TOF impact on tracking efficiency, purity, resolution

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on behalf of the ePIC ToF simulation team

Thanks to Tommy, Honey, Abdelghani, Ayuki, Zakaria

Disclaimer & Outline

Before We Start

- TOF MC team's primary “performance studies + software development”
- Tracking-related studies
  - recognized as important, but limited manpower so far
- No dedicated tracking studies: still preliminary
  - Going forward: Need more effort toward Review in the next few months
- New member joined since this April + Additional student joining ?

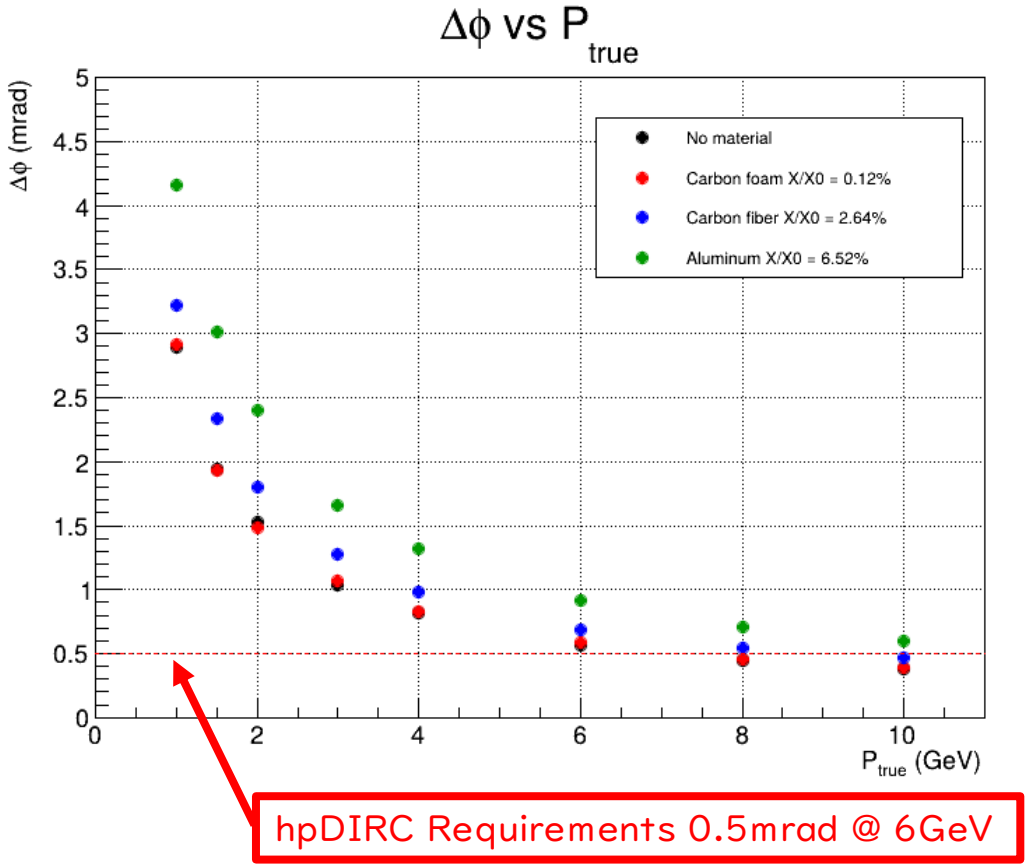
Today's Topics

1. Tracking performance and its effects on TOF
2. Angular resolution of downstream detectors due to TOF structure
3. TOF hit rate incl. physics + background
4. Tracking performance at TOF layer
5. Summary

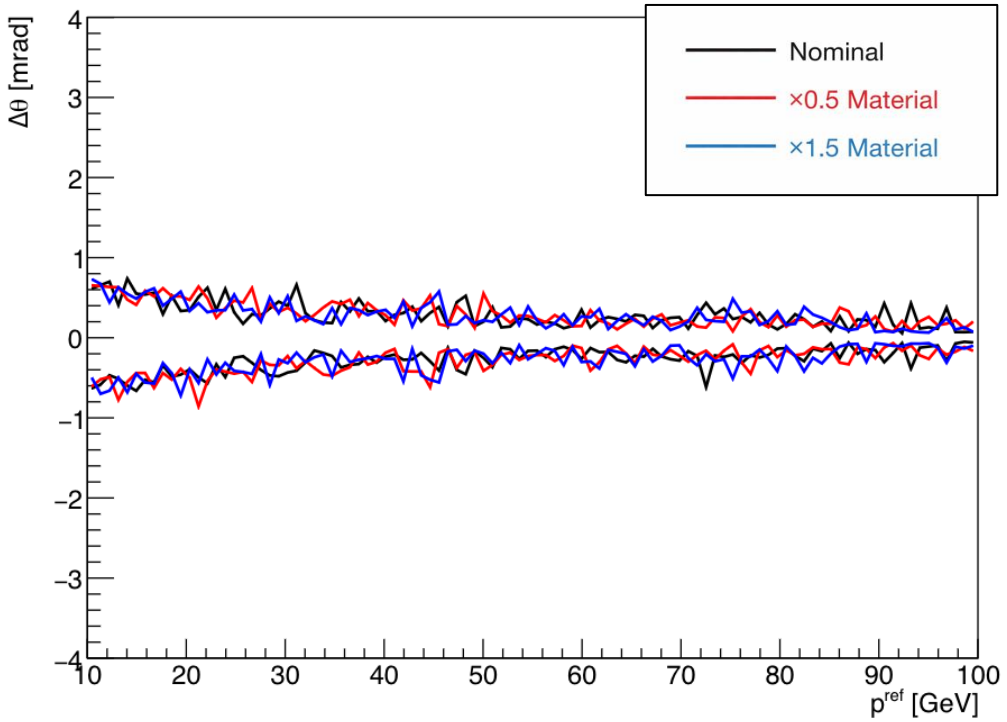
Angular Resolution of Downstream Detectors

- Impact of TOF structure/material on Downstream Detectors

BTOF → hpDIRC



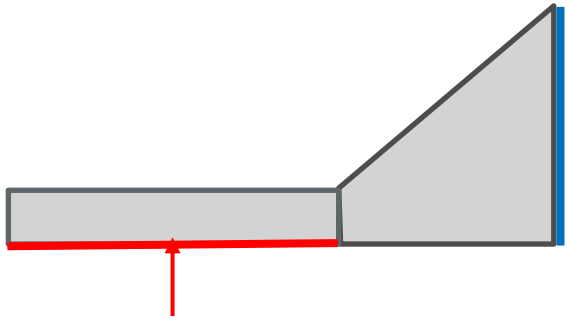
FTOF → dRICH



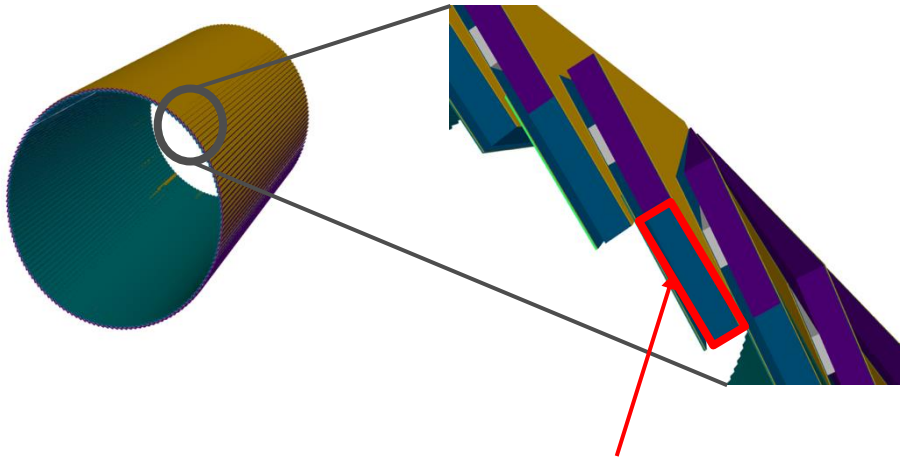
No visible impact from a slight change in the FTOF material budget

