Dilepton production in association with forward protons in AFP

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Photon-induced processes

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Context

PREVIOUS MEASUREMENTS OF $\gamma\gamma \to ll$ IN PROTON-PROTON COLLISIONS

- Previous measurements of $\gamma\gamma \to ll$ by the ATLAS Collaboration were performed **without proton-tagging**
  - 7 TeV: [PLB 749 (2015) 242-261]
  - 13 TeV: [PLB 777 (2018) 303]
- CMS + TOTEM reported **proton-tagged** dielectron (dimuon) production with 2.6σ (4.0 σ) significance at 13 TeV but no cross-sections were measured: [JHEP 07 (2018) 153]

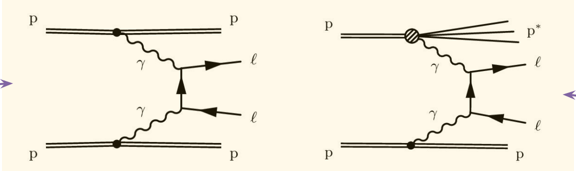
THIS TALK:

- Observation of forward proton scattering in association with lepton pairs produced via photon fusion in ATLAS 13 TeV data [PRL 125 (2020) 261801]
- First analysis to use AFP in high-luminosity LHC runs **$\langle\mu\rangle$= 36**
- Fiducial cross-section measurement
- Additional figures and tables here

Many thanks to Jesse and Lydia, whose beautiful slides/diagrams I have shamelessly stolen throughout this talk

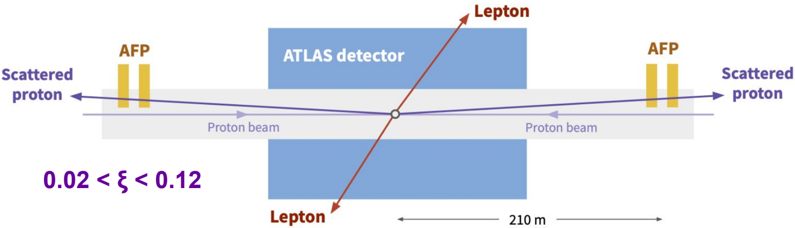
The signal process

SIGNAL: opposite-sign, same-flavour dilepton: $e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$
+ at least one proton in AFP



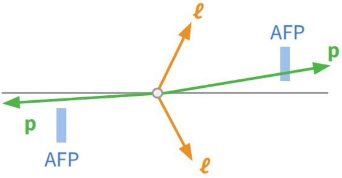
Exclusive signal simulated by HERWIG7

Single-diss signal simulated by LPAIR

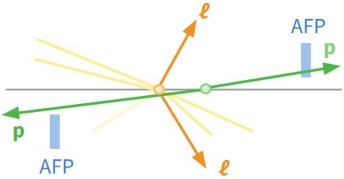


0.02 < ξ < 0.12

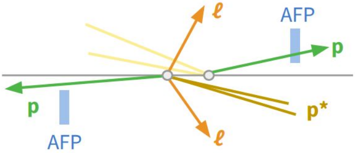
Combinatorial background



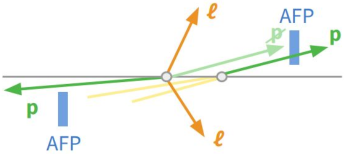
SIGNAL
Excl & SD proton in AFP acceptance
Proton reconstructed by AFP & matched



***NO REAL PROTONS* BACKGROUND**
Drell–Yan & DD has no real forward protons
Pileup fakes AFP proton



PROTON DISSOCIATION p* **BACKGROUND**
SD ‘in AFP acceptance’ proton dissociates
Pileup fakes AFP proton



PROTON FAILS RECO $\not{p}$ **BACKGROUND**
Excl & SD proton in acceptance fails AFP reco $\not{p}$
Pileup fakes AFP proton

Event selection

2017 dataset with AFP data quality selections = 14.7 fb^{-1}

AFP:

