The ATLAS AFP Proton Spectrometer

Paul Newman
University of Birmingham

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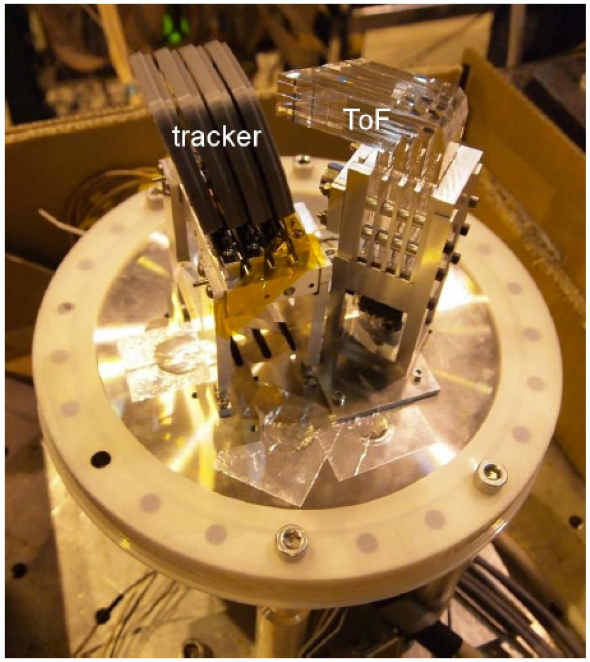
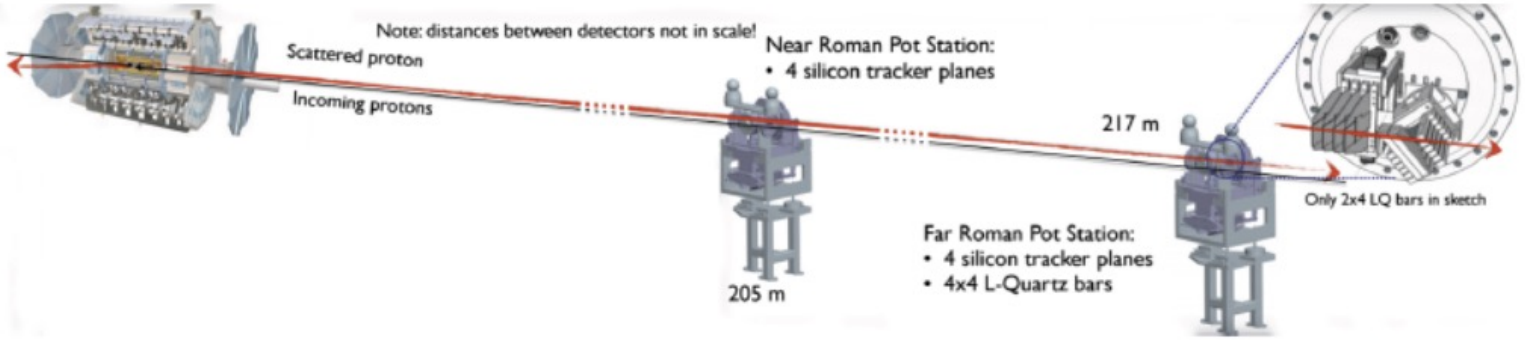




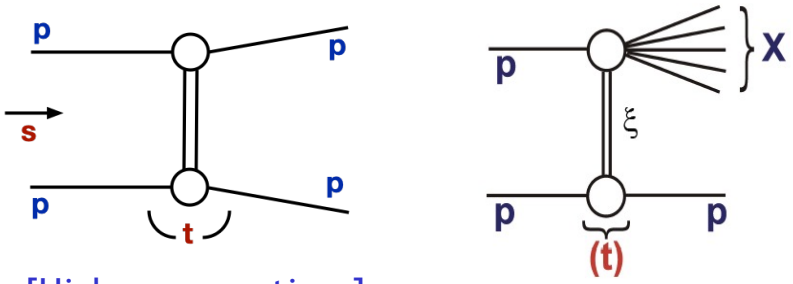
LHC Physics with Intact Protons

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

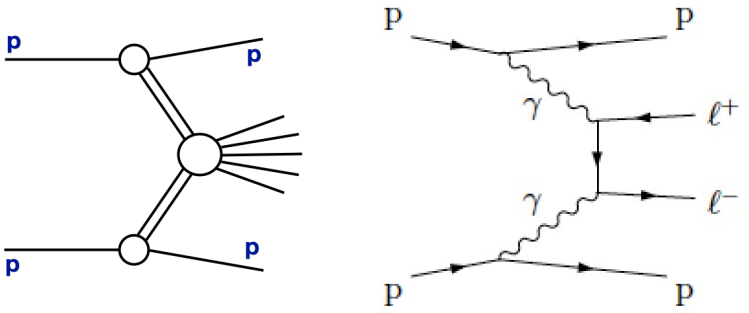
- Detectable using spectometers housed in 'Roman pot' vacuum-sealed insertions to the beam-pipe, well downstream of interaction point.

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

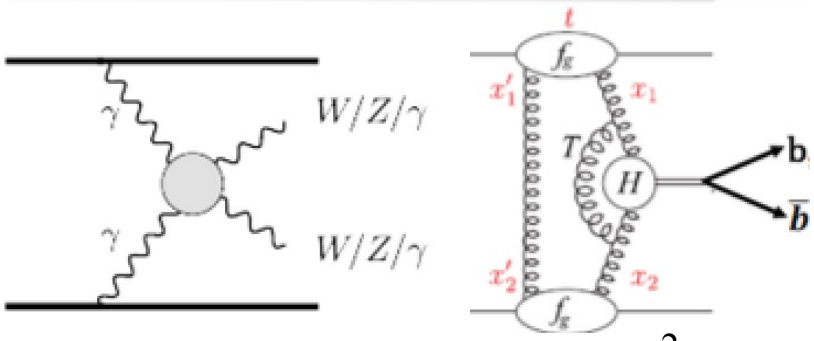
- Physics focus is now on rare and exotic processes … 2nd generation proton spectrometers need to collect data under 'normal' LHC running conditions



[High cross sections]

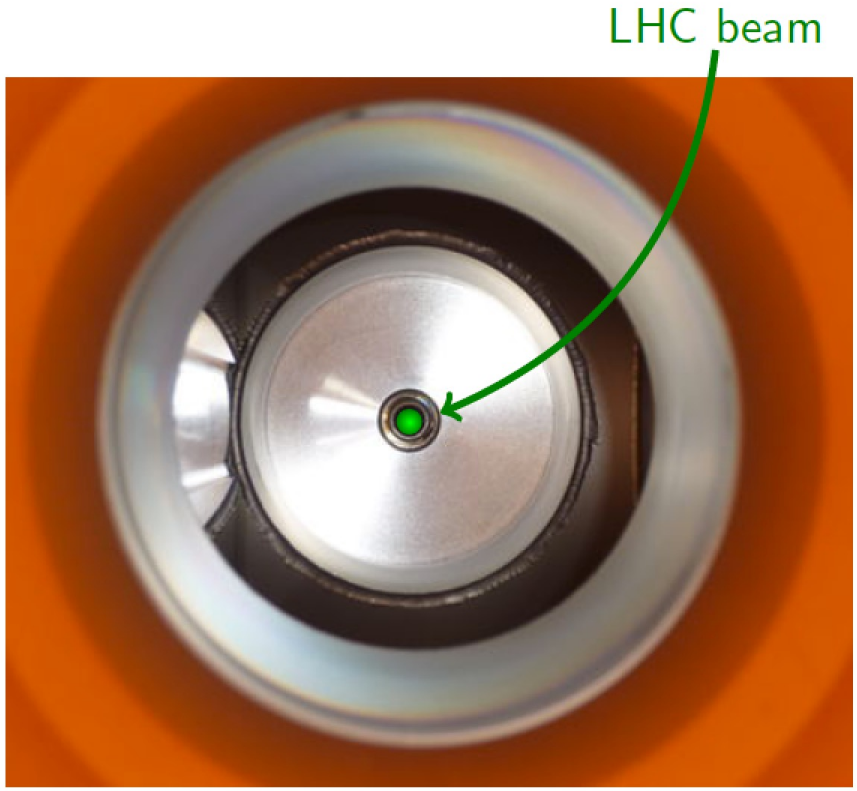


[Intermediate cross sections]



[Low cross section / exotic]

