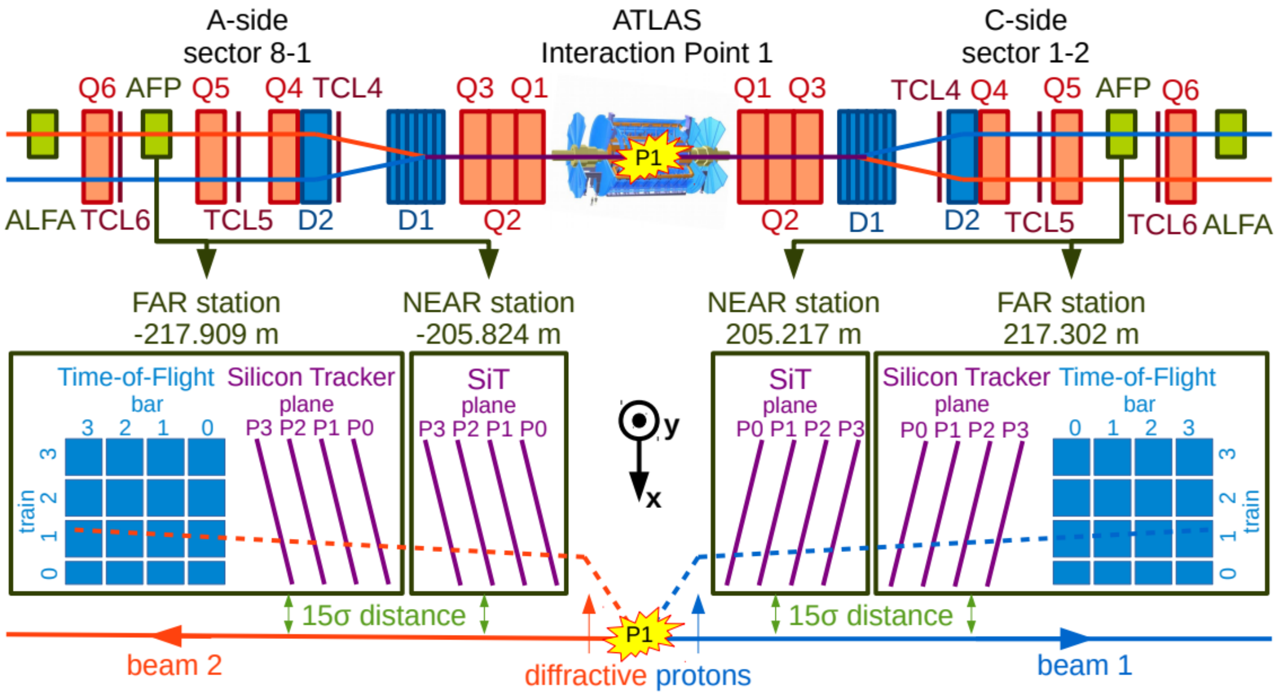
Performance of AFP Detector During 2022

JOSH LOMAS – ON BEHALF OF ATLAS FWD

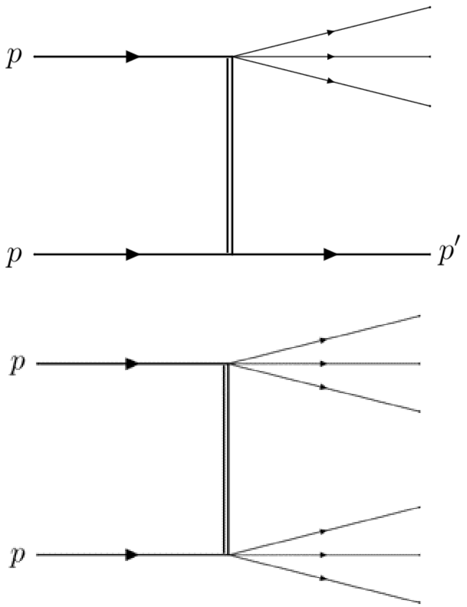
09/06/2023

AFP Overview

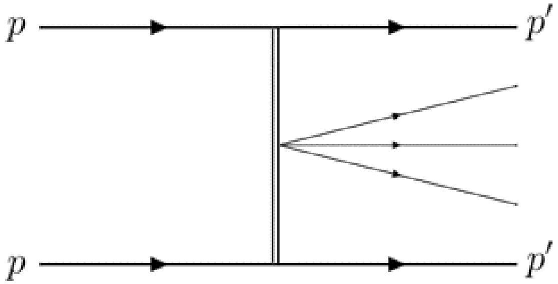
- **AFP** (ATLAS Forward Proton) detects **surviving protons** deflected from the central collision after undergoing **diffractive interactions or pp collisions**
- 4 sets of **3D silicon pixel detectors** (SiT), two (NEAR and FAR) on either side (A and C) of the IP at ~210 m
- Additional **Quartz time-of-flight detectors** (ToF) at each FAR station giving excellent resolution at 20-25 ps to reduce physics background



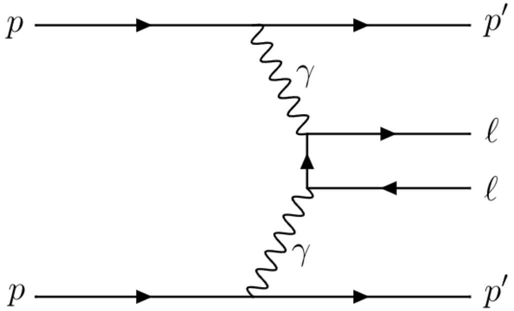
Physics Processes



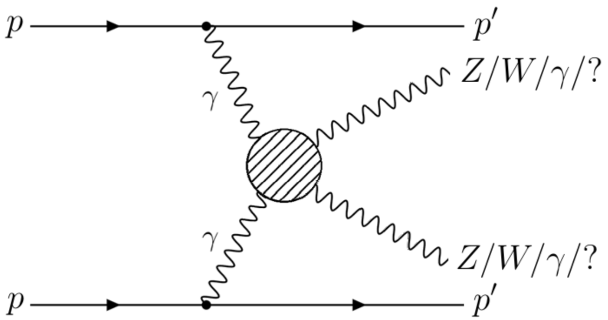
Inclusive diffraction
- Single/double diffractive dissociation



