Forward detectors in ATLAS: status, performance and new physics results

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on behalf of ATLAS Forward Detectors

Institute of Nuclear Physics
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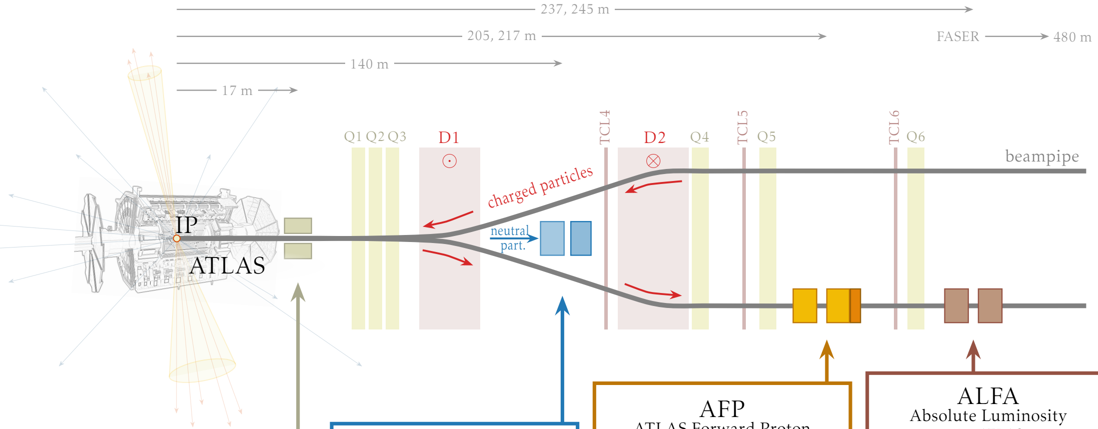


LUCID
Luminosity Cherenkov Integrating Detector

$5.6 < |\eta| < 5.9$

For luminosity measurement

ZDC + LHCf
Zero Degree Calorimeter
LHC Forward

Low-μ, $|\eta| > 8.0$

For cosmic-ray & heavy-ion physics

AFP
ATLAS Forward Proton

Low & high μ

$0.02 < \xi < 0.12$

soft & hard diffraction, $\gamma + \gamma$

- 4 Roman Pots, 2-4 mm from beam
- tracker: 3D sillicon pixel sensor
- spatial resolution $\sigma_x = 6\mu$m
- ToF: 16 Quartz Cherenkov bars
- **timing resolution $\sigma_t \approx 25$ ps**

ALFA
Absolute Luminosity
For ATLAS

Low-μ, $0 < \xi < 0.2$

special high-$\beta^\star$ optics

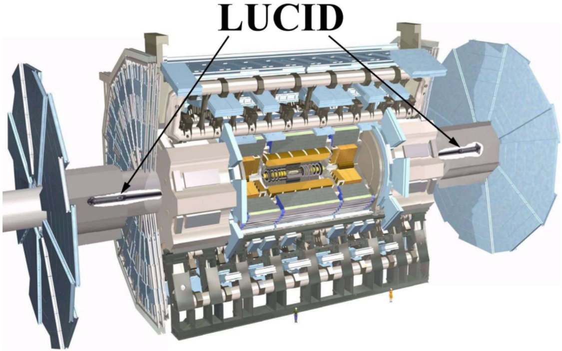
Elastic scattering, soft diffraction

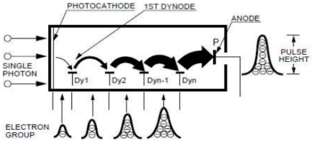
- 8 Roman Pots in 4 stations
- **<1 mm from beam**
- layered Scintilating Fibers
- spatial resolution $\sigma_y = 30\mu$m
- Multi-Anode-Photo-Multipliers

LUCID

LUminosity measurement using Cherenkov Integrating Detector

LUCID status

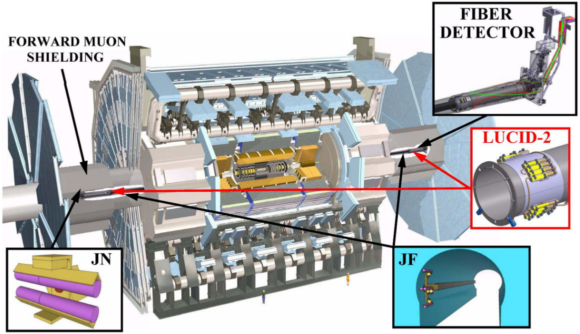


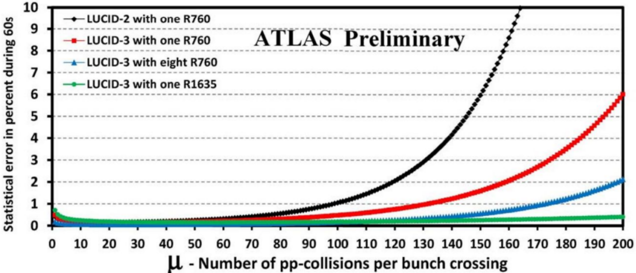


- **ATLAS luminosity measurement** strategy based on a redundancy of detectors with different technologies
- **LUCID-2** provided both **online and offline bunch-by-bunch luminosity** to ATLAS in Run 2 in all beam-conditions, luminosity ranges and type of colliding particles
  → 16 PMTs placed around the beam pipe at ±17 m from IP1
- **0.8% precision** achieved in Run 2!
  [EPJC 83 (2023) 982]
  → *"ATLAS delivers most precise luminosity measurement at LHC"*
  atlas.cern/updates/briefing/run2-luminosity
- LUCID-2 system continues to be used in Run 3

