Overview of ATLAS Forward Proton Detectors for LHC Run 3 and Plans for the HL-LHC

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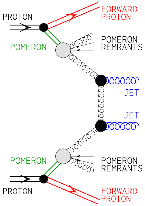
Physics of Interests

Yesterday talk by Hasko Stenzel *"Forward proton measurements with ATLAS"*

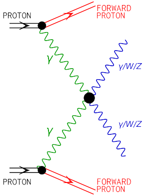
Characteristic observables:

- rapidity gap: no particles produced between central system and scattered proton,
- presence of scattered forward protons.



Hard diffractive processes:

- perturbative calculation methods,
- one or both interacting protons stay intact,
- example: double Pomeron exchange di-jet production.

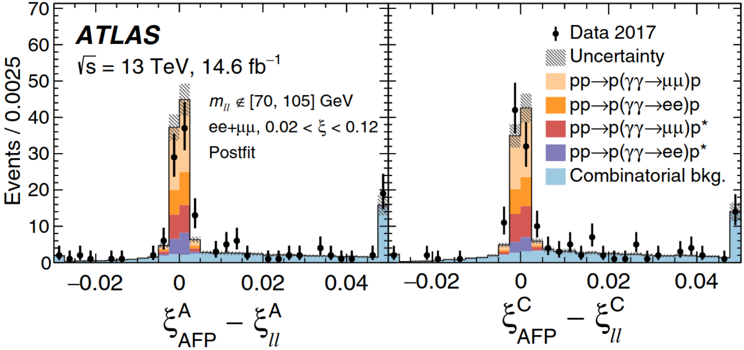


BSM processes:

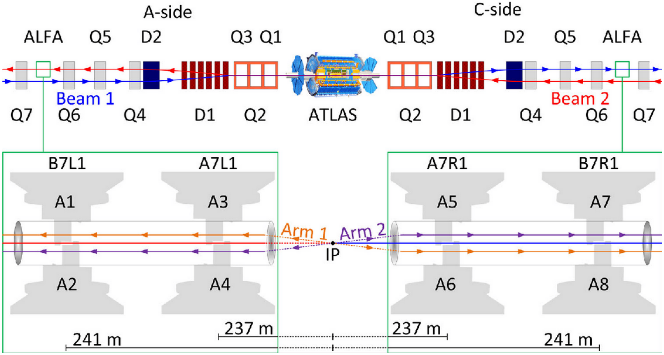
- focus on process with two intact protons,
- exclusivity – all produced particles are measured → strong background suppression wrt standard analysis,
- example: anomalous quartic couplings.

Physics Results

- ***Total cross section with ALFA at 7 TeV***, Nuclear Physics, Section B (2014), pp. 486-548
- ***Total cross section with ALFA at 8 TeV***, Phys. Lett. B (2016) 158
- ***Inclusive single diffractive dissociation cross-section of pp collisions at 8 TeV***, JHEP 02 (2020) 042 (Erratum)
- ***Photon-induced dilepton production with forward proton tag***, Phys. Rev. Lett. 125 (2020) 261801
  - AFP introduces a "powerful background rejection" based on kinematic match between proton and lepton system.
  - Great performance: 95% signal acceptance and 85% background rejection.
  - Background-only hypothesis rejected with a significance exceeding 5σ in each channel.

