The ATLAS AFP Proton Spectrometer

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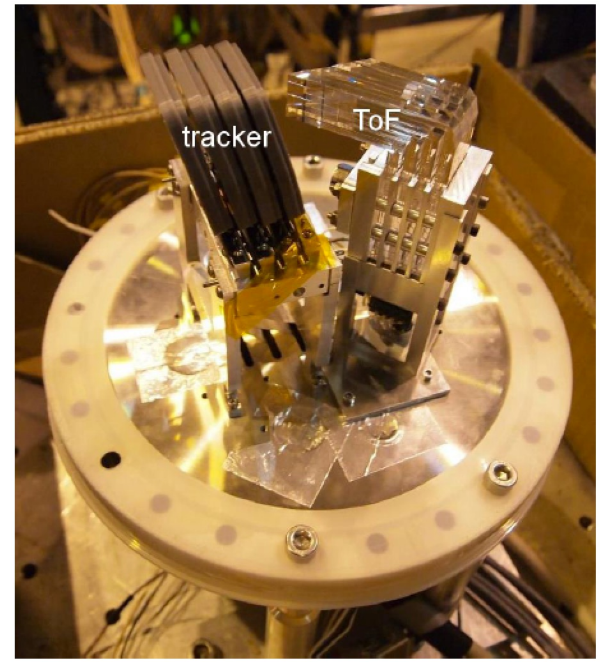
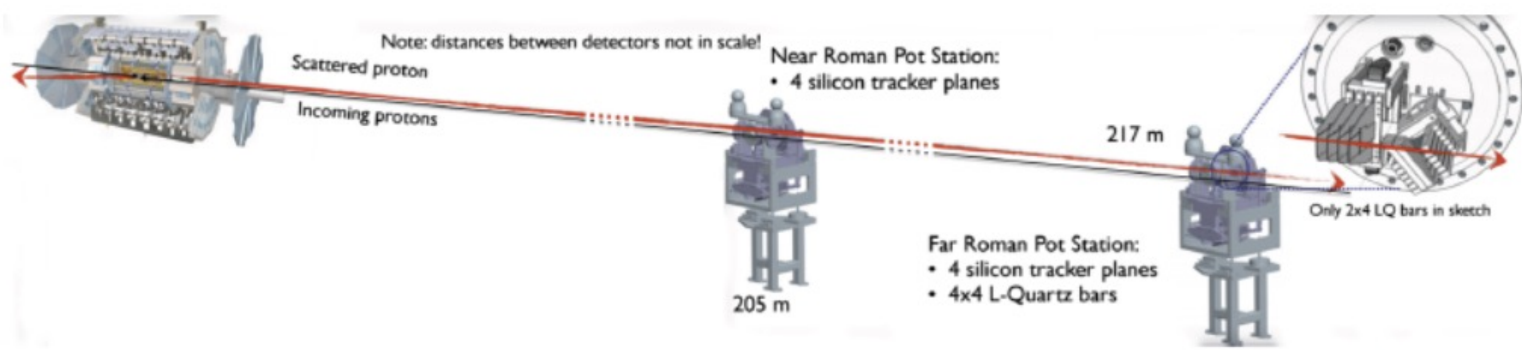
On behalf of ATLAS Forward Detectors



PSD'21
Birmingham
13 September 2021



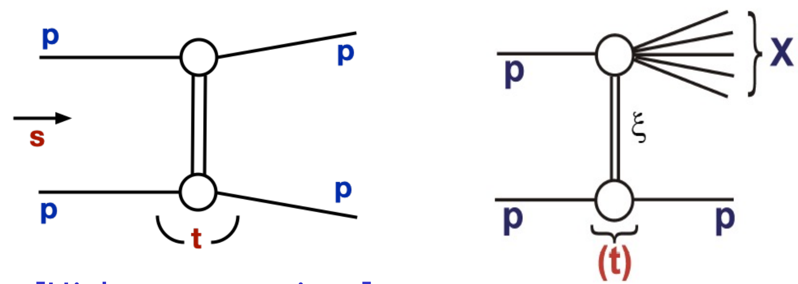
LHC Physics with Intact Protons

- Many important physics processes yield protons scattered at very small angles.

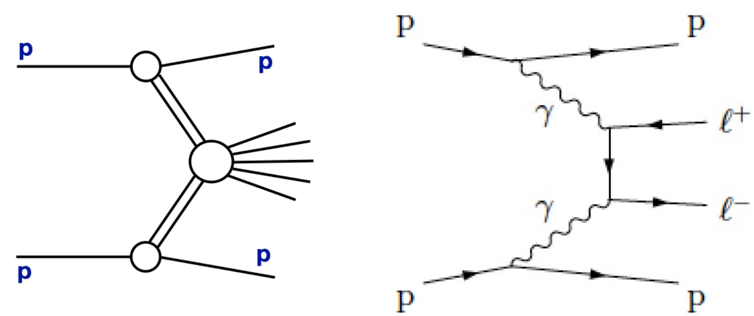
- Detectable using spectometers housed in ‘Roman pot’ vacuum-sealed insertions to the beam-pipe, well downstream of interaction point.

- High cross section processes already measured in special runs with 1st generation proton spectrometers

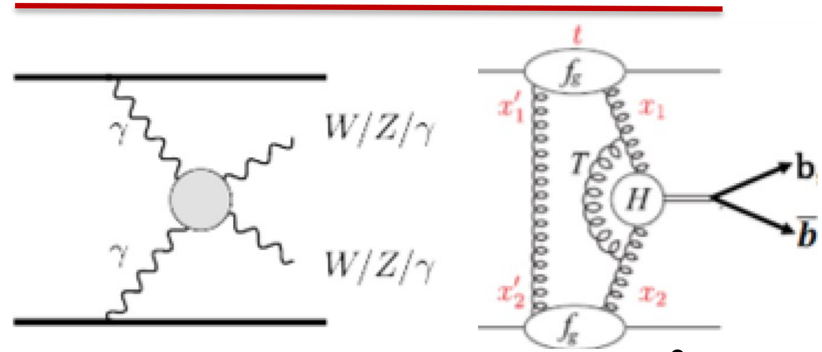
- Physics focus is now on rare and exotic processes … 2nd generation proton spectrometers need to collect data under ‘normal’ LHC running conditions



[High cross sections]

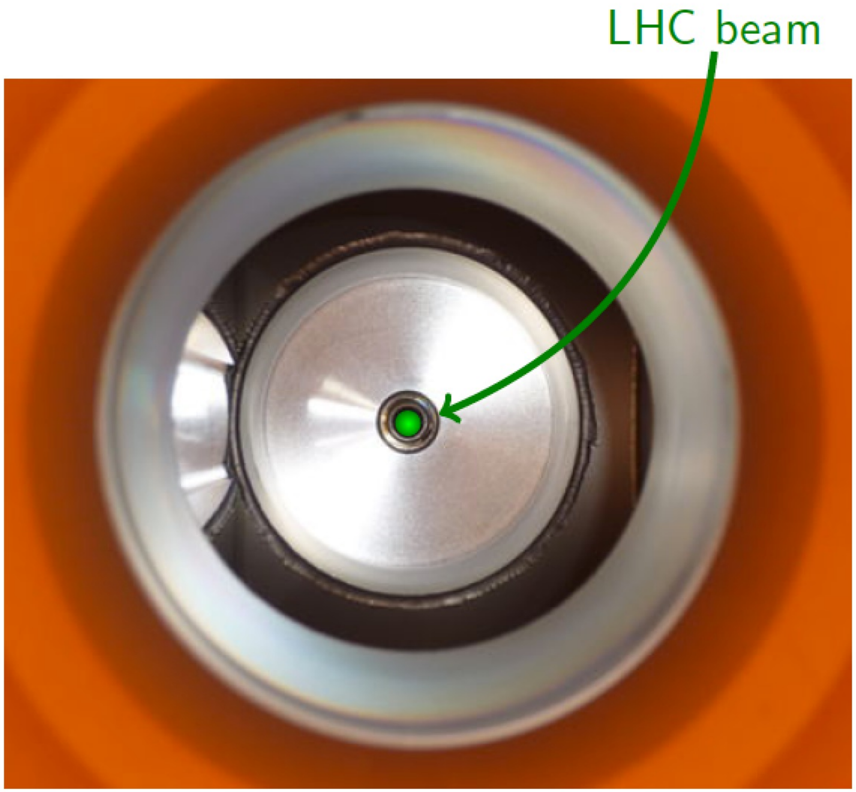


[Intermediate cross sections]

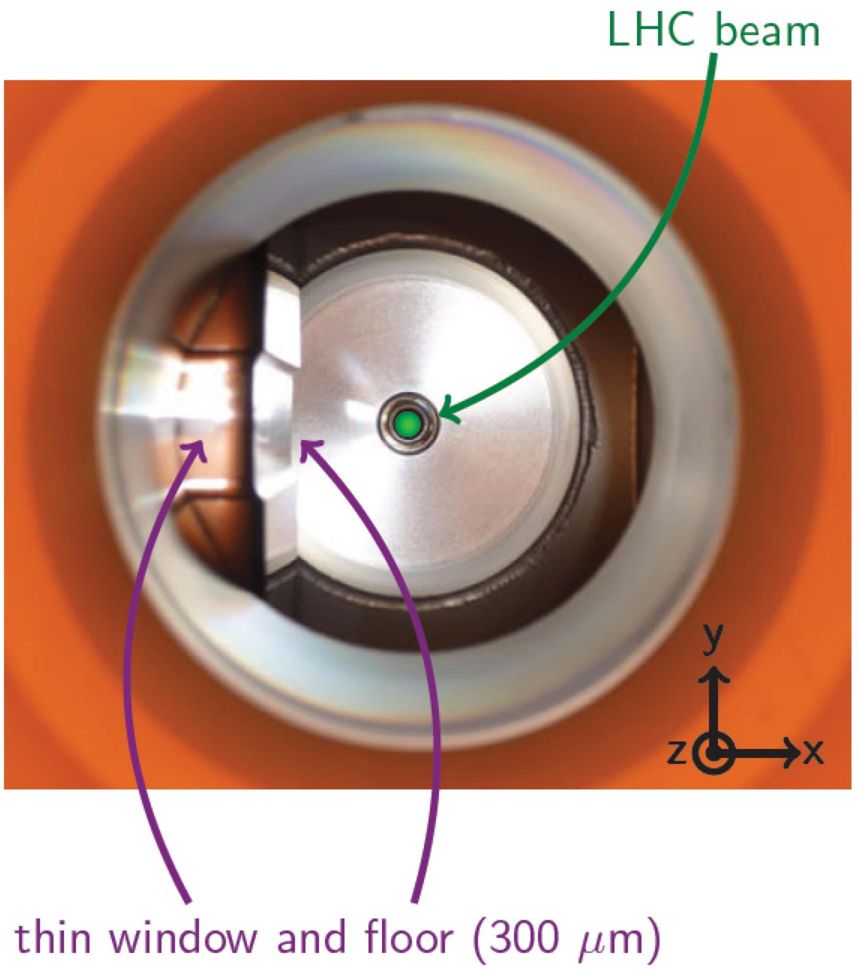


[Low cross section / exotic]

