# Overview of ATLAS Forward Proton Detectors in Run-2 and Outlook for Run-3 Analyses

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IEAP CTU in Prague

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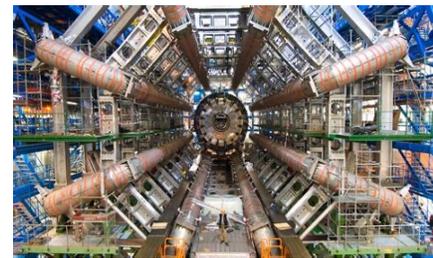
Outline

Overview of ATLAS ALFA detectors, see presentation by Peter Bussey

- Status of ATLAS Forward Proton Detectors (AFP)
  - Silicon Tracker (SiT)
  - Time of Flight (ToF)
- Luminosity
- Hit map
- Alignment
- Trigger
- SiT correlation with central ATLAS Inner Detector tracker/Calorimeters
- Matching of proton energy loss with ATLAS central di-leptons/di-photons
- Key physics results
- Outlook for Run-3
- Conclusions

AFP detectors at -200m and +200m from IP

ATLAS detector

AFP

A-side

proton

~+200 m

Dipole magnet

~+70 m

Magnetic field

AFP

proton

C-side

Dipole magnet

~−70 m

~−200 m

Tracking detector
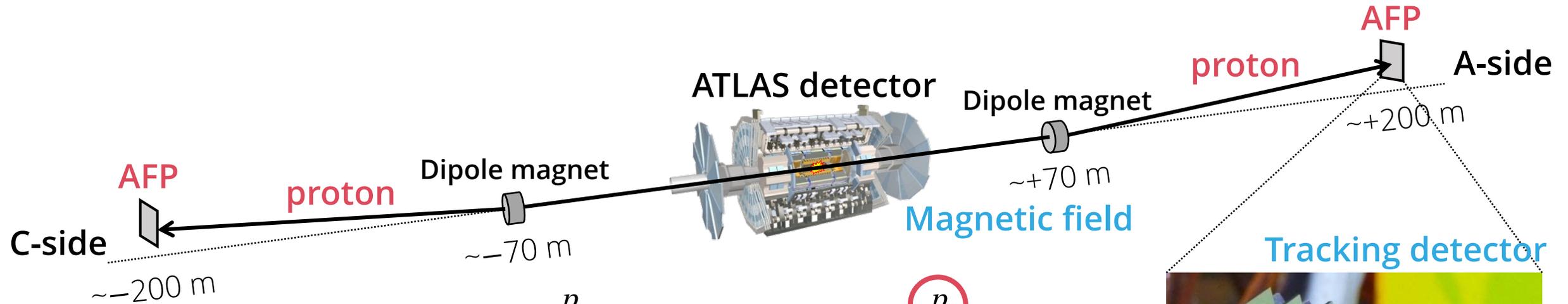
Example:
Register protons
from light-by-light
scattering

p p

γ

a γ

γ

γ

p p

DIS 2023, A.Sopczak
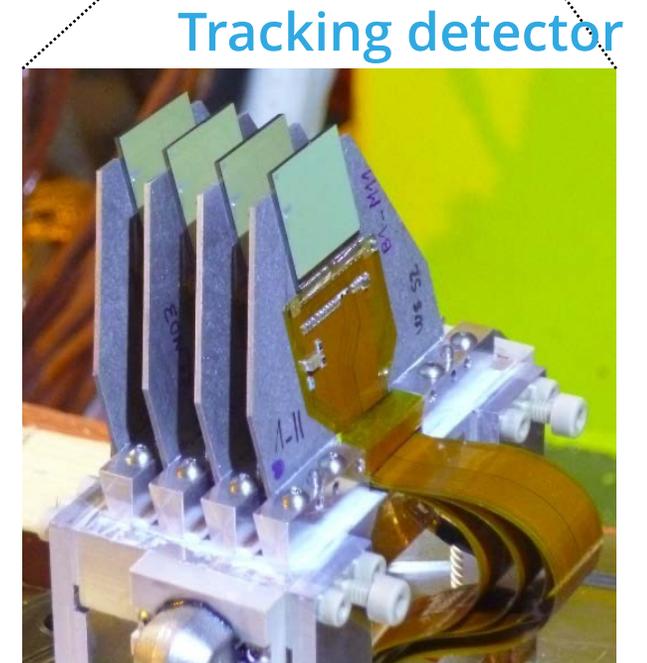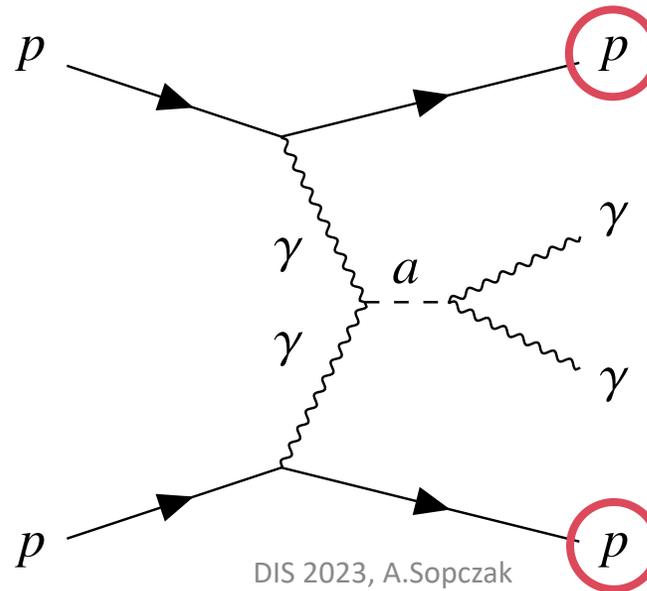
AFP detector

In $\gamma\gamma \rightarrow \gamma\gamma$ events, final state proton can be intact, record ATLAS forward proton (AFP) detectors
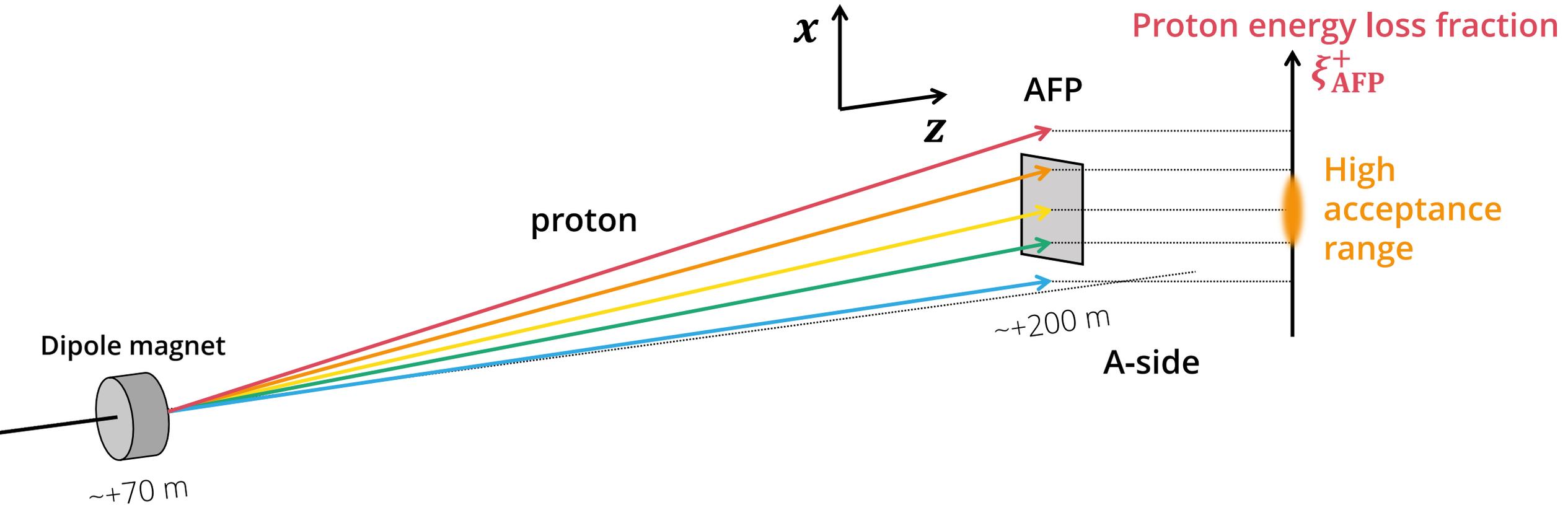
ATLAS Forward Proton (AFP) detector

- Each side of the AFP systems is referred to as an arm.

- For tracking the Silicon Tracker (SiT) is used,
which consists of four layers of silicon pixel detectors.

