Search for boosted diphoton resonances in the 10 to 70 GeV range using 138 fb^{-1} of 13 TeV pp collisions with the ATLAS detector

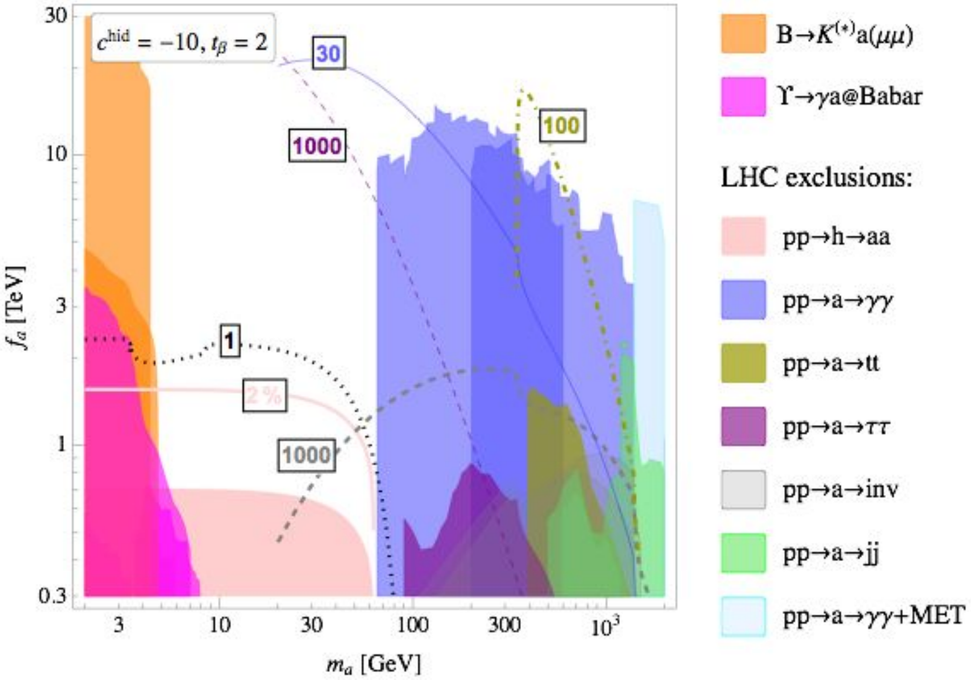
ATLAS-CONF-2022-018
preliminary results, first presented at Moriond QCD 2022

José Ocariz, LPNHE-Paris and Université Paris Cité
on behalf of the ATLAS collaboration

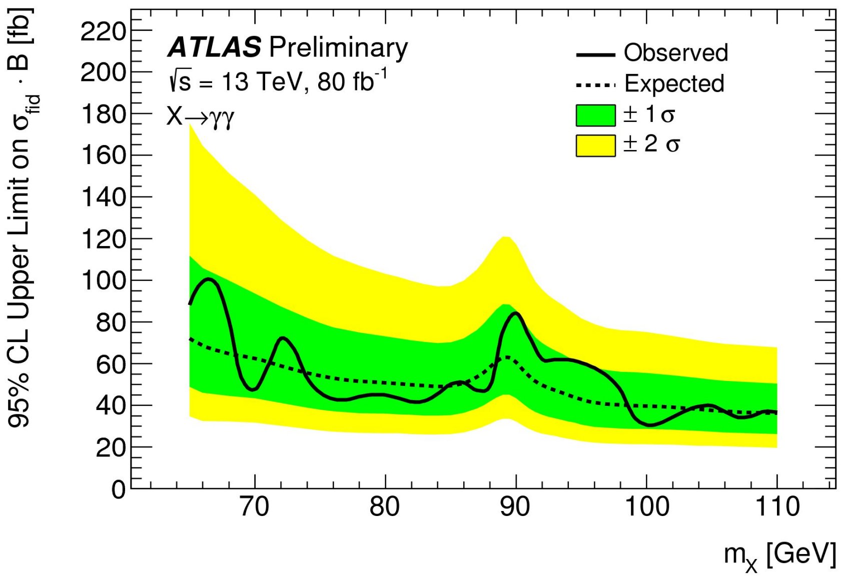
State of the art

- Several proposals for resonant Axion-Like Particles within the LHC mass reach
    - pNGBs associated to a spontaneously broken approximate symmetry above the TeV scale
- main interest as a possible DM mediator due to its weakly interacting nature
- ALPs below the Higgs mass would couple predominantly to gluons and photons
- both ATLAS and CMS have published diphoton resonance searches in mass ranges below the Higgs mass
    - no significant deviations with respect to SM predictions
- existing search gap in $\gamma\gamma$ channel resonance searches
- goal: push the current *65 GeV* limit towards lower masses, close the gap as much as possible !

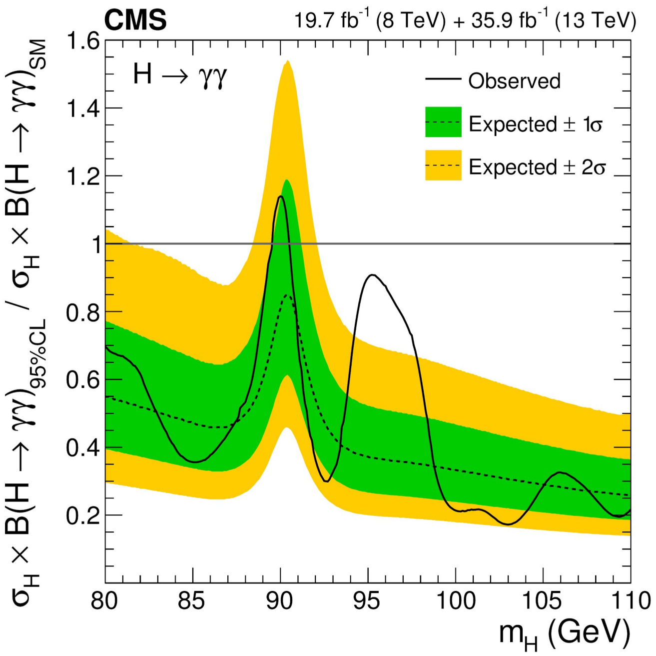
Phys.Rev.Lett. 119 (2017) 14, 141804
Phys.Lett.B 783 (2018) 13-18



