Performance of the ATLAS Forward Proton detector

Savannah Clawson (DESY),
on behalf of the ATLAS Forward Detectors group

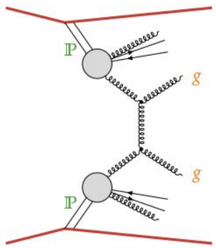
Forward Physics and QCD at the LHC and EIC
Physikzentrum Bad Honnef
23 Oct - 27 Oct 2023

HELMHOLTZ

DESY.

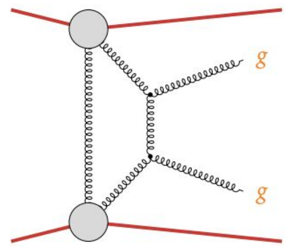
ATLAS EXPERIMENT

Physics motivation



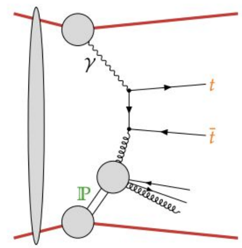
Diffractive jets

ATL-PHYS-PUB-2017-012



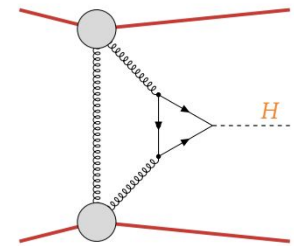
Exclusive jets

Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



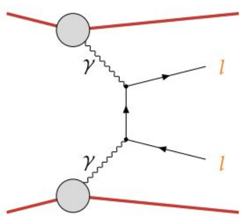
Top quarks

Goncalves et al 2007.04565
Howarth 2008.04249



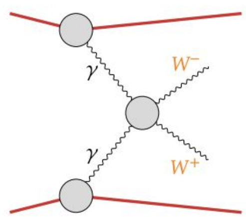
Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052



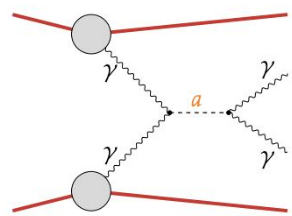
Leptons

CMS 1803.04496
ATLAS 2009.14537



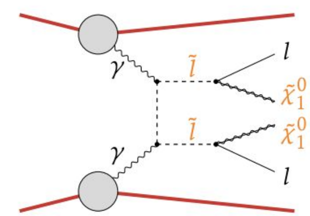
W bosons

Tizchang, Etesami 2004.12203
Baldenegro et al 2009.08331



Axion-like particles

Harland-Lang & Tasevsky 2208.10526
Baldenegro et al 1803.10835



SUSY dark matter

Beresford & Liu 1811.06465
Harland-Lang et al 1812.04886

Types of processes which allow protons to remain intact:

- **Diffraction** via pomeron exchange
- Exclusive **photon-photon fusion**

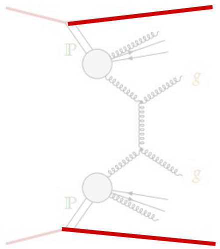
– **discrimination tool** for models:

- ▶ **QCD – hard and non-perturbative,**
- ▶ **probing electroweak scale,**
- ▶ **physics beyond SM.**

Natural ways to seek for diffraction

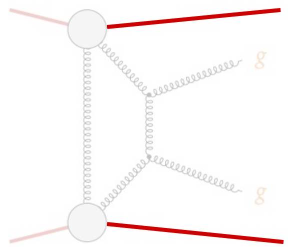
- rapidity gaps,
- **forward protons**

Physics motivation



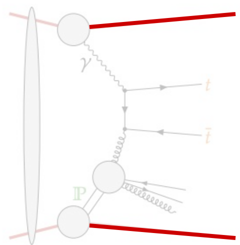
Diffractive jets

ATL-PHYS-PUB-2017-012



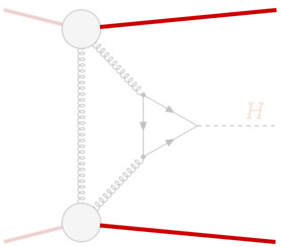
Exclusive jets

Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018



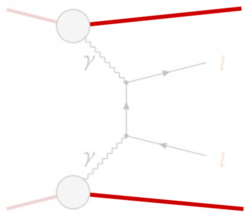
Top quarks

Goncalves et al 2007.04565
Howarth 2008.04249



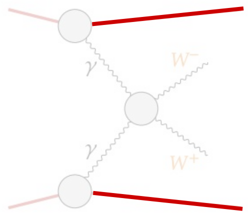
Higgs boson

Cox et al 0709.3035
Heinemeyer et al 0708.3052



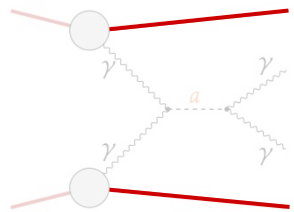
Leptons

CMS 1803.04496
ATLAS 2009.14537



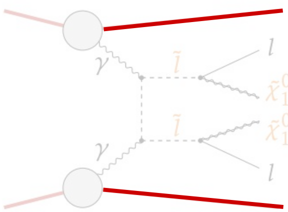
W bosons

Tizchang, Etesami 2004.12203
Baldenegro et al 2009.08331



Axion-like particles

Harland-Lang & Tasevsky 2208.10526
Baldenegro et al 1803.10835



SUSY dark matter

Beresford & Liu 1811.06465
Harland-Lang et al 1812.04886

Types of processes which allow protons to remain intact:

- **Diffraction** via pomeron exchange
- Exclusive **photon-photon fusion**

– **discrimination tool** for models:

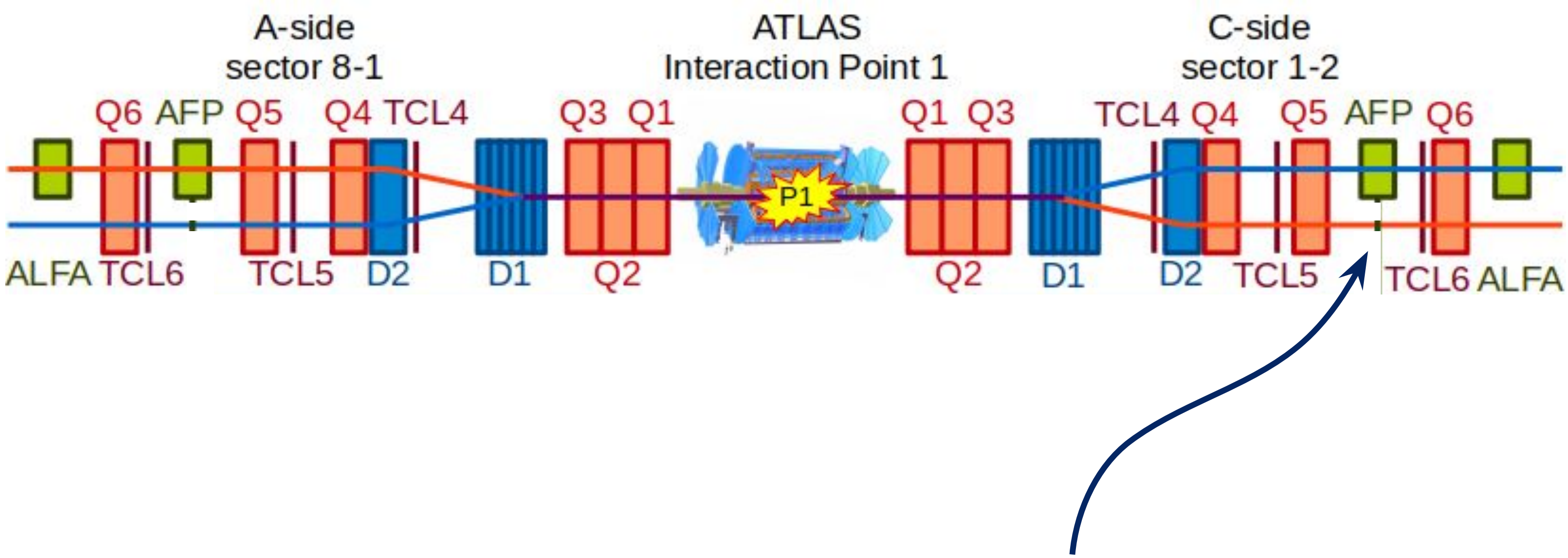
- QCD – hard and non-perturbative,
- probing electroweak scale,
- physics beyond SM.

Natural ways to seek for diffraction

- rapidity gaps,
- **forward protons**

What is the ATLAS Forward Proton detector?

What is AFP?



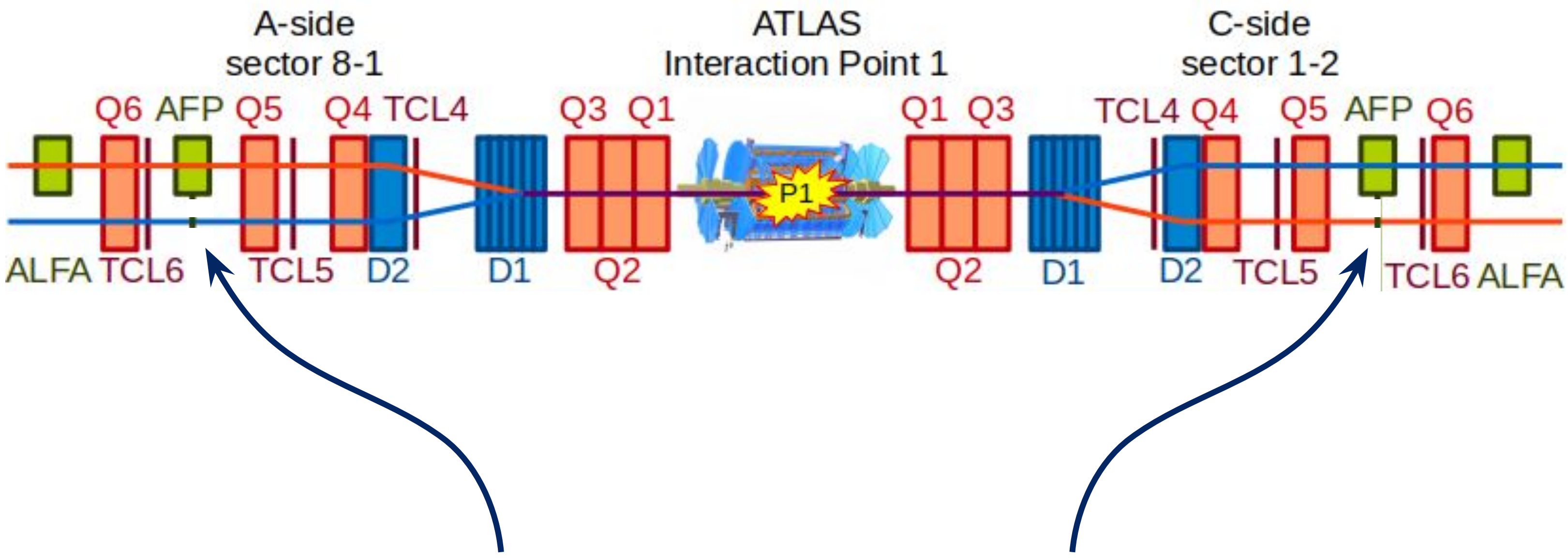
First side installed in 2016

[ATL-PHYS-PUB-2017-012]

Q = Quadrupole magnets
D = Dipole magnets
TCL = Beam collimators
ALFA = Absolute Luminosity For ATLAS

See also: poster by Maciej Trzebinski on ATLAS Roman Pot Detectors

What is AFP?

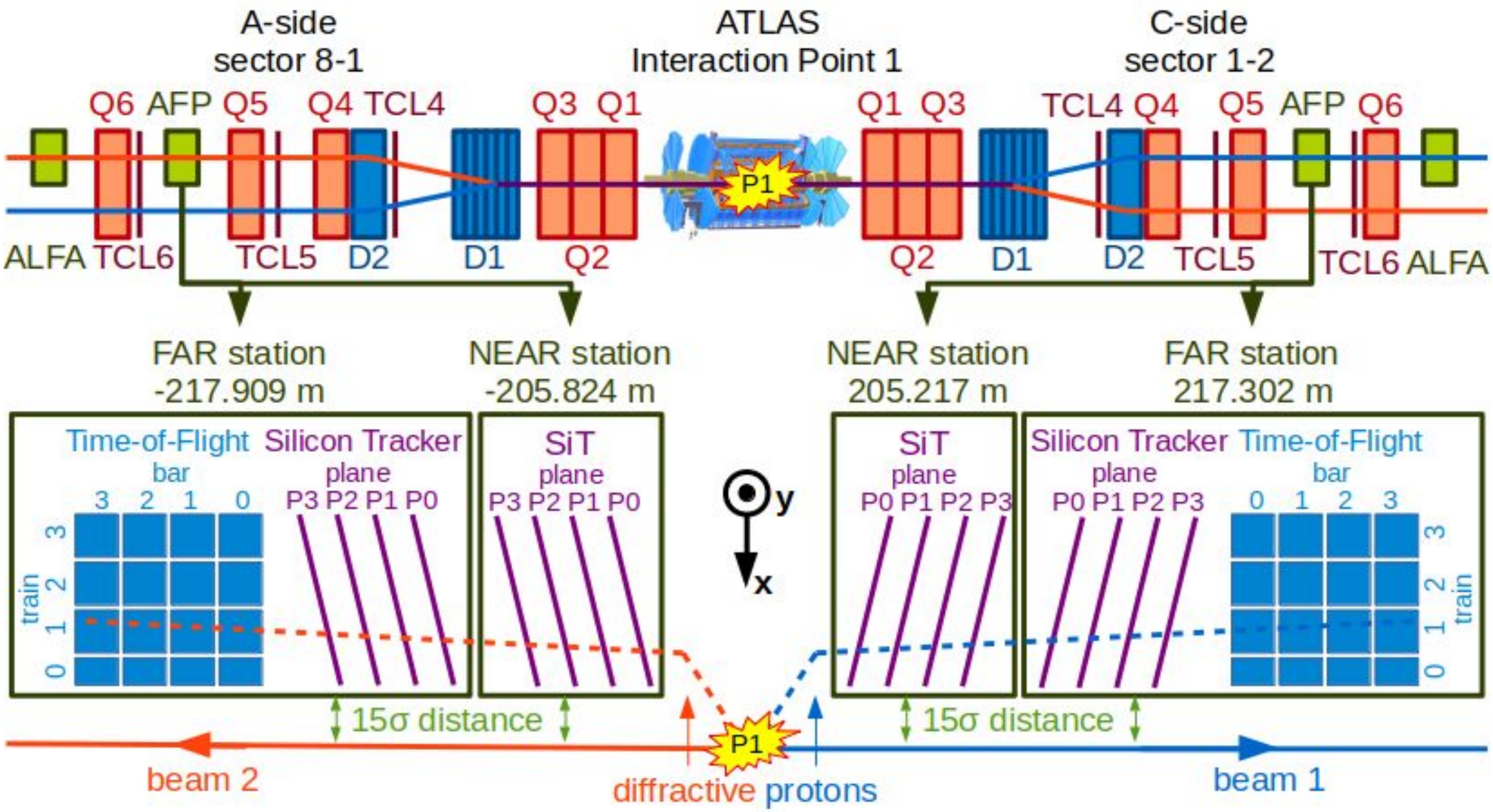


Both sides operational from 2017

Q = Quadrupole magnets
D = Dipole magnets
TCL = Beam collimators
ALFA = Absolute Luminosity For ATLAS

