Search for $\gamma\gamma$ and $Z\gamma$ Resonances with the ATLAS detector

Fuquan Wang
University of Wisconsin-Madison
On behalf of ATLAS collaboration

June 14, 2016
BEACH 2016
George Mason University, Virginia

ATLAS EXPERIMENT

Introduction

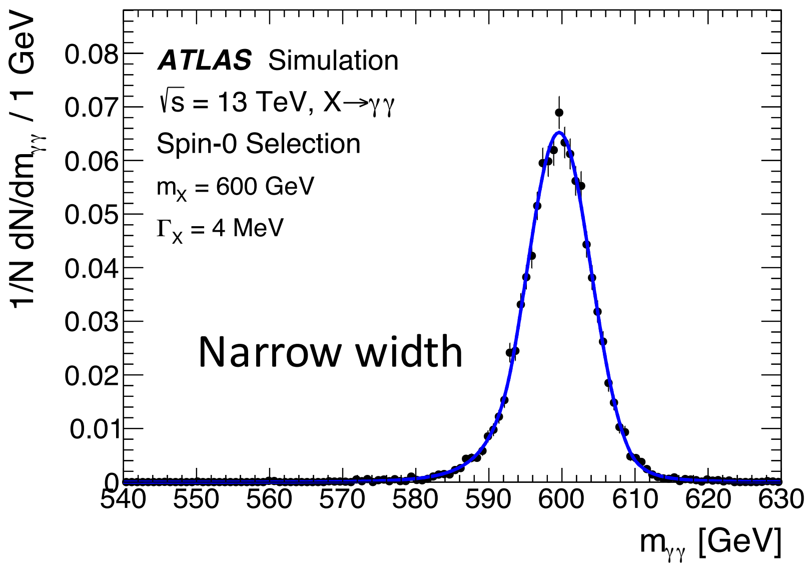
- Many models of physics beyond the Standard Model (SM) introduce new bosons through either an extension of the Higgs sector or through additional gauge fields.
  - Suggest interesting searches for new massive bosons
- Attractive decays from an experimental perspective are to $\gamma\gamma$, $Z\gamma$ or ZZ final states, since both Z bosons and photons can be well measured with good γ/jet separation
- The following searches will be presented
  - $\gamma\gamma$ final state (arXiv:1606.03833)
  - $Z\gamma$ final state (ATLAS-CONF-2016-010)
  - Both uses dataset: 3.2 fb^{-1} $\sqrt{s}$=13 TeV data collected in year 2015

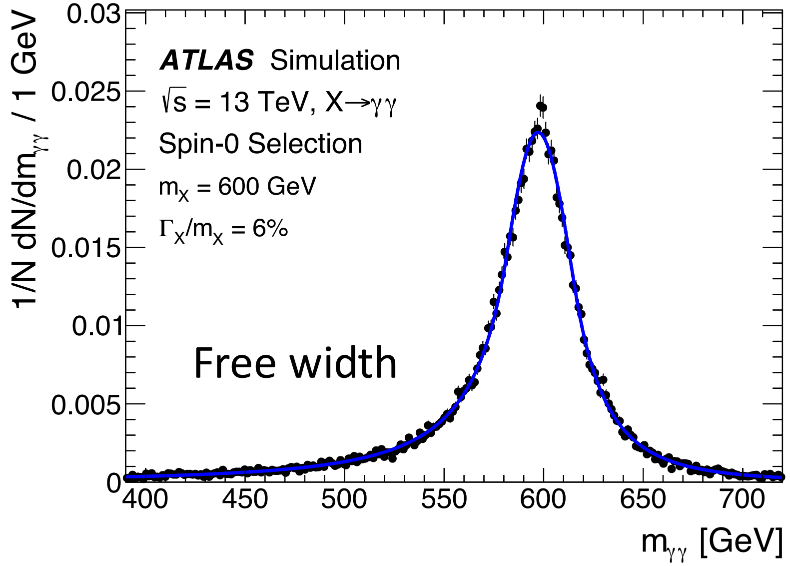
Di-photon analysis

- Trigger:
  - At least 2 γ's, with p_T larger than 35 and 25 GeV
  - Loose shower shape criteria in electromagnetic (EM) calorimeter
- Photon selection:
  - In the EM calorimeter acceptance, tight shower shape criteria
  - Calo isolation E_T^{iso} (sum of the E_T of energy clusters deposited in a ΔR<0.4 cone) less than $0.022 \times E_T^{\gamma}$+2.45 GeV
  - Track isolation p_T^{iso} (sum of track p_T originating from the di-photon primary vertex) less than $0.05 \times E_T^{\gamma}$
- Event selection:
  - Primary vertex selected with neural-network estimation using photon pointing and associated tracks
  - The E_T^{γ} leading two photons are used to reconstruct $\gamma\gamma$ pair
  - Spin-0 analysis: $E_T^{\gamma}>0.4(0.3)m_{\gamma\gamma}$, $m_{\gamma\gamma}$>150 GeV
  - Spin-2 analysis: E_T^{γ}>55 GeV for both photons, $m_{\gamma\gamma}$>200 GeV

Signals to be interpreted in $\gamma\gamma$ analysis

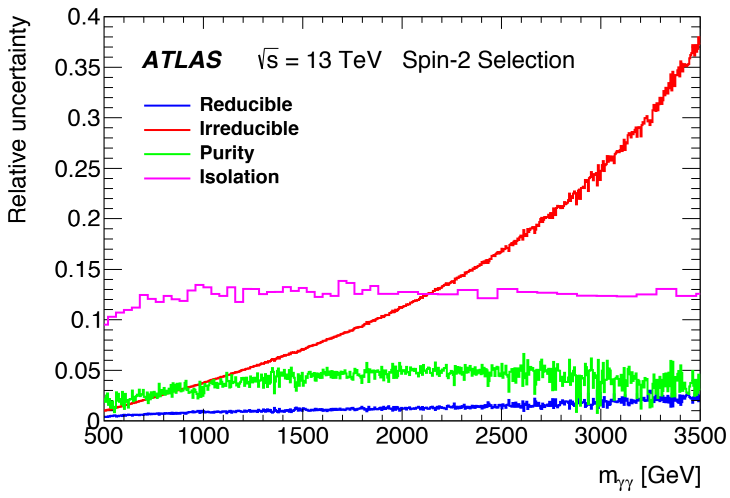
- Spin-0 resonances predicted with an extended Higgs sector
  - For both narrow width approximation (4 MeV width) and large width
- Spin-2 resonances use the Randall-Sundrum (RS) model graviton as a benchmark
  - Dimensionless coupling from 0.01 to 0.3
- Detector resolution of the signals are parameterized using the double-sided crystal-ball function
  - A Gaussian function with power-law tails on both sides

