# Searches for $Z\gamma$ and $\gamma\gamma$ resonances with the ATLAS detector

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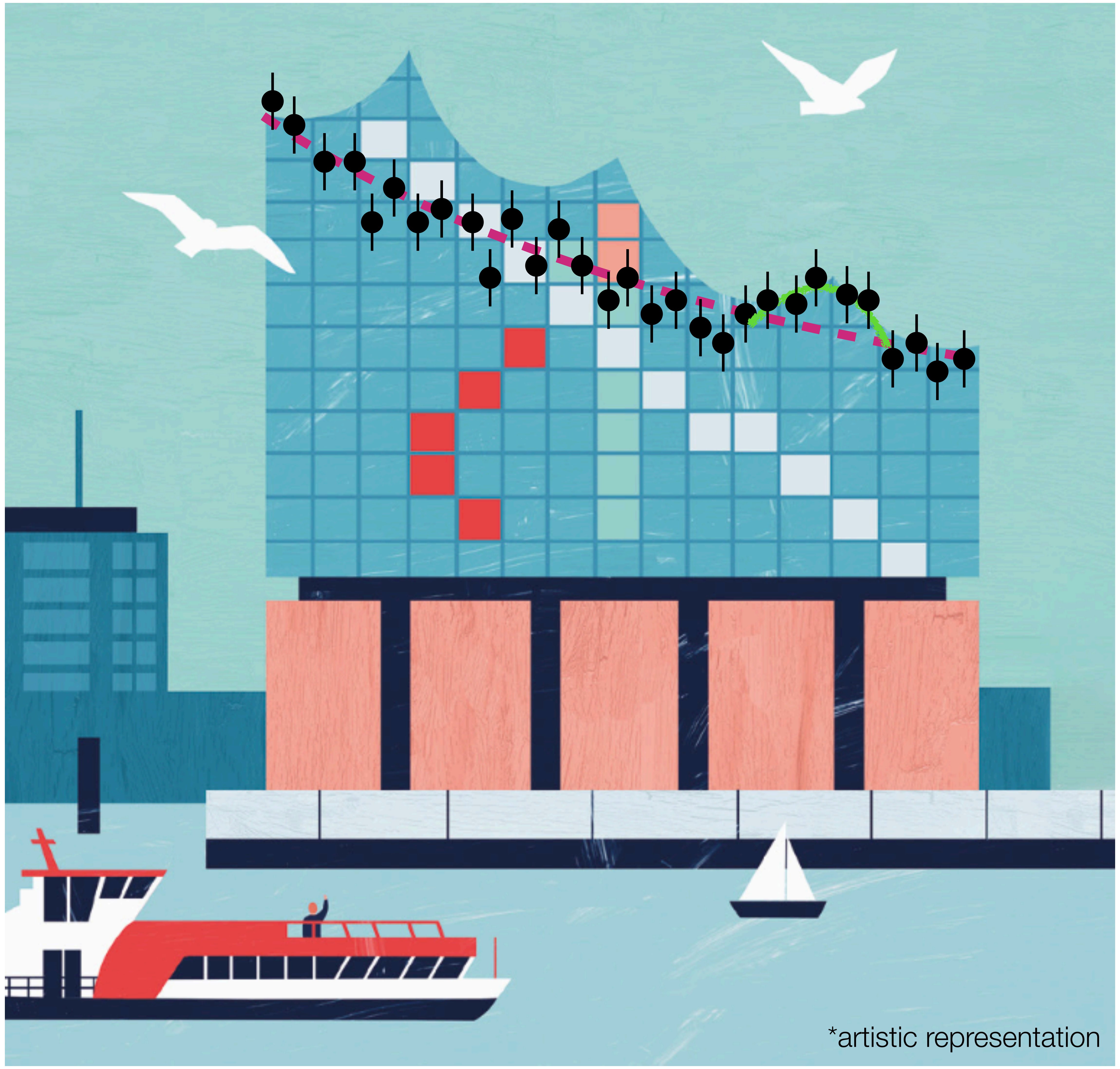
**Luis Pascual Domínguez**
On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

TEL AVIV UNIVERSITY אוניברסיטת תל אביב



# Outline

Resonances are a generic signature of many phenomena present in new Beyond Standard Model theories.

- Clean signatures of photons and Z bosons combined with excellent detector performances provide high sensitivity to a wide variety of such models.

Many popular models within the community include additional fields to motivate searches for such phenomena:

- Extensions of the Higgs sector are predicted in many BSM theories: Higgs doublets, triplets, composite Higgs,…
- New Physics fields weakly coupled to the SM (e.g. with axion-like particles or SUSY)

**Today**, I will present an overview of such searches performed with the ATLAS detector

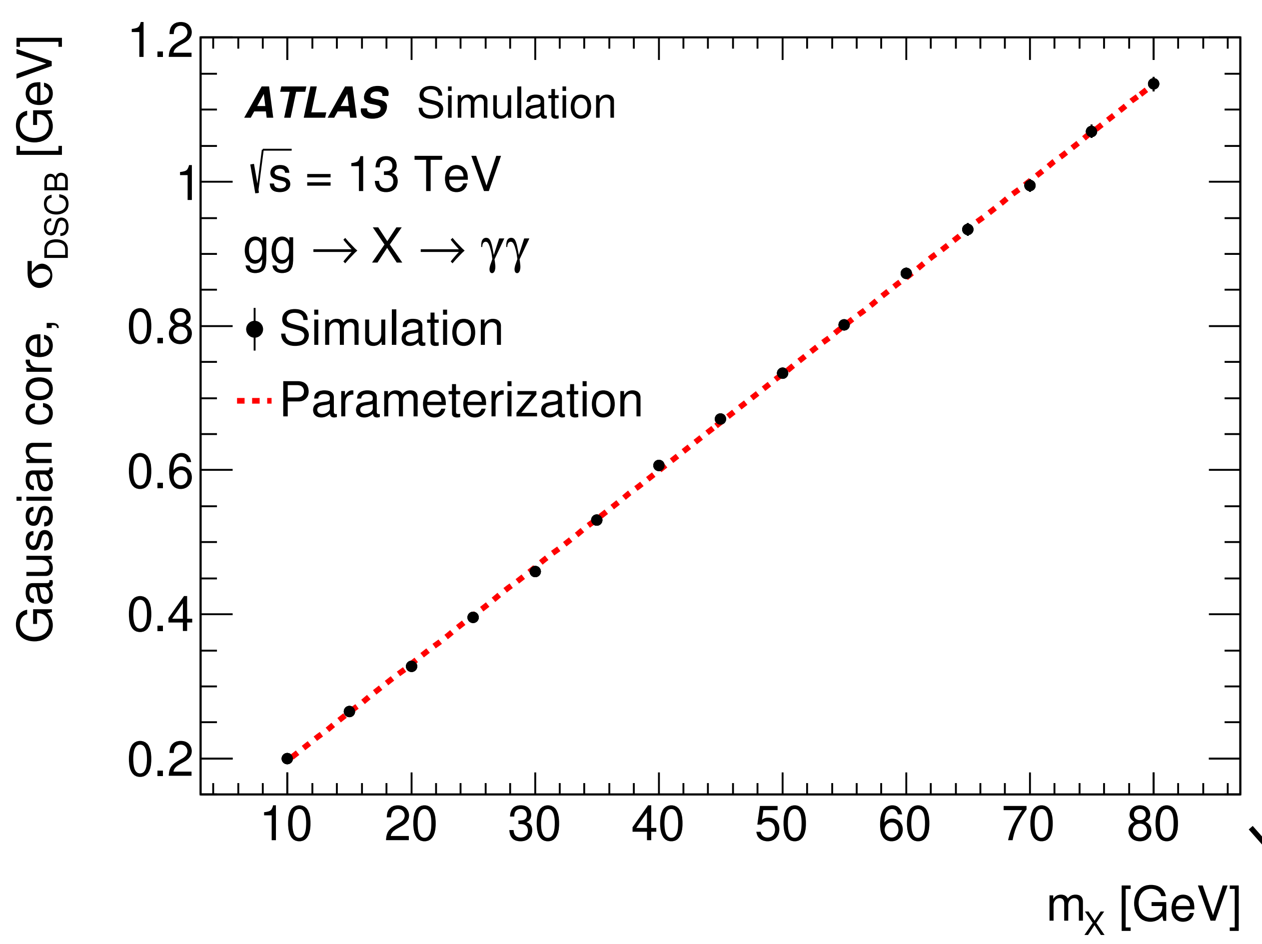
- Low mass diphoton resonance search (66-110 GeV) [ATLAS-CONF-2023-035]
- Very-low mass diphoton resonance search (10-70 GeV) [JHEP 07 (2023) 155]
- Z(→ll)$\gamma$ resonance search (220-3400 GeV) [ATLAS-CONF-2023-030]

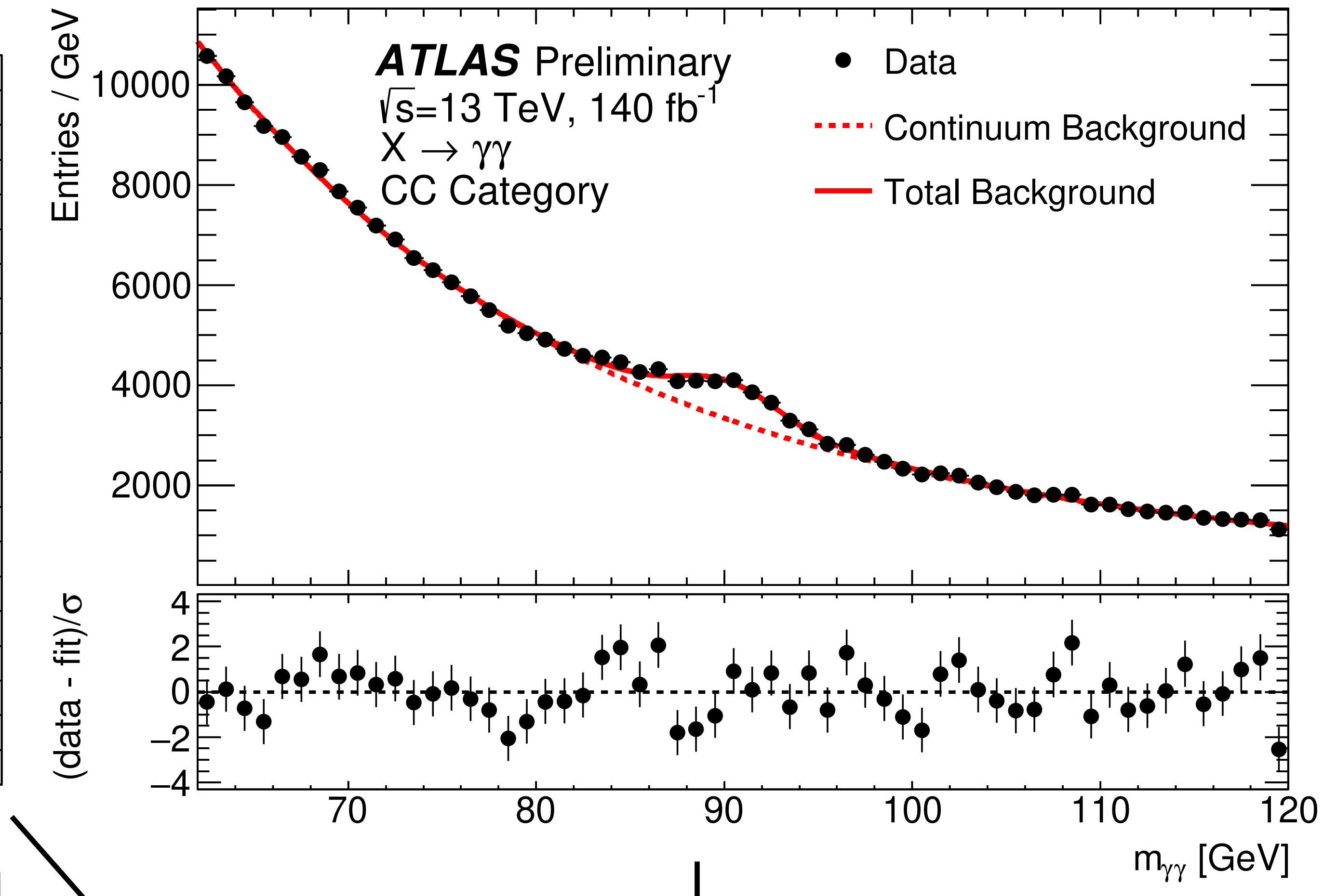
# Common strategy in (these) resonance searches

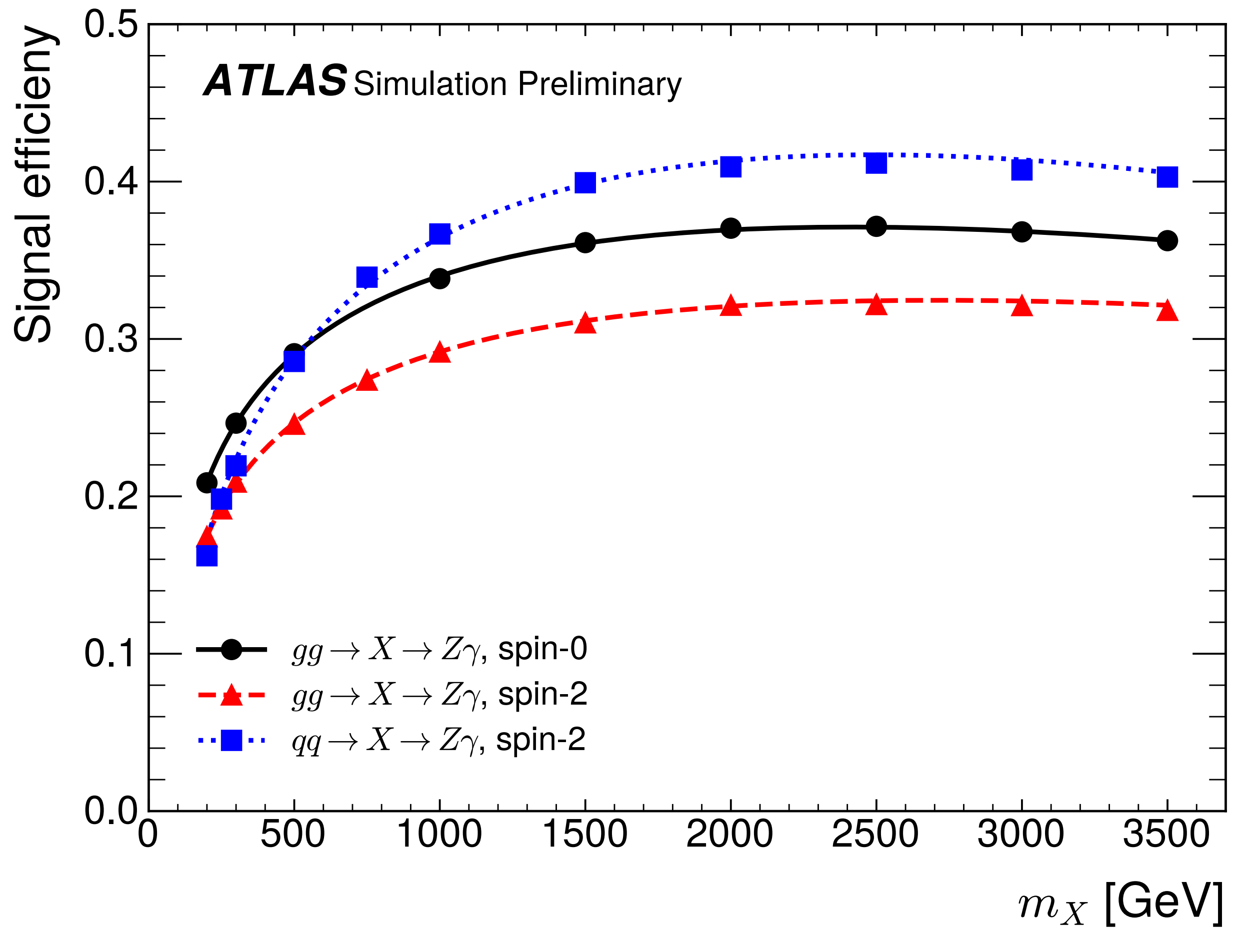
Benefit from very clean signatures and energy resolutions to look for event excesses over known SM backgrounds.

