UNIVERSITY OF BIRMINGHAM

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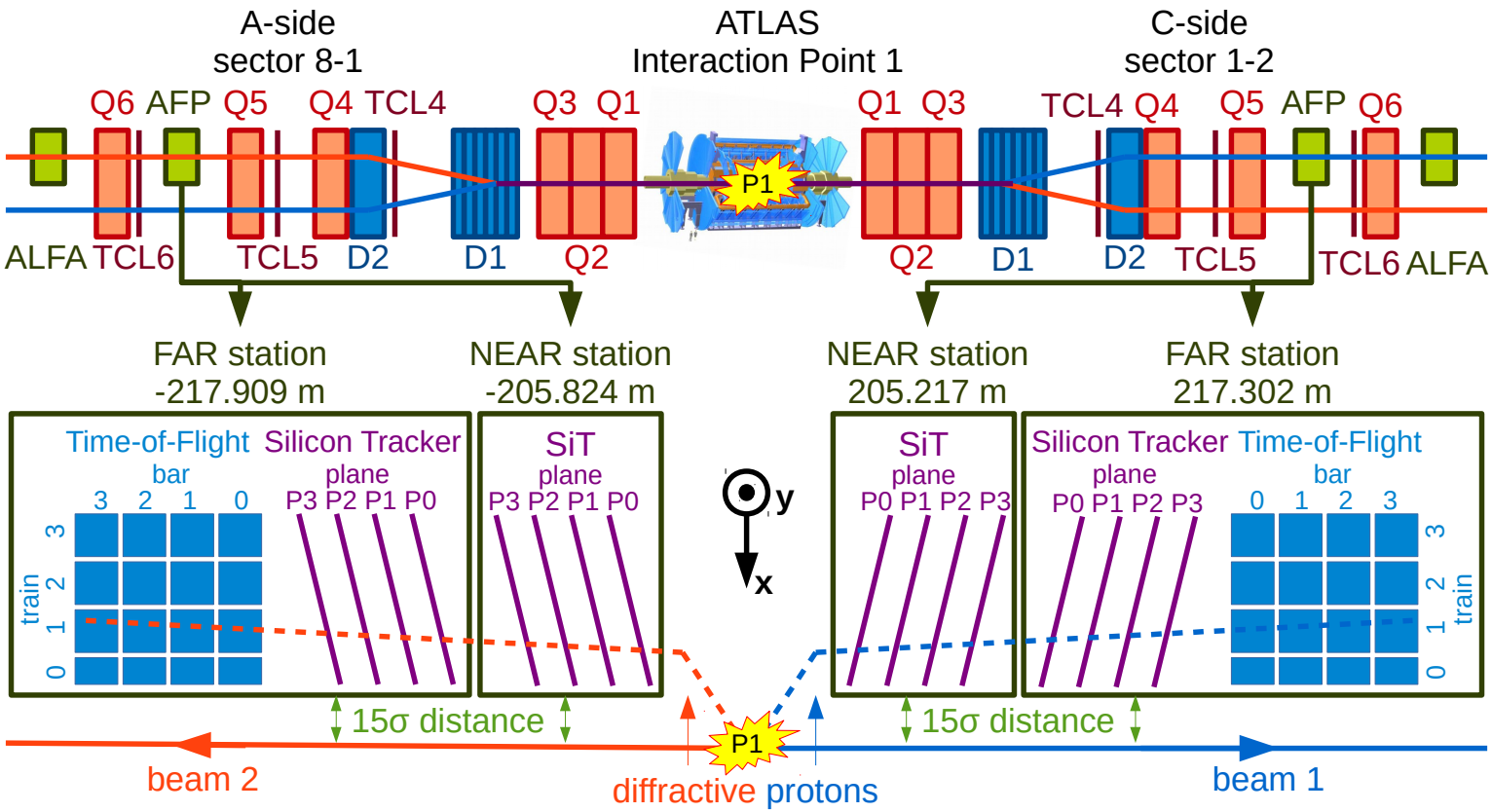
Overview of AFP Detector

Status, performance and new physics results

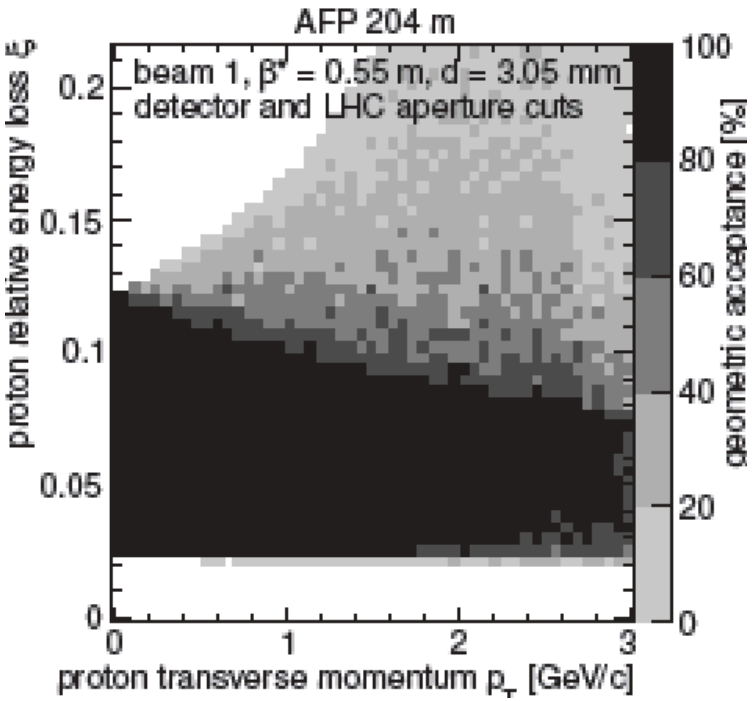
On behalf of ATLAS Forward Detectors

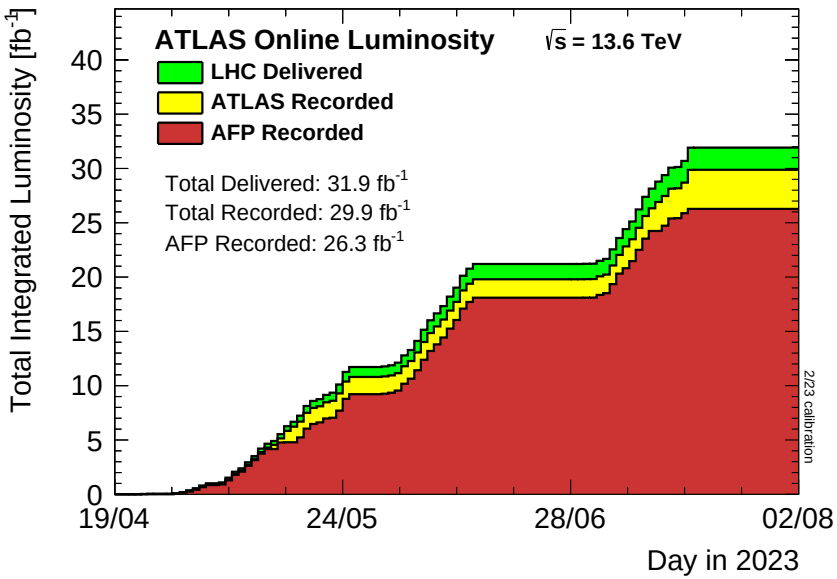
AFP Overview (1)

- 2 stations at $z \simeq 210$ m on each side of IP ("A-NEAR","A-FAR","C-NEAR","C-FAR")
- 4 planes of silicon tracking per stations
- FAR stations also have time-of-flight (ToF)



