# PID of BESIII and CEPC

**Linghui Wu**

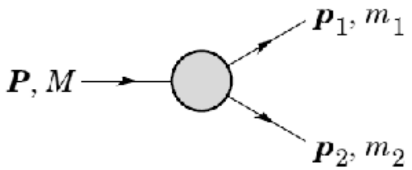
For the BESIII and CEPC PID working groups

# Why we need PID?

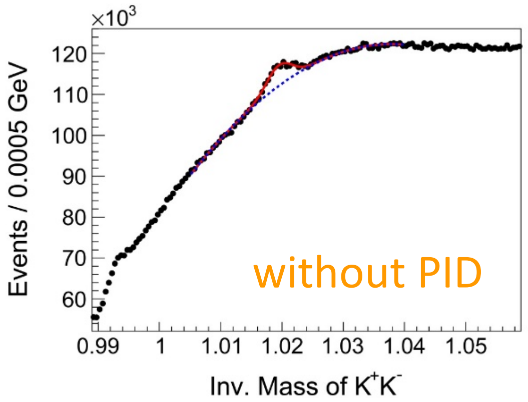
- PID of charged hadrons is essential for flavor physics and jet study
  - Suppressing combination background
  - Distinguishing between same topology final-states
  - Benefit flavor tagging
  - …