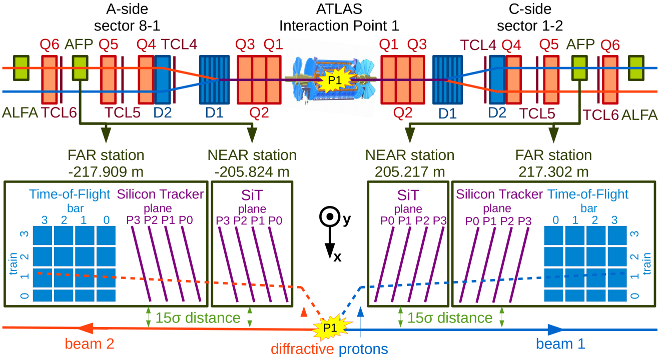


ALFA Detectors



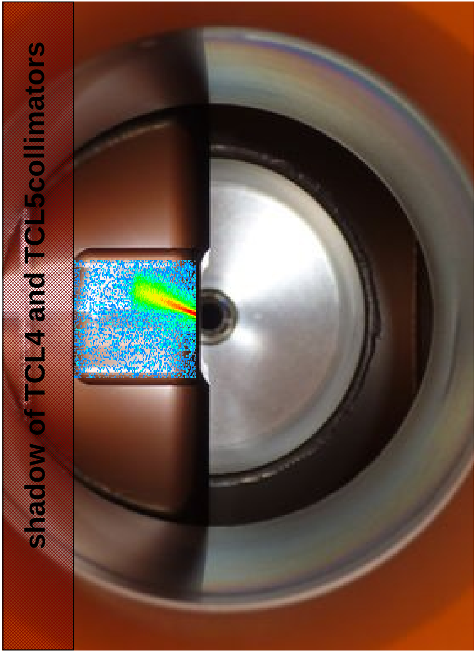
- four stations on each side of ATLAS (around 237 and 245 m from ATLAS IP),
- vertically inserted into LHC beam-pipe,
- each station consists of 20 layers of 64 scintillating fibre detectors,
- purpose: soft diffraction, especially elastic scattering,
- ALFA takes part during special runs: very low pile-up and (very) high β^* optics

AFP Detectors

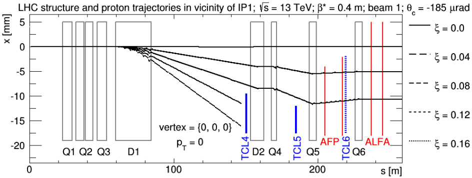


- two Roman pot stations on each side of ATLAS (around 210 m from ATLAS IP),
- horizontally inserted into LHC beam-pipe up to few mm from the beam,
- each station, commonly called Near/Far A/C, consists of four Silicon Trackers (SiT),
- Far stations host also Time of Flight (ToF) detectors,
- several LHC elements influence proton trajectory before AFP:
  - two dipole magnets (D1-D2) for beam separation (bending),
  - five quadrupole magnets (Q1-Q5) for beam focusing,
  - two collimators (TCL4, TCL5) for magnet protection.

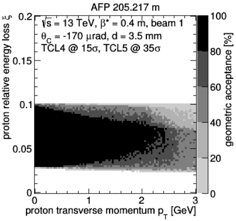
AFP Detectors Acceptance



- Due to influence of LHC magnets the proton trajectory is not straight line.
- Protons are bent according to the energy lost during the collision: $\xi = 1 - \frac{E_{proton}}{E_{beam}}$,

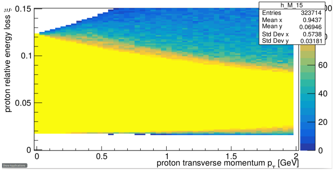


- AFP acceptance is limited by:
  - beam-detector distance – protons with too small energy loss are too close to the beam to be detected,
  - LHC collimators – protons with too high energy loss are filtered.
- In order to catch more forward protons, detector needs to be as close to the beam as it is possible.



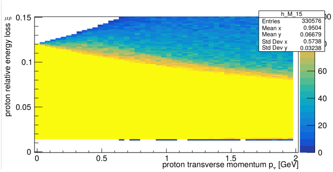
2016-2018:

- the geometric acceptance was $0.03 < \xi < 0.1$,
- the mass acceptance was $390 < M_{central} < 1300$ GeV,
- the AFP was inserted to d_{beam} between 2 and 4 mm from the beam (depending on station and optics).
- SiT resolution of 6 μm from TBs and an overall SiT efficiency in 2017 of 92% [Phys.Rev.Lett. 125 (2020) 26, 261801].



2022:

- the geometric acceptance is $0.02 < \xi < 0.12$,
- the mass acceptance is $260 < M_{central} < 1560$ GeV,
- the AFP insertion distance varies from 2.3 and 2.8 mm for Near stations and from 1.5 to 2.3 mm for Far stations.