**Step-by-step cookbook:**

- Parameterise signal shape and efficiencies as a function of the mass of the system ($\gamma\gamma$, $Z\gamma$, …)
- Estimate the expected background and describe its shape (e.g. with analytic functions)
- Look for event excesses compatible with the signal shape of interest.




**Discovery?**
**Limits?**

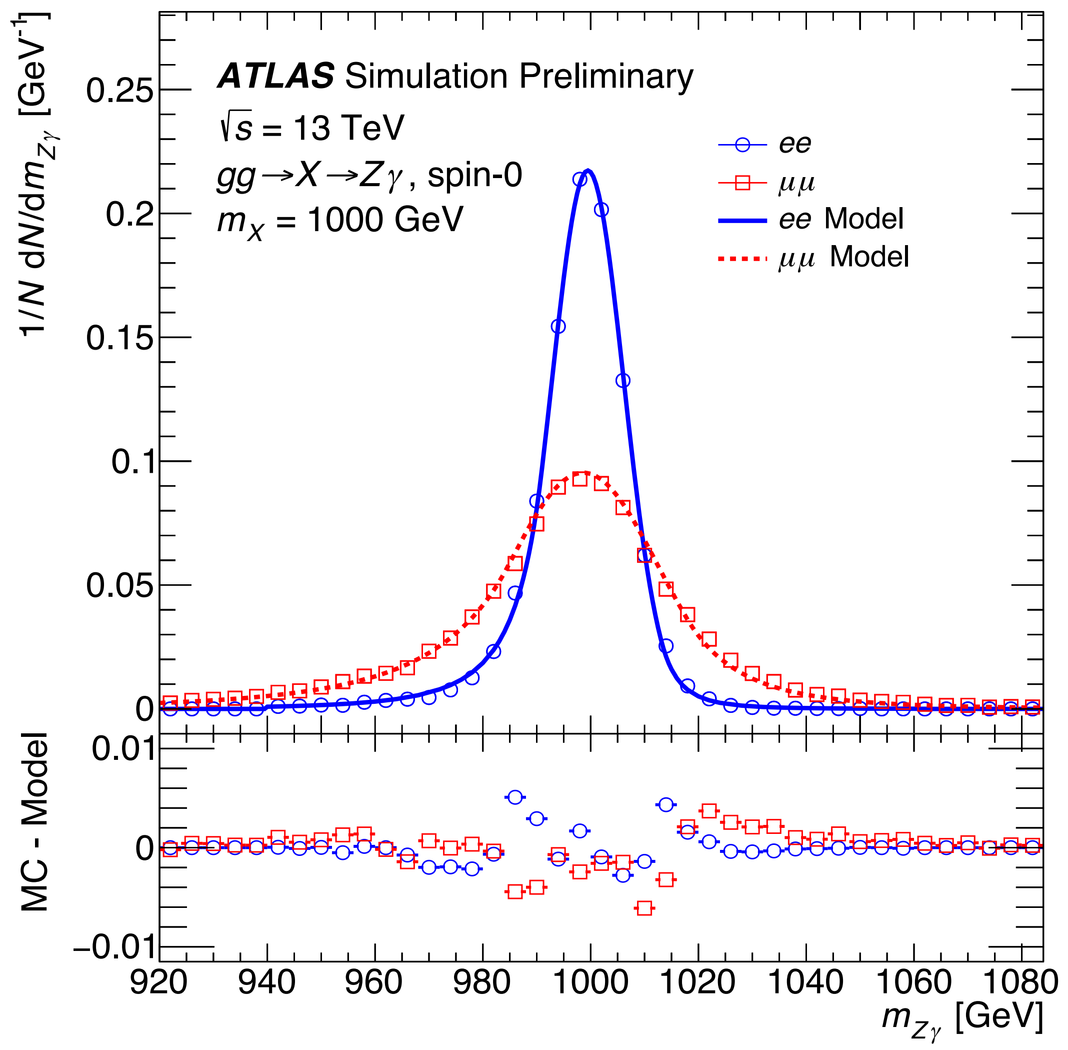
# Signal modeling

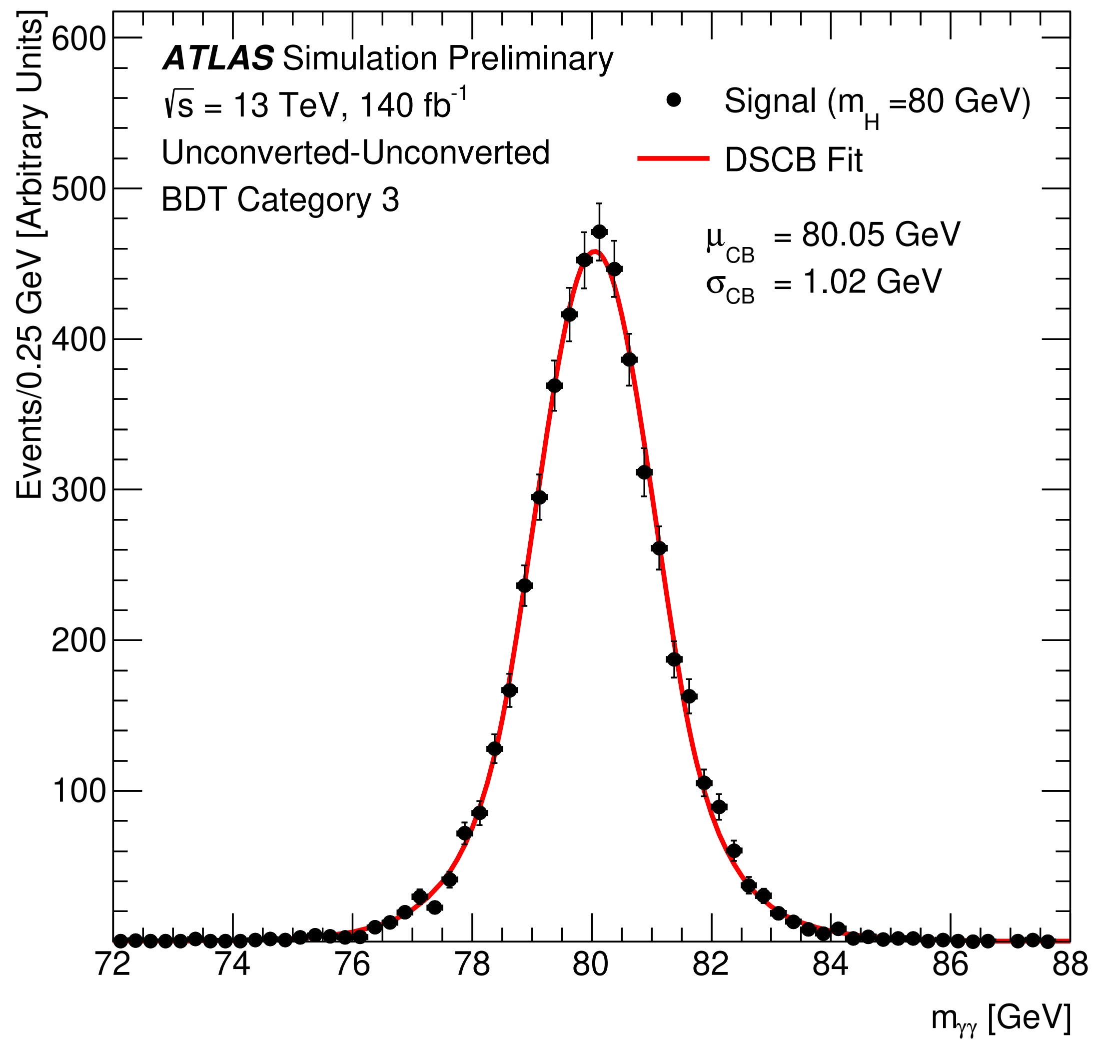
Common

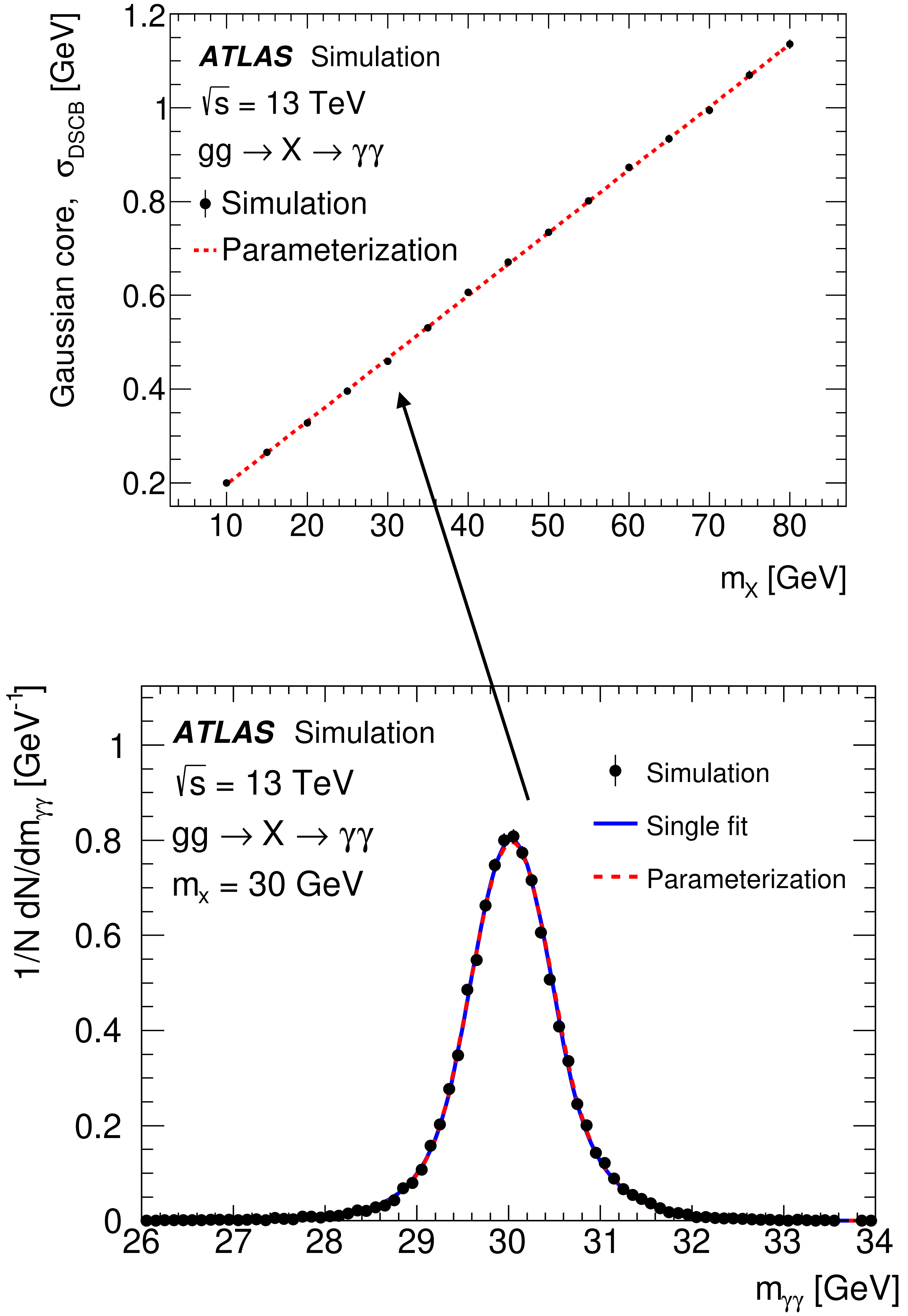
**The three analyses use (almost) the same approach!**

**Signal shape obtained from simulated samples**

- Individual mass points modelled with a double-sided Crystal Ball (Gaussian core + power law tails)
- Interpolation obtained using linear functions or simultaneous fits (uncertainties smaller than <0.1%)

