Observation of WZγ production in pp collisions at 13 TeV with the ATLAS detector

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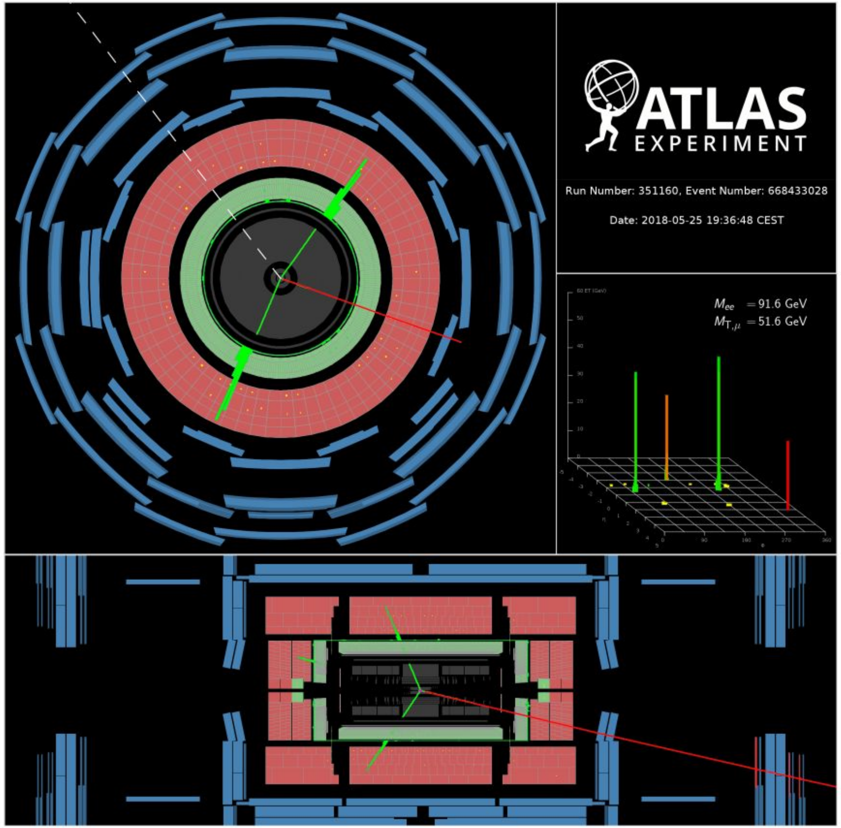
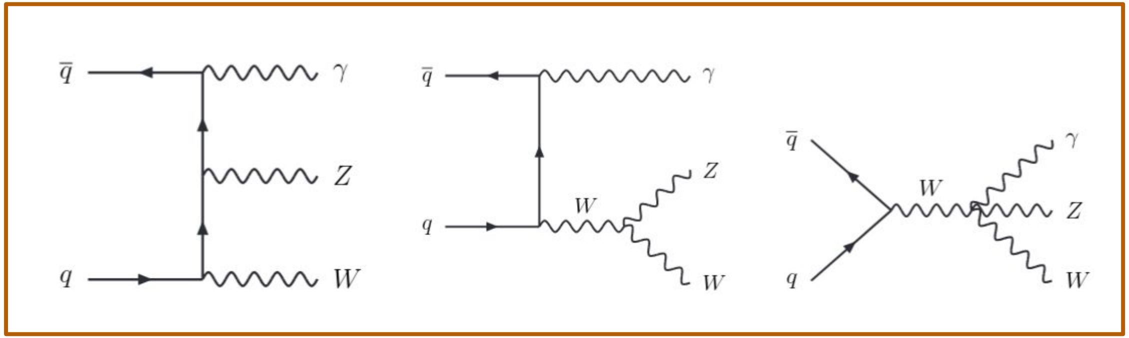
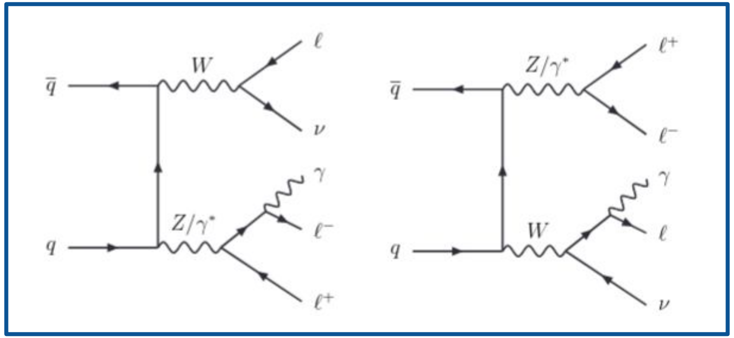


Motivation

- No observation of pp→WZγ reported yet
- Goals of this analysis
  - See evidence of WZγ production
  - Measure the integral cross section at 13 TeV in a region (m(ll)>81 GeV) that enhances WZγ (ISR/TGC/QGC) and suppresses FSR (considered to be WZ)





Individual contribution is not gauge invariantly separable

Event selection

- Using Run2 data
- Full leptonic states: μμμ, eμμ, eeμ, eee

	Photons	Electrons	Muons
$\|\eta\|$	$\|\eta\| < 2.37^{(*)}$	$\|\eta\| < 2.47^{(*)}$	$\|\eta\| < 2.5$
Identification	Tight	Tight	Medium
Isolation	FixedCutLoose	Gradient	PflowTight_FixedRad
Track origin	–	$\|d_0/\sigma(d_0)\| < 5$ $\|z_0 \sin\theta\| < 0.5$ mm	$\|d_0/\sigma(d_0)\| < 3$ $\|z_0 \sin\theta\| < 0.5$ mm
p_T	$p_T^{\gamma} > 15$ GeV	$p_T^{\ell_1,\ell_2,\ell_3} > 30, 20, 20$ GeV	
lepton veto	no "loose" lepton (Medium ID, and loose isolation for μ) with $p_T^{\ell_4} > 10$ GeV		
ℓ_Z selection	for eee, $\mu\mu\mu$: choose smallest $\|m_{\ell\ell} - m_Z\|$		
ΔR	$\Delta R(\ell,\gamma) > 0.4$, $\Delta R(\mu, e) > 0.2$		
$ZZ(e \to \gamma)$ rejection	$\|m(e_W,\gamma) - m_Z\| > 10$ GeV		
missing E_T	$E_T^{miss} > 20$ GeV		
Z candidate mass	$m_{\ell\ell} > 81$ GeV		