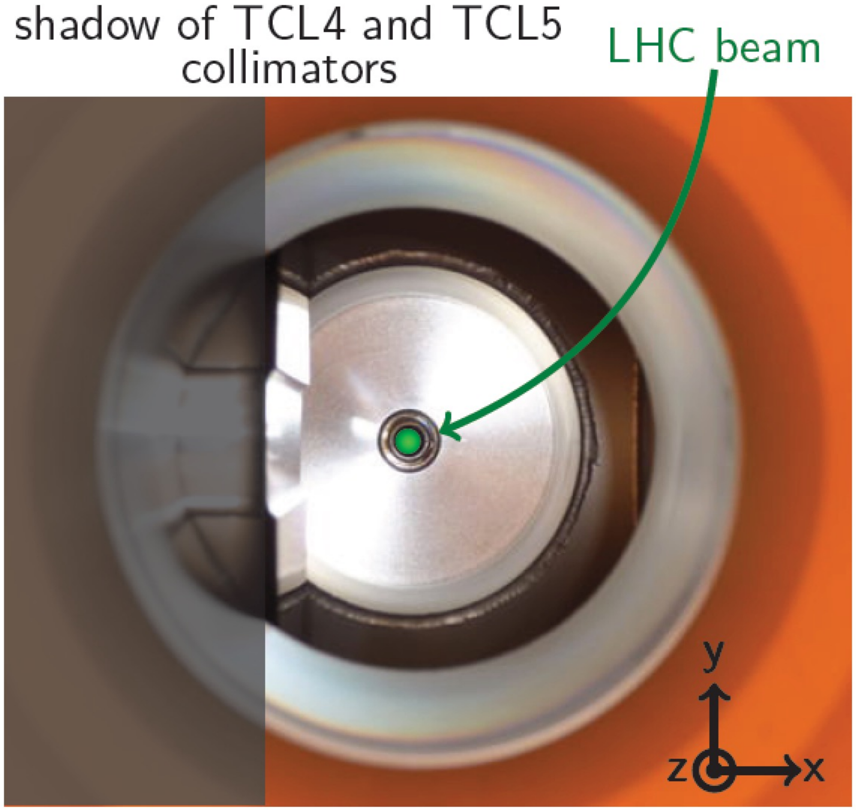
Principle of AFP Roman Pots



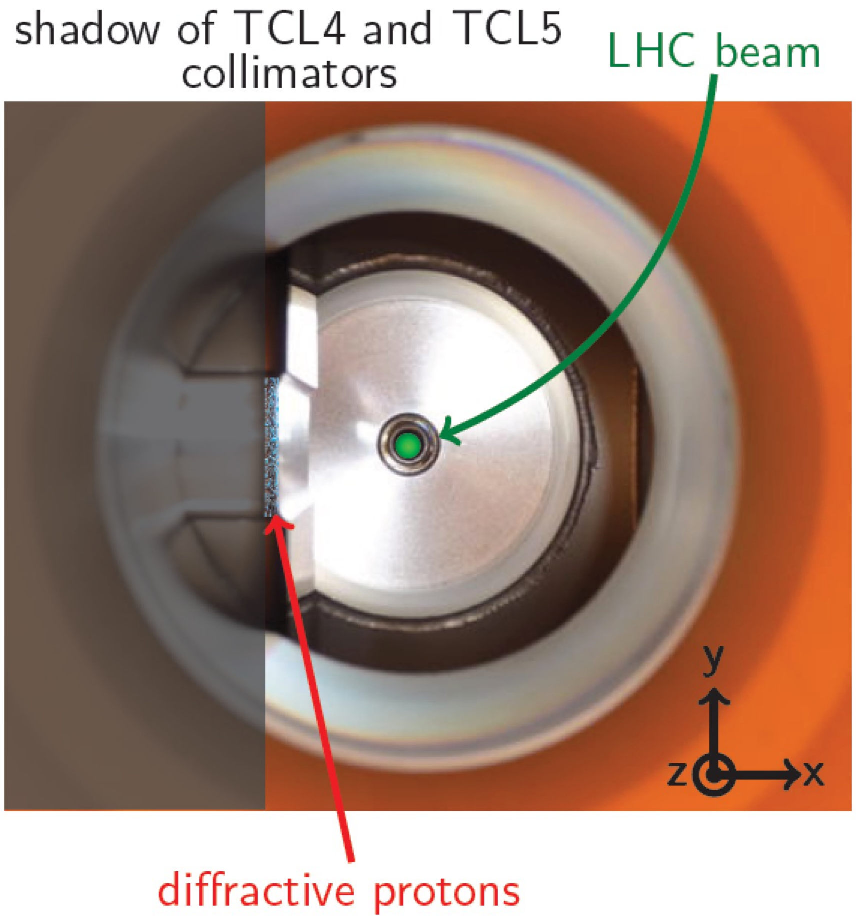
Principle of AFP Roman Pots



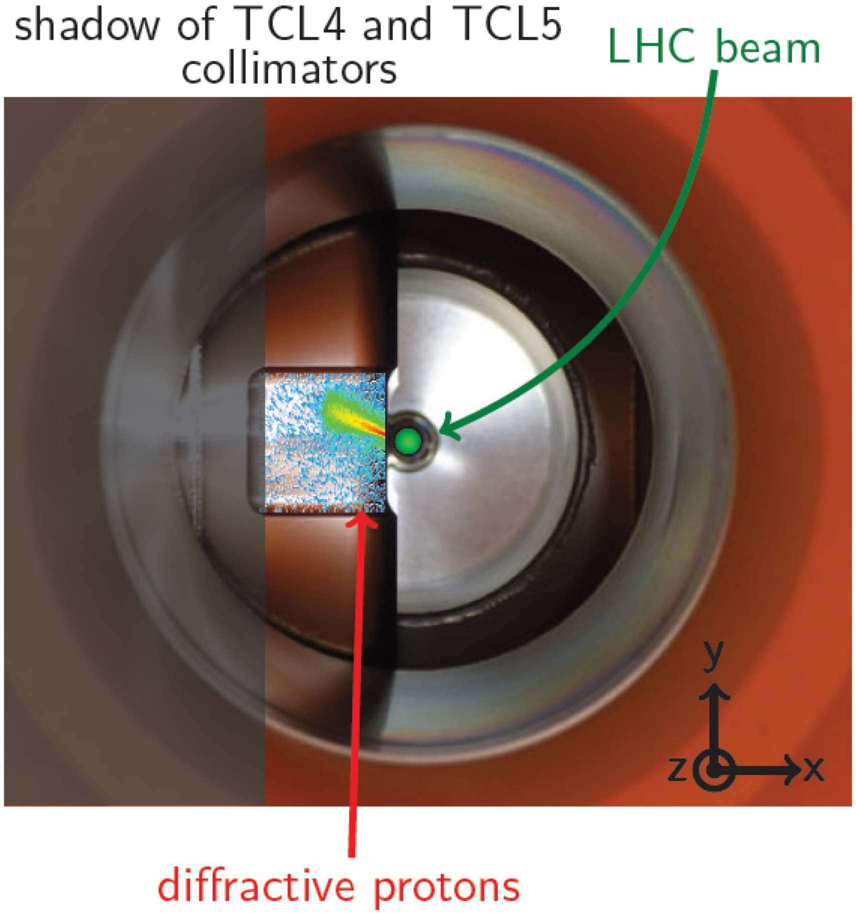
Principle of AFP Roman Pots



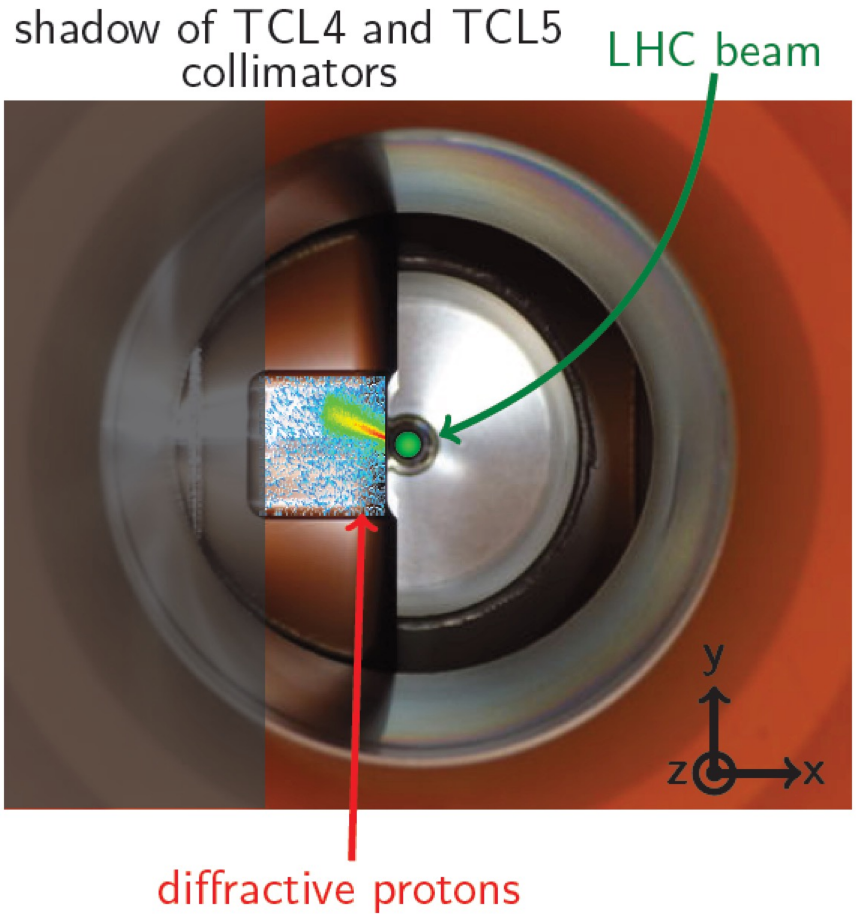
Principle of AFP Roman Pots



Principle of AFP Roman Pots



Principle of AFP Roman Pots



Challenges …

… detect and precisely reconstruct kinematics of proton tracks …

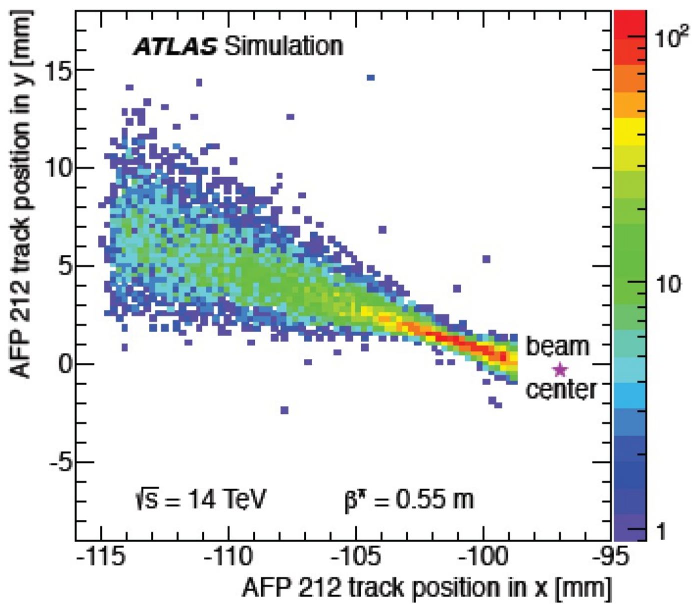
→ Well downstream (~200m)
→ Near to beam (~2mm)

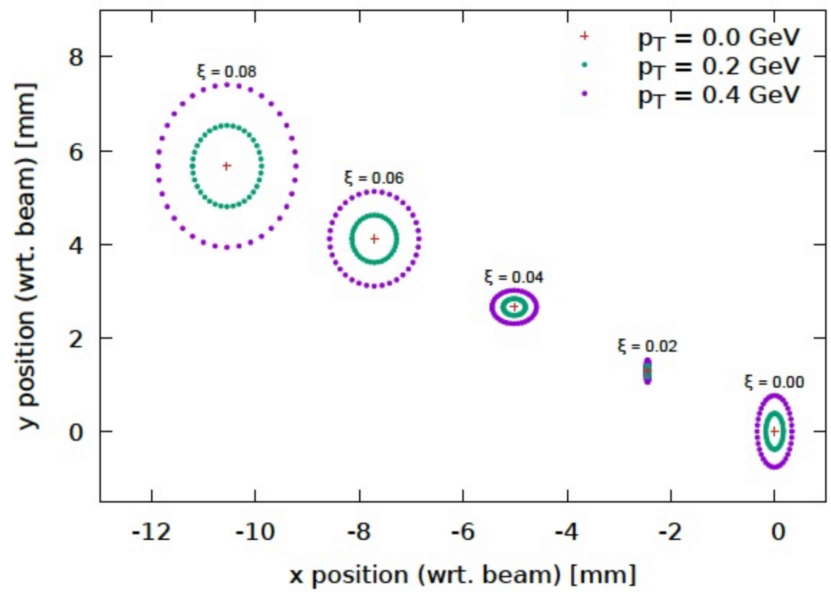
… in challenging conditions

