Measurements of inclusive neutral diboson production with ATLAS

on behalf of the ATLAS collaboration:
Stefan Richter (DESY)

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link to this talk

Overview

Motivation:

- Test electroweak (EWK) sector at LHC energies
- Search for anomalous neutral triple gauge couplings (aTGCs) $\notin SU(2)_L \times U(1)_Y$
- Rich electroweak and QCD phenomenology — see next slide!

Analyses:

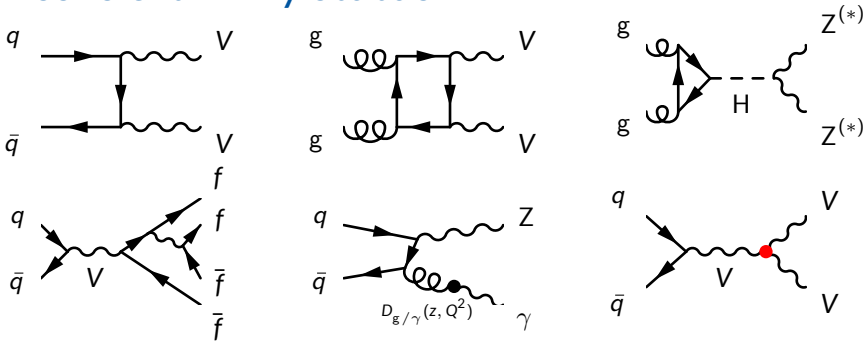
- pp $\to \ell^+\ell^-\ell'^+\ell'^-$ mass [STDM-2017-09]
- ZZ $\to \ell^+\ell^-\nu\bar{\nu}$ [STDM-2017-03]
- Z$\gamma \to \nu\bar{\nu}\gamma$ [STDM-2017-18]
- Z$\gamma \to \ell^+\ell^-\gamma$ [ATLAS-CONF-2019-034] (NEW!)

All use 36 fb^{-1} of 13 TeV proton-proton collision data, except Z$\gamma \to \ell^+\ell^-\gamma$ (139 fb^{-1})

Statistical uncertainty dominates for differential cross sections
(except for Z$\gamma \to \ell^+\ell^-\gamma$)

Inclusive with respect to hadronic jets
I.e. (almost) all observables are integrated over jet multiplicities and kinematics

Subprocesses & theory status



Colour-singlet final state $\rightarrow$ differential, fiducial NNLO calculations available

EWK corrections becoming available

Loop-induced gluon-gluon initiated subprocesses, with large LO $\rightarrow$ NLO QCD corrections

Fragmentation photon contribution can be removed by Frixione isolation [hep-ph/9801442]

Analysis strategies

Use fiducial phase spaces defined in terms of stable particles to limit model dependence

Reconstructed objects:

- Charged leptons:
  - If two leptons: *medium* identification, $p_T \gtrsim 25$ GeV, isolated
  - If four leptons: *loose* identification, down to $p_T \gtrsim 7$ GeV, isolated

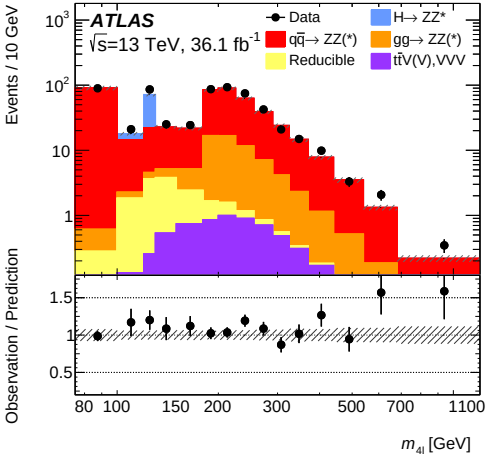
  (Inclusive p_T spectrum mostly determined by the electroweak scale)
- Photons:
  - If no charged leptons: require high $E_T > 150$ GeV, isolated
  - If charged leptons: require $E_T > 30$ GeV, isolated
- E_T^{miss} (neutrinos): poorer resolution, require $E_T^{miss} > 150$ GeV

Backgrounds with misidentified/non-prompt leptons or photons determined with partially data-driven methods

