Search for high-mass new resonances in diphoton final states with ATLAS detector

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Analysis overview

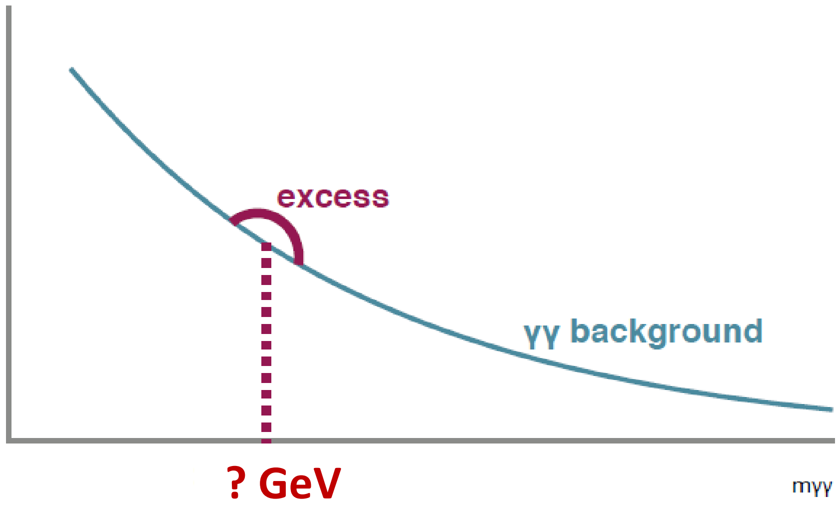
Full Run 2 dataset, 139 fb^{-1}

Diphoton final state is ideal for discovery of new particles, thanks to the excellent mass resolution of the detector and moderate rates of background with a smoothly falling shape of the mass distribution.

- **Search for a diphoton resonance in the high-mass spectrum ($m_{\gamma\gamma}$>160 GeV).**
  - spin-0: search for a narrow or large width resonance, up to Γ_X/m_X=10%.
  - spin-2: search for the RS1 graviton for 0.01<$k/\overline{M_{pl}}$<0.1.
- **In the absence of a significant excess, set limits on fiducial/total cross-section for spin-0/spin-2 resonance.**

Analysis strategy:

- fit data with analytical functions that model the background and signal shapes.



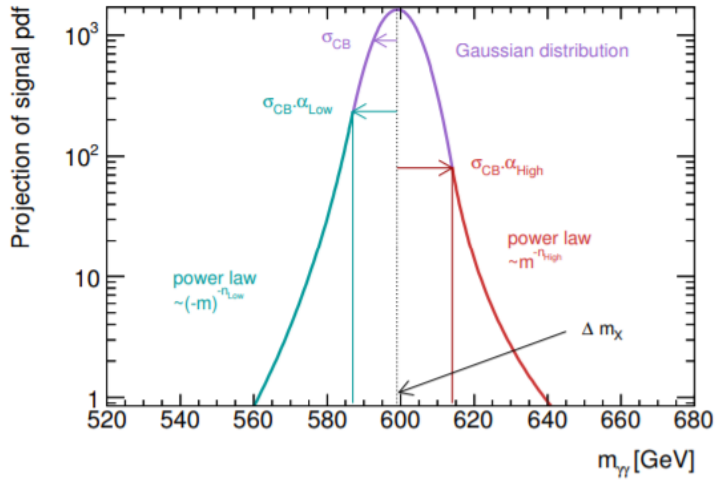
Event selection harmonized for spin-0/spin-2:

- Tight photon isolation and identification
- $m_{\gamma\gamma}$ >150 GeV
- $E_T^{\gamma 1}/m_{\gamma\gamma}$> 0.3, $E_T^{\gamma 2}/m_{\gamma\gamma}$> 0.25

Fiducial selection:

Kinematic selections and truth isolation imitating the reconstruction-level selection.

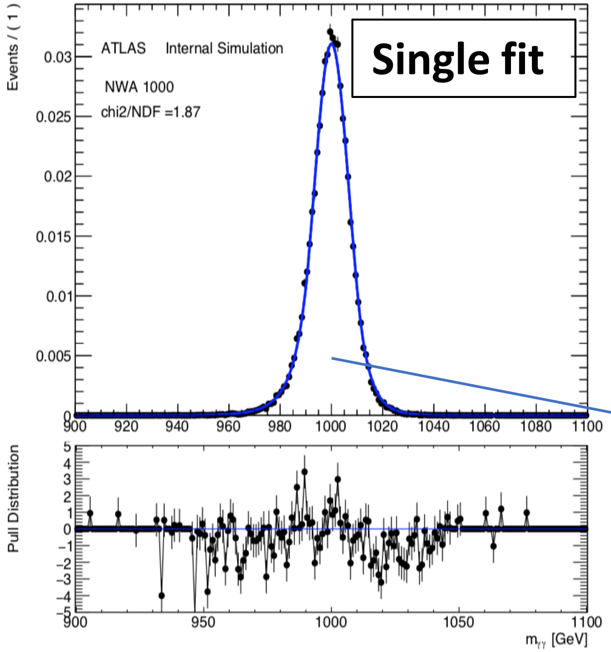
Signal modeling

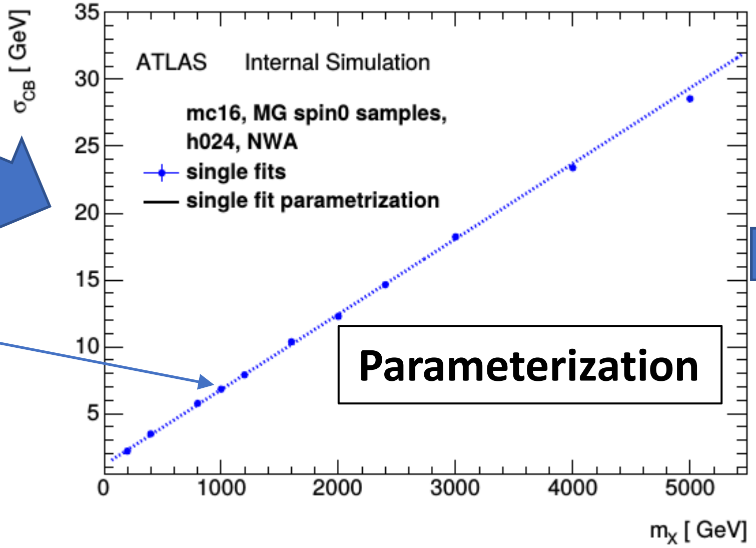


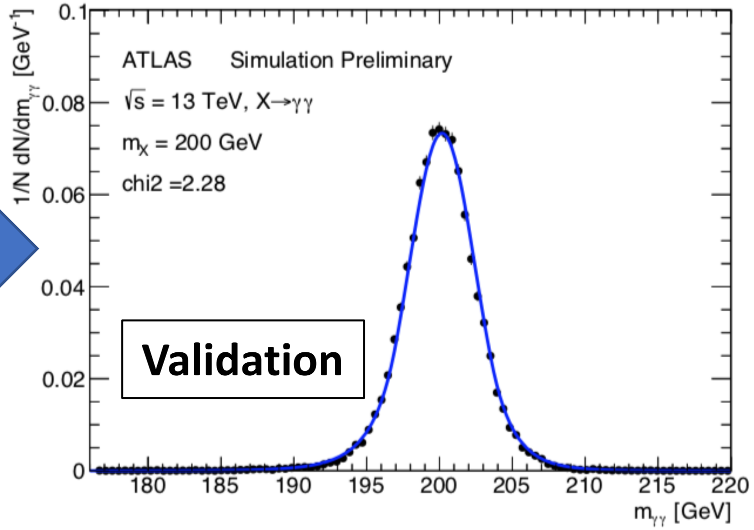
- **Narrow width approximation (NWA):**
  Signal shape dominated by detector resolution.
  - Modeled by a double-sided Crystal Ball function (DSCB).
  - Parameters of DSCB functions expressed as a function of m_X.

- **Large width (LW, $0.5\% \leq \Gamma_X/m_X \leq 10\%$):**
  - Convolving the resolution function and signal lineshape at generator level.
  - spin-2: graviton coupling $k/\overline{M_{pl}}$ is related to graviton width and mass:

$$\boldsymbol{\Gamma_{G^*} = 1.44(k/\overline{M_{pl}})^2 m_{G^*}}$$



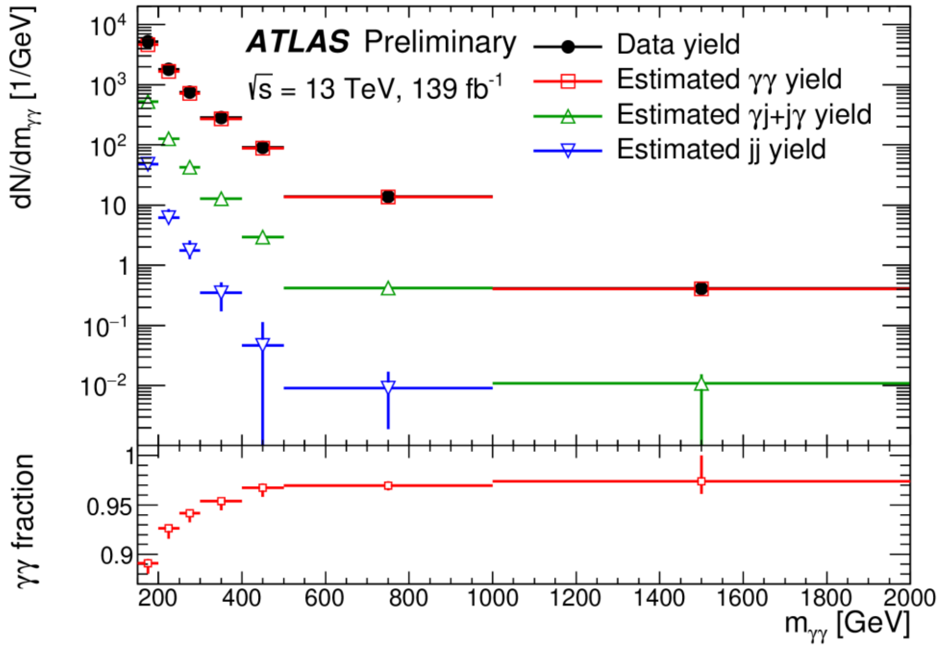




Background modeling

Background template is built from:

- real **γγ** events (irreducible background), modeled from Sherpa NLO MC simulation.
- **γ+jet**, **multi-jet** events (reducible background), modeled from data control region (CR).
    - ➢ inverting the identification requirement on the leading or sub-leading photon candidate
- The respective fraction of **γγ/γ+jet** (0.92/0.08) measured in data is used to normalize the background components.