→ Fierce (highly non-uniform) radiation environment … highest fluence near to beam & along line of diffractively scattered protons

→ High level of 'pile-up' background due to multiple interactions per bunch crossing

Principle of Proton Reconstruction





Most important kinematic quantity …

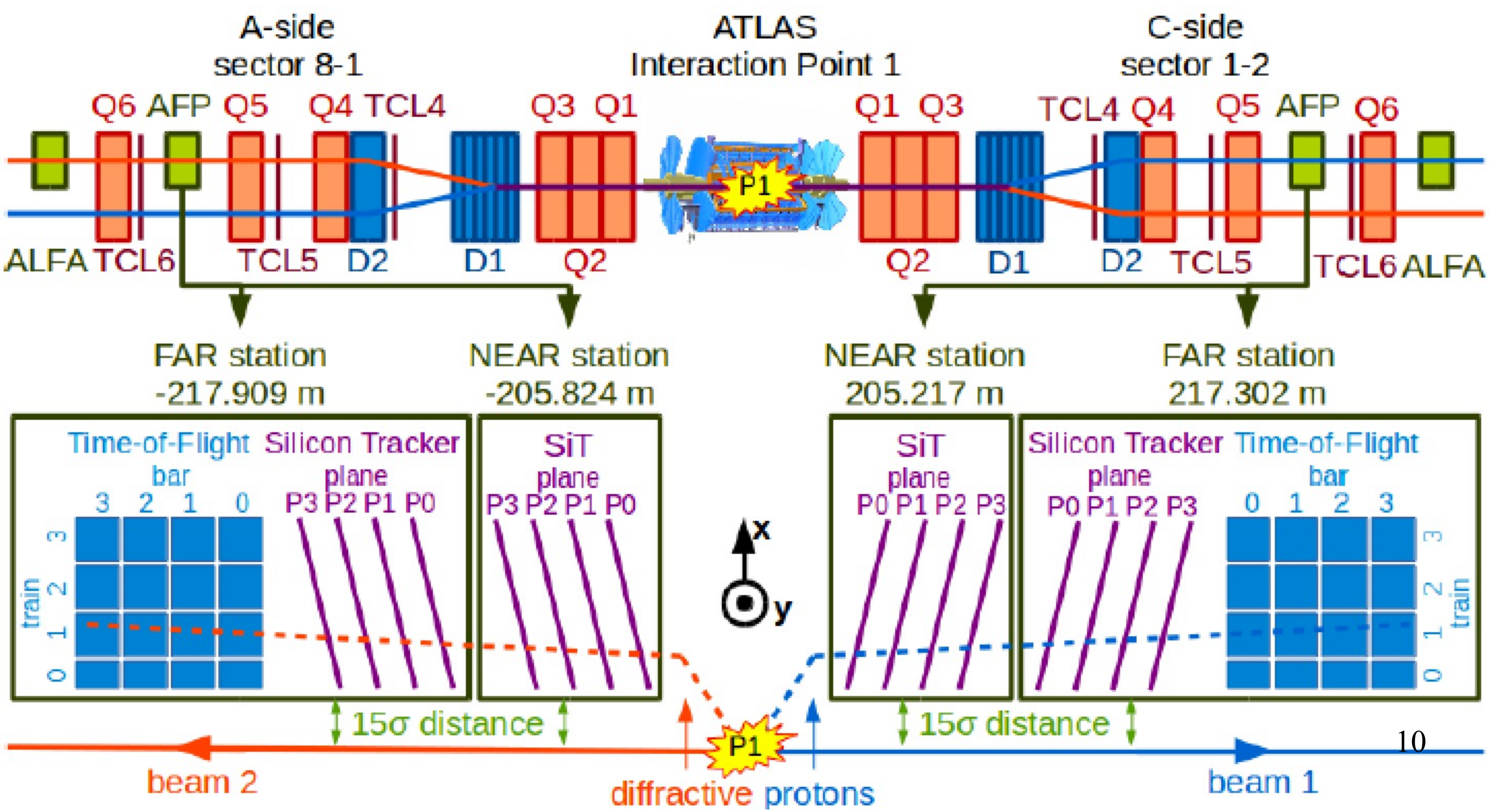
ξ **= fractional proton energy loss**

… principally determined by x position of proton trajectory / track a Roman pot station

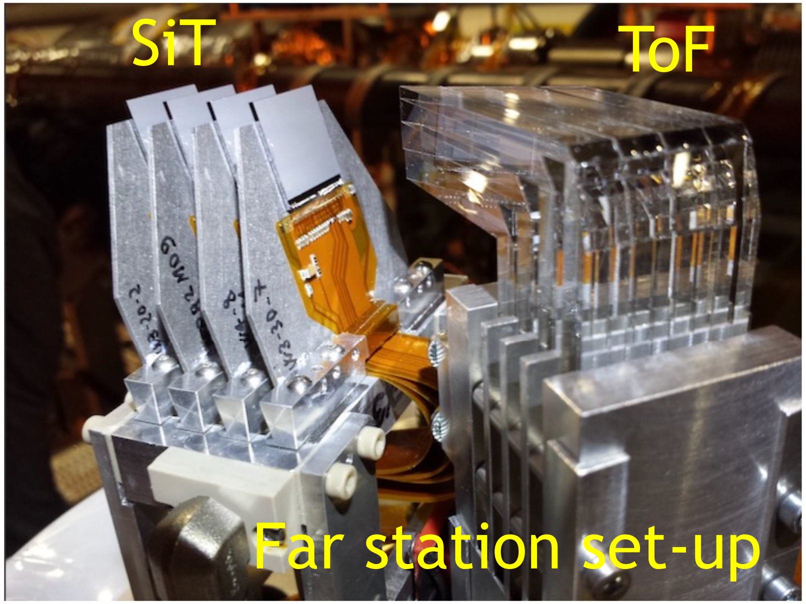
Ambiguity due to proton p_T (usually << 1 GeV) resolved by Δx between pairs of Roman pot stations

