Photon-photon fusion measurements at ATLAS

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The University of Manchester

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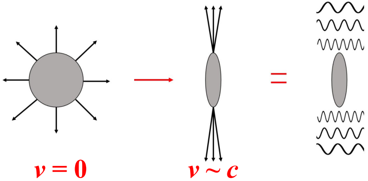
Top & Electroweak physics, July 29th

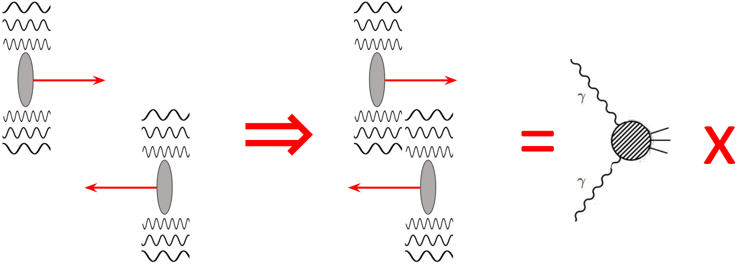
Introduction

Boosted charged particles are a source of photons:



Quasi-real photon flux:
E_{max} @LHC ~ 2 TeV (protons)
~ 80 GeV (Pb ions)

Photon-photon fusion in ultra-peripheral collisions (UPC):



Photon flux $\propto Z^2$ ⇒ larger flux for heavy ions (but lower energy) than protons

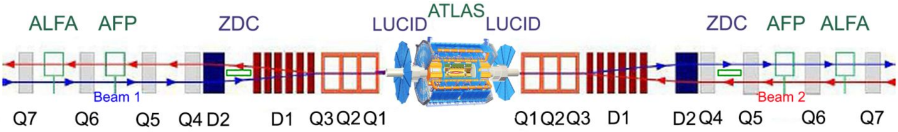
Exclusive processes

Photon-induced processes ⇒ exclusive final states:

Exclusivity definition 1 = little to no additional activity in central detector

Intact protons/ions or their remnants travel in the forward direction:

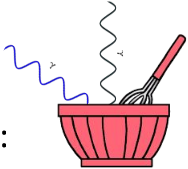
Exclusivity definition 2 = detect these very forward particles



AFP = ATLAS Forward Proton detector

WARNING: Additional soft interactions between protons/ions or their remnants can spoil exclusivity ⇒ soft survival factors

Talk outline



Turning the LHC into a photon-photon collider:

1. Light-by-light (LbyL) scattering $\gamma\gamma \to \gamma\gamma$

[JHEP 03 (2021) 243]
PbPb, $\sqrt{s}$ = 5.02 TeV

2. $\gamma\gamma \to ll$ with AFP proton tag

[PRL 125 (2020) 261801]
pp, $\sqrt{s}$ = 13 TeV, <μ> = 36

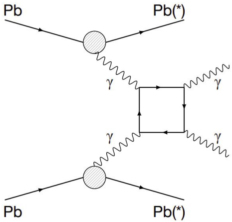
3. Observation of $\gamma\gamma \to WW$

[PLB 816 (2021) 136190]
pp, $\sqrt{s}$ = 13 TeV, <μ> = 33.7

LbyL scattering in PbPb

[JHEP 03 (2021) 243]

Leading order = virtual one-loop box diagram ⇒ very rare $O(\alpha^4_{EM})$ process

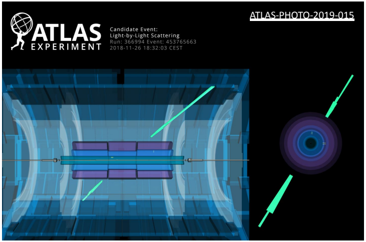


Previous measurements:

- 2015 data: ~4σ evidence for both ATLAS [1] and CMS [2]
- 2018 data: 8.2σ observation ATLAS [3]

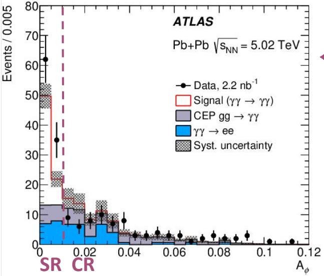
This result:

- Combination of 2015+2018 PbPb dataset
- Improvements in trigger efficiency and photon identification ⇒ 50% increase in signal yield
- Differential cross sections
- Limits on axion-like particle resonance



[1] Nat. Phys. 13 (2017) 852, [2] PLB 797 (2019) 134826 , [3] PRL 123 (2019) 052001