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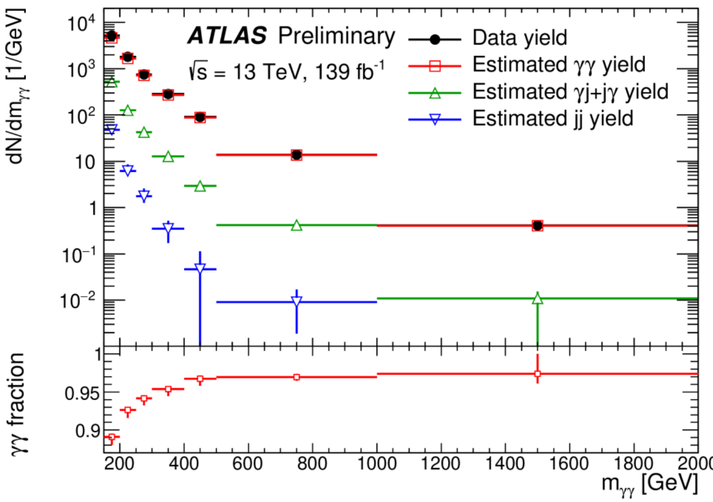
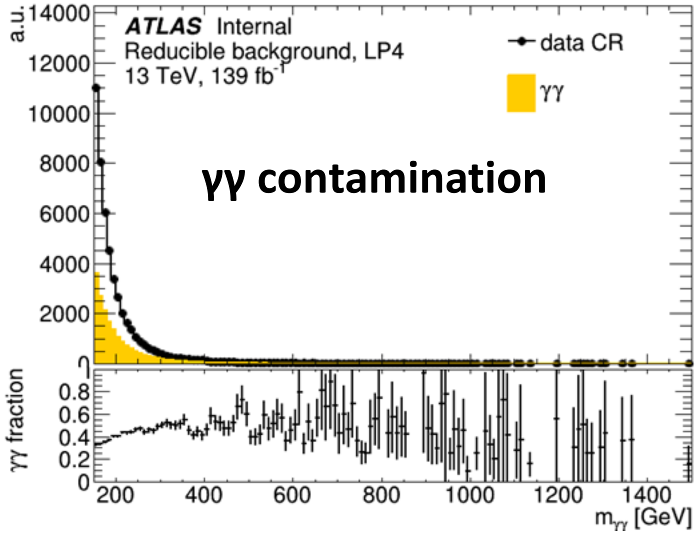
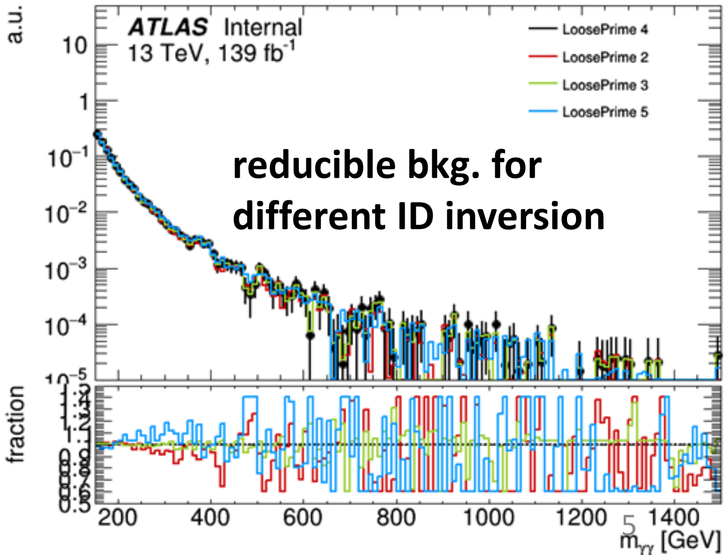


Shape of jet-enriched data CR might be biased:

- ➢ mismodeling of the γγ contamination
- ➢ definition of CR





Choice of background function

Total background template obtained by reweighting the γγ MC-based template to match the γγ+γjet shape.

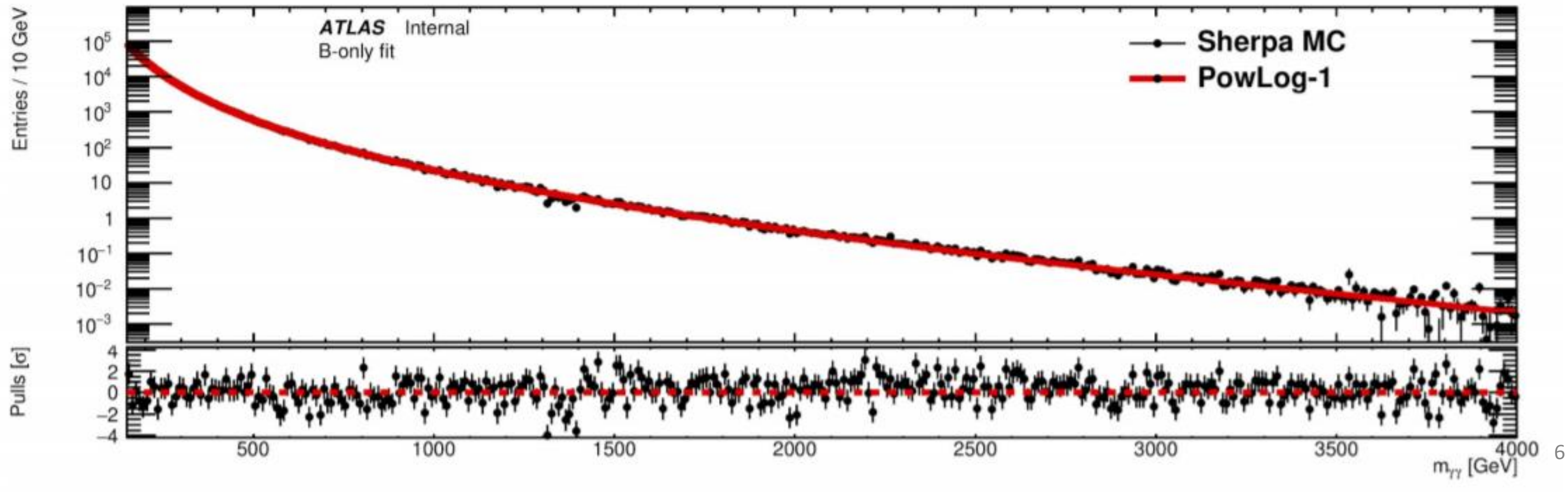
PowLog-n:

$$x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$$

$$f(x; \{a, a_i\}) = (1 - x^{1/3})^{a} \cdot x^{\sum_{i=0}^{n} a_i (\log x)^i}$$

Choice of background function: PowLog-1

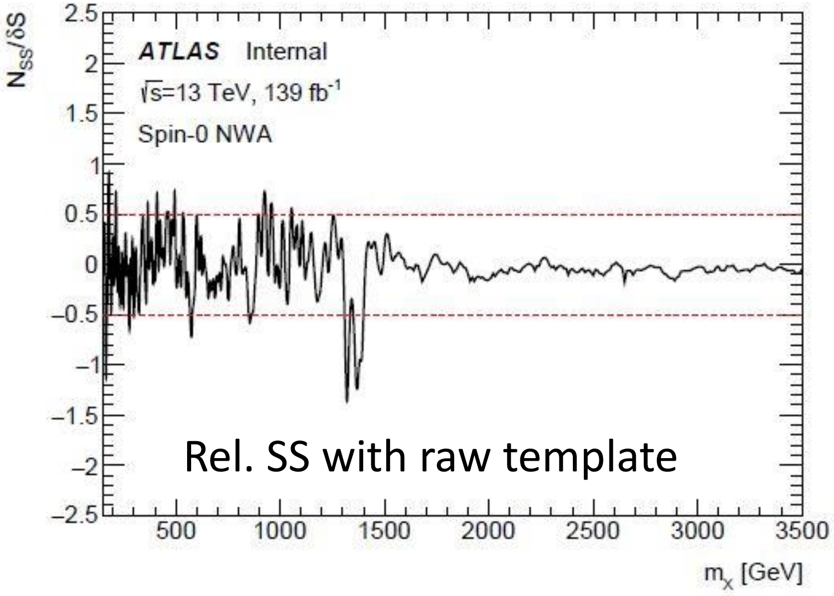
- Sufficient to fit the bkg. shape across 7 orders of magnitude with good fit quality ($p(\chi^2) > 0.35$).
- Flexible enough to describe all the systematic variations.

