First Tracking Performance Results from the ATLAS Fast TracKer (FTK)

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Overview

- **ATLAS Fast TracKer (FTK)** is a custom electronics system that performs **fast tracking** with **Associative Memory ASICs & FPGAs,** for use in **trigger decisions**
- Installation and commissioning in ATLAS is underway ⟶ **targeting Run 3 physics**
- In 2018, two FTK vertical *Slices* covering η-ϕ *Towers* were installed and tracks were collected → **assess and optimize tracking performance** and **validate firmware**
- These slides present **first tracking performance results from FTK Slice data**, as well as **expectations for full FTK system** based on simulation

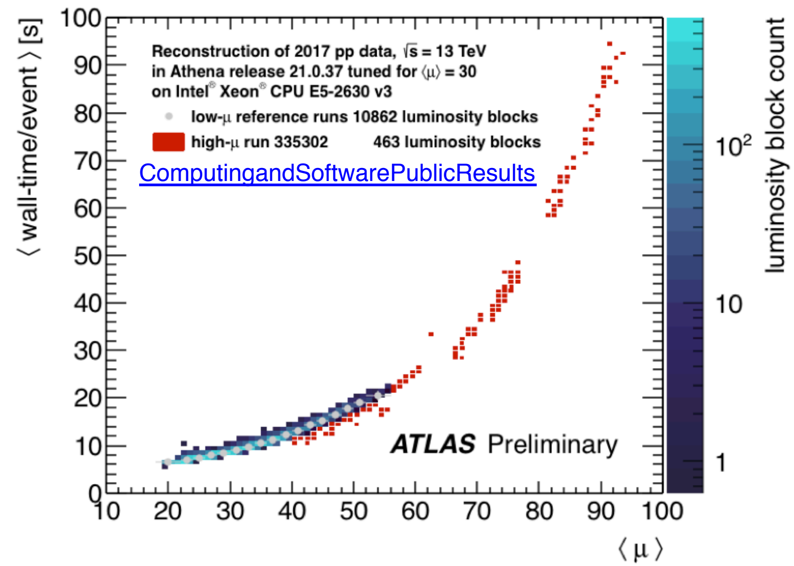
Motivation: Triggering on Tracks

- Dense environment in proton-proton collisions due to **pile-up interactions:**

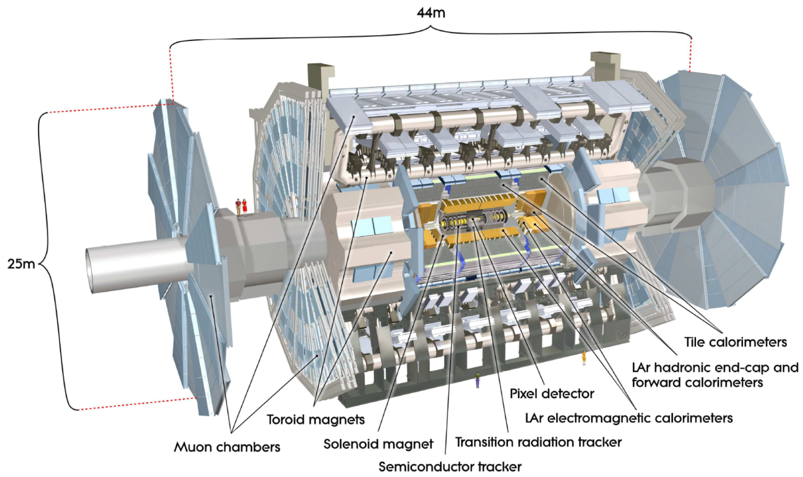
- Reconstructing **tracks** allows to determine the positions of the pile-up interactions and remove particles originating from them

- Software full-event tracking too slow for trigger
  - Level-1 (hardware) trigger accept rate ~ 100 kHz and latency constraint ~ 100 μs

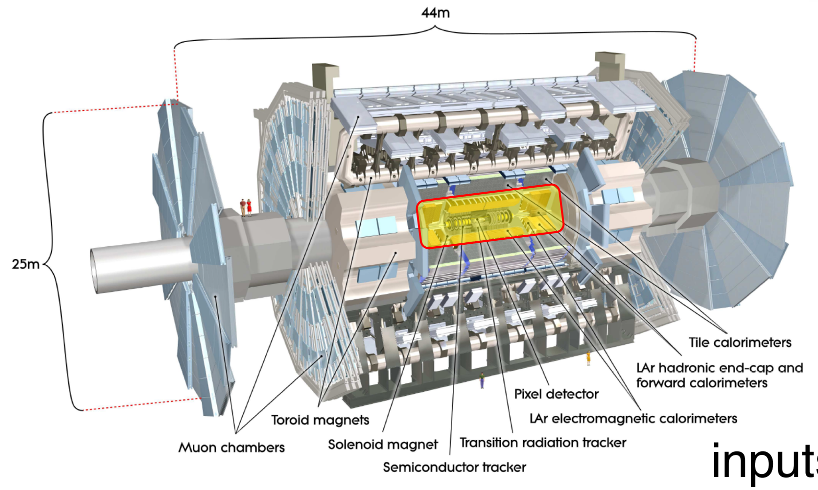
- **Hardware-based solution is needed for full-event tracking in the trigger → FTK**



The ATLAS Detector



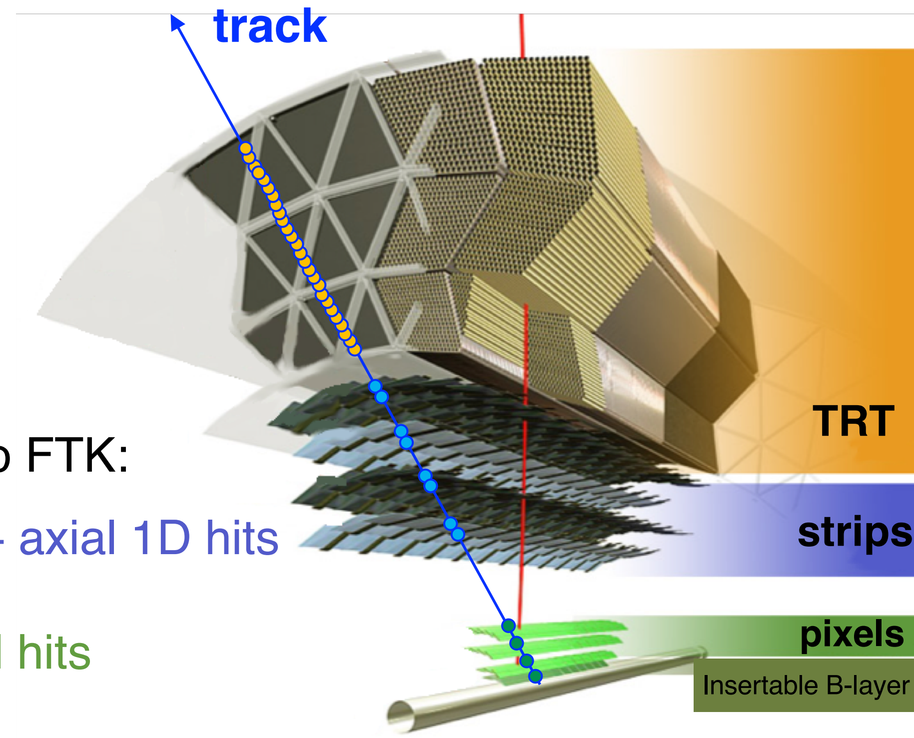
The ATLAS Tracker



inputs to FTK:

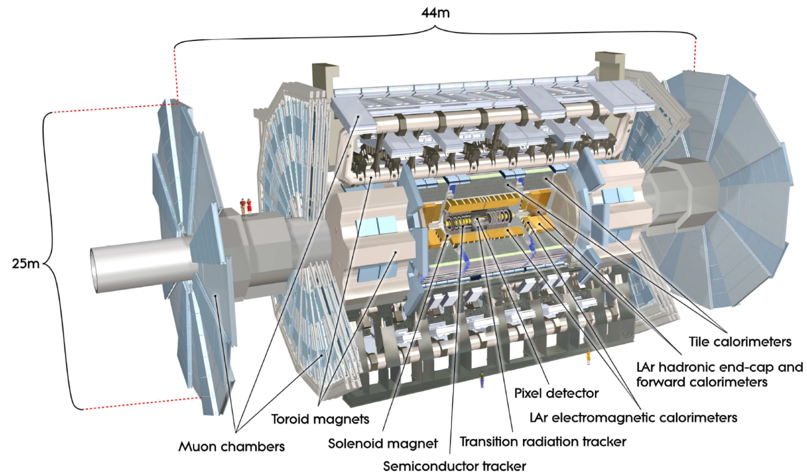
stereo + axial 1D hits

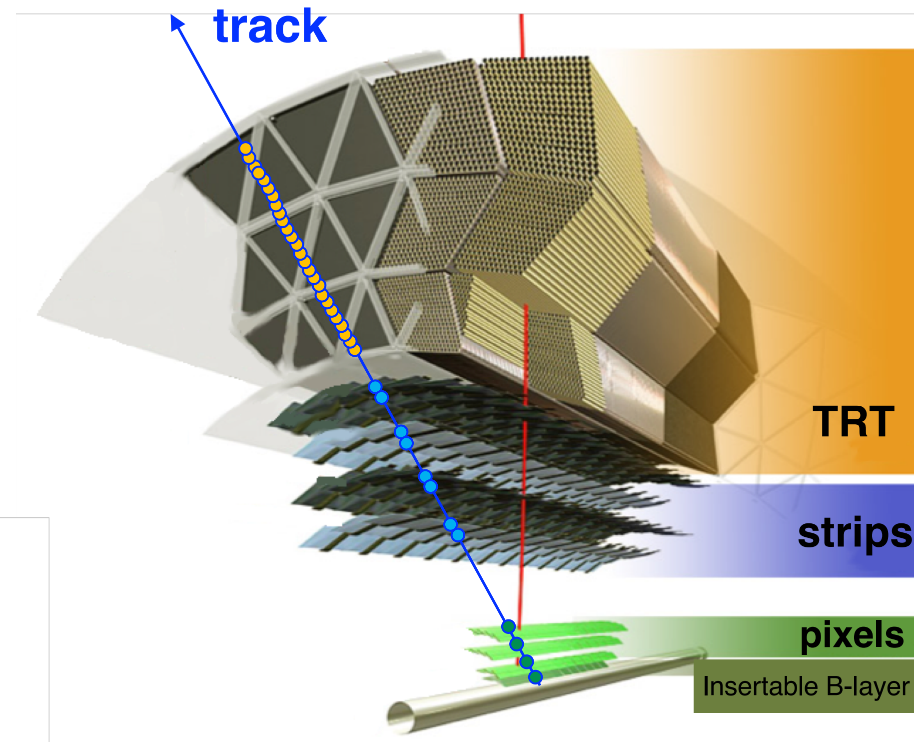
2D pixel hits

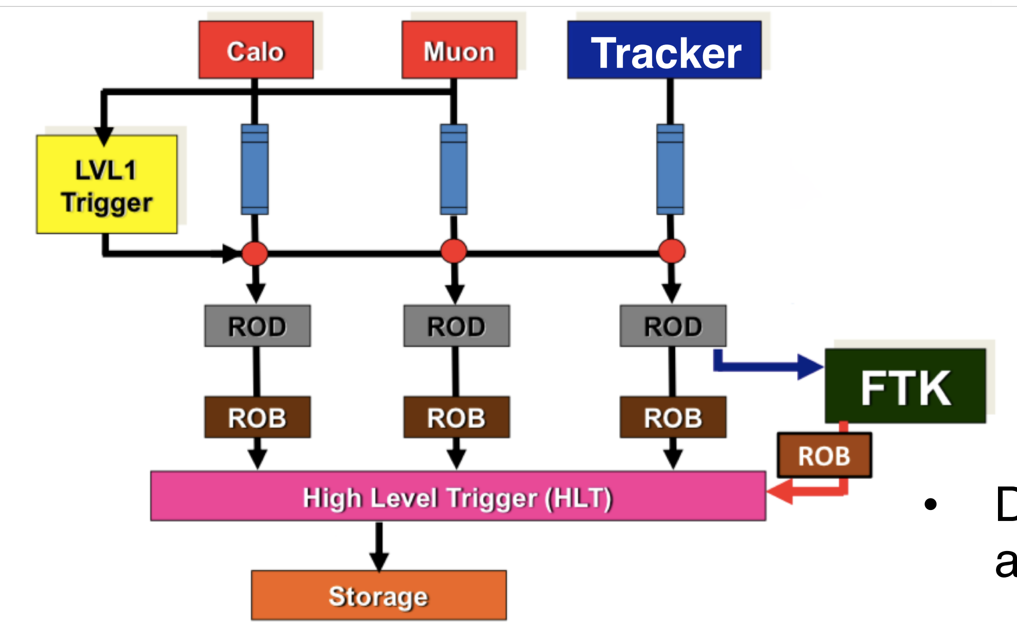


- ~100M **pixel** and **strip** electronic readout channels

Trigger and Data Acquisition (TDAQ)

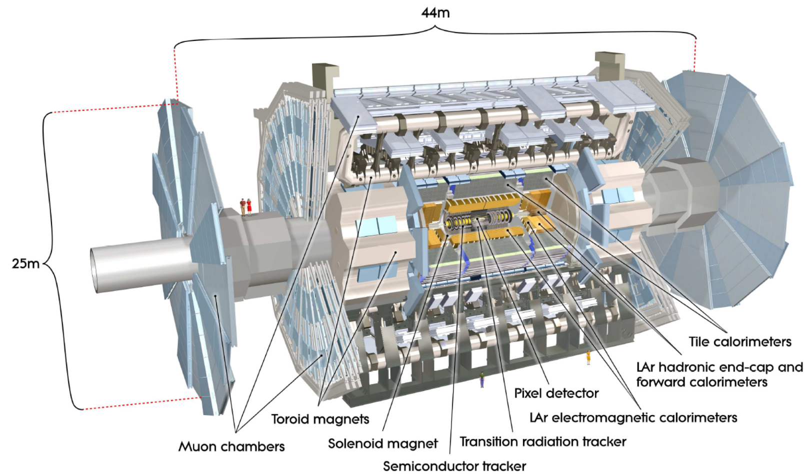


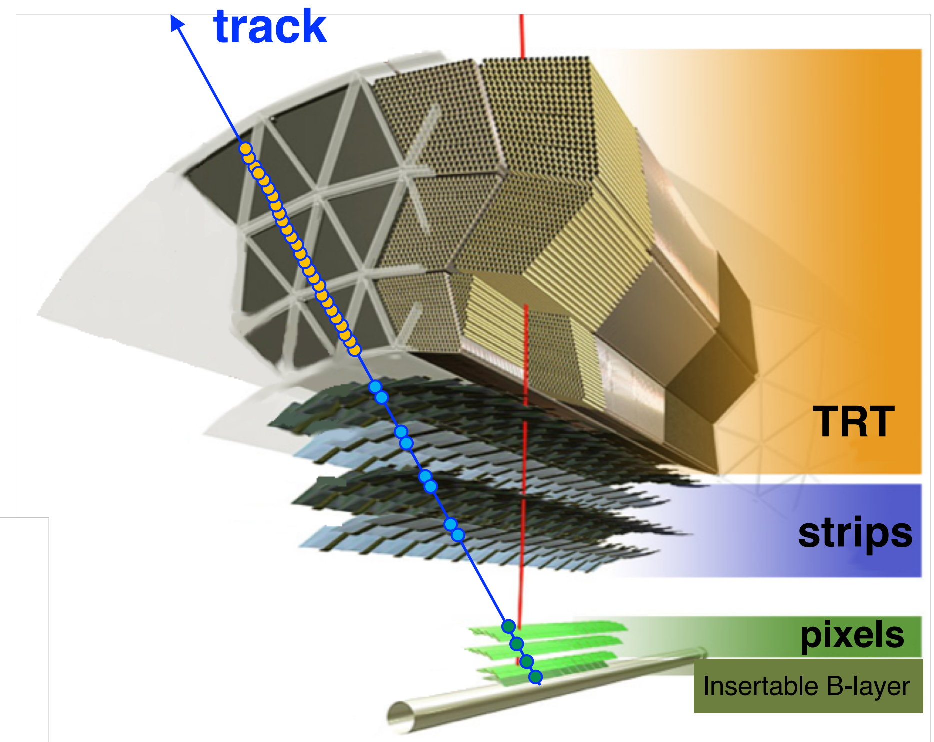


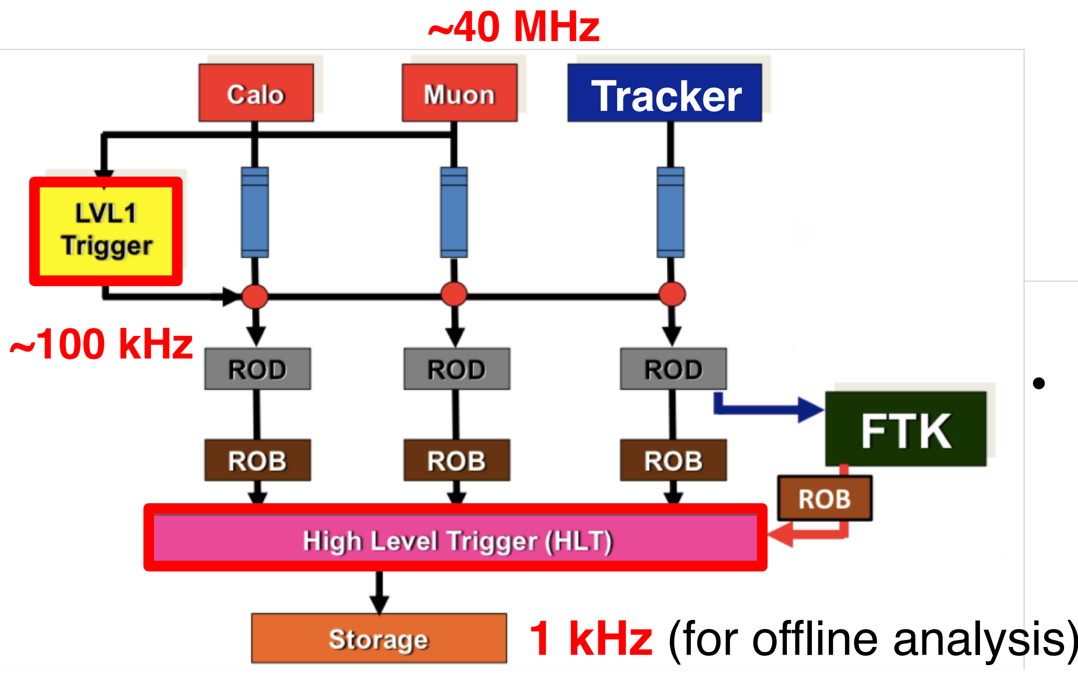


- Data from **calorimeters**, **muon detector**, and **tracker** is sent to TDAQ system