LbyL scattering in PbPb



[JHEP 03 (2021) 243]

← Expect photons to be produced back-to-back

Diphoton acoplanarity: A_ϕ < 0.01

Diphoton transverse momentum: p_T < 1 - 2 GeV

Backgrounds:

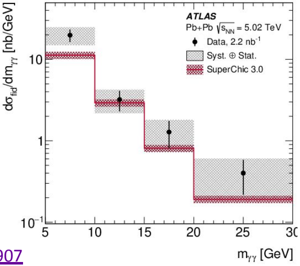
- $\gamma\gamma \to ee$ and $gg \to \gamma\gamma$
- estimated using data-driven methods

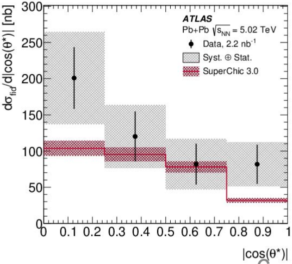
Fiducial cross section ~ 1.8σ higher than Leading Order (LO) predictions [1,2]

σ_{fid} = 120 ± 17 (stat.) ± 13 (syst.) ± 4 (lumi.) nb

SuperChic v3.0 = 78 ± 8 nb

Differential distributions probe the energy of the process and the angular correlation of the $\gamma\gamma$ system





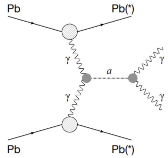
[1] EPJC 79 (2019) 39, [2] PRC 93 (2016) 044907

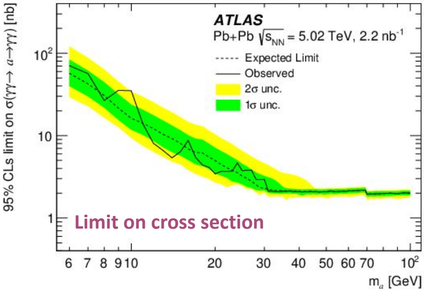
LbyL scattering in PbPb

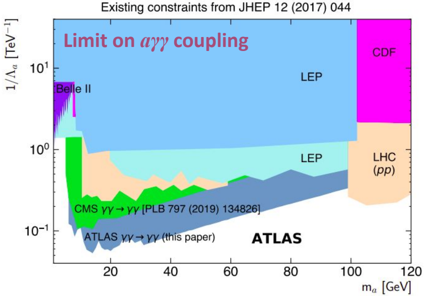
[JHEP 03 (2021) 243]

ALP = Axion-Like Particle

- Any particle coupling directly to photons could be produced in an *s*-channel process in photon–photon collisions
- Popular candidates for producing narrow diphoton resonance = ALPs
- SM LbyL becomes background
- Most stringent limits yet on ALP production in $6 < m_a < 100$ GeV region

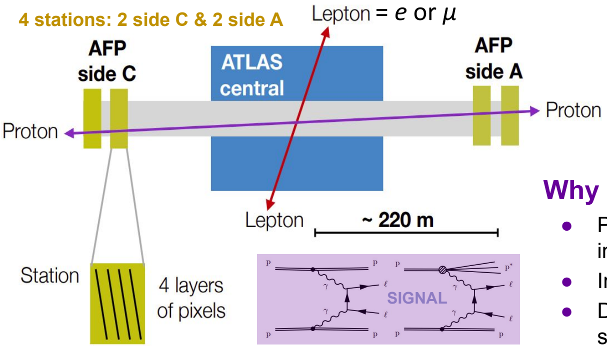






Dilepton production with AFP proton tag

[PRL 125 (2020) 261801]



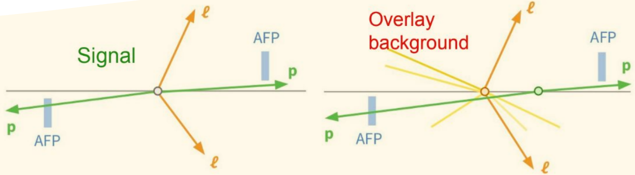
Previous measurements by ATLAS performed **without proton-tagging** at 7 TeV [1] and 13 TeV [2]

Why proton tagging?