- Only FAR stations equipped with the Time-of-Flight (ToF) detectors.
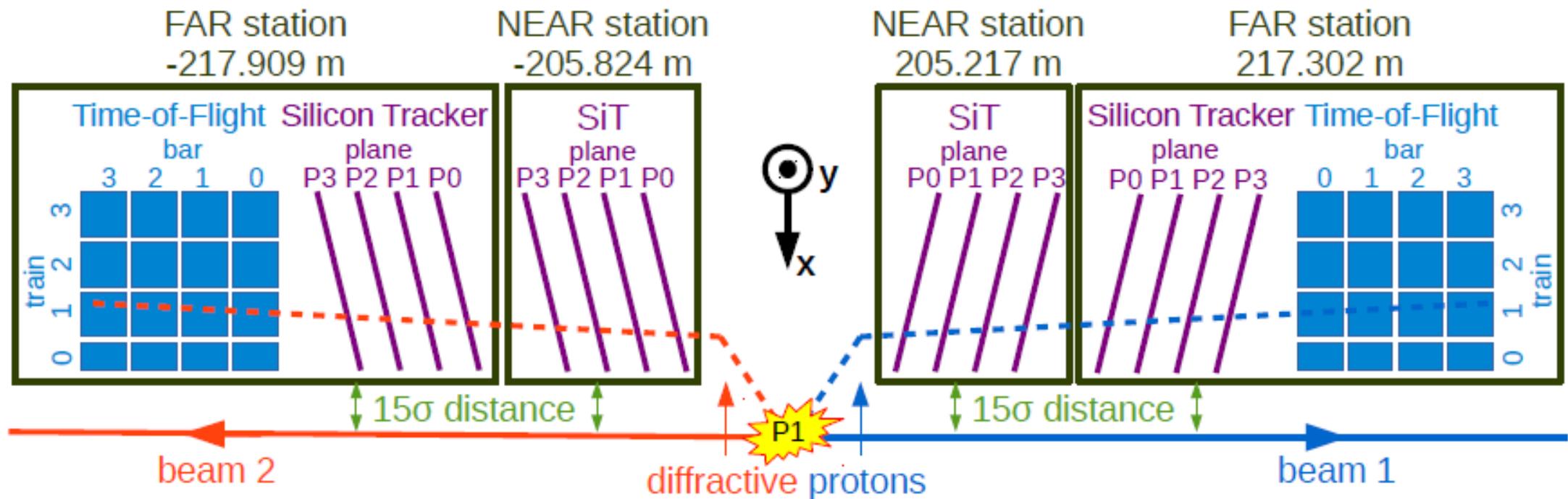
Time-of-Flight (ToF)

- AFP consists of four stations:
  NEAR and FAR, on anticlockwise (A) and clockwise (C) sides.

- Only FAR stations equipped with Time-of-Flight (ToF) detectors.

- ToF detectors collect Cherenkov photons created in L-shaped fused silica bars, placed behind the tracker plates.

- **Four bars** are placed one after another to form a train. There are **four trains** on each side.

- Each cell (0A, 1B, etc.) is called "channel".
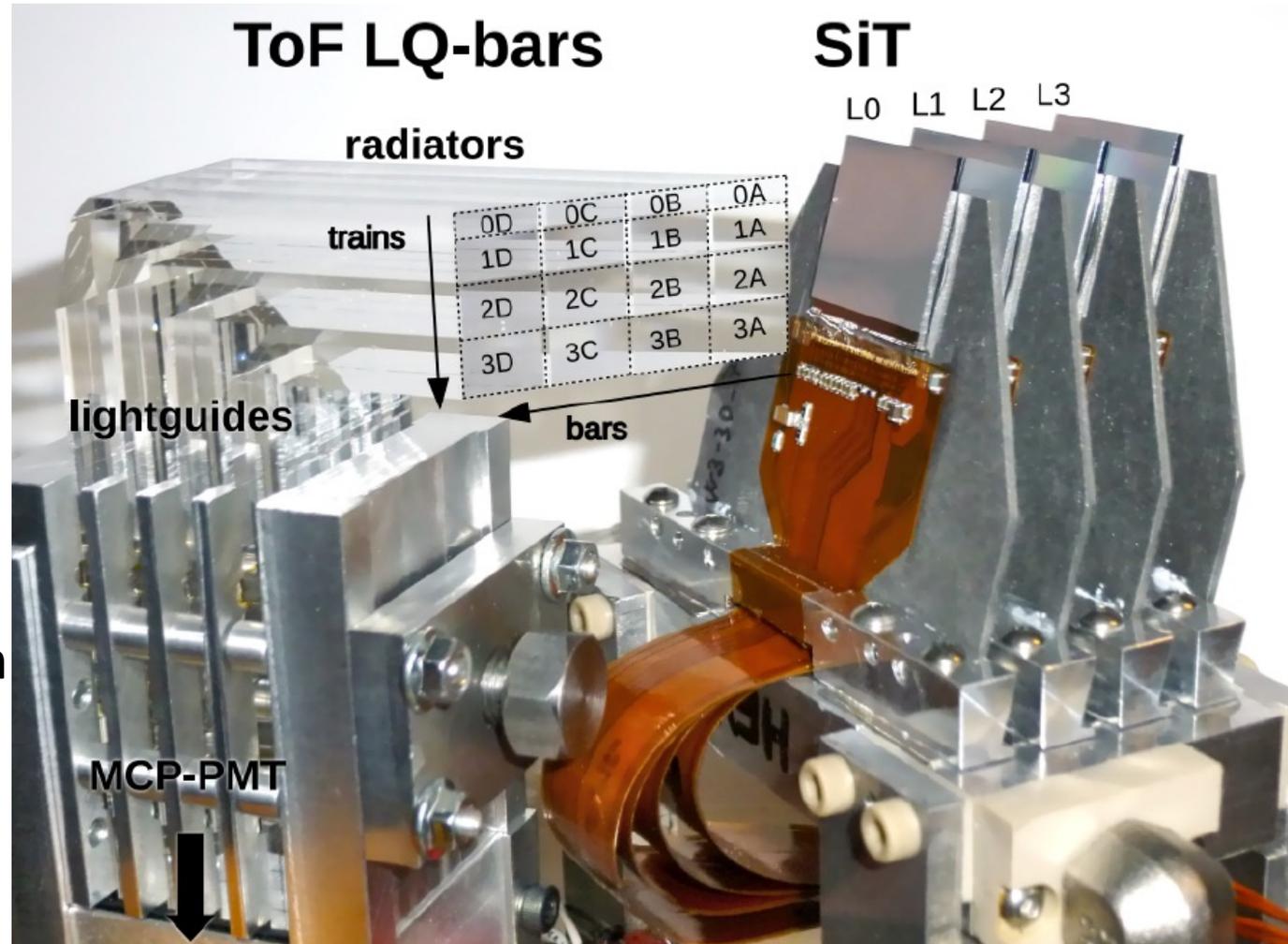
AFP Operation in 2017 and 2022

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun3
https://twiki.cern.ch/twiki/pub/AtlasPublic/ForwardDetPublicResults

- AFP Run-2 data-taking in 2017: 32 fb^{-1} at 13 TeV

- AFP Run-3 data-taking in 2022: 36.1 fb^{-1} at 13.6 TeV
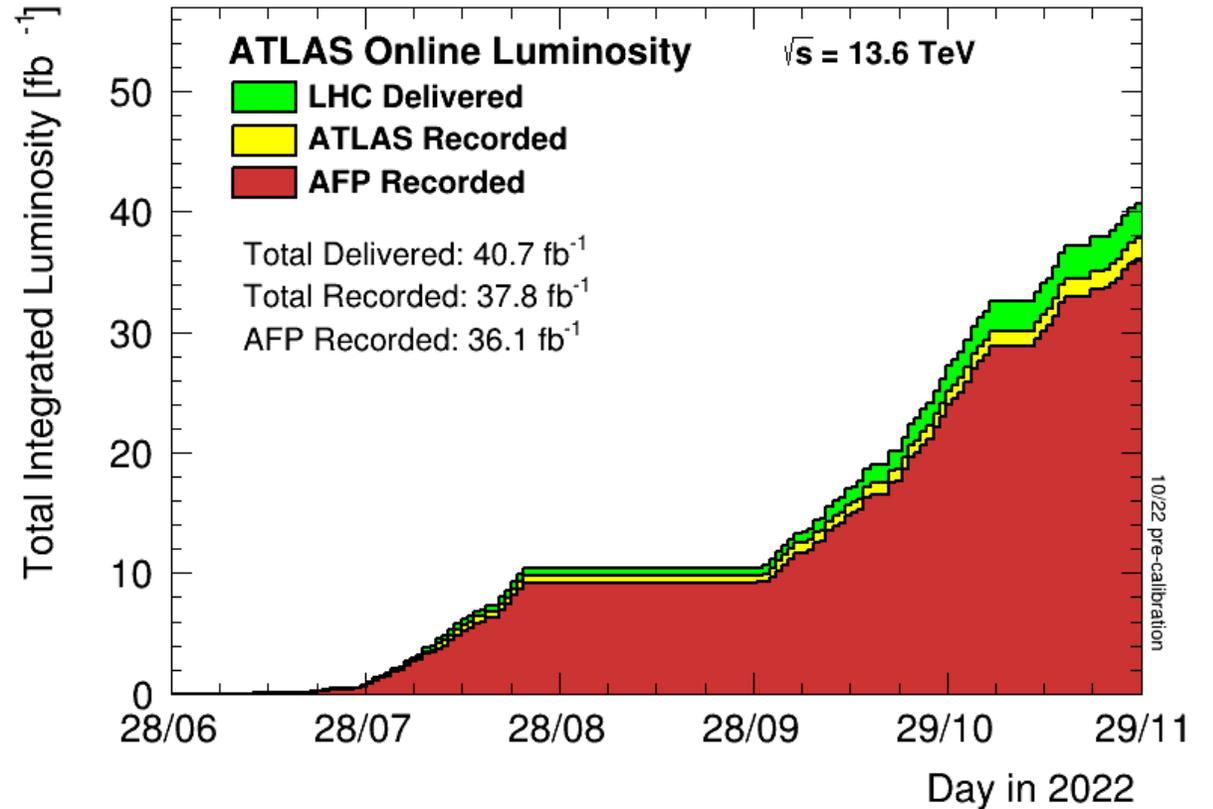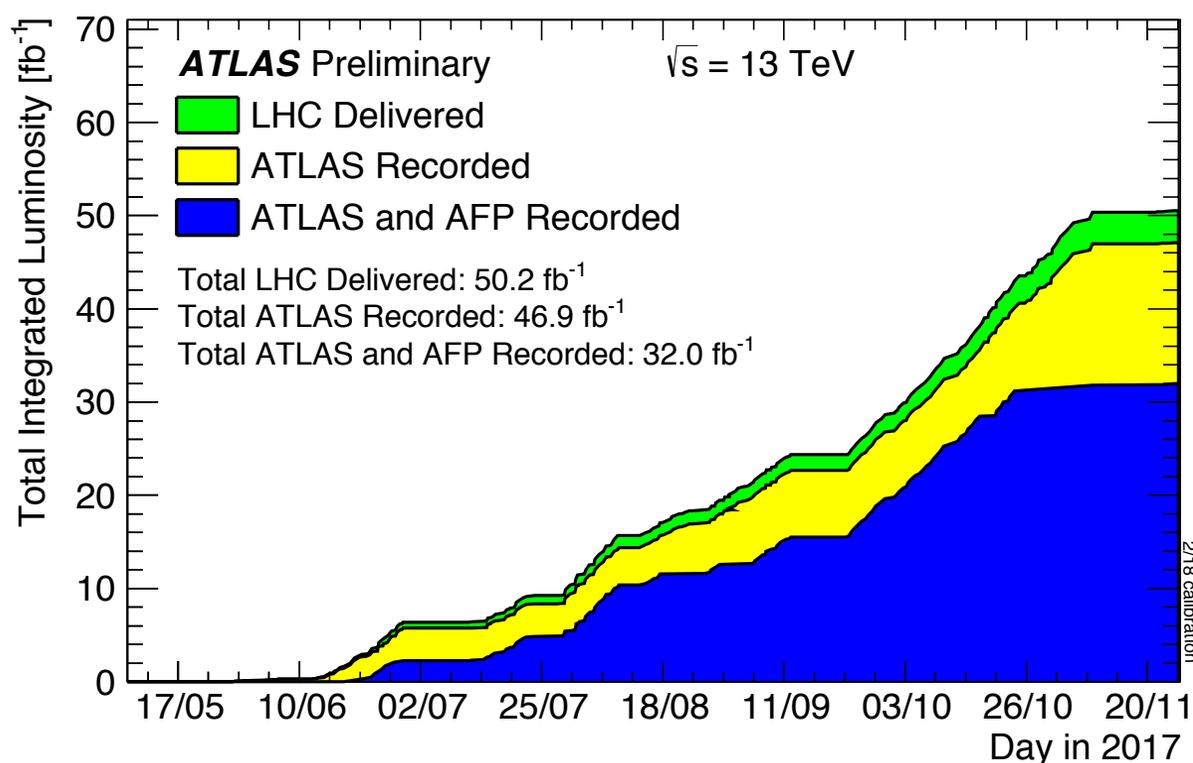
Luminosity monitoring with AFP detectors