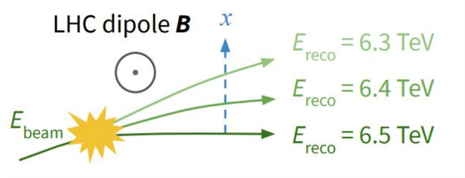
- Proton object reconstructed in at least one station of AFP
- Proton matched to dilepton system if **$|\xi_{AFP} - \xi_{ll}| < 0.005$**

Reminder: $\xi_{AFP} = 1 - E_{reco}/E_{beam}$

Central detector:

- Expect leptons to be produced **back-to-back**
  - Small $p_T^{\ell\ell} < 5$ GeV
  - Small acoplanarity $A^{\ell\ell}_{\phi} = 1 - |\Delta\phi_{\ell\ell}| / \pi < 0.01$
- Dilepton triggers: two electrons with $p_T > 18$ GeV **or** two muons with $p_T > 15$ GeV
- Dilepton mass > 20 GeV and outside Z-peak ($\notin$ [70, 105] GeV)
- **No tracks within ± 0.5 mm window** of dilepton vertex

Direct: AFP spectrometer measures ξ_{AFP}



Indirect: central ATLAS measures $\xi_{\ell\ell}$

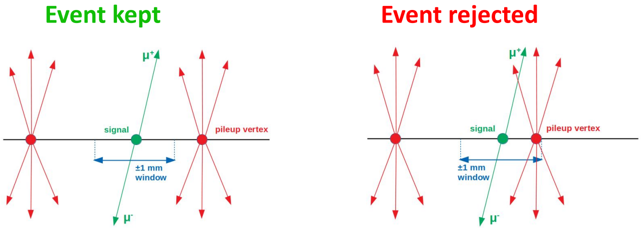
Measure lepton kinematics

$$\xi^{\pm}_{\ell\ell} = \frac{m_{\ell\ell}}{\sqrt{s}} e^{\pm y_{\ell\ell}}$$

Infer proton kinematics*

Challenges: pileup and track multiplicity modelling

- **Exclusivity selection:** No tracks within ± 0.5 mm window of dilepton vertex
- However, the exclusivity selection is very sensitive to the number of interactions per bunch crossing **= pileup**

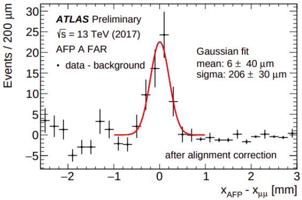


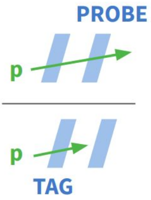
- Size of luminous region differs in MC and data
- Track multiplicity modelling in both pileup and underlying event difficult to model
    - See γγ→WW observation: [PLB 816 (2021) 136190]
- Focus on data-driven methods to measure signal efficiency and estimate background yields

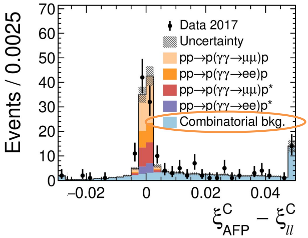
Analysis specifics

Several analysis specific methods were introduced:

- Many AFP systematics calculated for the first time, including in situ alignment calibration
- Tag-and-probe determination of the AFP reconstruction efficiency
- Combinatorial background estimated from data-driven event mixing + normalised from sideband fit