- Provides info on initial $\gamma\gamma$ system independently of central-detector
- Improved background suppression
- Direct measurement of proton soft survival factors

CMS and TOTEM reported proton-tagged ee (μμ) production with 2.6σ (4.0σ) significance at 7 TeV but no cross sections were measured [3]

2017 dataset with AFP detectors inserted = **14.6 fb^{-1}**



[1] PLB 749 (2015) 242-261, [2] PLB 777 (2018) 303, [3] JHEP 07 (2018) 153

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Dilepton production with AFP proton tag

[PRL 125 (2020) 261801]

Can fully reconstruct final state from forward proton information ⇒ protons from the $\gamma\gamma \rightarrow ll$ process are identified using AFP measurement and kinematic matching

Key variable = proton fractional momentum loss:

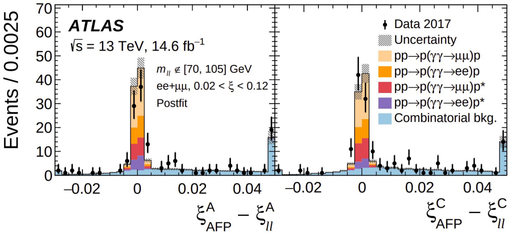
$$\xi_{AFP} = 1 - E_{proton} / E_{beam}$$

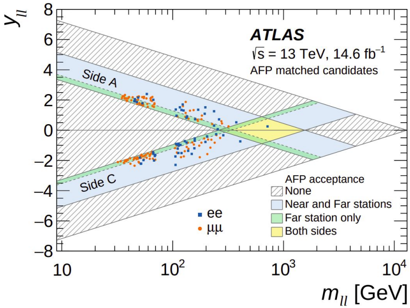
← **Expected from leptons**

$$\xi_{ll}^{A,C} = \frac{m_{ll}}{\sqrt{s}} e^{\mp y_{ll}}$$

Protons are matched if $|\xi_{AFP} - \xi_{ll}| < 0.005$

Backgrounds estimated from fully data-driven method



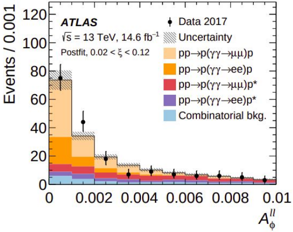


Dilepton production with AFP proton tag

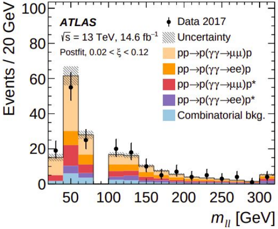
[PRL 125 (2020) 261801]

The background hypothesis rejected with a significance of 9.7σ in the *ee* and 13.0σ in the *μμ* channel

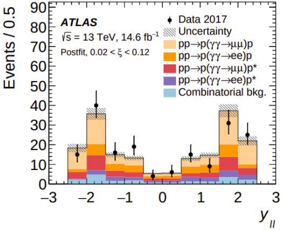
Dilepton acoplanarity



Dilepton mass



Dilepton rapidity



Cross section measurement

Comparing different proton soft survival modelling:

Accounts for additional proton rescattering effects

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [1,2]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [3]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

[1] EPJC 76 (2016) 255 [2] PLB 741 (2015) 66 [3] arXiv:2007.12704

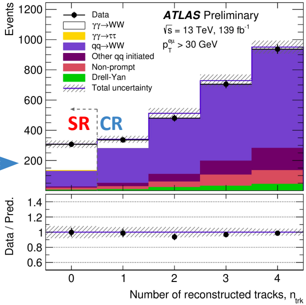
Exclusive *WW* production

[PLB 816 (2021) 136190]

- Process can only proceed via EW gauge boson couplings at LO ⇒ ideal probe for anomalous couplings (see e.g. [1])

  SIGNAL: opposite-sign, opposite-flavour dilepton: $e^{\pm}\mu^{\mp}$

- Previous evidence seen by both ATLAS [2] and CMS [3,4]
- Rare process so must utilise full dataset. Rely on central detector cuts to define exclusivity ⇒ **track veto requirement** (track-p_T > 500 MeV)



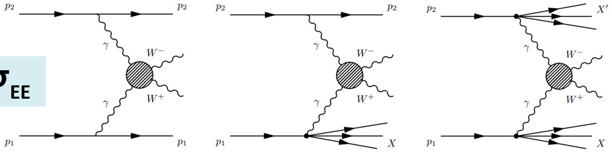
Full Run 2 dataset ⇒ 139 fb^{-1}

$n_{trk} = 0$

Dominant background = inclusive $qq \rightarrow WW$

Proton dissociation not included in theoretical prediction ⇒ data-driven signal cross-section correction:

$\sigma_{EE+SD+DD} = 3.59 \times \sigma_{EE}$



(a) Elastic production (EE) (b) Single-dissociation (SD) (c) Double-dissociation (DD)