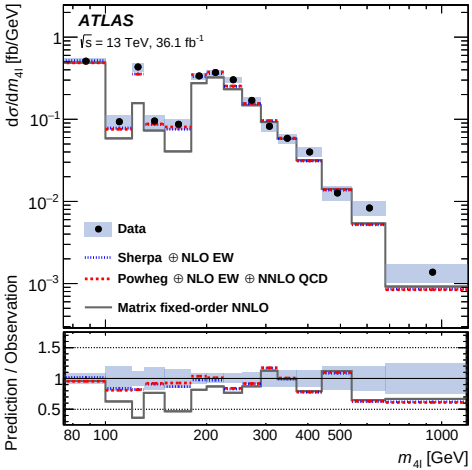
$\mathrm{pp} \to 4\ell$

STDM-2017-09

pp $\rightarrow 4\ell$: four-lepton mass



Reconstructed yields



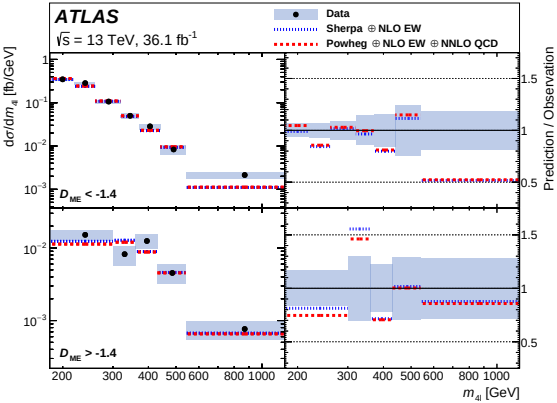
Unfolded cross section

Rich structure of contributing subprocesses

Fitted gg $\rightarrow 4\ell$ normalisation w.r.t. NLO prediction: $\mu_{\mathrm{gg}} = 1.3 \pm 0.5$ (exp. 1.0 ± 0.4)

W.r.t. LO: $\mu_{\mathrm{gg}} = 2.7 \pm 0.9$

pp $\rightarrow 4\ell$: $m_{4\ell}$ vs. matrix-element discriminant



Bottom: more (s-channel) "Higgs-like"

Constrain off-shell Higgs production cross section ($m_{4\ell} > 180$ GeV):
Upper limit of 6.5 times SM prediction (95% CL) — 1σ expected: [4.2, 7.2]
Dedicated measurement: 4.5 times SM prediction [HIGG-2017-06]

$ZZ \to 2\ell 2\nu$

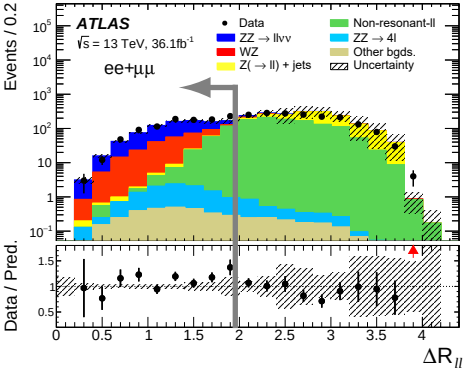
STDM-2017-03

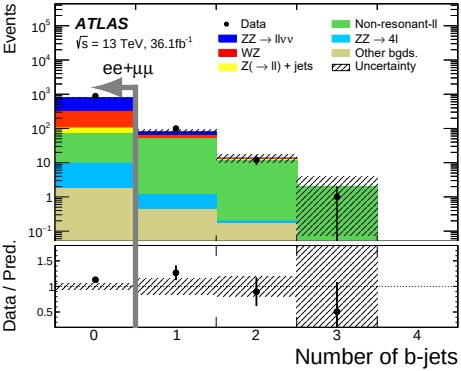
$ZZ \to 2\ell 2\nu$: overview

Larger cross section than the cleaner $ZZ \to 4\ell$ [STDM-2016-13]
$\sim$20% Z branching fraction vs. $\sim$7%.