→ Need to evaluate more substantial variations

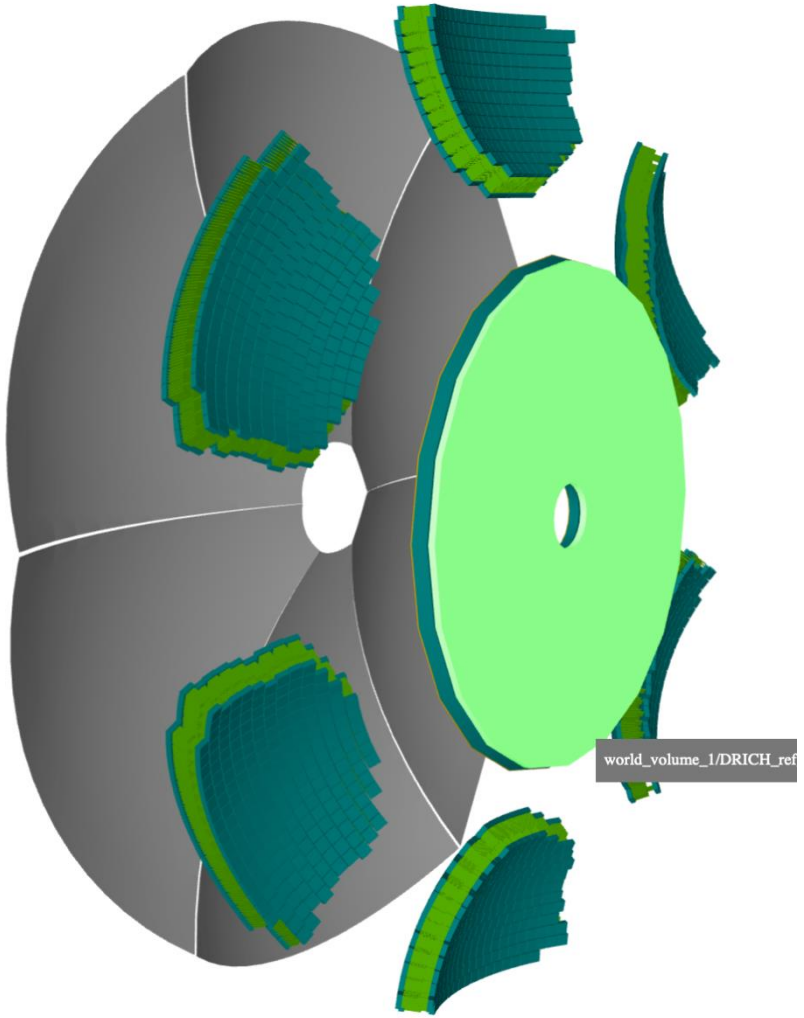
Dummy surface in front of hpDIRC/dRICH



Dummy sensitive layer

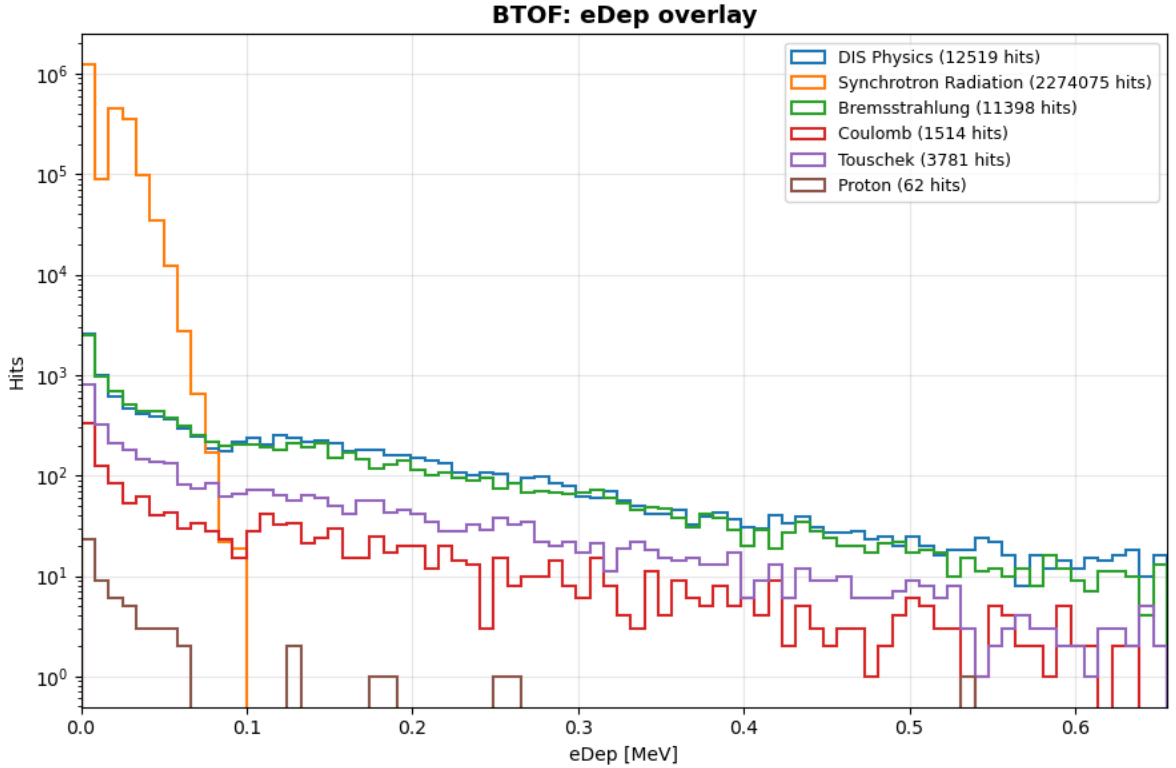


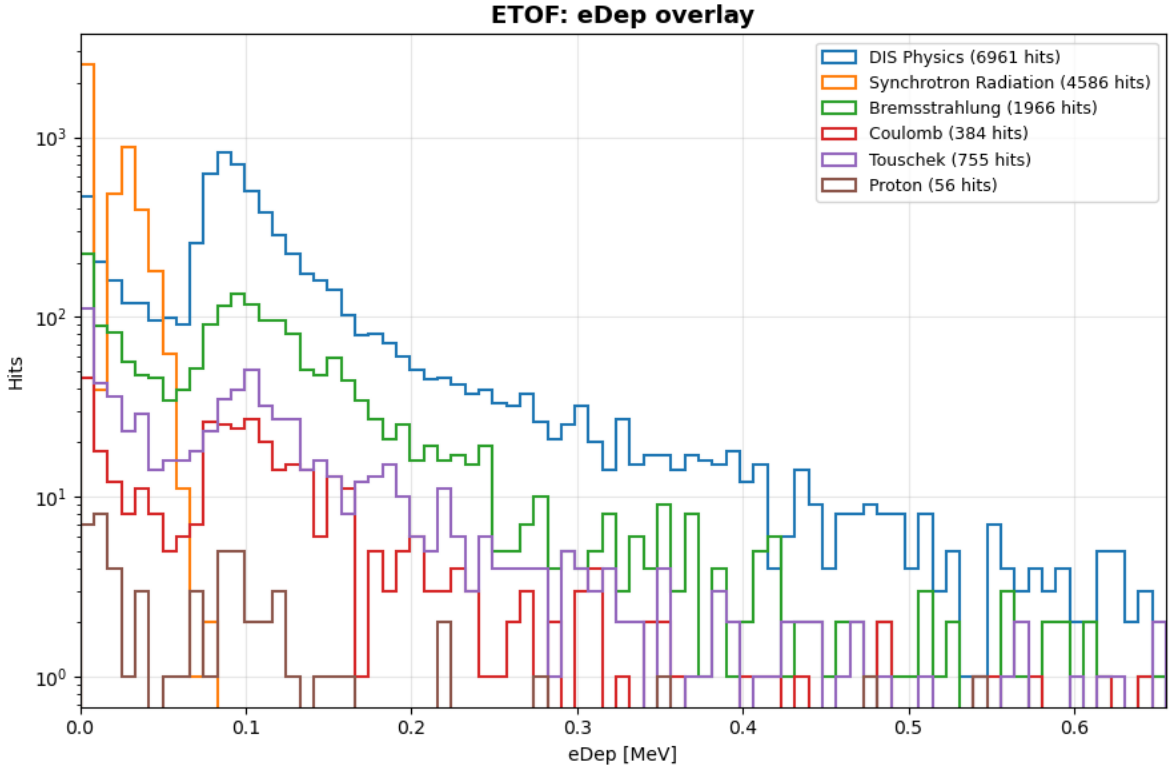
BTOF Support structure



TOF Hit Rate Including Background

- Background contribution quantified using DIS+Background sample
  - BTOF: dominated by SR
    - Can be suppressed by eDep cut
  - FTOF: Hit occupancy is low





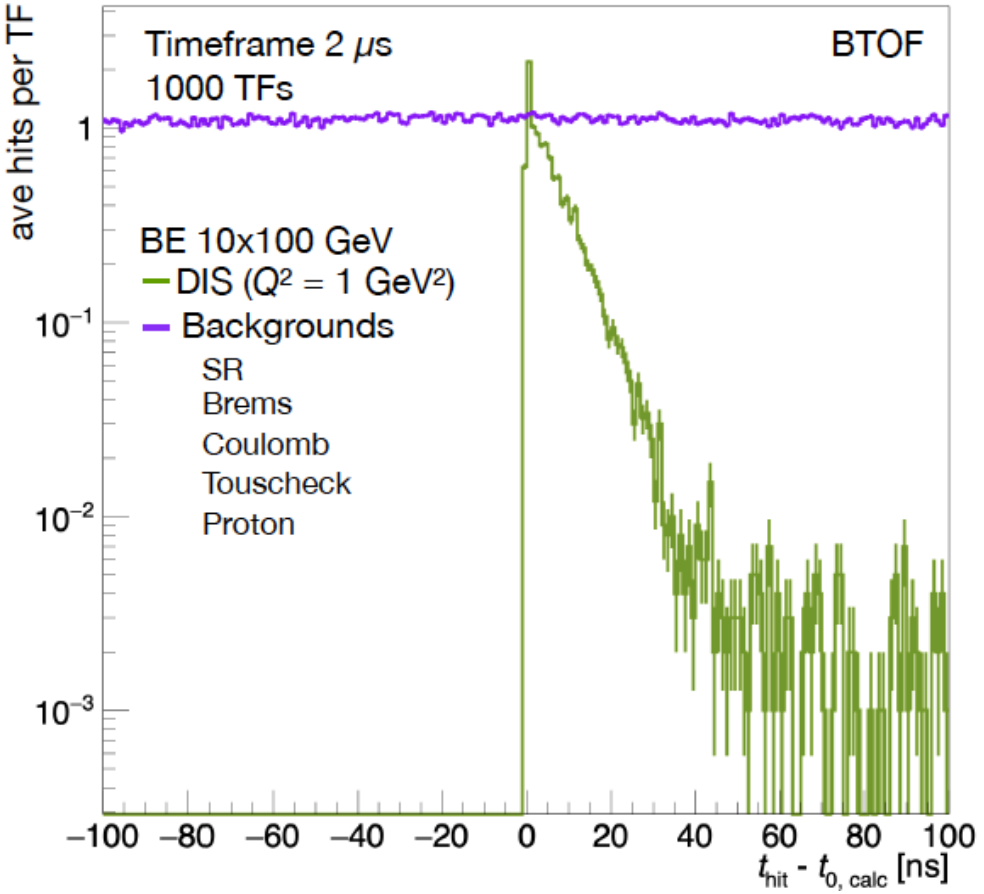
TIC meetin last month

Timing of hits or eDep

- TOF's key strength;
  - Fine time resolution

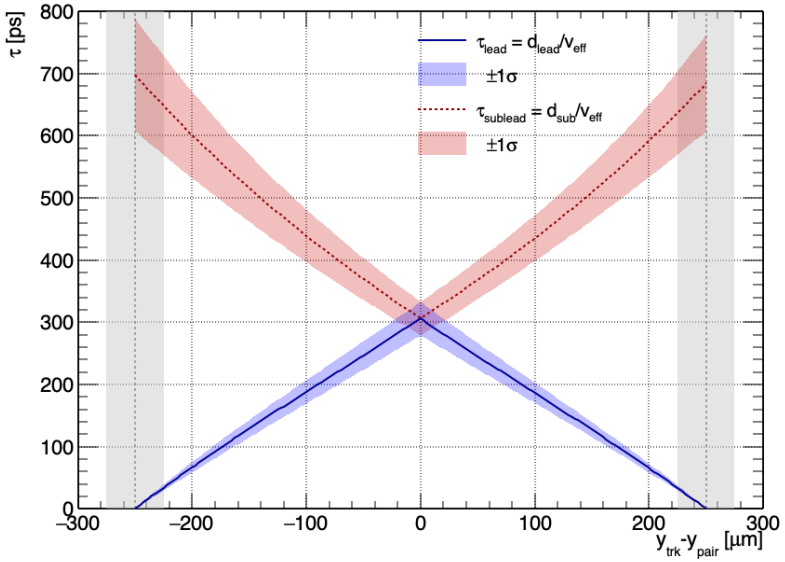
- Background timing distribute continuously
  - can be partially suppressed by TOF timing
  - But, not entirely
- eDep can be more powerful cut
  - Appropriate threshold tuning needed
  - *99.998%* of SR BKG reduction possible
  - Need to study how tracking efficiency can be recovered

