ACTS Tracking for FASER

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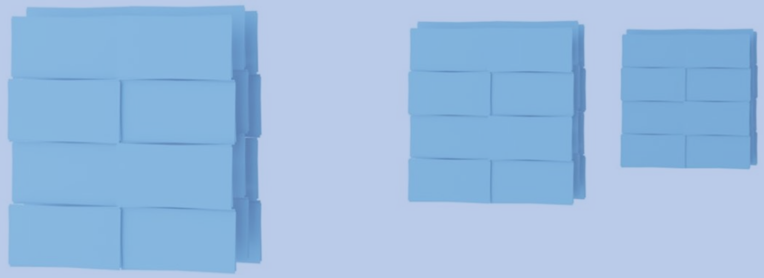
on behalf of FASER Collaboration

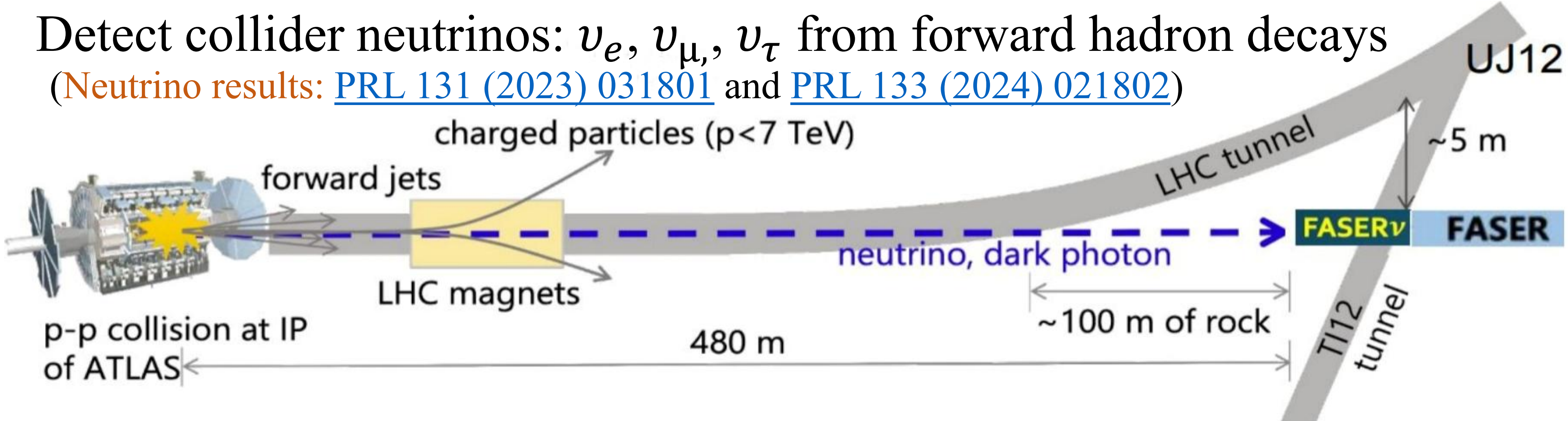


The 2nd Workshop on Tracking in Particle Physics Experiments, July 22 , 2025

IMP, CAS, Huizhou

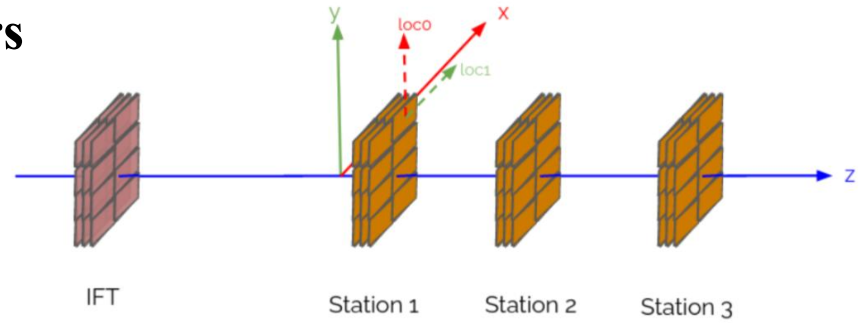
FASER Experiment

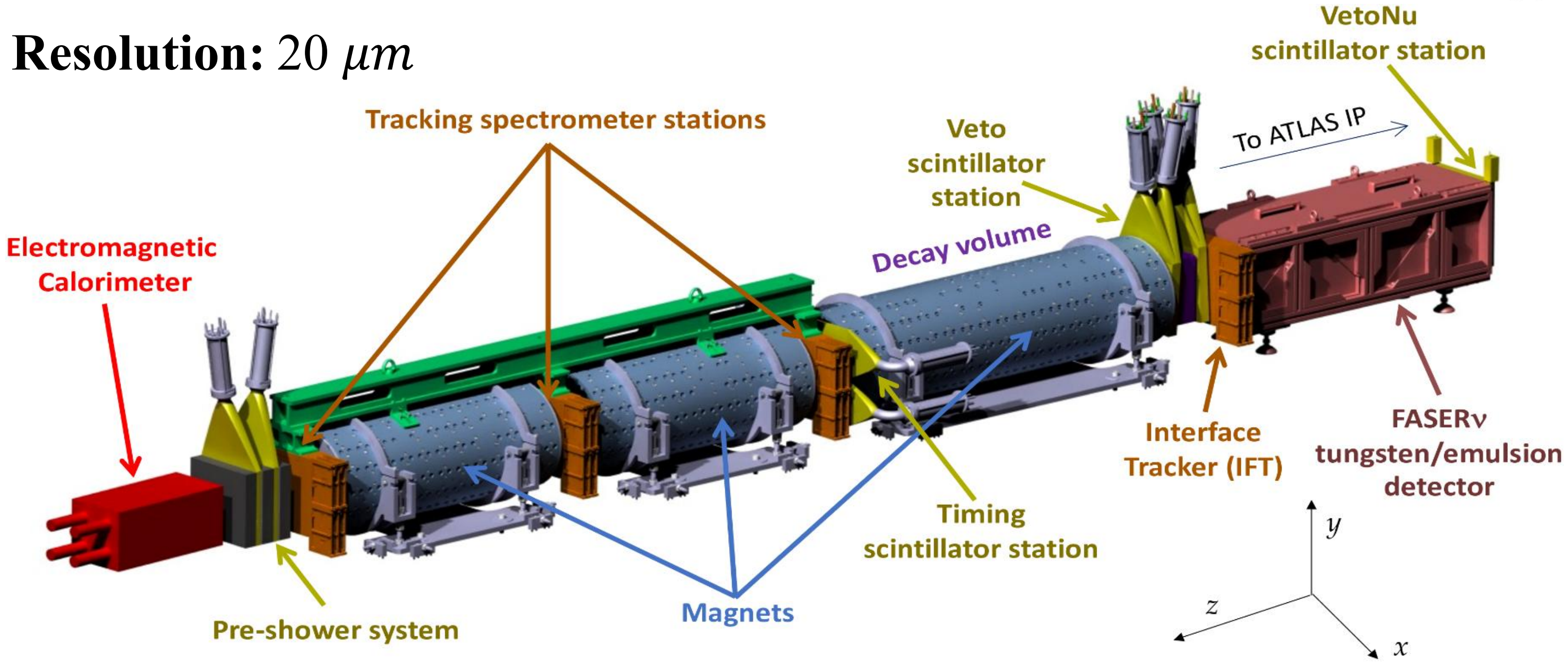
- **Location:**
  - 480 m downstream from ATLAS, aligned with the beam collision axis
  - Naturally clean environment: only LLPs, muons, neutrinos reach FASER
    - Charged particles deflected by LHC magnets
    - Neutral hadrons absorbed by TAN and ~100 m of rock
- **Motivation：**
  - Long-Lived Particles(LLPs) search: dark photon ($\pi^0 \rightarrow A'\gamma$), Axion-like particles(ALPs)… (LLPs results: PLB 848 (2024) 138378 and JHEP 01 (2025) 199)
  - Detect collider neutrinos: υ_e, $\upsilon_{\mu,}$, υ_τ from forward hadron decays (Neutrino results: PRL 131 (2023) 031801 and PRL 133 (2024) 021802)



FASER Detector— Tracking System

- Detector composed of scintillators, FASERυ, decay volume, tracking stations and calorimeter
- Tracking system: IFT(station0) and 3 stations inside magnetic field
  - each made of **3 layers** of **double-sided silicon micro-strip detectors**
  - Active area(per layer): **24 cm × 24 cm**
  - Each layer contains **8 SCT modules** (same as ATLAS SCT)
  - **Strip pitch**: 80 μm ; **Stereo angle**: 40 mrad
  - **Resolution:** 20 μm

