Overview of ATLAS Forward Proton detectors: status and performance

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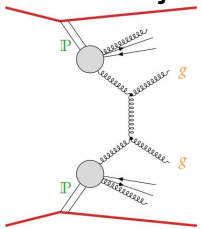
Physics Motivation

ATL-PHYS-SLIDE-2023-104

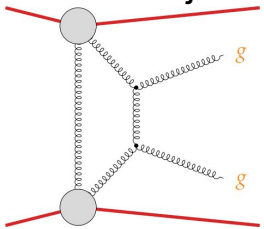
- Detection of events containing scattered intact protons
- Focused on low-cross section processes with high p_T objects in the final state
- Diverse physics program

Diffractive jets



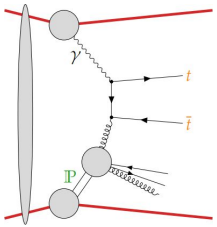
ATL-PHYS-PUB-2017-012

Exclusive jets



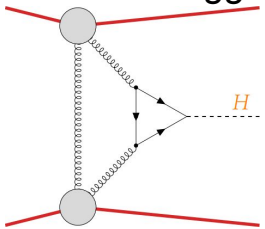
Trzebinski et al 1503.00699
Harland-Lang et al 1405.0018

Diffractive $t\bar{t}$



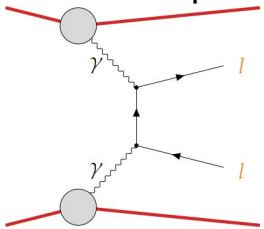
Goncalves et al 2007.04565
Howarth 2008.04249

Exclusive Higgs



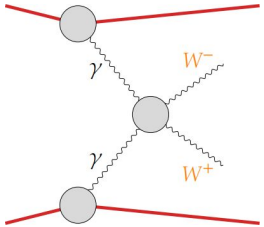
Cox et al 0709.3035
Heinemeyer et al 0708.3052

Exclusive Leptons



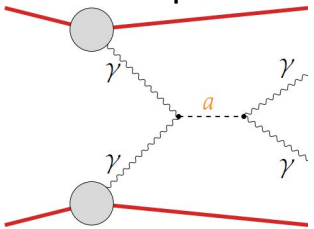
CMS 1803.04496
ATLAS 2009.14537

Exclusive W



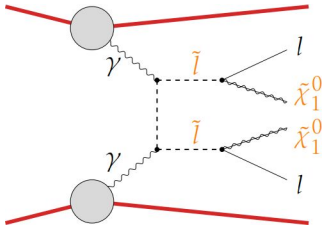
Tizchang, Etesami 2004.12203
Baldenegro et al 2009.08331

