Alignment of the ATLAS Forward Proton Detector

Ferhat Öztürk

Institute of Nuclear Physics Polish Academy of Sciences (IFJ PAN)

ferhat.ozturk@ifj.edu.pl

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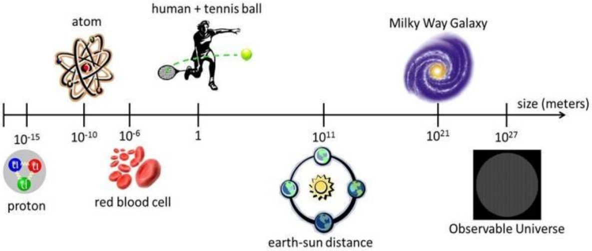
Overview

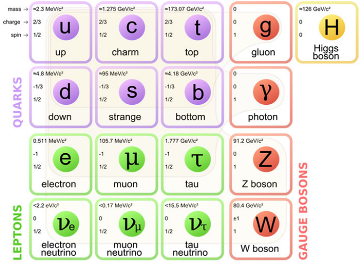
Particle Physics

Particle physics studies the fundamental particles that constitute matter and the forces governing their interactions, aiming to understand the universe's basic principles.



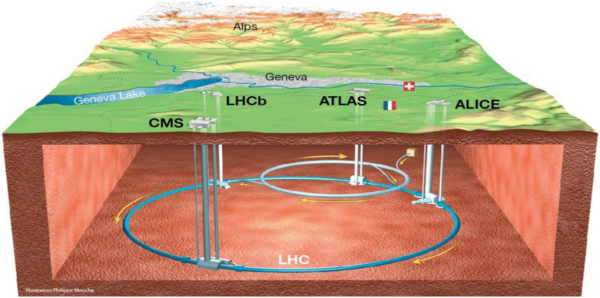
Standard Model (SM):

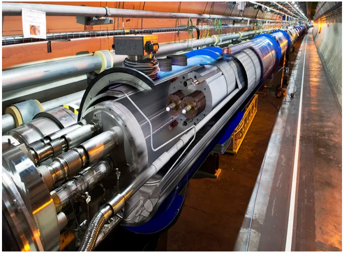
- Unification of Strong, Weak, and Electro-magnetic forces
- Higgs boson discovery in 2012
- Quite compatible with experiments
- Gravity not included yet



Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, constructed by the European Organization for Nuclear Research (CERN).

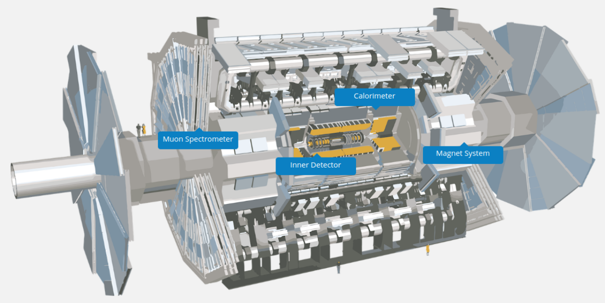


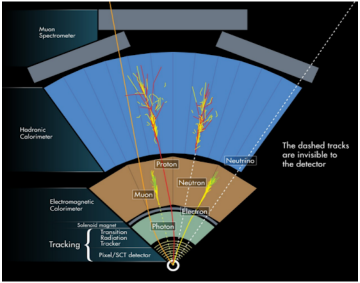


- Located 150 m beneath the France-Switzerland border
- Circumference of 27 km
- Collides protons (10^{10}) or heavy ions at 0.9999990 c
- Collision rate is 25 ns (40 TB/s data)

ATLAS Detector

The ATLAS detector is one of the largest and most complex experimental facilities at the LHC.

