Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector

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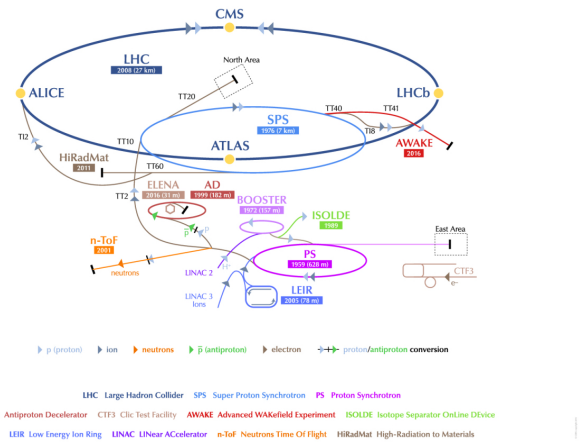
LHC 2015: 13 TeV

2015 run-2

- New energy frontier: **13 TeV**
- Collision rate reached design value: 40 MHz
- With a maximum peak luminosity of $5.1 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Average # of interactions per bunch crossing: 13
- $\approx$4 fb^{-1} of *pp* collisions delivered to ATLAS

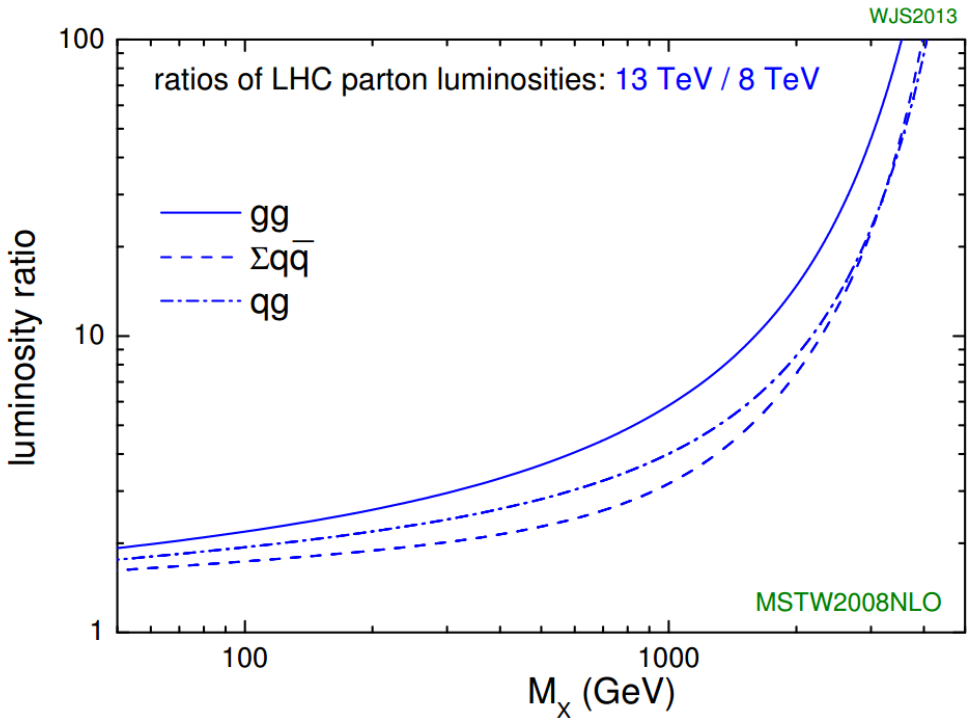


2010-2012 run-1

- $\sqrt{s}$: 7-8 TeV
- Collision rate: 20 MHz
- Maximum peak luminosity: $7.7 \cdot 10^{33} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Average # of inter. per BC: 21 (2012)
- $\approx$5 fb^{-1} of *pp* collisions @ 7 TeV (ATLAS)
- $\approx$20 fb^{-1} of *pp* collisions @ 8 TeV (ATLAS)
- Many Standard Model (SM) measurements, many searches for new physics
- A new elementary particle: **the 125 GeV Higgs boson**

From 8 TeV to 13 TeV

- Biggest improvement of the 2015 LHC run is the increase of the centre-of-mass energy from 8 TeV to 13 TeV
- Larger cross section for high-mass particle production
- Signal/background cross section ratio increased for many searches of new physics



$\sqrt{s}$ 8 $\rightarrow$ 13 TeV improves sensitivity of searches for new physics for many signatures and theoretical models

The ATLAS detector: main upgrades for run-2

Detector and services

- IBL: new layer for the Pixel tracker at 3.3 cm from beam line (previously innermost layer @ 5.05 cm)
- Consolidated muon spectrometer coverage
- Upgrade of luminosity detectors and monitors
- Repaired and improved several systems (RPC for muon trigger, calorimeters, TRT gas, cooling...)
- Installed new aluminium beam pipe

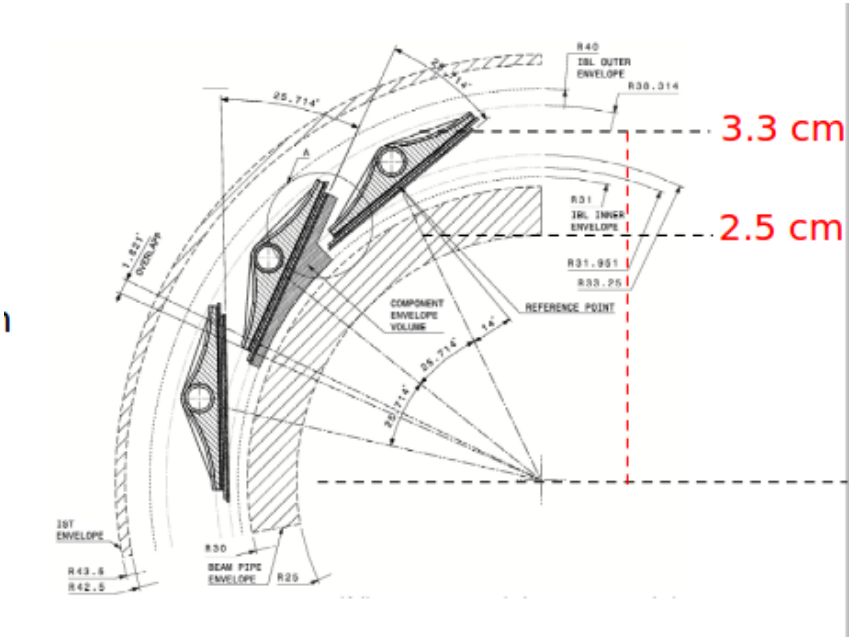
Trigger

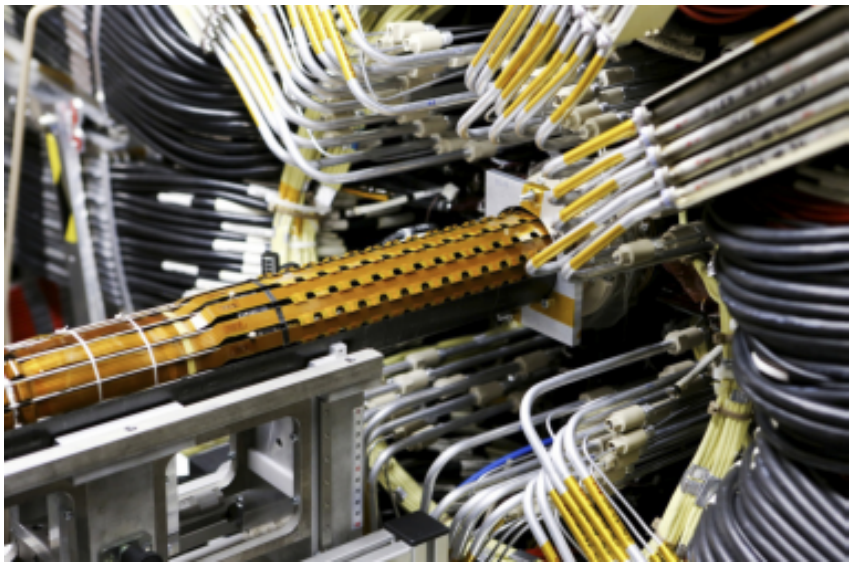
- Redesign, 3 $\rightarrow$ 2 level scheme
- Level-1 rate 75 kHz $\rightarrow$ 100 kHz
- Data acquisition rate: $\gtrsim$ 1 kHz