AFP Apparatus Overview

- Two Roman pot vacuum-sealed stations either side of interaction point
- Each pot houses 4 planes of silicon pixel sensors for proton tracking
- Far stations additionally house ToF detectors (pile-up suppression via vertex location from relative timing of protons on A side and C-side



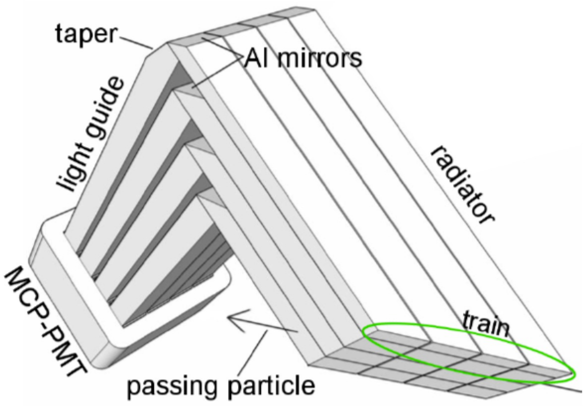
AFP Detectors

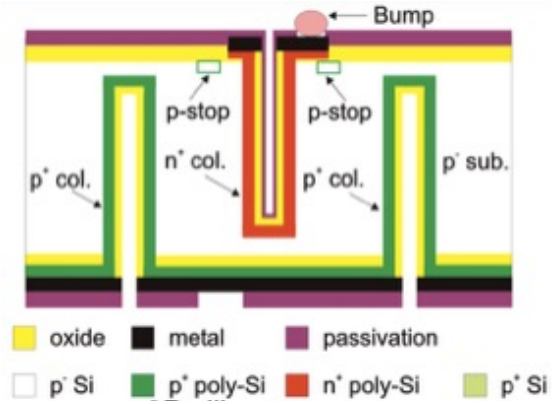


Tracking: four pixel sensor planes per station, based on Insertable B-Layer;

- Double-sided 3D sensors (CNM, FBK)
- Pixel sizes 50x250 μm
- 230μm thick
- Total area 1.7 x 2.0 cm^2
- Slim edge (<200 μm)
- 14^o tilt improves x coordinate (hence ξ)
- FE-I4 readout chips, RCE-based DAQ
- Trigger capability

→ Spatial resolutions δx = 6 μm, δy = 30 μm





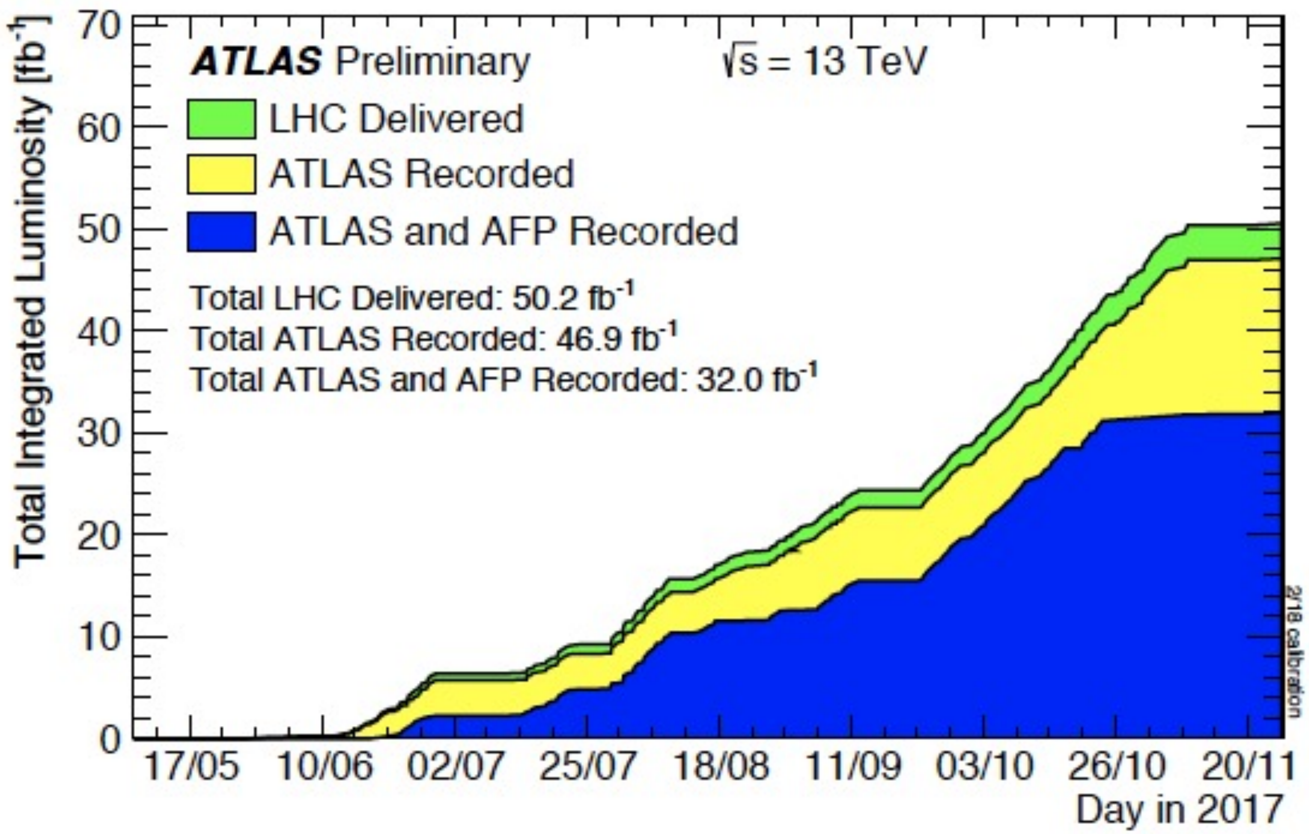
Timing: 4x4 quartz bars at Cerenkov angle to beam. Light detected via MCP- PMTs → resolution of 20-40 ps demonstrated, but with poor efficiency so far.

AFP Data Taking

2016: single side instrumented

2017: both sides instrumented

→ 32 fb^{-1} recorded, of which about half passes ‘good run’ requirements and Is suitable for use in analysis



Tagged proton physics with ~15fb^{-1} is completely revolutionary prior to AFP and corresponding CMS project (PPS)

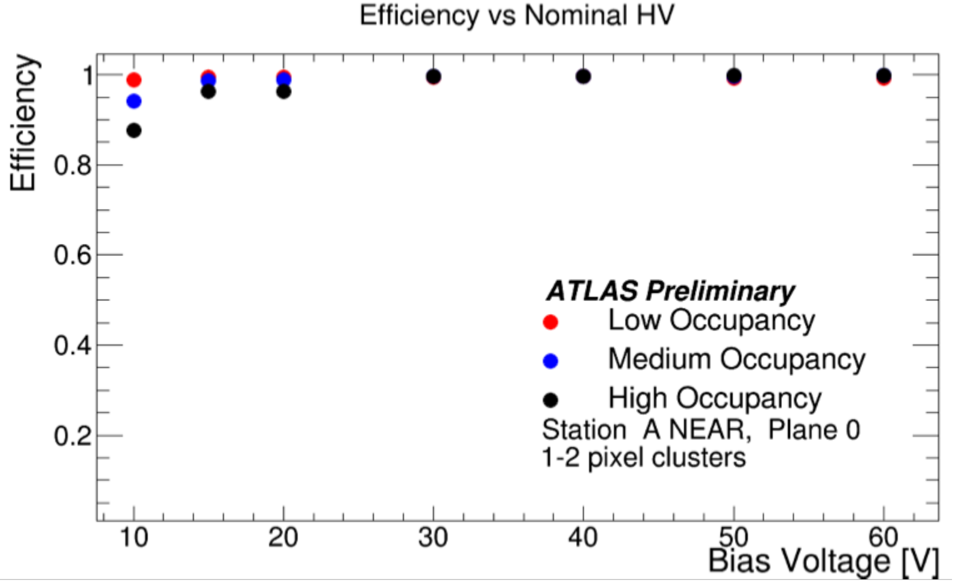
SiT Performance: Single Plane Efficiency

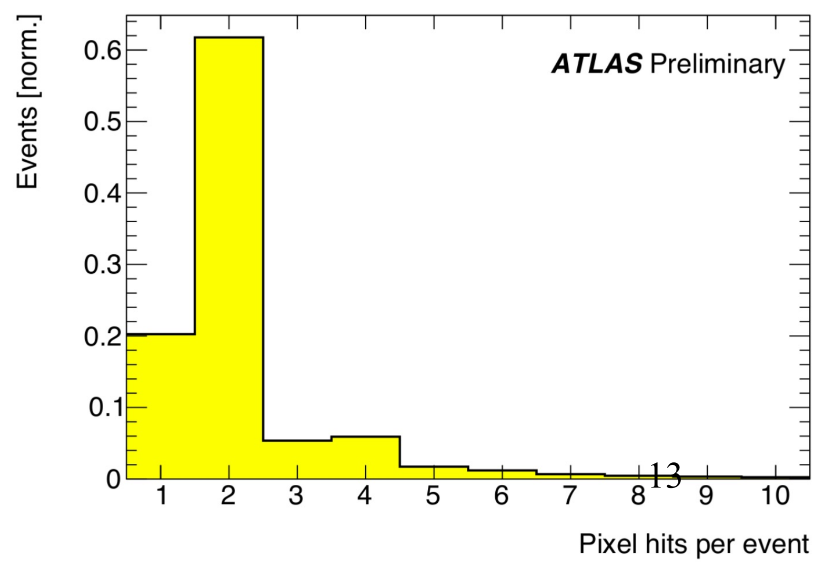
- Single hit efficiency determined from probability of hit in fourth plane of station given hits in the other three. → ~98% for bias voltage >~ 20V.