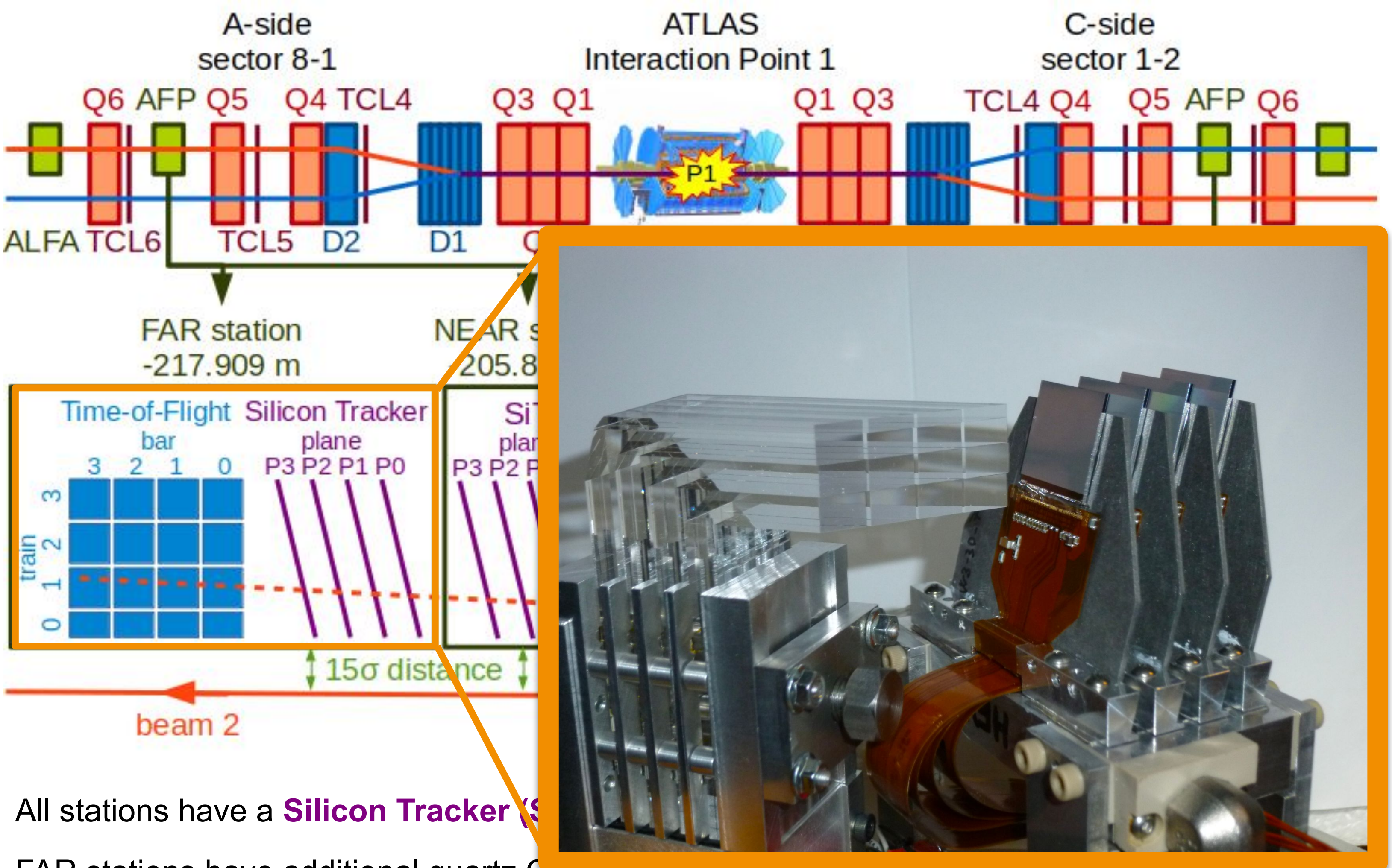
See also: poster by Maciej Trzebinski on ATLAS Roman Pot Detectors

What is AFP?



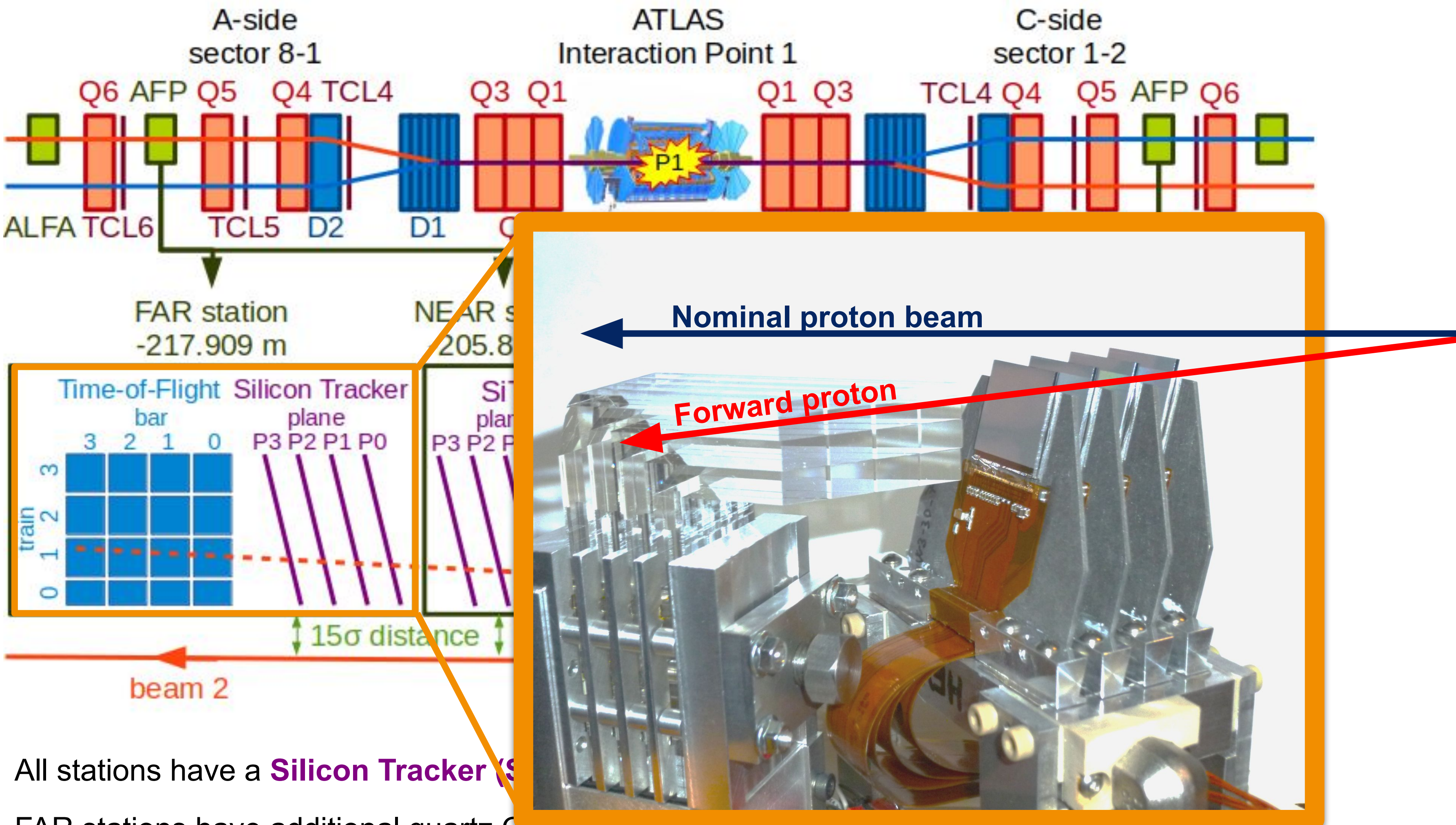
- All stations have a **Silicon Tracker (SiT)** with four planes of edgeless 3D silicon pixel sensors
- FAR stations have additional quartz Cherenkov **Time-of-Flight (ToF)** detectors
- All housed in **Roman Pots (RP)** inside the LHC vacuum chamber. When proton beams are circulating, the pots are moved mechanically towards the beam centre

What is AFP?



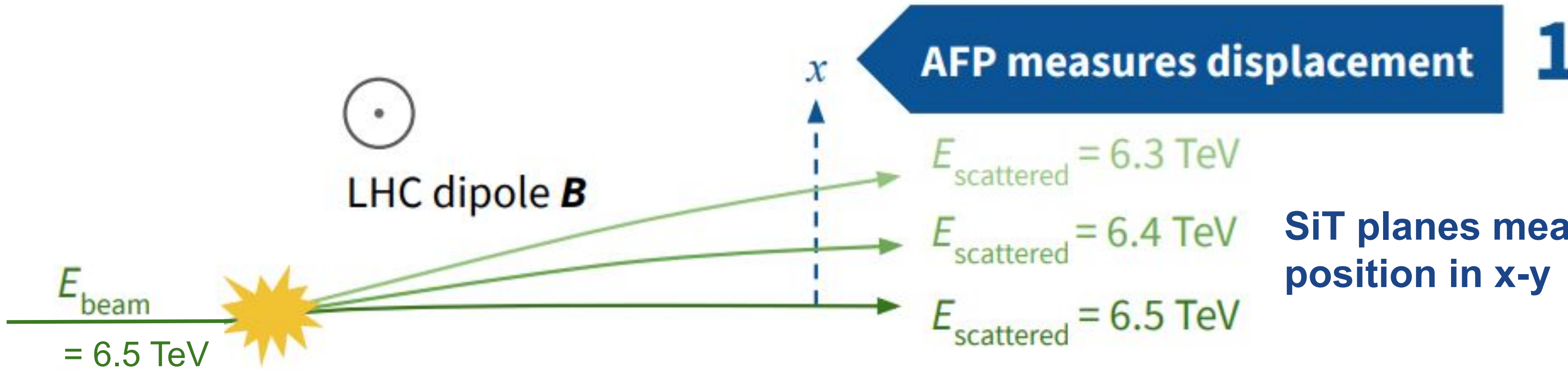
- All stations have a **Silicon Tracker** (S
- FAR stations have additional quartz Cherenkov **Time-of-Flight (ToF)** detectors
- All housed in **Roman Pots (RP)** inside the LHC vacuum chamber. When proton beams are circulating, the pots are moved mechanically towards the beam centre

What is AFP?



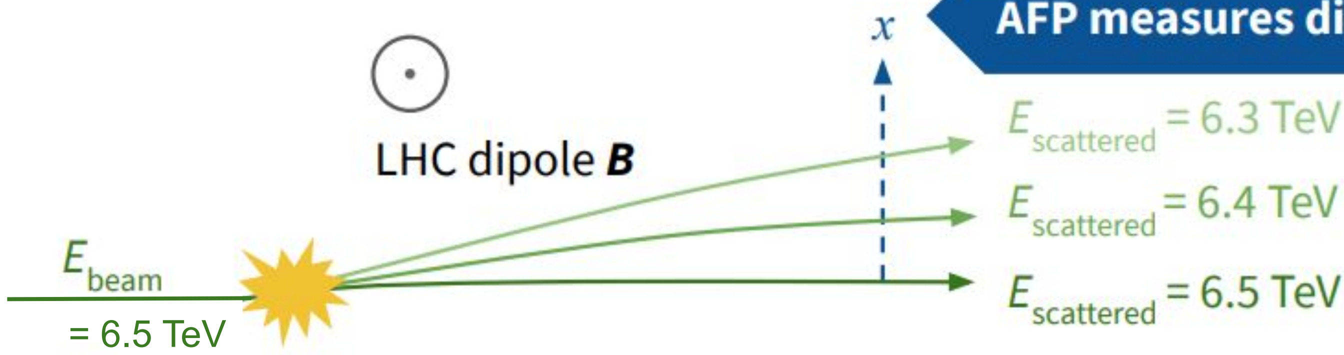
- All stations have a **Silicon Tracker** (S
- FAR stations have additional quartz Cherenkov **Time-of-Flight (ToF)** detectors
- All housed in **Roman Pots (RP)** inside the LHC vacuum chamber. When proton beams are circulating, the pots are moved mechanically towards the beam centre

How do we use SiT information?



SiT planes measure position in x-y

How do we use SiT information?

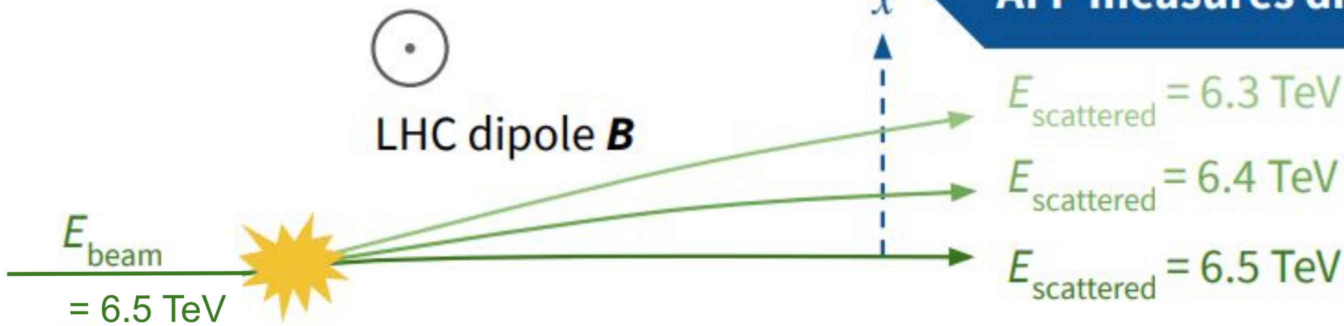


SiT planes measure position in x-y

$$\xi_{AFP} = 1 - E_{scattered} / E_{beam}$$

AFP station acceptance: 2% < ξ < 12%

How do we use SiT information?



