Search for high-mass diphoton resonances with the ATLAS detector

Kirill Grevtsov (LAPP)
on behalf of the **ATLAS** collaboration

Higgs Hunting 2016, Paris
1st September 2016

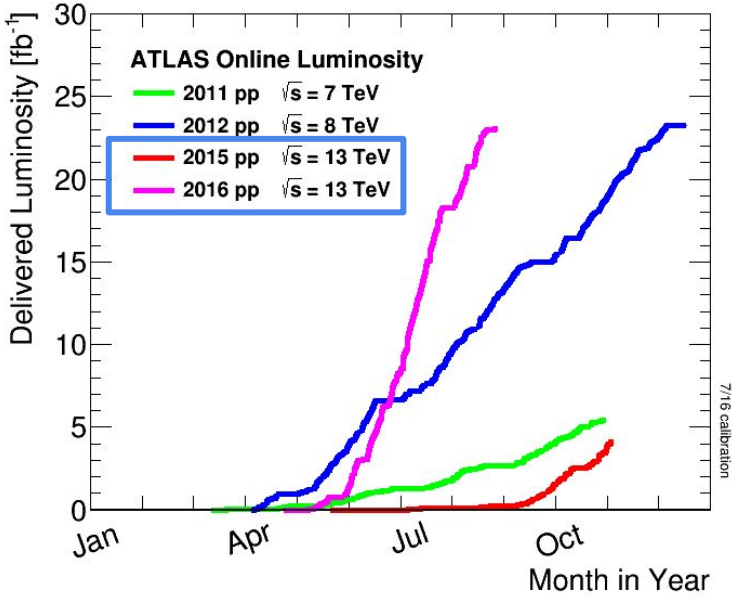
Data taking with √s=13 TeV

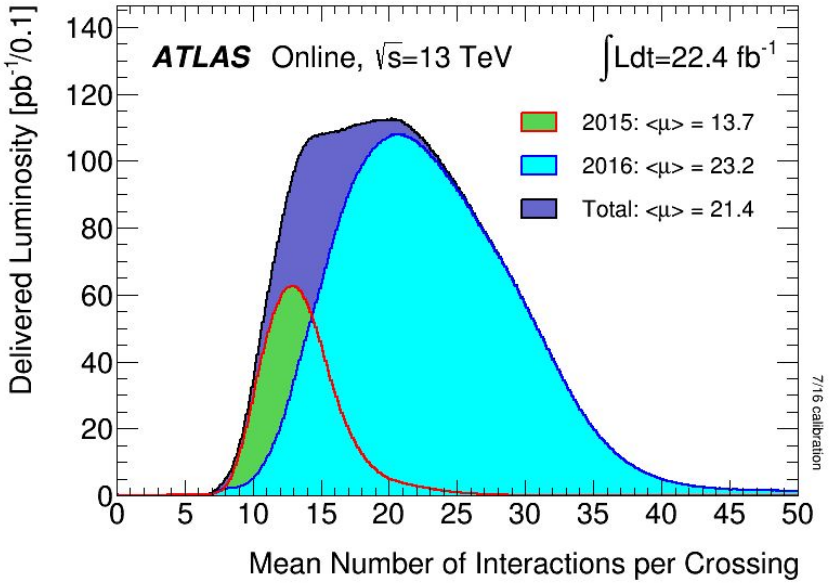
Operation of LHC and ATLAS detector in Run 2 with increased center of mass energy to **13 TeV**!

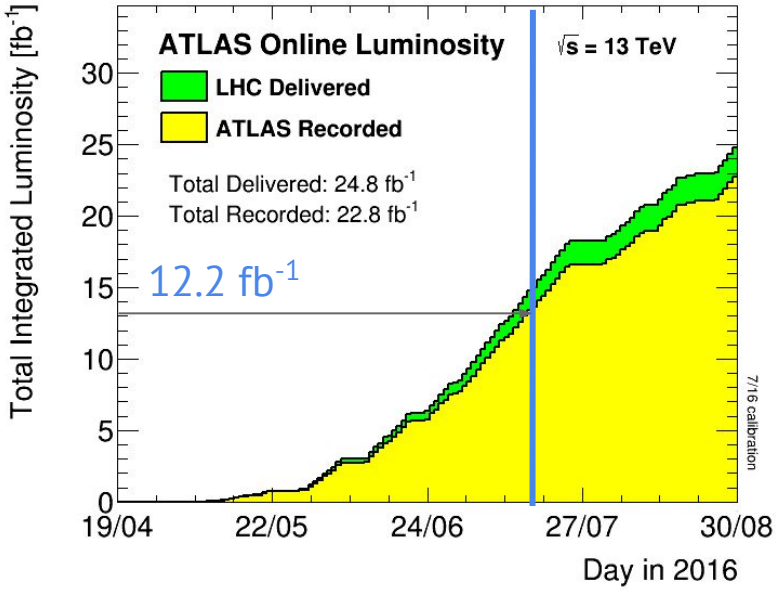
3.2 fb^{-1} collected in **2015** dataset

For **2016** data:

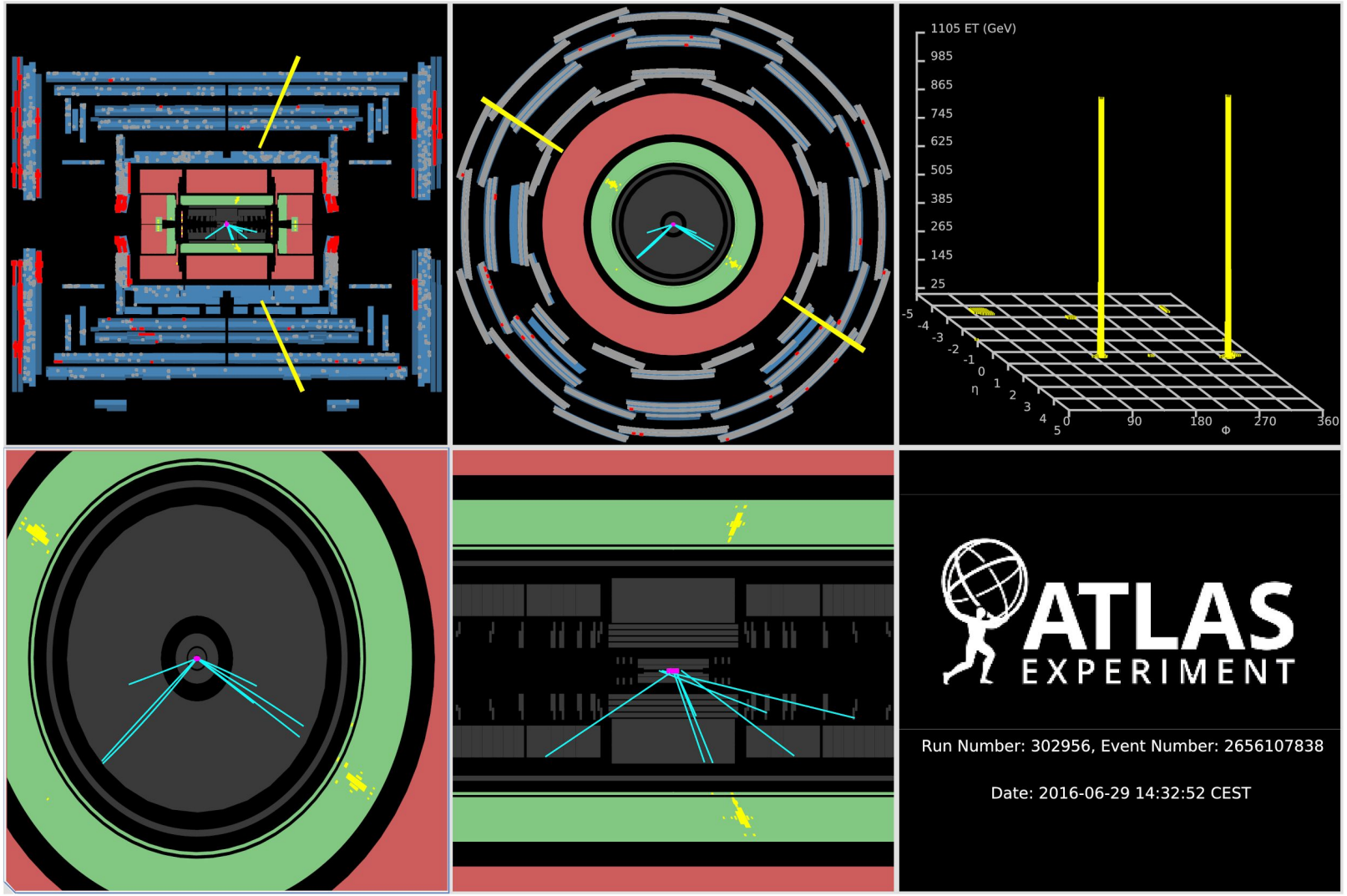
- Maximum peak luminosity **11.6×10^{33}** cm^{-2} s^{-1}
- High data-taking efficiency >90%
- About **23 fb^{-1}** collected
  - 12.2 fb^{-1} presented today collected by last week of July





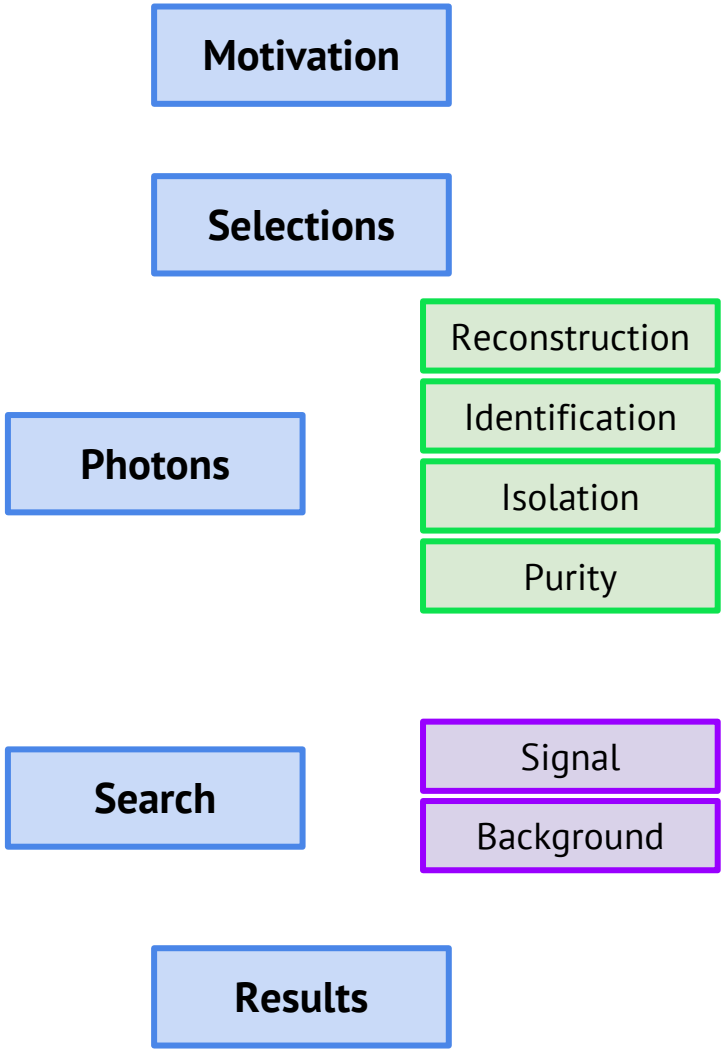


Event with highest invariant mass $m_{\gamma\gamma}$=2.2 TeV

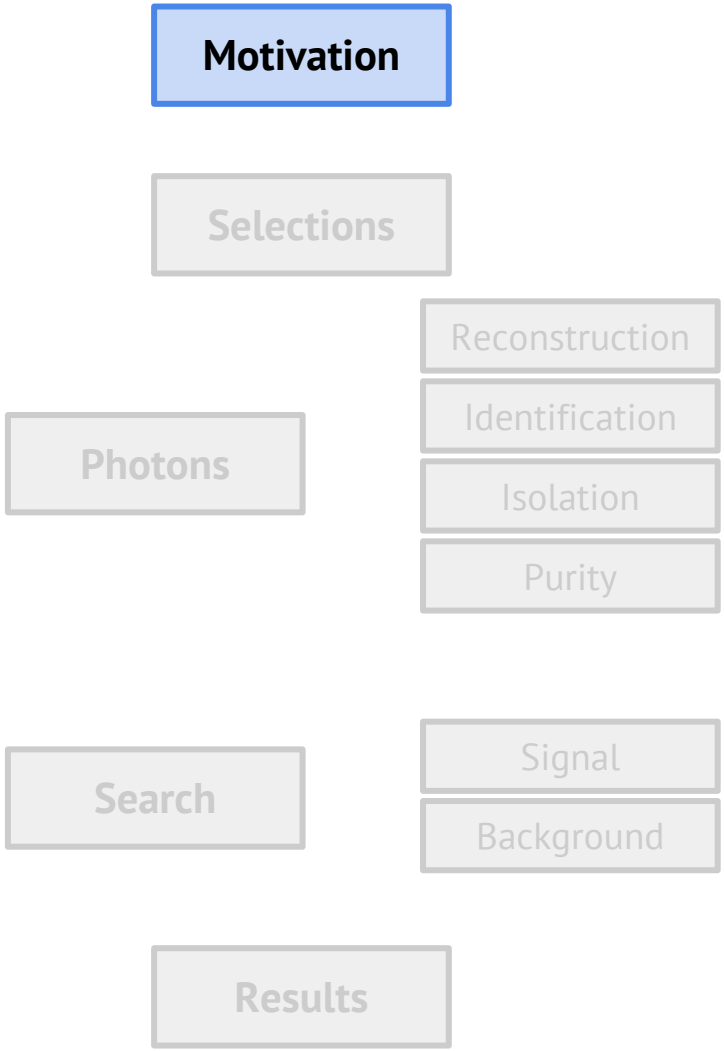


- **Leading photon:** unconverted, E_T = 1.1 TeV, η = 0.45, φ = −0.58, E_T^{iso} = 5.2 GeV
- **Subleading photon:** converted, E_T = 1.1 TeV, η = 0.41, φ = 2.56, E_T^{iso} = -1.0 GeV

Search for diphoton resonances

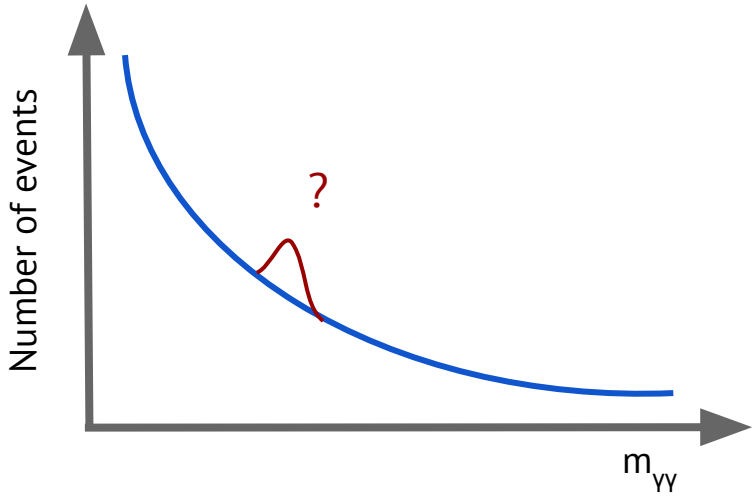


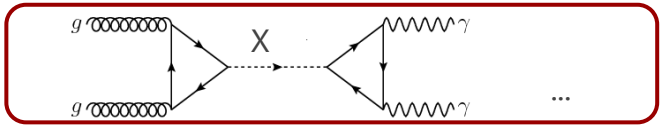
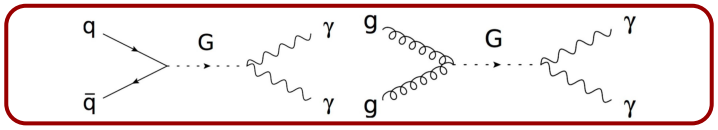
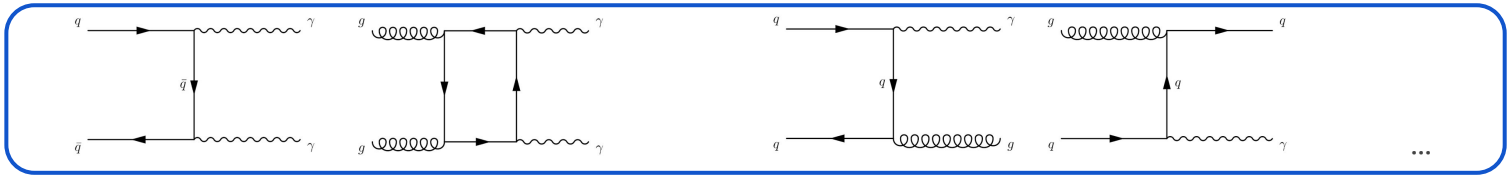
Search for diphoton resonances



Search for diphoton resonances

- Diphoton resonances predicted by several extensions of the Standard Model
- Clean experimental signature with excellent invariant mass resolution
- Smooth well known background



	Spin-0	Spin-2
Benchmark models	Extended Higgs sector 	Randall-Sundrum graviton 
Search range	m_X =[0.2 – 2.4 TeV] Γ_X/m_X = [0% - 10%]	m_G =[0.5 – 5 TeV] k/M_{Pl} = [0.01-0.3] ($\Gamma_G/m_G \sim 1.44\ (k/M_{Pl})^2$)
Backgrounds		

