Searches for high-mass resonances in the $Z\gamma$ decay mode in Run-2 proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector with the integrated luminosity of 139 fb^{-1}

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Overview

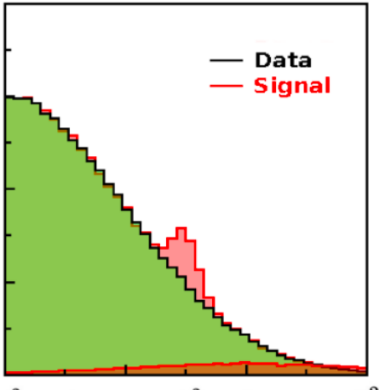
Introduction

11 years have passed since the discovery of the Higgs boson at the Large Hadron Collider, completing the Standard Model (SM).

Is that all, or is there something Beyond the Standard Model (BSM)?

- There is compelling indirect evidence for BSM physics.

Searching for heavy resonances probes new physics Beyond the Standard Model.

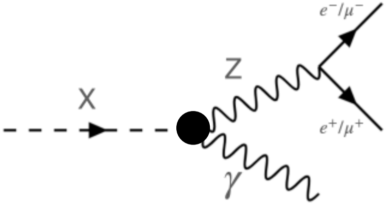


An unexplained bump in the invariant mass spectrum may indicate a new resonance.

Our Bump Hunting

Energies at the LHC allow for the possible creation of high-mass bosons up to several TeV.

We search for high-mass resonances (*X*) with spin-0 and spin-2 decaying into the $Z\gamma$ final state.



The lepton and photon signatures lead to a relatively clean experimental signature.

We use proton-proton collision data collected by the ATLAS detector.

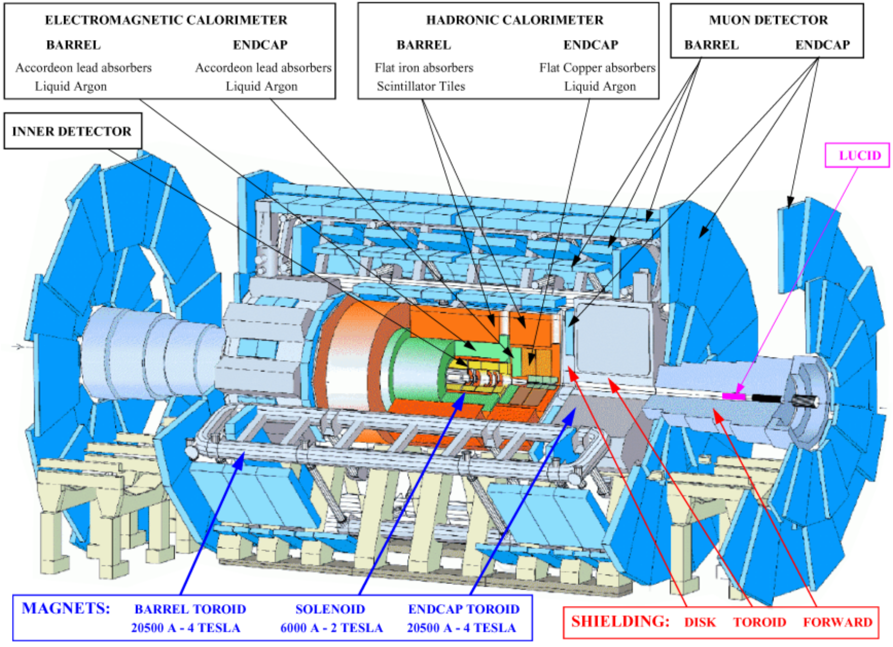
The data is interpreted using the Modified Frequentist method (*CLs* method).

- We perform a hypothesis test to evaluate the compatibility between data and the null hypothesis.
- The hypothesis test sets upper limits on the resonance production cross section times the decay branching ratio to $Z\gamma$.

We aim to set upper limits for $220 < m_X < 3500$ GeV. See the internal note for more details.

EXPERIMENTAL SETUP

ATLAS is the largest experiment at the Large Hadron Collider (LHC).