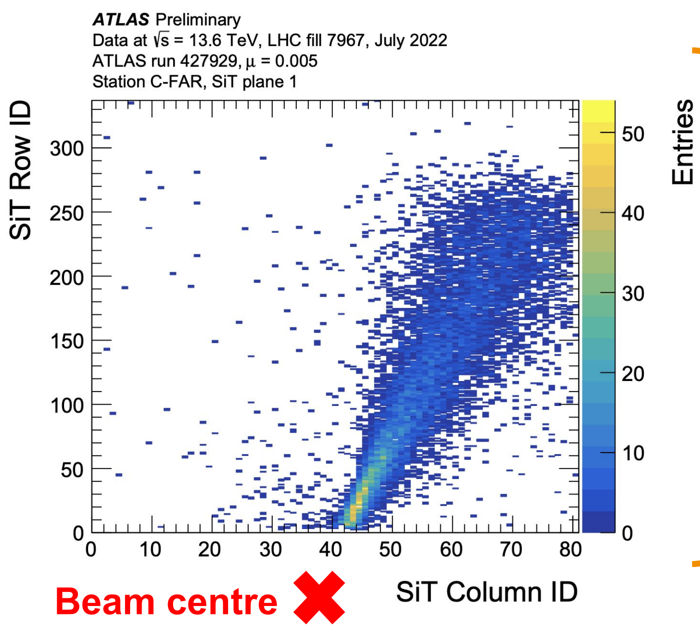
AFP measures displacement 1

SiT planes measure position in x-y

$$\xi_{AFP} = 1 - E_{scattered}/E_{beam}$$

Infer proton energy loss 2

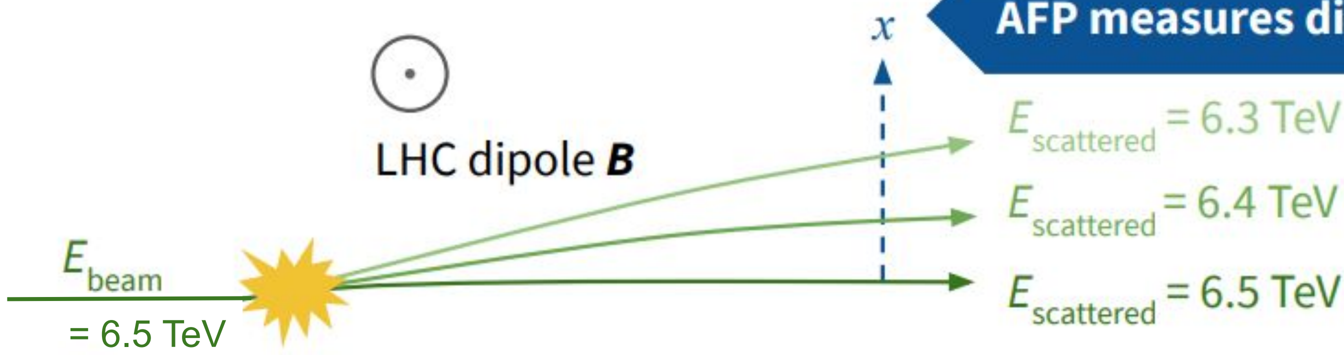
AFP station acceptance: 2% < ξ < 12%



SiT detector:

- 4 planes of 336 × 80 3D silicon pixels
- Individual pixel area of 50 × 250 μm^2
- 14° tilt of planes reducing spatial resolution in short pixel direction (x) to 6 μm

How do we use SiT information?

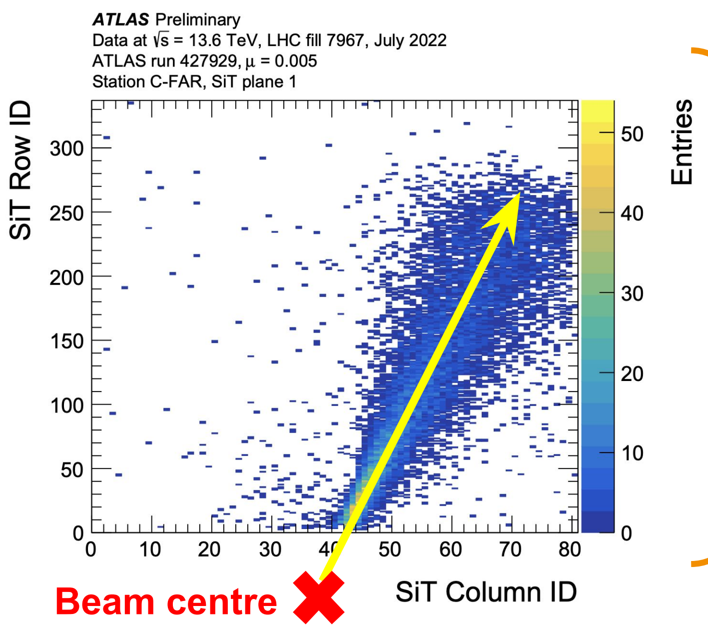


SiT planes measure position in x-y

$$\xi_{AFP} = 1 - E_{scattered}/E_{beam}$$

Infer proton energy loss 2

AFP station acceptance: 2% < ξ < 12%



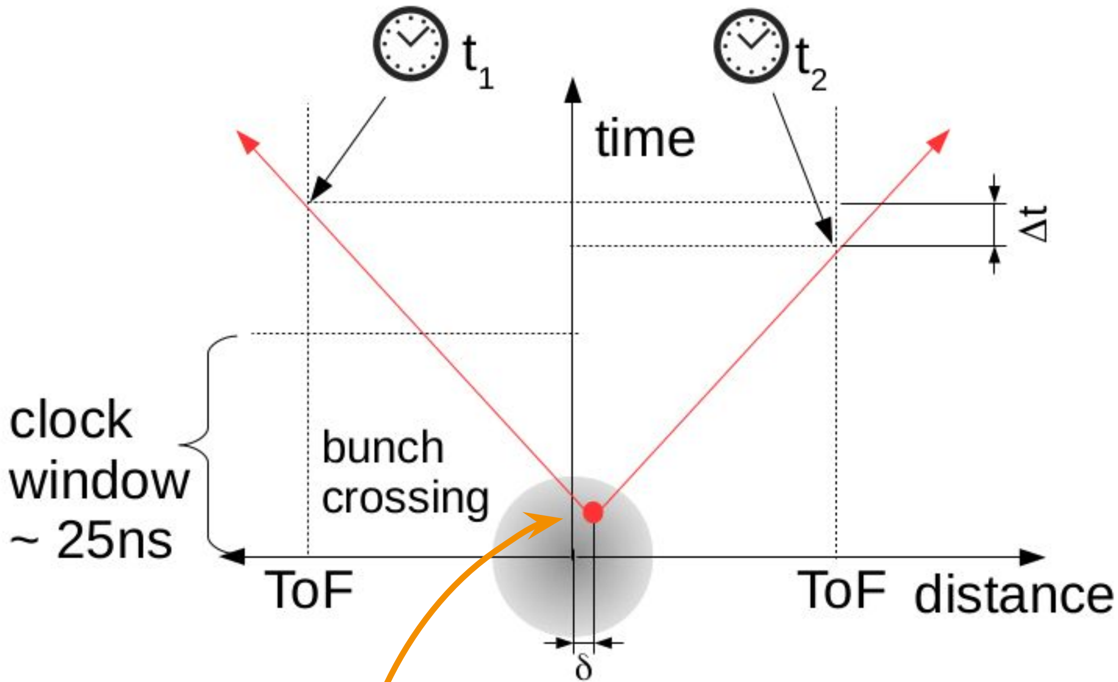
SiT detector:

- 4 planes of 336 × 80 3D silicon pixels
- Individual pixel area of 50 × 250 μm^2
- 14° tilt of planes reducing spatial resolution in short pixel direction (x) to 6 μm

Increasing proton energy loss (ξ)

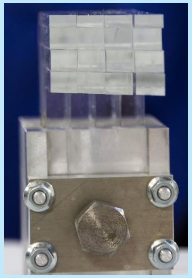
How do we use ToF information?

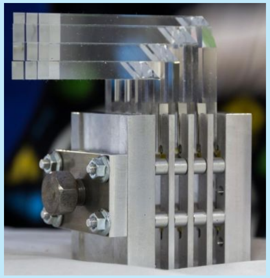
Figure adapted from [2021 JINST **16** P01030]



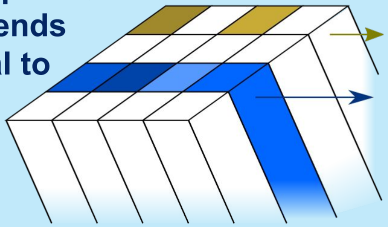
$$\delta = \frac{c}{2}\Delta t$$

Diffractive or photon-induced interaction occurs in central ATLAS





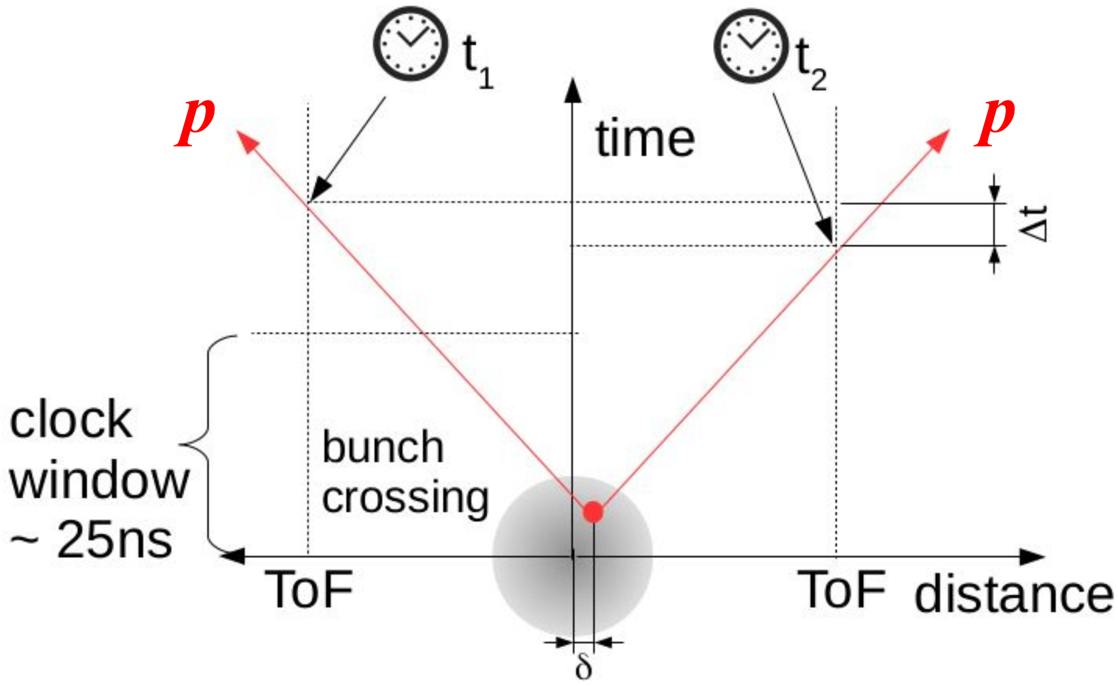
4x4 grid of L-shaped Quartz bars (LQ-bars) sends Cherenkov signal to a microchannel plate photomultiplier tube (MCP-PMT)



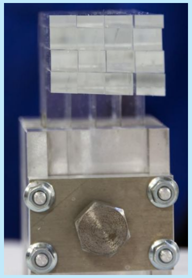
How do we use ToF information?

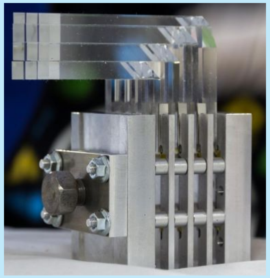
Figure adapted from [2021 JINST **16** P01030]

Intact protons travel ~200m to AFP

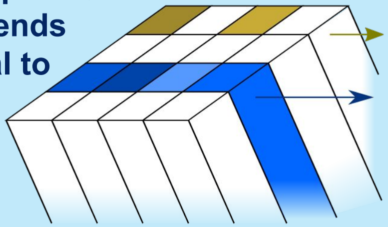


$$\delta = \frac{c}{2} \Delta t$$





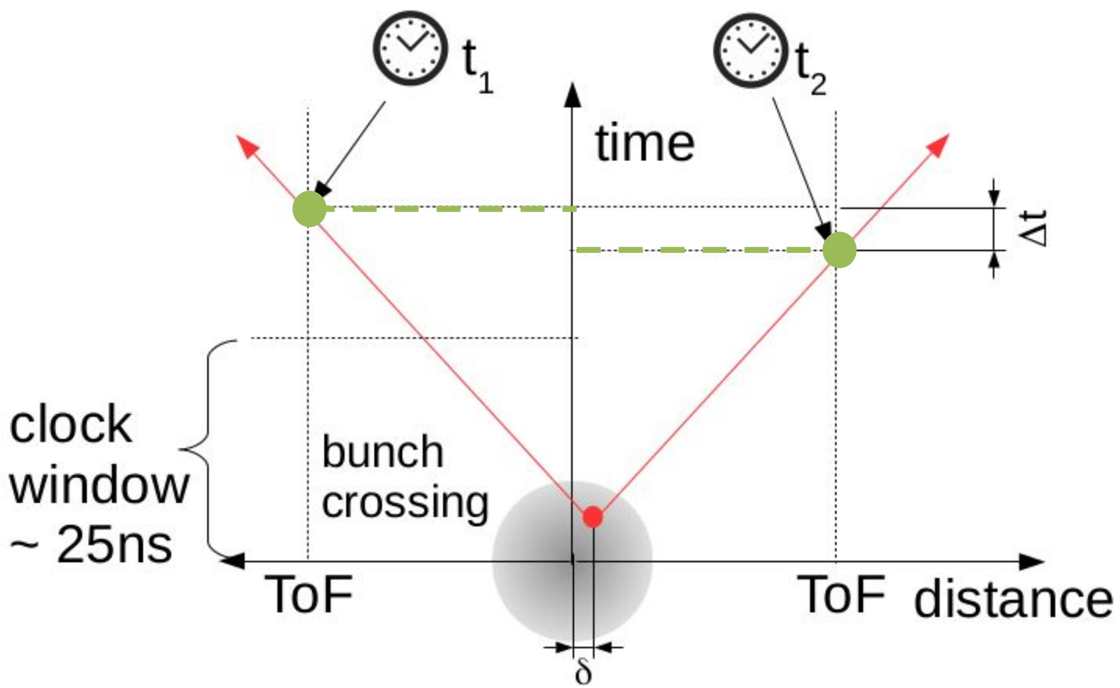
4x4 grid of L-shaped Quartz bars (LQ-bars) sends Cherenkov signal to a microchannel plate photomultiplier tube (MCP-PMT)



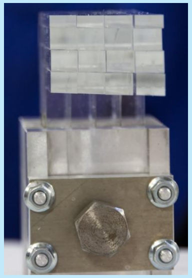
How do we use ToF information?