Software

- Improved event-reconstruction software, reduced processing time
- New analysis framework and more flexible data format

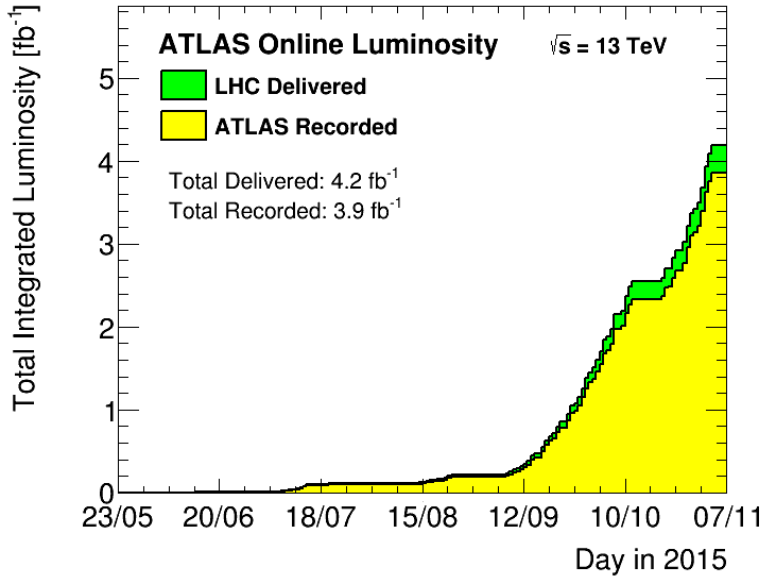
IBL layout, transverse view

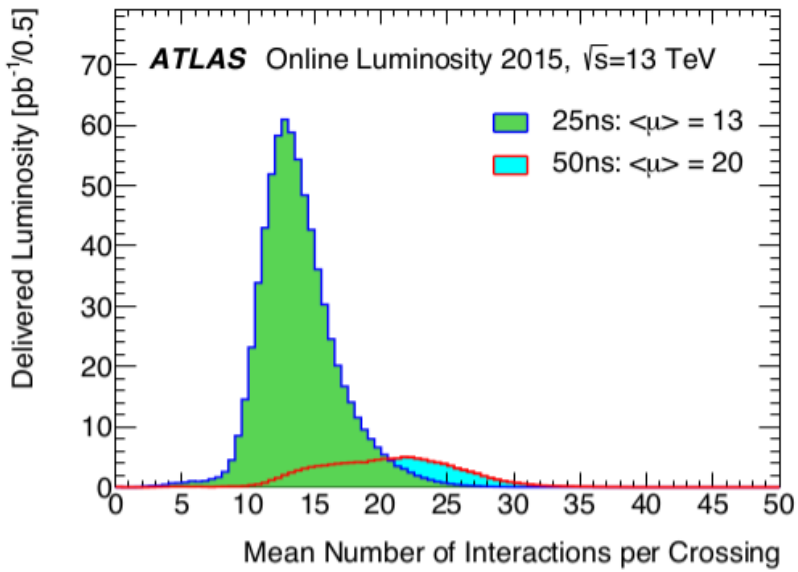




2015 ATLAS operation

- **3.9** fb^{-1} of data collected with 25 ns bunch crossing
  - ≈100 pb^{-1} of data collected with 50 ns bunch crossing
  - ≈680 $\mu\mathrm{b}^{-1}$ of heavy ion data collected
- Data taking efficiency: 92%
- Data quality efficiency: 93% (run-1 94%)
- When removing special and calibration runs the final **"all good" dataset is 3.2** fb^{-1} with a 5% luminosity uncertainty

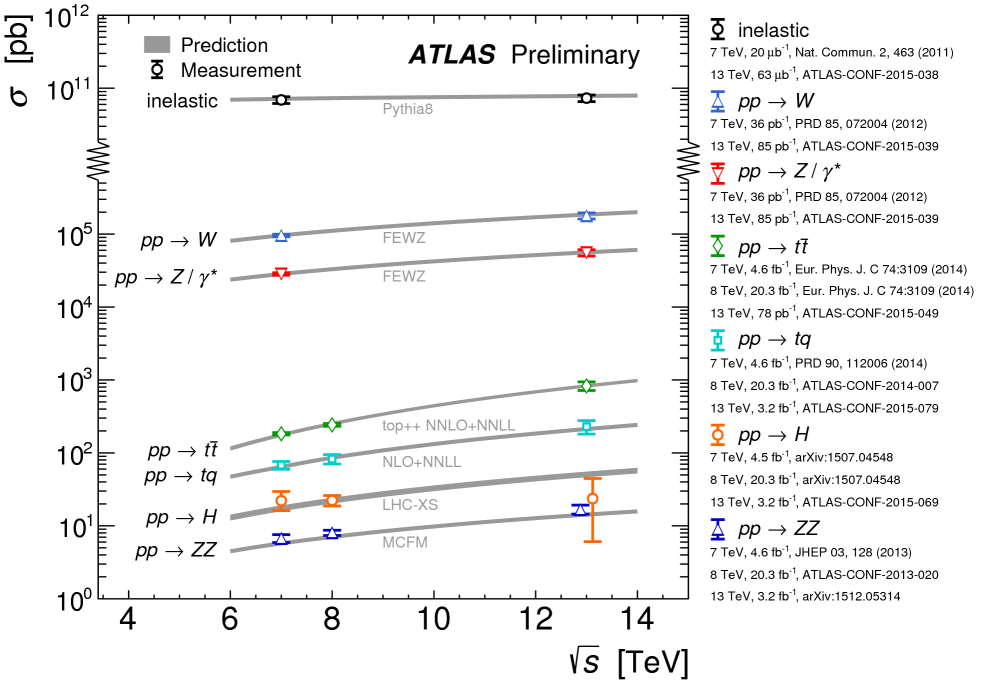


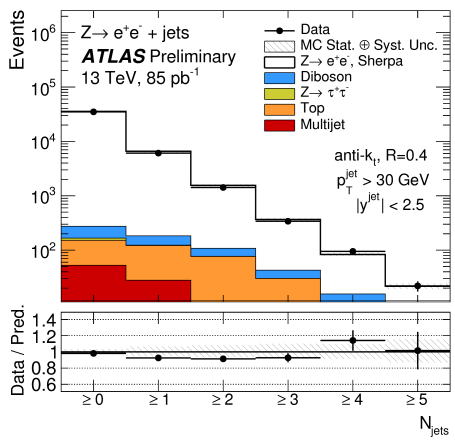


Excellent trigger and detector performance

Physics modelling and 2015 ATLAS results

- Physics modelling at 13 TeV tested on data:
  - Minimum bias
  - Jets, dilepton
  - W, Z, $W/Z + jets$
  - Diboson, triboson
  - Top pairs (+jets)
  - ...
- 24 conference notes released and 4 journal papers published on the full 2015 dataset!
  `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV`
  - ZZ cross-section[1]
  - Search for new phenomena with photon+jet events[2]
  - Search for new physics with multi-jet signatures[3]
  - Search for new physics in dijet mass and angular distributions[4]