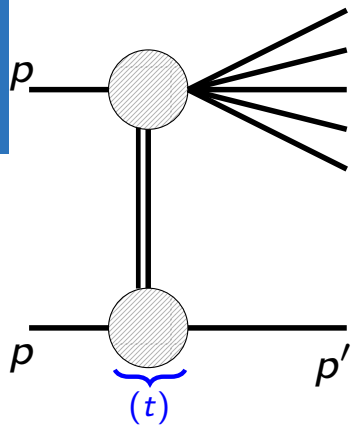
AFP Overview (2)





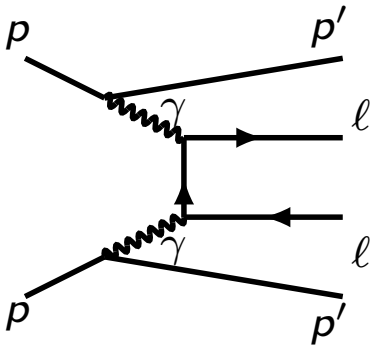
- Acceptance for protons losing $\simeq 2 - 12\%$ of their energy
- $32 + 34.1 + 26.3$ fb^{-1} recorded under high lumi. conditions in resp. 2017, 2022, 2023
  $\Rightarrow$ Revolutionary dataset for tagged proton physics
  $\Rightarrow$ Additional special runs (low μ, LHCf with 19.2m optics) also performed

Physics processes - examples



- Single proton diffractive dissociation
- Very large cross section ($\simeq 15\%$ of σ_{tot})
- Dominant source of protons in AFP (pile-up)

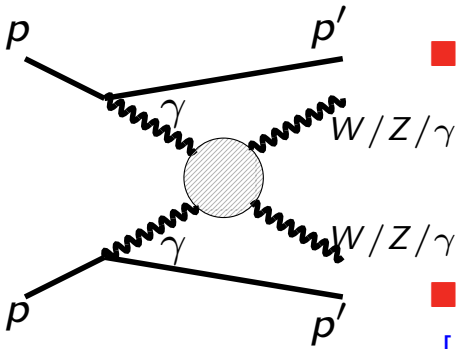
Large cross section



- Processes with two final state protons dominated by $\gamma\gamma$ scattering in ξ acceptance region
- Dileptons : Subject of first AFP publication
- Important calibration tool due to exclusivity

[ATLAS-CONF-2020-041]

Low cross section

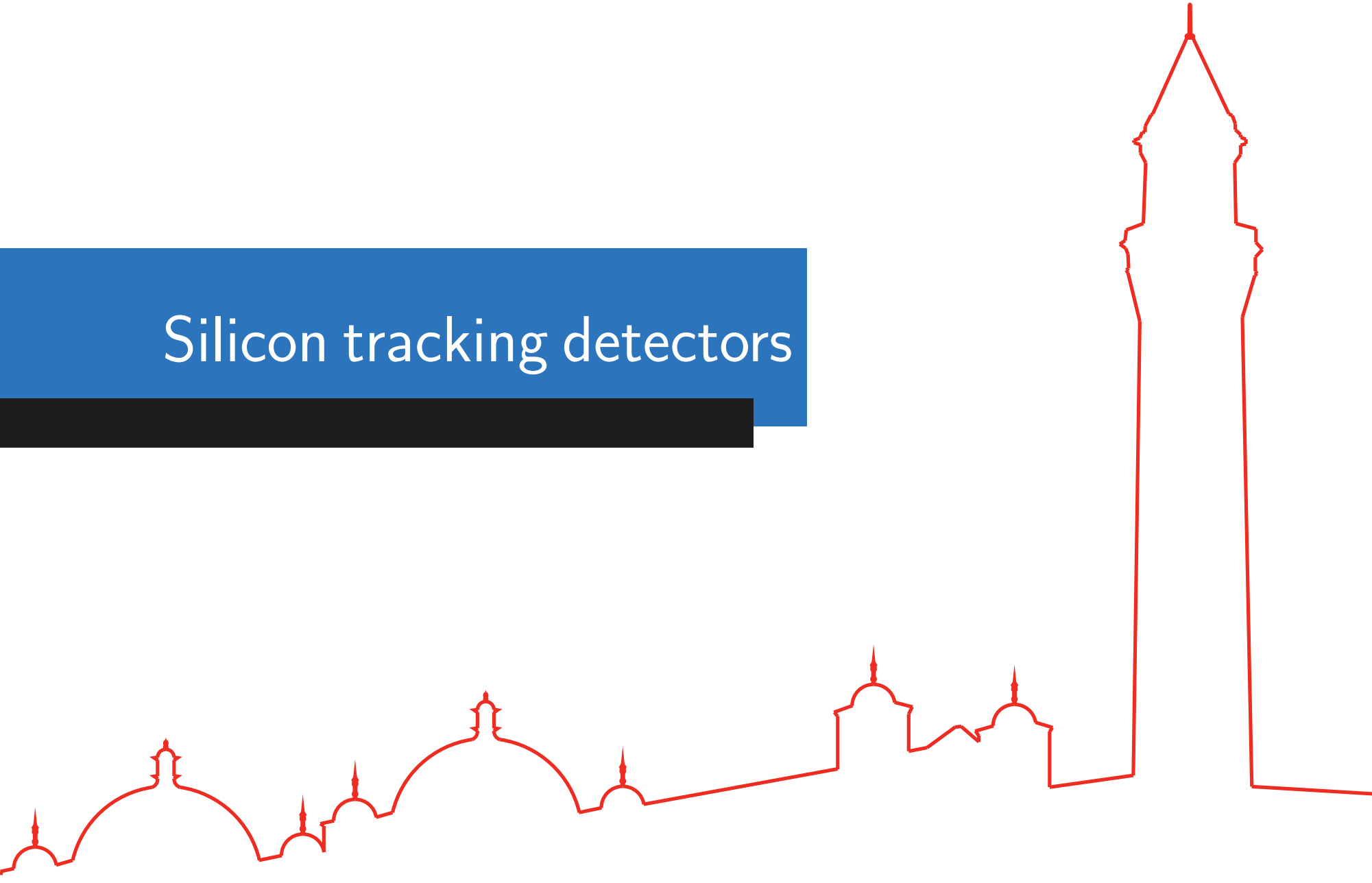


- Longer-term AFP program is mainly rare and exotic processes with $\gamma\gamma$ initial state and two tagged final state protons
- ALP search : Subject of recent AFP publication

[JHEP 07 (2023) 234]