$\sim$70% of background is partially identified $WZ \to \ell'\nu\ell^+\ell^-$
Shapes from MC, normalisation from 3-lepton control region

$ZZ \to 2\ell 2\nu$: kinematics and selection





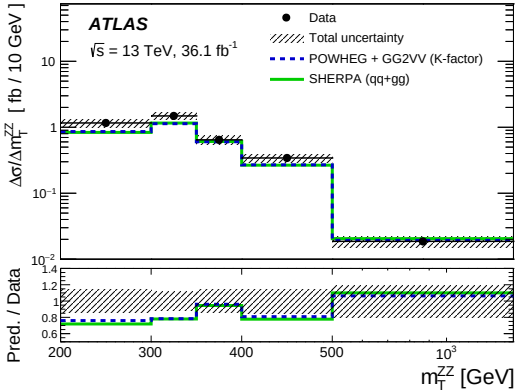
Selected regions indicated in the figures

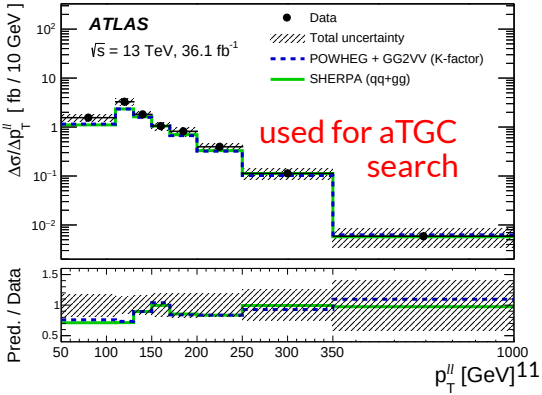
Requirements on all observables except the one shown are already applied

$ZZ \to 2\ell 2\nu$: cross sections

		Measured	Predicted
$\sigma^{\text{fid}}_{ZZ\to\ell\ell\nu\nu}$ [fb]	ee	12.2 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$\mu\mu$	13.3 ± 1.0 (stat) ± 0.5 (syst) ± 0.3 (lumi)	11.2 ± 0.6
	$ee + \mu\mu$	25.4 ± 1.4 (stat) ± 0.9 (syst) ± 0.5 (lumi)	22.4 ± 1.3
σ^{tot}_{ZZ} [pb]	Total	17.8 ± 1.0 (stat) ± 0.7 (syst) ± 0.4 (lumi)	15.7 ± 0.7

Extrapolated cross section agrees with 4ℓ-channel measurement:
σ^{tot}_{ZZ} = 17.2 $\pm$0.6 (stat) $\pm$0.4 (syst) $\pm$0.6 (lumi) pb



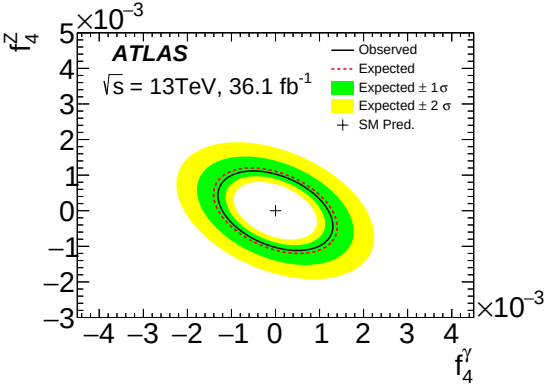


$ZZ \to 2\ell 2\nu$: search for ZZZ and ZZγ couplings

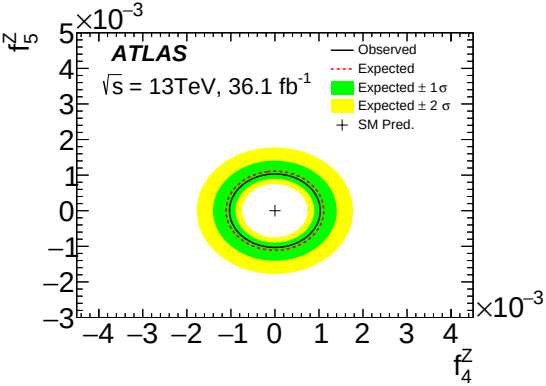
Search for new physics using unfolded $p_T(\ell\ell)$ distribution

Better BSM sensitivity than $ZZ \to 4\ell$

Fiducial cross section around the same size, but $\ell\ell\nu\nu$ has more events at high $p_T(\ell\ell)$



CP-conserving



CP-conserving vs. CP-violating

$Z(\rightarrow \nu\nu)\gamma$ & $Z(\rightarrow \ell\ell)\gamma$ (NEW!)