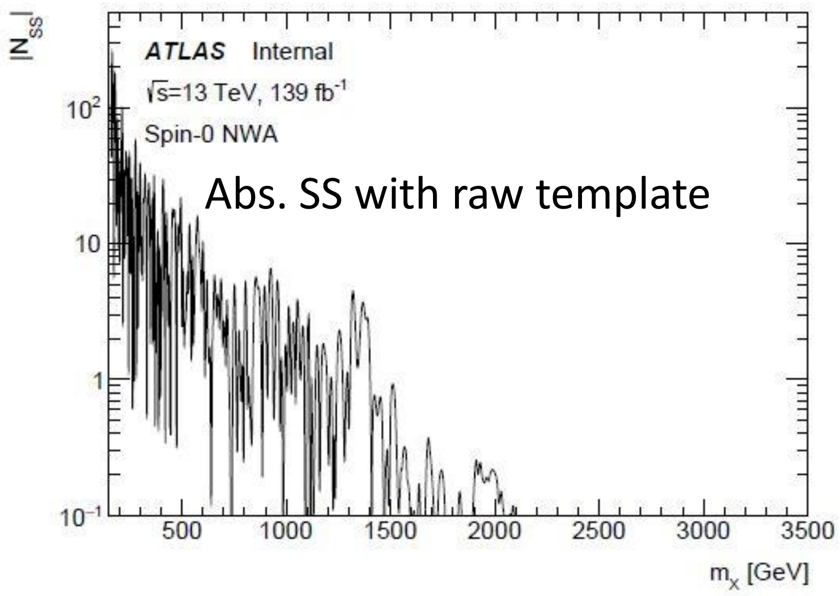


Spurious signal test and template smoothing

Bias on signal yield estimation from the background mismodeling, quantified by the extracted spurious signal yield (N_{SS}) when fitting the background-only template with signal+background model.

- Fluctuations from available MC statistics are dominating the estimation:
  - For $m_{\gamma\gamma}$~175-1.4 GeV, N_{MC} ~36×N_{data} → $N_{SS}/\delta S \sim 50\%.$
  - For $m_{\gamma\gamma}$>2 TeV, N_{MC} ~20k×N_{data} → negligible fluctuations.
- Precision of the SS estimation limited: template smoothed by fitting with a linear combination of a set of orthogonal exponential functions, in order to mitigate MC fluctuations.





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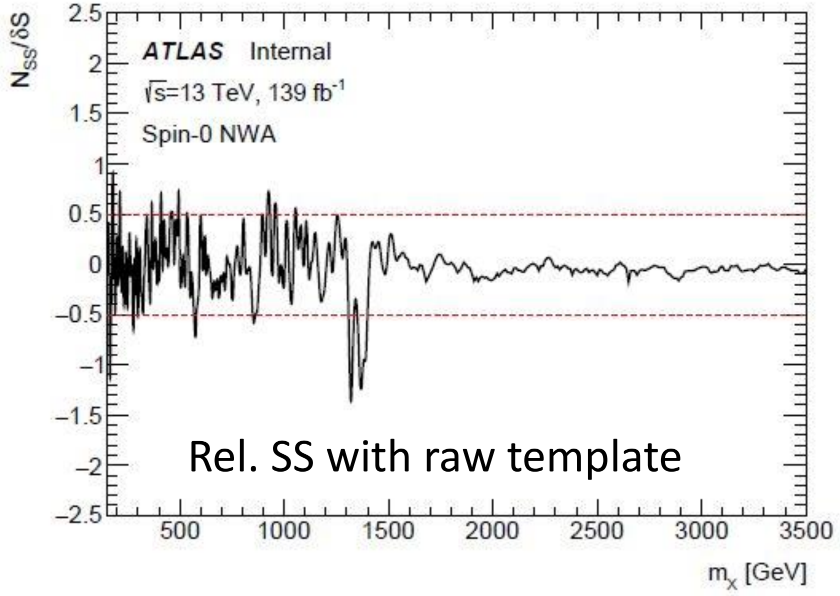
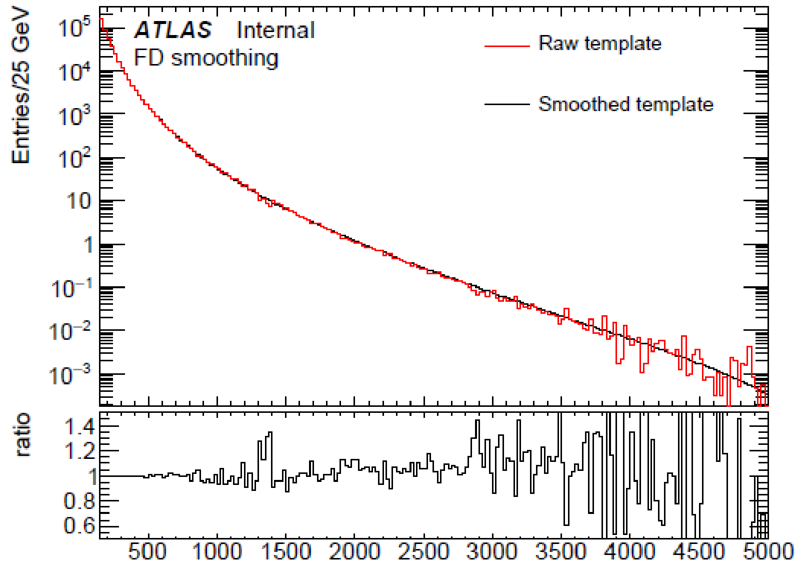
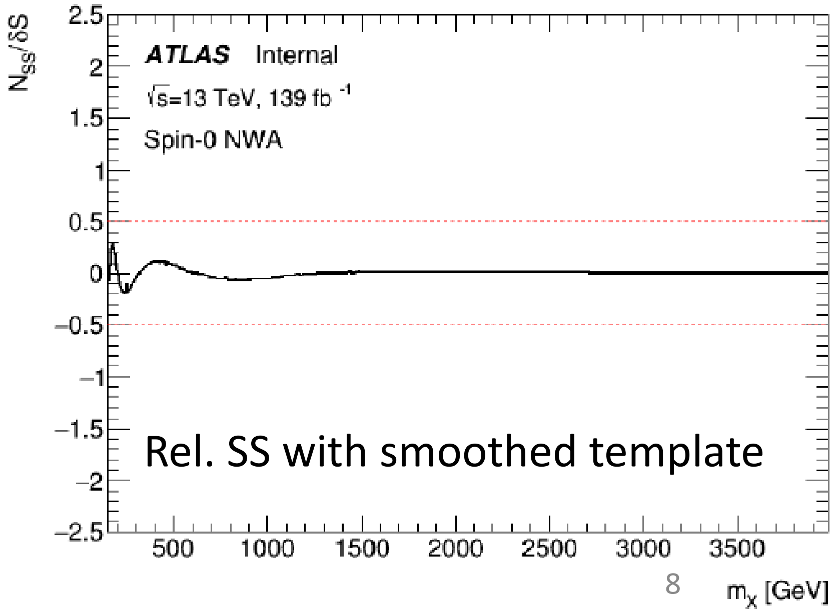






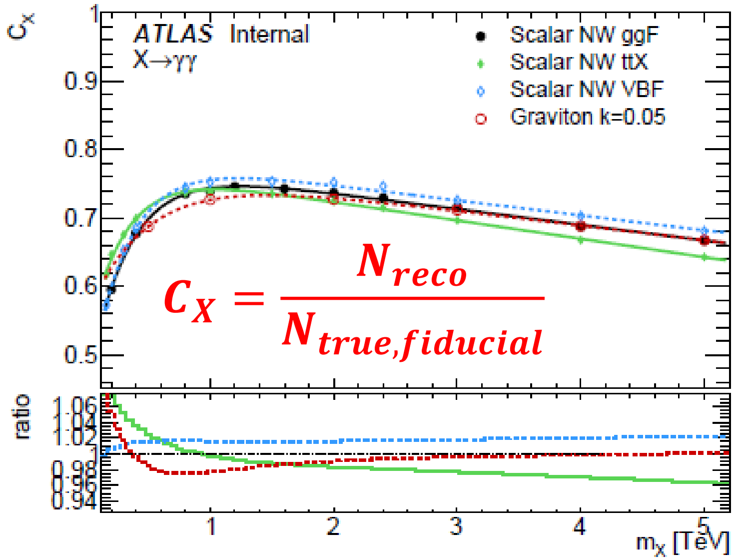
Fiducial and total acceptance corrections

Fitted signal yields are expressed as:

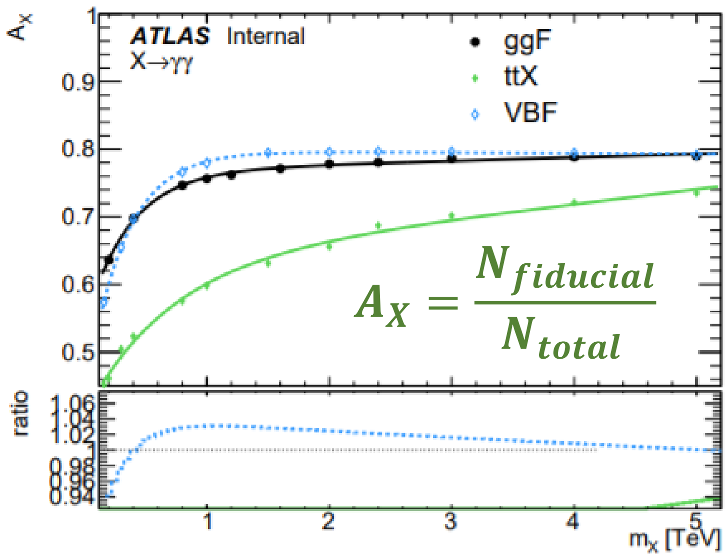
- **fiducial cross–section (Spin–0):** $\sigma_{X,fid} \cdot \mathcal{B}(X \to \gamma\gamma) = \frac{N_{sig}^{reco}}{C_X \cdot L_{int}}$
  - small difference seen in C_X between production modes, assigned as systematic uncertainty.
  - A_X factors provided as well for interpretations.
- **total cross–section (spin–2):** $\sigma_{X,total} \cdot \mathcal{B}(X \to \gamma\gamma) = \frac{N_{sig}^{reco}}{C_X \cdot A_X \cdot L_{int}}$
  - A_X independent of $k/\overline{M_{pl}}$.