ATLAS-CONF-2018-025



Phys.Lett.B 793 (2019) 320-347



Analysis strategy

Main limiting factors to reach diphoton masses below *65 GeV* :

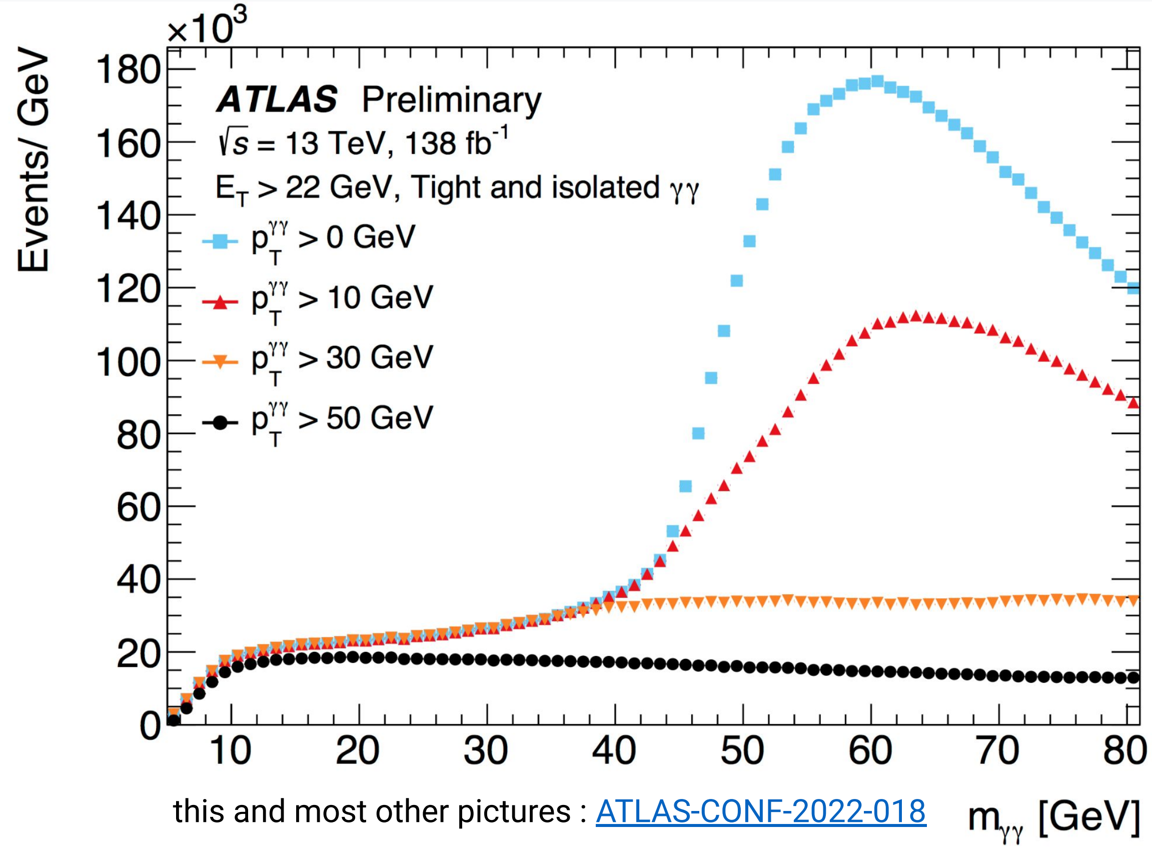
- diphoton trigger E_T thresholds at *20 GeV*
    - reduces signal acceptance
    - limits background modelling with analytical functions due to steep trigger turn-on
- decrease in photon identification and isolation efficiencies for low-ET photons

This analysis follows standard ATLAS diphoton selections

- data recorded with unprescaled diphoton triggers
- trigger thresholds and criteria evolved during Run-2
    - *20 GeV* E_T thresholds for most data (except for *21.6* fb^{-1} in 2016 with a *22 GeV* threshold)
    - additional trigger-level isolation criteria in 2017+2018
- two reconstructed photon candidates with $E_T > 22$ *GeV*
    - within the $|\eta|$ acceptance
    - passing *tight identification* criteria
    - passing *tight isolation* criteria (calorimetric+track)
- isolation computed in a $\Delta R < 0.2$ cone around the candidate

Events at low mass have large transverse momentum $p_T^{\gamma\gamma}$

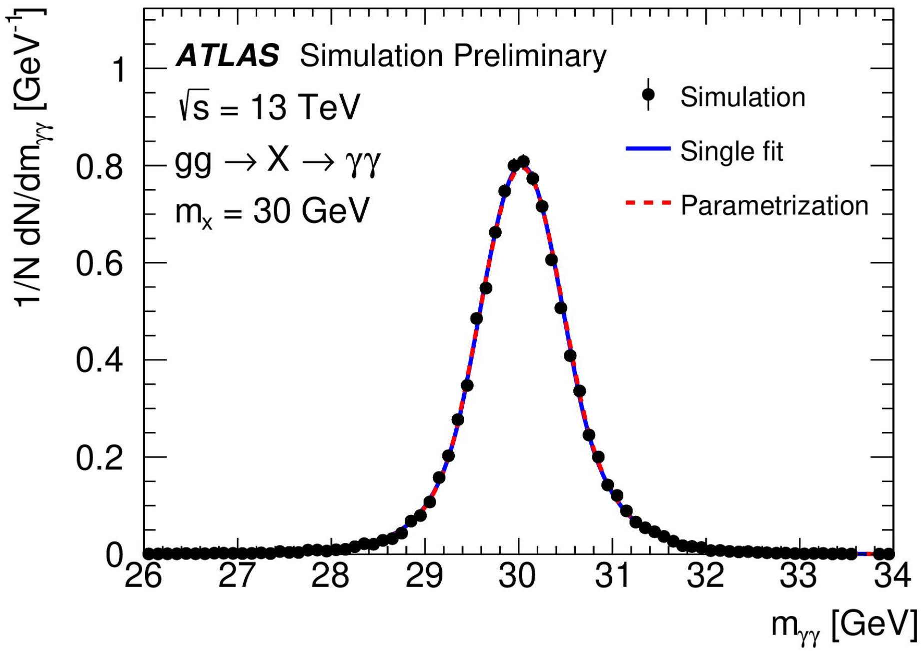
- add a boosted diphoton selection : $p_T^{\gamma\gamma} > 50$ *GeV*
- results in a smooth background spectrum down to *10 GeV*