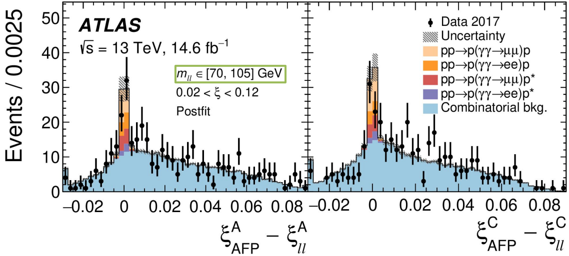






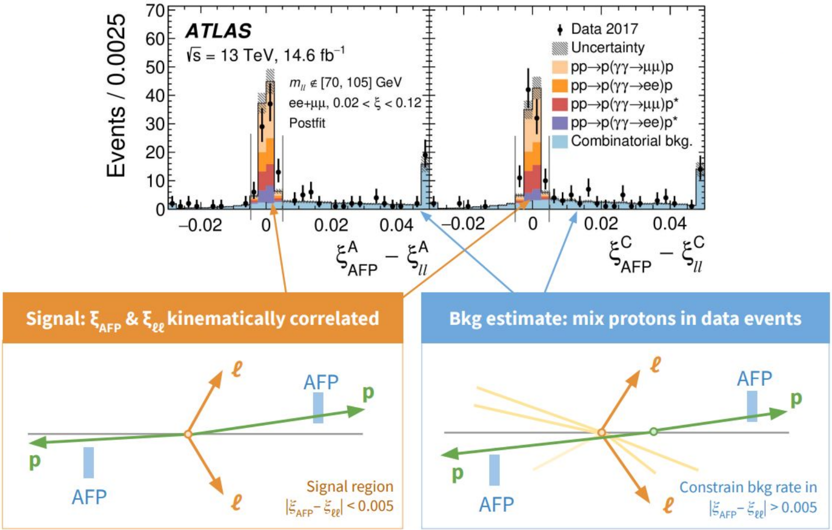
Data-driven background estimation

- Orthogonal data control sample created by switching the acoplanarity selection: $A^{\ell\ell}_{\phi} > 0.01$
- Mixed-event data sample constructed by randomly pairing each:
  - nominal measured $\xi_{\ell\ell}$ value, passing AFP acceptance $\xi_{\text{AFP}} \in [0.02, 0.12]$
  - with 100 values of ξ_{AFP} from the control sample
- The background normalisation is determined from a single-bin fit to the sideband region with $|\xi_{\text{AFP}} - \xi_{\ell\ell}| > 0.005$
- Background estimation validated in Z-peak region:



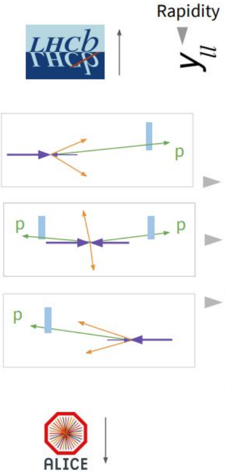
The power of proton tags: signal to background discrimination, even on the Z-peak!

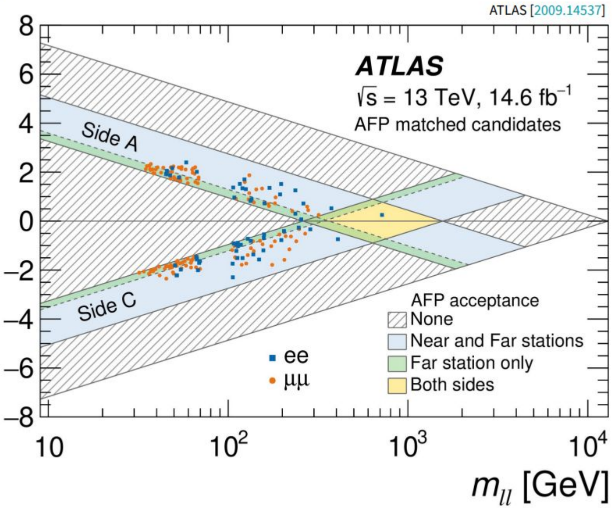
Signal candidates



Matched candidates

All events passing signal selection with $|\xi_{AFP} - \xi_{ll}| < 0.005$





Results

The background hypothesis was rejected with a significance of

9.7σ in the **ee** and

13.0σ in the **μμ** channel

$0.02 < \xi < 0.12$

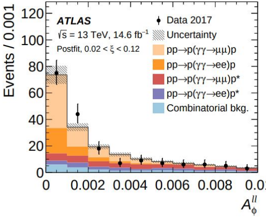
Fiducial cross-sections measured in a restricted acceptance to be