Axion-like particles



Baldenegro et al 1803.10835
ATLAS 2304.10953

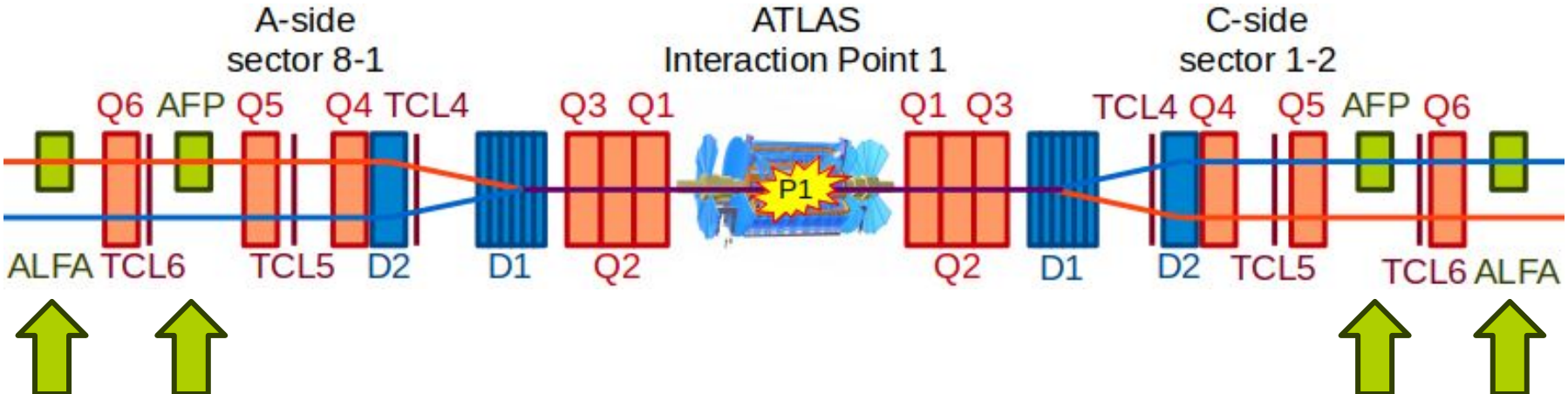
SUSY dark matter



Beresford & Liu 1811.06465
Harland-Lang et al 1812.04886

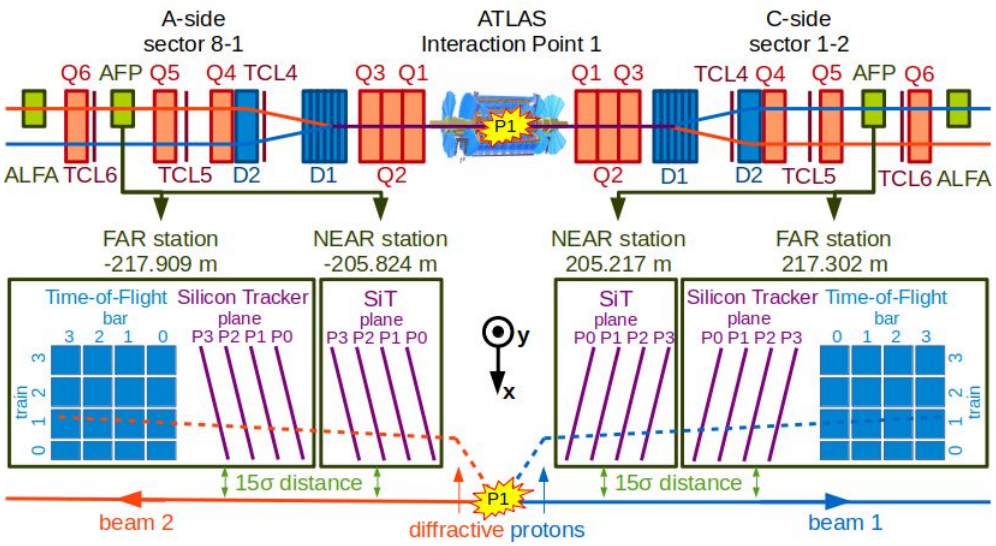
ATLAS Roman Pots

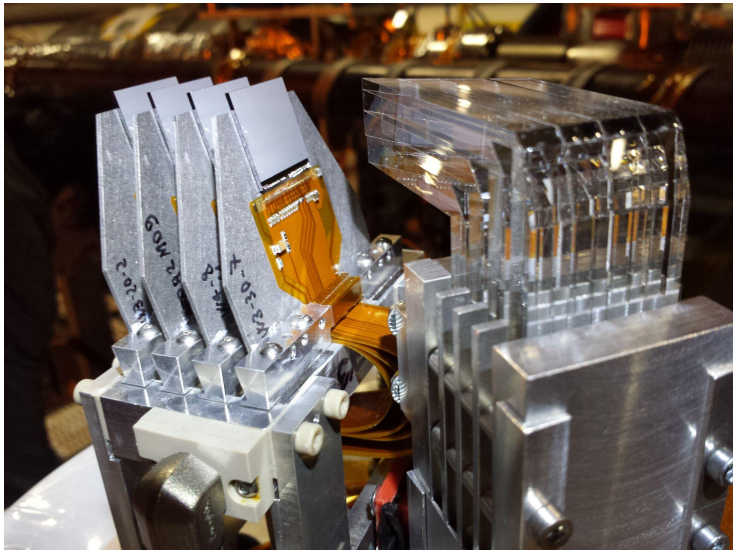
- Forward detectors - located in the LHC tunnel outside the ATLAS cavern
  - Around 210 meters from the ATLAS interaction point
- Move close to the beam (1-3 mm) once Stable Beams are declared
- Two detector systems
  - **ATLAS Forward Proton (AFP)**
  - Absolute Luminosity For ATLAS (ALFA) - not discussed in this talk



ATLAS Forward Proton (AFP)

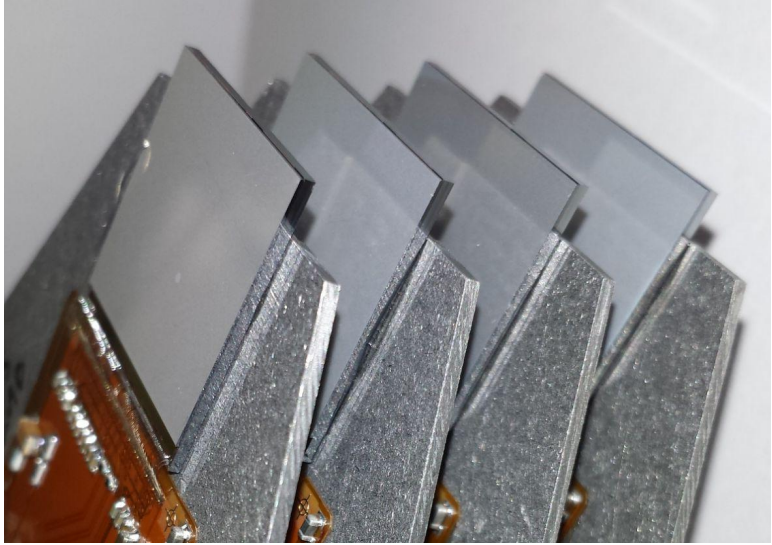
- Two stations on each side of ATLAS
- All stations host Silicon Tracker (SiT)
- Far stations host also Time-of-Flight (ToF) detector



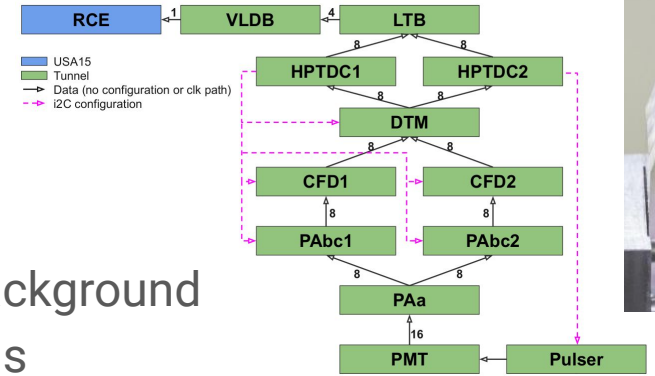


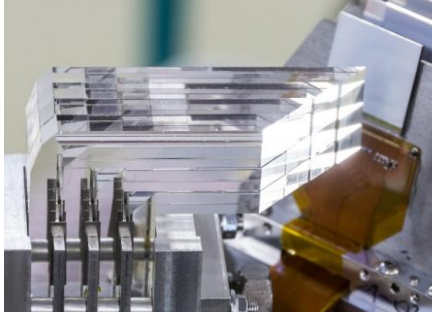
Silicon Tracker (SiT)