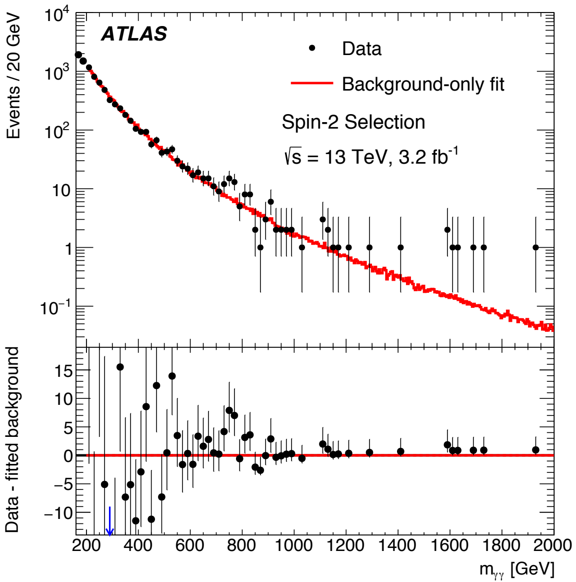




Background estimation for spin-2 interpretation

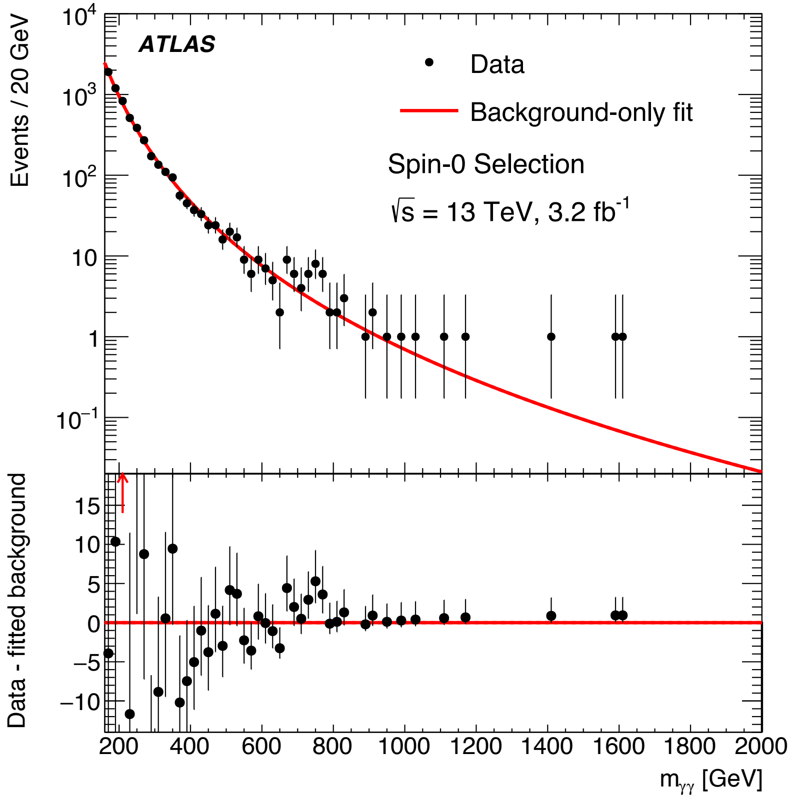
- $\gamma\gamma$ background (irreducible) samples are simulated with Sherpa generator and reweighted to Diphox NLO calculation
  - Include PDF, scale and isolation systematic uncertainties
- γjet background (reducible) component from data control region with photon(s) failing the tight identification
  - Fitted with a wide choice of functions
  - Difference of fitted functions are taken as systematic uncertainty
- Mixed with data-driven fractions of $\gamma\gamma$, γjet and di-jet
- Use 200-500 GeV mass range to normalize to data
  - Search for resonances above 500 GeV with S+B fits





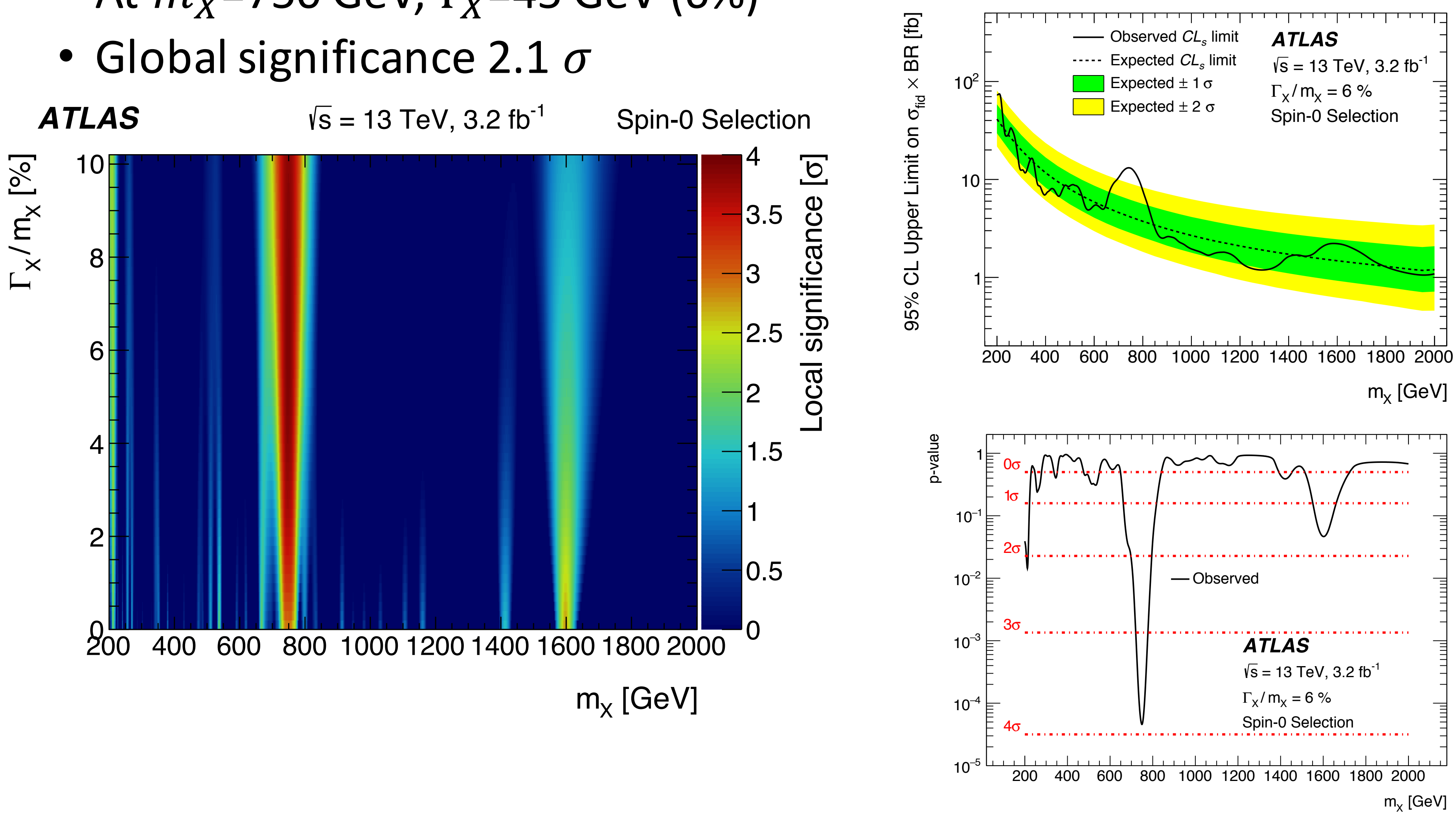
Background estimation for spin-0 interpretation

- The background is estimated by fitting the $\gamma\gamma$ invariant mass distribution to an analytical function, searching for an excess
- The function form is validated with large statistical background MC samples
  - Perform an S+B fit on the background only sample, and require the fitted signal very small
- Search the mass range above 200 GeV with S+B fits



