Exclusive $\gamma\gamma \rightarrow WW$ at ATLAS

Savannah Clawson

The University of Manchester

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Introduction

This talk will be focusing on the recent 13 TeV Run 2 observation of exclusive *WW* production in photon scattering with the ATLAS detector

Paper: PLB 816 (2021) 136190

ATLAS briefing: ATLAS observes W-boson pair production from light colliding with light

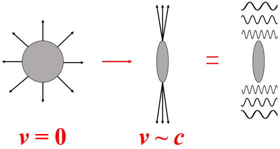
CERN press release: Rare phenomenon observed by ATLAS features the LHC as a high-energy photon collider

Previous evidence of the $\gamma\gamma \rightarrow WW$ process was seen by both ATLAS [1] and CMS [2,3] in Run 1

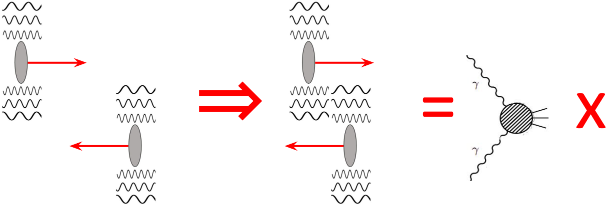
[1] PLB 816 (2021) 136190 [2] JHEP 07 (2013) 116, [3] JHEP 08 (2016) 119

Turning the LHC into a photon-photon collider

Boosted charged particles are a source of quasi-real photons



Leading to photon-photon fusion in peripheral collisions



Photon-induced processes ⇒ clean "exclusive" final states:

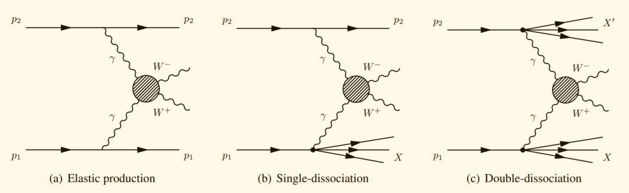
Exclusivity definition = little to no additional activity in the event

The signal process

- Process can only proceed via electroweak boson couplings at leading order
  ⇒ ideal probe for anomalous couplings (see e.g. [1])

SIGNAL: opposite-sign, different-flavour dilepton: $e^{\pm}\mu^{\mp}$ (+νν)

- Signal includes both elastic and dissociative contributions:



(a) Elastic production (b) Single-dissociation (c) Double-dissociation

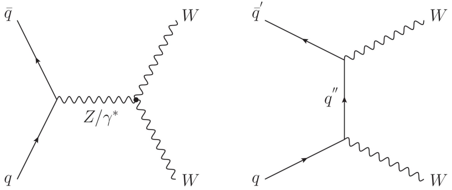
Elastic: photon radiation off the whole proton without disintegration

Dissociative: at least one of the photons can be considered as being radiated off a parton in the proton, causing the proton to break apart (dissociate)

[1] Phys. Rev. D 81 (2010) 074003

Backgrounds

- Dominant background = inclusive *WW* production, *qq*→*WW* (30% contribution in signal region)
- Hard-scatter process is accompanied by an **underlying event** = additional charged particles originating from initial-state radiation or secondary partonic scatters
- Inclusive backgrounds can pass our exclusivity requirement if additional charged particles are either too soft or too forward to be reconstructed



$$\sigma_{qq\rightarrow WW} = O(10^3) \times \sigma_{\gamma\gamma\rightarrow WW}$$

- Other backgrounds include exclusive dilepton production, $\gamma\gamma\rightarrow ll$ (~2%), Drell-Yan (DY) production, $qq\rightarrow Z/\gamma^*\rightarrow ll$, (~2%), top production (~2%) and non-prompt leptons from *W*+jets (~5%)

(list of main simulated samples in backup)

Event selection

- Rare process so must utilise full *pp* dataset

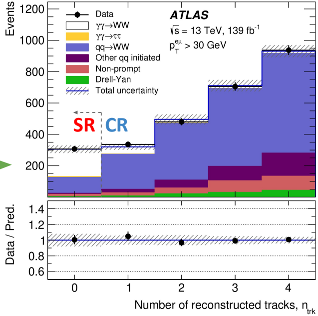
Full Run 2 dataset ⇒ 139 fb^{-1}

- Single lepton triggers → leading lepton p_T > 27 GeV, subleading p_T > 20 GeV
- Dilepton mass > 20 GeV to suppress low mass resonances
- Dilepton p_T > 30 GeV to suppress contributions from DY $Z/\gamma^* \rightarrow \tau\tau$