Principle of AFP Roman Pots



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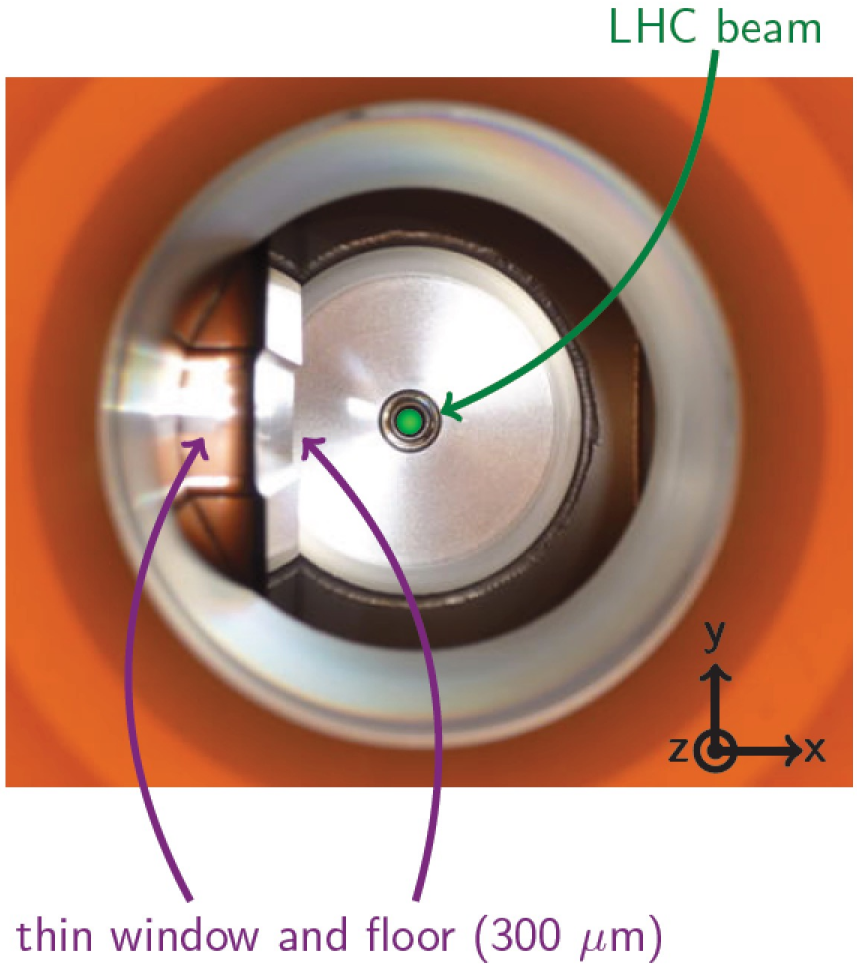

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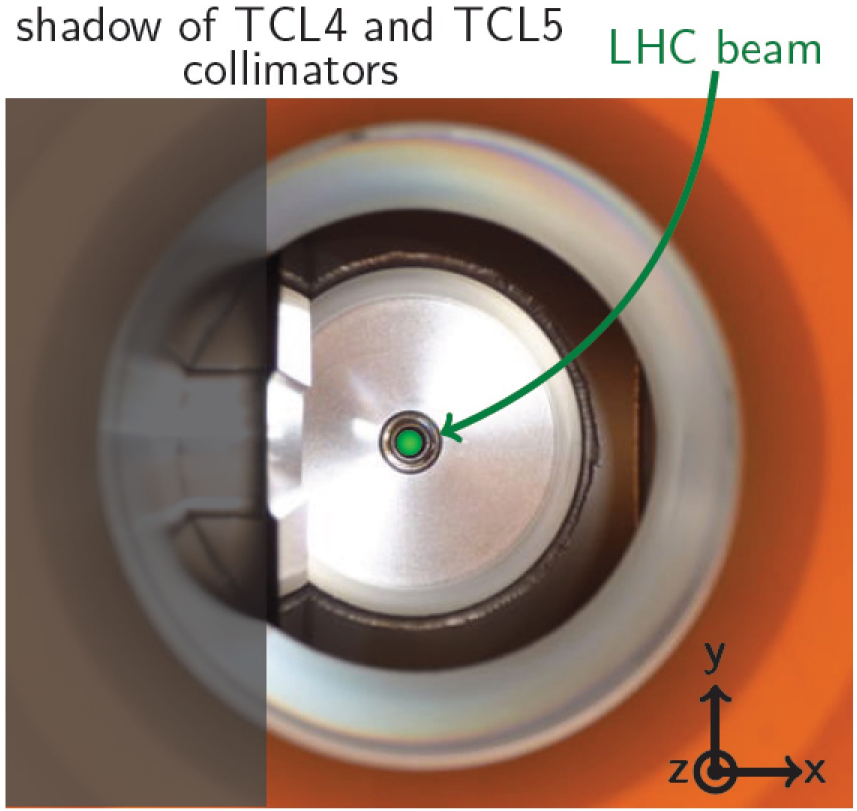

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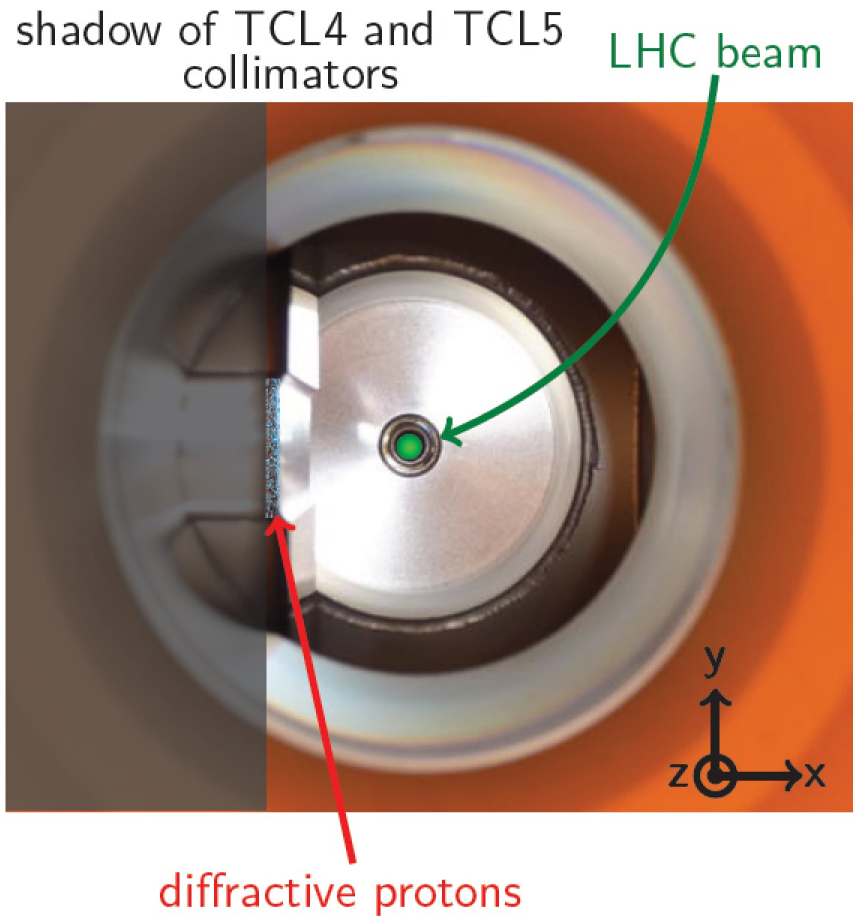
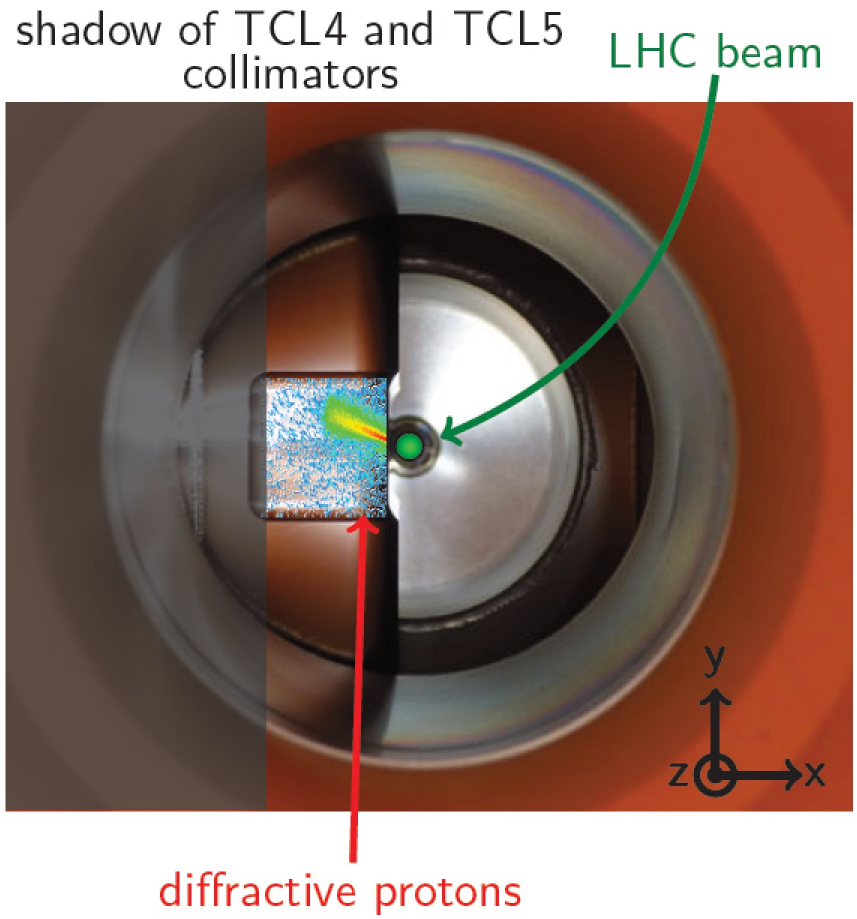