Search for diphoton resonances

Motivation

Selections

Photons

- Reconstruction
- Identification
- Isolation
- Purity

Search

- Signal
- Background

Results

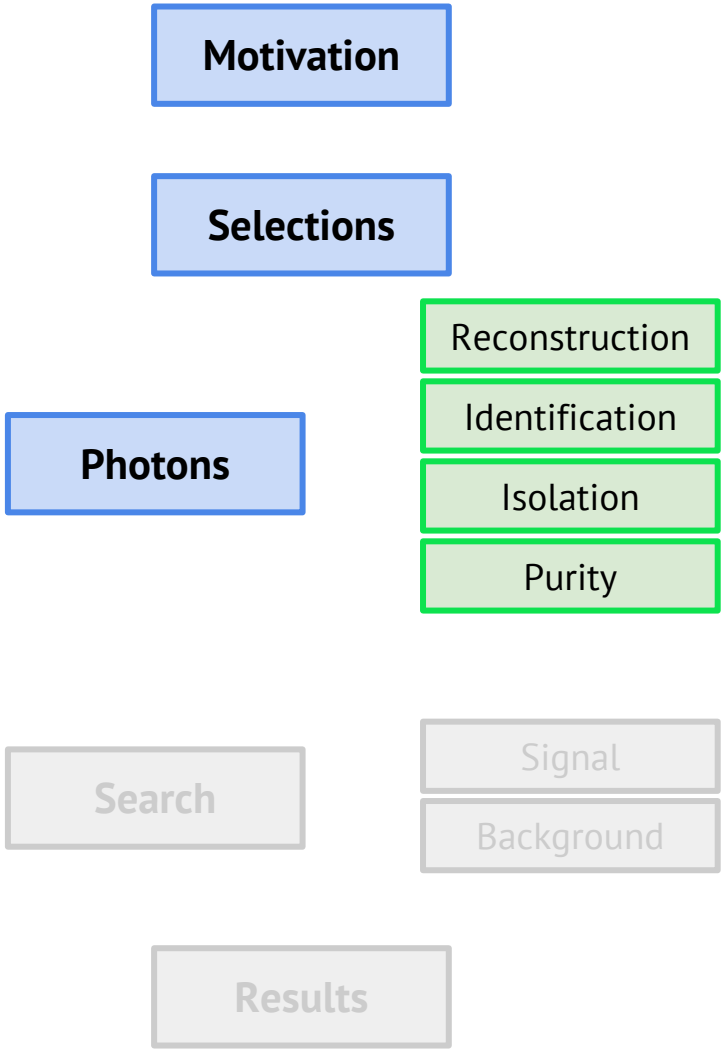
Overview of analyses

- Common selections & photon identification
  - Diphoton trigger: E_T >35 (25) GeV for leading (subleading) photon
  - Precision region of EM calorimeter: |η| < 2.37, 1.37-1.52 excluded
  - Tight identification, based on shower moments in EM + HAD calorimeters
  - Photon isolation (calorimeter and tracks)

	Spin-0	**Spin-2**
Kinematics	$E_T^{\gamma 1} > 0.4 m_{\gamma\gamma}$, $E_T^{\gamma 2} > 0.3 m_{\gamma\gamma}$ • +20% sensitivity for m_X>600 GeV wrt absolute cuts • Effectively deplete forward regions	$E_T^{\gamma 1}$ >55 GeV and $E_T^{\gamma 2}$ >55 GeV • Acceptance extended to large rapidities

- Published analysis paper (accepted to JHEP) based on 2015 data (3.2 fb^{-1})
- Results presented today 15.4 fb^{-1} (ATLAS-CONF-2016-059)

Search for diphoton resonances

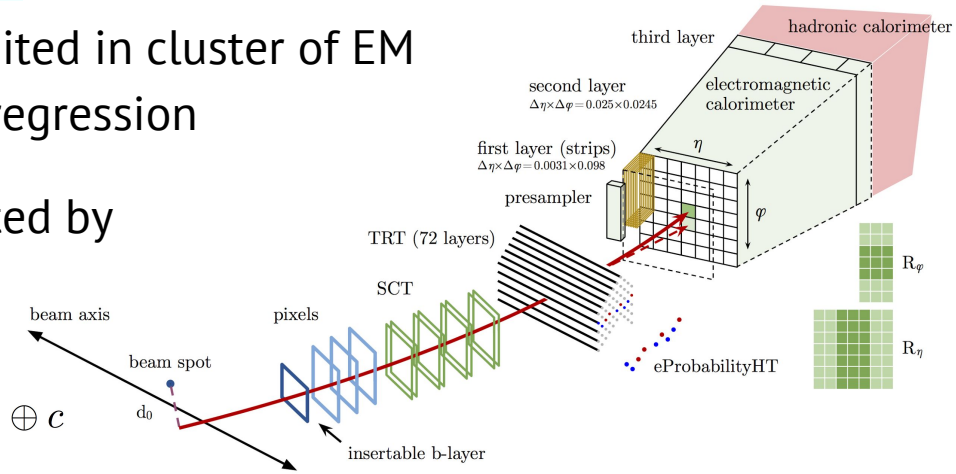


Photons in ATLAS

- Photons reconstructed from energy deposited in cluster of EM calorimeter, calibrated with multivariate regression

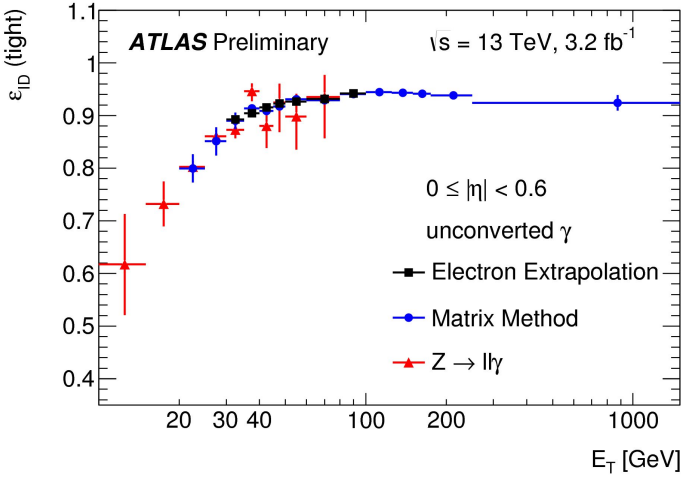
- At high E_T^{γ} (>200 GeV) resolution dominated by constant term (0.6%-1.5%, η-dependent)
  - σ=6.2 GeV @ $m_{\gamma\gamma}$=750 GeV
  - σ=15 GeV @ $m_{\gamma\gamma}$=2 TeV

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$



- Photons energy scale and resolution extrapolated from Z→ee events

  Uncertainties:
  - Energy scale : ±(0.5 – 2.0)%
  - Energy resolution (E_T = 300 GeV): ±(30–45)%

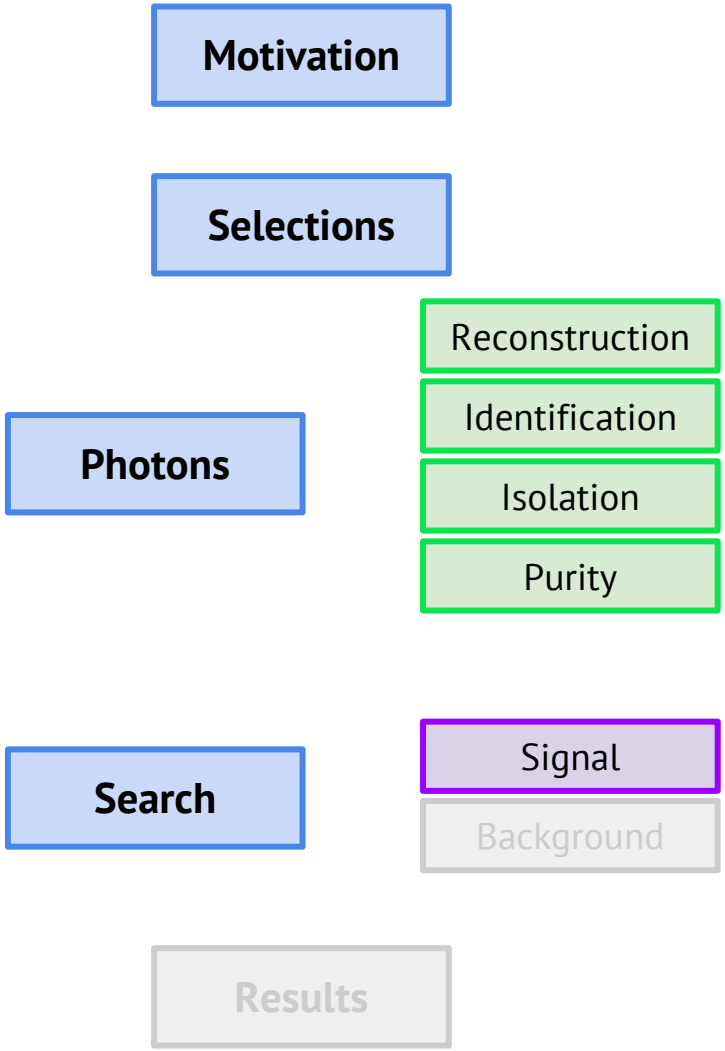


- The **tight identification** selections for converted and unconverted photons
  - ε^{ID}~95% (90%) for γ^{conv} (γ^{unconv}) E_T=200 GeV

- **Isolation**
  - Calorimeter (ΔR=0.4): $E_T^{iso} < 0.022\ E_T^{\gamma} + 2.45$ GeV
  - Track p_T^{iso} (ΔR=0.2): $p_T^{iso} < 0.05\ E_T^{\gamma}$

- **Purity** of diphoton passing selection is **~93%** for $m_{\gamma\gamma}$>200 GeV

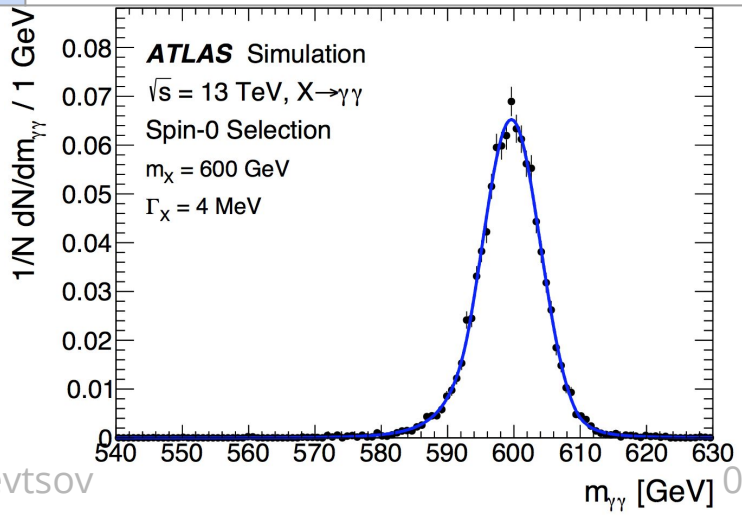
Search for diphoton resonances

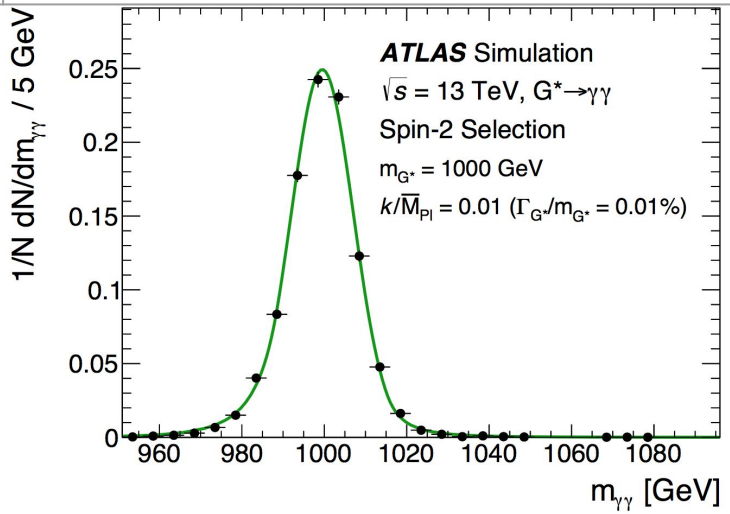


Signal modeling

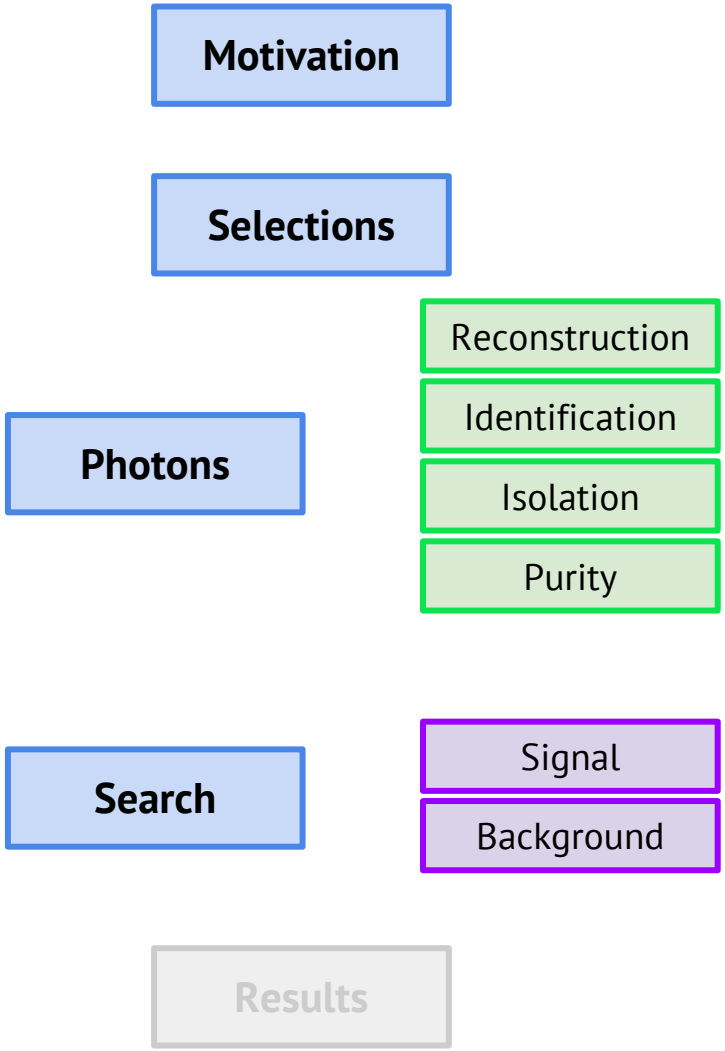
- Detector resolution parametrized with Double Sided Crystal Ball
  - Parameters of DSCB expressed as $f(m_{\gamma\gamma})$ - continuous description of detector resolution over the search range.
- Parametrizations over mass and width obtained with convolution (FFT) of detector resolution with theoretical lineshape, product of:
  - Breit-Wigner distribution (m,Γ)
  - squared matrix element of the production process
  - parton luminosity

	Spin-0	Spin-2
Narrow Width	Powheg-Box (MadGraph5_aMC@NLO for new results) Γ_X=4 MeV	Pythia κ/M_{Pl}=0.01, Γ_G/m_G=0.01%
Large Width	$\Gamma_X \leqslant 10\% \, m_X$	$\kappa/M_{Pl} \leqslant 0.3$





Search for diphoton resonances



Background modeling

Spin-0 - Functional form

- Fit data with analytical function with **free parameters**:

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

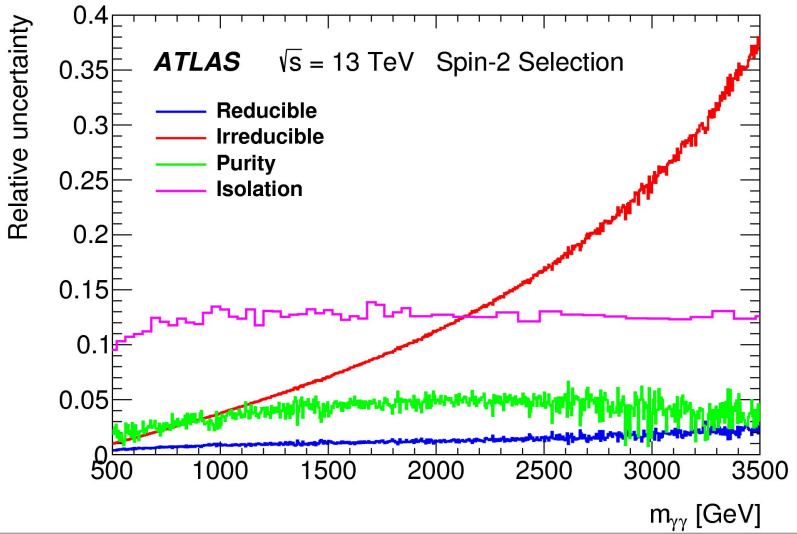
$$f(x; b, a) = N(1 - x^{1/3})^b x^a$$

- Validation of the function and uncertainty from MC+data template
  - Systematics smaller than 30% of statistical error

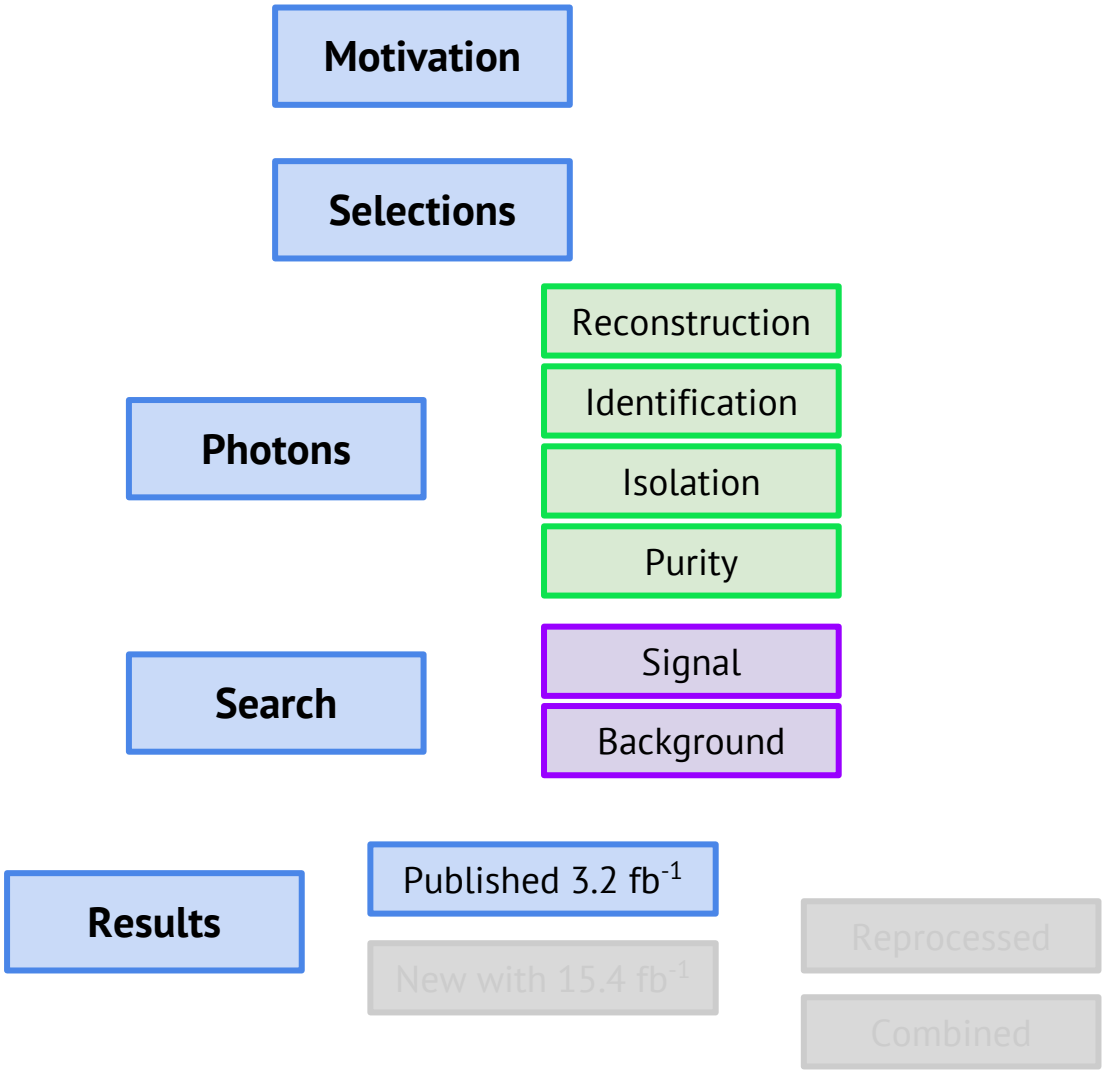
Spin-2 - Template fit

- Irreducible (γγ) from MC
  - DIPHOX NLO parton level, reweighted to SHERPA full detector simulation
- Reducible (γj,jγ,jj) from data
  - mixed according to the data driven background decomposition