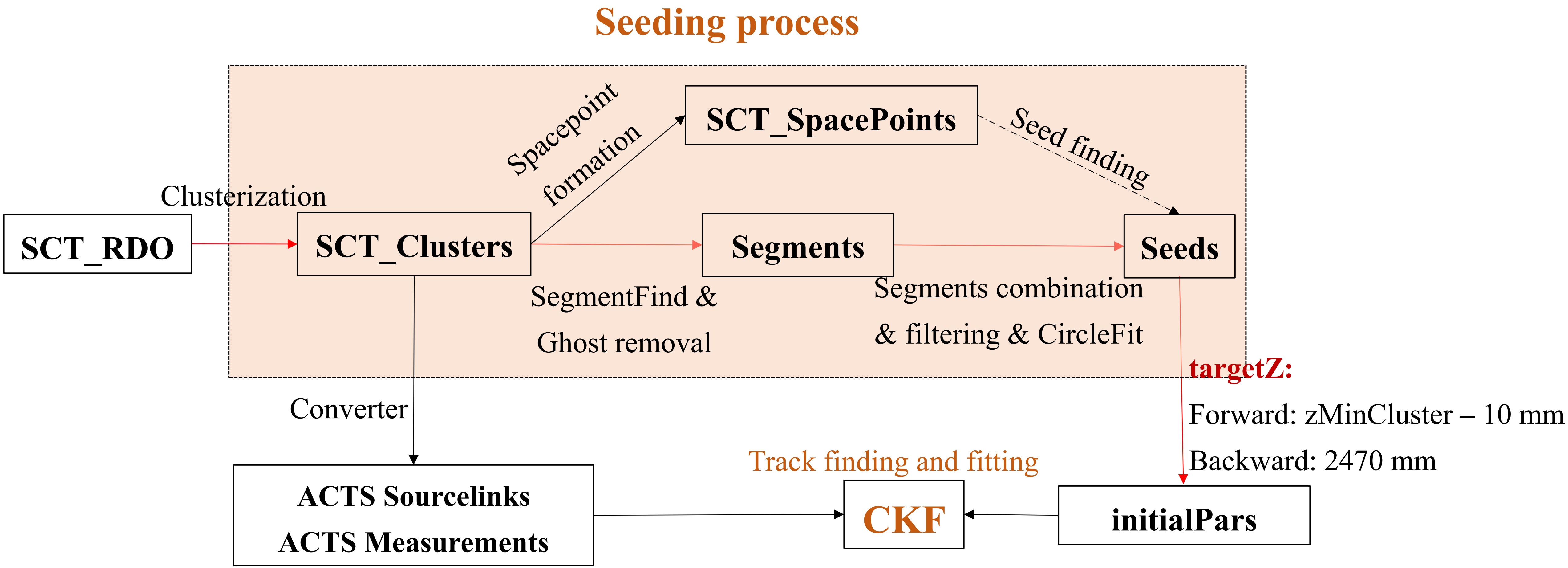




Tracking Strategy

- FASER adopted ACTS early and integrated it into its offline software Calypso (based on Athena)
- Tracking in FASER relies on ACTS Combinatorial Kalman Filter (CKF) for simultaneous track finding and fitting, and ACTS Kalman Filter (KF) for track refitting
- Dedicated seeding strategy matches FASER's telescope-like geometry
- **Vast Migration from centos7 (ACTS v14.1.0) to alma9 (ACTS v32.02) in June 2024 and revisited the tracking code/performance based on existing ACTS CKF pipeline**
  - Identify and fix potential performance spots

Tracking with ACTS in FASER

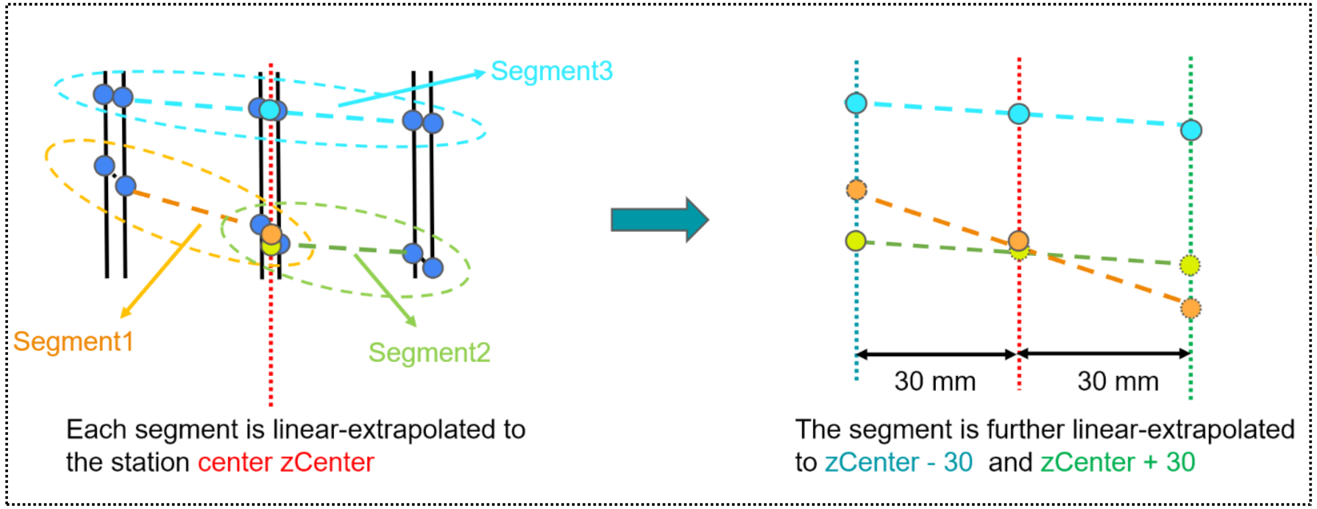


Four tracking modes:

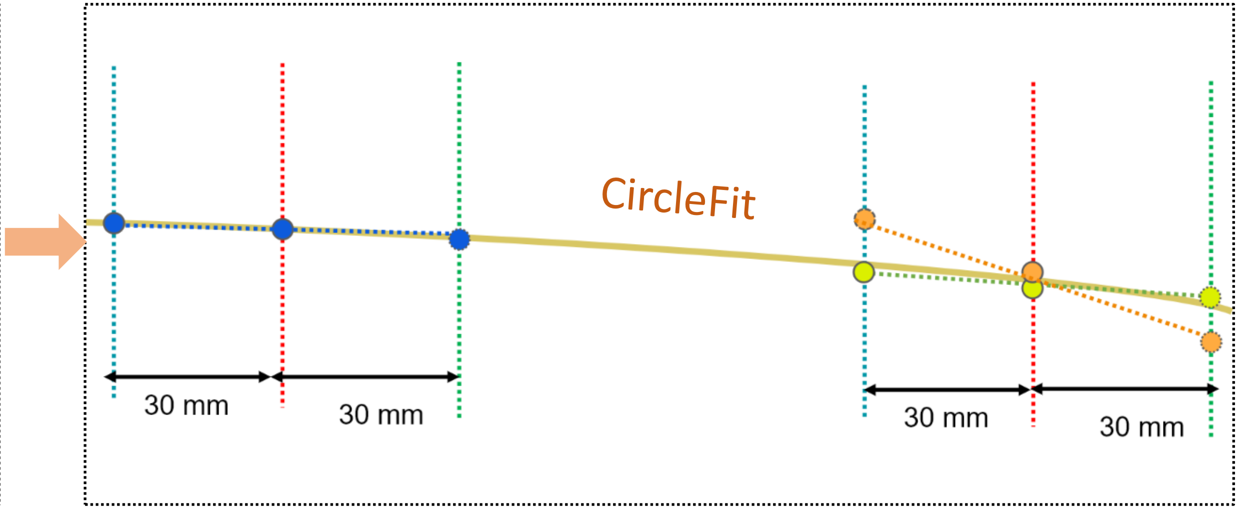
Forward tracking with or without station0

Backward tracking with or without station0

Seeding process



Segment Find

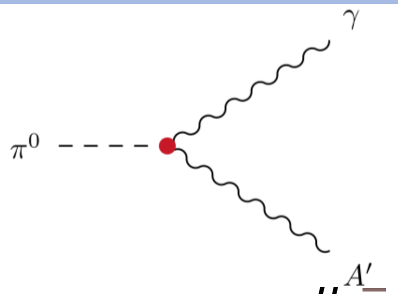


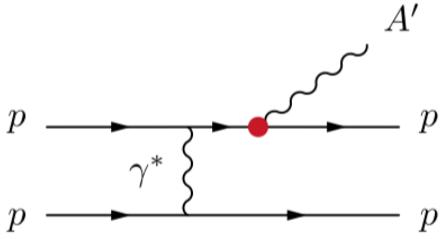
Segments combination

- **Segment Find:** Segments are independently constructed in each station from local clusters
- **Segments combination:**
  - Segments from different stations are combined sequentially

    In decreasing order of contributing stations (4 → 3 → 2 → 1)
  - Seeds are ranked by number of clusters and χ^2
  - Seeds with less than 10 clusters or more than 6 shared clusters are removed sequentially

MC samples





- Signal: LLP(A') $\rightarrow e^+ e^-$
- Model setup:
  - Lagrangian term: $\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon\, e \sum_f q_f A'^\mu \bar{f} \gamma_\mu f$
  - Production at FASER: Light meson decays (π^0/ η) and Dark bremsstrahlung
  - Decay and sensitivity:
    - FASER sensitive to $\epsilon \sim 10^{-5}$ and $m_{A'} \sim 10 - 100$ MeV
    - For $2m_e < m_{A'} < 2m_\mu \sim 211$ Mev, Br($A' \rightarrow e^+e^-$) ≈100%
- Three representative parameters are investigated (FORESEE):

  $m_{A'} = 100$ Mev, $\varepsilon = 1 \times 10^{-5}$; $m_{A'} = 10$ Mev, $\varepsilon = 1 \times 10^{-5}$;

  $m_{A'} = 10$ Mev, $\varepsilon = 1 \times 10^{-4}$
- Number of events : 60k

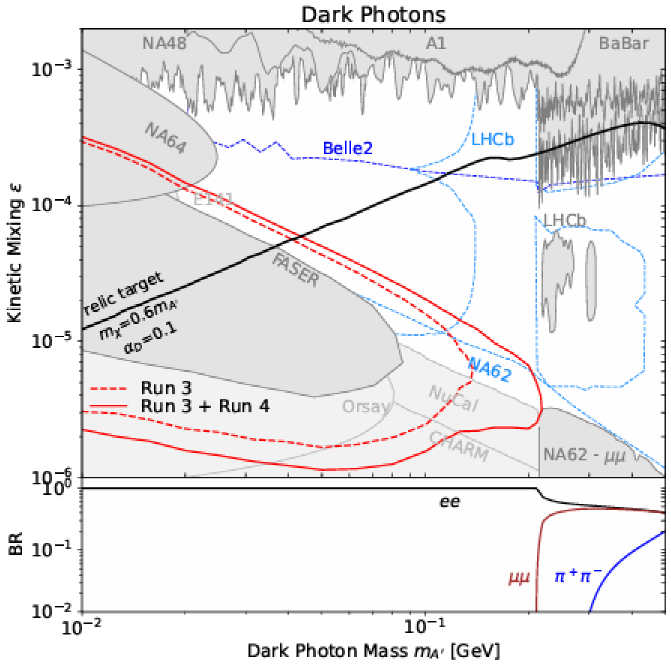


Figure from [Run4 request]