- 2018 AFP data

- Average number of interactions per bunch crossing, $<\mu>$, for each luminosity block (60s), from average number of AFP tracks.

- 31 runs of data-taking (12-24 hours).

- Results obtained compared with measurement by the ATLAS luminometer LUCID.

AFP-track counting

AFP Side-A Far

Mean and RMS
- Calibration run
- Other runs

$\sqrt{s}$= 13 TeV

ATLAS Preliminary

Date in 2018
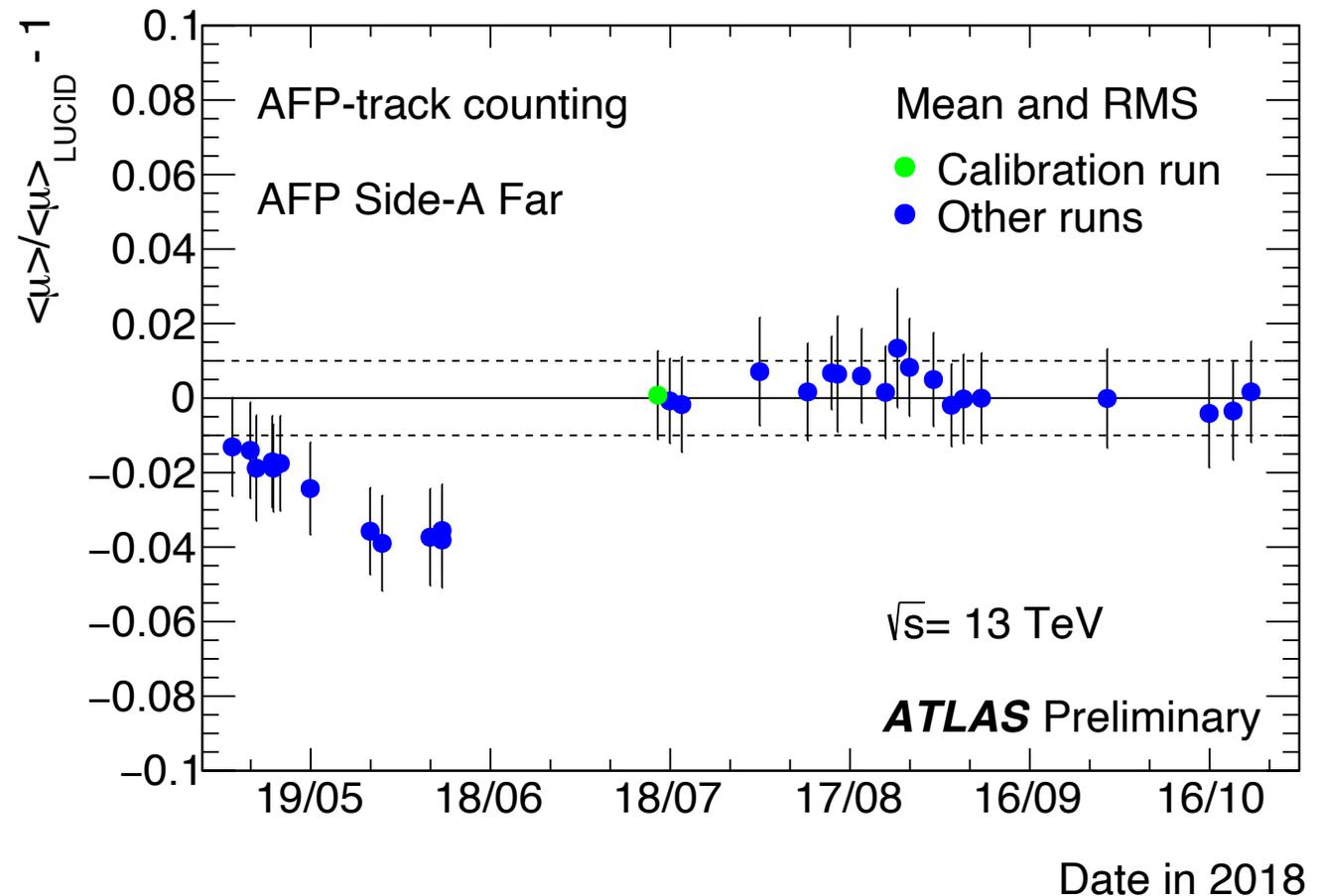
SiT data-taking, hit map July 2022 LHC Run-3

- SiT planes of the AFP detector 336×80 (row × column) pixels with dimensions of 50 μm × 250 μm.

- Two-dimensional representation of hits recorded by SiT plane 1, the second plane closest to the interaction point, at the AFP C-FAR station.

- SiT Column ID and SiT Row ID represent pixel column number and pixel row number, which are the y-axis and x-axis in ATLAS coordinate system.

- 1.5M events of run 427929, corresponding to luminosity block 200-206.

- Selection: only 1 track reconstructed per station, 1 cluster reconstructed per SiT plane and 1 or 2 hits recorded per SiT plane.
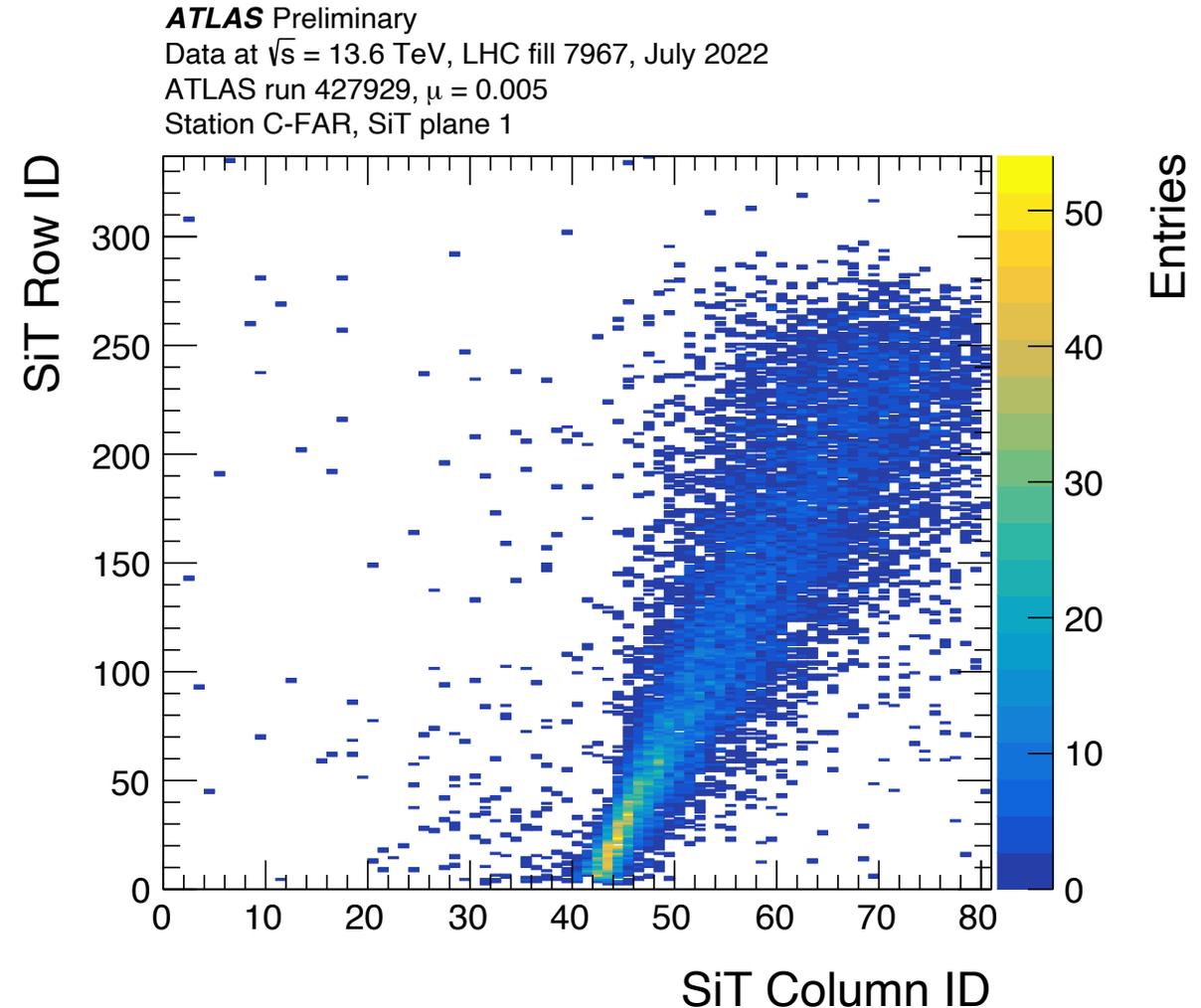
Global Alignment Run-2