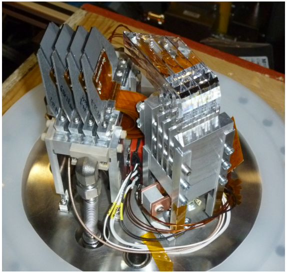


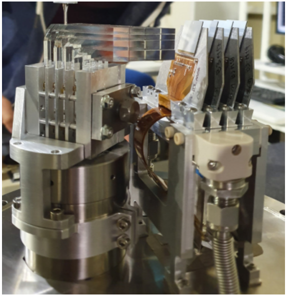
2023-2025:

- the geometric acceptance is $0.015 < \xi < 0.12$,
- the mass acceptance is $195 < M_{central} < 1560$ GeV,
- the AFP insertion distance varies from 2.3 and 1.7 mm for Near stations and 1.5 mm for Far stations.

Detector Upgrades During LS2

AFP Detector Package in Run 2





AFP Detector Package

After Upgrade

AFP:

- Significant ToF upgrade:
  - new R2D2 based MCP-PMT,
  - new design of detector flange: Out-of-Vacuum solution,
  - new glue-less LQBars,
  - new trigger module: possibility to trigger on single train,
  - pulser modules installed: full signal path cross check after installation and between runs,
  - all settings can be fully controlled remotely.
- Above items were successfully tested at DESY and SPS in 2020.
- Improvement in silicon detector cooling (new heat exchangers).
- With the upgrades AFP detectors is expected to run smoothly during Run 3 data taking, aiming for timing resolution of 20 ps for Run 3 (25 ps in Run 2, [ATL-FWD-PUB-2021-002]).

ALFA:

- Installation of new motherboards to replace ones damaged due to radiation.

Run 3 Data Taking Plans

AFP:

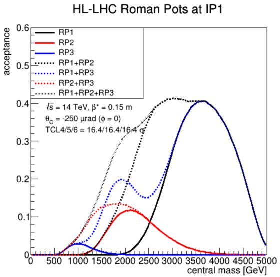
- **high-μ runs** – regularly take data (AFP integrated lumi. is expected to match ATLAS), **purpose:** high p_T exclusive processes, BSM searches;
- **low-μ runs** (various pile-up conditions, $0.005 < \mu < 1$) – run during LHC ramp-ups, **purpose:** soft diffraction, low p_T hard diffraction;
- **"LHCf run"** – with $\beta^* = 19$ m, **purpose:** diffractive studies, connection to cosmic ray physics;
- **medium-μ runs** ($\mu \sim 2$) – $\sim$1/fb of data planned to be collected, **purpose:** excellent sample to study medium/high p_T hard diffractive processes;
- **pp $\rightarrow$ PbPb** – reference run, **purpose:** sample for diffracive studies at lower energy.

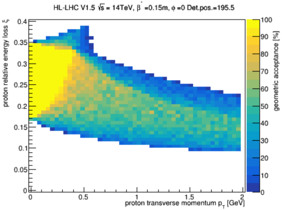
ALFA

- β^* **= 90 m run** in 2022;
- β^* **= 3/6 km run** – with $\sqrt{s} = 13.6$ TeV (planned early in 2023), **purpose:** measurement of elastic scattering at new energy.

ATLAS Roman Pots at HL-LHC

- Ongoing internal discussion within ATLAS community on the presence of Roman pots. Studies of gain wrt. to standard ATLAS measurement possibilities.
- At high pile-up and low β^* environment the main focus would be on photon induced processes and BSM searches – ALP/DM/anomalous couplings in $\gamma\gamma \to$ WW/ZZ/$t\bar{t}$/...





Space for pot installation at HL-LHC is **reduced** compared to current situation. Following distances from IP were considered: **RP1A/B:** 195.5/198.0 m, **RP2A/B:** 217.0/219.5 m, **RP3A/B/C:** 234.0/237.0/245.0 m.
On plot AFP mass acceptance for different scenarios:

- **4 stations:** solid black, blue and red lines,
- **8 stations:** doted black, blue and red lines,
- **12 stations:** dashed black line.

Mass acceptance depends on pot location – stations closer to IP have acceptance towards higher masses.