Principle of AFP Roman Pots



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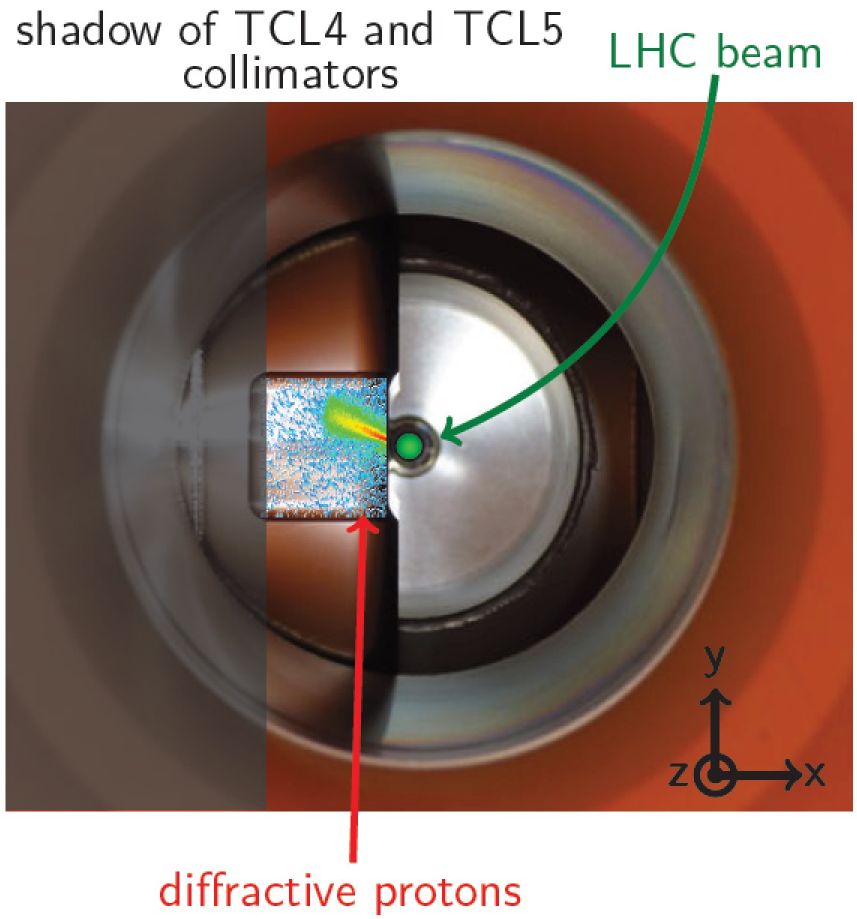


Challenges …

… detect and precisely reconstruct kinematics of proton tracks …

→ Well downstream (~200m)

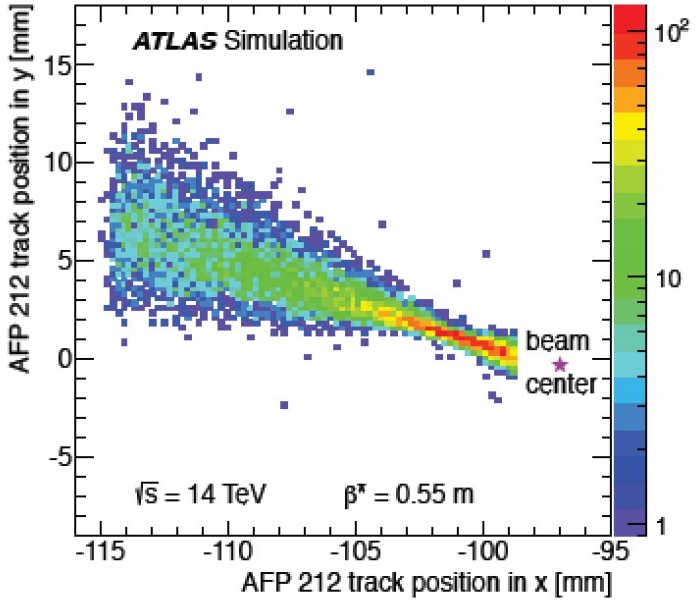
→ Near to beam (~2mm)