11.0 ± 2.6 (stat) ± 1.2 (syst) ± 0.3 (lumi) fb in the **ee** and

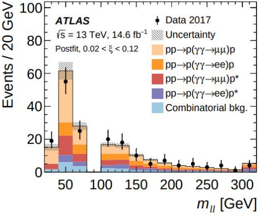
7.2 ± 1.6 (stat) ± 0.9 (syst) ± 0.2 (lumi) fb in the **μμ** channel

$0.035 < \xi < 0.08$

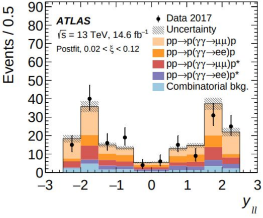
Acoplanarity



Mass



Rapidity

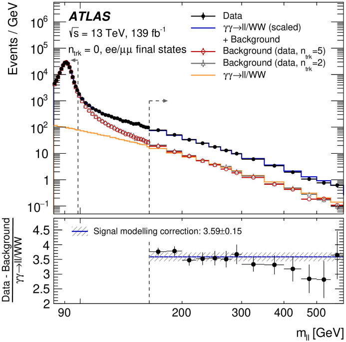


Why?

WHY PROTONS?

- Access to higher diphoton invariant mass than heavy ion collisions
- γγ→ll used to extract ratio of exclusive to dissociative events in γγ→WW analysis

[PLB 816 (2021) 136190]



- Method used in γγ→WW analysis implicitly accounts for proton soft survival
- Large uncertainties associated to transferability between γγ→ll to γγ→WW process
- Applicability discussed by S. Bailey, L. Hardland-Lang in [arxiv:2201.08403]

Why?

WHY PROTON TAGGING?

- Double-tag is an independent measure of diphoton mass
- Theoretical predictions have large associated uncertainties due to proton rescattering effects
  - Quantified by soft-survival factors
  - Not always well constrained, particularly at high masses
- Forward proton tagging allows **direct** measurement of proton soft survival
- Central detector measurements can only **indirectly** infer soft survival probability

Comparison to theory predictions

- Comparison to theoretical predictions with different soft survival models:

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [33, 34]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [97]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

theory predictions split into exclusive and single-diss in backup

- mll-dependent scaling applied to Herwig+LPAIR yields, according to Ref. [34]
- LPAIR yields scaled down by a further 15% to account for lower soft survival probability in single-diss events, according to Ref. [33]
- Alternative SuperChic4 predictions include full kinematic dependence on survival factors for exclusive and dissociative processes

[33] arXiv:1601.03772, [34] arXiv:1410.2983, [97] arXiv.2007.12704

Summary and outlook

WHAT?

- ATLAS observed dilepton production in association with forward protons in AFP
- Cross-sections measured in fiducial volume

WHY?

- Proton tagging allows direct measurement of proton soft survival, as well as separation of exclusive and dissociative processes
- Many AFP detector systematics defined for the first time

WHAT NEXT?

- Result limited by stat. uncertainty - expect much higher integrated lumi for AFP in Run 3
- AFP time-of-flight measurements in Run 3, allows further background suppression
  - Vital in analyses where there is missing energy, e.g. BSM processes, $\gamma\gamma \rightarrow WW$
- **General challenges:**
  - Modelling of proton soft survival
  - Impact of high pileup on analysis selections
  - Modelling of track multiplicity in pileup and the underlying event

Backup

Simulation details

SIGNAL

- Full-sim **exclusive** signal samples produced using Herwig7
- Fast-sim **single-dissociative** signal was generated using LPAIR4.0, with proton dissociation modeled using the Brasse et al. and Suri-Yennie structure functions interfaced with jetset7.408.