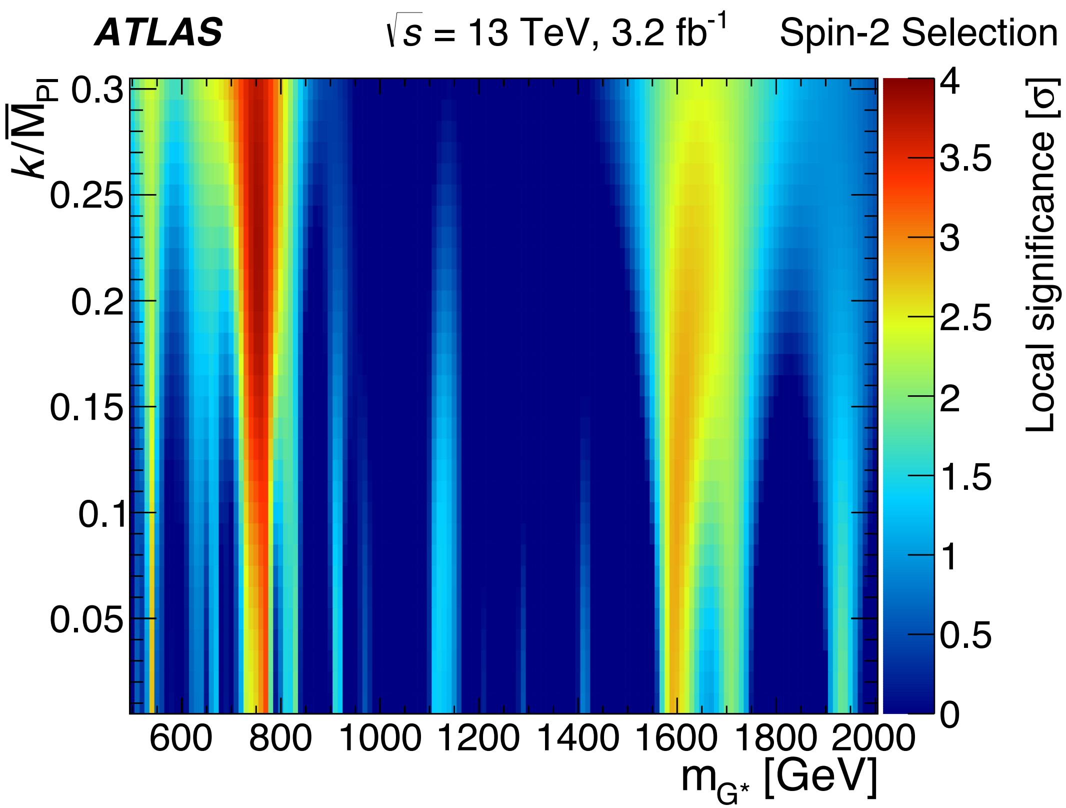
Results for spin-0 interpretation

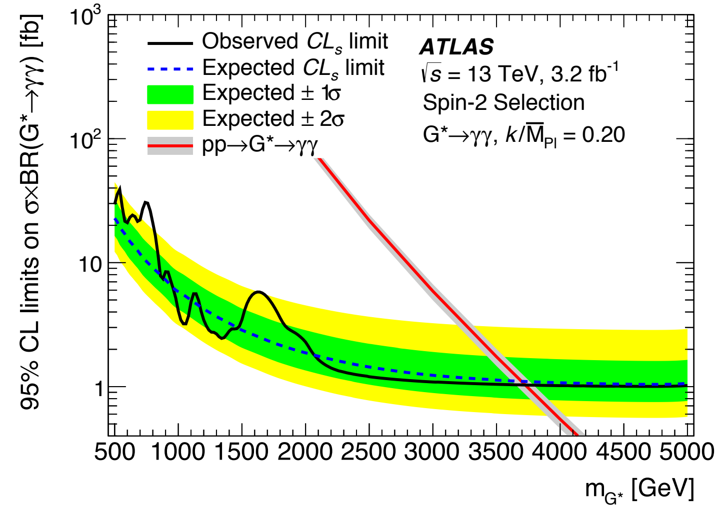
- The largest local significance is 3.9 standard deviations (σ)
  - At m_X=750 GeV, Γ_X=45 GeV (6%)
  - Global significance 2.1 σ

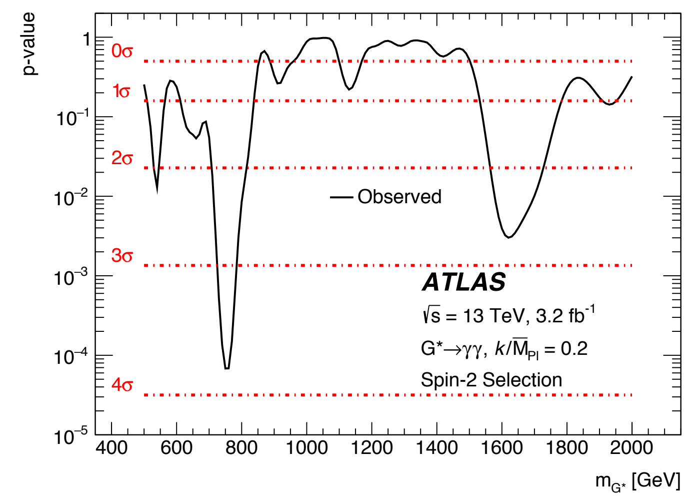


Results for spin-2 interpretation

- The largest local significance is 3.8 standard deviations (σ)
  - At m_X=750 GeV, $k/\overline{M}_{\rm Pl}$=0.23 (Γ_X=57 GeV, 8%)
  - Global significance 2.1 σ