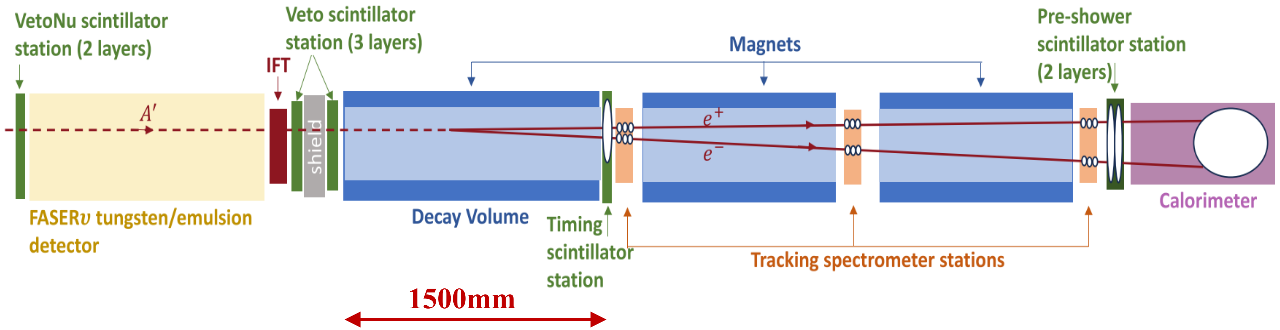
Metrics for tracking performance

- **Track-based Metrics (vs theta / P_T of charged particles at production vertex)**
  - **Efficiency =** $\frac{nSeeds/nTracks^{\{reco,matched\}}}{nParticles^{\{fiducial\}}}$

- **Event-based Metrics (vs ΔR_1)**
  - **Efficiency =** $\frac{nEvents^{\{nSeeds/nTracks\geq 2\}}}{nEvents^{\{nSeeds/nTracks\geq 1\}}}$
  - **TrackSeparation (ΔR_1):** Separation between the electron and positron at the station3 tracking station in the x-y plane

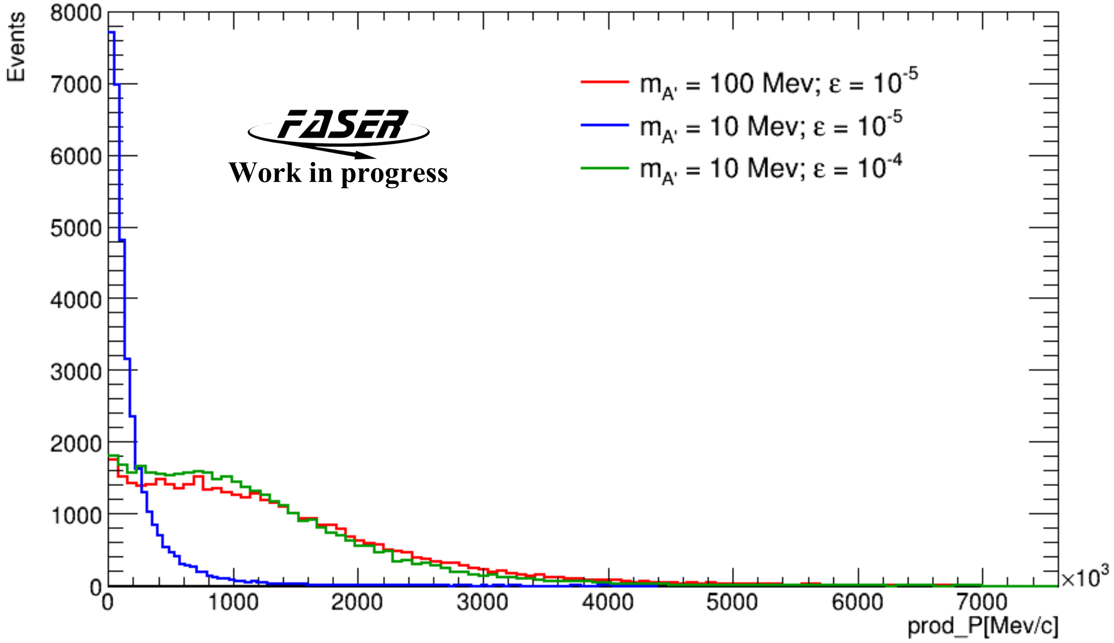
- **Truth-level particle:**
  - In fiducial region: $\bar{r}_{station1\backslash 2\backslash 3} \leq 100$ mm
  - nHits ≥ 18

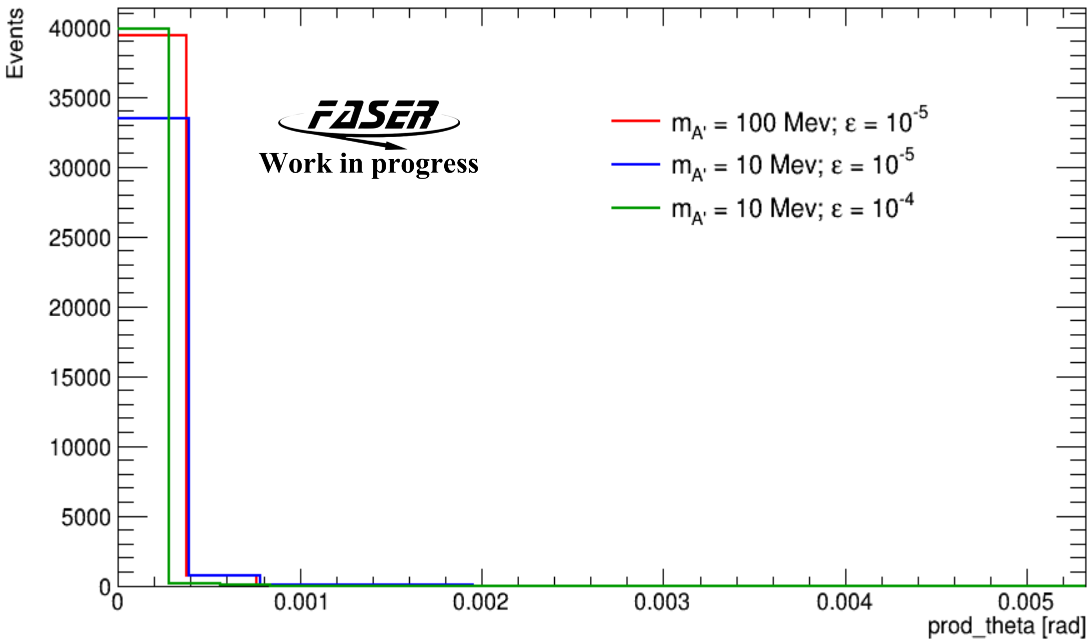
Figure from: PLB 848 (2024) 138378

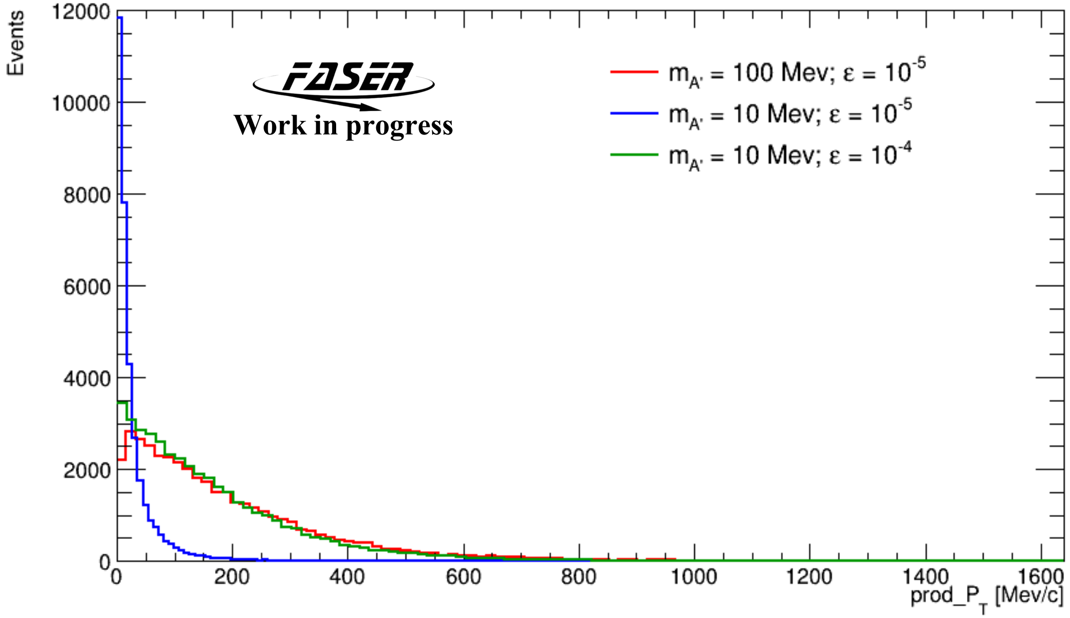


- Two highly collimated charged tracks (e.g. r < 95 mm, p > 20 GeV) → from dark photon decay ($A' \rightarrow e^+ e^-$ **in decay volume**)
- Charged particle has no hits at IFT station
  --The efficiency of the three-station tracking and the four-station tracking should be the same