DETECTOR

- AFP response is modelled by a fast simulation, where a Gaussian smearing is applied to track positions based on the AFP spatial resolution

BACKGROUNDS

- Background estimates fully data-driven, cross-checked with MC

Simulation details

Process	Generator	Slice/Filter	DSID
$Z/\gamma^* \to ee$	Powheg+Pythia8	$m_{\ell\ell} > 6$ GeV	361664, 361665, 361106
$Z/\gamma^* \to \mu\mu$	Powheg+Pythia8	$m_{\ell\ell} > 6$ GeV	361666, 361667, 361107
$Z/\gamma^* \to \tau\tau$	Powheg+Pythia8	$m_{\ell\ell} > 6$ GeV	361668, 361669, 361108
Alt. $Z/\gamma^* \to ee$	Sherpa 2.2.1	$m_{\ell\ell} \in [10, 40]$ GeV	364204–364209
		$m_{\ell\ell} > 40$ GeV	364114–364127
Alt. $Z/\gamma^* \to \mu\mu$	Sherpa 2.2.1	$m_{\ell\ell} \in [10, 40]$ GeV	364198–364203
		$m_{\ell\ell} > 40$ GeV	364100–364113
Alt. $Z/\gamma^* \to \tau\tau$	Sherpa 2.2.1	$m_{\ell\ell} \in [10, 40]$ GeV	364210–364215
		$m_{\ell\ell} > 40$ GeV	364128–364141
$t\bar{t}$	Powheg+Pythia8	Dilepton filtered	410472
$t + W$	Powheg+Pythia8	Dilepton filtered	410648, 410649
t t-channel	Powheg+Pythia8	Leptonic decay	410658, 410659
t s-channel	Powheg+Pythia8	Leptonic decay	410644, 410645
Diboson	Sherpa 2.2.2	1 to 4ℓ	364250, 364253–364255
		2 to 4ℓ 'lowMllPtComplement'	364288–364290
Exclusive $pp \to p(\gamma\gamma \to XX)p$			
$\gamma\gamma \to ee$	Herwig7	'LeptonFilter' $m_{\ell\ell} > 20$	363749–363752
$\gamma\gamma \to \mu\mu$	Herwig7	'LeptonFilter' $m_{\ell\ell} > 20$	363753–363756
$\gamma\gamma \to \tau\tau$ (35 mm beamspot)	Herwig7	'LeptonFilter' $m_{\tau\tau} > 20$	363757–363760
$\gamma\gamma \to WW$	Herwig7	'LeptonFilter'	363761
Single dissociative $pp \to p(\gamma\gamma \to XX)p^*$			
$\gamma\gamma \to ee$	Lpair	'LeptonFilter' $m_{\ell\ell} > 18$	363694–363696
$\gamma\gamma \to \mu\mu$	Lpair	'LeptonFilter' $m_{\ell\ell} > 6$	363697–363700
Double dissociative $pp \to p^*(\gamma\gamma \to XX)p^*$			
$\gamma\gamma \to ee$	Pythia8	'LeptonFilter' $m_{\ell\ell} > 18$	363672–363674
$\gamma\gamma \to \mu\mu$	Pythia8	'LeptonFilter' $m_{\ell\ell} > 6$	363675–363678
$\gamma\gamma \to \tau\tau$	Pythia8	'LeptonFilter' $m_{\ell\ell} > 6$	363679–363682

Systematic uncertainties

- Dominant **AFP systematics** are the global alignment (±300 μm), and the uncertainty on the beam crossing angle (±50 μrad)
- Dominant **central detector systematic** is the uncertainty on the Ntrack = 0 selection, calculated by comparing the exclusive efficiency calculated using the data-driven method to directly measuring around the dilepton vertex
- The uncertainty on the **background modelling** comes from limited stats in the sideband regions, kinematics of the orthogonal sample selection, number of pairs sampled and pileup dependence

Impact on cross-section

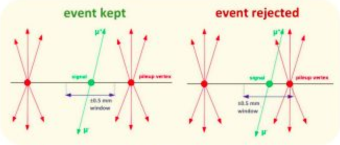
Source of systematic uncertainty	Impact
Forward detector	
Global alignment	6%
Beam optics	5%
Resolution and kinematic matching	3–5%
Track reconstruction efficiency	3%
Alignment rotation	1%
Clustering and track-finding procedure	$< 1\%$
Central detector	
Track veto efficiency	5%
Pileup modeling	2–3%
Muon 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%