LUCID plans for 2024+

- LUCID-2 will **saturate @ LHC-run-4 luminosity** ⟶ Mean Interactions per bunch-crossing increase from 60 → 140 (200?)
- **Baseline detector:** PMT detector located in the JFC-3 shielding
- Additional PMTs located in the JF shielding (**JN PMTs**)
- **Complementary detector:** Cherenkov-light fiber radiators on beam-pipe read-out by PMTs in low radiation area
- Reducing saturation:
  - Moving PMTs away from beam-pipe reduces flux by 30%
  - Use smaller PMTs : R760→R1635 (-30% acceptance)
- R1635 : Custom flat quartz widow: increased radiation resistance





Prototypes for all three currently installed in Run-3

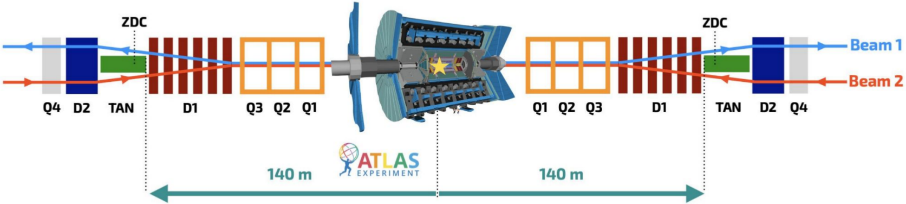
- LUCID3 JFC : similar non-linearities
- LUCID3 JN : reduced non-linearities
- LUCID3 fiber : Ongoing Run-3 analysis
  → Considerable improvement in degradation with radiation exposure, when using with UV filters

ZDC

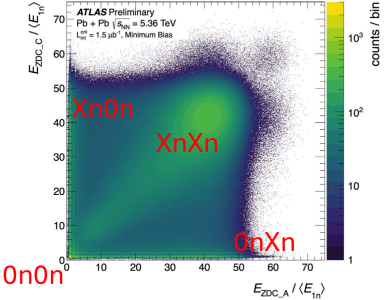
Zero Degree Calorimeter

ZDC status

- **ZDC** = Tungsten fused silica calorimeters located at ± 140 m from IP1 to detect forward spectator neutrons in Heavy Ion collisions
- Runs 1-3: located in LHC TANs 140 m from ATLAS
- Measures **forward neutral particles** $|\eta|>8.5 \rightarrow$ mostly spectator neutrons

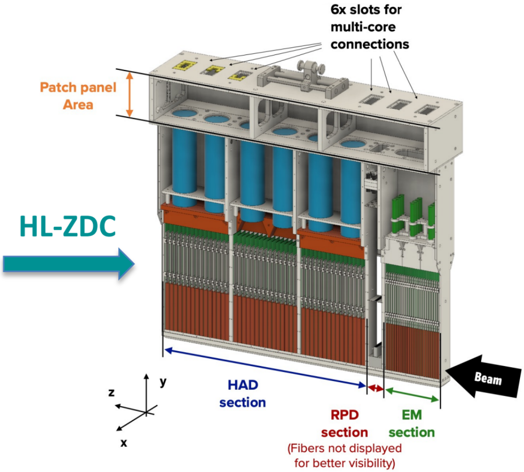


- **New Reaction Plane Detector (RPD)** samples 2D transverse shower profile
- Run 3 performance shows good neutron resolution
- RPD data analysis shows some differences in the two sides, possibly from different sized EM modules
- Different **forward neutron topologies** can give information on class of physics process $\longrightarrow$
- Critical for the **UPC programme** – also for triggering.



ZDC plans for 2024+

- **HL-ZDC** upgrade is essential for the ATLAS **Heavy Ion program** in Run 4 and beyond
  - **joint project** between ATLAS and CMS to tackle common challenges
  - Brand-new detectors need to be built to fit size constraints + with radiation hard materials
- TANs have bee redesigned for HL-LHC : TAXN, 127m from IP
- Challenges: 10 cm slot-width → 5 cm slot-width, higher radiation levels
- Baseline design of ZDC finalized
  - EM section
  - Reaction-Plane Detector (RPD)
  - Hadronic Section
  - Identical design for ATLAS and CMS up to Patch panel
- RPD design will be identical to Run-3 ZDC (8 fibre layers, 16 PMTs, $4 times 4$ segmentation in x-y.
- Front end electronics (same for LUCID and ZDC): 12 Bit ADC at 640MHz → testing prototypes

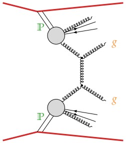


Forward proton spectrometers

AFP & ALFA

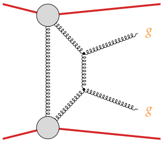
(ATLAS Forward Protons, Absolute Luminosity For ATLAS)

Forward proton scattering in a diverse physics program



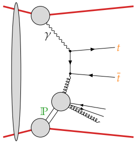
Diffractive jets

ATL-PHYS-PUB-2017-012



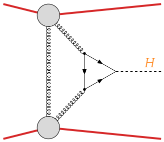
Exclusive jets

Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



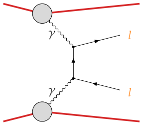
Heavy quarks

Goncalves et al 2007.04565
Howarth 2008.04249



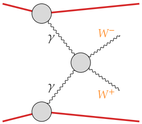
Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052