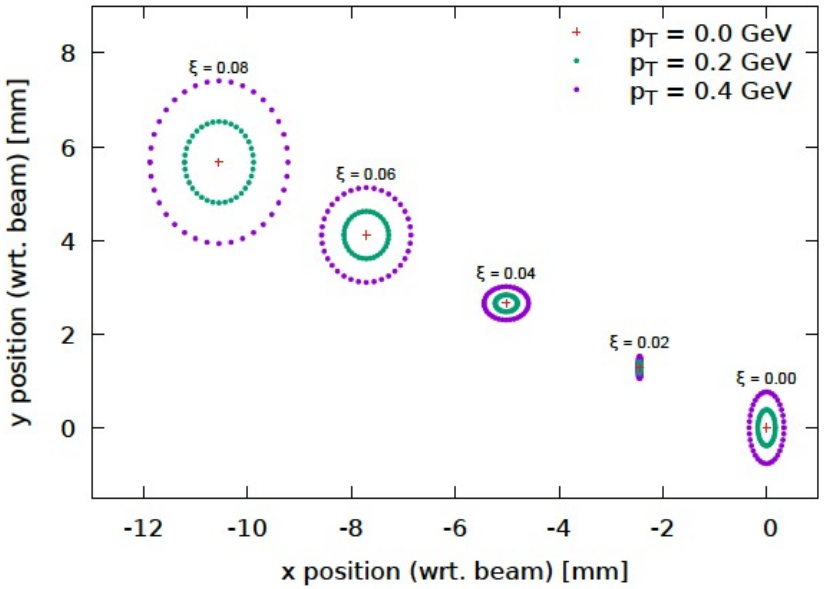
… in challenging conditions

→ 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 …

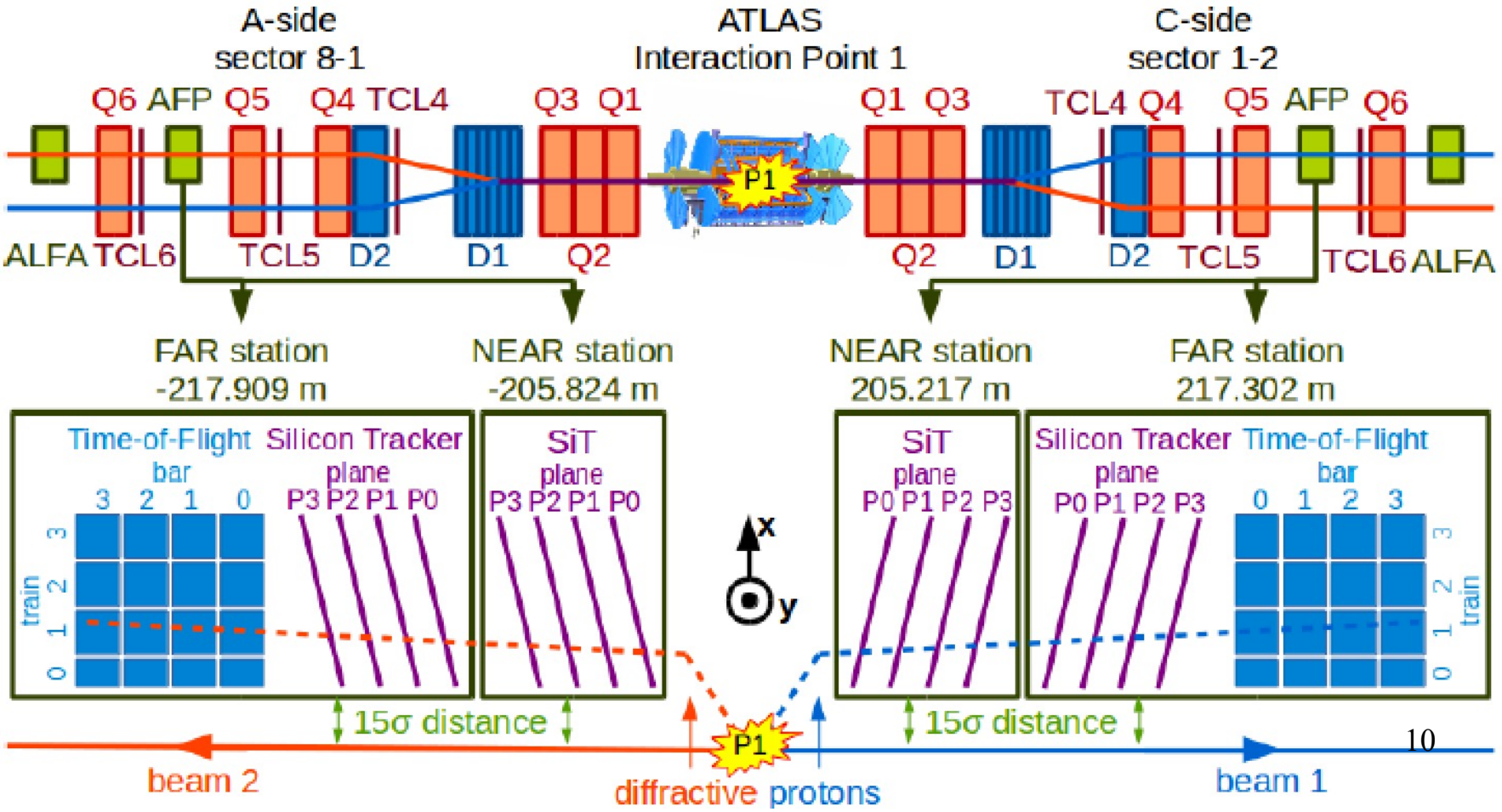
ξ **= fractional proton energy loss**

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

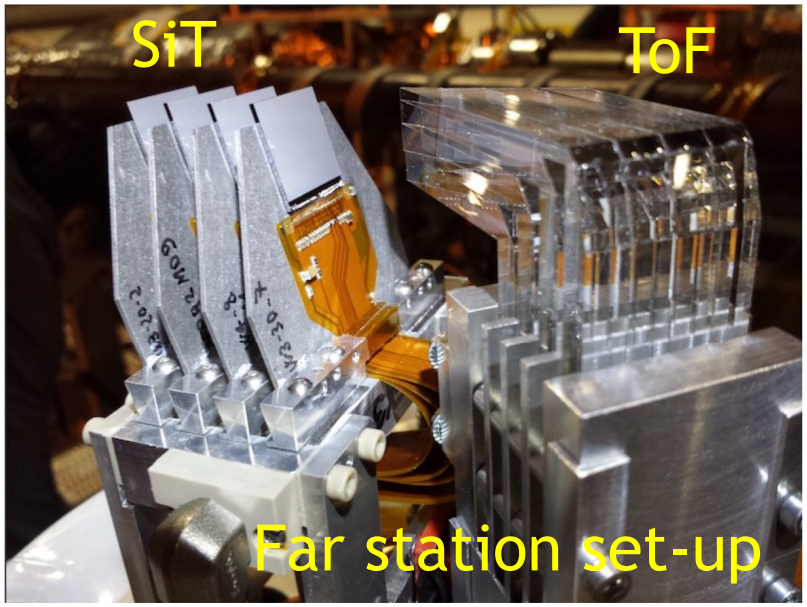
Ambiguity due to proton p_T (usually << 1 GeV) resolved by Δx between pairs of Roman pot stations

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



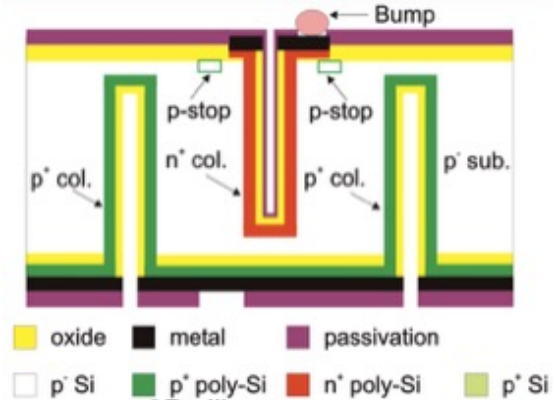
AFP Detectors

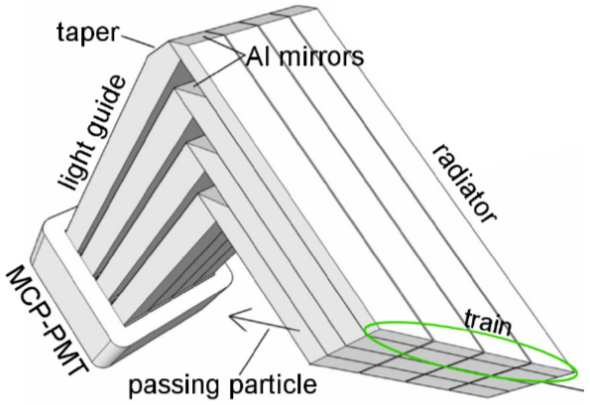


Tracking: four pixel sensor planes per station, based on Insertable B-Layer;

- 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





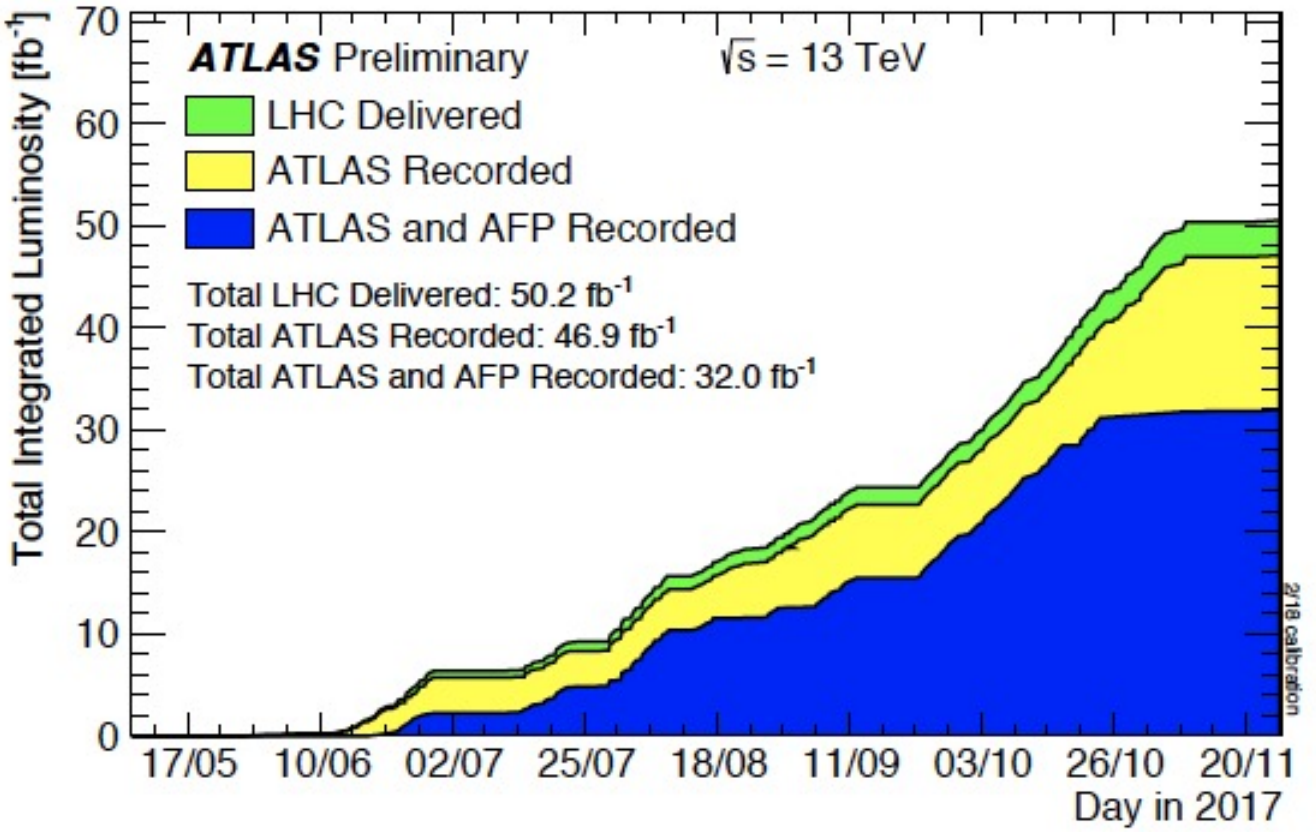
Timing: 4x4 quartz bars at Cerenkov angle to beam. Light detected via MCP- PMTs → resolution of 20-40 ps demonstrated, but with poor efficiency so far.

