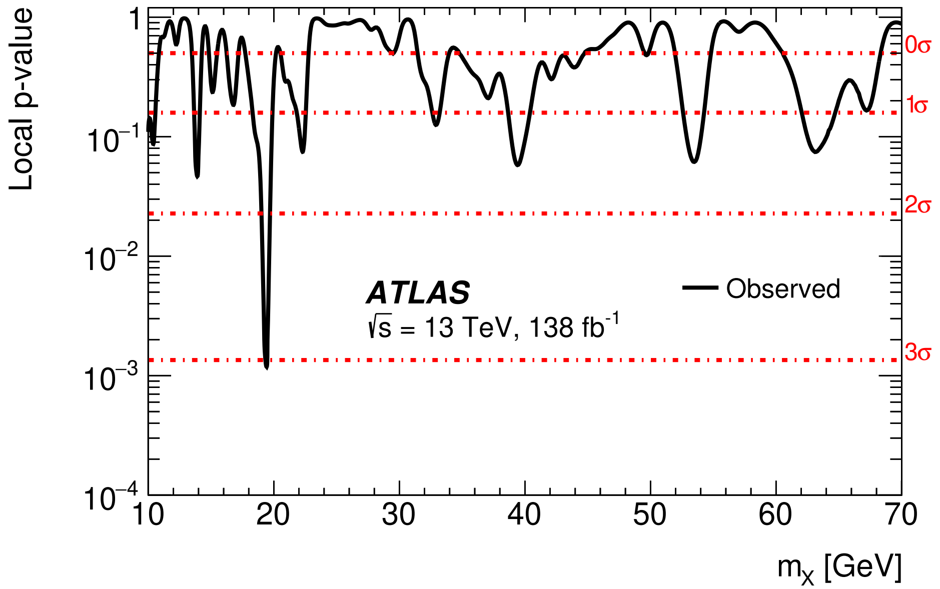
Source	Uncertainty [%]	Remarks
Signal yield		
Luminosity	±2	
Trigger eff.	±1.4 – 1.7	m_X-dependent
Photon identification eff.	±1.5 – 2.3	m_X-dependent
Isolation eff.	±4	
Photon energy scale	±0.13 – 0.49	m_X-dependent
Photon energy resolution	±0.053 – 0.28	m_X-dependent
Pile-up	±1.8 – 4.1	m_X-dependent
Production mode	±2.4 – 25	m_X-dependent
Signal modeling		
Photon energy scale	±0.3 – 0.5	m_X- and category–dependent
Photon energy resolution	±2 – 8	m_X- and category-dependent
Migration between categories		
Material	−2.0 / +1.0 / +4.1	category-dependent (UU/CU/CC)
Non-resonant Background		
Spurious Signal	128 / 104 / 79 (604 / 496 / 181 events)	ratio to the expected spurious signal uncertainty (category-dependent)
DY Background modeling		
Peak position	±0.1 – 0.2	category-dependent
Peak width	±2 – 3	category-dependent
Normalization	±9 – 21	category-dependent