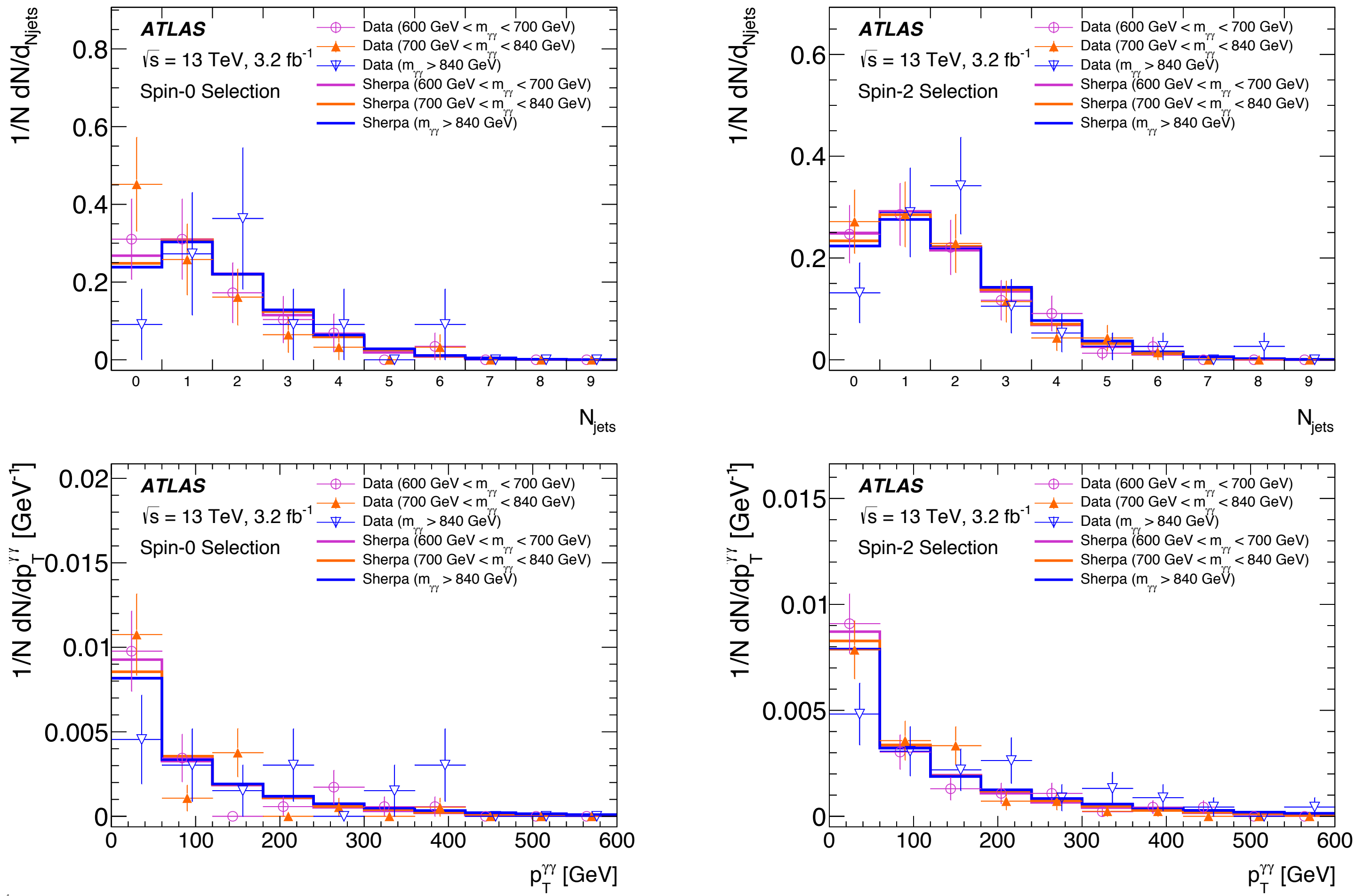






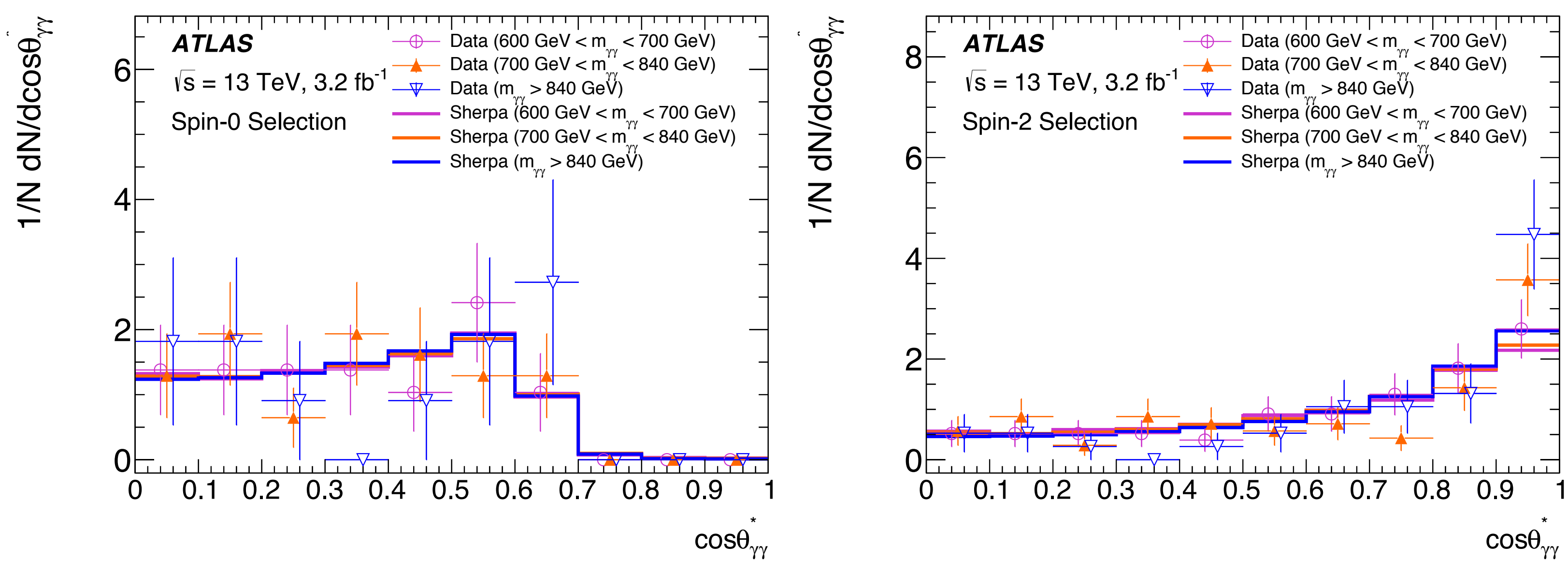
Interesting spectra in signal region

- No significant difference is observed in the properties of the events with a di-photon mass near 750 GeV compared to those at higher or lower masses.

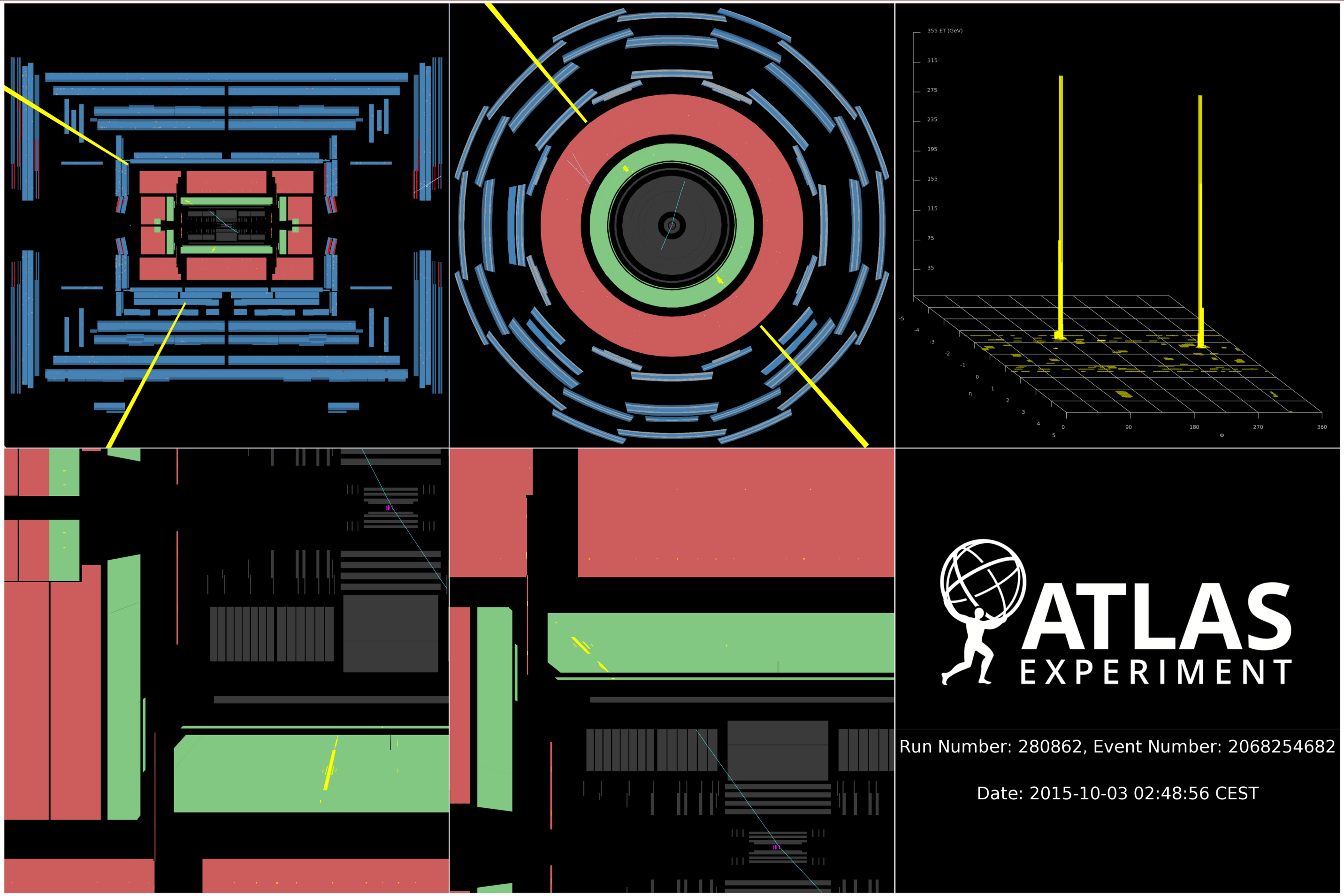


Compatibility between two analyses

- The spin-0 and spin-2 selections overlap
- The compatibility is studied with the bootstrap technique:
  - If spin-0 signal assumed, compatible within 0.2 σ
  - If spin-2 signal assumed, compatible within 0.5 σ
- The results of both analyses are consistent assuming either of the two benchmark signal models