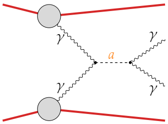
Leptons

CMS 1803.04496
ATLAS 2009.14537



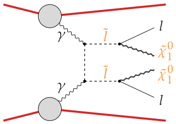
W bosons

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:

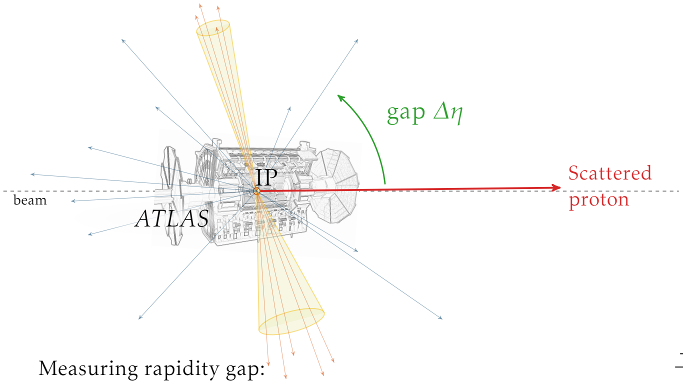
- Pomeron
  (two gluons + …)
- photon

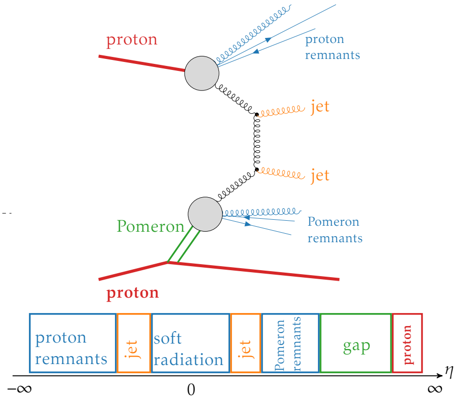
- **QCD – hard and non-perturbative**
- **probing electroweak scale**
- **physics beyond SM**

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, rescattering)
– **gap may be out of acceptance**
– **gap may be a statistical fluke**

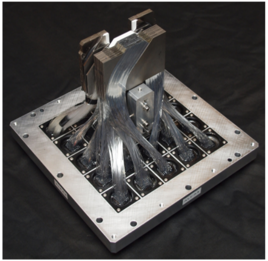
Measuring forward protons:

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

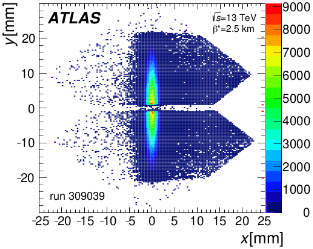
ATLAS, Eur.Phys.J.C 72 (2012) 1926
ATLAS, Phys.Lett.B 754 (2016) 214-234

ALFA and AFP detectors

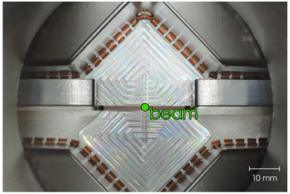
ALFA



The tracking devices - Scintillating Fibers in ALFA and Silicon Tracker with Time of Flight detector in AFP.

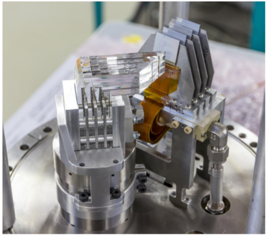


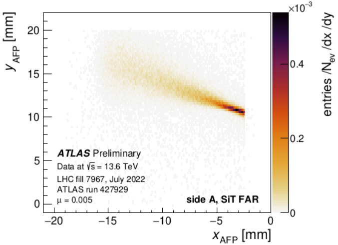
Distribution of track impact positions. The characteristic vertical (ALFA) and diagonal (AFP) patterns come from diffractively scattered protons.

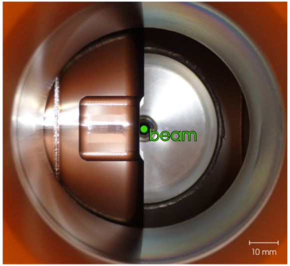


Forward proton detectors viewed from the beam perspective.

AFP

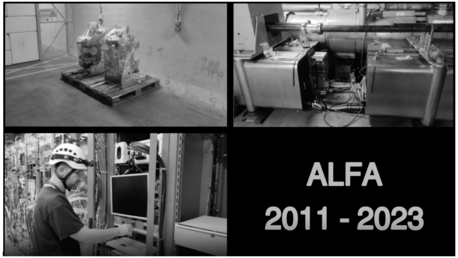


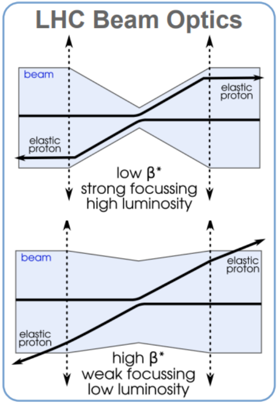




ALFA status

TOTAL in-beam time: 87h50
TOTAL acquired luminosity: 0.32893 nb^{-1}





ALFA Strategy for Run 3

- **Goal**: elastic data-taking at √s = 13.6 TeV with access to very low values of four-momentum ($-t \approx 4 \cdot 10^{-4}$ GeV^2).
- Baseline: keep Run 2 system operational.
- Refurbishment of readout electronics using spares.