Truth level fiducial selection

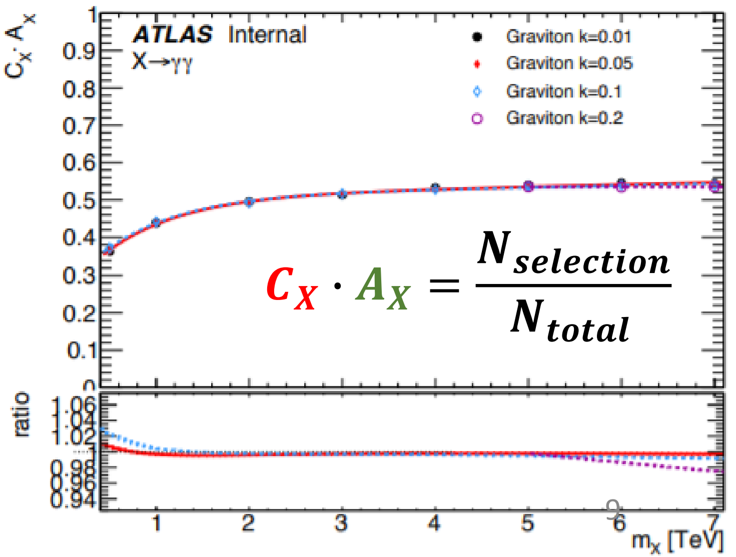
Object	Fiducial definition
Photons	$\lvert\eta^\gamma\rvert < 2.37$ (including crack)
	$\sum E_T^i < 0.05(E_T^\gamma + 120)$ GeV
Diphotons	$E_T^{\gamma_1}/m_{\gamma\gamma} > 0.3$, $E_T^{\gamma_2}/m_{\gamma\gamma} > 0.25$



(spin-0)



(spin-2)



Systematics overview

Signal yield			
Luminosity	±1.7%	Trigger	±0.5%
Photon identification	±0.5%	Photon isolation	±1.5%
Photon energy scale/resolution	negligible	Pile-up reweighting*	± (2–0.2) %
Spin-0 production process*	± (7–3) %		
*Signal modeling**			
Photon energy resolution	${}^{+14\%}_{-9.3\%}$ – ${}^{+51\%}_{-29\%}$		
Photon energy scale	±0.5%–±0.6%		
Pile-up reweighting	negligible		
*Spurious signal, Spin-0**			
NWA	114–0.04 events (m_X=160–2800 GeV)		
Γ_X/m_X= 2%	107–0.14 events (m_X=400–2800 GeV)		
Γ_X/m_X= 6%	223–0.38 events (m_X=400–2800 GeV)		
Γ_X/m_X= 10%	437–0.50 events (m_X=400–2800 GeV)		
*Spurious signal, Spin-2**			
$k/\overline{M}_{\mathrm{Pl}}$= 0.01	4.71–0.04 events (m_{G^*}=500–2800 GeV)		
$k/\overline{M}_{\mathrm{Pl}}$= 0.05	19.0–0.09 events (m_{G^*}=500–2800 GeV)		
$k/\overline{M}_{\mathrm{Pl}}$= 0.1	31.2–0.20 events (m_{G^*}=500–2800 GeV)		

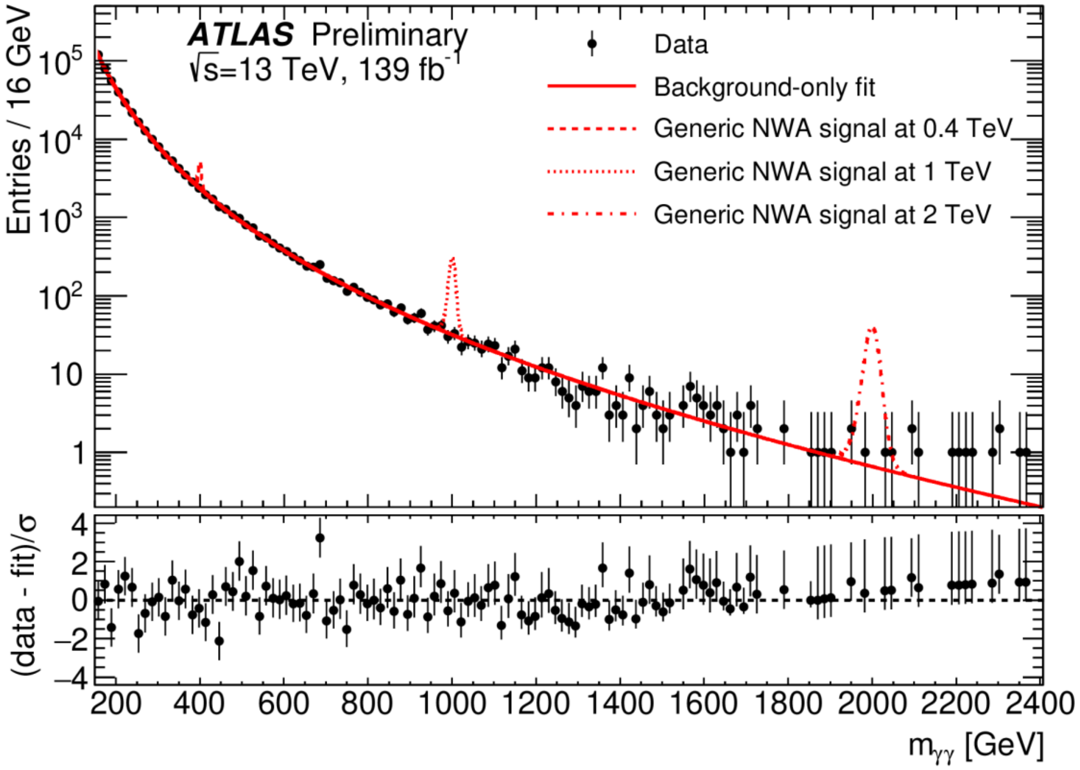
* mass-dependent

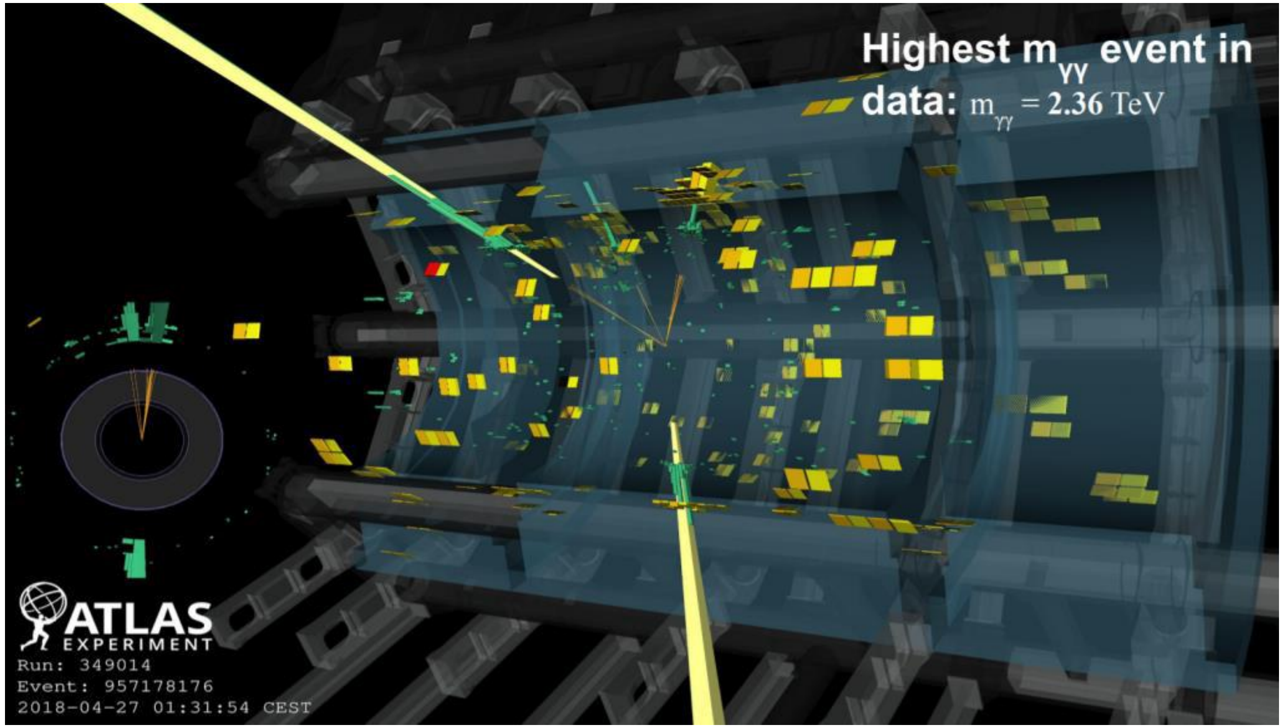
C_X correction uncertainty dominated by production mode dependence.