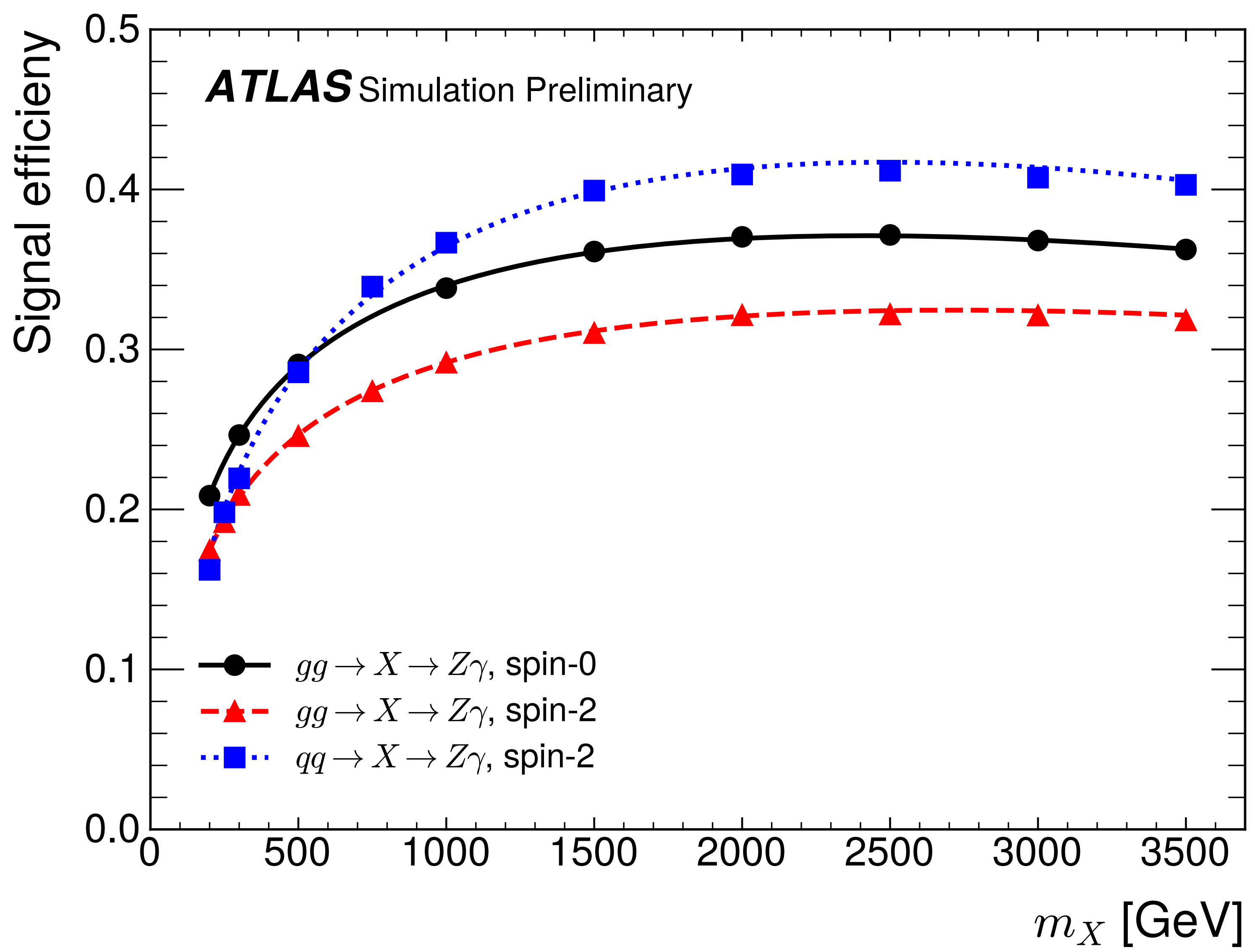


# Event selection






**Trigger**

- Combination of single and dilepton triggers + single photon

**Object selection**

- Opposite sign same flavour leptons with $|m_{ll} - m_Z| < 15$ GeV
- Standard identification and isolation + **special treatment for boosted topologies** (MVA)
  - Relies on shape of the EM shower in the calorimeter and tracking information to identify close-by electron showers

| Selection | Muon | Electron | Electron as photon | Photon |
|---|---|---|---|---|
| $p_T$ | > 10 GeV | > 10 GeV | > 50 GeV | > 15 GeV |
| $\|\eta\|$ | < 2.7 | < 2.47<br>Exclude [1.37, 1.52] | < 2.47<br>Exclude [1.37, 1.52] | < 2.37<br>Exclude [1.37, 1.52] |
| $\|d_0\|/\sigma_{d_0}$ | < 3 | < 5 | | |
| $\|\Delta z_0 \sin\theta\|$ | < 0.5 mm | < 0.5 mm | | |
| Identification | *Medium* | Mixed * | MVA | *Tight* |
| Isolation | Track-based *Tight* | Track-based *Tight* | | *Loose* |
| $\Delta R(\text{track}, \gamma)$ | | | < 0.1 | |
| $ee$ or $\mu\mu$ pair | $\geq 2$, opposite charge | | | |
| $e\gamma$ pair | | | $\Delta R(e,\gamma) < 1$<br>$\|p_T^e - p_T^\gamma\|/p_T^{e \text{ or } \gamma} > 5\%$ | |
| Categorization | lepton pair closest to $m_Z = 91.2$ GeV, decide electron or muon channel | | | |
| Event selections | $\|m_{\ell\ell}^{\text{corrected}} - m_Z\| < 15$ GeV, $m_Z = 91.2$ GeV<br>Trigger match, overlap removal<br>$p_T^\gamma/m_{Z\gamma} > 0.2$, SR: $200 < m_{Z\gamma} < 3500$ GeV | | | |

*Mixed → MVA + Medium

# Background estimation

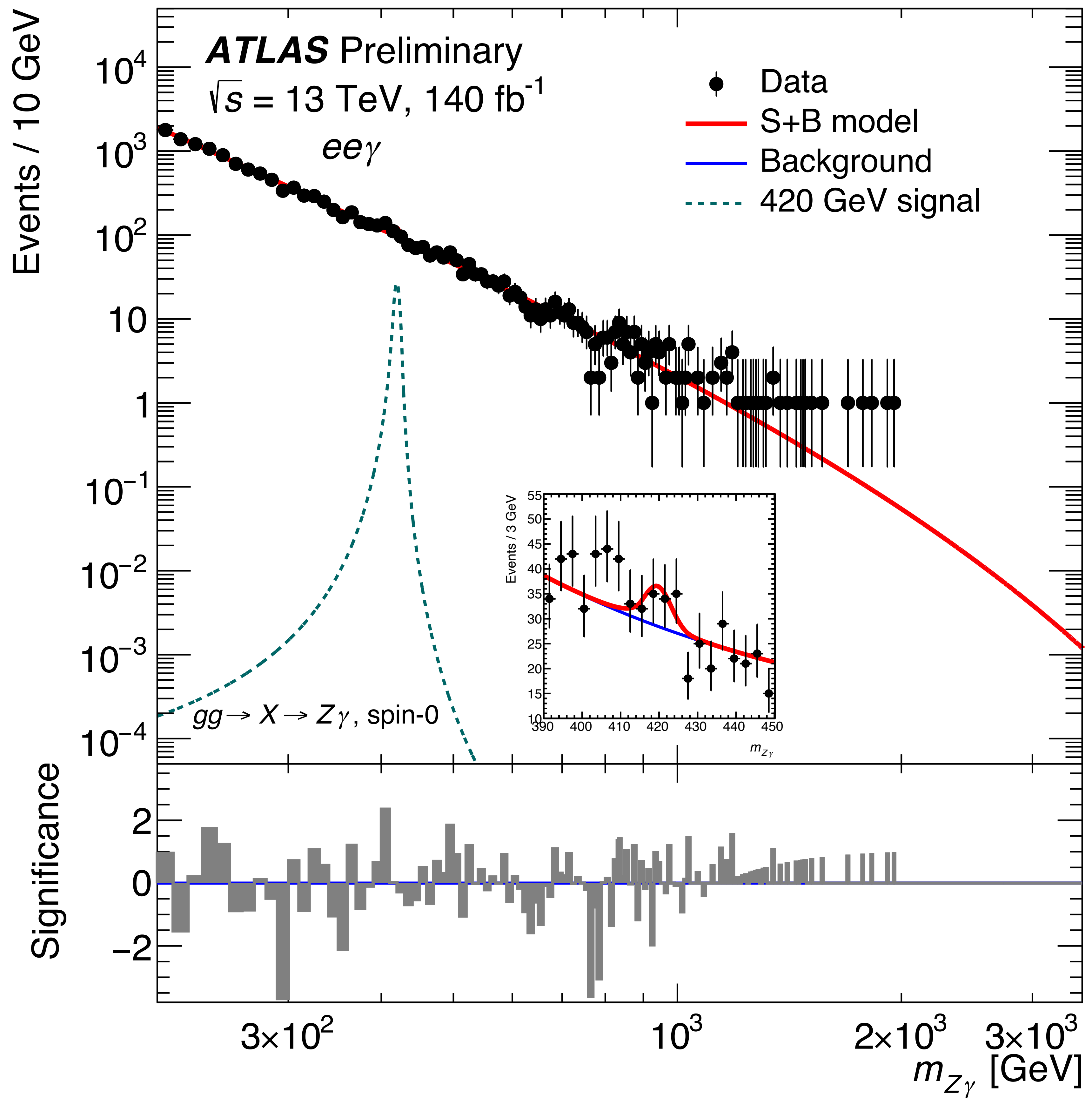
**Dominant backgrounds**

- Irreducible ($Z\gamma$): Non resonant Z + $\gamma$ (high stat. MC)
- Reducible (Zjet): Z + mis-reconstructed jet as a photon (control regions from data)

**Modelling strategy**

- Relative contribution of $Z\gamma$ and Zjet from a simultaneous fit to isolation energy distributions.
- Background template obtained from reweighted $Z\gamma$ MC
- Shape described with a "Dijet" function

$$f(x; b, a_0) = N(1 - x)^b x^{a_0}$$



# Systematic uncertainties

$Z\gamma$ resonance searches

| Category | $\mu\mu\gamma$ | $ee\gamma$ |
|---|---|---|
| Luminosity | 0.83% | |
| *Signal Efficiency* | | |
| Photon ID/ISO/TRIG efficiency | 1.0 – 1.5% | 1.0 – 1.7% |
| Muon ISO efficiency | 1.0 – 1.2% | – |
| Muon RECO efficiency | 0.22 – 6% | – |
| Muon TTVA efficiency | 0.14 – 0.23% | – |
| Muon TRIG efficiency | 0.6 – 1.0% | – |
| Electron ID/ISO/RECO/TRIG efficiency | – | 2.9 – 4% |
| Customized electron ID efficiency | – | 1.0 – 1.1% |
| Pile-up | $< 0.016\%$ | – |
| *Signal modelling on $\mu_{CB}$* | | |
| Electron and photon energy scale | 0.33 – 0.4% | 0.15 – 0.7% |
| Muon momentum scale/sagitta bias | $< 0.023\%$ | – |
| *Signal modelling on $\sigma_{CB}$* | | |
| Electron and photon energy resolution | 2.5 – 10% | 7 – 60% |
| Muon ID resolution | 0.4 – 1.8% | – |
| Muon MS resolution | 0.6 – 1.9% | – |
| Extra Smearing on muon $p_T$ | 2.4% | – |
| *Background modelling* | | |
| Spurious signal | 0.01 – 10.00 | 0.003 – 9.44 |

Search statistically limited

- Fit bias (spurious signal): dominant systematic uncertainty
- Additional uncertainty of ~1% to account for the custom electron identification for merged topologies.