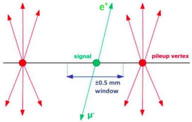
Exclusivity requirement

- Veto additional activity ⇒ **track veto requirement** (track-p_T > 500 MeV)
- No additional tracks within a symmetric ± 1 mm window of the dilepton vertex
- Pileup can spoil this selection

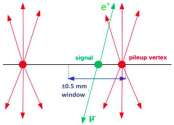
$n_{trk} = 0$



event kept



event rejected



Analysis method

Many novel experimental techniques needed to measure rare process:

Vertex definition

Beamspot width rescaling

Pileup modelling correction

Exclusive efficiency

Charged particle multiplicity correction

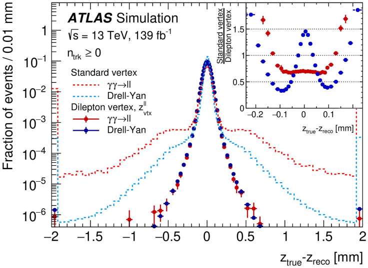
Signal modelling correction

Analysis method: Vertex definition

- Standard ATLAS primary vertex (PV) reconstruction uses sum of squared p_T to select PV
- This is not optimal for PVs with a low number of tracks, like expected from *γγ→WW*
- Redefine the PV as the weighted average of the two lepton tracks:

$$z_{\mathrm{vtx}}^{\ell\ell} = \frac{z_{\ell_1}\sin^2\theta_{\ell_1} + z_{\ell_2}\sin^2\theta_{\ell_2}}{\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2}}$$

where 1/sinθ approximately parametrises the lepton *z*-resolution



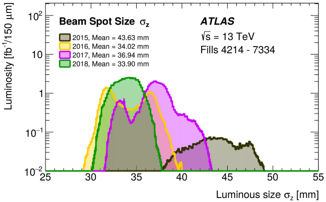
- Dilepton vertex 30% more efficient than standard ATLAS PV selection

Analysis method: Pileup modelling

- The efficiency of the $n_{\text{trk}} = 0$ requirement is very sensitive to the **track density**
- Track density depends on beamspot parameters like longitudinal width, σ_z
- Beamspot parameters in MC “guesstimated” before the end of data-taking

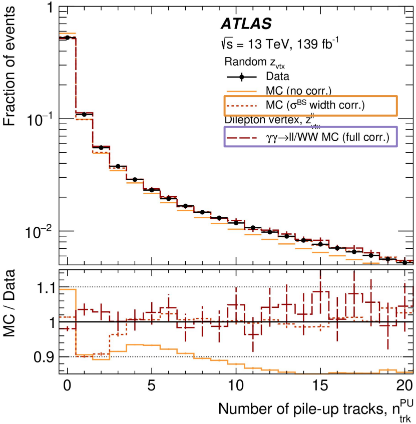
$$\langle\sigma_z\rangle_{\text{data}} = 35\text{ mm}$$

$$\sigma_{z,\text{MC}} = 42\text{ mm}$$



- Shift track positions to resize the beamspot in simulation

- Additional data-driven correction applied to correct the pileup **track multiplicity**

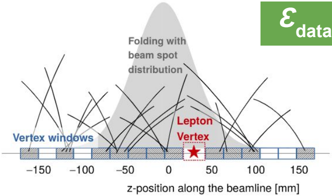


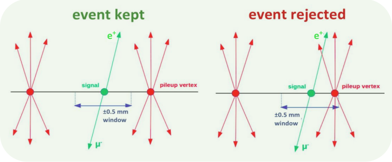
Analysis method: Exclusive efficiency

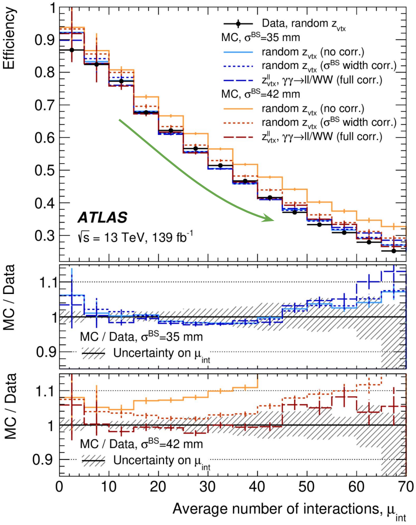
Need to quantify how often we reject our exclusive signal due to pileup:

- This is the efficiency of the $n_{\mathrm{trk}} = 0$ requirement
- Data-driven method to count pileup tracks in *z*-windows across the beamspot width
- The exclusive efficiency drops as pileup increases
- Average pileup in Run 2 was ⟨μ⟩ = 33.7

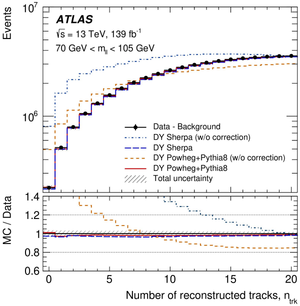
$\varepsilon_{\mathrm{data}} = 52\%$





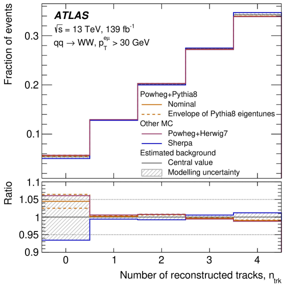


Analysis method: Charged particle multiplicity



- Only way to distinguish inclusive *WW* background from signal is due to additional tracks in the underlying event (UE)
- These tracks originate from soft interactions and are therefore challenging to model accurately
- Low charged-particle multiplicity is particularly poorly modelled

- Data-driven correction derived bins of dilepton p_T using same-sign dilepton events on the *Z*-peak
- Even after applying these corrections, different generators/tunes vary significantly for n_{trk} = 0
- This is the largest source of systematic uncertainty in the analysis



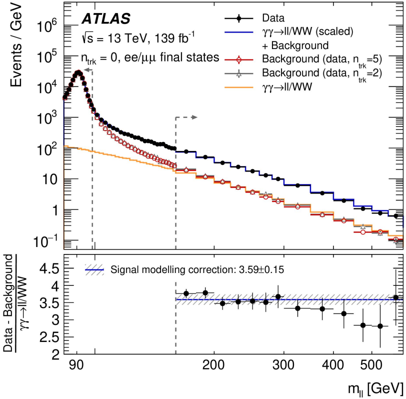
Analysis method: Signal modelling

- Signal MC only includes elastic (EE) contribution to the cross-section
- Fully data-driven method used to correct the elastic cross-section in MC to account for single-dissociative (SD) and double dissociative (DD) contributions

- Dissociative contribution estimated from a γγ→*ll* control sample in data with $m_{ll} > 2m_W$
- This correction also accounts for proton soft survival - the probability that the proton does not rescatter

$$\sigma_{EE+SD+DD} = (3.59 \pm 0.15) \times \sigma_{EE}$$

- This correction factor is applied to γγ→*WW* / *ll* MC in the $n_{trk} = 0$ region

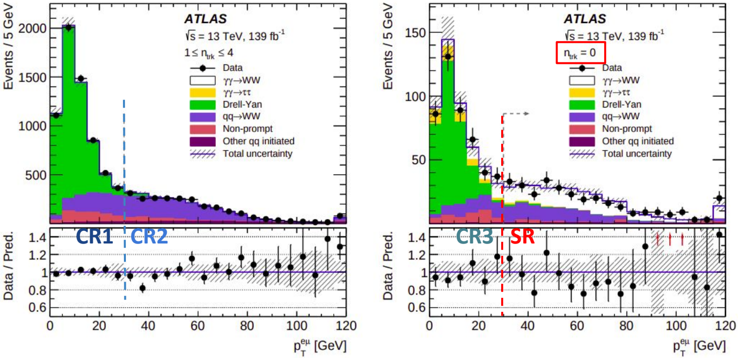


Result

Simultaneous profile likelihood fit performed to yields in signal and control regions:

- Background hypothesis rejected with a significance of **8.4σ**
- Measured fiducial cross-section of **3.13 ± 0.31 (stat.) ± 0.28 (syst.) fb**

Theory predictions consistent with measurement when accounting for proton survival factors

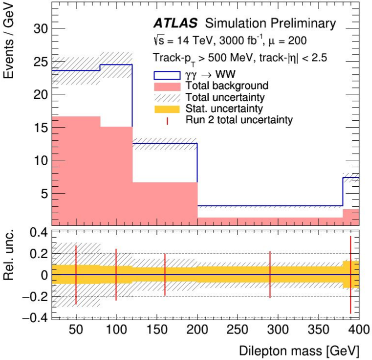


In Run 3 ⇒ possibility to tag the outgoing protons with dedicated forward detectors like the ATLAS Forward Proton (AFP) spectrometer, allowing full reconstruction of the *WW* system

