# Status report
# TOF Simulations and Software


## Kentaro Kawade

### Shinshu Univ.

### on behalf of the ePIC ToF simulation team

# Simulation team & tasks

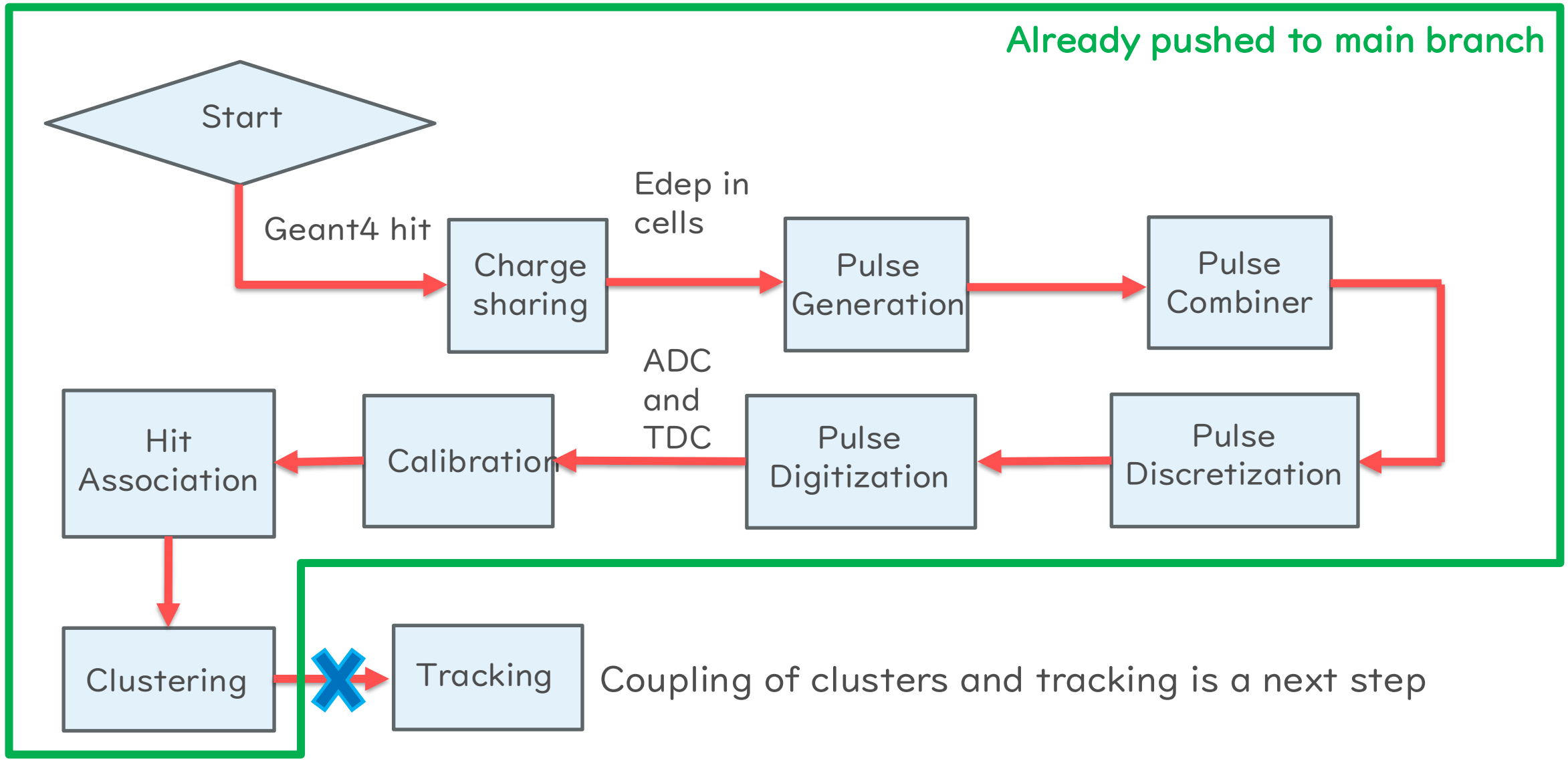
| | Task Category | System | Assignee | Progress |
|---|---|---|---|---|
| | PID performance | BTOF | Kentaro + Kyohei | Done (Jul 2025) |
| | | FTOF | Abdelghani   | **Result (New)** |
| | Material Budget | BTOF | Kyohei   | Done (Jul 2025) |
| | | FTOF | Honey + Abdelghani | **Started** |
| | Effect on Tracking | FTOF | Tommy | **Ongoing** |
| | Digitization | BTOF | Tommy | Done (July 2025) |
| | | FTOF | Honey | **Ongoing** |
| | Geometry | BTOF/FTOF | Tommy | Up-to-date |

- Important note
  - Performance studies and digitization works run in parallel with own framework
  - Need to rerun everything after full digitized simulation will be available

# TOF Digitization

## Tommy and Honey

# BTOF digitization work-flow design



# ToF digitization work-flow design; FTOF

Geant4 hits

↓

2-D Gaussian smearing and Charge sharing

↓ Completed

Pulse generation, combiner and discretization

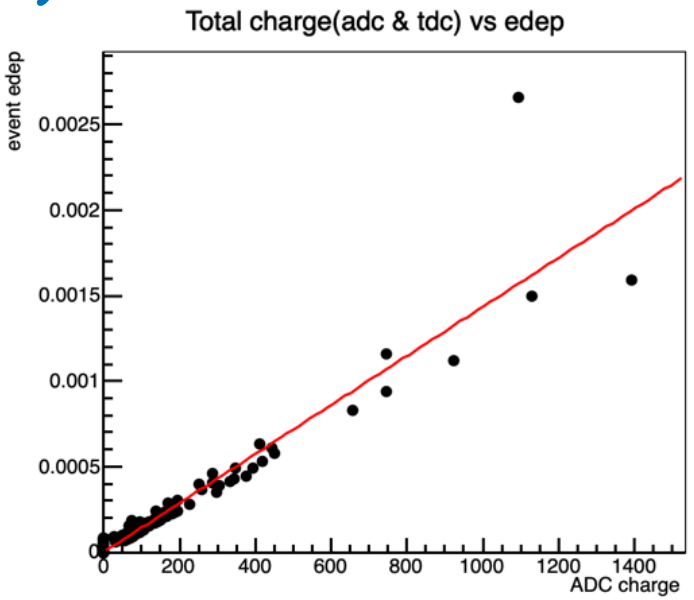
↓ ADC and TDC values(Completed)

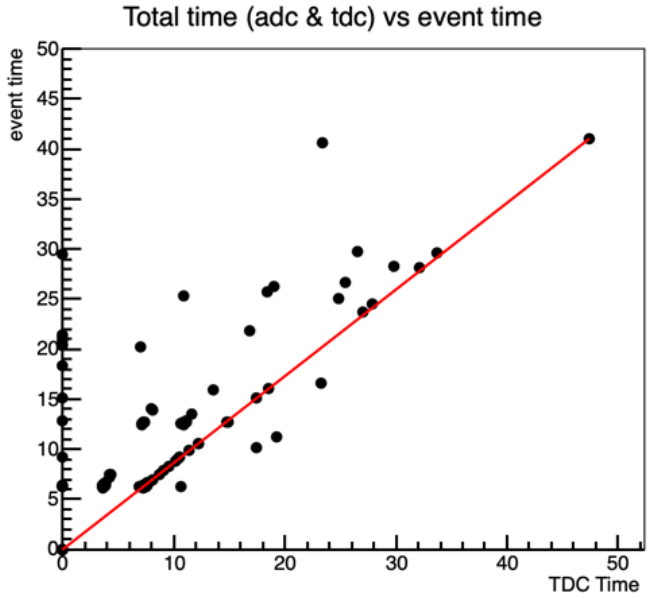
Pulse Digitization

↓ Future plan

Calibration

**Need to complete**

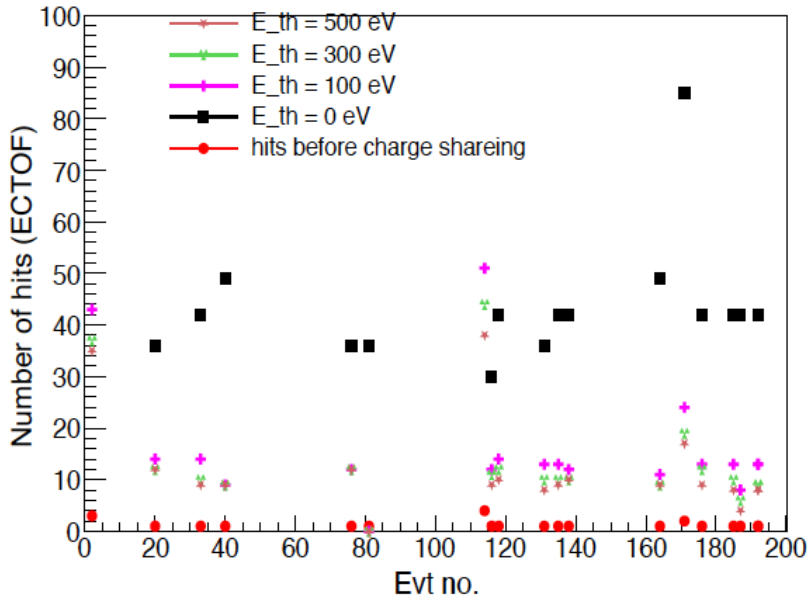


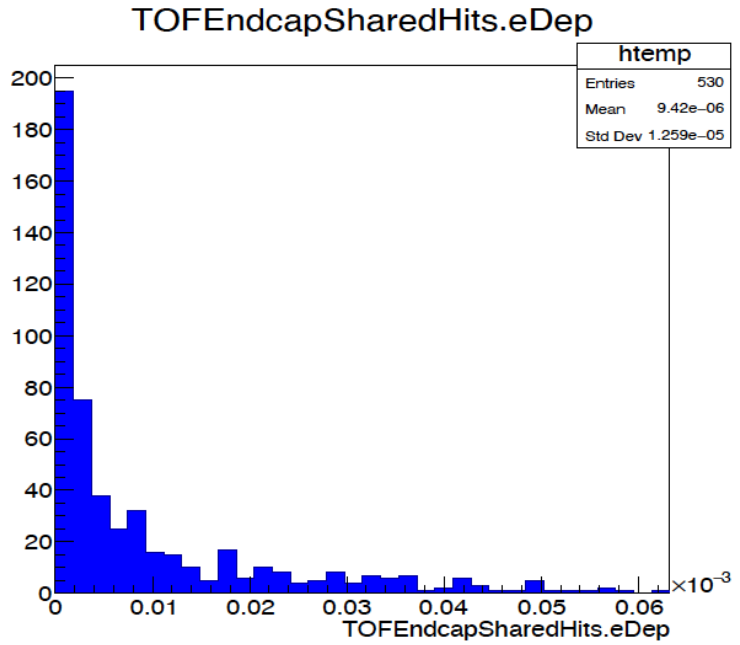



# FTOF; Charge sharing

- Charge sharing steps is now implemented to FTOF
- Sanity check for charge sharing code →
  - Worked as expected
    - But, need to optimize
      - Energy threshold
      - Distribution sigma

  → Once the actual sensor performances are revealed, need to incorporate those results into the simulation to make it more realistic.