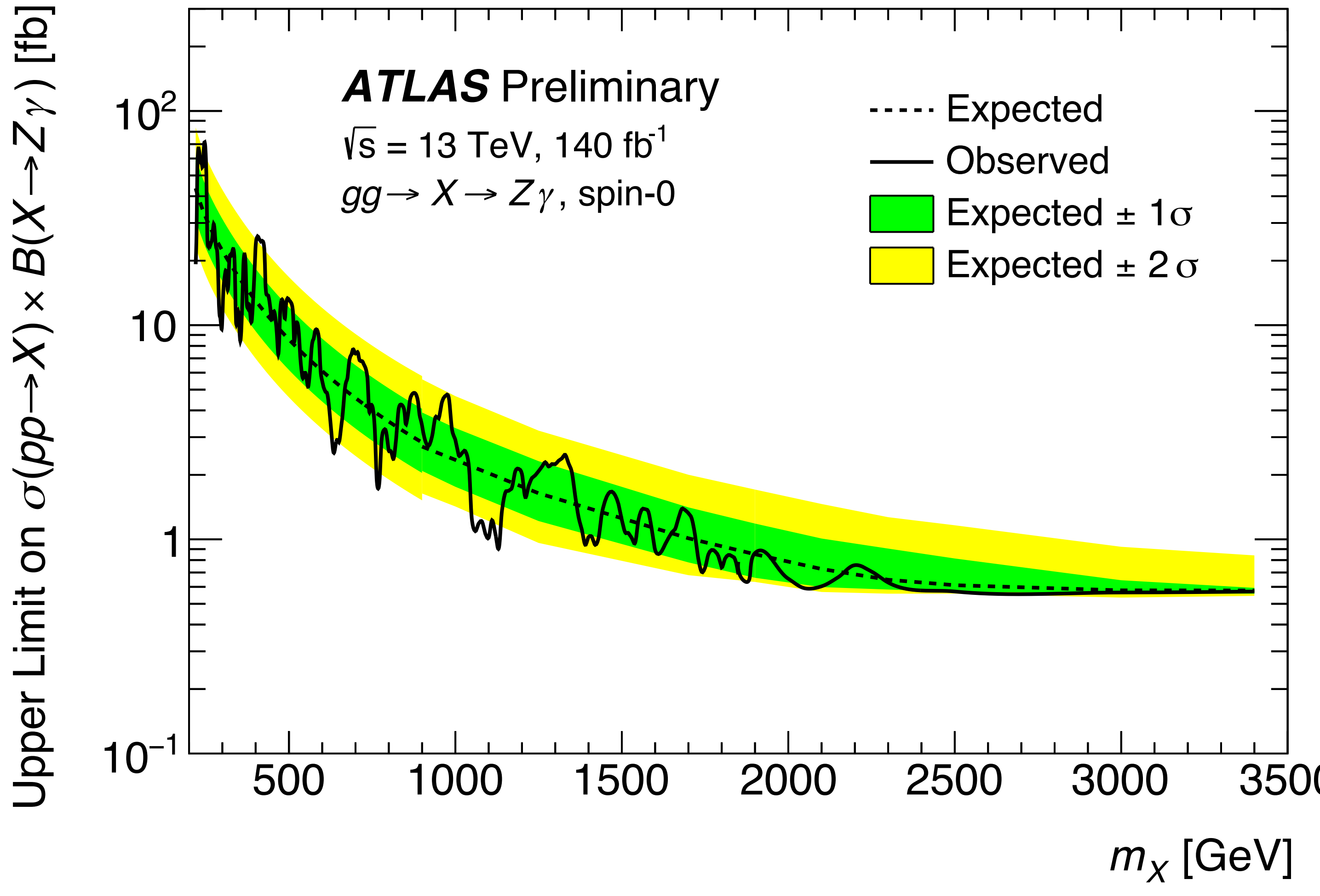
# Results

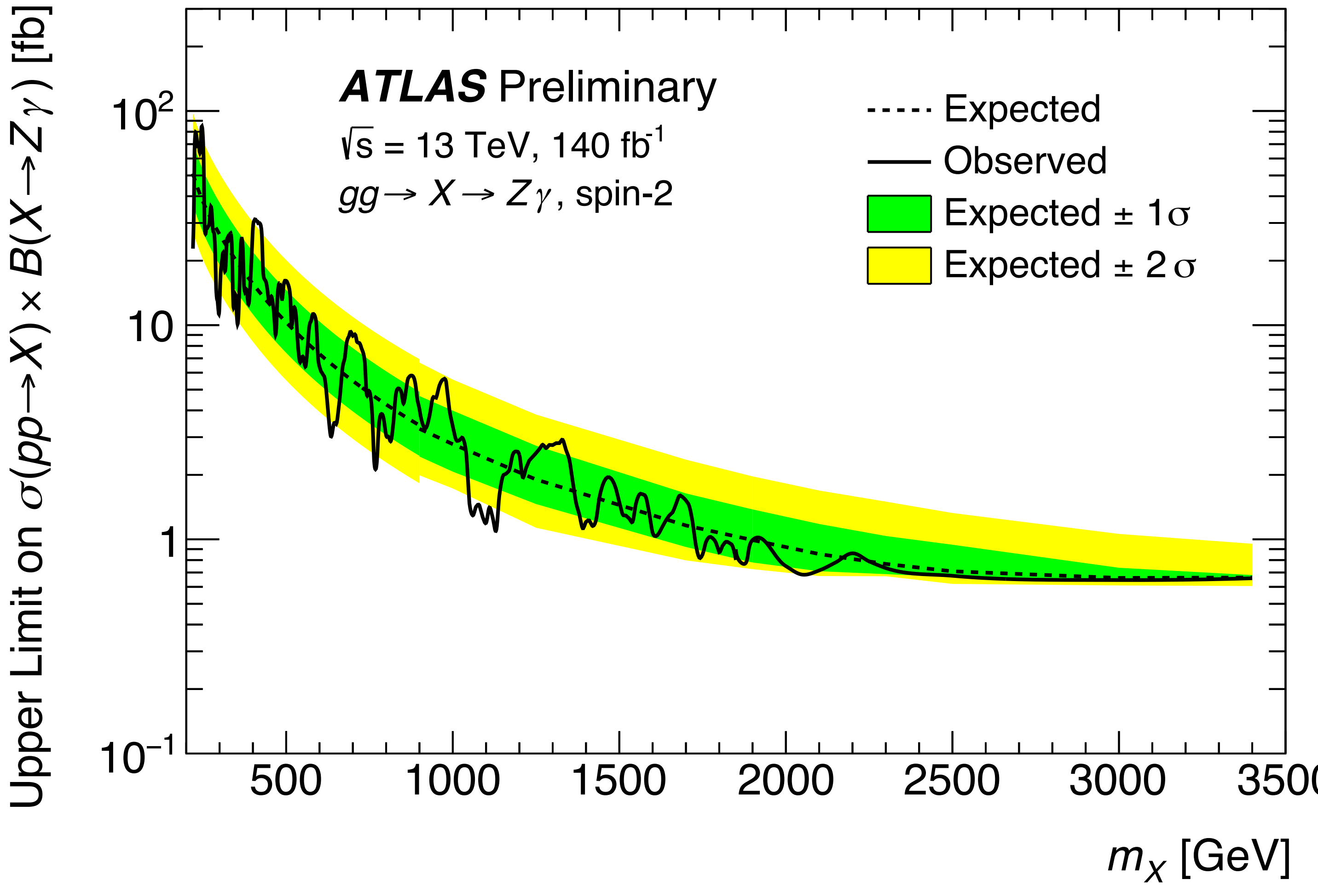
Results presented for spin-0 and spin-2 signal hypotheses

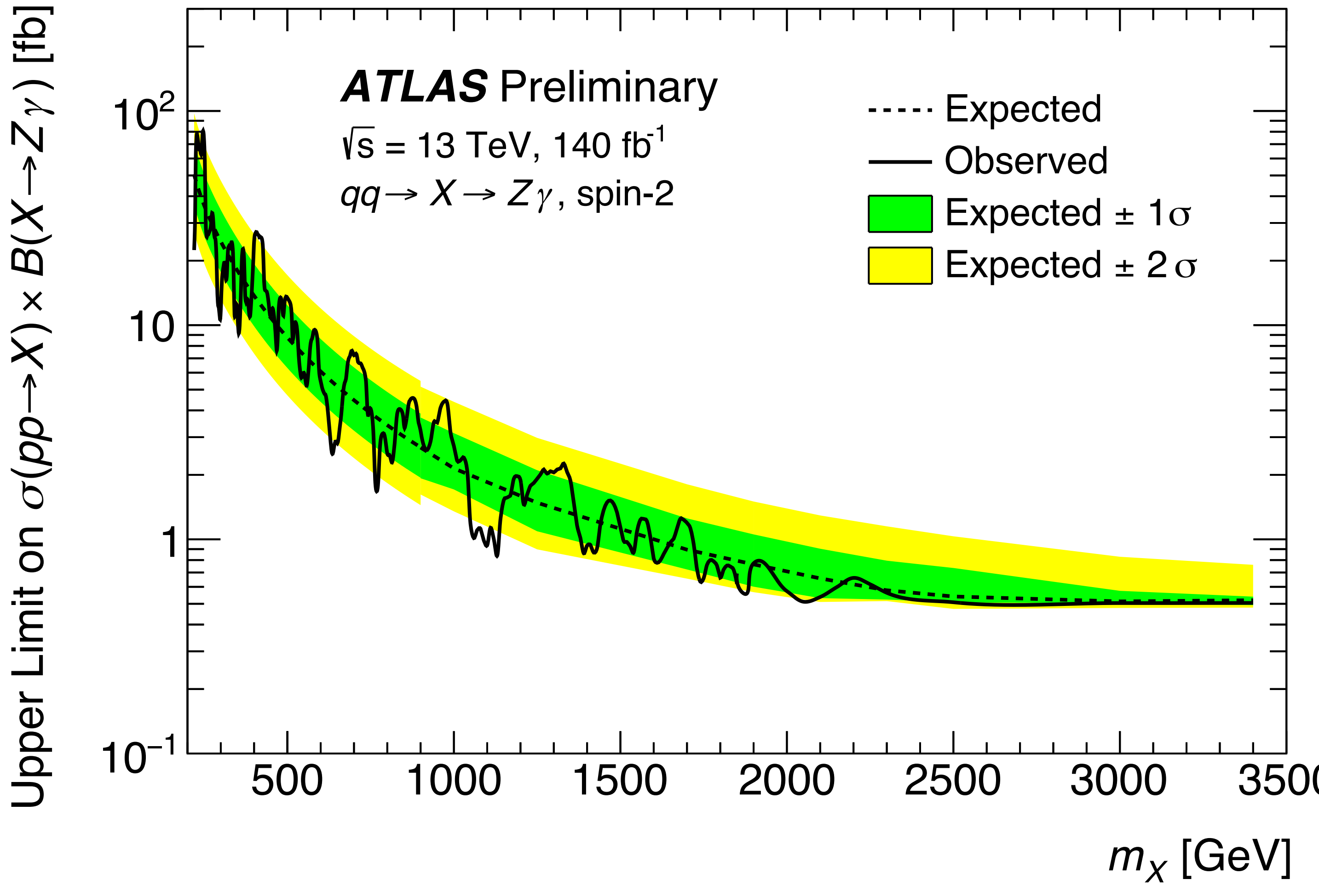
- Sensitivity improved from 1.9 to 4 compared to previous round (36.1fb-1)
- No significant excess observed

Improvements

- More luminosity → extended range up to 3.4 TeV
- Improved electron ID for merged topologies



# Event selection - baseline

Diphoton resonance searches

**Trigger**

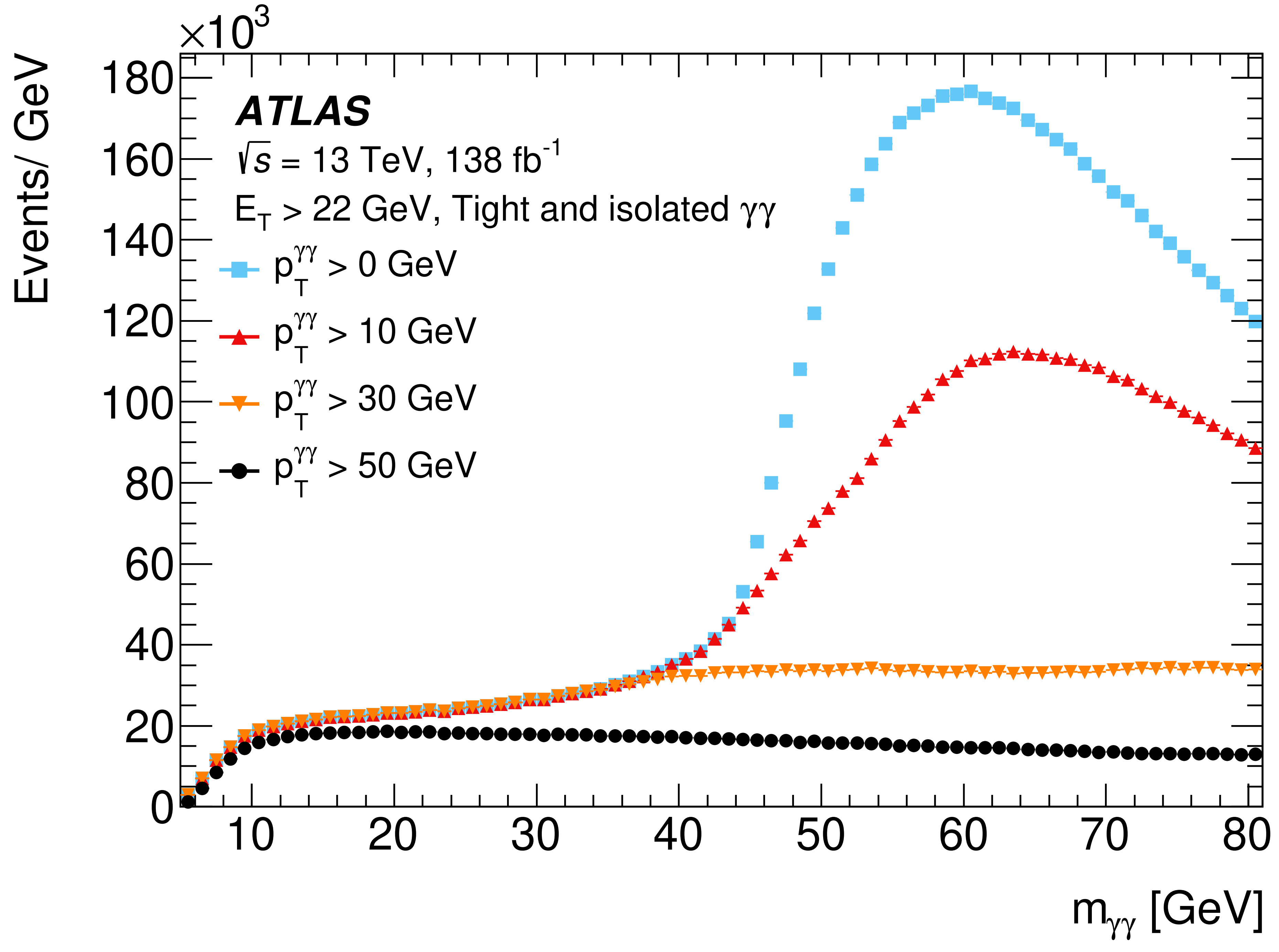
- Lowest unprescaled diphoton triggers (two candidates with $E_T > 20$ GeV)
- Additional identification and isolation requirements to keep rate under control

**Object selection**

- Two photons with $E_T > 22$ GeV in the acceptance of the detector (|η|<2.37)
- "Tight" identification and "Loose" isolation

**Special selection for very-low mass**

- **Boosted selection:** ease background modelling from trigger turn-on → $p_T^{\gamma\gamma} > 50$ GeV