- Unprescaled single electron and single muon triggers
- Event vetoed if a 4th lepton passing looser critria and pT > 10 GeV is present
- MET > 20 GeV to suppress backgrounds (ZZγ, ZZ(e→γ), ZZγ)
- m(e_W, γ) away from Z to suppress ZZ(e→γ) background
- m(ll) > 81 GeV and ΔR(l, γ)>0.4 to suppress FSR contribution

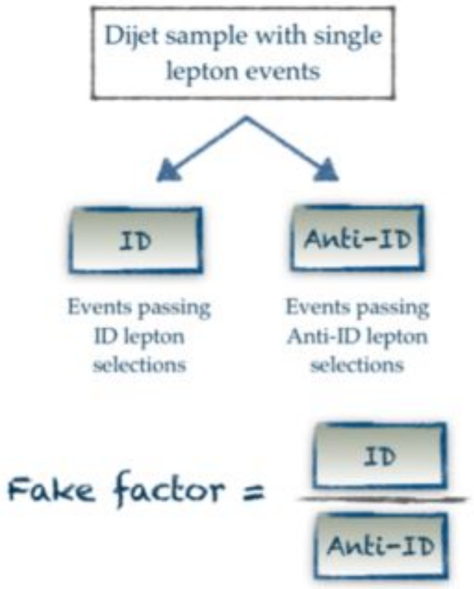
Fiducial region

- The lepton and photon are required to be not from hadron or τ
- Build Z by find the same flavor, opposite-charged dilepton pair closest to Z
- Build W using the third lepton and the same flavor leading neutrino

Quantity	cut
Photon and Lepton $\|\eta\|$ cuts	$\|\eta^{\gamma}\| < 2.37$, $\|\eta^{\ell}\| < 2.5$
Photon pt cut	$p_T^{\gamma} > 15$ GeV
Lepton pt cuts	$p_T^{\ell_1} > 30$ GeV, $p_T^{\ell_2}, p_T^{\ell_3} > 20$ GeV, $p_T^{\nu} > 20$ GeV
Photon isolation	$E_T^{cone20}/E_T^{\gamma} < 0.07$
Overlap Removal	$\Delta R(l, \gamma) > 0.4$
Mass cuts	$m_{\ell\ell} > 81$ GeV

Background estimation

- Non-prompt lepton (jet→l) or photon (jet→γ) background
  - Data driven estimation based on fake factor of lepton-like/photon-like jet
- ZZγ (including ZZ with FSR γ) and ZZ with electron faking photon (e→γ)
  - MC estimation with dedicated CRs
- WZ+pileup γ
  - Overlay MC
- Zγγ (γ→e)
  - MC estimation

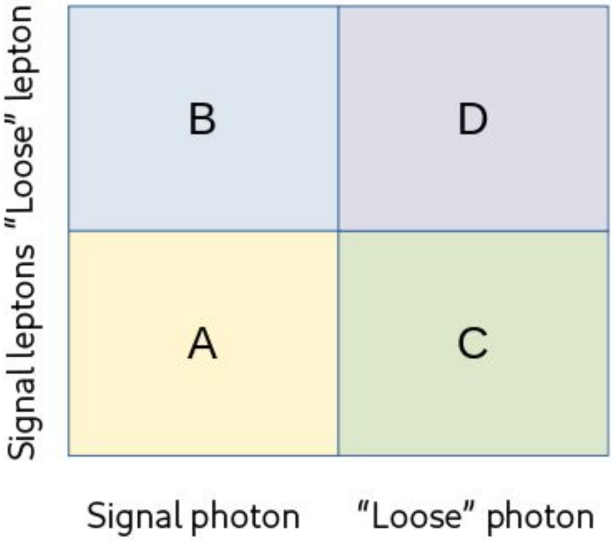


Separation between ZZ(jet→γ) and ZZ(e→γ) is based on truth information of selected photon

Non-prompt background

$$N_X^{data} = \sum_i (N_{X,i}^{prompt} + N_{X,i}^{non-prompt})$$

$$N_{X,i}^{prompt} = \mu_{sig} \cdot N_{X,i}^{WZ\gamma} + \mu_{ZZ\gamma} \cdot N_{X,i}^{ZZ\gamma} + \mu_{ZZ(e\to\gamma)} \cdot N_{X,i}^{ZZ(e\to\gamma)} + N_{X,i}^{Z\gamma\gamma} + N_{X,i}^{Pile-up\ \gamma}$$



$$F_i^{\ell} = \frac{N_{A,i}^{dijet}}{N_{B,i}^{dijet}} = \frac{N_{C,i}^{dijet}}{N_{D,i}^{dijet}}$$

$$F_i^{\gamma} = \frac{N_{A,i}^{Z+jets}}{N_{C,i}^{Z+jets}} = \frac{N_{B,i}^{dijet}}{N_{D,i}^{Z+jets}}$$

$$N_A^{non-prompt} = \sum_i F_i^{\ell} \cdot (N_{B,i}^{data} - N_{B,i}^{prompt}) + \sum_j F_j^{\gamma} (N_{C,j}^{data} - N_{C,j}^{prompt}) - \sum_{i,j} F_i^{\ell} F_j^{\gamma} (N_{D,i,j}^{data} - N_{D,i,j}^{prompt})$$