ALFA Data-taking (2011 - 2023)

Year	β*	√s [TeV]	Comments
2011	90 m	7	elastics: NPB 889 (2014) excl. $\pi^+\pi^-$: EPJC 83 (2023) 627
2012	90 m	8	elastics: PLB 761 (2016) single diff.: JHEP 02 (2020) 042
2012	1 km	8	elastics dataset
2013	0.8 m	2.76	proton-lead dataset
2013	0.8 m	2.76	proton-proton reference dataset
2015	90	13	diffractive dataset
2016	2.5 km	13	elastics: EPJC 83 (2023) 441
2018	90 m	13	elastic (large *t*) and diff. datasets
2018	11 m	0.9	elastics (large *t*) dataset
2018	50/100m	0.9	elastics dataset
2023	3/6 km	13.6	elastics dataset

- In 2023, **ALFA** successfully **finished its data-taking** programme!
- Initial focus to measure properties of **elastic scattering** was extended to measure **diffractive events**
  - Lots of interesting datasets to be analysed!
  - A unique example: **p-Pb** collisions from 2013

PHYSICS HIGHLIGHTS:

- Exclusive **pion pair production** in pp collisions at $\sqrt{s} = 7$ TeV [EPJC 83, 627 (2023)]
- **Total cross section** and ρ-parameter from **elastic scattering** in pp collisions at $\sqrt{s} = 13$ TeV [EPJC 83, 441 (2023)]

More on **ALFA decomissioning**: [LHC FWD WG meeting pres. by B. Dziedzic]

AFP status

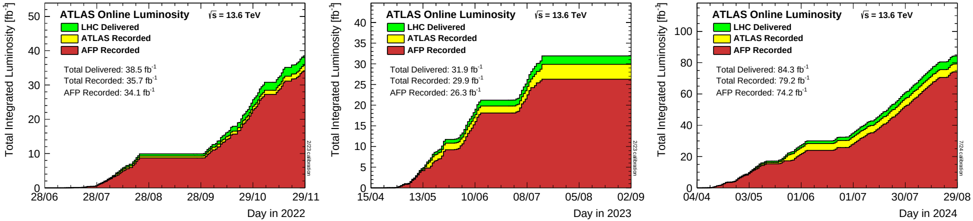
AFP Upgrades since Run 2

- Goal: regular, day-by-day, **high pile-up data-taking**.
- Few **low pile-up runs** for dedicated diffractive studies.
- New design of detector support: **Out-of-Vacuum solution for ToF** detectors.
- **New SiT modules** replaced older ones damaged by radiation.
- Improvement of **SiT cooling** - new heat exchangers.
- **New photo-multipliers** to address ToF inefficiency issues observed during Run 2.
- Design and installation **pot heat-sink**.
- Production of **new readout electronics**.

Special runs, low pile-up:

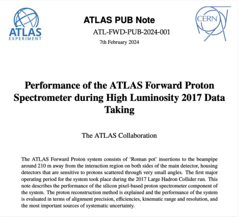
- 2022
  $0.46\ \mathrm{nb}^{-1}$ at $\mu \sim 0.005$
  $34.6\ \mathrm{nb}^{-1}$ at $\mu \sim 0.05$
  $170\ \mathrm{nb}^{-1}$ at $\mu \sim 0.02$
  (special optics)
- 2023
  $230\ \mathrm{nb}^{-1}$ at $\mu \sim 1$
  $35\ \mathrm{nb}^{-1}$ at $\mu \sim 0.2$
  $63\ \mathrm{nb}^{-1}$ at $\mu \sim 0.05$
  $1.76\ \mathrm{nb}^{-1}$ at $\mu \sim 0.005$
  (low B-field)

Standard runs, high pile-up:



AFP performance

- Run 2 documentation for both **SiT** and **ToF** performance is now public!
- Lots of lessons learned from Run 2, improved operation and understanding of performance in Run 3
- Dataset available to analysis more than doubled with 2022 alone!

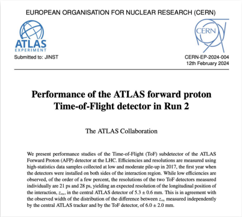


ATLAS PUB Note
ATL-FWD-PUB-2024-001
7th February 2024

Performance of the ATLAS Forward Proton Spectrometer during High Luminosity 2017 Data Taking

The ATLAS Collaboration

The ATLAS Forward Proton system consists of 'Roman pot' insertions to the beampipe around 210 m away from the interaction region on both sides of the main detector, housing detectors that are sensitive to protons scattered through very small angles. The first major operating period for the system took place during the 2017 Large Hadron Collider run. This note describes the performance of the silicon pixel-based proton spectrometer component of the system. The proton reconstruction method is explained and the performance of the system is evaluated in terms of alignment precision, efficiencies, kinematic range and resolution, and the most important sources of systematic uncertainty.