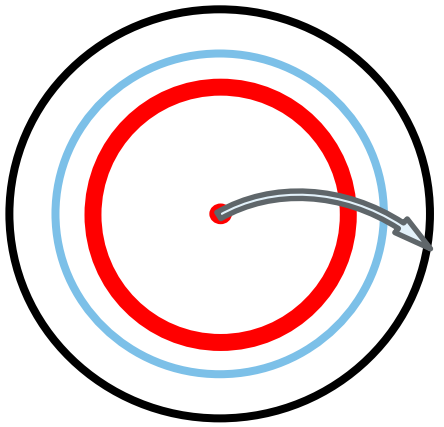
# Material effect Study

We only show BTOF study here, but study of FTOF material effect on dRICH is just started

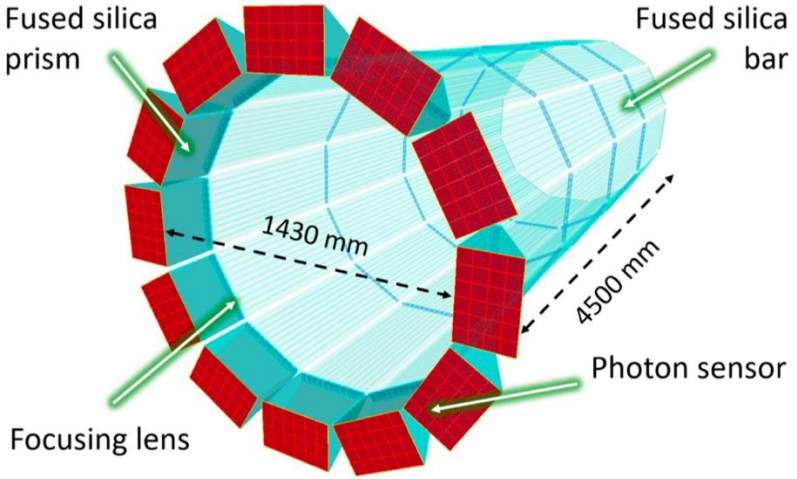
# Reminder: Material budget

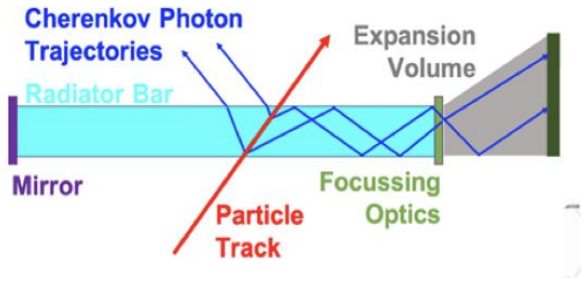
- Estimate the impact of BTOF material budgets on the outer hpDIRC angular resolution
  - To optimize the BTOF design and performance
  - Crucial inputs for sensors, structures and readout PCBs
    to relax the tight requirement ( $1\%\ X_0$)

- hpDIRC is a **Cherenkov** particle identification detector
  → Angular resolution at the surface is important
    - Target@6 GeV/c: $\Delta\theta = 0.5$ [mrad]
  - Material budget of BTOF
    → Affects on angular resolution due to multiple scattering effects
    Determine the upper limit of the BToF material budget



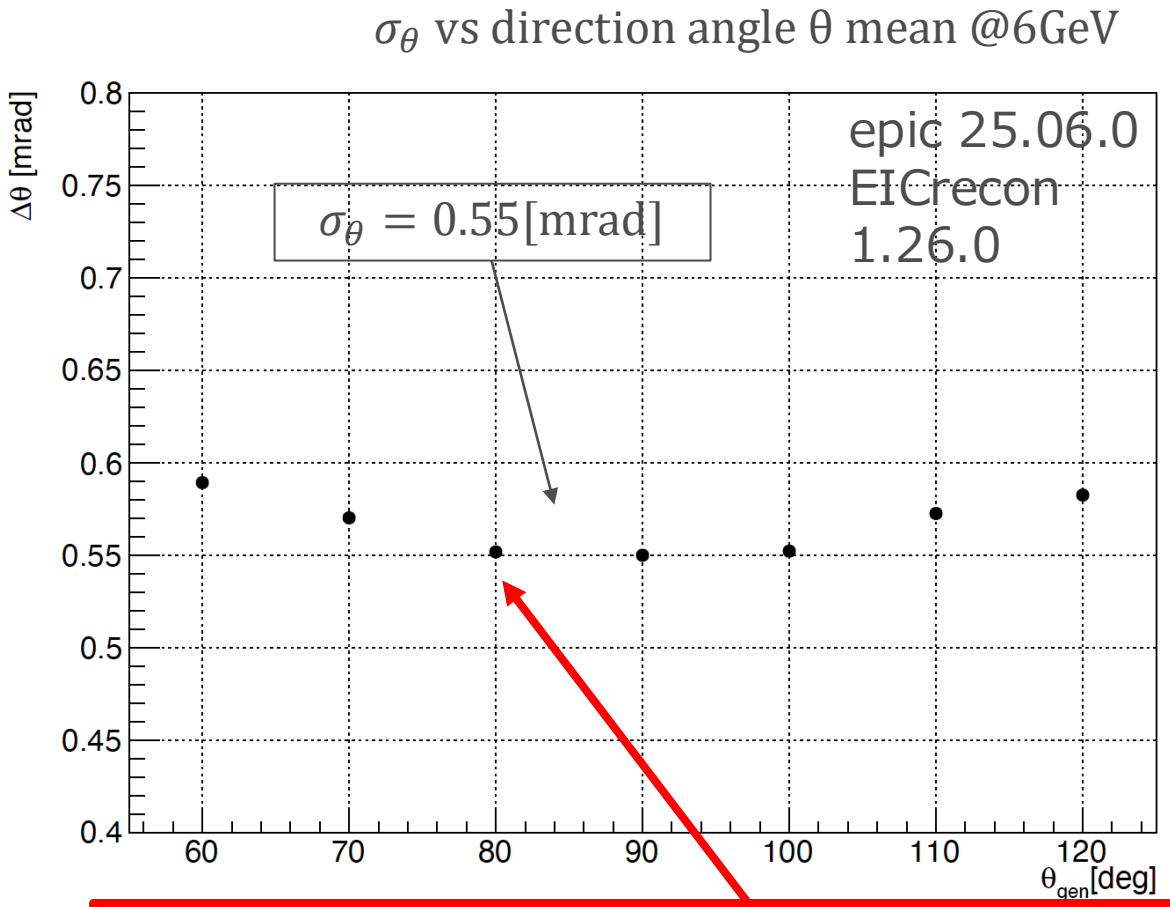

hpDIRC:
high performance Detection of Internally Reflected Cherenkov light

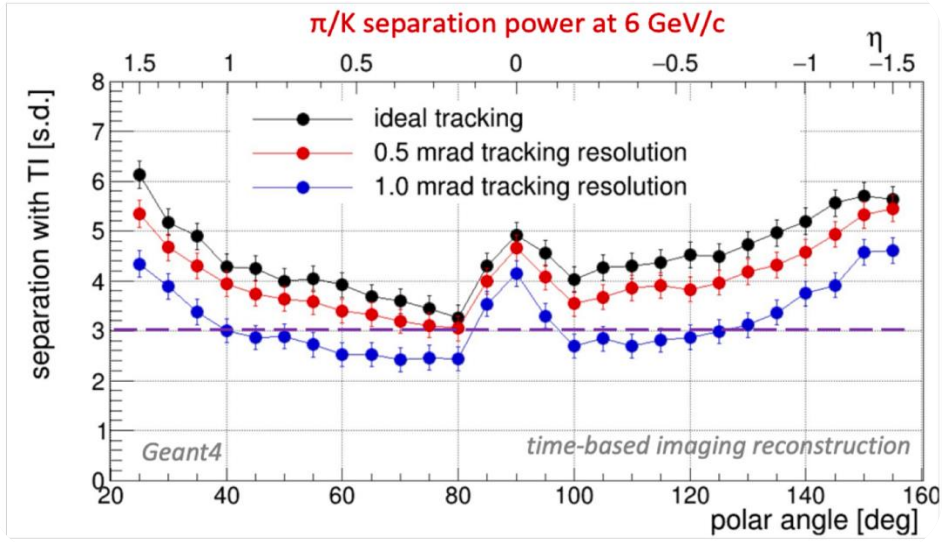


# Angular Resolution vs. angle

- Best resolution achieved at $\theta \approx 90^{\circ}$ (as expected)
  - But; Still does not match the requirement **"0.5 mrad @ 6 GeV"**

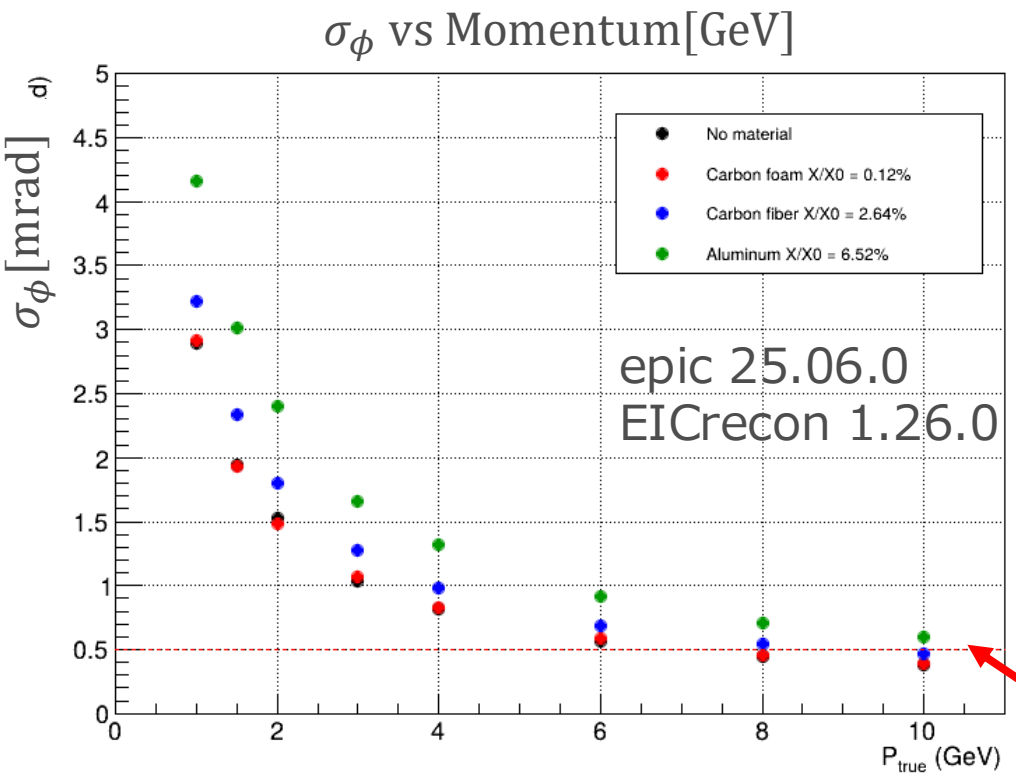


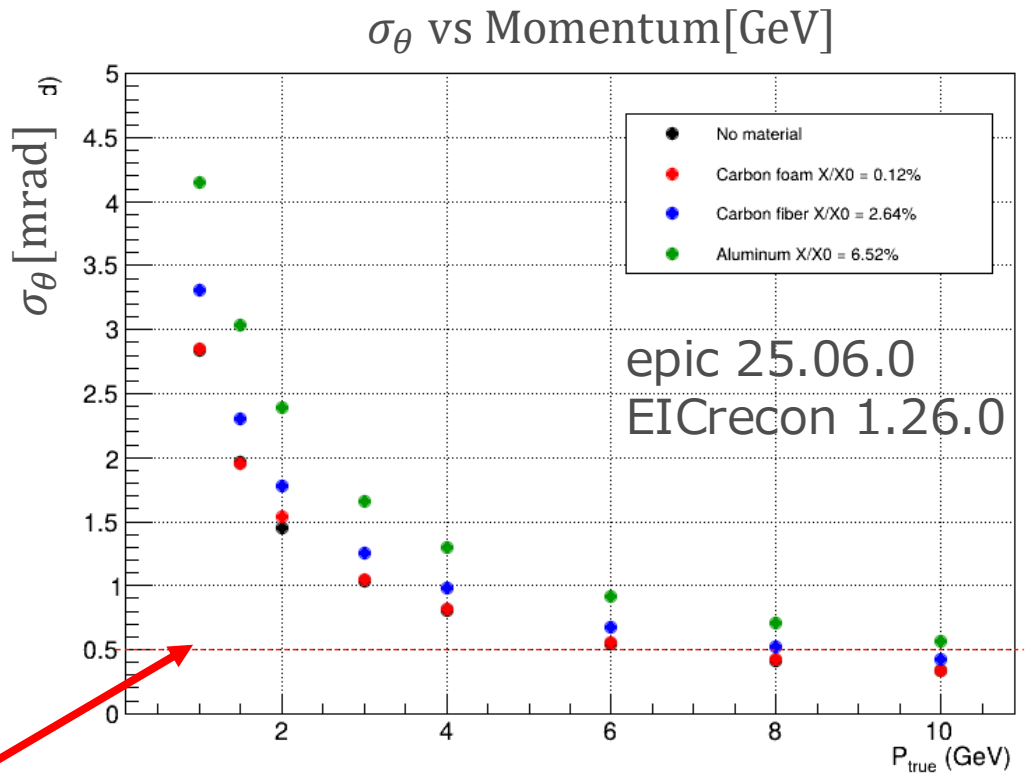




Detector Requirements 0.5mrad @ 6GeV @ 80°

# Angular Resolution for different Materials

- Slight performance degradation observed with increasing material budget
  - Carbon foam keep the resolution close to requirement
  - **But, not very sensitive to material budget !**