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)

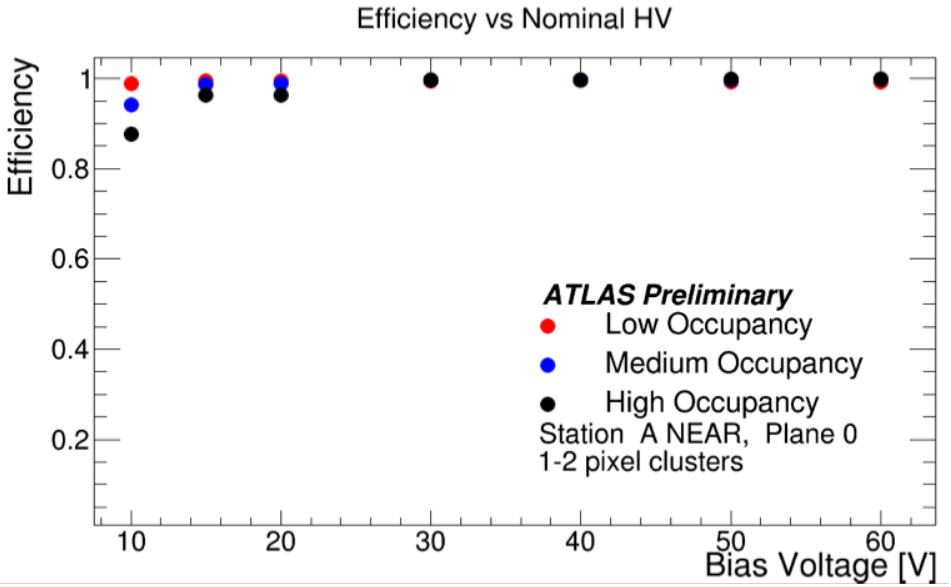
SiT Performance: Single Plane Efficiency

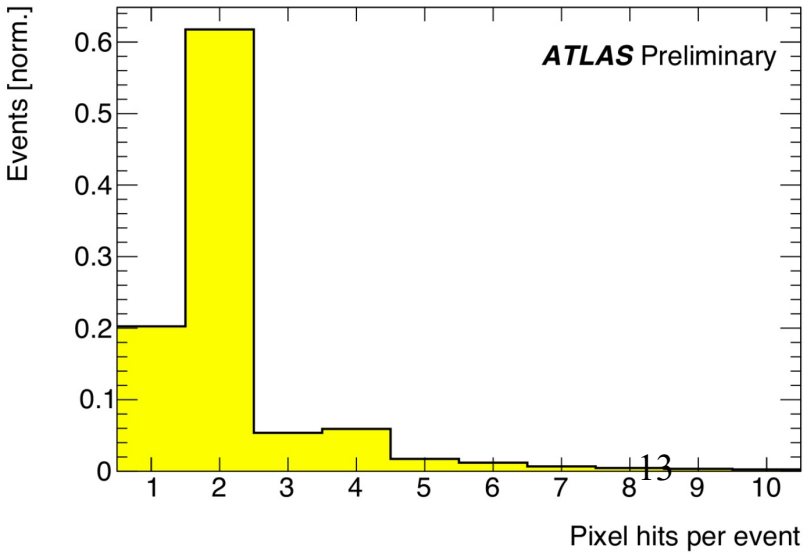
- Single hit efficiency determined from probability of hit in fourth plane of station given hits in the other three. → ~98% for bias voltage >~ 20V.

- 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)

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



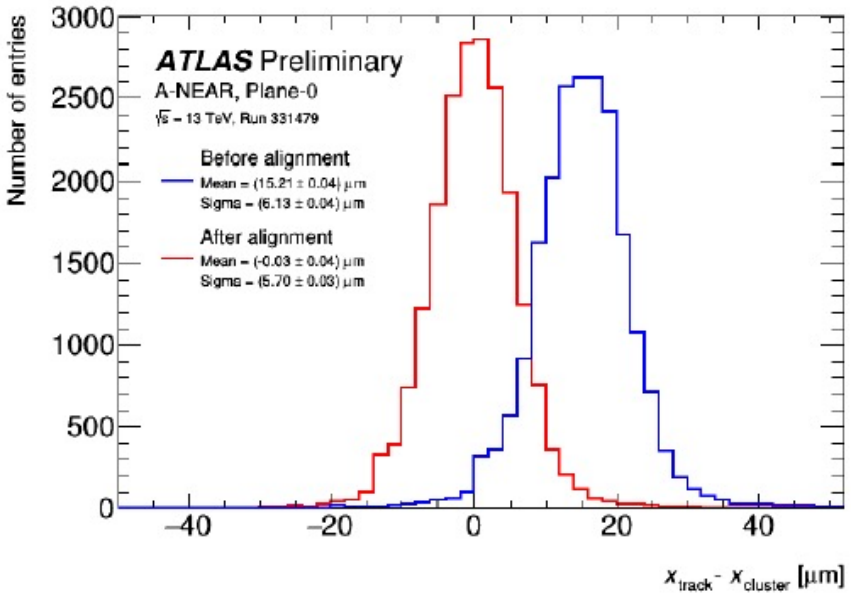


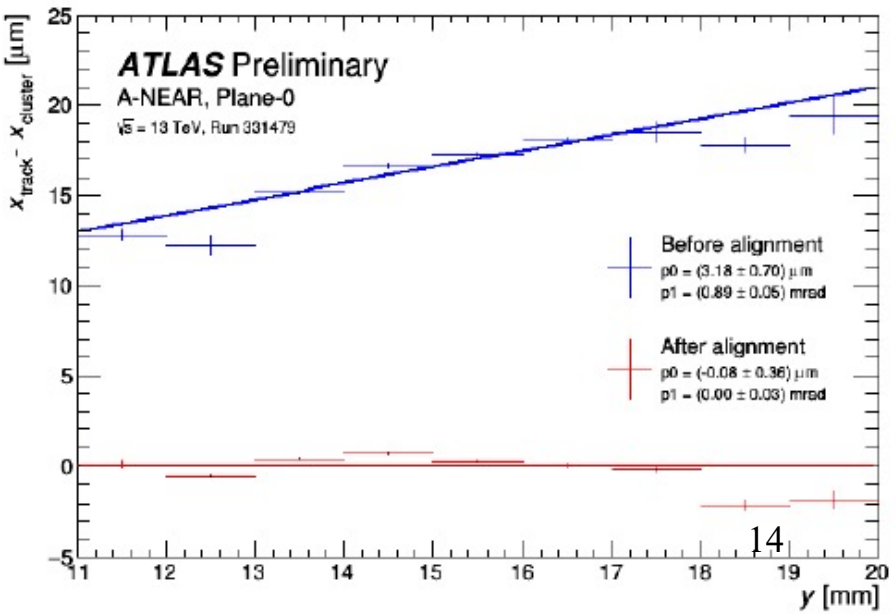
Individual Plane Alignment

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

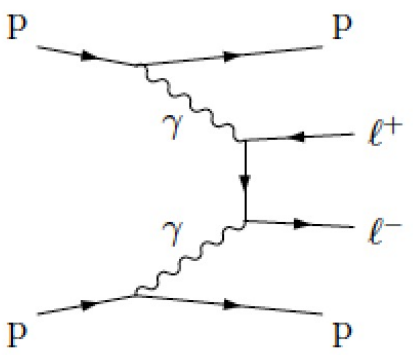
→ Form residuals in each plane relative to reconstructed tracks
→ Correct for shifts in x and y direction and rotation about z axis
→ Iterate

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





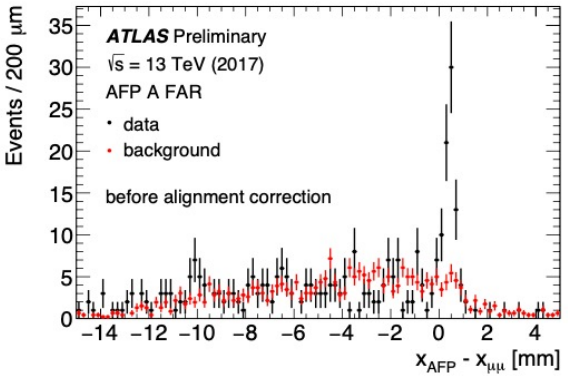
Global Alignment (of each station)



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

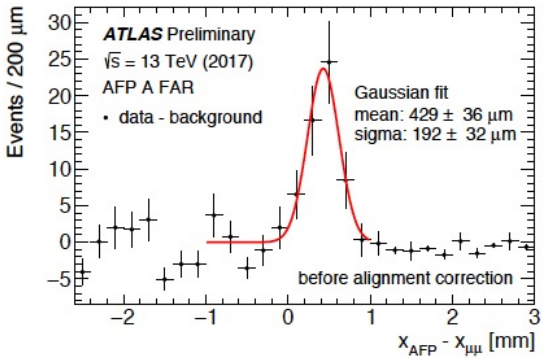
- ξ (and equivalently x coordinate in AFP) can be predicted from the leptons:

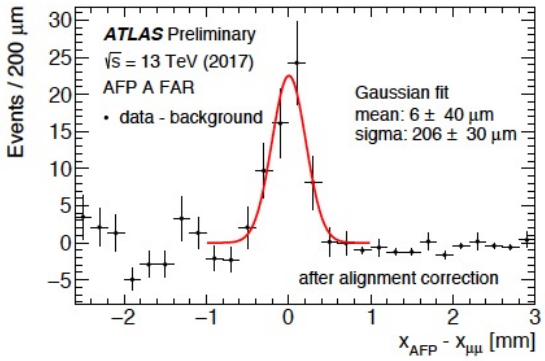
$$\xi^{\pm}_{\mu\mu} = \frac{m_{\mu\mu}}{\sqrt{s}} e^{\pm y_{\mu\mu}} \qquad \xi = 1 - E'_p / E_p$$

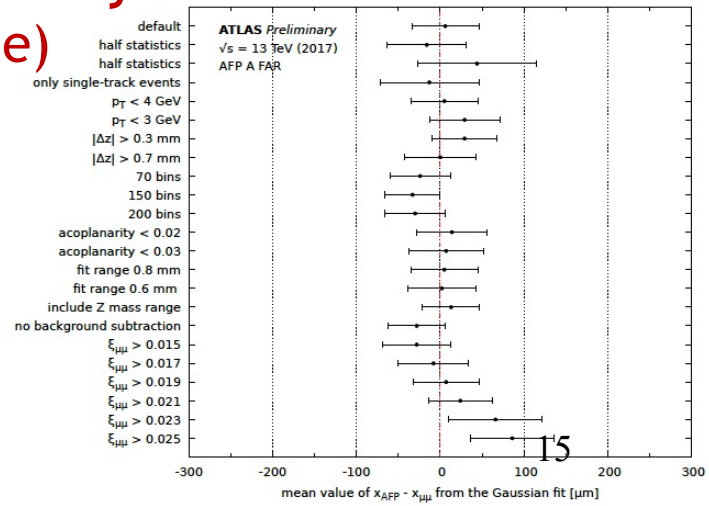


- (small) background well modelled by event mixing

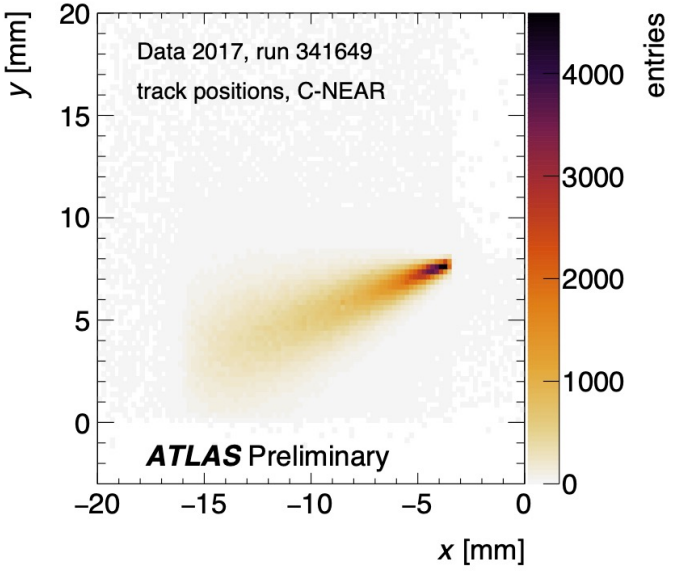
- **Global alignment precision uncertainty currently quoted as 300 μm** (but 100 μm seems achievable)

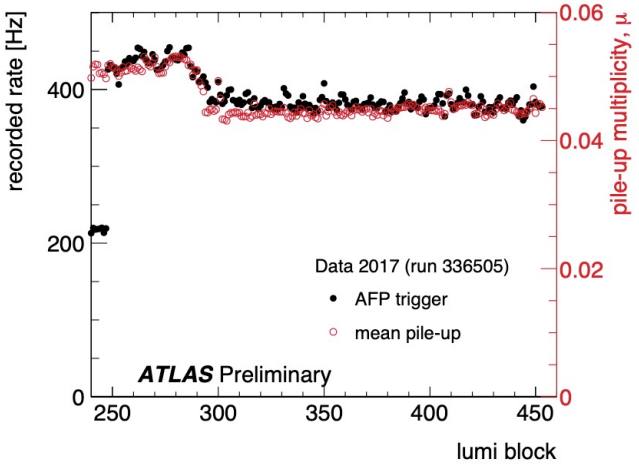


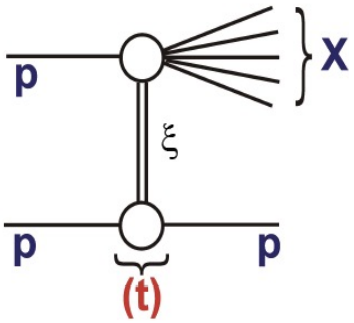




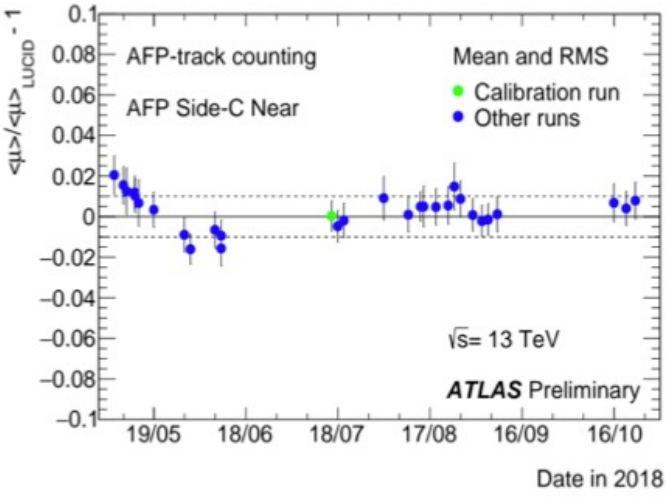
Reconstructed Proton Signal







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

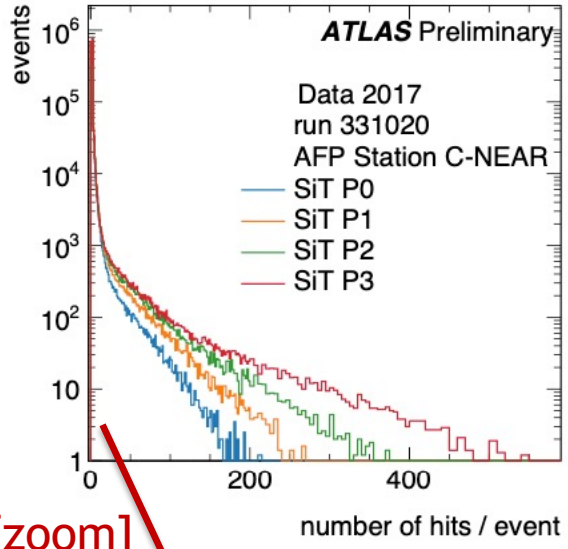


- Trigger rate (2 out of 3 coincidence of selected SiT planes) follows pile-up rate … i.e. beam-induced backgrounds small

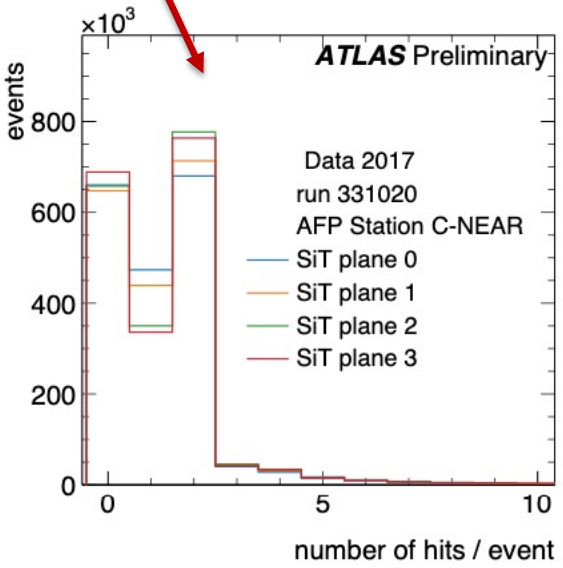
- Rate stable with respect to other forward detetors /luminosity monitors (LUCID)