Distribution of P/theta/ P_T at production vertex



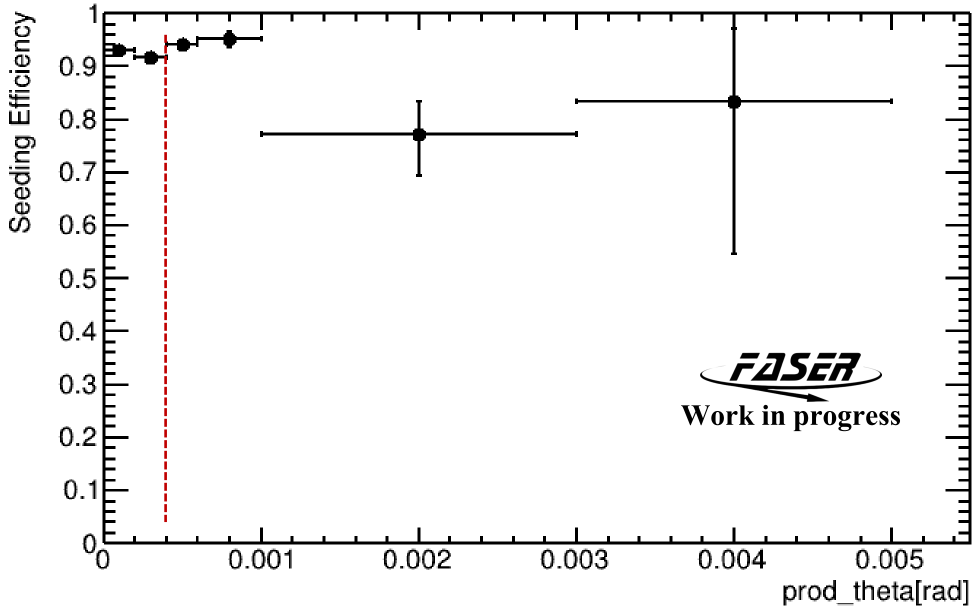


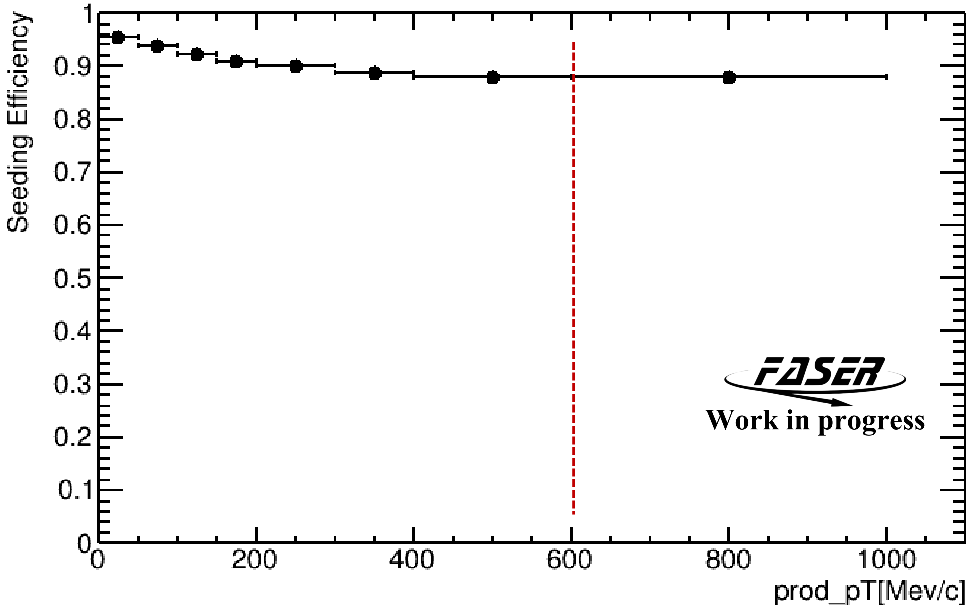


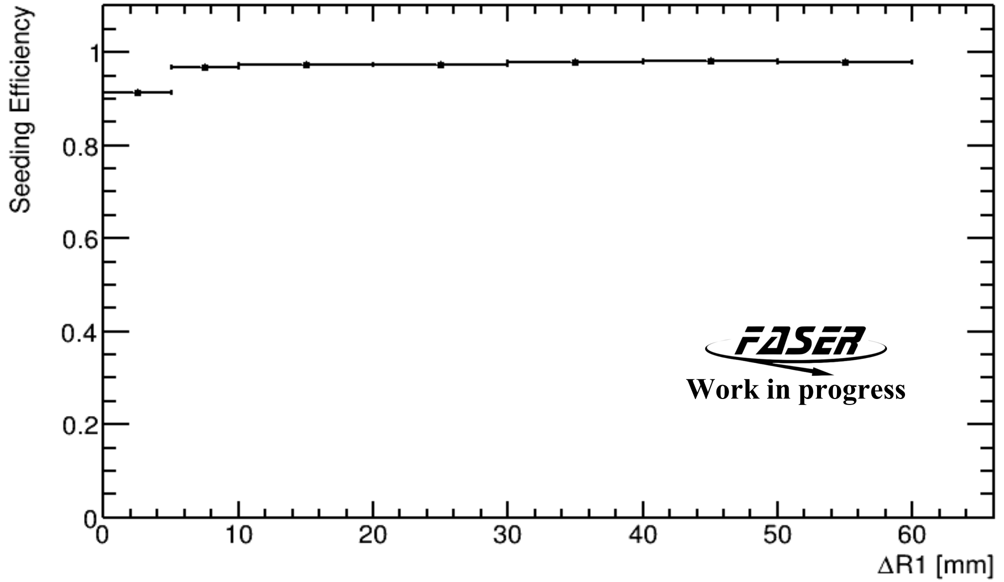
- Main region of interest:

  $P_T \approx$ 0 - 600 MeV/c, θ ≈ 0 - 0. 4 mrad

Evaluation of Seeding Efficiency



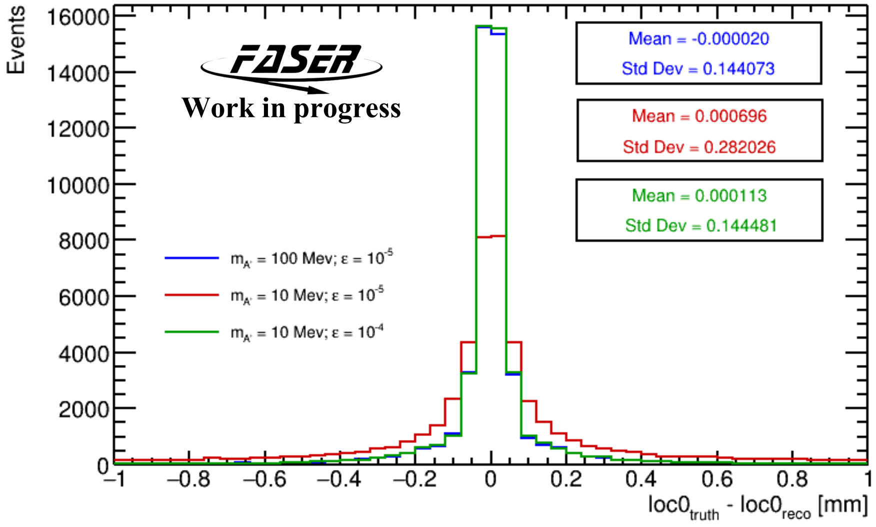


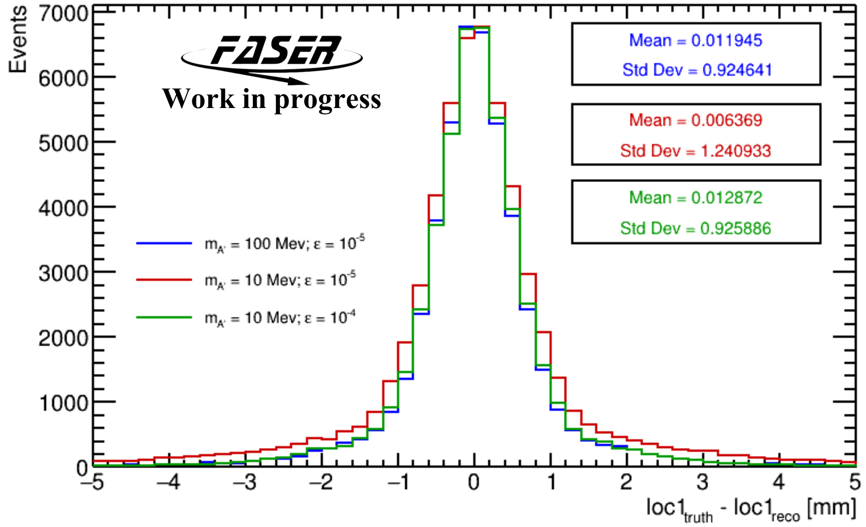


- Track-based efficiency vs theta/P_T
  Efficiency peaks at ~95%, gradually decreases in low-theta and full P_T region.
- Event-based efficiency vs ΔR_1
  Efficiency remains high (~98%) ,with only a slight dip at very small separations.