- Position measurement of scattered protons
  - Reconstruction of its kinematics
- 4 silicon pixel sensors
  - Spaced 9 mm apart
  - Each sensor 336x80 pixels
  - Pixel size 50x250 μm^2
  - Sensor size 16.8x20 mm^2
- Read out by FE-I4B chips
  - Same as ATLAS Pixel IBL
- 14° angle wrt. beam axis
  - To improve reconstruction resolution
    - ~6 μm in x and ~30 μm in y

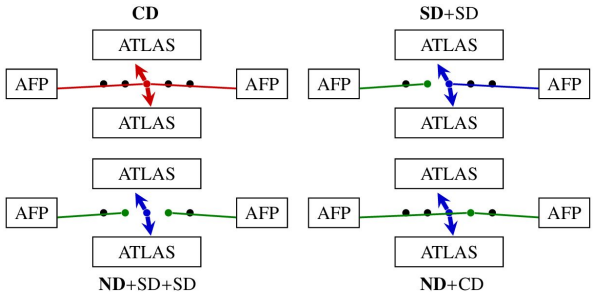


Time-of-Flight (ToF)

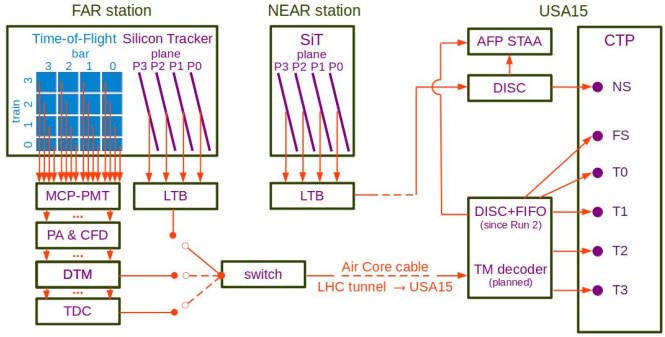




- Suppression of combinatorial background
- 16 quartz bars grouped in 4 trains
- Train/bar widths are 3 mm, 3 mm, 5 mm, 5.5 mm
- Directing light to Micro-Channel Plate Photo-Multiplier Tube (MCP-PMT)
- Amplified by 3-stages of Pulse Amplifiers (PAa and PAbc)
- Processed by Constant Fraction Discriminator (CFD)
- Passed through Digital Trigger Module (DTM)
- Processed by High-Performance Time-to-Digital Converter (HPTDC)
- Double PAbc, CFD, and HPTDC; each for 2 trains



Trigger

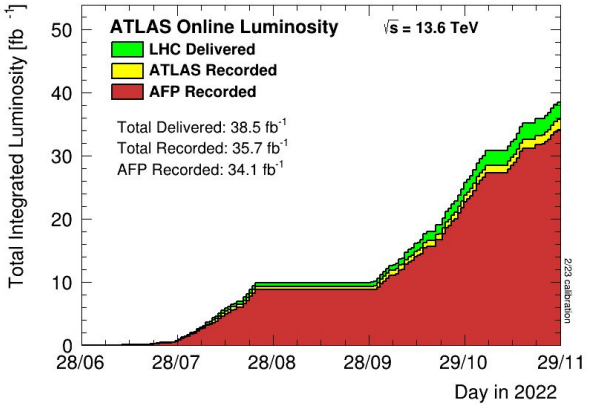


- SiT trigger signal sent by Local Trigger Board (LTB)
  - Standardly, requires signal from at least 3 planes
  - Can be reprogrammed to different logic
  - 400 ns deadtime
- ToF trigger signal sent by Digital Trigger Module (DTM) and Time-to-Digital Converter (TDC)
  - Requires signal from at least N bars in a train
- Far stations can trigger either on SiT or ToF
- Passed to ATLAS cavern (USA15) by ultra-fast Air Core cables
  - To arrive in time to trigger the "central" detector
- Far station signal connected to 5 Central Trigger Processor (CTP) inputs
  - 1 SiT and 1 for each ToF train
- Different latency for SiT and ToF triggers
  - Dedicated timing-in campaigns

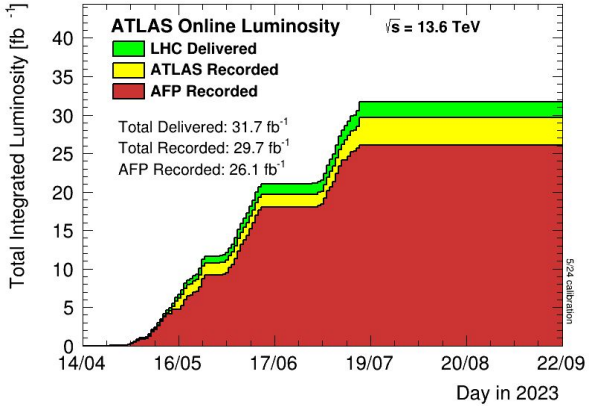
LHC Run-3 data-taking

Total in LHC Run-3 so far:
AFP recorded: 84.4 fb^{-1}
89.7 % wrt. ATLAS recorded
83.8 % wrt. LHC delivered

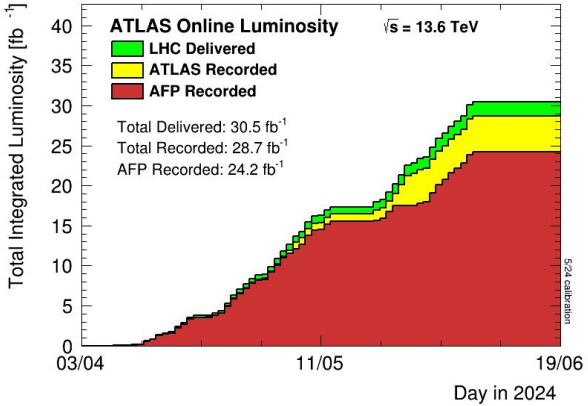
2022 at $\sqrt{s}$=13.6 TeV
AFP recorded: 34.1 fb^{-1}
95.5 % wrt. ATLAS recorded
88.6 % wrt. LHC delivered