Signal model systematics dominated by photon energy resolution uncertainty.

Signal yield systematics from spurious signal is significant for $m_X < 400$ GeV and for large width signals.

Background-only fit to data





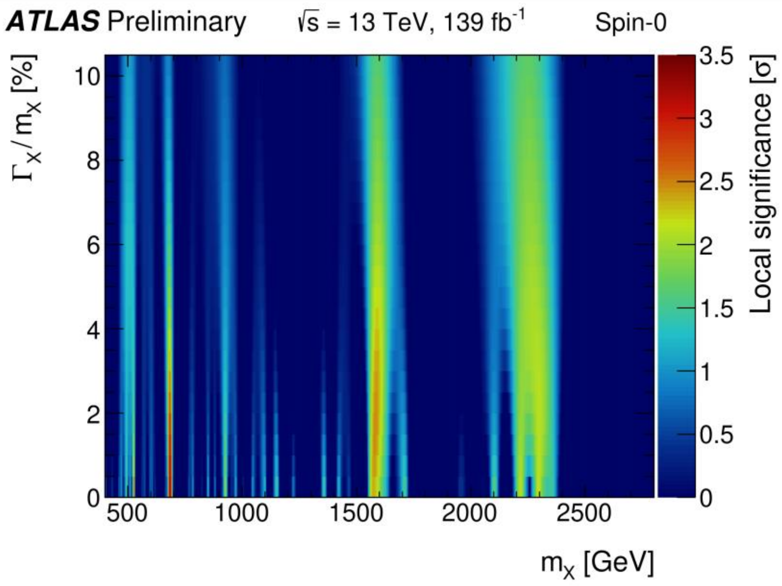
Background function: PowLog-1

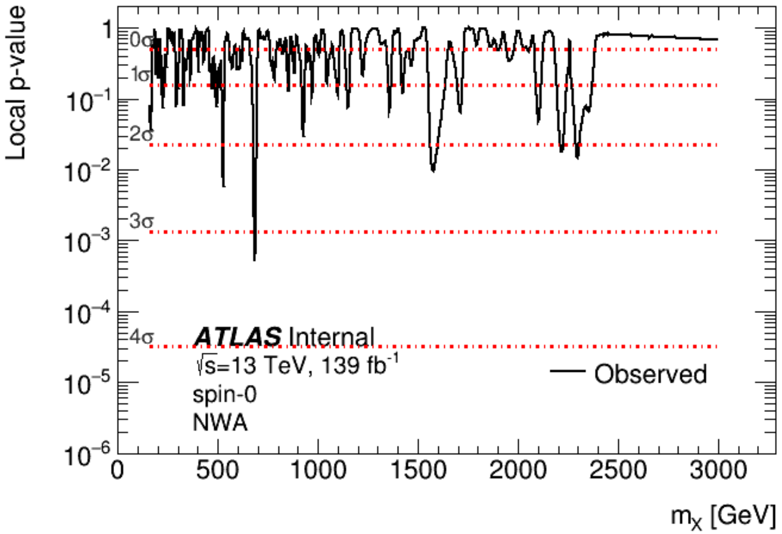
$$f(x; a, a_0) = (1 - x^{1/3})^a \cdot x^{a_0}$$

(generic narrow-width signal shapes shown to illustrate the signal resolution)

Highest $m_{\gamma\gamma}$ observed in data: 2.36 TeV.

Spin-0 results

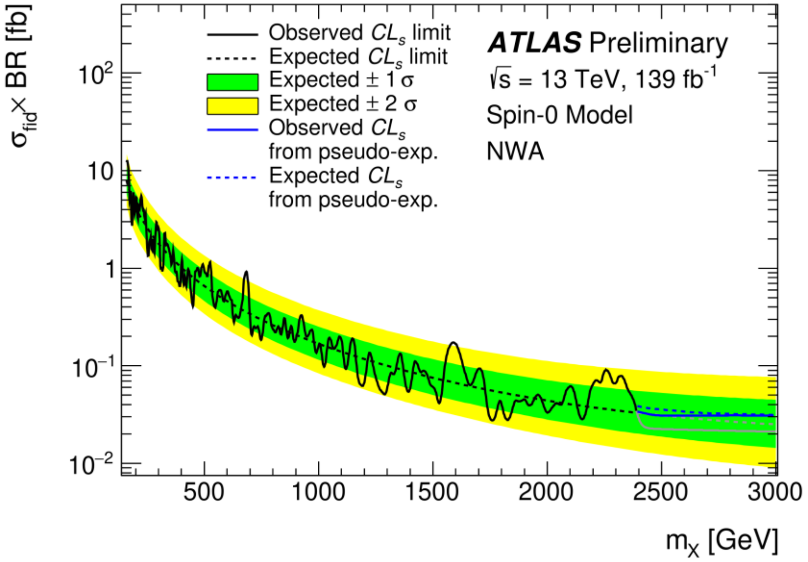




Local p-value is scanned in both resonance mass and width in the range:

- m_X = [160, 3000] GeV for NW
- m_X = [400, 2800] GeV for LW
- Γ_X/m_X = [0, 0.1]

(Scanned in 2 GeV steps in m_X and 0.005 steps for Γ_X/m_X)



Largest deviation found at m_X = 684 GeV (NWA):

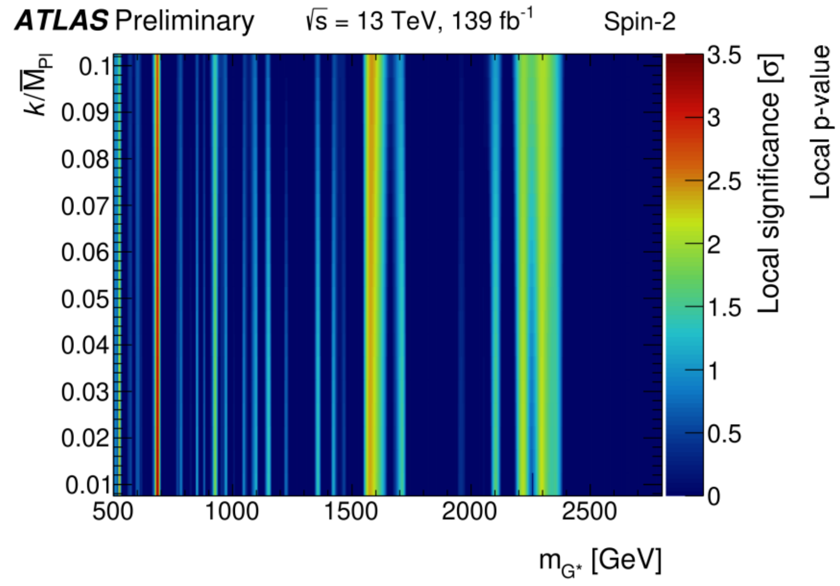
- 3.29σ local, 1.3σ global significance considering look-elsewhere effect.

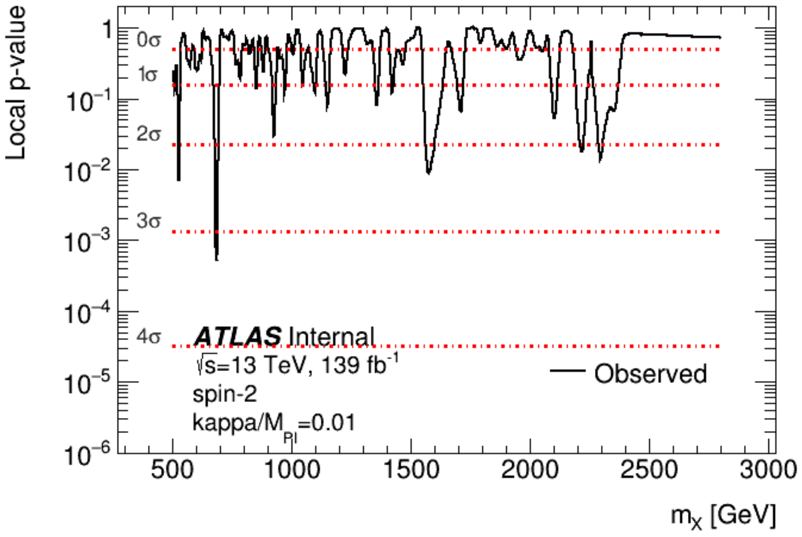
Observed limits set on the fiducial cross-section times branching ratio:

m_X	400 GeV	2800 GeV
NWA	1.1 fb	0.03 fb
Γ_X/m_X= 2%	2.5 fb	0.03 fb
Γ_X/m_X= 6%	4.4 fb	0.03 fb
Γ_X/m_X= 10%	8.3 fb	0.03 fb