[1] PRD 81 (2010) 074003, [2] PLB 816 (2021) 136190 [3] JHEP 07 (2013) 116, [4] JHEP 08 (2016) 119

Exclusive *WW* production

[PLB 816 (2021) 136190]

Many other non-standard corrections needed:

Vertex definition

ATLAS vertex reconstruction biased for exclusive vertices

Beamspot width rescaling

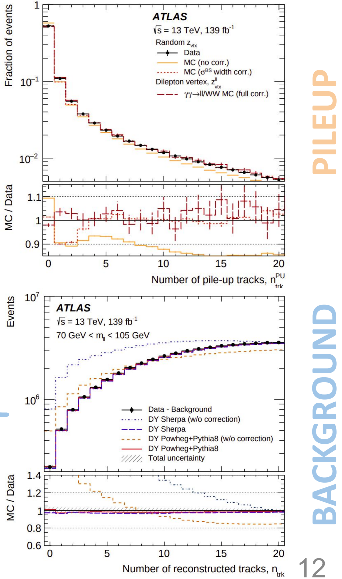
Beamspot size in MC does not match data.
Scale track z-positions to resize the beamspot

Pileup modelling correction

Track-veto requirement very sensitive to pileup.
Any pileup mismodelling in MC must be corrected

Charged particle multiplicity correction

Expect additional tracks from inclusive backgrounds due to non-perturbative interactions in the underlying event
Difficult to model and needs to be corrected to better match data



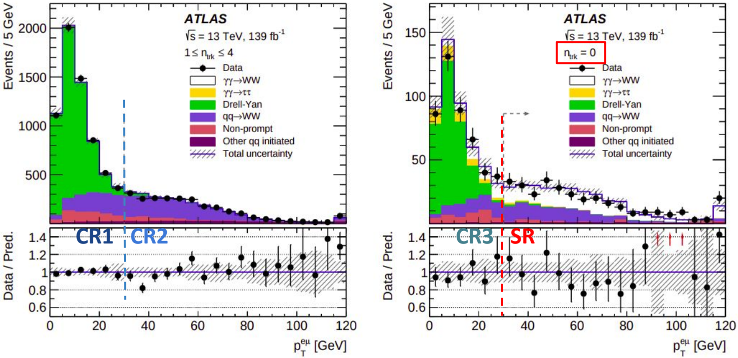
Exclusive *WW* production

[PLB 816 (2021) 136190]

Simultaneous fit performed to yields in SR and 3 CRs:

- 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

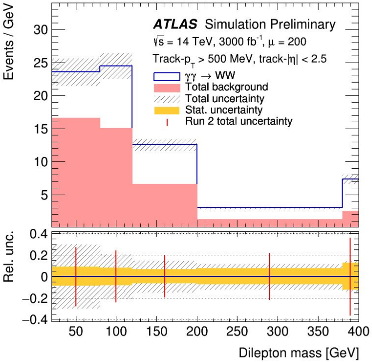


Expect much larger collected luminosity for AFP in Run 3 ⇒ can utilise proton tagging with AFP-ToF to fully reconstruct the *WW* system

NEW this week

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

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: $\langle\mu\rangle = 33.7$

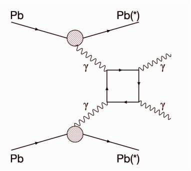
HL-LHC: $\mu = 200$

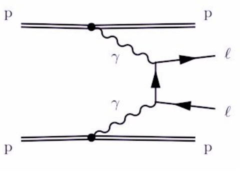
- HL-LHC operating conditions bring challenges for identifying exclusive final states
- However, the increase in available statistics opens up avenues for precision differential measurements

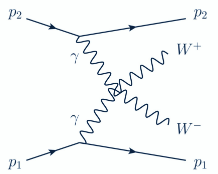
Summary

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

- First observation of light-by-light scattering and now differential cross-section measurements and ALP limit setting
- First high-pileup AFP proton tagging result and measuring proton soft survival factor
- First observation of photon-induced WW production







Backup

LbyL scattering in PbPb

Event selection:

Trigger:
2015: calorimeter 5 < ET < 200 GeV.
2018: 1 EM cluster with ET > 1 GeV and total 4 < ET < 200 GeV
or > 1 clusters with ET > 1 GeV with total ET < 50 GeV.

