Overview of ATLAS Forward Proton Detectors:
Status, Performance and Physics Results

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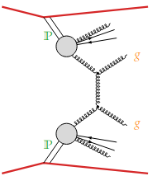
Outline

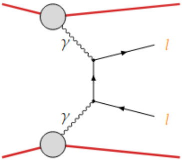
1. Physics Motivation
2. AFP Overview
   - Stations and systems
   - Proton trajectories & Optics
   - Reconstruction
3. AFP Performance
   - Local and Global Alignment
   - Reconstruction efficiency
   - Proton kinematics resolution
   - ToF
4. Physics Results
   - Exclusive Lepton Production
   - ALP searches
5. Conclusions & Outlook

Physics Motivation

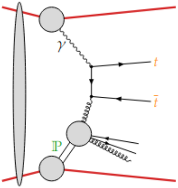
Double Pomeron Exchange Jets



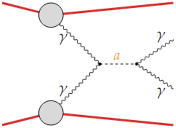
Exclusive Di-leptons



Diffractive $t\bar{t}$

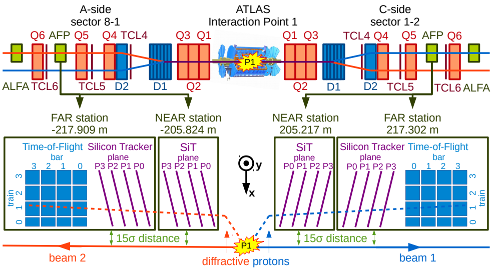


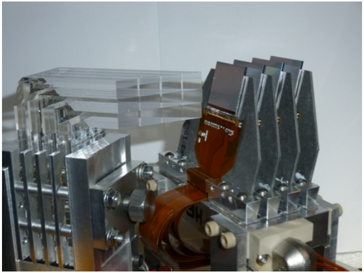
Axion-like Particles



- Variety of collisions at the LHC result in processes having one or both intact interacting protons.
- In order to have such proton "survive" interaction, its quantum numbers must not be changed (i.e. color singlet exchange):
  - electromagnetic interaction: photon,
  - strong interaction: so-called Pomeron.
- Characteristic observables:
  - rapidity gaps: can are easily "destroyed" due to presence of pile-up,
  - scattered protons: need of dedicated, "forward" detectors.
- Very rich programme: from QCD and electroweak measurements to Beyond the Standard Model Searches.

Atlas Forward Proton Detector

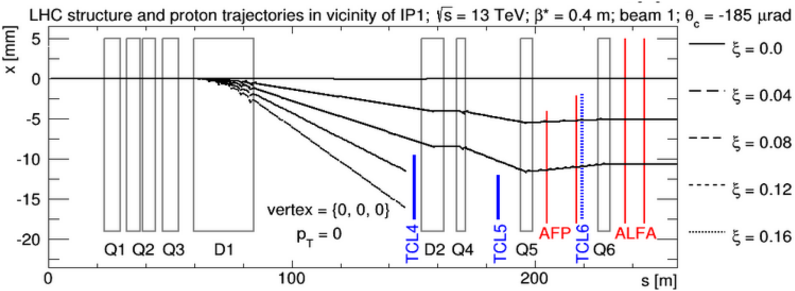




- Two Roman pot stations, called NEAR and FAR, on each side of ATLAS, $\sim$ 210 meters from its interaction point.
- Silicon Tracker (SiT): a set of four planes in each Roman Pot (RP) station:
  - matrix of 336 x 80 3D silicon pixels,
  - 50 x 250 x 230 μm pixel size,
  - 14° plane tilt to improve resolution,
  - measured resolution: $\sigma_x = 6\ \mu$m, $\sigma_y = 30\ \mu$m.
- Time-of-flight (ToF): reduce background by reconstructing the primary vertex z-coordinate:
  - matrix of 4 x 4 L-shaped quartz bars organized in 4 trains,
  - train thickness 3/3/5/5.5 counting from the beam,
  - tilted at Cherenkov angle to guide light induced by passing protons,
  - measured resolution: $\sigma_t \approx 25$ ps.