Spin-2 results

$$\Gamma_{G^*} = 1.44(k/\overline{M_{pl}})^2 m_{G^*}$$

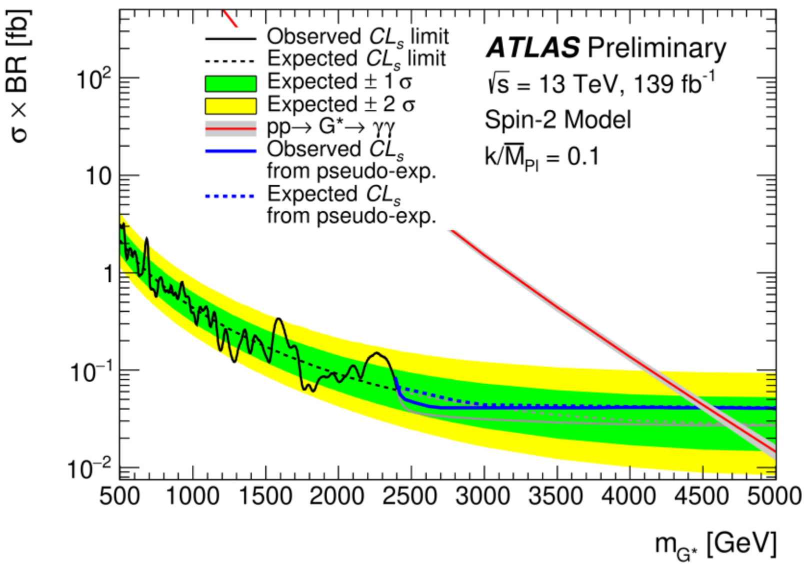




Local p-value is scanned in both resonance mass and width in the range:

- m_{G^*} = [500, 2800] GeV
- $k/\overline{M_{pl}}$ = [0.01, 0.1]

(Scanned in 2 GeV steps in m_{G^*} and 0.005 steps for $k/\overline{M_{pl}}$)



Largest deviation found at m_X = 684 GeV ($k/\overline{M_{pl}}$ = 0.01):

- 3.29σ local, 1.36σ global significance considering look-elsewhere effect.

Observed limits set on the total cross-section times branching ratio:

m_{G^*}	500 GeV	5000 GeV
$k/\overline{M}_{\mathrm{Pl}}$= 0.01	1.9 fb	0.04 fb
$k/\overline{M}_{\mathrm{Pl}}$= 0.05	2.3 fb	0.04 fb
$k/\overline{M}_{\mathrm{Pl}}$= 0.1	3.2 fb	0.04 fb

Summary

- Results of the search for a new resonance in the diphoton final state with full Run 2 data published on ICHEP 2020 (ATLAS-CONF-2020-037), paper aiming PLB under preparation.

- No significant excess observed from the Standard Model expectation considering the look-elsewhere effect. For both spin-0 and spin-2 signal, largest deviation (3.29σ local, ~1.3σ global significance) found at m_X = 684 GeV.

- Limits on the spin-0 and spin-2 resonance determined. The RS1 graviton model is excluded for m_{G^*} below 2.2, 3.9 and 4.5 TeV for coupling $k/\overline{M}_{pl}$ of 0.01, 0.05 and 0.1 respectively.

BACK UP

Data and MC samples

Samples used in this analysis:

- **Data** 2015-2018 (~139fb^{-1}), recorded with diphoton triggers
  - **HLT_g35_loose_g25_loose** for 2015-2016 (37 fb^{-1})
  - **HLT_g35_medium_g25_medium_L12EM20VH** for 2017-2018 (102 fb^{-1})

- **MC** signal spin-0/spin-2 (same samples as for 37 fb^{-1} paper)
  - aMC@NLO ggF production of scalars with narrow or large width (2%, 6%, 10% of m_X)
  - Alternative samples: Powheg ggF, VBF and Pythia VH, ttH for systematic studies
  - Pythia spin-2 graviton with couplings/widths $\mathrm{k}/\overline{M}_{Pl}$[0.01→0.1]

- **MC** background
  - Sherpa 2.2.4 diphoton (NLO) mc16(a+d+e) events

Generator	$m_{\gamma\gamma}$ range [GeV]	Cross section [pb]	Filter efficiency	N_{events}
Sherpa+Fastsim	90–175	51.822	1	50.8M
	175–2000	10.999	1	35.3M
	1400–2000	$3.992 \cdot 10^{-3}$	1	400k
	2000–∞	$703 \cdot 10^{-6}$	1	400k

Event selection and harmonization

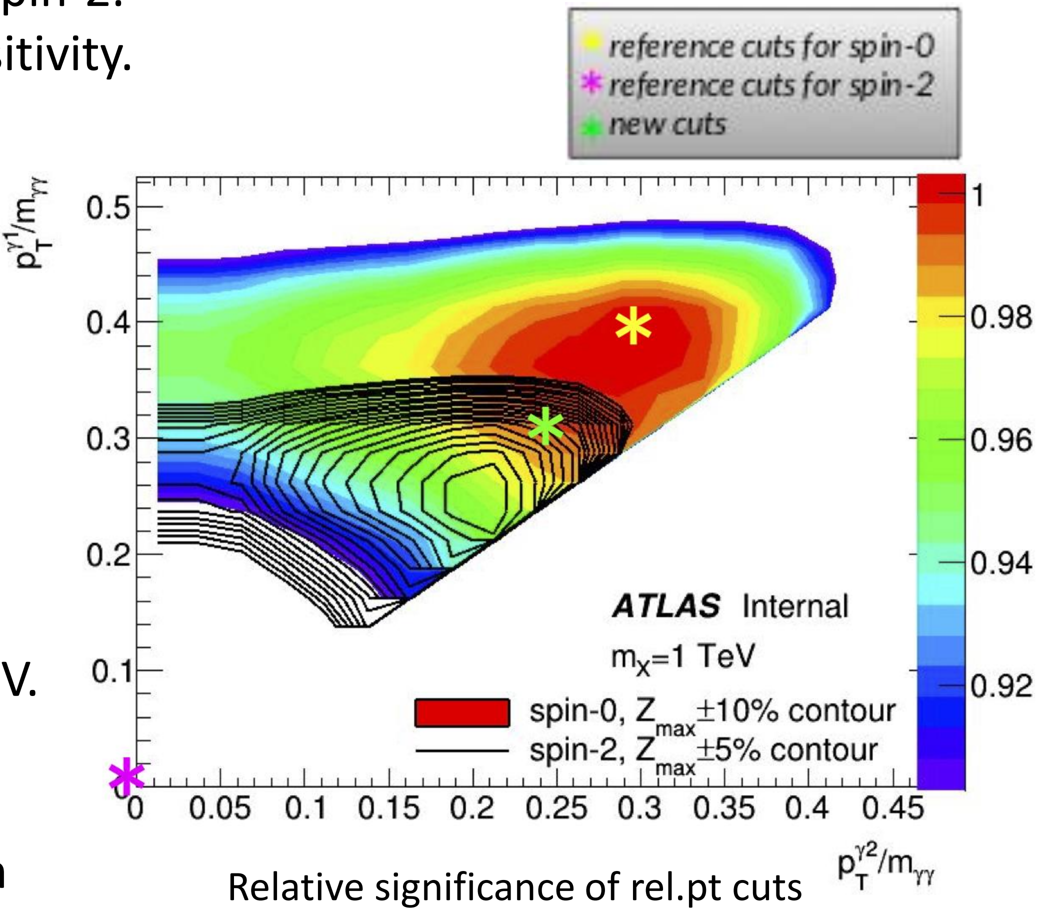
- Minimal optimizations w.r.t. the 37 fb^{-1} paper.
- Harmonized kinematic and isolation selections for spin-0/spin-2.
- Same background estimation method, minimal loss in sensitivity.

Event selection:

- Fixed kinematic cuts: $E_T^{\gamma1} > 40$ GeV, $E_T^{\gamma2} > 30$ GeV
- $|\eta^{\gamma}| < 2.37$, excluding crack region
- Isolation working point: FixedCutTight (etcone40 used)
- Photon ID: Tight
- Relative E_T cuts: $E_T^{\gamma1}/m_{\gamma\gamma} >$ **0.3**, $E_T^{\gamma2}/m_{\gamma\gamma} >$ **0.25**

Sensitivity with new relative $E_T^{\gamma}/m_{\gamma\gamma}$ cuts:

- Spin-0: slightly suboptimal < 400 GeV, but better above 1 TeV.
  - At 1 TeV, ~1% worse than optimal cuts.
- Spin-2: worse at lower masses, better above 1 TeV.
  - At 1 TeV, ~2% worse than optimal cuts, 10% better than no rel. E_T cuts.