X= A, B, C, D, i(j) means the lepton(photon) pt/eta/flavor bin number

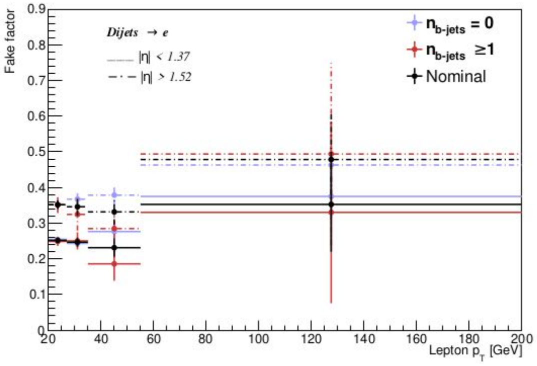
F_l (F_γ) is the fake factor of lepton-like(photon-like) jet

- Denoted as “Lepton (photon) fake factor”
- Determined from dijet (Z+jets) events

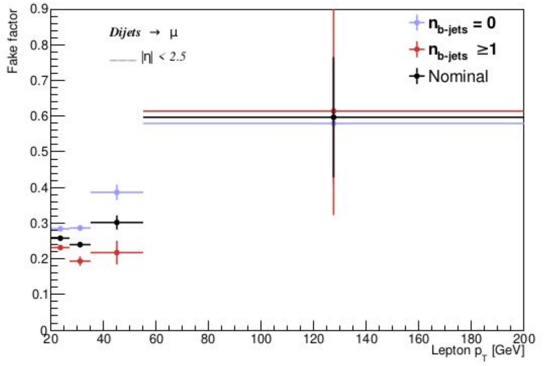
Determined lepton&photon fake factor

- Lepton fake factor is derived separately with b jet requirement (b-jets >= 1) and b jet veto (b-jets = 0). The average between $N_{b\text{-jets}}$ = 0 and $N_{b\text{-jets}}$ >= 1 is used as the nominal value
- Integral value of photon fake factor used: F_γ = 0.399 +/- 0.030

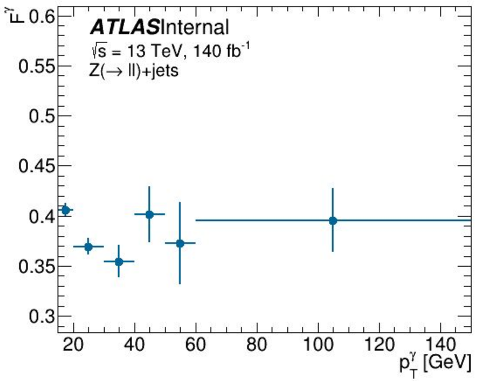
Electron fake factor



Muon fake factor



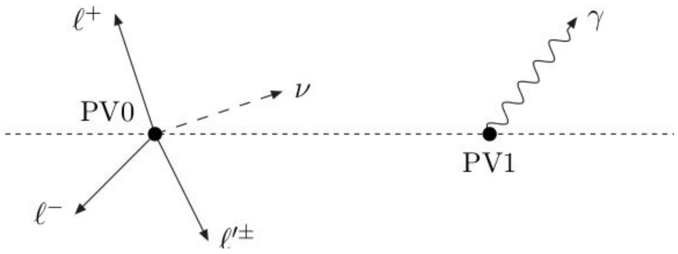
Photon fake factor



Pile-up γ estimation

- Using Overlay MC method:
  - Simulate the WZ+pile-up γ at truth-level, $N^{FR}_{WZ+\gamma}$
  - Apply detector efficiency ($C_{WZ+\gamma}$) correction to the overlayed sample

	Overlay MC
$WZ+\gamma$	1.62 ± 0.60
$(WZ)_\tau + \gamma$	0.02 ± 0.02
$(WZ)_{\text{bgd}} + \gamma$	0.27 ± 0.27
sum (total prompt)	**1.91 ± 0.68**



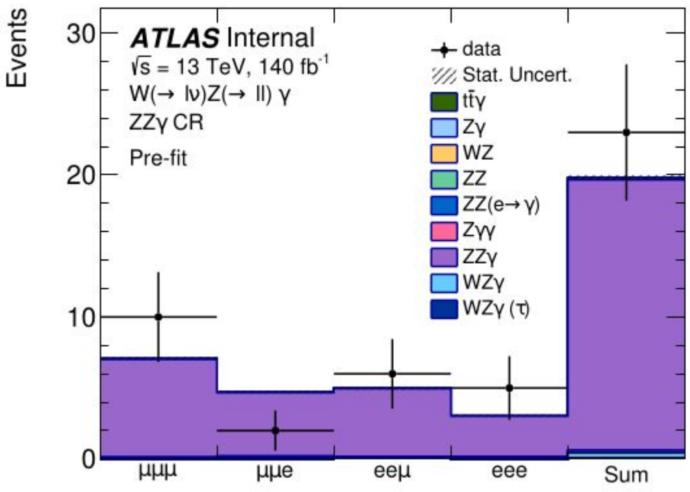
Source	Relative uncertainty
MC event statistics	2.5%
σ_γ scale variations	28%
σ_γ PDF $\oplus$ α_s	2.4%
σ_{WZ} (ATLAS measurement)	4.6%
Modelling of $WZ+\gamma$ pileup events	16%
Detector efficiency	3.3%
Integrated luminosity	1.7%
Total uncertainty	33%
$(WZ)_{\text{bgd}} + \gamma$ component	100% (33% corr.)
Total uncertainty	36%

Dominant sys. from γ+jets modelling and WZ+pile-up γ modelling

ZZγ and ZZ(e→γ) backgrounds estimation

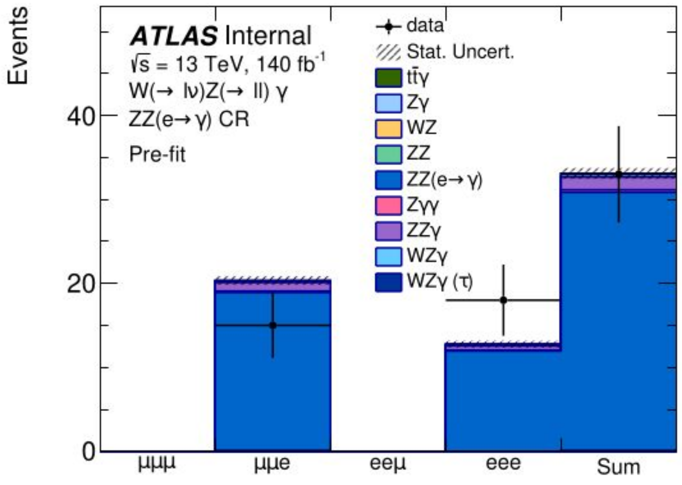
ZZγ CR

- ➔ Requiring 4th lepton with pt >10 GeV and passing "loose" criteria
- ➔ Removing MET cut
- ➔ m(ll) > 40 GeV