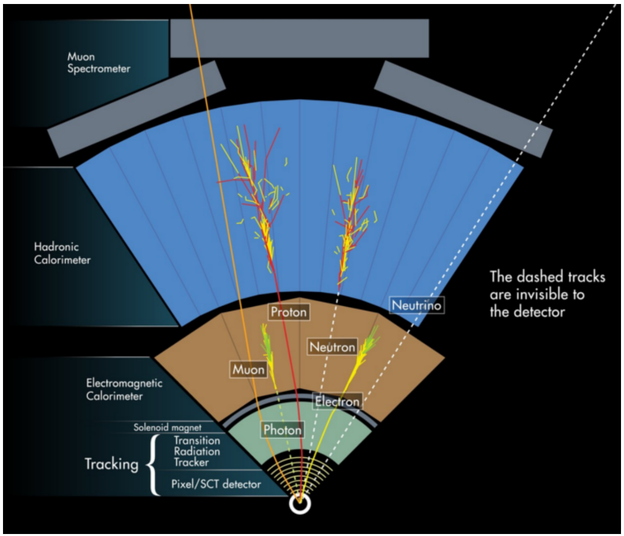
It consists of tracking detectors, calorimeters, and muon chambers that cover almost the entire solid angle around the collision point.

How ATLAS Detects Particles

Photons : Reconstructed from energy deposits in the calorimeters

Electrons : Reconstructed from hits in the inner detector and energy deposits in the calorimeters

Muons : Reconstructed by combining tracks in the inner tracking detectors and the muon spectrometer



Cut	Electron	Electron as photon	Muon	Photon
$p_T > 10$ GeV	> 50 GeV	> 10 GeV	> 10 GeV	
$\|\eta\|$	$\|\eta\| < 2.47$ Exclude [1.37, 1.52]	$\|\eta\| < 2.47$ Exclude [1.37, 1.52]	$\|\eta\| < 2.7$	$\|\eta\| < 2.37$ Exclude [1.37, 1.52]
$\|d_0\|/\sigma_{d_0}$	< 5		< 3	
$\Delta z_0 sin\theta$	< 0.5 mm		< 0.5 mm	
ID	Mixed ID	MVA $(e(\gamma))$ ID	Medium	Loose
ISO	TightTrackOnly _VarRad		TightTrackOnly _VarRad	
$ee(\gamma)$ cut		$\Delta R(e, e(\gamma)) < 1$ $\frac{\|p_T^e - p_T^{e(\gamma)}\|}{p_T^e (or\, p_T^{e(\gamma)})} > 5\%$ $\Delta R(track, e(\gamma)) < 0.1$		

- Requirements on impact parameters suppress secondary leptons from heavy flavor hadron decay chains
- The ID and ISO variables are the defined by dedicated performance groups.
- $ee(\gamma)$ cuts resolve ambiguity between reconstructed photons and electrons

Event Selections

- $Z + \gamma$ and Z+jets events are the dominant backgrounds.
- Additional selection requirements are made to reconstruct $X \to Z(\ell\ell)\gamma$ events and reject background events.

Requirements	Description
Initial event selection	GRL, PV, Event Quality, Triggers
Object selection	See previous slide
Categorization	≥ 2 good leptons, opposite sign (OS), and one loose photon
Overlap removal	Remove overlap between photons, electrons, muons, jets
Trigger Matching	Events must pass lepton and photon triggers
Z-mass constraint	$76.18\,\text{GeV} < m_{\ell\ell}^{\text{constraint}} < 106.18\,\text{GeV}$
Photon selection	$p_{\mathrm{T}} > 15\,\text{GeV}$, Tight ID, FixedCutLoose WP (isolation)
High-mass cut	$m_{\ell\ell\gamma} > 200\,\text{GeV}$
Relative photon p_{T} cut	$p_{\mathrm{T}}^{\gamma}/m_{\ell\ell\gamma} > 0.2$

GRL, PV: Data from the Good Run List and reconstructed primary vertex.

Object Selection: Discussed in the previous slide.

Overlap removal: Ensures well-isolated objects in selected events.