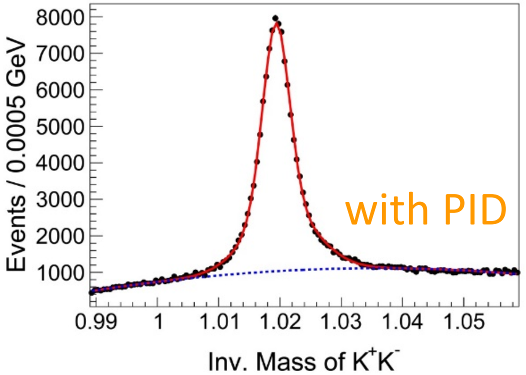
Invariant mass of two particles

$$M^2 = m_1^2 + m_2^2 + 2(E_1E_2 - p_1p_2cos\theta)$$

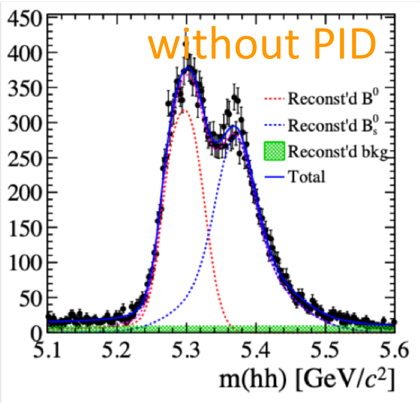


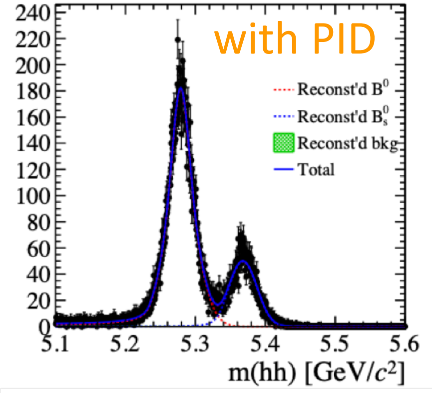

Invariant mass distribution of $\phi \to K^+K^-$



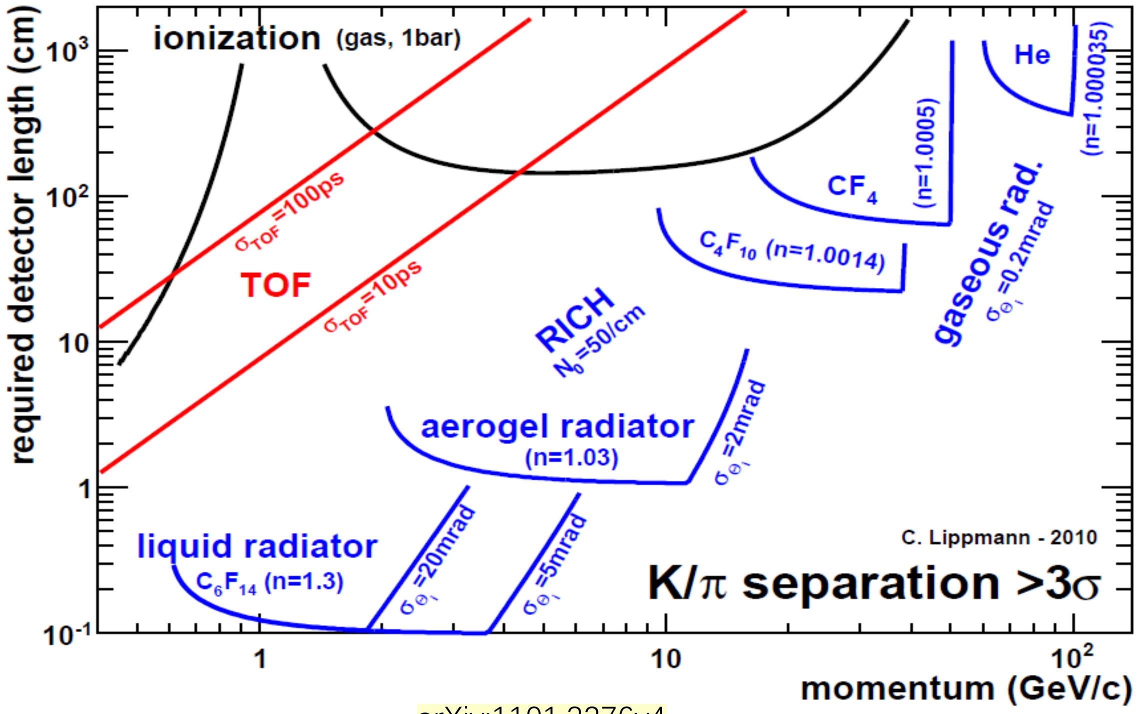




Distinguish various $B_S^0(B^0) \to h^+h^-$ in same topology final-states (simulation at CEPC)



# PID techniques




arXiv:1101.3276v4

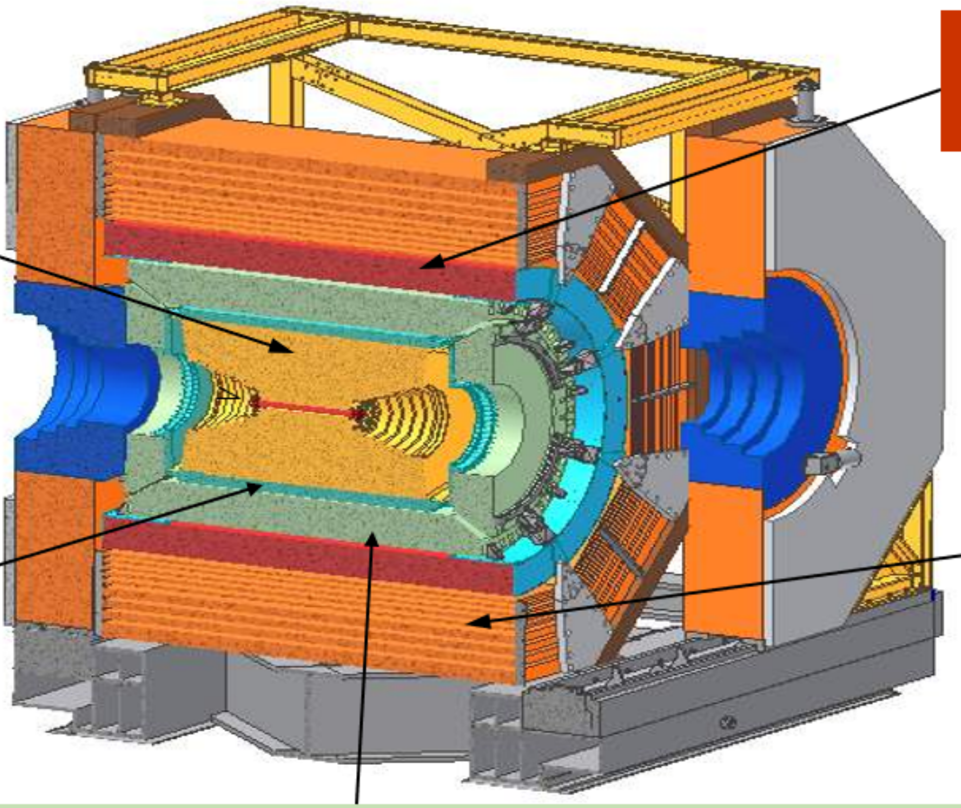
| Technique | BESIII | CEPC |
|---|---|---|
| Ionization | √ (dE/dx with DC) | √ (dN/dx with DC or TPC) |
| TOF | √ (plastic scintillator + MRPC) | √ (LGAD) |
| Cherenkov | | Under consideration |