Tracking in TDAQ System

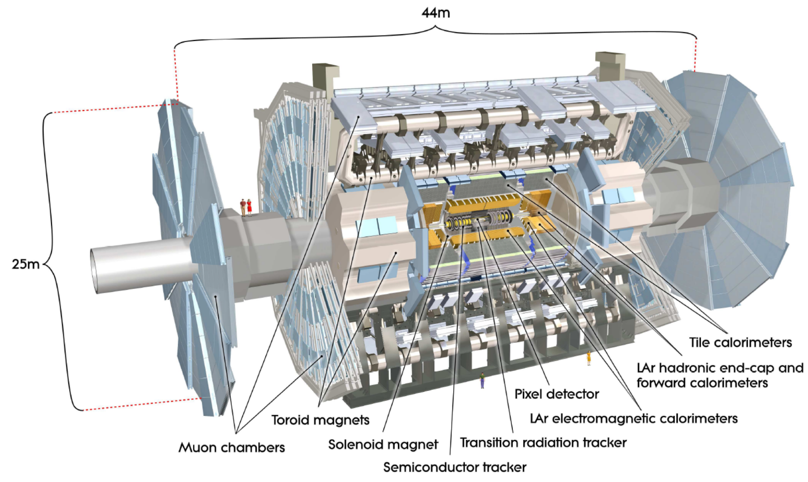


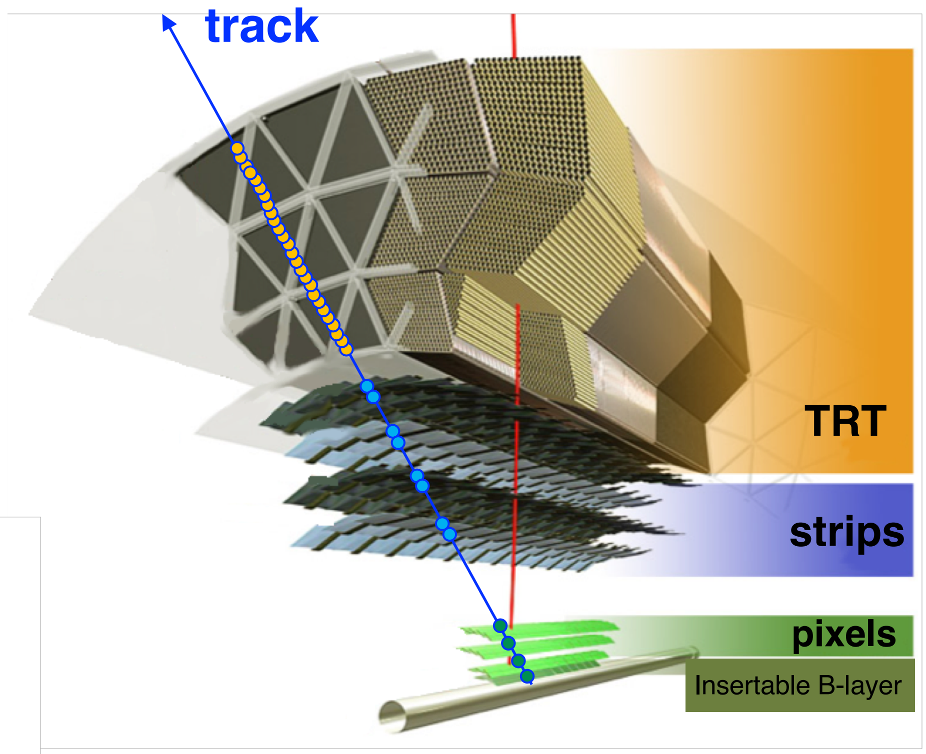


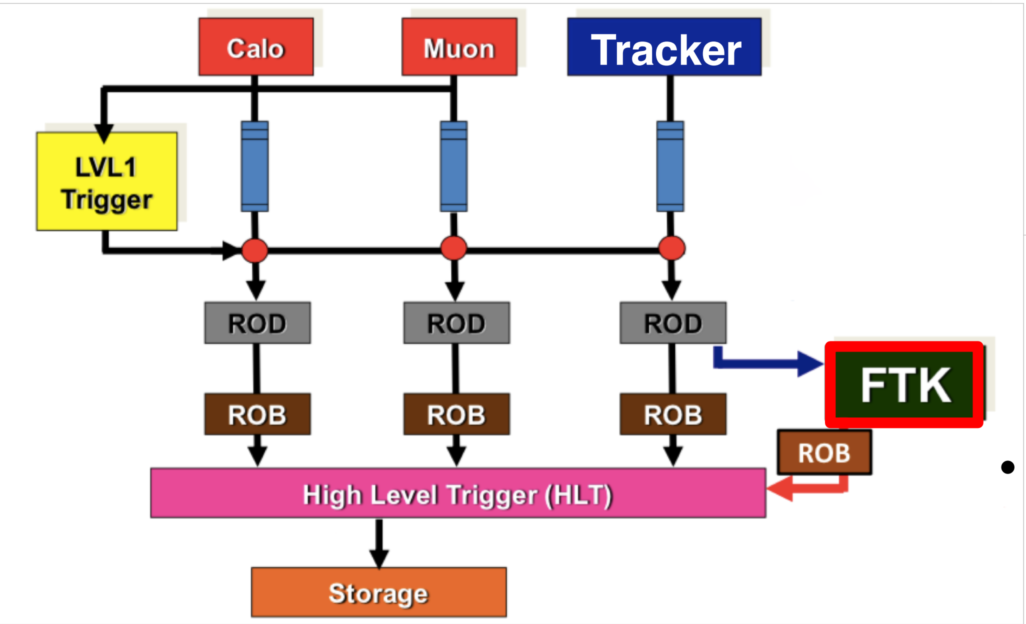


- **2-tiered trigger system:**
  - Level-1 (hardware): no tracking
  - HLT (software): tracking only in Regions-of-Interest (ROI)

The Fast TracKer (FTK)

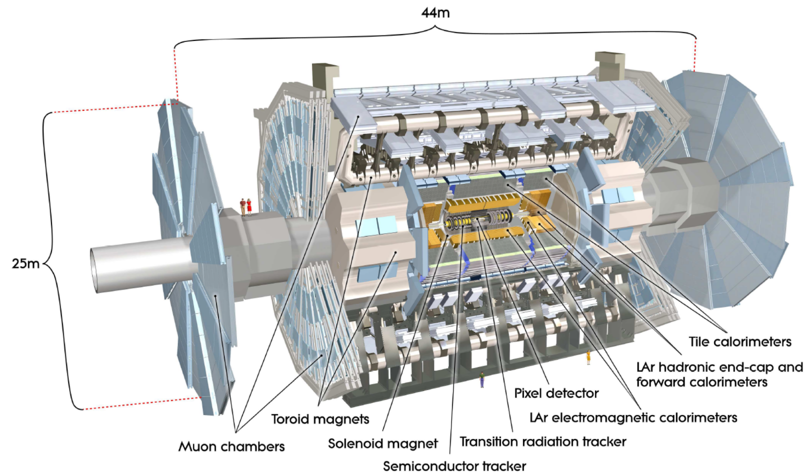


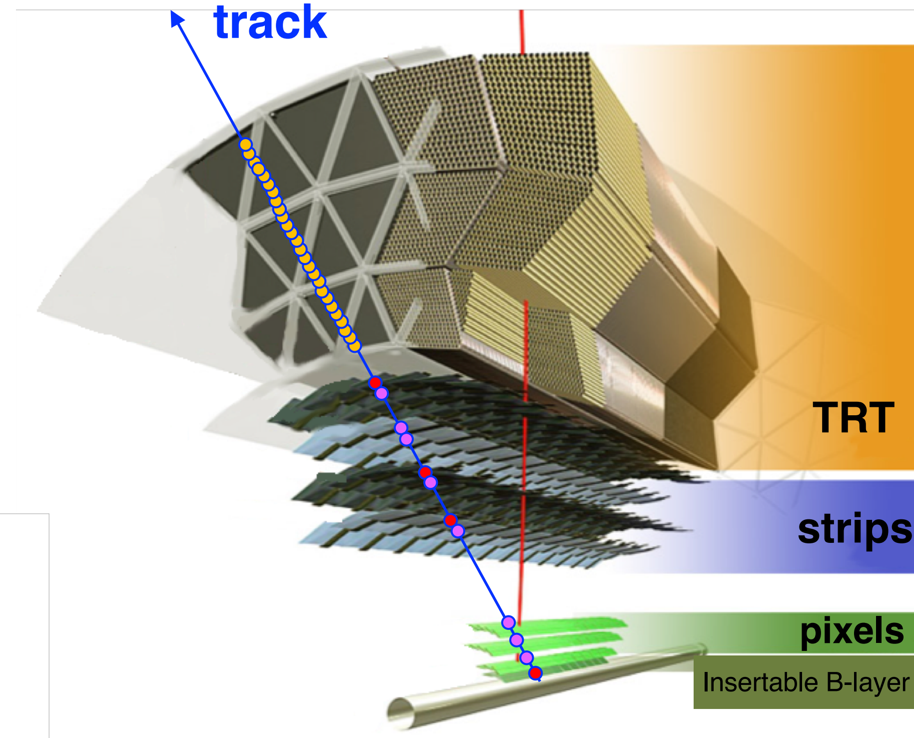


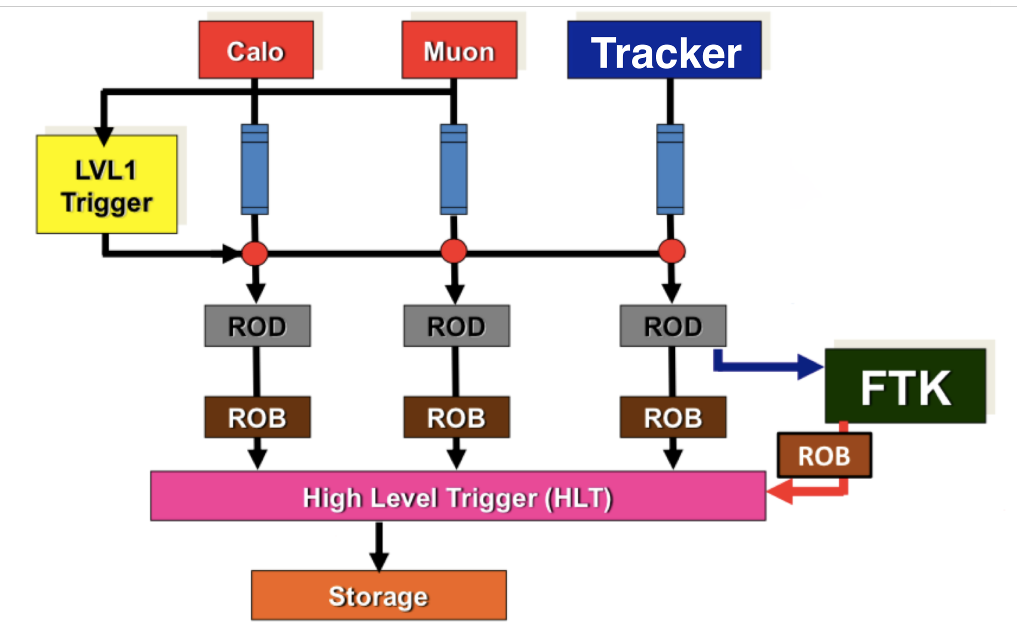


- FTK uses AM chips and FPGAs to reconstruct tracks with **p_T > 1 GeV** over **full detector**