[1] arXiv:1512.05314
[2] arXiv:1512.05910
[3] arXiv:1512.02586
[4] arXiv:1512.01530

ATLAS search for di-photon heavy resonances in run-2

Preliminary results of a search for high-mass resonances in $\gamma\gamma$ final states have been released in a public conference note: ATLAS-CONF-2015-081

- Dataset: 3.2 fb^{-1} of pp collisions @ 13 TeV

The basic strategy

- select events with **two high-E_T isolated photons**
- study the $\gamma\gamma$ invariant mass distribution, search for bumps

- This analysis is inspired to the $H \to \gamma\gamma$ run-1 measurement[1]
- There is an analogous run-1 search for $\gamma\gamma$ resonances up to 600 GeV[2]

ATLAS NOTE
ATLAS-CONF-2015-081
December 15, 2015

Search for resonances decaying to photon pairs in 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector

The ATLAS Collaboration

ATLAS-CONF-2015-081
15 December 2015

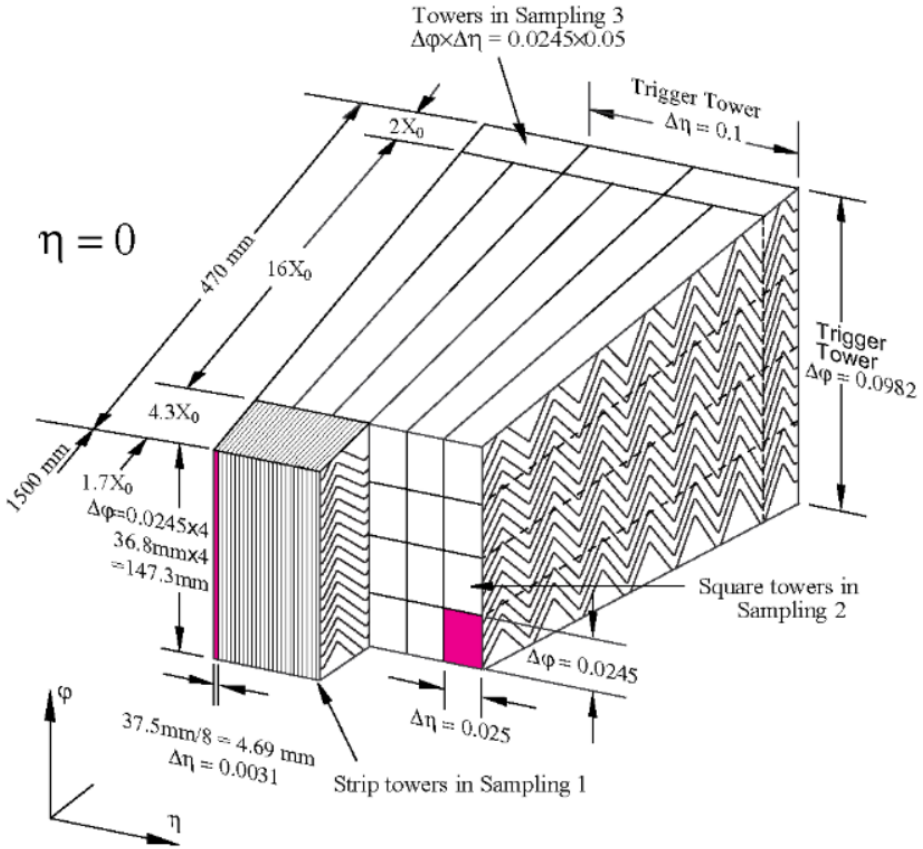
Abstract

This note describes a search for new resonances decaying to two photons, with invariant mass larger than 200 GeV. The search is optimized for scalars such as those expected, for example, in models with an extended Higgs sector. The dataset consists of 3.2 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV recorded with the ATLAS detector at the Large Hadron Collider. The data are consistent with the expected background in most of the mass range. The most significant deviation in the observed diphoton invariant mass spectrum is found around 750 GeV, with a global significance of about 2 standard deviations. A limit is reported on the fiducial production cross section of a narrow scalar boson times its decay branching ratio into two photons, for masses ranging from 200 GeV to 1.7 TeV.

[1] Phys. Rev. D 90, 112015 (2014)
[2] Phys. Rev. Lett. 113, 171801 (2014)

Photon reconstruction

- *EM* calorimeter: sampling, Liquid Argon and accordion-shaped lead absorbers
- e/γ reconstruction seeded from EM calorimeters cells with E_T >2.5 GeV
- Clustering efficiency close to 100% for E_T >25 GeV[1]
- Clusters are then associated with Inner Detector tracks and classified as e, γ or $\gamma_{converted}$



- 97% of γ are correctly identified
- 2-15% of e are misidentified as γ
- Energy calibration determined in Run-1 $Z \to ee$ events[2] and corrected for the 13 TeV data taking conditions

[1] ATL-PHYS-PUB-2011-007

[2] Eur. Phys. J. C (2014) 74:3071

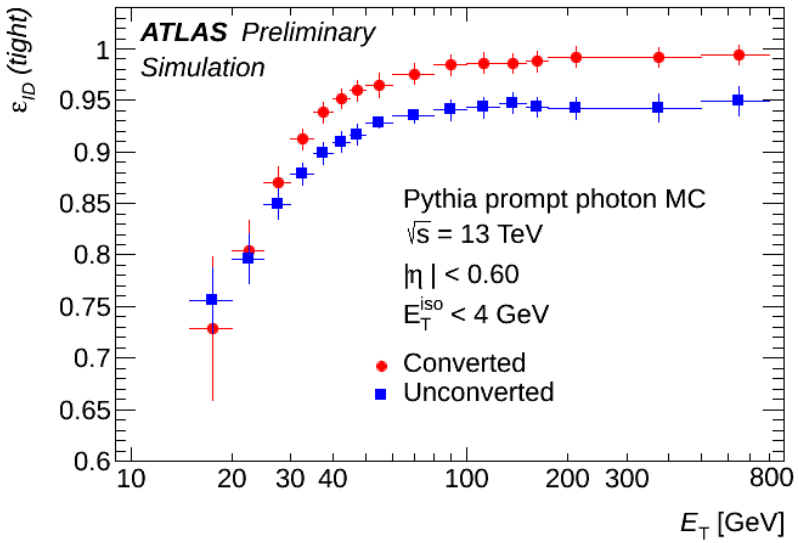
Candidate photon selection

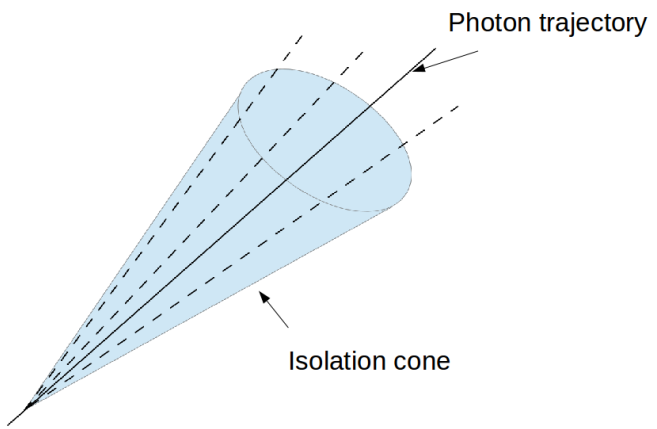
- Trigger: two γ, with $E_T^{\gamma 1}$ >35 GeV, $E_T^{\gamma 2}$ >25 GeV (>99% signal efficiency)
- Pre-selection:
  - γ quality criteria: shower shape, leakage in the hadronic calorimeter
  - $E_T^{\gamma 1}$ >40 GeV, $E_T^{\gamma 2}$ >30 GeV
  - $|\eta^{1,2}| < 2.37$, excluded $1.37 \leq |\eta| < 1.52$
- $\epsilon_{identification} = 85\%$ (90%) for unconverted (converted) γ for $E_T = 25$ GeV
- It asymptotically reaches 95% (98%) for $E_T > 200$ GeV
- γ are required to be **isolated**, i.e. to have little activity in the Inner Detector/calorimeters in a ΔR[1] cone around them