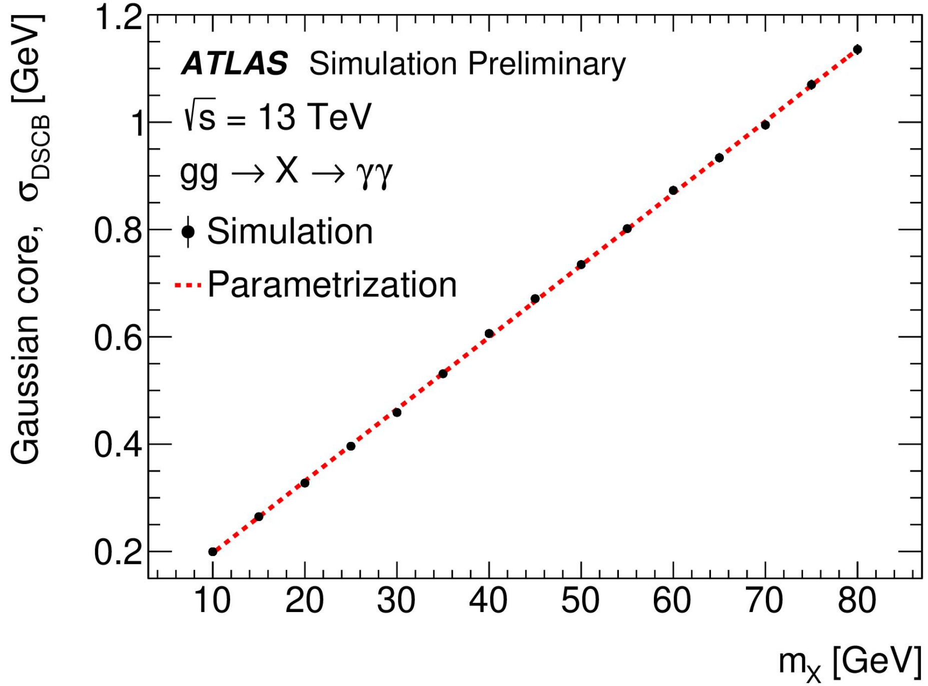
this and most other pictures : ATLAS-CONF-2022-018

Signal control samples and Signal modelling

- Signal MC control samples :
  - EFT framework: scalar “Higgs-like” resonance
  - gluon-fusion production only
  - generated with MadGraph at LO+0,1,2 jets
- Invariant diphoton mass resolution described with a Double Sided Crystal Ball (DSCB) function
  - narrow-width approximation (fixed *Γ = 4.07 MeV*)
  - DCSB parameters are linear functions of the mass point being tested
  - biases on fitted signal yields below the ±1% level on the full mass range



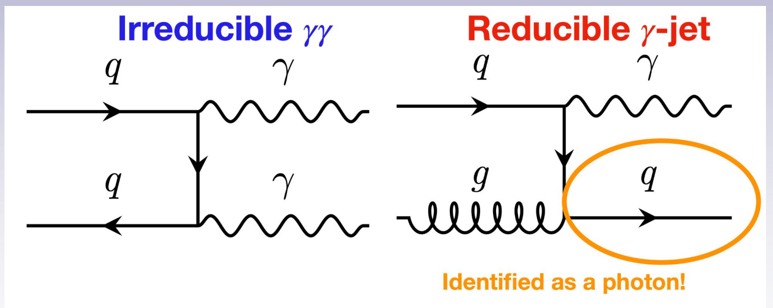
ATLAS-CONF-2022-018



Background composition

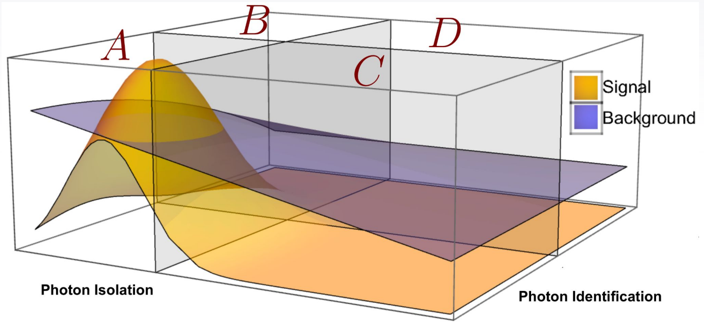
Non-resonant backgrounds:

- irreducible ($\gamma\gamma$) from QCD diphoton production
- reducible (γj+$j\gamma$+jj) from QCD with 1 or 2 jets misidentified as photon
- other backgrounds (i.e. from electrons) found to be negligible

