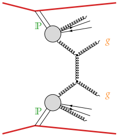
Overview of ATLAS Forward Proton detectors for LHC Run 3 and plans for the HL-LHC

Maciej Lewicki
on behalf of ATLAS Forward Detectors

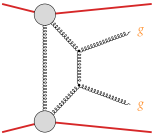
Institute of Nuclear Physics
Polish Academy of Sciences

Forward proton scattering in a diverse physics program



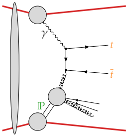
Diffractive jets

ATL-PHYS-PUB-2017-012



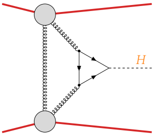
Exclusive jets

Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



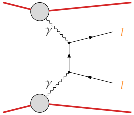
Top quarks

Goncalves et al 2007.04565
Howarth 2008.04249



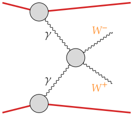
Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052



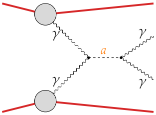
Leptons

CMS 1803.04496
ATLAS 2009.14537



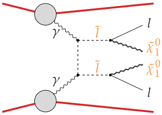
W bosons

Tizchang, Etesami 2004.12203
Baldenegro et al 2009.08331



Axion-like particles

Fichet et al 1312.5153
Baldenegro et al 1803.10835



SUSY dark matter

Beresford & Liu 1811.06465
Harland-Lang et al 1812.04886

Diffraction
≡ colour singlet exchange:

- photon
- Pomeron
  (two gluons + ...)

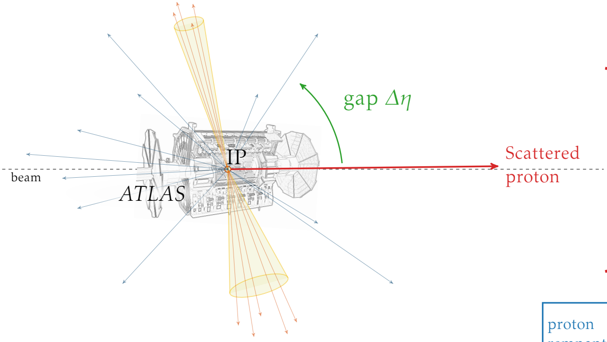
Measurements of diffractive processes –
– **discrimination tool** for models:

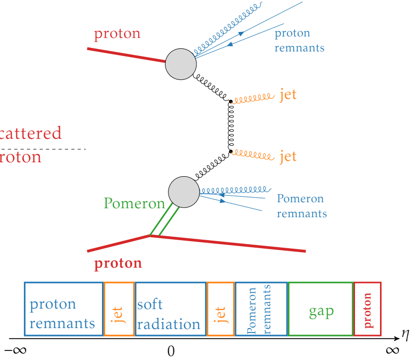
- **QCD – hard and non-perturbative,**
- **probing electroweak scale,**
- **physics beyond SM.**

Natural ways to seek for diffraction

- rapidity gaps,
- **forward protons**

Measurements methods





Measuring rapidity gap:

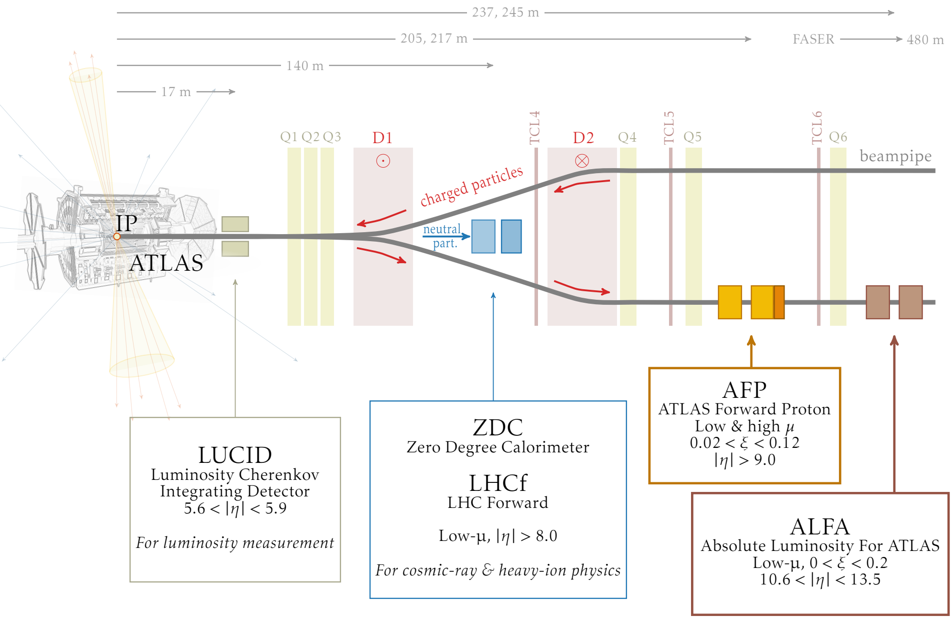
+ widely used for diffractive pattern recognition
+ no need for additional detectors
– **gap is frequently destroyed** (pile-up background)
– **gap may be out of acceptance**

ATLAS, Eur.Phys.J.C 72 (2012) 1926
ATLAS, Phys.Lett.B 754 (2016) 214-234

Measuring forward protons:

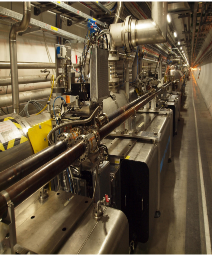
+ **Protons measured directly** (deflection→$\vec{p}, E$)
+ **Suitable for pile-up environment**
– Protons are scattered at very small angles
– Additional detectors required far downstream.