Low cross section / Exotic

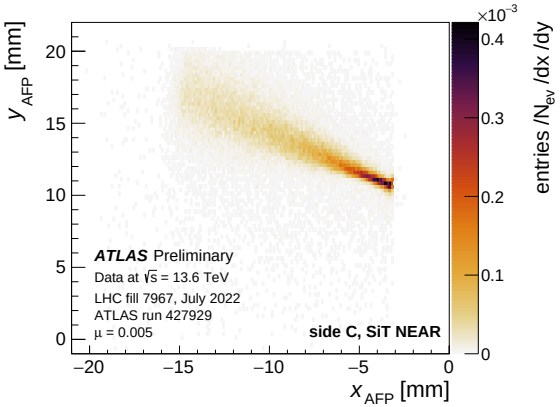
Silicon tracking detectors

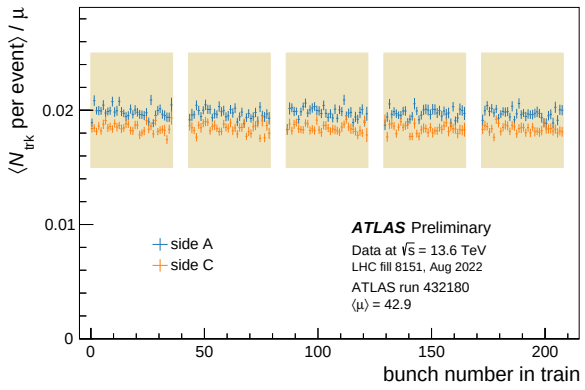


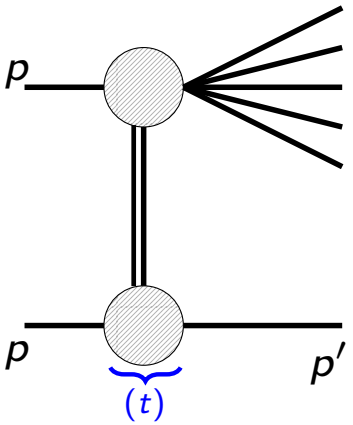
SiT overview

- Matrix of 336 $\times$ 80 3D pixels, 50 $\times$ 250 μm^2, resolution of $\sigma_x \simeq 6$ μm, $\sigma_y \simeq 30$ μm
- 3D silicon pixel sensor planes
  - Technology also used in ATLAS IBL detector
  - Requires lower bias voltage and less cooling than planar approach
  - More radiation hard due to reduced drift path
- 14° angle to vertical results in two pixel hits per plane in most cases
- 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
- Determine deflection in x direction $\rightarrow \xi$ (proton energy loss) $\rightarrow$ mass of central system

Reconstructed proton signal





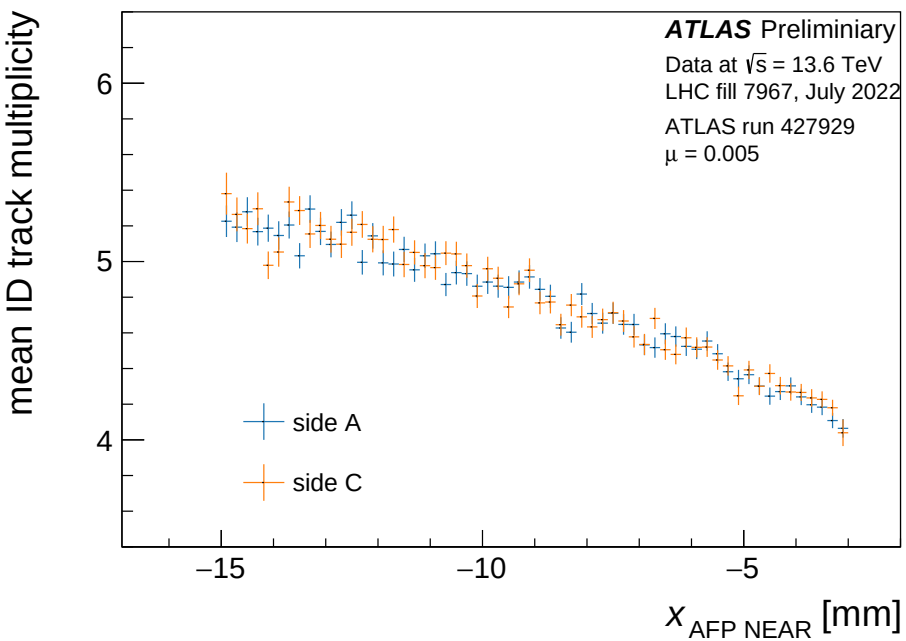


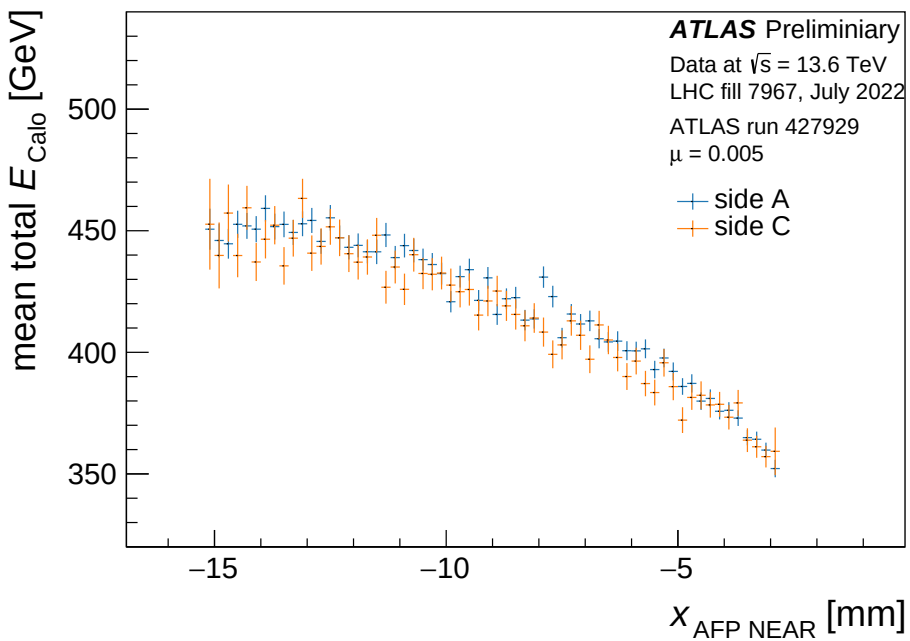
- Characteristic diffractive signal (dominantly single dissociation $pp \to pX$)
- Average track multiplicity for each side weighted by pile-up shows no visible dependence on bunch number in train (*i.e* very small deadtime in the SiT readout)

Correlation with ATLAS

- Correlation (in low-μ events) between the x position of reconstructed tracks in Near stations and
  - Charged track multiplicity in the ATLAS Inner Detector (*cf. left plot*)
  - Total energy measured by the ATLAS calorimeters (*cf. right plot*)

Plots are for raw data $\rightarrow$ *no corrections have been made for efficiency and migrations in the track multiplicity and calo energy*



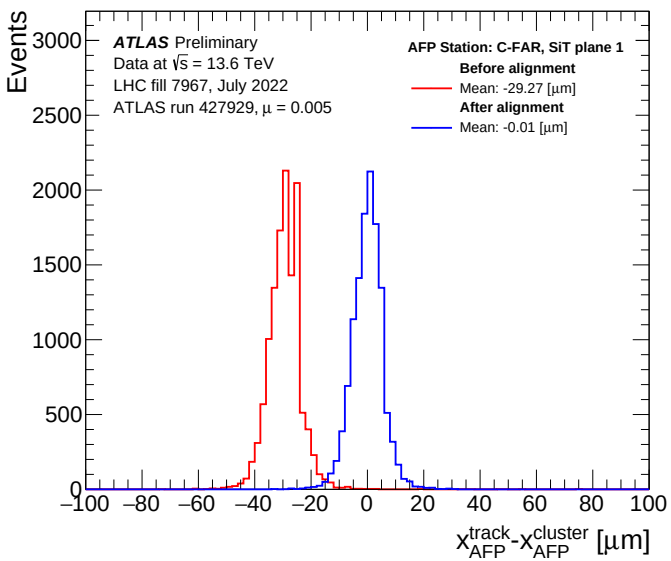


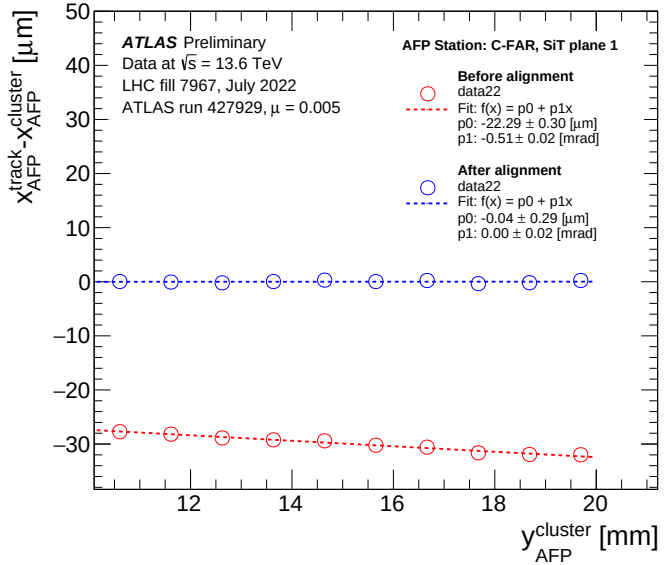
Local alignment

Local alignment of each plane within a station was determined using redundancy with respect to other planes.