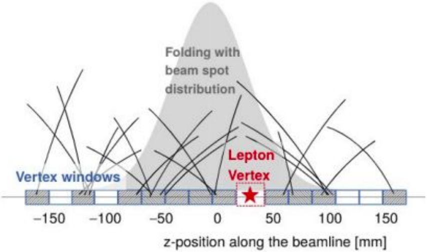
Exclusivity selection (track-veto) systematic

Two approaches used to determine the track veto efficiency systematic:

1. **Data-driven (nominal):** Use method developed in the exclusive WW team to sample the pileup distribution

2. **MC-driven:** vary beamspot width from 42mm to 35mm as a cross-check





track veto efficiencies:

$\mu\mu$	Data-driven	Lepton vertex
data17	39.82 ± 0.03	–
MC (42 mm)	44.5 ± 0.2	42.6 ± 0.3
ee	Data-driven	Lepton vertex
data17	40.85 ± 0.04	–
MC (42 mm)	44.6 ± 0.3	38.4 ± 0.4

$k_{excl} = \varepsilon_{data}/\varepsilon_{MC} = 0.894$ (5% syst)

Difference in efficiencies between data/MC applied as a scale factor, k_{excl}, to MC

Systematic taken from closure of data-driven method with efficiency of lepton vertex in MC

Increase in non-closure in ee channel known and understood

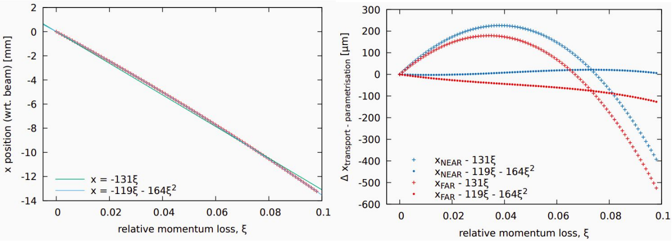
Challenges: from position to energy loss

IN SIMULATION:

- No full-sim AFP simulation available
- Parametrised Gaussian smearing of the kinematics of the truth protons based on SiT resolution
- No pileup included in AFP fast simulation. Signal MC has at most one proton per side
- Proton transport through LHC lattice simulated with MAD-X and parametrised response used to convert measured position to energy loss

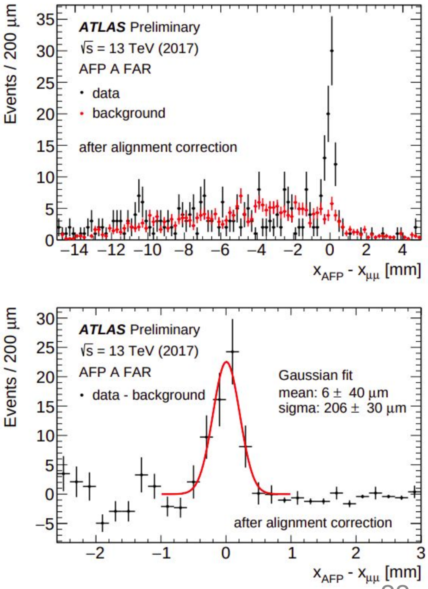
IN DATA:

- Proton spatial position measured in AFP
- Invert parametrisation from proton transport simulation to calculate ξ_{AFP}



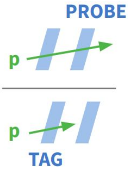
Global alignment

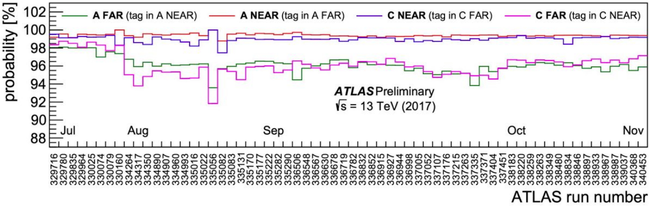
- Global alignment considers the relative position of the beam centre at each station location and the distance of the edge of the silicon sensors to the beam axis
- Beam central position is determined by beam-based alignment and beam-position monitoring techniques
- Residual differences in AFP sensor locations calculated in-situ with dimuon candidates with very high purity selections