- **Normalization of template is free**
- Uncertainties
  - Isolation (±10%), PDF (2-35%)

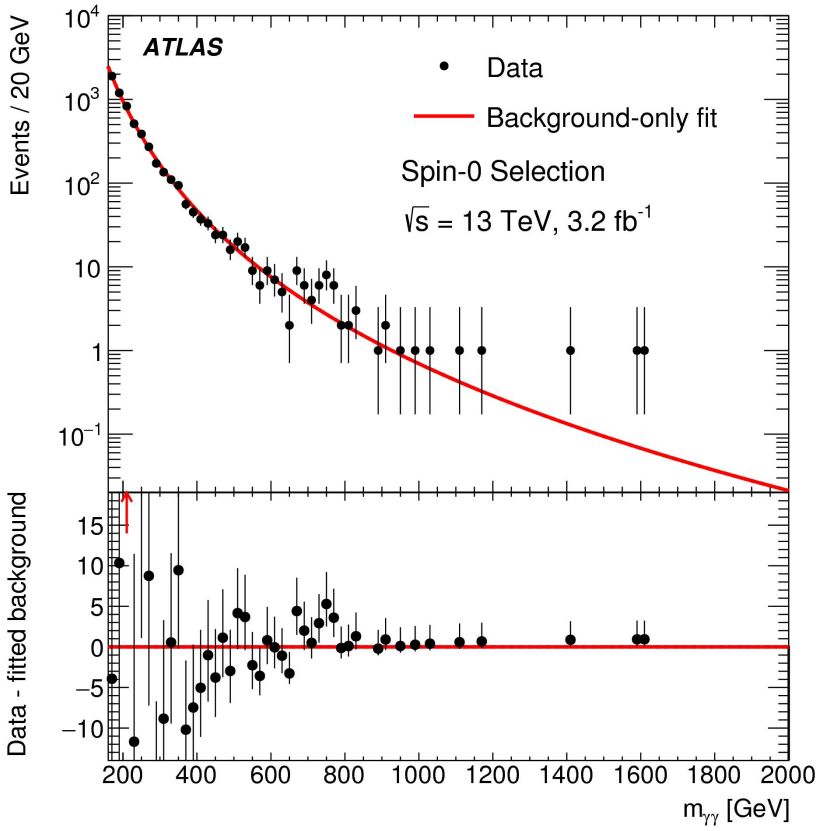


Search for diphoton resonances

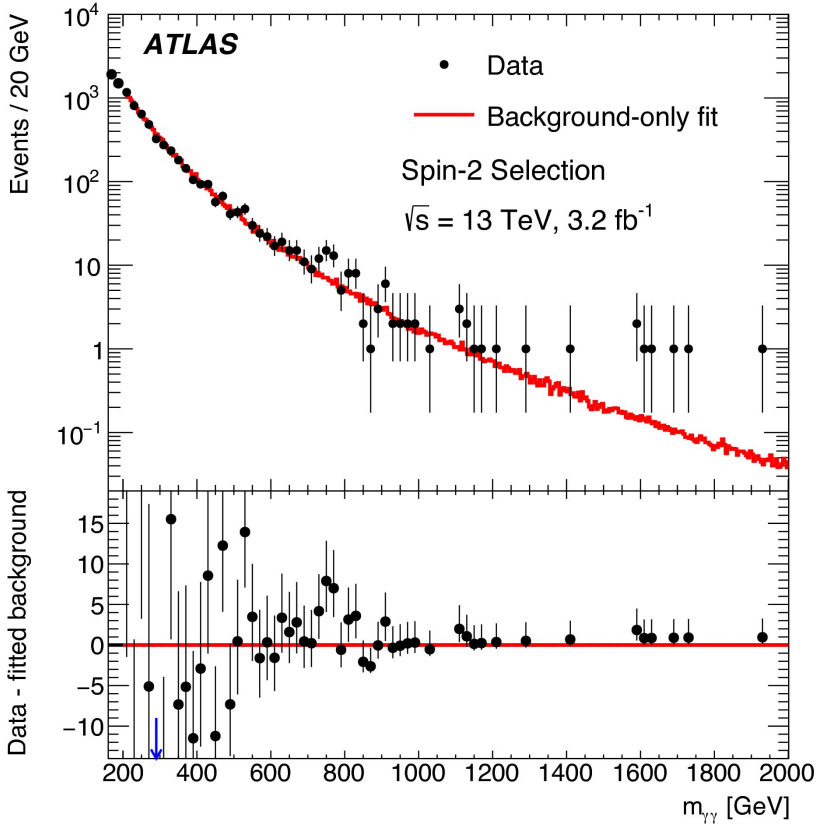


2015 data (arxiv:1606.03833)

Spin-0



Spin-2



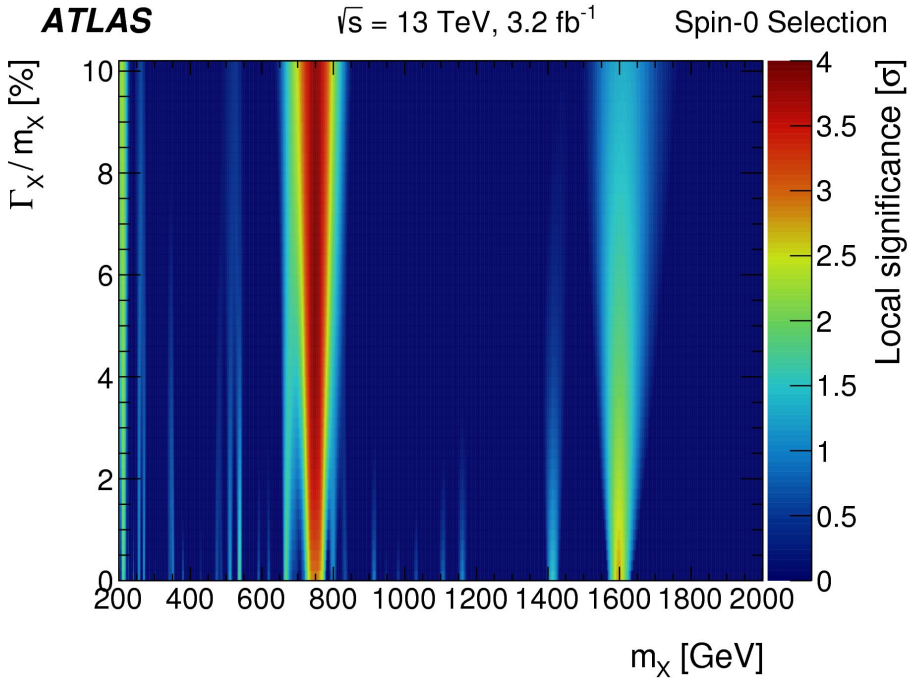
Broad excess around $m_{\gamma\gamma}$ = 750 GeV

3.9σ local for Γ_X/m_X=6%

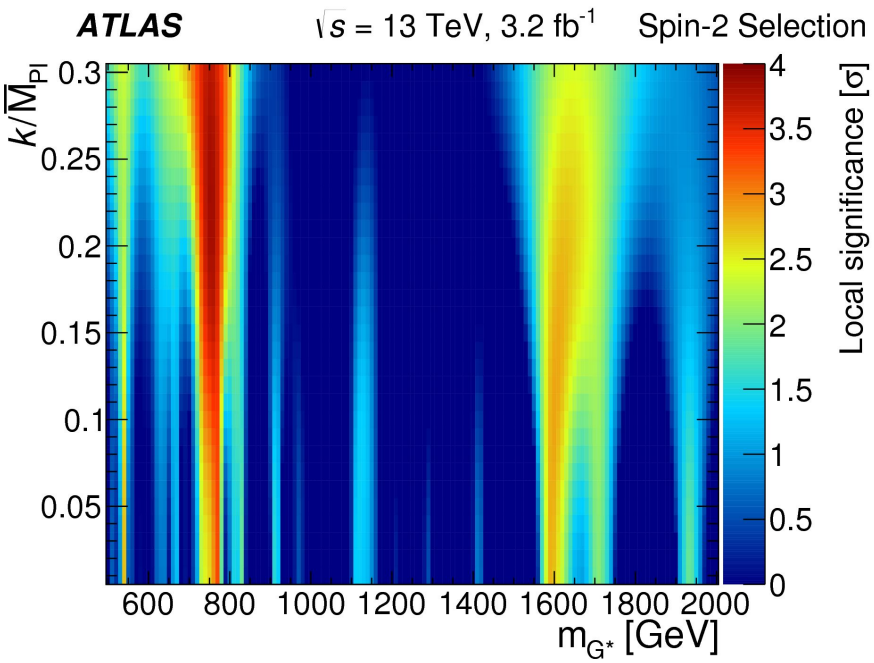
3.8σ local for k/M_{pl}=0.23

2015 data (arxiv:1606.03833)

Spin-0



Spin-2



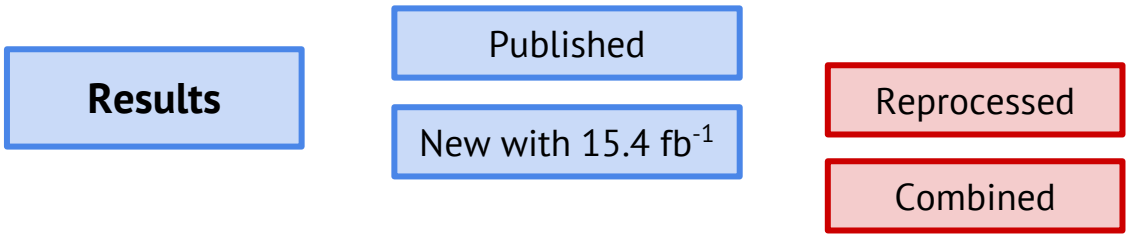
Broad excess around $m_{\gamma\gamma}$ = 750 GeV

3.9σ local significance for Γ_X/m_X=6%

3.8σ local significance for k/M_{pl}=0.23

2.1σ global significance (in search range)

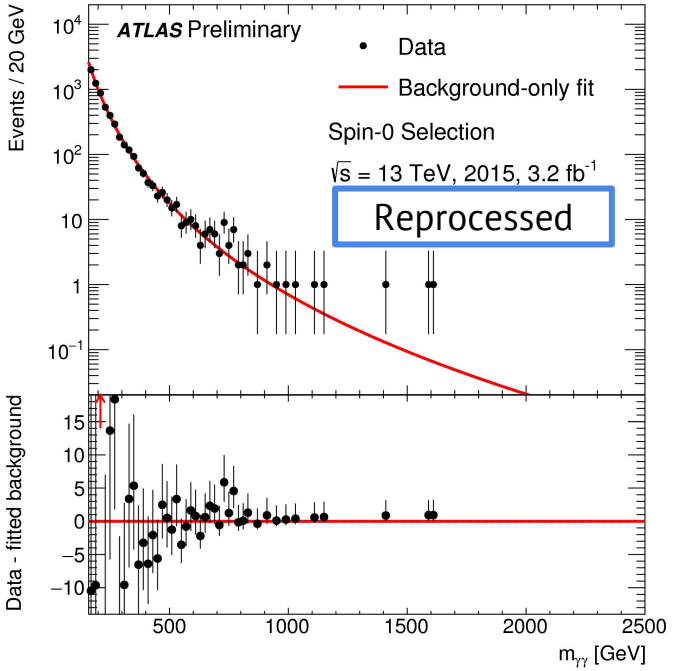
Search for diphoton resonances



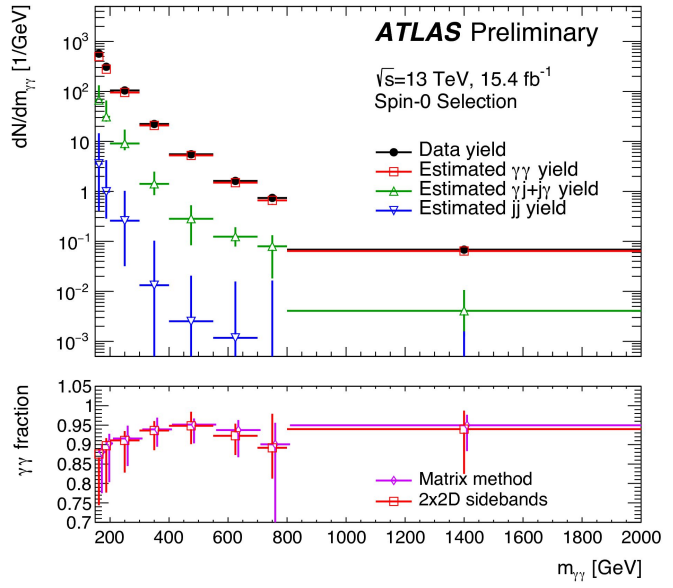
Combined dataset

- Changes in 2015 re-analysis
  - Improved reconstruction and energy calibration

Impact on results for reprocessed 2015 dataset
for Spin-0 selection:
m_X=750 GeV → m_X=734 GeV
Γ_X/m_X=6% → Γ_X/m_X=8%
3.9σ → 3.4σ

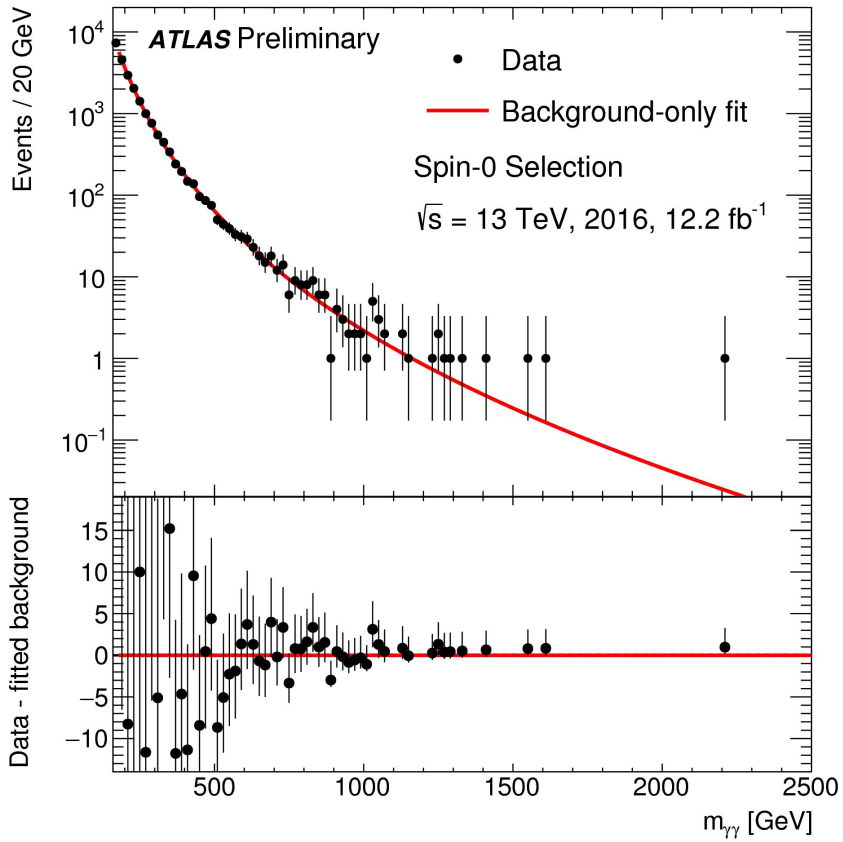


- Purity of diphoton events passing Spin-0 selection in 15.4 fb^{-1} combined sample ~90%
  - $(93^{+3}_{-8})\% \rightarrow (90^{+3}_{-10})\%$
- Increased pileup in 2016 wrt 2015 data-taking
  - more work is needed to complete the analysis in the extended acceptance of the spin-2 selection