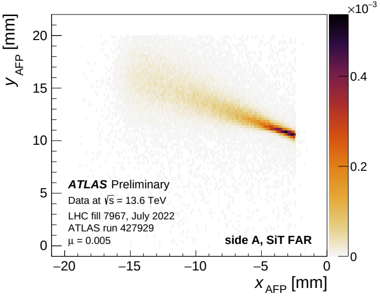


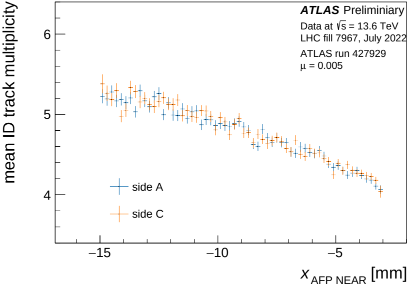
EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)
Submitted to: JINST
CERN-EP-2024-004
12th February 2024

Performance of the ATLAS forward proton Time-of-Flight detector in Run 2

The ATLAS Collaboration

We present performance studies of the Time-of-Flight (ToF) subdetector of the ATLAS Forward Proton (AFP) detector at the LHC. Efficiencies and resolutions are measured using high-statistics data samples collected at low and moderate pile-up in 2017, the first year when the detectors were installed on both sides of the interaction region. While low efficiencies are observed, of the order of a few percent, the resolutions of the two ToF detectors measured individually are 21 ps and 28 ps, yielding an expected resolution of the longitudinal position of the interaction, z_{vtx}, in the central ATLAS detector of 5.3 ± 0.6 mm. This is in agreement with the observed width of the distribution of the difference between z_{vtx} measured independently by the central ATLAS tracker and by the ToF detector, of 6.0 ± 2.0 mm.

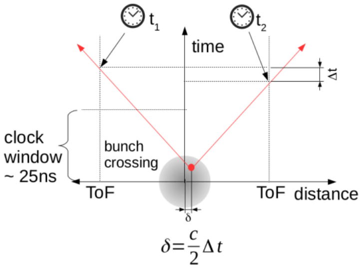




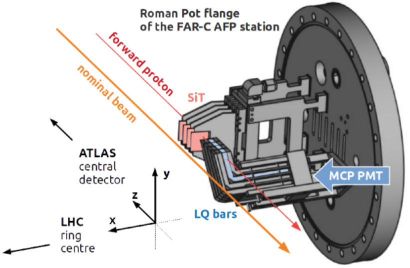
- Uncertain future of AFP in Run 3 due to inner triplet radiation mitigation strategies (more on next slides)

AFP Time-of-Flight Detectors

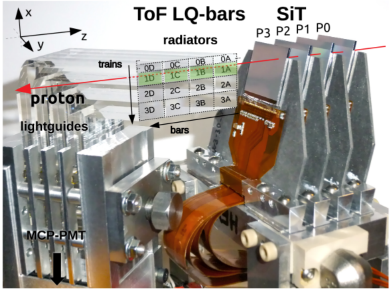
Concept of ToF measurement:



Sketch of mounting SiT and ToF (Run 2 design):



Detector package before installation (Run 2 design):



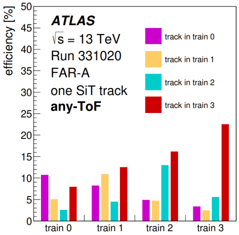
- **Purpose:** Assign protons to collision vertex in IP1 (reducing background due to pile-up).
- **Concept:**
  - measure ToF difference: $\Delta t = (t_A - t_C)/2$,
  - calculate vertex position: $z_{\mathrm{ToF}} = c\Delta t$,
  - compare vertex z position reconstructed by ATLAS and AFP ToF.
- **Detectors:** 4×4 matrix of quartz bars, L-shaped and rotated 48deg w.r.t. LHC beam (Cherenkov angle).
- **Timing:** aim for 20 ps [Opt. Express] resolution for Run 3,
  30 ps at the beginning (in Run 2) [JINST 11 (2016) P09005].

AFP ToF performance

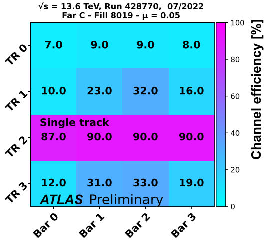
- **Challenges** with ToF in Run 2: excellent resolution, but very **low efficiency** due to fast degradation of the PMTs.
- ToF remains challenging in Run 3 – **difficulties with sustaining high efficiency** in high track rate environment – possible radiation damage.
- Significant amount of work going into **operation and performance studies**.
- **ToF modules removed** from the tunnel in August to **avoid radiation damage** in high pile-up runs
  → prioritizing high-statistics low pile-up data
  (pp reference run, $\mu \sim 5$, $\mathcal{L} \sim 100\ \text{pb}^{-1}$, $\sqrt{s} = 5$ TeV)

Efficiency

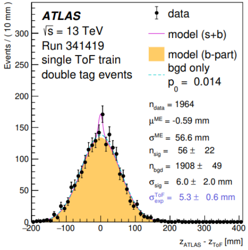
2017, $\mu = 2$:

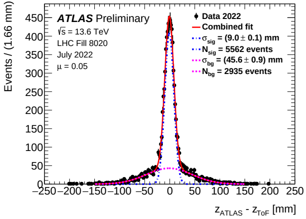


2022, $\mu = 0.05$:



Resolution

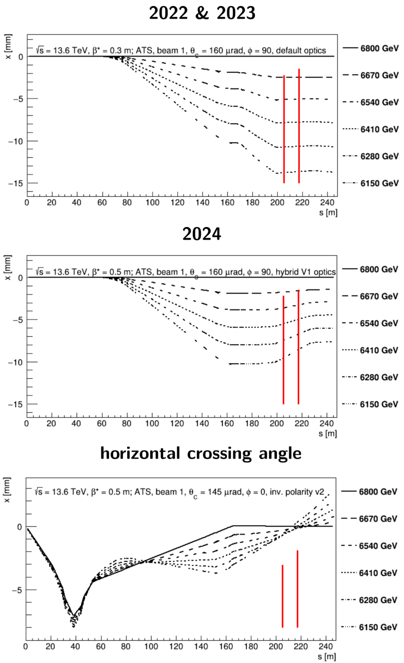




Impact of LHC optics on AFP acceptance

The acceptance of AFP is heavily dependent on the **optics settings of the LHC**

- Some experts from LHC expressed concerns about **damage of the inner triplet** and separation dipoles due to **radiation**.
- The mitigation re-cabling the inner triplet (change magnet polarity) plus change **from vertical to horizontal crossing angle**.
- Horizontal crossing angle at ATLAS would result in **no acceptance for AFP**
  → end of data taking (see bottom plot).
- For 2024 data-taking inner triplet was re-cabled impacting proton trajectories (see plots above).
- Question about optics 2025+ remains open.



AFP plans in 2024 and beyond

<u>2024</u>

- New **SiT modules**, new **RP heat-sink**, new and refurbished **readout electronics**
- AFP is taking data with a **legacy ToF system (HPTDC)** in 2024
  - Decision on **changing to picoTDC** to be taken shortly
- AFP is participating **all standard high-μ runs**
- Expect proton resolution to be slightly worse than 2023 due to **change in LHC optics**
- Getting ready for data-taking during the **pp reference run** in October
  - Assumption is that ToF will be fully efficient

<u>2025+</u>

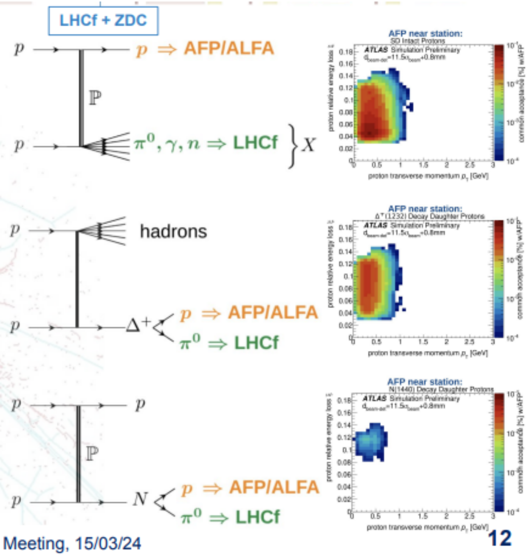
- AFP plans for 2025 depend on outcome of inner triplet radiation dose mitigation strategies put in place this year
  - If **triplet polarity switch** in 2024 means there is no crossing plane change in 2025, AFP expects to take part in all standard high-μ runs
  - If there is a change in crossing plane (V→H at IP1), AFP has no acceptance
    → In this case, will only partake in special runs
- AFP would like to participate in both **proton-oxygen and oxygen-oxygen runs** planned for 2025
  - Insertion on both **proton and oxygen side** should be possible
  - Will require additional beam based alignment
- No AFP in Run 4

Combined AFP+LHCf+ZDC

- Feasibility **[PUB note]** released last summer
  AIM: Provide input to **cosmic ray background modelling** (soft-QCD)
- Large differences in **generator predictions**:
  - Position of shower maximum
  - Particle multiplicities
  - Insufficient tuning data
- **Proton excited states in diffractive regime** not been measured at the LHC before
- LHCf Calorimeters
  - Neutral particles ($\gamma, \pi^0 \to \gamma\gamma, n$) at $|\eta| > 8.4$
  - Special runs with $\mu_{\max} = 0.05$

Analysis of 2022 LHCf special run ongoing.

See the details: pres. by C. Leitgeb at LHC FWD Workshop.



Thank you for your attention!

Acknowledgments

This work was supported by the Polish National Science Centre grant 2023/48/C/ST2/00195.

Backup Slides

Collisions at LHC

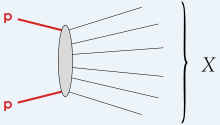
Usual proton-proton collisions at the LHC

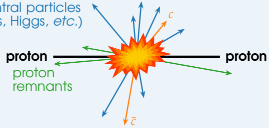
→ protons collide head-on

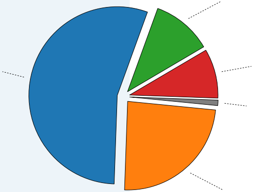
→ both protons break up

→ collision products are emitted in the central region

→ proton remnants may be found in the forward regions







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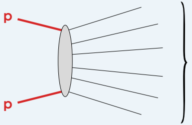
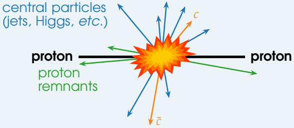
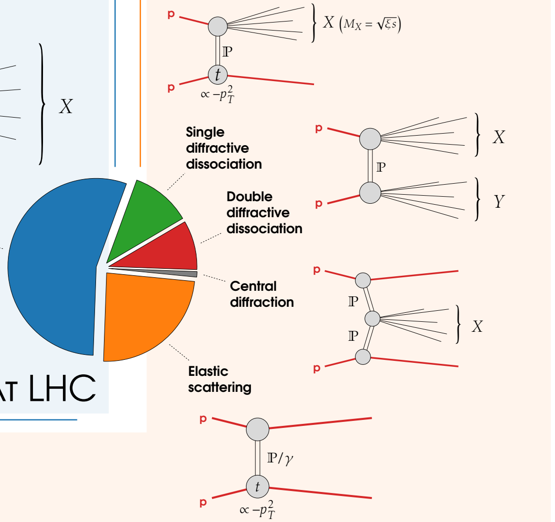
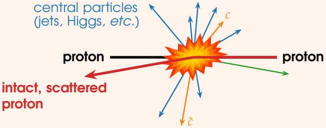