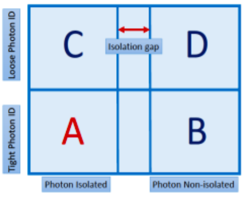
Trigger Matching: Requires firing of di-lepton and high photon p_{T} triggers.

Z-mass constraint: Reconstructed $m_{\mu^-\mu^+}$ and $m_{e^-e^+}$ with a 15 GeV window around the Z mass, improving background discrimination.

Relative photon p_{T} cut: No single photon p_{T} cut is efficient for the whole mass range.

Background Composition

- The sum of $Z+\gamma$ and $Z+$ jets yields a smooth $Z\gamma$ invariant mass distribution
- The parameters of this distribution are obtained from a fit to the data
  - Studying the background composition allows to combine the $Z+\gamma$ and Z+jets samples when performing spurious signal studies



- The regions are defined based on the ID and ISO variables

$$N_A^{Z\gamma} = N_A^{\mathrm{data}} - (N_B^{\mathrm{data}} - c_B N_A^{Z\gamma}) \frac{(N_C^{\mathrm{data}} - c_C N_A^{Z\gamma})}{(N_D^{\mathrm{data}} - c_D N_A^{Z\gamma})} R^{Zj}$$

- Background composition studies are detailed in the 2021 SAIP proceedings

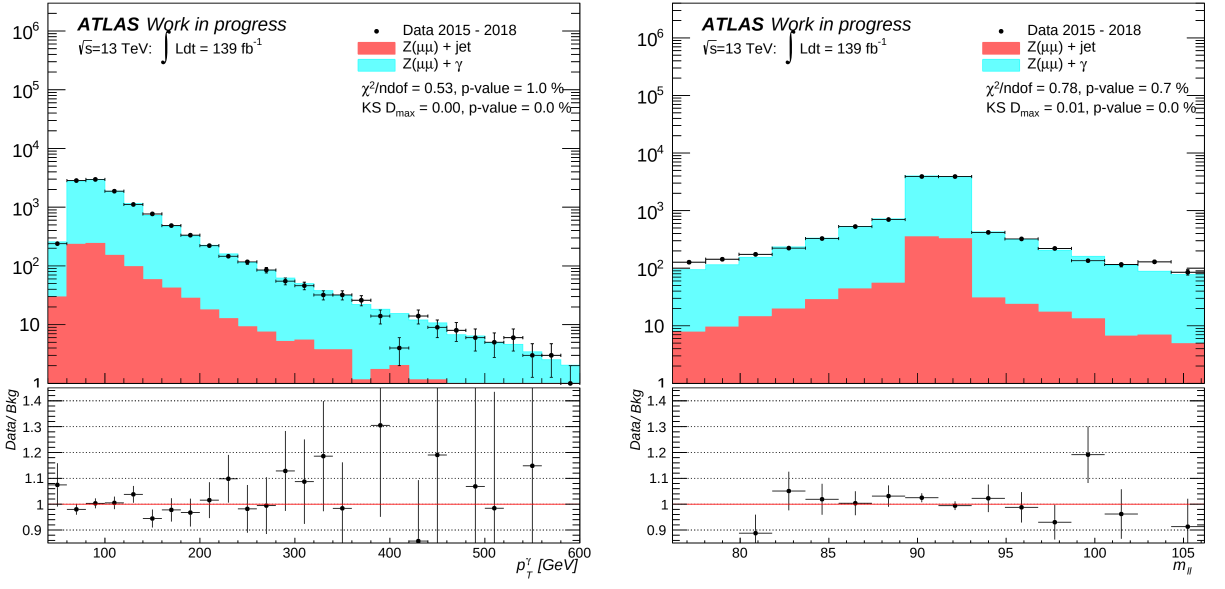
Table. Measured Purity of $Z+\gamma$ Events

Channel	Purity
ee	0.904 ± 0.003
$\mu\mu$	0.914 ± 0.004

The following background samples were used in the analysis:

- Z+γ events: Simulated using SHERPA
- Z+jet events: Obtained by inverting the photon identification variable.

DATA - MC COMPARISONS



- Our modelling of the background processes sufficiently describes the data.