- Plane of crossing angle must be opposite at IP1 and IP5: vertical at IP5 $\to$ horizontal at IP1.
- Vertical crossing angle results in acceptance towards lower masses (strongly preferred by CT-PPS).
- On plot geometric acceptance for RP1A and horizontal crossing angle.

Summary

Run 2:

- Ongoing elastic, diffractive, and (semi-)exclusive analyses based on Run 2 data.

Run 3:

- All AFP stations installed and qualified to be inserted.
- Upgraded AFP ToF system: successful test beams at DESY and SPS, aim for 20 ps resolution.
- AFP will take part in both high-μ and special low-μ runs, providing data for BSM searches and studies exclusive processes and soft/hard diffraction.
- ALFA requests to take part in very high β^* run to study properties of elastic scattering at new energy.

HL-LHC:

- Physics programme being discussed within ATLAS.
- Ongoing discussion on specific detector localization and technology.

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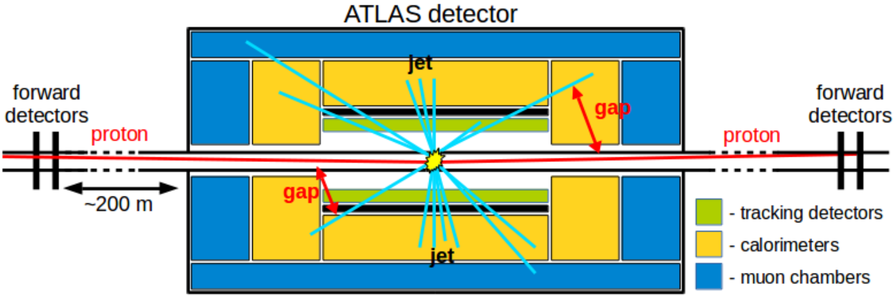
Backup

Detection Methods

Typical diffractive topology:

- one or both forward protons stay intact plus a central system in the main detector,
- each forward proton accompanied by a large rapidity gap.



Method 1 (rapidity gap):

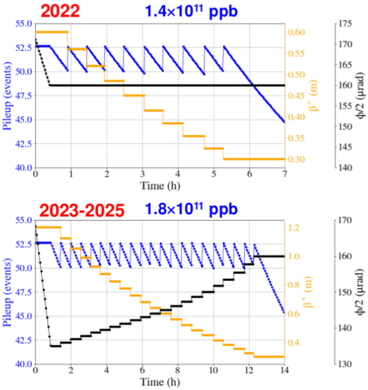
+ "classical" recognition method
+ no need to install additional detectors
− gap may be populated by *e.g.* particles from pile-up
− gap may be outside acceptance of central detector

Method 2 (forward protons):

+ protons are directly measured
+ can be used in pile-up environment
− protons are scattered at very small angles (few μrad)
− necessity to install forward proton detectors far from IP and with limited acceptance

Run 2 and Run 3 Optics

- Settings of LHC elements is named optics.
- Optics is often named accordingly to value of betatron function at collision point: β^*.



2023-2025: indicative, details may vary !

2016-2018:

- Constant β^*: 40/30 cm
- Levelling of β^* in 3 steps: 30 cm $\rightarrow$ 25 cm,
- Levelling of θ^*_C in steps (270$\rightarrow$250$\rightarrow$230$\rightarrow$215 or 270$\rightarrow$230$\rightarrow$215$\rightarrow$195) or continuous (300$\rightarrow$240).
- Achromatic Telescopic Squeezing (ATS) – magnetic field will not change around IP1 during β^* levelling $\rightarrow$ less complicated unfolding of proton kinematics.

2022 – levelling (ATS)

- 10 steps in β^*: 60 cm $\rightarrow$ 30 cm after 5h,
- Change of crossing angle only at the beginning of run (60 cm step) from 170 to 160 μrad; afterwards constant value of 160 μrad,

2023-2025 – levelling (ATS)

- 21 steps in β^*: 120 cm $\rightarrow$ 25 cm after 12h,
- change of crossing angle only at the beginning of run (120 cm step) from 170 to 135 μrad; afterwards certain value for each β^* (change from 135 to 160 μrad), change of crossing angle will make a difference $\rightarrow$ to be addressed in the proton reconstruction procedure.