STDM-2017-18 & ATLAS-CONF-2019-034

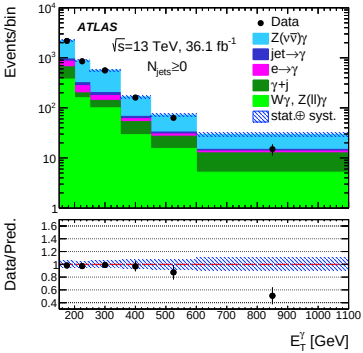
$Z\gamma$: overview

$Z(\to \nu\nu)\gamma$ has larger cross section than $Z(\to \ell\ell)\gamma$,
still less background than $Z(\to q\bar{q})\gamma$ (QCD jets!)

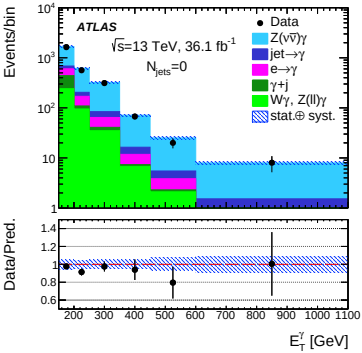
Backgrounds:

- Jet $\rightsquigarrow$ photon (fitted in 2D sideband with inverted photon ID and/or isolation)
- In $Z(\to \nu\nu)\gamma$:
  - Electron $\rightsquigarrow$ photon (fake factor from $Z \to ee$ events, applied to $W \to e\nu$ events)
  - $W(\to \tau\nu, \mu\nu, e\nu)\gamma$ and γ + jets
    Normalisation fitted to data in control regions: 1-lepton, small E_T^{miss} significance
    $\to$ significantly reduces systematic uncertainty w.r.t. 8 TeV [STDM-2014-01]
- In $Z(\to \ell\ell)\gamma$:
  - Pileup of $Z \to \ell\ell$ and γ (fitted to $z_\gamma - z_{vertex}$), around 2% of total expected yield

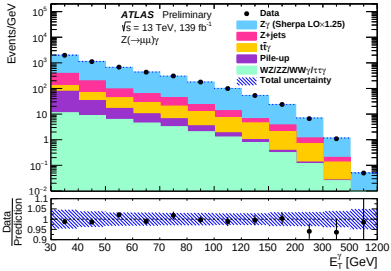
$Z\gamma$: kinematics



$Z(\to \nu\nu)\gamma$ without jet veto

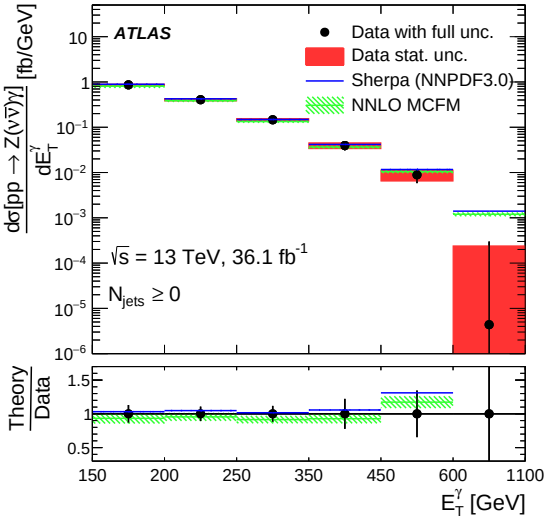


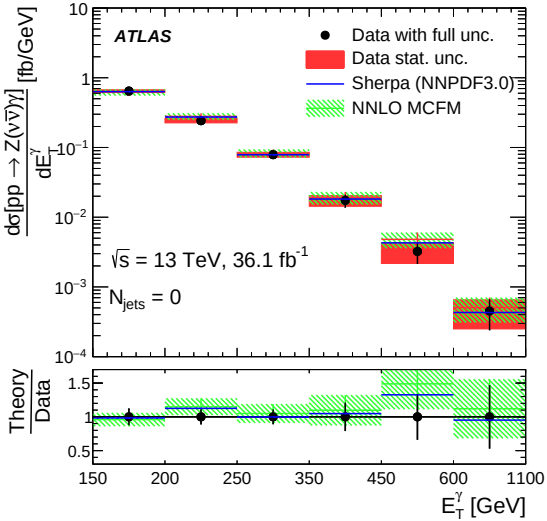
$Z(\to \nu\nu)\gamma$ with jet veto (gives higher purity at large E_T^γ)