2-stage Tracking



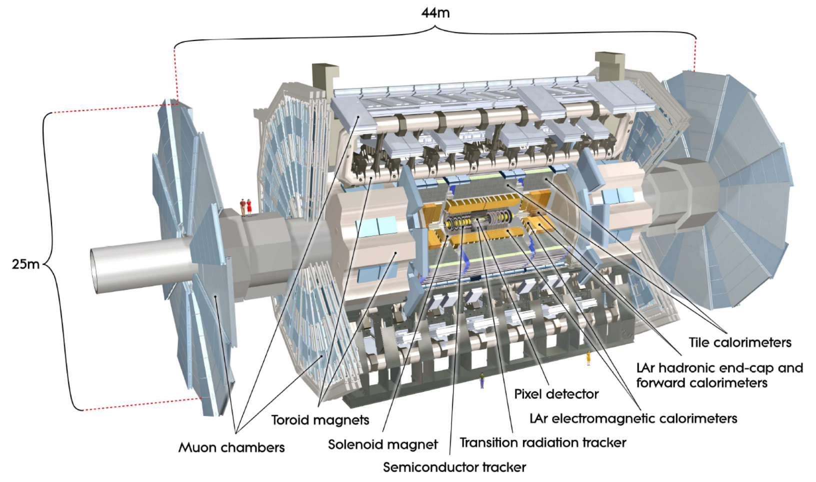


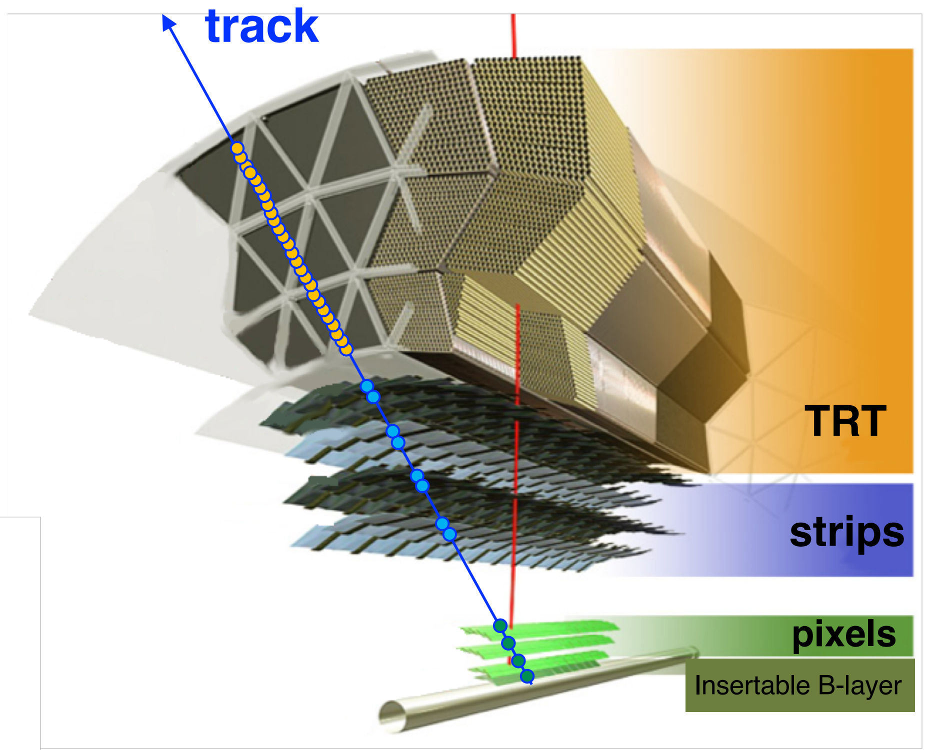


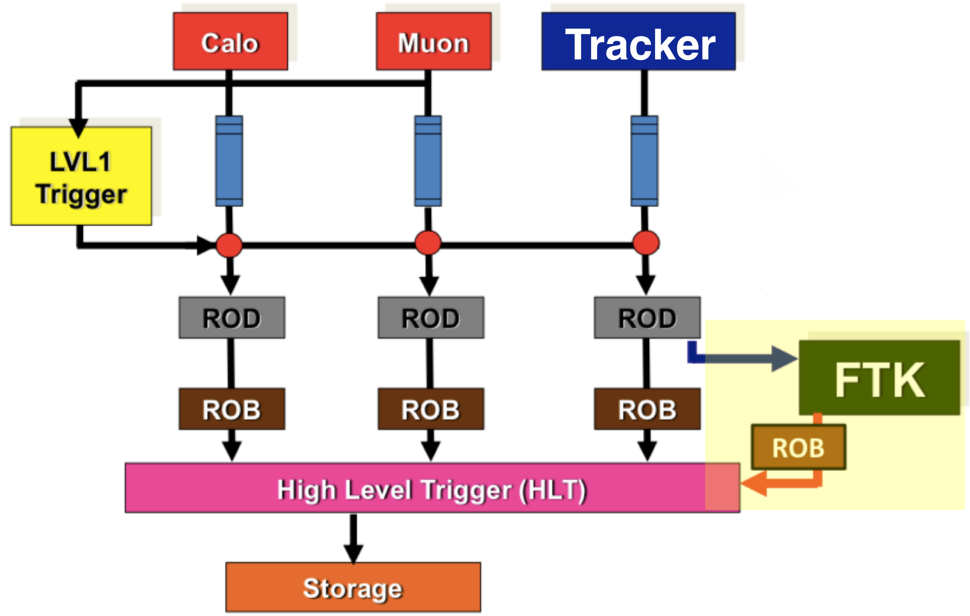
Tracking is performed in **two stages:**

- 1st stage considers 8 tracker *layers*
- 2nd stage extends 8-layer tracks to all 12 *layers*

FTK → High-Level Trigger

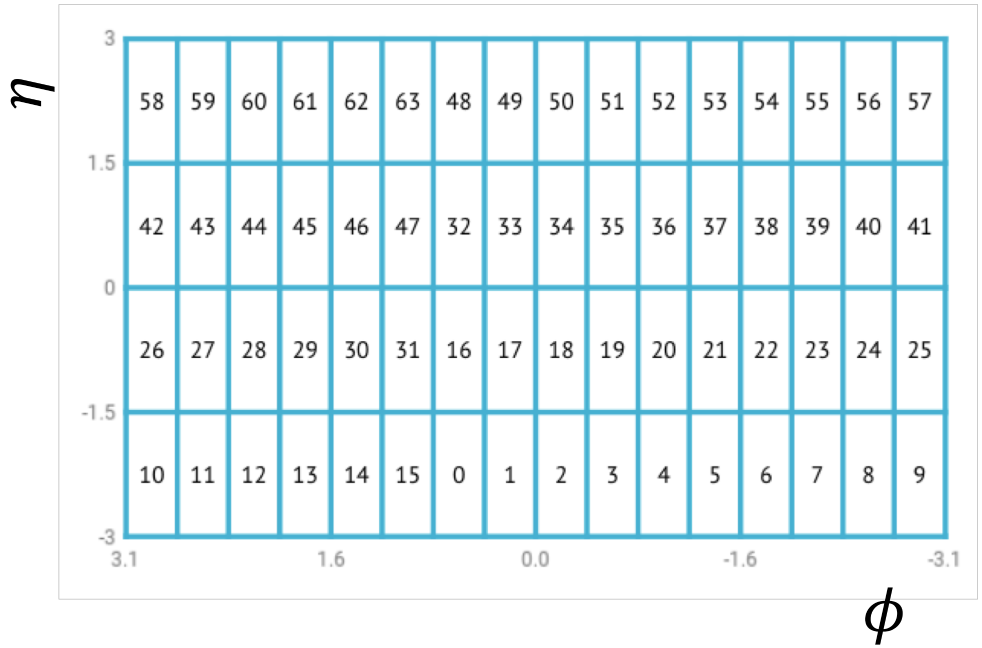






- FTK tracks provided at **start** of HLT
  - Use directly or refit quickly in HLT

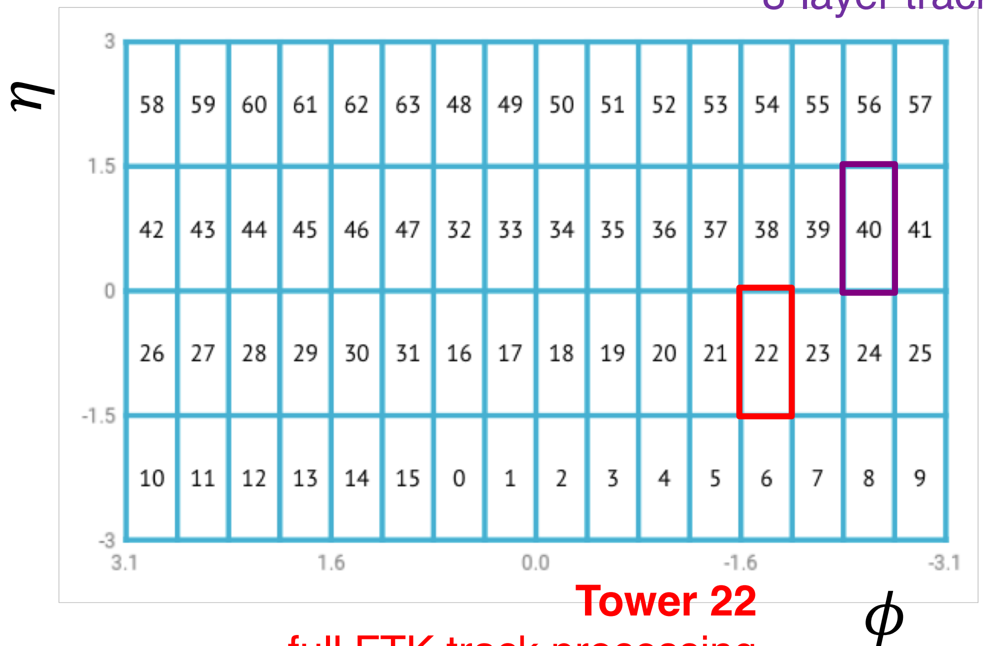
FTK Track Processing Strategy



- **Step 1) Parallelize:** FTK processing is performed simultaneously in 64 independent η-Φ “Towers”

FTK Track Processing Strategy

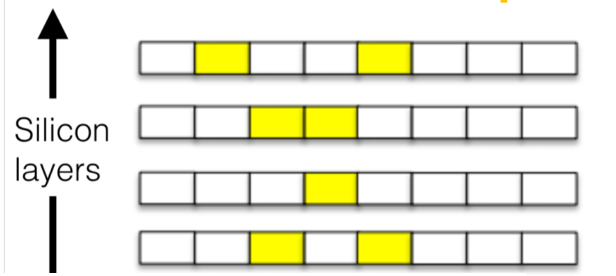
Tower 40
1st stage FTK track processing
8-layer tracks



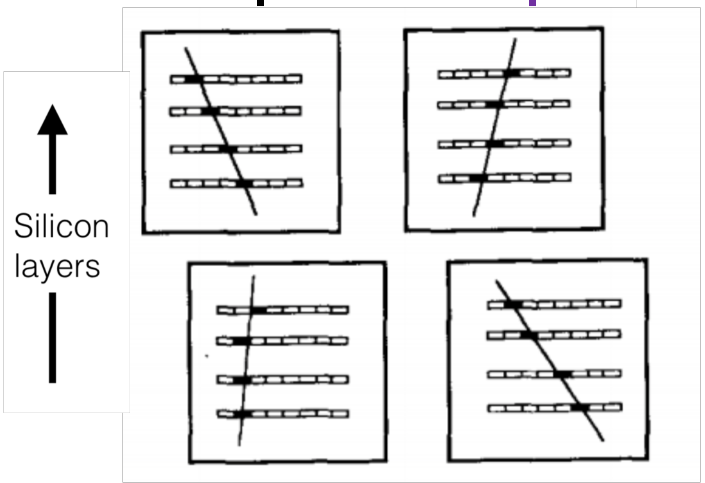
Tower 22
full FTK track processing
12-layer tracks

- **Step 1) Parallelize:** FTK processing is performed simultaneously in 64 independent η-Φ "Towers"
  - 2 towers were installed in 2018 → commission FTK with collisions data

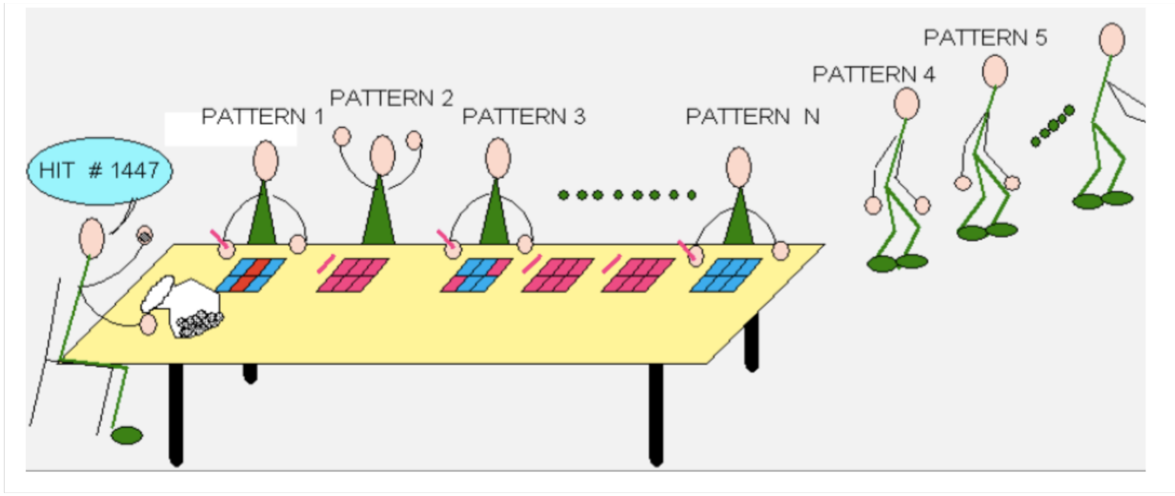
Coarse resolution superstrips



Pre-computed track patterns



Playing bingo with Associative Memory (AM) chips



- **Step 2) Track-finding**: pixel & strip hits are grouped into coarse ***superstrips*** and compared to ~1B pre-computed track ***patterns*** in AM **at the same time**
  - Patterns are trained using ~1B fully-simulated muons