# PID of BESIII

# BESIII detector

Main Drift Chamber (MDC):
Helium based small-celled
$\sigma_{xy}$= 130 μm
$\triangle P/P$ = 0.5 %@1 GeV
$\sigma_{dE/dx}$= 6-7 %

Super-conducting
Magnet: 1.0 Tesla

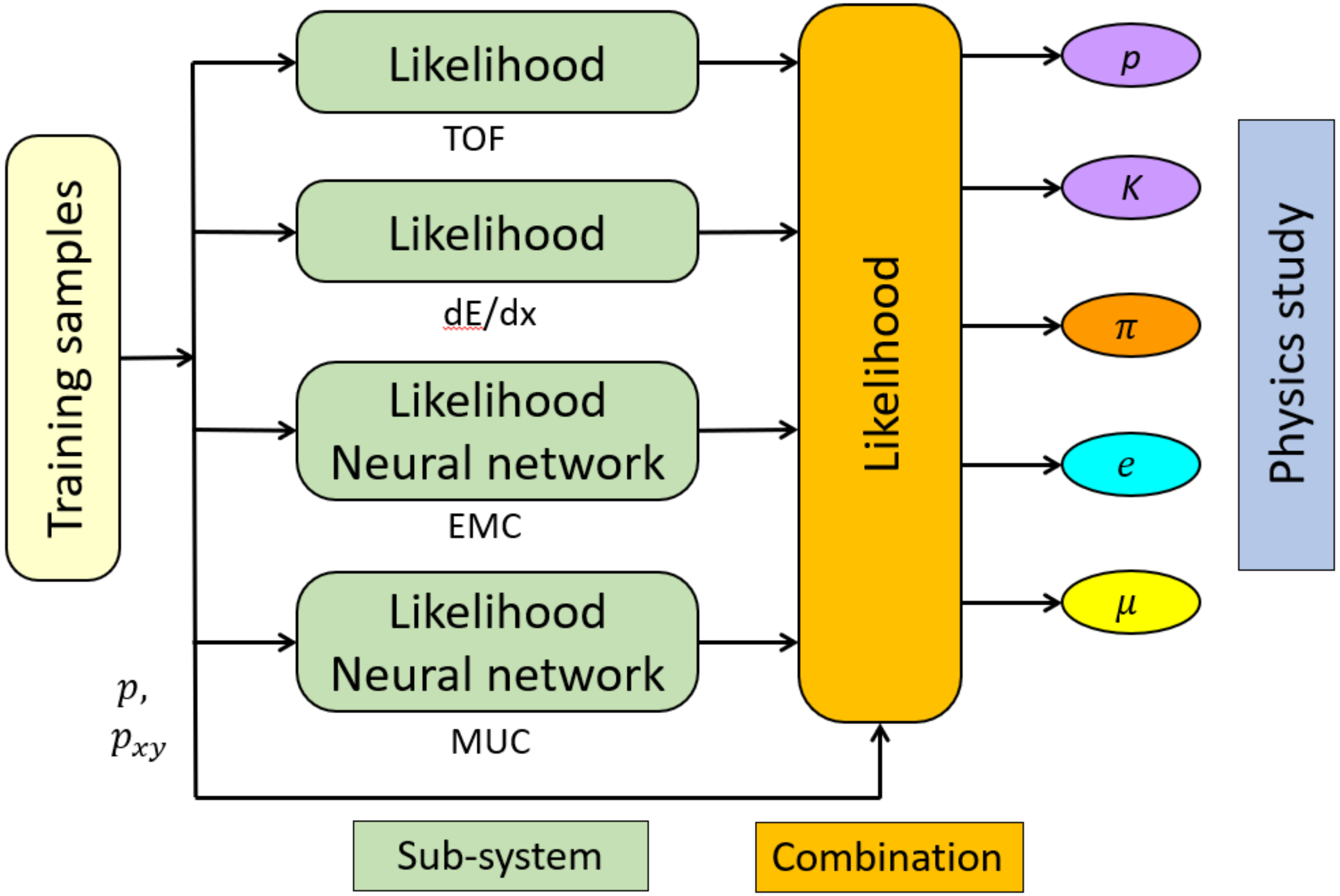


TOF System:
$\sigma$= 68 ps barrel
60 ps endcap

Muon Chamber (MUC):
RPC based

EM Calorimeter (EMC) : $\triangle E/E$ = 2.5 % @ 1 GeV
CsI crystal array $\sigma_{z,\phi}$= 0.6 cm @ 1 GeV