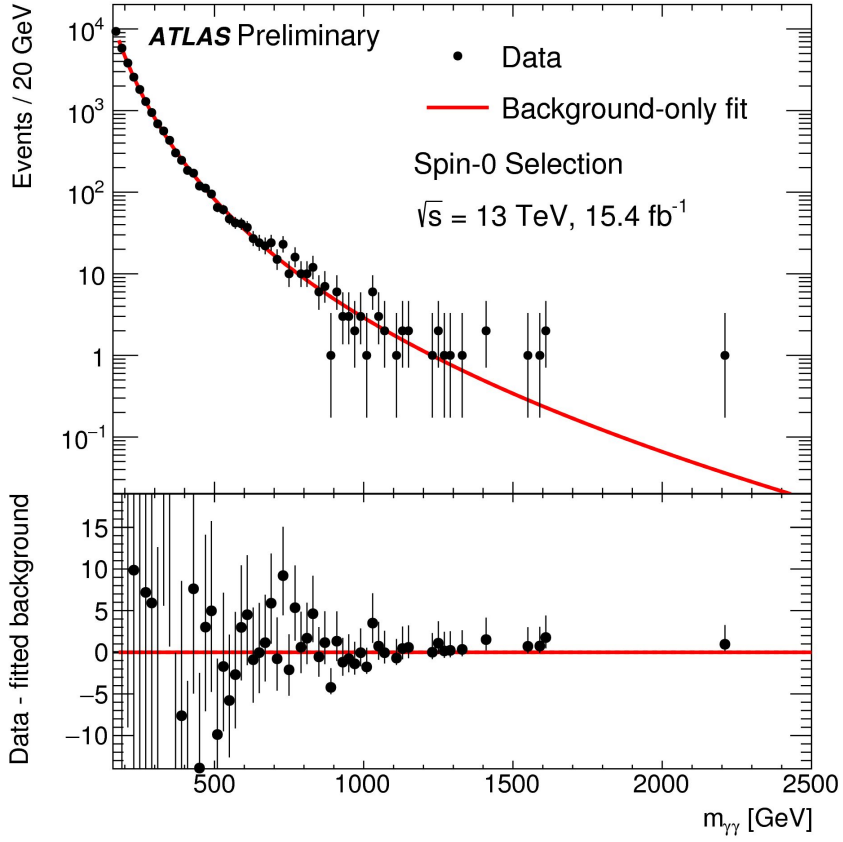


2016 data and 2015+2016 Spin-0 selection

Spin-0 2016 only



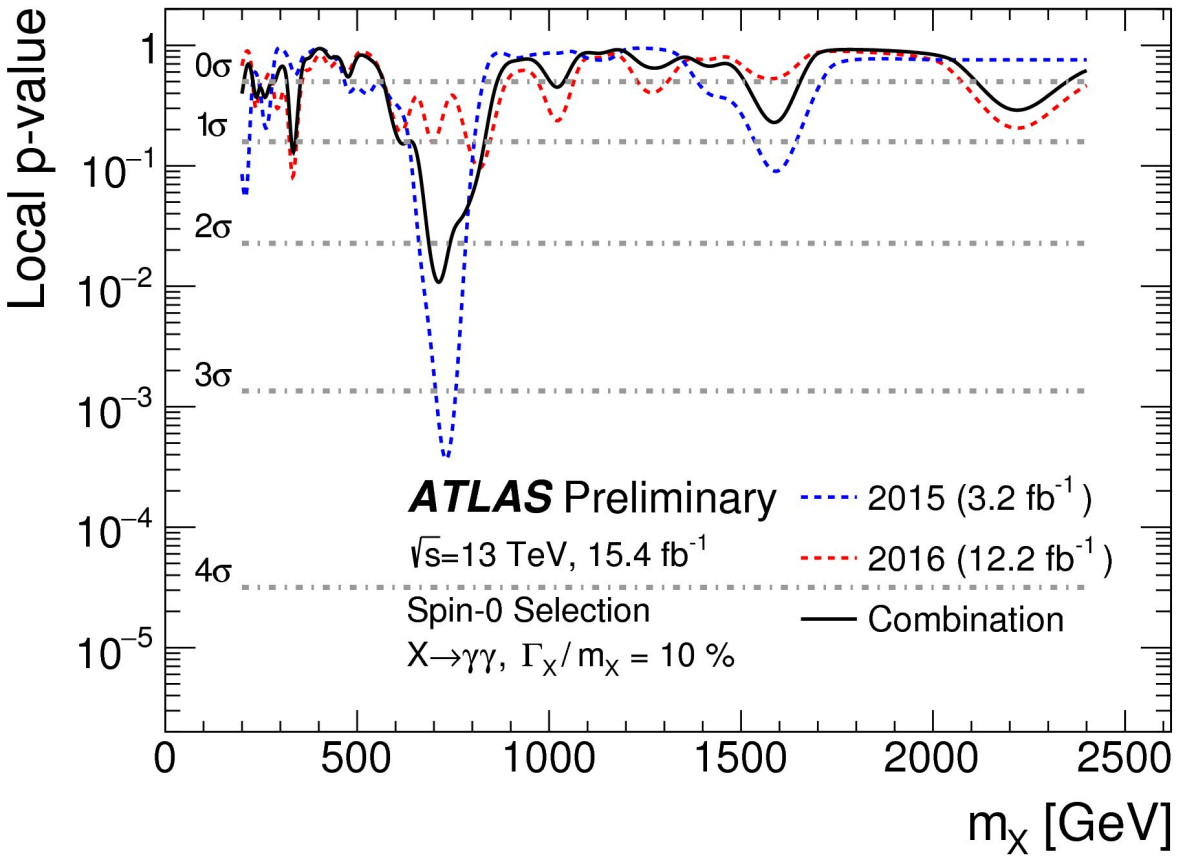
Spin-0 2015 + 2016



No significant excess observed

Significance for combination

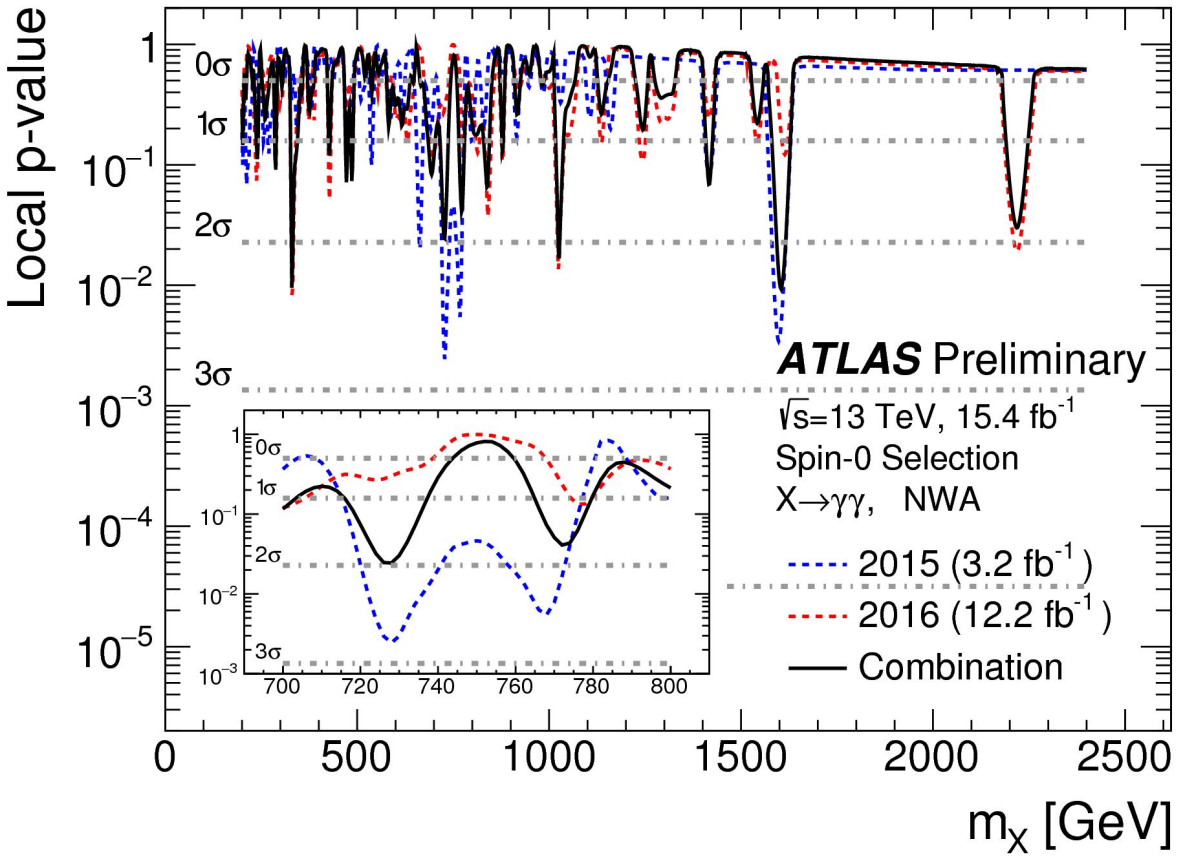
- **Spin-0 Large width** Γ_X/m_X=10%



- Largest significance observed for combined dataset 15.4 fb^{-1} 2.3σ local @ 710 GeV
- Compatibility between 2015 and 2016 datasets for signal cross-section 2.7σ @ 730 GeV
- Global significance below 1σ

Significance for combination

- **Spin-0 Narrow width** Γ_X = 4 MeV

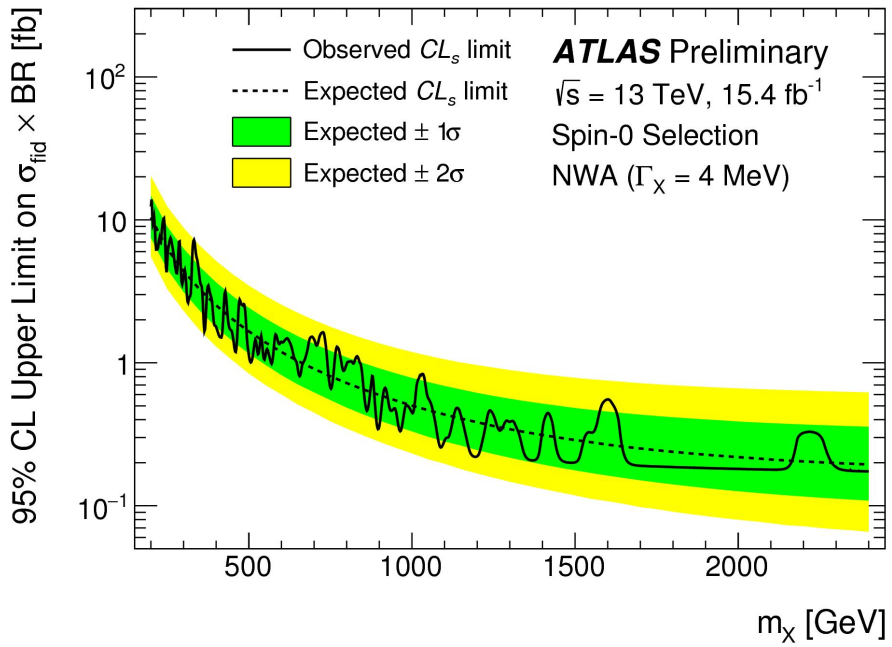


- Largest significance observed for combined dataset 15.4 fb^{-1} 2.4σ local @ 1.6 TeV
- Compatibility between 2015 and 2016 datasets for signal cross-section 2.7σ @ 730 GeV
- Global significance below 1σ

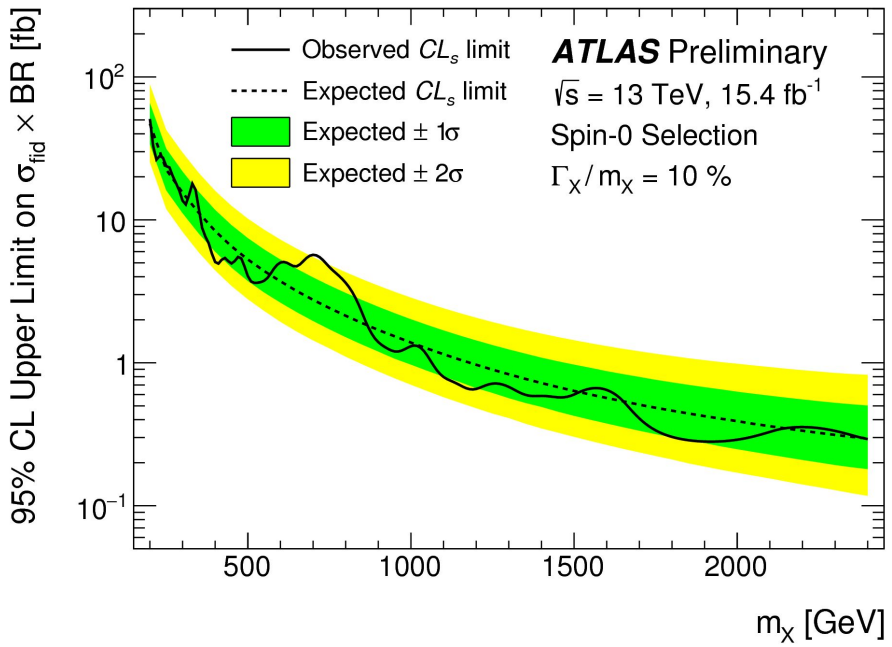
Cross section limits

- A fiducial volume matching analysis cuts chosen to minimize the model-dependence of the result
- Fiducial cross-section is measured
  - 1.14 fb @ 500 GeV to 0.18 fb @ 2 TeV for Narrow width signal
- Limits extended from 2 to 2.4 TeV with 2016 data

Spin-0 Narrow Width



Spin-0 Large width Γ_X/m_X=10%



Conclusions on diphoton search

Diphoton resonance search performed with two analysis targeting two scenarios

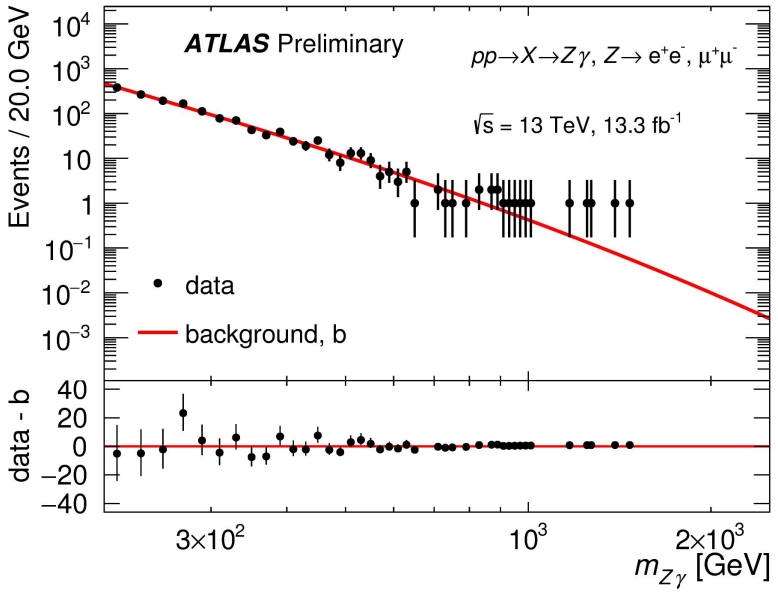
- Spin-0 Higgs-like
- Spin-2 Randall-Sundrum graviton

- **Spin-2** - more work is needed to complete the analysis in the extended acceptance of the spin-2 selection
- **Spin-0** analysis updated with combined 3.2 fb^{-1} reprocessed 2015 and 12.2 fb^{-1} 2016 data
  - Data consistent with Standard Model expectations (global significance below 1σ)
  - Appears that the 2015 excess was a statistical fluctuation

Searches for X→Zγ

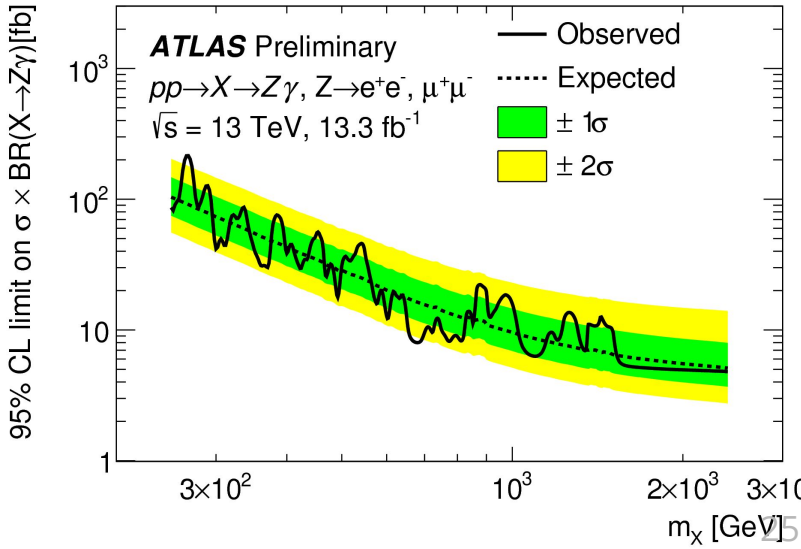
A search for new resonances decay to Zγ using 13.3 fb^{-1} performed (ATLAS-CONF-2016-044)

- Mass range [0.25 - 2.4 TeV]
- Leptonic Z boson decays l^+l^- (l = e, μ)
- Signal modeling:
  - Narrow width signal
  - with DSCB for each Z boson decay channel
- Background modeling:
  - Functional form $f_{\mathrm{bkg}}(x) = \mathcal{N}(1 - x^k)^{p_1} x^{p_2}$



Results:

- No significant excess observed
  - 2.2σ @ m_X=268 GeV
- Upper limits on σ(pp → X) × BR(X → Zγ) set



Summary

ATLAS high mass searches:

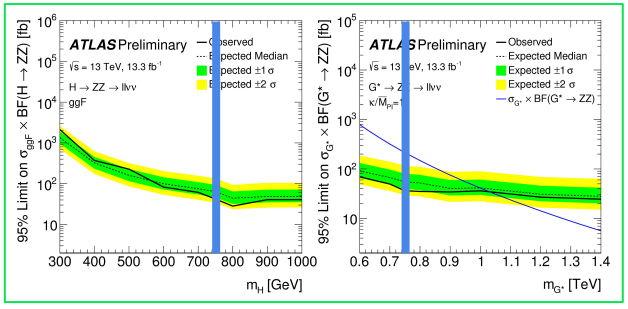
- Searches for high mass diphoton resonances
  ATLAS-CONF-2016-059
- Searches for new physics in the Z+photon channel
  ATLAS-CONF-2016-044
- Searches for new physics in the ZZ->llnn channel
  ATLAS-CONF-2016-056
- Searches for new physics in the high mass WW channel
  ATLAS-CONF-2016-074
- Searches for heavy Higgs bosons decaying to tautau
  ATLAS-CONF-2016-085
- Searches for new high mass resonances decaying to top quarks at 8 TeV (ATLAS-CONF-2016-073)

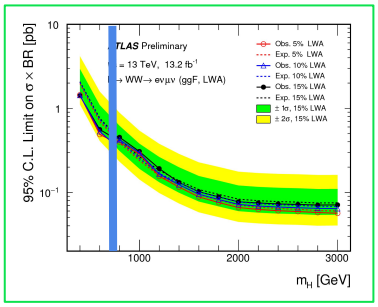
Discussed in the talk

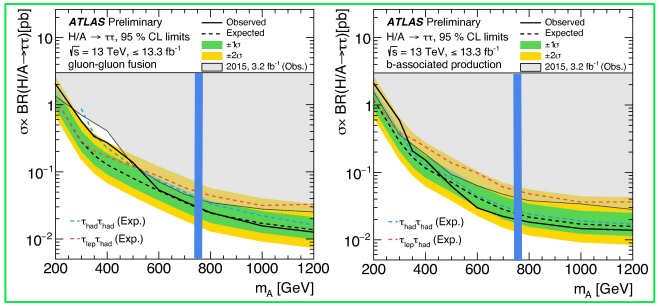
Searches performed
No excess observed
Limits set