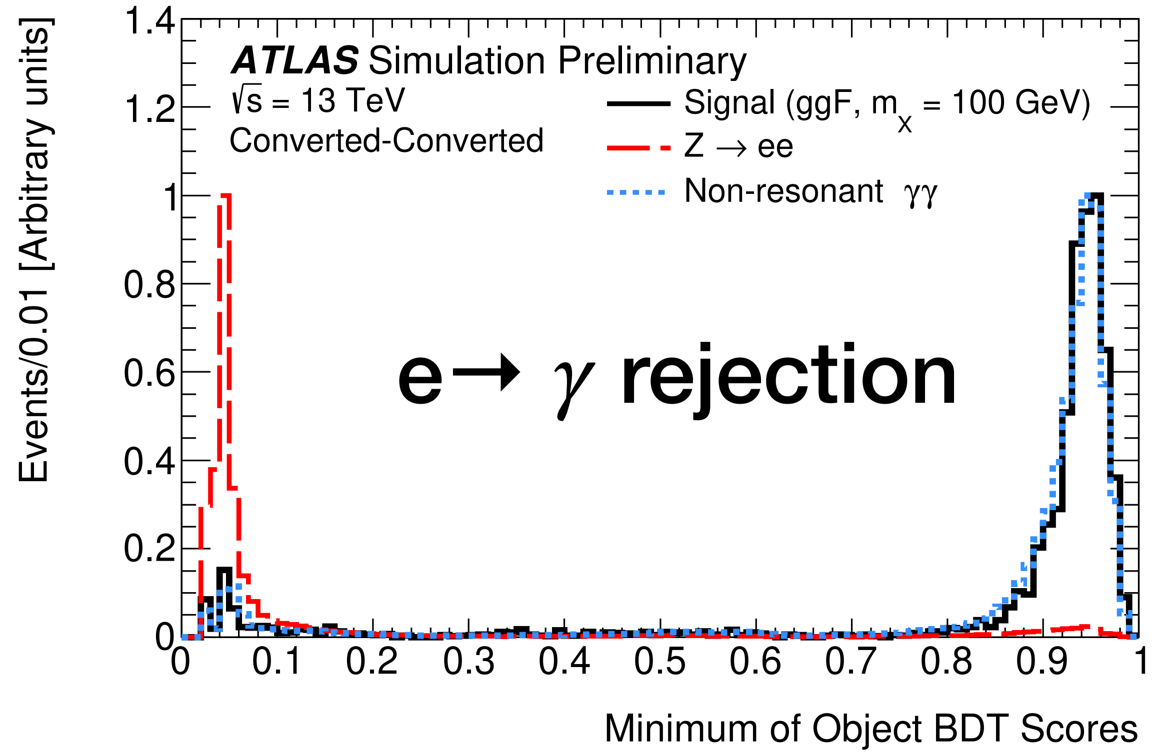
# Event selection - low mass

**Baseline categorization from previous round** (ATLAS-CONF-2018-025) to improve sensitivity

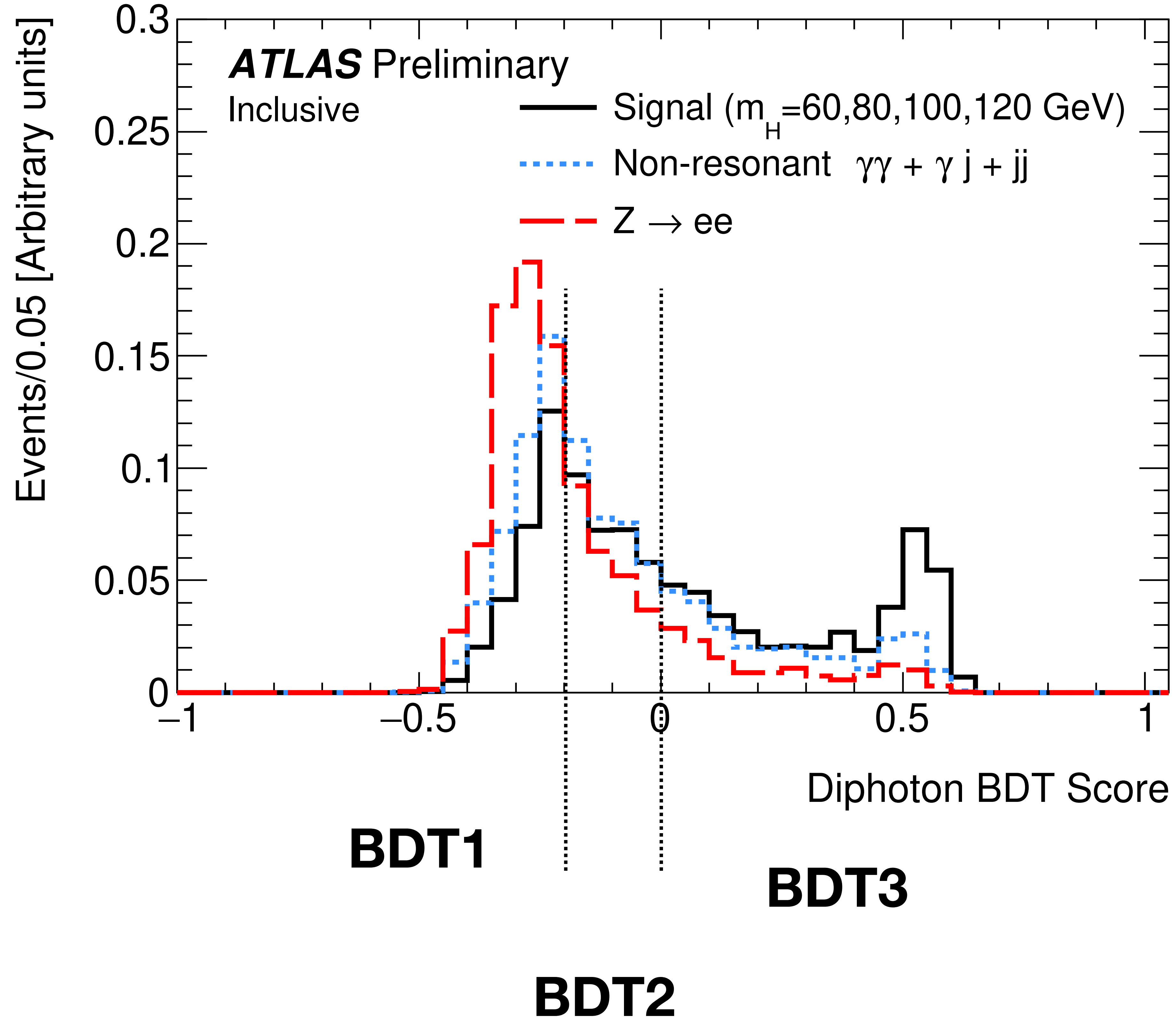
- Events categorized depending on conversion status (unconverted/converted photon): UU/UC/CC

…but also **many improvements**!

- Better electron→photon rejection using gradient BDT
- Additional 3 categories to produce a model-dependent result (assuming SM-like cross-sections) from a TMVA trained BDT: UU1/UU2/UU3/…




**Model dependent BDT**



# Background estimation

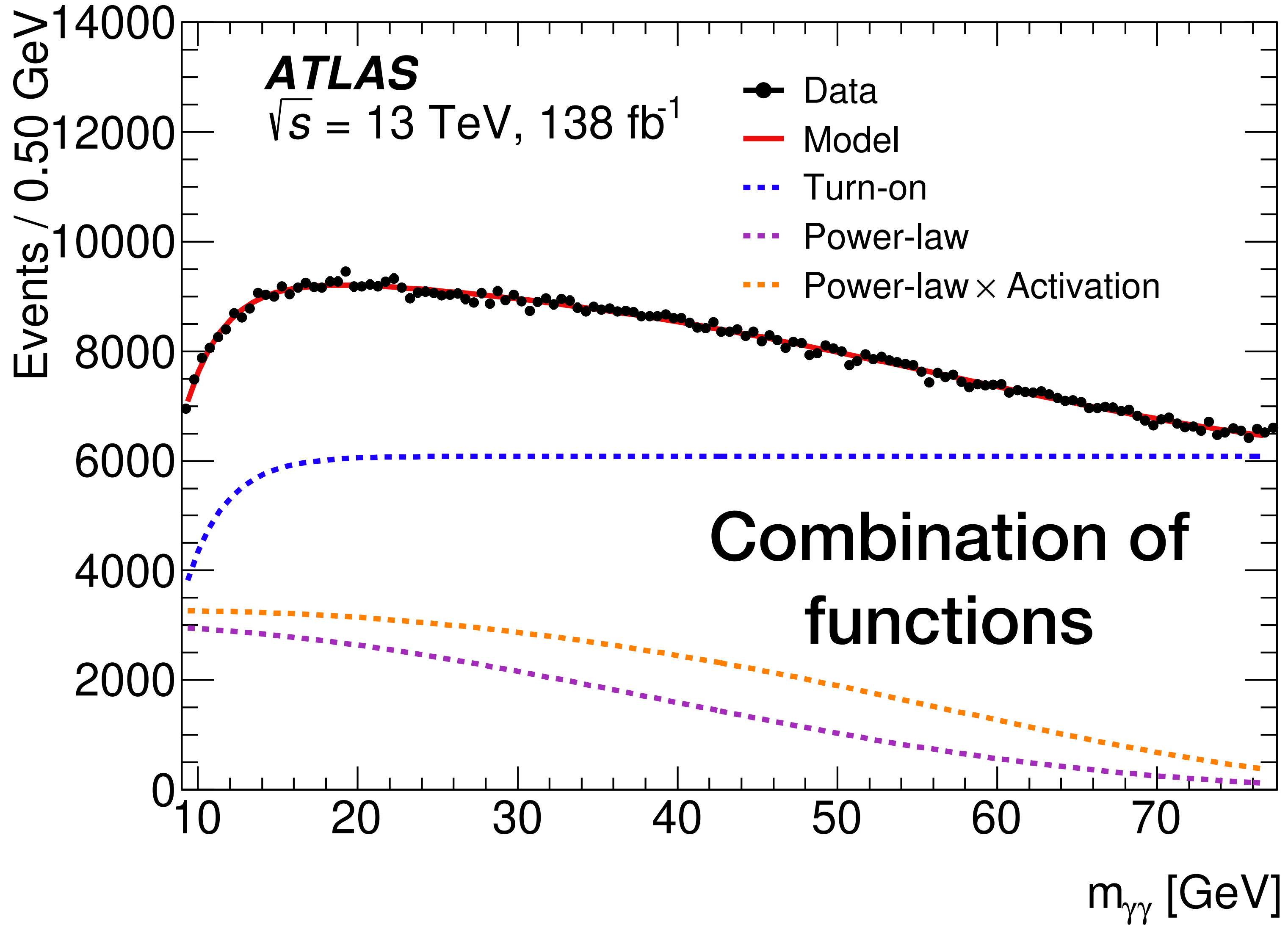


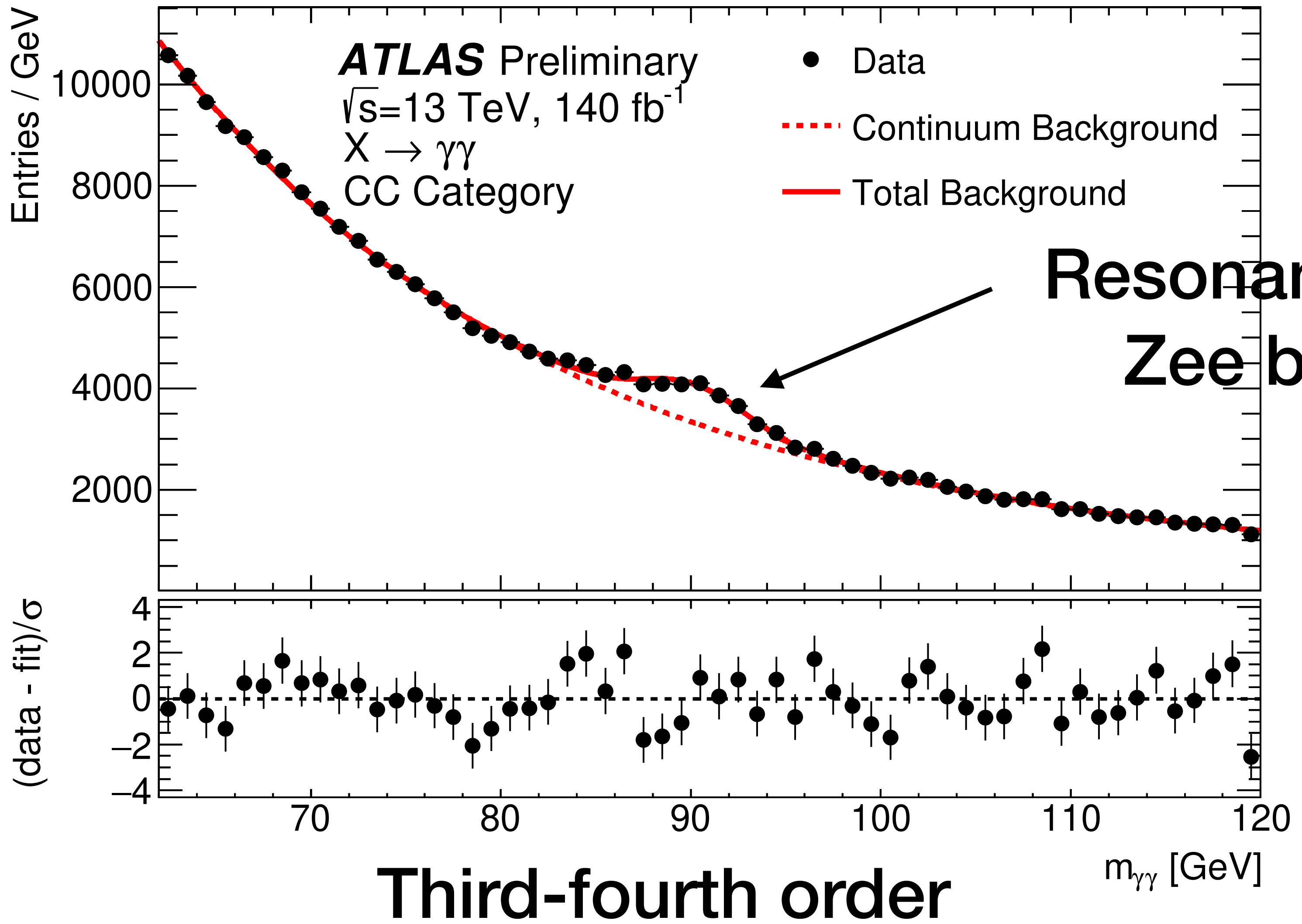
**Dominant backgrounds**

- **Irreducible ($\gamma\gamma$)**: QCD photon pairs
- **Reducible ($\gamma$j/j$\gamma$/jj)**: mis-reconstructed jet(s) as photon(s)
- **(Exclusive to low-mass)** mis-reconstructed electron pairs from Z decays as $\gamma\gamma$

**Modelling strategy**

- Relative contribution of $\gamma\gamma$ and $\gamma$j from two-dimensional ABCD method (relaxed photon ID vs isolation)
- Background template obtained from reweighted $\gamma\gamma$ MC + (**exclusive to low mass**) DY Zee MC normalized from data.
- Shape described with analytic functions