ZZ(e->γ) CR

- ➔ $|m(e_W, \gamma) - mZ| > 10$ GeV
- ➔ MET < 20 GeV



Signal extraction

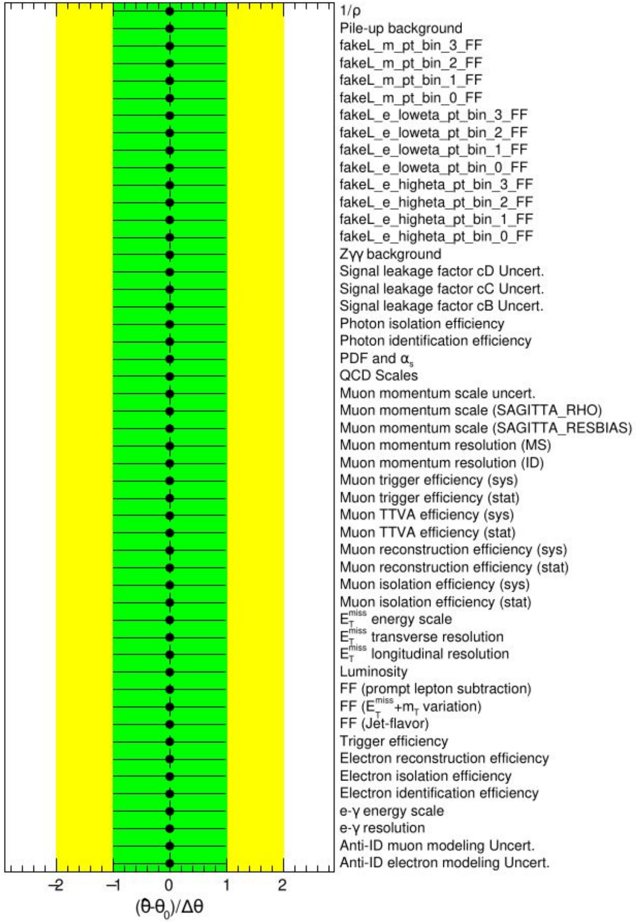
- Profile likelihood fit to extract the signal strength μsig together with $\mu_{ZZ\gamma}$ and $\mu_{ZZ\,(e\rightarrow\gamma)}$ (three POIs) in three bins (SR + 2 CRs)

$$
\begin{aligned}
L(n,\theta^0|\mu_{\rm sig},b,\theta) &= P_{SR}\times P_{CR}\times C_{\rm syst} \\
&= P(n_S|\lambda_S(\mu_{\rm sig},b,\theta))\times\prod_{i\in CRs}P(n_i|\lambda_i(\mu_{\rm sig},b,\theta))\times G(\theta^0,\theta)
\end{aligned}
$$

- Inputs for parameterizing non-prompt background: F_l, F_γ, N_X^{data}, N_X^{prompt} (X=B, C, D)

$$
N_A^{non-prompt} = \sum_i F_i^\ell\cdot(N_{B,i}^{data}-N_{B,i}^{prompt})+\sum_j F_j^\gamma(N_{C,j}^{data}-N_{C,j}^{prompt})-\sum_{i,j}F_i^\ell F_j^\gamma(N_{D,i,j}^{data}-N_{D,i,j}^{prompt})
$$

Nuisance parameters



- CP systematics
- Luminosity
- From non-prompt background estimation
  - Lepton/photon Fake factor
  - Modelling of prompt backgrounds in loose lepton/photon region
  - Statistics of data&prompt backgrounds in loose lepton/photon region
- Pile-up γ background uncertainty
- Zγγ background (30% uncertainty is assigned based on ATLAS Zγγ analysis)
- Uncert. from theoretical modelling of MC (PDF, as, QCD scales)

Break-down uncertainty on measured cross section

Sources	Relative uncertainty [%]
Photon identification and isolation efficiency	2.5
Electron identification, isolation, reconstruction efficiency	0.3
Electron–photon resolution and energy scale	0.6
Muon identification, isolation, reconstruction, momentum resolution and scale	2.4
Missing E_{T} resolution and energy scale	0.3
Lepton fake factor	1.9
Photon fake factor	2.2
Prompt lepton modelling in loose-lepton region	2.2
Prompt photon leakage factor in loose-photon region	0.9
Pile-up γ background	0.9
Signal PDF and α_s, QCD Scales	1.1
Integrated luminosity	0.9
$Z\gamma\gamma$ cross-section	0.2
Signal MC statistics	1.2
Background MC statistics	0.4
Data statistics in loose-lepton and/or loose-photon region	5.4
Total systematic uncertainty	7.7
$ZZ\gamma$ and $ZZ(e \to \gamma)$ normalisation	2.6
Data statistics	14.8
Total statistical uncertainty	15.1

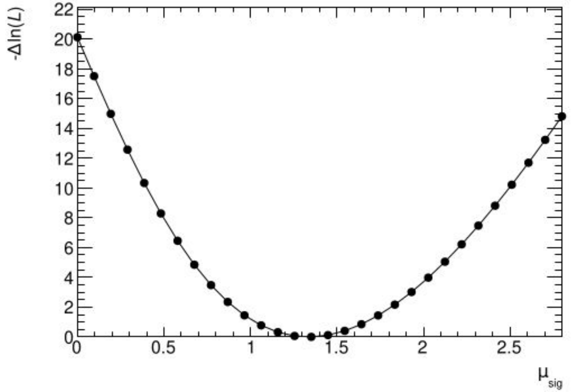
CP systematics (3.3%)