One event with $m_{\gamma\gamma}$ near 750 GeV



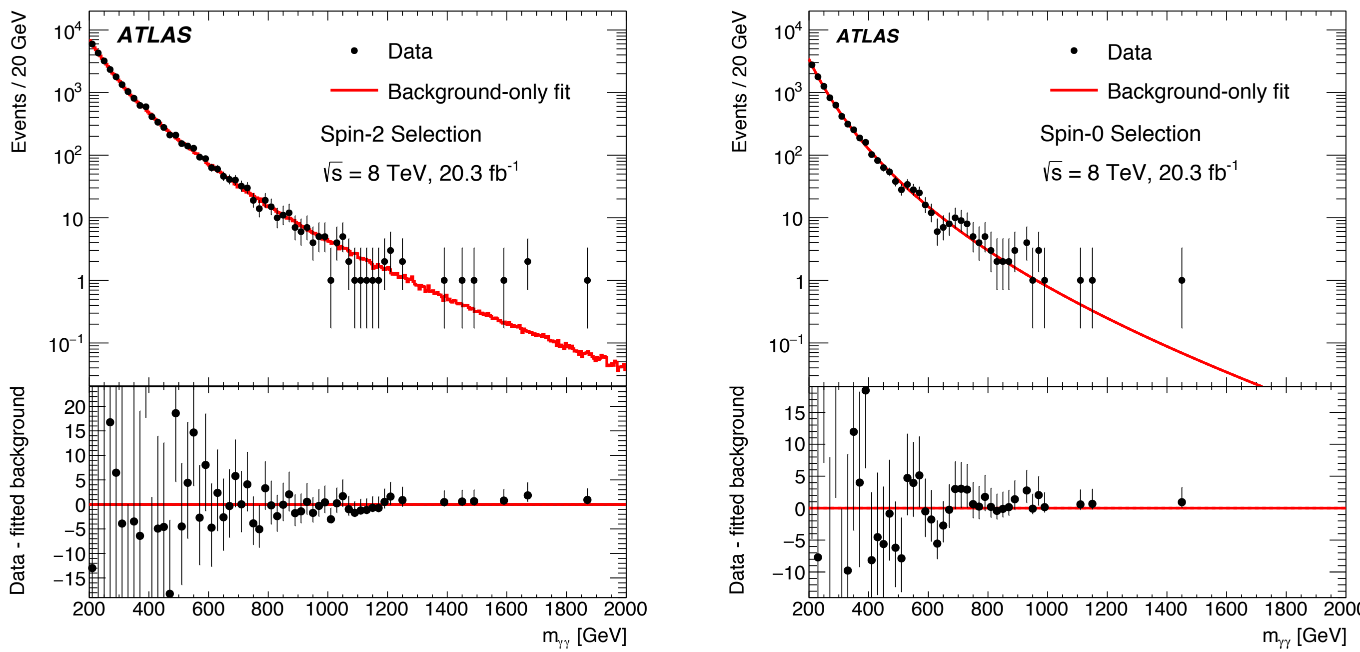
$m_{\gamma\gamma}$ = 728 GeV

Leading photon E_T, η, ϕ, E_T^{iso} = 322 GeV, -1.33, -0.27, 0.86 GeV

Subleading photon E_T, η, ϕ, E_T^{iso} = 316 GeV, -2.32, 2.86, -0.21 GeV

Compatibility with 8 TeV data

- The same selections and signal interpretations are also done for 20.3 fb^{-1} 8 TeV data collected in 2012
  - Redone with the final 8 TeV calibration
- No significant excess around 750 GeV is seen.
- The difference between two datasets is
  - Spin-0 selection: 1.2 σ for gg production and 2.1 σ for $q\bar{q}$ production
  - Spin-2 selection: 2.7 σ for gg production and 3.3 σ for $q\bar{q}$ production



$Z(ee,\mu\mu)\gamma$ analysis

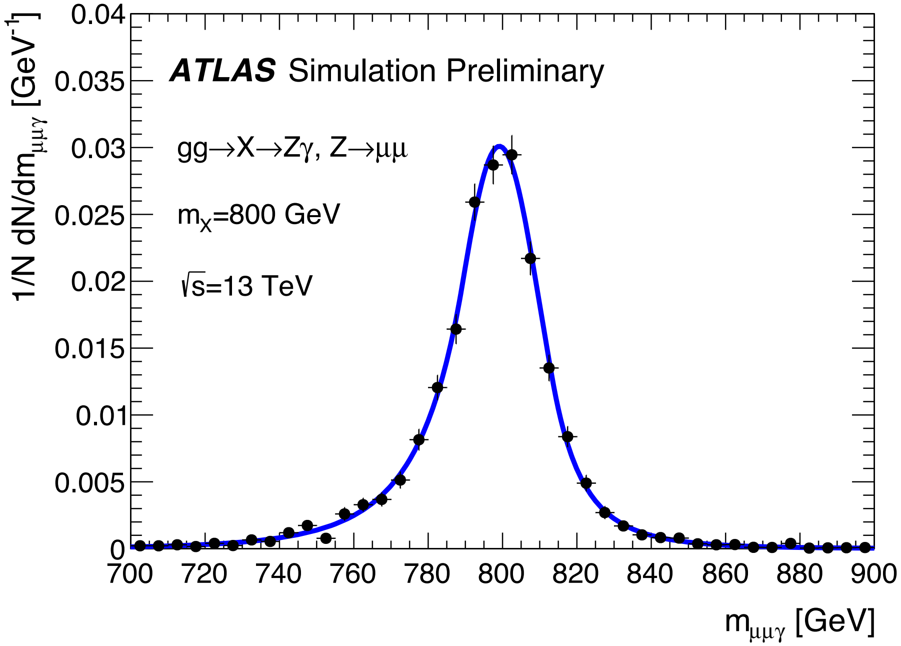
- Lowest-threshold unprescaled single or di-lepton triggers.
- Photon candidates are selected similarly as $\gamma\gamma$ analysis except E_T^{γ} lowered to 15 GeV and no p_T^{iso} cut
  - E_T^{γ} leading photon is chosen to build the $Z\gamma$ resonance
- Electrons are selected within EM calorimeter, p_T^{e}>10 GeV, and pass likelihood-based identification criteria.
- Muons are selected with $|\eta|$<2.7, p_T^{μ}>10 GeV and pass quality cuts based on Inner Detector and Muon Spectrometer.
- Leptons candidates are required to be isolated.
- Same flavor opposite sign lepton pairs with m_{ll} closest to Z boson mass is kept and required to be $|m_{ll}$-$m_Z|$<15 GeV

$Z(q\bar{q})\gamma$ analysis

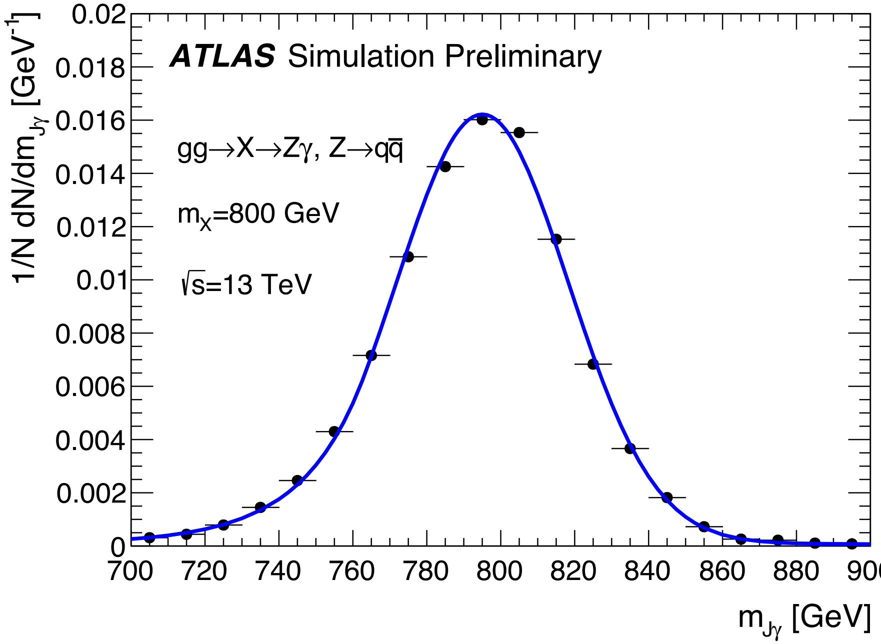
- Trigger on single photon with E_T^γ>120 GeV and pass loose identification requirements
- Same photon selection as leptonic analysis, with E_T^γ>250 GeV
  - E_T^γ leading photon is chosen to build the $Z\gamma$ resonance
- Use massless topological clusters to reconstruct large-radius jets, based on the anti-k_t algorithm, radius parameter R=1.0
  - p_T^J>200 GeV, $|\eta|$<2.0, not overlapping with photon candidates
  - Quark- or gluon-like jets are rejected using the jet substructure
  - 80 < m_J < 110 GeV, isolated from additional hadronic activities
- $Z\gamma$ invariant mass is required to be larger than 640 GeV to be sufficiently far from the kinematic turn-on

Signal model in $Z\gamma$ analyses

- The $m_{ll\gamma}$ distribution is modelled with a double-sided Crystal Ball function