Pere's talk

This and more results in Luca's talk - BSM part 2

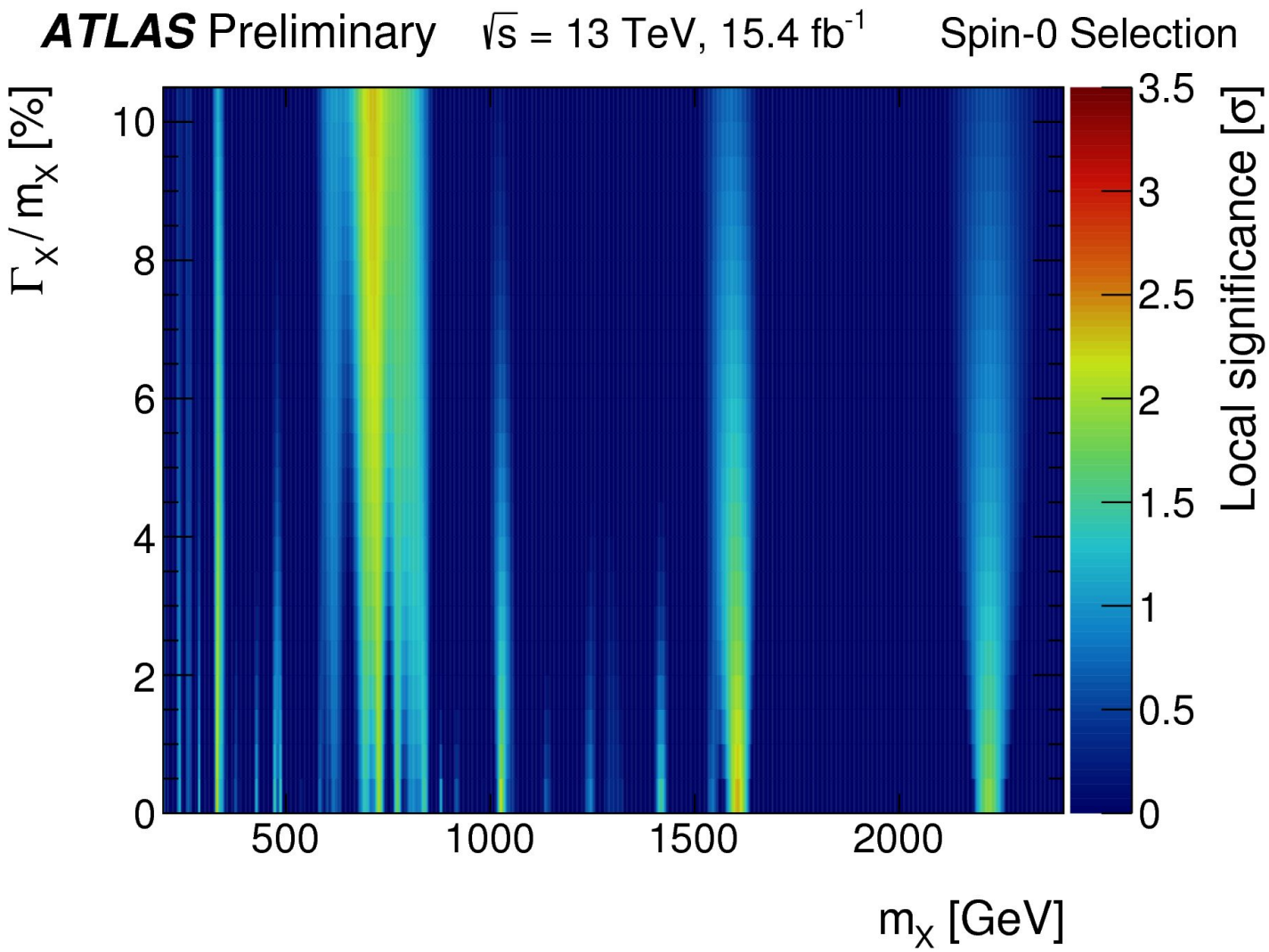






Backup

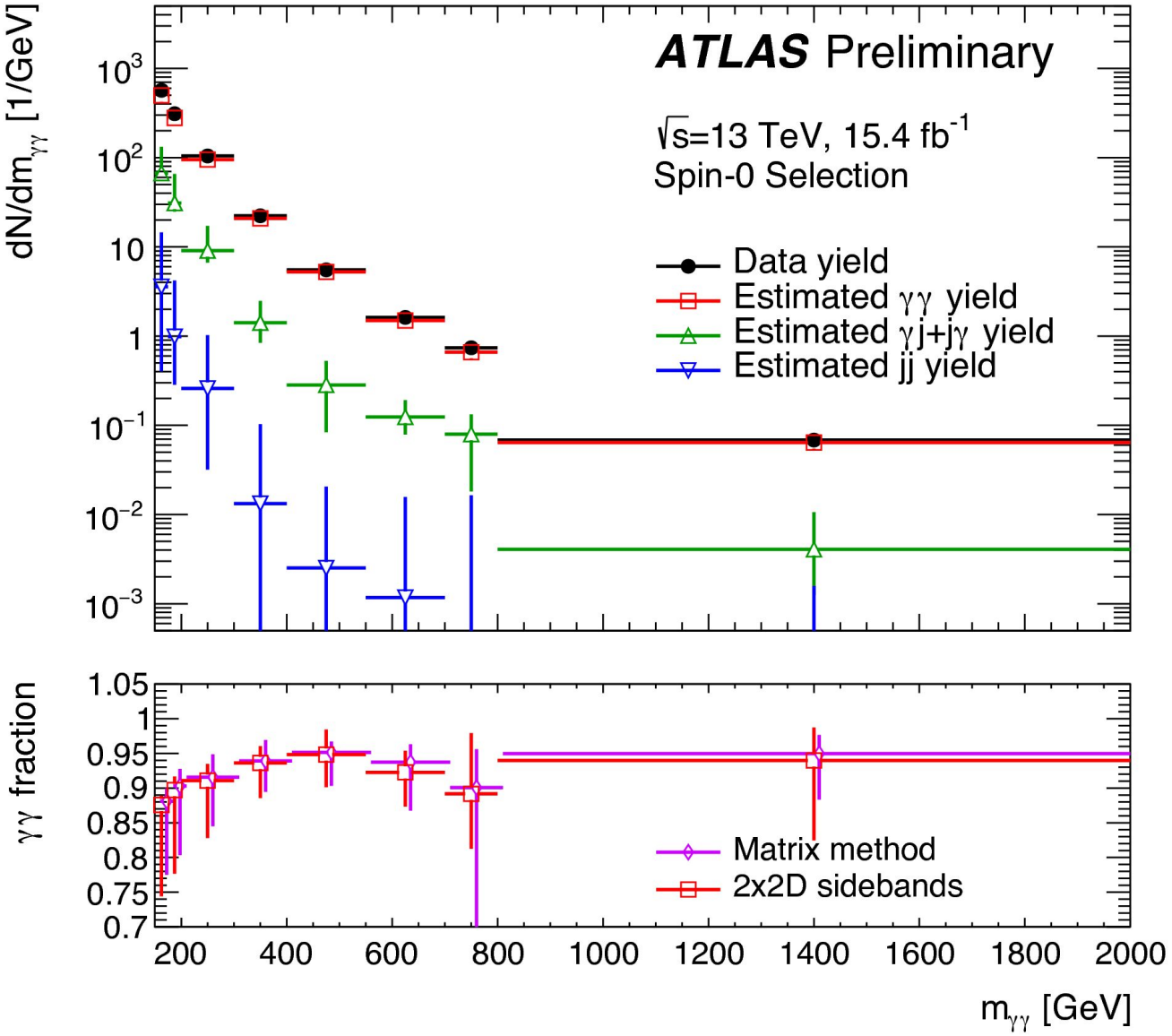
Significance vs mass and width



Sample composition

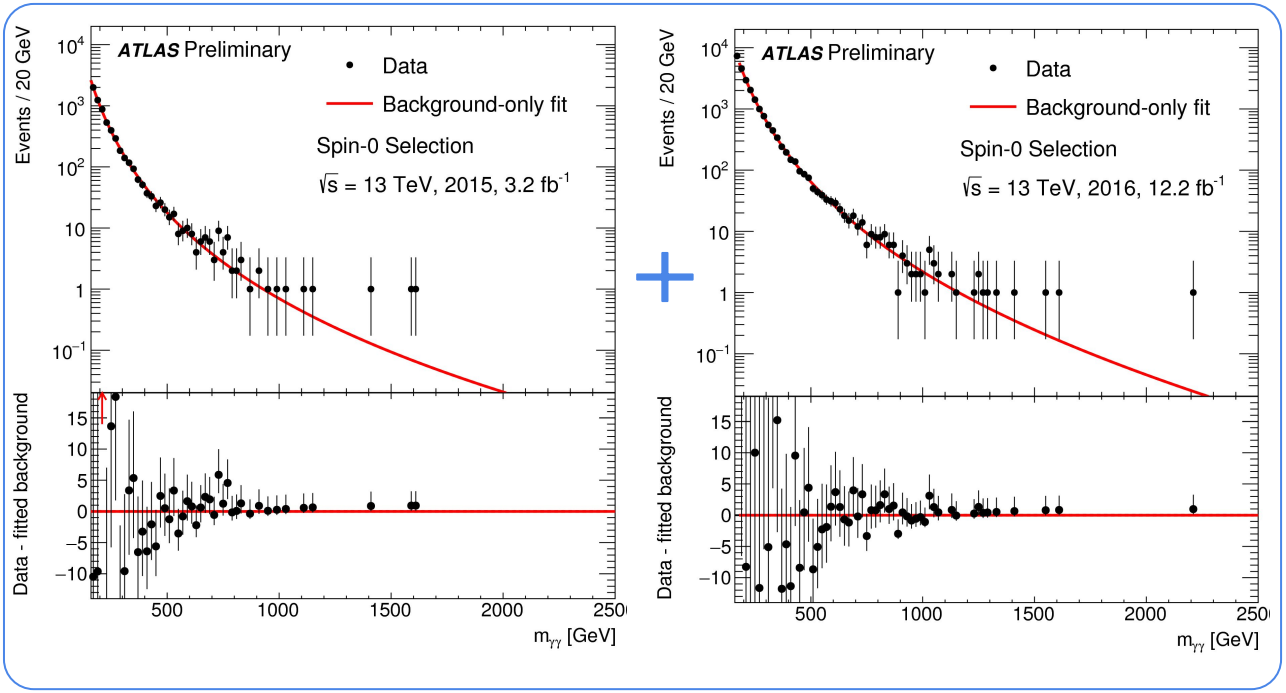
Purity

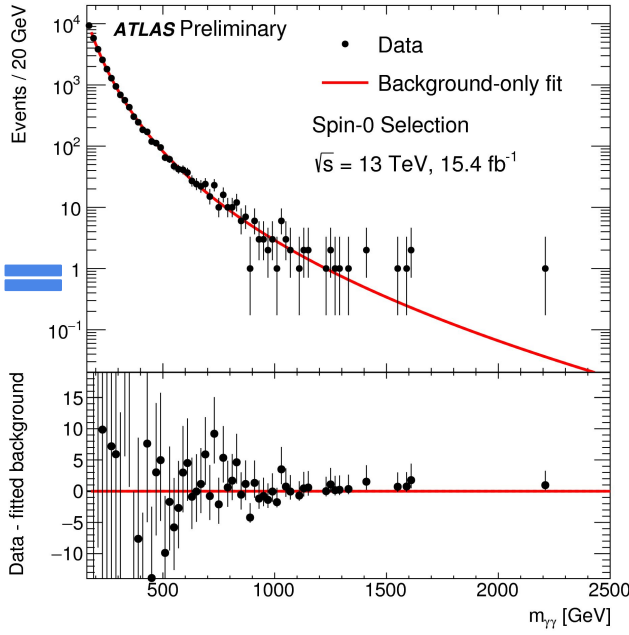
$(90^{+3}_{-10})\%$



2015, 2016 and 2015+2016 Spin-0 selection

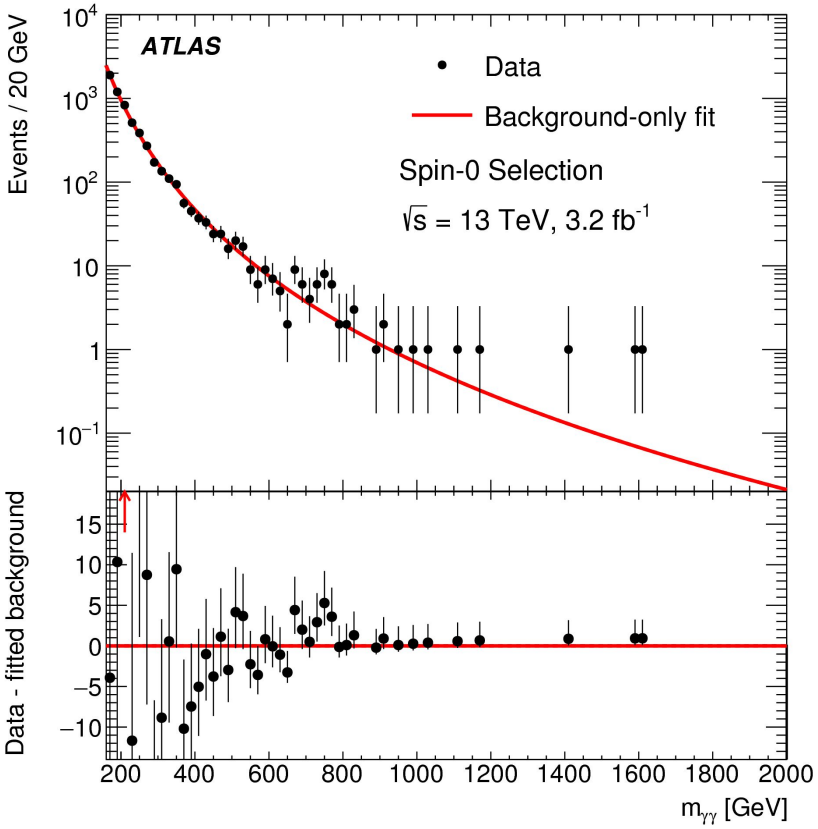
2015 reprocessed **2016** **2015+2016**



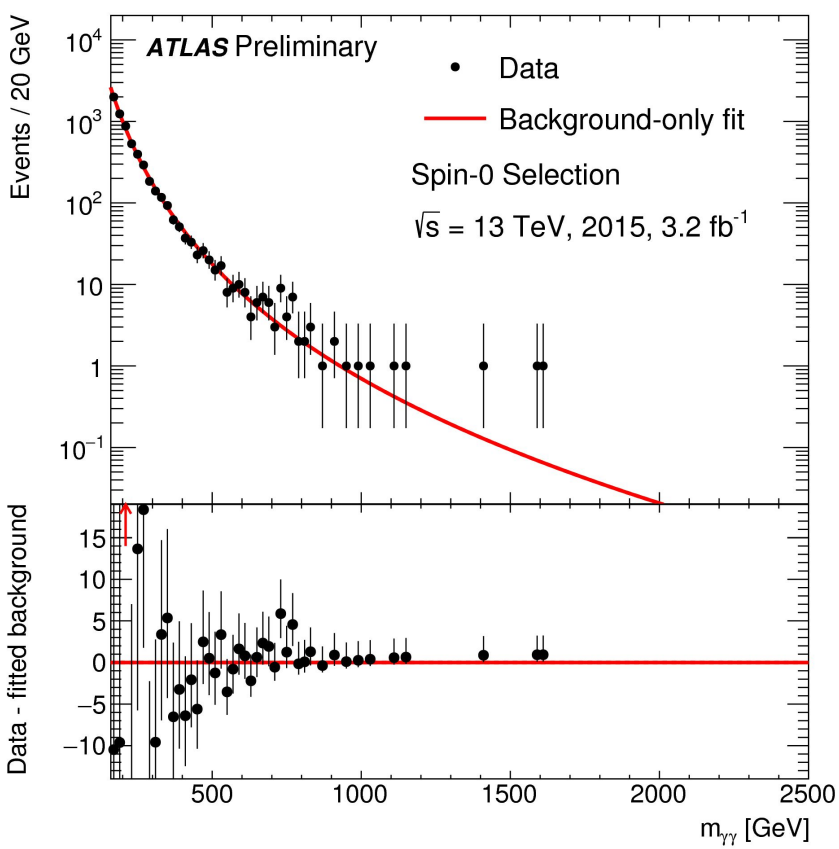


2015 Spin-0 selection

2015 in paper



2015 reprocessed



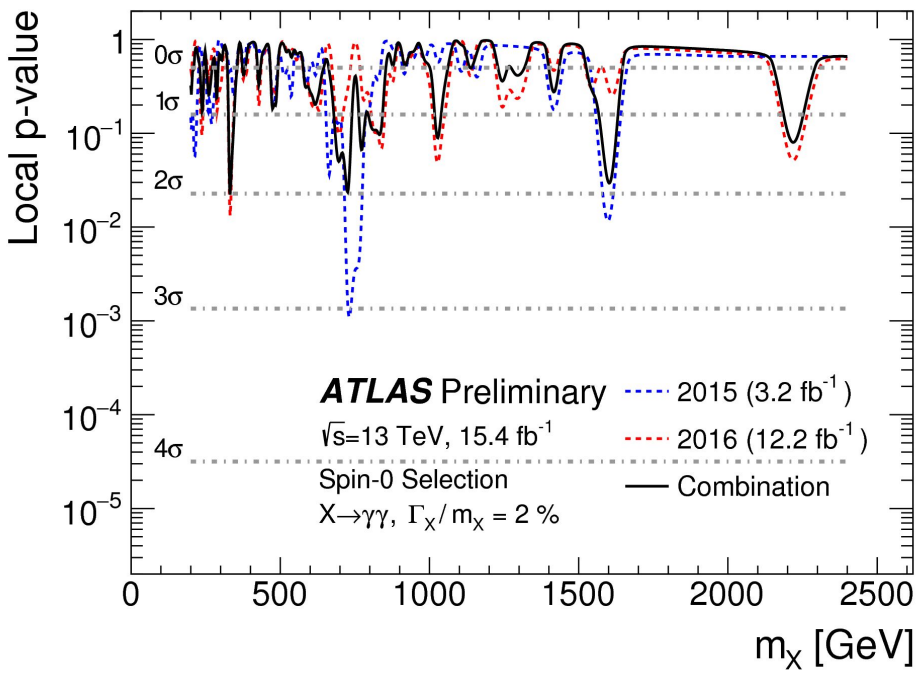
m_X=750 GeV → m_X=734 GeV

Γ_X/m_X=6% → Γ_X/m_X=8%

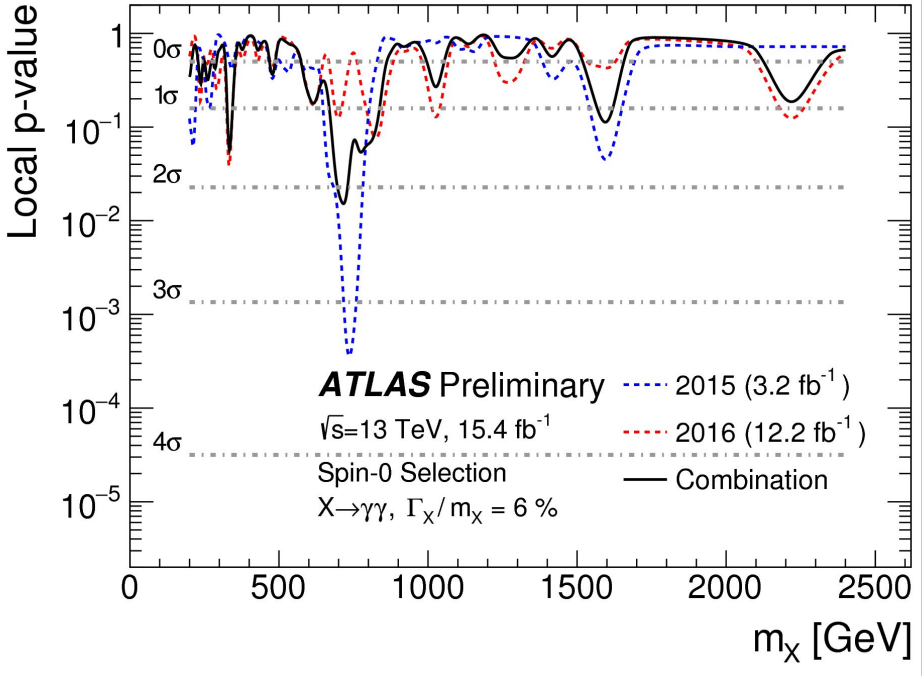
3.9σ → **3.4σ**

Significance for new result and combination

Spin-0 Large width Γ_X/m_X=2%



Spin-0 Large width Γ_X/m_X=6%

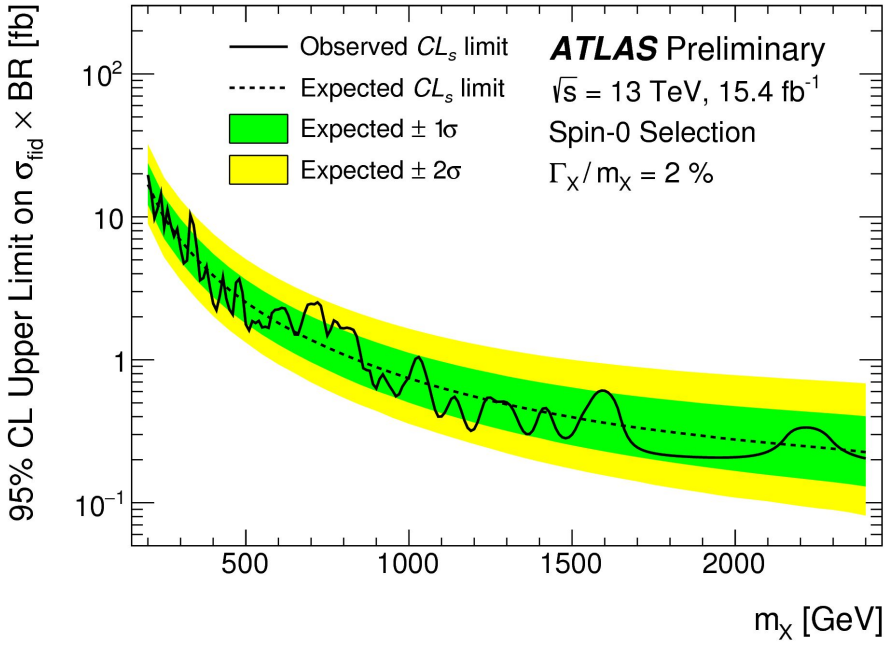


No significant excess observed

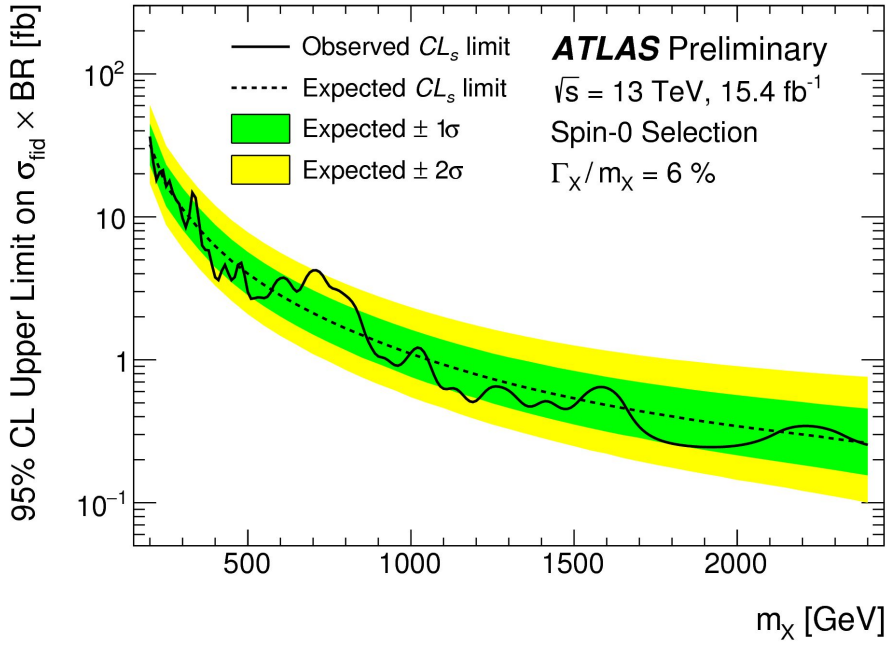
Limits on cross section for combined results

- A fiducial volume matching analysis cuts chosen to minimize the model-dependence of the result
  - Analysis kinematic selections
  - Lifetime > 10 ps at generator level
  - Additional isolation cut at particle level, to match reconstruction level
- Fiducial cross-section is measured.
  - 2.93 fb @ 500 GeV to 0.25 fb @ 2 TeV for 6%$m_{\gamma\gamma}$ width signal

Spin-0 Large width Γ_X/m_X=2%

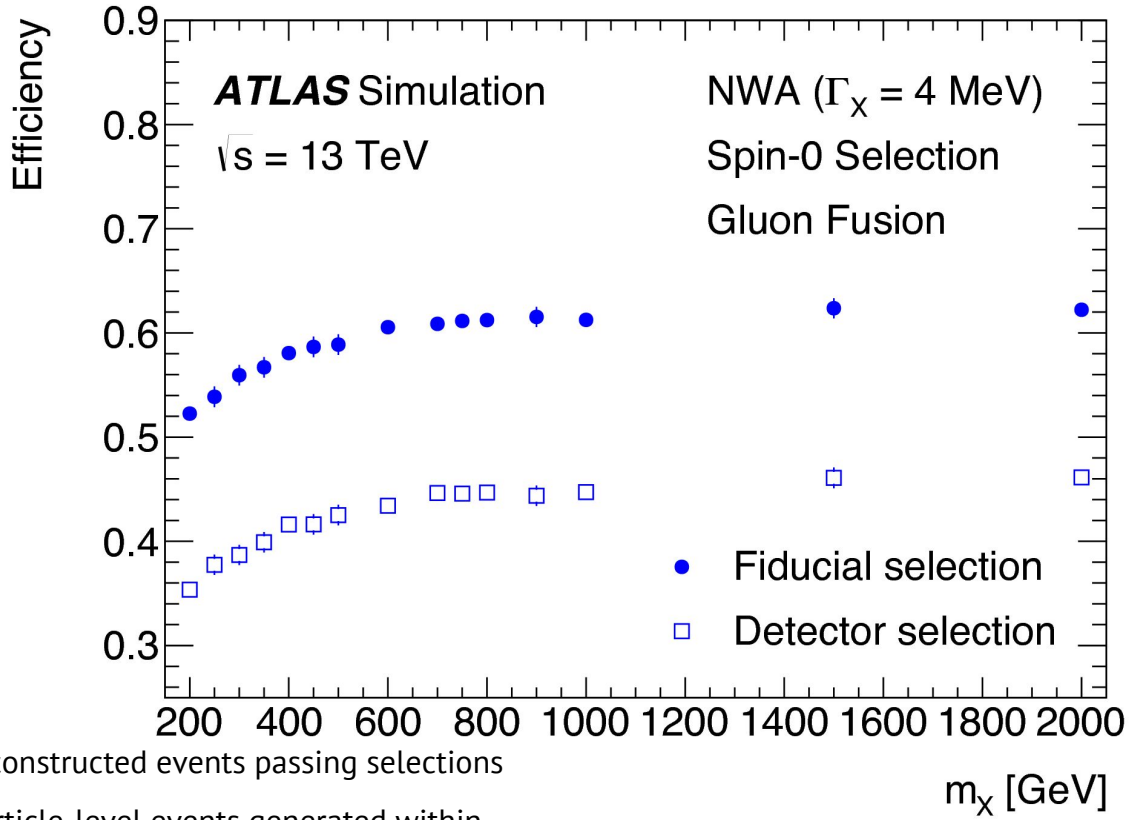


Spin-0 Large width Γ_X/m_X=6%



Fiducial selections

- $|\eta_{\gamma\gamma}|<2.37$
- $E_T>0.4(0.3)*m_{\gamma\gamma}$
- lifetime>10ps at generator level
- $E_T^{iso}<0.05 \times E_T^{\gamma}+6$ GeV - at particle level, to match reconstruction level



$$C_X = \frac{N_{\text{selection}}}{N_{\text{fiducial}}}$$