# Workflow of PID

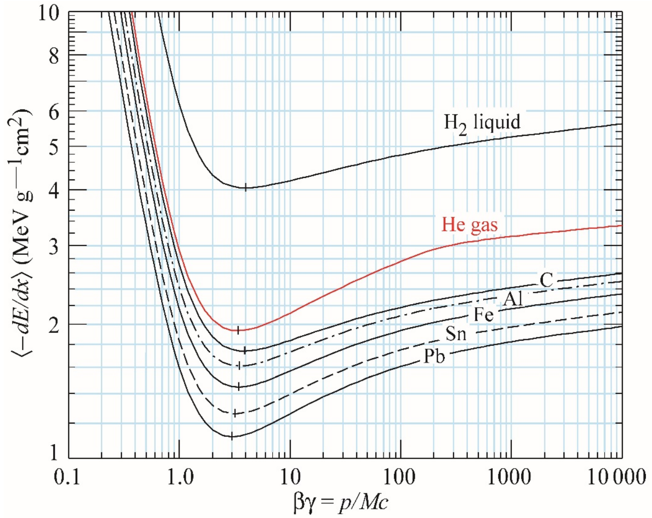



- Running stably for more than ten years

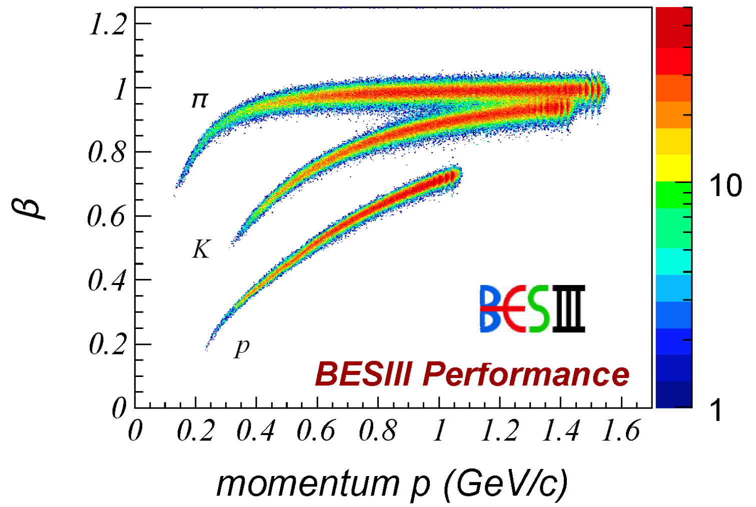
# PID of charged hadrons

- PID of charged hadrons, especially K/π identification, is essential for flavor physics study
- Achieved by combining dE/dx and TOF $\chi^2_{PID} = \chi^2_{dE/dx} + \chi^2_{TOF}$
  - dE/dx with MDC: $\left\langle \frac{dE}{dx} \right\rangle \propto \frac{z^2}{\beta^2}\left(\log \frac{\sqrt{2m_e c^2 E_{cut}}\,\beta\gamma}{I} - \frac{\beta^2}{2} - \frac{\delta}{2}\right)$ $P = m \cdot \beta\gamma$
  - TOF: $\beta = \frac{p \cdot c}{E} = \frac{1}{\sqrt{\left(\frac{m \cdot c}{p}\right)^2 + 1}}$ $\beta = \frac{L}{c \cdot t}$