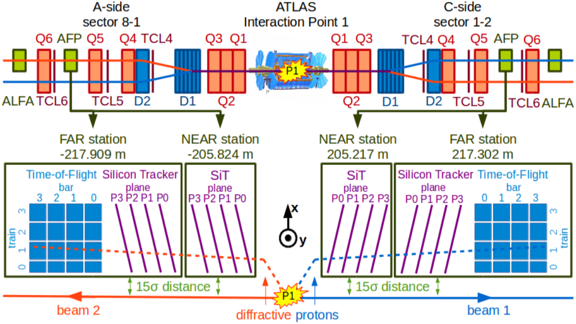


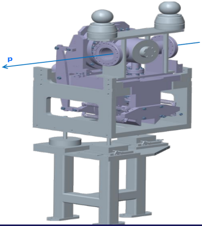


- 46 m long and 25 m in diameter
- 7,000 tonnes
- Consists of various layers and components
- Designed to detect a wide range of particles

ATLAS Forward Proton Detector

The ATLAS Forward Proton (AFP) project aims to extend the physics reach of ATLAS towards processes in which one or both protons remain intact by detecting those very forward protons.

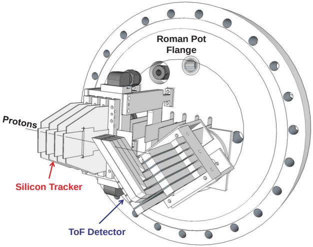


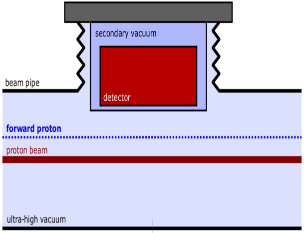


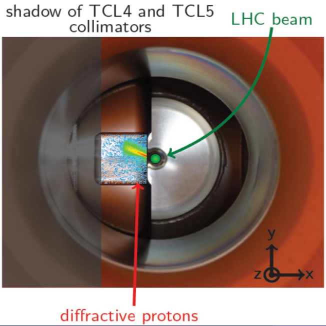
- Roman Pots (RP) are located at 205 m and 217 m from the interaction point (IP) on both sides.
- NEAR stations are equipped with Silicon Tracker (SiT) detectors only.
- FAR stations have SiT and Time of Flight (ToF) detectors.

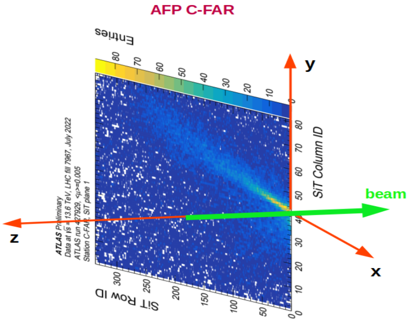
ATLAS Forward Proton Detector

The AFP detector is inserted into the LHC beam-line to receive data.



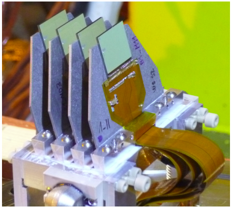






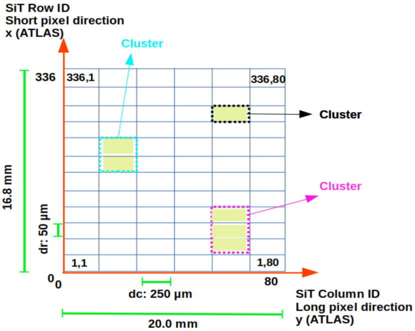
AFP Reconstruction

Silicon Tracker (SiT) planes

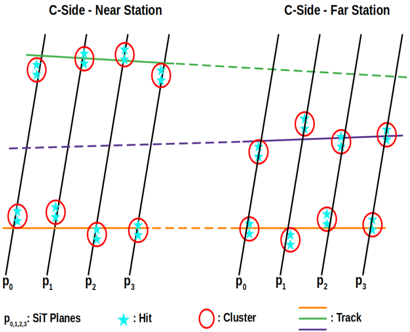


- 3D silicon pixel sensors (336 × 80 pixels)
- Pixel size: 50 μm × 250 μm
- Plane thickness: 230 μm
- The planes are tilted at a 14° about the y-axis
- Resolution: σ_x = 6 μm and σ_y = 30 μm