Arising from non-prompt background estimation (6.6%)

Dominated by Stat. Uncert. (15%)

Nuisance parameters

- **Observed (expected) significance: 6.3 (5.0)σ**
- Measured cross section: $\sigma_{meas} = \sigma_{pred} \cdot \mu_{sig}$
  - μ_{sig} = 1.34 ± 0.20 (stat.) ± 0.10 (syst.) ± 0.07 (theory)
  - $\sigma_{pred}(pp \to WZ\gamma)$ = 1.50±0.06 fb (NLO QCD and LO EW)
  - $\sigma_{meas}(pp \to WZ\gamma)$ = 2.01±0.30 (stat)±0.16 (syst) fb

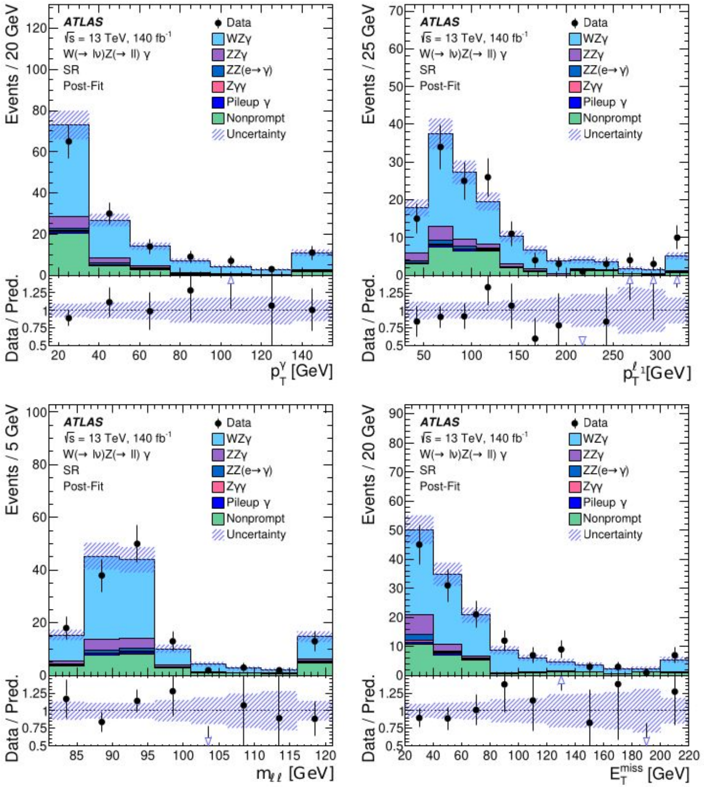


Post-fit yields

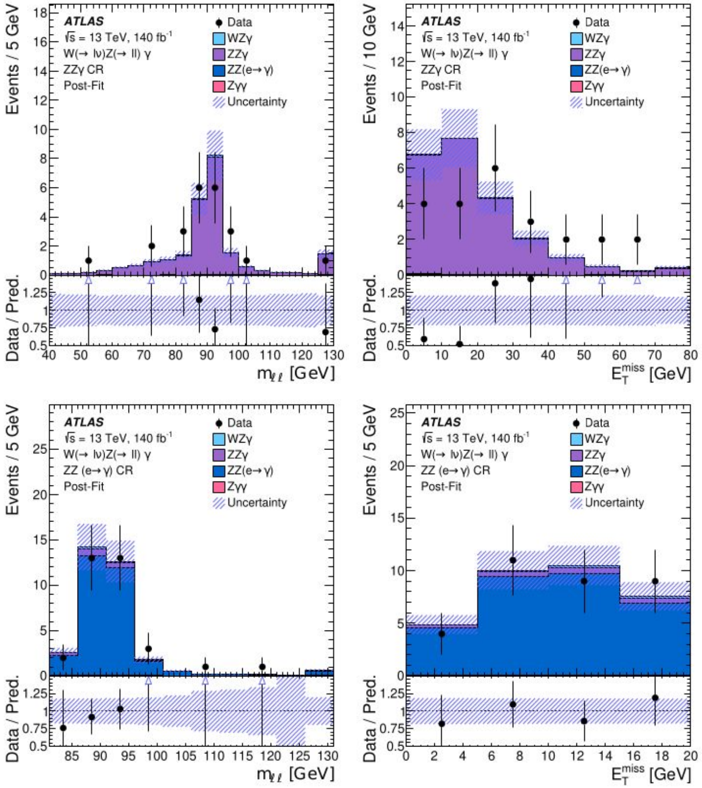
Process	SR	ZZγ CR	ZZ(e → γ) CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Nonprompt background	30 ± 6	-	-
Pileup γ	1.9 ± 0.7	-	-
Total yield	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

Post-fit distributions

SR



CRs



Summary

- Using ATLAS Run2 data, **WZγ production in pp collisions at 13 TeV is observed with 6.3σ** !
- Data-driven estimation for the dominant backgrounds (non-prompt background, ZZγ, ZZ(e->γ))
- The measured fiducial cross section is 2.01±0.34 fb compared to prediction cross section of 1.50±0.07 fb (consistent within 1.5σ)
- Accepted by PRL on Nov 8, 2023

Backup

Estimation of lepton fake factor

- Follow procedure used in ATLAS ssWW analysis

Dijet event selection
GRL
Trigger
Trigger matching
$N_l = 1$ and $p_T^l > 20\,GeV$
$N_{jet} > 0$
$p_T^{tagging\,jet} > 25(30)$ GeV
$\lvert\Delta\phi(l,j)\rvert > 2.8$
$E_{T,track}^{miss} + m_T < 50$ GeV
ID or Anti-ID lepton

ID electron	Anti-ID electron
$p_T > 20$ GeV	
$\lvert\eta\rvert < 1.37$ and $1.52 < \lvert\eta\rvert < 2.47$	
$\lvert d_0/\sigma_{d_0}\rvert < 5$	
$\lvert z_0 \sin\theta\rvert < 0.5$ mm	
LHTight ID	LHMedium ID
Gradient isolation	-
	Fail LHTight ID || fail Gradient isolation