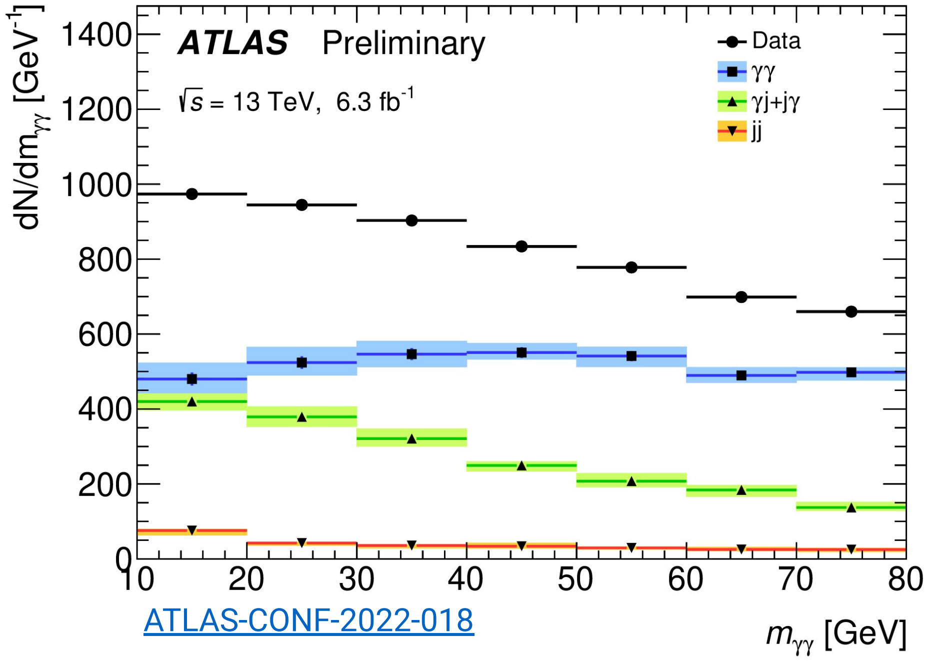


Extract composition from double-ABCD method (aka 2x2D)

- using Isolation and Identification on each photon
- irreducible shapes extracted from Sherpa QCD diphoton
- reducible shapes extracted from control regions in data
  - photon candidates failing a subset of identification criteria



(borrowed from Phys.Rev.D 103 (2021) 3, 035021)

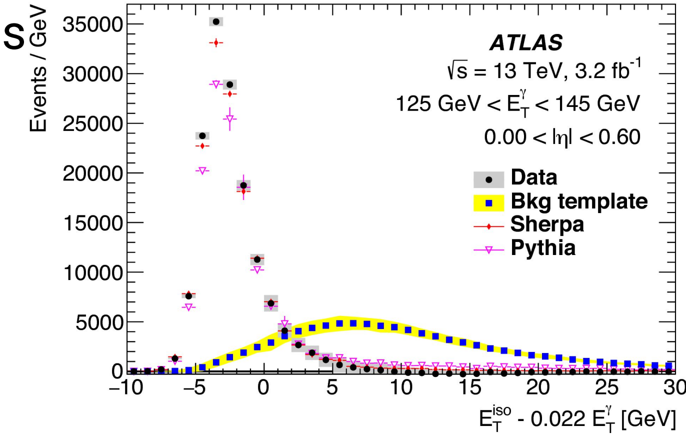


ATLAS-CONF-2022-018

2x2D composition on a control sample passing a (prescaled) diphoton trigger with looser trigger-level ID requirements

large diphoton purity at higher masses

reducible background becomes dominant at very-low masses



JHEP 09 (2016) 001 (for illustration only)

Background modelling

Background shape qualitatively divided into two regions:

- fast turn-on region for masses below *~20 GeV*
    - described with an exponentially-saturating function (“Flat”)
- slowly decreasing region above, with a mild change in curvature between the mid- and higher- mass regions
    - described with the product of a power-law (“PowLaw”) times an “Activation” function

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

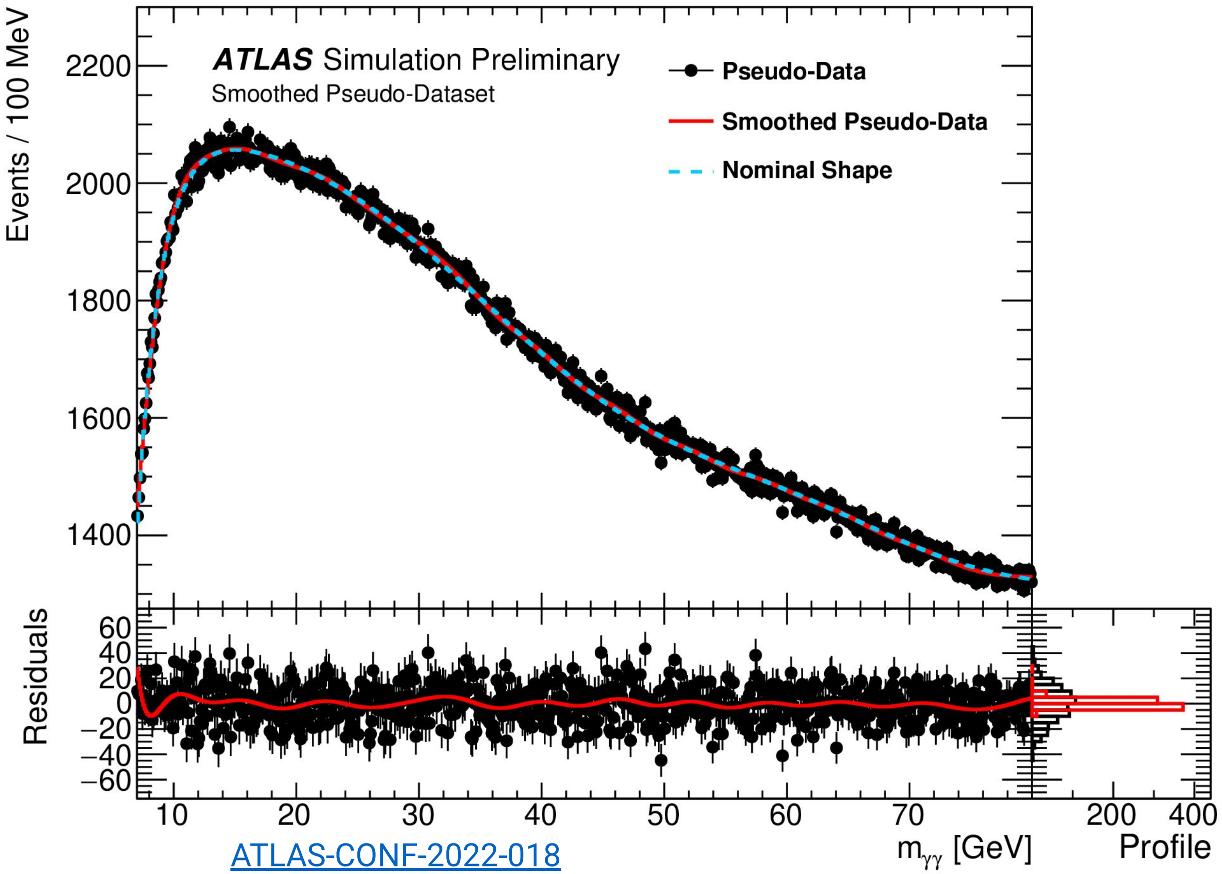
$$= \left[1-(1-f_0)e^{-\frac{m_{\gamma\gamma}-10}{\tau_{flat}}}\right] frac + (1-frac)\left[\underbrace{\left(1-\left(\frac{m_{\gamma\gamma}}{c_1}\right)^{a_0}\right)^{c_0}}_{\textbf{PowLaw}} \underbrace{\left(1+\frac{e^{\frac{m_{\gamma\gamma}-\delta_{tail}}{\tau_{tail}}}}{1+e^{-\frac{m_{\gamma\gamma}-\delta_{thresh}}{\tau_{thresh}}}}\right)}_{\textbf{Activation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