Central Diffraction
- Includes central exclusive production, double-Pomeron exchange, diffractive photoproduction
- Both protons can be detected in AFP
- Central detector signature



Two-photon Processes
- Dominated by diphoton scattering in AFP ξ acceptance
- Dilepton final state has been studied: (PRL 125 (2020) 26, 261801)
- Light-by-light scattering mediated by an axion-like particle: (arXiv:2304.10953)

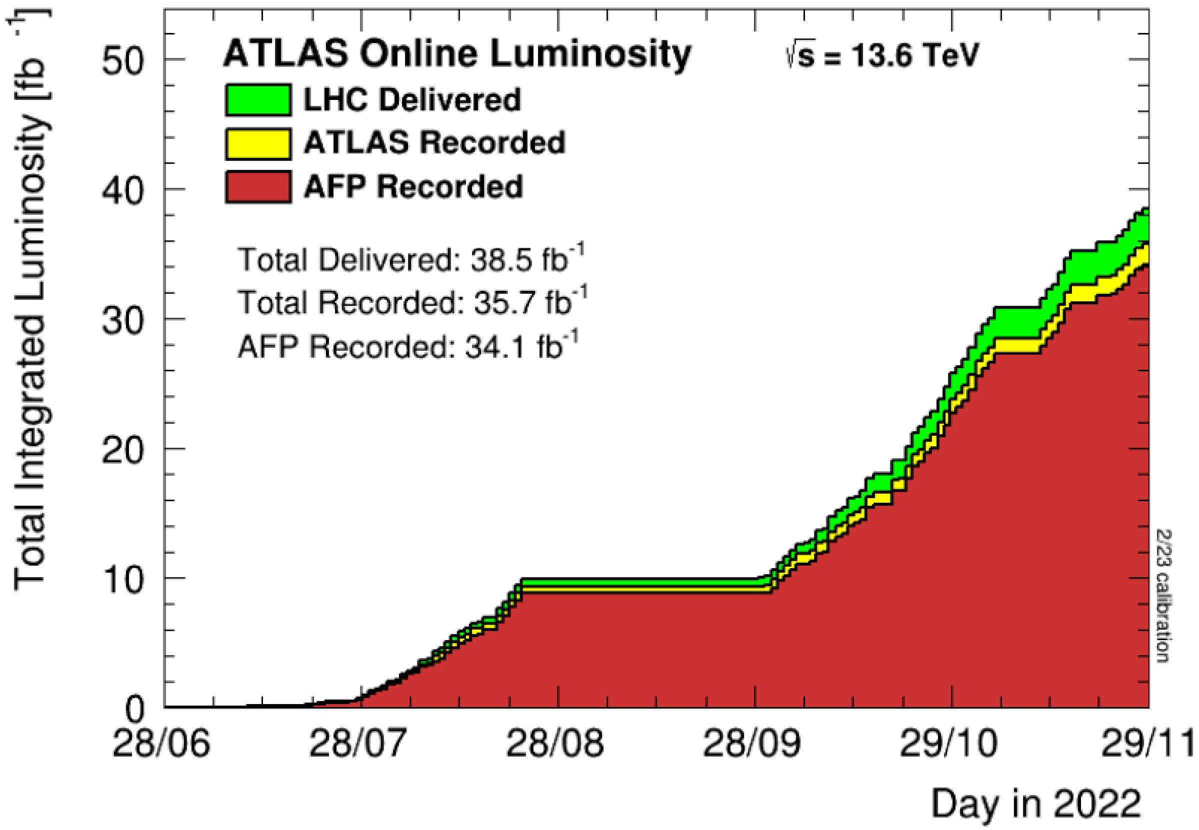


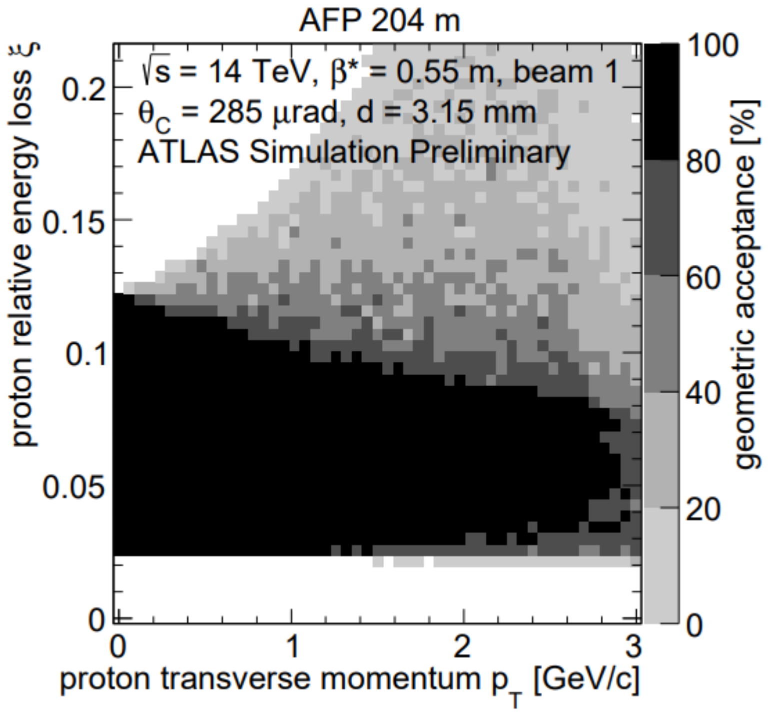
Rare/exotic Processes
- Rare/exotic interactions with BSM couplings
- Final state can include bosons or invisible/exotic particles