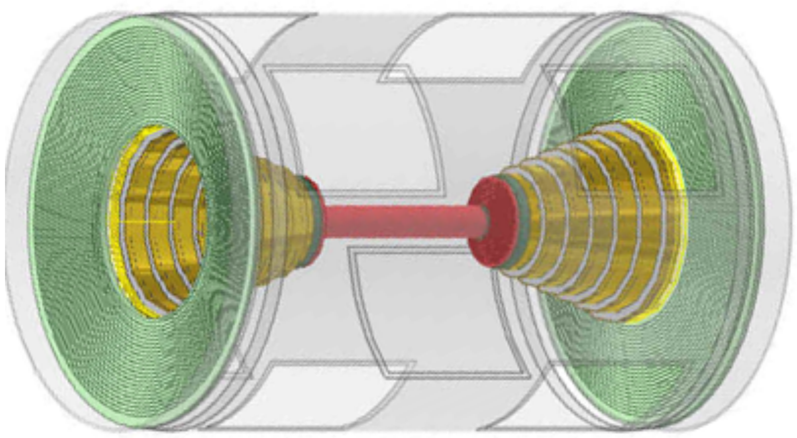
dE/dx

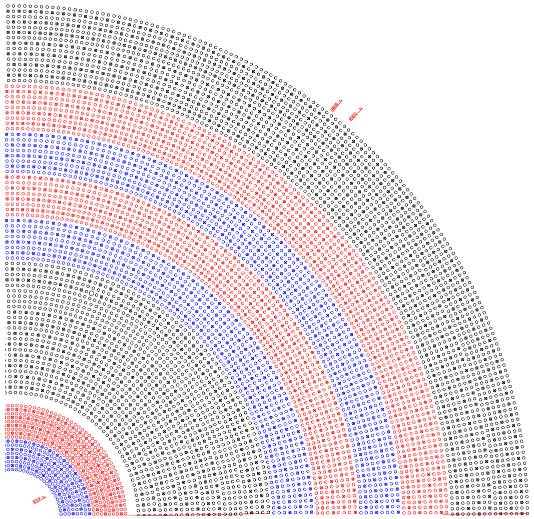



TOF



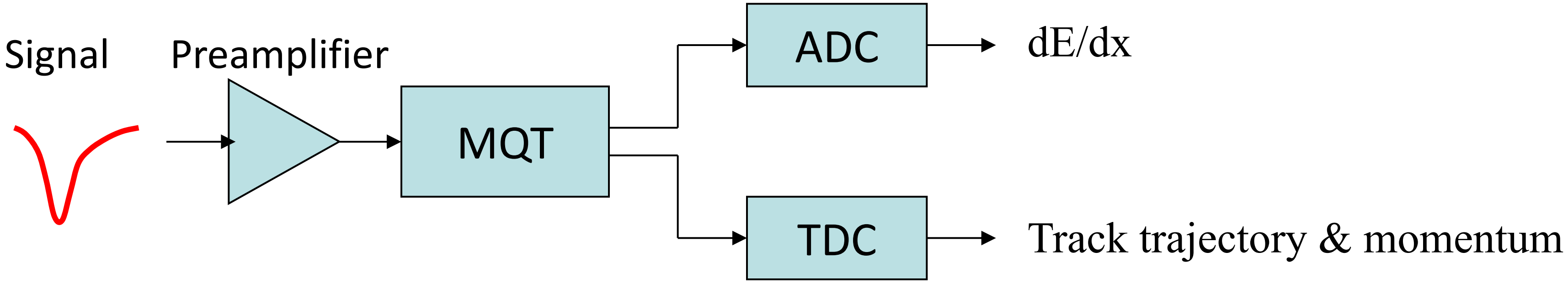
# dE/dx measurement with MDC





MDC parameters:

- End-plates :ladder shape
- cosθ from -0.93 to 0.93
- 43 sense layers (19 axial layers + 24 stereo layers)
- 6796 drift cells
- Gas: He+$C_3H_8$ (60/40)



# dE/dx reconstruction

Track reconstruction

Corrections of Q

- Correction of track length
- Run by run gain correction
- Gain correction of single cell
- Correction of drift distance & incident angle
- Correction of space charge effect