ID muon	Anti-ID muon
$p_T > 20$ GeV	
$\lvert\eta\rvert < 2.5$	
$\lvert z_0 \sin\theta\rvert < 0.5$ mm	
Medium ID	
$\lvert d_0/\sigma_{d_0}\rvert < 3$	$\lvert d_0/\sigma_{d_0}\rvert < 10$
PflowTight_FixedRad isolation	PflowLoose_FixedRad isolation
-	$\lvert d_0/\sigma_{d_0}\rvert > 3$ or fail PflowTight_FixedRad isolation

Estimation of photon fake factor

- Follow and extend procedure for fake background estimation in ATLAS Zγ analysis

Signal photon	Loose photon
$p_T > 15$	
$\|\eta\| < 1.37$ and $1.52 < \|\eta\| < 2.37$	
Tight	LoosePrime5 ID
FixedCutLoose	$p_T^{iso} < 0.05 \times E_T^{\gamma}$ (track isolation)
	Fail Tight || $E_T^{iso} > 0.065 p_T + E_{\text{gap}}$

Zγ event selection

	Photons	Electrons	Muons
Kinematics:	$E_T > 30$ GeV	$p_T > 30, 25$ GeV	$p_T > 30, 25$ GeV
	$\|\eta\| < 2.37$	$\|\eta\| < 2.47$	$\|\eta\| < 2.5$
	excl. $1.37 < \|\eta\| < 1.52$	excl. $1.37 < \|\eta\| < 1.52$	
Identification:	Tight [55]	Medium [55]	Medium [56]
Isolation:	FixedCutLoose [55]	FCLoose [55]	FCLoose_FixedRad [56]
	$\Delta R(\ell, \gamma) > 0.4$	$\Delta R(\mu, e) > 0.2$	
Event selection:	$m(\ell\ell) > 40$ GeV, $m(\ell\ell) + m(\ell\ell\gamma) > 182$ GeV		

Yield of Z+jets in signal/loose region is estimated using data-driven method

Uncertainty of non-prompt background estimation

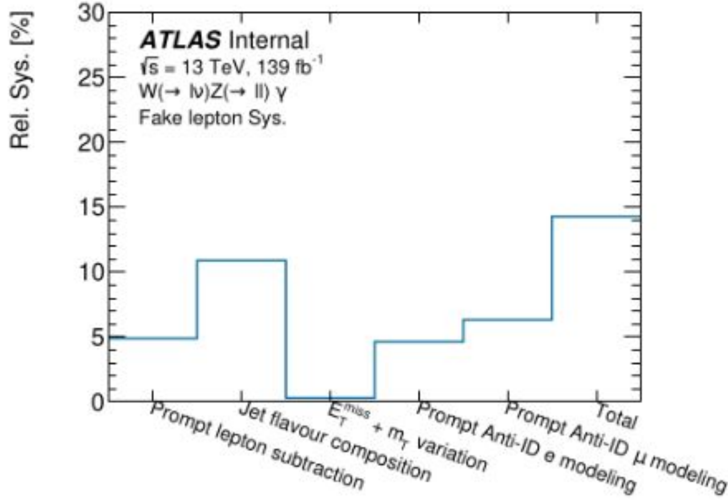
$$N_A^{non-prompt} = \sum_i F_i^{\ell} \cdot (N_{B,i}^{data} - N_{B,i}^{prompt}) + \sum_j F_j^{\gamma}(N_{C,j}^{data} - N_{C,j}^{prompt}) - \sum_{i,j} F_i^{\ell} F_j^{\gamma}(N_{D,i,j}^{data} - N_{D,i,j}^{prompt})$$

- From F_l determination (follow uncertainty estimation in ATLAS ssWW analysis)
  - Vary prompt lepton backgrounds being subtracted by +/-5% (prediction and data agree within 5% in W+jets CR dominated by those prompt lepton backgrounds)
  - Jet flavor composition (difference between $N_{b\text{-jets} = 0}$ and $N_{b\text{-jets} >= 1}$)
  - Vary $E^{miss}_{T,\,track}$ + m_T cut
- From F_γ determination (follow uncertainty estimation in ATLAS Zγ analysis)
  - Zγ signal leakage factor
  - Z+jets correlation factor R
  - Fake photon pT spectrum difference between Z+jets and WZ+jets
- From modelling of prompt backgrounds in B, C,D
- From statistics of data in B, C, D region (dominant)
- From statistics of MC in B, C, D region

Fake lepton background uncertainty

- From fake factor determination using dijet events (analogous to ssWW analysis)
  - Vary prompt lepton backgrounds being subtracted by +/-5% (prediction and data agree within 5% in W+jets CR dominated by those prompt lepton backgrounds)
  - Jet flavor composition (difference between Nb-jets = 0 and Nb-jets >= 1)
  - Vary $E^{miss}_{T,\text{track}}$ + m_T cut (e.g. +/- 5 GeV)

- From prompt-lepton modeling in Anti-ID region
  - 20% (30%) for electron/muon (based on José Pretel's studies here)

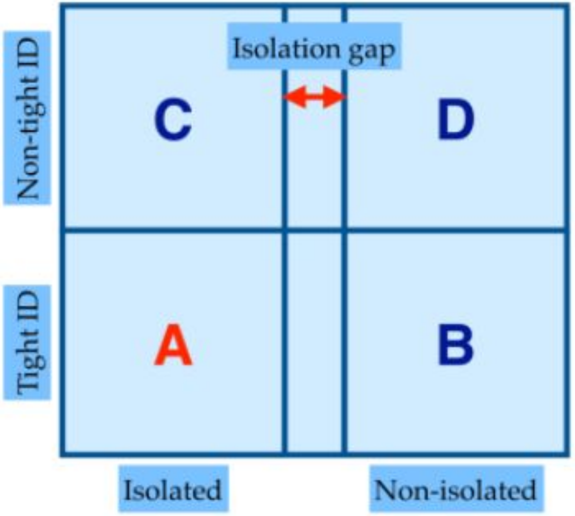


Fake photon estimation

- Use extended ABCD method based on fake photon ratio (ρ-value), i.e. fake photons failing the tight but passing the loose selection to those passing tight selection:

$$\rho = \frac{N(\gamma_f^L)}{N(\gamma_f^T)},$$

- ρ-value derived from Z+jets events using standard ABCD method as in ATLAS Zγ analysis
  - Tight region: A
  - Loose region: B+C+D