Collisions at LHC



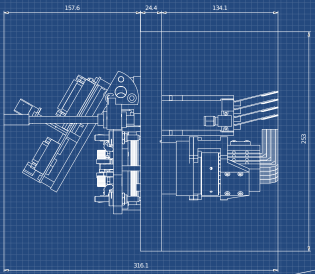
How can proton(s) remain intact?



Proton can exchange objects that do not change its quantum numbers:

→ photon (γ) – via electromagnetic interactions

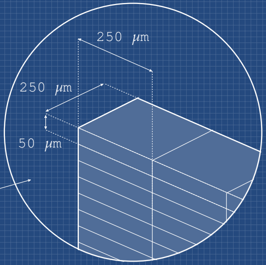
→ Pomeron ($\mathbb{P}$) – via strong nuclear force

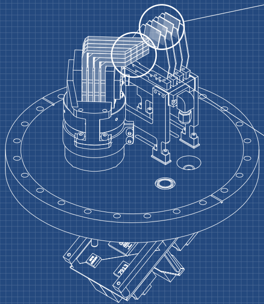


4 Roman Pots @ 205 & 207 m from **IP1**

2–4 mm from the beam

measuring protons with
$\xi = 1 - E_{\textbf{proton}}/E_{\textbf{beam}} \in (0.02, 0.12)$

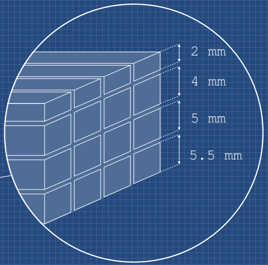




Tracker:

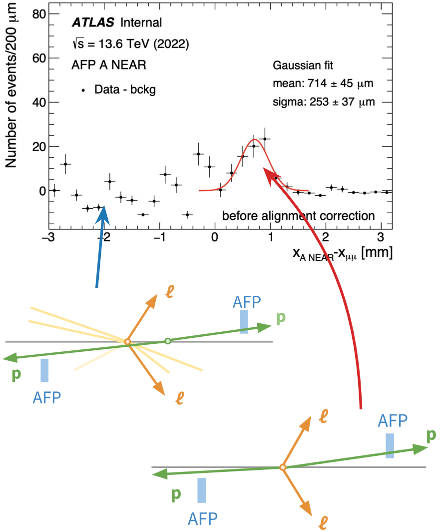
- 3D silicon pixel sensor
- 4 planes of 336 × 80 pixel array
  ~ 17 mm × 20 mm in size
- 50 μm × 250 μm granularity
  250 μm thick
- spatial resolution @ 14° tilt
  $\sigma_x = 6\ \mu$m

Time-of-Flight detector:



- 16 Quartz Cherenkov bars
- oriented at Cherenkov angle
- timing resolution $\sigma_t \approx 25$ ps

In situ AFP global alignment with exclusive di-muon events

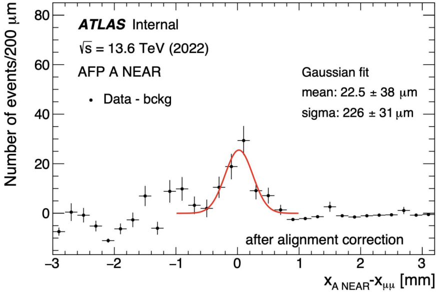


$(\gamma\gamma \to \mu\mu) + p$ as a "standard candle":

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}

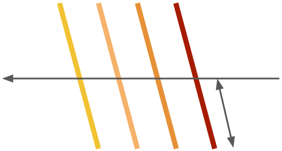


- Background – small and well modelled by event mixing,
- Alignment precision estimated safely at 300 μm

AFP Inter-plane local alignment

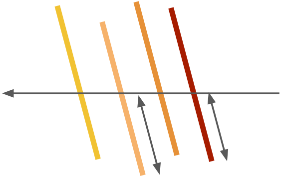
- Proton traversing AFP SiT creates charge deposits in each plane, measured at x position relative to the edge.

Ideal alignment:

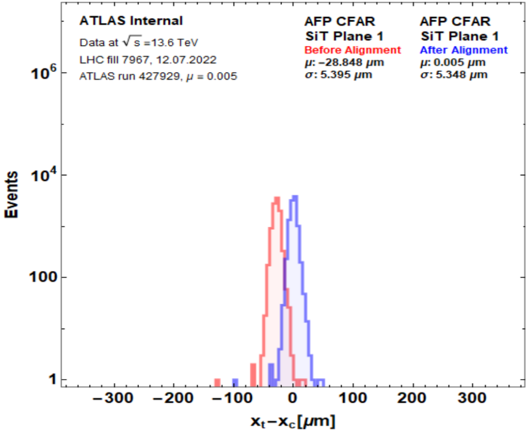


Hit to edge distance:
→ same for all planes

In reality:



Hit to edge distance:
→ may differ for each plane



Employed procedures account for:

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

LUCID in Run 2 (and 3)

LUCID is and has been the main ATLAS Luminosity monitor: the only detector able to measure luminosity both integrated and bunch by bunch, online and offline, in any LHC L range.