NEW: *γγ→WW* at the HL-LHC

Sensitivity to exclusive *WW* production in photon scattering at the High Luminosity LHC [ATL-PHYS-PUB-2021-026]

Signal and background yields from the Run 2 observation were extrapolated to the HL-LHC, assuming an integrated luminosity of 3000 fb^{-1} and μ = 200



Exclusivity definition is very sensitive to pileup

Run 2: $\langle\mu\rangle$ = 33.7

HL-LHC: μ = 200

- HL-LHC operating conditions bring challenges for identifying exclusive final states
- However, the increase in available statistics opens up avenues for precision differential measurements

Summary

Vibrant photon-photon fusion programme in ATLAS allowing fundamental tests of the electroweak sector

- First observation of γγ→*WW* made by ATLAS with a significance of 8.4σ
- Many novel experimental techniques needed to measure rare process
- Ideal probe for anomalous couplings (BSM physics)

In the future...

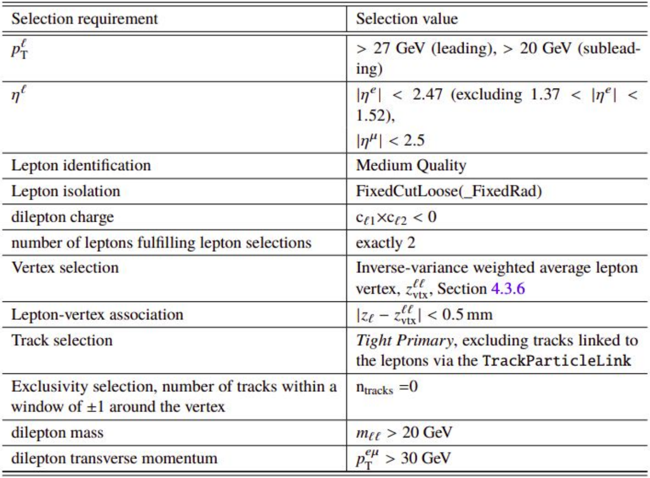
- Run 3 and beyond: possibility to utilise forward proton tagging to fully reconstruct *WW* system
- HL-LHC will bring challenges for identifying exclusive final states but will open up avenues for testing the tails of distributions that were statistically limited in previous runs