Detector Requirements 0.5mrad @ 6GeV

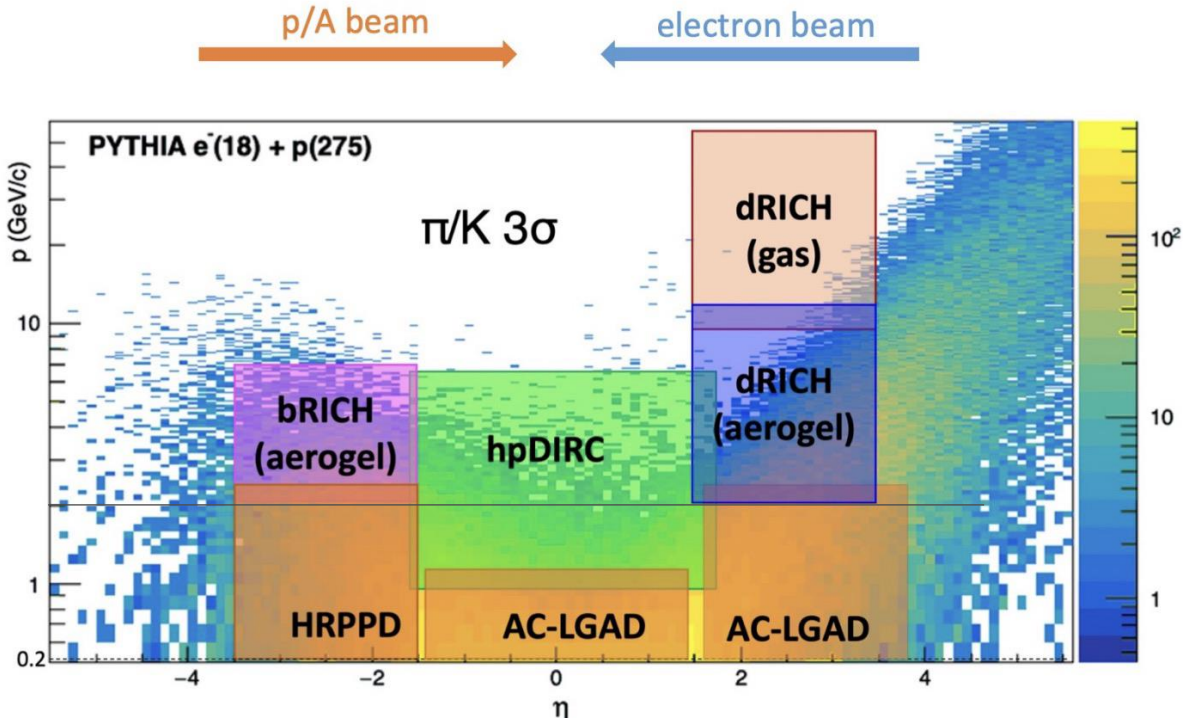
# TOF PID performance

# Note

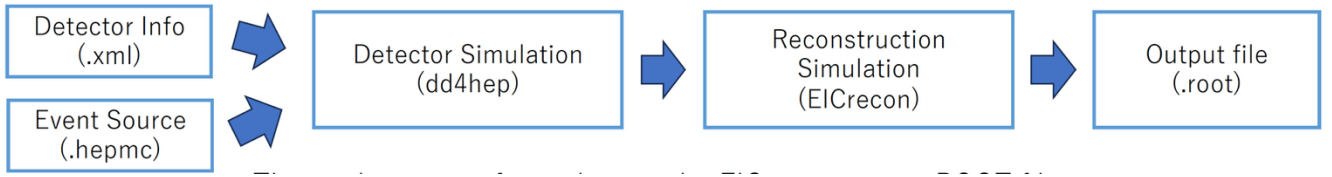
- Generators
  - BTOF/FTOF: Pythia NCDIS
    - $N_{events}$: 200k
    - Energy: 18x275 GeV
  - BTOF: pi/K/proton
    - $N_{events}$: 100k for each
    - $0.1 \leq p \leq 5.0\ \mathrm{GeV}$
    - Eta&Phi: Flat
  - epic ver.
    - BTOF 25.04.1
    - FTOF 25.08.0

- Reconstruction framework
  - EIC Recon ver.
    - BTOF 1.24.2
    - FTOF 1.29.0

- Own developed offline analysis code



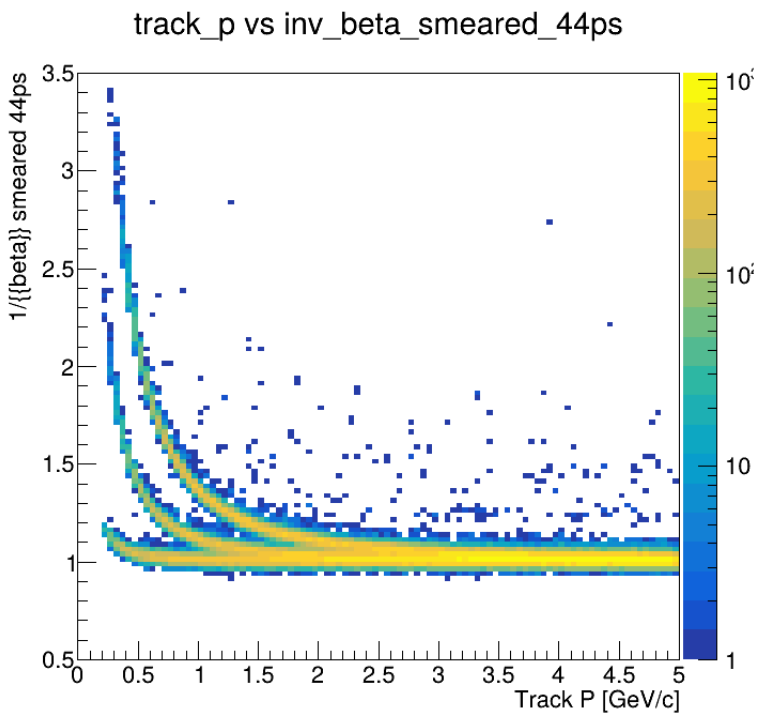

ePIC PID requirement

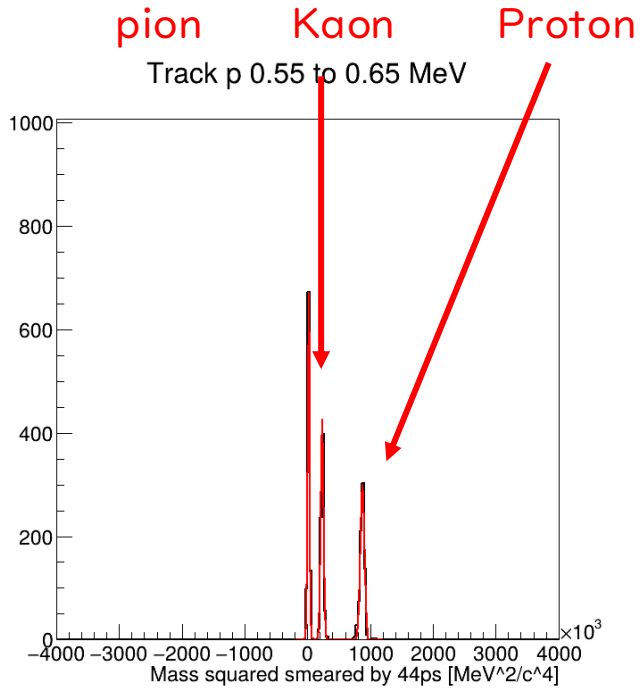


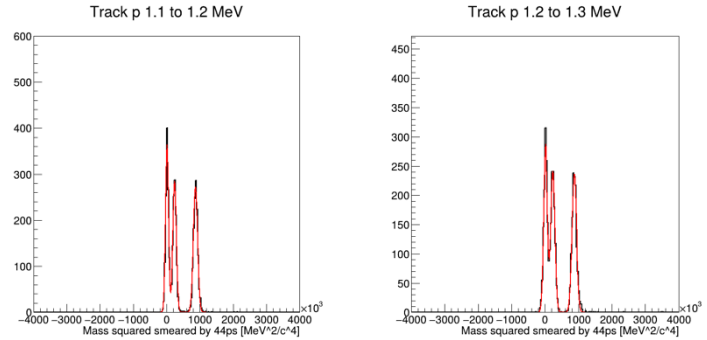

- PID performance when considering finite timing resolution will be shown

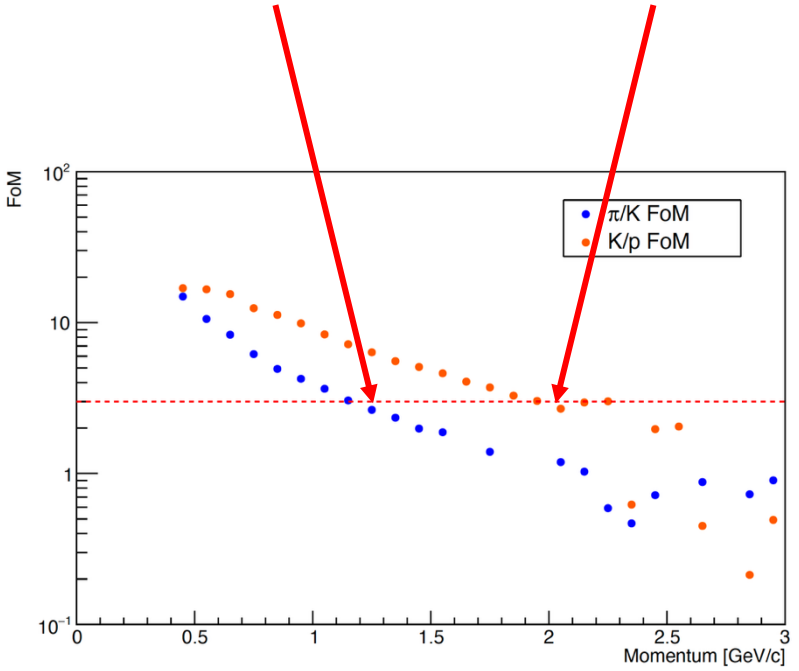
# BTOF: Results w/ $\sigma_t$=44 ps

- This (44ps total timing resolution) is a realistic option (Others in Backup)