FTK Track Processing Strategy

track parameters
(d0, z0, η, Φ, $1/p_T$, goodness-of-fit χ^2)

relative **hit positions**
in each layer

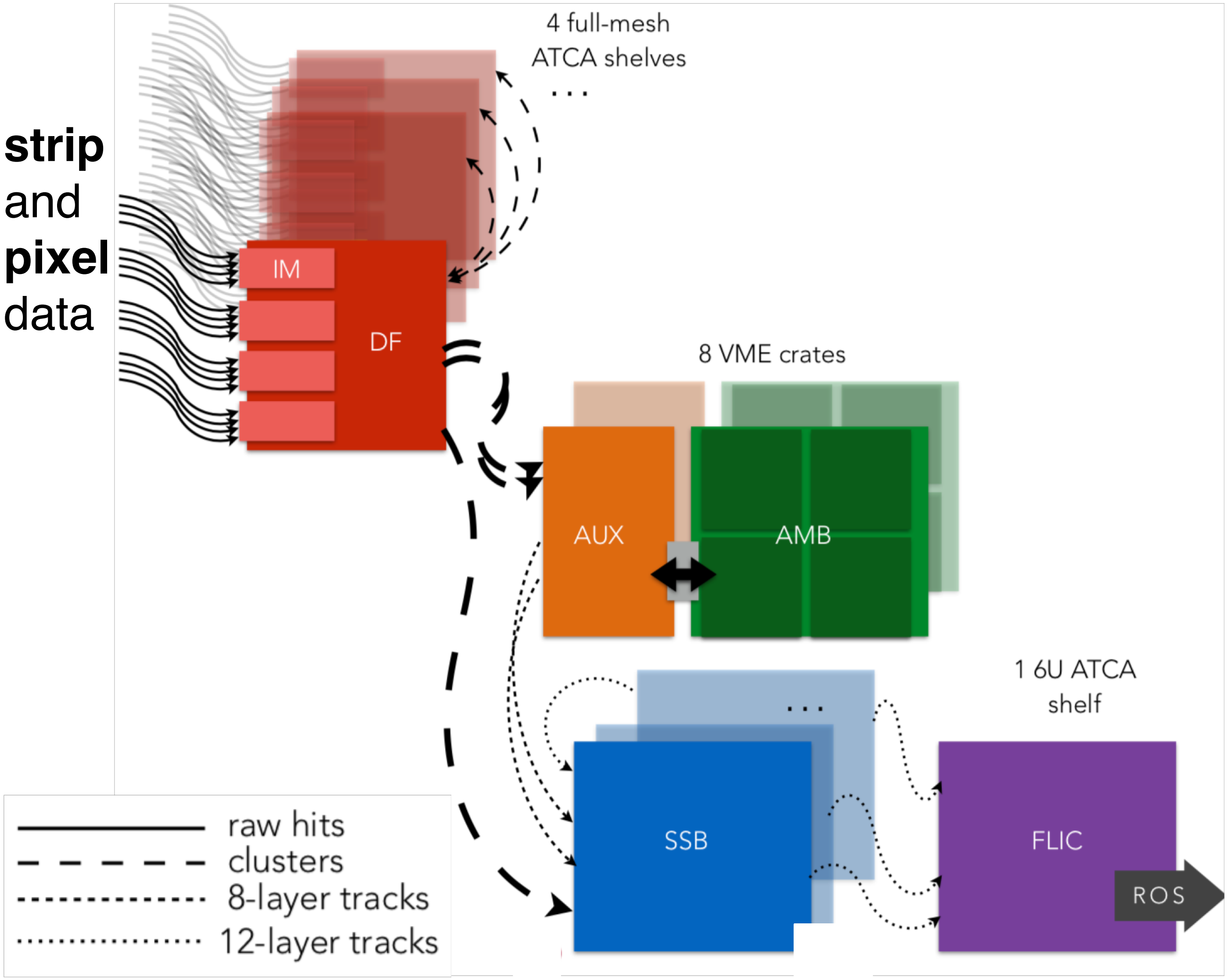
$$p_i = \sum_j C_{ij} \cdot x_j + q_i$$

fit constants

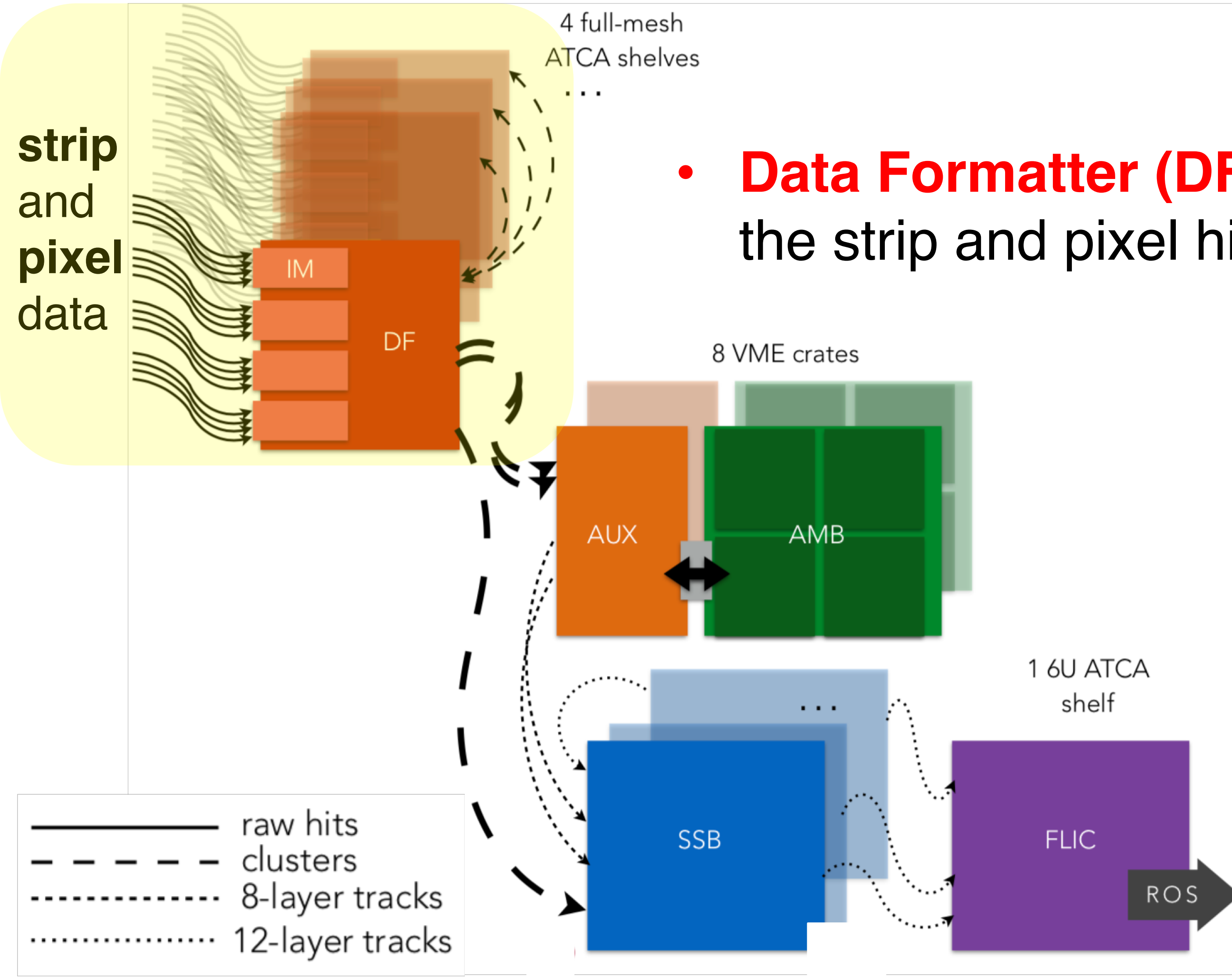
- **Step 3) Track-fitting: track parameters** are estimated from **hit positions** using a linear approximation to full helix fit
    - **Fit constants** for each ***sector*** (defined by set of ~1 cm^2 Silicon modules, one in each layer), evaluated from ~1B fully-simulated muons