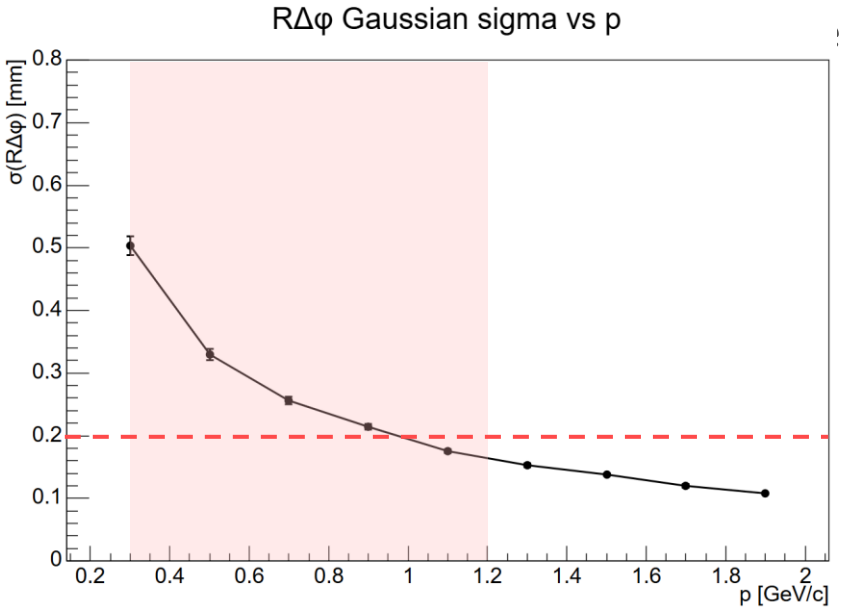
Thanks to T. Kumaoka

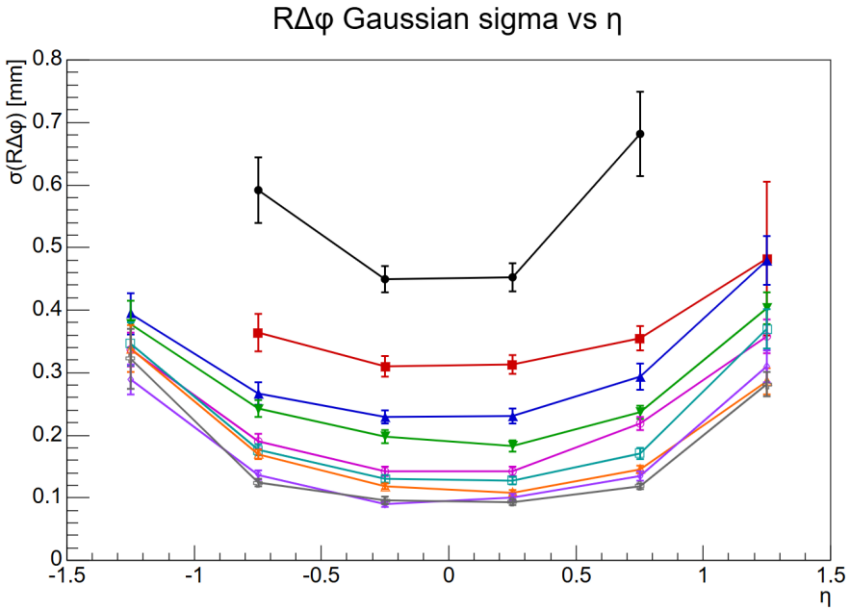


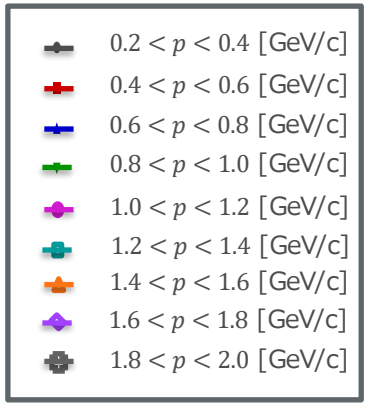
Tracking Performance at TOF Position

- Hit-position determination is crucial for correcting timing delays caused by signal propagation inside the sensor
  - Propagation speed; $v_{\mathrm{prop}} = \sim 0.8\ \mu\mathrm{m/ps}$
  - See Satoshi' s report in this meeting
  - TOF requirement: ~10 μm level
- Current position resolution at surface
  - ~200 um (correspond to ~0.2 mrad)





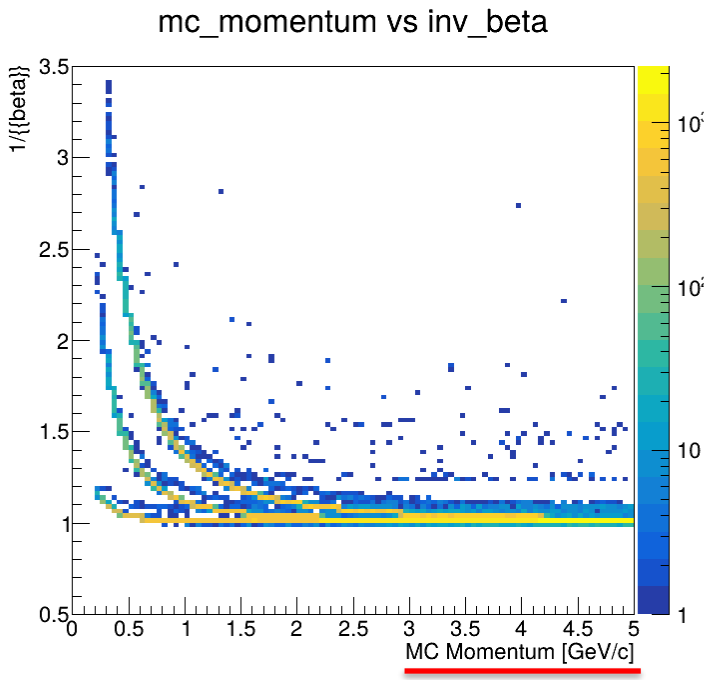


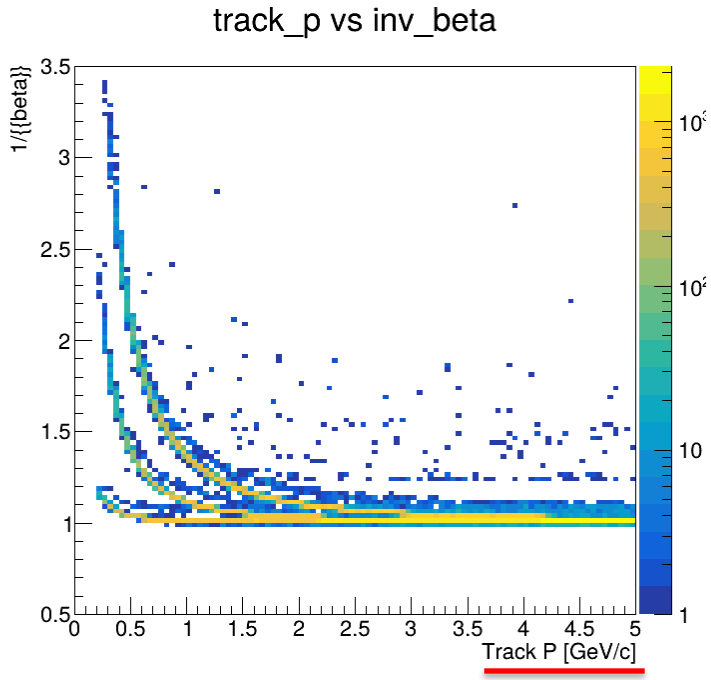


Slides TOF DSC meeting

1 / β vs track momentum or truth momentum

- β can be calculated from "track path length" and ToF time
- Track momentum reconstruction looks OK
  - MC Truth momentum and reconstructed momentum showed identical relation
- Path length reconstruction was not sufficient when we did this study