$Z(\to \ell\ell)\gamma$

$Z(\rightarrow \nu\nu)\gamma$: differential cross sections

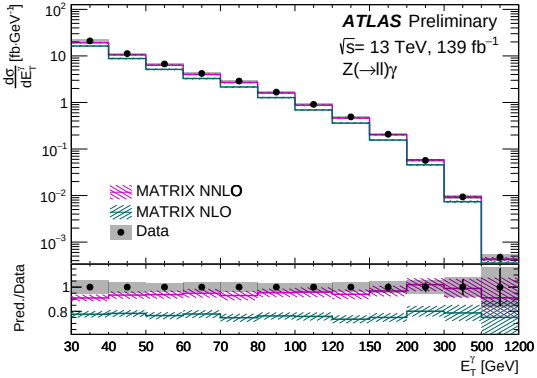


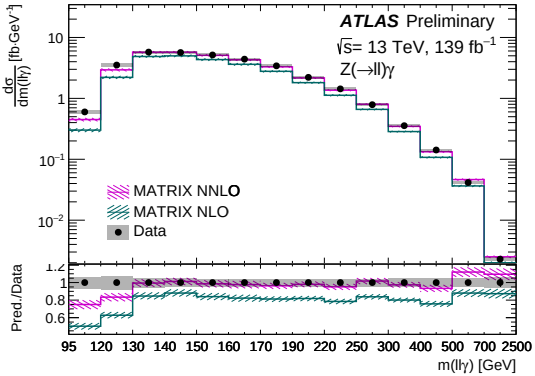


Extrapolated to simplified "extended fiducial region"

(no charged-lepton veto, no E_T^{miss} significance and direction requirement)

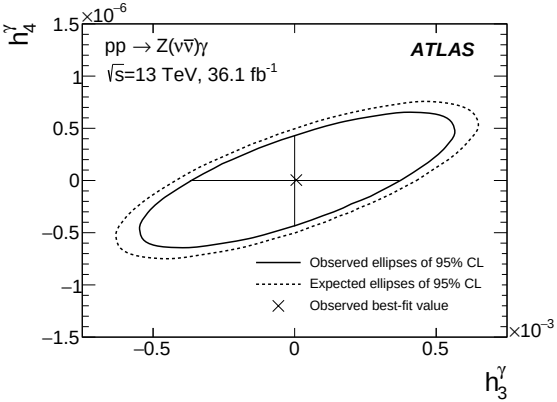
$Z(\to \ell\ell)\gamma$: differential cross sections

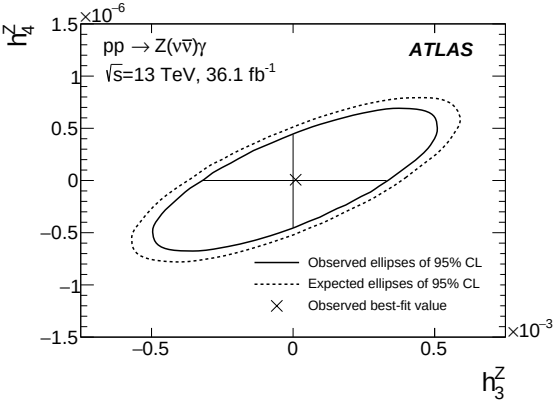




Not measurable in $Z(\to \nu\nu)\gamma$

$Z(\to \nu\nu)\gamma$: search for $ZZ\gamma$ and $Z\gamma\gamma$ couplings





Search uses the yield in the bin $E_T^\gamma > 600$ GeV with jet veto (previous slide)

Only CP-conserving coefficients considered

The confidence intervals for the corresponding CP-violating ones are very similar

Currently world's best limits on neutral aTGCs

Summary

Rich programme of inclusive neutral diboson measurements

Strengths of different Z decay channels:

- Charged leptons: higher precision and acceptance at low p_T,
  $\rightarrow$ good for inclusive cross section measurements
- Neutrinos: higher cross section,
  $\rightarrow$ good for BSM sensitivity at high scales

Search for aTGCs

- No deviation from the SM observed
- Set world-leading limits

Model-independence and interpretability have high priority
Searches/interpretations using unfolded cross sections

Statistical uncertainty will decrease with more data

Thank you for your attention!