The FTK Hardware

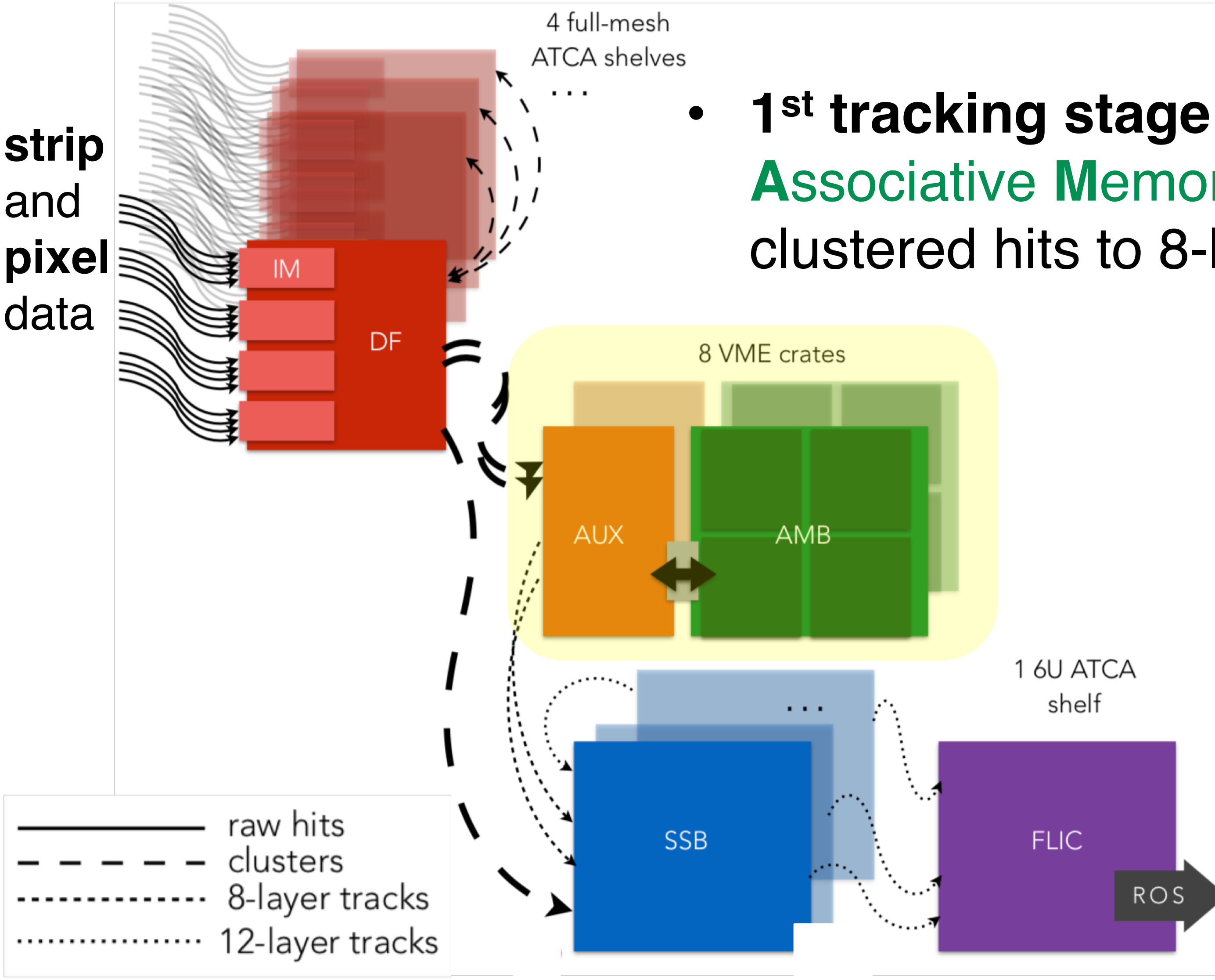
strip and **pixel** data



The FTK Hardware



- **Data Formatter (DF) board** clusters the strip and pixel hits from tracker

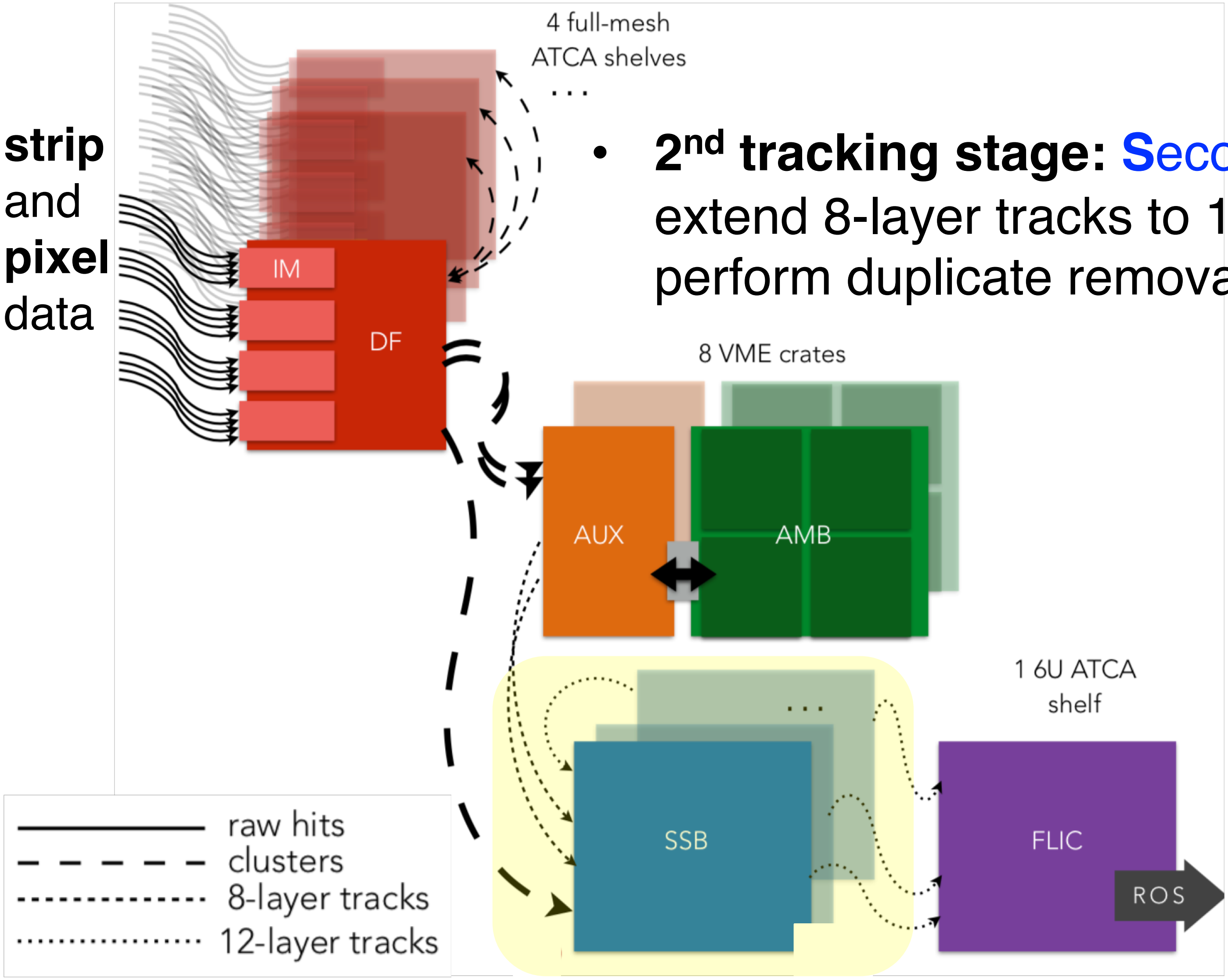


- **1st tracking stage: AUX** board uses **A**ssociative **M**emory chips to match clustered hits to 8-layer patterns

The FTK Hardware

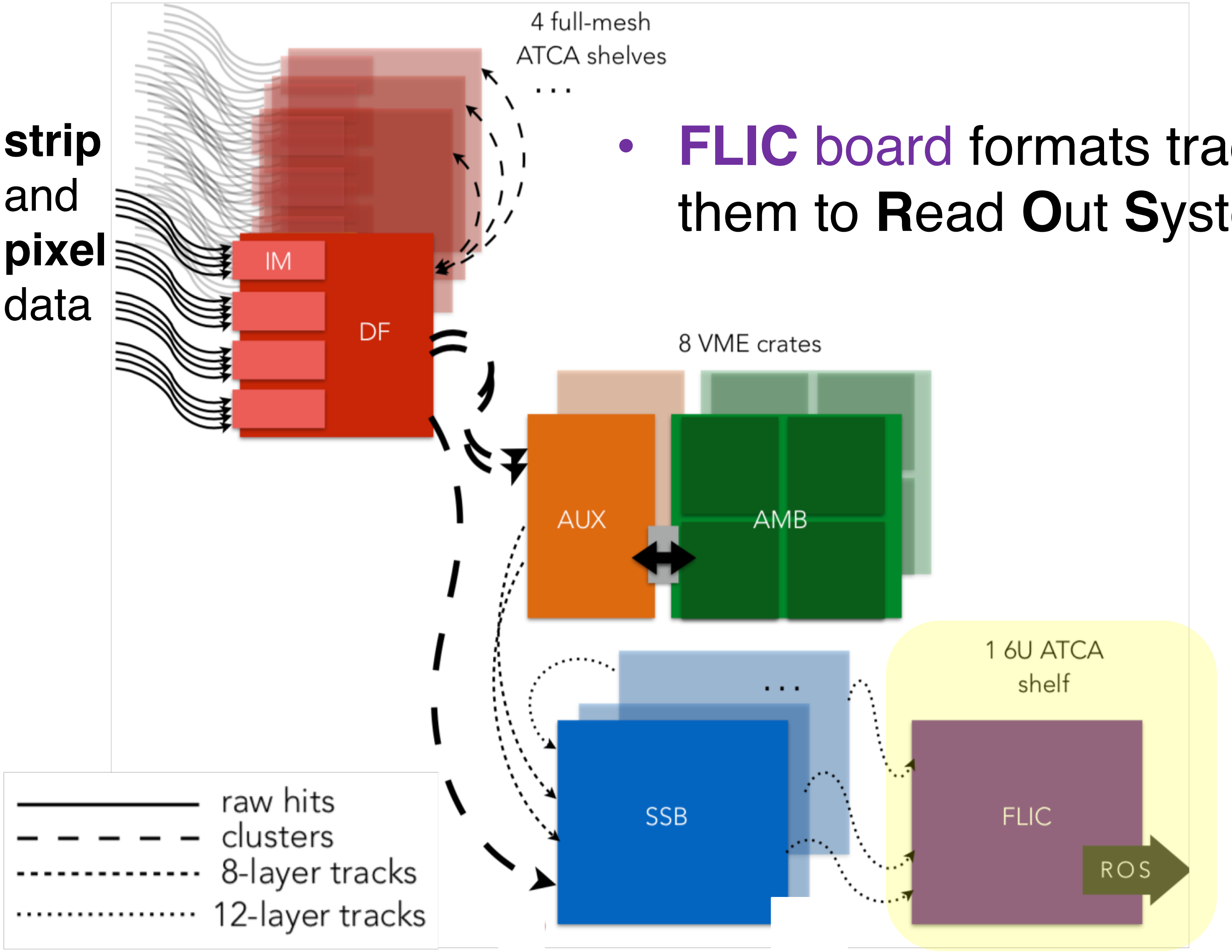
strip and **pixel** data

- **2nd tracking stage: Second Stage Boards** extend 8-layer tracks to 12-layer tracks and perform duplicate removal



The FTK Hardware

strip and pixel data



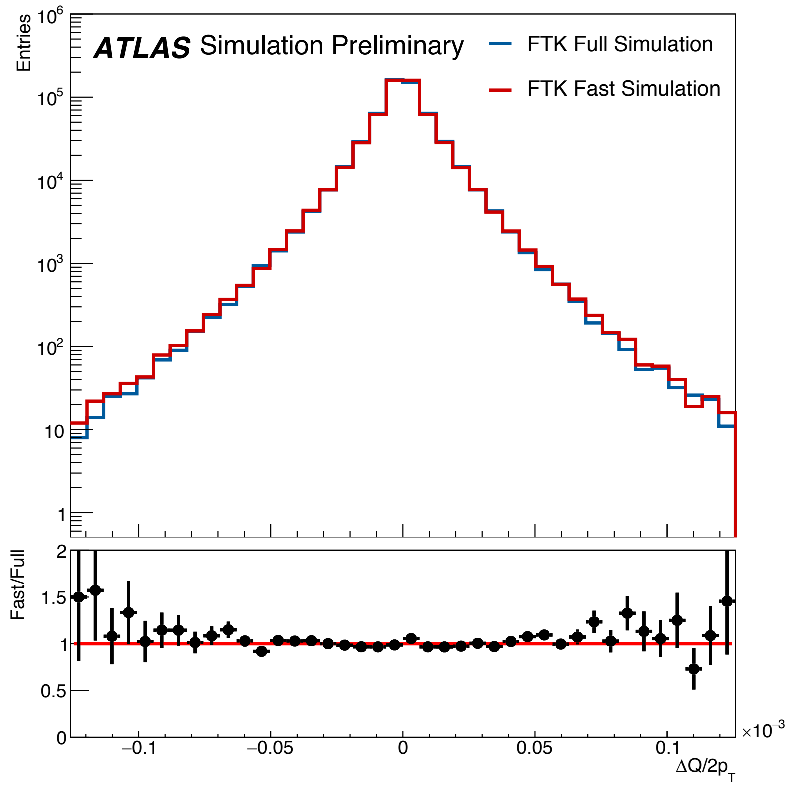
- **FLIC board** formats tracks and sends them to **R**ead **O**ut **S**ystem

Data Sample

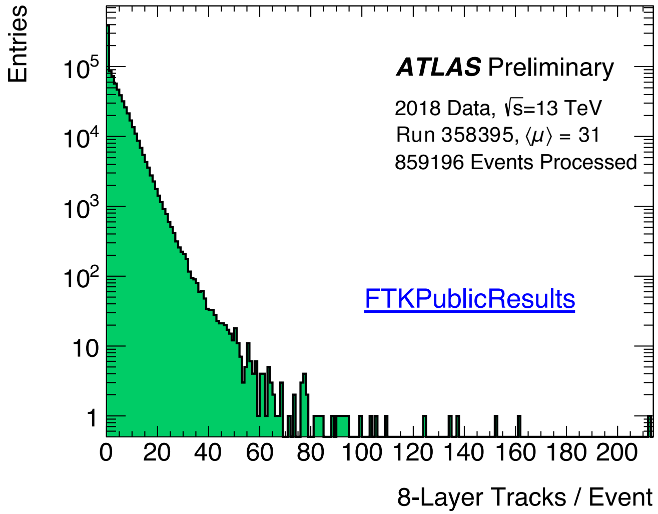
- Use special high pile-up $\mu = 82$ commissioning run collected October 2018
- Tower22 slice ran stably for ~2 hours and outputted tracks to ATLAS special data stream for trigger development and rate predictions
- Using **single Data Formatter** with **partial coverage** of Tower22
- **Collected ~0.5M FTK tracks**
- **FTK tracks with Insertable B-layer (IBL) hits were excluded**, due to a FTK module ordering problem that caused incorrect hit positions in the run (cause is understood and the fix is being implemented)