- IBL / AFP test-beam irradiations showed only small deterioration with up to 5 x 10^{15} n_{eq}/cm^2 (equivalent to ~200fb^{-1} in region of maximum fluence), including non-uniform exposure patterns

- In situ, some evidence for ageing … efficiency drop at low bias voltage for regions of planes with highest occupancy (closest to beam)

- 14^o angle to the vertical results in two pixel hits per plane in most cases



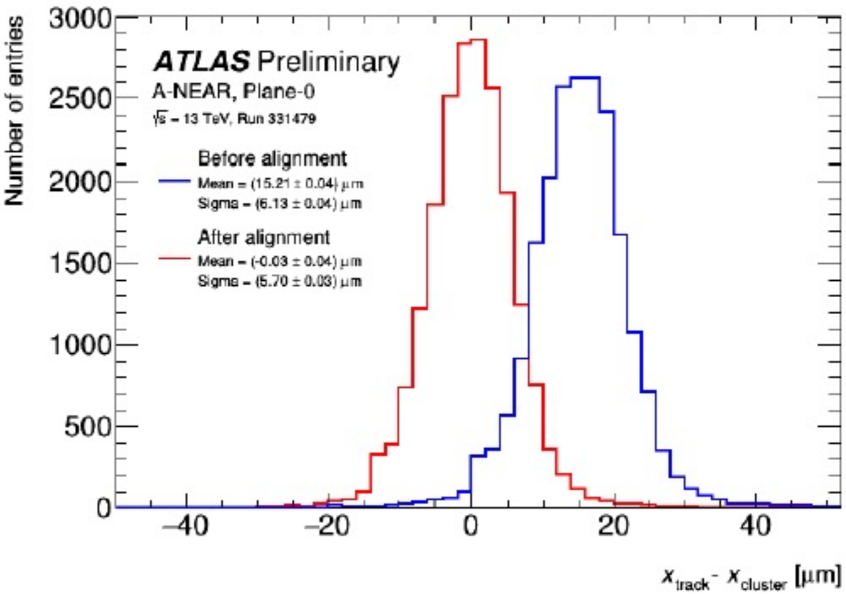


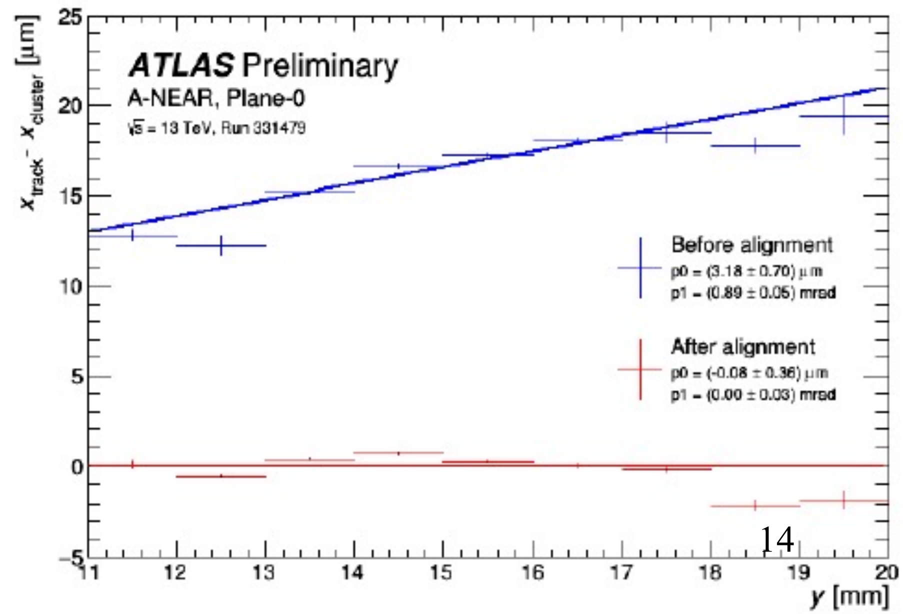
Individual Plane Alignment

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

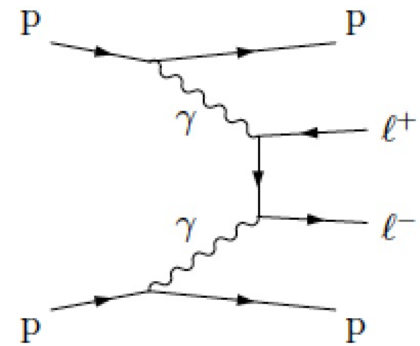
→ Form residuals in each plane relative to reconstructed tracks
→ Correct for shifts in x and y direction and rotation about z axis
→ Iterate

… aligned to better than 10μm within a Roman pot station





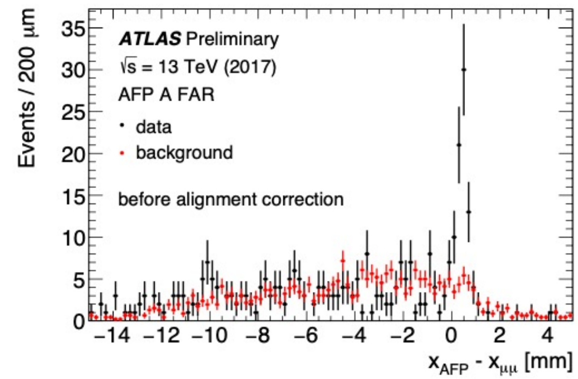
Global Alignment (of each station)



- Alignment of stations relative to one another exploits redundancy in kinematics in exclusive dilepton data …

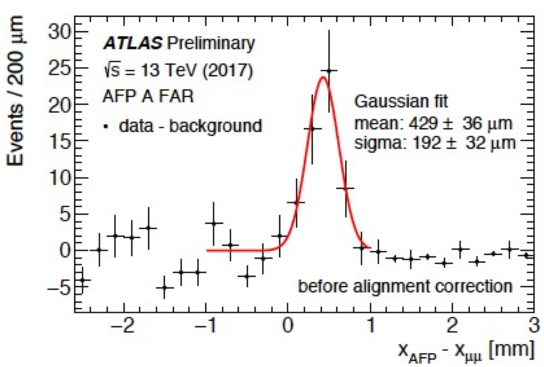
- ξ (and equivalently x coordinate in AFP) can be predicted from the leptons:

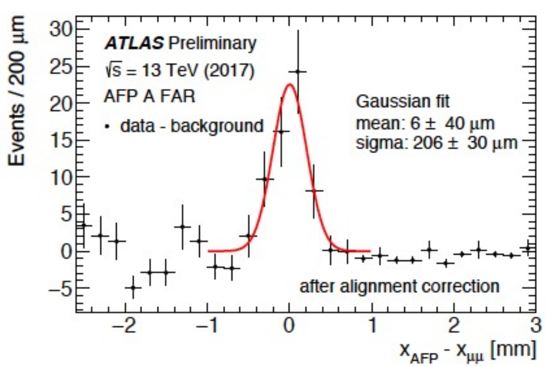
$$\xi^{\pm}_{\mu\mu} = \frac{m_{\mu\mu}}{\sqrt{s}} e^{\pm y_{\mu\mu}} \qquad \xi = 1 - E'_p/E_p$$

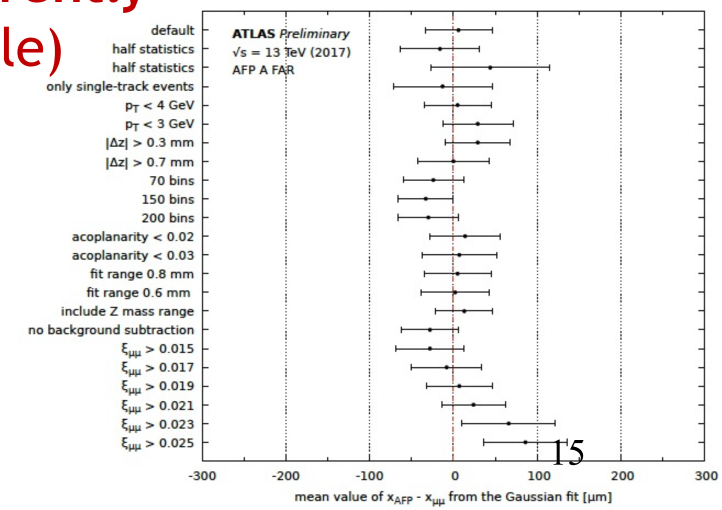


- (small) background well modelled by event mixing

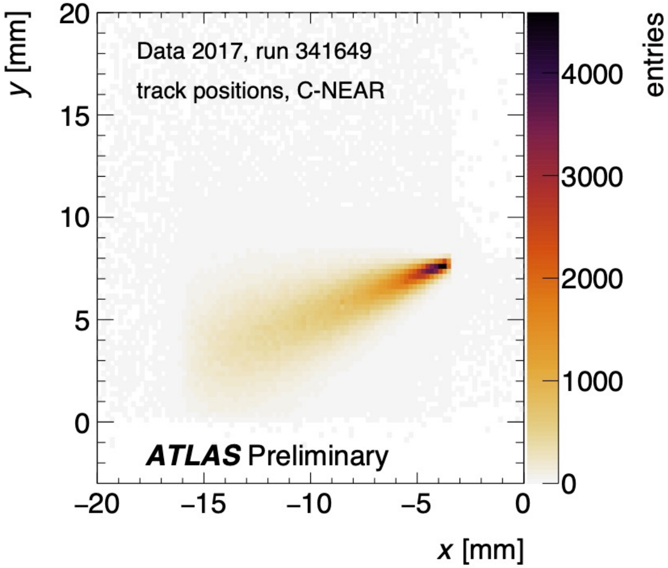
- **Global alignment precision uncertainty currently quoted as 300 μm** (but 100 μm seems achievable)