Forward Detectors in ATLAS

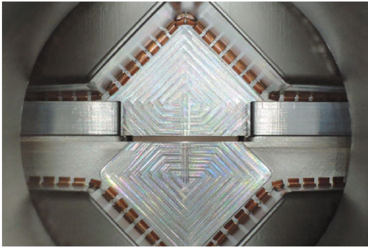


Absolute Luminosity For ATLAS

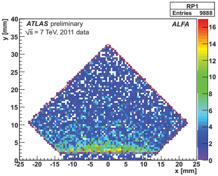
JINST **11** (2016) P11013



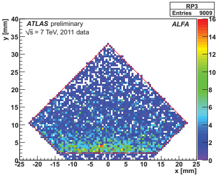
- Soft diffraction, elastic scattering
- Input for MC generators:
  cosmic ray showers,
  pile-up simulation



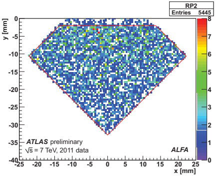
- 4 vacuum-sealed spectrometers housed in **Roman Pots** (RP), inserted vertically; NEAR and FAR on both sides of IP (at 237 and 241/245 m, < 2mm from beam).
- Trigger capability
- Multi-layer scintillating fibre (SciFi)
- Tracking detectors, resolution: $\sigma_x = \sigma_y = 30\mu$m
- Read-out by Multi-Anode-Photo-Multipliers
- Special runs: low pile-up, high β^* optics



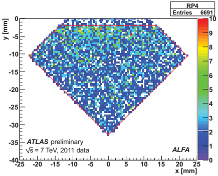
(a) RP 1



(b) RP 3

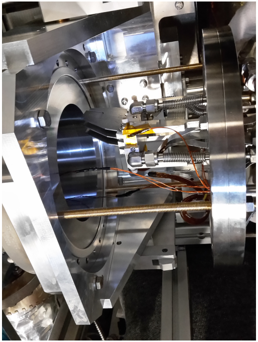


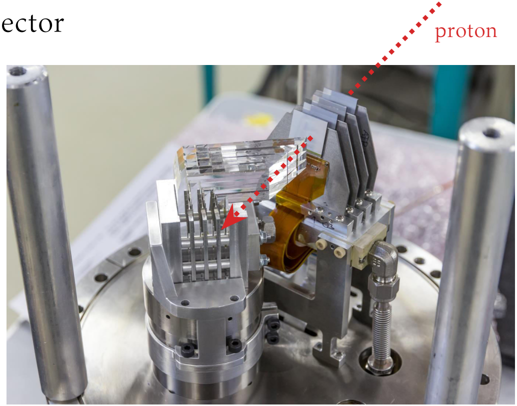
(c) RP 2



(d) RP 4

ATLAS Forward Proton detector



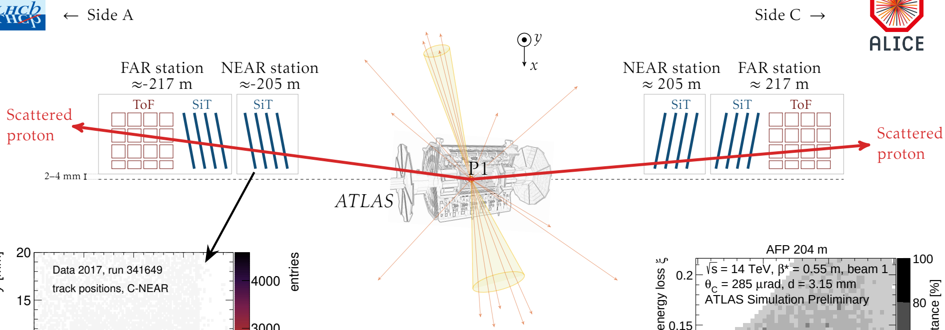


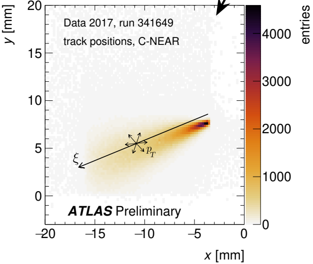
- 4 **Roman Pots** devices:
  NEAR and FAR, both sides of IP (205, 217 m), inserted horizontally onto beam.
- 4 **Silicon Tracker** (SiT) planes in each RP:
  - 336×80 pixels, 50×250 μm^2, 230 μm thick,
  - SiT **resolution**: σ_x=6 μm at 14° tilt.
- FE-I4 readout chips; as in ATLAS IBL
- Trigger capability

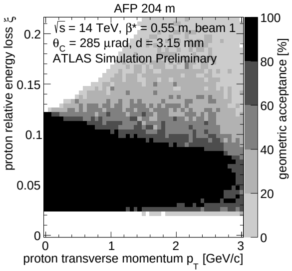
- Time of Flight (ToF) detectors in FAR stations:
  - 16 Quartz Cherenkov bars,
  - ToF resolution $\sigma_t \approx 25$ ps.
  - Light gathered by: Micro-Channel Plate Multi-Anode PMT

ATLAS-TDR-024

ATLAS Forward Proton detector







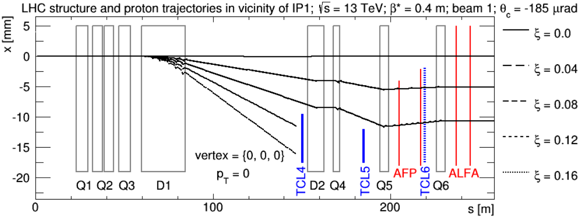
Main observable:

$$\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}$$

Typical **acceptance**:

$$0.02 < \xi < 0.12, \quad p_T \lesssim 3 \text{ GeV}/c$$

Unfolding proton kinematics



Position in the AFP ⟷ proton kinematics at IP:

- At the IP the proton is described by six variables:

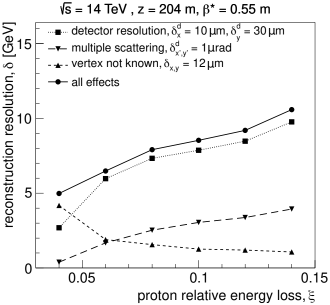
position:	x_{IP}, y_{IP}, z_{IP}
p_T:	p_x, p_y
energy:	E_{IP}

- They translate to positions at the AFP:

$$x_{AFP}, y_{AFP}, \frac{dx_{AFP}}{dz}, \frac{dy_{AFP}}{dz}$$

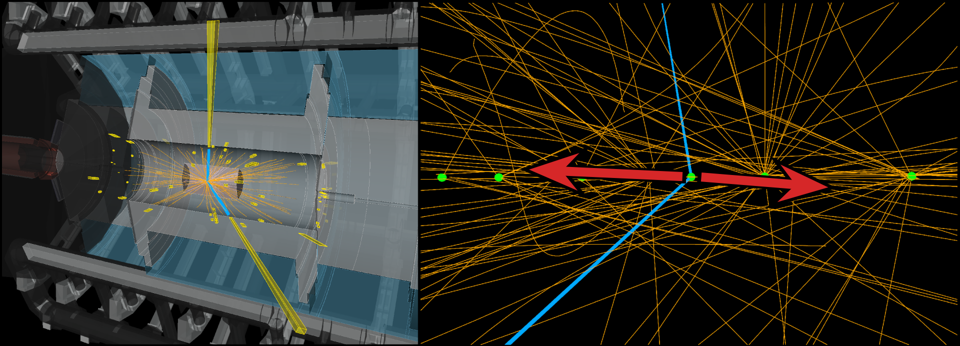
- **Challenges:**
  non-uniform high radiation environment, background from showers, **high pile-up**

- Detector resolution directly affects precision of measuring proton kinematics:



ATLAS EXPERIMENT

Run 190644, Event 51422085
Time 2011-10-09, 16:29 CEST

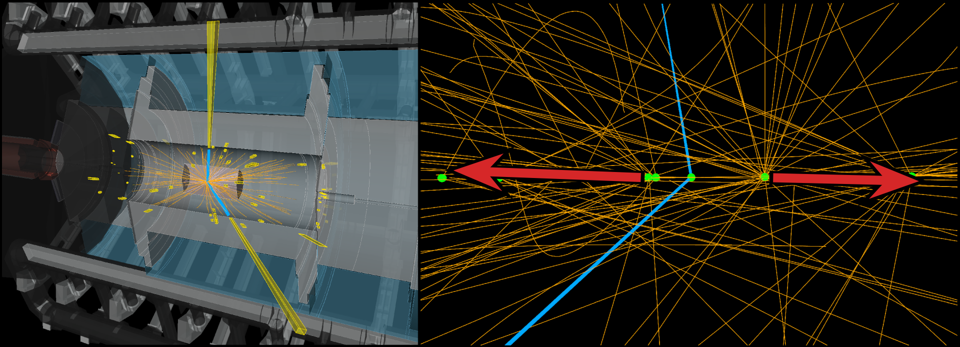


Signal: $pp \rightarrow p + (\gamma\gamma \rightarrow ee) + p$

Scattered protons originate from the signal vertex

ATLAS EXPERIMENT

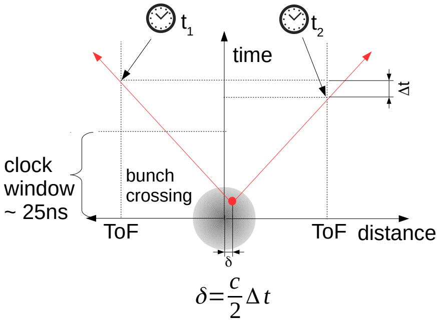
Run 190644, Event 51422085
Time 2011-10-09, 16:29 CEST



Background: Non-diffractive di-lepton production
+ forward protons from pile-up

Scattered protons originate from pile-up vertices

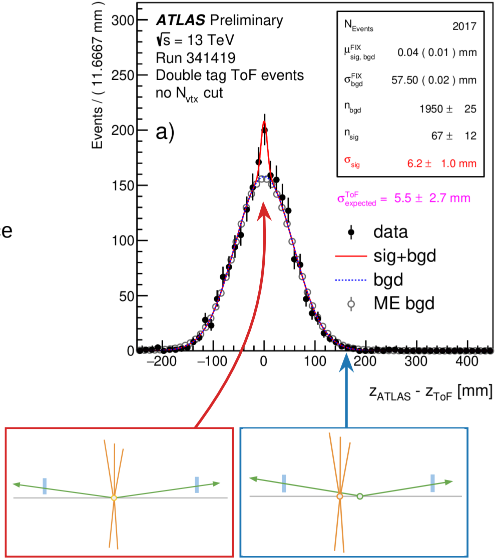
Reducing physics background with ToF



$$\delta = \frac{c}{2}\Delta t$$

For events with double proton tag:

- Measure ToF difference: $\Delta t = (t_A - t_C)/2$
- Calculate vertex position: $z_{\text{ToF}} = \frac{c}{2}\Delta t$
- Compare z positions reconstructed by ATLAS and AFP ToF:

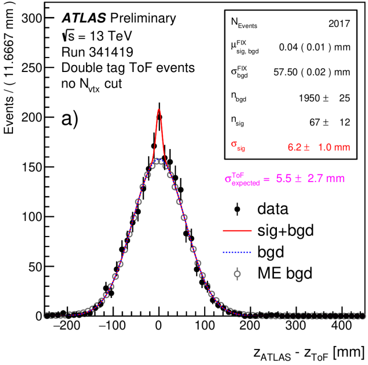


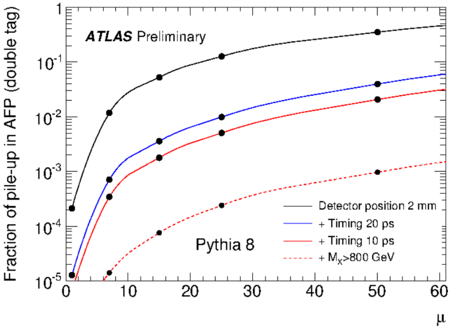
ToF performance in Run 2

Performance analysis (2017 data, $\mu \approx 2$) ATL-FWD-PUB-2021-002:

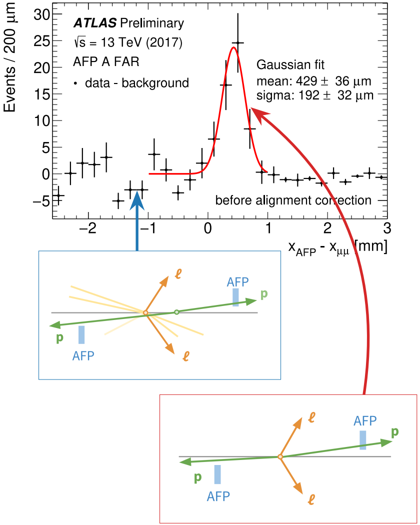
- **Measured time resolution:** 20 ± 4 ps (A), 26 ± 5 ps (C)
- **Measured pp vertex resolution:** 5.5 ± 2.7 mm

- Poor efficiency (few %) in Run 2 due to fast PMT degradation.
- Improvements ongoing for Run 3 data taking.
- Long-lifetime PMTs to ensure higher efficiencies.
- More on Run 2 performance & Run 3 perspectives: ATL-FWD-PROC-2020-001 ATL-FWD-SLIDE-2021-545





In situ AFP global alignment with exclusive di-muon events

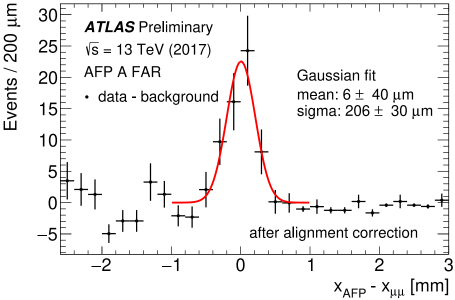


$(\gamma\gamma \to \mu\mu) + p$ as a "standard candle":

1. Compare:

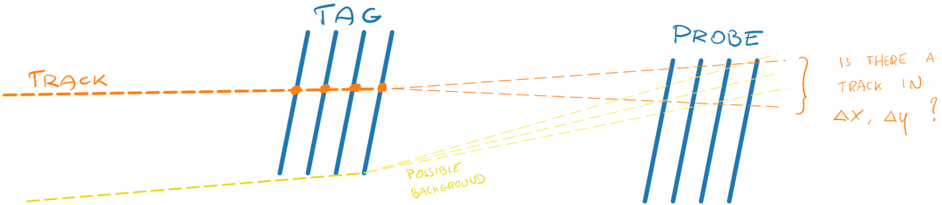
$$\xi_{AFP} = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}} \quad \text{with} \quad \xi_{ll}^{A/C} = \frac{m_{ll}\, e^{(+/-)y_{ll}}}{\sqrt{s}}$$

2. Adjust global RP shift to match ξ_{AFP} to ξ_{ll}



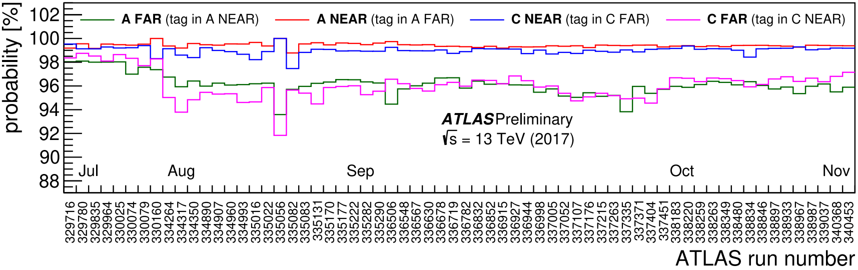
- Background – small and well modelled by event mixing,
- Alignment precision uncertainty currently quoted as 300 μm
  → Ongoing work to improve – 100 μm seems realistic.

Track reconstruction efficiency & data stability

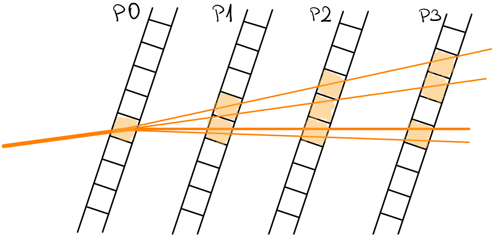


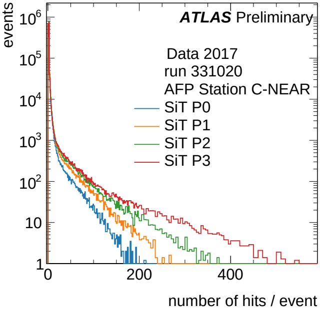
Efficiency ≡ probability of recording track in "PROBE" station if one was recorded in "TAG" station.

- Lower efficiencies in FAR stations - radiation degradation? showers?