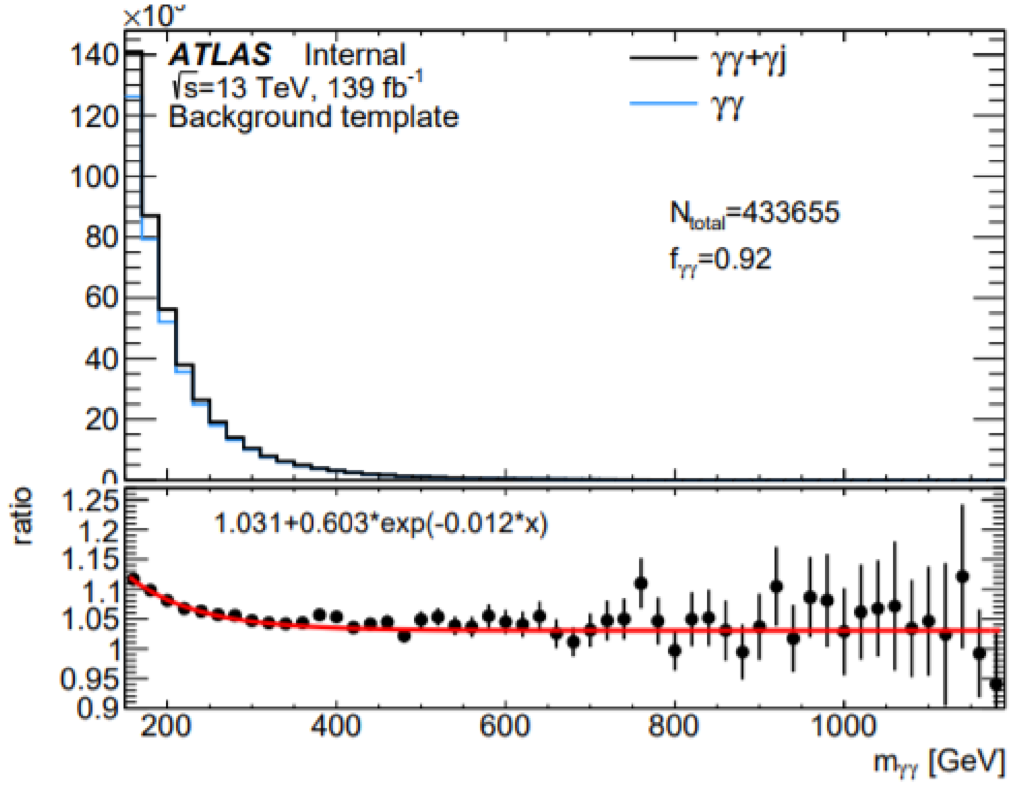


Relative significance of rel.pt cuts compared to reference cuts used in 37/fb publication

Reducible background smoothing

ID name	Cuts
Loose	$R_{\text{had}1}$, R_{had}, R_η, $w_{\eta 2}$
Tight	Loose + R_ϕ, w_{s3}, F_{side}, ΔE, E_{ratio}, $w_{s1,\text{tot}}$
LoosePrime 2	Tight – w_{s3}, F_{side}
LoosePrime 3	Tight – w_{s3}, F_{side}, ΔE
LoosePrime 4	Tight – w_{s3}, F_{side}, ΔE, $w_{s1,tot}$ default
LoosePrime 5	Tight – w_{s3}, F_{side}, ΔE, E_{ratio}, $w_{s1,tot}$

Data control region has limited statistics, and we need smooth γ+jet shape to add to γγ component.



Procedure to smooth γjet:

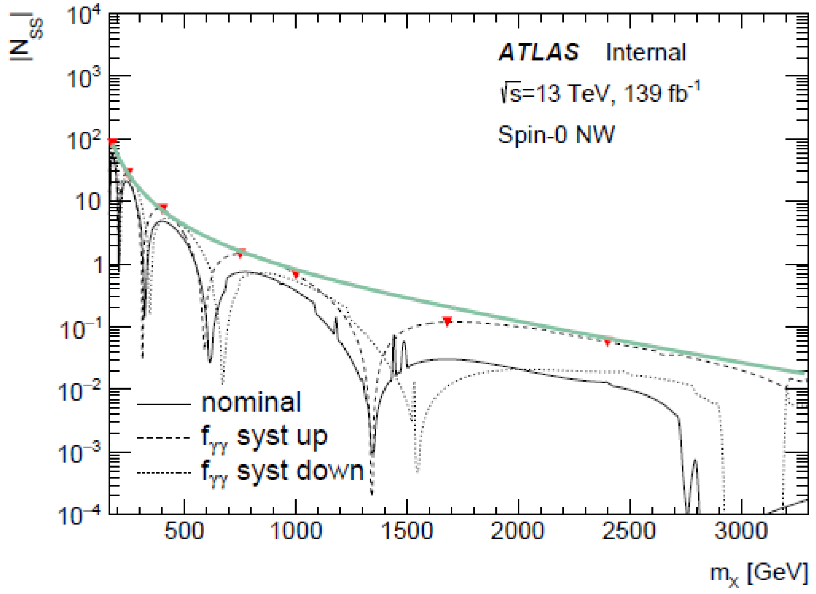
- Template from MC γγ → normalize to $f_{\gamma\gamma} \times N_{data}$
- Template from data CR (γj) → normalize to $(1 - f_{\gamma\gamma}) \times N_{data}$
- Fit the ratio (γγ+γj)/γγ → easy to model with a simple exponential function
- Use the function to reweight γγ to match the shape of the total background

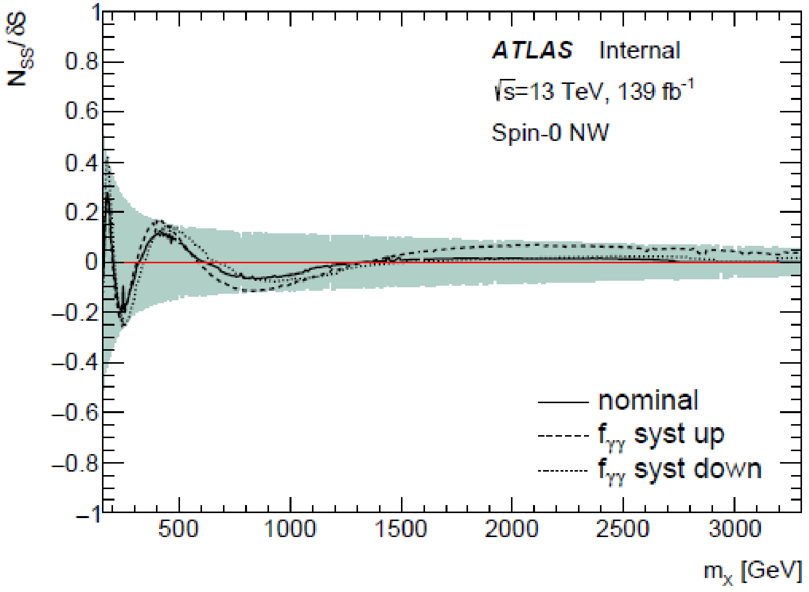
Spurious signal parameterization

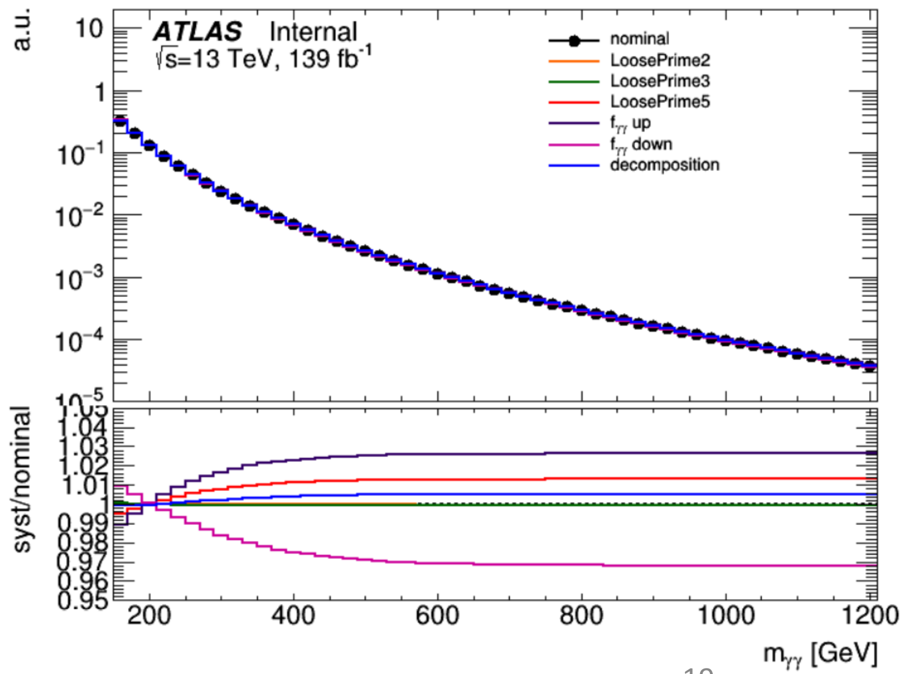
Bias on signal yield estimation from the background mismodeling, quantified by the extracted spurious signal yield (N_{SS}) when fitting the background-only template with signal+background model.

Parameterization:

- Recompute N_{SS} with all the systematic variations of background shape.
- Fit the local maxima N_{SS} to get an envelope as a function of m_X.