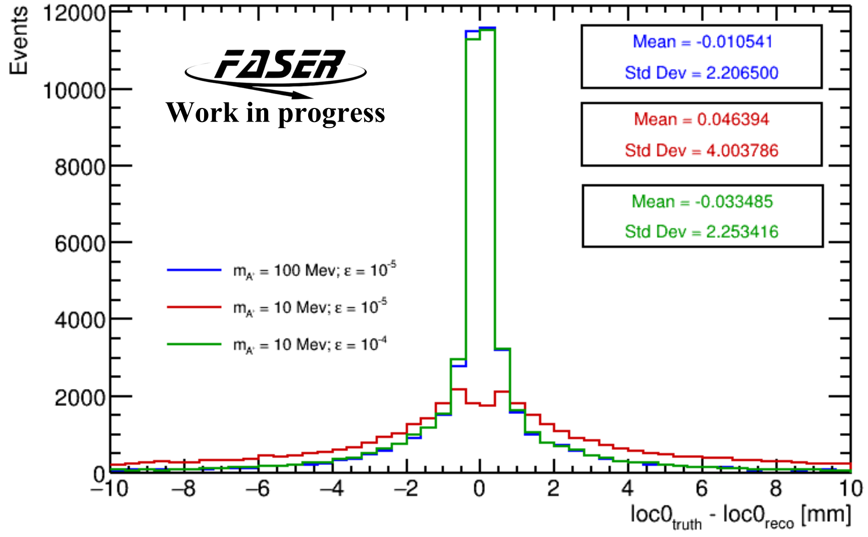
Seeding Resolution

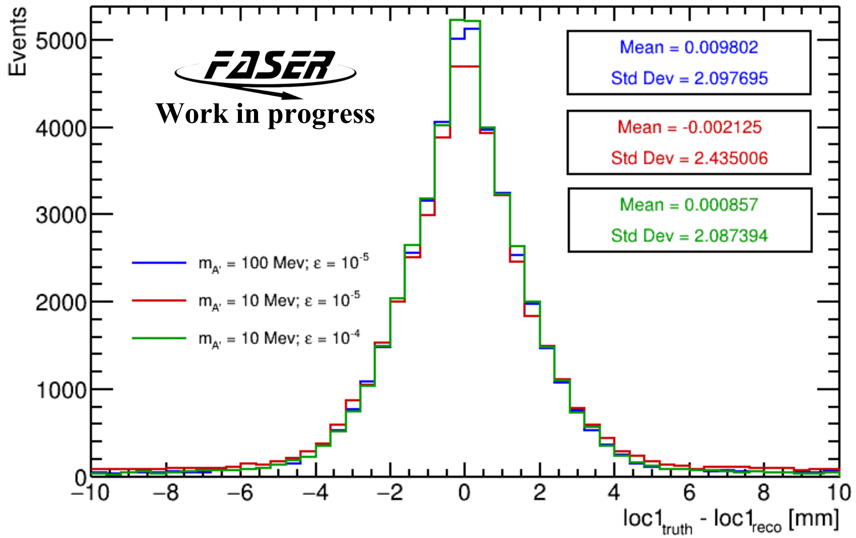
targetZ = zMinCluster – 10 mm





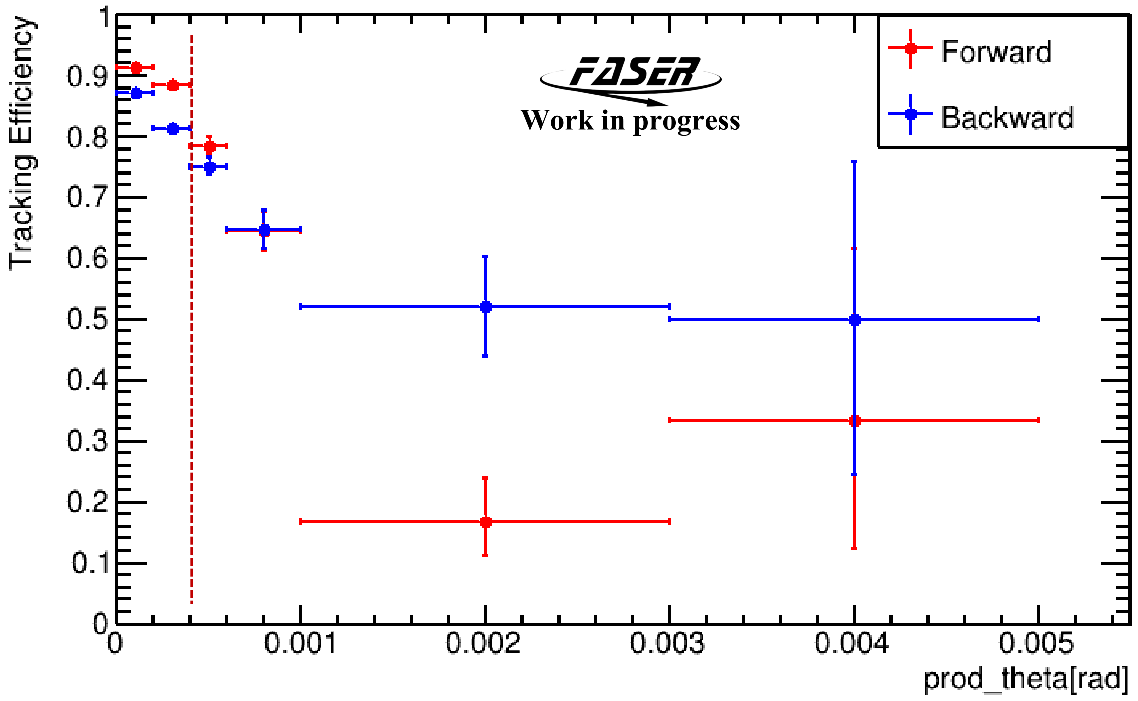
targetZ = 2470 mm

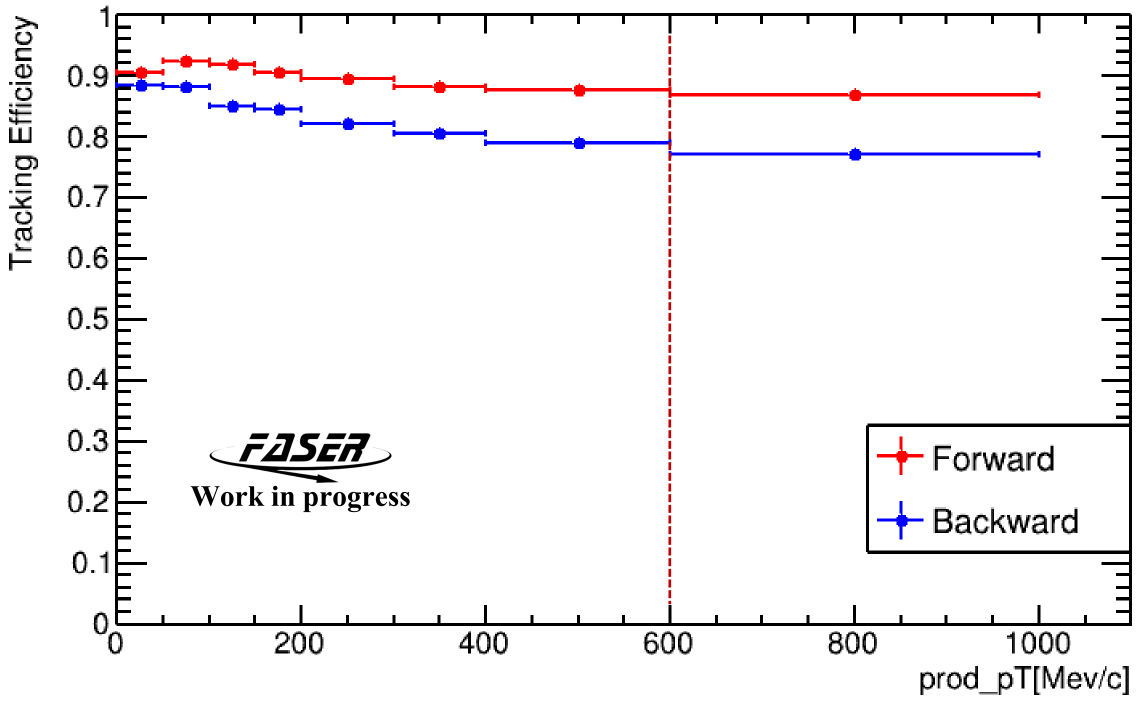




Evaluation of CKF tracking efficiency (Track-Based)

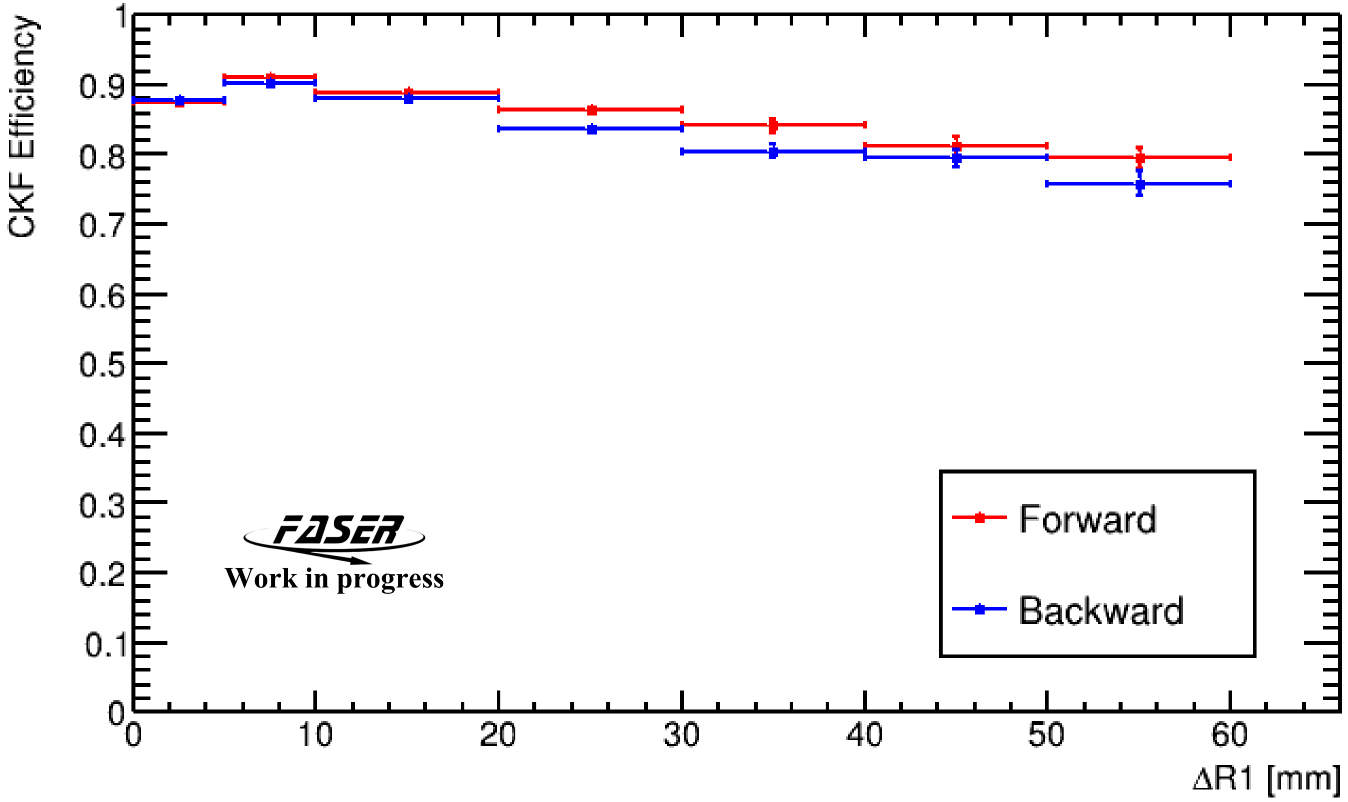
Track selection : nMeasurements ≥ 12, nSharedHits ≤ 6