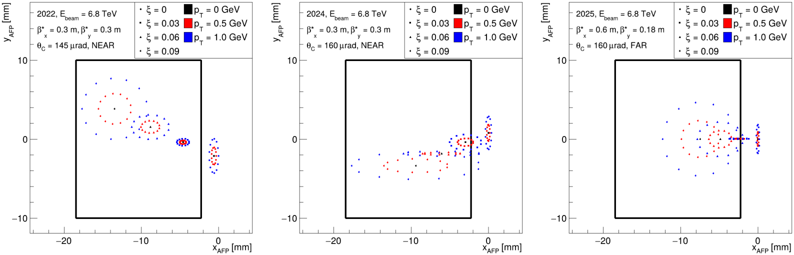
Scattered Proton Trajectories

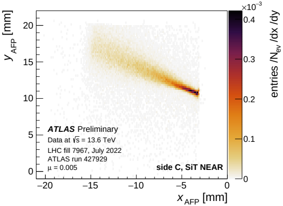
- Position of scattered proton depends on:
  - magnetic field of LHC elements, here dipoles (D) and quadrupoles (Q),
  - energy loss on the interaction $\xi = 1 - \frac{E_{proton}}{E_{beam}}$,
  - proton transverse momentum p_T,
  - (x, y, z) location of interaction vertex.
- Proton presence at the detector location is limited by LHC aperture and collimators (TCL4, TCL5) $\rightarrow$ high-ξ cut.
- Beam-detector distance sets limits on the minimal ξ.



LHC Optics: Scattered Proton Positions at AFP

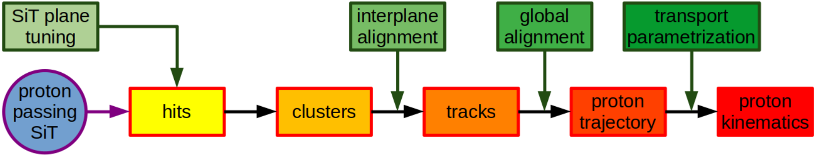
- During Run 3 LHC operates with various settings of magnetic fields in vicinity of experiments.
- Each setting, called optics, has an impact on proton positions.
- On plots – examples of settings used during:
  - 2022 and 2023 (left): nominal settings of inner triplet (IT; i.e. Q1+Q2+Q3), vertical crossing angle (θ_C),
  - 2024 (middle): inverted polarity of IT, vertical θ_C,
  - 2025 (right): nominal settings of IT, horizontal θ_C,





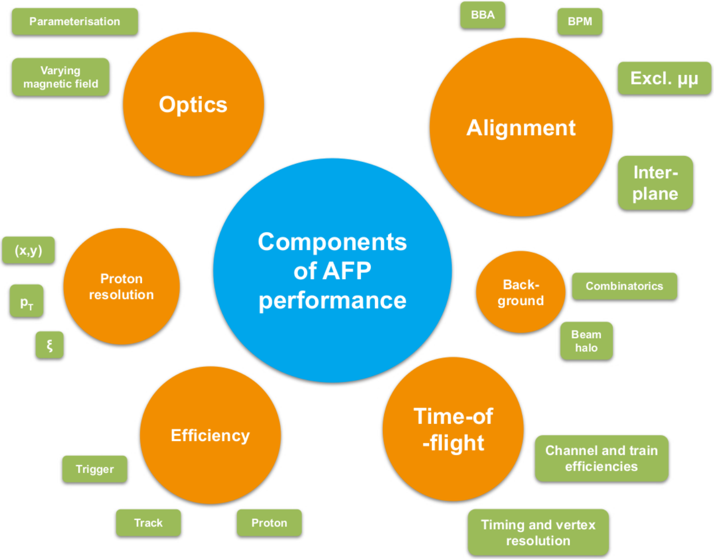
- Example – hit pattern in AFP C NEAR station during one of 2022 runs:
  - clear agreement with expectations,
  - limits due to detector geometry clearly visible and pot-beam distance.