- *Total Run 2 offline luminosity measured with a 0.83% uncertainty and a better than 0.1% stability over time.*
- *Main systematic: **van der Meer (VdM) calibration**(0.65%).*

Design strategies:

- A fast, low-background and rad-hard PMT-based Cherenkov detector (Hamamatsu R760).
- Quartz fiber coupled with PMTs to reduce radiation damage to PMTs.
- Fast electronics handling hit and charge algorithms.
- Stable, flexible and redundant operation thanks to gain calibration system and layout

New PMT detector

Main strategy: reduction of acceptance

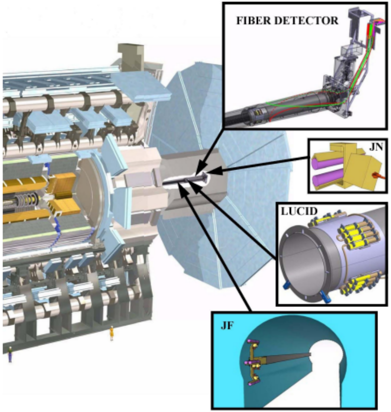
- Smaller PMTs (Hamamtsu R1635)
- New location further away from beampipe

LUCID JF (main detector):

- PMTs attached to forward shielding via a rail system -> easy to replace and lower radiation exposition during maintenance
- Smaller acceptance wrt LUCID-2

LUCID JN (auxiliary detector)

- PMT behind forward shielding -> very low acceptance
- Improved linearity wrt μ



LUCID-3 prototypes

Prototypes of PMT and fiber detector under study to validate LUCID-3 possible design:

- Statistical error
- Linearity with respect to μ
- Long term stability

HL-LHC challenges

Luminosity requirements:

- Offline precision ~ 1%.
- Online stability and precision (~3%) in 2s-long periods.
- Working point far from saturation.

Challenging conditions: pile-up (μ) <= 200 and L = 4000 fb^{-1}

- Leading to potential saturation of the PMT acceptance and high total dose and current.
- Large (and not-predictable) non-linearity in the larger μ-range.

Different ATLAS TDAQ infrastructure:

- New electronic infrastructure required.

New Fiber detector

Fiber detector introduced in Run 1, improved in Run 2, upgraded prototype in Run 3:

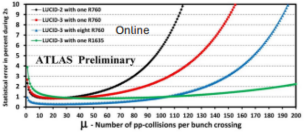
- New calibration system
- New quartz fiber with better radiation hardness
- UV filter in one of the detector to improve long term stability

Improved calibration system wrt LUCID-2

- PMT gain monitored with the ^{207}Bi (like all PMTs),
- LEDs to monitor fiber ageing,
- Possibility to correct offline for fiber ageing.

Main advantage:

- Very good linearity wrt μ
- PMT placed in a less radioactive area



Statistical error

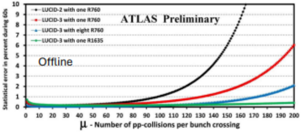
2s time window (online lumi):

- Goal: <2/3%
- LUCID-2 reaches only μ = 80
- Just 1 R1635 reaches μ = 200

60s time window (offline lumi):

- Goal: <1%
- LUCID-2 reaches only μ = 100
- Just 1 R1635 reaches μ = 200

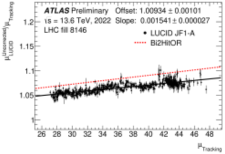
Drawback: 8 R1635 in VdM

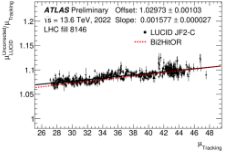


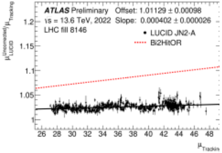
Linearity

Comparison of various LUCID algorithm with track vs μ

- JF1-A (R1635): slightly better linearity wrt LUCID-2
- JF2-C (R760): slightly better linearity wrt LUCID-2
- JN2-A (R760): linearity 3/4 times better wrt LUCID-2



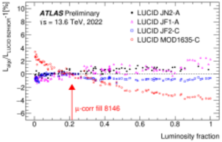




PMT long term stability

Compare fill-by-fill prototype lumi measurement wrt to LUCID-2:

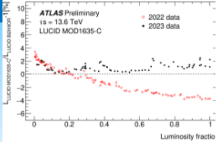
- JF1-A and JF2-C similar to LUCID-2
- JN2-A larger fluctuation compared to LUCID-2



LUCID MOD1635

Test: use new R1635 in LUCID-2 position

- Large drift in 2022: this PMT produce shorter pulses that current electronics cannot digitize perfectly
- Pulse widened in 2023: improved stability
- electronics under redesign to cope with R1635 signals and new ATLAS-TDAQ scheme



Fiber long term stability

Long term stability strongly influenced by fiber ageing

- Large loss of light in UV region -> UV filter in one of the prototype

Comparison between L measured by LUCID-2 and fiber

- Large loss without filter
- Sawtooth shape problem with gain monitoring
  - Indication of mitigation in 2024