2023 at $\sqrt{s}$=13.6 TeV
Recorded: 26.1 fb^{-1}
87.9 % wrt. ATLAS recorded
82.3 % wrt. LHC delivered



First half of 2024 at $\sqrt{s}$=13.6 TeV
Recorded: 24.2 fb^{-1}
84.3 % wrt. ATLAS recorded
79.3 % wrt. LHC delivered



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

New control systems in LHC Run-3

Data Quality

- Evaluate usability for physics analysis
  - AFP participating in data-taking
  - AFP in physics position
  - Enough SiT planes working
  - All ToF parts working

Automatic Recovery

- Reconfiguration of modules
- Scheduling of next reconfiguration attempts after failed attempt
- Optional power-cycle after several failed attempts

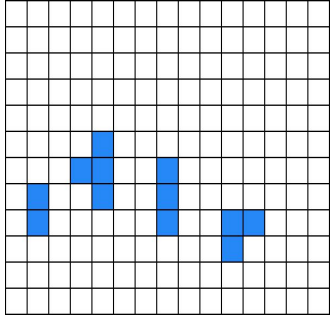
Improved online monitoring

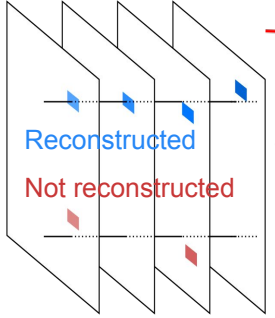
- Lots of new histograms
- Increased statistics

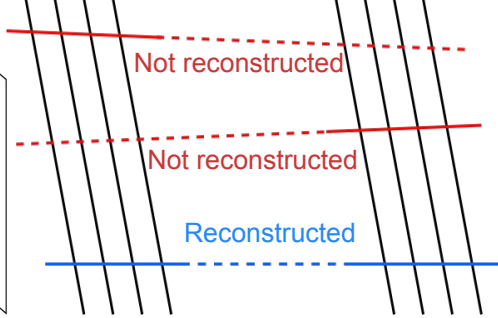
Mattermost Bot

- Sending messages about AFP state
- Sending warnings about issues which need to be acted on

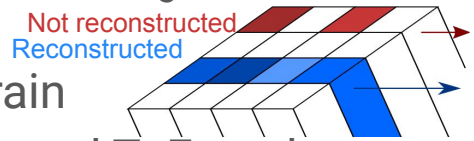
“Proton” Reconstruction

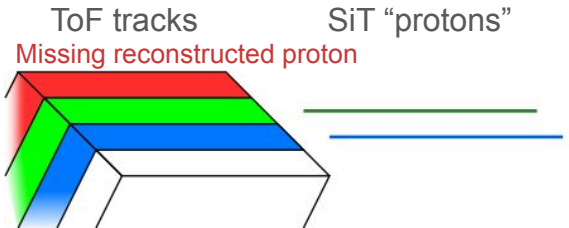


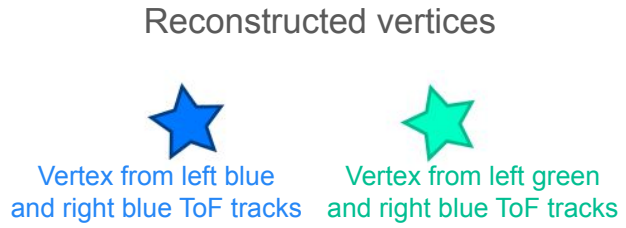


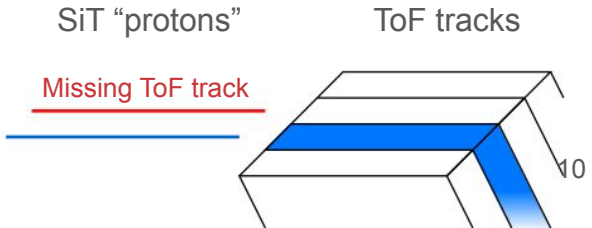


- Starting with SiT and ToF hits
- SiT cluster reconstruction by grouping of adjacent SiT hits
- SiT track reconstruction using Kalman Filter with clusters on the input
- Proton reconstruction by combining SiT tracks from Near and Far stations
  - Knowledge of the LHC magnetic field, the proton position, and the elevation angle allows for reconstruction of the proton kinematics (energy and momentum)
- ToF track reconstruction by grouping ToF hits in a single train
- Vertex reconstruction by combining reconstructed protons and ToF tracks from each side









Data Quality results

Fraction of good luminosity after Data Quality wrt. ATLAS:

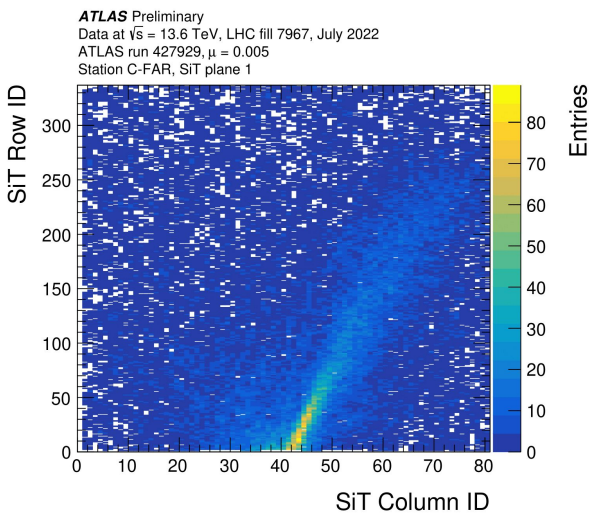
	2022*	2023** preliminary
All of AFP	83.4 %	76.4 %
Silicon Tracker only	92.5 %	81.4 %
A side Silicon Tracker only	96.8 %	84.5 %
C side Silicon Tracker only	93.7 %	82.1 %
Time-of-Flight only	83.6 %	77.7 %