Variations on the template shape are used to evaluate the flexibility of the background modelling :

- different control region definitions
- different $\gamma\gamma$ purity
- varied $p_T^{\gamma\gamma}$ threshold

All variations lead to sizable changes in the spectrum

- all well described with the nominal model



ATLAS-CONF-2022-018

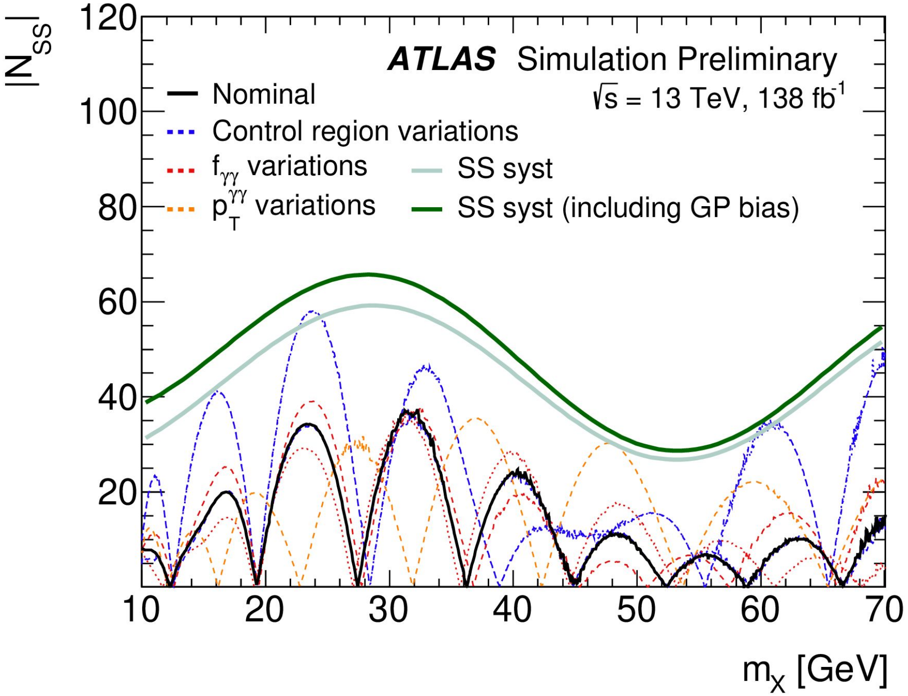
Spurious signal and GPR

Estimation of bias arising from the choice of the background model :

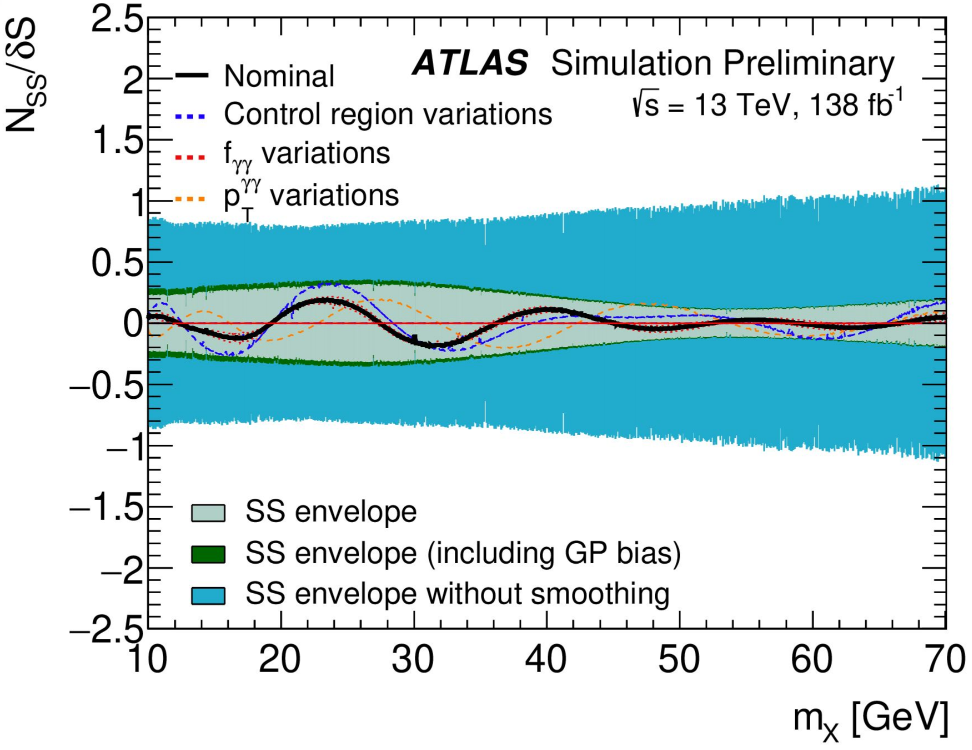
- signal-plus-background fits to background-only templates
- any fitted signal yield is denoted “spurious signal” (SS) and is a systematic uncertainty