FTK Simulation

- Implemented full functional emulation of FTK in C++ (**FTKSim**)
  - Used to train sectors & constants and patterns and validate firmware with bit-level comparisons to FTK tracks
  - Very slow! 600 HS06 seconds per event
- For large-scale MC sample productions, developing parameterized **FastSim** approach with weights and smearings
  - Track parameter resolutions extracted from FTKSim and modeled with Double-Gaussian resolution functions
  - **Good modeling of core and tails of resolution function**

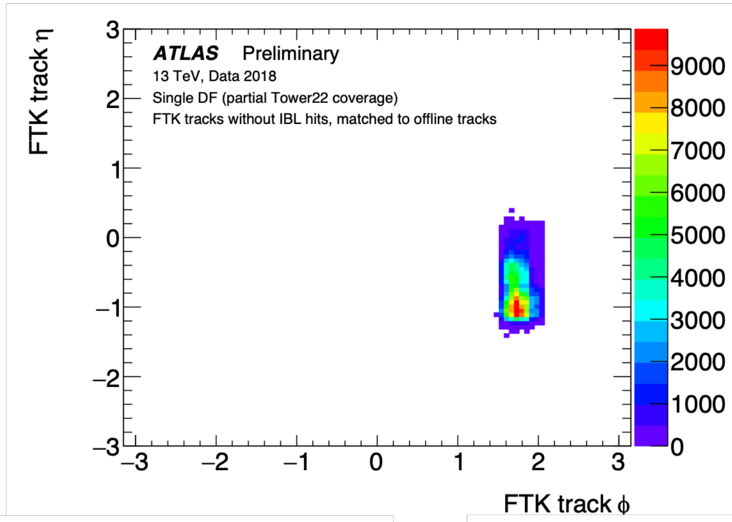


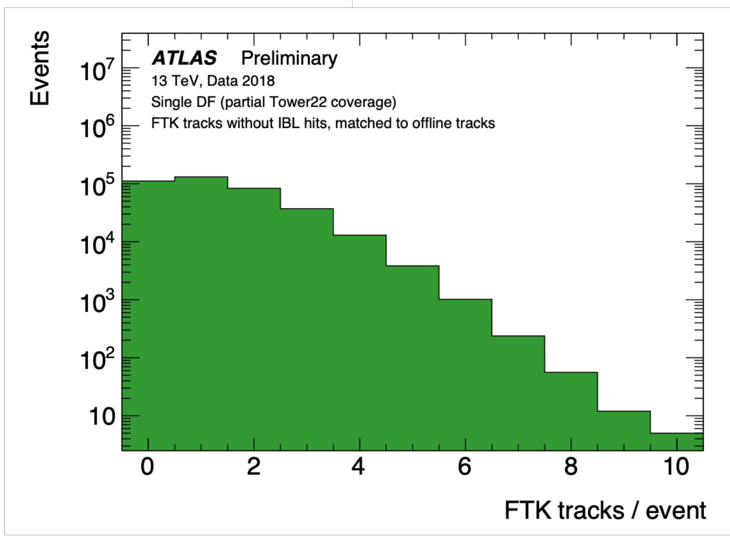
First Commissioning Results

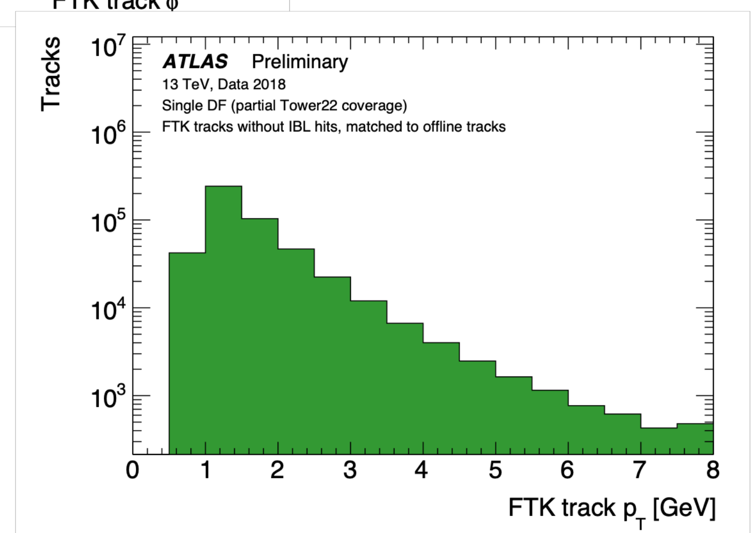


- 1st tracking stage is outputting tracks
- Validation of AUX firmware

12-layer Track Kinematics

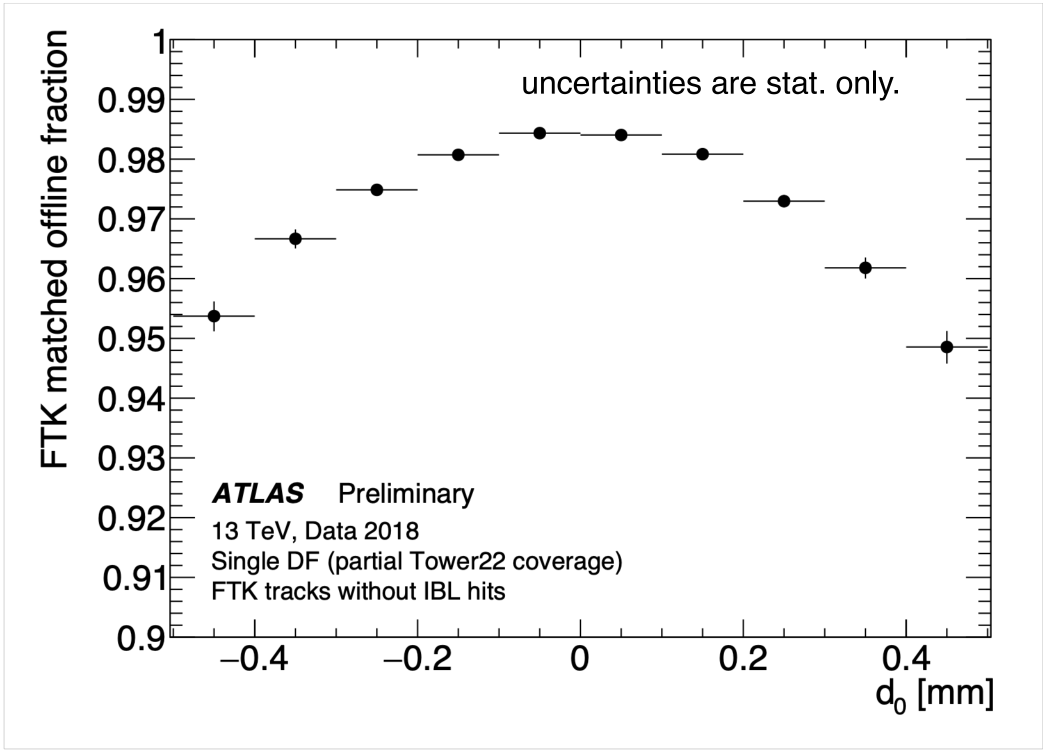






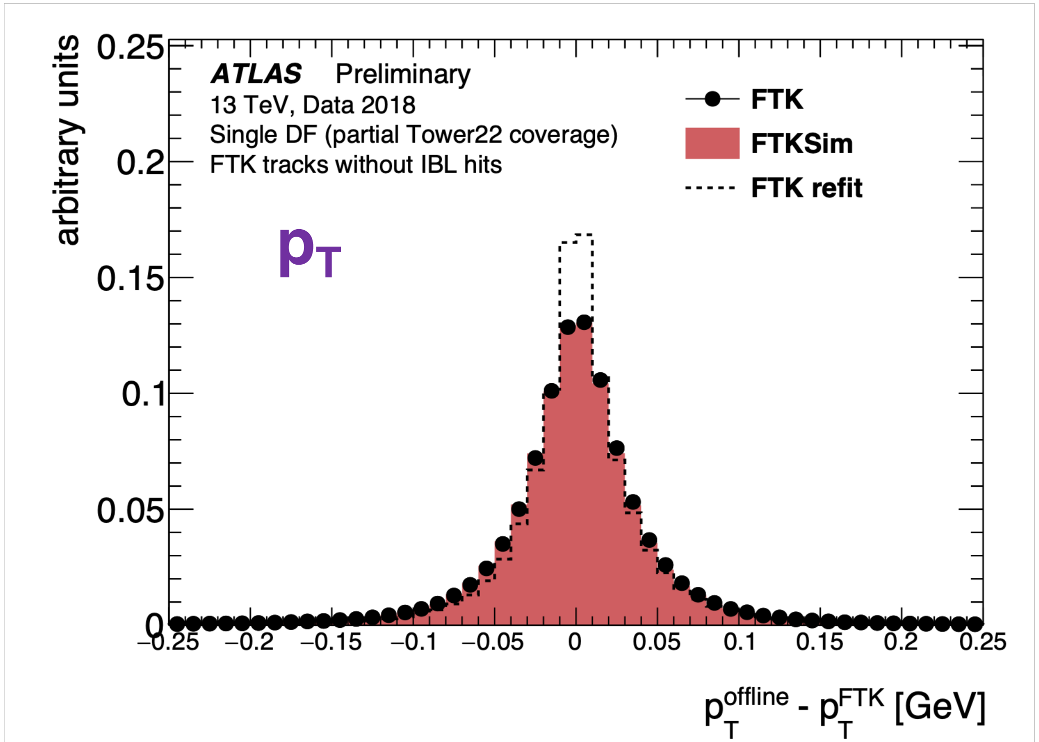
- Collected sample 0.5M 12-layer FTK tracks matched to offline tracks

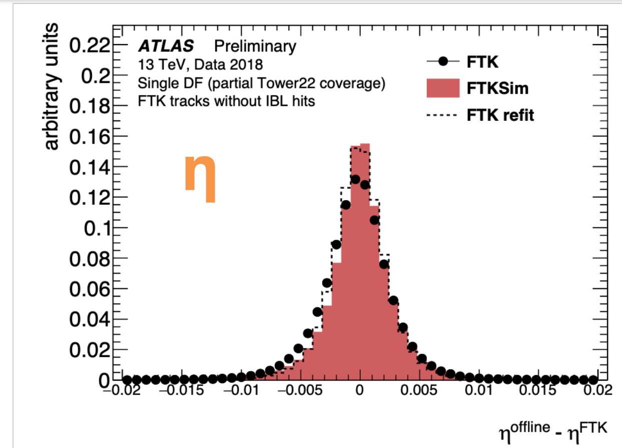
Matched Offline Fraction

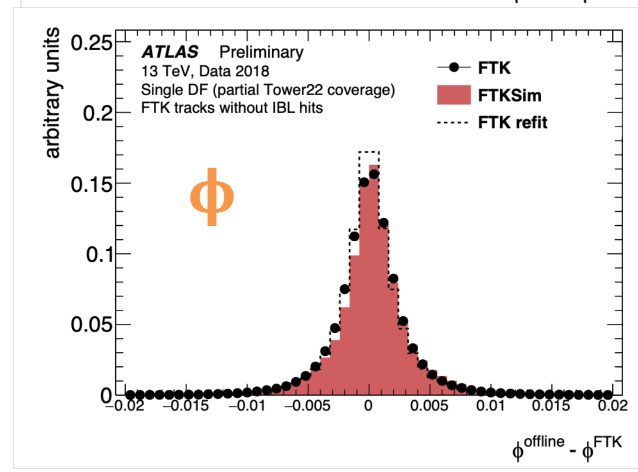


- Quantify the fraction of FTK tracks with a matched offline track within $\Delta R < 0.02$
- >95% of FTK tracks have a nearby matched offline track → FTK is reconstructing good 12-layer tracks