- Alignment of SiT with respect to actual beam (later: with respect to beam pipe)
- Mean of alignment of 300 μm (over stations and data taking) defines systematic uncertainty
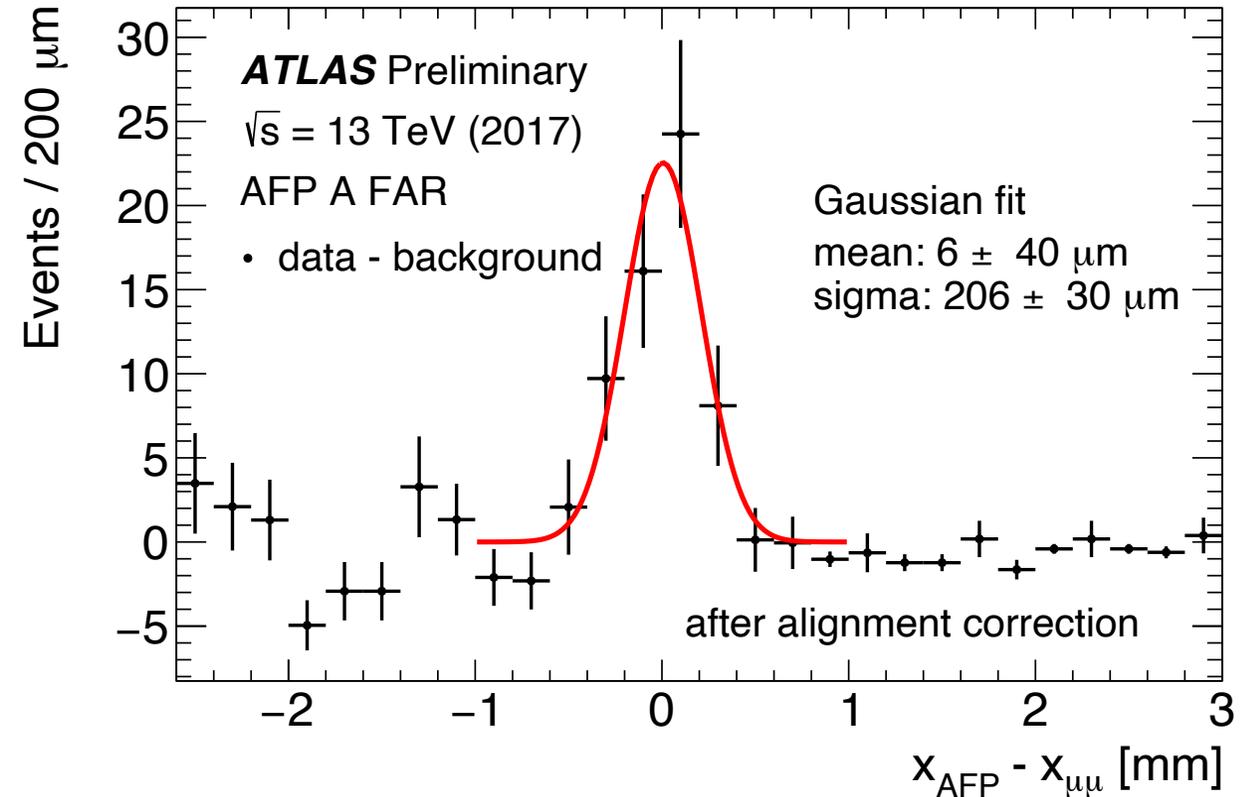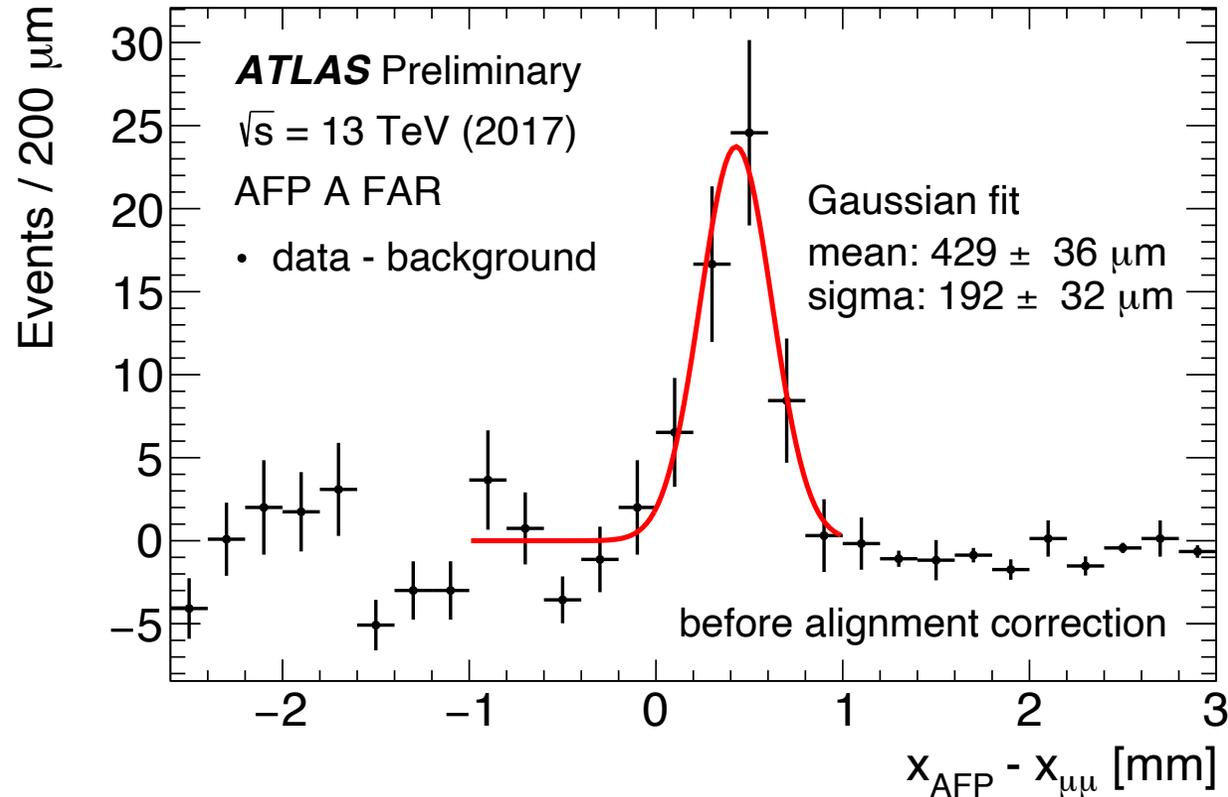
Local Alignment Run-3

- Evolution of the offset value (δx) in the x-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.

- Corrections are applied to the alignment parameters with each iteration.