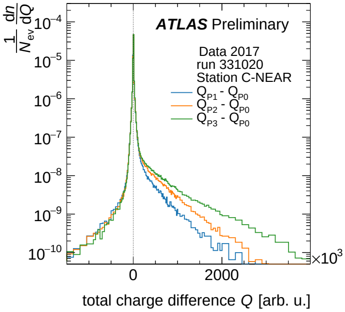


Showers in SiT planes and RP walls





- Evidence of showers in SiT material
  → long non-Poisson tail in hit multiplicity per plane, higher for each consecutive pixel layer.
  → farther layers record higher charge.
- Electromagnetic – creation of δ-electrons.
- Strong – high-multiplicity hadron showers.
- Showers also evident in comparing multiplicities in FAR and NEAR stations.
- Largest contribution to inefficiency of reconstruction.



Data

Run 2

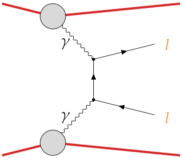
- $\sqrt{s} = 13$ TeV, $\beta^* = 0.3$ m, 0.4 m
- Two setups (2016, 2017):
  - one-arm
  - two-arms (+ TOF *(poor efficiency)*)
- Data taken during in **low pile-up runs**:
  - $0.03 \lesssim \mu \lesssim 0.05$
    int. lumi.: ≈ 100 nb^{-1},
    main goal: soft diffraction
  - $0.3 \lesssim \mu \lesssim 1$
    int. lumi.: ≈ 1.15 pb^{-1},
    main goal: low-p_t jets
  - $\mu \approx 2$:
    int. lumi.: ≈ 150 pb^{-1},
    main goals: electro-weak physics,
    hard diffraction, SD $t\bar{t}$
- Data taken during **standard runs**:
  - int. lumi.: ≈ 46.9 fb^{-1}
    goal: hard diffraction

Run 3 plans

- $\sqrt{s} = 13$ TeV, $0.2 < \beta^* < 1.1$ m
- Setup: two-arms setup + TOF
- Data to be taken mainly at **high-μ**
- Requesting special **low pile-up runs**:
  - $\mu \approx 0$
    main goal: soft diffraction
  - $\mu \approx 1$
    main goal: low-p_t jets
  - $\mu \approx 2$:
    main goals: electro-weak physics,
    hard diffraction, SD $t\bar{t}$

ATLAS + AFP $\rightarrow 32$ fb^{-1}
+ GRL $\rightarrow \approx 15$ fb^{-1}
Unprecedented amount of data
for diffractive physics!

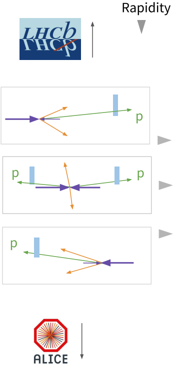
First High Lumi AFP Publication

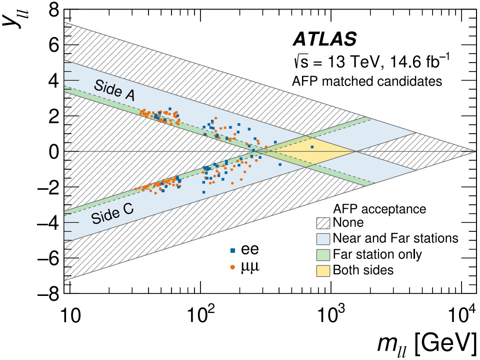


Phys. Rev. Lett. 125, 261801 (2020):

Observation and Measurement of ***Forward Proton Scattering*** *in Association with* ***Lepton Pairs Produced via the Photon Fusion*** *Mechanism at ATLAS*

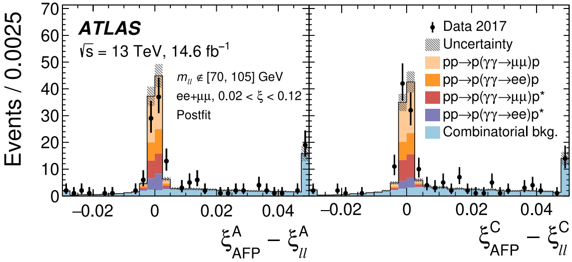
- $\approx$15 fb^{-1}, single proton tag (so far)
- More in talk by Krzysztof Cieśla (today at 18:00)





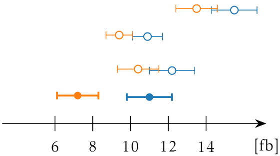
- Exclusive di-leptons, $pp \to pl^-l^+p$:
  – proton(s) measured in AFP,
  – leptons ($\mu^+\mu^-$, e^+e^-) measured in ATLAS
- 2017 data; $\sqrt{s} = 13$ GeV$/c$; $L = 14.6$ fb^{-1}
- 57 (123) candidates in the $ee + p$ ($\mu\mu + p$) final state.

Physics Analysis: Exclusive Di-lepton Measurement with AFP Tag



- Proton energy resolution at $\lesssim$10% (FWHM≈0.005)
- Powerful **background rejection** with AFP:
  – proton tagging,
  – kinematics match: proton vs lepton system
- Great performance: 95% signal acceptance with 85% background rejection
- Background-only hypothesis rejected with a significance exceeding **5σ** in each channel.