- Form residuals (*cf. left plot*) on each plane relative to reconstructed tracks
- Correct for shifts in x and y direction and rotation about z axis (*cf. right plot*)
- Iterate ↻

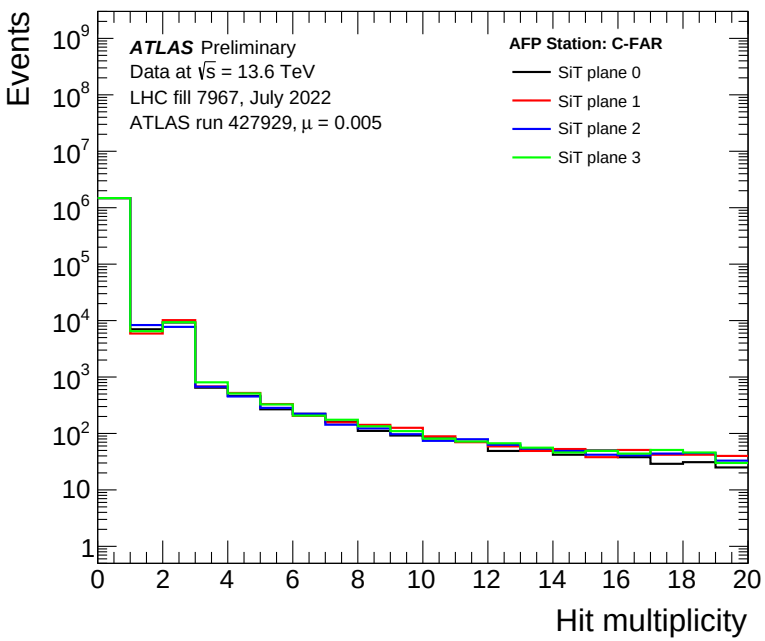
Aligned to better than 10 μm within a Roman pot station

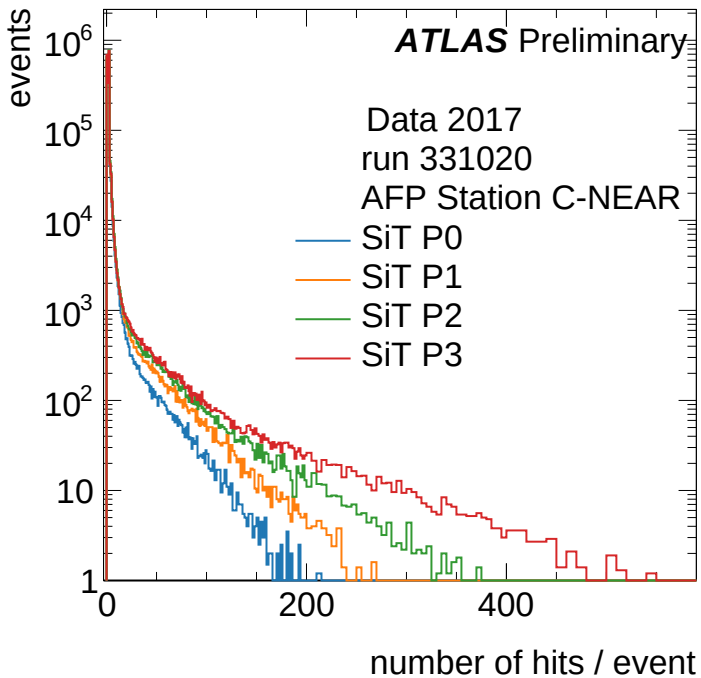




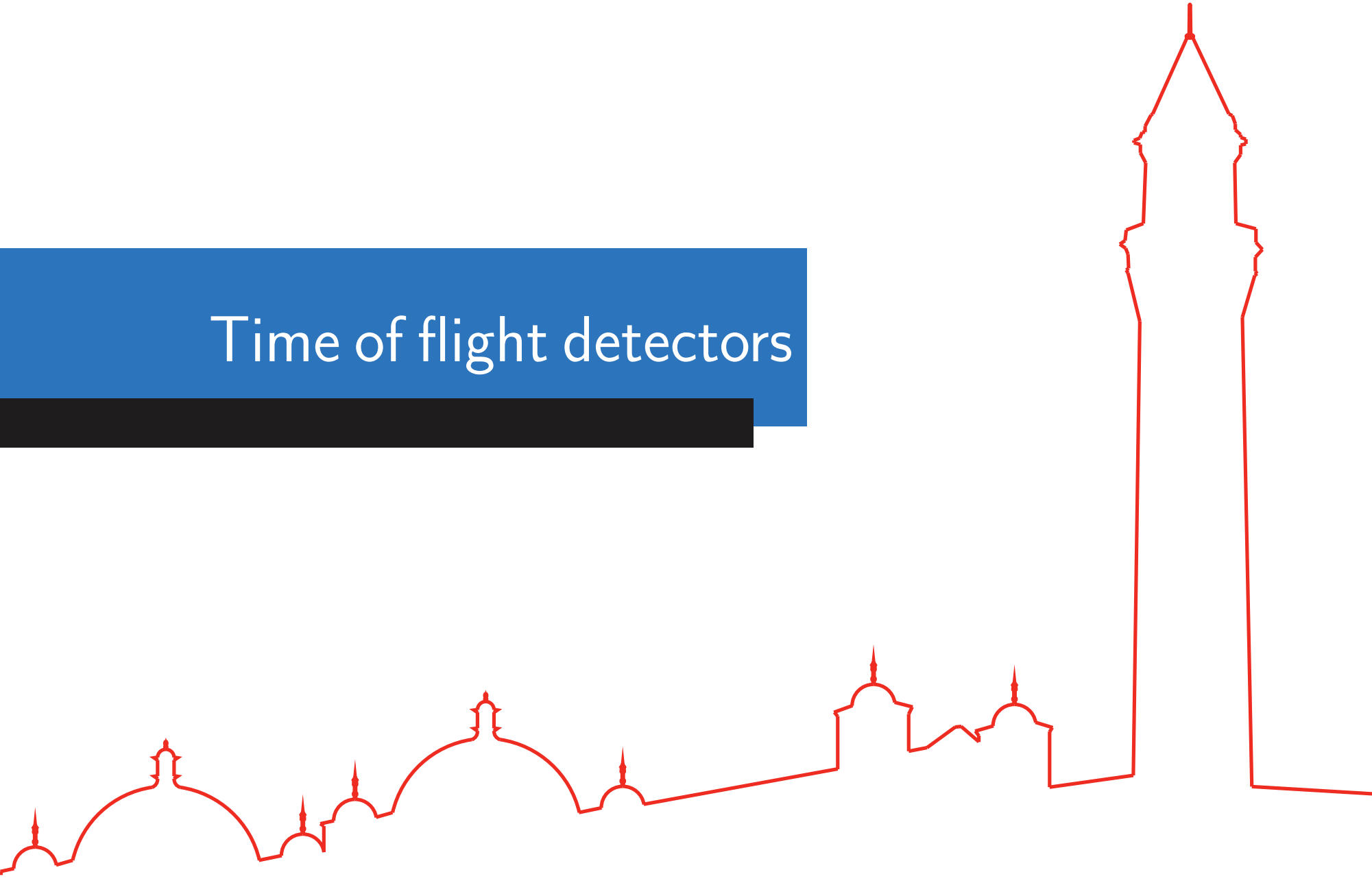
Showering in SiT planes and pot walls

- Local maximum at two hits as a result of tilting the planes by 14°
- 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
- Evidence for interplane showering in material of SiT planes (tail of distribution)
  - Showering also takes place in pot windows and floor
  - Largest contribution to inefficiencies