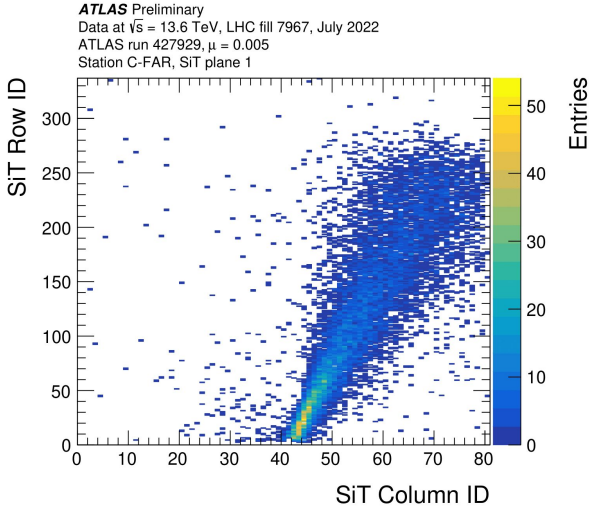
*based on Good Run List for analyses relying on jet, met or b-jet triggers (data22_13p6TeV.periodAllYear_DetStatus-v109-pro28-04_MERGED_PHYS_StandardGRL_All_Good_25ns)

**based on Good Run List for analyses relying on jet triggers at L1 or HLT (data23_13p6TeV.periodAllYear_DetStatus-v110-pro31-06_MERGED_PHYS_StandardGRL_All_Good_25ns)

SiT Hit Map

- First 1.5M events of run 427929 (LBs 200-206)
- Top: Raw distribution of hits in a single SiT plane
- Bottom: Effect of signal cleaning
  - Single track reconstructed per station
  - Single cluster reconstructed per plane
  - Only 1 or 2 hits recorded per plane
- “Diffractive pattern”
  - Caused by settings of LHC magnet between ATLAS interaction point and AFP detectors

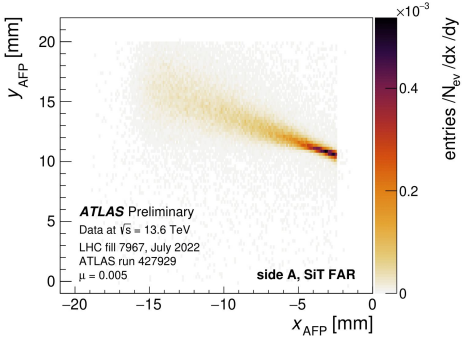


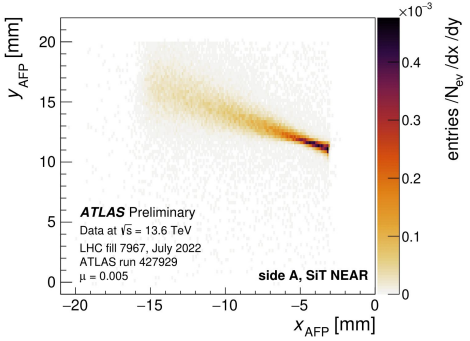


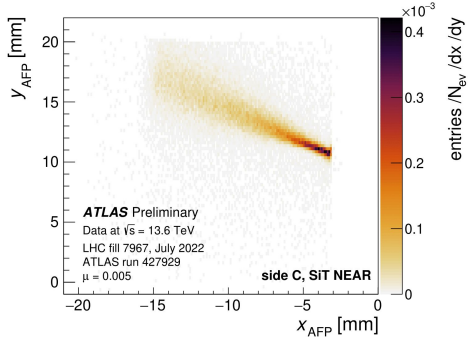
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults

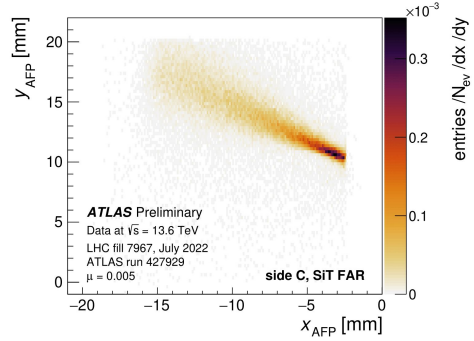
SiT Track Map

- Distribution of reconstructed tracks
- Center of beam pipe at (0, 10 mm)
- Selection:
  - Events triggered by Minimum-Bias Trigger Scintillators (MBTS)
  - Reconstructed primary vertex
  - Single track in each station on a given side
- Expected relation of scattered proton's x-position in SiT to energy lost in the interaction
  - Due to LHC magnetic field