Backup

Simulated samples

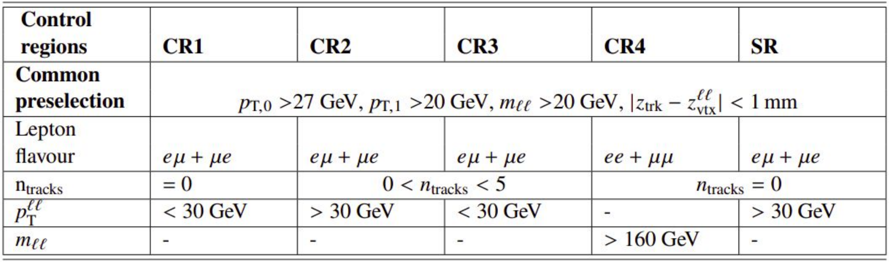
Process	Matrix element (alternative)	PDF set	UEPS (alternative model)	UE tune (alternative model)	Prediction order for total cross-section
$\gamma\gamma \to WW$ (EE)	BudnevQED	n/a	Herwig 7	n/a	LO
	(MG5_aMC@NLO)		(Pythia 8)	n/a	
$\gamma\gamma \to WW$ (SD)	MG5_aMC@NLO	CT14qed	Pythia 8	n/a	
$\gamma\gamma \to WW$ (DD)	MG5_aMC@NLO	CT14qed	Pythia 8	n/a	
$\gamma\gamma \to \ell\ell$ (EE)	BudnevQED	n/a	Herwig 7	n/a	LO
	(MG5_aMC@NLO)		(Pythia 8)	n/a	
$\gamma\gamma \to \ell\ell$ (SD)	LPAIR	n/a	LPAIR	n/a	LO
	(MG5_aMC@NLO)	(CT14qed)	(Pythia 8)	n/a	
$\gamma\gamma \to \ell\ell$ (DD)	Pythia 8	NNPDF23QED	(Pythia 8)	n/a	LO
	(MG5_aMC@NLO)	(CT14qed)	(Pythia 8)	n/a	
$qq, qg \to WW$	Powheg-Box v2	NNPDF3.0 NLO	(Pythia 8)	AZNLO [37]	NNLO QCD
	(Sherpa v2.2.2)	(NNPDF3.0 NNLO)	(Sherpa v2.2.2)	(Sherpa v2.2.2)	
$gg \to WW$	Sherpa v2.1.1	CT10	Sherpa v2.1.1	Sherpa v2.1.1	NLO
$gg \to H$	Powheg-Box v2	NNPDF3.0 NLO	Pythia 8	AZNLO [37]	NNLOPS
WW VBS	Sherpa v2.2.2	NNPDF3.0 NNLO	Sherpa v2.2.2	Sherpa v2.2.2	LO
$WZ/W\gamma^{\star}/ZZ/Z\gamma^{\star}$	Sherpa v2.2.2	NNPDF3.0 NNLO	Sherpa v2.2.2	Sherpa v2.2.2	NLO
$W\gamma/Z\gamma$	Sherpa v2.2.2	NNPDF3.0 NNLO	Sherpa v2.2.2	Sherpa v2.2.2	NLO
$t\bar{t}$	Powheg-Box v2	NNPDF3.0 NLO	Pythia 8	A14 tune [47]	NNLO+NNLL
Wt	Powheg-Box v2	NNPDF3.0 NLO	Pythia 8	A14 tune [47]	NLO
W	Sherpa v2.2.1	NNPDF3.0 NNLO	Sherpa v2.2.1	Sherpa v2.2.1	NNLO
$Z/\gamma^{\star}$	Powheg-Box v1	NNPDF3.0 NLO	Pythia 8	AZNLO [37]	NNLO
	(Sherpa v2.2.1)		Sherpa v2.2.1		

Event selection



Selection requirement	Selection value
p_{T}^{ℓ}	> 27 GeV (leading), > 20 GeV (subleading)
η^{ℓ}	$\lvert\eta^{e}\rvert < 2.47$ (excluding $1.37 < \lvert\eta^{e}\rvert < 1.52$), $\lvert\eta^{\mu}\rvert < 2.5$
Lepton identification	Medium Quality
Lepton isolation	FixedCutLoose(_FixedRad)
dilepton charge	$c_{\ell 1} \times c_{\ell 2} < 0$
number of leptons fulfilling lepton selections	exactly 2
Vertex selection	Inverse-variance weighted average lepton vertex, $z_{\mathrm{vtx}}^{\ell\ell}$, Section 4.3.6
Lepton-vertex association	$\lvert z_{\ell} - z_{\mathrm{vtx}}^{\ell\ell}\rvert < 0.5$ mm
Track selection	*Tight Primary*, excluding tracks linked to the leptons via the `TrackParticleLink`
Exclusivity selection, number of tracks within a window of ±1 around the vertex	$n_{\mathrm{tracks}} = 0$
dilepton mass	$m_{\ell\ell} > 20$ GeV
dilepton transverse momentum	$p_{\mathrm{T}}^{e\mu} > 30$ GeV