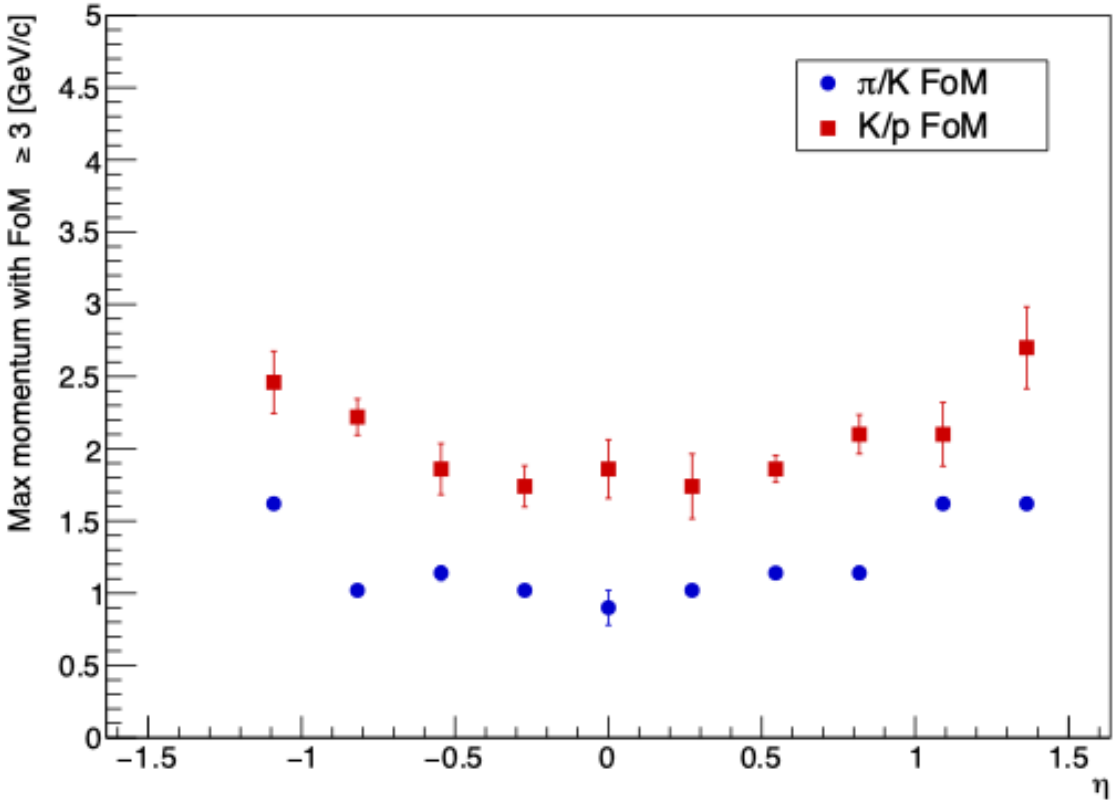




- pi/K 1.2 GeV
- K/p 2.0 GeV

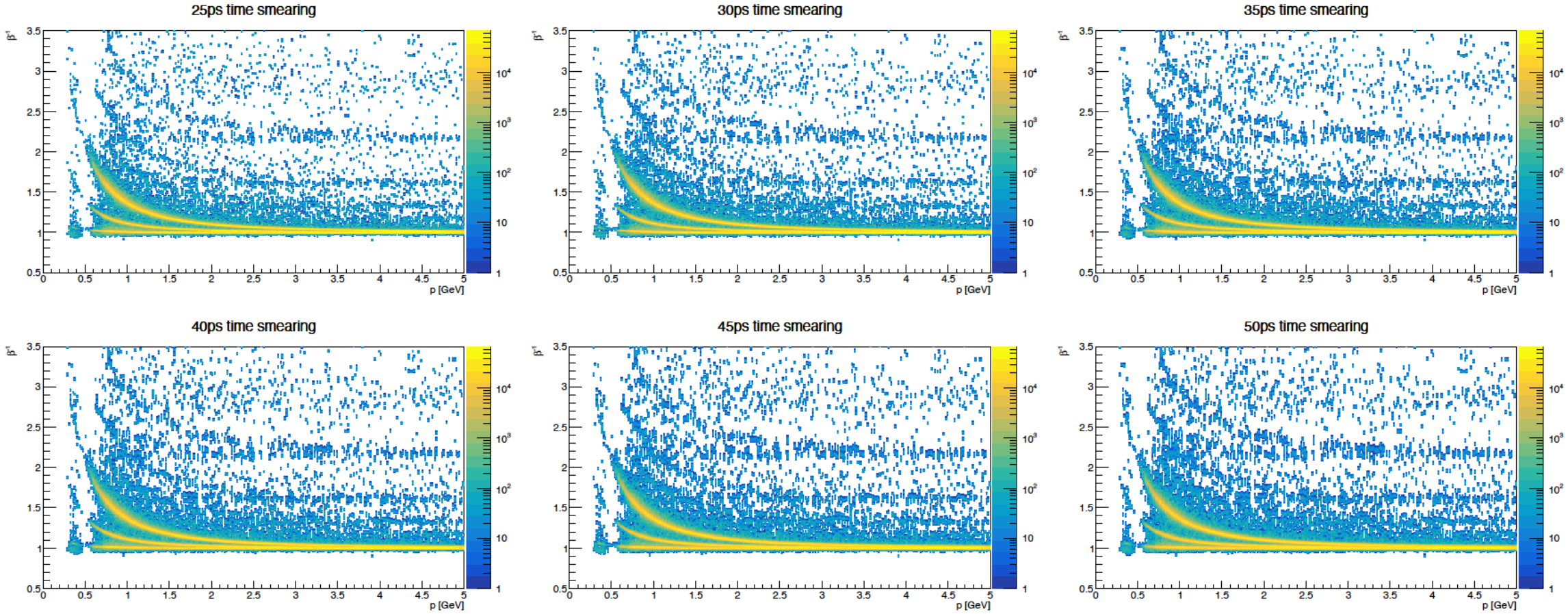
# 3 σ separation vs eta

- Perform same analysis differentially in eta bin
- No strong dependence



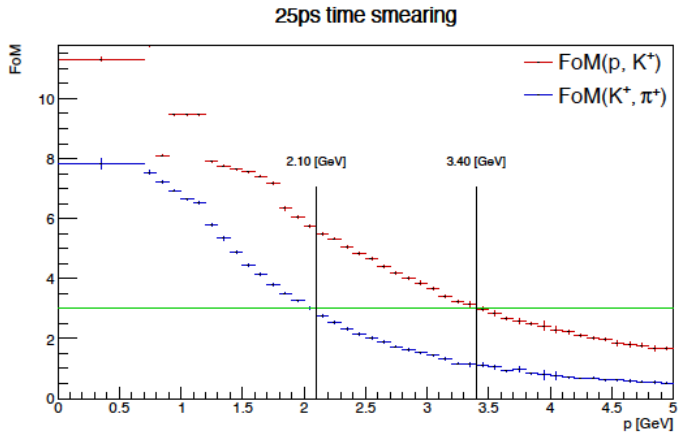
# FTOF: beta- I

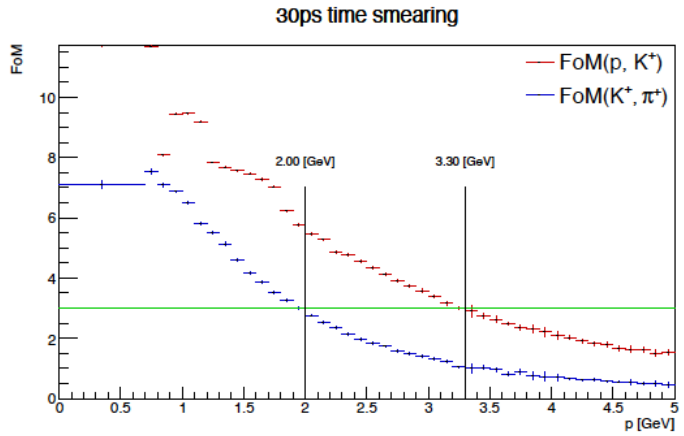
- Momentum vs beta with different timing resolution
- Same way with BTOF to estimate PID performance

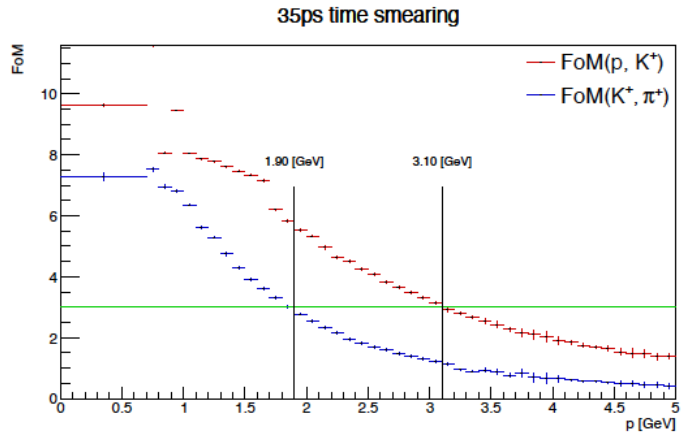


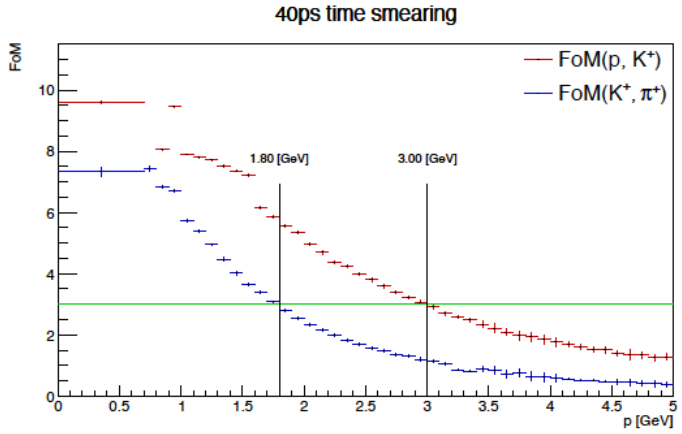
# FTOF: 3 $\sigma$ separation power

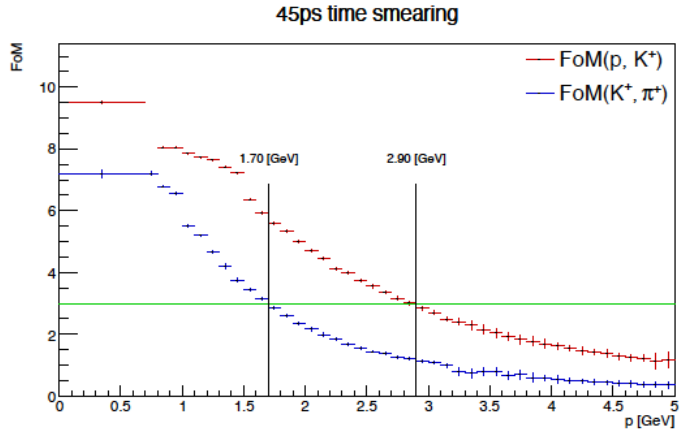
- Slightly worse than FTOF requirement
  - At 40ps timing resolution, 3 $\sigma$ separation upto pi/K 1.8 GeV and K/p 3.0 GeV