Backup

$ZZ \to 2\ell 2\nu$: fiducial definition

Total phase space	Born-level leptons (ee or $\mu\mu$) $66 < m_{\ell\ell}, m_{\nu\nu} < 116$ GeV
Fiducial phase space	Dressed leptons (e or μ): $p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.5$ Jets: $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 4.5$ Reject leptons if overlapping with a jet within $\Delta R < 0.4$ Two leptons with leading (subleading) $p_{\mathrm{T}} > 30$ (20) GeV $76 < m_{\ell\ell} < 106$ GeV $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV and $V_{\mathrm{T}}/S_{\mathrm{T}} > 0.65$ $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 2.2$ radians and $\Delta R_{\ell\ell} < 1.9$

$ZZ \to 2\ell 2\nu$: event selection

Step	Selection criteria
Two leptons	Two opposite-sign leptons, leading (subleading) $p_{\mathrm{T}} > 30$ (20) GeV
Jets	$p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 4.5$, and $\Delta R > 0.4$ relative to the leptons
Third-lepton veto	No additional lepton with $p_{\mathrm{T}} > 7$ GeV
$m_{\ell\ell}$	$76 < m_{\ell\ell} < 106$ GeV
Hard jets	$p_{\mathrm{T}} > 25$ GeV for $\lvert\eta\rvert < 2.4$, $p_{\mathrm{T}} > 40$ GeV for $2.4 < \lvert\eta\rvert < 4.5$
$E_{\mathrm{T}}^{\mathrm{miss}}$ and $V_{\mathrm{T}}/S_{\mathrm{T}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 110$ GeV and $V_{\mathrm{T}}/S_{\mathrm{T}} > 0.65$
$\Delta R_{\ell\ell}$	$\Delta R_{\ell\ell} < 1.9$
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}})$	$\Delta\phi(\vec{p}_{\mathrm{T}}^{\ell\ell}, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}) > 2.2$ radians
b-jet veto	$N(b\text{-jets}) = 0$ with b-jet $p_{\mathrm{T}} > 20$ GeV and $\lvert\eta\rvert < 2.5$

$ZZ \to 2\ell 2\nu$: yields

	ee	$\mu\mu$
Data	371	416
Signal		
$qqZZ$	$194 \pm 3 \pm 12$	$202 \pm 3 \pm 12$
$ggZZ$	$25.1 \pm 0.3 \pm 7.7$	$26.4 \pm 0.3 \pm 8.1$
Backgrounds		
WZ	$92.9 \pm 3.0 \pm 4.8$	$100.7 \pm 3.2 \pm 5.2$
Non-resonant-$\ell\ell$	$25.5 \pm 3.4 \pm 1.8$	$31.5 \pm 4.2 \pm 2.2$
$Z +$ jets	$4.7 \pm 0.2 \pm 2.3$	$5.9 \pm 0.3 \pm 2.8$
$ZZ \to 4\ell$	$3.8 \pm 0.2 \pm 0.3$	$4.2 \pm 0.2 \pm 0.3$
Others	$0.87 \pm 0.03 \pm 0.17$	$0.87 \pm 0.03 \pm 0.17$
Background expected	$128 \pm 5 \pm 6$	$143 \pm 5 \pm 6$
Total expected	$347 \pm 5 \pm 15$	$372 \pm 6 \pm 16$

pp $\rightarrow 4\ell$: event selection

Physics Object preselection		
	ELECTRONS	MUONS
Identification	*Loose* working point [23]	*Loose* working point [22]
Kinematics	$E_{\mathrm{T}} > 7$ GeV and $\lvert\eta\rvert < 2.47$	$p_{\mathrm{T}} > 5$ GeV and $\lvert\eta\rvert < 2.7$ $p_{\mathrm{T}} > 15$ GeV if calorimeter-tagged [22]
Interaction point constraint	$\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm	$\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
Cosmic-ray muon veto		$\lvert d_0\rvert < 1$ mm