Decreasing Cross Section

AFP Collected Data

- **34.1 fb^{-1}** recorded in 2022 with $\sqrt{s} = 13.6\,\mathrm{TeV},\ 0.3 < \beta^* < 0.6\,\mathrm{m}$
  - Mainly high luminosity, high pile-up LHC runs
  - Additional special runs (e.g. low-μ, low β*) also performed
- Main observable: $$\xi = 1 - \frac{E_{\mathrm{proton}}}{E_{\mathrm{beam}}}$$
- Typical acceptance: $$0.02 < \xi < 0.12,\ p_T \lesssim 3\,\mathrm{GeV}$$





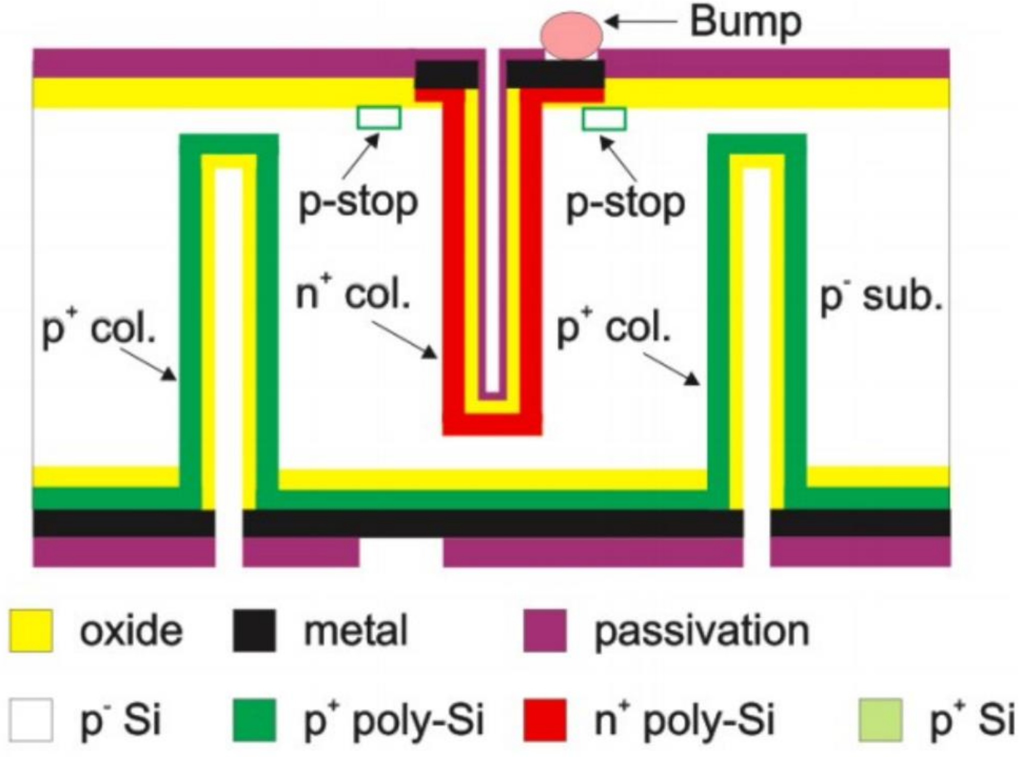
AFP Collected Data

- **Wide range of data types** collected in 2022, each with different physics purposes:

Data Type	μ	Int. Luminosity	Additional Description	Physics Purpose
High-μ	~60	34.1 fb^{-1}	Normal LHC data-taking	High p_T exclusive processes, BSM searches
Medium-μ	13-20	168.2 nb^{-1}	Low-β^* Beam-based Alignment (BBA)	N/A (Calibration data)
Low-μ	0.05	34.6 nb^{-1}	600b low-μ fills	Soft diffraction, low p_T hard diffraction
LHCf	0.02	170 nb^{-1}	LHCf β^* = 19.2 m runs	Diffractive studies, connection to cosmic ray physics
Extremely Low-μ	0.005	0.46 nb^{-1}		Soft diffraction, low p_T hard diffraction, extremely small pile-up background

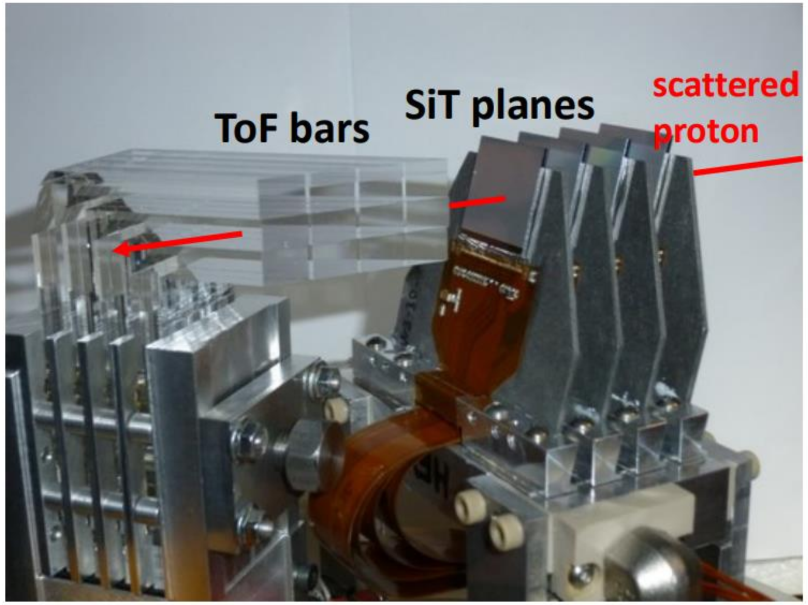
Silicon Tracking Detectors (SiT)