Isolation

- Calorimeter: $E_T^{iso} < 2.45 + 0.022 \cdot E_T^{\gamma}$ in $\Delta R < 0.4$
- Inner detector: $p_T^{iso} < 0.05 \cdot E_T^{\gamma}$ in $\Delta R < 0.2$

Central photon efficiency @ 13 TeV (simulation)[2]



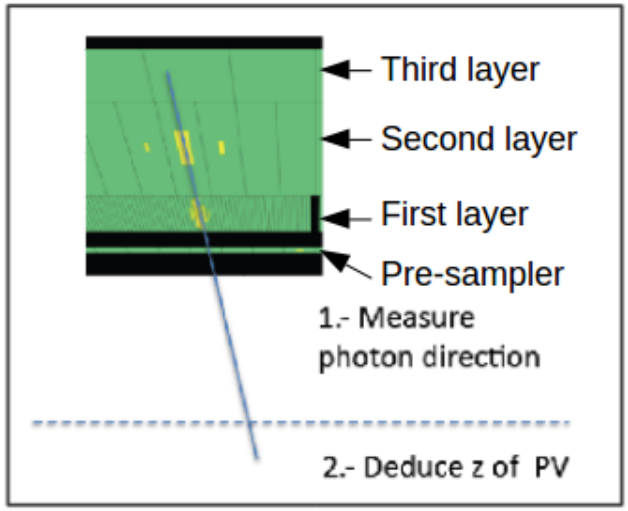


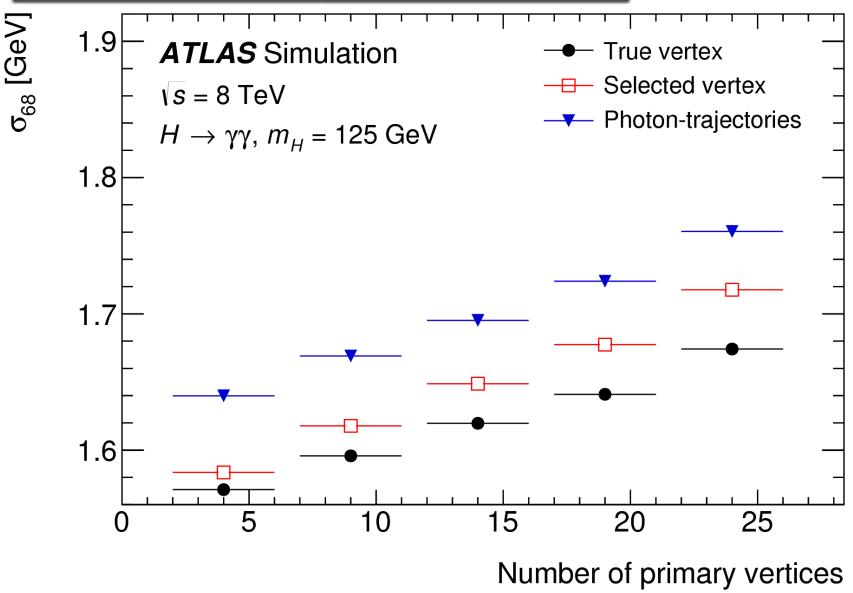
[1] $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

[2] EGAM-2015-002

Di-photon vertexing

- reconstruction of $m_{\gamma\gamma}$ and track-based isolation require **correct $\gamma\gamma$ vertex identification**
- γ trajectories measured exploiting the longitudinal segmentation of the calorimeter
- the $\gamma\gamma$ vertex is selected among the reconstructed vertices with a neural network (NN) algorithm[1]
- inputs used from the NN are:
  - z position of γ extrapolation
  - $\sum p_T^2$
  - $\sum p_T$
  - $\delta\phi$ between di-photon system and vector sum of track momenta
- efficiency of identifying a vertex within 0.3 mm for the true one is **80-95%**, depending on the number of reconstructed vertices in the event





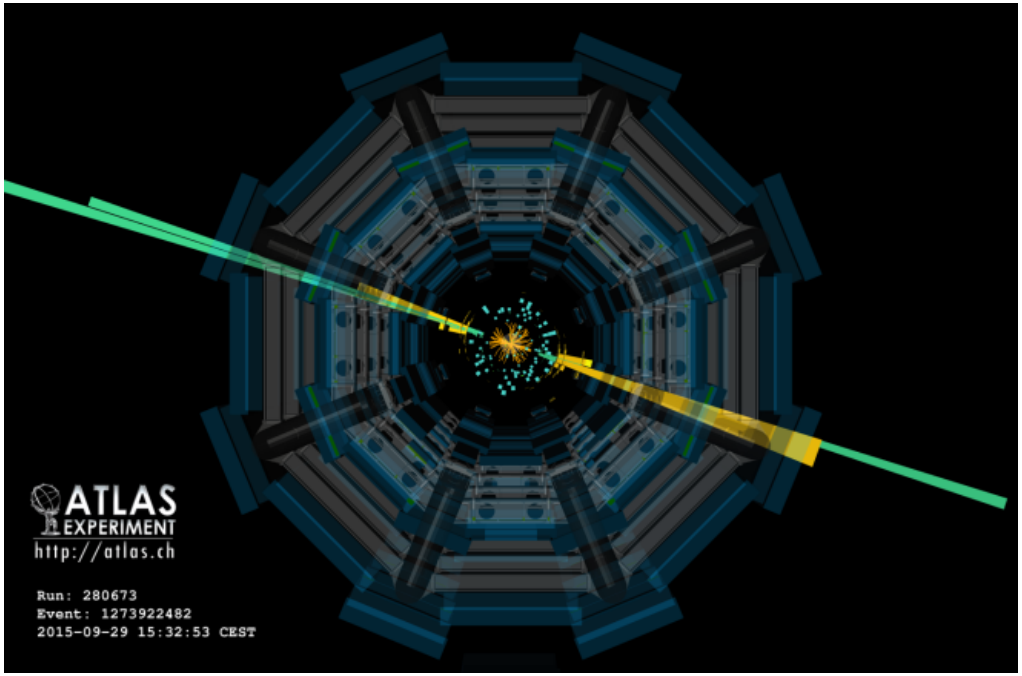
Resolution on simulated 125 GeV $H \to \gamma\gamma$ sample as a function of N_{vertex} when using onlyγ trajectories (blue), NN algorithm (red) or truth info (black)

[1] ATLAS-CONF-2015-060

Final di-photon selection

- efficiency of isolation cuts: >90% for a gluon-gluon fusion (ggF) Higgs-like signal with $m_X > 800$ GeV

  $\rightarrow$ exp. significance increase >20% for $m_X > 600$ GeV
- require $E_T^{\gamma 1}/m_{\gamma\gamma} > 0.4$ and $E_T^{\gamma 2}/m_{\gamma\gamma} > 0.3 \rightarrow$ exp. significance increase by 20% for a scalar resonance with $m_X = 600$ GeV