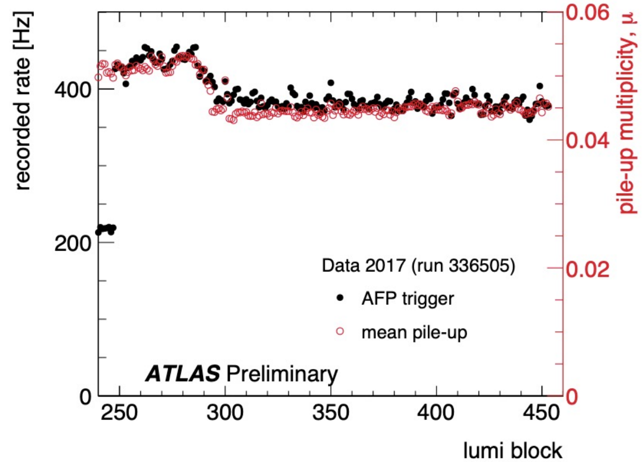


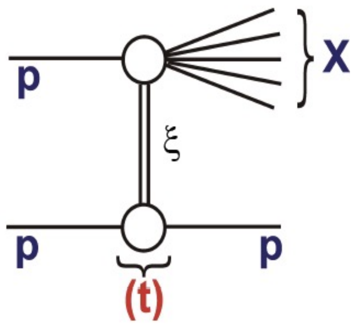




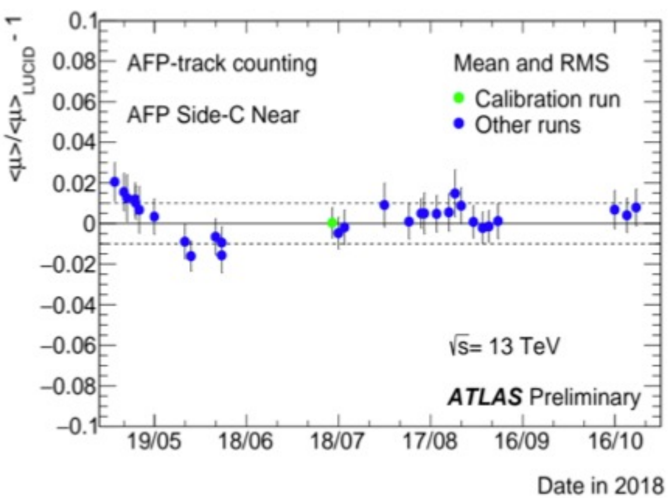
Reconstructed Proton Signal







- Clear characteristic diffractive signal (dominantly single dissociation pp→pX)

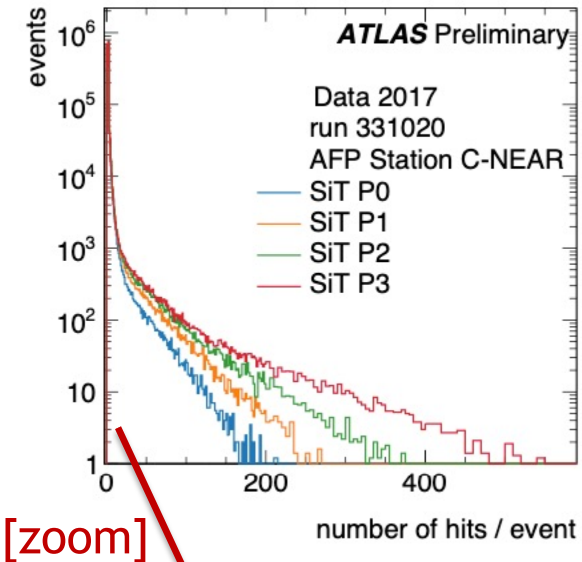


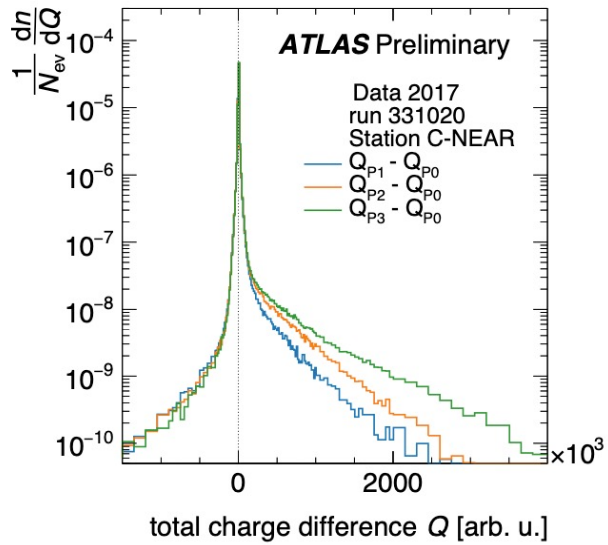
- Trigger rate (2 out of 3 coincidence of selected SiT planes) follows pile-up rate … i.e. beam-induced backgrounds small

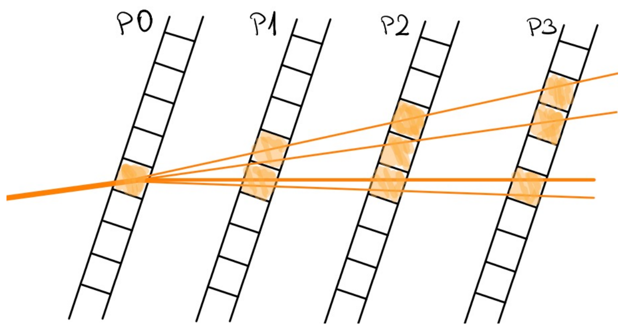
- Rate stable with respect to other forward detetors /luminosity monitors (LUCID)

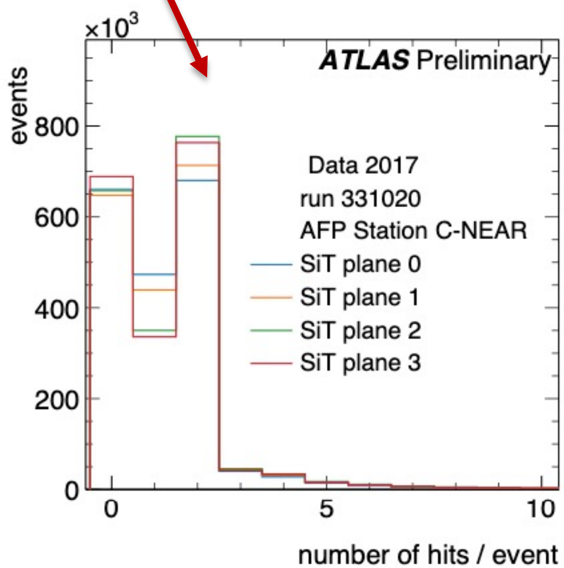
- Occupancy ~0.02 reconstructed track segments per pot station per pp collision

Showering in SiT Planes and Pot Walls







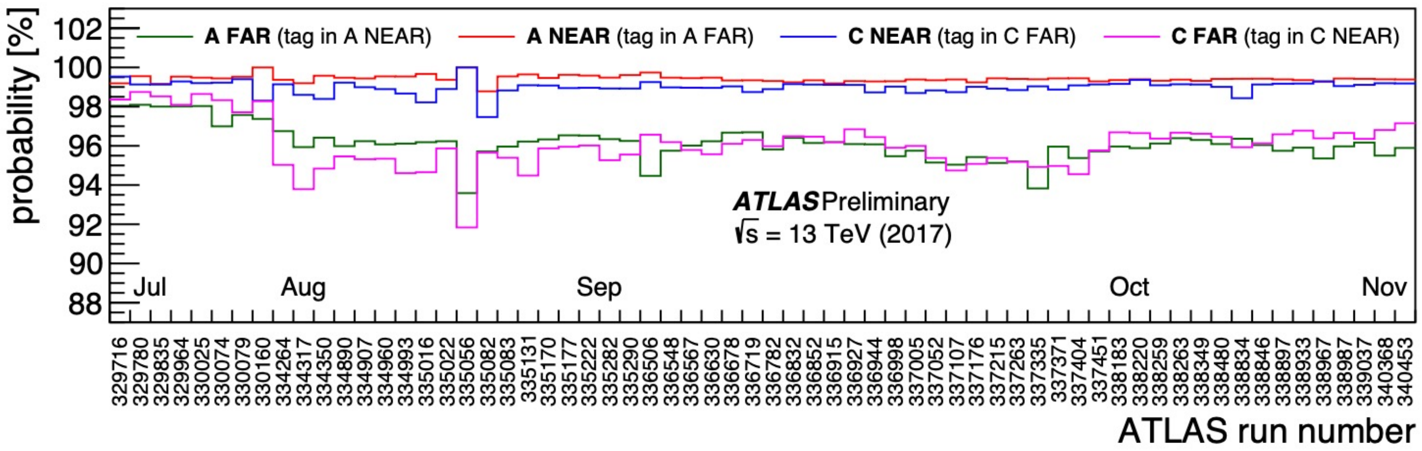


- Evidence for modest level of showering in material of SiT planes (long non-Poisson tail in hit multiplicity per plane, growing with distance from track start).

- Showering also takes place in POT windows – (seen by comparing FAR station multiplicities with NEAR stations).