- **Four 3D silicon pixel sensor planes** in each station to determine the horizontal deflection of scattered protons (x) from which ξ and hence the mass of the central system can be determined
- Using the same 3D pixel technology as used in the ATLAS IBL detector
- In 3D pixel sensors, n- and p-type **column-like electrodes** penetrate the substrate defining the pixel configuration
  - Requires **lower bias voltage** and **less cooling** than the standard planar approach
  - Reduced drift path makes 3D devices more **radiation hard**



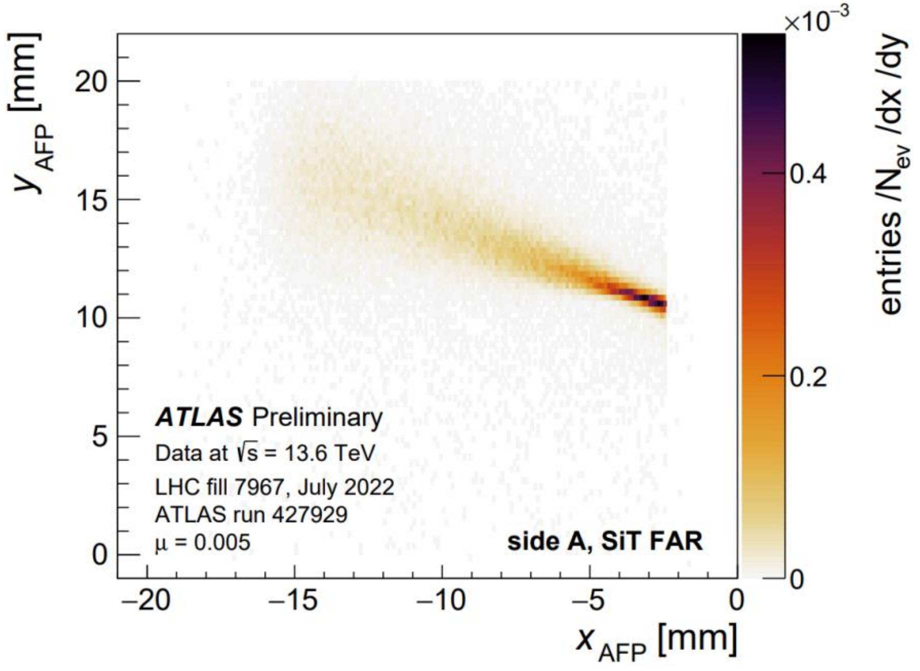
Silicon Tracking Detectors (SiT)

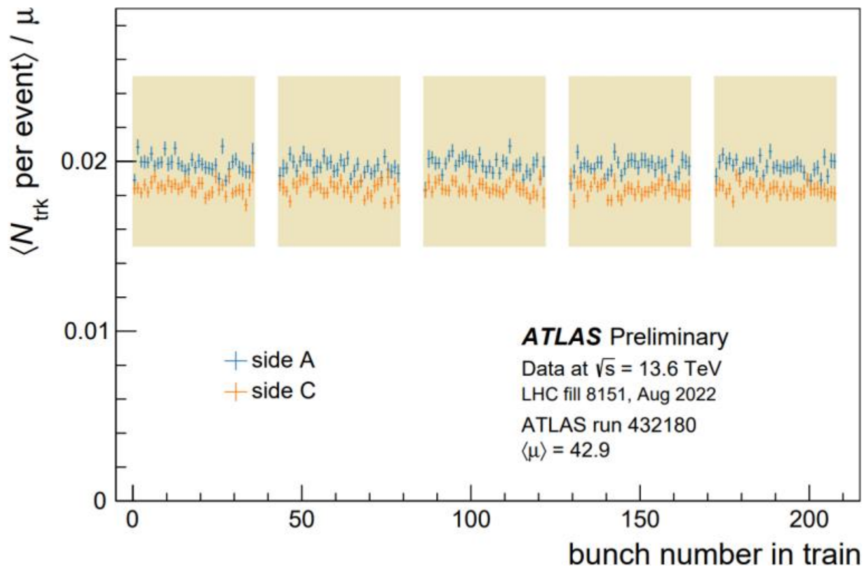
- Each plane has **336 × 80 pixels, 50 × 250 μm²** in size and is 230 μm thick
  - Total active area of 1.68 × 2.00 cm²
  - Per pixel resolution: $\boldsymbol{\sigma_x \approx 6\ \mu m}$, $\boldsymbol{\sigma_y \approx 30\ \mu m}$
  - **Tilted 14°** from vertical to maximise the probability of 2+ pixel hits per track
  - **Slim edge** to approach beam as closely as possible
  - **High radiation hardness** to withstand close proximity to the beam resulting in intense and non-uniform irradiation (up to 3×10^{15} n_{eq}/cm^2 in 3 years)
- Each sensor is connected via bump-bonding to a **FE-I4 readout chip** which in turn is glued and wire-bonded to a flexible printed circuit
  - Readout chip has a **tuneable threshold**
  - Performs **charge measurement** (via Time-over-Threshold)
  - Provides **trigger signal**