- $m_{\gamma\gamma}$ resolution increases $\approx$ linearly **from 2 GeV** ($m_{\gamma\gamma} = 200$ GeV) **to 13 GeV** ($m_{\gamma\gamma} = 2$ TeV)
- **purity of $\gamma\gamma$ sample, measured in data, is >90%** (i.e. small $\gamma-$jet and jet-jet contributions)
- **total signal selection efficiency is >40%** for a ggF produced Higgs-like resonance with m_X **>600 GeV**
- the efficiency is larger for *VBF* and smaller for *ttH* production, due to kinematics

Statistical treatment and signal modeling

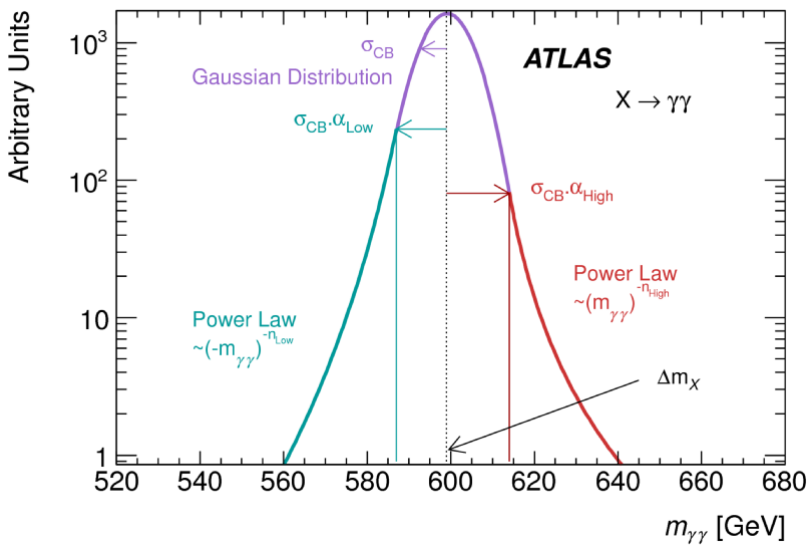
- N_{signal} and N_{bkg} events obtained from **unbinned maximum likelihood fits** of $m_{\gamma\gamma}$ distribution for several hypothesis on m_X and on Γ_X

- signal modeled with a **double-sided Crystal Ball function** ($\approx$ same as for run-1 Higgs analysis)

  $\rightarrow$ i.e. a gaussian-core switching to a power-law below (above) a given mass value α_{low} (α_{high})
- **narrow signal (NWA)**: width dominated by detector resolution
- **wider signal (LW)**: $\Gamma/m_X \in [1-10\%]$ values are tested

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

where $t = \dfrac{m_X - \mu_{CB}}{\sigma_{CB}}$

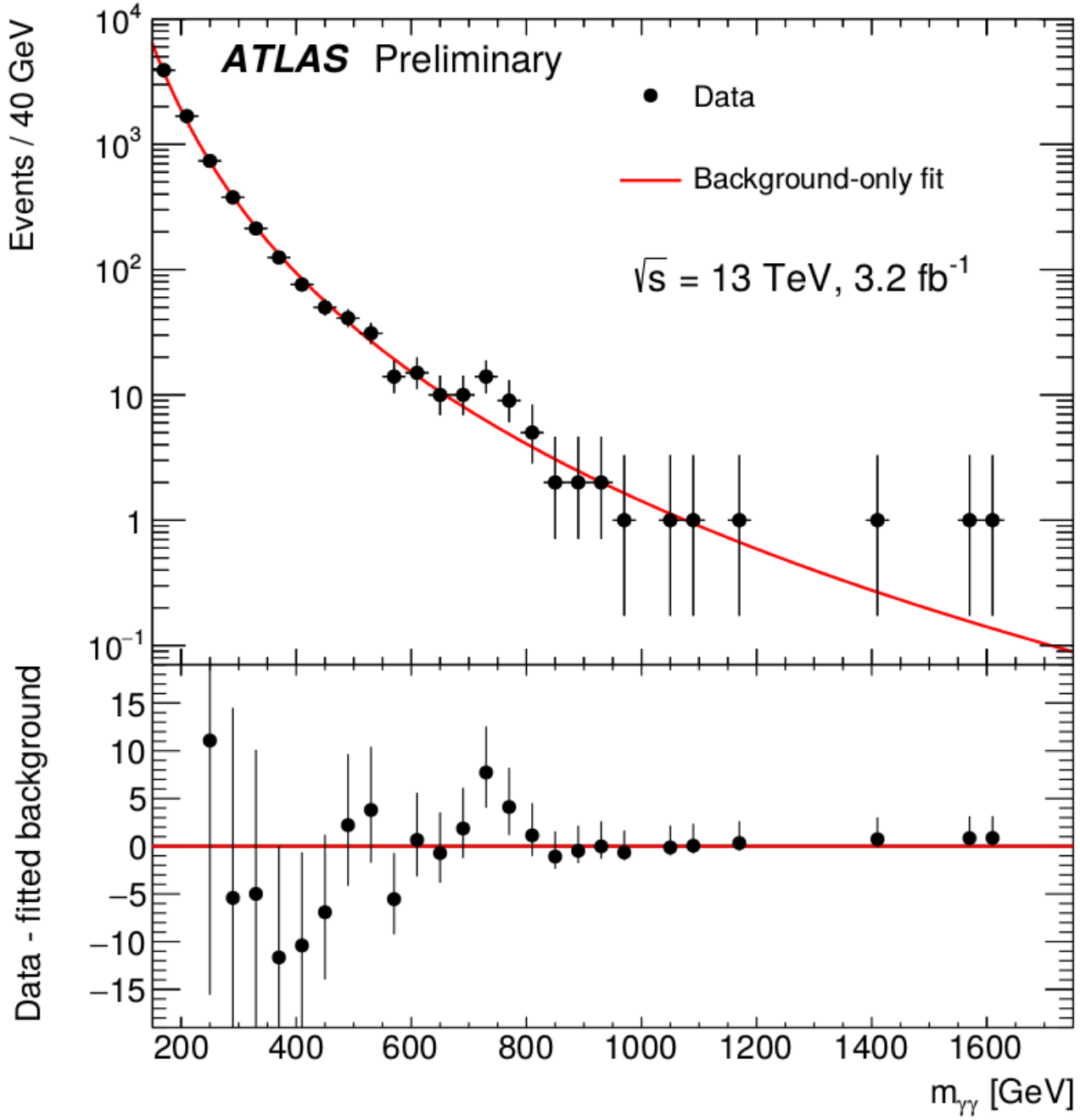


- polynomial parametrizations of signal function parameters (m_X,Γ/m_X) from Monte Carlo
- bias due to usage of the ggF shape wrt to the other production modes is found to be negligible

Background modeling

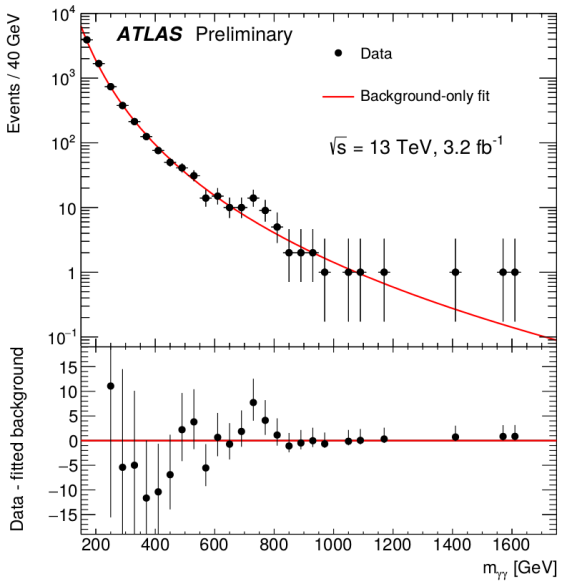
- simple function found to describe correctly the backgroumnd shape over the whole $m_{\gamma\gamma}$ spectrum: $f = (1 - x^{1/3})^b x^a$, with $x = m_{\gamma\gamma}/\sqrt{s}$
- function validation performed on simulation and on $\gamma-$jet enriched data sample
- more complex functions have also been tested
- bias on N_{signal}^{fitted} due to the particular function choice required to be $<$20% of the statistical uncertainty on N_{signal}^{fitted}. The bias is estimated on simulation
- possibility of unexpectedly needing more degrees of freedom in data is checked with a statistical test, no signifcant improvement is found