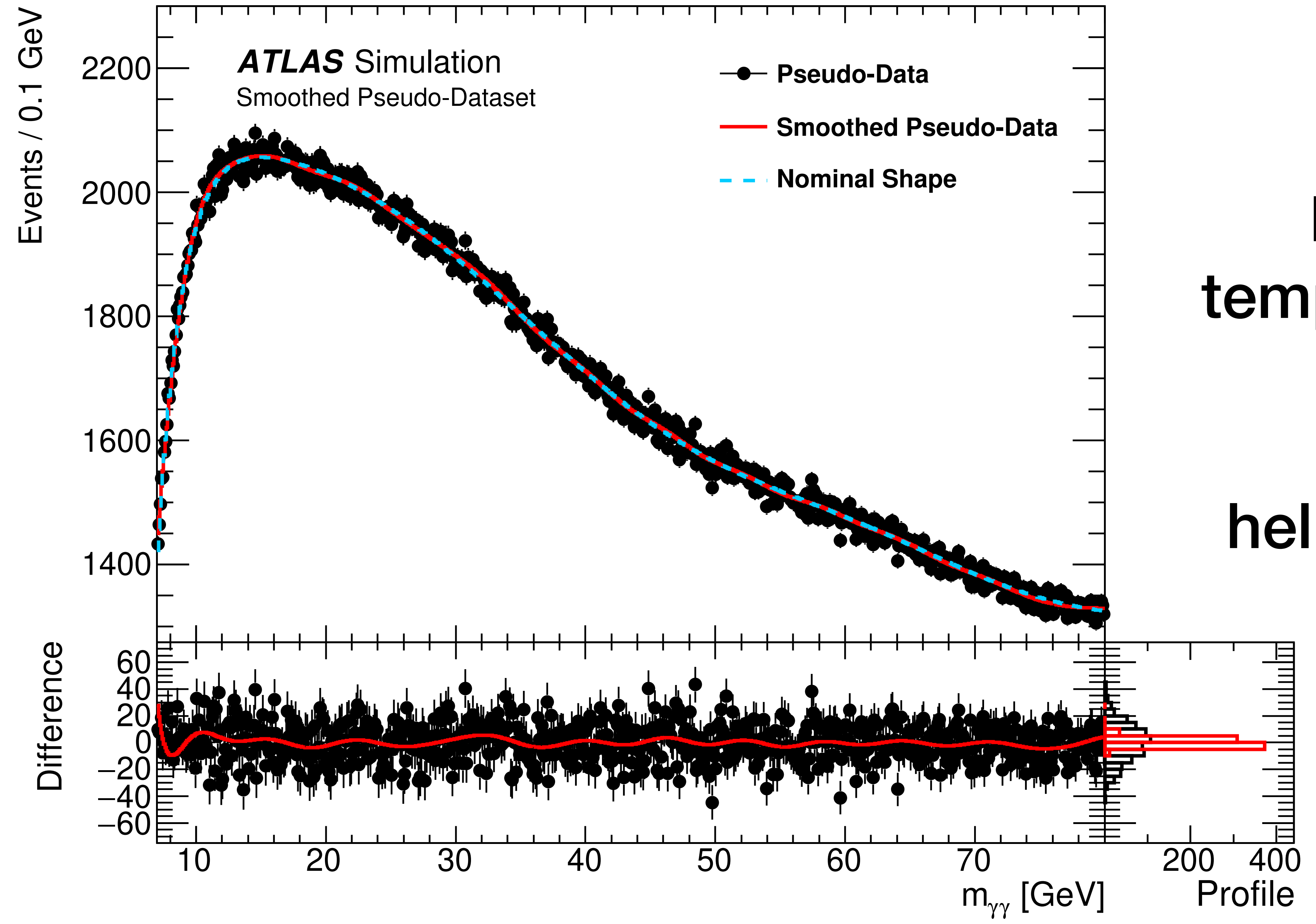

Resonant DY Zee bkg

Third-fourth order exponential

# Background modelling uncertainty

Similar source of largest systematic uncertainties: **fit bias**

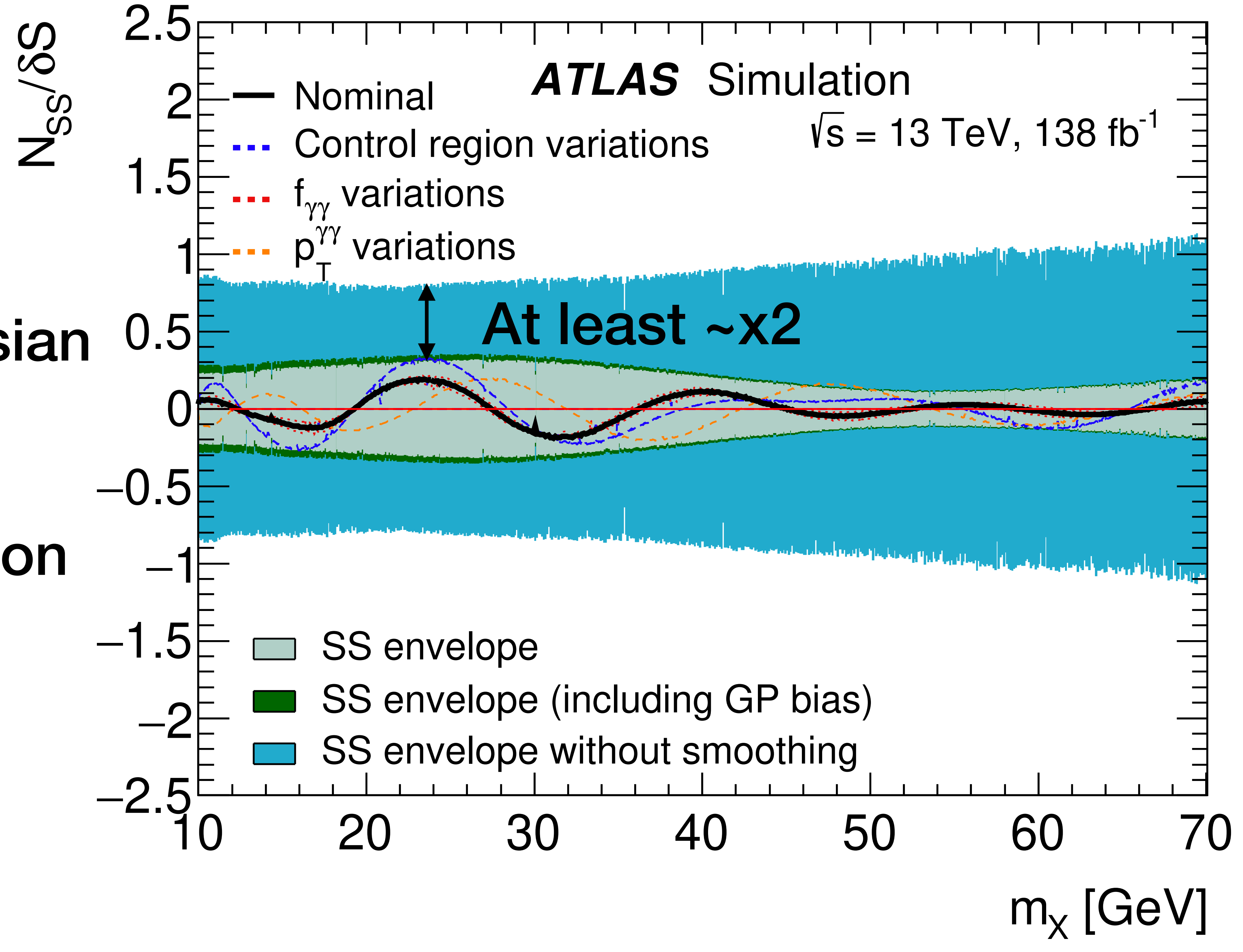
- Lack of template statistics → huge uncertainty on the bkg shape
- **Both analyses** now benefit from a reduced spurious signal uncertainty (dominant systematic uncertainty in previous $\gamma\gamma$ searches between 65 and 110 GeV)




**Better knowledge of the template shape using Gaussian Process Regression**

→

**helps reducing uncertainty on the model**



# Systematic uncertainties

Similar impact on the different sources of systematic uncertainties

Both analysis are **statistically limited**

Very-low mass (10-70 GeV)

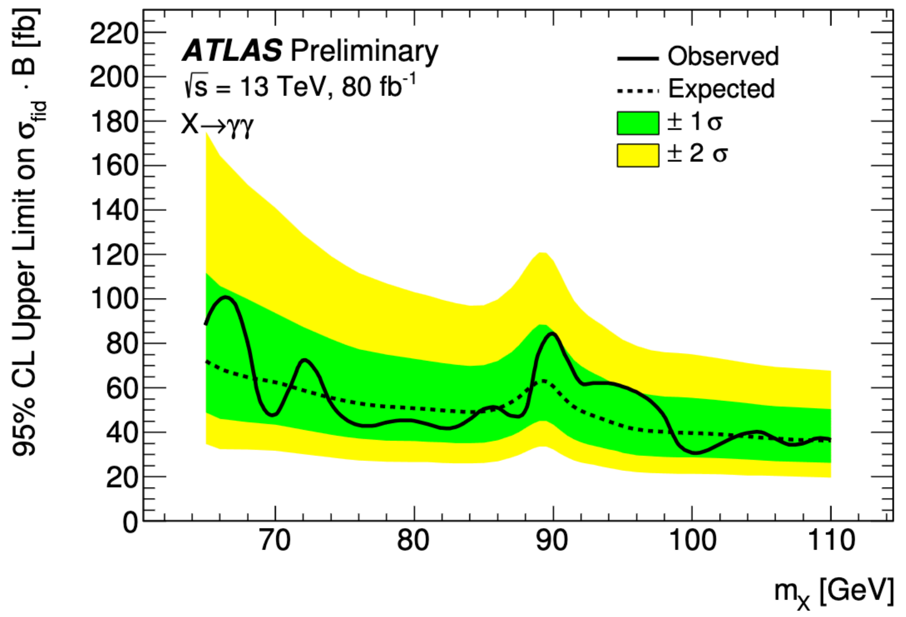
| Source | Uncertainty |
|---|---|
| | On $\sigma_{\text{fid}} \cdot \mathcal{B}(X \to \gamma\gamma)$ [%] |
| Pile-up modelling | ±3.5 (at 10 GeV) to ±2 (beyond 15 GeV), mass dependent |
| Photon energy resolution | ±2.5 to ±2.7, mass dependent |
| Scale and PDFs uncertainties | ±2.5 to ±0.5, mass dependent |
| 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 $\delta S$) | 30–65 events (10%–30%), mass dependent |

Low mass (66-110 GeV)

| Source | Uncertainty [%] | Remarks |
|---|---|---|
| *Signal yield* | | |
| Luminosity | ±0.83 | |
| Trigger efficiency | ±1.0 – 1.5 | $m_X$-dependent |
| Photon identification efficiency | ±1.8 – 3.0 | $m_X$-dependent |
| Photon isolation efficiency | ±1.6 – 2.4 | $m_X$-dependent |
| Photon energy scale | ±0.1 – 0.3 | $m_X$-dependent |
| Photon energy resolution | ±0.1 – 0.15 | $m_X$-dependent |
| Pile-up | ±1.6 – 5.0 | $m_X$-dependent |
| Production mode | ±4.3 – 29 | $m_X$-dependent (model-independent only) |
| *Signal modeling* | | |
| Photon energy scale | ±0.3 – 0.5 | $m_X$- and category–dependent |
| Photon energy resolution | ±3 – 10 | $m_X$- and category-dependent |
| *Migration between categories* | | |
| Material | −2.0 / +1.0 / +4.1 | category-dependent |
| *Non-resonant Background* | | |
| Spurious Signal | 20 – 50 | category-dependent |
| *DY Background modeling* | | |
| Peak position | ±0.1 – 0.2 | category-dependent |
| Peak width | ±1.2 – 2.3 | category-dependent |
| Normalization | ±6.1 – 9.0 | category-dependent |

# Results

Previous round:
ATLAS-CONF-2018-025



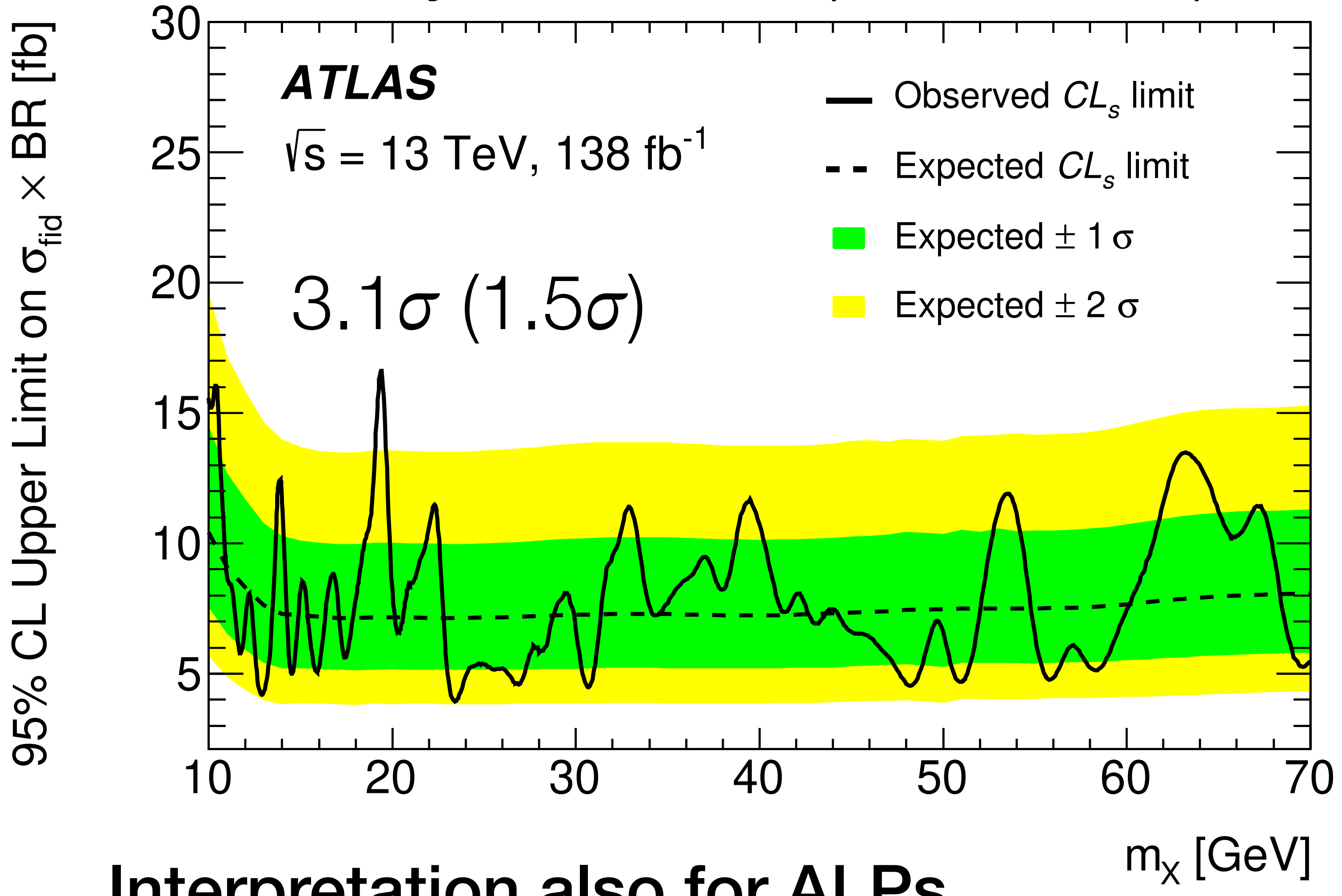

**Diphoton resonance searches**

No significant excesses observed

- Large improvements due to systematic uncertainties reduction
- Model-dependent result presents a more competitive result: observed limit ranges from 19 to 102 fb