SiT: Proton Reconstruction



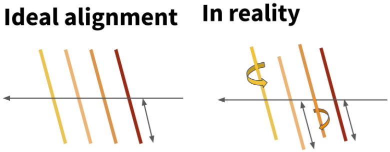
- SiT detector register the passing of particles as hits on its planes.
- A clustering algorithm group hits into clusters within a given plane.
- From clusters, particle tracks are reconstructed using either a custom-written "overlay algorithm" or a Kalman filter:
  - considering relative position of planes wrt. each others – so-called inter-plane alignment,
  - using events with at least three (can be lowered to 2) planes with registered clusters.
- Using information about track position in NEAR and FAR station, proton trajectory is reconstructed, taking into account position of a station wrt. proton beam – so-called global alignment.
- Information about proton trajectory, together with knowledge of the LHC optics (transport parametrization) is used to reconstruct proton kinematics.

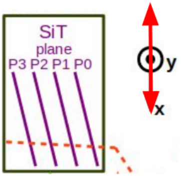
Detector Performance

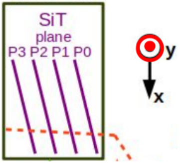


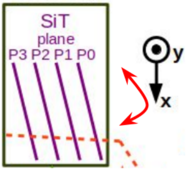
Performance Studies: Inter-plane Alignment

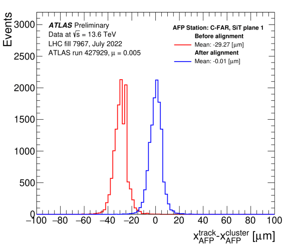
- One plane (P0) is fixed, others are aligned wrt. it using data-driven methods.
- Two translations: x (along pot movement direction) and y (vertical); and one rotation α (around z) are considered.
- Performance plots can be found here.

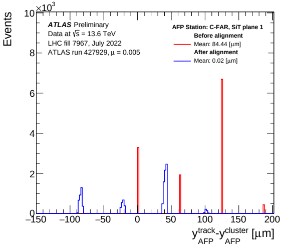


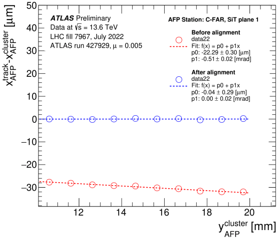






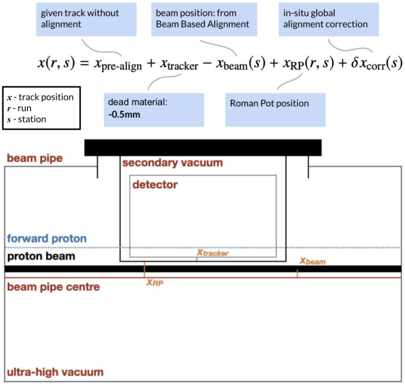


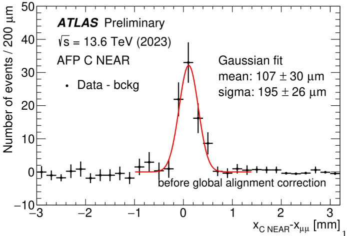




Performance Studies: Global Alignment (using di-leptons)

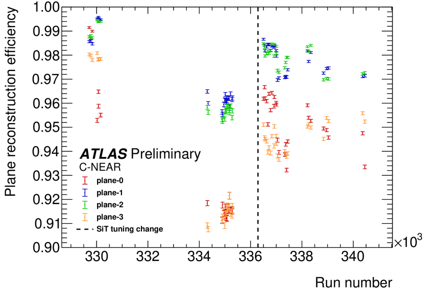
- Tracker is precisely positioned inside the pot during the installation process (height calibration).
- Beam-pot distance is obtained during a dedicated procedure called Beam Based Alignment.
- Roman pot position is measured using motor steps count and, independent, readout from Linear Variable Differential Transformer.
  - Recent studies provide also information about pot rotation during the insertion.
- In-situ global alignment correction is obtained using exclusive di-lepton production process $pp \to pl^+l^-p$:
  - exclusivity criterion: kinematics of proton and lepton systems should match,
  - in practice: proton position measured in AFP is compared to the one calculated from di-lepton system.
- Example (bottom plot): difference in "proton" position computed from di-muon kinematics and from AFP track reconstruction.