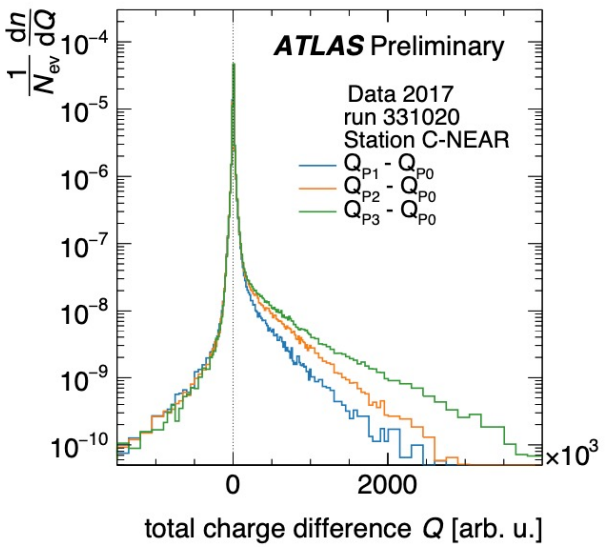
- Occupancy ~0.02 reconstructed track segments per pot station per pp collision

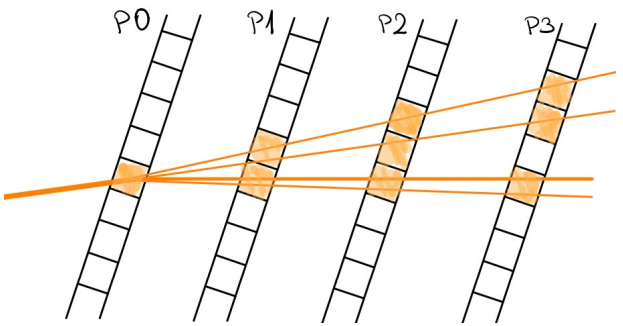
Showering in SiT Planes and Pot Walls



[zoom]





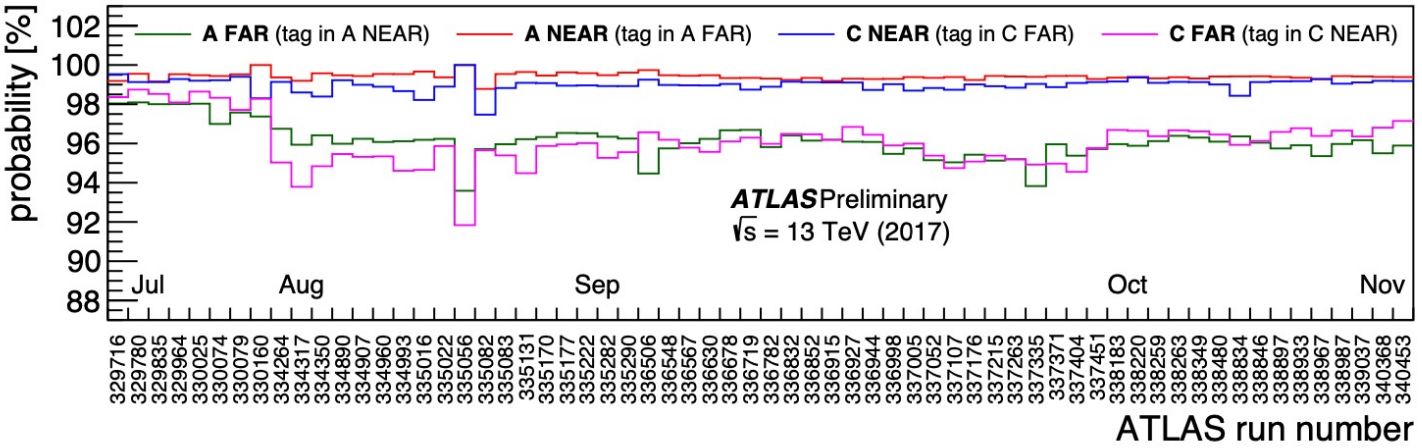


- Evidence for modest level of showering in material of SiT planes (long non-Poisson tail in hit multiplicity per plane, growing with distance from track start).

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

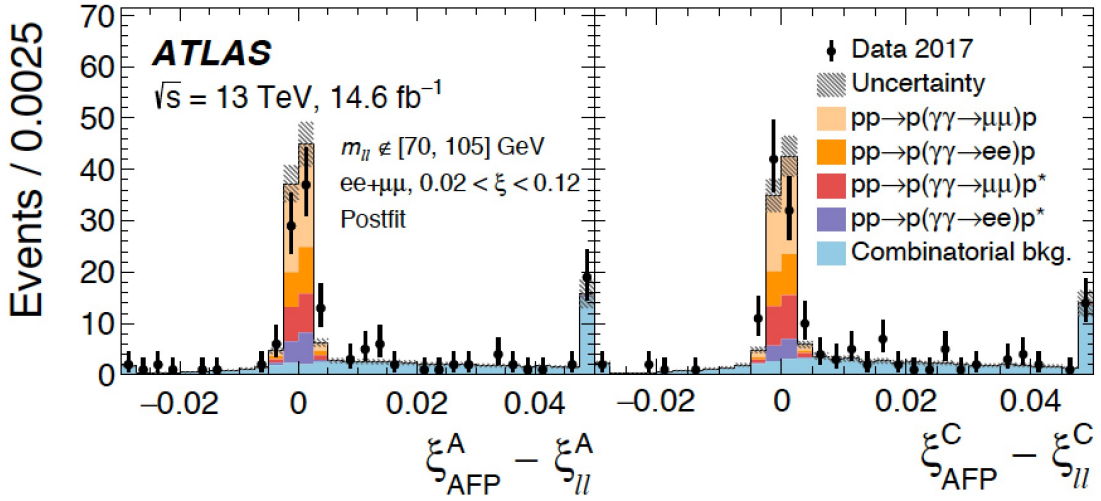
- Largest contribution to inefficiencies…

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

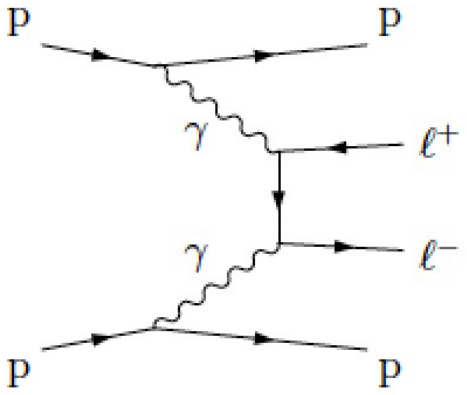
First High Lumi AFP Publication (15 fb^{-1})

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)



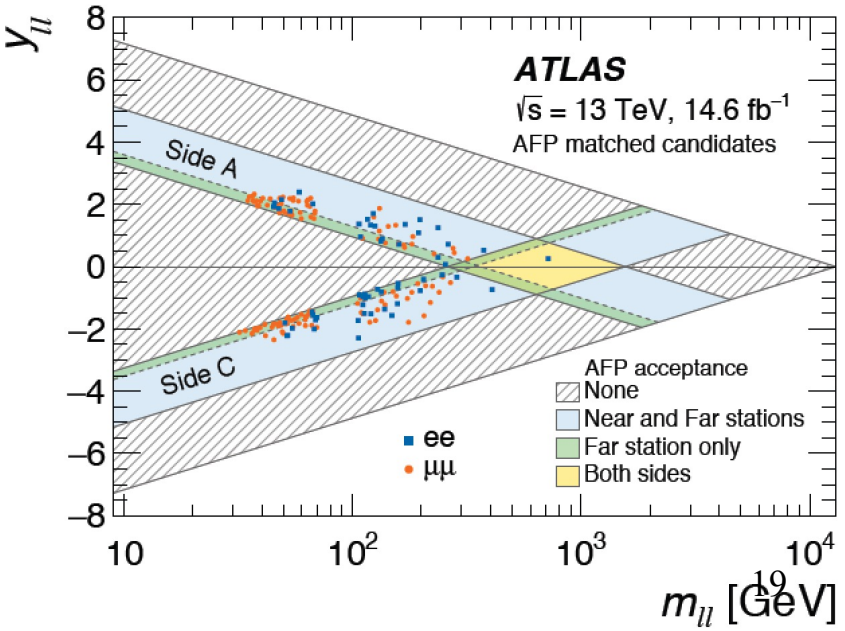
γγ → ee
or μμ

$\sigma_{\text{HERWIG+LPAIR}} \times S_{\text{surv}}$	$\sigma^{\text{fid.}}_{ee+p}$ [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