SiT Performance

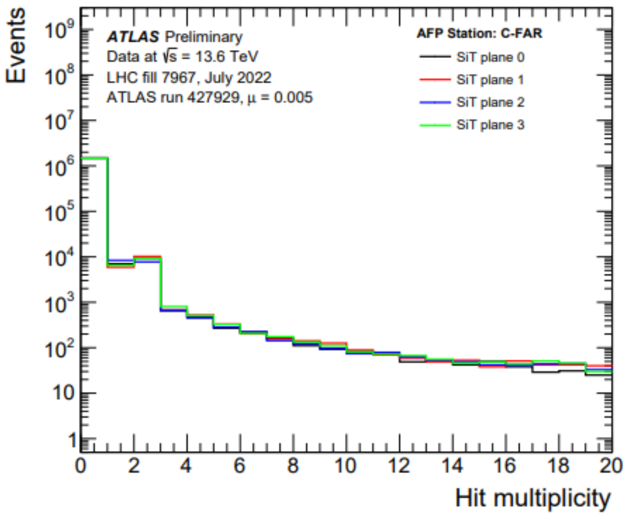
- Positions of tracks reconstructed in AFP for low-μ events triggered by the MBTS trigger, with reconstructed primary vertex and exactly one track in both stations
  - Characteristic **diffractive signal** is visible





- Average track multiplicity for each side weighted by pile-up shows no visible dependence on bunch number in train
  - Indicates **very small deadtime** in the SiT readout.

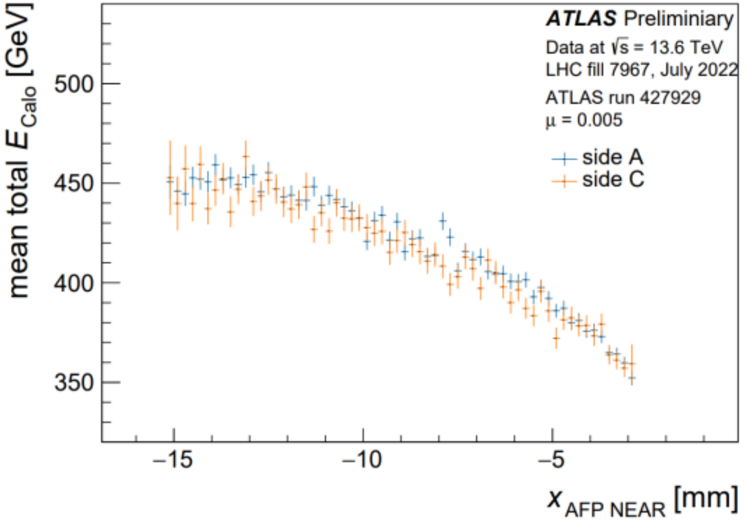
SiT Performance

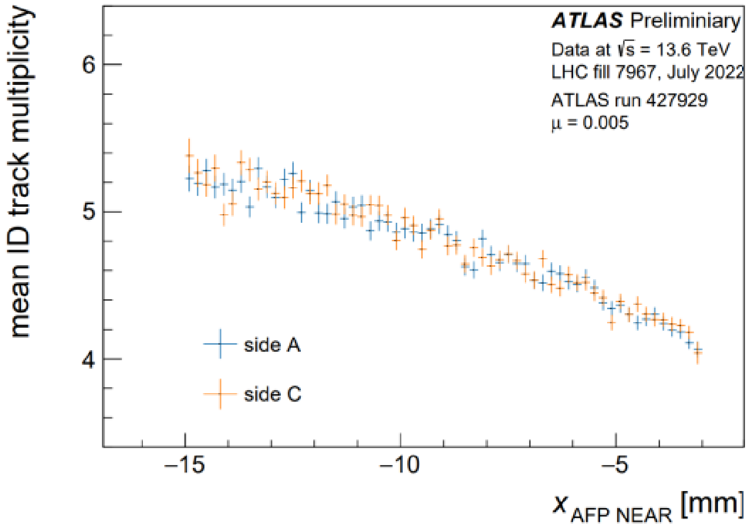


- Hit multiplicity recorded by SiT planes at AFP C-FAR station in low-μ events
  - **Local maximum at two hits** as a result of tilting the planes by 14 degrees
  - Events with zero hits are due to: trigger on side A or on ATLAS central detector (no proton expected on C side) or, much less likely, the plane inefficiency.
  - The tail of the distribution is due to **shower events** mainly from the Roman Pot floor and from upstream interactions with beam instrumentation

- **Correlation** between the x position of reconstructed tracks in Near stations and:
  - **Total energy** measured by the ATLAS calorimeters.
  - **Charged track multiplicity** in the ATLAS Inner Detector.