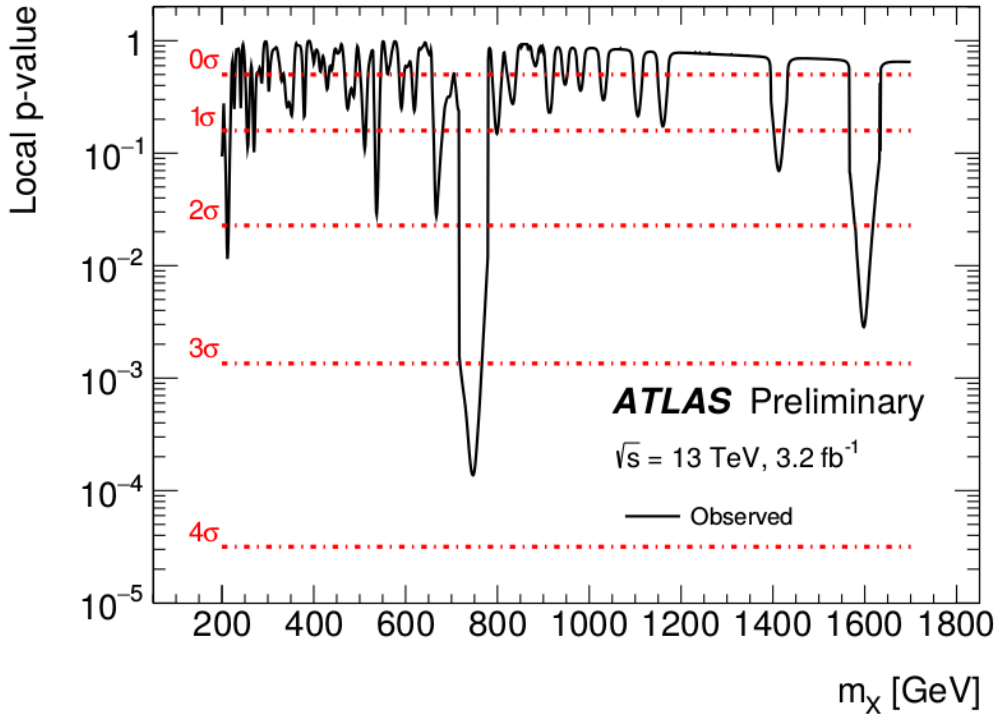
$m_{\gamma\gamma}$ spectrum in 2015 run



- $m_{\gamma\gamma}$ spectrum obtained on the $3.2\mathrm{fb}^{-1}$ of pp collisions @ 13 TeV collected by ATLAS in 2015
- an excess is visibile for $m_{\gamma\gamma}$ ≈750 GeV

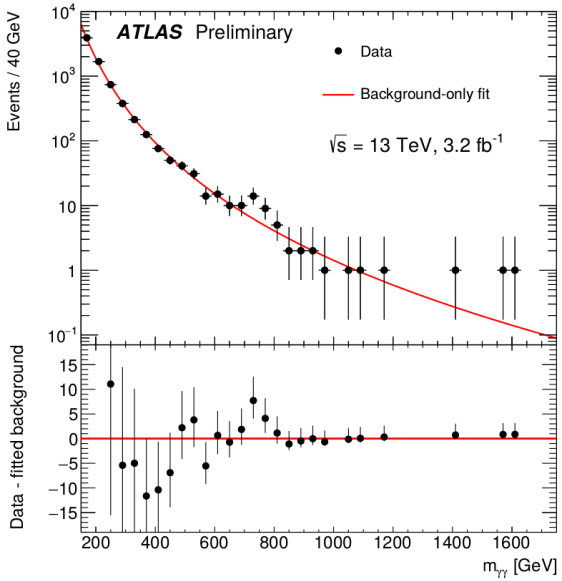
Results

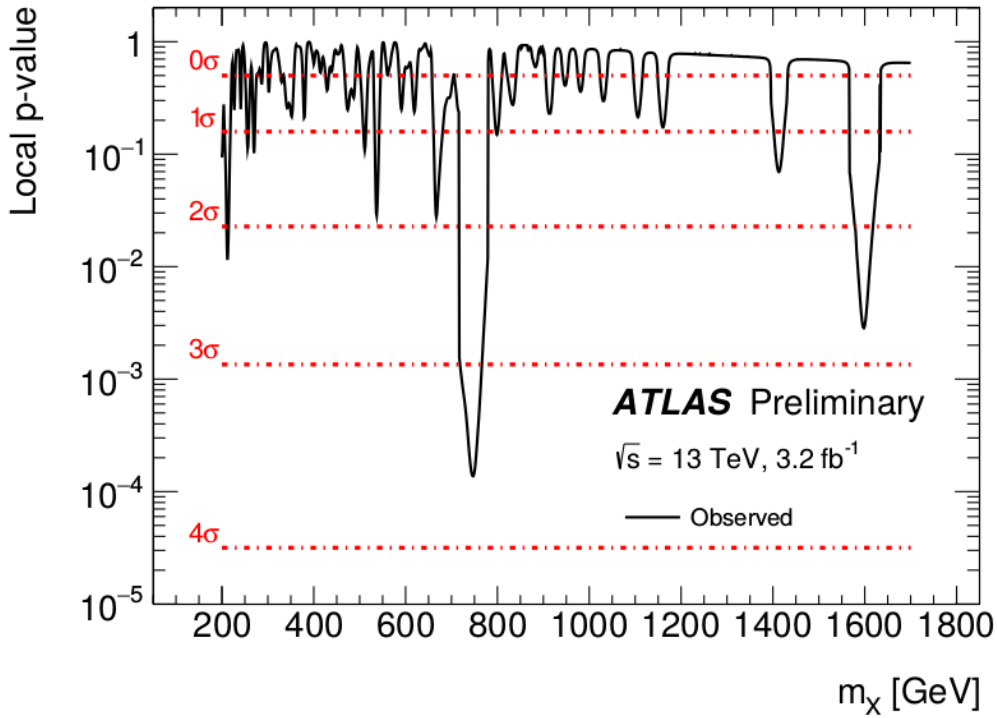




- local $p-$value obtained with unbinned maximum likelihood fit in the NWA
- systematic uncertainties are taken into account:
  - width of signal funct. due to γ **energy resolut.**: from $^{+55\%}_{-20\%}$ @ 200 GeV to $^{+110\%}_{-40\%}$ @ 2 TeV
  - N^{fitted}_{signal} bias due to **choice of bkg function form**: $2 - 10^{-3}$ events, m_X-dependent
  - N^{fitted}_{signal} bias due to **stat. unc. on bkg component of the fit**: from 50% of the total uncertainty @ 200 GeV to 20% @ 2 TeV
- other uncertainties (e.g. γ energy scale, signal modeling for different production modes) are found to be negligible