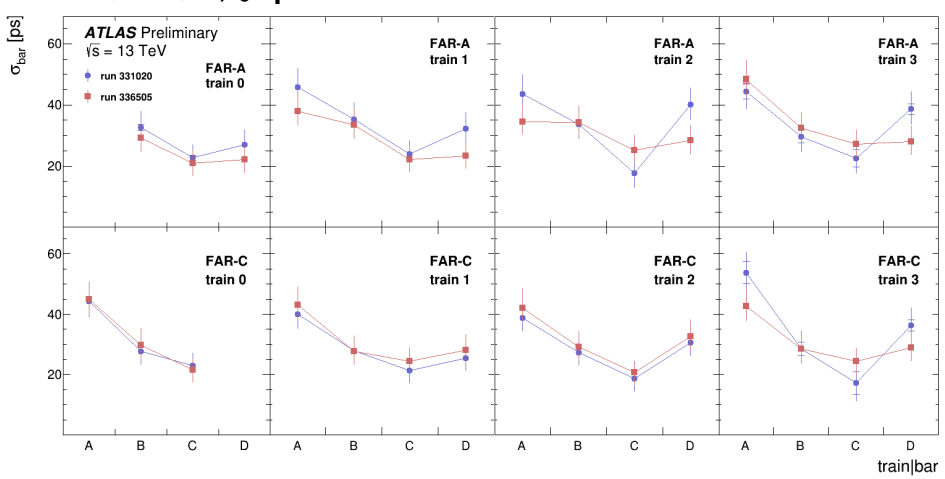


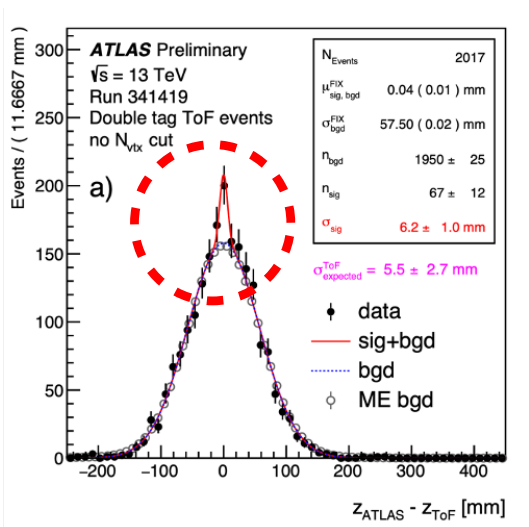
Time of flight detectors



ToF overview / Run 2 performance

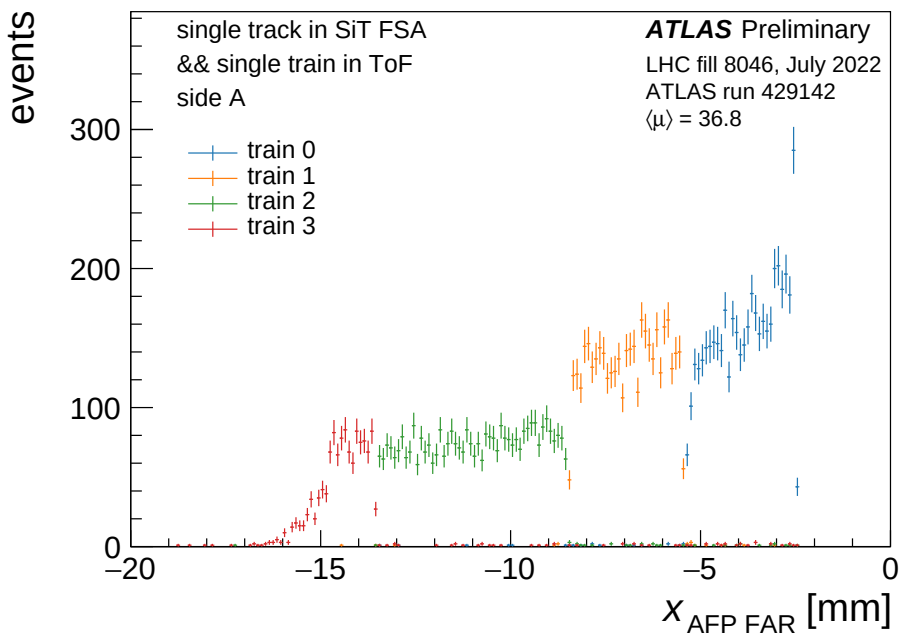
- One ToF module (4×4 matrix of L-shaped quartz bars) present in each FAR station to reduce the combinatorial background from high pile-up runs via time matching between the two stations (double tag events)
- Run 2 performances :
  - Time resolutions at 30 ps level for single channels ($\simeq$ 20 ps when integrated over train) (*cf. left plot*)
  - Corresponding vertex resolution $\simeq 6 \pm 1$ mm (*cf. right plot*)
  - Poor efficiencies in first AFP runs (PMTs degraded fast)
    - 1-9 % single channel
    - 5-10 % per 4-bar train