  in low-μ events

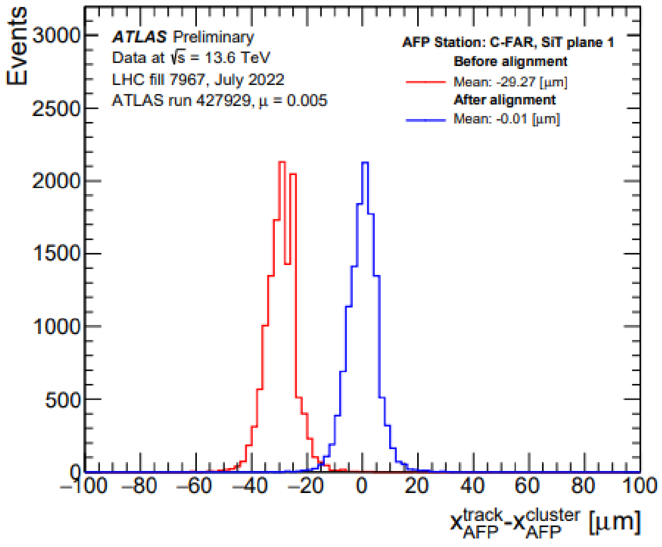


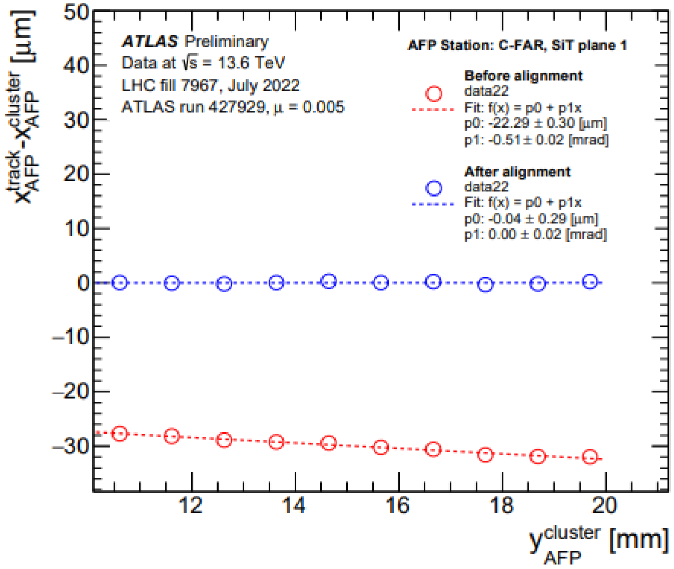


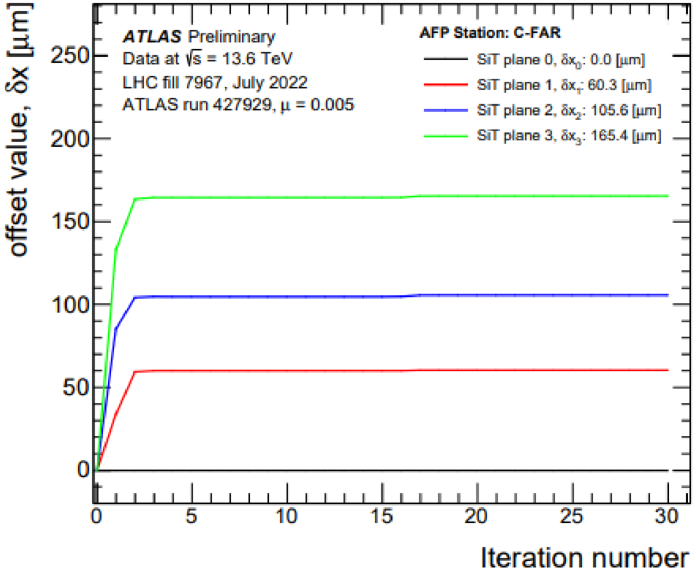
SiT Local Alignment

Alignment Procedure:

- All interplane alignment parameters start at zero
- Residuals between reconstructed tracks and clusters calculated for each plane
- Corrections applied in each axis to reduce residuals



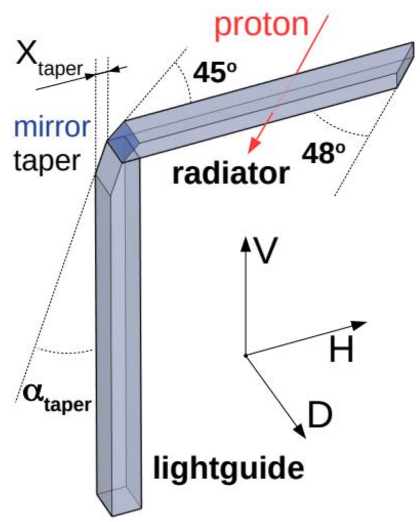


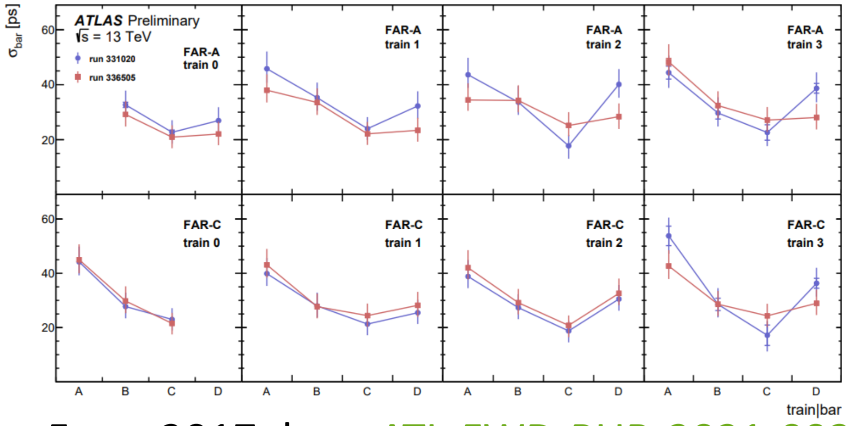


- Comparing distributions of residuals in SiT plane 1 at the AFP C-FAR station with all interplane alignment parameters set to zero and after performing the interplane alignment procedure for low-μ events
  - After alignment, the distribution is **centred around zero as expected**

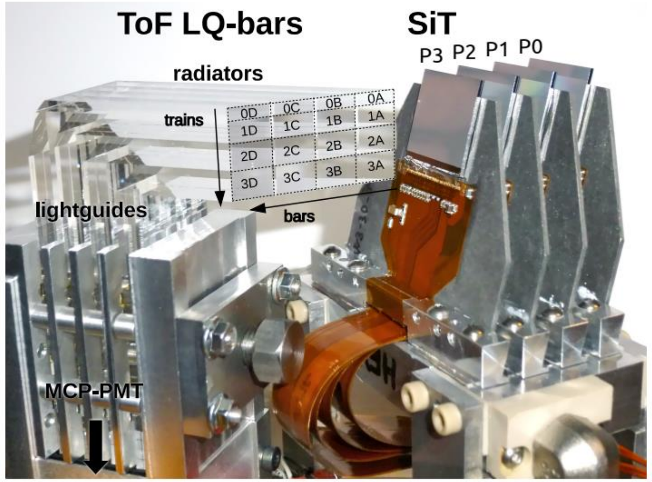
Time of Flight Detectors (ToF)