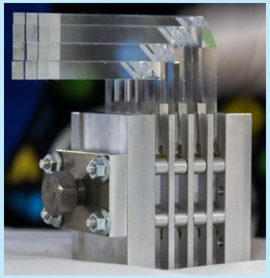
Figure adapted from [2021 JINST **16** P01030]

Proton time-of-flight measured by AFP ToF detectors

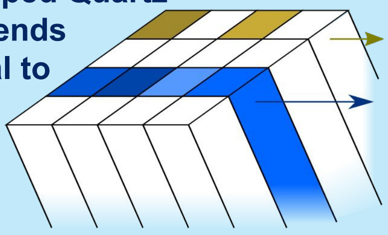


$$\delta = \frac{c}{2} \Delta t$$



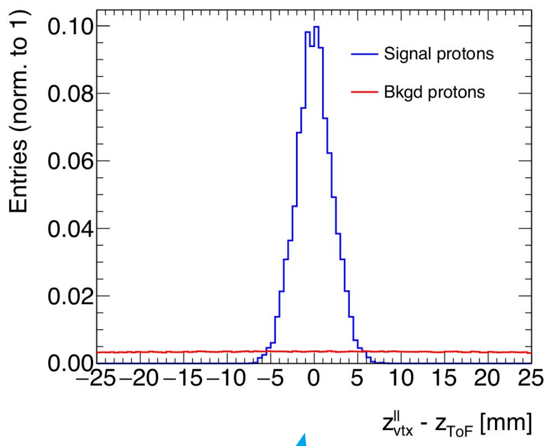


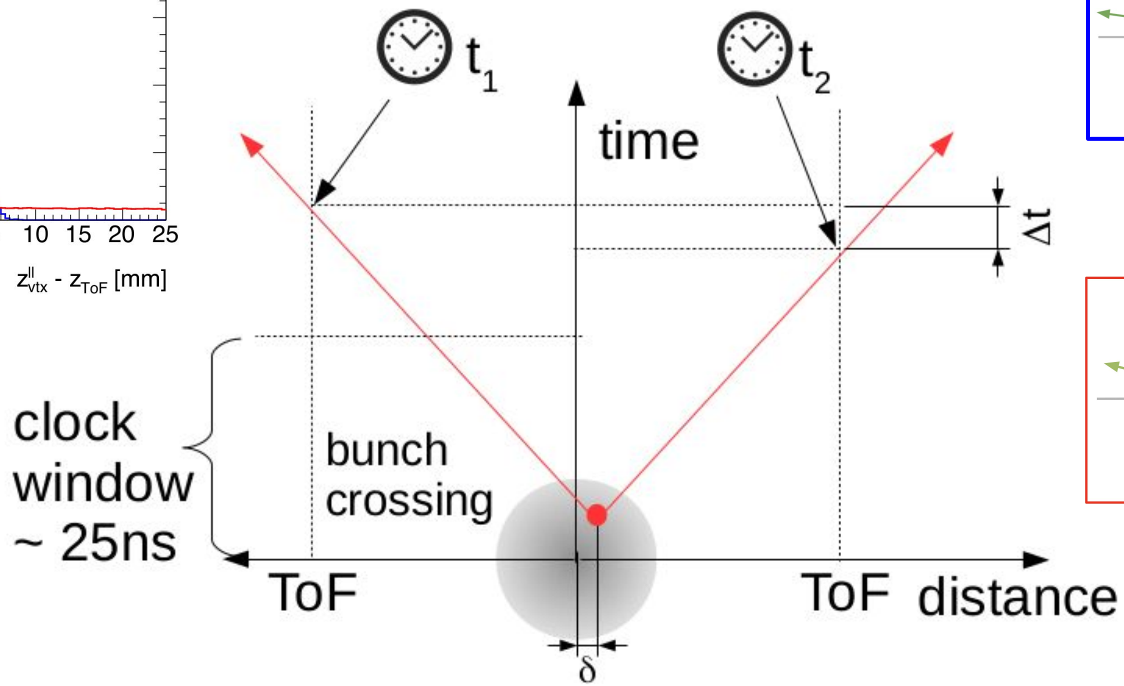
4x4 grid of L-shaped Quartz bars (LQ-bars) sends Cherenkov signal to a microchannel plate photomultiplier tube (MCP-PMT)



How do we use ToF information?

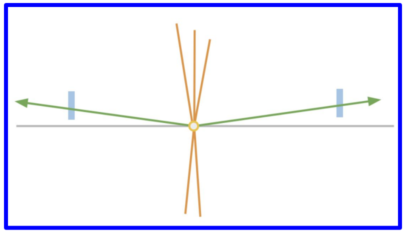
Figure adapted from [2021 JINST **16** P01030]



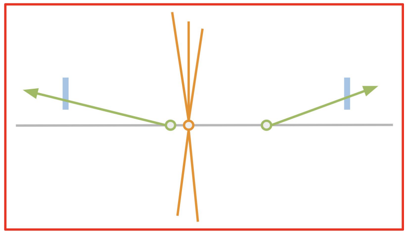


$$\delta = \frac{c}{2} \Delta t$$

SIGNAL



BACKGROUND



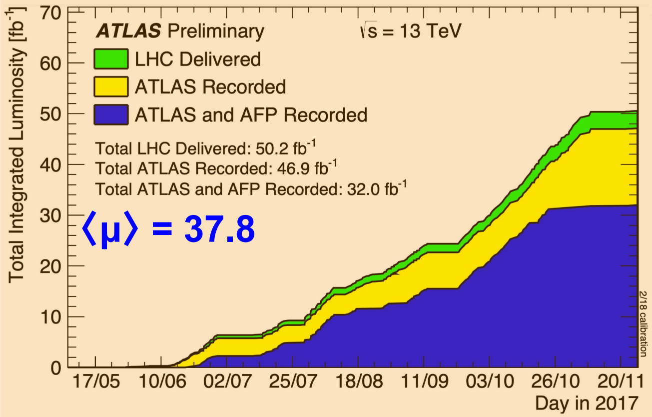
Difference in time-of-flight used to calculate interaction vertex position and compare to reconstructed primary vertex in central ATLAS detector

AFP Performance

Available data

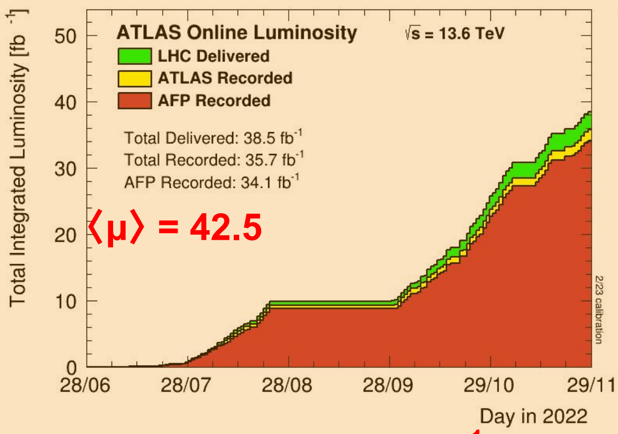
STANDARD RUNS

2017



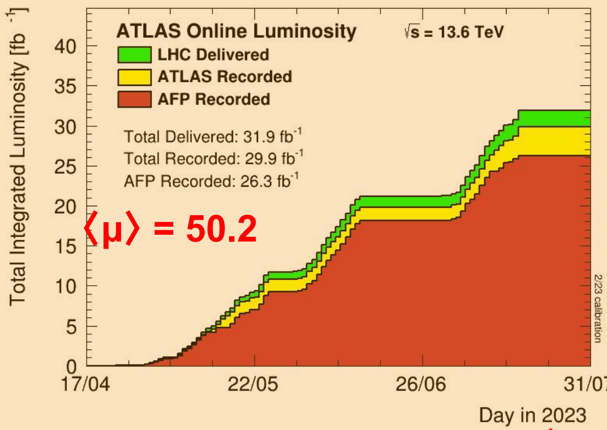
- AFP recorded **32.0 fb^{-1}**
- After ATLAS+AFP GRL = **14.6 fb^{-1}**

2022



- AFP recorded **34.1 fb^{-1}**
- After ATLAS+AFP GRL ≈ **25–30 fb^{-1}**

2023



- AFP recorded **26.3 fb^{-1}** as of the end of July

PHYSICS MOTIVATION: photon-induced processes, central exclusive diffraction

SPECIAL RUNS

2017

- $0.03 \lesssim \mu \lesssim 0.05$ = 100 nb^{-1}
- $0.3 \lesssim \mu \lesssim 1$ = 1.15 pb^{-1}
- $\mu \approx 2$ = 150 pb^{-1}

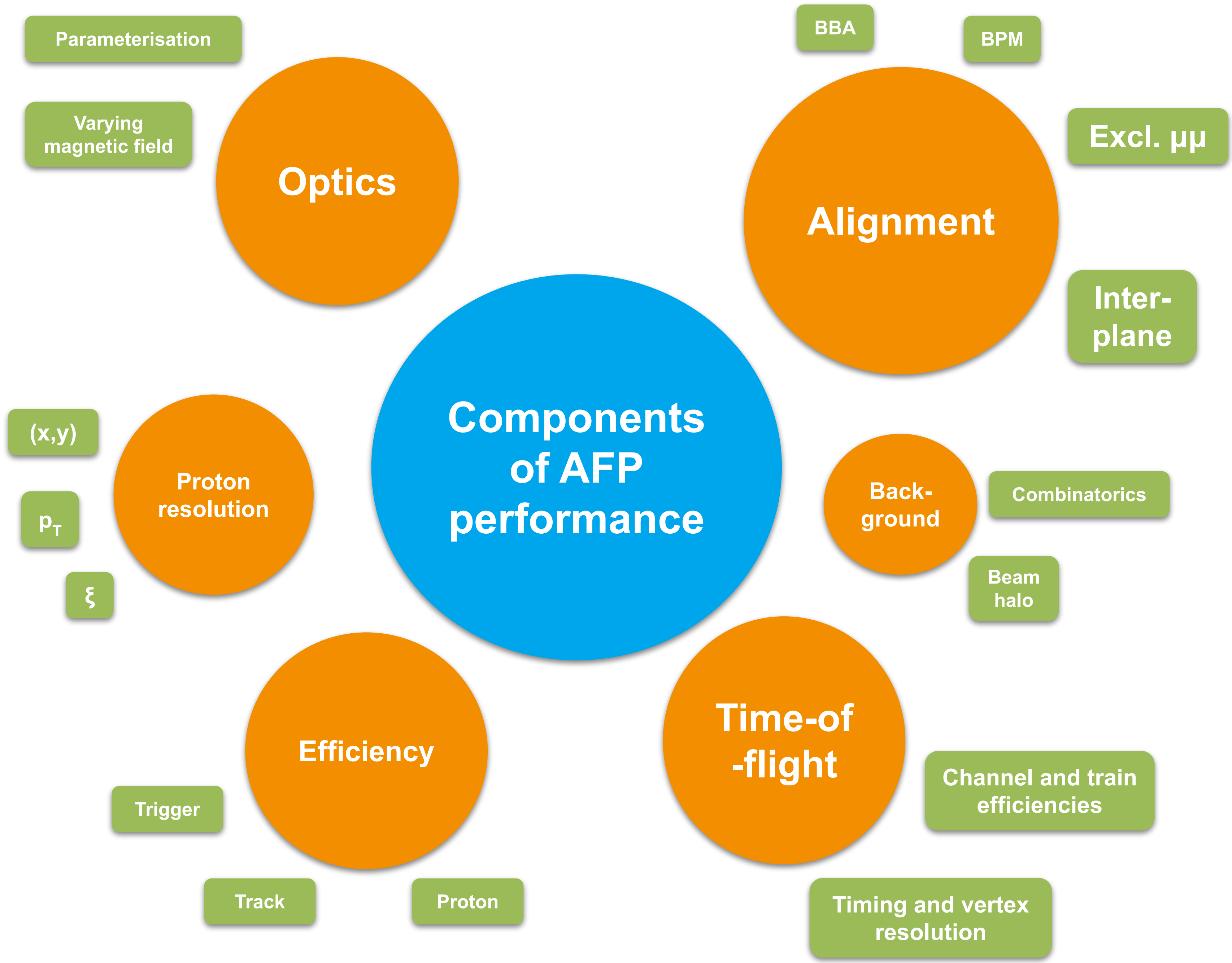
2022

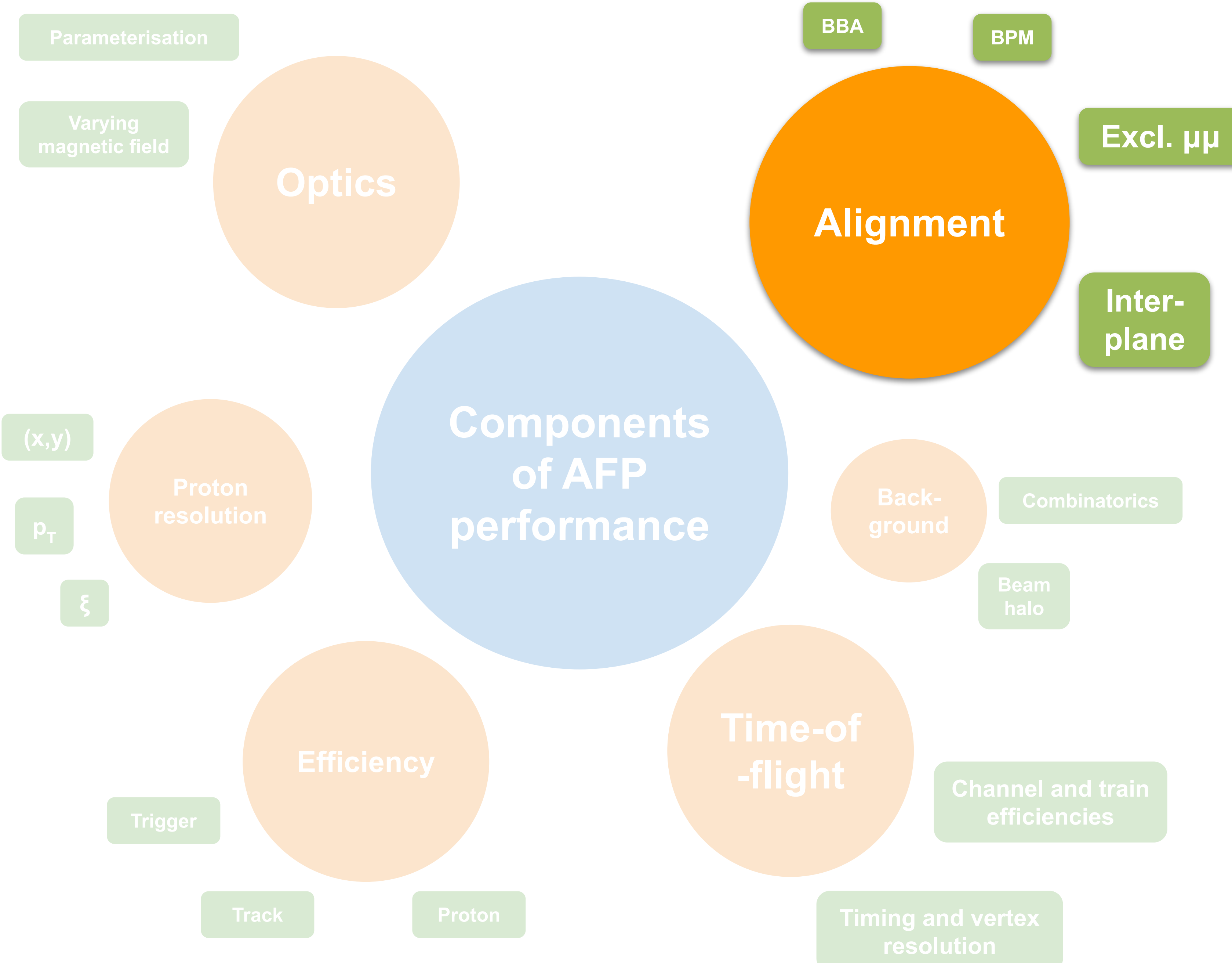
- $\mu \approx 0.005$ = 0.4 nb^{-1}
- $\mu \approx 0.05$ = 35 nb^{-1}
- $\mu \approx 0.02$–1.0 = 170 nb^{-1}