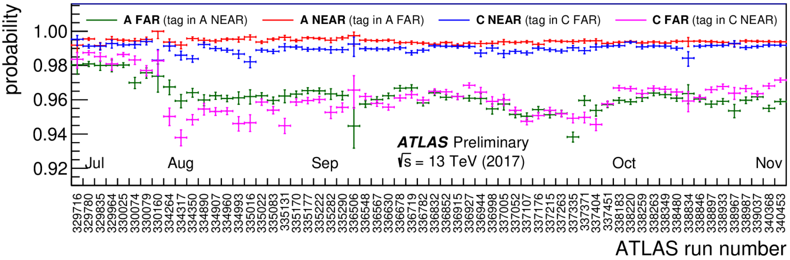




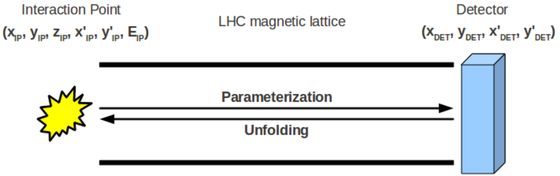
Performance Studies: Cluster and Track Reconstruction Efficiency

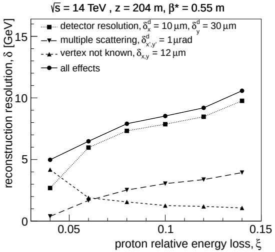
- Up to now, cluster reconstruction efficiency remains high, usually above 98%.
  - An example of C NEAR during 2017 data-taking is shown on right plot.
  - Note that during some periods of data-taking, due to more general issues some SiT planes were off causing, naturally, plane efficiency going to 0.
- Track reconstruction efficiency also remains high.

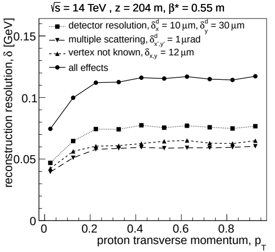




Performance Studies: Proton Kinematics Reconstruction Efficiency



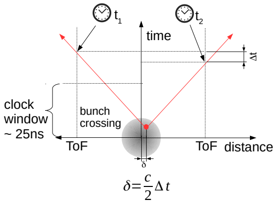




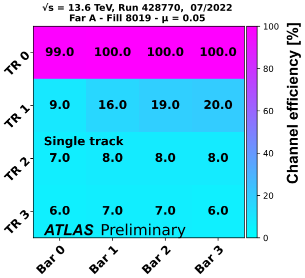
- Six parameters are needed to describe proton trajectory: (x, y, z) position and (p_x, p_y, ξ).
- Four independent parameters are measured at AFP: (x, y) position at both NEAR and FAR stations.
- Assuming knowledge of LHC optics and omitting information about production vertex allow to reconstruct proton kinematics using information about track position registered in AFP.
- Several items contribute to proton kinematics reconstruction inefficiency, the three main ones being (see right figures):
  - SiT detector reconstruction resolution,
  - lack information about interaction vertex (assuming production at $(0, 0, 0)$),
  - multiple scattering of proton.
- Faulty pixels, degradation of reconstruction efficiency due to radiation burning and misalignment are possible extra causes in actual data → under study.

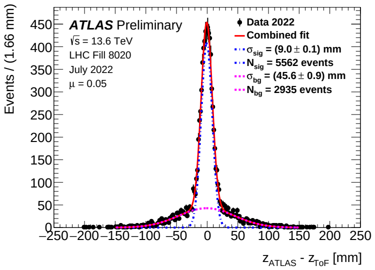
Performance Studies: Time-of-Flight

- AFP Time-of-Flight (ToF) detectors measure the arrival time of the protons, which allows to reconstruct the longitudinal position of the event: $z_{ToF} = \frac{c}{2} t_A - t_C$.
- Comparison of ATLAS vertex to ToF allows to reduce background by neglecting events not originating from the same interaction.