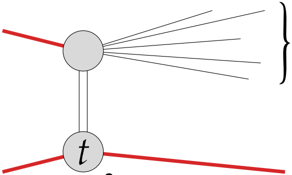
$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ (fb)	$\sigma^{\text{fid.}}_{\mu\mu+p}$ (fb)
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using EPJC 76 (2016) 9, PLB 741 (2015) 66	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC	12.2 ± 0.9	10.4 ± 0.7
Measurement	**11.0 ± 2.9**	**7.2 ± 1.8**



Physics analysis: Single Diffraction with ALFA tag

First single diffraction ALFA publication!
JHEP 02 (2020) 042:

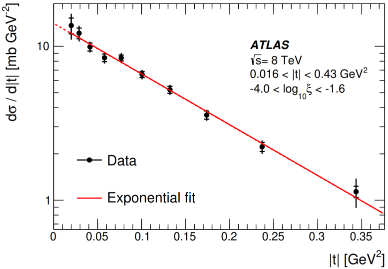
Measurement of differential cross sections for single diffractive dissociation in $\sqrt{s}$ = 8 TeV pp collisions using the ATLAS ALFA spectrometer



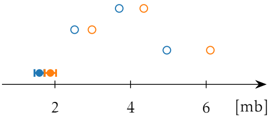
$X \left(M_X = \sqrt{\xi s} \right)$

$\propto -p_T^2$

- $\sqrt{s}$ = 8 TeV, very low μ,
- intact proton reconstructed in ALFA ($10^{-4} < \xi < 0.025$),
- remnants X measured in ATLAS,
- measured also: $d\sigma/d\xi$, $d\sigma/dt$, $d\sigma/d\Delta\eta$
- Regge interpretation: Pomeron intercept $\alpha(0) = 1.07 \pm 0.09$



Distribution	$\sigma_{SD}^{\text{fiducial}(\xi,t)}$ [mb]	$\sigma_{SD}^{t-\text{extrap}}$ [mb]
Pythia8 A2 (Schuler-Sjöstrand)	3.69	4.35
Pythia8 A3 (Donnachie-Landshoff)	2.52	2.98
Herwig7	4.96	6.11
Measurement	**1.59 ± 0.13**	**1.88 ± 0.15**



Status and plans

No major changes between Run 2 and Run 3 detector design.

AFP hardware updates:

- improvements on **cooling of silicon detectors** (new heat exchangers),
- production and installation of **new tracking modules**,
- **major update of ToF detectors**:
  new Out-of-Vacuum design of detector flange, R2D2 based MCP-PMT, modified back-end electronics, single-channel pre-amps and trigger, trigger decoder, pulser modules, picoTDC
- successful **test beams** at DESY and CERN-SPS (OoV solution, trigger module, new ToF PMTs)
- both NEAR **stations installed** just before COVID-19 lock-down,
  installation of FAR stations completed this month.

ALFA hardware updates:

- improvement and maintenance of **cooling system**,
- **exchange of readout** system due to radiation damage,
- installation of **radiation shielding**: concrete blocks around LHC beampipe upstream ALFA.

Ready for Run 3 data-taking!

Status and plans

Software and analysis:

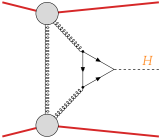
- Proton CP group: alignment, optics, cuts, performance and more
  → proton physics object delivered to ATLAS, used in several physics analyses across working groups in ATLAS (SM, EWK, TOP, EXOTICS, ...)
- Understanding of the proton object:
  → reducing systematic uncertainties, studies of reconstruction efficiency
- Work towards tuning full Geant4 simulation.

Run 3 data-taking:

- AFP: standard (high-μ) runs,
- ALFA:
  only for $\sqrt{s} \geq 13.5$ TeV and very high-β^* optics for measurement of elastic scattering:
  - $\beta^* = 3$ km, $\sqrt{s} = 14$ TeV,
  - $\beta^*_x = 3$ km, $\beta^*_y = 6$ km, $\sqrt{s} = 13.5/14$ TeV, flat optics
  - $\beta^* = 6$ km, $\sqrt{s} = 14$ TeV,

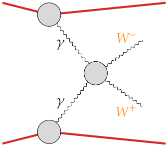
Run 4 potentially rich physics programme!

Exclusive Higgs
($b\bar{b}$ decay, spin, QCD mechanism)



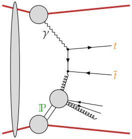
JINST 4 (2009) T10001: *"Higgs and New Physics with forward protons at the LHC"*
JHEP 090(2007) 0710: *Detecting Higgs bosons in the bb decay channel using forward proton tagging at the LHC*
EPJ C 53 (2008) 231–256: *Studying the MSSM Higgs sector by forward proton tagging at the LHC*

SM E-W: $\gamma\gamma \rightarrow W$



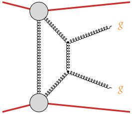
JHEP 07 (2020) 191: *"Pinning down the gauge boson couplings in WWγ production using forward proton tagging"*
JHEP 12 (2020) 165: *"Central exclusive production of W boson pairs in pp collisions at the LHC in hadronic and semi-leptonic final states"*

Top quarks production



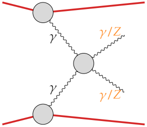
arXiv:2008.04249: *"Elastic Potential: A proposal to discover elastic production of top quarks at the Large Hadron Collider"*
Phys. Rev. D 102 (2020) 074014: *"Top quark pair production in the exclusive processes at LHC"*

Exclusive jets (SM & BSM)



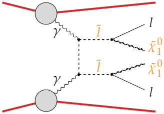
Eur. Phys. J. C (2015) 75: 320: *"On the Possibility of Measuring the Single-tagged Exclusive Jets at the LHC"*

New physics in two-photon processes at high mass
($\gamma\gamma \rightarrow \gamma\gamma, \gamma\gamma \rightarrow ZZ/Z\gamma$)



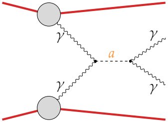
JHEP 02 (2015) 165: *"Light-by-light scattering with intact protons at the LHC: from Standard Model to New Physics"*
0808.0322: *"Anomalous WWγ coupling in photon-induced processes using forward detectors at the LHC"*

Searches for SUSY



PRL 123 141801: *"Search Strategy for Sleptons and Dark Matter Using the LHC as a Photon Collider"*
JHEP 04 (2019) 010: *"LHC searches for Dark Matter in compressed mass scenarios: challenges in the forward proton mode"*

Searches for ALPS
($\gamma\gamma \rightarrow$ invisible, $\gamma\gamma \rightarrow \gamma\gamma$)



JHEP 06 (2018) 131: *"Searching for axion-like particles with proton tagging at the LHC"*

HL-LHC with AFP?