Background templates are affected from low statistics :

- the Gaussian Process Regression (GPR) method
  - mitigates statistical fluctuations on the background shape
  - GPR decreases the SS systematics uncertainty
  - the bias from the GPR methodology is also accounted for

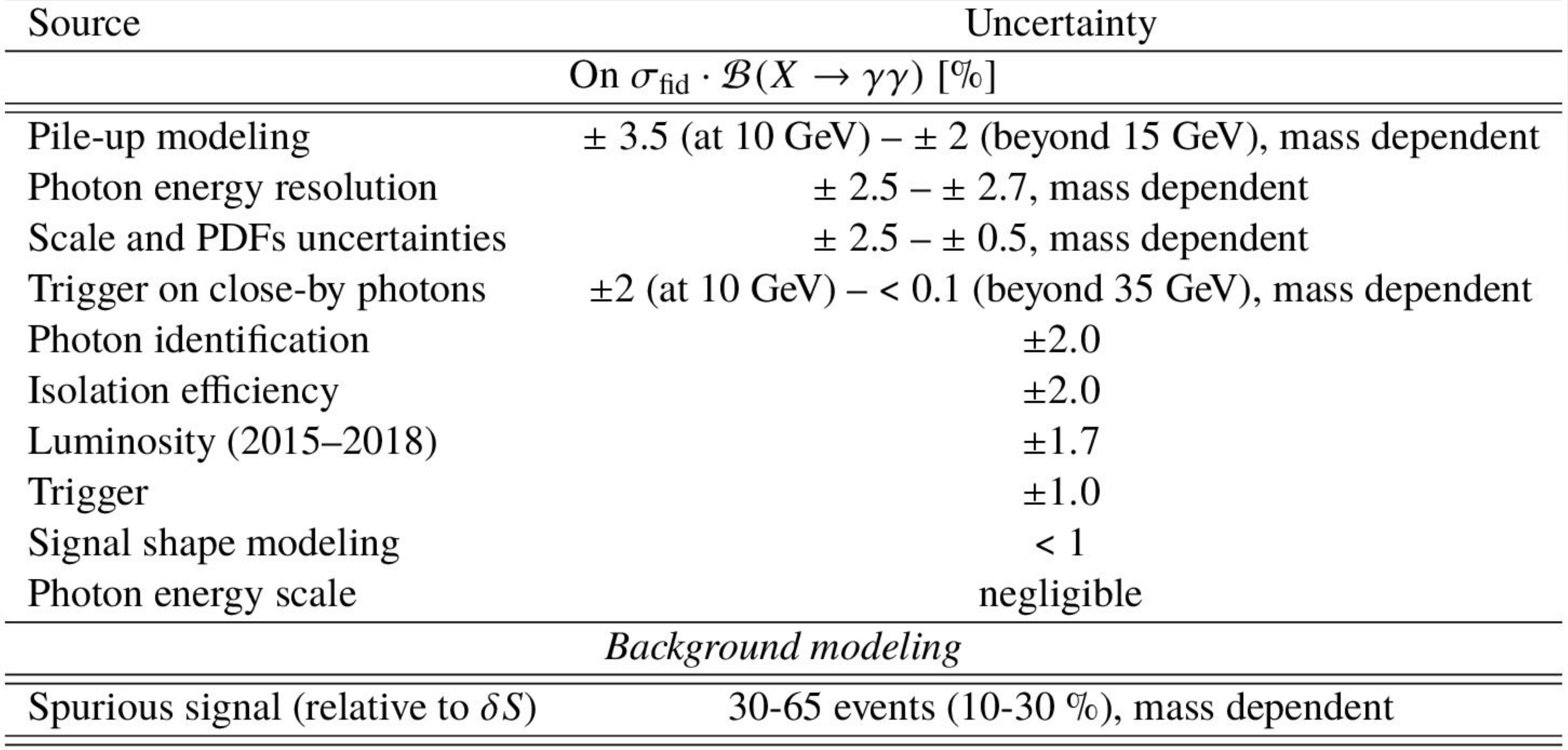


ATLAS-CONF-2022-018



Summary of systematics

ATLAS-CONF-2022-018



Source	Uncertainty
	On $\sigma_{\text{fid}} \cdot \mathcal{B}(X \rightarrow \gamma\gamma)$ [%]
Pile-up modeling	± 3.5 (at 10 GeV) – ± 2 (beyond 15 GeV), mass dependent
Photon energy resolution	± 2.5 – ± 2.7, mass dependent
Scale and PDFs uncertainties	± 2.5 – ± 0.5, mass dependent
Trigger on close-by photons	±2 (at 10 GeV) – < 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 modeling	< 1
Photon energy scale	negligible
	Background modeling
Spurious signal (relative to δS)	30-65 events (10-30 %), mass dependent