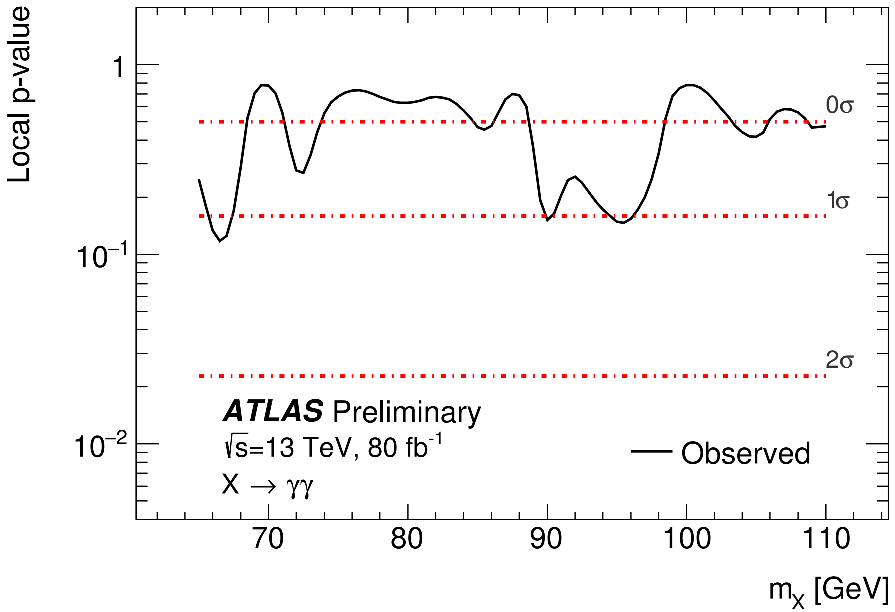
Talk outline

1. Event selection
2. Continuum background (γγ, γj, jj)
3. Z→ee background
4. Scalar signal
5. Uncertainties
6. Results



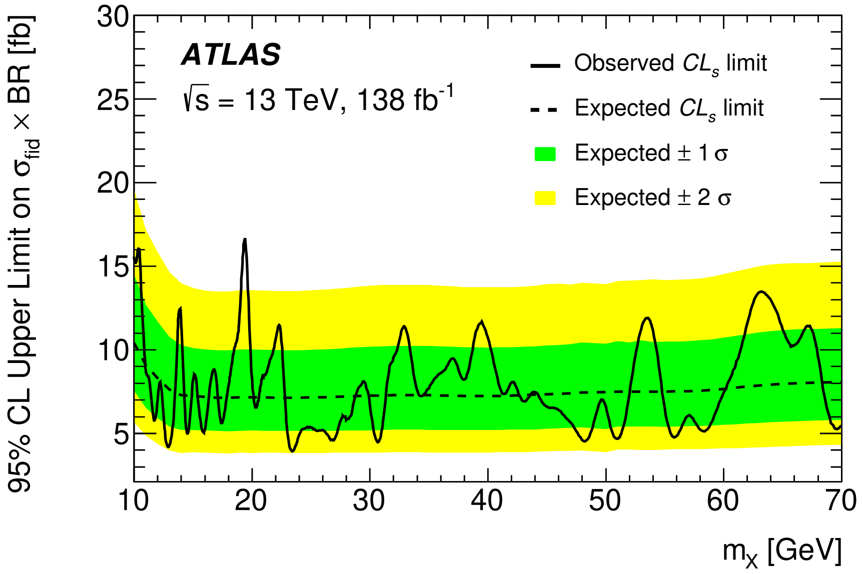
Any significant bumps? Sadly no :-(

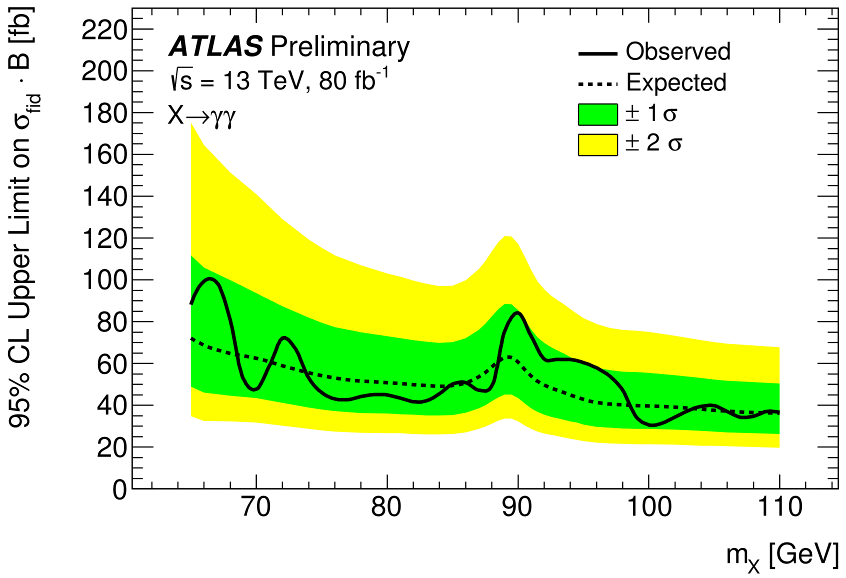




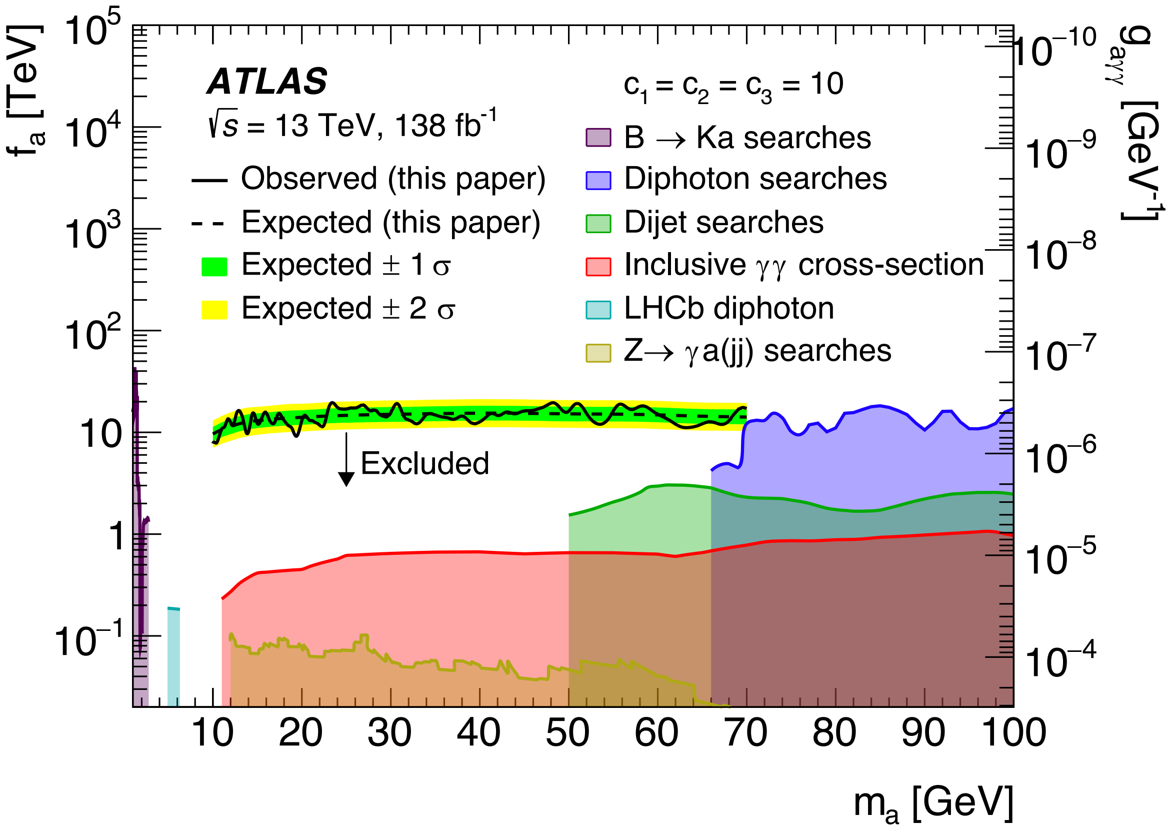
Local → 3.1 σ / Global → 1.5 σ

Upper limits





Overview of axion limits