Background Modelling

- The analytic background function is fitted directly to data to avoid dependence on the simulated samples.
- The following analytical functions were considered

FKO $f = x^{a_0}(1 - \sqrt[3]{x})^{a_1}$

Dijet $f = x^{a_0}(1 - x)^{a_1}$

DijetHighmass $x^{a_0}(1 - \sqrt[3]{x})^{a_1}$ assuming $a_0 < 0$

Dijec2HighMass $f = x^{a_0}(1 - \sqrt[3]{x})^{a_1}$ assuming $a_0 < 0$

where $x = m_{Z\gamma}/13000$

- The background and signal modelling studies are detailed in the 2021 SAIP proceedings
- Spurious signal studies are performed to select the analytic function to be used in the analysis

- All functions have the same number of parameters

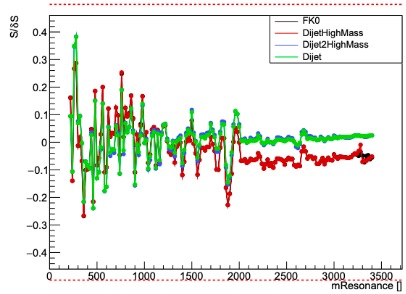


Figure. Spurious signal in the *ee*- channel

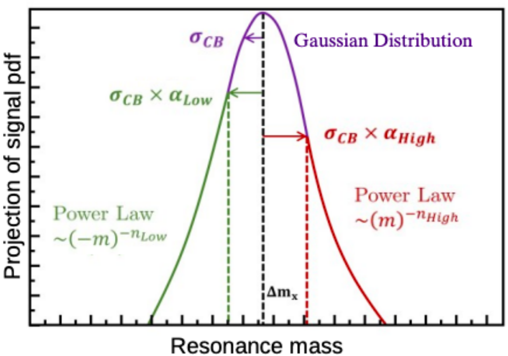
The function with the smallest $S/\delta S$ is chosen
The Dijet function is selected for both electron and muon channels

Signal Modeling

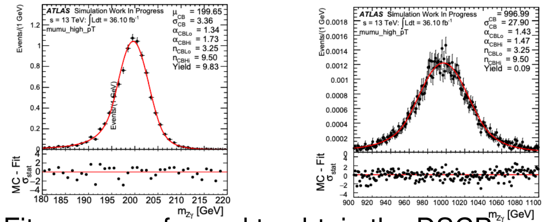
- The resonance at mass m_X is modeled using a Double-sided Crystal Ball (DSCB) function.

$$DSCB(x) = N \times \begin{cases} e^{-t^2/2}, & \text{if } -\alpha_{\text{low}} \leq t \leq \alpha_{\text{high}} \\ e^{-\frac{1}{2}\alpha_{\text{low}}^2}\left[\frac{1}{R_{\text{low}}}\left(R_{\text{low}} - \alpha_{\text{low}} - t\right)\right]^{-n_{\text{low}}}, & \text{if } t < -\alpha_{\text{low}} \\ e^{-\frac{1}{2}\alpha_{\text{high}}^2}\left[\frac{1}{R_{\text{high}}}\left(R_{\text{high}} - \alpha_{\text{high}} - t\right)\right]^{-n_{\text{high}}}, & \text{if } t > \alpha_{\text{high}} \end{cases}$$

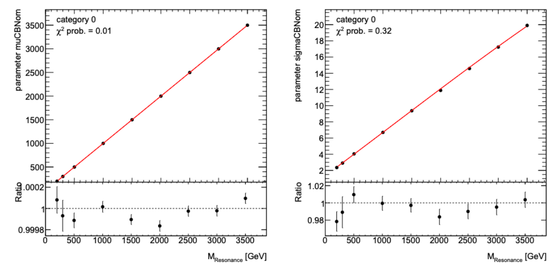
- The DSCB function is parameterized by $t = (x - \mu_{\text{CB}})/\sigma_{CB}$, $R_{\text{low}} = \frac{\alpha_{\text{low}}}{n_{\text{low}}}$, and $R_{\text{high}} = \frac{\alpha_{\text{high}}}{n_{\text{high}}}$.



- Signal samples at different mass points were generated using Powheg and Pythia8 for parton showering.