Proton reconstruction efficiency

- Tag-and-probe method developed to calculate proton reconstruction efficiencies per AFP station for the first time





- FAR station efficiencies lower due to proton showering between stations

- Double-station reco efficiency quoted as 0.92+0.02, independent of side

Comparison to theory predictions

- Comparison of measured cross-section to theoretical predictions with different soft survival models, here split into exclusive and single-dissociative predictions

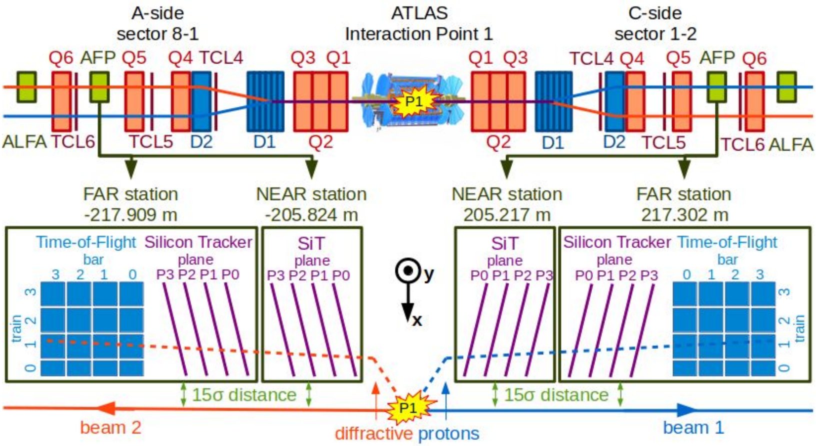
	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
Measurement	11.0 ± 2.9	7.2 ± 1.8
Predictions		
$S_{\text{surv}} = 1$		
Herwig+Lpair	15.5 ± 1.2	13.5 ± 1.1
Herwig	9.3 ± 0.7	8.0 ± 0.6
Lpair	6.2 ± 1.1	5.5 ± 0.9
S_{surv} using Refs. [31,30]		
Herwig+Lpair	10.9 ± 0.8	9.2 ± 0.7
Herwig	7.0 ± 0.5	5.9 ± 0.4
Lpair	3.9 ± 0.7	3.4 ± 0.6
SuperChic 4 [94]		
Exclusive + single-dissociative	12.2 ± 0.9	10.4 ± 0.7
Exclusive	8.6 ± 0.6	7.3 ± 0.5
Single-dissociative	3.6 ± 0.6	3.1 ± 0.5

[30] arXiv:1601.03772, [31] arXiv:1410.2983, [94] arXiv.2007.12704

Cut flow in MC

	Number of events	
Requirement	$pp \to p(\gamma\gamma \to ee)p$	$pp \to p(\gamma\gamma \to \mu\mu)p$
$\sigma \times \mathcal{L}$	44790	44740
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}}$	11570	11560
$\sigma \times \mathcal{L} \times \epsilon_{\text{filter}} \times w_{\text{SF}}$	11440	11190
Exactly two signal leptons	1217	3628
Trigger matched	968	2641
Opposite charge	964	2641
Same flavor	964	2641
$p_{\text{T}}^{\ell\ell} < 5\ GeV$	931	2594
$A_{\phi}^{\ell\ell} < 0.01$	913	2520
$N_{\text{tracks}}^{0.5\text{ mm}} = 0$	378	1138
$m_{\ell\ell} > 20\ GeV$	378	1138
$m_{\ell\ell} \notin [70, 105]\ GeV$	283	960
$\xi_{\ell\ell}^{\text{A}} \in [0.02, 0.12]$ or $\xi_{\ell\ell}^{\text{C}} \in [0.02, 0.12]$	69.8	155
$\xi_{\ell\ell}^{\text{A}} \in [0.035, 0.08]$ or $\xi_{\ell\ell}^{\text{C}} \in [0.035, 0.08]$	18.2	28.9
$\lvert\xi_{\text{AFP}} - \xi_{\ell\ell}\rvert < 0.005$	17.8	27.8