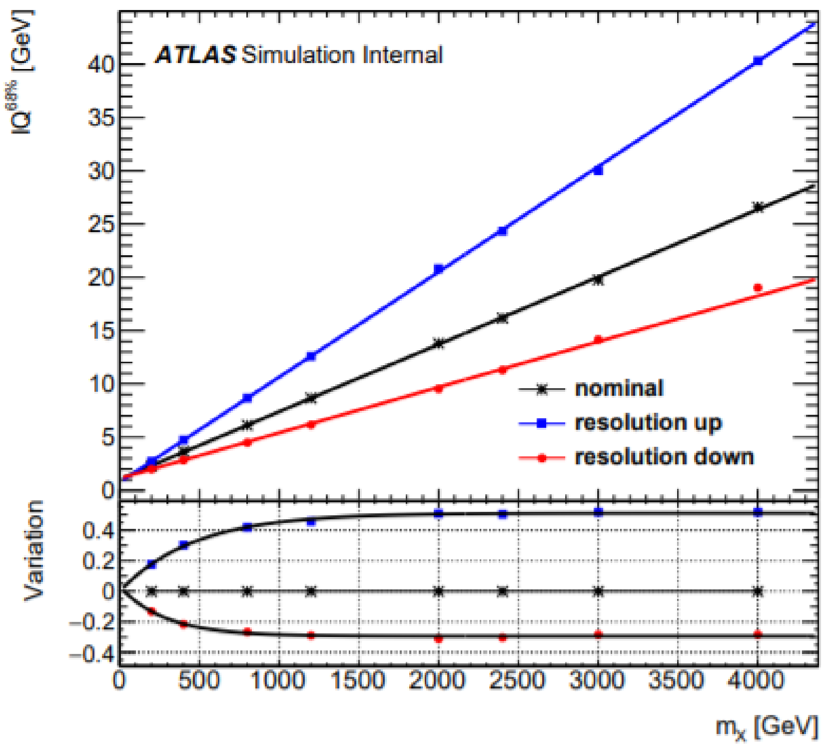


Signal modeling systematics: Exp. uncertainty

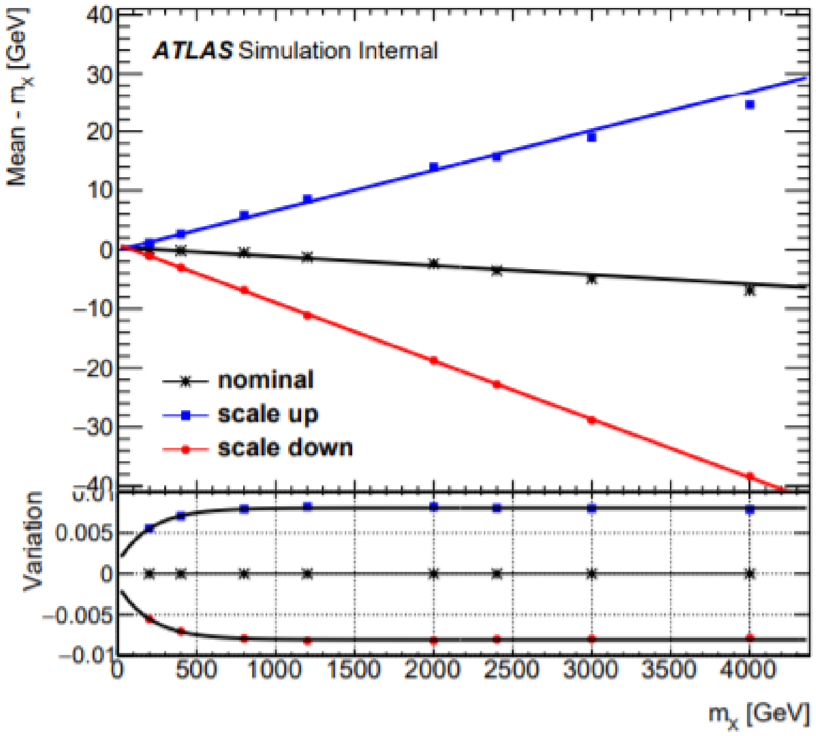
In order to compute the systematic uncertainty associated with the photon energy scale and resolution, the energy of the photon candidates selected in the signal MC samples is shifted up and down by the corresponding uncertainties.

- **Energy resolution:** estimated from the difference in the 68% interquantile (IQ_{68}) of the signal inv. mass distribution compared to nominal.
- **Energy scale:** estimated from the shift of the mean value of the signal inv. mass distribution compared to nominal.

- Validated for all mass points.

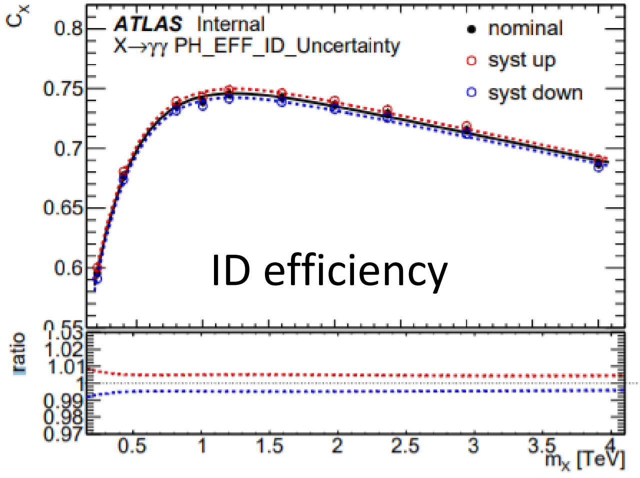


Resolution systematic on σ of DSCB described exponentially as a function of m_X: <+51%/-29%

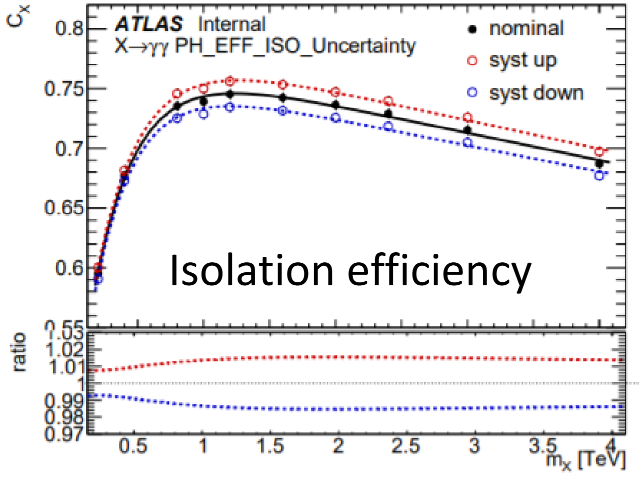


Energy scale uncertainty on m_X: <1%

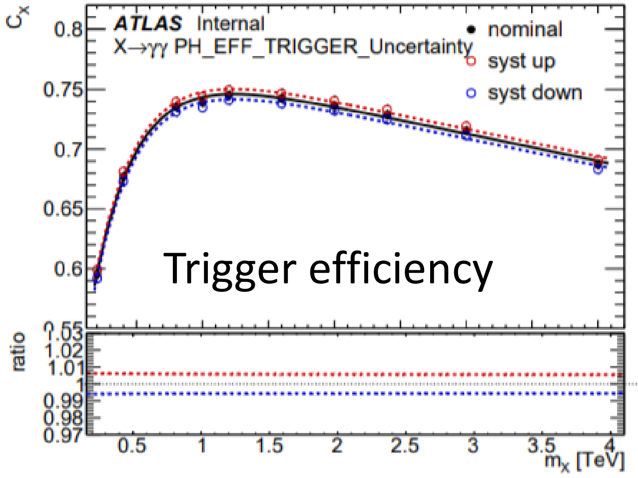
Systematics on C_X factor



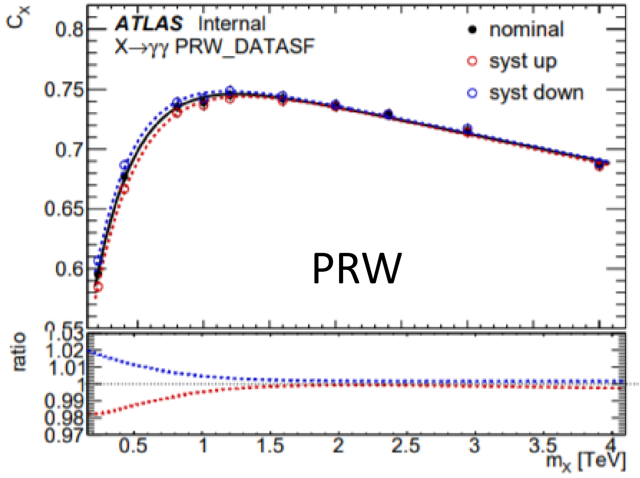
(a)



(b)

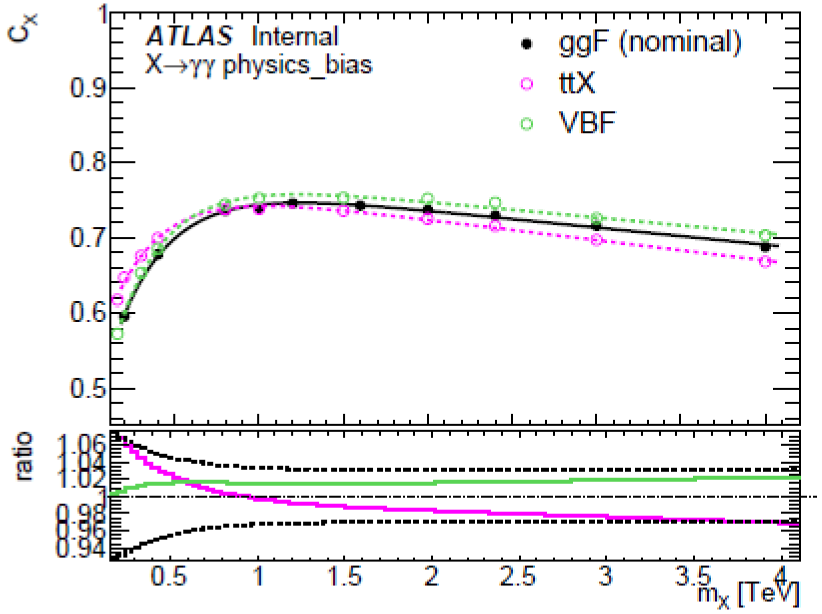


(c)



(d)

Effect of several sources of experimental uncertainty on the correction factor.



Effect of different signal kinematics associated with the assumed production mode on the correction factor.

Maximum effect coming from experimental uncertainties ~2% (PRW), while <7% effect from assumed production mode.