- All values are calculated with reference to SiT plane 0. δx 0,1,2,3 are final value of δx for the planes.
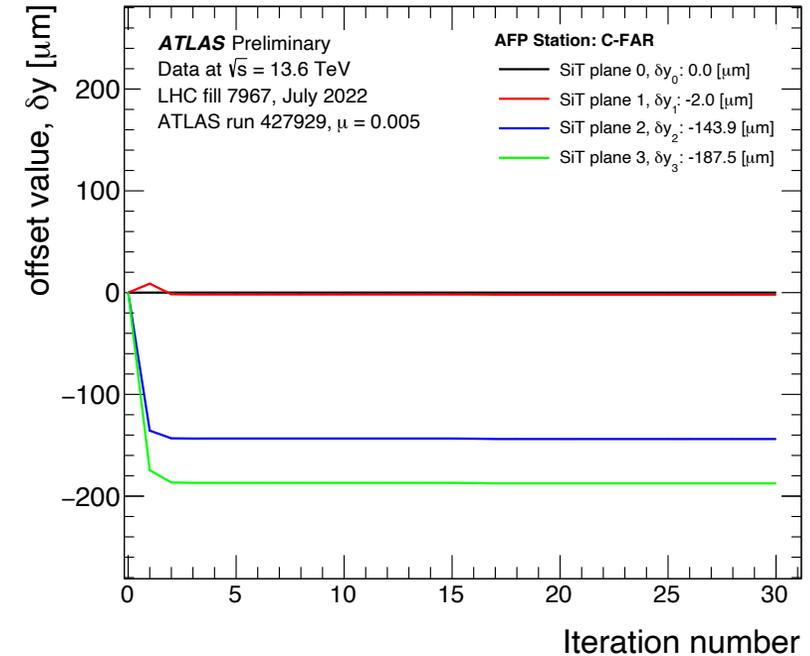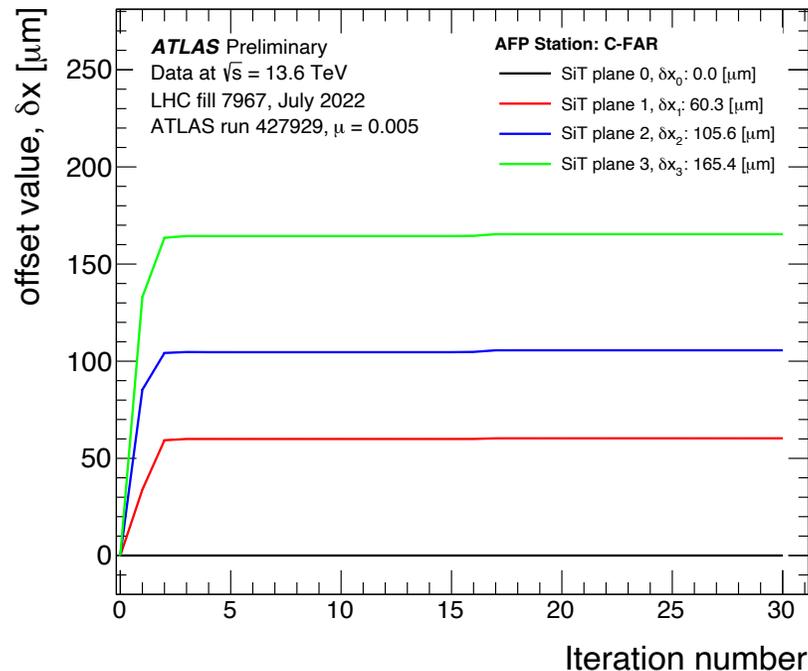
AFP trigger

- AFP is part of the ATLAS data acquisition system
- Trigger rates sent from the AFP detector at nominal 20 sigma position from the beam as a function of number of colliding bunches during LHC luminosity ramp up.
- 2015-2016 data-taking
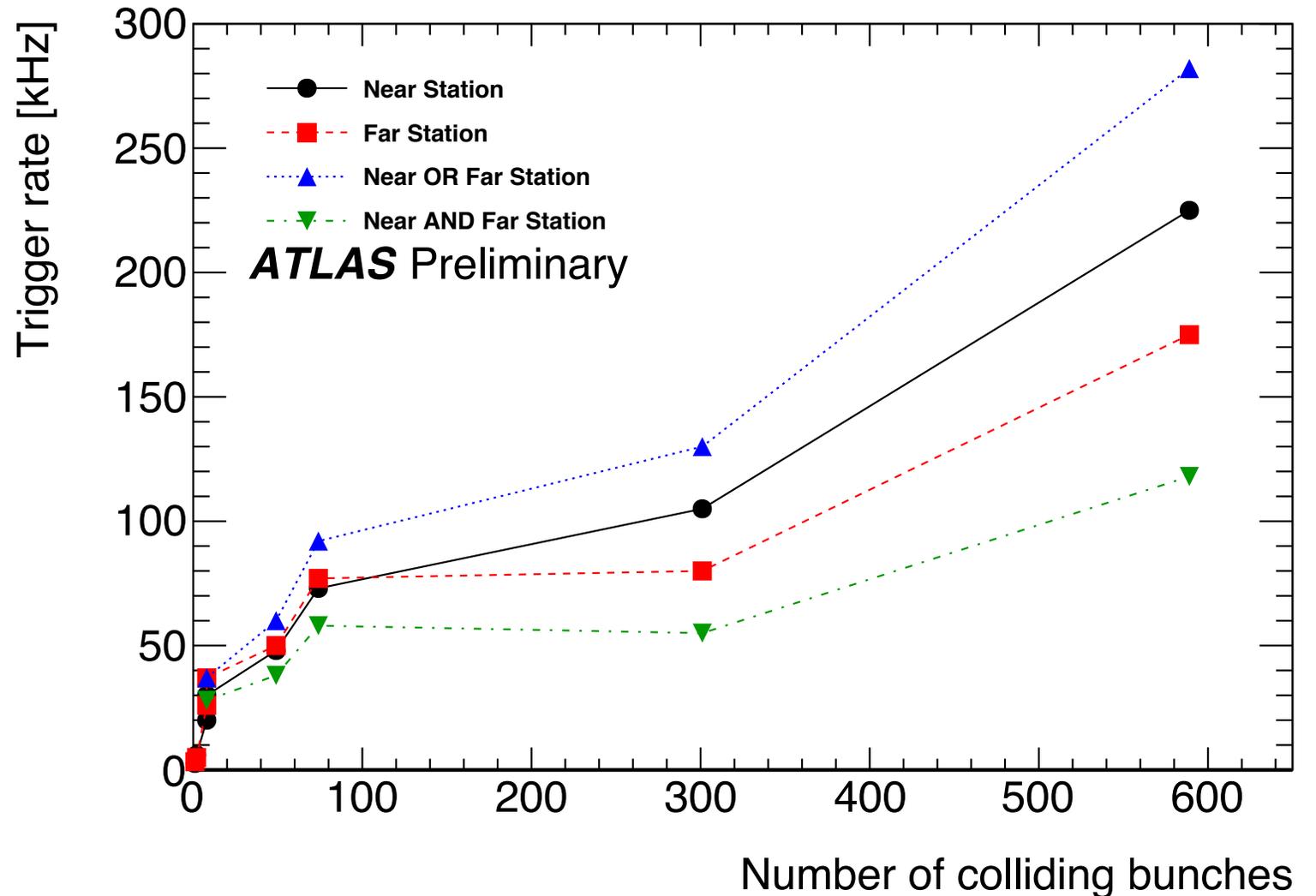
ToF Vertex Reconstruction

- 2017 data:
  expected and measured resolution 5 mm
- 2022 operating in Run-3 data taking

ATLAS Preliminary
$\sqrt{s} = 13$ TeV
Run 341419
Double tag ToF events
no N_{vtx} cut

N_{Events}	1954
$\mu^{FIX}_{sig, bgd}$	-4.15 (0.01) mm
σ^{FIX}_{bgd}	59.77 (0.01) mm
n_{bgd}	1896 ± 24
n_{sig}	58 ± 11
σ_{sig}	5.2 ± 0.9 mm

$\sigma^{ToF}_{expected} = 4.9 \pm 0.7$ mm

data
sig+bgd
bgd

$z_{ATLAS} - z_{ToF}$ [mm]
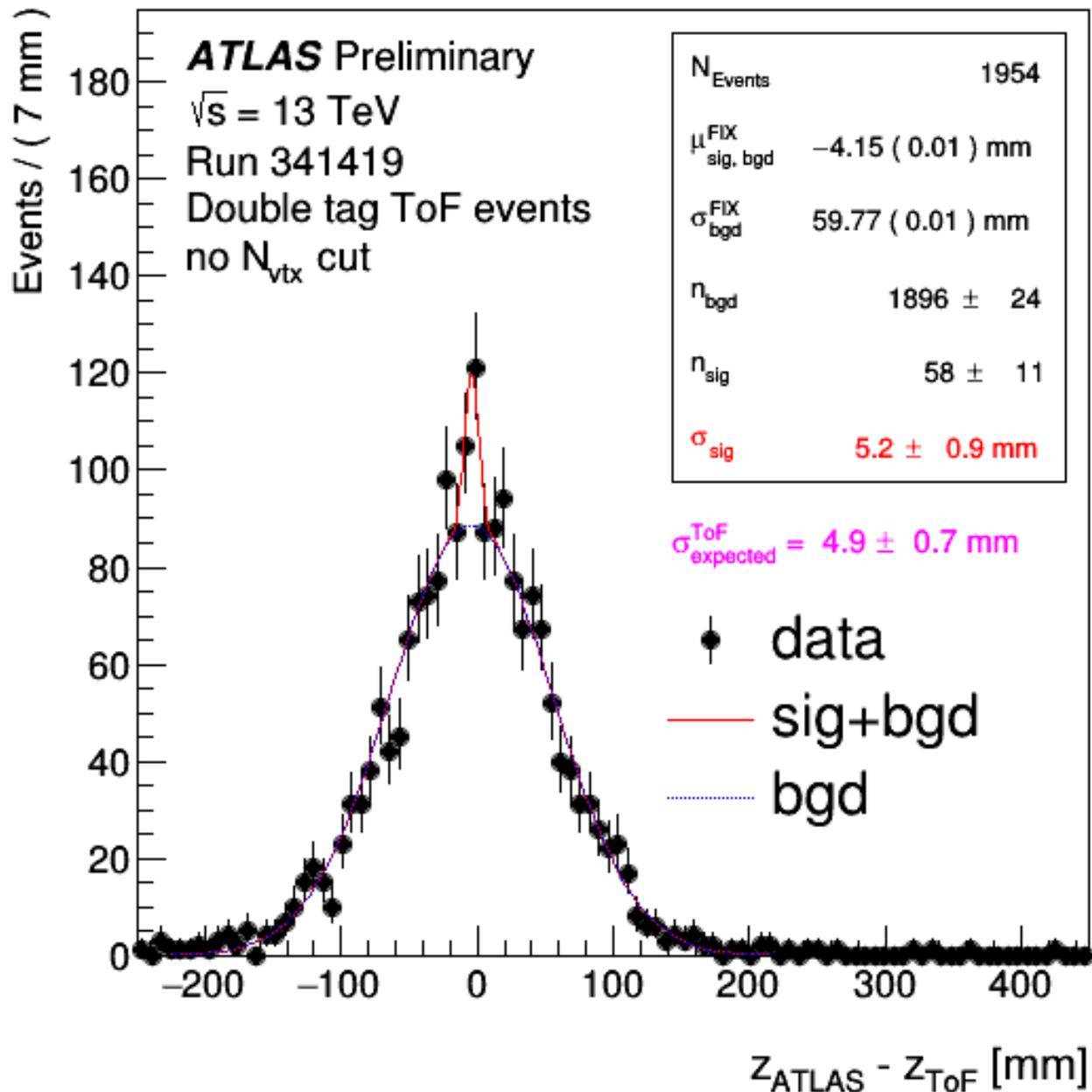
SiT track with ToF single train signal

- x position of track reconstructed in AFP SiT (FAR station) in events in which a single-train signal in ToF detector was observed.