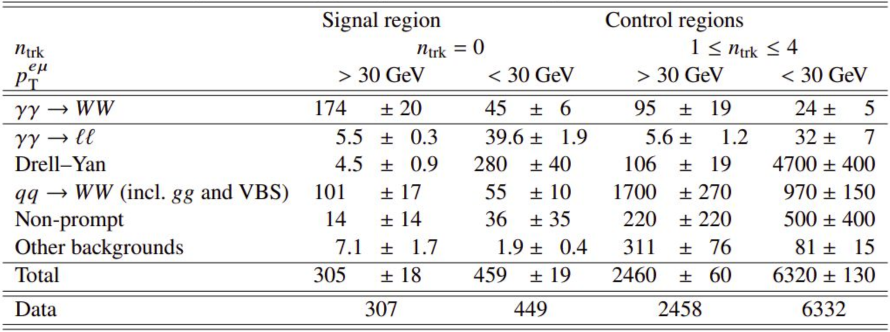
Control regions



Control regions	**CR1**	**CR2**	**CR3**	**CR4**	**SR**
Common preselection	$p_{T,0}$ >27 GeV, $p_{T,1}$ >20 GeV, $m_{\ell\ell}$ >20 GeV, $\lvert z_{\mathrm{trk}} - z_{\mathrm{vtx}}^{\ell\ell}\rvert < 1$ mm				
Lepton flavour	$e\mu + \mu e$	$e\mu + \mu e$	$e\mu + \mu e$	$ee + \mu\mu$	$e\mu + \mu e$
$\mathrm{n_{tracks}}$	$= 0$	$0 < n_{\mathrm{tracks}} < 5$		$n_{\mathrm{tracks}} = 0$	
$p_T^{\ell\ell}$	< 30 GeV	> 30 GeV	< 30 GeV	-	> 30 GeV
$m_{\ell\ell}$	-	-	-	> 160 GeV	-

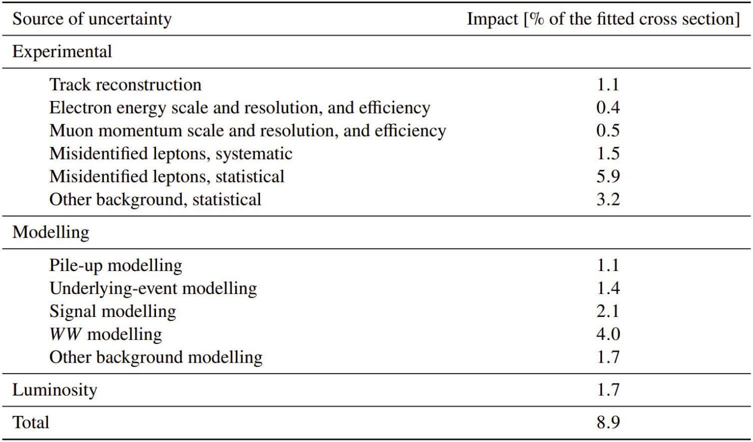
- CR1: check the modeling of γγ → ττ process
- CR2: The main inclusive WW production modelling region
- CR3: Region to check modelling of DY(ττ) and inclusive WW production
- CR4: The exclusivity scale factor is measured in this region

Event yields (post-fit)



	Signal region		Control regions	
n_{trk}	$n_{\text{trk}} = 0$		$1 \leq n_{\text{trk}} \leq 4$	
$p_{\text{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332

Main sources of uncertainty



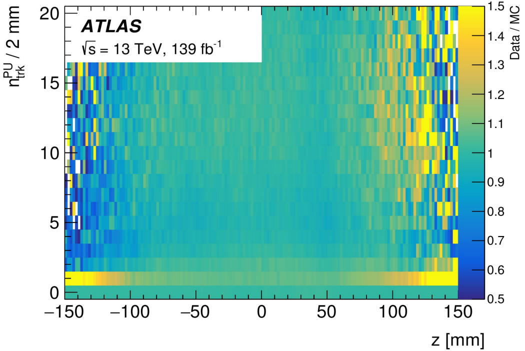
Source of uncertainty	Impact [% of the fitted cross section]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

Misidentified leptons

- Misidentified leptons from non-prompt leptons expected to have smaller contribution than in inclusive WW analyses due to additional activity expected (fail track veto)
- Dominant contribution from W+jets where one lepton is prompt and the other originates from light-hadron or heavy-flavour decays
- Large (>100%) statistical uncertainty on W+jets predictions from simulation
- Control sample defined in data with same kinematic selections as signal but where one of the leptons must fail quality/isolation requirements
- Event must be triggered on the lepton passing nominal selection (correction applied to account for trigger efficiency losses resulting from this selection)
- Control sample predicts significantly more events from misidentified leptons than from simulation
- Large systematic uncertainty from subtraction of prompt leptons in MC ranging between 50% and 100% depending on the region
- The statistical uncertainty in the control region for the estimation of background from misidentified leptons is a significant source of uncertainty in the final measurement

Pileup reweighting

- Standard ATLAS pileup reweighting (PRW) applied but further correction needed
- Additional data-driven correction derived by counting $n_{\mathrm{trk}}^{\mathrm{PU}}$ in 2 mm z-bins far from primary vertex (to avoid bias from hard-scatter tracks)
- Ratio of normalised data to MC distribution used to reweight MC:



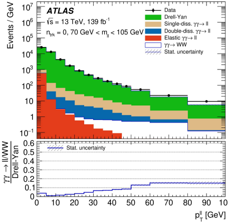
- Since z-rescaled MC is used, this mostly corrects for the physics mismodelling of the minimum bias interactions used to model pile-up in the ATLAS simulation (Pythia8 A3 tune)
- A more detailed analysis showed that the p_T distribution of PU tracks was not well modelled

Charged particle multiplicity correction method

Track multiplicity expected to be fairly process-independent (for colourless final states), once its dependence on the pT of the underlying system is properly taken into account. Many cross-checks done to check the process independence.