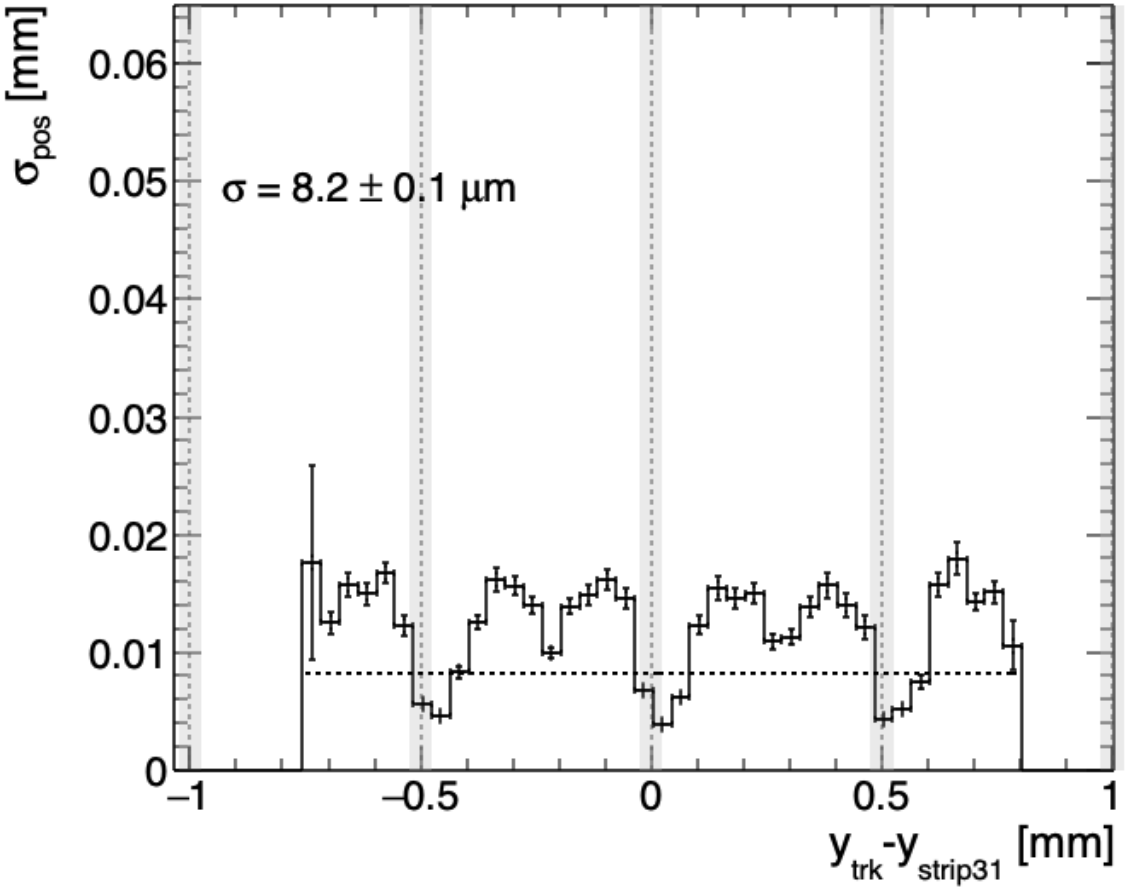


Truth momentum

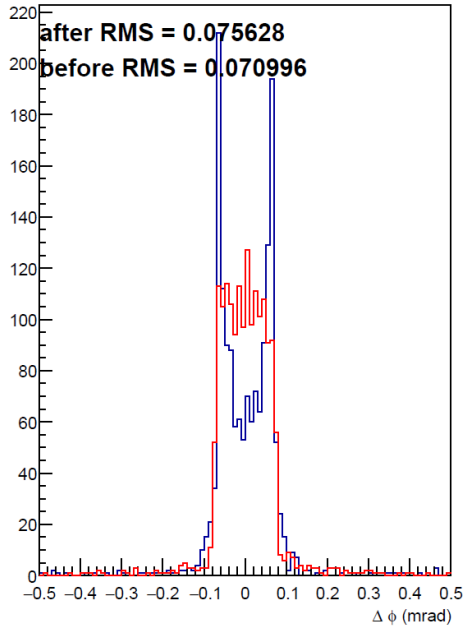
Reconstructed momentum

Position resolution from the recent beam test

Thanks to S. Yano

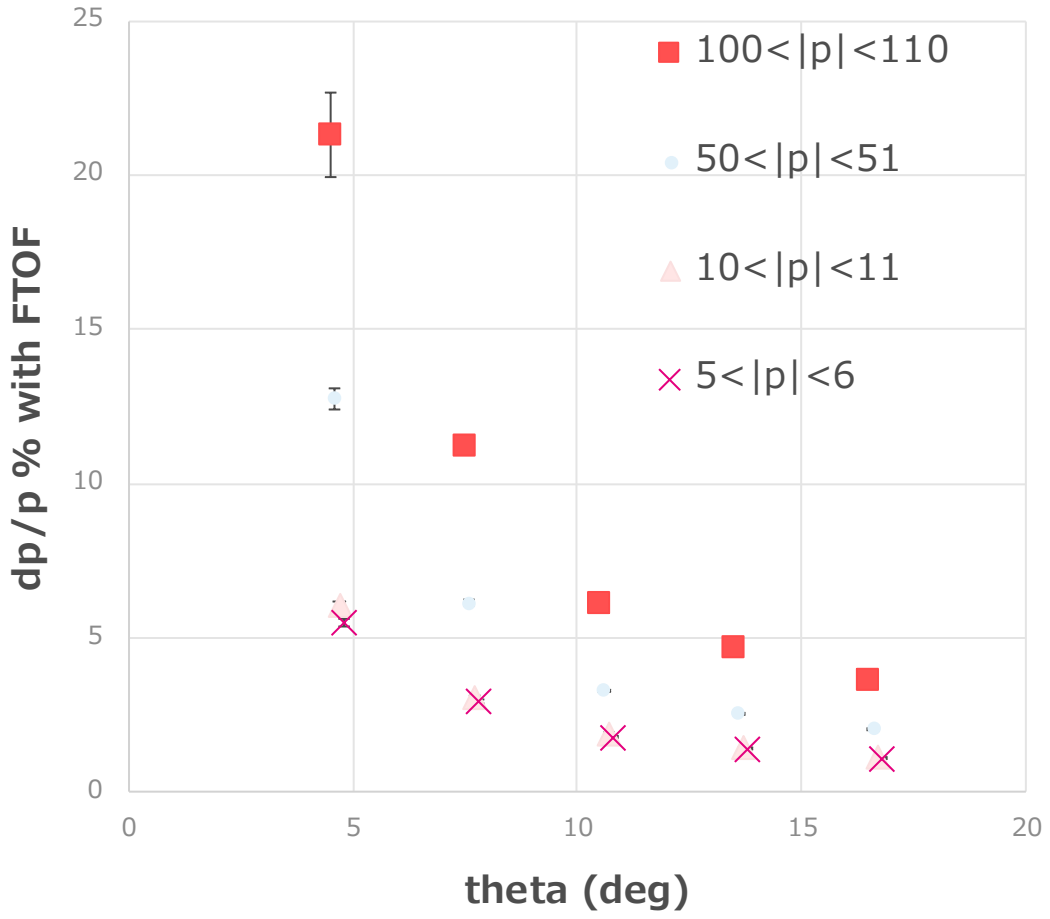


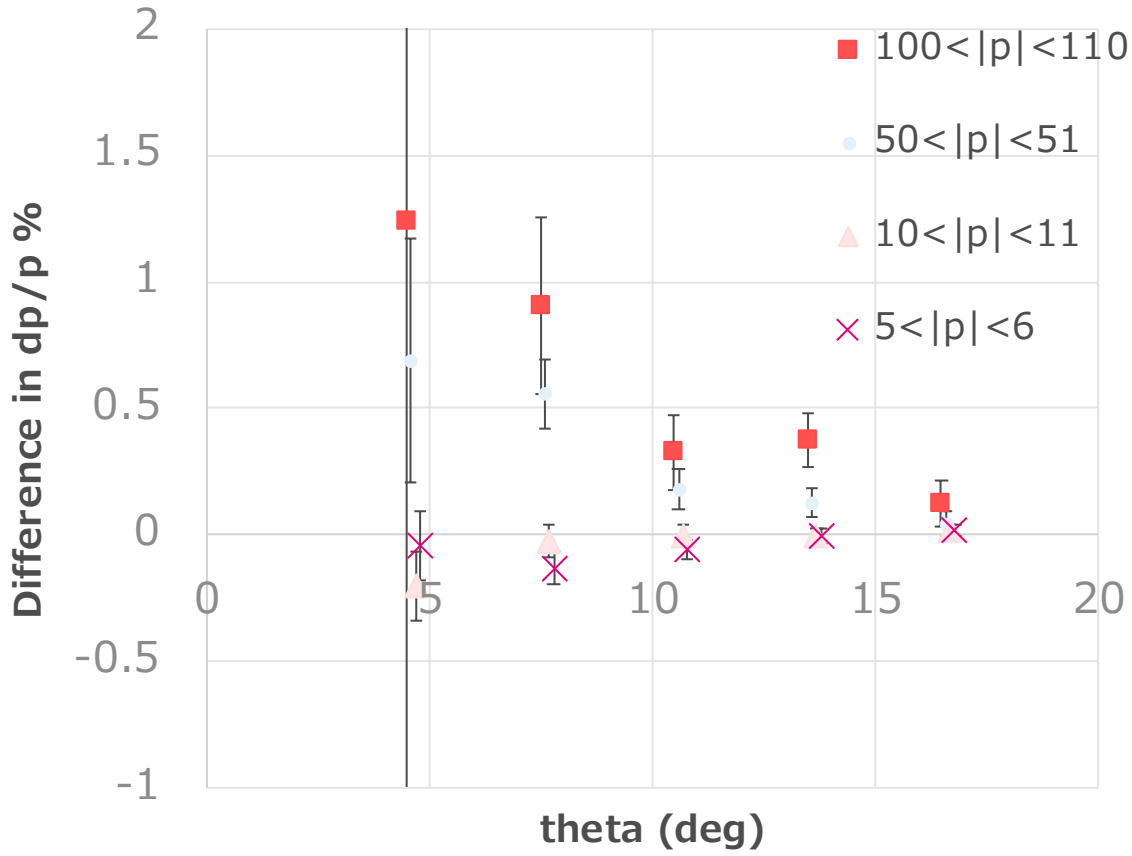
- Positioning resolution of BTOF strip sensor is studied in DESY test beam@Dec.2025
- $\sigma = \sim 8\,um$
  - very good!
  - owing to charge sharing !
  - MC does not reproduce
    - 100 um level
- Want to study about impact on the tracking



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





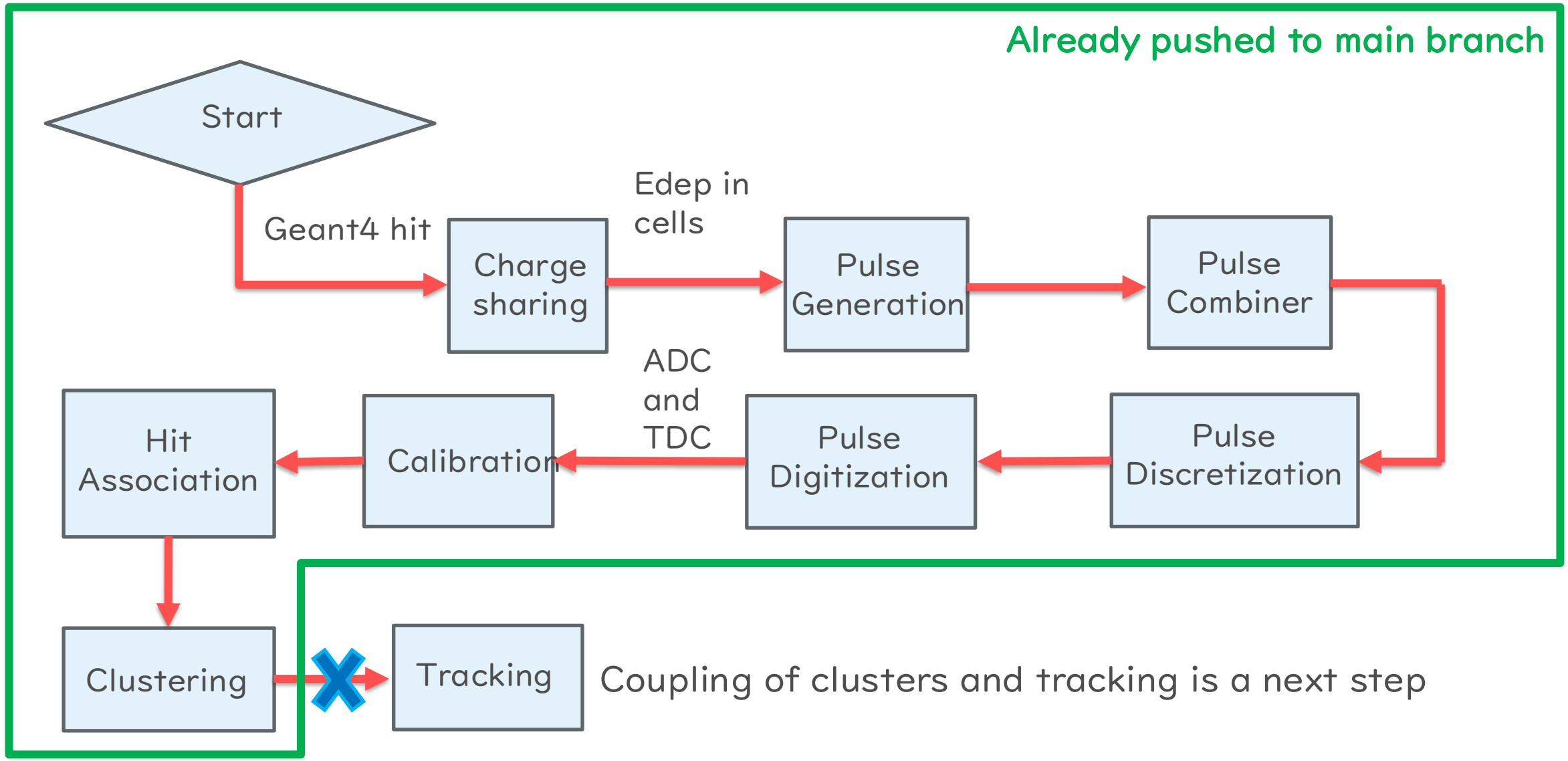
Summary

- Angular resolution in the downstream detectors: TOF contribution quantified
  - TOF structure
- Hit rate study:
  - background suppression feasible through threshold tuning
  - time-based selection alone: insufficient
  - Next step: check tracking efficiency recovery
- Tracking @ TOF layer
  - current spatial resolution ~200 μm
  - while requirement ~10 μm
  - TOF sensor have sufficient positioning resolution
    - Can improve tracking performance ??

- New members and more manpower incoming
  - detail tracking studies can be performed, if required

Backup

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

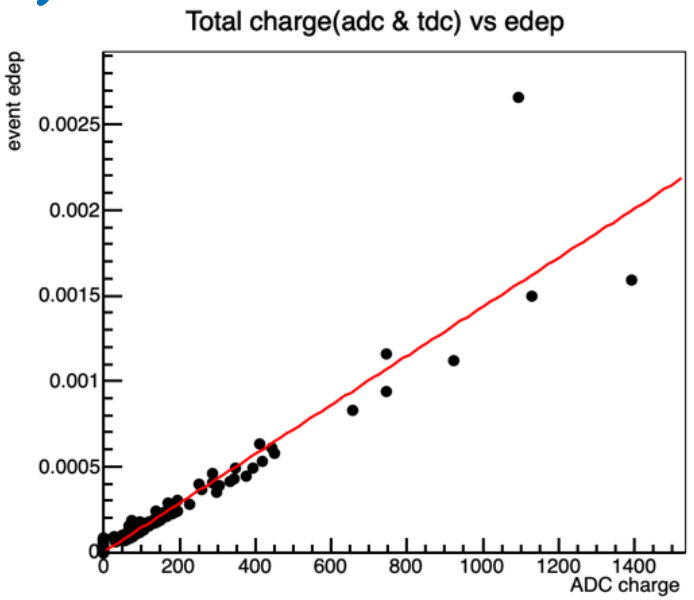
↓ ADC and TDC values(Completed)