2023

- $\mu \approx 0.05$ = 61 nb^{-1}
- $\mu \approx 0.2$ = 29 nb^{-1}
- $\mu \approx 1$ = 175 nb^{-1}

PHYSICS MOTIVATION: single-diffractive production, pomeron structure, rapidity gaps

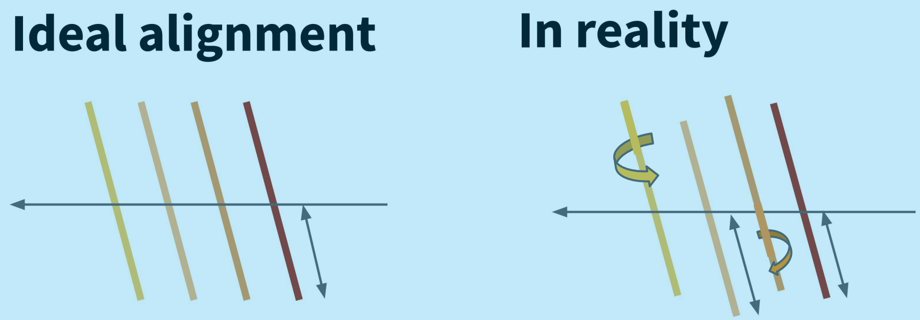

Components of AFP performance
Optics
Parameterisation
Varying magnetic field
Alignment
BBA
BPM
Excl. μμ
Inter-plane
Proton resolution
(x,y)
p_T
ξ
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution


Parameterisation
Varying magnetic field
Optics
BBA
BPM
Alignment
Excl. μμ
Inter-plane
Components of AFP performance
(x,y)
p_T
ξ
Proton resolution
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution

Components of AFP alignment

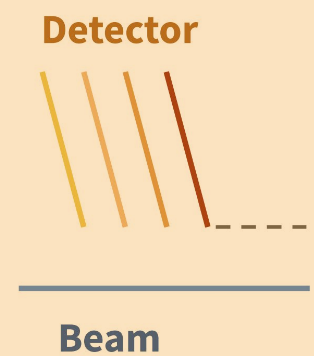
- Track reconstruction relies on knowing the relative alignment of SiT planes in each station

LOCAL



- Preliminary alignment calculated for Run 3 ✅
- Investigating alternative global χ^2 method to remove weak modes and incorporate more parameters

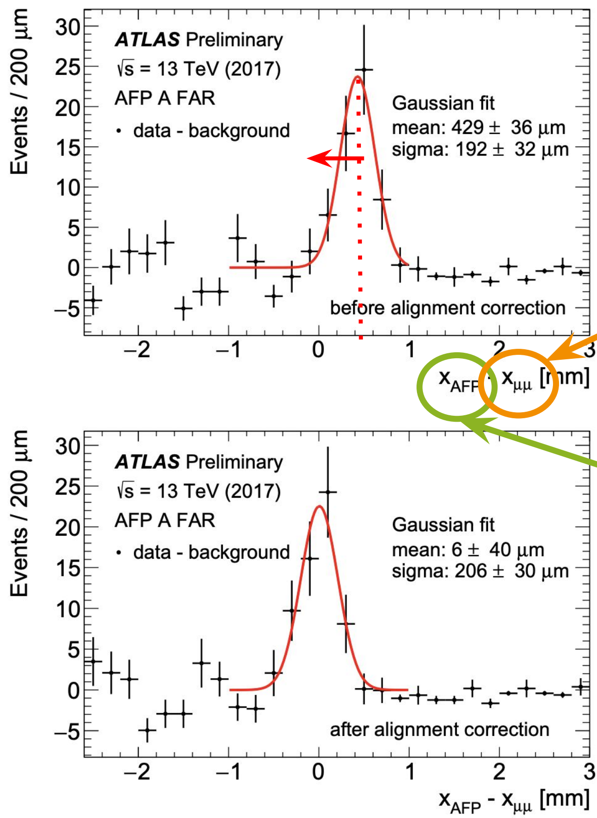
GLOBAL DOMINANT SYSTEMATIC IN RUN 2



- Accurate reconstruction of proton position and therefore energy loss relies on knowing the relative position of AFP stations wrt the beam
- Several components to this "global alignment"
  - → Distances related to beam–detector distance measured with Beam-Based Alignment (**BBA**) and Beam-Position Monitoring (**BPM**) methods ✅
  - → Residual corrections derived from **exclusive dimuon** data IN PROGRESS

Global alignment: exclusive dimuons

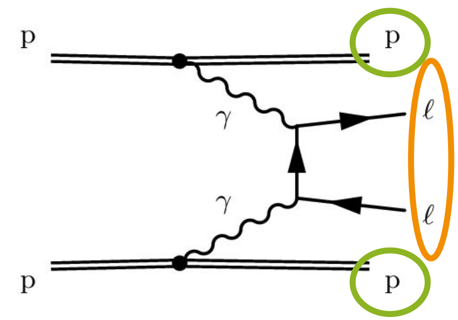
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults



- Residual corrections calculated from AFP "standard candle" = γγ→μμ process:

Predict proton position from pure dimuon data sample

And compare to proton positions measured in AFP



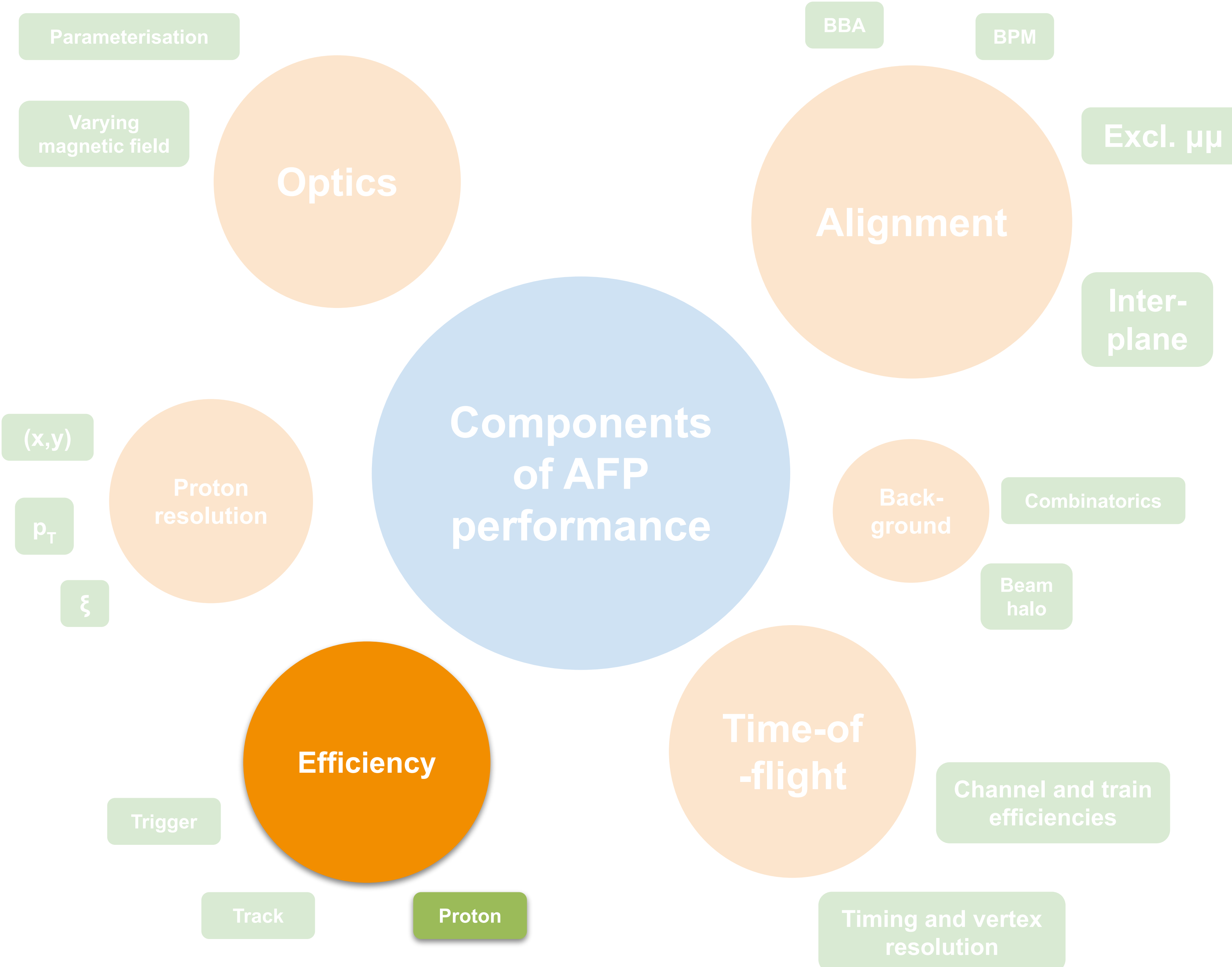
$$\xi^{\pm}_{\mu\mu} = \frac{m_{\mu\mu}}{\sqrt{s}} e^{\pm y_{\mu\mu}}$$

- Systematic uncertainty in Run 2 of ± 300 μm
  - → ~10% signal yield uncertainty in [1], 6% impact on cross-section measurement in [2]

IN RUN 3

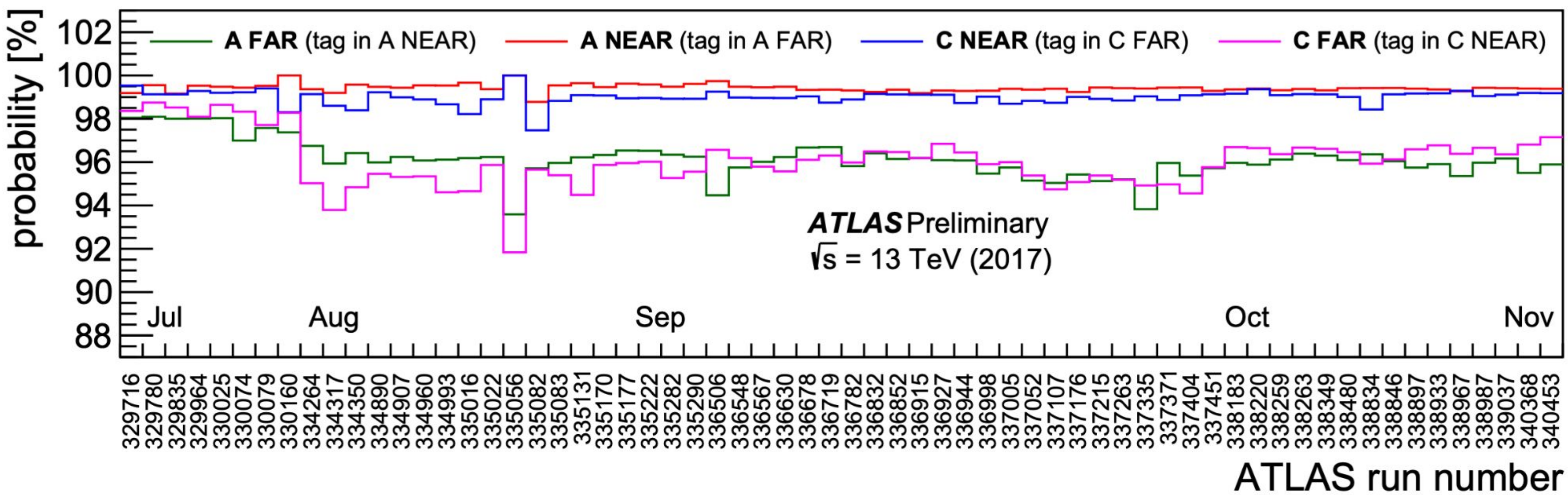
- Hoping to reduce systematic to ~100 μm
- Needs understanding of LHC beam optics **IN PROGRESS**
  - → **See poster by Sergio Javier Arbiol Val**

[1] ALP search with AFP JHEP 07 (2023) 234, [2] Dileptons + AFP proton tag PRL 125 (2020) 261801

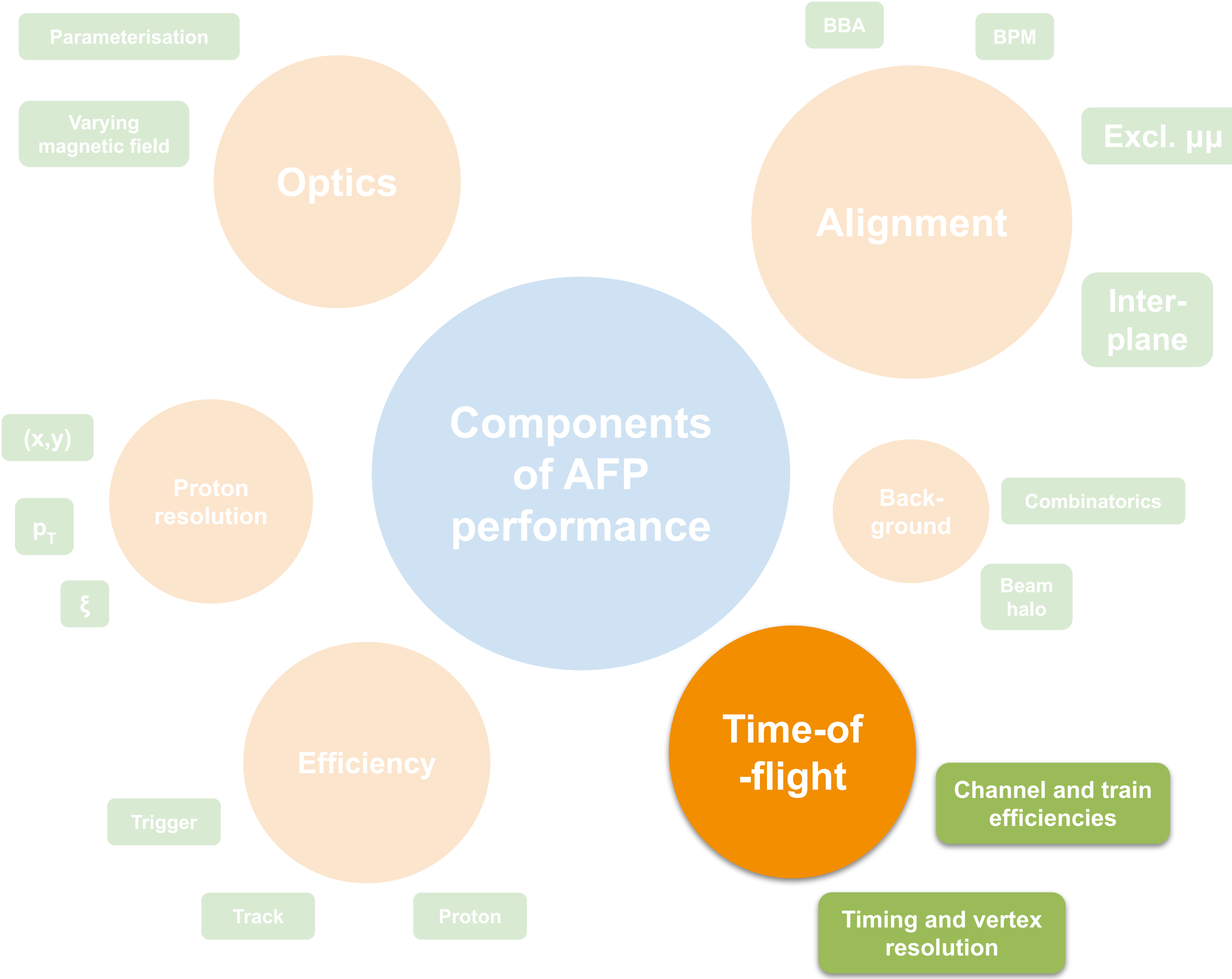

Parameterisation
Varying magnetic field
Optics
BBA
BPM
Excl. μμ
Alignment
Inter-plane
(x,y)
p_T
ξ
Proton resolution
Components of AFP performance
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution

Proton reconstruction efficiency in Run 2

- Station tag-and-probe method used to find efficiency of reconstructing a proton



- Efficiency in outer (FAR) stations is lower due to proton showering between stations
- Default proton reconstruction requires a proton track in both NEAR and FAR station → **proton reconstruction efficiency = 92 ± 2 %**



Parameterisation
Varying magnetic field
Optics
BBA
BPM
Excl. μμ
Alignment
Inter-plane
(x,y)
p_T
ξ
Proton resolution
Components of AFP performance
Back-ground
Combinatorics
Beam halo
Efficiency
Trigger
Track
Proton
Time-of-flight
Channel and train efficiencies
Timing and vertex resolution

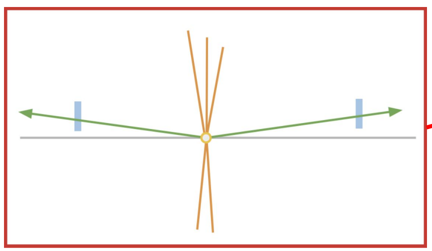
Time-of-flight: Run 2

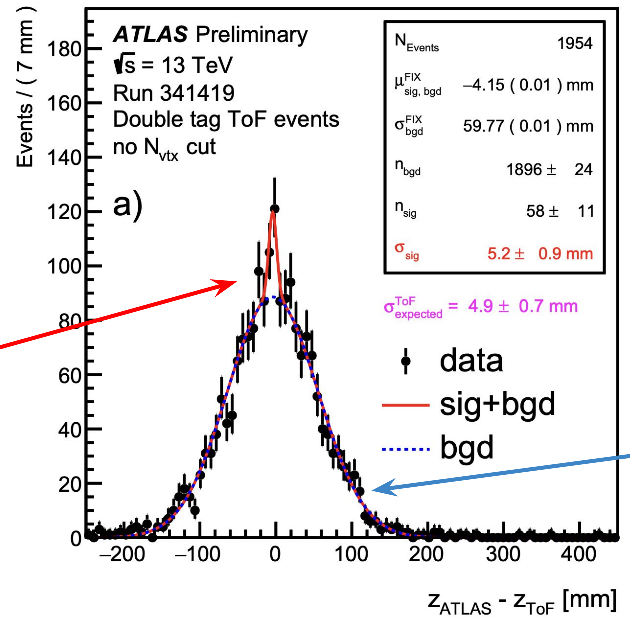
[ATL-FWD-PUB-2021-002](https://)

- Overall timing resolution measured to be between 20 – 30 ps
  - ➞ Equal to ~**5 mm vertex resolution**, improving background suppression in high pileup runs

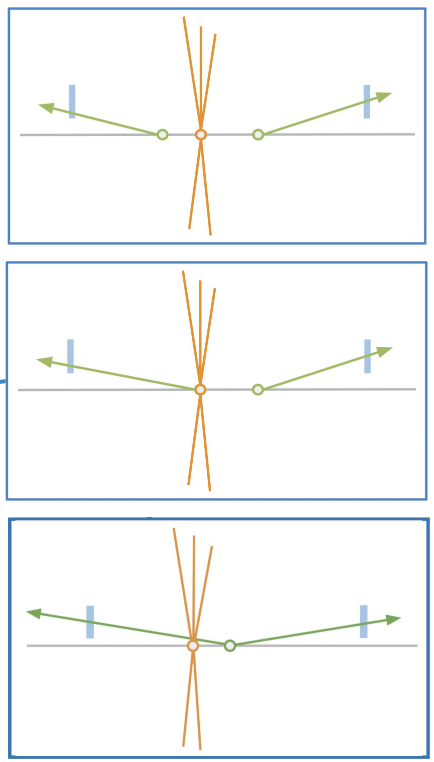
Initial timing resolution goal of < 30 ps
Ultimate resolution goal of 10 ps
[ATL-TDR-024]

SIGNAL





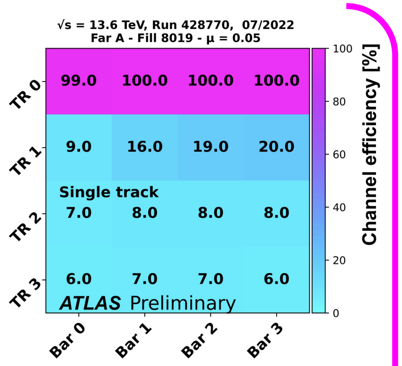
BACKGROUNDS

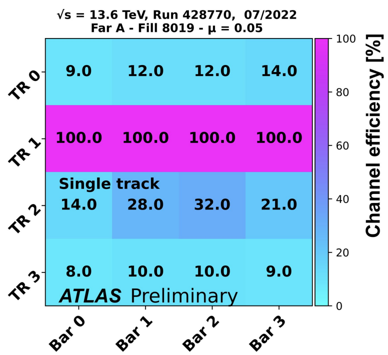


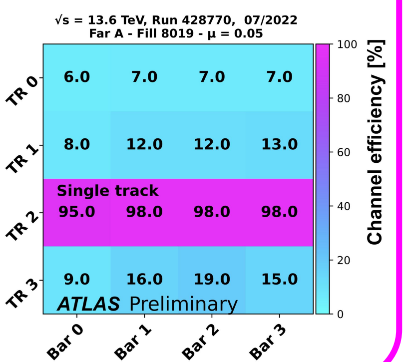
- However, **train efficiency < 7%** for the majority of data-taking
  - ➞ Due to fast degradation of the PMTs in harsh operating conditions

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

NEW: Time-of-flight in Run 3





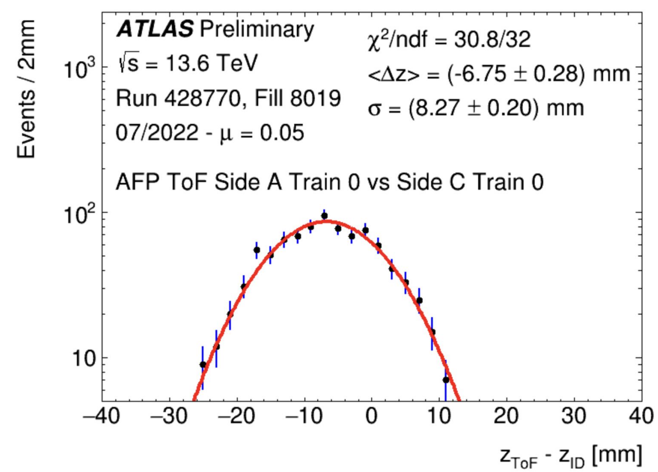


What's new?

- New PMTs and Out-of-Vacuum solution in Run 3 to address ToF inefficiency
- New trigger module: possibility to trigger on single train

Impact:

- Early low-pileup data shows high ToF channel efficiency
- Performance in higher pileup runs and over time is under study



Vertex resolution 8–9 mm

Summary

- Improved understanding of AFP operation and performance in Run 3
- Dominant systematics in Run 2 analyses arose from LHC beam optics effects and global alignment

  → Lots of effort in Run 3 to reduce these

- Early Run 3 low-pileup data shows high ToF efficiency

Lots of new physics from Run 2 and 3 still to come!

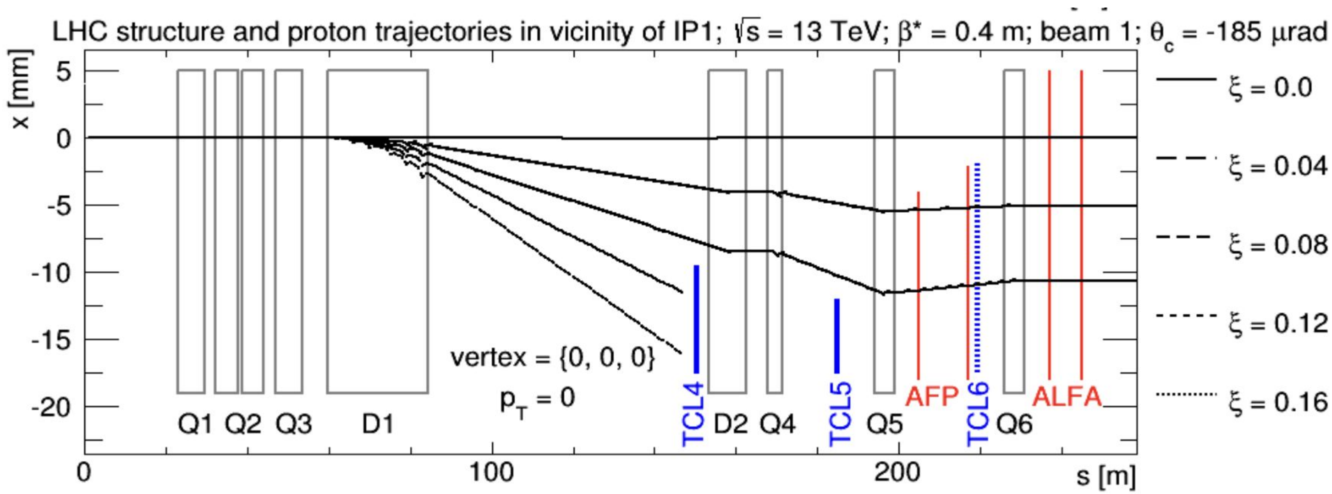
AFP public physics results:

- ATL-PHYS-PUB-2015-003 Exclusive Jet Production with Forward Proton Tagging Feasibility Studies for the AFP Project
- ATL-PHYS-PUB-2017-012 Proton tagging with the one arm AFP detector
- PRL 125 (2020) 261801 Observation and measurement of forward proton scattering in association with lepton pairs produced via the photon fusion mechanism at ATLAS
- JHEP 07 (2023) 234 **Search for an axion-like particle with forward proton scattering in association with photon pairs at ATLAS**

Backup

Optics

- Proton trajectories and therefore **AFP acceptance** depend heavily on LHC **beam optics**

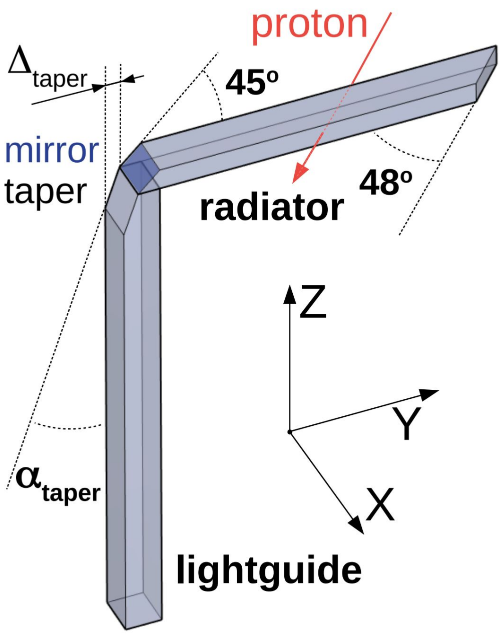


- Proton transport determined from MAD-X simulation to relate proton position in AFP to proton energy loss. From Run 2 dilepton measurement PRL 125 (2020) 261801:

$$x(\xi) = -119\xi - 164\xi^2$$

- Systematic uncertainties determined by varying beam crossing angle in MAD-X. **Large uncertainty in many Run 2 analyses**.
- **In Run 3:** Studies on varying magnetic fields to cross-check results and reduce systematic uncertainties

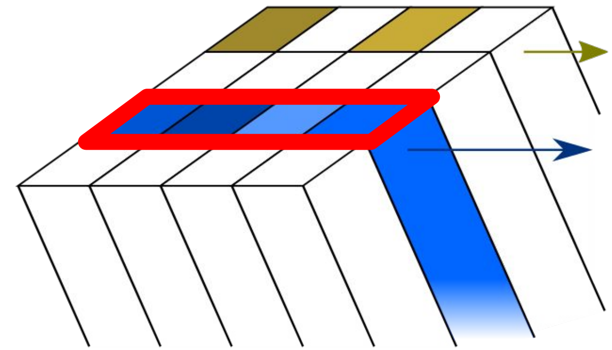
AFP-ToF: LQ bar dimensions (Run 2)



haped quartz bar
)-bar) sends
erenkov signal to
icrochannel plate
otomultiplier tube
CP-PMT)

4 channels aligned along proton trajectories to form "trains"

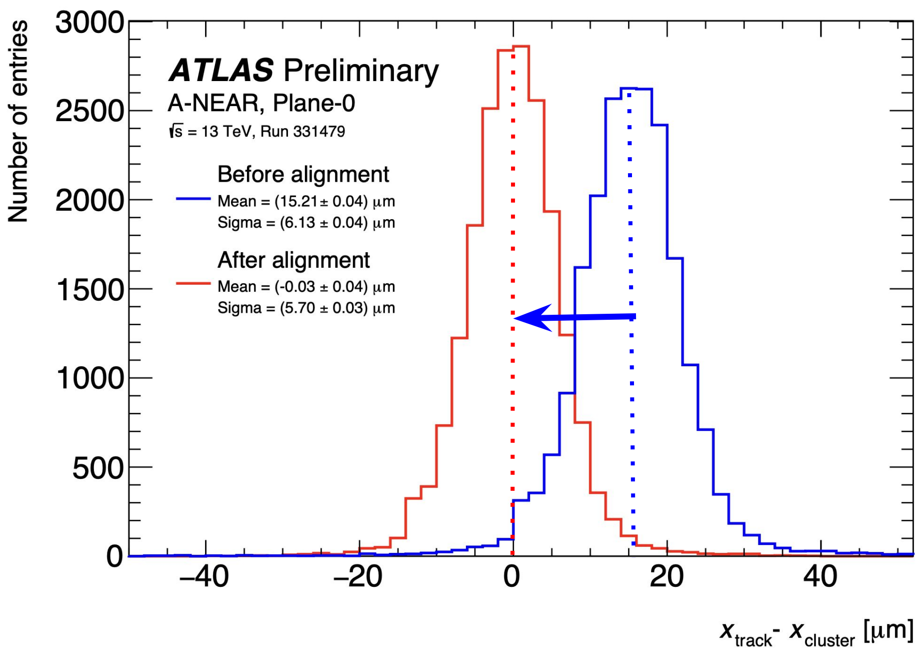
The transverse size of the LQ-bars range from **2 mm** (closest to beam) to **5 mm** (farthest from the beam)