- # reconstructed events passing selections

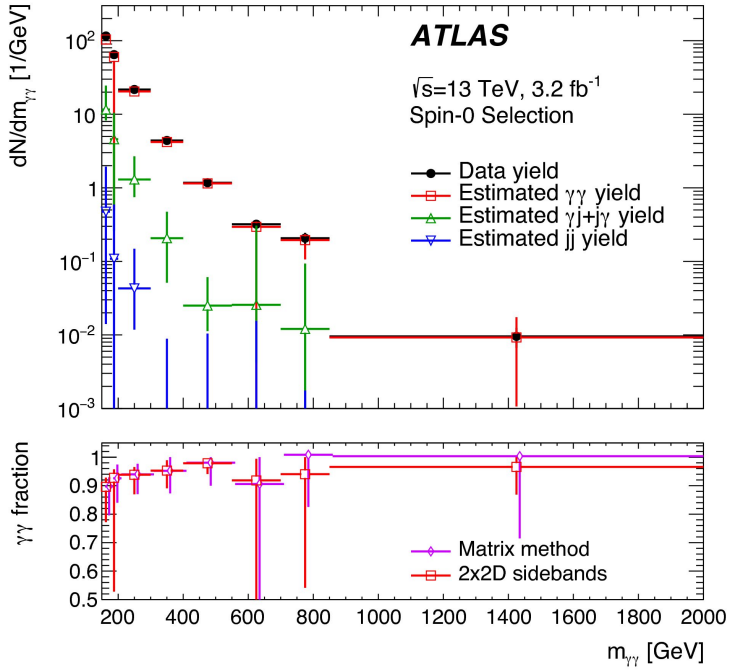
- # particle-level events generated within the fiducial volume

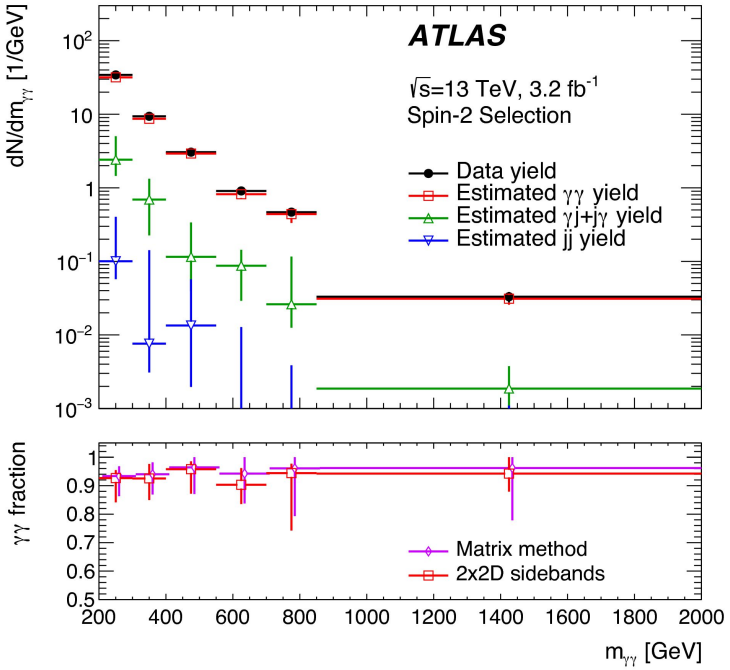
Sample composition

- Estimate fractions of diphoton, photon-jet and dijet events (γγ, jγ, γj, jj)

  The relative amount of each final state is estimated by the 2x2D-sidebands and the matrix methods by looking in enriched regions for each component.

	Spin-0	Spin-2
Purity	$(93^{+3}_{-8})\%$	$(94^{+3}_{-7})\%$





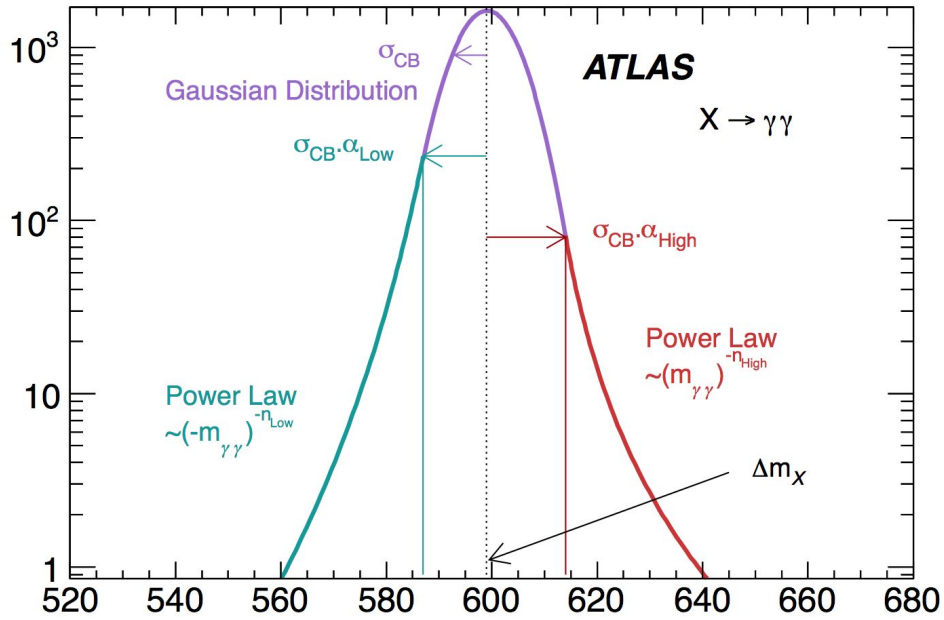
- Purity of diphoton passing selection is >93% for $m_{\gamma\gamma}$>200 GeV
- Fractions of γγ/γj/jγ/jj components measured in data are inputs for the SM background predictions

Narrow Width Signal Modeling

Detector response is modeled with DSCB for both Spin-0 and Spin-2 Analysis.

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{\text{low}} \le t \le \alpha_{\text{high}} \\ \dfrac{e^{-0.5\alpha_{\text{low}}^2}}{\left[\frac{\alpha_{\text{low}}}{n_{\text{low}}}\left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t\right)\right]^{n_{\text{low}}}} & \text{if } t < -\alpha_{\text{low}} \\ \dfrac{e^{-0.5\alpha_{\text{high}}^2}}{\left[\frac{\alpha_{\text{high}}}{n_{\text{high}}}\left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t\right)\right]^{n_{\text{high}}}} & \text{if } t > \alpha_{\text{high}}, \end{cases}$$

$$t = \Delta m_X / \sigma_{CB}, \Delta m_X = m_X - \mu_{CB}$$

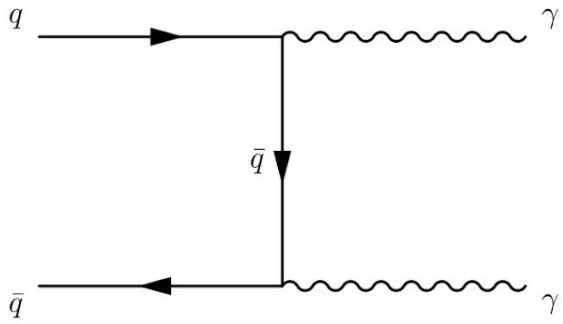


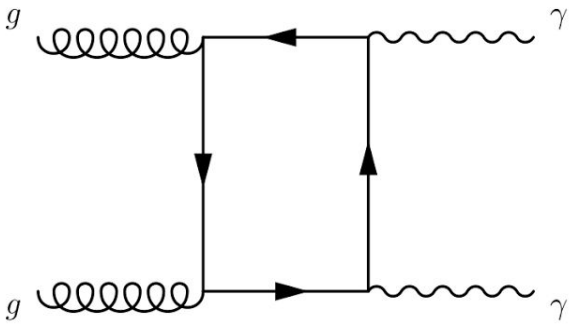
The parameters μ_{CB} , σ_{CB} , α_{low} and α_{high} are parameterized as second order polynomials of the mass. The parameters of these second order polynomials are fitted with the values from the individual fits.