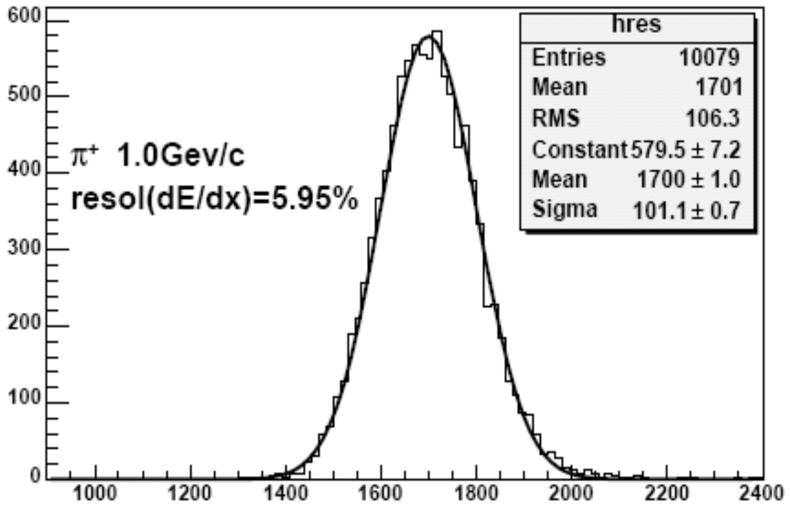
Truncation mean

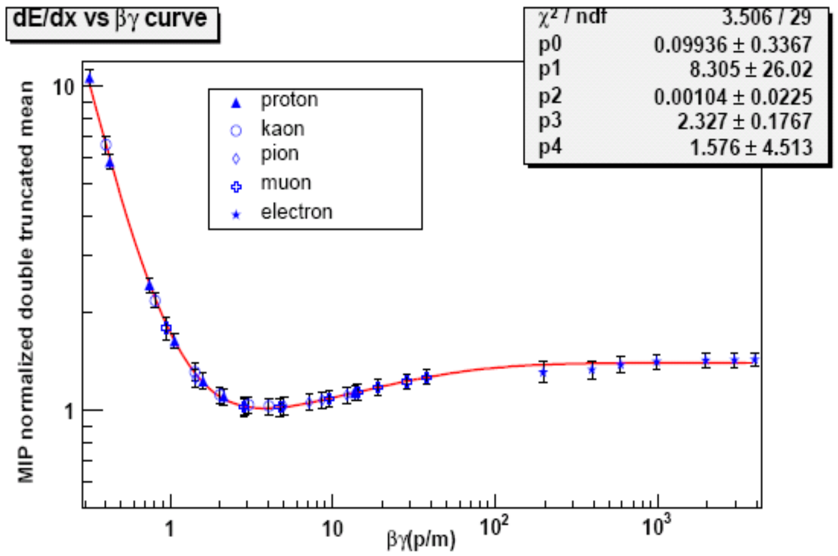
$$\chi = \frac{dE/dx_{mea} - dE/dx^{i}_{predict}}{\sigma(dE/dx)}$$

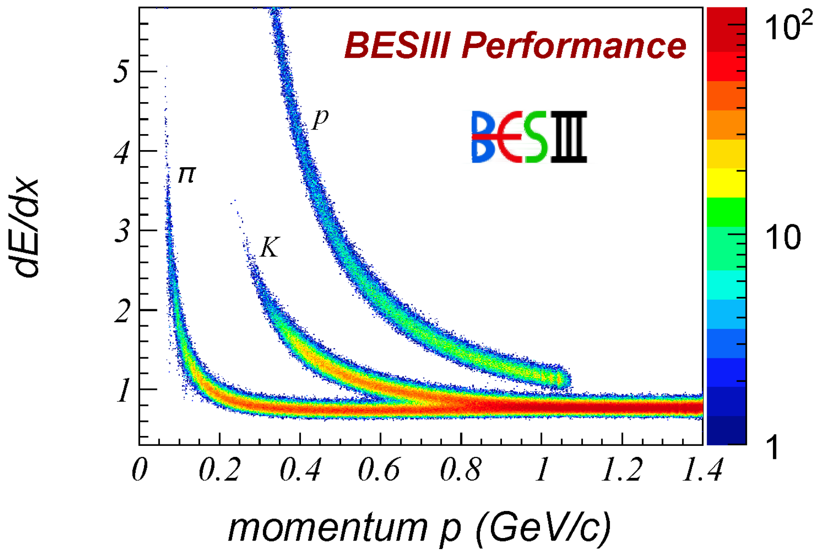
- $dE/dx_{mea}$: dE/dx from measurement
- $dE/dx^{i}_{predict}$ : dE/dx from prediction
  $i = e, \mu, \pi, K, p$