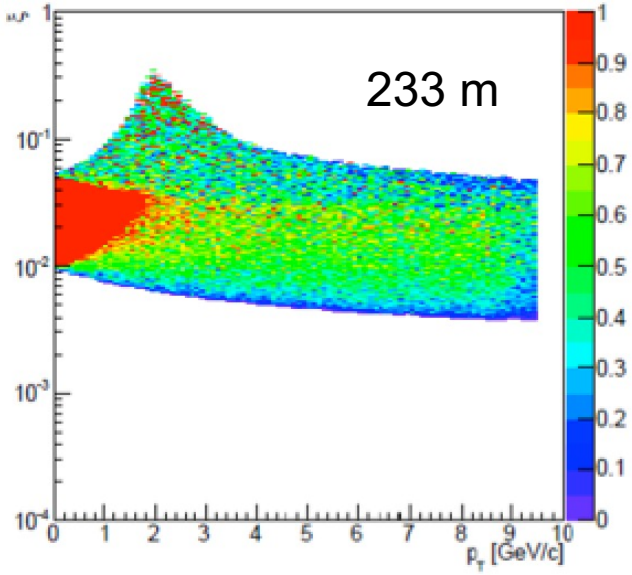
- ToF: New PMTs with new out-of-vacuum / POT solution
- Various more minor consolidation projects
- Successful test beams at DESY
- Installation proceeded either side of COVID.
- Data taking with full system (expect factor >10 more data)

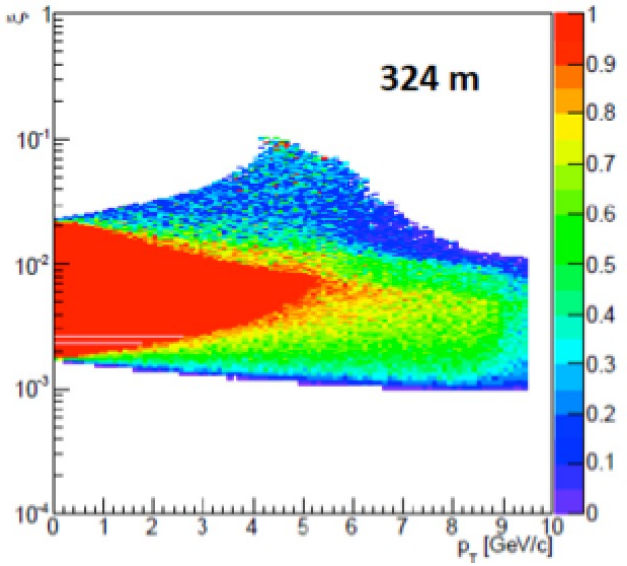
Run 4 (at HL-LHC)

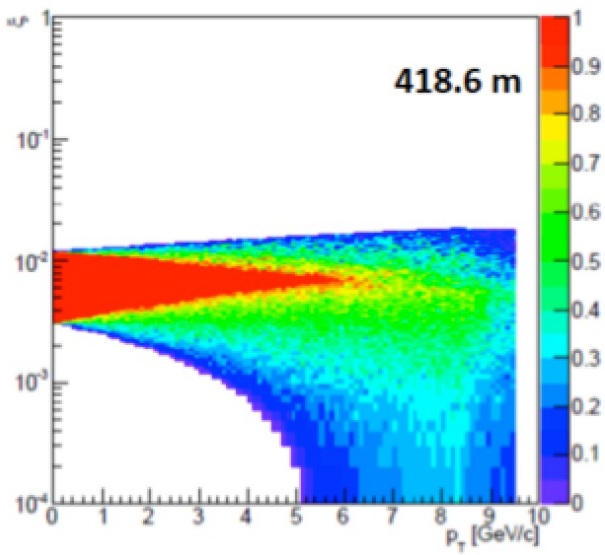
- Potentially rich physics programme (further factor >10 more data)
- New level of challenges in terms of radiation environment and pile-up
  (→ ToF detector with <10ps resolution)
- Studies of acceptance at various possible pot locations with currently foreseen HL-LHC optics well underway

Early Studies with nominal HL-LHC Optics

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



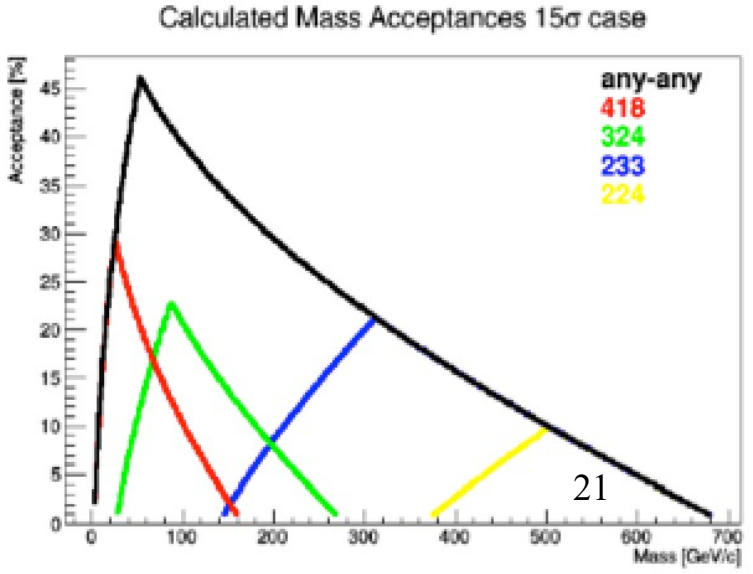




233m: Reduced ξ acceptance relative to that now in AFP region

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

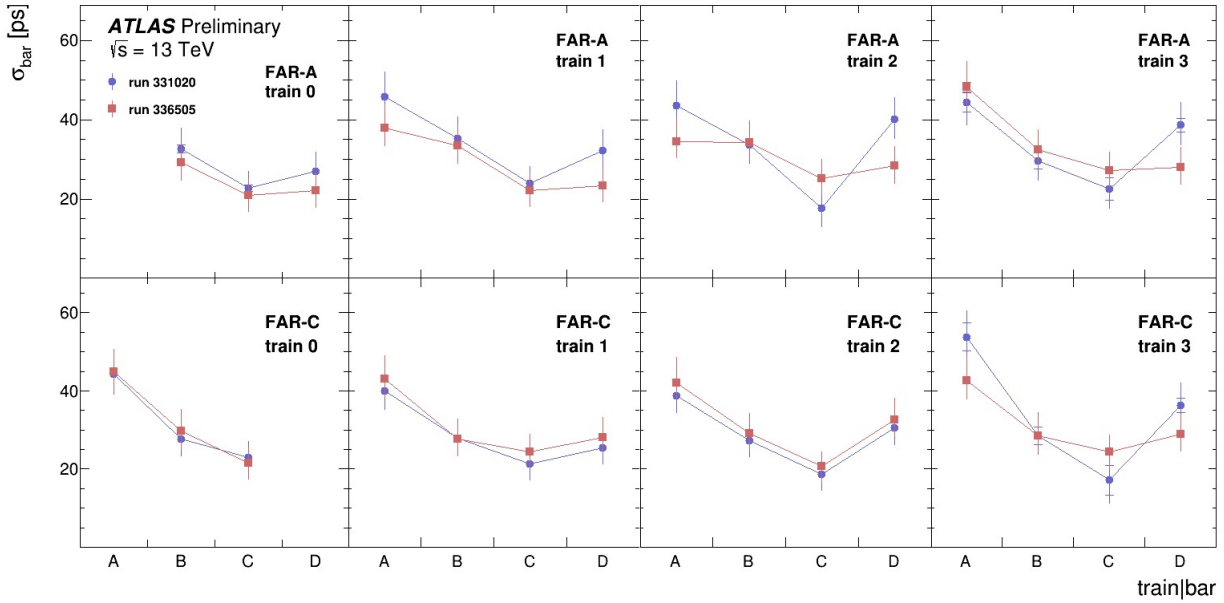
First physics result on $\gamma\gamma \rightarrow l^+l^-$ published in PRL

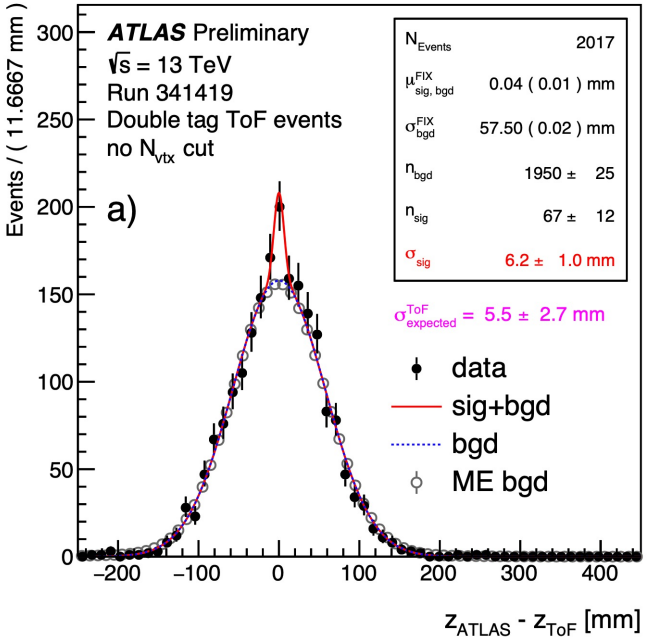
Expect to collect much more data in Run 3 (also with ToF)

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.