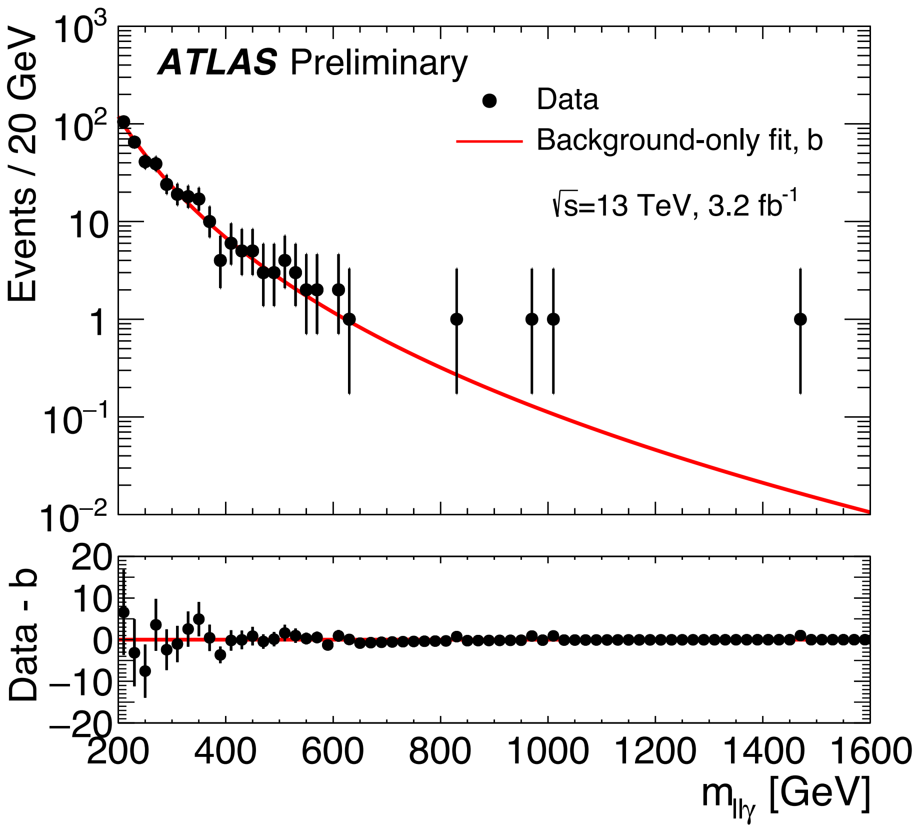


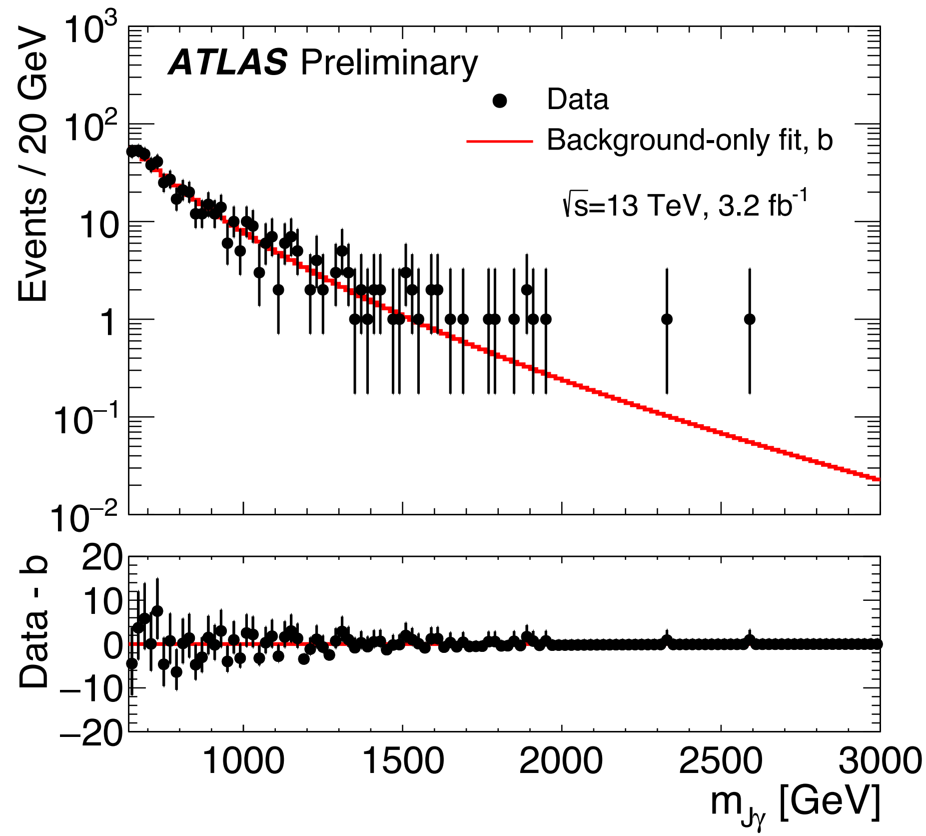
- The $m_{J\gamma}$ distribution is modelled with the sum of a Crystal Ball function and a small, wider Gaussian component.



Results for $Z\gamma$ analyses

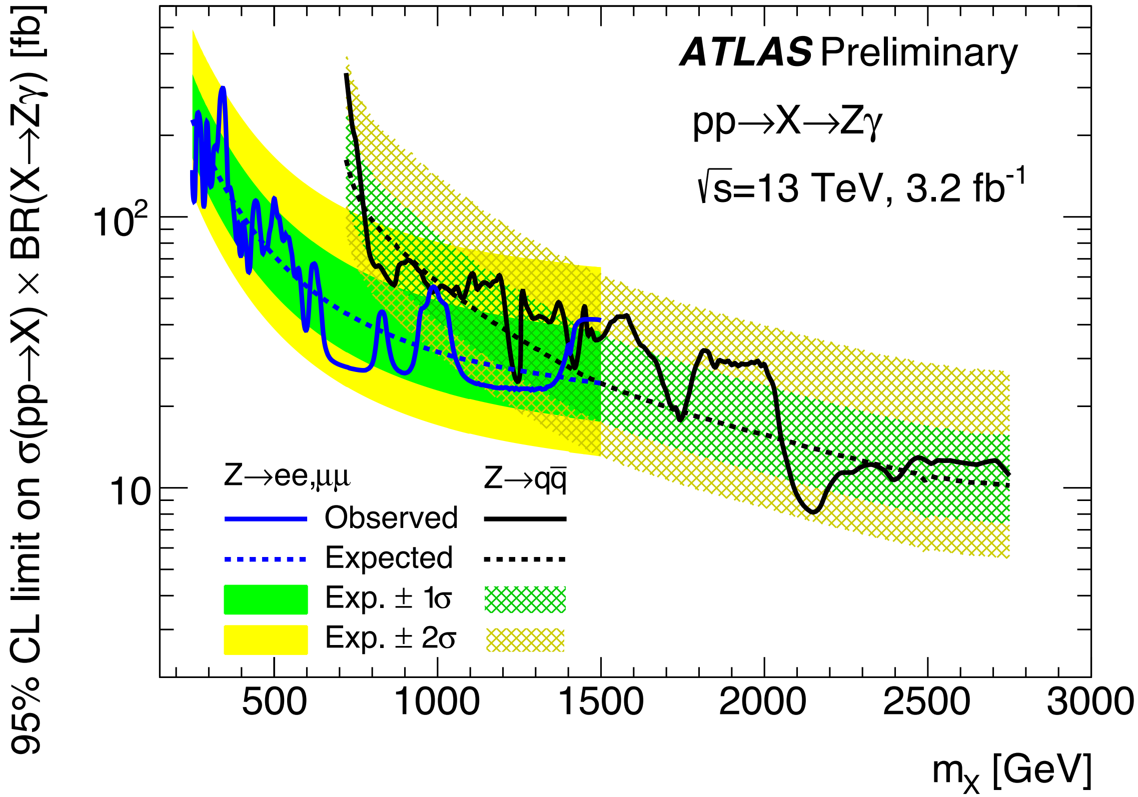
- No significant excess with respect to the background
  - Hunt for resonances with S+B fits