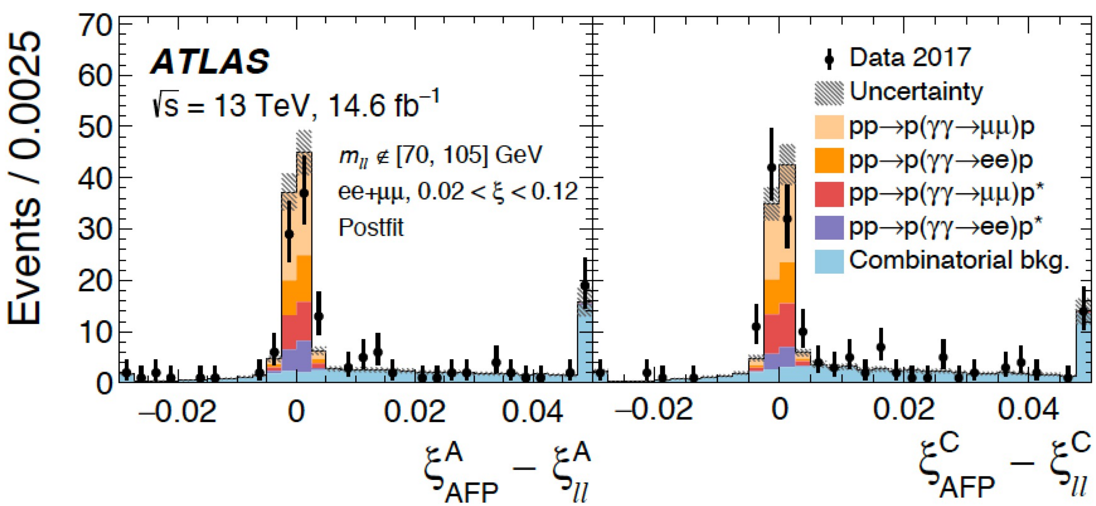
- Largest contribution to inefficiencies…

Proton Reconstruction Efficiency



- Efficiencies from 'tag and probe' (eg tag Near, probe Far
- ~99% in Near station, ~95% in Far Station (showering)

Proton Reconstruction Resolution



- Resolution on fractional energy loss, ξ ~ 10%

- Main contributions from intrinsic detector resolution and (at lowest ξ) multiple scattering

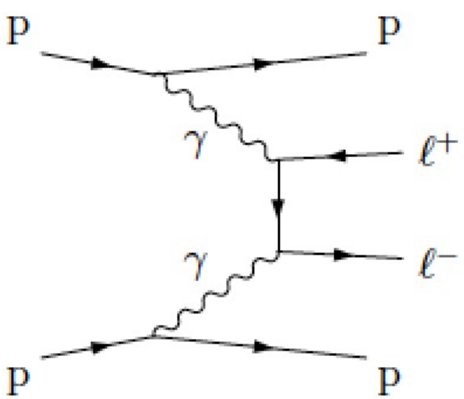
First High Lumi AFP Publication (15 fb^{-1})

PHYSICAL REVIEW LETTERS **125,** 261801 (2020)

Observation and Measurement of Forward Proton Scattering in Association with Lepton Pairs Produced via the Photon Fusion Mechanism at ATLAS

G. Aad *et al.**
(ATLAS Collaboration)

(Received 2 October 2020; revised 30 October 2020; accepted 23 November 2020; published 23 December 2020)



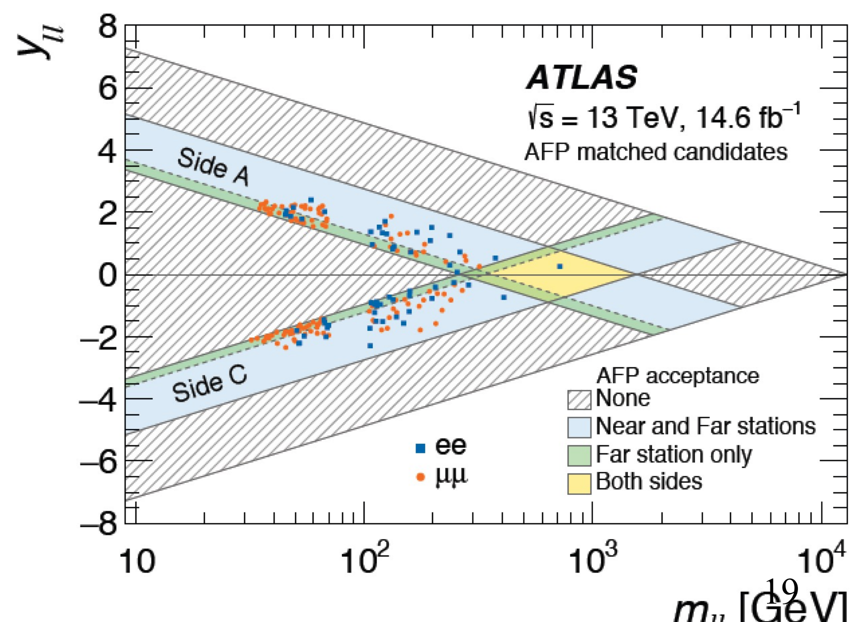
$\gamma\gamma \rightarrow$ ee or μμ

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [fb]	$\sigma^{\text{fid.}}_{\mu\mu+p}$ [fb]
$S_{\text{surv}} = 1$	15.5 ± 1.2	13.5 ± 1.1
S_{surv} using Refs. [30, 31]	10.9 ± 0.8	9.4 ± 0.7
SUPERCHIC 4 [94]	12.2 ± 0.9	10.4 ± 0.7
Measurement	11.0 ± 2.9	7.2 ± 1.8

- Single proton tagged (so far)

- Background suppression with low combined lepton p_T and acoplanarity, and mass cut to to avoid Z peak

- Proton energy loss ξ from proton or from l^+l^- pair → Establish signal from the correlation



Future Prospects

Run 3

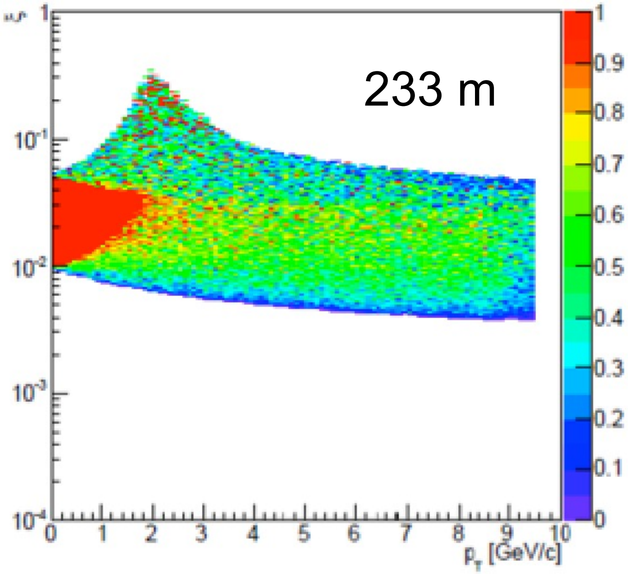
- ToF: New PMTs with new out-of-vacuum / POT solution
- Various more minor consolidation projects
- Successful test beams at DESY
- Installation proceeded either side of COVID.
- Data taking with full system (expect factor >10 more data)

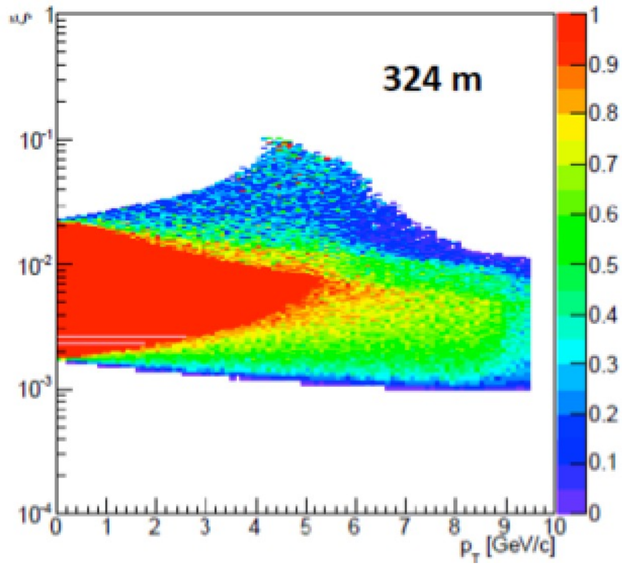
Run 4 (at HL-LHC)

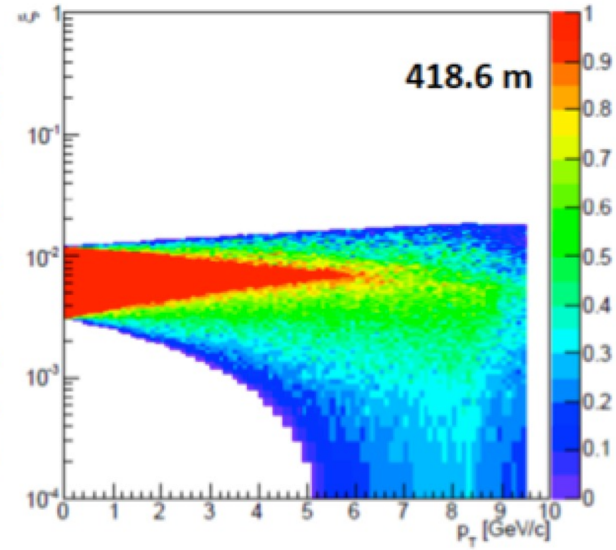
- Potentially rich physics programme (further factor >10 more data)
- New level of challenges in terms of radiation environment and pile-up (→ ToF detector with <10ps resolution)
- Studies of acceptance at various possible pot locations with currently foreseen HL-LHC optics well underway

Early Studies with nominal HL-LHC Optics

Acceptances for 2x2cm detector @ 15σ+0.5mm, no collimators



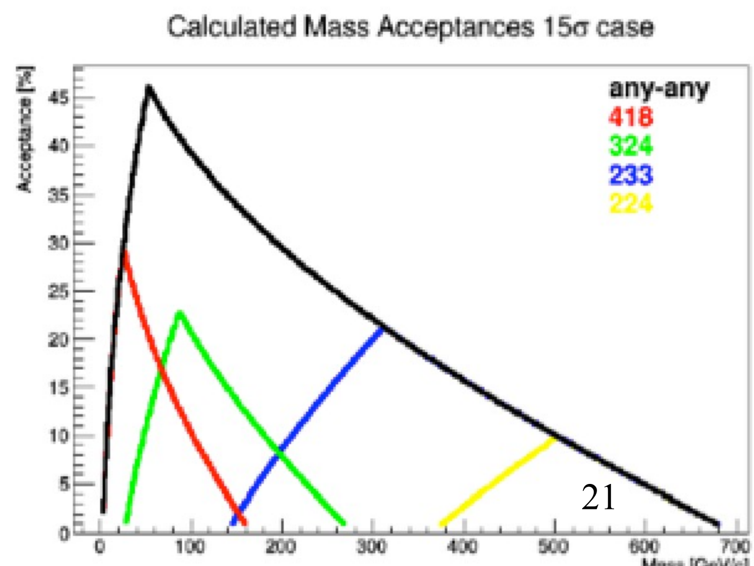




233m: Reduced ξ acceptance relative to that now in AFP region

Strongly dependent on horizontal v vertical crossing angle scheme

324,420m: Potentially attractive ξ acceptance extending into SM Higgs region at possible deployment points in cold sections