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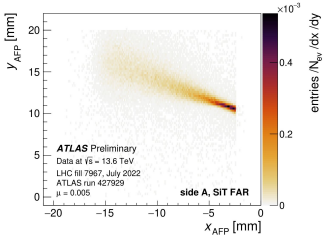
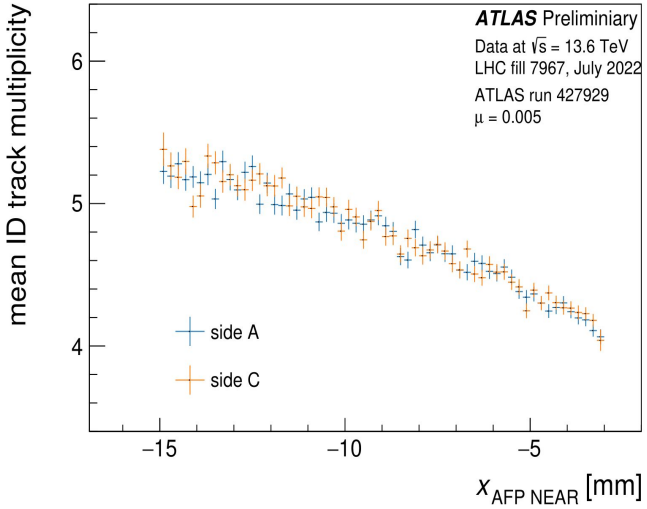
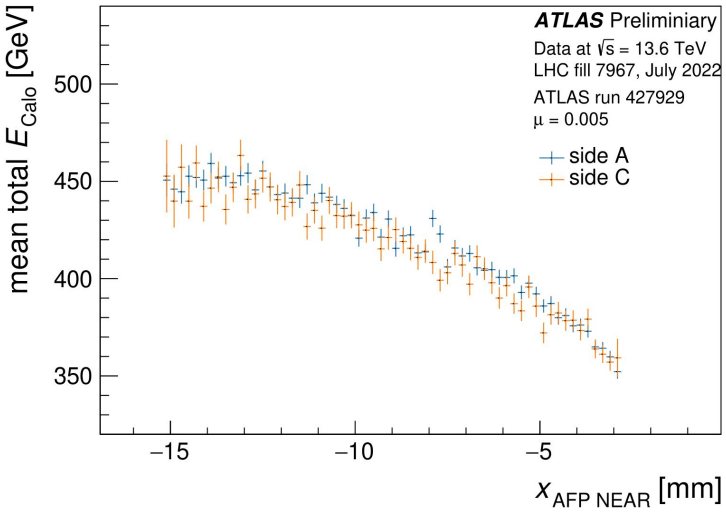
Correlation to ATLAS



- Correlation of track x-position to charged track multiplicity of the Inner Detector (ID)
- Selection:
  - Single AFP track in each station on given side
  - ID track p_T > 500 MeV
  - ID track |η| < 2.5
  - Reconstructed primary vertex



- Correlation of track x-position to total energy measured by ATLAS Calorimeters
- Selection:
  - Only one AFP track in each station on given side
  - Reconstructed primary vertex



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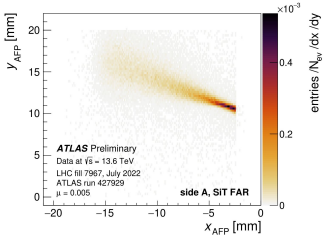
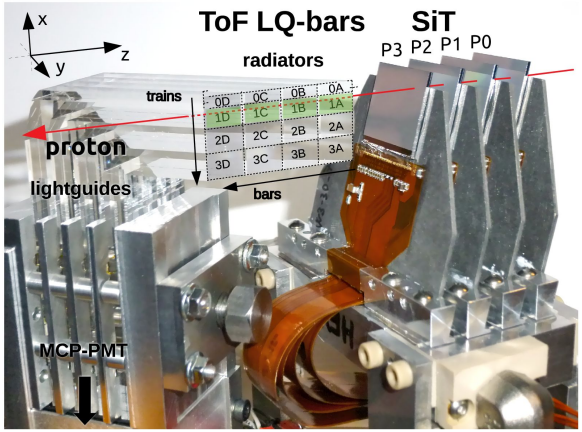
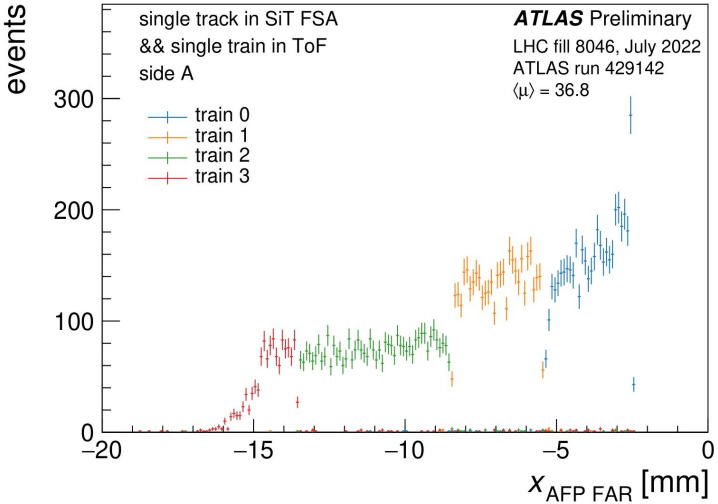
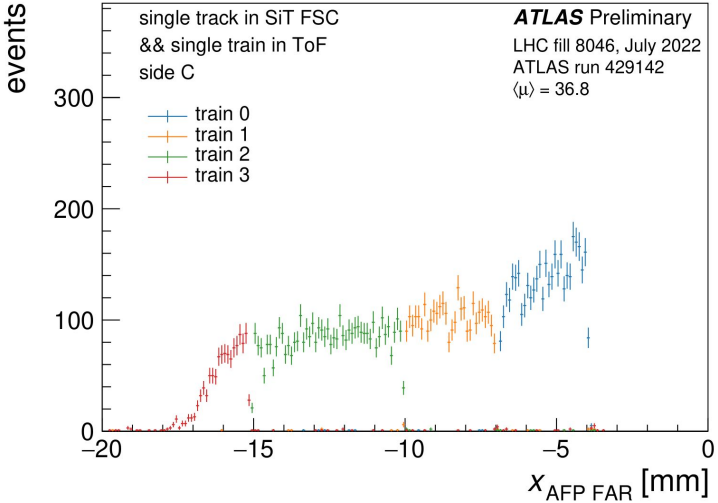
ToF-SiT alignment



- Correlation of SiT track x-position to ToF train signal
- Selection:
  - Single SiT track in the station
  - Single ToF train signal in the station