- Fits were performed to obtain the DSCB parameters



- Other parameters of the DSCB are parameterized similarly.

Statistical Analysis

Putting it all together

The composite function

- The expected number of signal plus background events at a given m_X is given by

$$\begin{aligned} f_{\mathrm{S+B}} &= N_{\mathrm{sig}} \cdot f_{\mathrm{sig}} + N_{\mathrm{spur}} \cdot f_{\mathrm{sig}} + N_{\mathrm{bkg}} \cdot f_{\mathrm{bkg}} \\ &= \epsilon_{\mathrm{sig}} \cdot \sigma(pp \to X) \cdot \mathrm{BR}(X \to Z\gamma) \cdot \mathcal{L}_{\mathrm{int}} \cdot f_{\mathrm{sig}} + N_{\mathrm{spur}} \cdot f_{\mathrm{sig}} + N_{\mathrm{bkg}} \cdot f_{\mathrm{bkg}} \end{aligned}$$

  where f_{sig} and f_{bkg} are the normalized signal and background functions.
- It also takes into account the selection efficiency, production cross section, branching ratios, and luminosity.

Likelihood definition

$$\mathcal{L}\big((\alpha,\theta)|\{m^i_{Z\gamma}\}_{i=1..n}\big) = \frac{e^{-N(\alpha,\theta)} N^n(\alpha,\theta)}{n!} \left(\prod_{n}^{i=1} f_{\mathrm{S+B}}(m^i_{Z\gamma},\alpha,\theta) \right) \times G(\theta)$$

where α, θ, and n are the parameters of interest, nuisance parameters, and the observed numbers of events, respectively. $\alpha = \sigma(pp \to X) \cdot \mathrm{BR}(X \to Z\gamma)$ is our parameter of interest, and $G(\theta)$ represents the constraint terms.

Statistical Analysis Cont.

p-value calculation

- The compatibility of data with a hypothesis assuming $\alpha = \mu$ is given by a *p*-value.
- Following ATLAS recommendations, a test statistic is defined as follows:

$$q(\mu) = -2\ln\left(\frac{\mathcal{L}(\mu, \hat{\hat{\theta}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})}\right)$$

where the parameter $\hat{\hat{\theta}}$ is chosen to maximize the likelihood in a background-only fit, and $\hat{\mu}$ and $\hat{\theta}$ maximize the likelihood function over the whole parameter space.

Limit Setting

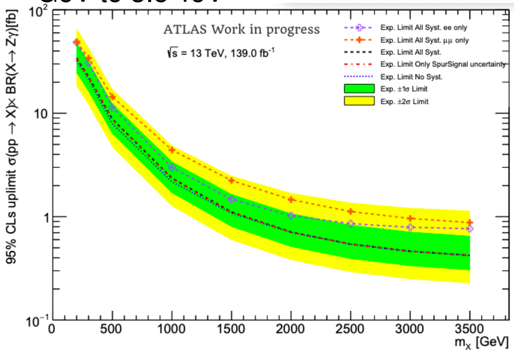
- To establish upper limits on $\sigma(pp \to X) \cdot \mathrm{BR}(X \to Z\gamma)$, a test statistic is defined as follows:

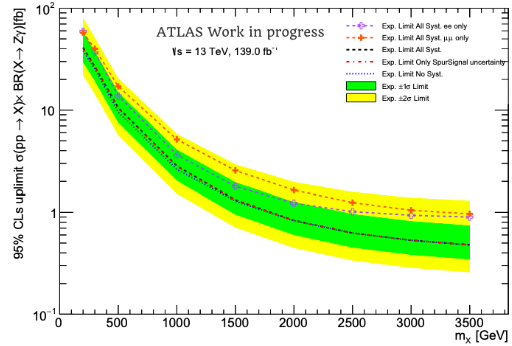
$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(0,\hat{\hat{\theta}}(0))} & \hat{\mu} < 0 \\ -2\ln\frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} & 0 \le \hat{\mu} \le \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

- The best agreement occurs at $\mu = 0$ for a model where $\mu \ge 0$ and $\hat{\mu} < 0$.
- Data with $\hat{\mu} > \mu$ cannot be taken as representing less compatibility with μ than the data obtained.