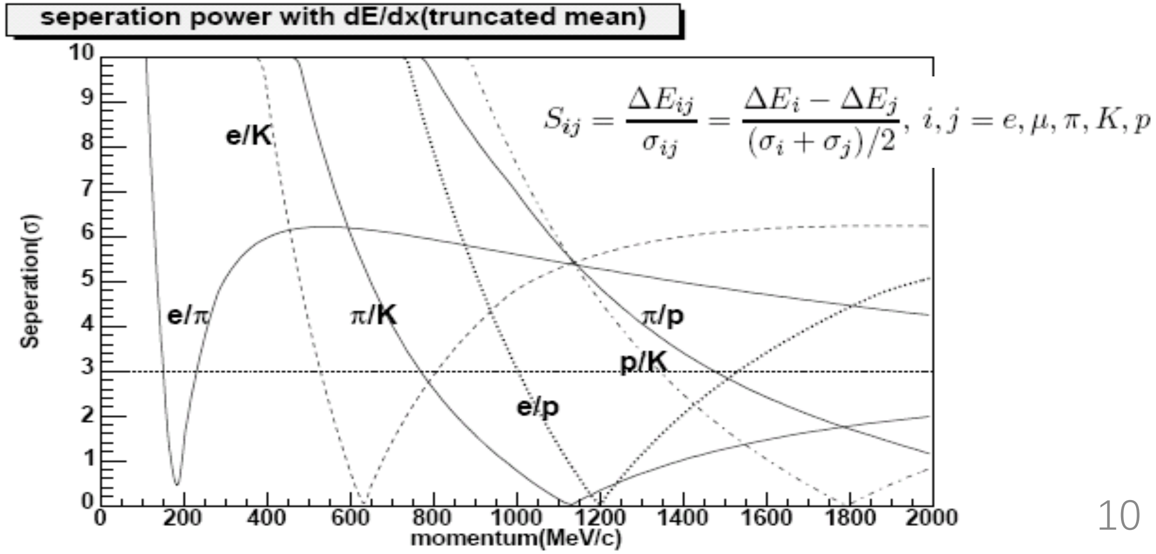
- $\chi$ with different particle assumptions, used for PID

# dE/dx performance



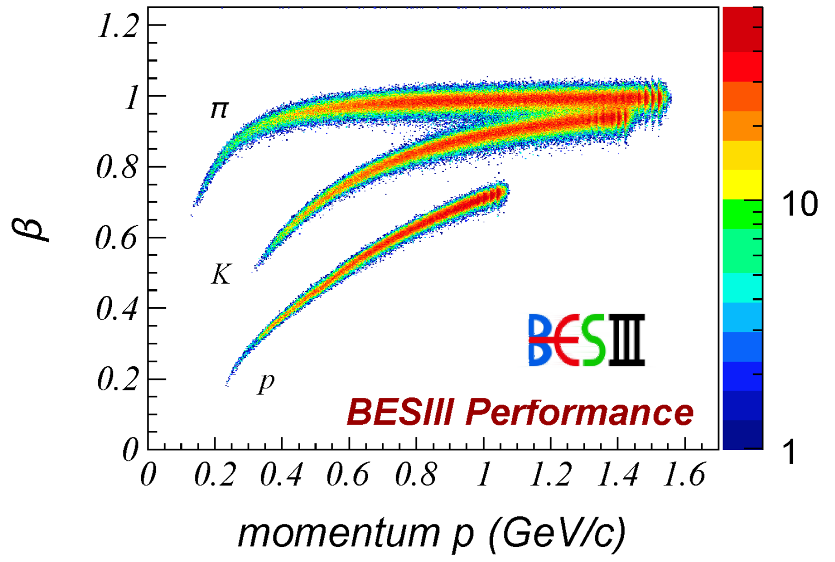
# TOF measurement

- Estimate the velocity of the particle by measuring the flight time $t_{mea}$ over the flight length from the track trajectory $L$

$$\beta = \frac{L}{c \times t_{\text{mea}}}, \quad m^2 = p^2 \times \frac{1-\beta^2}{\beta^2};$$