Hits recorded in a SiT plane

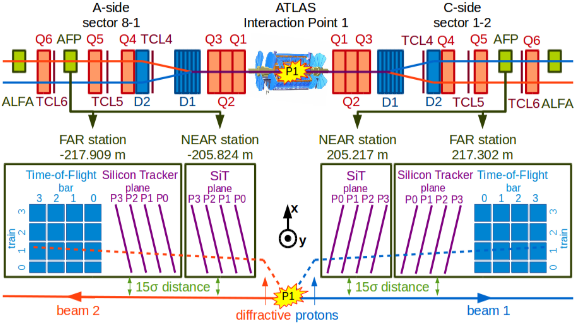


Hits → Cluster → Track → Proton



AFP Alignment

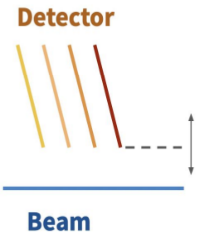
Misalignment of the AFP detectors biases the reconstruction of the proton kinematics, which impacts the measurements.



- **Inter-plane alignment**
  The relative position of each plane within a station.
- **Global alignment**
  Determining the position of each station in relation to the beam position.
- **Relative alignment**
  The alignment between the NEAR and FAR Stations.

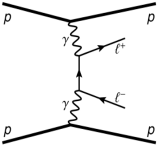
Global Alignment

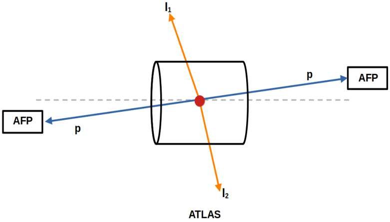
- **Beam-Based Alignment (BBA)**: Determining the nominal beam positions by moving collimators toward the beam.
- **Beam Position Monitoring (BPM)**: Monitoring the real-time position of a particle beam during normal accelerator operation.
- **RP Rotations**: Detecting the rotation of the pot during insertion through the use of SICK Laser measurements.
- **Exclusive Dimuon Production:** Comparing the x-positions of protons calculated by dimuon and AFP systems in the $pp \to p(\gamma\gamma \to \mu\mu)p$ process.



Global Alignment

Exclusive dimuon production

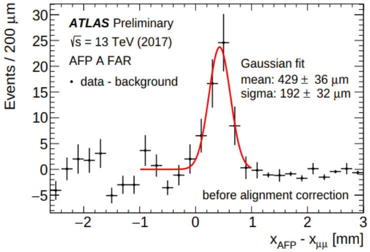


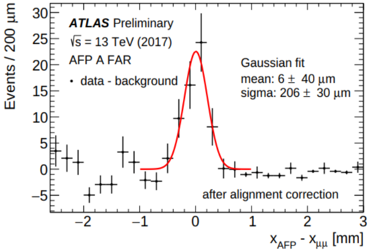


Expected x-position of the protons in AFP derived from the dimuon system (ξ is proton's fractional momentum loss):

$$\xi^{A,C}_{\mu^+\mu^-} = m_{\mu^+\mu^-}\frac{e^{\pm y_{\mu^+\mu^-}}}{\sqrt{s}}$$

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

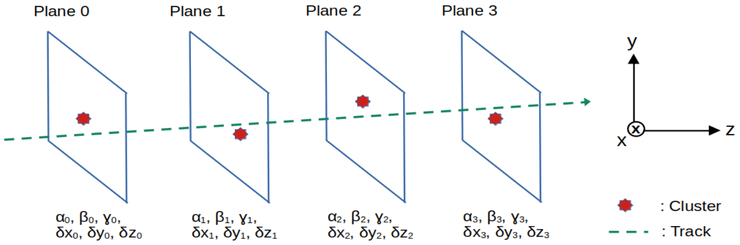




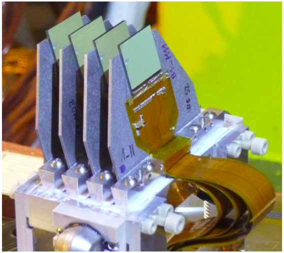
In Run 2, a systematic uncertainty from Global Alignment is ±300 µm (dominant one).