Quadruplet Selection		
QUADRUPLET FORMATION	Procedure and kinematic selection criteria as in Table **??**	
LEPTON ISOLATION		
	ELECTRONS	MUONS
Track isolation	$\sum_{\Delta R \leq 0.2} p_{\mathrm{T}} < 0.15 E_{\mathrm{T}}^{e}$	$\sum_{\Delta R \leq 0.3} p_{\mathrm{T}} < 0.15 p_{\mathrm{T}}^{\mu}$
Calorimeter isolation	$\sum_{\Delta R = 0.2} E_{\mathrm{T}} < 0.2 E_{\mathrm{T}}^{e}$	$\sum_{\Delta R = 0.2} E_{\mathrm{T}} < 0.3 p_{\mathrm{T}}^{\mu}$
	Contributions from the other leptons of the quadruplet not considered	
LEPTON TRANSVERSE IMPACT PARAMETER		
	ELECTRONS	MUONS
	$d_0/\sigma_{d_0} < 5$	$d_0/\sigma_{d_0} < 3$
4ℓ VERTEX FIT		
χ^2/ndof	< 6 (4μ) or < 9 $(4e,\ 2e2\mu)$	

pp $\rightarrow 4\ell$: fiducial definition

Physics Object Preselection	
Muon selection	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electron selection	$p_{\mathrm{T}} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Quadruplet Selection	
Lepton pairing	Assign SFOS lepton pairs with smallest and second-smallest $\lvert m_{\ell\ell} - m_Z\rvert$ as primary and secondary lepton pair, defining exactly one quadruplet
Lepton kinematics	$p_{\mathrm{T}} > 20/15/10$ GeV for leading three leptons
Mass window, primary pair	50 GeV$< m_{12} <$ 106 GeV
Mass window, secondary pair	$f(m_{4\ell}) < m_{34} <$ 115 GeV
Lepton separation	$\Delta R_{ij} > 0.1(0.2)$ for same (opposite) flavour leptons
J/ψ veto	$m_{ij} > 5$ GeV for all SFOS pairs
Mass interval of measurement	70 GeV$< m_{4\ell} <$ 1200 GeV

$\mathrm{pp} \to 4\ell$: secondary dilepton mass

Piecewise definition of lower mass requirement of secondary dilepton:

$$f(m_{4\ell}) = \left\{ \begin{array}{ll} 5\mathrm{GeV}, & \text{for } m_{4\ell} < 100\mathrm{GeV} \\ 5\mathrm{GeV} + 0.7 \times (m_{4\ell} - 100\mathrm{GeV}), & \text{for } 100\mathrm{GeV} < m_{4\ell} < 110\mathrm{GeV} \\ 12\mathrm{GeV}, & \text{for } 110\mathrm{GeV} < m_{4\ell} < 140\mathrm{GeV} \\ 12\mathrm{GeV} + 0.76 \times (m_{4\ell} - 140\mathrm{GeV}), & \text{for } 140\mathrm{GeV} < m_{4\ell} < 190\mathrm{GeV} \\ 50\mathrm{GeV}, & \text{for } m_{4\ell} > 190\mathrm{GeV} \end{array} \right\}$$

pp $\to 4\ell$: matrix-element discriminant

$$D_{\mathrm{ME}} = \log_{10} \frac{\tilde{M}^2_{gg\to H^{(*)}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}{\tilde{M}^2_{gg\left(\to H^{(*)}\right)\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right) + 0.1\cdot \tilde{M}^2_{q\bar{q}\to ZZ^{(*)}\to 4\ell}\left(p^{\mu}_{1,2,3,4}\right)}$$

where

$$\tilde{M}^2_{X}\left(p^{\mu}_{1,2,3,4}\right) = \frac{\left|\mathcal{M}_X\right|^2\left(p^{\mu}_{1,2,3,4}\right)}{\left\langle\left|\mathcal{M}_X\right|^2\right\rangle\left(m_{4\ell}\right)}$$