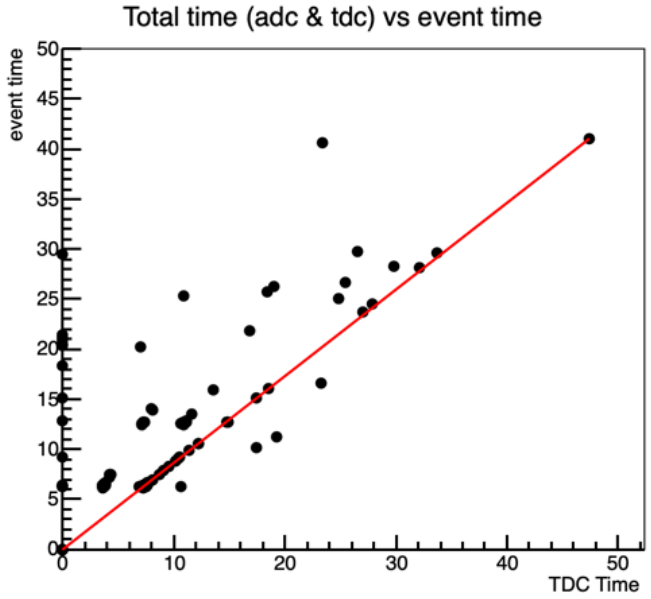
Pulse Digitization

↓ Future plan

Calibration

Need to complete

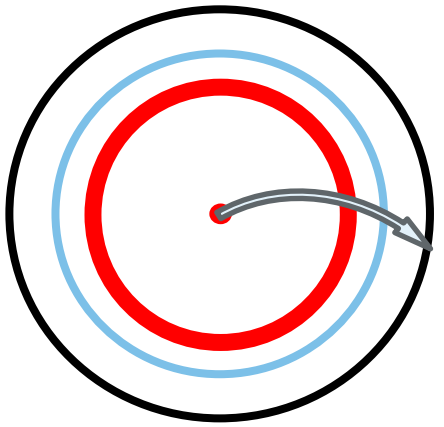




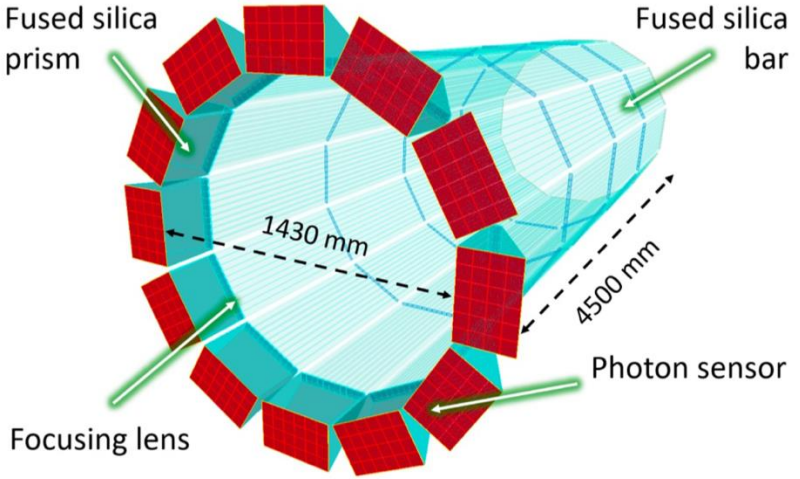
Reminder: Material budget

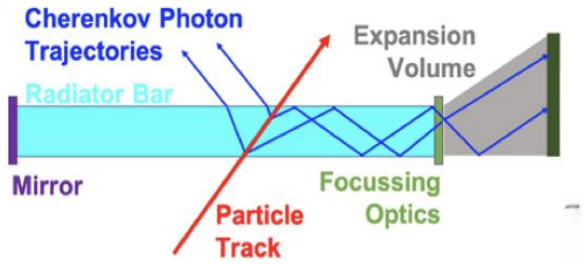
- Estimate the impact of BTOF material budgets on the outer hpDIRC angular resolution
  - To optimize the BTOF design and performance
  - Crucial inputs for sensors, structures and readout PCBs
    to relax the tight requirement ($1\%\ X_0$)

- 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



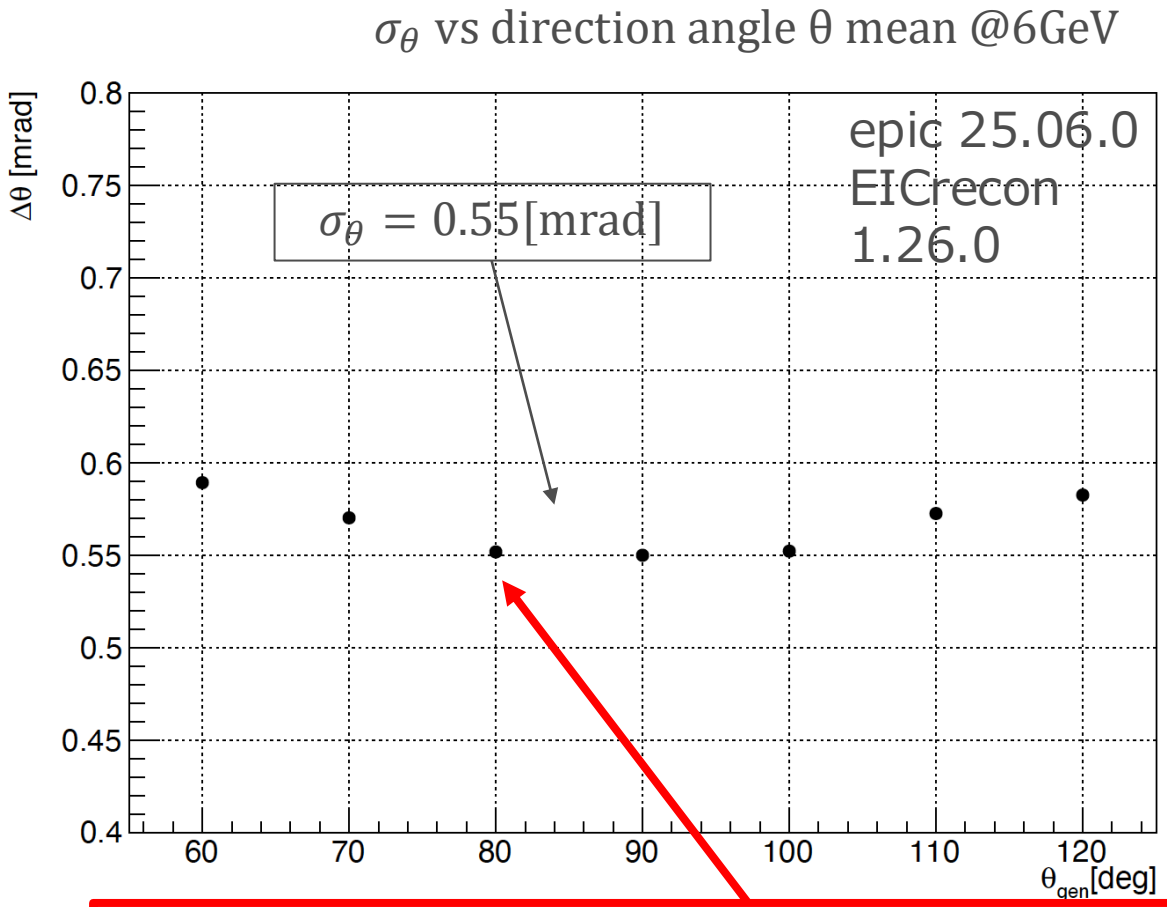
hpDIRC:
high performance Detection of Internally Reflected Cherenkov light

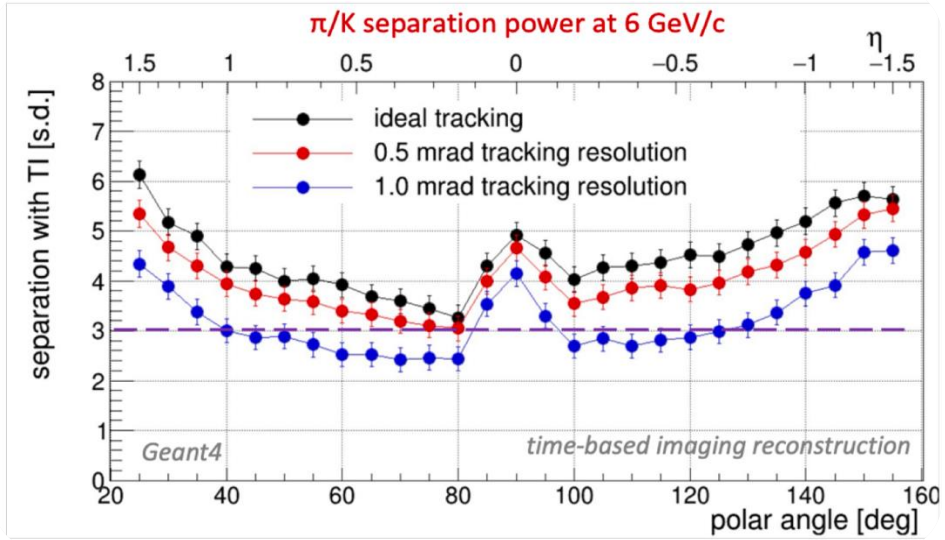




Angular Resolution vs. angle

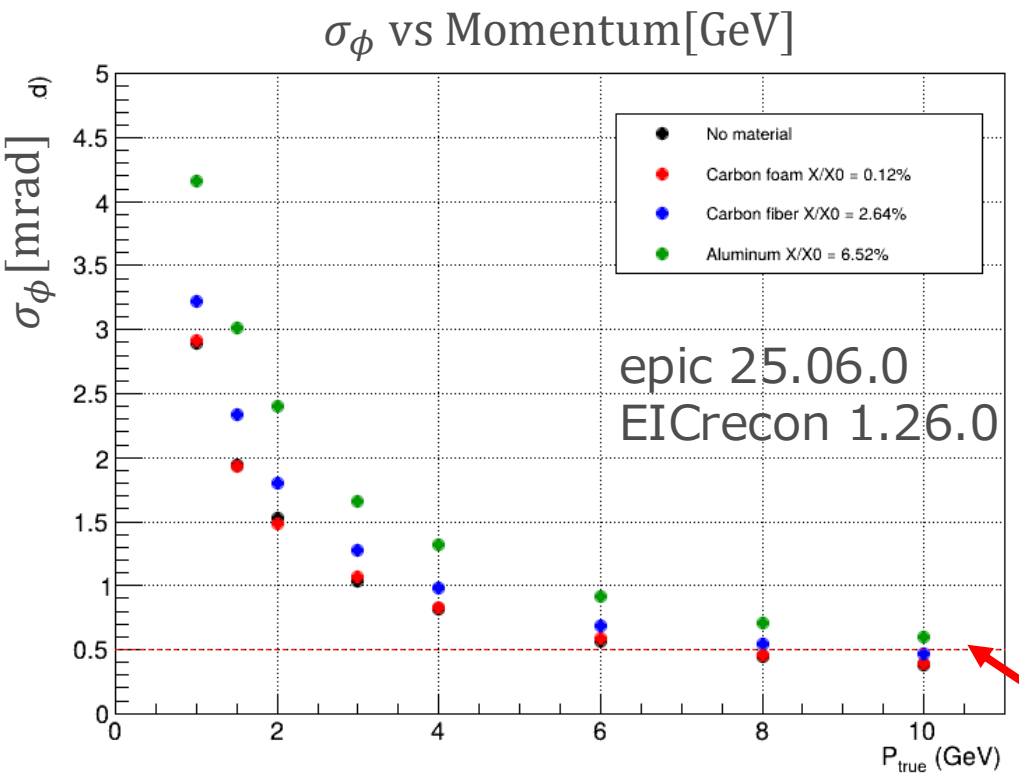
- Best resolution achieved at $\theta \approx 90^{\circ}$ (as expected)
  - But; Still does not match the requirement **"0.5 mrad @ 6 GeV"**