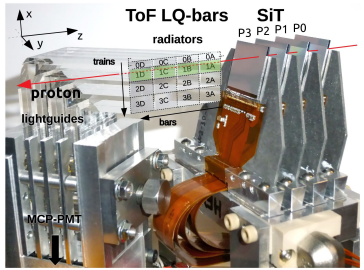


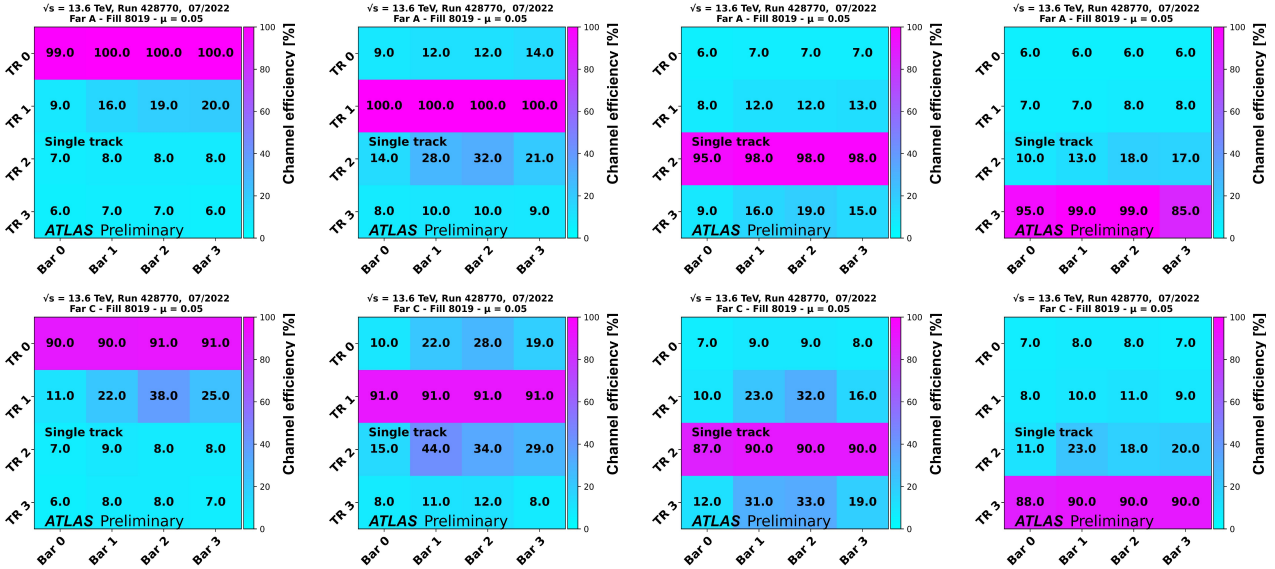


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults

ToF Efficiency

- Probability of getting hit in the ToF detector during the low-μ run in July 2022
- Tag and Probe method
- Tagged by SiT
- Single track only
- Selection:
  - Single SiT track in the station





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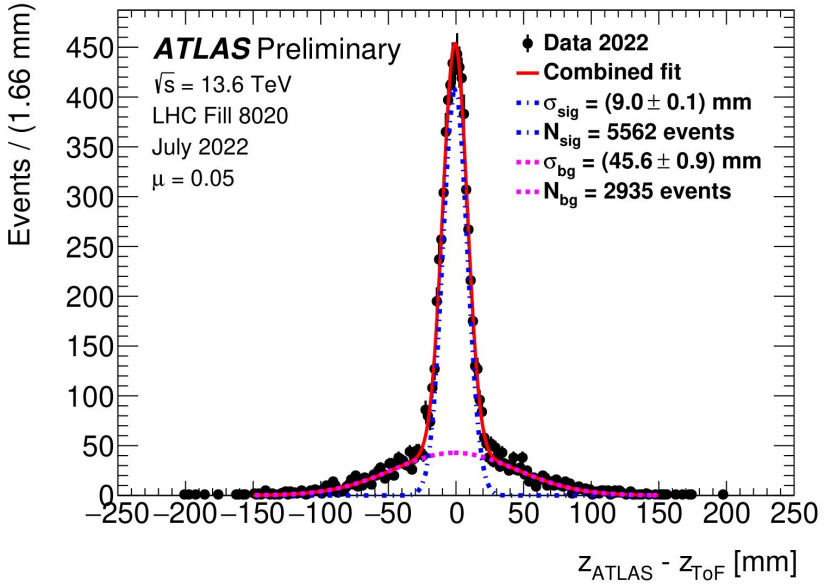
ToF Vertex Matching

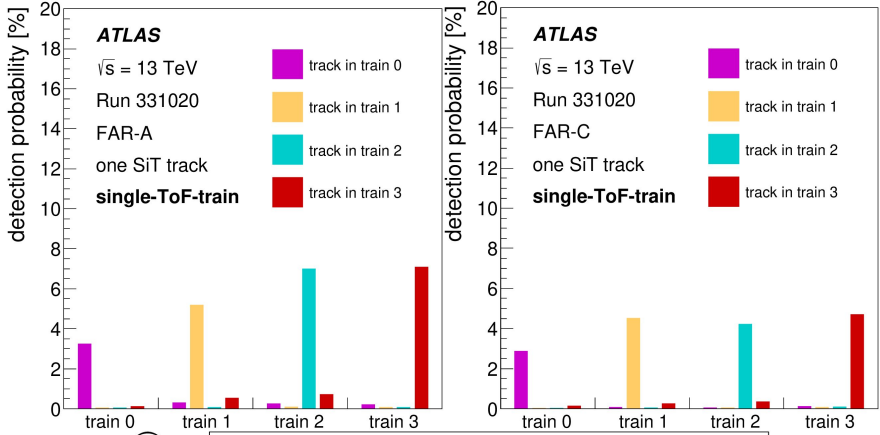
- Difference between longitudinal vertex position measured with AFP ToF and ATLAS Inner Detector (ID) measured during μ=0.05 run taken in July 2022
- Resolution 9.0 ± 0.1 mm (30 ps)
- Small initial background contribution wrt. signal
  - Low pile-up data-taking conditions
- Visible advantage of ToF information use
  - Much smaller difference in vertex position in case of signal
- Selection:
  - Primary vertex in ATLAS ID
  - Single AFP ToF train signal in each far station
  - Maximum of one hit in each ToF channel
  - Single track in AFP SiT in each far station
  - SiT track position matching the ToF train position