Interplane Alignment

The inter-plane alignment aims to provide an accurate description of each plane's relative position in the station.

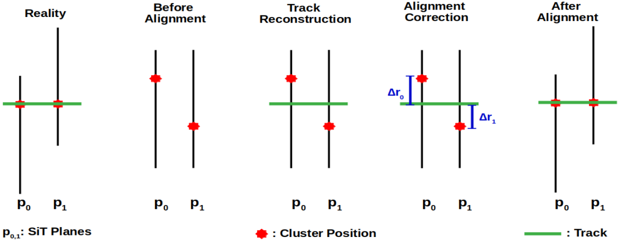


- The tracks can serve as an approximate method of aligning SiT planes (Track based alignment).
- A total of 24 free parameters must be determined in a station for interplane alignment.
- **Residuals Minimization:** Minimizing the difference between cluster and track positions by studying the distributions.
- **Global χ^2 Minimization:** Minimizing the residuals using Global χ^2 method (Ongoing).



Interplane Alignment: Residuals Minimization

The method based on reducing the differences between cluster and track positions, known as residuals ($\Delta\vec{r}$), in each plane.



Residuals calculation:

$\vec{r}_t = R(\alpha, \beta, \gamma) \cdot \vec{r}_c(x, y, z) + \delta\vec{r}(\delta x, \delta y, \delta z)$

$\vec{r}_t - \vec{r}_c = \Delta\vec{r} = (\Delta x, \Delta y, \Delta z)$

r_t, r_c : Track and cluster positions

α, β, γ : rotation about z, y, x axis

$\delta x, \delta y, \delta z$: offset values

Small angle approximation!

Analysis Parameters:

- Only 3 parameters per plane: $(\delta x, \delta y, \alpha)$
- 9 parameters per station by fixing the first plane: $(\delta x_0 = 0, \delta y_0 = 0, \alpha_0 = 0)$

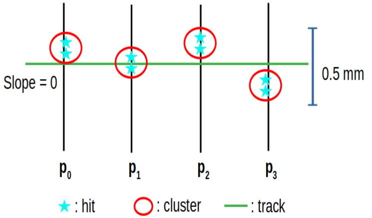
Analysis Algorithm:

- Initial alignment parameters
- Event reconstruction
- Event cleaning
- Iteration (30 times)

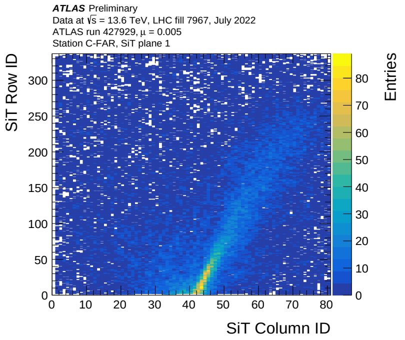
Interplane Alignment: Event Selection

Event reconstruction and cleaning:

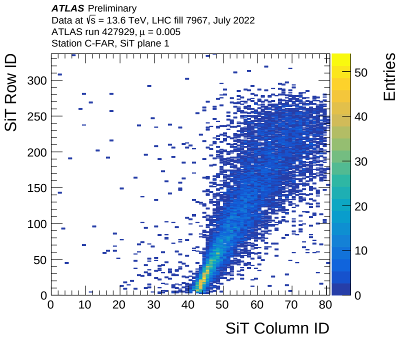
- 1 track reconstructed per station
- 1 cluster reconstructed per plane
- 1 or 2 hits recorded per plane
- Transverse dist between clusters < 0.5 mm
- Slope of the tracks are neglected