Results-2

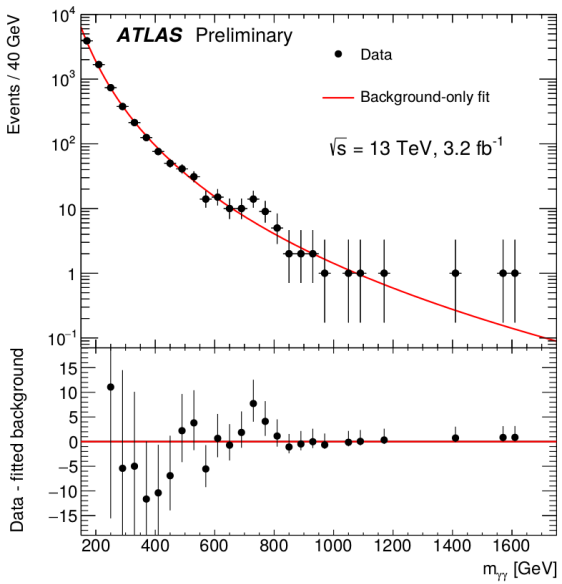


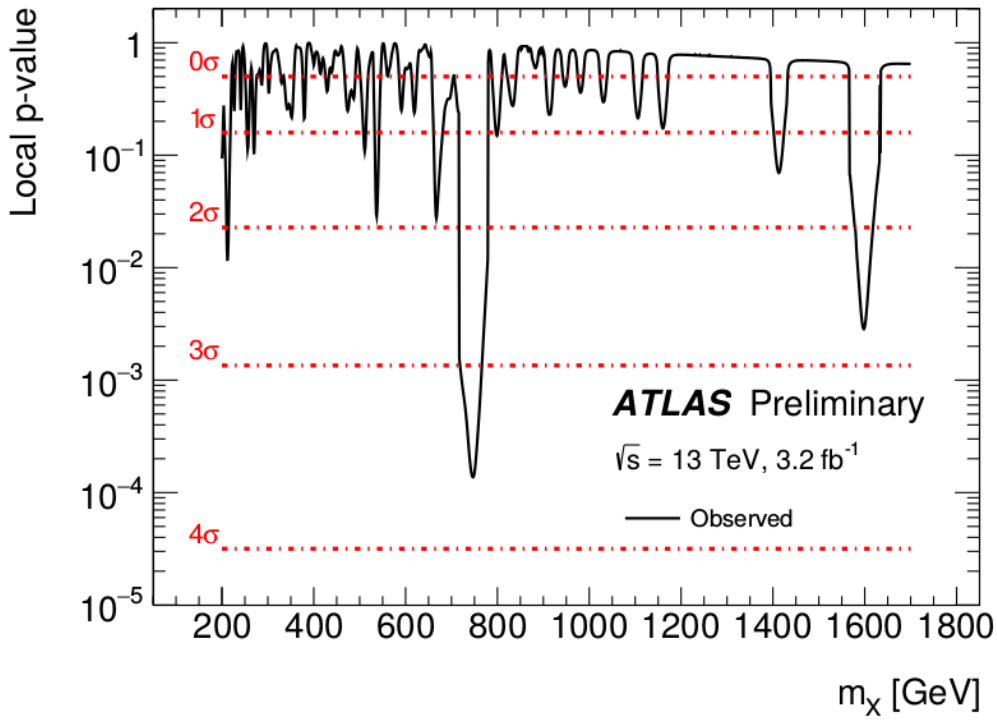


- biggest deviation from the bkg-only hyp. is at 750 GeV with **local signif. of 3.6** σ for NWA
- considering the look-elsewhere effect[1], **global signif. is 2.0** σ for NWA
- the excess is broader than experimental $m_{\gamma\gamma}$ resolution, thus signals with resonances wider than the detector uncertainty have been tested
- biggest discrepancy from bkg-only hyp. for LWA has been found for $\Gamma \approx 45$ GeV, with **local signif. 3.9** σ **and global signif. 2.3** σ

[1] Eur. Phys J C70 (2010) 525

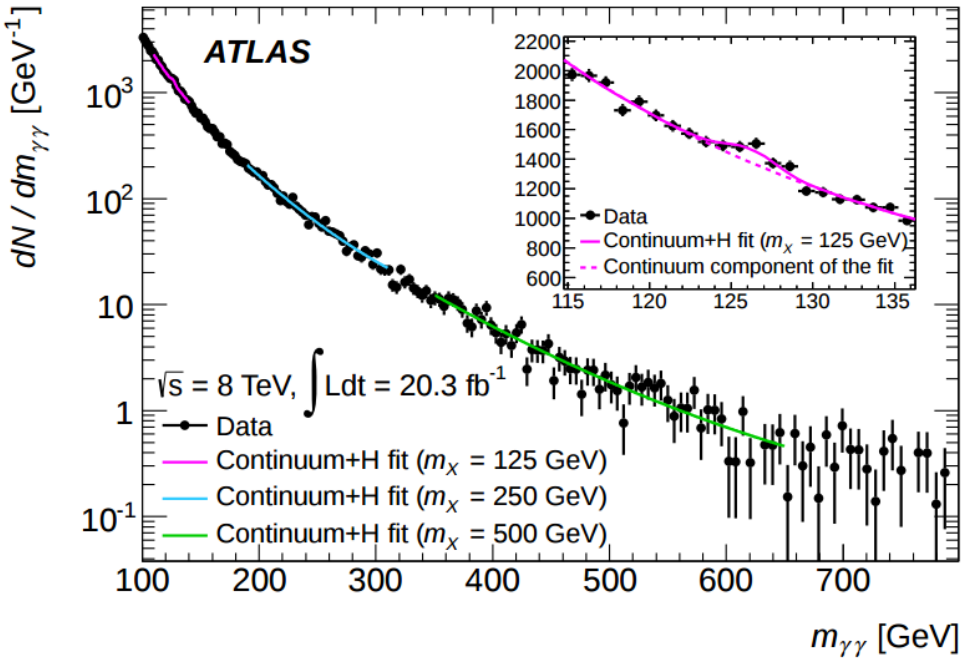
Results-3

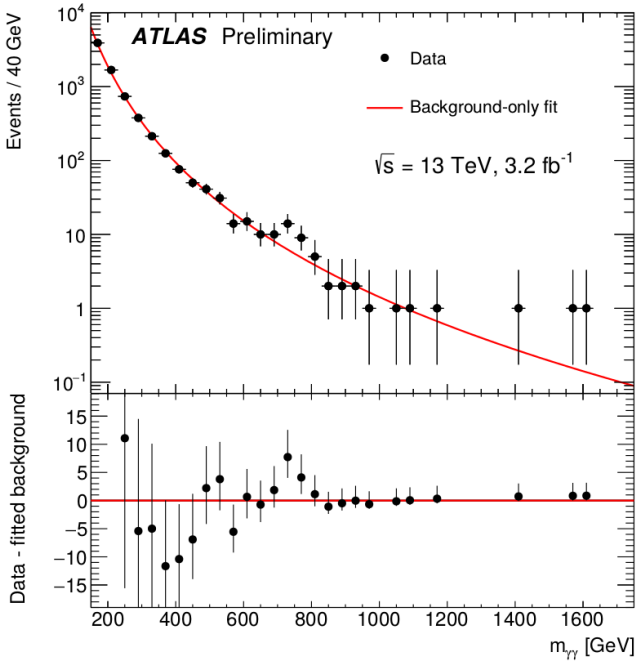




- no detector or reconstruction effect that could explain this larger rate was found
- no indication of anomalous background contamination was found
- the kinematic properties of events in the excess region have been compared with those below and above that region, no significant difference was found

Is the excess compatible with Run-1?