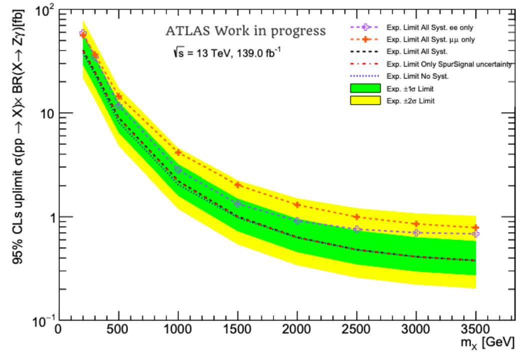
RESULTS

Expected upper limits at 95% CL on $\sigma(pp \to X) \cdot \mathrm{BR}(X \to Z\gamma)$ are set for a mass range from 200 GeV to 3.5 TeV





Channel	Spin	Range [fb]
ggF	Spin-0	34.22 – 0.42
ggF	Spin-2	41.03 – 0.48
$q\bar{q}$	Spin-2	40.38 – 0.38



Expected limits for the *ee* and $\mu\mu$ channels

Conclusion

- An unexplained bump in the invariant mass spectrum may indicate a new resonance.

- Our analysis focuses on the search for high-mass resonances (X) with spin-0 and spin-2 decaying into the $Z\gamma$ final state.
- Using proton-proton collision data collected by the ATLAS detector, we perform a hypothesis test to evaluate the compatibility between data and the null hypothesis.
- The Modified Frequentist method (*CLs* method) is adopted to interpret the data and set upper limits on the resonance production cross section times the decay branching ratio to $Z\gamma$.
- We aim to set upper limits for $220 < m_X < 3500$ GeV, the expected limits have already been set.

SOURCES OF SYSTEMATIC UNCERTAINTIES

Category	$\mu\mu\gamma$	$ee\gamma$
Luminosity	0.83%	
Signal Efficiency		
Photon ID efficiency uncertainty	0.5 – 0.8%	0.5 – 0.9%
Photon isolation efficiency uncertainty	0.6 – 1.3%	0.6 – 1.7%
Photon trigger efficiency uncertainty	0.00 – 0.03%	–
Pile-up	0.00 – 0.03%	–
Muon isolation efficiency (stat.)	0.06 – 0.5%	–
Muon isolation efficiency (sys.)	0.7 – 1.2%	–
Muon reconstruction efficiency (stat.)	0.09 – 0.13%	–
Muon reconstruction efficiency (sys.)	0.34 – 9%	–
Muon reconstruction efficiency (stat. lowpt)	0.00 – 0.03%	–
Muon reconstruction efficiency (sys. lowpt)	0.00 – 0.05%	–
Muon efficiency (ttva stat.)	0.08 – 0.12%	–
Muon efficiency (ttva sys.)	0.07 – 0.19%	–
Muon efficiency (trig. stat. uncertainty)	0.09 – 0.16%	–
Muon efficiency (trig. sys. uncertainty)	0.6 – 1.7%	–
Electron ID efficiency (total)	–	2.7 – 4%
Electron Iso. efficiency (total)	–	0.13 – 0.20%
Electron Reco. efficiency (total)	–	0.28 – 0.6%
Electron Trig. efficiency (total)	–	0.04 – 0.11%
Electron TrigEff. efficiency (total)	–	0.000 – 0.004%
Signal modelling on μ_{CB}		
Electron and photon energy scale (all)	0.33 – 0.4%	0.15 – 0.7%
Muon momentum scale	0.00%	–
Muon Sagitta pho [36]	0.02%	–
Muon Sagitta Resbias [36]	0.01%	–
Signal modelling on σ_{CB}		
Electron and photon energy resolution (all)	2.5– 10%	7 – 60%
Muon ID resolution	0.4 – 1.8%	–
Muon MS resolution	0.6 – 1.9%	–
Extra Smearing on muon p_T	2.4%	–
Background modelling		
Spurious signal	0.01 – 10.00	0.00 – 9.44
Customized electron ID signal efficiency		
MVA ID only	–	0.2 – 0.5%
Mixed ID	–	1.0%