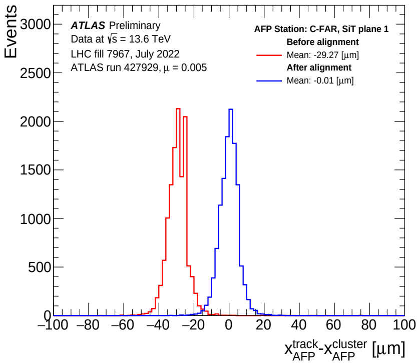
Before Event Cleaning

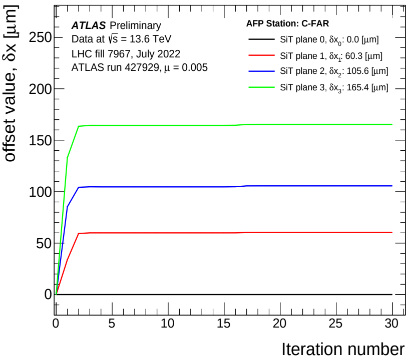


After Event Cleaning



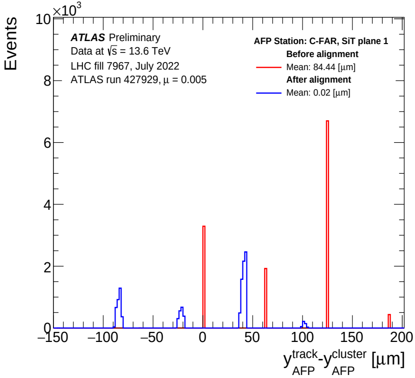
Results: Offset value δx

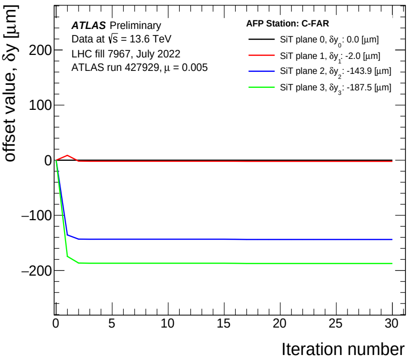




- δx is obtained from the mean value of the differences between the reconstructed tracks and the clusters.
- Example: Plane 1 is misaligned by 60.3 μm in the x-axis with respect to Plane 0.

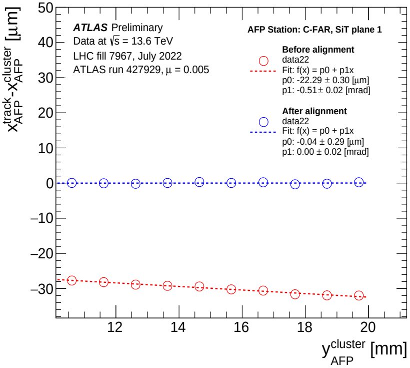
Results: Offset Value δy

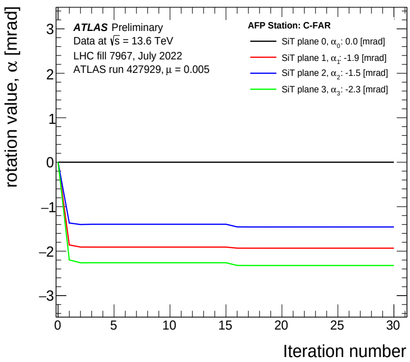




- δy is obtained from the mean value of the differences between the reconstructed tracks and the clusters.
- The multi-peak structure in the distribution is a result of low and non-Gaussian resolution in the SiT plane along the y-axis (long-pixel direction).
- The fact that red values are "exact" while blue values are a bit "smeared" is due to plane rotation considered in the alignment procedure.

Results: Rotation Angle α





- The rotation angle about the z-axis (α) can be obtained from difference between x-position of reconstructed track and cluster plotted in a function of y-position of a cluster: $\alpha = \frac{\partial \Delta x}{\partial y}$.
- α is extracted from a linear fit applied to the data points.