Results for $Z\gamma$ analyses

- Observed and expected upper limits on the $pp \rightarrow X$ cross section times $X \rightarrow Z\gamma$ branching ratio
  - m_X 250 to 1500 GeV for leptonic analysis
  - m_X 720 to 2750 GeV for hadronic analysis



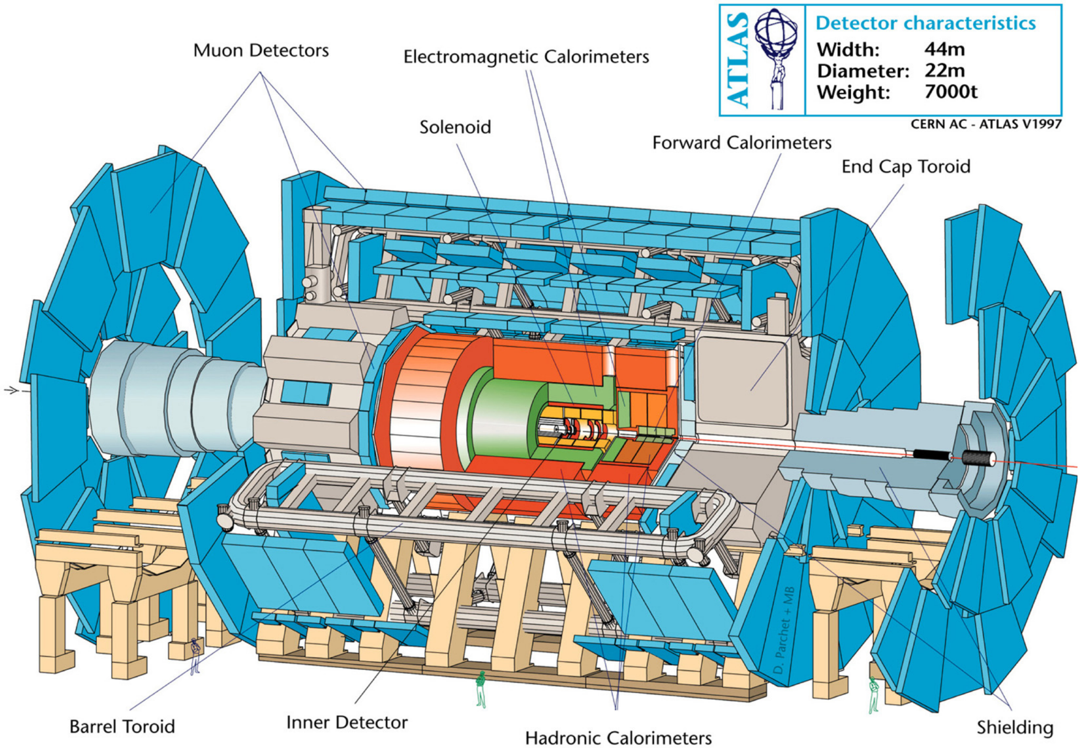
Summary

- The searches for high-mass resonances are performed in the $\gamma\gamma$ and $Z\gamma$ final states with the 3.2 fb^{-1} $\sqrt{s}$=13 TeV data collected by ATLAS experiment in 2015
- In $\gamma\gamma$ analysis:
  - 3.9 σ in spin-0 selection at m_X=750 GeV and 6% width
  - 3.8 σ in spin-2 selection at m_X=750 GeV and 8% width
  - 2.1 σ in global significance for both analyses
  - Same analysis performed on 8 TeV data collected in 2012 but no significant excess is seen
- In $Z\gamma$ analysis:
  - No significant excess observed in either leptonic or hadronic decays of Z bosons
- LHC is generating 13 TeV data quickly, please stay tuned!

backup

ATLAS detector

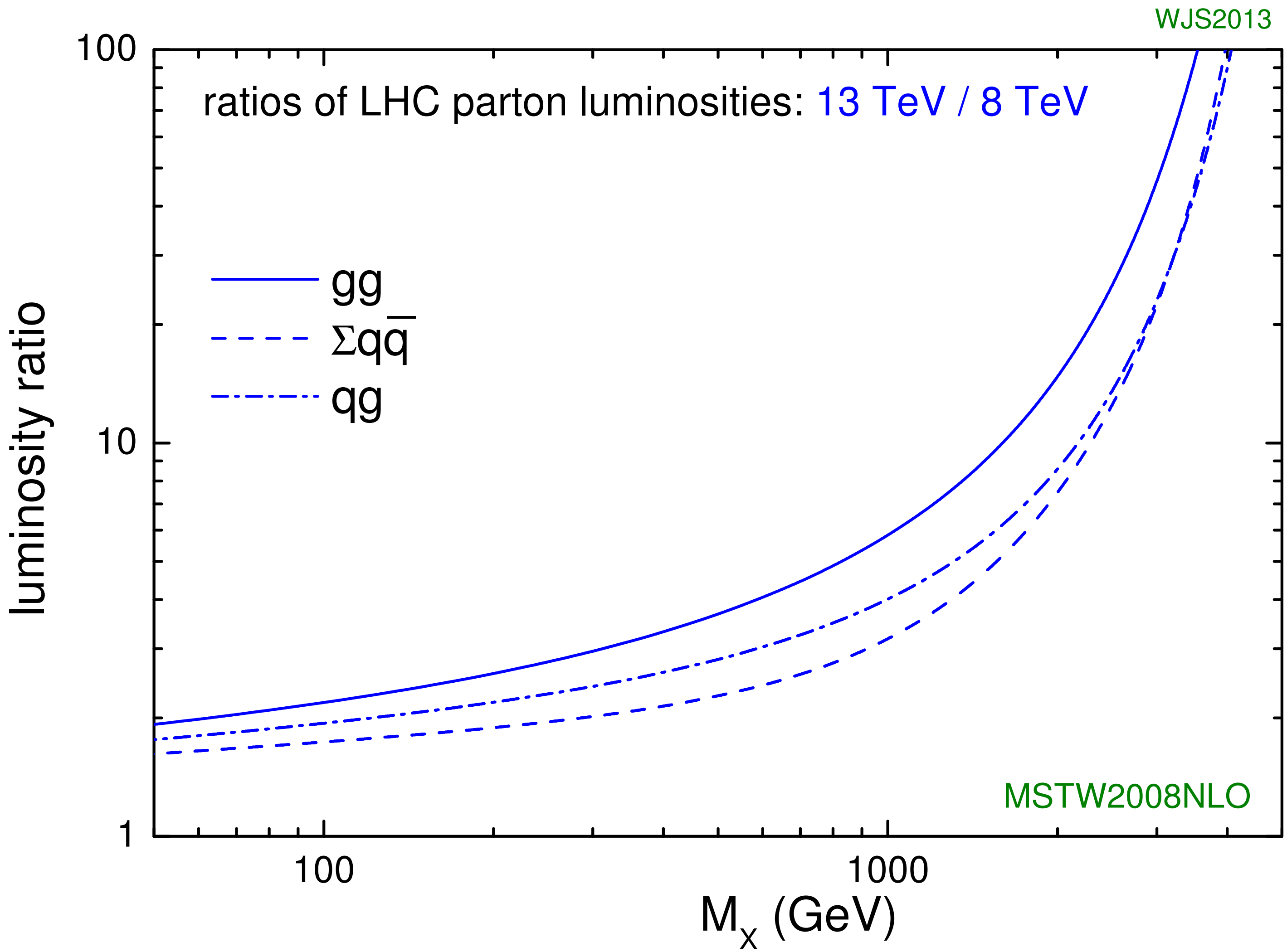
- The ATLAS detector is a multi-purpose particle detector with approximately forward-backward symmetric cylindrical geometry.
- A two-level trigger system selects events to be recorded for offline analysis.