ATLAS Forward Proton (AFP)



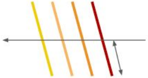
- Each station houses a silicon tracker (SiT) with four planes of edgeless silicon pixel sensors
- The sensors have 336 × 80 pixels with area 50 × 250 μm^2
- Spatial resolution of σ_x = 6 μm

"A TeV spectrometer"

AFP interplane alignment

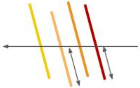
- Offsets and rotations of silicon planes relative to each other within each station
- Much smaller effect than global alignment (all corrections within global alignment uncertainty)

Ideal alignment

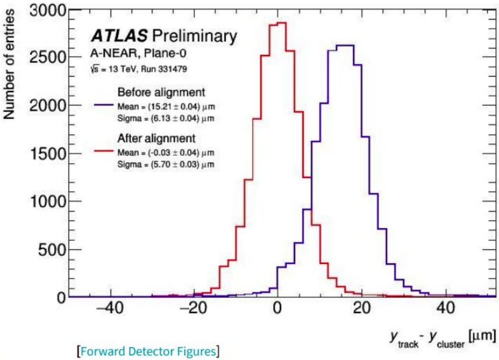


Cluster to edge distance is the same for all planes

In reality

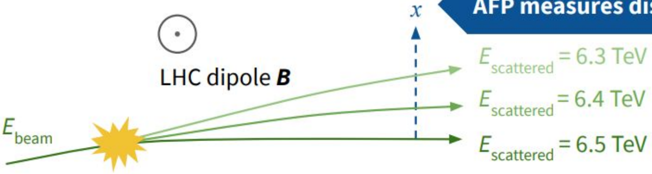


Cluster positions relative to plane edge can be different before interplane alignment



[Forward Detector Figures]

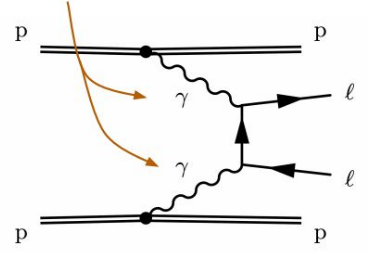
How do we use AFP?



AFP measures displacement 1

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

Infer proton energy loss 2



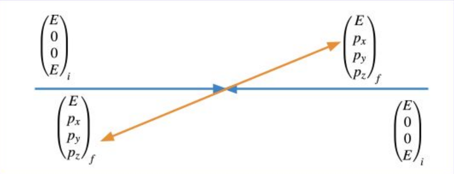
Know initial photon energy 3

and match this to the kinematics of the reconstructed final state

AFP potential

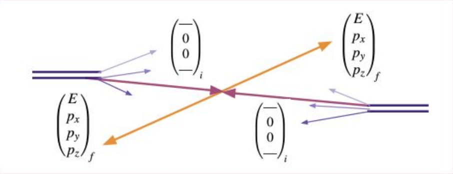
LEPTON COLLIDER

All initial & visible final state 4-vectors measurable



HADRON COLLIDER (NO AFP)

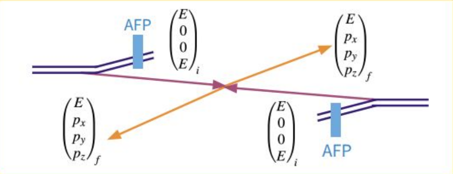
p^{z}_{initial} immeasurable



HADRON COLLIDER (+ AFP)

⇒ Full p_{initial} measurable

New event kinematic information!



Protons vs heavy ions at the LHC