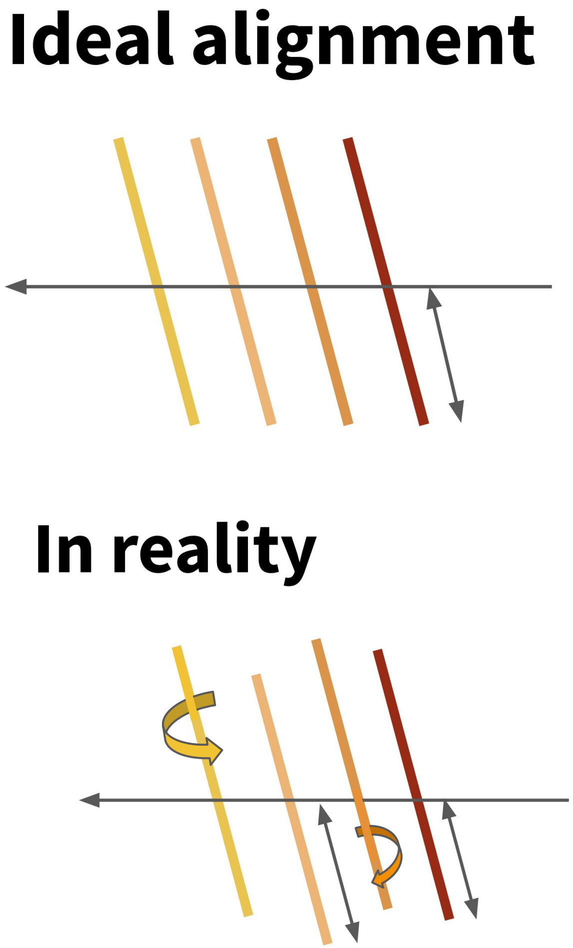


LQ bar dimensions: $Z \times Y \times X$ [mm] / α_{taper} [°] / Δ_{taper} [mm]					
train	radiators A	radiators B	radiators C	radiators D	lightguides
0	$2 \times 62.41 \times 6$	$2 \times 56.78 \times 6$	$2 \times 51.15 \times 6$	$2 \times 45.52 \times 6$	$71.3 \times 5 \times 6/18/3$
1	$4 \times 58.16 \times 6$	$4 \times 52.53 \times 6$	$4 \times 46.9 \times 6$	$4 \times 41.27 \times 6$	$67.2 \times 5 \times 6/18/1$
2	$5 \times 52.91 \times 6$	$5 \times 47.28 \times 6$	$5 \times 41.65 \times 6$	$5 \times 36.02 \times 6$	$62.1 \times 5 \times 6/0/0$
3	$5.5 \times 46.6 \times 6$	$5.5 \times 43.03 \times 6$	$5.5 \times 35.4 \times 6$	$5.5 \times 29.77 \times 6$	$56.6 \times 5.5 \times 6/0/0$

AFP-SiT: Local (inter-plane) alignment

- Track reconstruction requires knowledge of the relative position of SiT planes within each station
- Offsets typically O[10 μm] and rotations O[mrad]

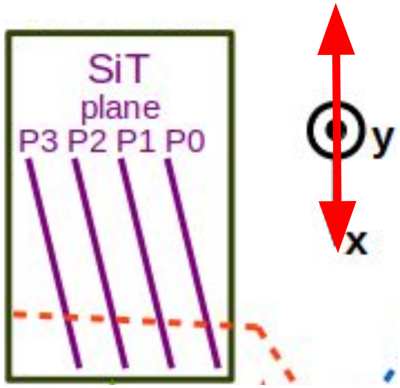


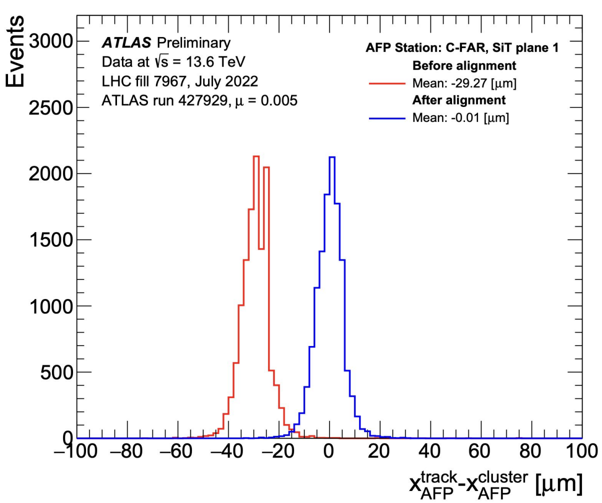


- Preliminary alignment calculated for 2022 ✅
- Iterative method planned to be updated with global χ^2 method (used for ATLAS inner detector alignment)

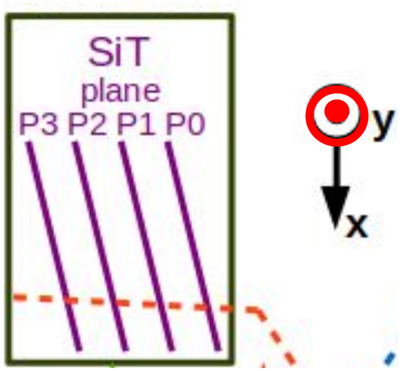
2022 preliminary inter-plane alignment

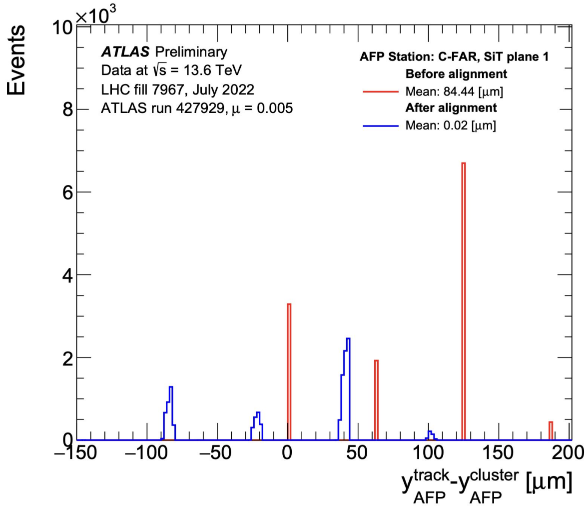
Offsets in x



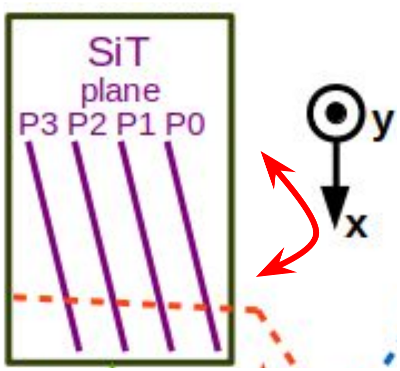


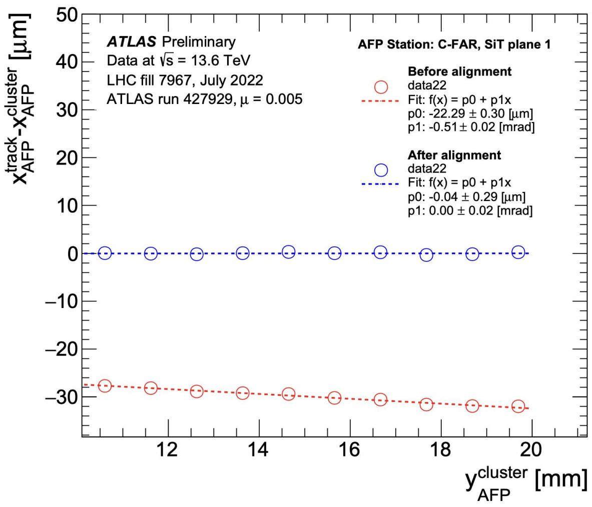
Offsets in y



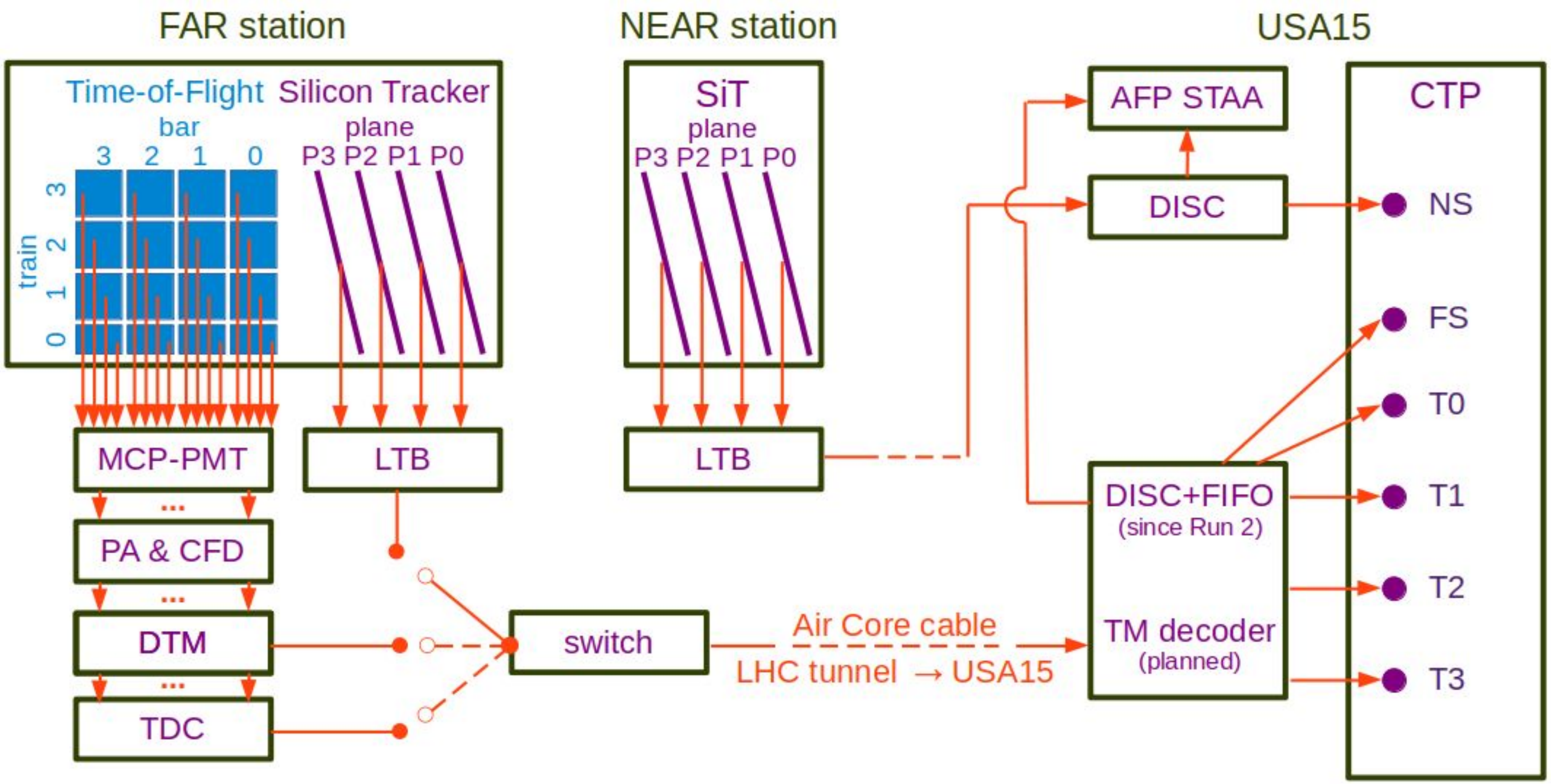


Rotations about z





AFP trigger system



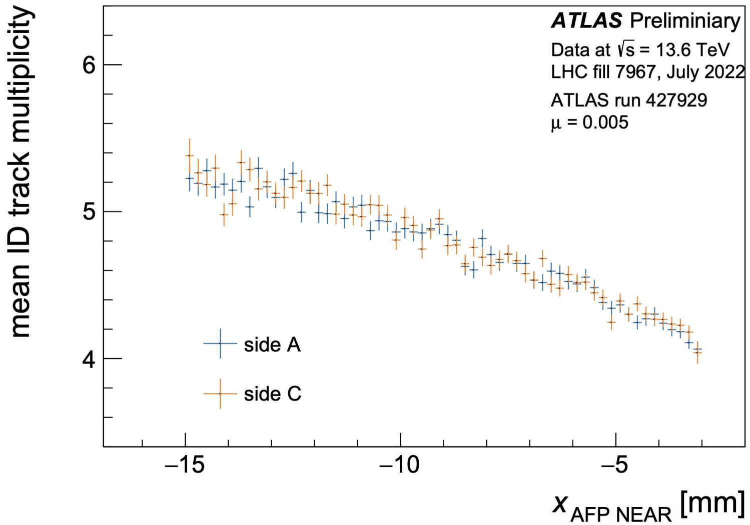
SiT trigger dead-time is 400 ns (= 16 bunch crossings) and therefore SiT trigger is only used in low pileup runs

Correlation with ATLAS in Run 3

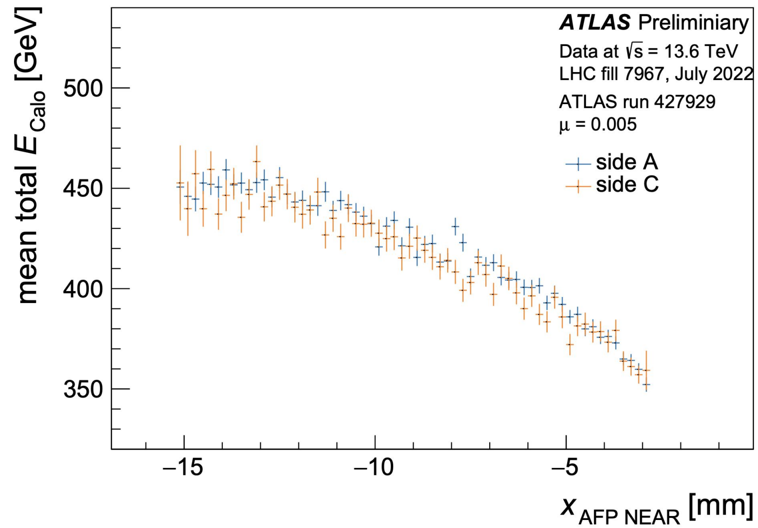
- Analysis of AFP performance is underway, with first checks for correlation with activity in central ATLAS

Correlation of proton position in AFP (related to proton energy loss) with

Number of inner detector tracks:



Energy deposited in calorimeter:

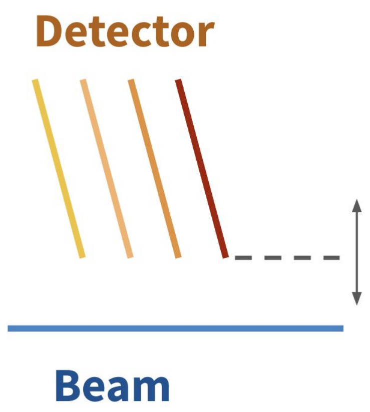


- Requirement of exactly one track reconstructed in each AFP station
- The more activity seen in ATLAS, the more energy the proton in AFP has lost ✅