Statistical approach

- The numbers of signal and background events are obtained from maximum likelihood fits of the $m_{\gamma\gamma}$ distribution of the selected events
- The function used to describe the data can be written as $N_S\, f_S\,(m_{\gamma\gamma})\ +\ NB\ f_B(m_{\gamma\gamma})$
  - f_S and f_B are the mass distributions of the signal and backgrounds
- Uncertainties are included in the fit via nuisance parameters
  - Unconstraint for background function parameters
  - Constraint by a Gaussian or log-normal penalty terms for other nuisance parameters
- The local p-value (p_0) for the compatibility with the background-only hypothesis when testing a given signal hypothesis (m_X, α) is based on scanning the $q_0(m_X, \alpha)$ test statistic
  - $q_0(m_X, \alpha) = -2\log\frac{L(0, m_X, \alpha, \hat{\nu})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})}$

LHC parton luminosity ratio between 13/8 TeV

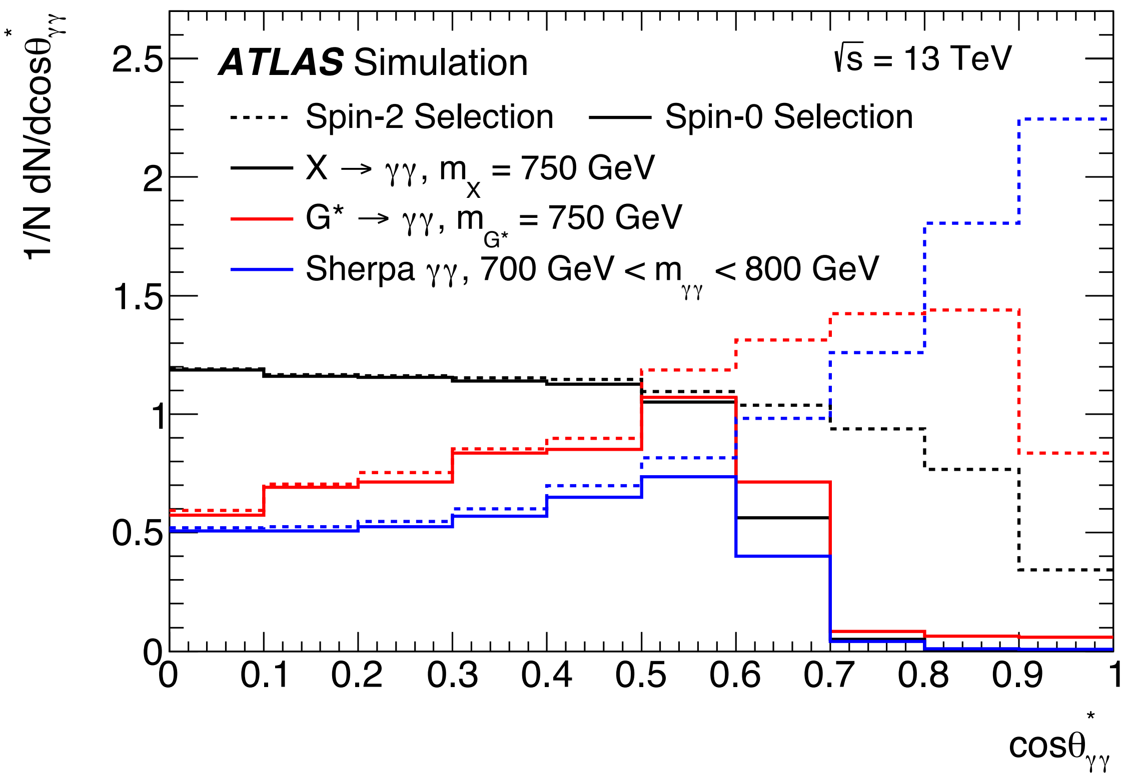


Systematics ($\gamma\gamma$ analysis)

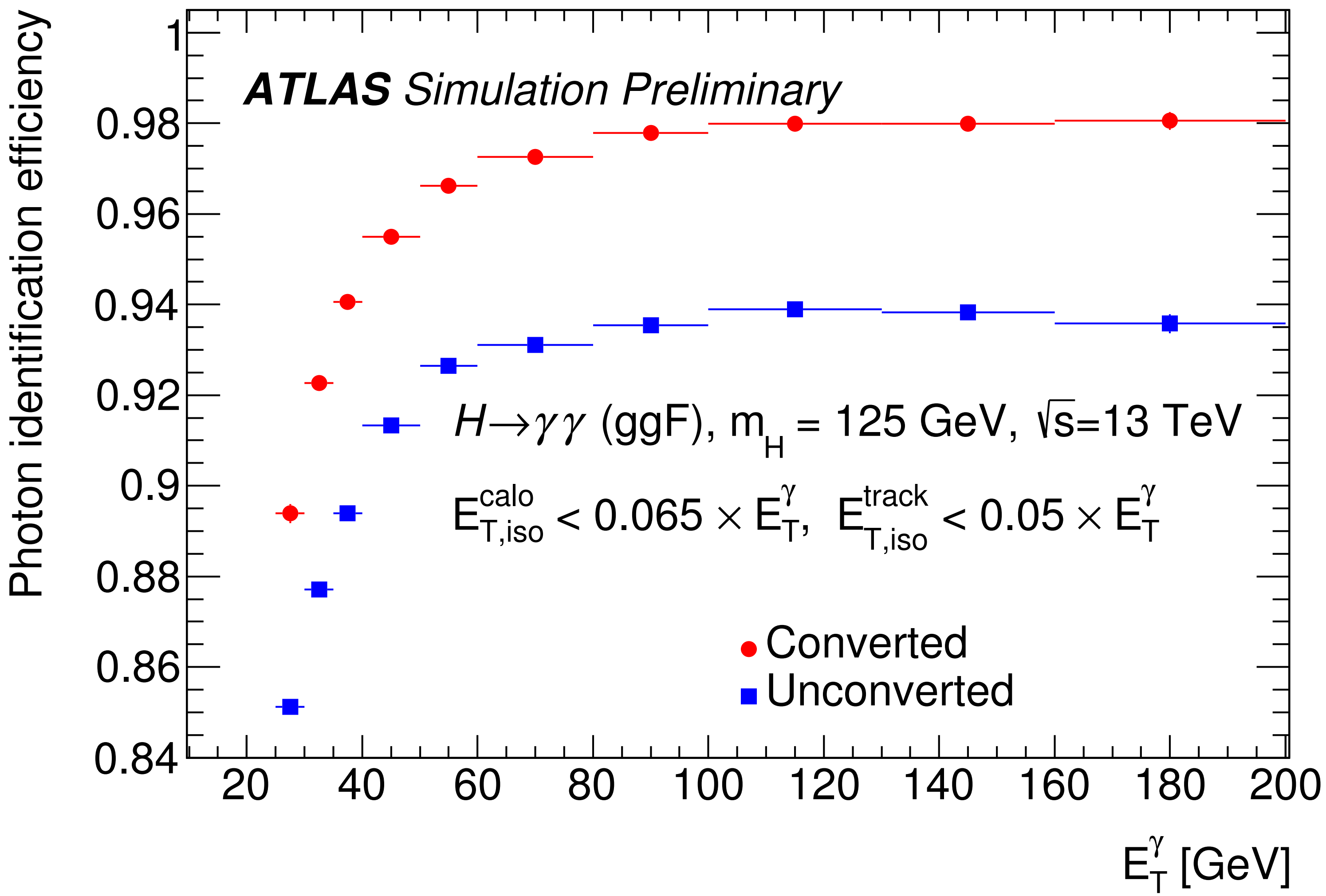
Uncertainty	Spin-2 search	Spin-0 search
Signal mass resolution (mass dependent)	$^{+(30-60)}_{-(20-40)}\%$	$^{+(40-60)}_{-(30-45)}\%$
Signal photon identification (mass dependent)	$\pm(2–3)\%$	
Signal photon isolation (mass dependent)	$\pm(2–1)\%$	$\pm(4–1)\%$
Signal production process	N/A	$\pm(3–6)\%$ depending on Γ
Trigger efficiency	$\pm0.6\%$	
Luminosity	$\pm5.0\%$	

$|\cos\theta^*|$ comparison ($\gamma\gamma$ analysis)

- $|\cos\theta^*|$ is defined as di-photon angle in the pair rest frame
- A key variable to distinguish between spin-0 or spin-2 boson decays.



Photon reconstruction efficiency



Event reconstruction efficiency ($Z\gamma$ analysis)