Evidence of $ZZ\gamma$ production with the ATLAS detector

Wenjing Wang[1], Xiaocong Ai[1], on behalf of the analysis team
[1]Zhengzhou University

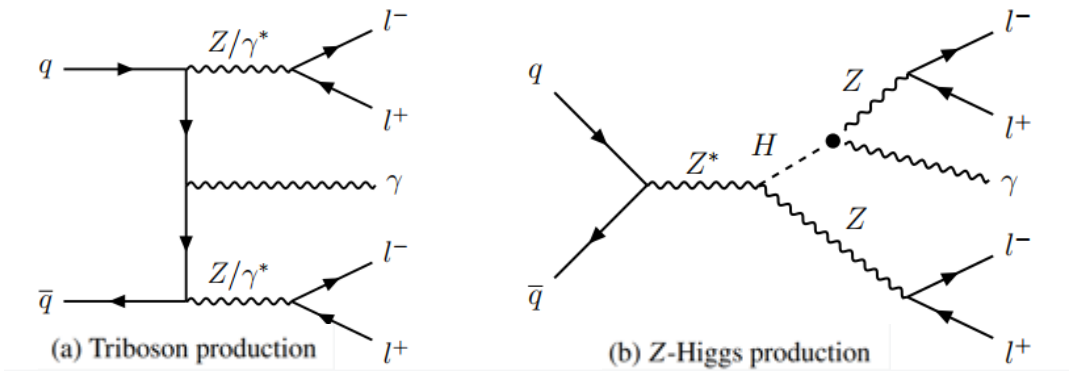
中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会,2026年7月13日-19日，广州

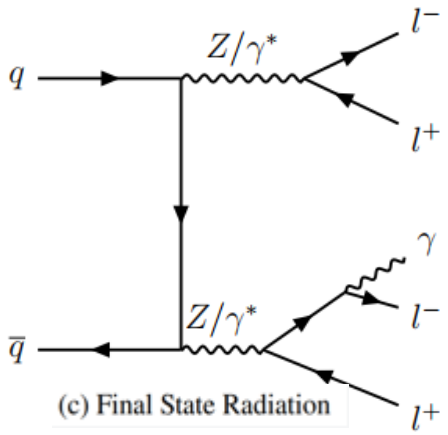
Motivation

- **Rare electroweak triboson process**
  - $ZZ\gamma$ production has a very small cross section.
  - Provides a test of the electroweak gauge structure of the SM.
- **Current status**
  - No observation of $pp \to ZZ\gamma$ before this analysis.
  - CMS reported preliminary evidence with a significance of 3.7σ.
- **Goals of this analysis**
  - Search for evidence of $ZZ\gamma$ production with ATLAS detector.
  - Measure the fiducial cross section at $\sqrt{s} = 13$TeV.

Signal and background definition

- **Signal**
  - $pp \to ZZ\gamma$
  - $ZH, H \to Z\gamma$
- **Background**
  - $ZZ + FSR$
- **Final state**
  - $4l + \gamma$
- **Dataset and MC samples**
  - full Run-2 dataset ($140 fb^{-1}$)
  - Signal MC





Event selection

- **Lepton**
  - two opposite-sign same-flavor lepton pairs
  - $m_{ll} > 40GeV$
  - pair assignment by minimizing:

    $$| m_{\ell\ell,1} - m_Z | + | m_{\ell\ell,2} - m_Z |$$
- **Photon**
  - $p_T > 20GeV$
  - Tight ID
  - Loose isolation
- **FSR rejection**
  - $m_{ll\gamma} + m_{ll} > 2mZ$

	Electrons	Muons	Photon
Kinematics	$p_T > 30, 25, 10, 10$ GeV		$p_T > 20$ GeV
	$\|\eta\| < 2.47$	$\|\eta\| < 2.5$	$\|\eta\| < 2.37$
excluded	$1.37 < \|\eta\| < 1.52$		$1.37 < \|\eta\| < 1.52$
Isolation	Loose	Loose	Loose
	$\Delta R(\mu, e) > 0.2$		$\Delta R(\ell, \gamma) > 0.4$
Identification	Medium	Medium	Tight
$d0$ significance	< 5	< 3	
Multiplicity	≥ 2 OSSF pairs		≥ 1 photon
Mass	$m_{\ell\ell} > 40$ GeV, $(m_{\ell\ell\gamma} + m_{\ell\ell}) > 2 \cdot m_Z$		