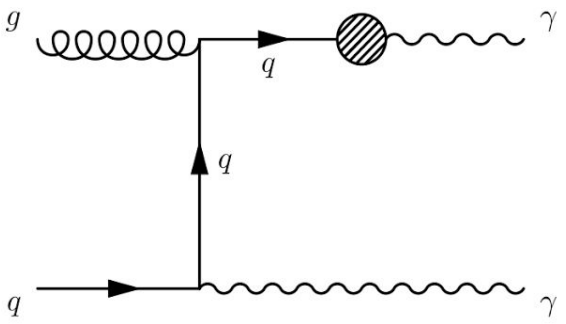
Parameter	Parametrization
Δm_X	$a+bm_{nX}+cm^2_{nX}$
σ_{CB}	$a+bm_{nX}$
α_{Low}	$a+bm_{nX}+cm^2_{nX}$
n_{Low}	a
α_{High}	$a+bm_{nX}+cm^2_{nX}$
n_{High}	a

Background

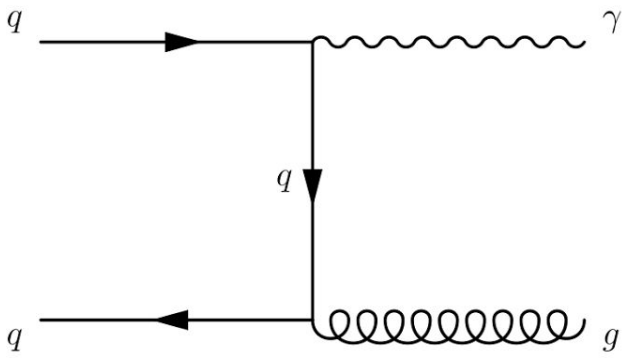
Irreducible

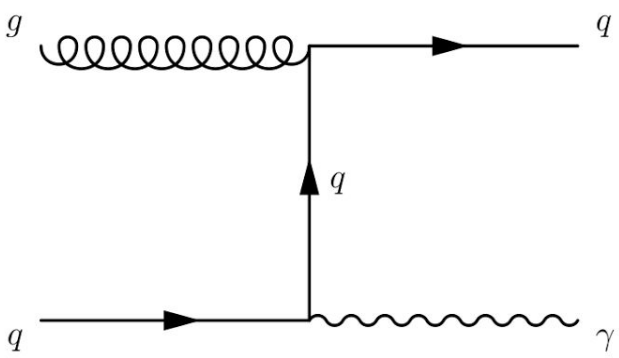


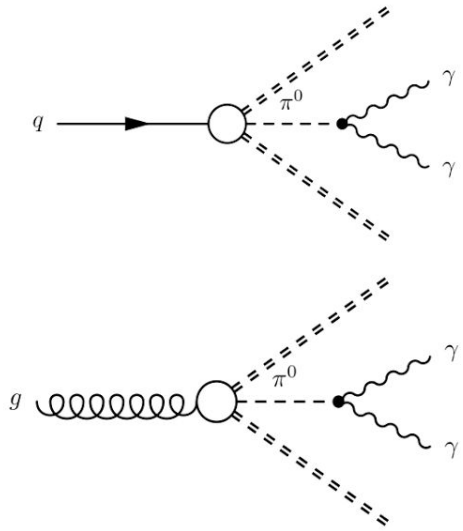




Reducible



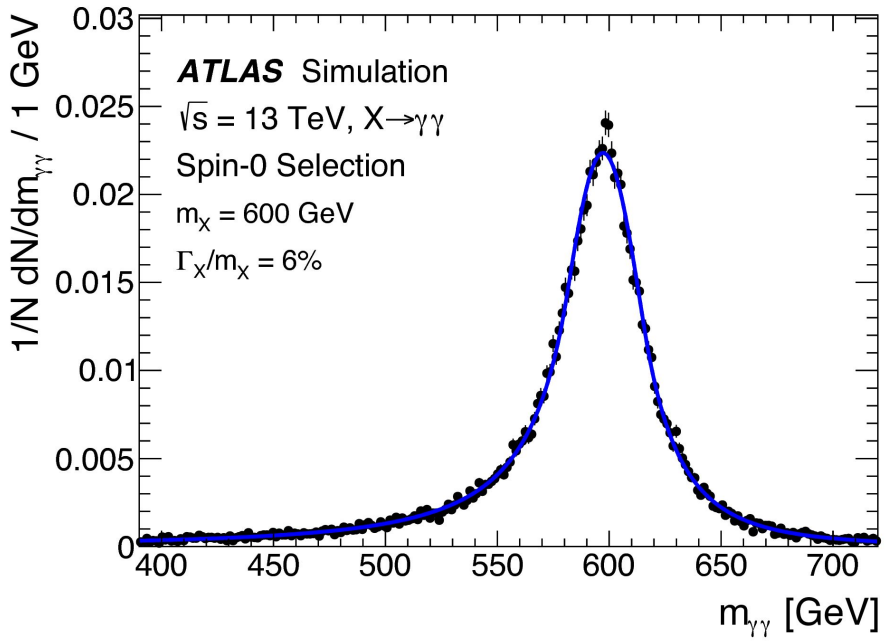


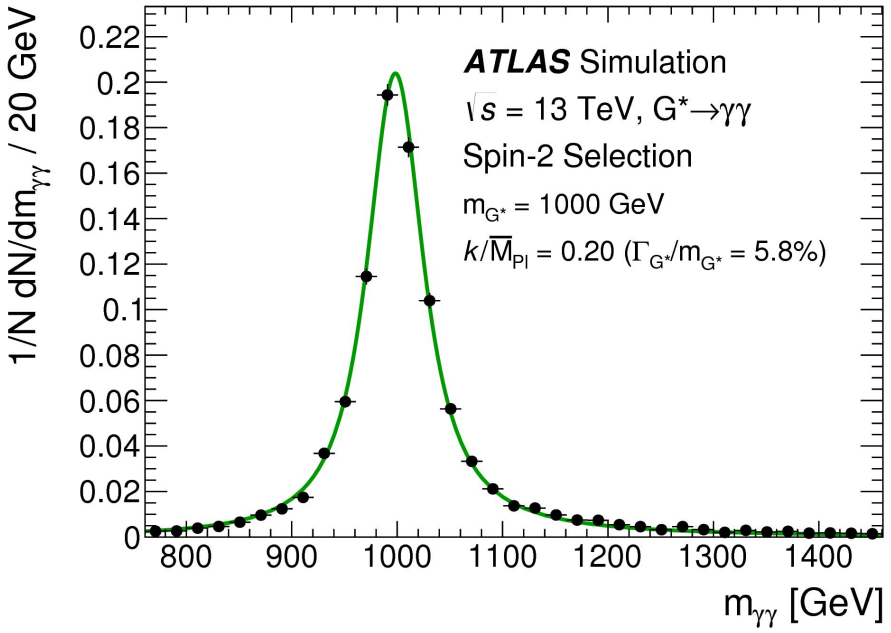


Large Width Signal Modeling

The Narrow Width signal shape parameterised by the DSCB are numerically convoluted using a Fast Fourier Transform with the product of the theoretical *BW*(m,Γ) lineshape term with the parton luminosity and squared matrix element

	Spin-0	Spin-2
Large Width	m_X = 600 GeV, Γ_X = 6% m_X	m_{G^*} = 1000 GeV, κ/M_{Pl} = 0.2 (Γ_{G^*} = 5.8% m_{G^*})





Benchmark models

Spin-0, extended Higgs sector

2HDM with 5 physical states:

- the CP even neutral Higgs bosons ***h*** and ***H*** (heavier than ***h***)

  the "alignment limit" $h,H \rightarrow H_{125}^{SM}$
- two charged Higgs bosons $H^{\pm}$
- the CP odd pseudoscalar ***A***

One of various models predicting high-mass diphoton state.
Model independent search presented

Spin-2, Randall-Sundrum graviton

Light Kaluza-Klein graviton states

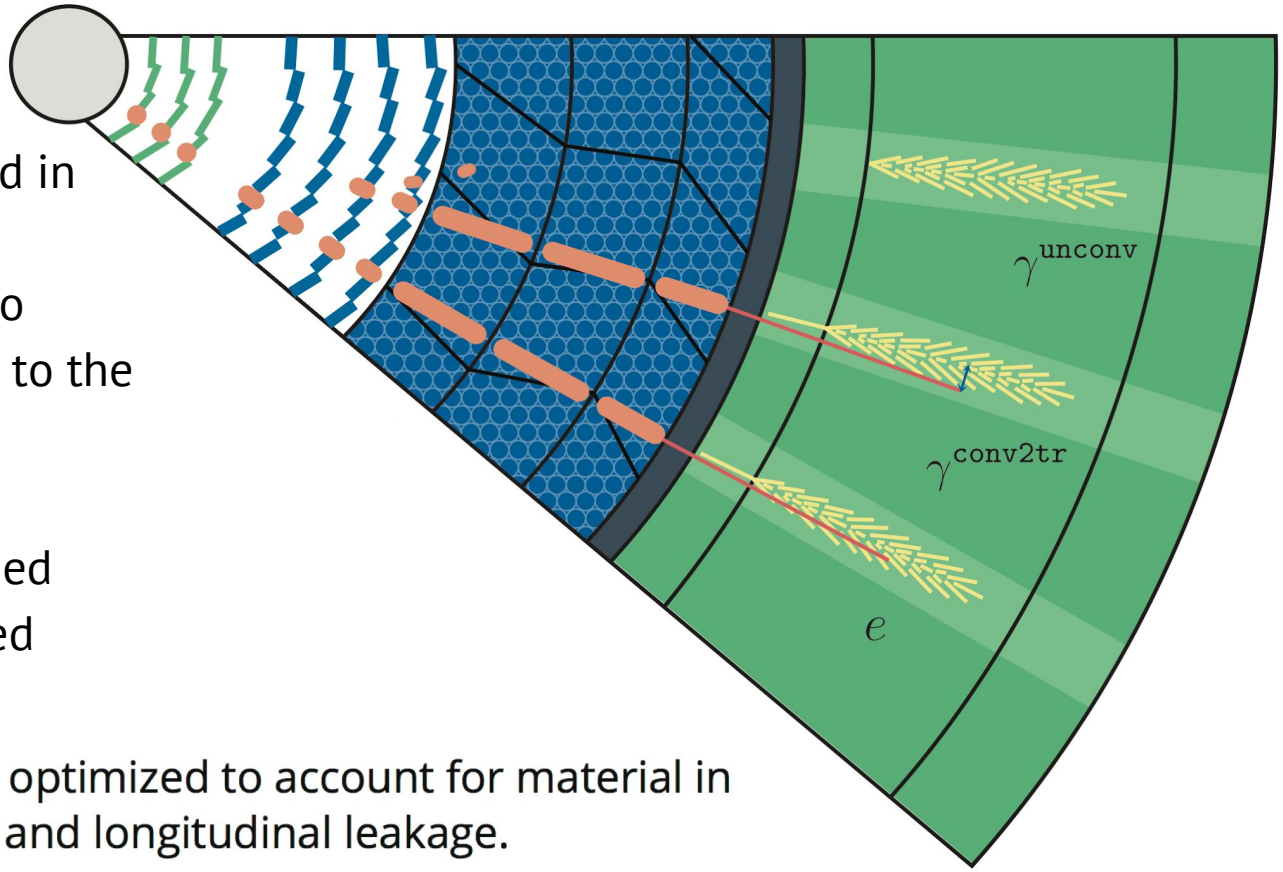
- G^* lightest KK excitation
- κ/M_{Pl} - dimensionless coupling to SM fields

RS benchmark used for limit presented here

Photon conversion

Photons can be reconstructed in calorimeter as:

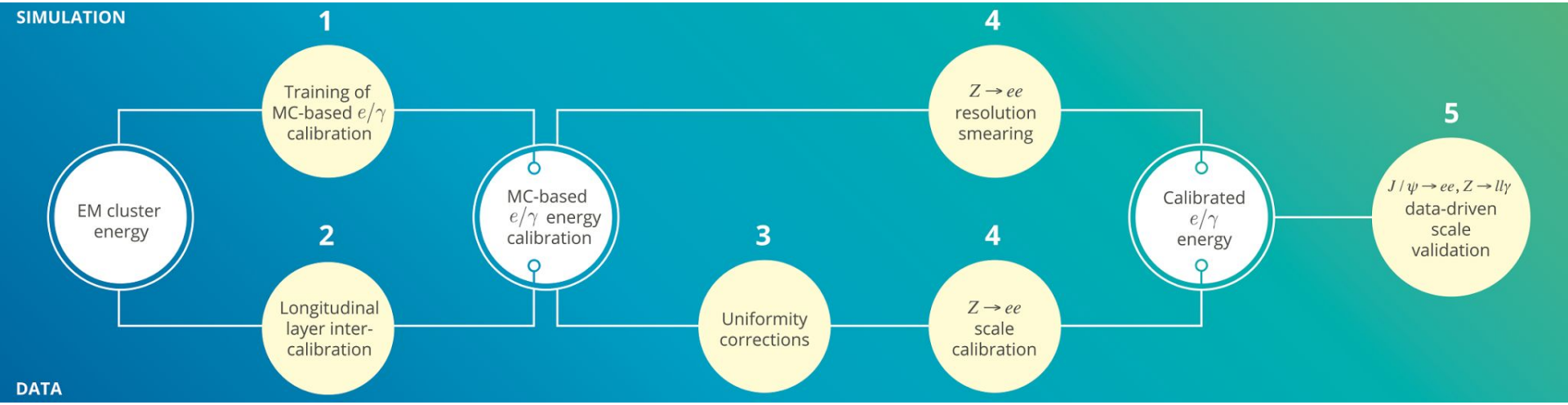
- unconverted photons (no vertex or track matched to the cluster)
- converted photons
  - double track matched
  - single track matched



Final cluster reconstruction optimized to account for material in front of calorimeter, lateral and longitudinal leakage.
Cluster size in cells ($\Delta\eta \times \Delta\phi$=0.025×0.025) of second layer of the calorimeter used in Run I and Run II (if different)

	e and γ^{conv}	γ^{unconv}
Barrel	3×7	3×5 (3×7)
Endcap	5×5	

Calibration in ATLAS



1 - Optimisation of E_{reco}/E_{truth} using multivariate algorithm (MC-based)

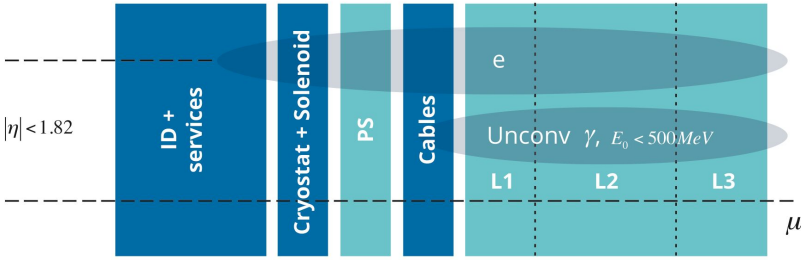
Inputs: $E_{accordion}, E_0 / E_{accordion}, X, \eta_{cluster}, \eta^{calo}_{cluster}, \varphi^{calo}_{cluster}$

energy deposited in the cluster

ratio of presampler to cluster energies

shower depth

position parameters



2,3 - specific data handling:

- Intercalibration of the 1st and 2nd calorimeter layers
- uniformity corrections

4 - energy scale and resolution:

difference in response between data and simulation

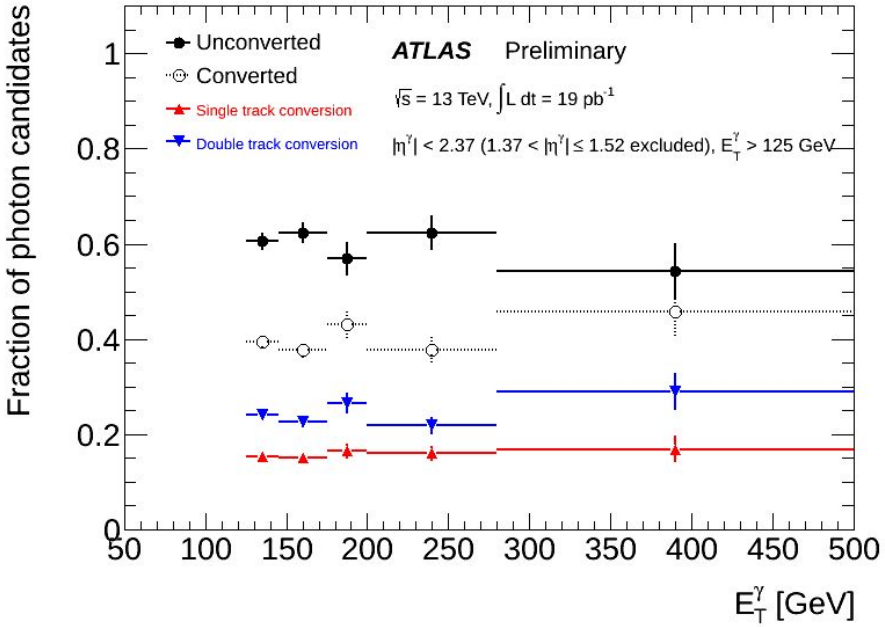
5 - data-driven validation

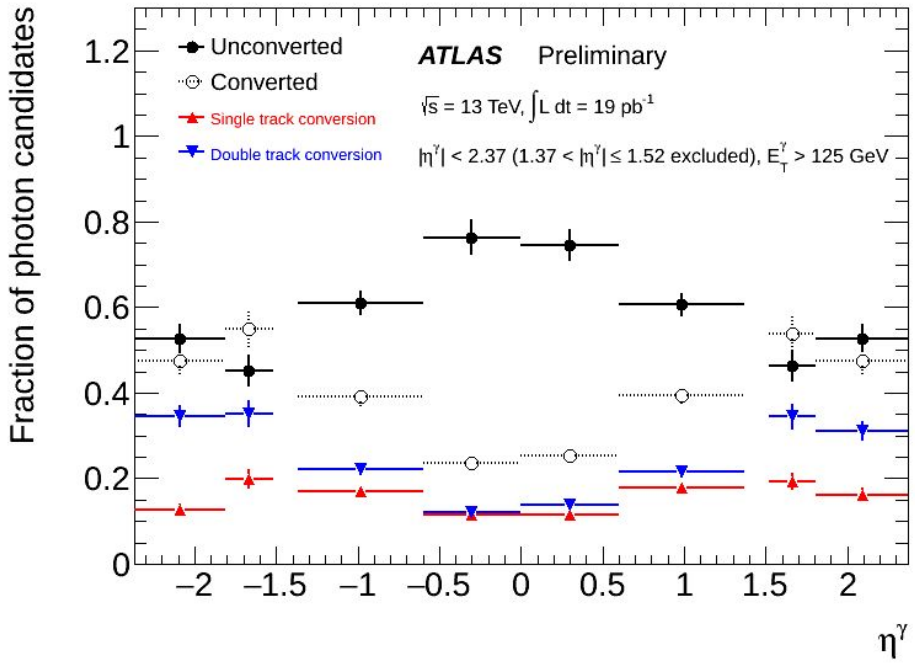
Photon conversion

Using first 2015 data, the performance of the ATLAS detector was tested.