- Different colors to visualize SiT regions corresponding to individual trains.

- Machined x-width of ToF bars 3/3/5/5.5 mm for train 0/1/2/3.

single track in SiT FSA
&& single train in ToF
side A

ATLAS Preliminary
LHC fill 8046, July 2022
ATLAS run 429142
$\langle\mu\rangle = 36.8$

train 0
train 1
train 2
train 3

events

$x_{\text{AFP FAR}}$ [mm]
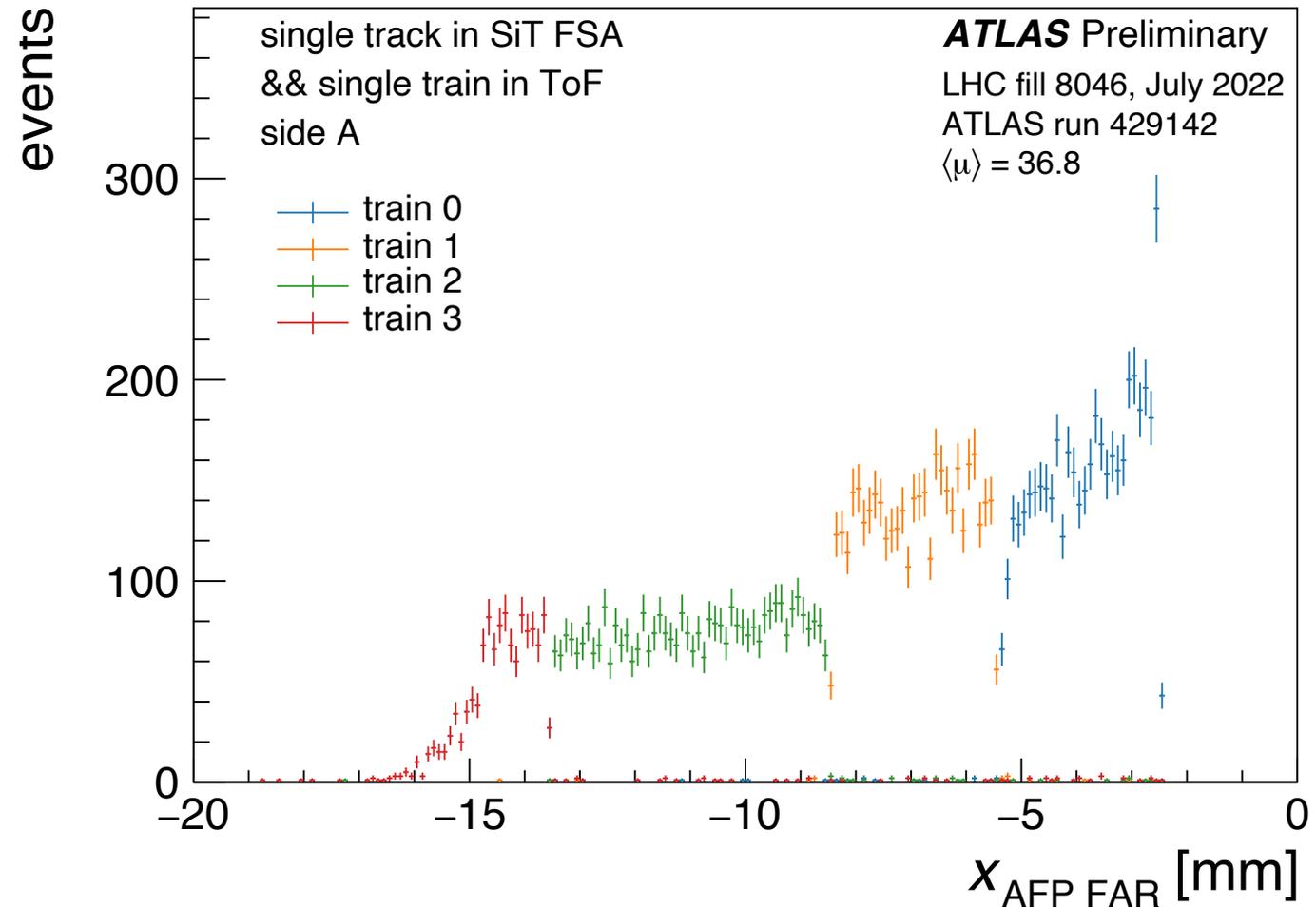
SiT correlation with ATLAS central Inner Detector tracker & calorimeters

- Correlation between x-position of reconstructed tracks in AFP NEAR stations and (left) the charged track multiplicity in the ATLAS Inner Detector (ID) (right) the total energy measured by the ATLAS Calorimeters with a proton on side A or C.

- Exactly one reconstructed AFP track in each station and side and reconstructed primary vertex.

- ID track selection requirements of $p_T > 500$ MeV and $|\eta| < 2.5$, and

- Events with smaller x AFP NEAR are further from beam and thus expected to originate from protons with higher energy loss. Statistical uncertainty of the mean value.


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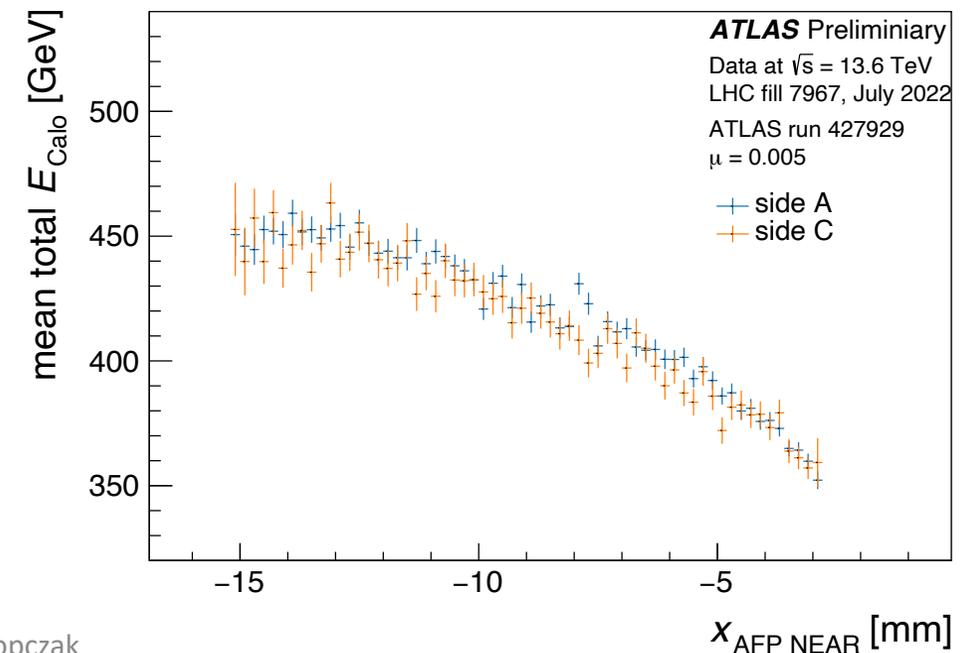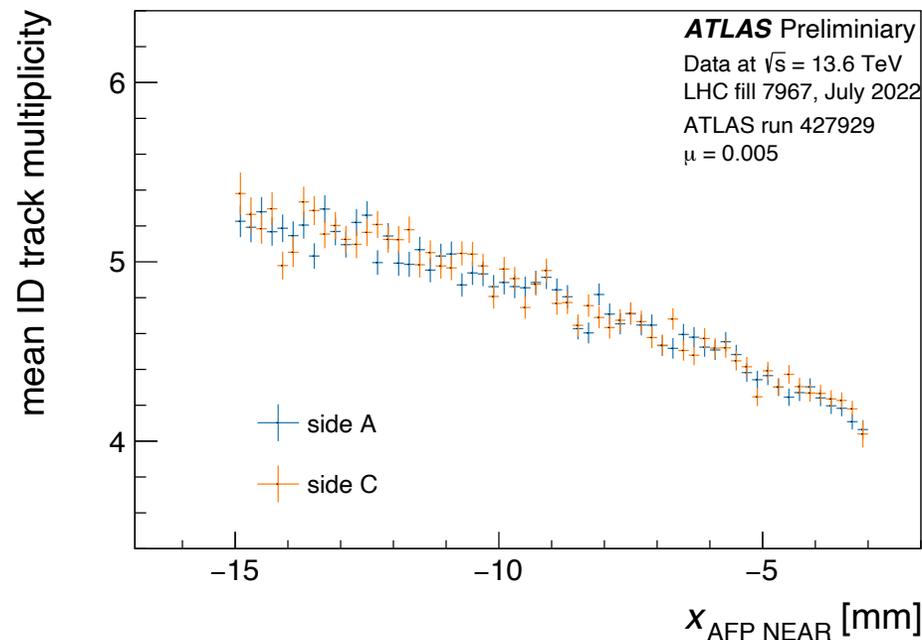
Matching of lepton pair and proton kinematics $\xi_{\ell\ell}, \xi_{AFP}$

PRL 125 (2020) 261801, 14.6 fb^{-1}

- Photon-induced di-lepton production with forward proton tag at 13 TeV

- AFP detection range $0.02 < \xi < 0.12$

- Signal and combinatorial background processes

- p* dissociated proton

$$\xi_{\ell\ell} = (m_{\ell\ell}/\sqrt{s})e^{\pm y_{ll}}, \xi_{AFP} = 1 - E_p/E_{beam}$$

ATLAS
$\sqrt{s} = 13$ TeV, 14.6 fb^{-1}
$m_{ll} \notin [70, 105]$ GeV
ee+$\mu\mu$, $0.02 < \xi < 0.12$
Postfit

- Data 2017
- Uncertainty
- $pp \to p(\gamma\gamma \to \mu\mu)p$
- $pp \to p(\gamma\gamma \to ee)p$
- $pp \to p(\gamma\gamma \to \mu\mu)p*$
- $pp \to p(\gamma\gamma \to ee)p*$
- Combinatorial bkg.