The matrix elements are evaluated at LO with MCFM 8.0

pp $\to 4\ell$: Z $\to 4\ell$ branching ratio

Measurement	$\mathcal{B}_{Z\to 4\ell}/10^{-6}$
ATLAS, $\sqrt{s} = 7$ TeV and 8 TeV [8]	$4.31 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})$
CMS, $\sqrt{s} = 13$ TeV [6]	$4.83\ ^{+0.23}_{-0.22}(\text{stat})\ ^{+0.32}_{-0.29}(\text{syst}) \pm 0.08(\text{theo}) \pm 0.12(\text{lumi})$
ATLAS, $\sqrt{s} = 13$ TeV	$\mathbf{4.70 \pm 0.32(stat) \pm 0.21(syst) \pm 0.14(lumi)}$

$Z(\to \nu\nu)\gamma$: fiducial definition

Photons	Leptons	Jets
$E_{\mathrm{T}} > 150$ GeV $\lvert\eta\rvert < 2.37$, excluding $1.37 < \lvert\eta\rvert < 1.52$	$p_{\mathrm{T}} > 7$ GeV $\lvert\eta\rvert < 2.47(2.7)$ for $e(\mu)$, excluding $1.37 < \lvert\eta^{e}\rvert < 1.52$	$p_{\mathrm{T}} > 50$ GeV $\lvert\eta\rvert < 4.5$ $\Delta R(\mathrm{jet}, \gamma) > 0.3$
Event selection		
$N^{\gamma} = 1, \quad N^{e,\mu} = 0, \quad E_{\mathrm{T}}^{\mathrm{miss}} > 150$ GeV, $\quad E_{\mathrm{T}}^{\mathrm{miss}}$ signif. > 10.5 GeV$^{1/2}$, $\quad \Delta\phi(\vec{E}_{\mathrm{T}}^{\mathrm{miss}}, \gamma) > \pi/2$ Inclusive : $N_{\mathrm{jet}} \geq 0$, Exclusive : $N_{\mathrm{jet}} = 0$		

$Z(\rightarrow \nu\nu)\gamma$: extended fiducial definition

Category	Requirement
Photons	$E_{\mathrm{T}}^{\gamma} > 150$ GeV
	$\lvert\eta\rvert < 2.37$
Jets	$\lvert\eta\rvert < 4.5$
	$p_{\mathrm{T}} > 50$ GeV
	$\Delta R(\mathrm{jet}, \gamma) > 0.3$
	Inclusive : $N_{\mathrm{jet}} \geq 0$, Exclusive : $N_{\mathrm{jet}} = 0$
Neutrino	$p_{\mathrm{T}}^{\nu\nu} > 150$ GeV

$Z(\to \nu\nu)\gamma$: yields

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{W\gamma}$	$650 \pm 40 \pm 60$	$360 \pm 20 \pm 30$
$N^{\gamma+\text{jet}}$	$409 \pm 18 \pm 108$	$219 \pm 10 \pm 58$
$N^{e\to\gamma}$	$320 \pm 15 \pm 45$	$254 \pm 12 \pm 35$
$N^{\text{jet}\to\gamma}$	$170 \pm 30 \pm 50$	$140 \pm 20 \pm 40$
$N^{Z(\ell\ell)\gamma}$	$40 \pm 3 \pm 3$	$26 \pm 3 \pm 2$
$N^{\text{bkg}}_{\text{total}}$	$1580 \pm 50 \pm 140$	$1000 \pm 40 \pm 90$
$N^{\text{sig}}(\text{exp})$	$2328 \pm 4 \pm 135$	$1710 \pm 4 \pm 91$
$N^{\text{sig+bkg}}_{\text{total}}$	$3910 \pm 50 \pm 190$	$2710 \pm 40 \pm 130$
$N^{\text{data}}(\text{obs})$	3812	2599

$Z(\to \nu\nu)\gamma$: integrated cross sections

$\sigma^{\text{ext.fid.}}$ [fb] Measurement	$\sigma^{\text{ext.fid.}}$ [fb] NNLO MCFM Prediction
$N_{\text{jets}} \geq 0$	
$83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.)	78.1 ± 0.2(stat.)± 4.7(syst.)
$N_{\text{jets}} = 0$	
$52.4^{+2.4}_{-2.3}$ (stat.)$^{+4.0}_{-3.6}$ (syst.)$^{+1.2}_{-1.1}$ (lumi.)	55.9 ± 0.1(stat.)± 3.9(syst.)

Extrapolated to simplified “extended fiducial region”