I studied the fraction of the three types of photon candidates

Requiring high E_T cut, isolation and η region we selected photon candidates with 95% purity

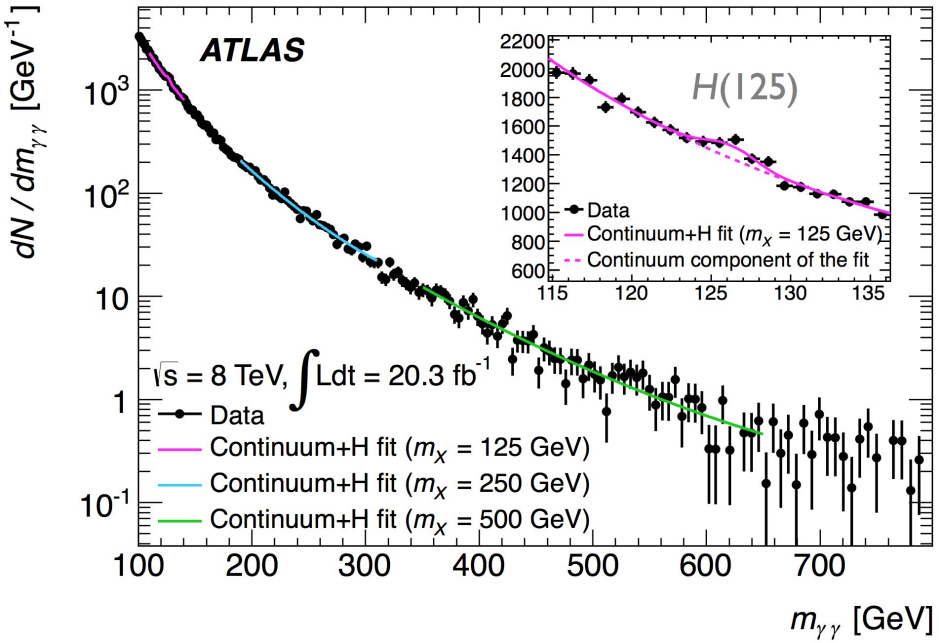




Run I results

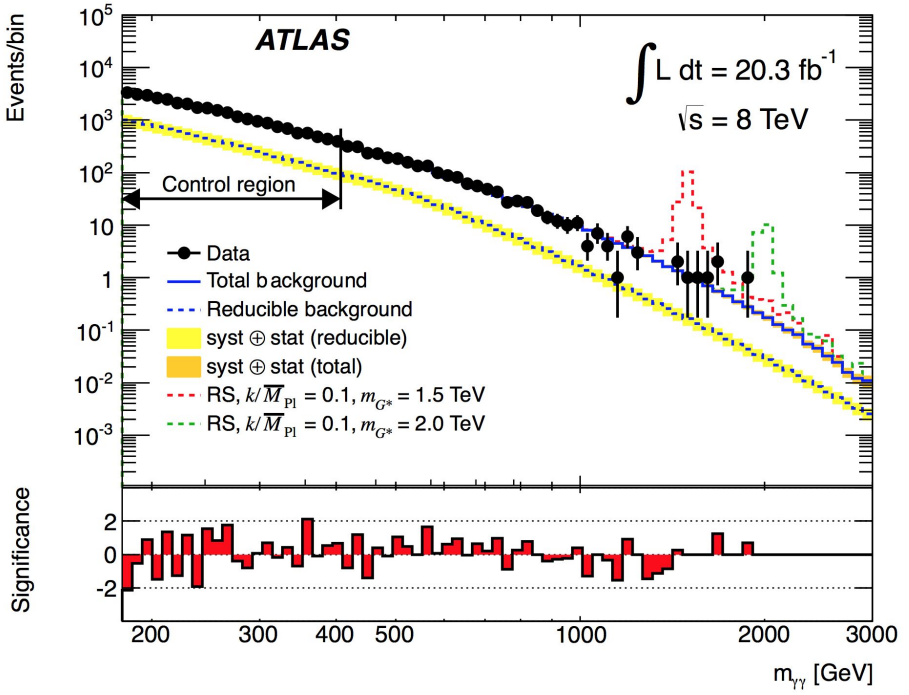
Spin-0

Search for scalar diphoton resonances in the mass range 65-600 GeV with the ATLAS detector in pp collision data at √s = 8 TeV



Spin-2

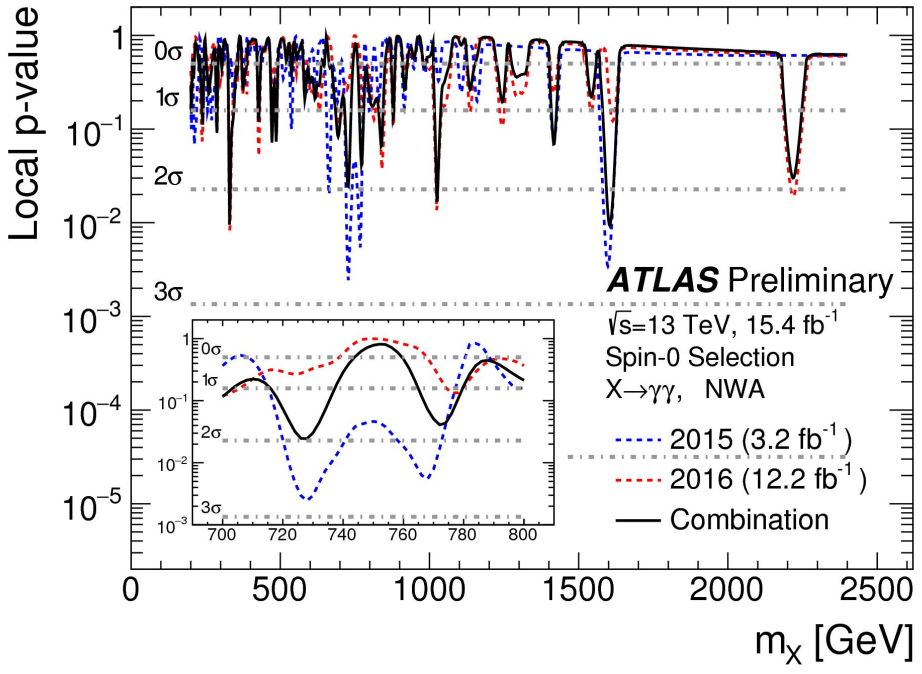
Search for high-mass diphoton resonances in pp collisions at √s = 8 TeV with the ATLAS detector



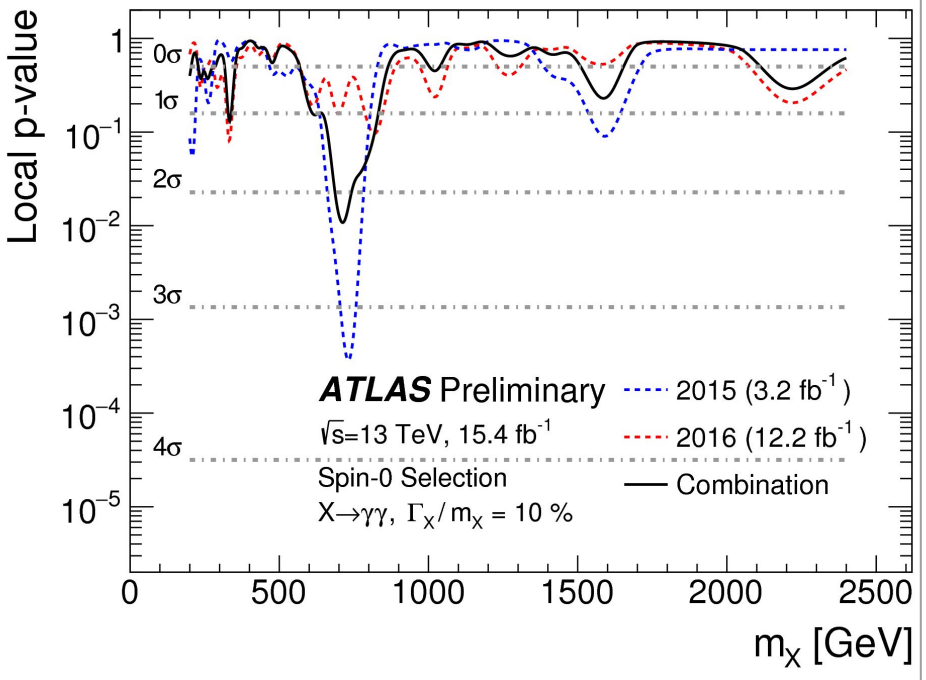
Extra dimensions 7 TeV, RS 7 TeV

Significance for new result and combination

Spin-0 Narrow Width



Spin-0 Large width Γ_X/m_X=10%



Largest significance observed for combined dataset 15.4 fb^{-1}:

2.4σ local @ 1.6 TeV

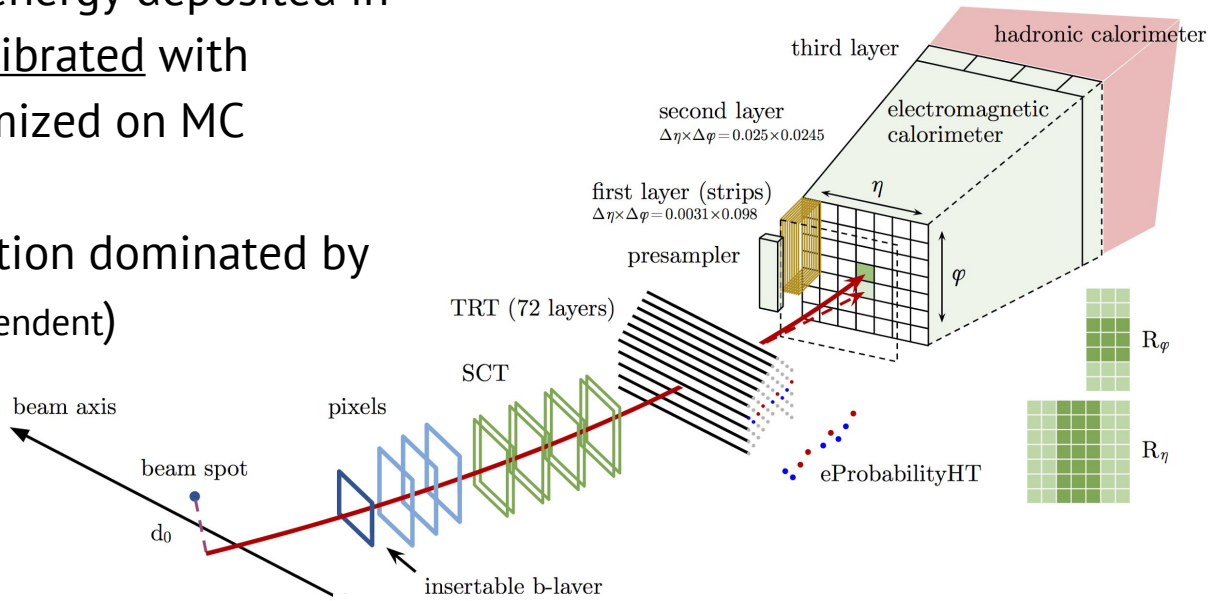
2.3σ local @ 710 GeV

Compatibility between two datasets for signal cross-section 2.7σ @ 730 GeV

Photons in ATLAS

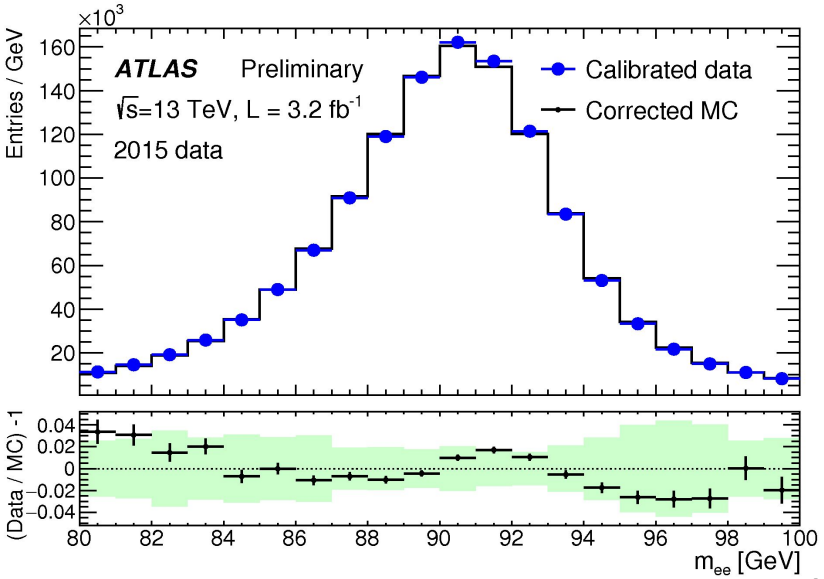
- Photons reconstructed from energy deposited in cluster of EM calorimeter, calibrated with multivariate regression, optimized on MC

- At high E_T^{γ} (>200 GeV) resolution dominated by constant term (0.6%-1.5%, η-dependent)
  - σ=6.2 GeV @ $m_{\gamma\gamma}$=750 GeV
    σ=15 GeV @ $m_{\gamma\gamma}$=2 TeV



- Photons energy scale and resolution extrapolated from Z⟶ee events (2015 and 2016 data)

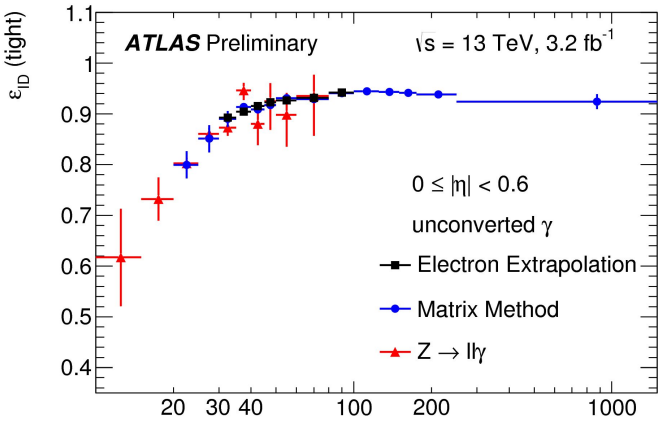
  Uncertainties:
  - Energy scale : ±(0.5 – 2.0)%
  - Energy resolution (E_T = 300 GeV): ±(30–45)%



Identification and isolation

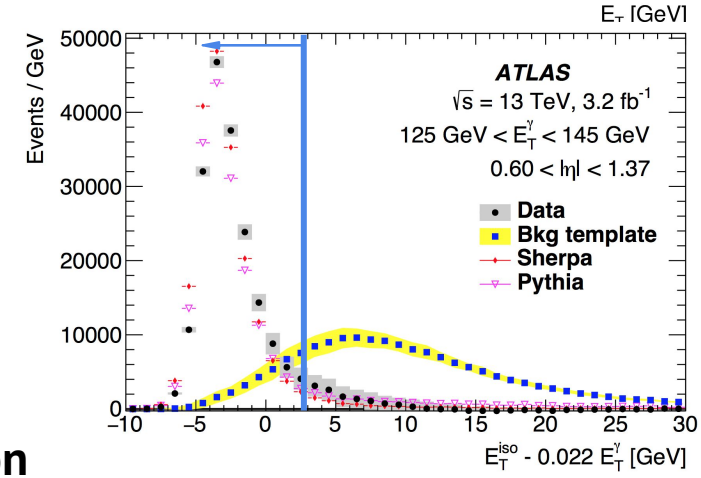
- **Identification**

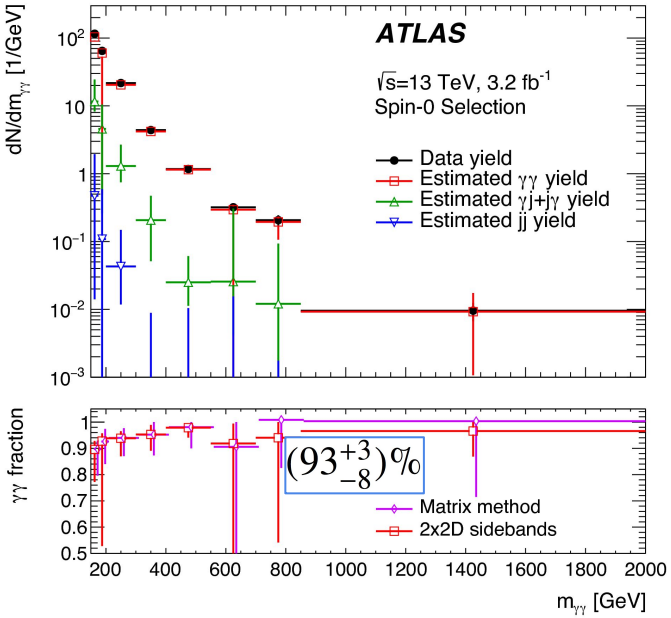
  The **tight** identification selections were optimized for the 2015 data taking, separately for converted and unconverted photons (γ^{conv} , γ^{unconv})
  - ε~90% (E_T=50 GeV) - 95% (E_T=200 GeV) for γ^{conv}
  - ε~85% - 90% for γ^{unconv}



- **Isolation**

  Studied with Z→ee, llγ and γ+X
  - Calorimeter (ΔR=0.4): $E_T^{iso} < 0.022\ E_T^{\gamma} + 2.45$ GeV
  - Track p_T^{iso} (ΔR=0.2): $p_T^{iso} < 0.05\ E_T^{\gamma}$





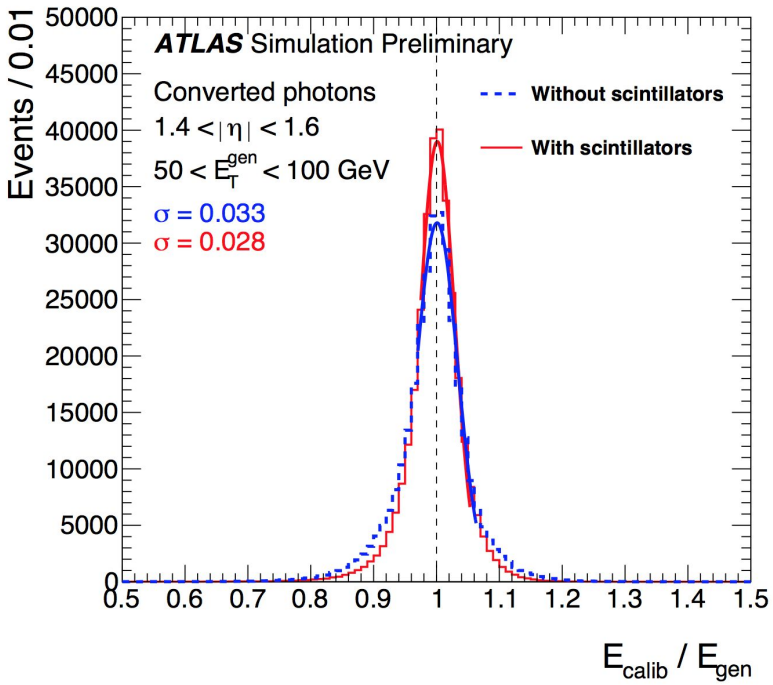
- **Sample composition**

  The relative amount of diphoton, photon-jet and dijet (γγ, jγ, γj, jj) final state is estimated by looking in enriched regions for each component.

  Purity of diphoton passing selection is ~93% for $m_{\gamma\gamma}$>200 GeV

Changes in 2015 re-analysis

- Improved reconstruction and energy calibration
  - update of track isolation for converted photons
  - updated electron track reconstruction
  - improved conversion identification
  - improved calibration
    - Input to calibration replaced with correlated, but better modeled variable
    - Improved calibration of photons near |η| =[1.37-1.52], using scintillators (part of the Intermediate Tile Calorimeter)
- Updated luminosity measurements and uncertainty



Signal Modeling 2016

Spin-0, m_X = 800 GeV	
Narrow Width, Γ_X = 4 MeV	Large Width, Γ_X = 6% m_X