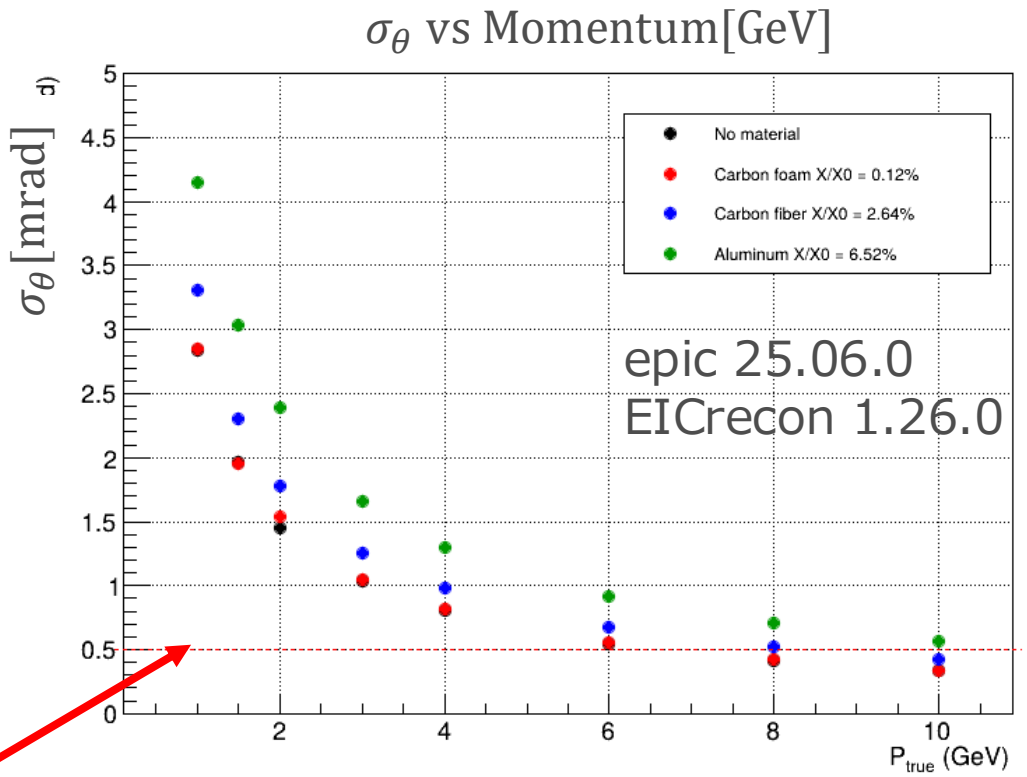




Angular Resolution for different Materials

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

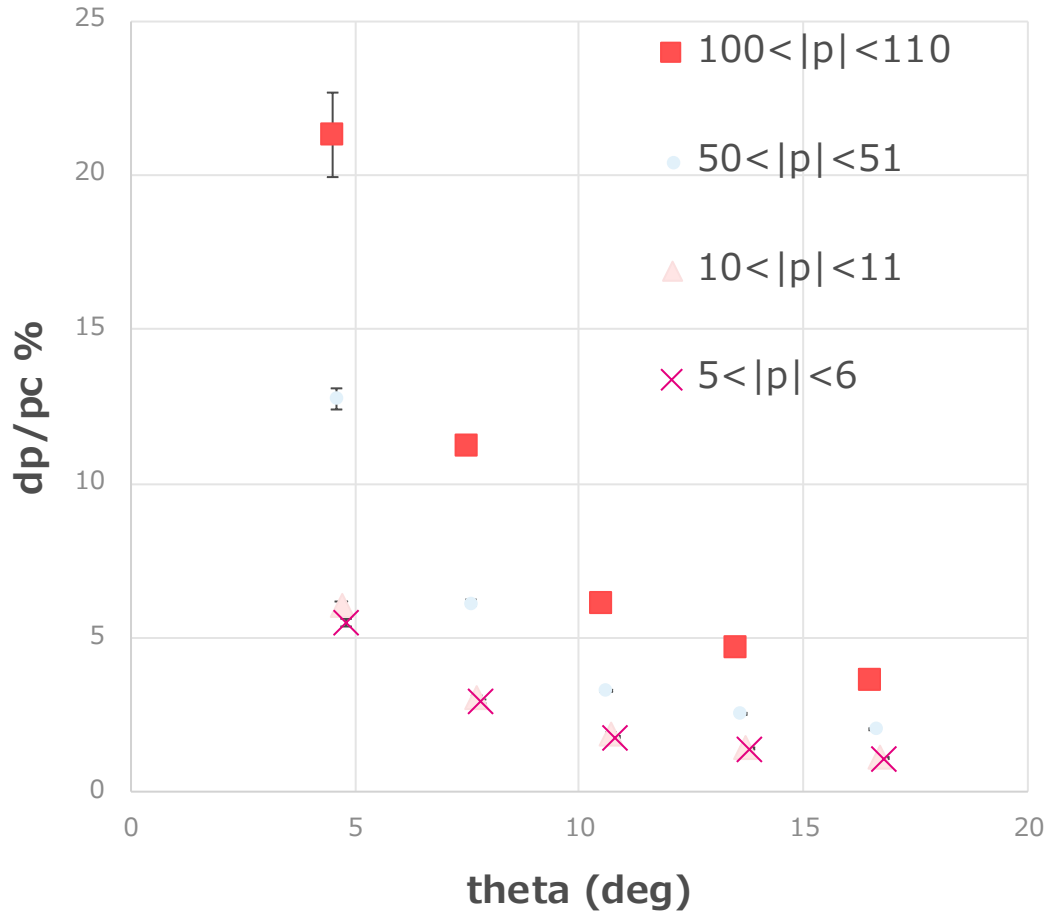


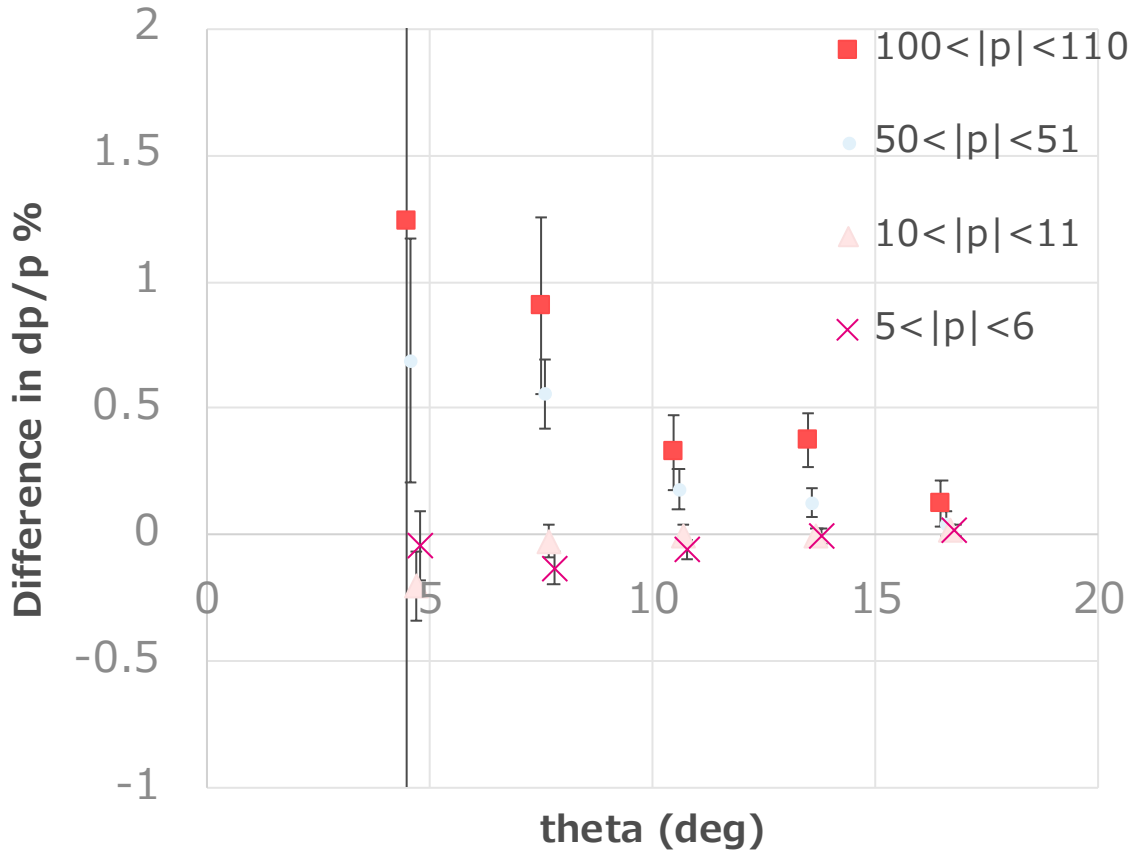


Detector Requirements 0.5mrad @ 6GeV

TOF impact on tracking

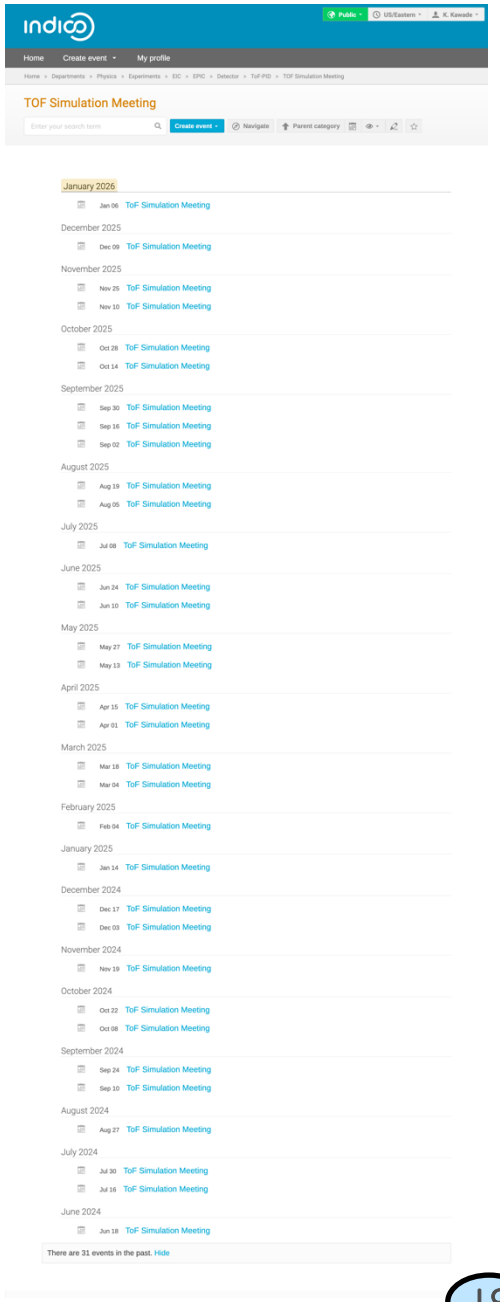
- Compare momentum resolution with or without TOF (FTOF) in tracking process
  - Without TOF hits, see some degrade especially in high momentum track