Events / 0.0025

$\xi_{AFP}^A - \xi_{ll}^A$

$\xi_{AFP}^C - \xi_{ll}^C$
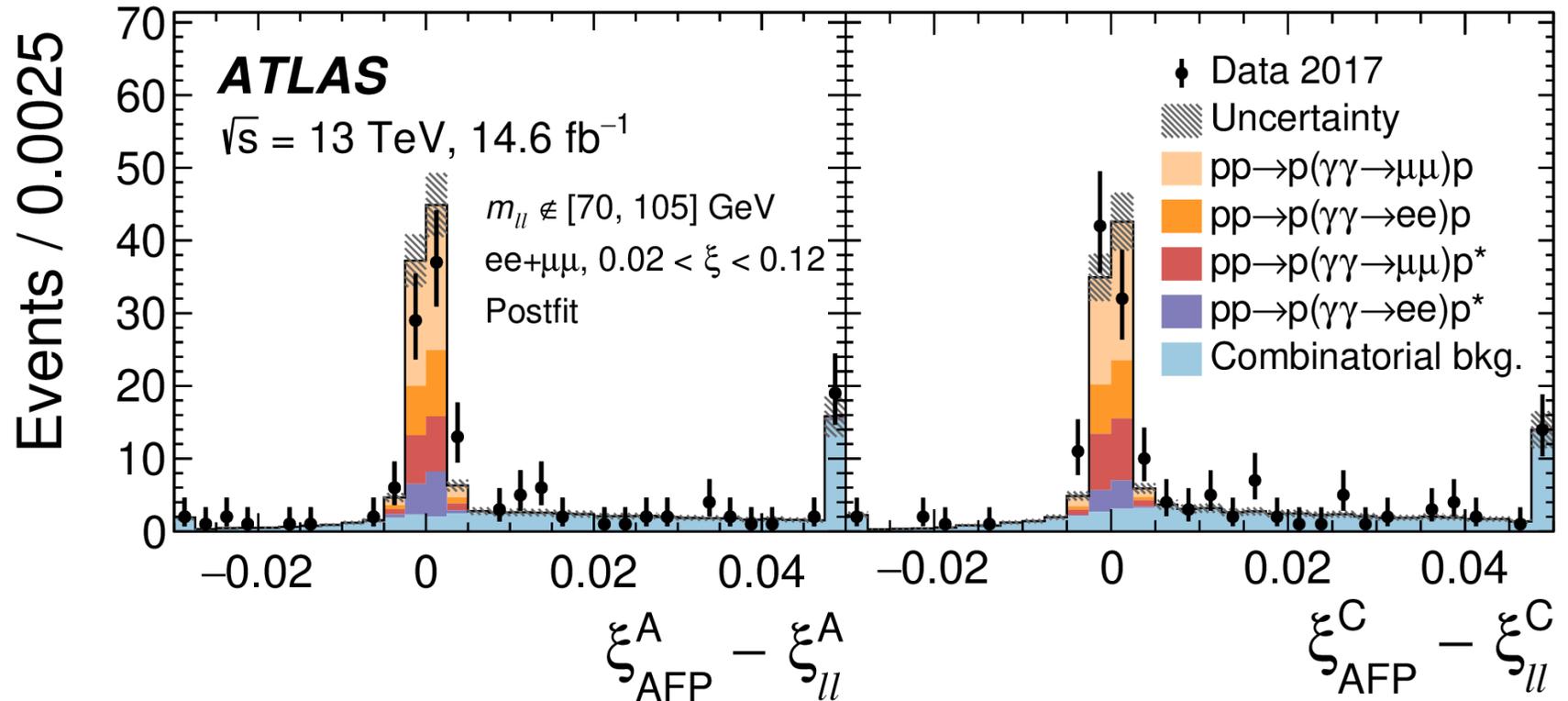
# Di-lepton events: rapidity $y_{\ell\ell}$ versus $m_{\ell\ell}$ plane

PRL 125 (2020) 261801, 14.6 fb^{-1}

- Event selection and kinematic matching $|\xi_{AFP} - \xi_{\ell\ell}| < 0.005$ on at least one side

- Shaded (hatched) areas denote the acceptance (no acceptance) for the AFP stations

- Areas neither shaded nor hatched correspond to $\xi \notin [0, 1]$
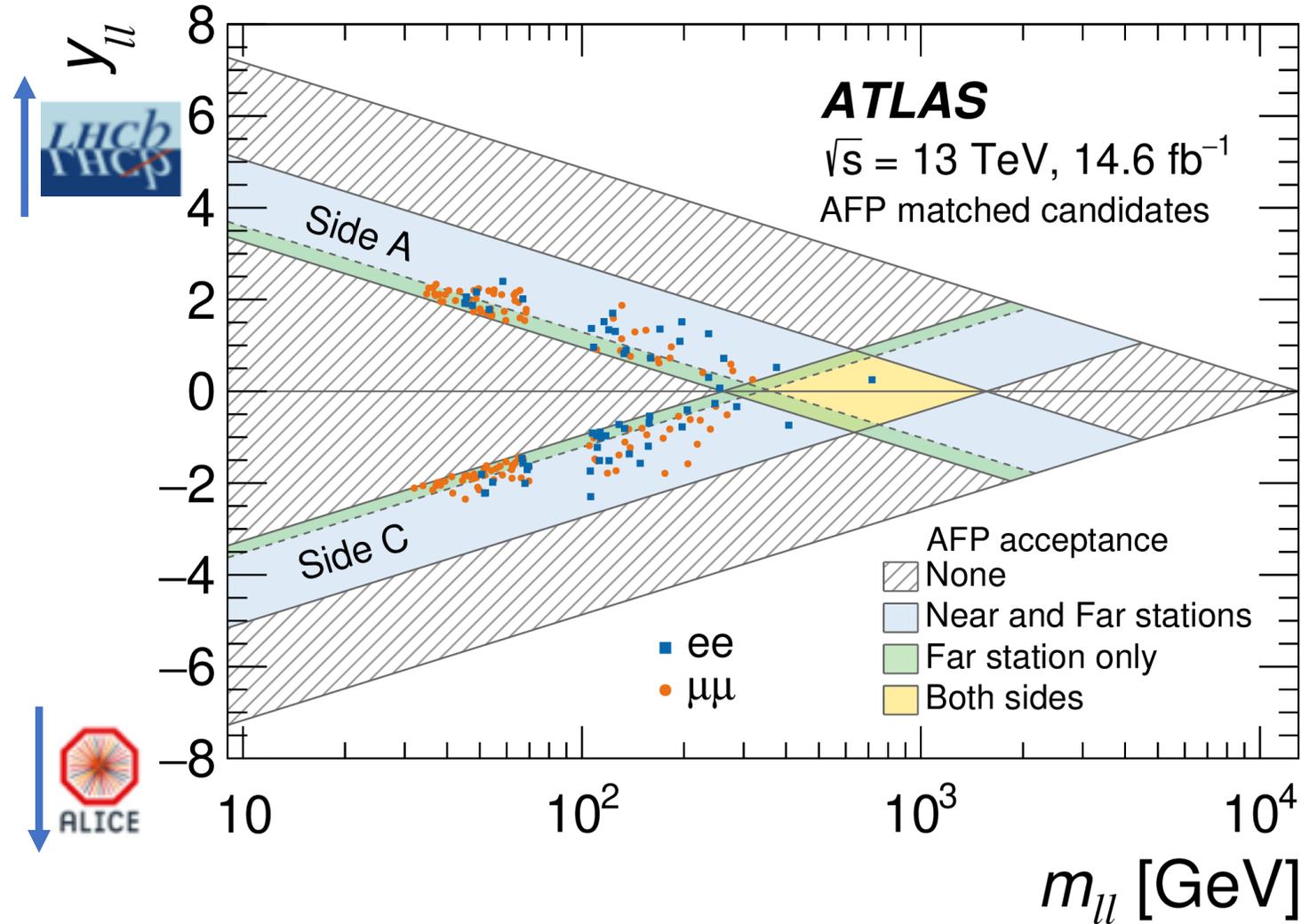
# Matching of photon pair and proton kinematics $\xi_{\gamma\gamma}, \xi_{AFP}$
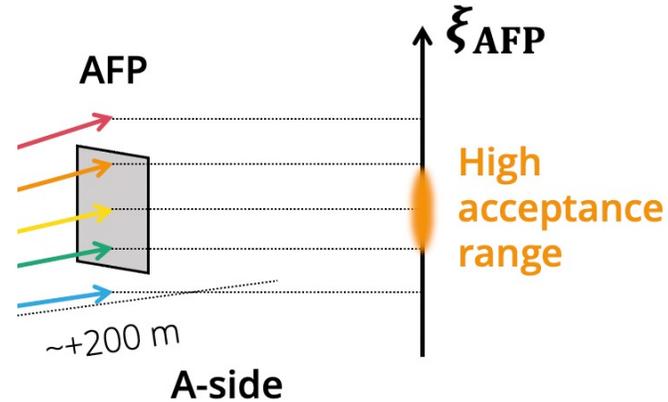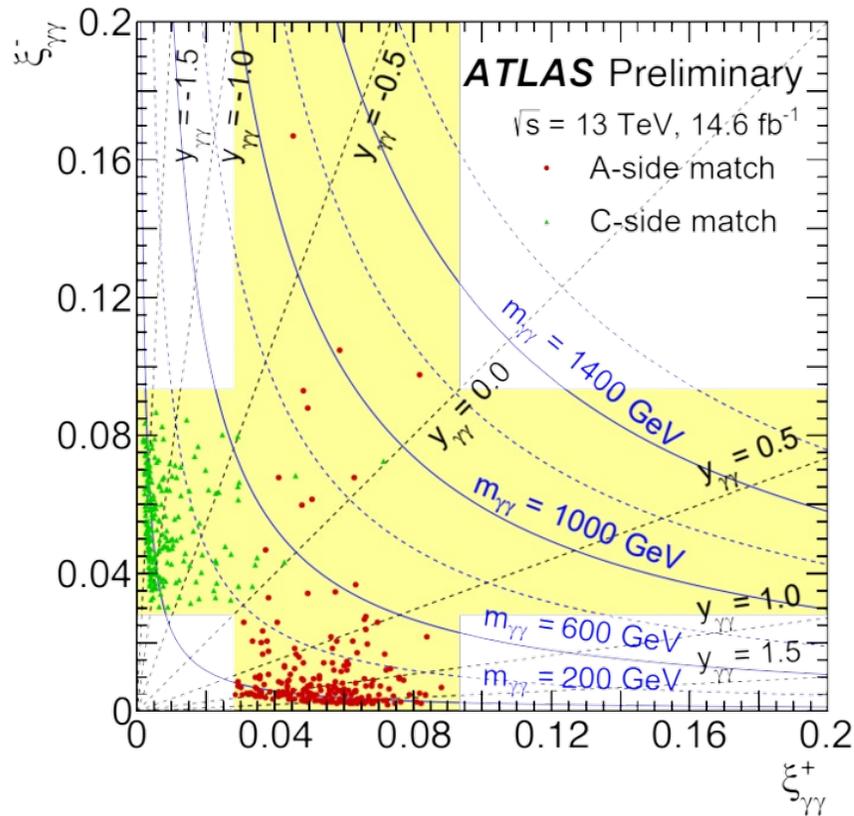
Dominant systematic uncertanity: AFP global alignment