- One detector present in each **FAR station** to reduce the **combinatorial background** from high pile-up runs via time matching between the two stations
  - Only for double-tag events (one proton per side)
- Measures proton time-of-flight via **Cherenkov radiation** produced by protons traversing a **4 × 4 matrix of L-shaped quartz bars** rotated 48° with respect to the LHC beam
- Photons travel through lightguides and are gathered by the Micro-Channel Plate Multi-Anode PMT (MCPPMT) producing a voltage pulse
- Pulse is processed by the constant fraction discriminator (CFD) and high-performance time-to-digital converter (HPTDC) for time measurement.
- Each bar (channel) provides a measurement of time
- Set of four bars is called a **train**
- Run 2 full-train time resolution: **20 ± 4 ps (side A) and 26 ± 5 ps (side C)**
  - **~6 ± 1 mm z-resolution** of the primary vertex in the central detector

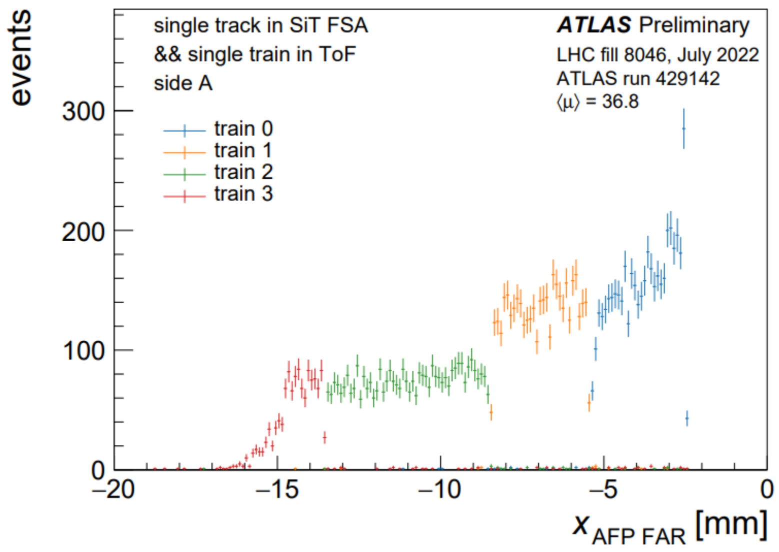


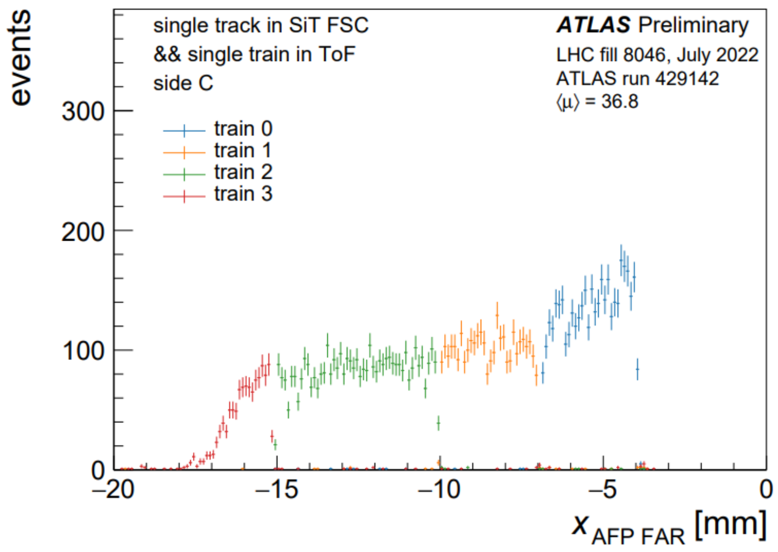


From 2017 data: ATL-FWD-PUB-2021-002



ToF Performance

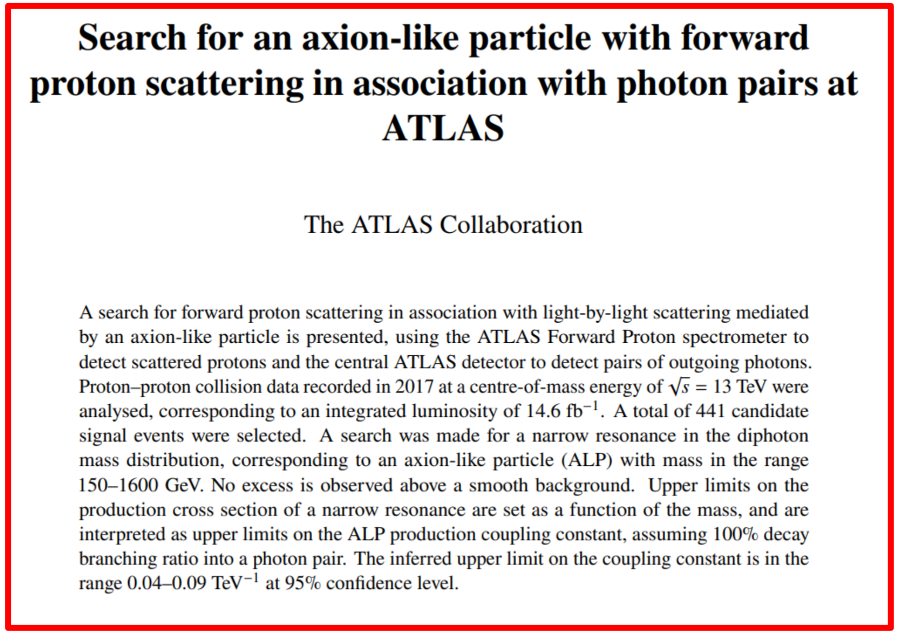




- The x position of the track reconstructed in AFP SiT (FAR station) in events with a single-train signal in ToF detector
  - **Correlation between ToF event rate and SiT position** as expected
  - The differences between sides are due global alignment corrections not being applied