Fiducial region

- The cross section is measured in a particle-level fiducial region.
- The fiducial selection is designed to closely follow the detector-level signal selection, reducing dependence on detector corrections and theoretical extrapolations.
- Leptons assigned to Z using min(| $m_{\ell\ell,1} - m_Z$ |+| $m_{\ell\ell,2} - m_Z$ |)

Quantity	cut
Photon and Lepton $\|\eta\|$ cuts	$\|\eta^{\gamma}\| < 2.37$, $\|\eta^{\ell}\| < 2.5$
Photon pt cut	$p_T^{\gamma} > 20$ GeV
Lepton pt cuts	$p_T^{\ell_1} > 30$ GeV, $p_T^{\ell_2} > 25$ GeV, $p_T^{\ell_{3,4}} > 10$ GeV
Photon isolation	$E_T^{cone20}/E_T^{\gamma} < 0.07$
Overlap Removal	$\Delta R(l,\gamma) > 0.4$
Mass cuts	$m_{\ell\ell} > 40$ GeV, $m_{\ell\ell\gamma} + m_{\ell\ell} > 2 \cdot m_Z$

Background estimation

Background	Source	Method
Fake photon(dominant)	Jet $\rightarrow \gamma$ (mainly π^0)	Data-driven fake photon ratio
Fake lepton	Non-prompt / jet $\rightarrow \ell$	Matrix Method
Pileup lepton	Photon from another pp collision	Particle-level overlay

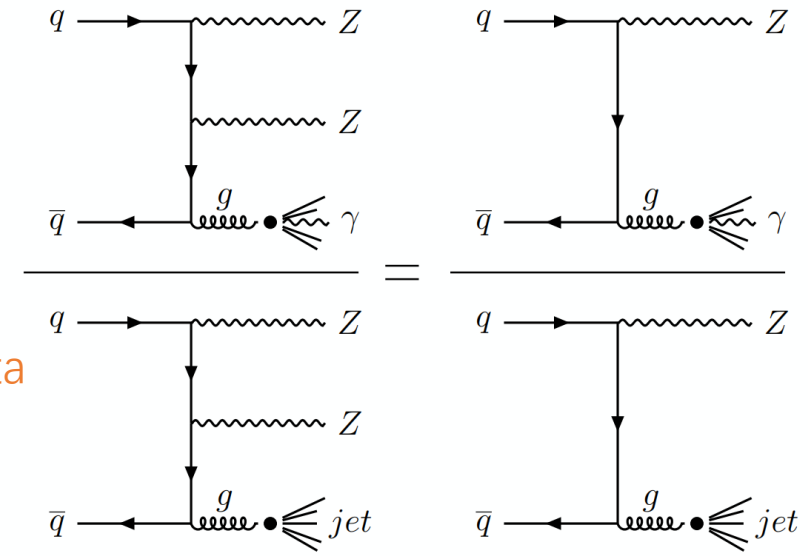
- Because of the very low statistics, data-driven techniques are used whenever possible.

Fake photon estimation

- Define the $Z\gamma$ control region
- A jet to be misidentified as a photon depends only on itself, and is independent of the number of Z bosons in the event
- Fake photon ratio

$$\frac{N_{ZZ\gamma,\,\gamma_{\text{fake}}}}{N_{ZZ+\text{jets}}} = \frac{N_{Z\gamma,\,\gamma_{\text{fake}}}}{N_{Z+\text{jets}}} \Rightarrow N_{ZZ\gamma,\,\gamma_{\text{fake}}} = N_{Z\gamma,\,\gamma_{\text{fake}}} \frac{N_{ZZ+\text{jets}}}{N_{Z+\text{jets}}}$$

Obtain from data



- How to obtain $N_{Z\gamma,\gamma_{fake}}$?
  - Define $P = \frac{N_{Z\gamma}}{N_{Z\gamma}+N_{Z\gamma,\gamma_{fake}}}$ (2x2D Sideband)
  - $N_{Z\gamma,\gamma_{fake}} = (N^{\text{obs}} - N_{t\bar{t}\gamma}^{\text{MC}} - N_{WZ}^{\text{MC}} - N_{ZZ}^{\text{MC}}) \cdot (1 - P)$

$$N_{ZZ\gamma,\gamma_{\text{fake}}} = 0.71 \pm 0.02\,(\text{stat.}) \pm 0.13\,(\text{syst.})$$