ρ value estimation

In Zγ analysis:

- N^{sig} is the yield of Zγ signal
- N^{bg} is yield of prompt photon backgrounds including $t\bar{t}\gamma$, WZ, WWγ, ZZ, WZγ, ττγ, ZZγ

$$R = \frac{N_A^{Z+jets} \times N_D^{Z+jets}}{N_B^{Z+jets} \times N_C^{Z+jets}}, \qquad c_B = \frac{N_B^{sig}}{N_A^{sig}}, c_C = \frac{N_C^{sig}}{N_A^{sig}}, c_D = \frac{N_D^{sig}}{N_A^{sig}},$$

$(N_A - N_A^{bg})$, $(N_B - N_B^{bg})$, $(N_C - N_C^{bg})$ and $(N_D - N_D^{bg})$

$$N_A^{sig} = N_A - N_A^{bg} - N_A^{Z+jets} = N_A - N_A^{bg} - R\frac{[(N_B - N_B^{bg}) - c_B N_A^{sig}][(N_C - N_C^{bg}) - c_C N_A^{sig}]}{(N_D - N_D^{bg}) - c_D N_A^{sig}}.$$

Solve this equation to get N_A^{sig}

$$\begin{aligned} N_A^{\text{Z+jets}} &= N_A - N_A^{bg} - N_A^{sig}, \\ N_B^{\text{Z+jets}} &= N_B - N_B^{bg} - c_B \times N_A^{sig}, \\ N_C^{\text{Z+jets}} &= N_C - N_C^{bg} - c_C \times N_A^{sig}, \\ N_D^{\text{Z+jets}} &= N_D - N_D^{bg} - c_D \times N_A^{sig} \end{aligned}$$

$$\rho(Z + \gamma_f) = \frac{(N_B^{\text{Z+jets}} + N_C^{\text{Z+jets}} + N_D^{\text{Z+jets}})}{N_A^{\text{Z+jets}}}$$

Estimated value:

ρ = 2.508 ± 0.041 (stat.) ± 0.185 (sys.)

Fake photon background uncertainty

- From prompt photon backgrounds subtraction in Tight, Loose region
- From WZγ Signal leakage factor c
- From ρ-value estimation
  - Zγ signal leakage factor
  - Z+jets correlation factor R
  - Fake photon p_T spectrum difference between Z+jets and WZ+jets
    - Integral ρ-value re-estimated with fake photon pT in Z+jets scaled to WZ+jets

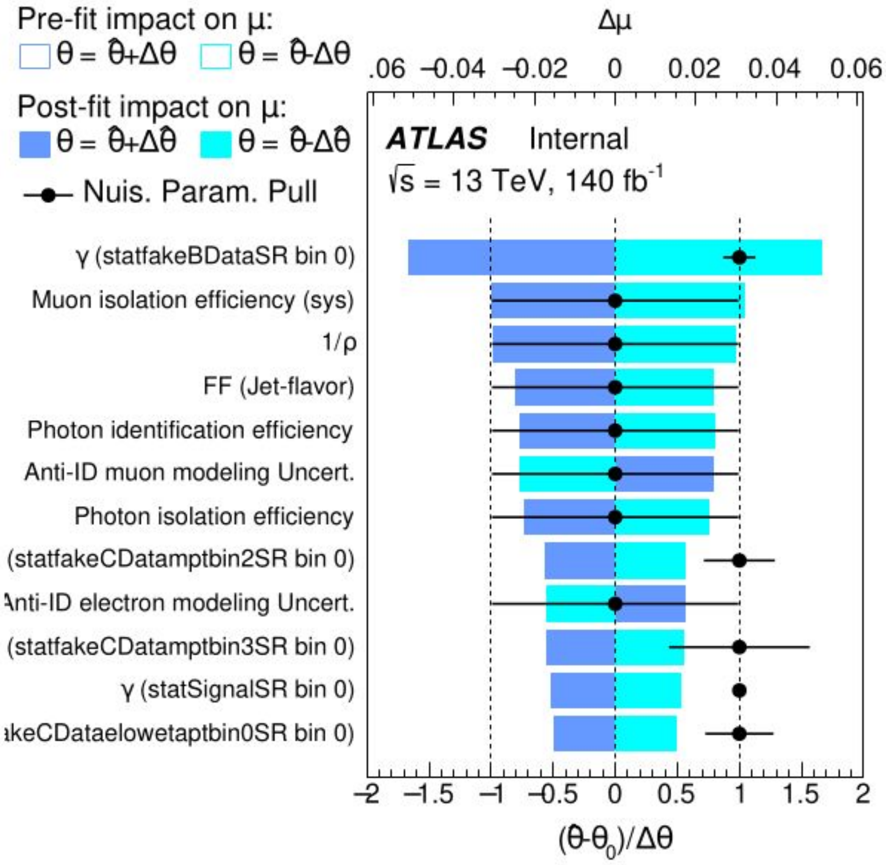
Sources	Relative Sys. (%)
N_{BG}	2.9
c_B, c_C and c_D in $WZ\gamma$ c_B, c_C and c_D in $Z\gamma$	4.5
R in $Z\gamma$	7.1
Fake photon shape difference	10.6
Total	13.8