Summary / Prospects

AFP silicon proton tracking spectrometer operated successfully in 2017 → 15fb^{-1} high quality data

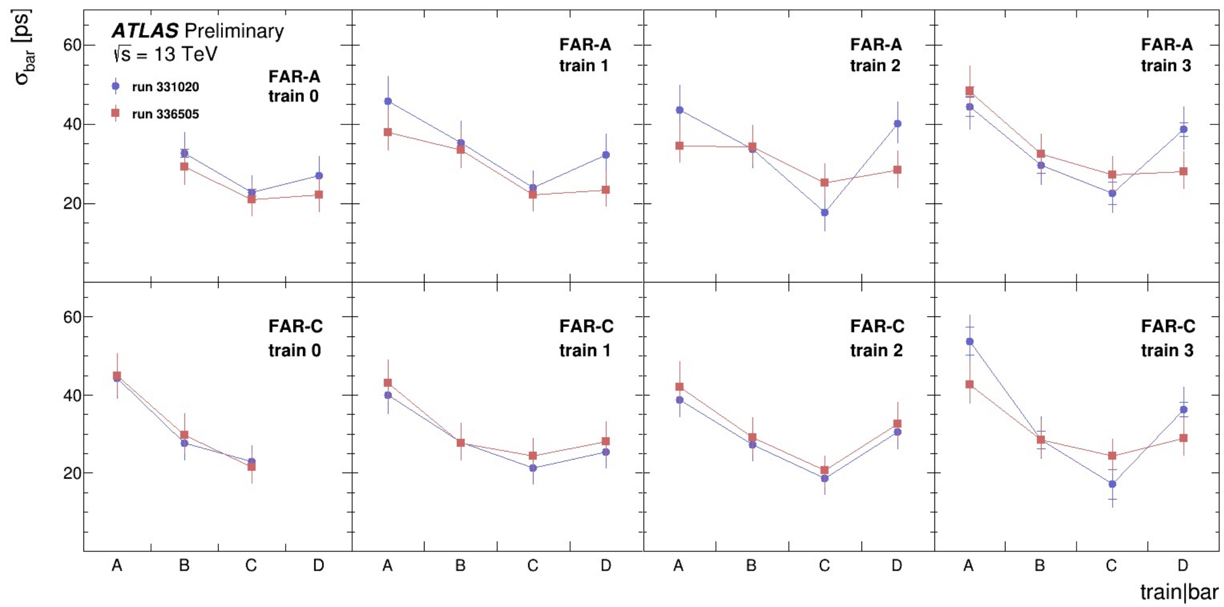
First physics result on $\gamma\gamma \rightarrow l^+l^-$ published in PRL

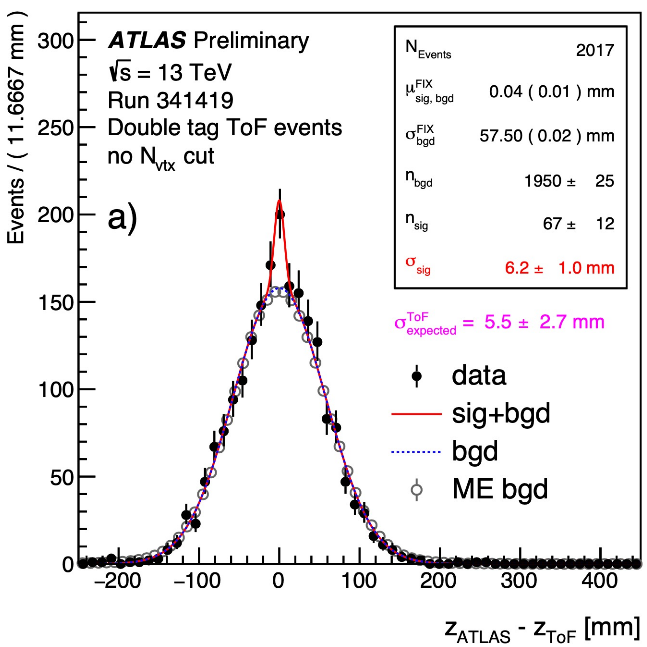
Expect to collect much more data in Run 3 (also with ToF)

HL-LHC is challenging … possibilities under study

ToF Performance

- Poor efficiencies in first AFP run (1-9% single channel, 5-10% per 4-bar train). PMTs degraded fast





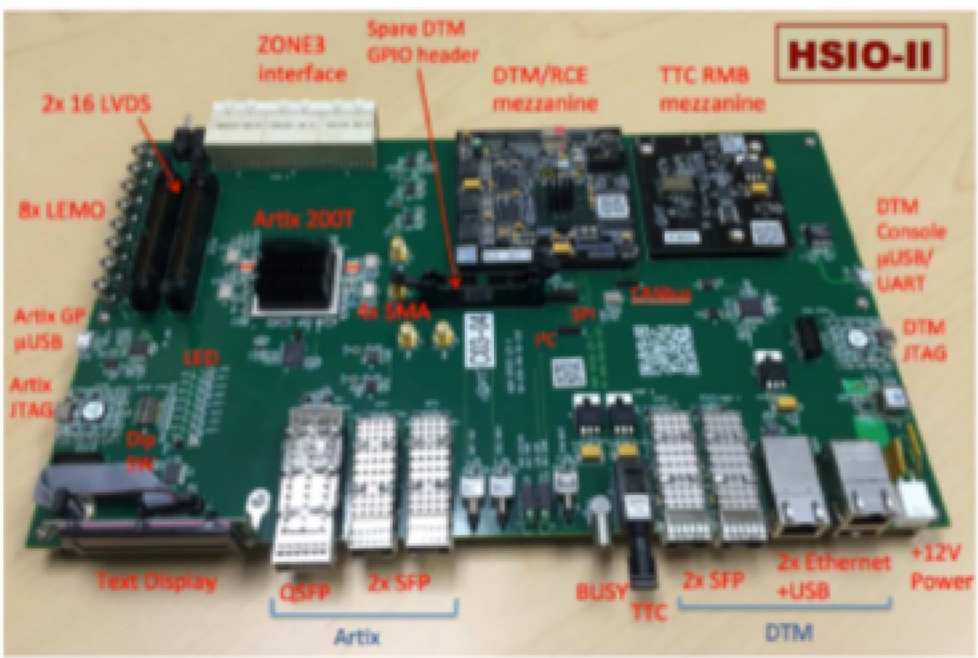
- Timing resolutions at 20-40 ps level for single channels. ~ 20ps when integrated over train, exceeding specification

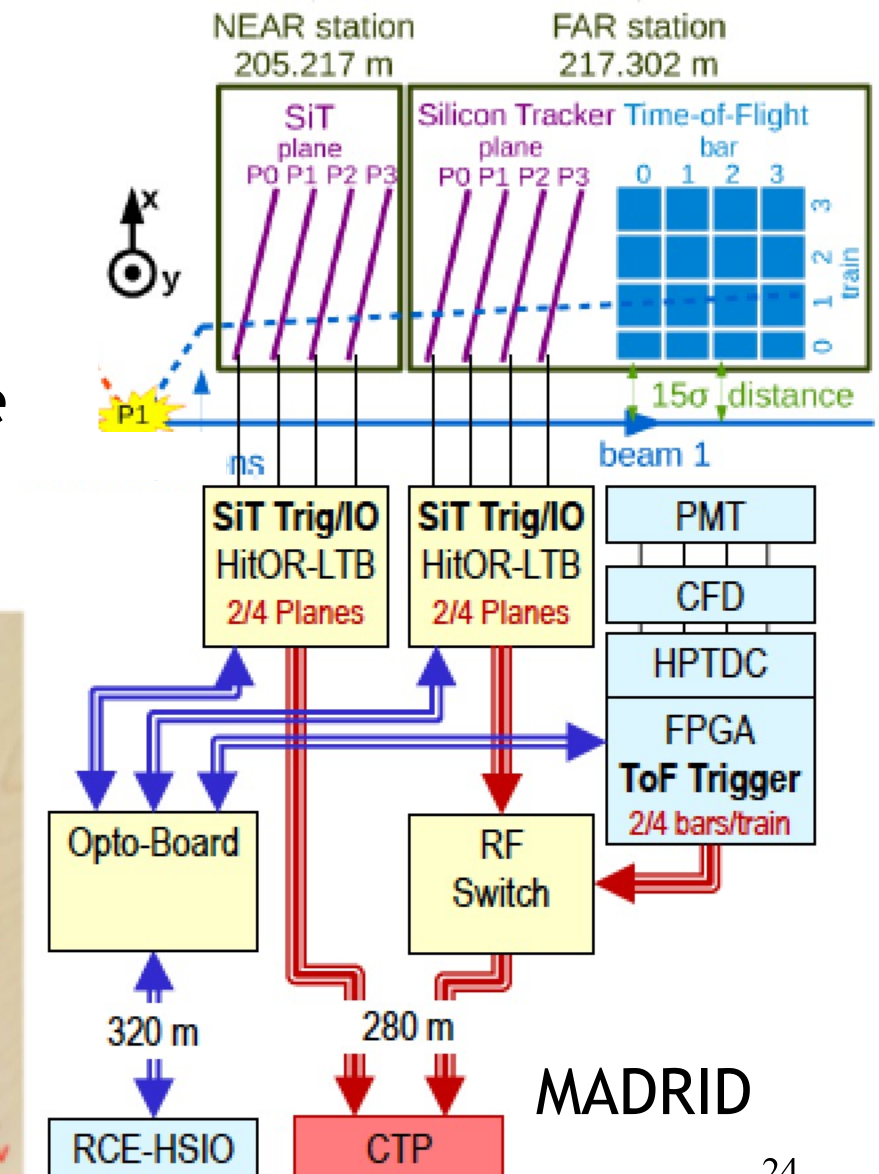
- Signal for pp→pXp events in double-tagged sample. Corresponding vertex resolution ~ 6 ± 1mm.

- Promising for future runs.

Trigger and Data Acquisition

AFP fully integrated into ATLAS TDAQ system and able to deliver first level triggers within the 85 bunch crossing latency (fast air-core cables) according to field-programmable criteria.





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