Source	Rel. uncertainty [%]					
	purity (MC)		purity (data)		subtraction	
	MC ratio	data ratio	MC ratio	data ratio	MC ratio	data ratio
Statistics (tot.)	0.41%	2.60%	0.48%	2.61%	1.72%	3.09%
Integrated luminosity	0.83%	0.83%	0.83%	0.83%	0.83%	0.83%
MC systematics	11.52%	2.32%	11.28%	-	16.96%	12.67%
Purity measurement (tot.)	17.93%	17.93%	13.61%	13.61%	-	-
Modelling uncertainty	7.04%	7.04%	6.57%	6.57%	-	-
Quark-gluon variations	10.00%	10.00%	10.00%	10.00%	10.00%	10.00%
Total Uncertainty	24.59%	22.00%	21.37%	18.33%	19.78%	16.45%

Fake lepton estimation

- Real and fake leptons have different efficiencies for passing the tight selection.
  - Real efficiency($ZZ\gamma$ Signal MC)
  - Fake efficiency from $Z + 1l\ CR$ (three leptons)
- Estimate fake leptons in ZZ CR by matrix method.
- Extrapolate the fake-lepton estimate from the ZZ **CR to the** $ZZ\gamma$ **SR.**
- $\frac{N_{ZZ\gamma}^{\ell\ \text{fake}}}{N_{ZZ\gamma}} = \frac{N_{ZZ}^{\ell\ \text{fake}}}{N_{ZZ}}$ $\Rightarrow$ $N_{ZZ\gamma}^{\ell\ \text{fake}} = N_{ZZ}^{\ell\ \text{fake}} \frac{N_{ZZ\gamma}}{N_{ZZ}}$ Obtain from MC

$$\mathrm{N}_{\mathrm{ZZ\gamma}}^{\ell\ \mathrm{fake}} = 0.122 \pm 0.022(\mathrm{stat.}) \pm 0.078(\mathrm{syst.})$$

Source	Rel. uncertainty
Statistics	18%
$N_{ZZ}^{\text{fake }\ell}$ syst.	56%
Modelling	31%
Systematic uncertainty	64%
Total Uncertainty	66%

Mainly from prompt lepton subtraction during fake efficiency estimation

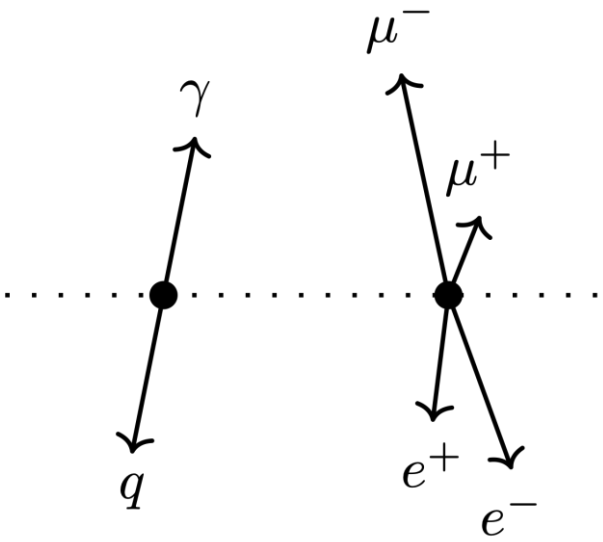
Considering the the difference of the lepton p_T in the ZZ CR and the SR

Pileup photon estimation

- Since photons do not produce tracks, their production vertex cannot be directly identified. A photon from a pileup collision may therefore be misassociated with a ZZ event, resulting in a $ZZ + \gamma$ pileup background.
- $pp \rightarrow ZZ \rightarrow 4l$
- $pp \rightarrow \gamma + jet$

} Overlay

- A correction factor is applied to correct for detector effects and reconstruction inefficiencies.
  - $N_{PU} = C \times N_{particle}$



$$N_{\mathrm{PU}} = 0.089 \pm 0.002\ (\mathrm{stat.}) \pm 0.022\ (\mathrm{syst.})$$

Source	Rel. Uncertainty
MC Statistics	1.8%
σ_γ scale variations	28%
σ_γ PDF $\oplus\alpha_s$	2.4%
σ_{ZZ} (ATLAS measurement)	6%
Integrated Luminosity	0.83%
Correction Factor	1.5%
Total Uncertainty	29%

Dominant uncertainty from σ_γ (i.e. $\gamma + jets$ modelling)

Results

- This table compares the expected signal and background yields with the observed data.
- Good agreement between data and the SM prediction.