Challenges and open questions:

- **Novel beamline:** crab cavities, collimators, magnets vs AFP at 180 / 200 / 220 m?
- **Crossing angle complementarity:** Points 1 and 5 with different optics and different RP acceptance.
- **Pile-up rejection at ≈200 vertices:** demands sub-10 ps ToF with Silicon/LGAD/Cherenkov technology + additional timing devices in the central detector.
- **Data acquisition and analysis:** demand new algorithms (ML?) and solutions
- **Reproducibility principle:** HL-LHC+RP discovery science needs 2 independent experiments?
- **Community:** attract + sustain talent and resources for 20+ years?

Run 4+ (HL-LHC) Optics – high lumi, low β^*

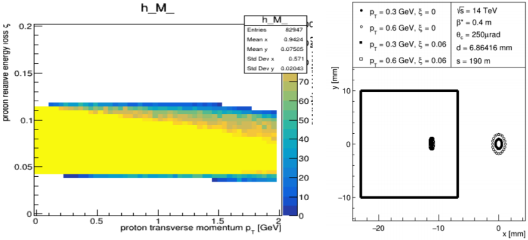
Preliminary studies done with HL-LHC optics ver. 1.4:

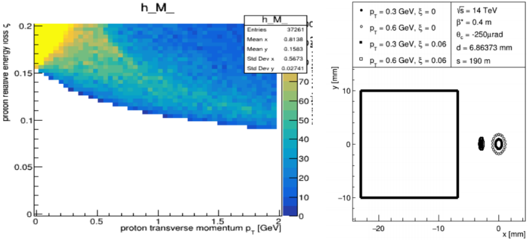
- RP at 15σ+0.5 mm from the beam, example acceptance at 190 m.
- $\beta^* = 0.4$ m
- Crossing angle $\phi = 180°$ disadvantageous for AFP:

  $\rightarrow$ diffr. protons closer to the beam

  $\rightarrow$ affecting energy resolution – large difference in energy loss translates to small spatial distance.

crossing angle $\phi = 0°$





crossing angle $\phi = 180°$

Summary

Run 2:

- Continuation of performance studies.
- Ongoing elastic, diffractive and (semi-)exclusive analyses based on Run 2 data $\rightarrow$ stay tuned!

Run 3:

- AFP ToF system: new PMTs, new design – Out-of-Vacuum solution.
- Successful test beams at DESY and SPS with AFP.
- All stations installed! $\rightarrow$ Commissioning.
- ALFA: request data-taking in Run 3 if $\sqrt{s} \geq 13.5$ TeV
- Almost ready for Run-3 data taking – expecting factor 10 more data!

Run 4:

- Physics programme being discussed within ATLAS,
- Output will set the constraints on preferred detector localization and technology (position and timing resolutions),
- Optimization of Run 4 optics to enhance acceptance is considered.

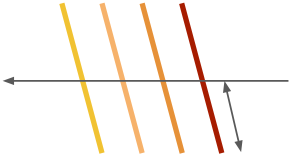
This work was partially supported by the Polish National Science Centre grant: 2019/34/E/ST2/00393

Backup Slides

AFP Inter-plane local alignment

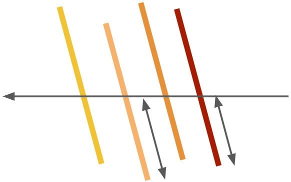
- Proton traversing AFP SiT creates charge deposits in each plane, measured at x position relative to the edge.

Ideal alignment:

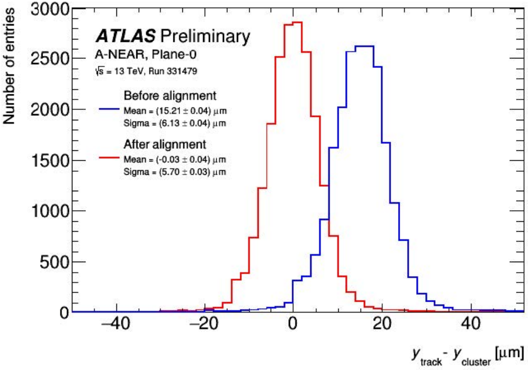


Hit to edge distance:
→ same for all planes

In reality:



Hit to edge distance:
→ may differ for each plane



Employed procedures account for:

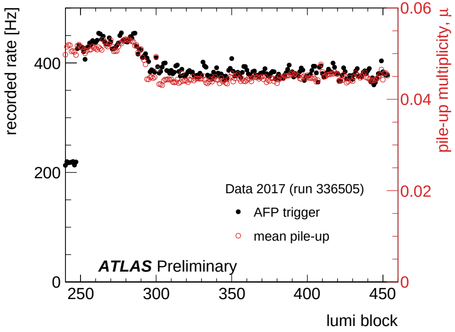
- offsets in x and y,
- (rotation about z axis.)