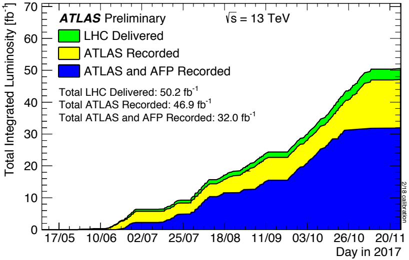


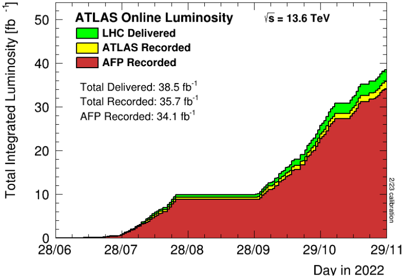
- During LHC Run 2 ToF achieved a very good reconstruction resolution, but suffered from significant inefficiency.
- At the beginning of Run 3 ToF efficiency was good and the achieved vertex reconstruction precision was: $9.0 \pm 0.1 mm$ (30 ps).
  - During Run 3 the efficiency significantly degraded → under investigation.

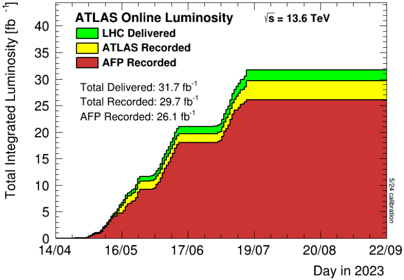


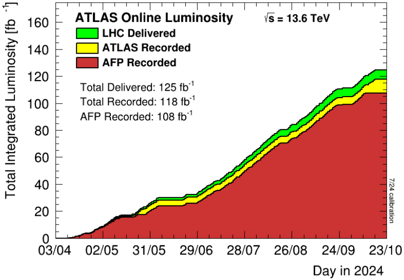


Physics Results



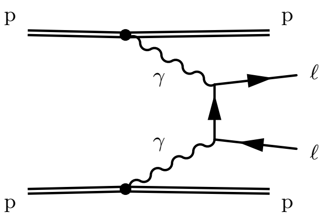


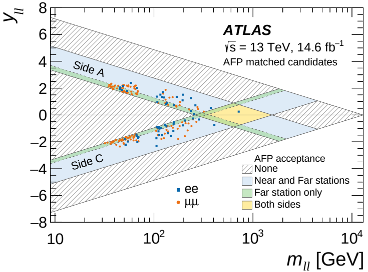




Exclusive Lepton Production (I)

- Motivation: direct observation of proton-tagged di-lepton production via photon fusion: $\gamma\gamma \to \ell^+\ell^-$:
  - two channels: e^+e^- and $\mu^+\mu^-$,
  - strong background rejection due to presence of scattered proton and proton-leptons kinematics match.
- Analysis done using 14.6 fb^{-1} collected during $\sqrt{s}$ = 13 TeV pp collisions in 2017.
- Forward-scattered protons were detected in AFP while leptons were reconstructed by ATLAS “central” detector:
  - $\xi_{AFP \leftrightarrow \xi_{\ell\ell}}$ matching ($|\Delta\xi| < 0.005$),
  - Dilepton mass $m_{\ell\ell} > 20\ GeV$, veto $70 < m_{\ell\ell} < 105\ GeV$ (Z/quarkonia),
  - $p_T^{\ell\ell} < 5\ GeV$ + acoplanarity .
- Observation:
  - 57 candidates in $ee + p$ and
  - 123 in $\mu\mu + p$ channel.
- More details are in: Phys. Rev. Lett. 125, 261801 (2020).



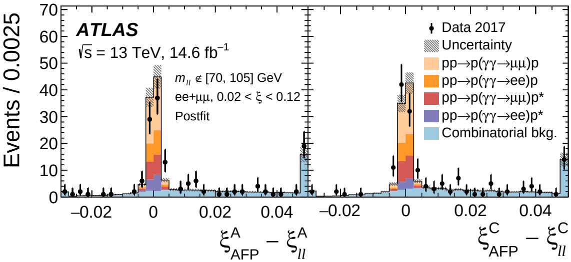


Exclusive Lepton Production (II)

- Fiducial cross-sections:

$$\sigma_{ee+p} = 11.0 \pm 2.6\,(\text{stat}) \pm 1.2\,(\text{syst}) \pm 0.3\,(\text{lumi})\,\text{fb},$$
$$\sigma_{\mu\mu+p} = 7.2 \pm 1.6\,(\text{stat}) \pm 0.9\,(\text{syst}) \pm 0.2\,(\text{lumi})\,\text{fb}.$$

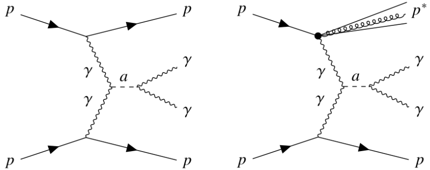
- Background-only hypothesis rejected with $> 5\sigma$ significance.