	Number of events
SHERPA 2.2.11 $4\ell\gamma$	6.28 ± 0.09 (stat.) ± 0.18 (syst.)
POWHEG+PYTHIA8 $ZH \to ZZ\gamma$	0.76 ± 0.03 (stat.) ± 0.03 (syst.)
Signal	7.04 ± 0.09 (stat.) ± 0.18 (syst.)
Fake photons	0.71 ± 0.02 (stat.) ± 0.13 (syst.)
Fake leptons	0.12 ± 0.02 (stat.) ± 0.08 (syst.)
Pileup	0.09 ± 0.002 (stat.) ± 0.02 (syst.)
Total background	0.92 ± 0.03 (stat.) ± 0.15 (syst.)
N_{tot} prediction	7.96 ± 0.09 (stat.) ± 0.23 (syst.)
N_{tot} data	8

Signal extraction and measured cross section

- Perform a profile-likelihood fit
  - Observed significance = 4.4σ
  - Extracted the signal strength: $\mu_{\mathrm{sig}} = \frac{\sigma_{\mathrm{measured}}}{\sigma_{\mathrm{SM}}}$

$$\mu = 1.01^{+0.45}_{-0.36}(\mathrm{stat.})^{+0.05}_{-0.03}(\mathrm{syst.})^{+0.06}_{-0.03}(\mathrm{theory})$$

- Consistent with the Standard Model prediction.
- Cross section:
  - Measured cross section: $\sigma_{measured} = \mu_{sig} \times \sigma_{SM}$

$$\sigma_{measured} = 0.144 \pm 0.058(stsa.) \pm 0.006(syst.)fb$$

Agreement with the Standard Model

  - Predicted cross section:

$$\sigma^{\mathrm{SM}}_{\mathrm{fid.}} = 0.143 \pm 0.001\ (\mathrm{stat.}) \pm 0.002\ (\mathrm{PDF}+\alpha_S)^{+0.007}_{-0.003}\ (\mathrm{scale})\ \mathrm{fb}$$

Uncertainty on measured cross section

Source	Relative uncertainty [%]
Non-prompt photon	1.9
Non-prompt lepton	1.2
Pileup background	0.4
Photon identification and isolation efficiency	1.7
Pileup reweighting	1.6
Muon identification, isolation, reconstruction, momentum resolution and scale	0.9
Electron identification, isolation, reconstruction efficiency	0.6
Electron–photon resolution and energy scale	0.5
Signal PDF and α_s, QCD Scales	1.4
Signal MC statistics	1.4
Integrated luminosity	0.9
Total systematic uncertainty	4.1
Data statistics	40
Total uncertainty	41

2.3% from background estimation

2.6% from CP

Dominated by Stat. (40%) !

Summary

- First evidence of $ZZ\gamma$ production with ATLAS using $(140\ \mathrm{fb}^{-1})$Run-2 data at 13 TeV.
- Dominant fake backgrounds estimated using data-driven methods.
- 8 events observed with 0.92 ± 0.15 expected background, corresponding to 4.4σ significance.
- Measured fiducial cross section:

$$\sigma_{ZZ\gamma} = 0.144^{+0.064}_{-0.051}(\mathrm{stat.})^{+0.007}_{-0.005}(\mathrm{syst.})\ \mathrm{fb}$$

  consistent with the SM prediction.
- Run3 $ZZ\gamma$ analysis has kicked-off, providing opportunities for more precise measurements and future studies of anomalous gauge couplings.
- The paper has been accepted by Physical Review Letters.

  arXiv: Evidence of $\boldsymbol{ZZ\gamma}$ production with the ATLAS

BACKUP