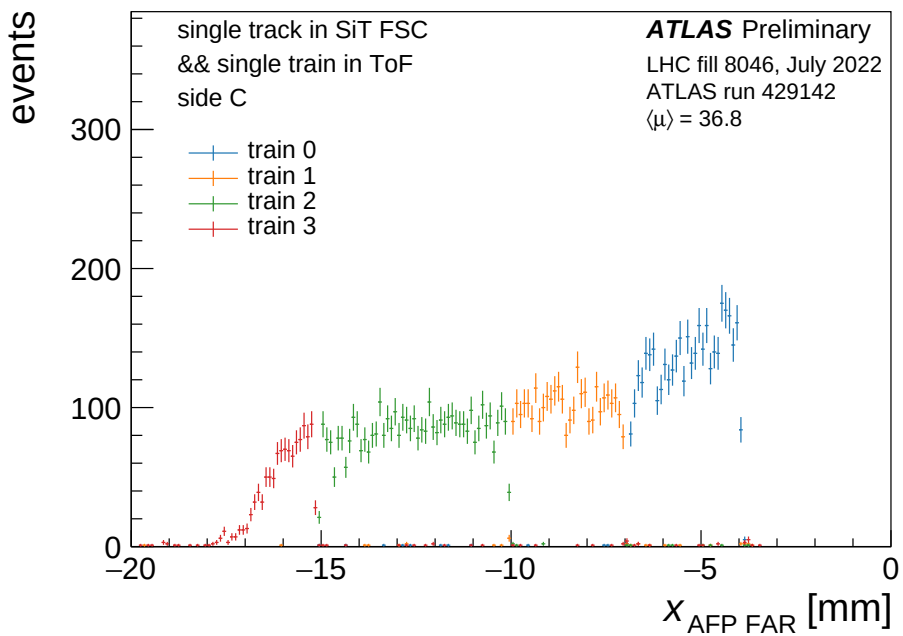




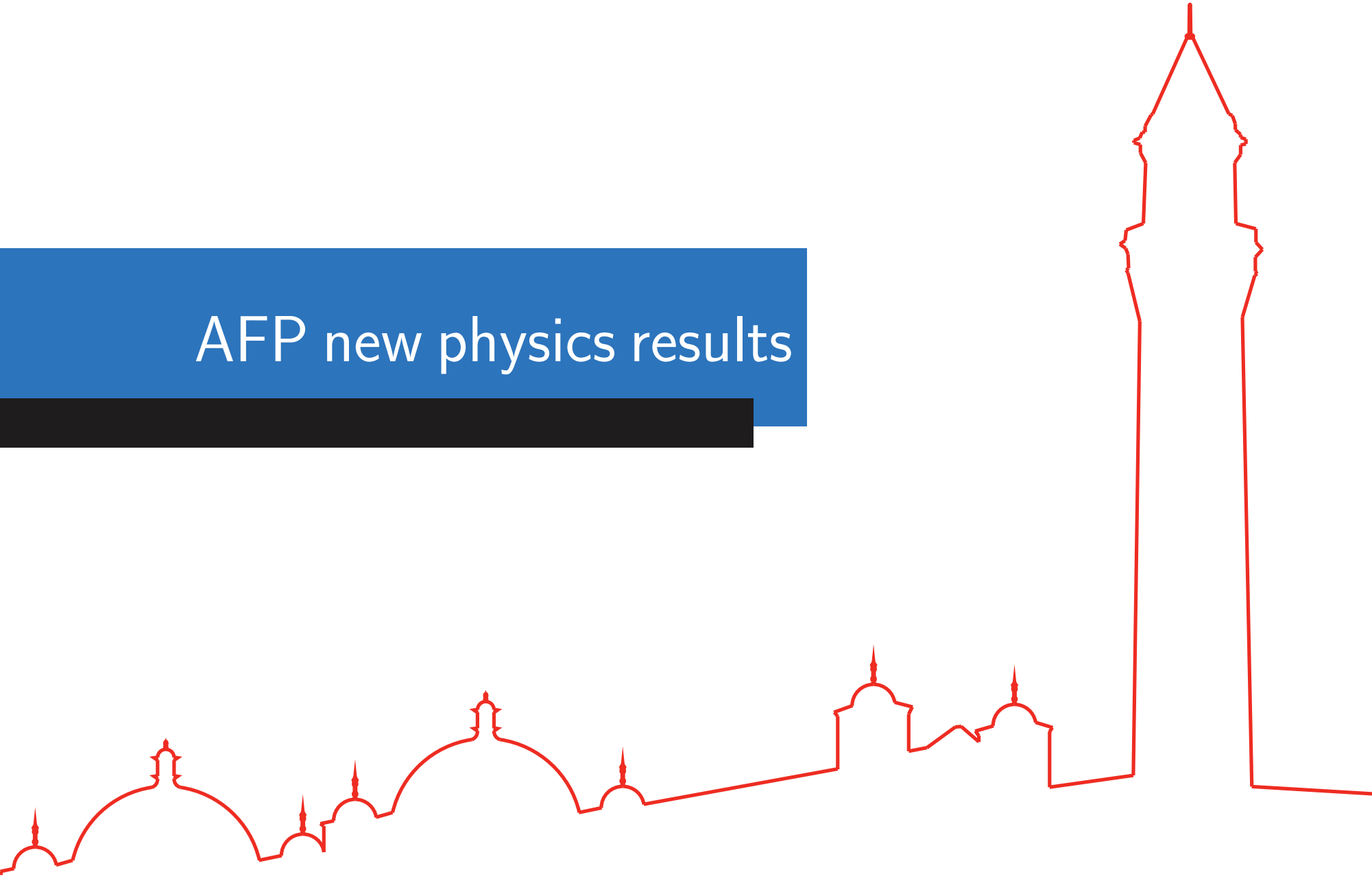
ToF Run 3 performances

- x position of the track reconstructed in AFP SiT (FAR station) in events with a single-train signal in ToF detector
  - Correlation between ToF hits and x position of the tracks
    - ToF and SiT are properly synchronised and they register common signal (not noise)
  - The differences between sides are due global alignment (alignment between stations) corrections not being applied





AFP new physics results



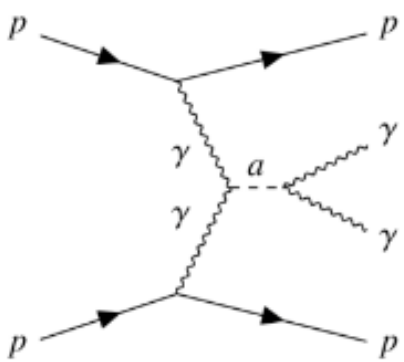
New AFP physics result (1)

New AFP result published this year searching for axion-like particles using 14.6 fb^{-1} of data collected in 2017 [JHEP 07 (2023) 234]

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.

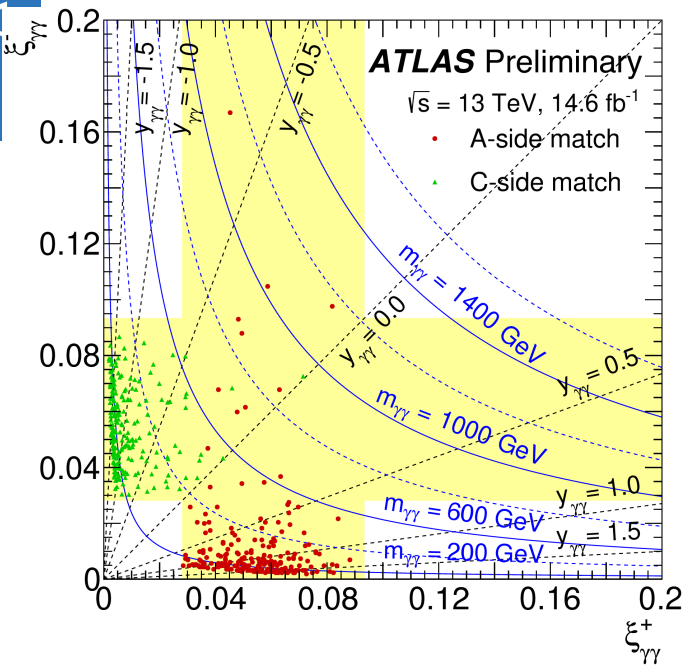


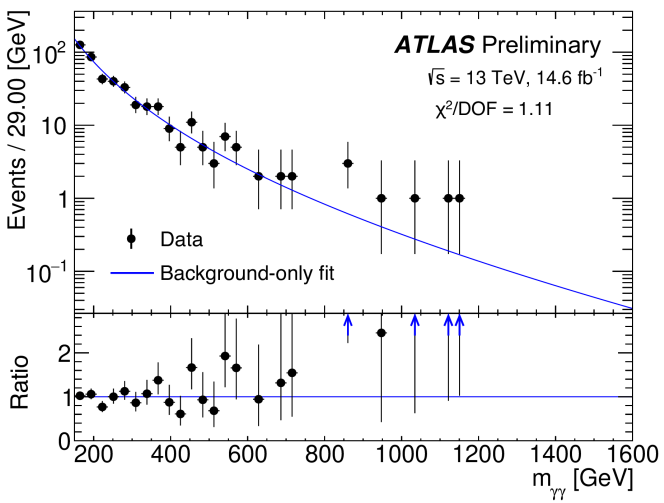
- The target ALP mass range is 150–1600 GeV, constrained by AFP acceptance
- Kinematic matching between AFP and central detector through ξ (proton energy loss) variable

$$\xi^{\pm}_{\gamma\gamma} = \frac{m_{\gamma\gamma}}{\sqrt{s}} e^{\pm y_{\gamma\gamma}} \quad ; \quad \xi_{\text{AFP}} = 1 - \frac{E'_p}{E_p}$$

- Single-tag signature used, saving statistics
- Event-mixing method to estimate the combinatorial background

New AFP physics result (2)