Forward activity veto: Measurements in MBTS/FCal consistent with noise

Pixel veto: The number of pixel detector hits was required to be at most 10 in 2015, and at most 15 in 2018.

Photon PID: ET > 2.5 GeV and $|\eta|$ < 2.37, excluding the calorimeter transition region 1.37 < $|\eta|$ < 1.52

Preselection: Exactly two photons satisfying the above selection criteria

Invariant mass: myy > 5 GeV.

Track veto: no tracks with pT > 100 MeV, $|\eta|$ < 2.5
no 'pixel tracks' in the vicinity of the photon candidate with pT > 50 MeV, $|\eta|$ < 2.5

Vertex: No primary vertex is reconstructed. Photon direction estimated using the barycentre of the cluster with respect to the origin of the ATLAS coordinate system.

Diphoton transverse momentum: pT < 1 GeV for myy < 12 GeV and pT < 2 GeV for myy > 12 GeV

diphoton acoplanarity: $A\phi$ = (1 − $|\Delta\phi|/\pi$) < 0.01

LbyL scattering in PbPb

Main sources of systematics:

Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%

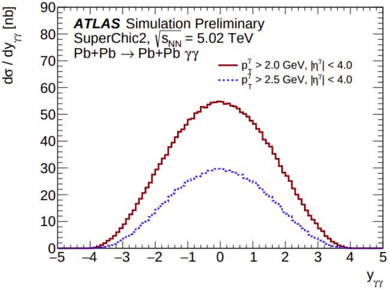
LbyL scattering in PbPb

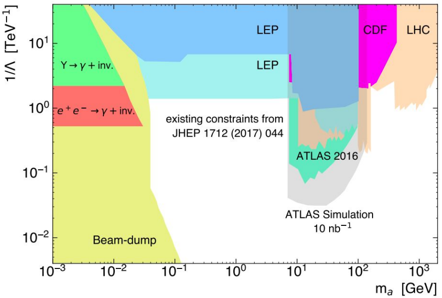
ATL-PHYS-PUB-2018-018

Future prospects for LbyL scattering:

- Expected integrated luminosity of 10 nb^{-1}
- Phase-II detector upgrades before HL-LHC
- All silicon ITk at will lead to a smaller probability of photon conversions
- Increased ITk acceptance

Lowering photon p_T by 0.5 GeV increases cross-section by factor of 2!





Dilepton production with AFP proton tag

Event selection:

Observable	Preselection		
N_{leptons}	Exactly 2 baseline, exactly 2 signal		
Trigger	Fired and both leptons matched		
Flavour/charge	e^+e^- or $\mu^+\mu^-$		
$p_{\text{T}}(e/\mu)$	$> 18/15$ GeV		
$m_{\ell\ell}$	> 20 GeV		
$p_{\text{T}}^{\ell\ell}$	< 5 GeV		
	Excl-Zveto is Preselection plus:		
$A_{\phi}^{\ell\ell}$	< 0.01		
$N_{\text{tracks}}^{0.5\text{ mm}}$	Exactly 0		
$m_{\ell\ell}$	$\notin [70, 105]$ GeV		
	No-AFP cross-check	*Pre-match cross-check*	*Final selection*
Observation regions	SR-noAFP-X	SR-preMatchX	SR-matchX
$\xi_{\ell\ell}^{X}$	$\in [0.02, 0.12]$	$\in [0.02, 0.12]$	$\in [0.02, 0.12]$
ξ_{AFP}^{X}	—	$\in [0.02, 0.12]$	$\in [0.02, 0.12]$
$\lvert\xi_{\text{AFP}}^{X} - \xi_{\ell\ell}^{X}\rvert$	—	—	< 0.005
Measurement regions	SR-fid-noAFP	SR-fid-preMatchX	SR-fid-matchX
$\xi_{\ell\ell}^{X}$	$\in [0.035, 0.08]$	$\in [0.035, 0.08]$	$\in [0.035, 0.08]$
ξ_{AFP}^{X}	—	$\in [0.035, 0.08]$	$\in [0.035, 0.08]$
$\lvert\xi_{\text{AFP}}^{X} - \xi_{\ell\ell}^{X}\rvert$	—	—	< 0.005
Background regions	CR-onZ	VR-onZ-preMatchX	VR-notMatch (sideband)
$m_{\ell\ell}$	$\in [70, 105]$ GeV	$\in [70, 105]$ GeV	$\notin [70, 105]$ GeV
$\xi_{\ell\ell}^{X}$	< 0.02 (both $X = A, C$)	$\in [0.02, 0.12]$	$\in [0.02, 0.12]$
ξ_{AFP}^{X}	—	$\in [0.02, 0.12]$	$\in [0.02, 0.12]$
$\lvert\xi_{\text{AFP}}^{X} - \xi_{\ell\ell}^{X}\rvert$	—	—	> 0.005