New AFP Publication

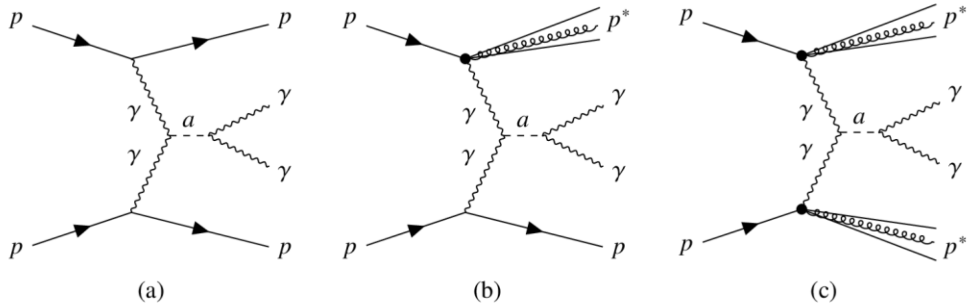
New AFP result published this year searching for **axion-like particles** using 14.6 fb^{-1} of data collected in 2017



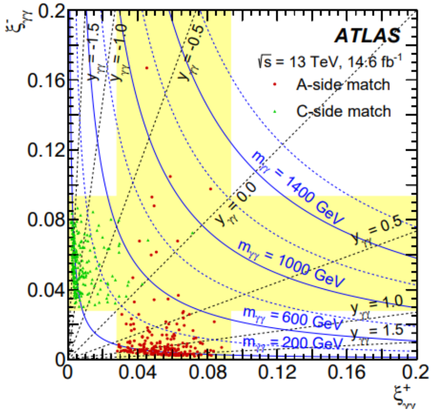
Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS

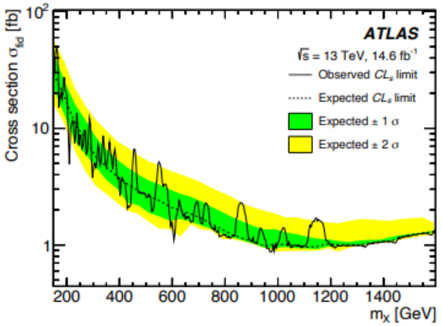
The ATLAS Collaboration

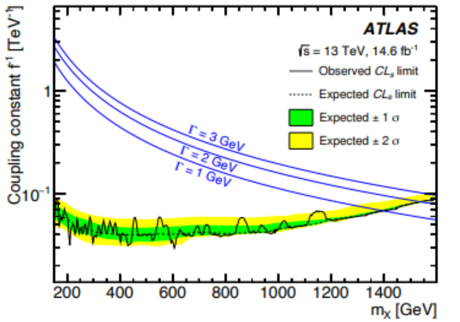
A search for forward proton scattering in association with light-by-light scattering mediated by an axion-like particle is presented, using the ATLAS Forward Proton spectrometer to detect scattered protons and the central ATLAS detector to detect pairs of outgoing photons. Proton–proton collision data recorded in 2017 at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV were analysed, corresponding to an integrated luminosity of 14.6 fb^{-1}. A total of 441 candidate signal events were selected. A search was made for a narrow resonance in the diphoton mass distribution, corresponding to an axion-like particle (ALP) with mass in the range 150–1600 GeV. No excess is observed above a smooth background. Upper limits on the production cross section of a narrow resonance are set as a function of the mass, and are interpreted as upper limits on the ALP production coupling constant, assuming 100% decay branching ratio into a photon pair. The inferred upper limit on the coupling constant is in the range 0.04–0.09 TeV^{-1} at 95% confidence level.



- 441 events observed in the range 150 < $m_{\gamma\gamma}$ < 1600 GeV
- 219 (222) events passed the selection for the A(C)-side
- No event passed for both the A-side and C-side
- Most significant excess observed at m_X = 454 GeV, with local significance of 2.51σ.
- Global p-value for the null hypothesis > 0.5
    - **No significant excess** over the background-only hypothesis is observed.
- Able to reach similar exclusion limits to previous CT-PPS analysis while covering a lower mass region despite ~4 times lower statistics:
    - Using single-tag signature, saving statistics
    - Performant event-mixing method to estimate the combinatorial background







AFP Data-Taking in 2023 so far

- $\sim$ **13.0 fb^{-1} recorded so far** in 2023 with $\sqrt{s} = 13.6\,\mathrm{TeV}$
  - Mainly high luminosity, high pile-up LHC runs ($\mu \sim 60$)

Additional expected runs:

- 400b Low-μ runs expected after TS1 (late June)
  - $\sqrt{s} = 13.6\,\mathrm{TeV},\ 0.3 \lesssim \beta^* \lesssim 1.2\,\mathrm{m}$
  - μ = 1 for 1h, μ = 0.2 for 1h, μ = 0.05 for at least 4h
- Low-B field, low-μ run with Van der Meer optics also planned following TS1
- Strong interest to take part in pp → PbPb reference runs ((short) BBA + Loss Maps needed)
- Participation in all low-μ runs with low β^* optics

Summary

- **Large amount of good data collected in 2022!**
    - 230% increase in available data from 2017
    - All runs are well documented
- Detector performance still to be studied for large portion of the data
- Physics publications continue to be released
- Data taking proceeding well in 2023