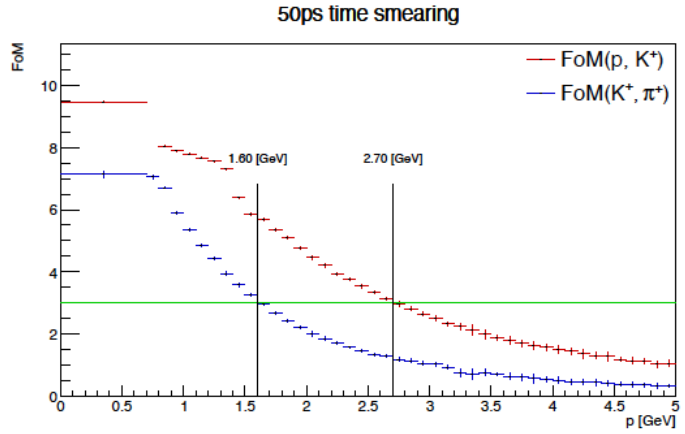


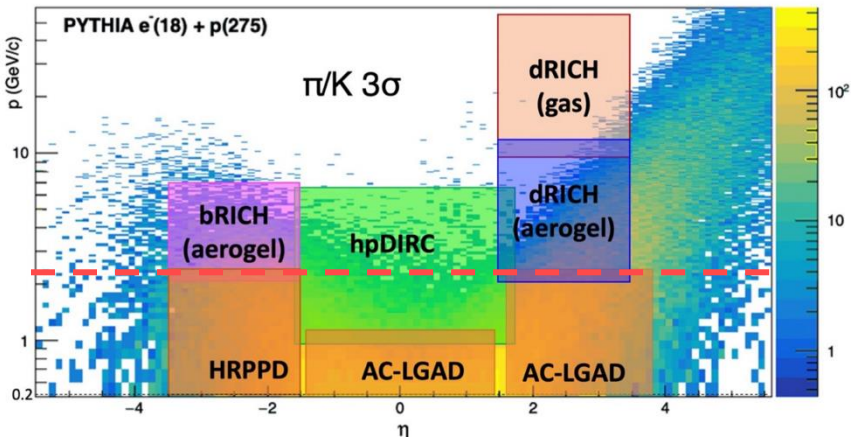



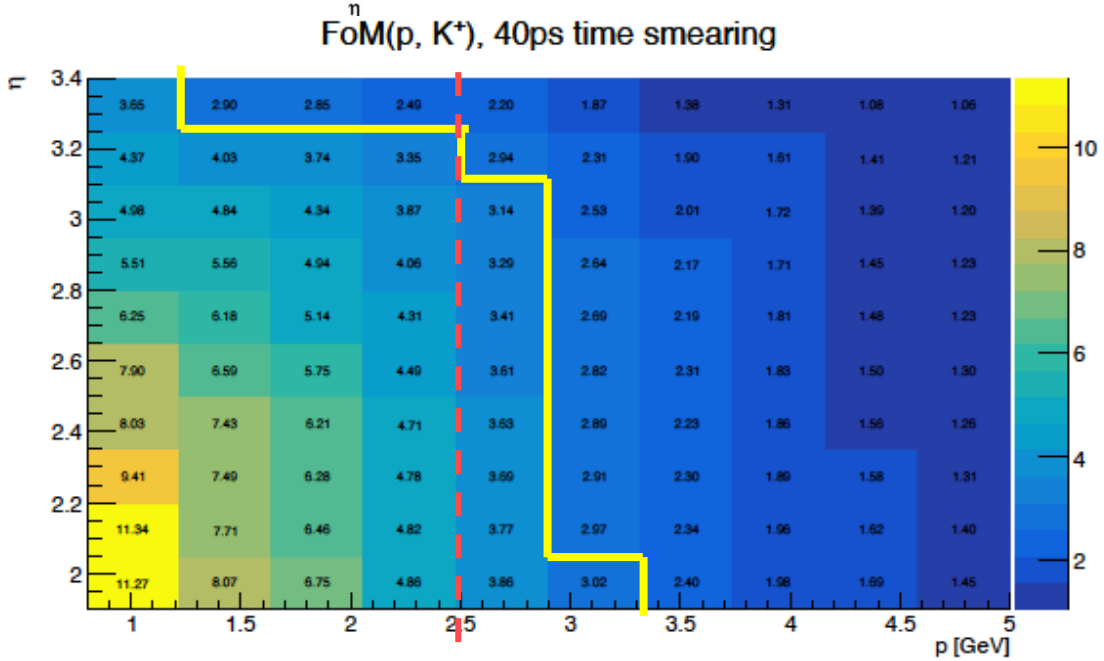



# FTOF: eta dependence



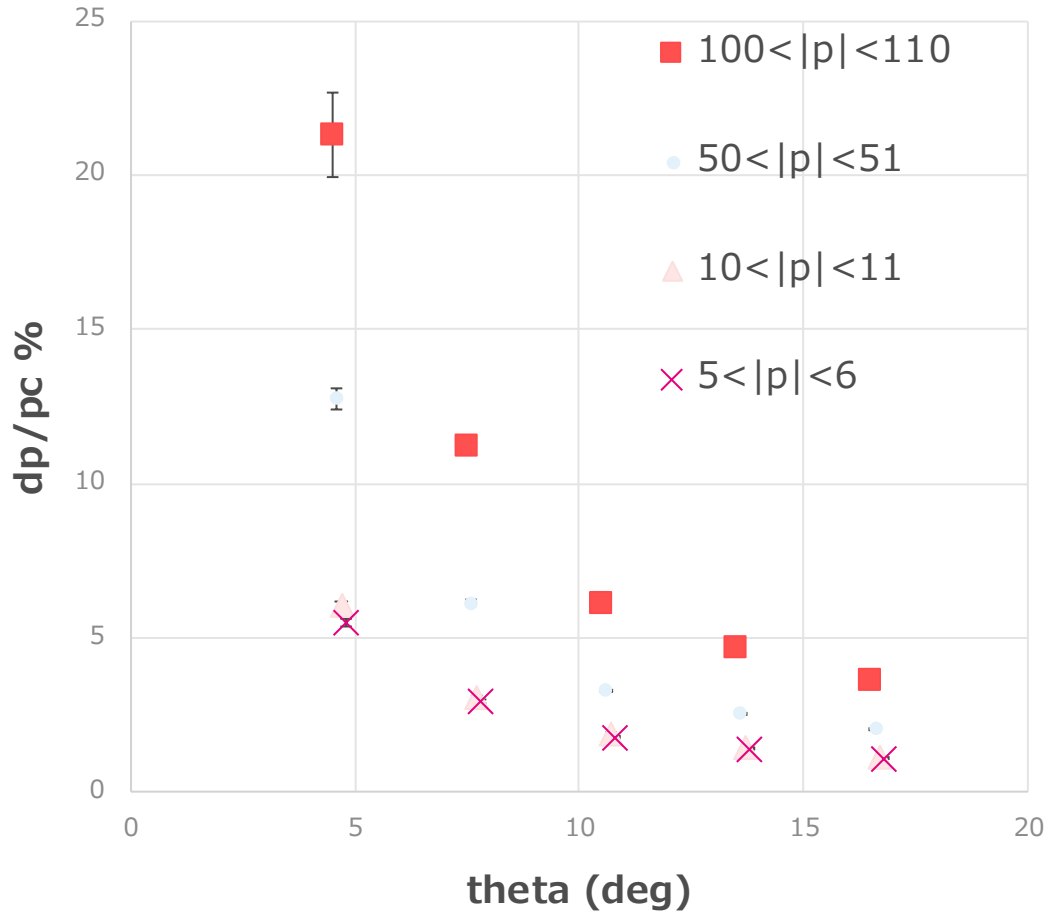

pi/K 2.5 GeV

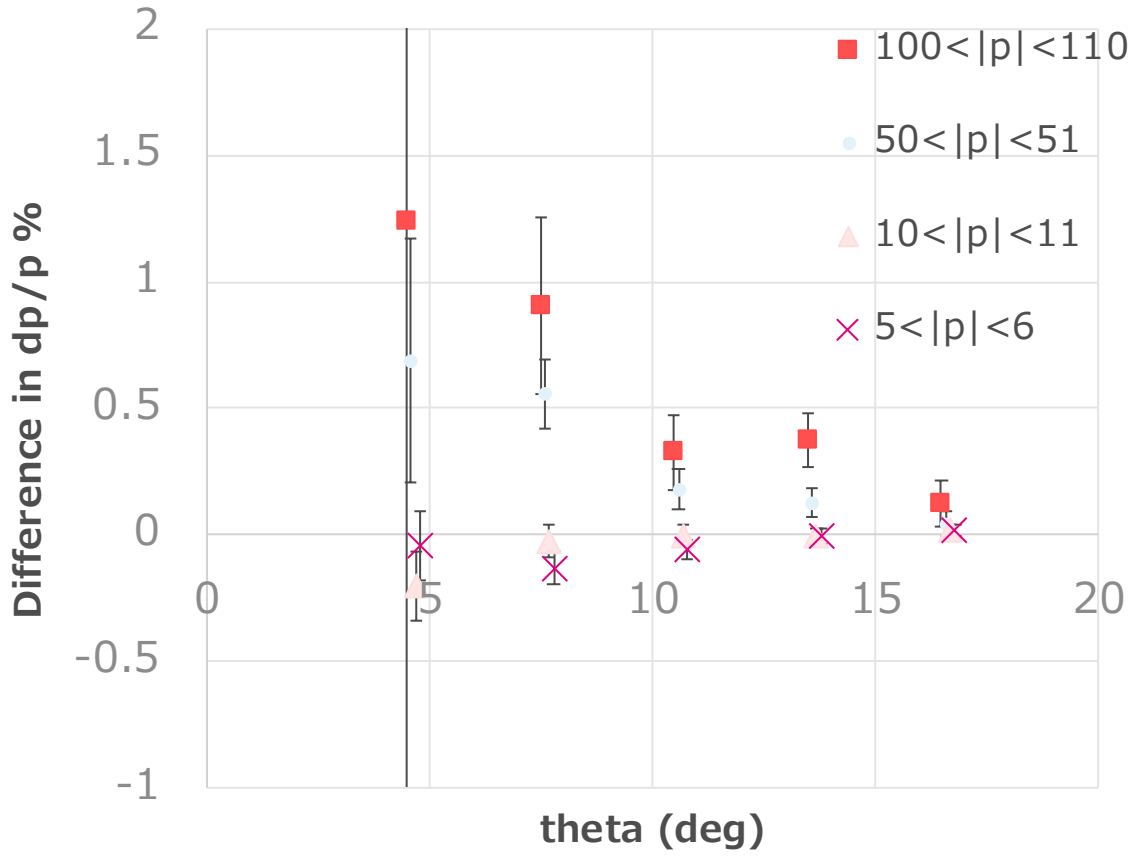



- Not like BTOF, FTOF has strong eta dependence in PID performance
- Only eta > 3.2 region fails PID requirement

# TOF impact on tracking

- Compare momentum resolution with or without TOF (FTOF) in tracking process
  - Without TOF hits, see some degrade especially in high momentum track



# Summary and next steps

**Current Status**

- The TOF Simulation team operates with a small number of members while covering a wide range of tasks
  - In addition to previously showed BTOF results,
    we showed initial PID performance results for FTOF
  - The BTOF digitization tool is ready
    → while synchronization with the performance study is required.
  - FTOF digitization is progressing but still needs further development
- Due to student graduations, securing manpower is essential
  - New Japanese students are expected to join (likely)
  - Those who interested are welcome!