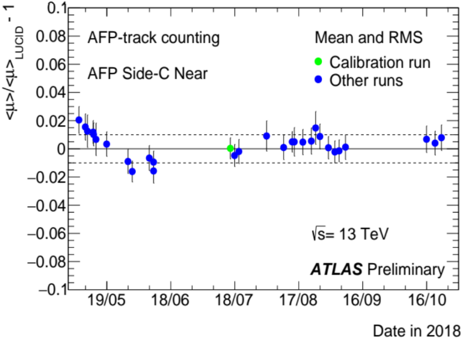
Systematic uncertainties in $pp \to ppll$

in measurements of cross-sections

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%

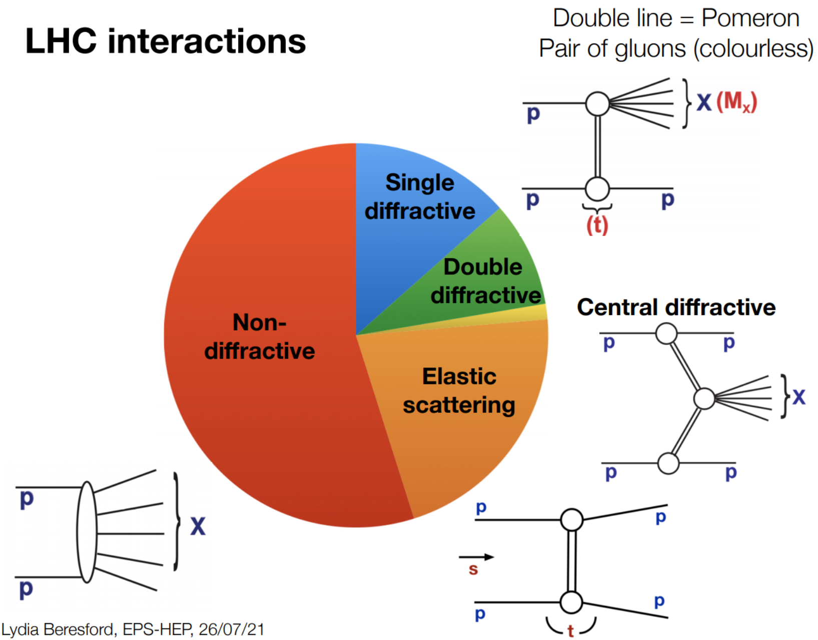
AFP SiT trigger rate



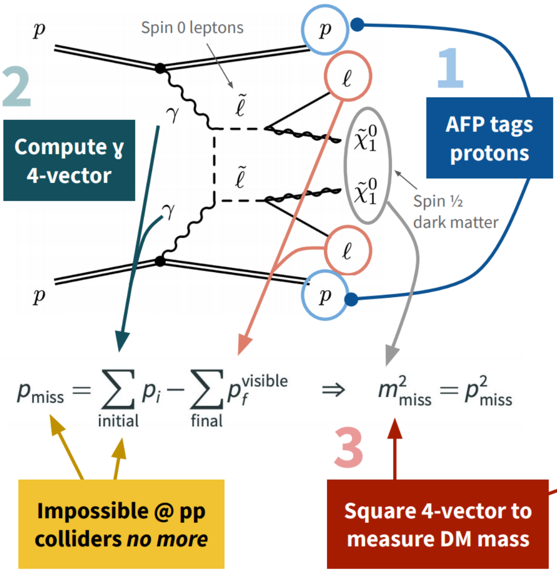


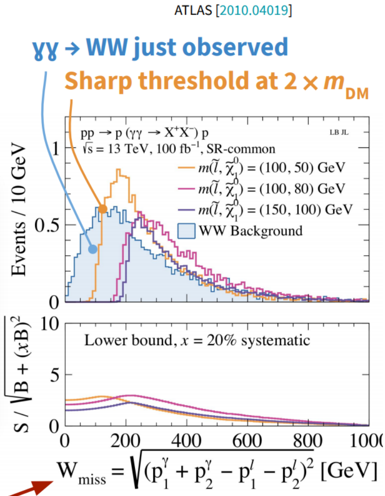
- Trigger rate (2/3 SiT planes majority vote) follows pile-up rate –
  → beam-induced backgrounds are small.
- - Rate stable with respect to other forward detectors /luminosity monitors (LUCID)

LHC interactions



p_{missing} 4-vector for dark matter searches





Run 3: rich physics enabled by ~10x good quality data with efficient time-of-flight

Exclusive jets

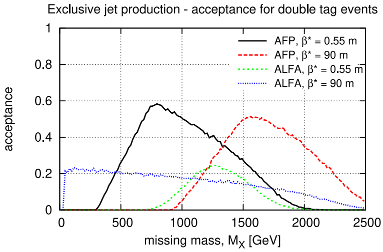


Fig. 3 The acceptance for events with both protons in the forward detectors as a function of the missing mass.

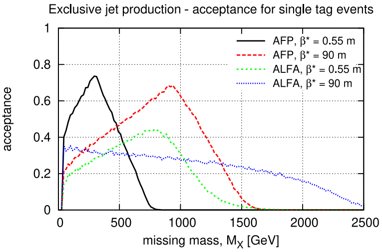


Fig. 5 The acceptance for events with exactly one proton in the forward detector as a function of the missing mass.

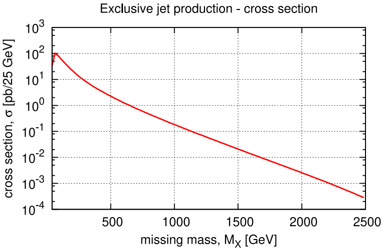


Fig. 4 Exclusive jet production cross section as a function of the missing mass.

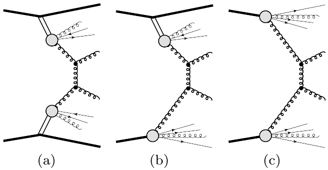


Fig. 6 Diagrams of background events: double Pomeron exchange (a), single diffractive (b) and non-diffractive (c) jet production. The double line marks the Pomeron exchange.

Diffractive $t\bar{t}$ production

Exclusive Higgs

W boson production in diffractive events

Search for axion-like particles in diffractive events