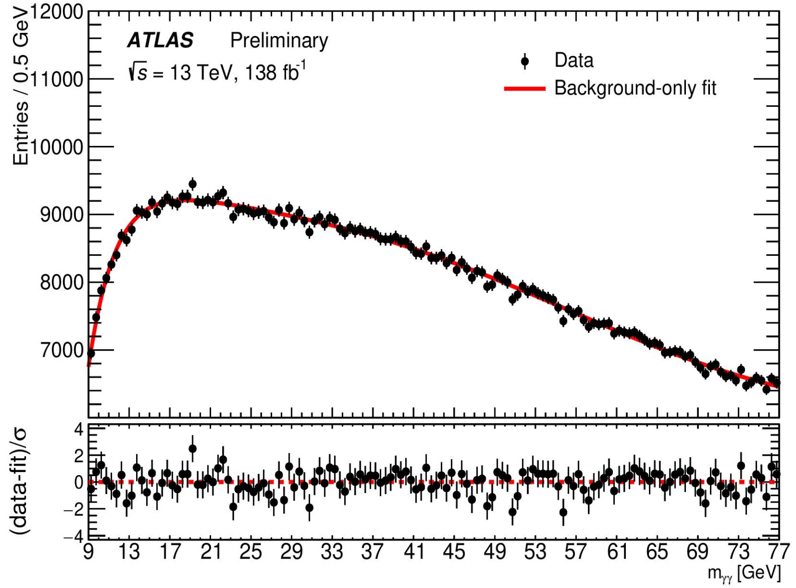
Most systematic uncertainties are percent-level or smaller

- the dominant systematics arises from the background modelling uncertainties
  - spurious signal (SS) and GPR bias combined

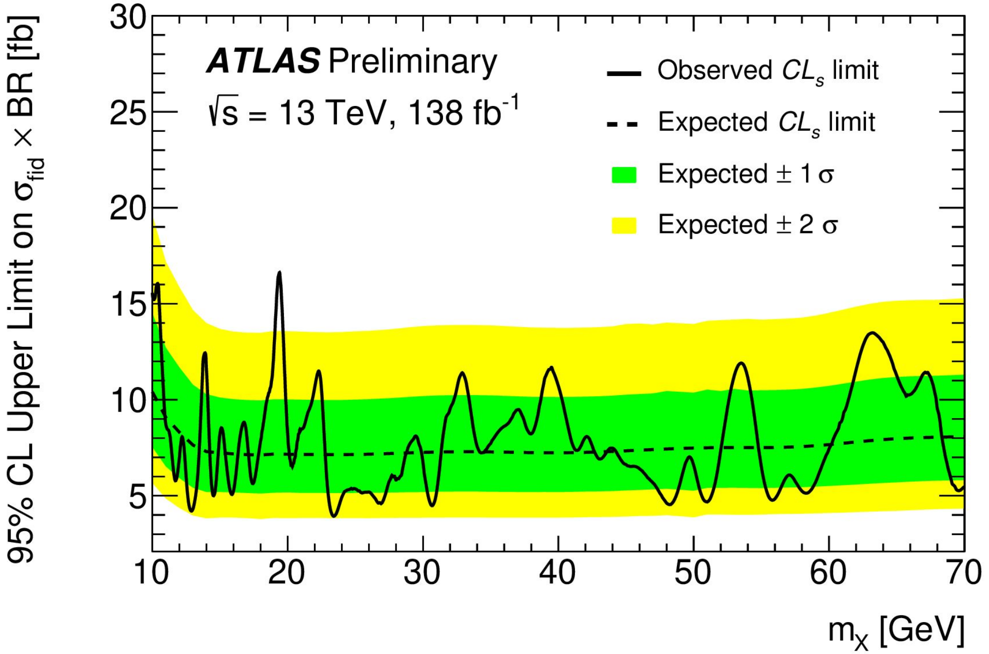
Results

Search performed in the *[10,70] GeV* mass range

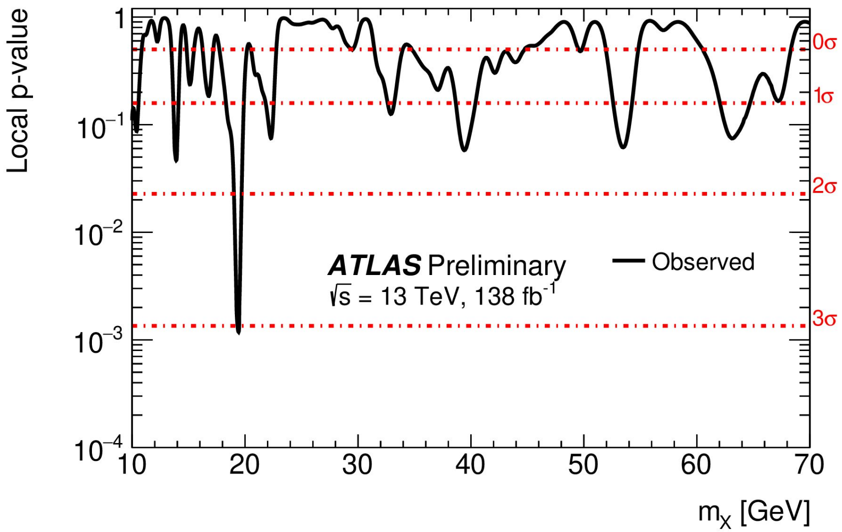
- binned likelihood fit in the *[9,77]* range
    - (at least *5σ* lever-arm from edges)
- parameter of interest: $\sigma_{fid}\times BR(X\rightarrow\gamma\gamma)$
- good description of the data with the background model
    - no significant deviation wrt the SM
    - largest deviation at *19.4 GeV*, with *3.1σ* local significance
        - *(1.48±0.02)σ* global significance, evaluated with pseudo-data



Limits set on the $\sigma_{fid}\times BR(X\rightarrow\gamma\gamma)$ of a resonance decaying to two photons



ATLAS-CONF-2022-018



Phenomenological interpretation: ALP landscape

Limits recast into the ALP parameter space
- strongest limits on a hypothetical resonance produced in gluon fusion that decays to two photons