$d \approx 2 - 3$ mm

$\sigma_d \approx 300 \, \mu$m
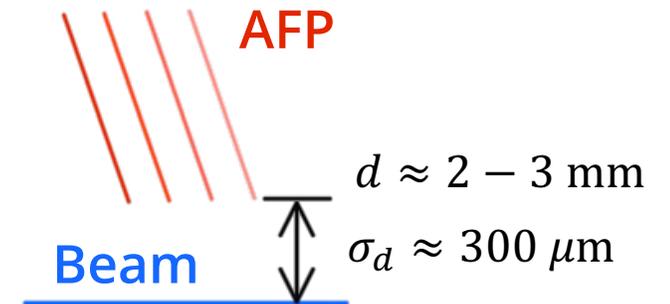
$$|\Delta\xi| \equiv |\xi_{AFP} - \xi_{\gamma\gamma}| < 0.004 + 0.1\xi_{\gamma\gamma}$$

2017 data: 441 events single matching, no double matching.

Key physics results: $\gamma\gamma \to \ell\ell$ and $\gamma\gamma \to \gamma\gamma$

Measurement of $\gamma\gamma \to \ell\ell$ and

PRL 125 (2020) 261801, 14.6 fb^{-1}.

- 57 (123) candidates e^+e^-+p ($\mu^+\mu^-$+p)

- Background-only hypothesis rejected with a significance $>5\sigma$ in each channel

- Cross-section measurements in the fiducial detector acceptance $\xi \in [0.035; 0.08]$

$\sigma(ee+p)=11.0\pm2.6$ (st) ±1.2 (sy) ±0.3 (lumi)fb

$\sigma(\mu\mu+p)=7.2\pm1.6$ (st)±0.9 (syst)±0.2 (lumi)fb

- Comparison with proton soft survival (no additional soft re-scattering) models:

10.0 ± 0.8 fb (ee+p) and 9.4 ± 0.7 fb ($\mu\mu$+p)

limit on $\gamma\gamma \to \gamma\gamma$

ATALS-CONF-2023-002
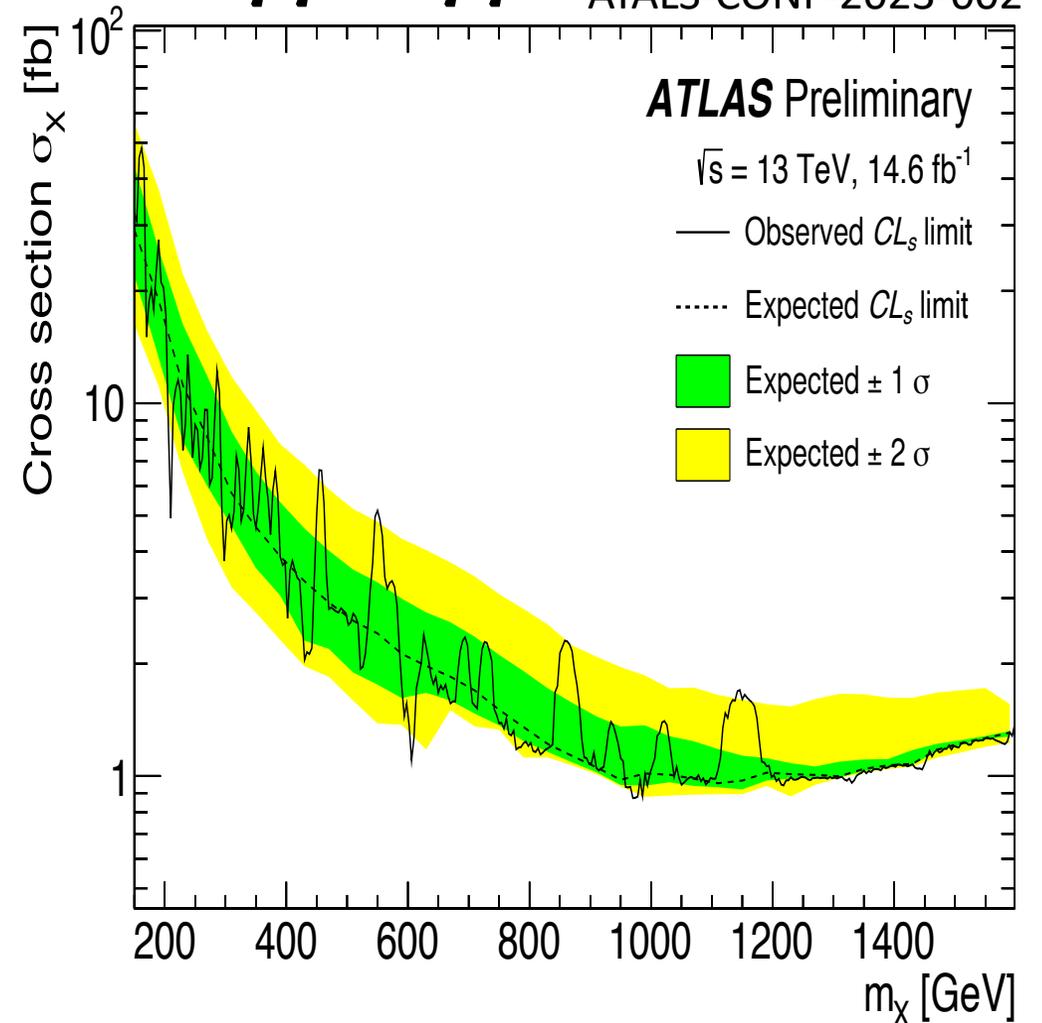
AFP Run-3 (2022-2025) planning

- high-μ runs – regularly data (AFP integrated lumi expected to match ATLAS),
  purpose: high pT exclusive processes, BSM searches.

- low-μ runs (various pile-up conditions, $0.005<\mu<1$) runs during LHC ramp-ups,
  purpose: soft diffraction, low pT hard diffraction.

- "LHCf run" – with β = 19 m,
  purpose: diffractive studies, connection to cosmic ray physics.

- medium-μ runs ($\mu \approx 2$) – 1/fb of data planned to be collected,
  purpose: excellent sample to study medium/high pT hard diffractive processes

- pp $\rightarrow$ PbPb – reference run,
  purpose: sample for diffractive studies at lower energy.

Conclusions

- Successful ATLAS Forward Proton (AFP) detector operation at LHC Run-2 and Run-3 (2022 data)
  - Silicon Tracker (SIT)
  - Time-of-Flight (ToF)

- Single dissociative (soft QCD) and re-scattering probed in photon-induced di-lepton production with forward proton tag

- Light-by-light scattering in BSM search with forward proton tag

- Future precision increase with analysis of Run-3 data
  - larger/new data sets (2023-2025)
  - using ToF for improved vertex reconstruction (background rejection)

References

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults#AFP_figures

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2018-16/

- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-002