For this reason, we use DY events on the Z-peak to measure the charged particle distribution in several intervals of pT(ll) and calculate a data-to-MC correction to apply to all DY/diboson samples. An additional pT(Z) correction is also applied. The pT(WW) distribution is reweighted to the theoretical calculation at NNLO accuracy in perturbative QCD with resummation of soft gluon emissions up to N3LL accuracy.

1. Subtract photon-induced dilepton events (largest contribution in ntrk=0 bin of 5.5%)
2. Subtract pileup tracks using a data-driven method
3. Unfold reconstructed hard-scatter tracks to particle level using Bayesian iterative unfolding (1 iteration in MC, 4 iterations in data)
4. Derive weights to correct nch in MC to data in bins of dilepton pT (= pT(Z))
5. Apply to DY,WW,WZ,ZZ MC in bins of (di)boson pT
6. Small non-closure arises from imperfect pileup subtraction



$\gamma\gamma \rightarrow WW$ at the HL-LHC

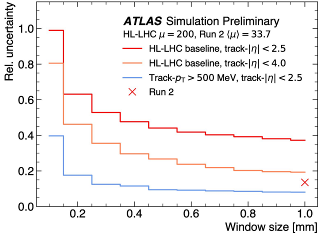
HL-LHC configurations

- Assuming an integrated luminosity of 3000 fb^{-1} and μ=200
- Three HL-LHC configurations investigated:

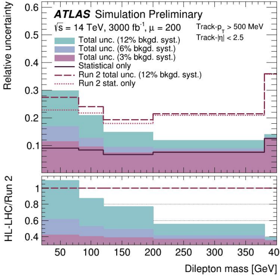
1. HL-LHC baseline [1], track-|η| < 2.5 = nominal analysis
2. HL-LHC baseline, track-|η| < 4.0 = forward tracking with the ITk
3. Track-p_T > 500 MeV, track-|η| < 2.5 = low-p_T reconstruction

- All three configurations tested as a function of track-veto window size

[ATL-PHYS-PUB-2021-026]

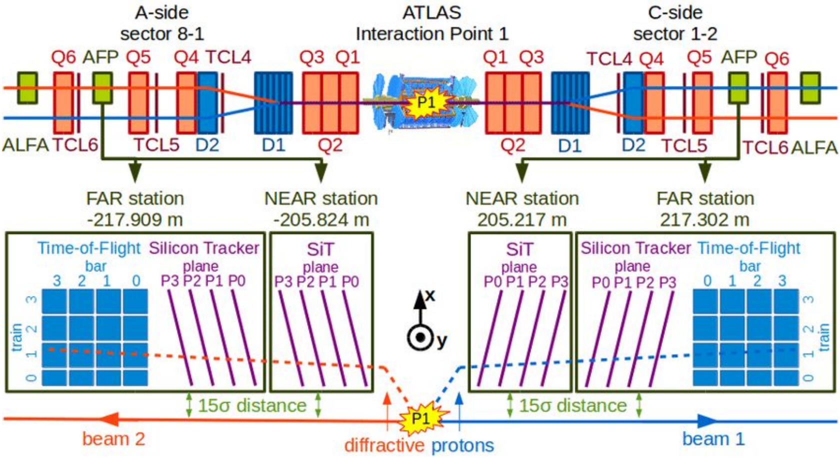


- Low-p_T tracking (nominal LHC threshold = 900 MeV) was the only configuration found to improve on the Run 2 sensitivity for an integrated cross-section measurement
- Sensitivity was then investigated for a differential measurement using the optimal configuration and a small window size to maximise statistics
- The effect of reduced background systematics were also investigated



[1] Expected Tracking Performance of the ATLAS Inner Tracker at the HL-LHC [ATL-PHYS-PUB-2019-014]

Overview of the ATLAS Forward Proton (AFP) detector



Towards Point 8 (LHCb)

Towards Point 2 (ALICE)