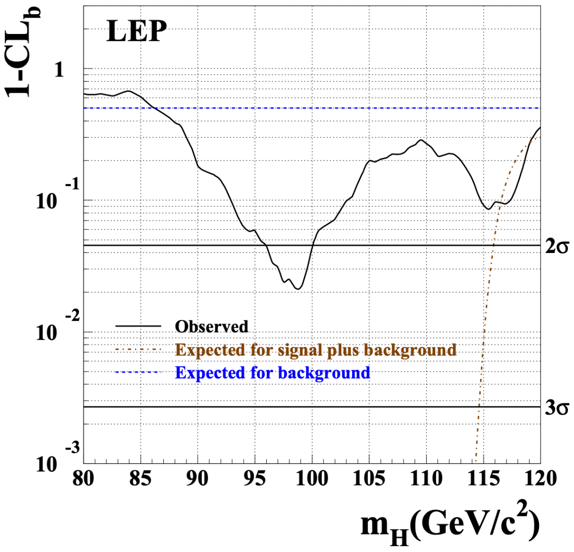


Summary

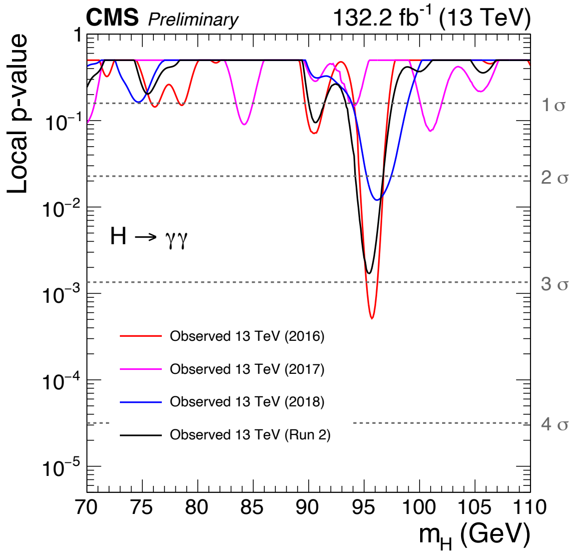
- No low-mass diphoton resonances found (yet)
- Continuing to improve techniques to keep background uncertainties smaller than statistical uncertainties
- Stay tuned for future results!

Always something to look forward to…

[hep-ex/0306033](hep-ex/0306033)



[CMS-PAS-HIG-20-002](CMS-PAS-HIG-20-002)



To be updated…