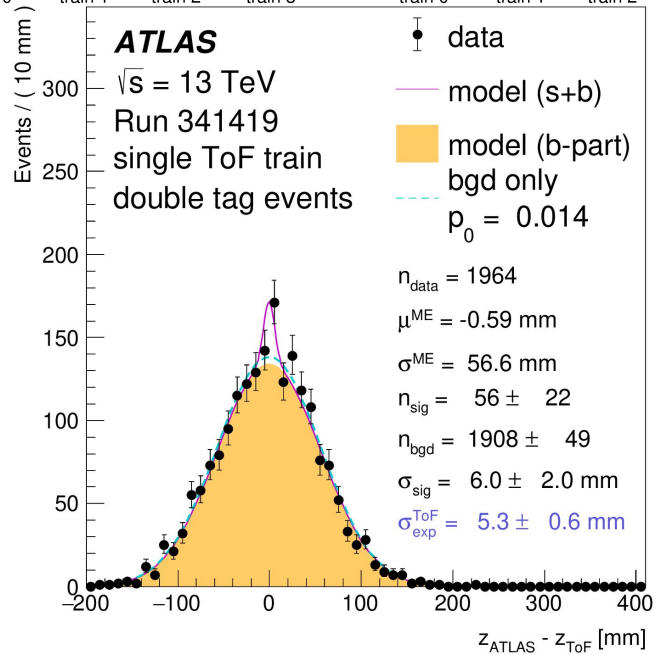


https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ForwardDetPublicResults

ToF Performance in LHC Run-2

- This year's publication
  [JINST 19 (2024) P05054]
- Full-train efficiency of ~4-6 %
- "While low efficiencies are observed,
  of the order of a few percent,
  the resolutions of the two ToF detectors
  measured individually are 21 ps and 28 ps"
- Resolution of 6.0 ± 2.0 mm





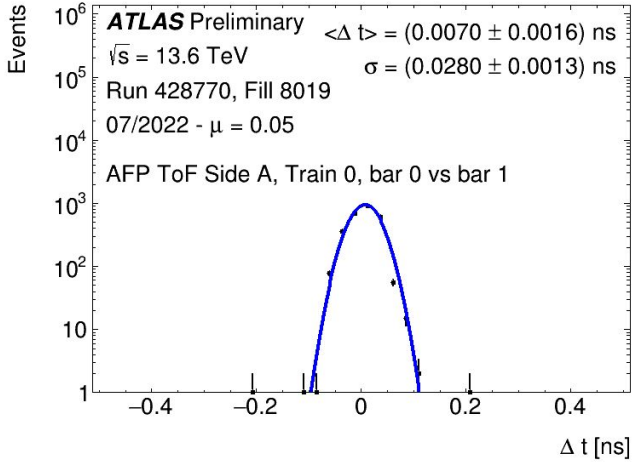
Summary

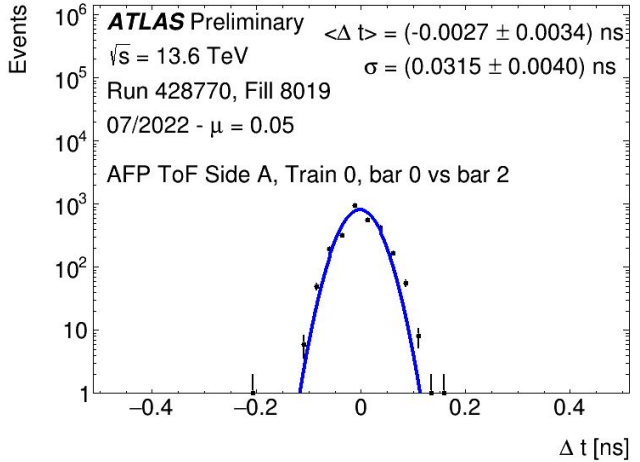
- Diverse physics programme possible with AFP - enhancement of ATLAS measurement capabilities:
  - Measurements of Standard Model processes, like diffractive and exclusive jets or exclusive leptons
  - Searches for a New Physics, like Anomalous Gauge Couplings, axion-like particles or SUSY Dark Matter.
- Promising, high performance of SiT detectors. Good efficiency and timing reconstruction resolution of ToF detectors in the low-μ campaigns.
- Efficient data-taking during the high-μ campaigns as well as during special, low-μ runs:
  - AFP team bigger and younger than in Run 2
  - Continues work to improve data-taking efficiency
  - Data analyses ongoing
- Two analyses published, more is expected in the near future:
  - Diphoton resonance search with AFP tag, JHEP 07 (2023) 234 (2009.14537)
  - Observation of forward proton scattering in association with lepton pairs produced in photon fusion, Phys. Rev. Lett. 125 (2020) 261801 (2304.10953)
- AFP ToF Performance in LHC Run-2, JINST 19 (2024) P05054

Backup

ToF Resolution Indication

- Time difference between two channels of the same ToF train
- Selection:
  - Single SiT track in the station
  - SiT track pointing to the given ToF train
  - Single ToF train signal in the station





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