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

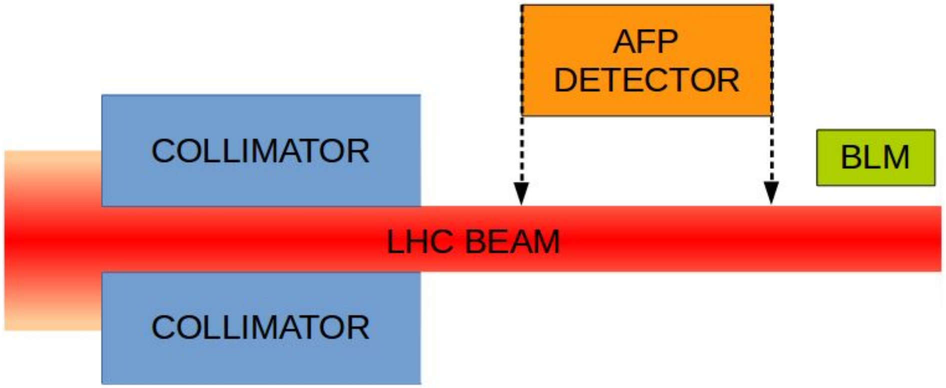
BBA and BPM procedures

- Position of SiT sensors wrt. the beam must be known accurately to reconstruct proton position and energy loss
- Beam–station distance calculated with Beam Based Alignment (BBA) and Beam Position Monitoring (BPM) methods



BBA

- AFP moved into beam until signal measured in beam loss monitor (BLM)
- BLM intercept secondary particles showers caused by beam particles

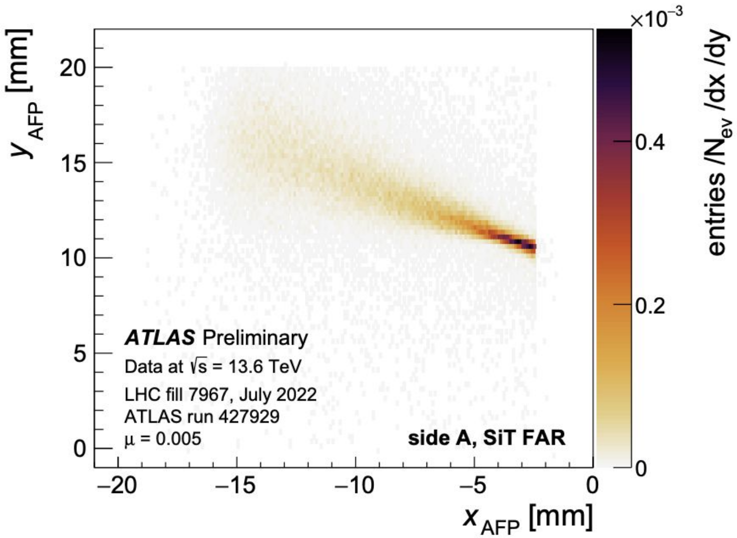


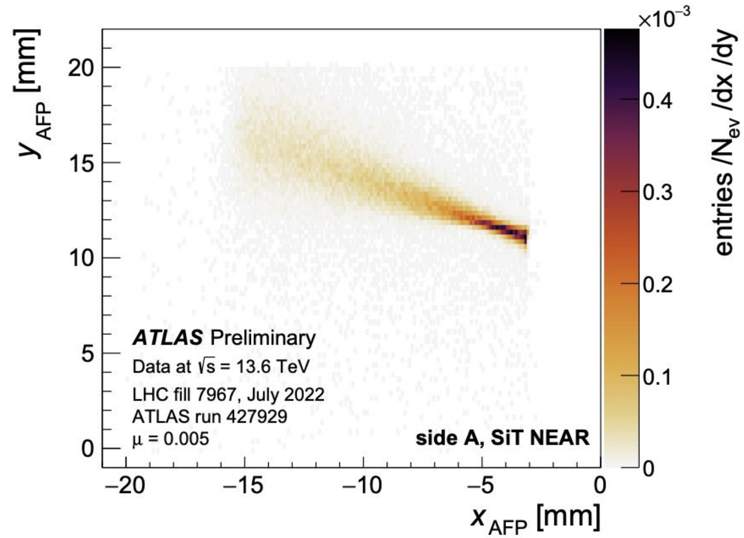
BPM

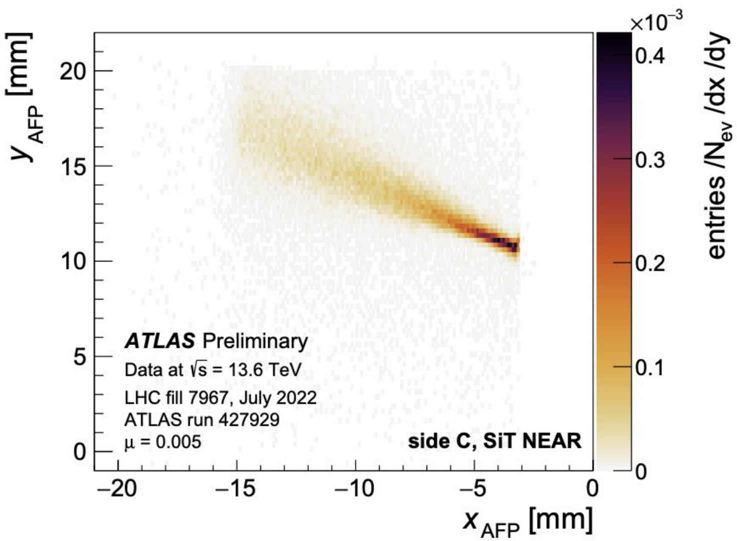
- Results from BBA cross-checked with BPM on shorter time-scales
- Non-destructive diagnostic scans to find the beam centre and monitor longitudinal shape

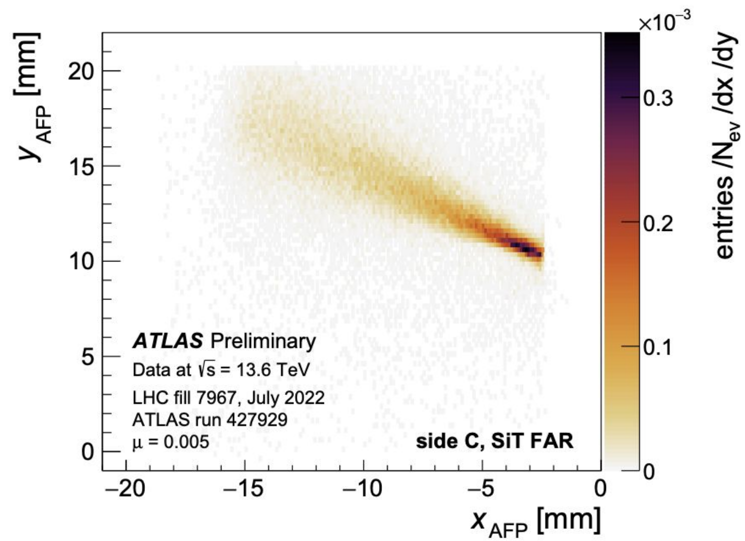
Run 3: Track position in AFP

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





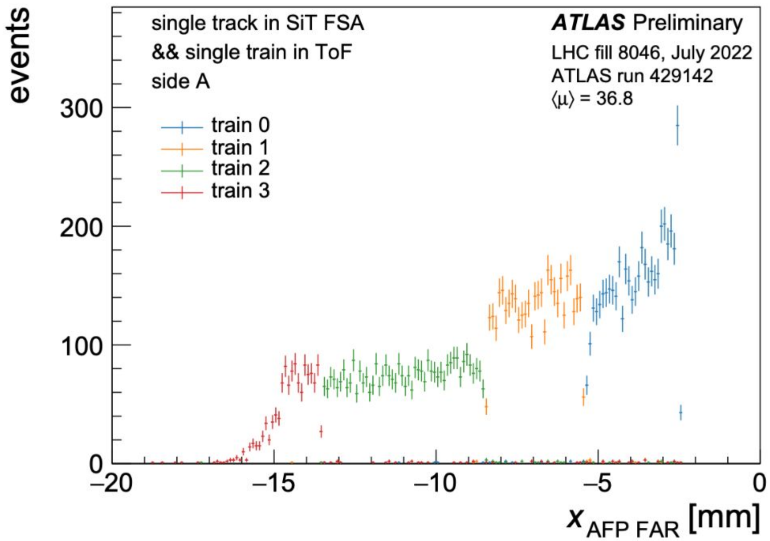


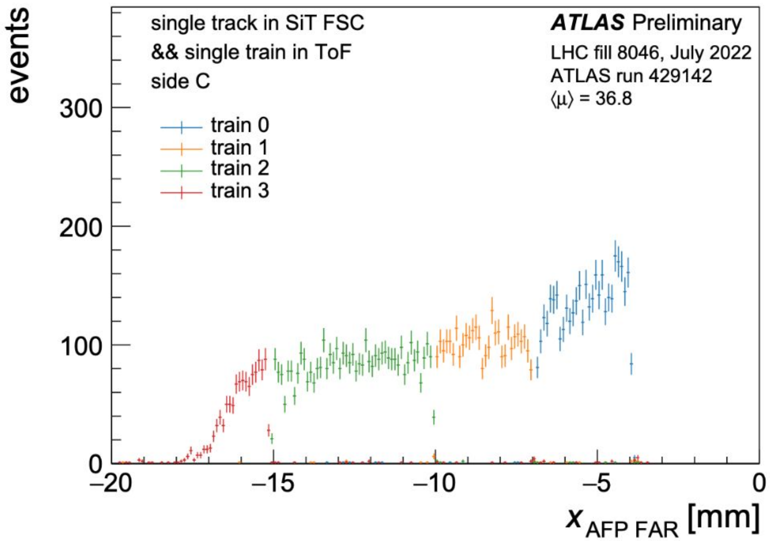


Events triggered by MBTS, with reconstructed primary vertex and exactly one track in both NEAR and FAR stations on a given side.

Time-of-flight: Run 3

Correlation between SiT and ToF detectors



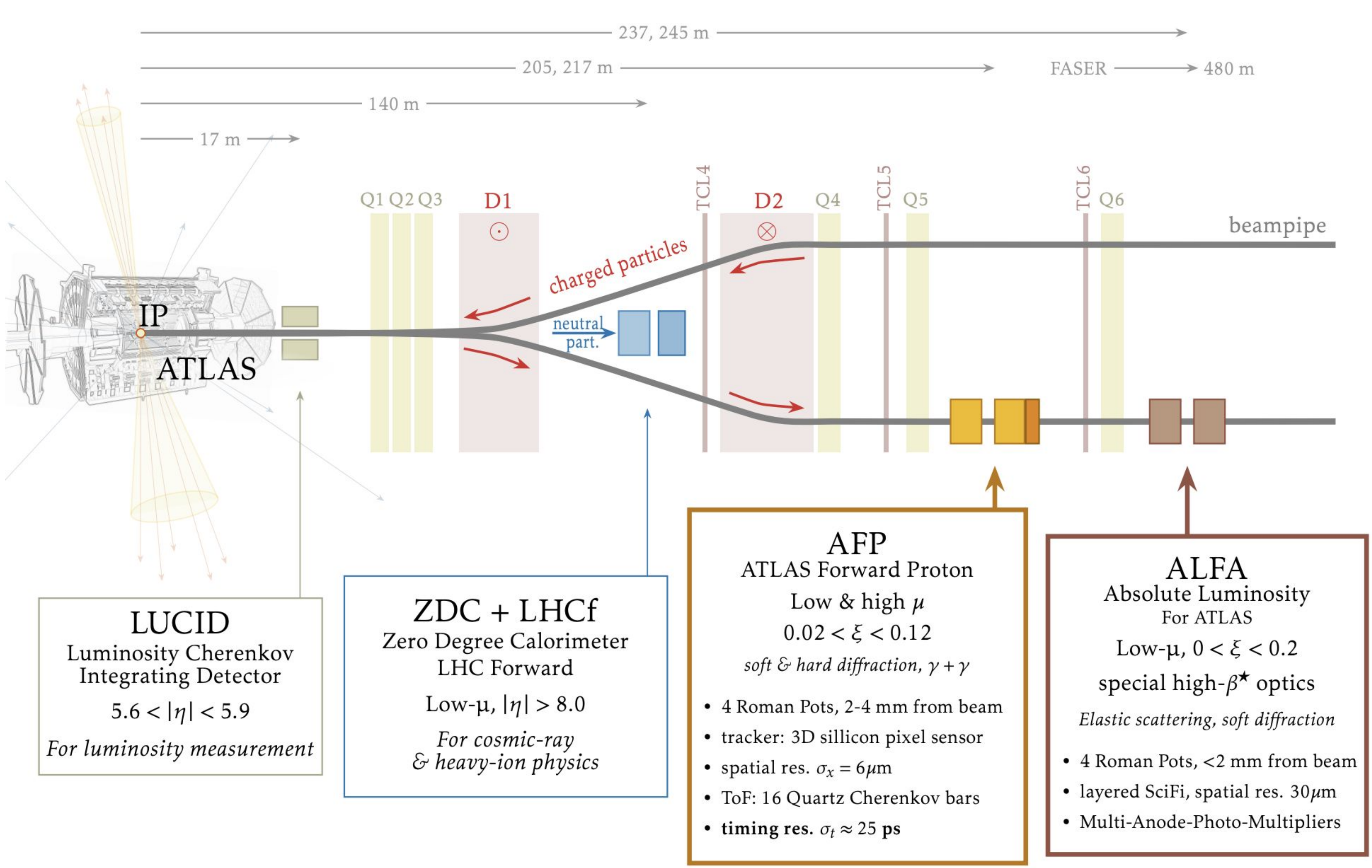


The x position of the track reconstructed in AFP SiT (FAR station) in events in which a single-train signal in ToF detector was observed. Different colors were used to visualize the SiT regions corresponding to individual trains. The machined x-width of the ToF bars is 3/3/5/5.5 mm for train 0/1/2/3. The differences in the xAFP FAR between sides are due to inaccuracy of global alignment

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

ATLAS forward detectors

Diagram by Maciej Lewicki



AFP physics goals

[Nice summary of diffractive physics at the LHC: arXiv:1909.10830]

INCREASING LUMINOSITY DEMAND

Low-μ runs

- Study of rapidity gaps in diffractive processes
- Study of single-diffractive production of W, Z, and jets
- Study of the pomeron structure in soft and hard diffraction

High-μ (standard) runs

- Study of Central Exclusive Production (CEP) in which the entire momentum loss of the protons goes into the creation of the central system
- Measure photon-induced WW production to probe anomalous gauge couplings

List of acronyms used in this talk

AFP = ATLAS Forward Proton

ALFA = Absolute Luminosity For ATLAS

ALP = Axion-Like Particle

ATLAS = A large Toroidal LHC Apparatus

BBA = Beam Based Alignment

BPM = Beam Position Monitoring

LHC = Large Hadron Collider

MBTS = Minimum Bias Trigger Scintillator

(MCP)PMT = (MicroChannel Plate) PhotoMultiplier Tube

SiT = Silicon Tracker

SM = Standard Model

ToF = Time of Flight