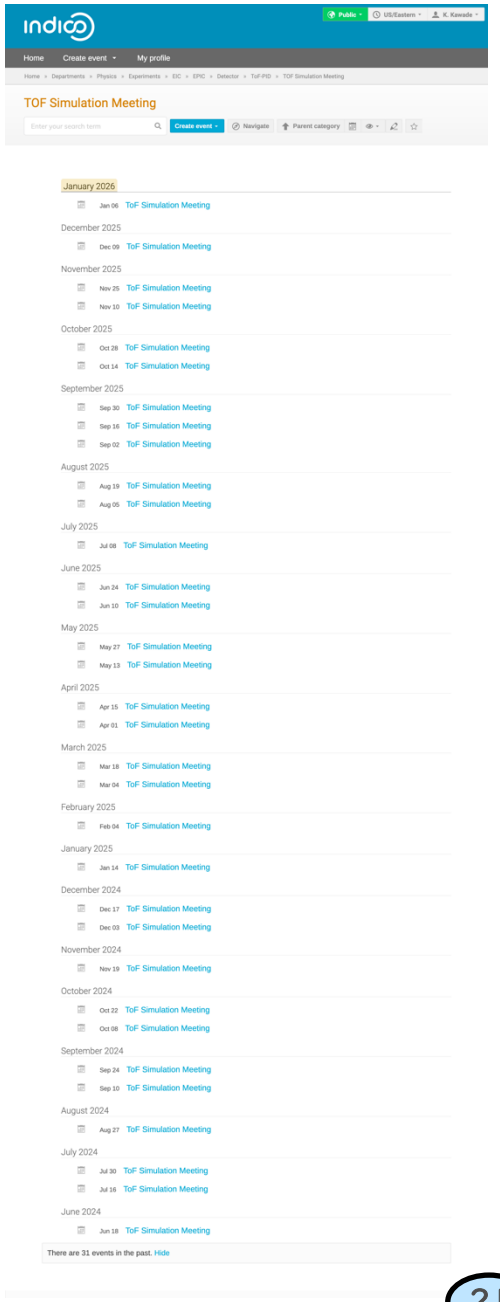
Next steps

- Digitization work and performance studies are currently independent
  → integrate them into a continuous workflow is important
- We use own performance benchmark
  → We recongnized adopting more widely used benchmarks would be beneficial

# BACKUP

# TOF Simulation Working Group

https://indico.bnl.gov/category/569



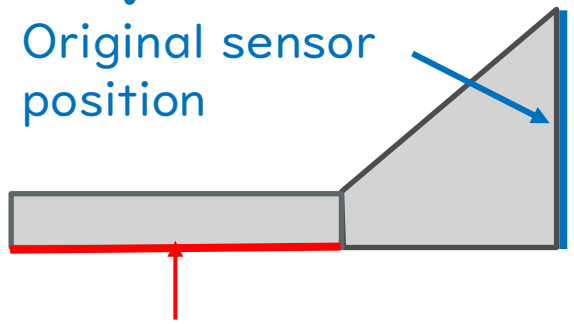

- Coordinators
  - Kentaro Kawade, Tommy Tsang Chun Yuen
- Holding biweekly expert meeting
- Current Activities
  - Tommy (KSU)
    - Digitization for BTOF
    - Implement new TOF geometry/design
  - Honey Khindri (IIT Madras)
    - Digitization for FTOF
    - Impact of FTOF material budgets on dRICH resolution

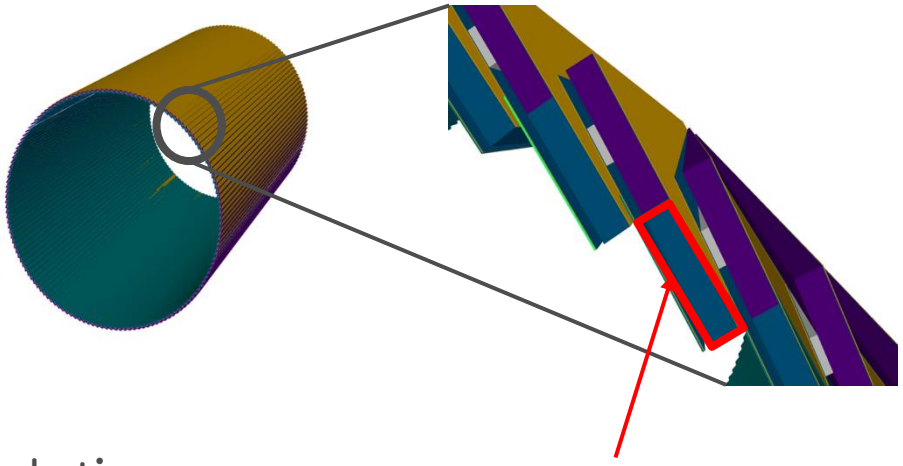

  - Kyohei Ono (Shinshu)
    - Impact of BTOF material budgets on hpDIRC resolution
  - Kentaro Kawade (Shinshu)
    - Evaluate PID performance for BTOF


  - **Abdelghani El Ouardi (Mohammed V)**
    - **Evaluate PID performance for FTOF**

# Simulation setup: Angle & Material Study

1. Added sensitive layer at the hpDIRC surface
   - To take truth hit position at the surface
2. Different BToF Support structure materials
   - Carbon foam (default) : 0.09 g/cm$^3$ (0.12% X/X$_0$)
   - Carbon fiber : * g/cm$^3$ (2.64% X/X$_0$)
   - Aluminum : 2.65 g/cm$^3$ (6.52% X/X$_0$)
3. Single particle full Detector simulation in DD4hep
   - Particle: $\pi^-$
   - Fixed Momentum: $1,\ 1.5,\ 2,\ 4,\ 6,\ 8,\ 10\ \mathrm{GeV}$
   - Direction
     - $\phi : 0^\circ \leq \phi \leq 360^\circ$
     - $\theta : 58^\circ - 62^\circ,\ 68^\circ - 72^\circ$ ...
4. EICrecon to perform tracking and calculate angular resolution
   - Take angular resolution using the **"Residual method"**



# Calculate Angular Resolution –Residual method

1. Reconstruct tracks using all tracker hits with a Kalman filter
2. Propagate the fitted tracks to the hpDIRC surface

   → Use the intersection as a reconstructed hit position

$$\theta_{prop} = \arctan2\left(\sqrt{{p_x}^2 + {p_y}^2}, p_z\right)$$

$$\phi_{prop} = \arctan2(p_x, p_y)$$

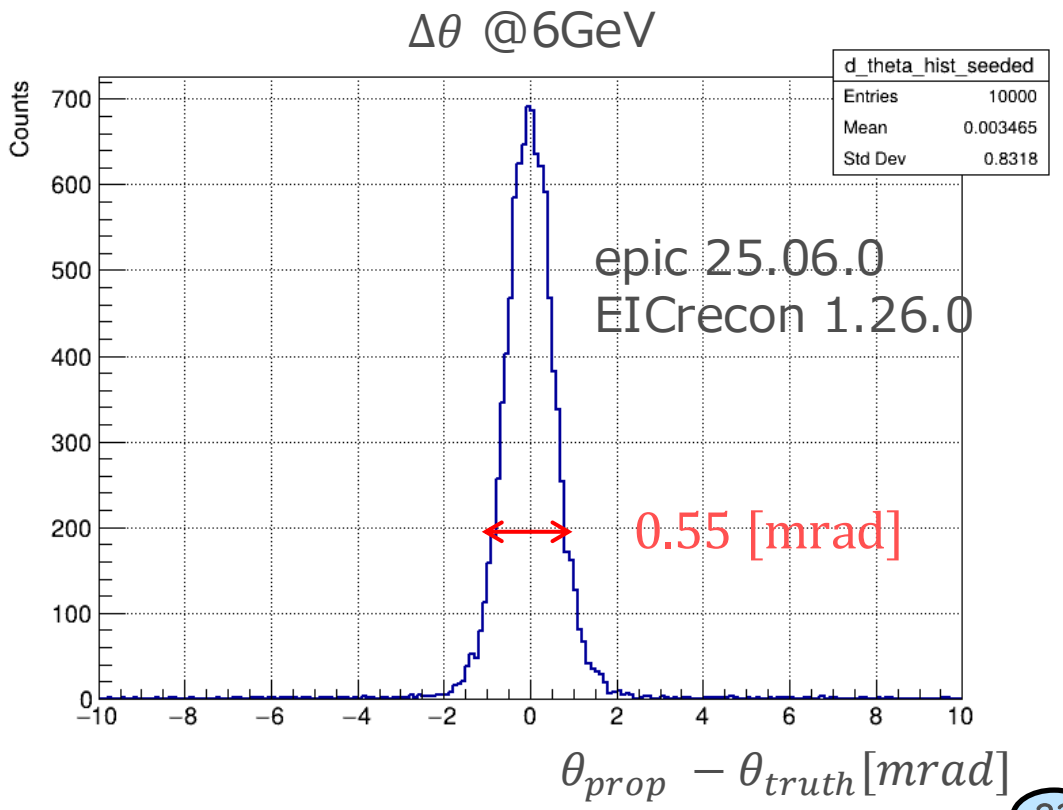
3. Take difference of propagated track angles and truth hit angles

$$\Delta\theta = \theta_{prop} - \theta_{truth}$$

$$\Delta\phi = \phi_{prop} - \phi_{truth}$$

   – Resolution is given by Gaussian sigma

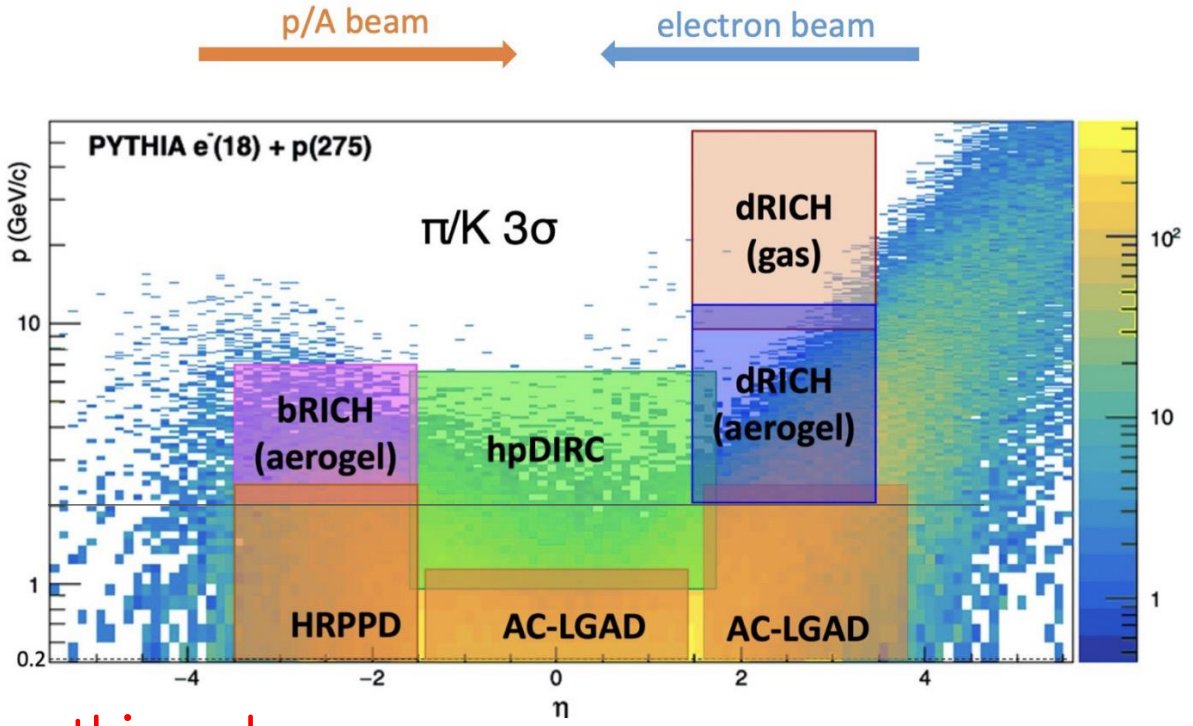
   Ex) $\sigma_\theta = 0.55$ [mrad] @ 6 GeV



# Note

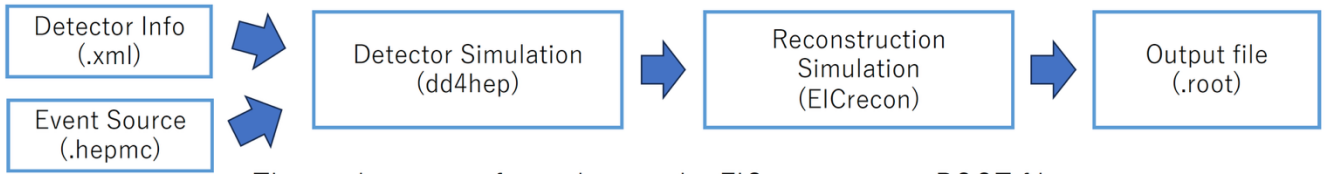
- Generators
  - Pythia NCDIS
    - $N_{events}$: 200k
    - Energy: 18x275 GeV
  - **Particle Gun: pi/K/proton**
    - $N_{events}$: 100k for each
    - $0.1 \leq p \leq 5.0$ GeV
    - Eta&Phi: Flat
  - epic ver 25.04.1