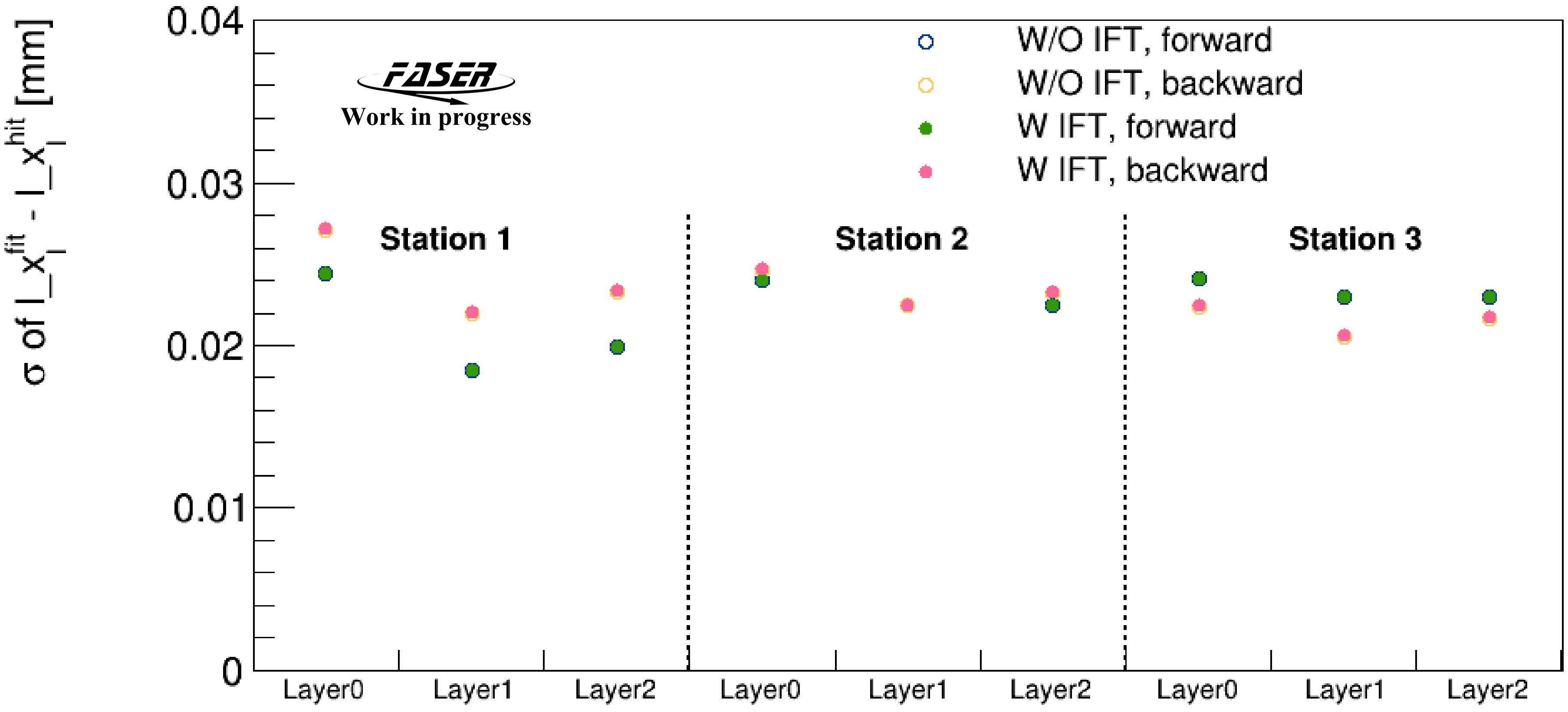
- CKF tracking efficiency starts **around 90%** and decreases gradually with increasing theta or P_T.
- Backward tracking efficiency is slightly lower than forward tracking in the low theta region and across the full P_T range.

Evaluation of CKF tracking efficiency (Event-based)



- CKF efficiency stays relatively stable **(~90%)**, but shows a slight drop with increasing separation.
- Consistent with trend observed in track-based CKF efficiency.

CKF Resolution



- Residual = $loc0^{fit} - loc0^{hit}$
- CKF residual resolution per layer remains stable around **20 μm**.

  --indicates high-precision track fitting

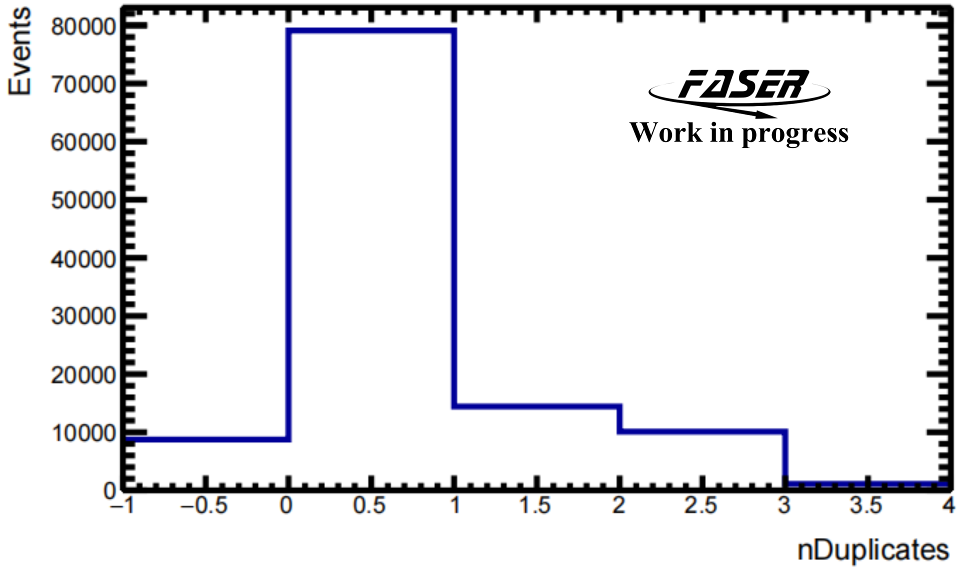
Summary

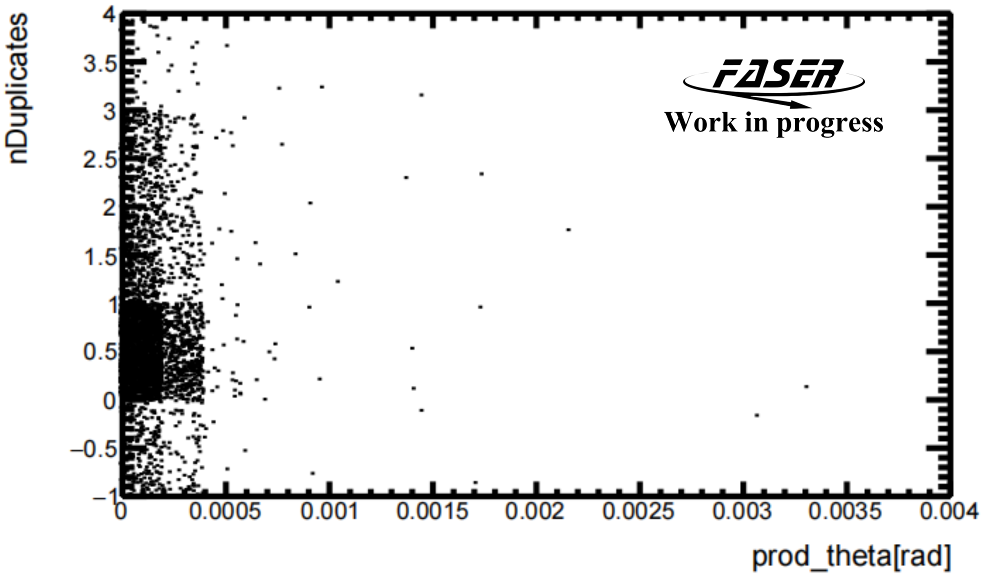
- Summary
  - ACTS tracking pipeline successfully applied for data production in FASER Run
    - Driving the first direct collider neutrino discovery and lots of LLPs search
  - Seeding shows robust performance
  - CKF performance degrades at large angles and wider track separations
    - Related to tracking station geometry definition in ACTS

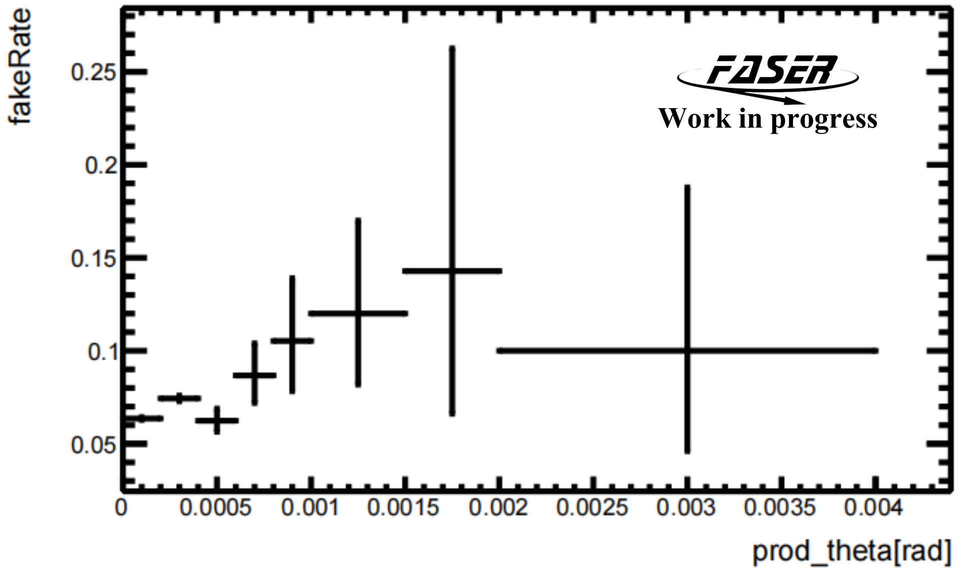
- Outlook
  - Define tracking geometry in ACTS along global x axis (instead of global z axis)
  - Improve CKF efficiency by merging tracks from forward and backward tracking
  - Investigate other tracking algorithms (Hough Transform, GNN) in ACTS