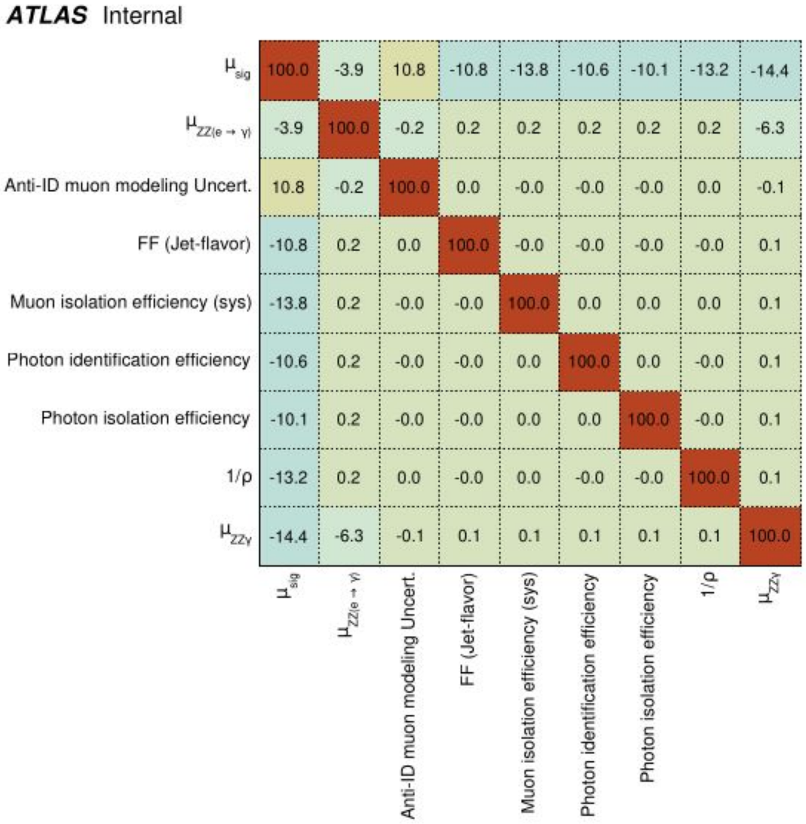
Taking advantage of relevant sys. estimation in ATLAS Zγ analysis

Triggers

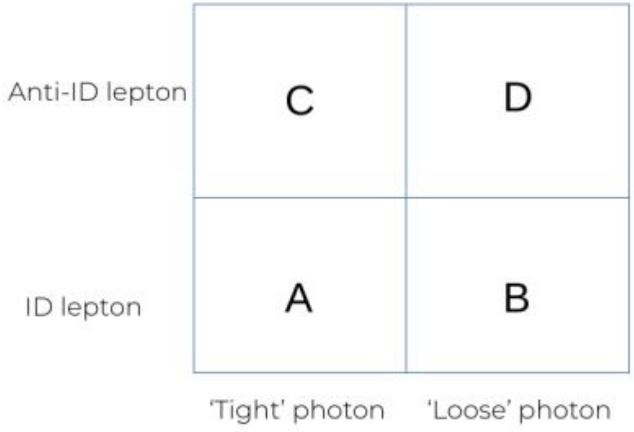
Electron triggers:
2015: e24_lhmedium_L1EM20VH, e60_lhmedium, e120_lhloose
2016-2018: e26_lhtight_nod0_ivarloose, e60_lhmedium_nod0, e140_lhloose_nod0

Muons triggers:
2015: mu20_iloose_L1MU15, mu50
2016-2018: mu26_ivarmedium, mu50


Pre-fit impact on μ:
θ = θ̂+Δθ θ = θ̂-Δθ
Post-fit impact on μ:
θ = θ̂+Δθ̂ θ = θ̂-Δθ̂
Nuis. Param. Pull
Δμ
ATLAS Internal
√s = 13 TeV, 140 fb-1
γ (statfakeBDataSR bin 0)
Muon isolation efficiency (sys)
1/ρ
FF (Jet-flavor)
Photon identification efficiency
Anti-ID muon modeling Uncert.
Photon isolation efficiency
(statfakeCDatamptbin2SR bin 0)
Anti-ID electron modeling Uncert.
(statfakeCDatamptbin3SR bin 0)
γ (statSignalSR bin 0)
akeCDataelowetaptbin0SR bin 0)
(θ-θ0)/Δθ


ATLAS Internal
μsig
μZZ(e→γ)
Anti-ID muon modeling Uncert.
FF (Jet-flavor)
Muon isolation efficiency (sys)
Photon identification efficiency
Photon isolation efficiency
1/ρ
μZZγ
100.0 -3.9 10.8 -10.8 -13.8 -10.6 -10.1 -13.2 -14.4
-3.9 100.0 -0.2 0.2 0.2 0.2 0.2 0.2 -6.3
10.8 -0.2 100.0 0.0 -0.0 -0.0 -0.0 0.0 -0.1
-10.8 0.2 0.0 100.0 -0.0 -0.0 -0.0 -0.0 0.1
-13.8 0.2 -0.0 -0.0 100.0 0.0 0.0 0.0 0.1
-10.6 0.2 -0.0 -0.0 0.0 100.0 0.0 -0.0 0.1
-10.1 0.2 -0.0 -0.0 0.0 0.0 100.0 -0.0 0.1
-13.2 0.2 0.0 -0.0 0.0 -0.0 -0.0 100.0 0.1
-14.4 -6.3 -0.1 0.1 0.1 0.1 0.1 0.1 100.0

Yields in Anti lepton/photon region



Process	ID lepton, Loose photon	Anti-ID lepton, Tight photon	Anti-ID lepton, Loose photon	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
data	59	89	32	23	33
$WZ\gamma$ (no τ rejection)	8.3± 0.2	20.4± 0.4	2.6± 0.1	0.1± 0.0	0.4± 0.1
$ZZ\gamma$	1.2± 0.0	3.3± 0.1	0.5± 0.0	18.9± 0.1	1.5± 0.0
$ZZ(e \to \gamma)$	0.5± 0.1	1.4± 0.1	0.3± 0.1	0.0± 0.0	30.6± 0.6
$Z\gamma\gamma$	0.2± 0.1	0.8± 0.1	0.0± 0.1	0.2± 0.0	0.3± 0.0

Table 20: The yields of processes in the regions for Anti-ID lepton or/and Loose photon, and CRs for $ZZ\gamma$ and $ZZ(e \to \gamma)$.