TOF Simulation Working Group

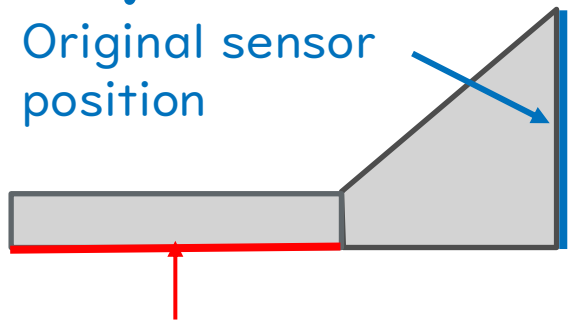
https://indico.bnl.gov/category/569

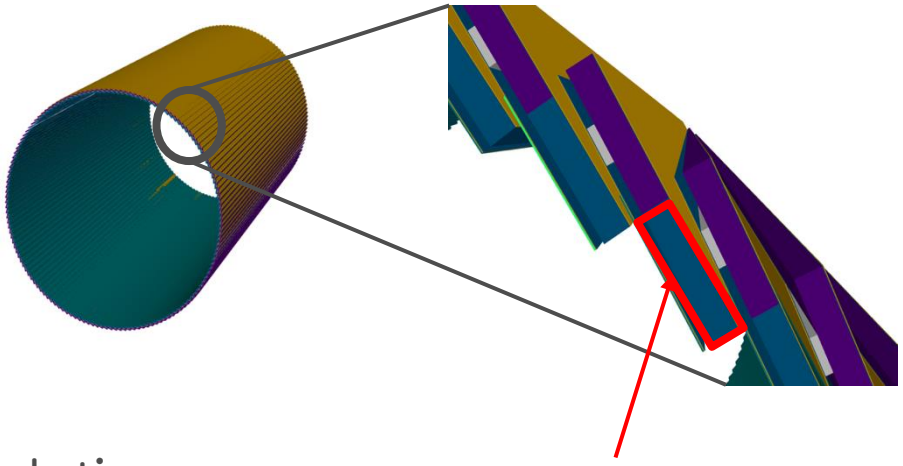


- Coordinators
  - Kentaro Kawade, Tommy Tsang Chun Yuen
- Current Activities
  - Tommy (KSU)
    - Digitization for BTOF
    - Implement new TOF geometry/design
  - Honey Khindri (IIT Madras)
    - Digitization for FTOF
    - Background rate study
  - Kentaro Kawade (Shinshu, 信州)
    - Evaluate PID performance for BTOF + etc.
  - Abdelghani El Ouardi (Mohammed V)
    - Evaluate PID performance for FTOF
    - Impact of FTOF material budgets on dRICH resolution
  - Ayuki Watanabe (Tohoku, 東北) NEWCOMER
    - Tracking resolution at the TOF position
  - Zakaria Elouakili (Mohammed I) NEWCOMER
    - Background rate study

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: π^-
   - 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

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

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

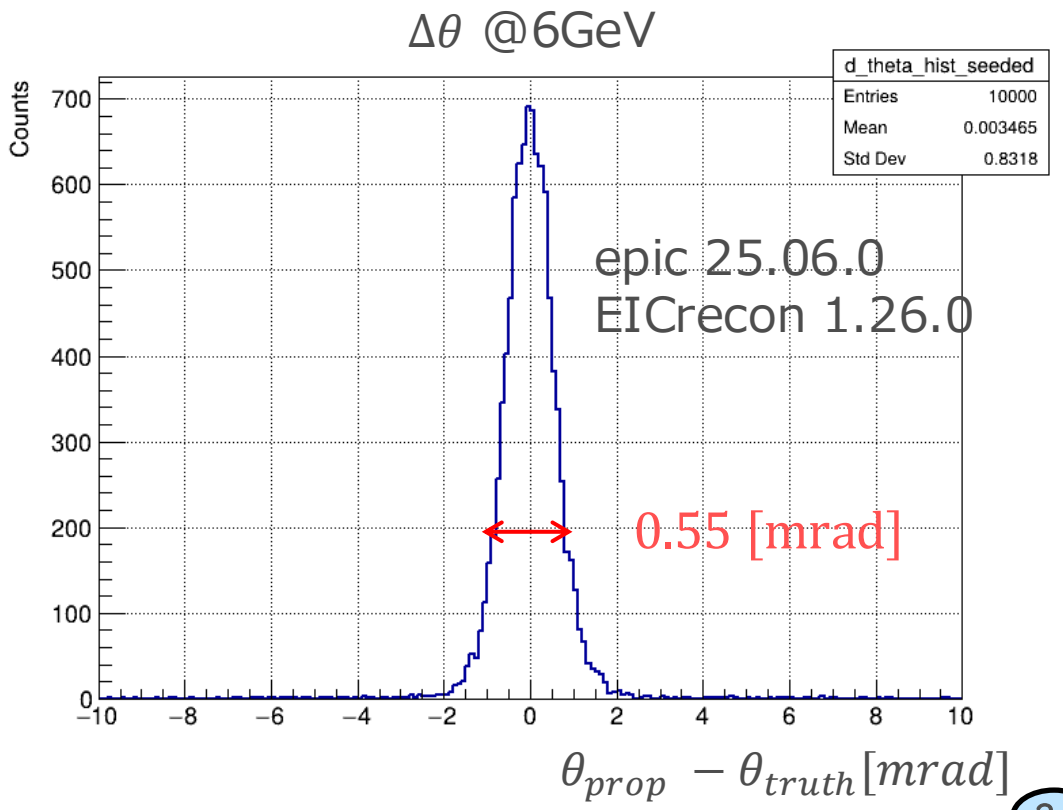
3. Take difference of propagated track angles and truth hit angles

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

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

   – Resolution is given by Gaussian sigma

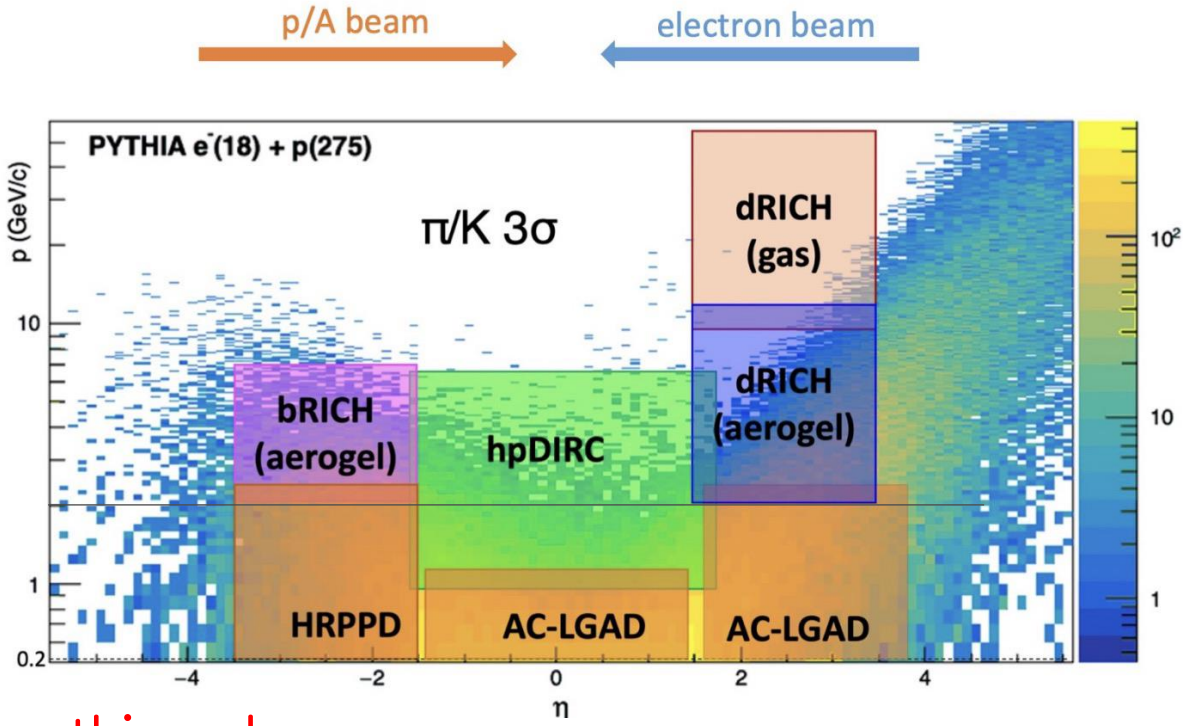
   Ex) $\sigma_\theta = 0.55$ [mrad] @ 6 GeV



Note

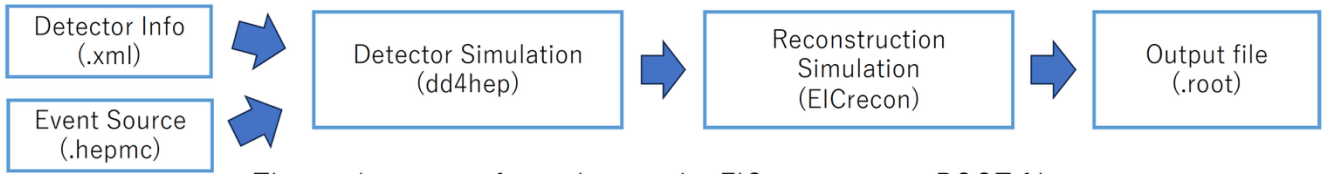
- Generators
  - Pythia NCDIS
    - N_{events}: 200k
    - Energy: 18x275 GeV
  - **Particle Gun: pi/K/proton**
    - N_{events}: 100k for each
    - $0.1 \leq p \leq 5.0$ GeV
    - Eta&Phi: Flat
  - epic ver 25.04.1

This report focus on this only



ePIC PID requirement

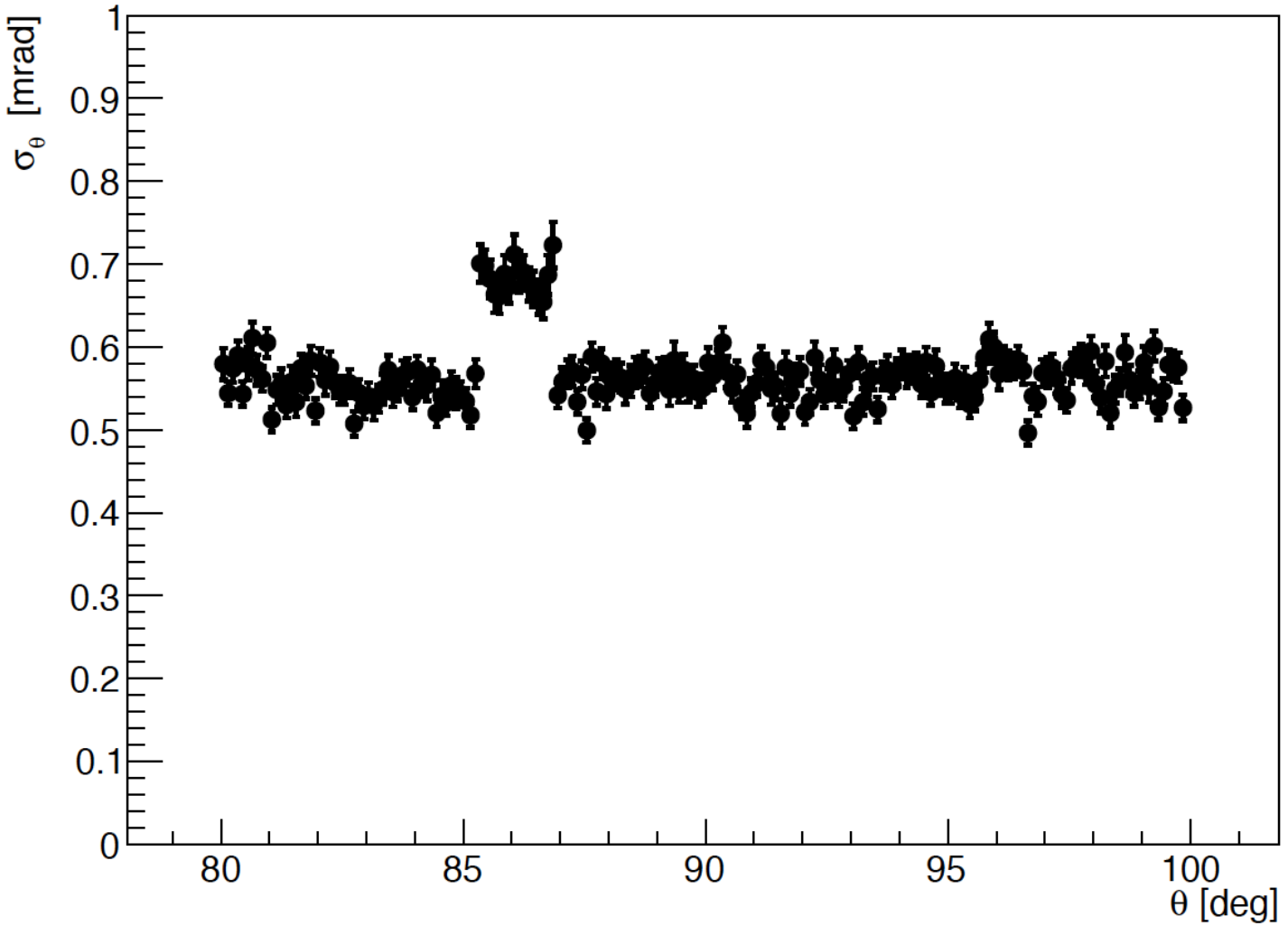
- Reconstruction framework
  - **EIC Recon Version 1.24.2**