Back up

Seeding FakeRate & Duplicates

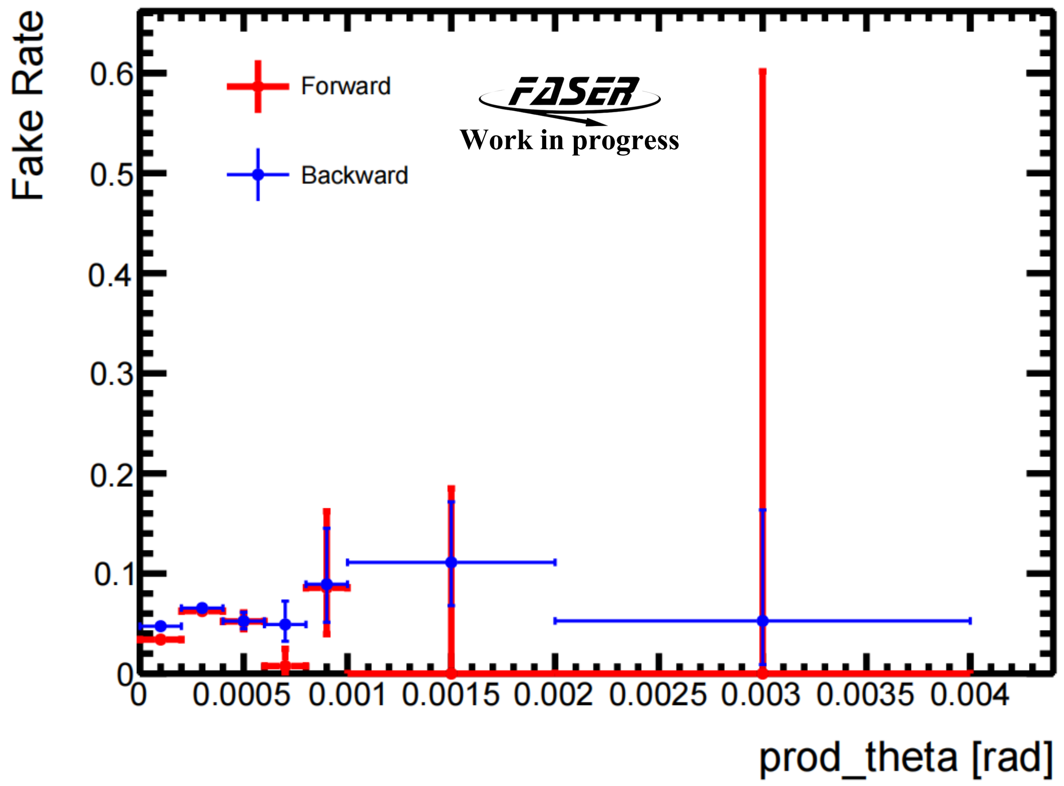


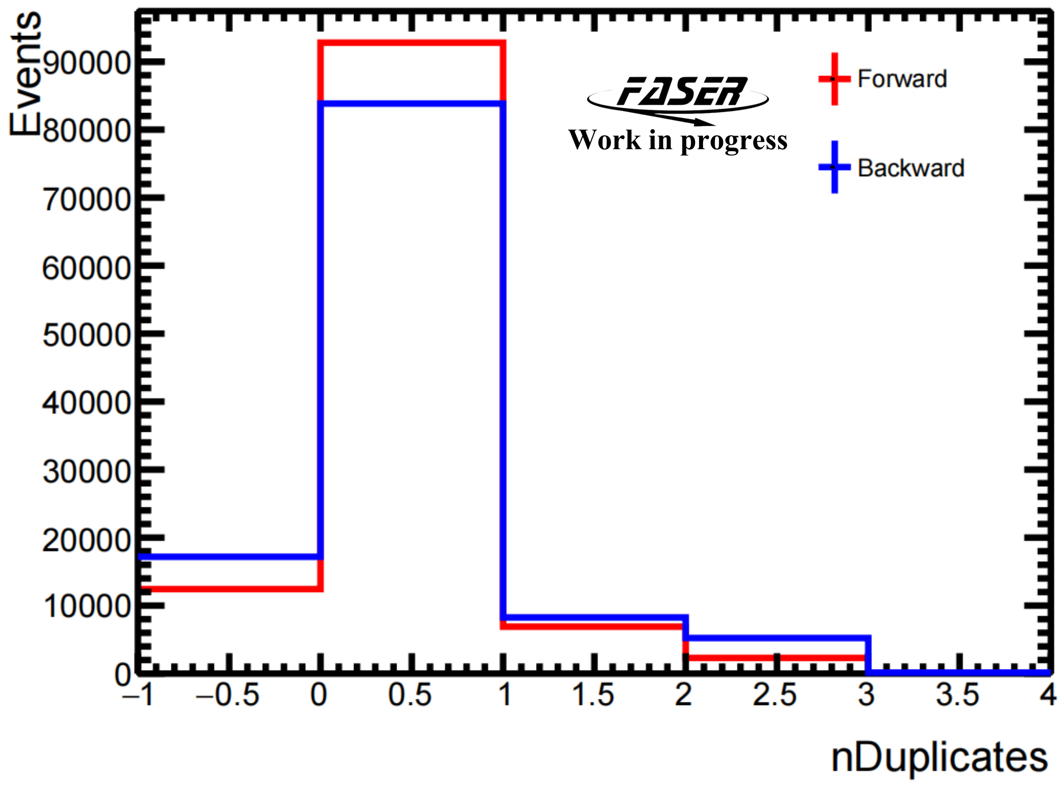




- fakeRate definition: $\frac{reco\ \text{seeds}^{truthHitsRatio<0.5}}{reco\ seeds^{matched\ truth\ particle}}$
- nDuplicates = -1： truthParticle has no matching seeds

CKF FakeRate & Duplicates



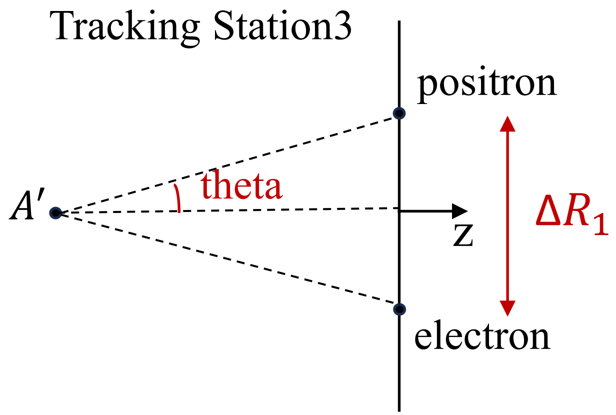


- fakeRate definition: $\frac{reco\ tracks^{truthHitsRatio<0.5}}{reco\ tracks^{matched\ truth\ particle}}$
- nDuplicates = -1: truthParticle has no matching tracks

TrackSeparation

Track separation(ΔR_1): Separation between the electron and positron at the station3 tracking station in the x-y plane

- e^+/e^- better separated in station3 after magnetic bending
- Station 1 has limited resolution for close tracks
- from MC truth



The production vertex of charges particles

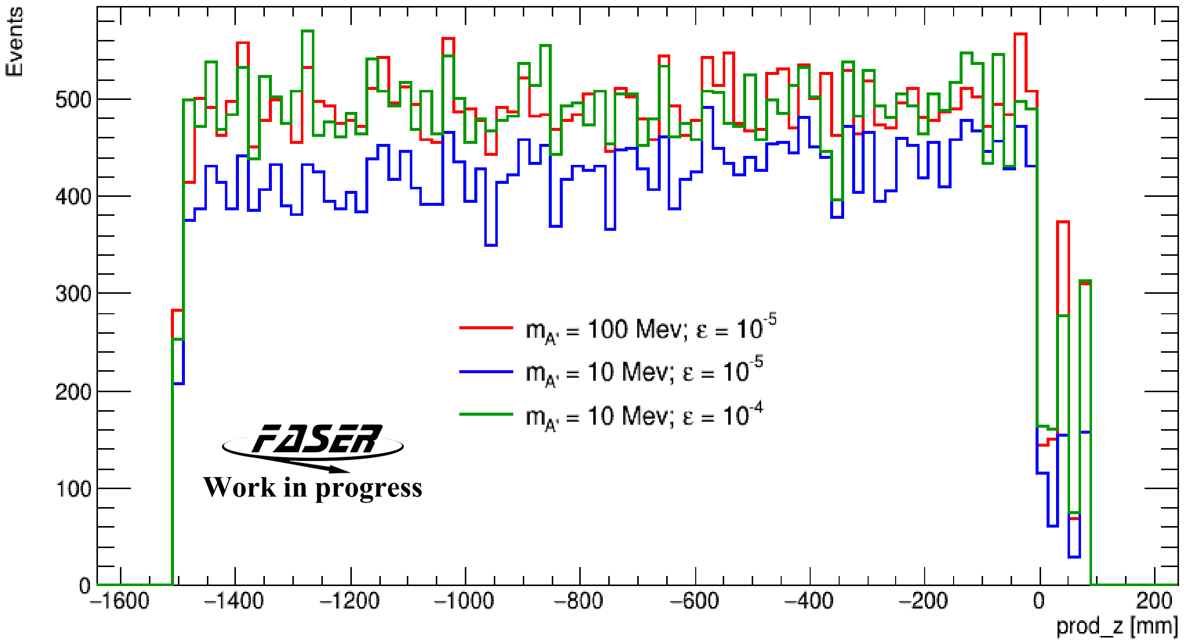
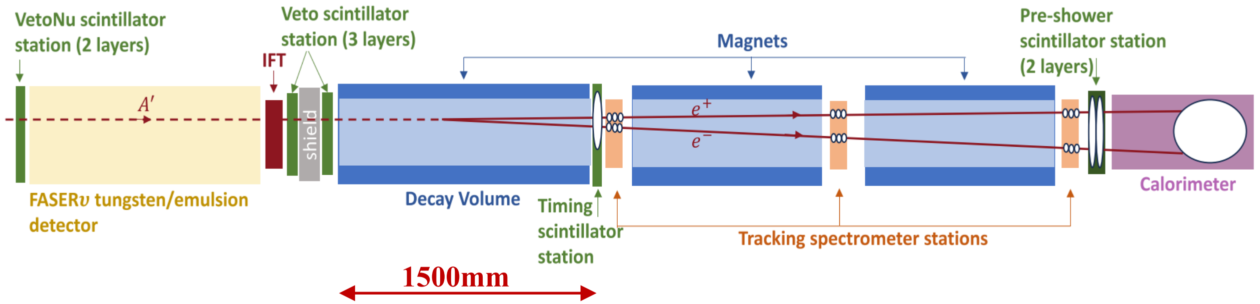
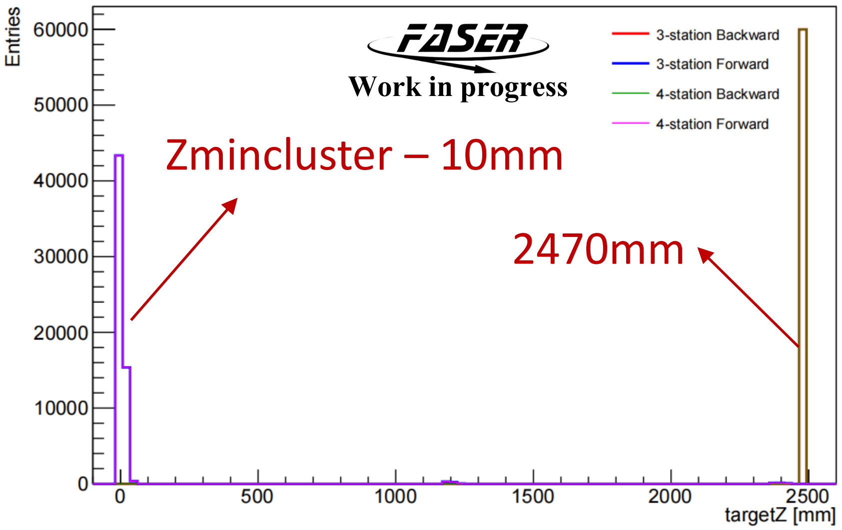
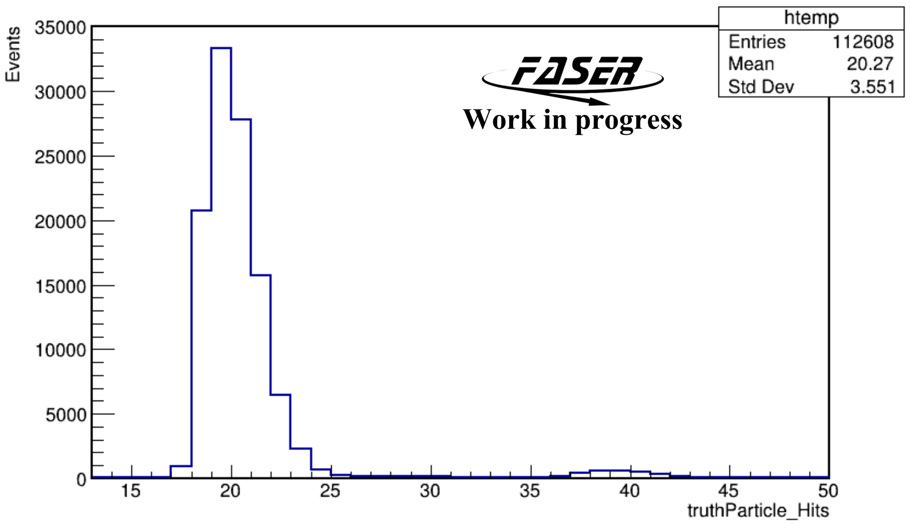