Future Developments: Global χ^2 Minimization

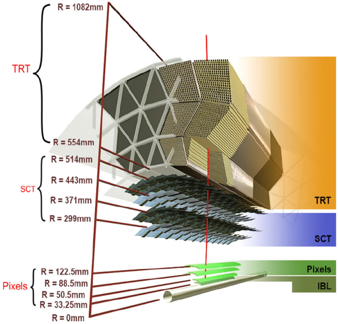
Global χ^2:

$$\chi^2(\alpha,\tau)_g = \sum_{i=\text{tracks}} \chi_i^2(\alpha,\tau) = \sum_{i=\text{tracks}} r_i^T(\alpha,\tau) V^{-1} r_i^T(\alpha,\tau)$$

Solution (Newton Raphson Method):

$$\alpha_1 = \alpha_0 - \left(\left. \frac{d^2\chi_g^2(\alpha,\tau)}{d\alpha^2} \right|_{\alpha=\alpha_0} \right)^{-1} \left(\left. \frac{d\chi_g^2(\alpha,\tau)}{d\alpha} \right|_{\alpha=\alpha_0} \right)$$

- Finding a solution within a few iterations.
- Working with a large number of degrees of freedom.
- Identifying and eliminating weak modes.
- Allowing the application of constraints from the detector's geometry and measurements.

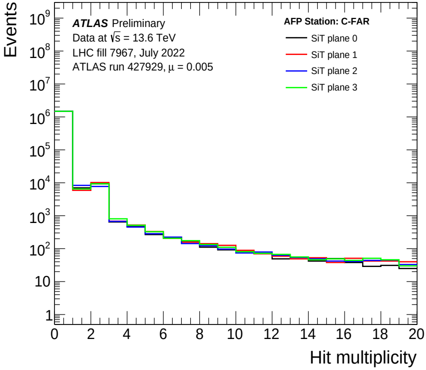


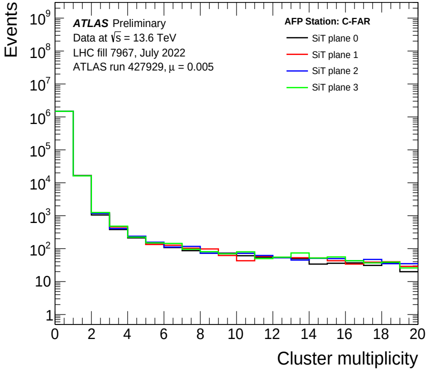
Summary

- The AFP detector plays a crucial role in extending the ATLAS physics program by detecting the forward scattered protons that remain intact during pp collisions.
- The alignment of the AFP is essential for achieving precise proton measurements and is divided into two main tasks: local and global alignment.
  1. Global alignment based on Beam-Based Alignment, exclusive dileptons, Roman Pot rotations, LHC survey data:
     - the use of Beam Position Monitors under investigation,
     - Run 2 systematic uncertainty: 300 μm (will be reduced for Run 3).
  2. Local Alignment based on minimization of residuals.
     - The strategy will shift to the Global χ^2.
- All studies are ongoing for Run3 data.

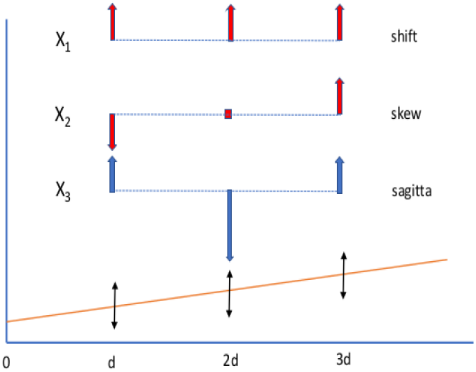
Thank You

Hit and Cluster Distributions





Weak Modes



PROC-CTD2020-02, Pawel Brückman de Renstrom

- Weak modes due to poorly constrained alignment parameters.
- Global detector movements that leave a track's χ^2 unchanged.