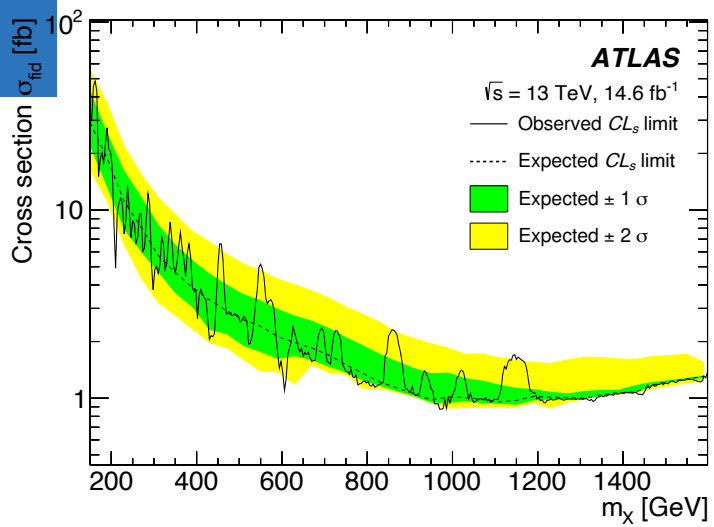


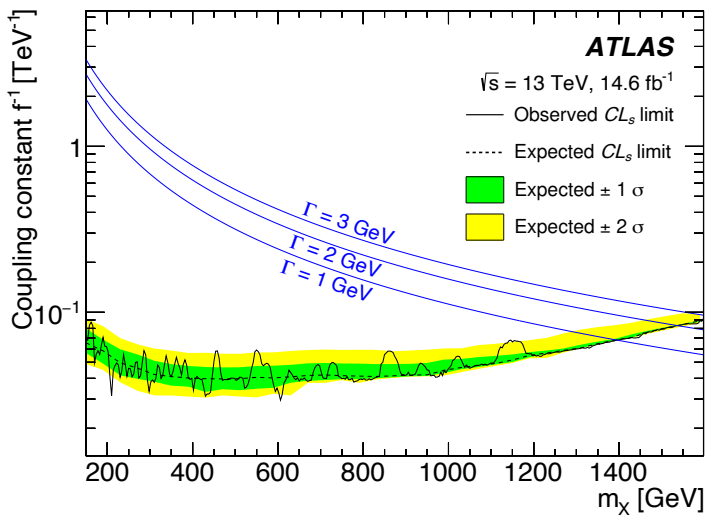
- Diphoton selection
  - At least two isolated photon candidates with $p_T > 40$ GeV and $|\eta| < 2.37$
  - Photons back-to-back
- AFP selection
  - Proton ξ_{AFP} value required to be within $\xi_{\mathrm{AFP}} \in [0.035; 0.08]$
- Kinematic matching
  - Protons in AFP must match predicted energy loss from diphoton system within resolution effects

$$|\xi_{\mathrm{AFP}} - \xi_{\gamma\gamma}| < 0.004 + 0.1\xi_{\gamma\gamma}$$

- A total of 441 events pass signal selection

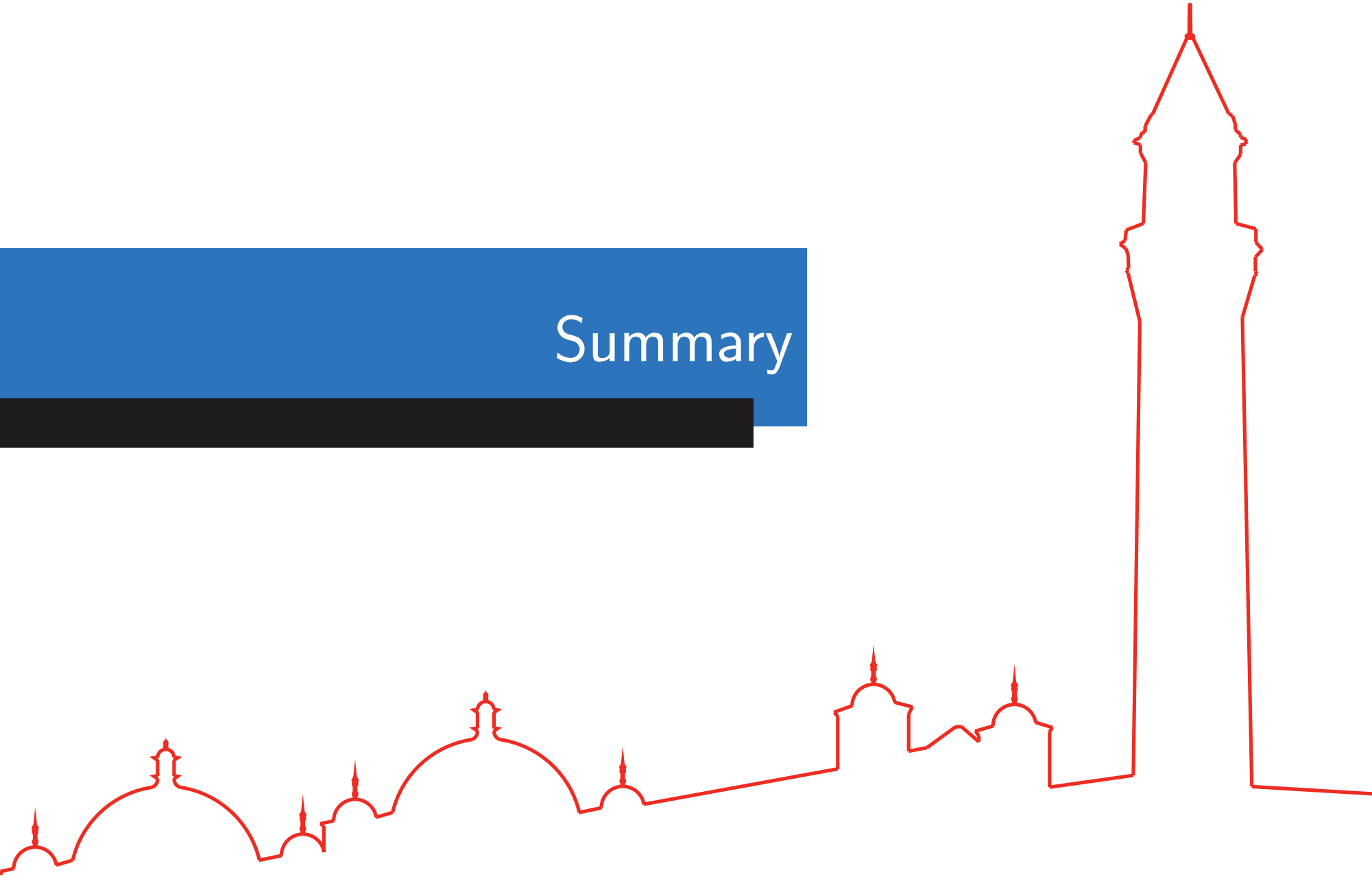
New AFP physics result (3)





- Most significant excess observed at $m_X = 454$ GeV, with local significance of 2.51σ
- 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 $\sim$4 times lower statistics