FTK Tracking Resolutions



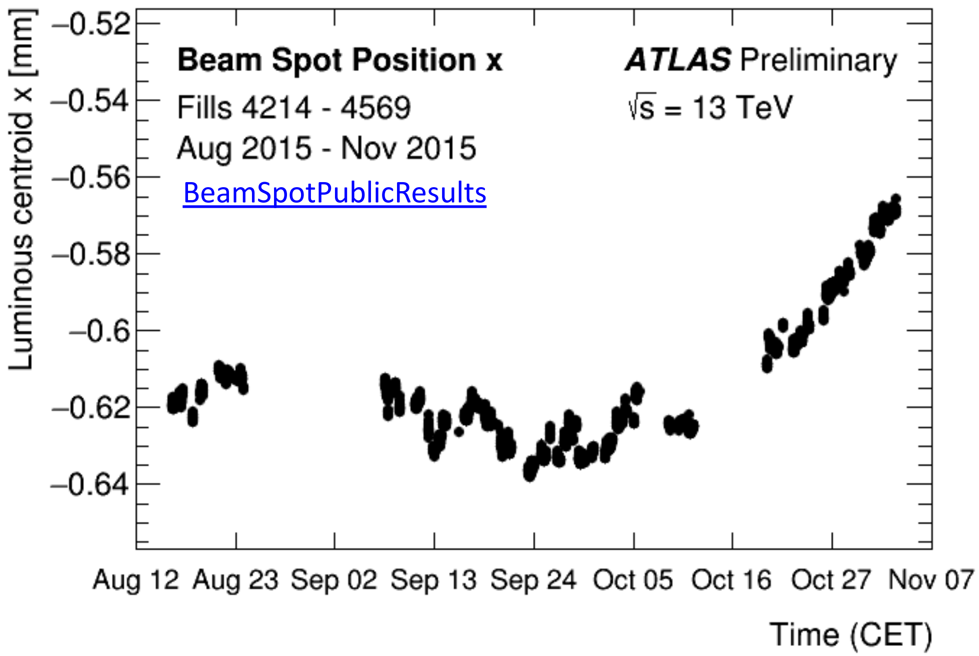




- Compare **FTK** / **FTK full simulation** / **FTK refit** tracks to matched offline tracks with $\Delta R < 0.02$
- **FTK reconstructs tracks with correct momentum and direction!**
- FTK refit improves resolutions by ~10-20% (full helix fit vs. linear approx. and additional hit position corrections, e.g. Lorentz angle)

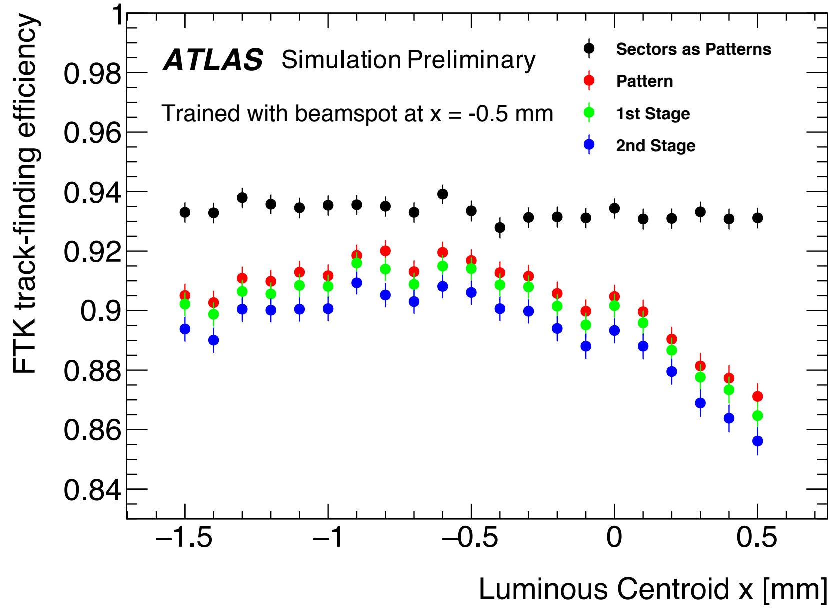
Coping with Changing Conditions

beamspot x position vs. time



- FTK performance depends on conditions that can shift during a run
  - e.g. beamspot displacements, typically limited to $\Delta x < 100\ \mu m$ over run
- In Run 3, need strategy to quickly adapt to changing conditions

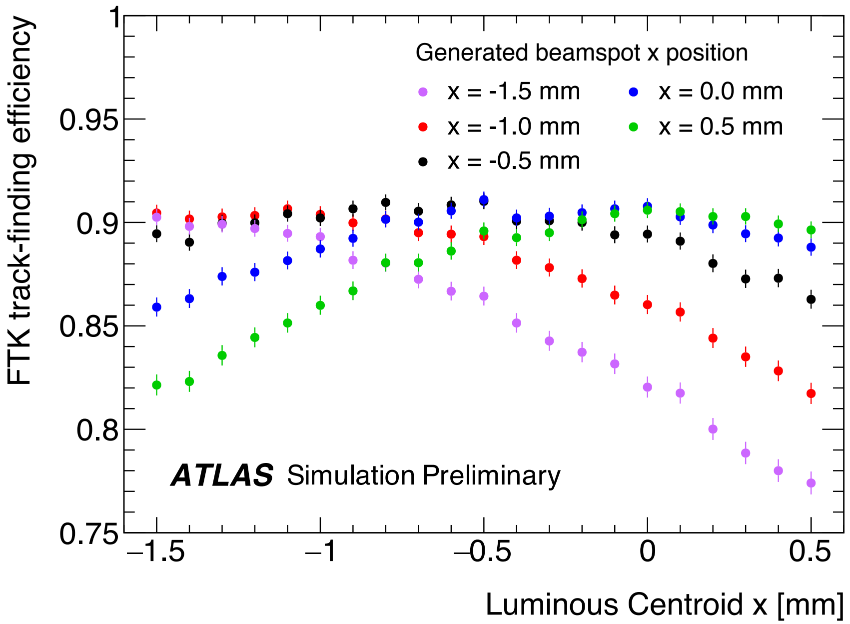
Step-by-Step Efficiencies



- Quantify tracking efficiencies for several steps of FTK track processing:
  - Efficiency for track to fall within a **defined sector**
    - Does not depend on beamspot position ⟶ **only one set of Sectors & Constants is needed**
  - Efficiency for track to fall within a **defined pattern**
    - Limited pattern coverage is main source of inefficiency
  - Efficiencies after **1st** and **2nd** tracking stages
    - ~1% inefficiencies from hits/holes requirements, 8-layer⟶12-layer extrapolation, duplicate removal

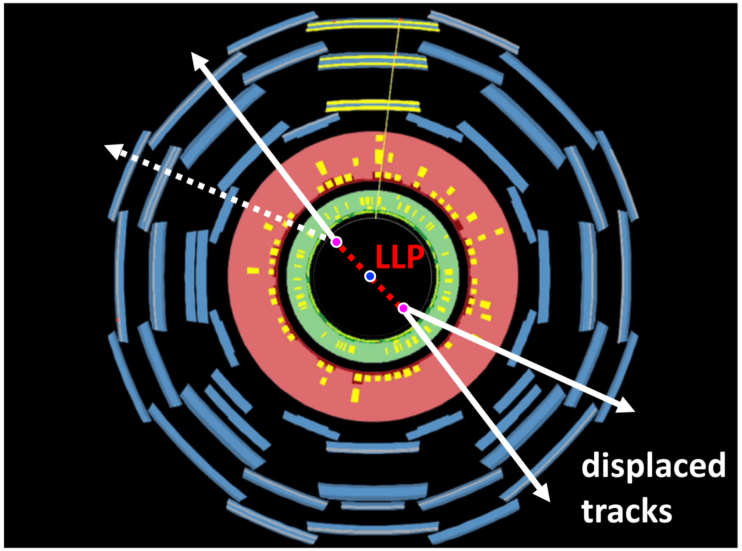
Toward Run-III: Coping with Changing Beamspot

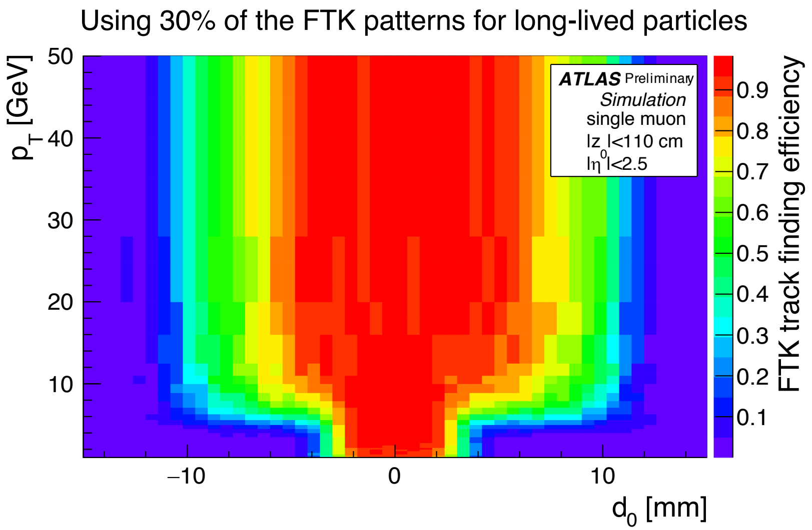
- Study dependence by generating patterns with various beamspot x positions and plotting tracking efficiency vs. actual beamspot x in simulation
- Can maintain max efficiency with a set of pattern banks with generated beamspot x positions **every 0.5 mm**



FTK for Long-Lived Particles (LLPs)

- LLPs are theoretically well-motivated but not yet exhaustively explored
  - Excellent physics target for Run-3, in which energy and lumi won't increase by large factors
- FTK allows to trigger directly on displaced tracks that are characteristic signatures
- Developed specialized pattern bank with 30% of patterns dedicated to high d_0, high momentum tracks
- **Able to extend coverage to large d_0 without degrading the prompt efficiency (by <1%)**





Summary

- Collected sample of half a million tracks with FTK Slice covering η-ϕ region of ATLAS detector
- Presented first tracking performance results
  - **FTK is producing good tracks with reasonable track parameters**
- Laying the groundwork for Run-3 physics…
  - Commissioning **Fast Simulation**
  - Coping with **changing beamspot position**
  - Preparing **specialized patterns for long-lived particles**
- Developing **Phase-II upgrade Hardware Track Trigger**
  - See talk by Richard Brenner in next session…