This report focus on this only




ePIC PID requirement

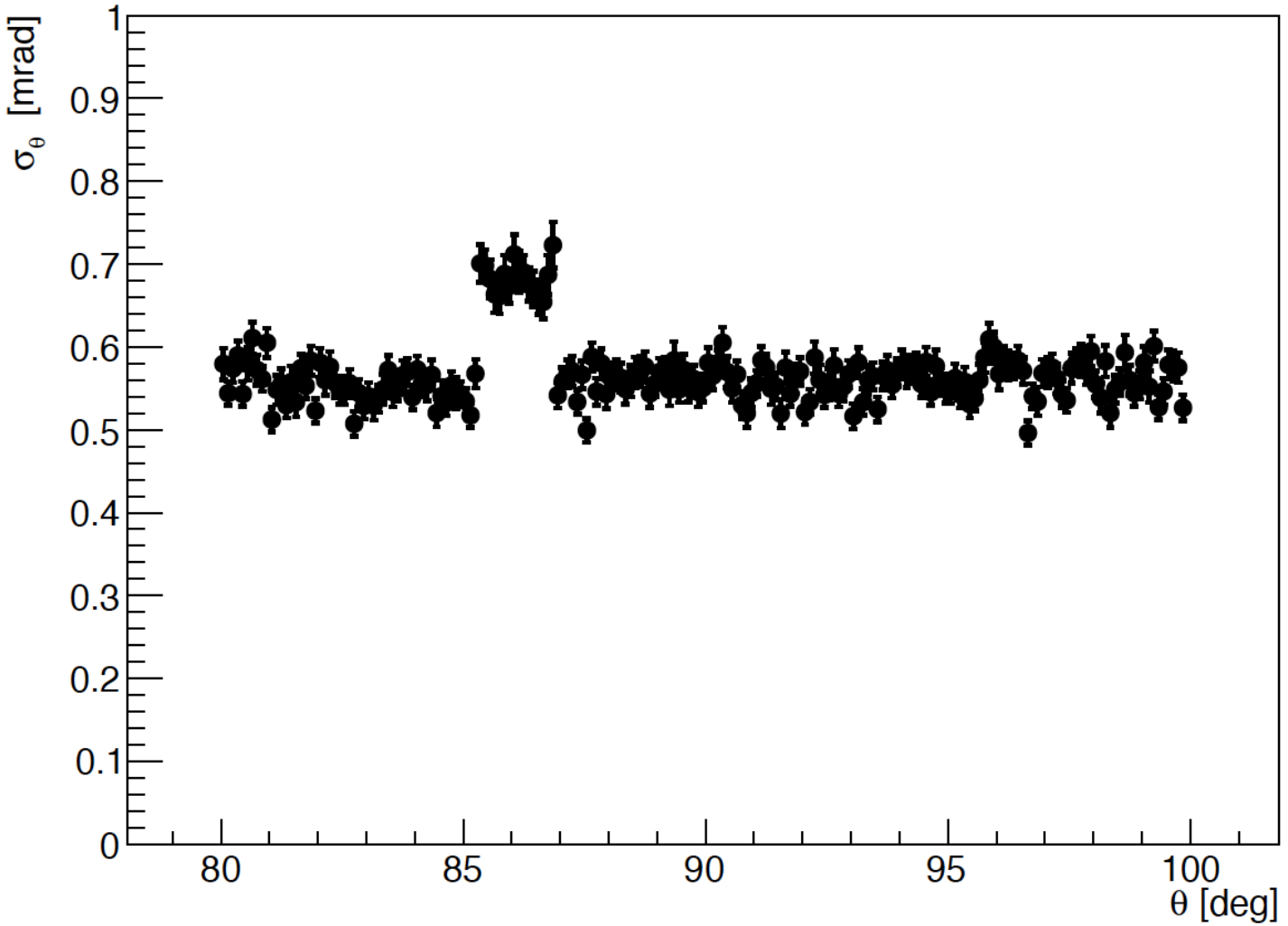
- Reconstruction framework
  - **EIC Recon Version 1.24.2**




- Own developed offline analysis code

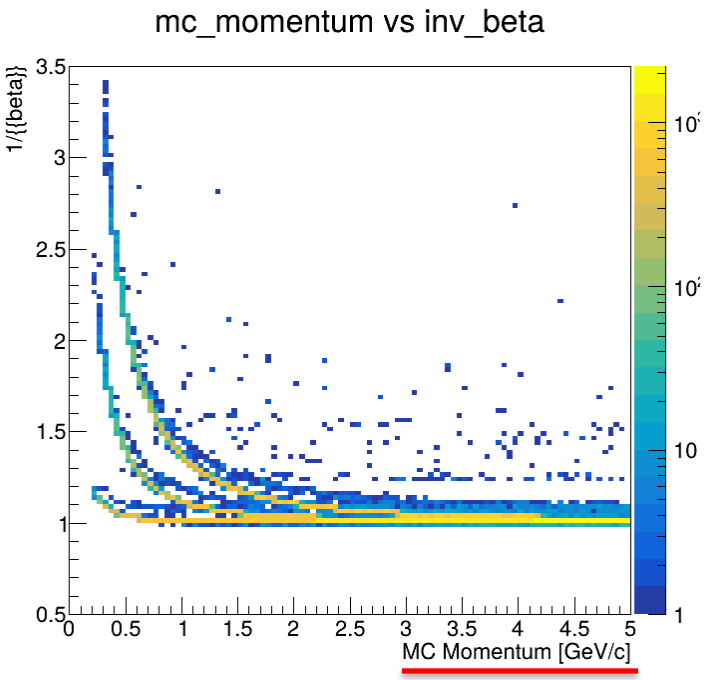
- PID performance when considering finite timing resolution will be shown

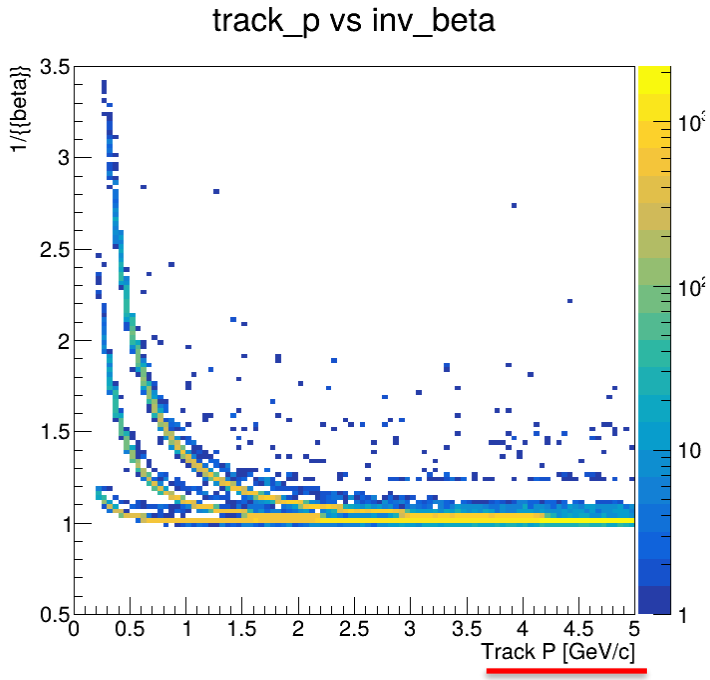
# Tracking performance w.r.t theta

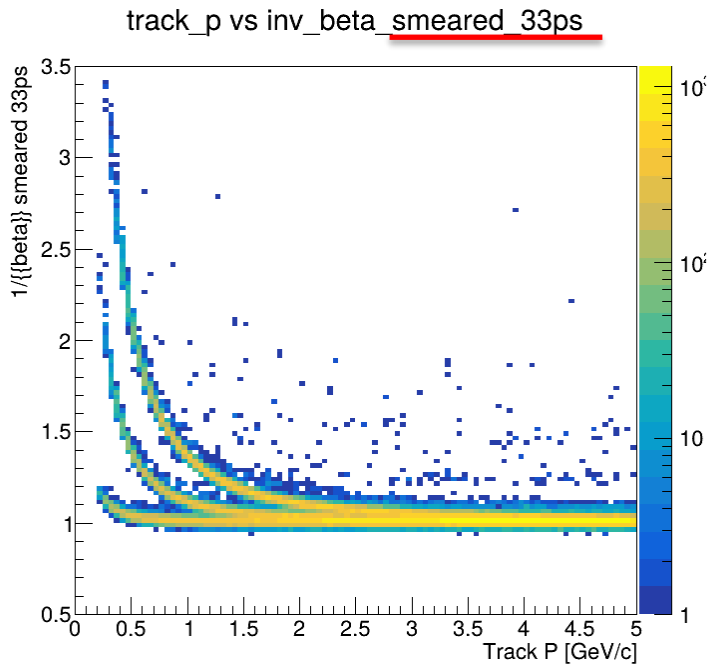


# 1 / β vs track momentum or truth momentum

- β can be calculated from track path length and ToF time
  - For PID use mass^2 from β and momentum
- Track momentum reconstruction looks OK
  - MC Truth momentum and reconstructed momentum showed identical relation



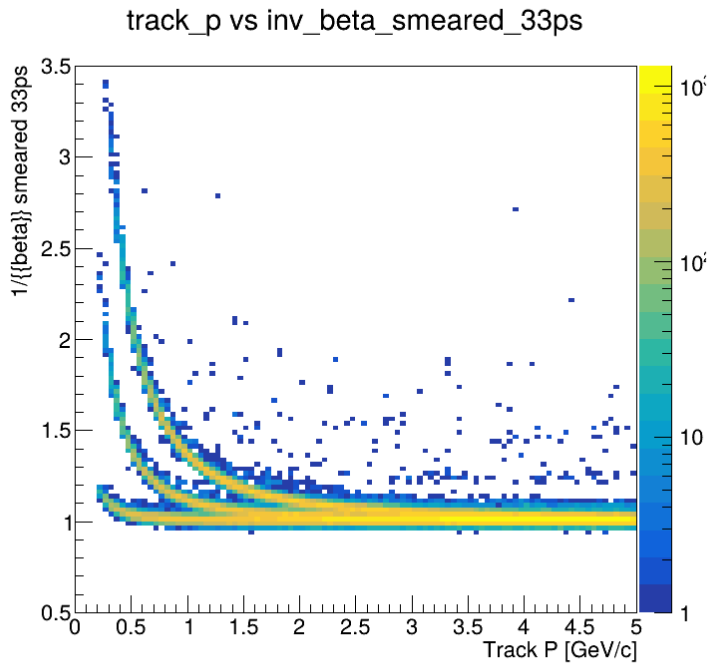



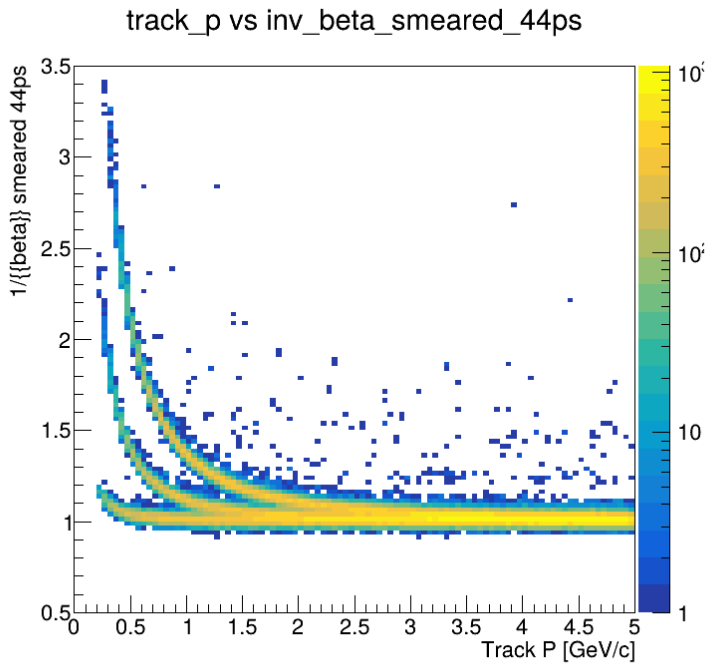

Truth momentum

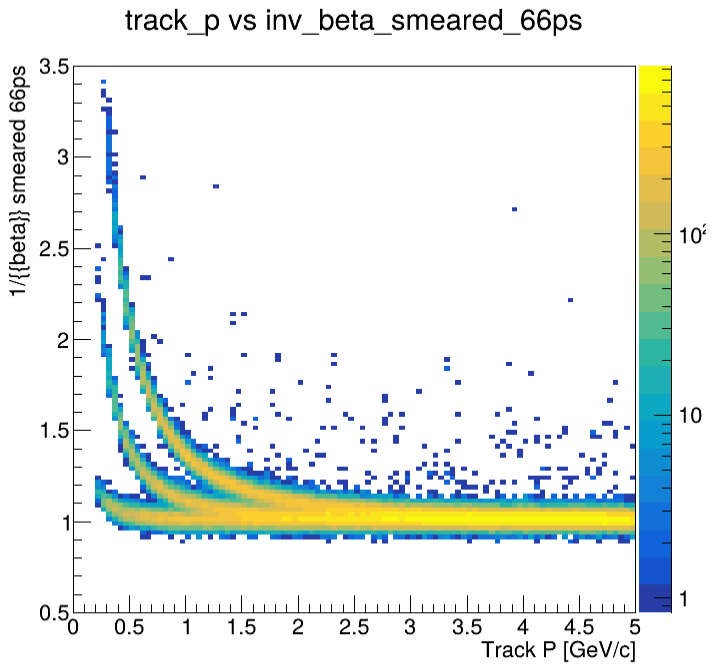
Reco momentum

# $1/\beta$ vs track momentum + timing smearing

- Timing resolution looks crucial for beta estimation
  - 33 ps smearing: Aggressive scenario
  - 44 ps smearing: Baseline scenario (including $\sigma_{sensor}$ , $\sigma_{Elec}$, $\sigma_{T0}$)
  - 66 ps smearing: Worst case scenario