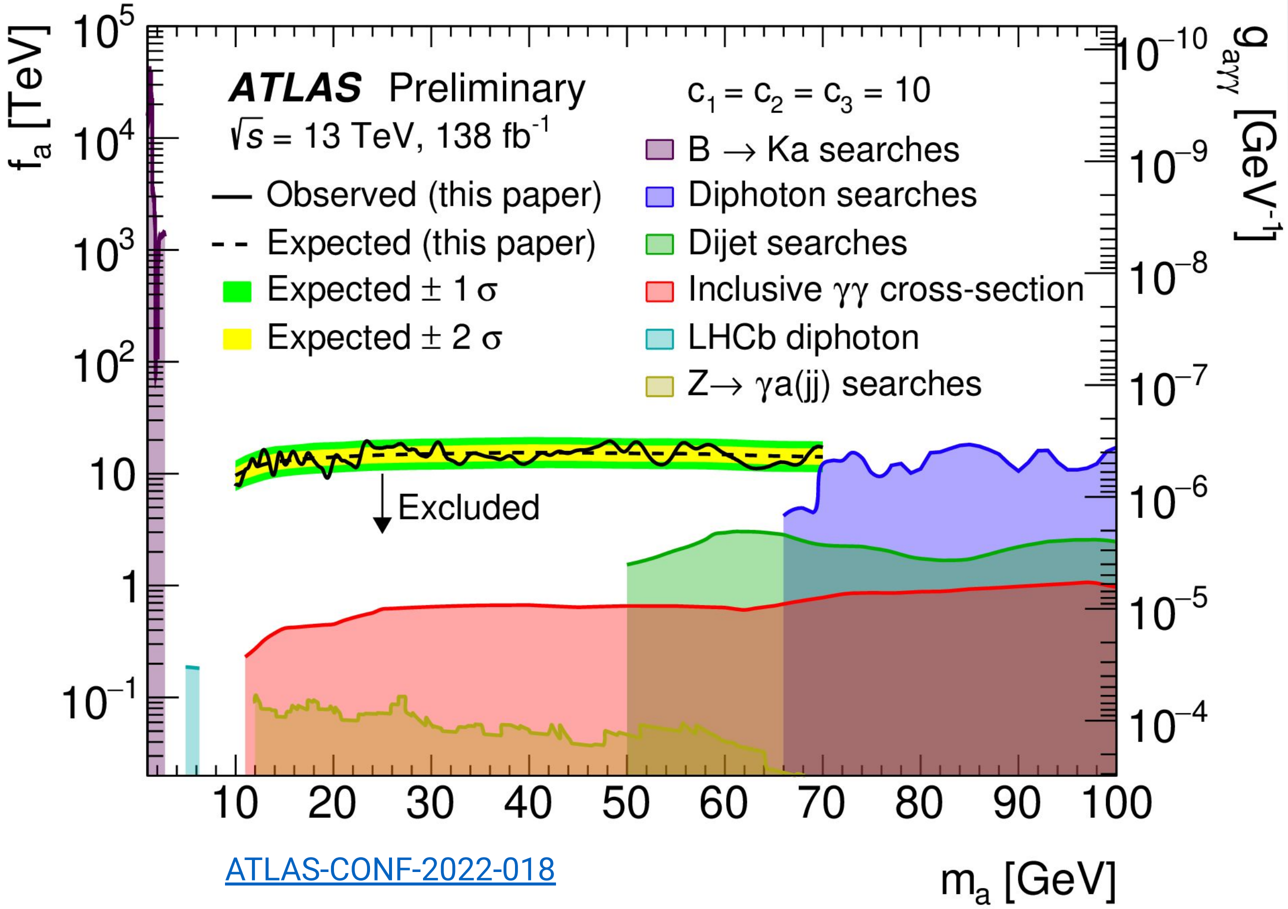
Other searches probing the same mass range:

- light-by-light scattering in heavy ion collisions significantly limited by the production mechanism
- dijet searches disfavoured by mass resolution

Other diphoton searches in proton proton collisions:

- CMS 13 dominates down to *70 GeV* (*35.9 fb*$^{-1}$)
- ATLAS extends the limit down to *65 GeV* (*80 fb*$^{-1}$)

A large piece of the $\gamma\gamma$ gap is now covered !



ATLAS-CONF-2022-018

Summary

ATLAS searched for boosted resonances in the diphoton channel, with masses in the *10* to *70 GeV* range

Analysis strategy:

- strongly relies on the excellent performance of the EM calorimeter
- novel selection of boosted diphoton pairs to reach masses below the trigger turn-on
- observed data in agreement with the SM-only (no excess) hypothesis
- largest deviation found at *19.4 GeV*
    - corresponding to a 3.1σ (1.5σ) local (global) significance
- limits on $\sigma_{fid} \times BR(X \to \gamma\gamma)$ from *4 fb* to *17 fb*
- the total uncertainty is dominated by statistics
        - impact of background modelling mitigated by GPR

This analysis provides the strongest upper limits up to date using pp collisions:

- on the cross-section times branching ratio of a resonance that decays to two photons
- in the mass range below *65 GeV*, and down to *10 GeV*
- and in the ALP parameter space in that same mass range

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-018/

Backup: more on the phenomenological interpretation

New Physics scenario being considered:

- all heavy states are beyond the reach of the LHC
  - no deviations from the SM behavior are expected in the TeV range
- a scalar a, singlet of the SM gauge group, naturally lighter than the EW scale exists
  - a is abundantly produced in proton-proton collisions
  - a decays promptly into a pair of SM particles with a narrow width
- a “KSVZ-ALP” model is considered, inspired by the simplest QCD axion model of the scalar a :

$$\mathcal{L}_{\text{int}} = \frac{a}{4\pi f_a}\left[\alpha_3 c_3 G^a \tilde{G}^a + \alpha_2 c_2 W^i \tilde{W}^i + \alpha_1 c_1 B\tilde{B}\right]$$

- barring a huge hierarchy among the anomaly coefficients:
  - for $m_a \lesssim m_Z$, the relevant two-body decays of a are to photons and to jets
  - the width into gluons dominates over the one into photons
  - the total width is dominated by its coupling to gluons and is always small compared to its mass