Dilepton production with AFP proton tag

Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	< 1%
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon scale and resolution	3%
Muon trigger isolation, reconstruction efficiencies	1%
Electron trigger, isolation, reconstruction efficiencies	1%
Electron scale and resolution	1%
Background modeling	2%
Luminosity	2%

CENTRAL DETECTOR

- Central systematics dominated by track veto efficiency for both flavour channels
- Track veto efficiency depends on track density, which itself depends on the beamspot parameters
- Nominal MC BS has σ_z = 42 mm
- Varies in data with average in 2017 of 38 mm

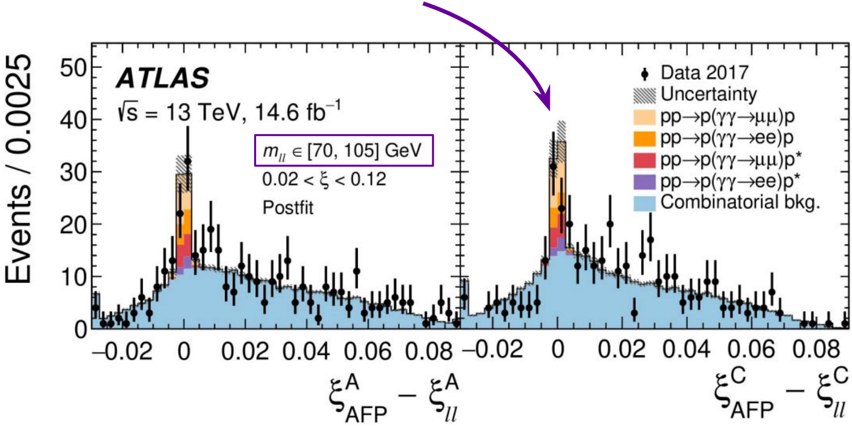
FORWARD DETECTOR

- Analysis prompted rapid development of AFP performance
- Many of these systematics have been defined for the first time

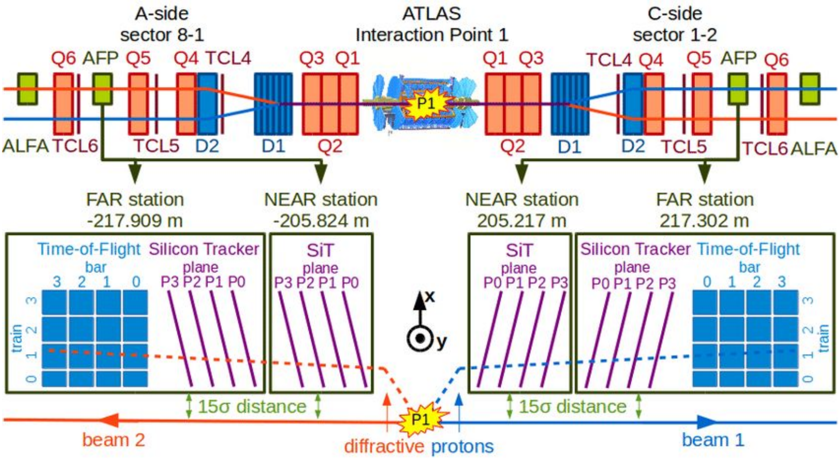
Dilepton production with AFP proton tag

The power of proton tagging:

Signal to background discrimination even on the Z peak!



Overview of the ATLAS Forward Proton (AFP) detector



Towards Point 8 (LHCb)

Towards Point 2 (ALICE)

Exclusive WW production

Event selection:

Selection requirement	Selection value
p_{T}^{ℓ}	$>$ 27 GeV (leading), $>$ 20 GeV (subleading)
η^{ℓ}	$\|\eta^{e}\| < 2.47$ (excluding $1.37 < \|\eta^{e}\| < 1.52$), $\|\eta^{\mu}\| < 2.5$
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	$\|z_{\ell} - z_{\mathrm{vtx}}^{\ell\ell}\| < 0.5$ 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

Exclusive WW production

Main sources of systematics:

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

Impact of pileup on exclusivity definition:

- efficiency of track-veto drops as pileup increases
- average pileup in Run 2 was <μ> = 33.7