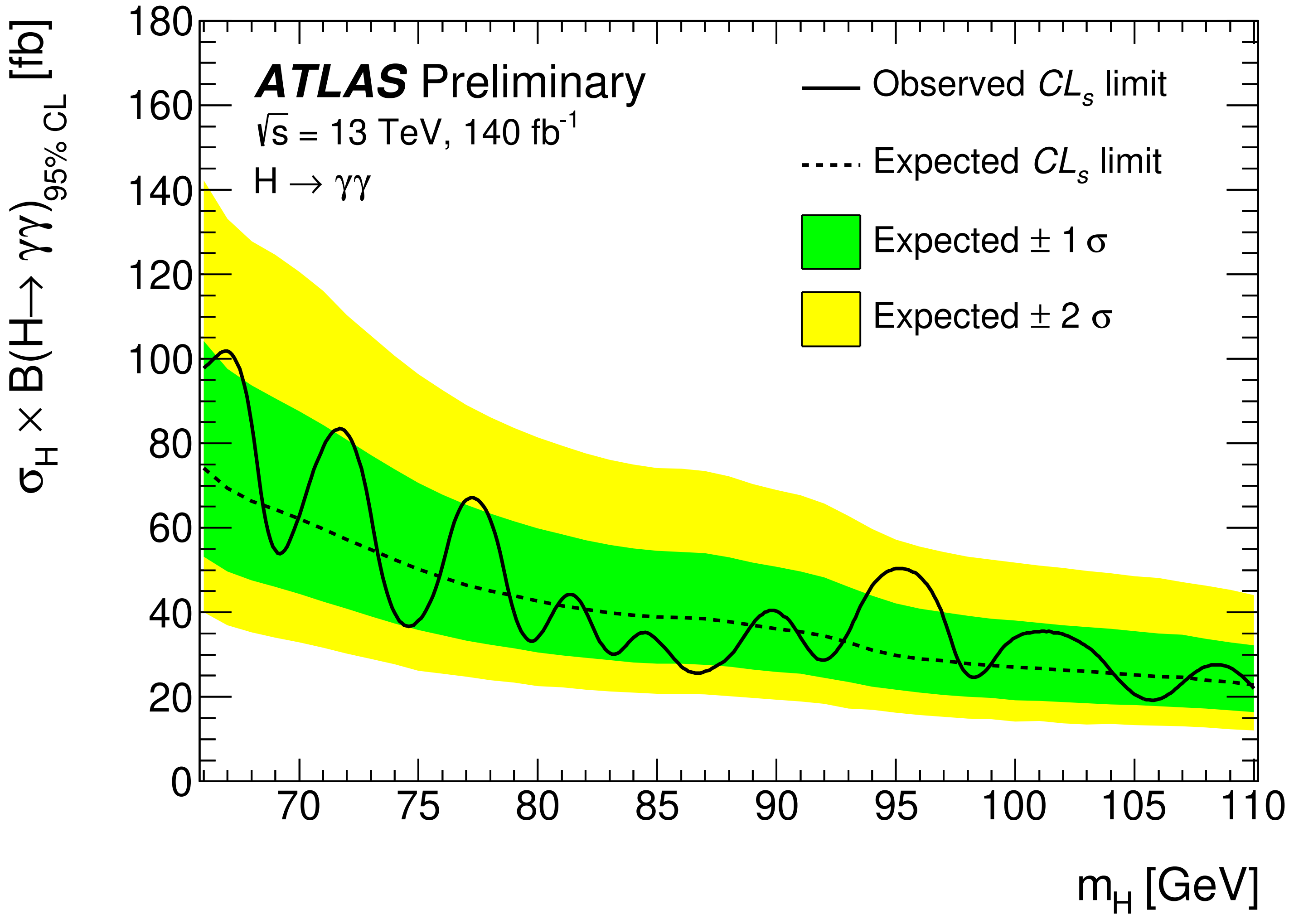
**Factor 1.6-2.4 improvement!**

Very-low mass (10-70 GeV)

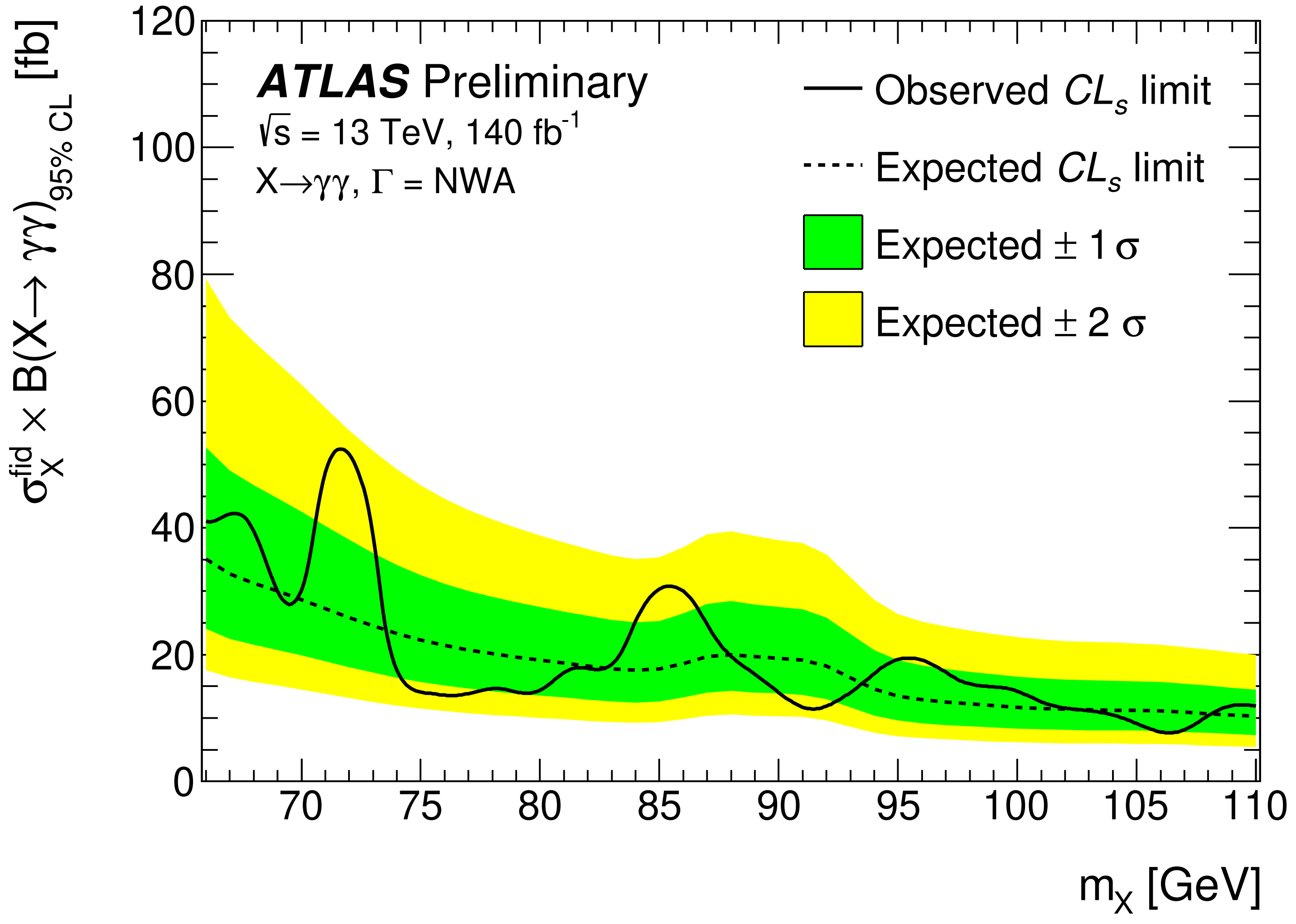



**Interpretation also for ALPs**

Model-dep (66-110 GeV)




Model-indep (66-110 GeV)



# Conclusion

This talk has covered searches with a Z boson and a photon and two photons in the final state using 140 fb-1 of *pp* collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector.

- No significant deviations have been observed

Increase in statistics and desire for improving results lead to creative/different approaches in the analysis of data to…

- Reduce impact of systematics (**GPR**)
- Improve signal efficiencies for boosted topologies (**MVAs** for merged electron ID)
- And more that often is hidden in performance!

**Stay tuned for Run 3 results!**

# Backup

# Background modelling strategy

Background shape qualitatively divided into two regions:

- Very-low mass turn-on region (below ~20 GeV)
- Smoothly falling component that approaches a non-zero value.

Functional form described by two pieces:

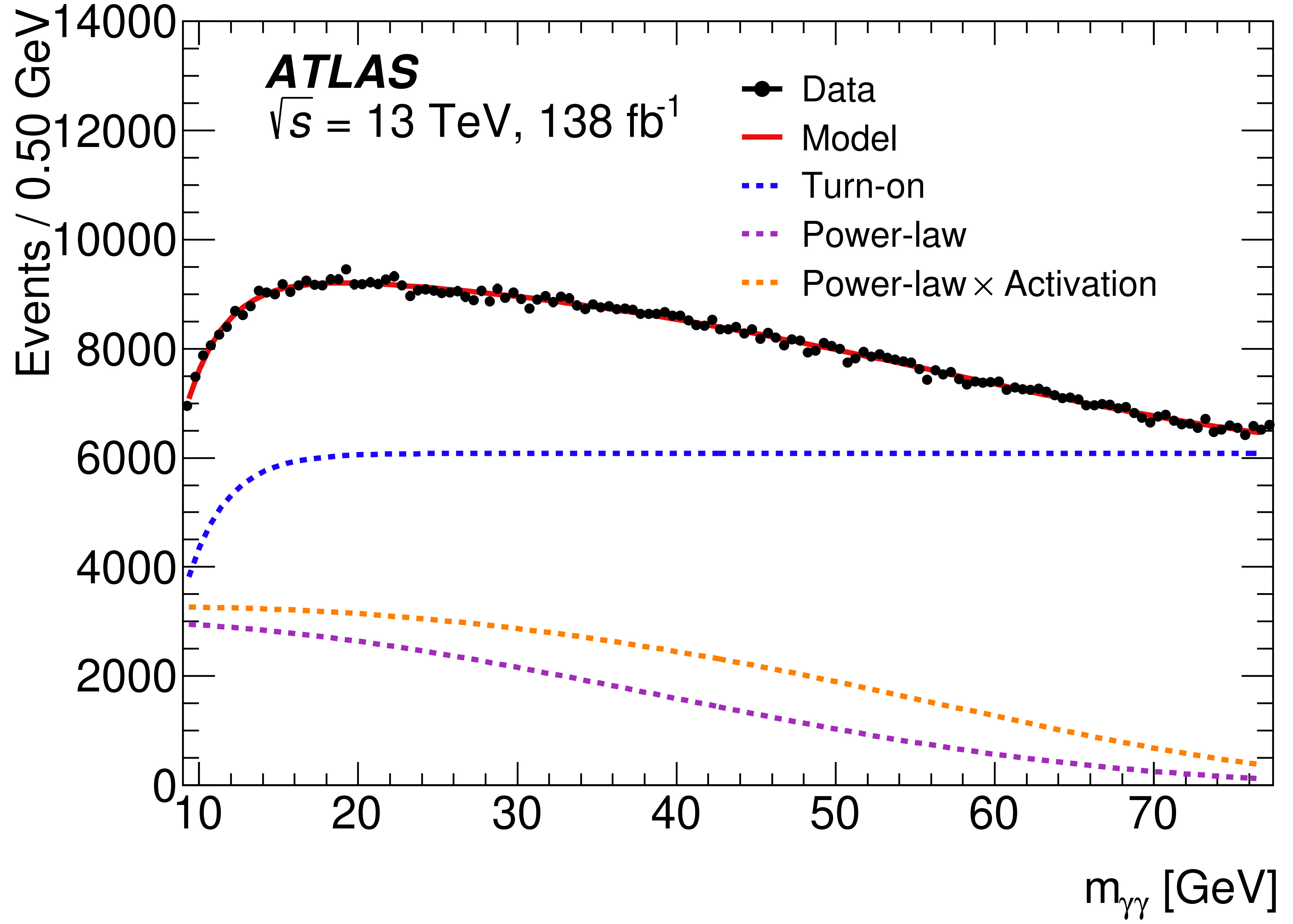
- Turn-on function that saturates beyond ~20 GeV.
- Smoothly falling power law multiplied by an *activation* function
  - Changes in the curvature between the low- and high-mass regions.

$$f\left(m_{\gamma\gamma}, \vec{\theta}\right) = Turn-on + \left[PowLaw \times Activation\right] =$$

$$= \left[1 - (1 - f_0)e^{-\frac{m_{\gamma\gamma} - 10}{\tau_{flat}}}\right] frac + (1 - frac)\left[\left(1 - \left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}\left(1 + \frac{e^{\frac{m_{\gamma\gamma} - \delta_{tail}}{\tau_{tail}}}}{1 + e^{-\frac{m_{\gamma\gamma} - \delta_{thresh}}{\tau_{thresh}}}}\right)\right]$$

**Power-law** **Activation function**

7 out of 10 parameters are free: The optimal set of floating parameters is chosen from toy-based studies.




Variations of the template shape are used to evaluate flexibility of the chosen background model:

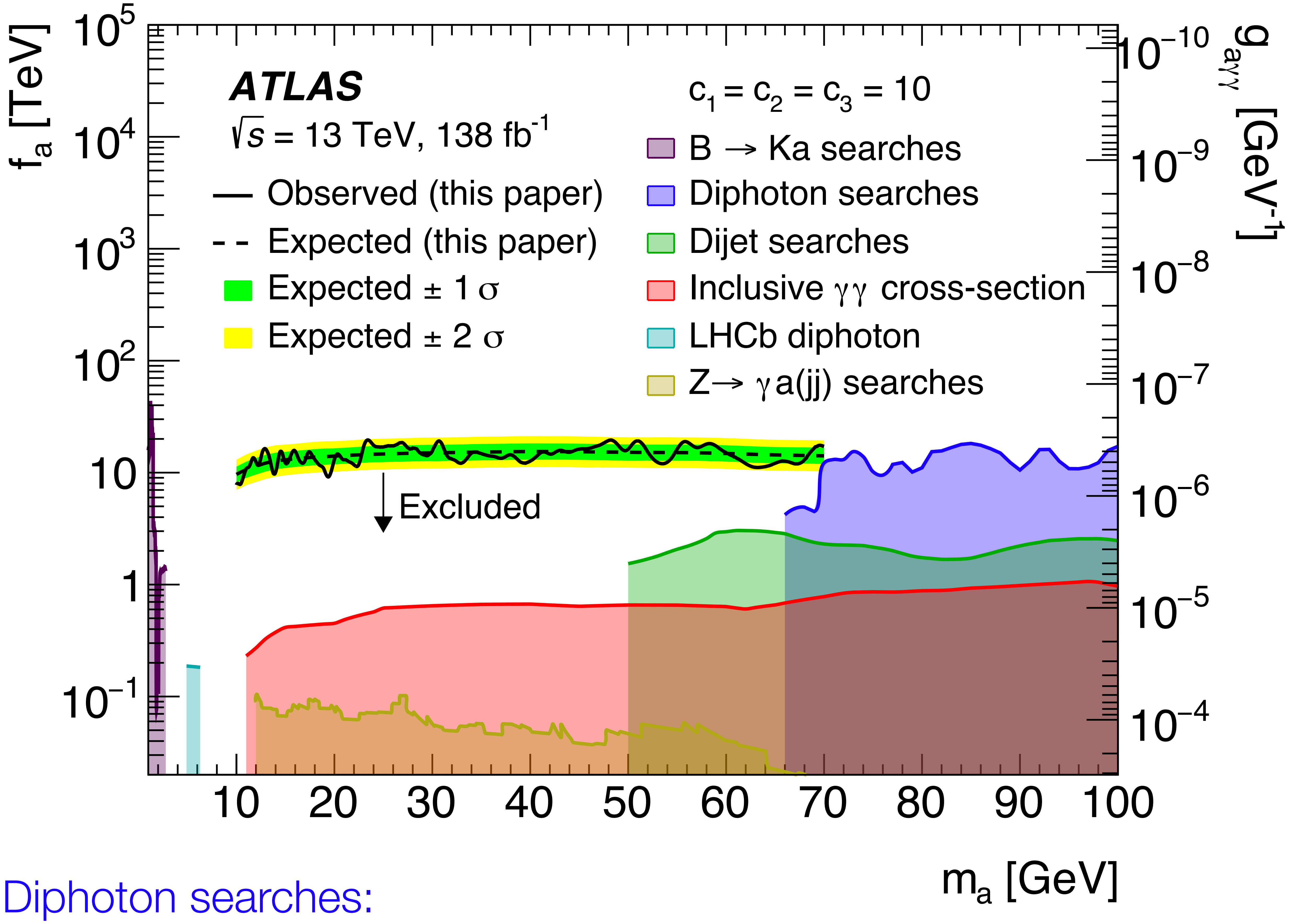
- Different control region definitions
- Different $\gamma\gamma$ purity
- Varied $p_T^{\gamma\gamma}$ threshold

# Where are our limits placed in the ALP landscape?

Limits recasted into the ALP parameter space.