- Own developed offline analysis code

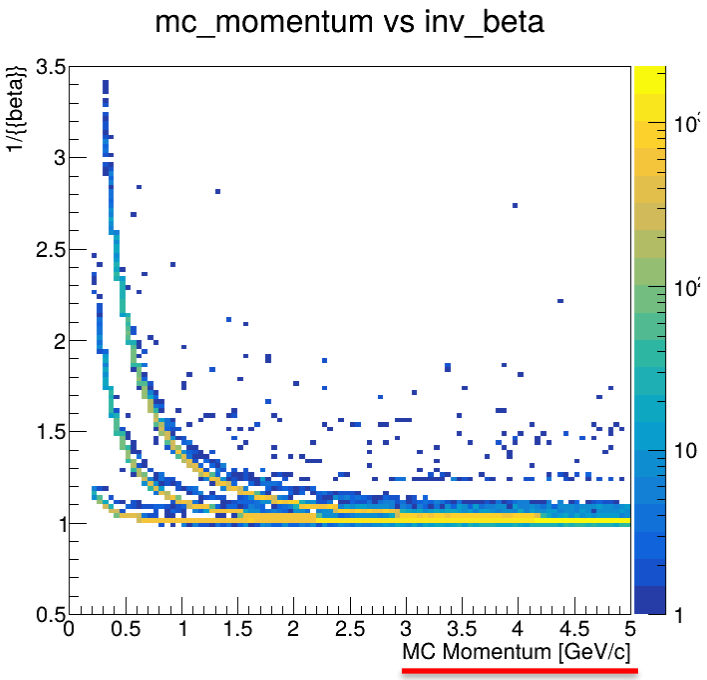
- PID performance when considering finite timing resolution will be shown

Tracking performance w.r.t theta (Older result)

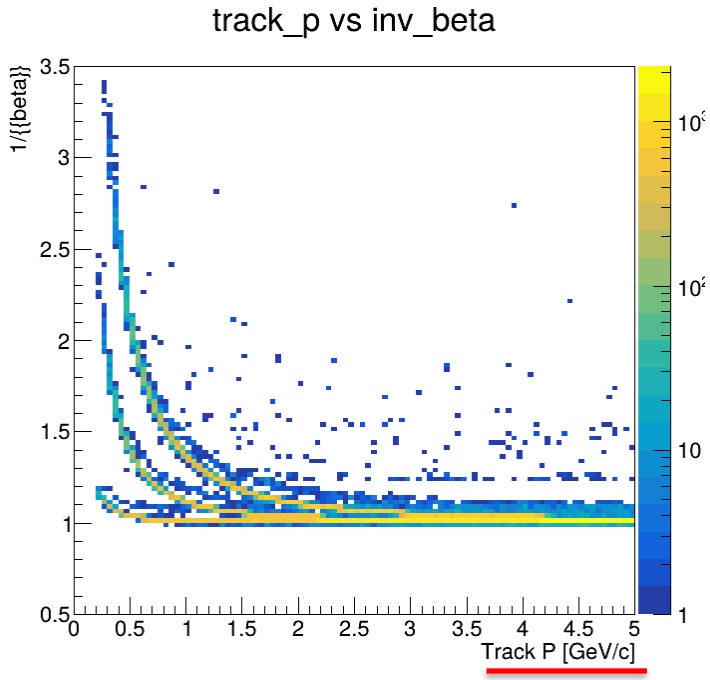


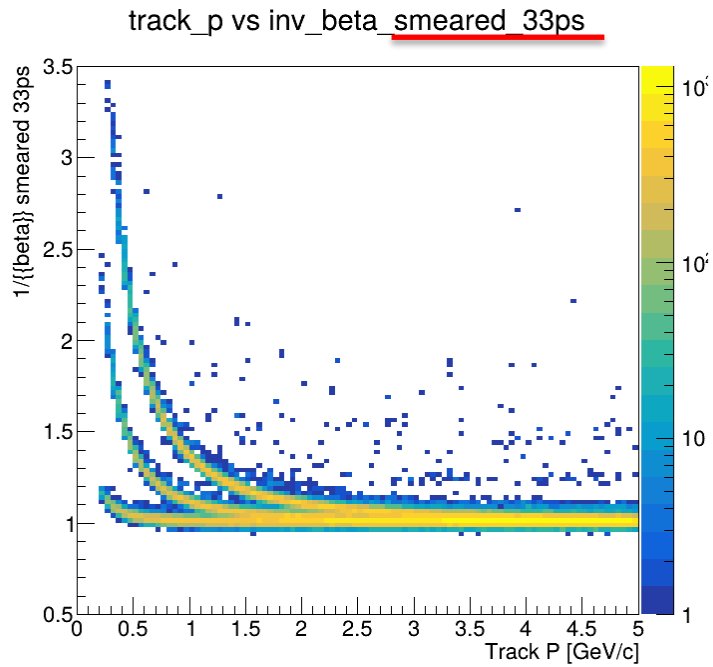
1 / β vs track momentum or truth momentum

- 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

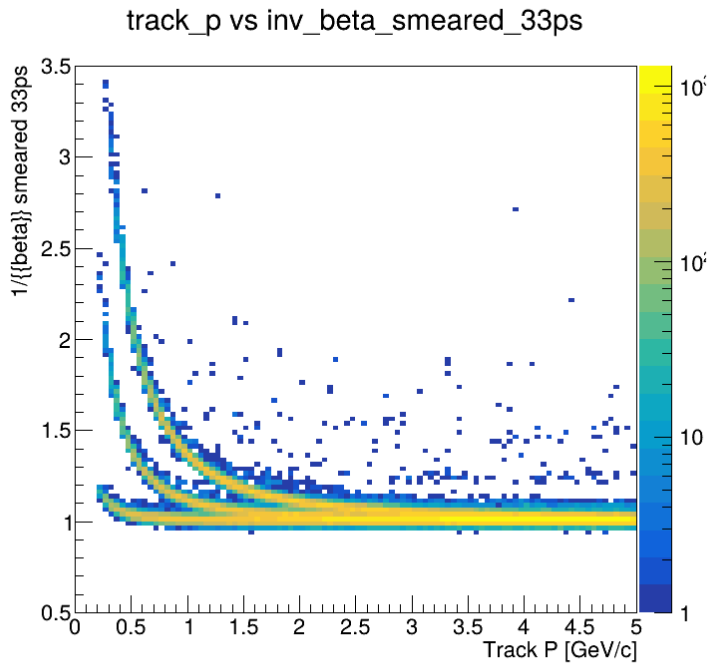


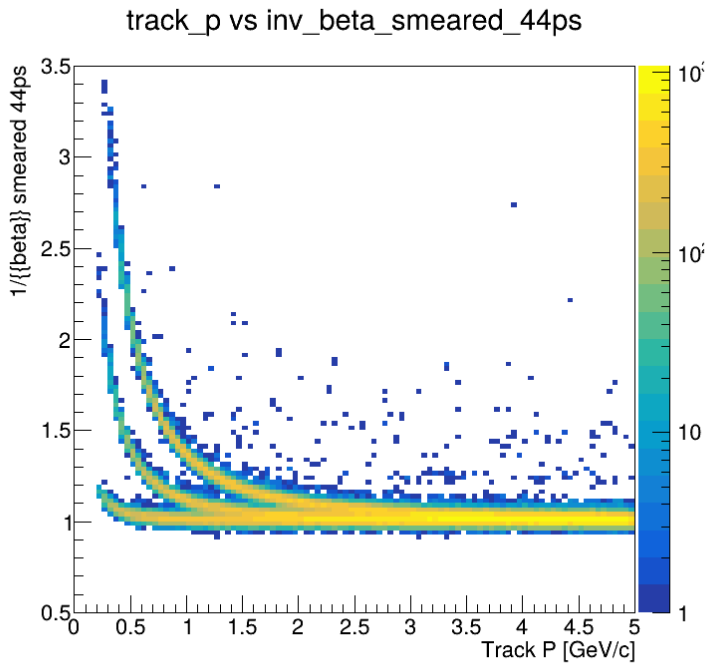


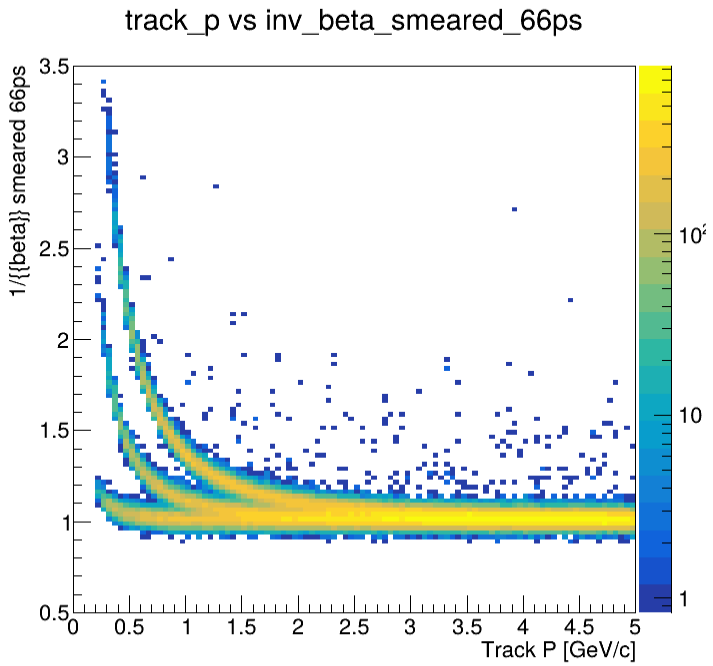
Reco momentum

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

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







MC setup for tracking study by A. Watanabe

- How to get Truth hits
- Making dummy sensor on BTOF
  - $r = 63.0\text{cm},\ l = 260.0\text{cm},\ z_{offset} = 17.5\text{cm},\ d = 10\mu\text{m}$
    material : Silicon

- Association of track to the truth hit
  - Matching MC particle index between track points and truth hits
  - Evaluate the track points in BTOF
  - Choosing nearest track points to truth hits
  - Select : $\frac{\boldsymbol{p}_{track}\cdot\boldsymbol{p}_{truth}}{|\boldsymbol{p}_{track}|\cdot|\boldsymbol{p}_{truth}|} \geq 0.9$ ($\boldsymbol{p}$: momentum at the hit or track position)