Figure from: [PLB 848 (2024) 138378]

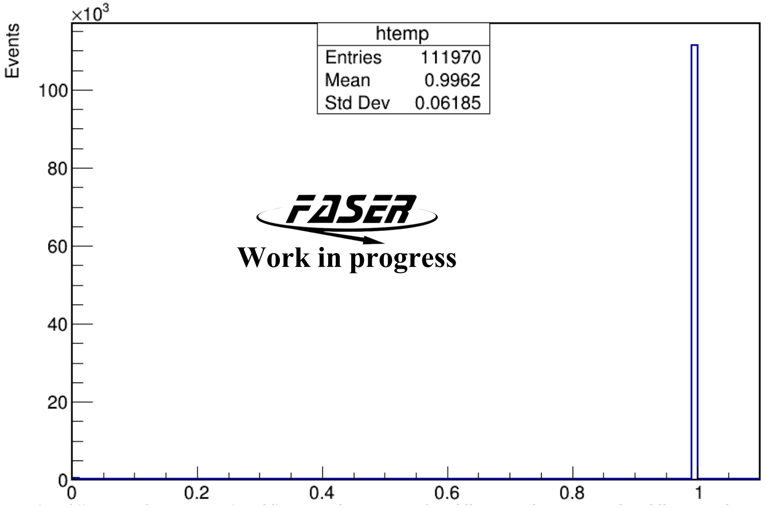


Truth information





Limit: per layer has hit

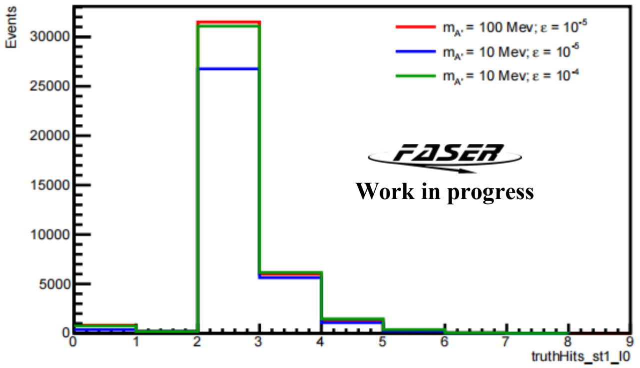


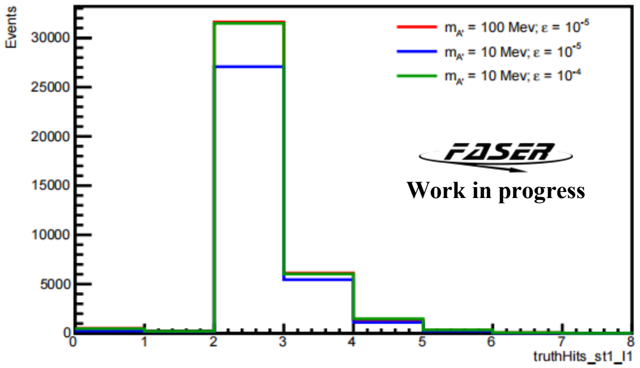
Per layer has hit

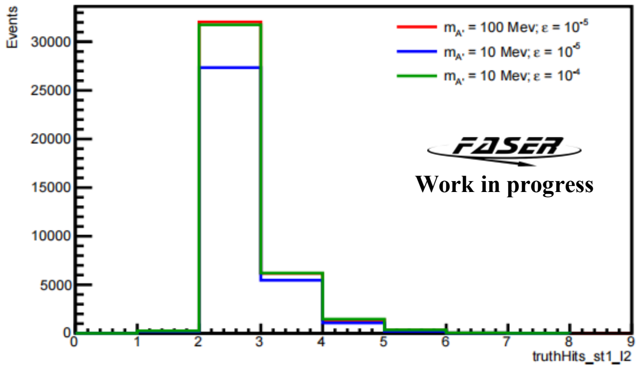
(condition: truthParticle_Hits ≥ 18)

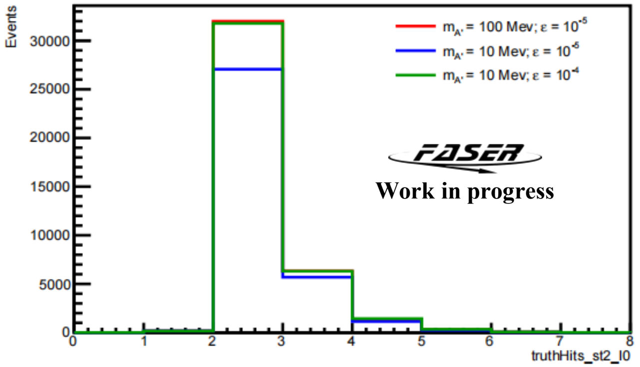
- Setting "truthParticle_Hits ≥ 18" basically ensures that there will be at least one hit in each layer.

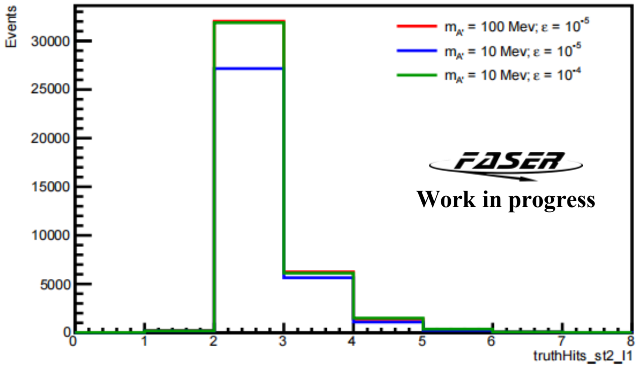
The distribution of truth_nHits per layer

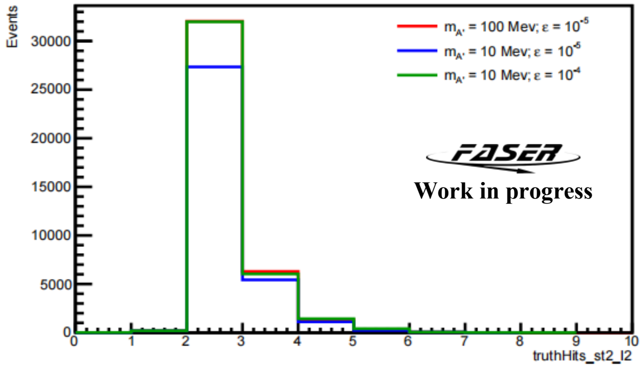


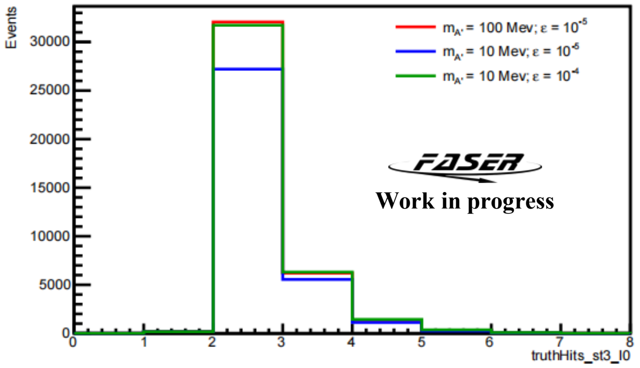


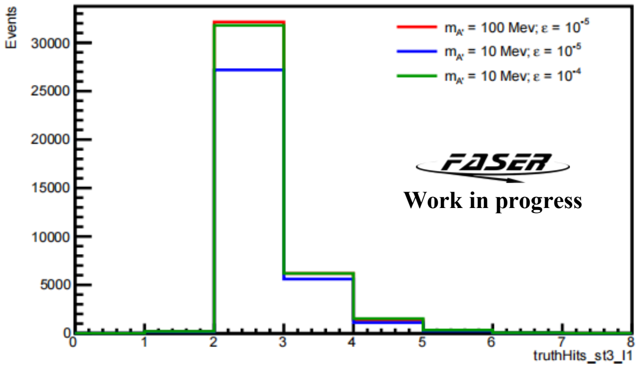


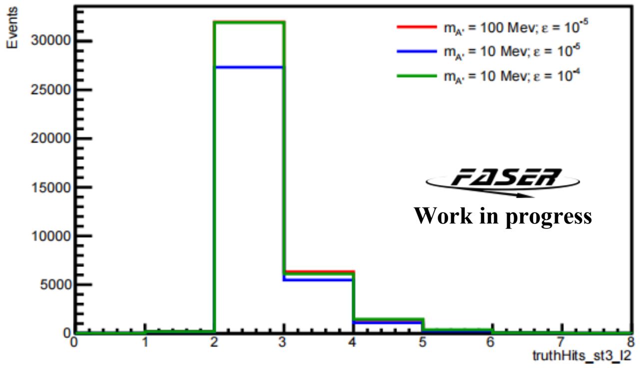












Track merging strategy

- Goal: **Recover full track** by merging compatible forward & backward tracks
- The way of mergeTracks (from Lawson):
  - **Method 1**: GreatestMeasurements
    - Sort all tracks (forward & backward) by number of measurements (↓) and χ^2 (↑)
    - Remove tracks that share more than 6 measurements with higher-ranked ones
  - **Method 2**: SeenByBothForwardAndBackward
    - Match forward & backward tracks based on parameter proximity at same z (e.g. $\Delta r < 5$ mm)
    - For each matched pair, keep track with smaller χ^2