This analysis provides the **strongest limits** on a hypothetical resonance produced in gluon fusion that decays to two photons.

- Other searches probing the same mass range, are significantly limited by the production mechanism (light-light scattering in heavy ion collisions vs ggF)



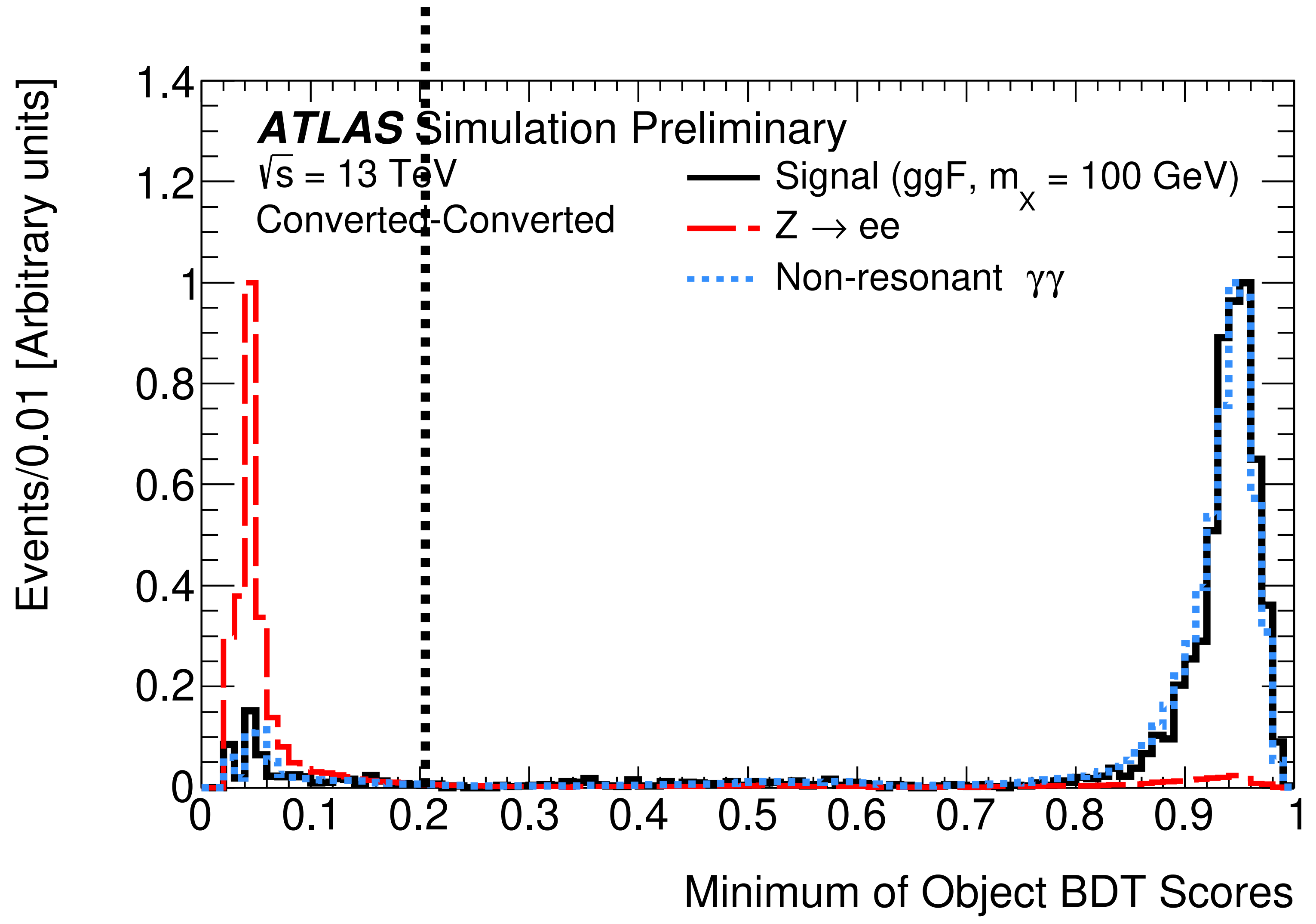

Diphoton searches:

- Tightest upper limit among all (no combination)
- CMS 13 TeV dominates down to 70 GeV (35.9 fb$^{-1}$)
- ATLAS 8 TeV extends the limit down to 65 GeV (80 fb$^{-1}$)

# Electron-photon ambiguity BDT

A gradient BDT is used for electron-photon discrimination.

- Requiring both object BDT scores to be above 0.2 results in a signal selection efficiency above 93% and a reduction of $ee$ backgrounds between 65 to 90% , where the largest reduction is seen for events with two converted photons

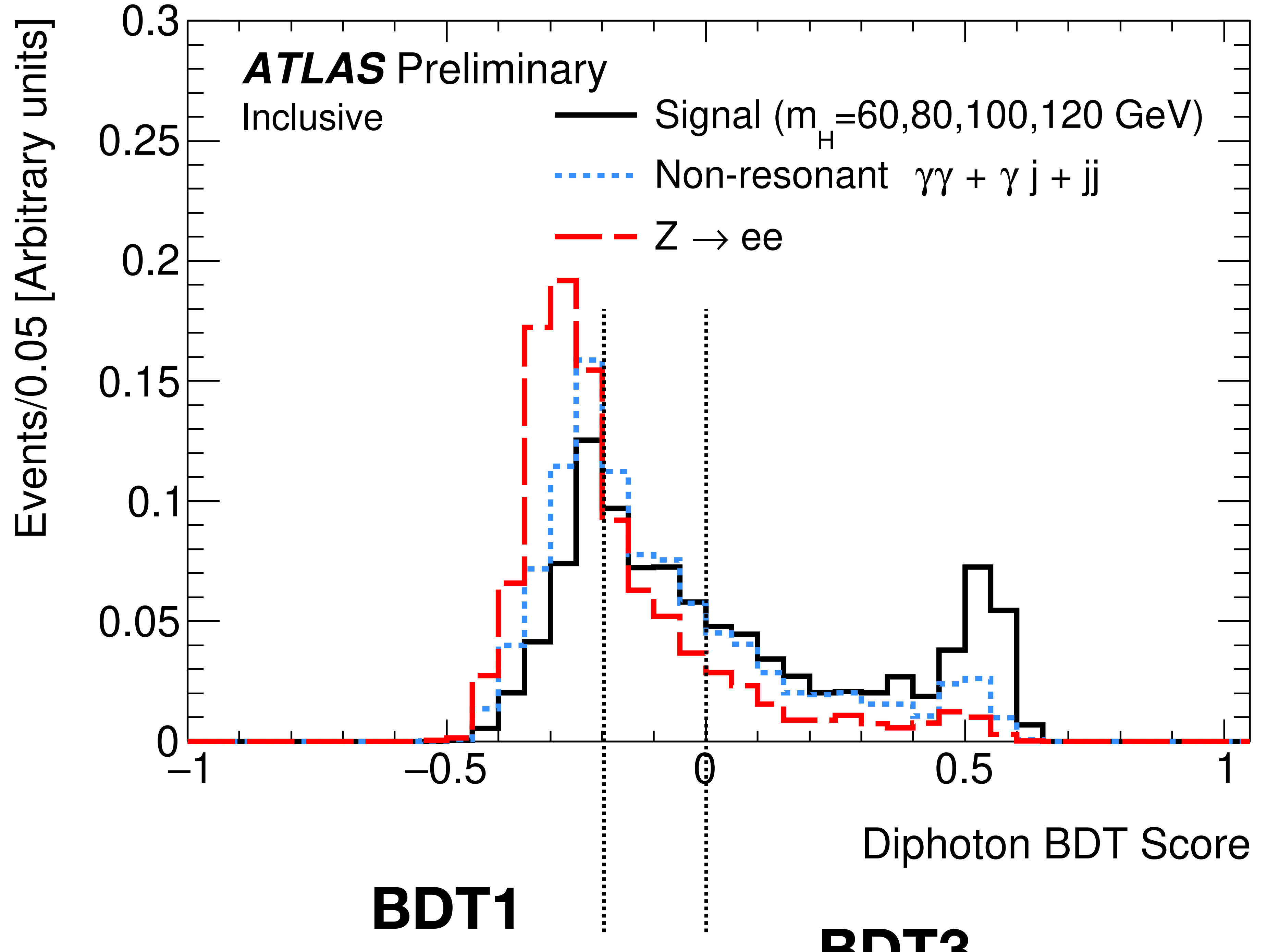


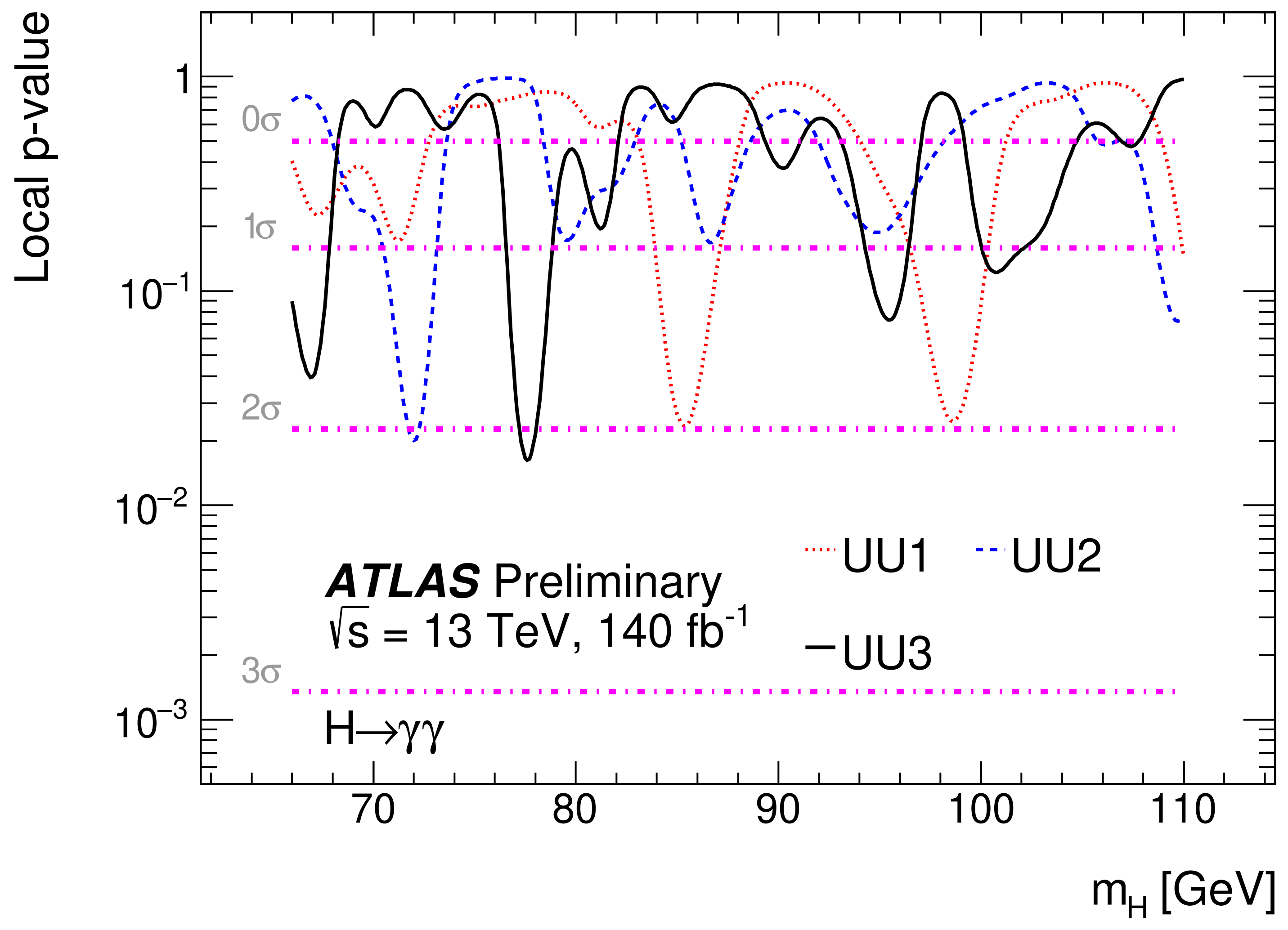

# Model dependent result

An additional model-dependent result is also considered in the 66-110 GeV $\gamma\gamma$ search.

- A BDT is trained with signal samples assuming the h(125) branching ratios
- Allows for an additional categorization in exclusive BDT-score regions.

Model dependent BDT




| BDT Category | SM-like Higgs boson ($m_H$ = 90 GeV) Total | ggF [%] | VBF [%] | WH [%] | ZH [%] | ttH [%] | Background Total [GeV$^{-1}$] | DY [GeV$^{-1}$] |
|---|---|---|---|---|---|---|---|---|
| 1 | 741 | 97.1 | 1.2 | 1.0 | 0.6 | 0.1 | 18877 | 2179 |
| 2 | 942 | 93.4 | 2.9 | 2.1 | 1.2 | 0.4 | 14014 | 713 |
| 3 | 1187 | 72.4 | 13.5 | 6.7 | 4.0 | 3.4 | 6522 | 294 |
| Total | 2870 | 85.7 | 6.8 | 3.7 | 2.2 | 1.6 | 39413 | 3186 |