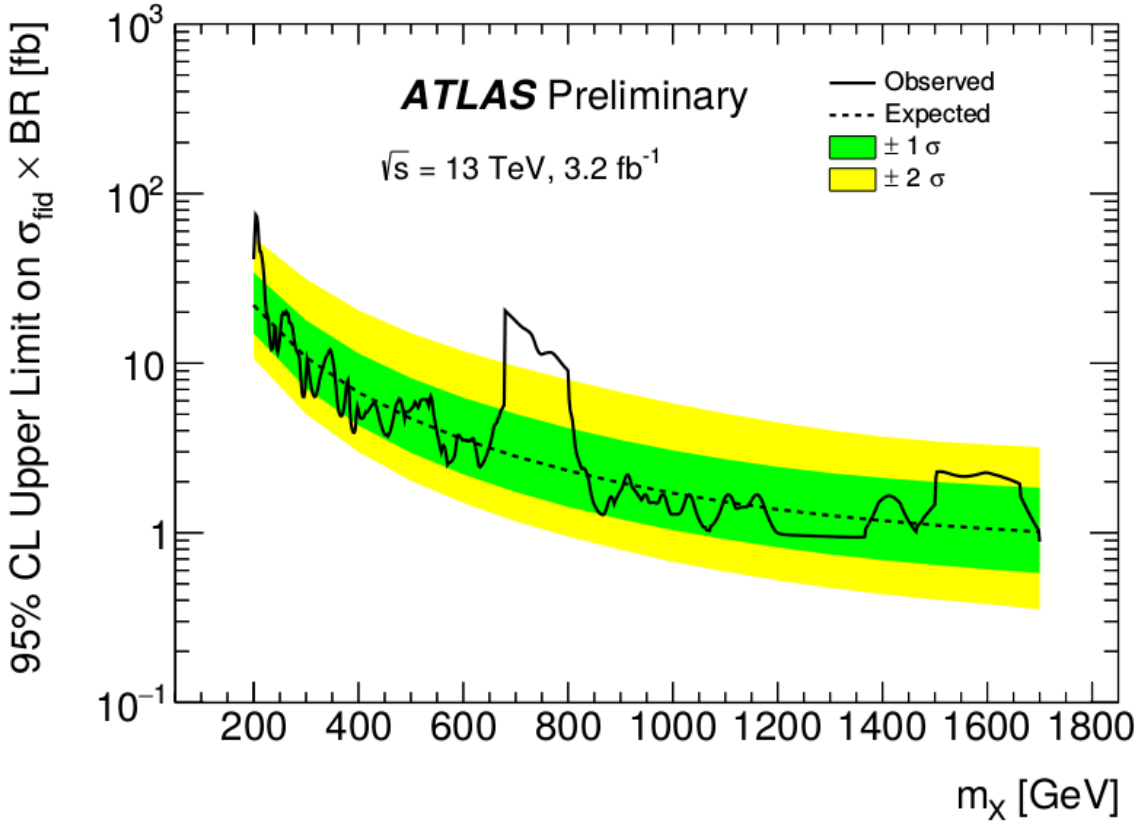
- the run-1 $X \to \gamma\gamma$ search[1] has been extended above 600 GeV by using the same background model as for the run-2 one
- the $s-$channel gluon-initiated resonant process 13 TeV/8 TeV ratio is assumed to be 4.7[2]
- while results on the run-1 dataset show no significant excess, they are compatible with run-2 results within 2.2 σ for narrow resonances, within 1.4 σ for a resonance with $\Gamma \approx 45$ GeV

[1] Phys. Rev. Lett. 113, 171801 (2014)

[2] Eur. Phys. J. C 63 (2009) 189

Limits on $\sigma_{fid} \times BR$ for a scalar resonance

Limits on $\sigma_{fid} \times BR$[1] for a scalar resonance using the NWA



Limits on $\sigma_{fid} \times BR$ for a scalar resonance take into account additional uncertainties:

- trigger: 0.6%
- γ identification: 3-2% depending on $m_{\gamma\gamma}$
- γ isolation: 4-1% depending on $m_{\gamma\gamma}$
- production mode: 3%
- luminosity: 5%

- sharp rise and fall of limits around 750 GeV due to pull of nuisance parameter associated to the photon energy resolution
- when considering wide resonances, the NWA underestimates the signal yield by $< 10\%$ for $\Gamma = m_X \cdot 0.4\%$ and $< 20\%$ for $\Gamma = m_X \cdot 1.4\%$
- the reach of run-1 limits (600 GeV) has been significantly extended

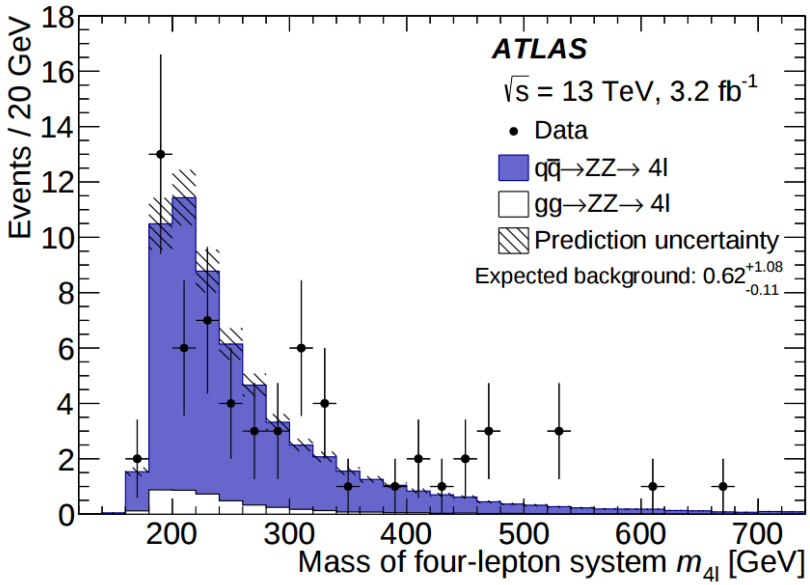
[1] σ_{fid} is the cross-section defined in the kinematic phase space of the analysis selection

What can we do now?

- while no detector or background mismodeling effects were found to explain the excess, this is not statistically conclusive, and compatible with an upward fluctuaction of the background
- we will have a clearer picture by next summer, when more data will be available

What can we do now? -2

- Several searches already performed on the 13 TeV dataset
  `https://twiki.cern.ch/twiki/bin/view/AtlasPublic/December2015-13TeV`
- No other relevant deviations from the background-only hypothesis have been observed elsewhere



4-lepton invariant mass in ZZ events with 13 TeV data

- a search for dijet resonances and a $ZZ \to 4\ell$ analysis on full 2015 dataset have been already published[1]

  $\to$ dijet search limited to $m_{jj} > 1.1$ TeV due to trigger, $ZZ \to 4\ell$ analysis has no statistics above 700 GeV
- preliminary results for heavy $H \to ZZ \to 4\ell$ have been released[2]
- more results for other signatures and analysis of the data expected soon

[1] arXiv:1512.05314, arXiv:1512.01530
[2] ATLAS-CONF-2015-059

Conclusion and outlook

- LHC run-2 started with 13 TeV *pp* collisions in 2015
- ATLAS collected 3.2 fb^{-1} of high quality data, with excellent detector performance
- Data analysis in progress, 4 papers and 24 conference notes on the full dataset have already been published
- A search for high-mass resonances has been conducted in $\gamma\gamma$ events, preliminary results are available in ATLAS-CONF-2015-081
- Limits have been set on $\sigma_{fid} \times BR$ which extend significantly the reach of the run-1 search (600 GeV)
- Around a mass value of 750 GeV an excess is found with respect to the background-only hypothesis, with a global significance of 2.0 σ when considering a narrow-width resonance
- Assuming wider resonances, the maximum deviation from the bkg-only hypothesis is 2.3 σ for a resonance with $\Gamma \approx 45$ GeV
- More data are needed to clarify the nature of this excess