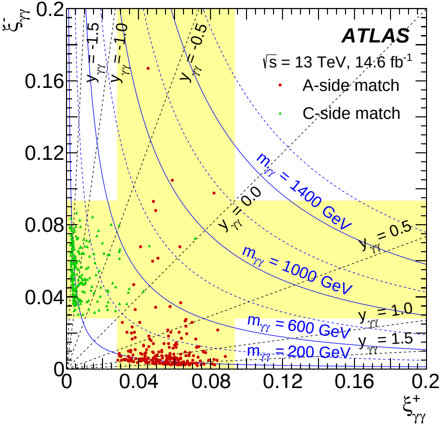


- Besides being a very interesting result, this measurement:
  - demonstrated AFP's capability in high-luminosity environments,
  - showed viability of AFP use to reduce combinatorial background.

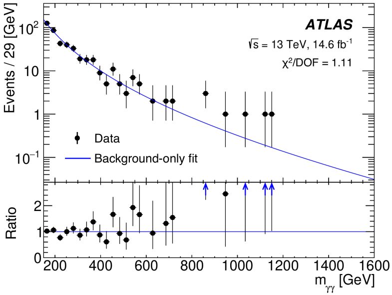
Search for Axion-like Particles (I)

- Axion-like-particles (ALPs) are proposed BSM particles that might act as axions but posses higher masses.
- They may be produced in photon collision and decay into photons → see diagrams.
- This study: look for a resonance in mass range [150, 1600] GeV.
- Analysis is based on kinematic matching between AFP and ATLAS "central" detector:
  - $\xi^{\pm}_{\gamma\gamma} = \frac{m_{\gamma\gamma}}{\sqrt{s}} e^{\pm y_{\gamma\gamma}}$
  - $|\Delta\xi| = |\xi_{AFP} - \xi_{\gamma\gamma}| = 0.004 + 0.1\xi_{\gamma\gamma}$
- 441 events pass event selection for proton tagged on one AFP side; none pass for both sides.
- More in JHEP 07 (2023) 234.

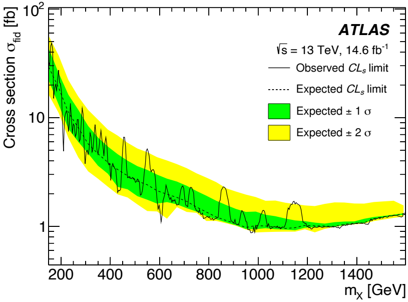


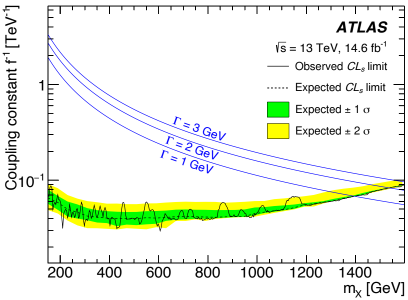


Search for Axion-like Particles (II)



- No significant excess observed above background-only hypothesis.
- Uncertainty dominated by statistics.
- Exclusion limits were set on the cross-section and coupling strength.





Conclusions and Outlook

- Since its full installation in 2017, AFP regularly takes data together with ATLAS "main" detector:
  - ~ 200 fb^{-1} of data recorded at high pile-up,
  - several dedicated, low-μ data-taking campaigns.
- Proton Combined Performance team works hard to deliver final performance of "proton object".
- Results obtained so far clearly show the viability of AFP use to reduce background and demonstrate its capability to operate in the high-luminosity environment.
- Many physics analyses ongoing, even more in plans $\rightarrow$ stay tuned!

Backup