Summary



Summary

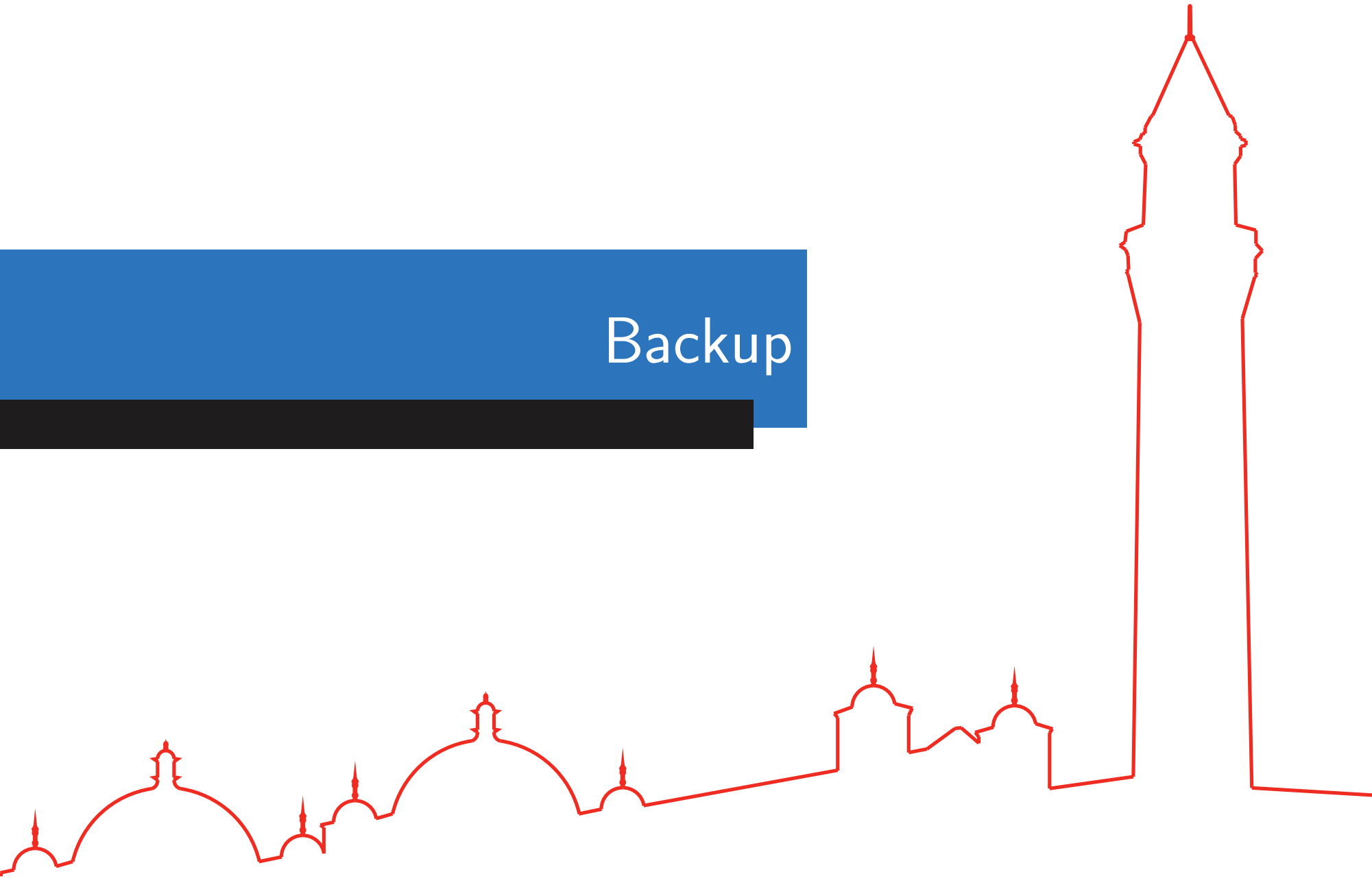
- SiT performance was studied in Run 2 and early Run 3 data showing excellent efficiency
- Excellent ToF resolution for Run 2, efficiencies largely improved in early Run 3 data
- Further optimisations ongoing
  - Understanding of systematics
- 230% increase in available data from 2017
- $\simeq 26.3$ fb^{-1} recorded so far in 2023 with $\sqrt{s} = 13.6$ TeV and high pile-up ($\mu \simeq 60$)
- Data is being analysed and many new, exciting results are expected to be published in the near future
  - Many ongoing Run 2 analyses using low and high μ data
  - Large Run 3 dataset yet to fully exploit (already being analysed)

Conclusion

Thank you for your attention !

Special thanks to J. Lomas for his help preparing this talk and to the ATLAS Forward Physics group for their amazing work !

Backup



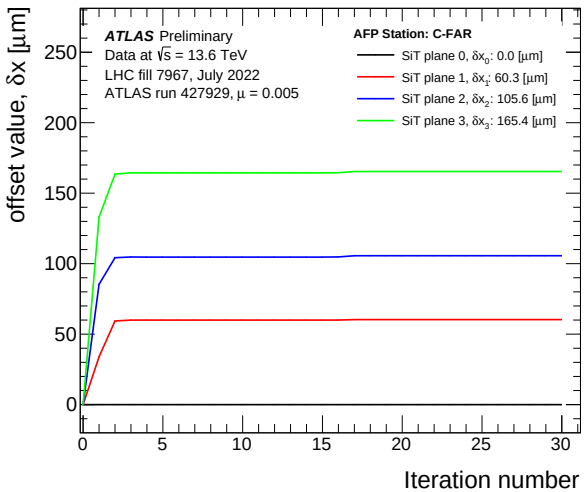
Collected data

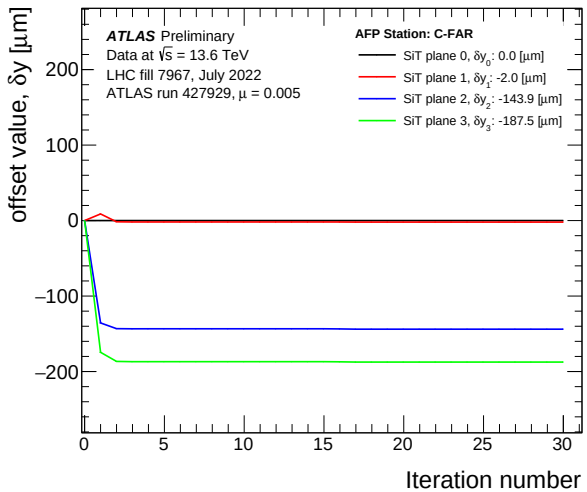
Wide range of data types collected in 2022, each with different physics purposes :

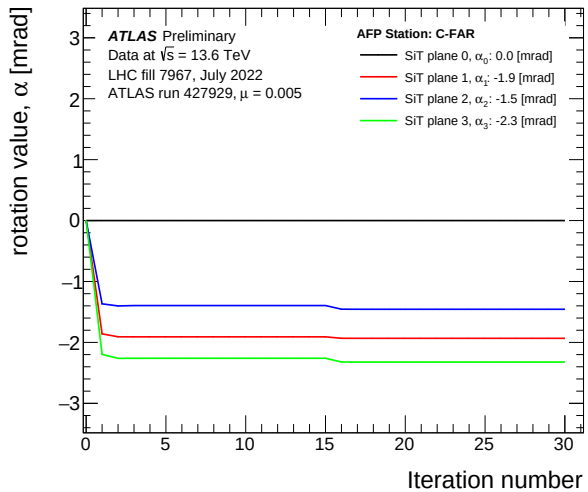
Data type	μ	**Int. lumi.**	**Description**	**Physics purpose**
High-μ	60	34.1 fb^{-1}	Nominal LHC data-taking	High p_T exclusive processes BSM searches
Medium-μ	13-20	168.2 nb^{-1}	Low-β^* beam-based alignment (BBA)	Calibration data
Low-μ	0.05	34.6 nb^{-1}	600b low-μ fills	Soft diffraction, low p_T hard diffraction
LHCf	0.02	170 nb^{-1}	LHCf $\beta^* = 19.2$m runs	Diffractive studies, cosmic ray physics
Extremely low-μ	0.005	0.46 nb^{-1}	/	Soft-diffraction, low p_T hard diffraction Extremely small PU background

Backup

Local alignment







The evolution of the offset value (δx, δy, α) in the x, y, z-axis (in ATLAS coordinates) of the SiT planes according to the number of iterations. The alignment process starts from the first iteration, which indicates all interplane alignment parameters are set to zero. All values are calculated with reference to SiT plane 0.

ToF detector

- 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 channel provides a measurement of time and then integrated over a train (4 bars)