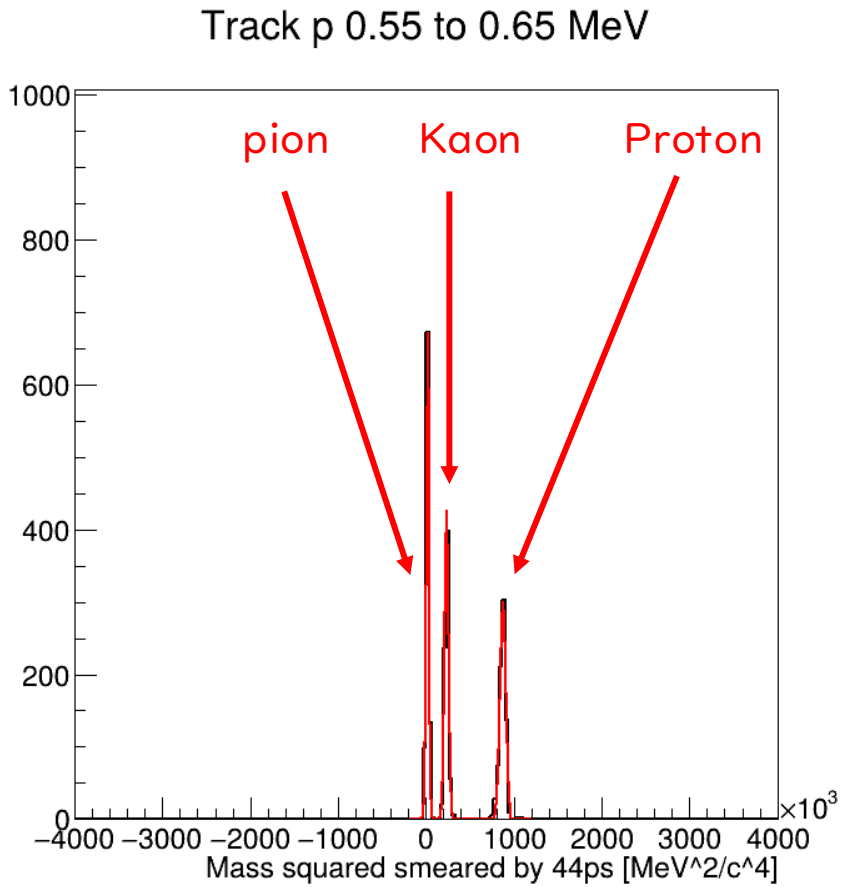


# PID performance evaluation: Gaussian fit

- Obtain each mass peak and its width
  - inclusive 3 gaussian fitting



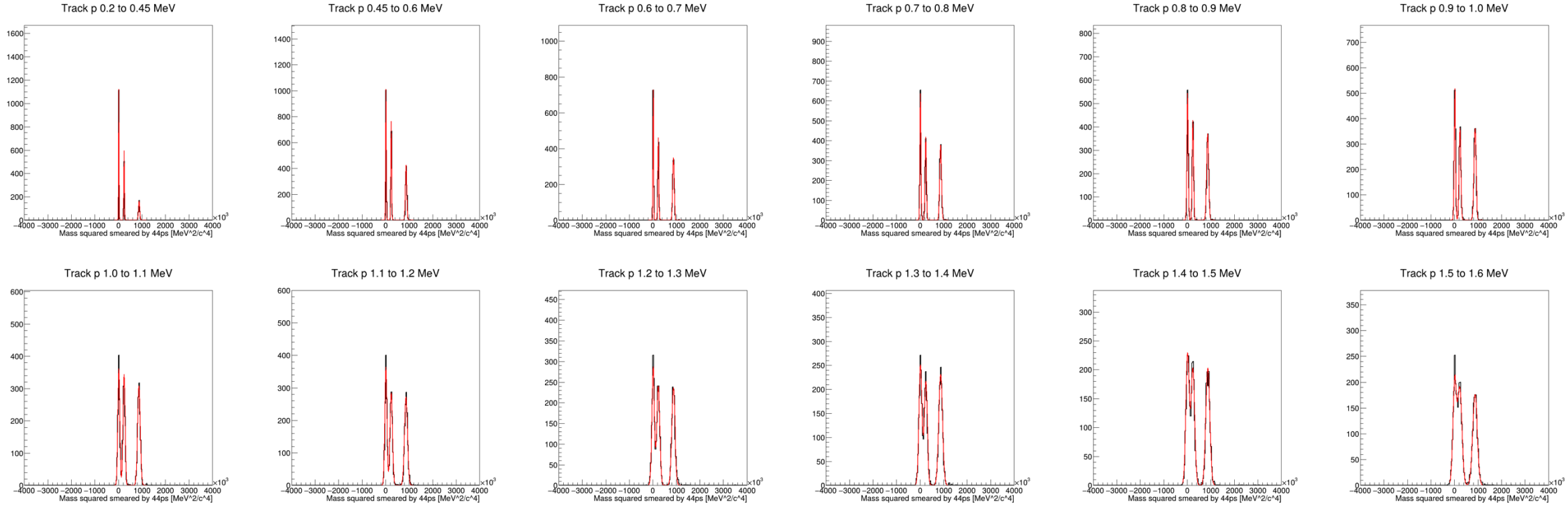

- Introduce Figure of Merit (FoM), to assess the PID performance quantitatively

$$\mathrm{FoM} = \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}}$$

  - $\mu$ : mass$^2$ peak position
  - $\sigma$ : gaussian width

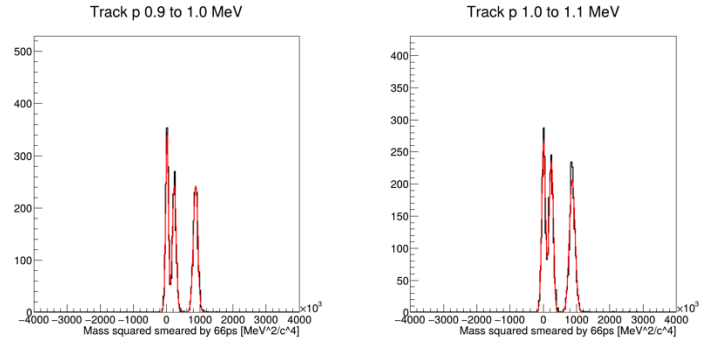
# Fitting over each track momentum bin

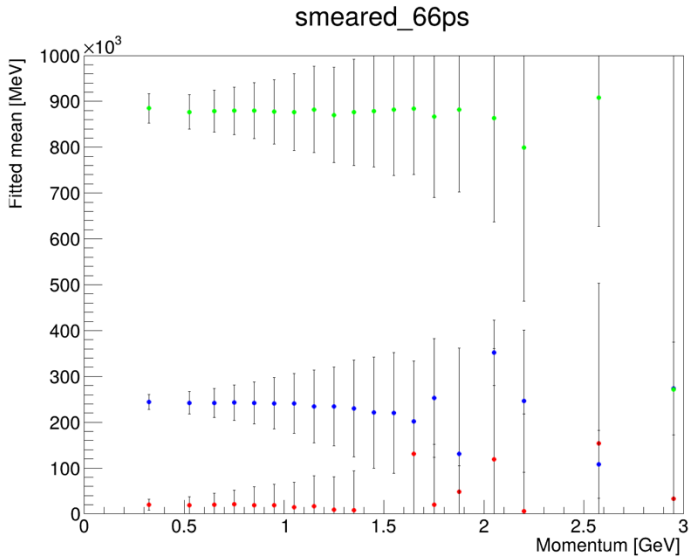
- Minimum bin interval is chosen such that each bin contain at least 2000 events to stabilize the fitting

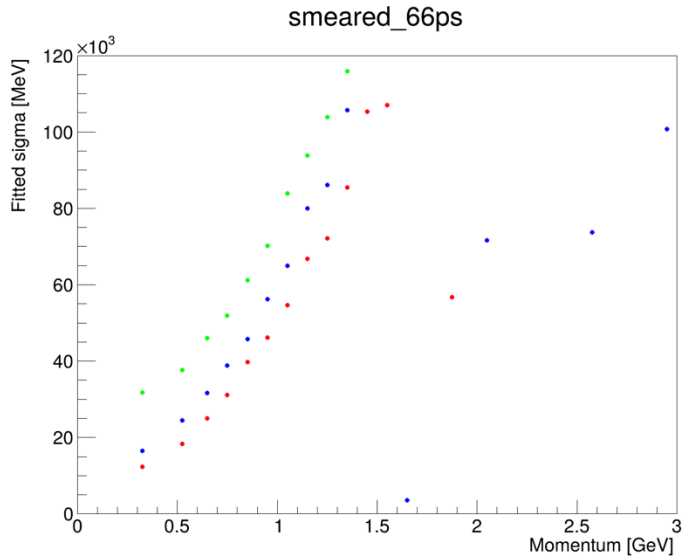



- Fitting worked OK for most of bins

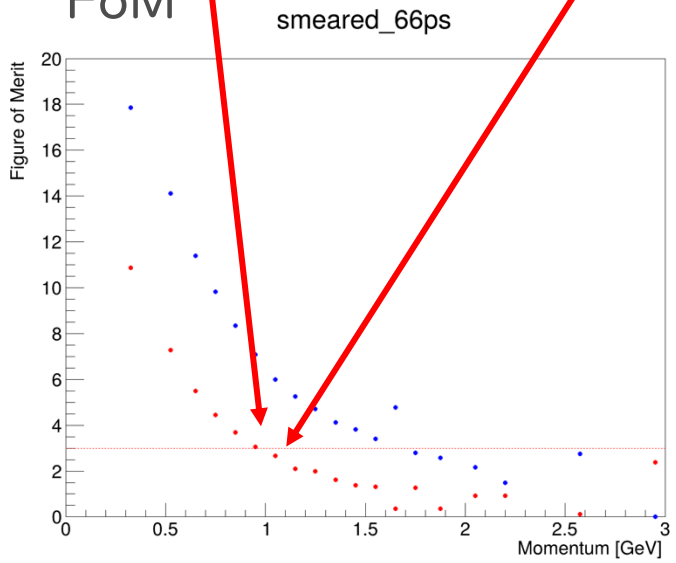
# Results: 3. 66 ps smearing




- FoM




- 3 $\sigma$ separation
  - pi/K 1.0 GeV
  - K/p 1.6 GeV