Define $\chi$ for particle identification

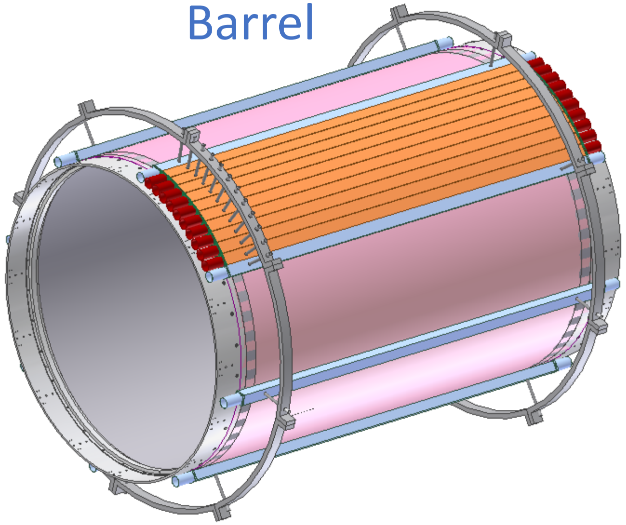
$$\chi = \frac{\Delta t}{\sigma} = \frac{t_{measure} - t^{i}_{predict}}{\sigma} \qquad i = e, \mu, \pi, K, p$$



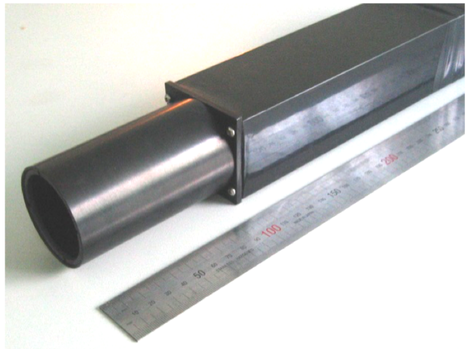
# TOF detector

- Barrel: double layers of plastic scintillator & PMT
- Endcaps
  - Before upgrade： plastic + PMT
  - After upgrade： MRPC

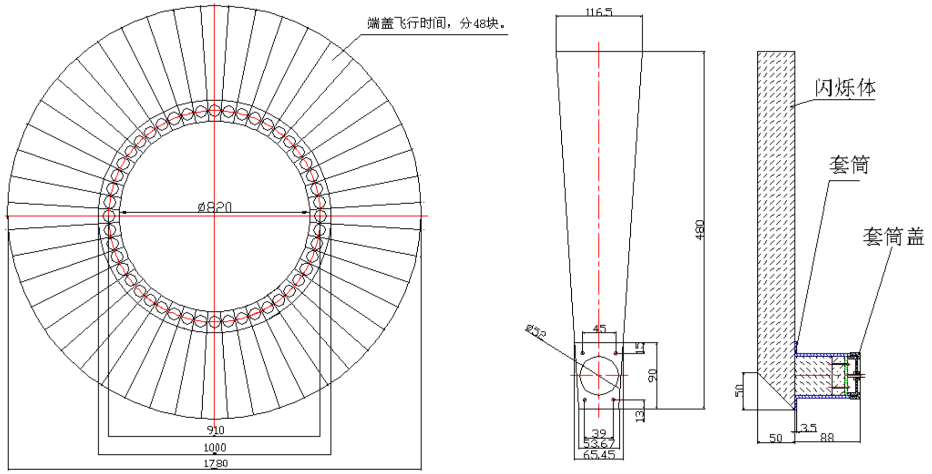
Barrel



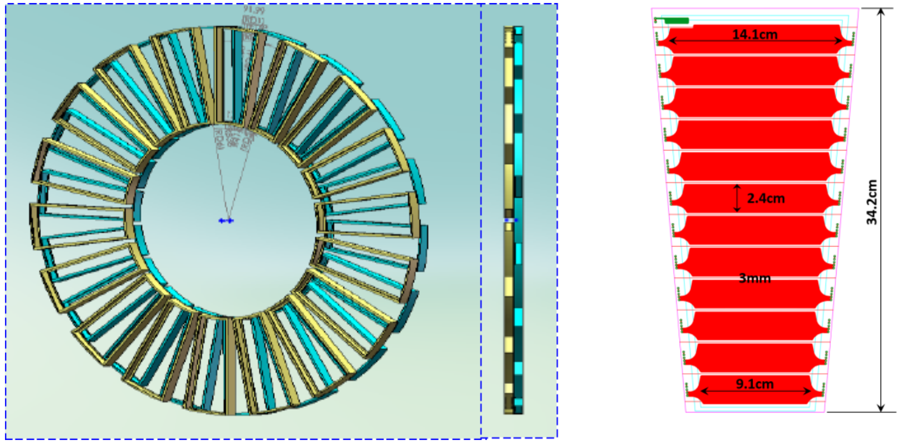
PMT



Endcap before upgrade



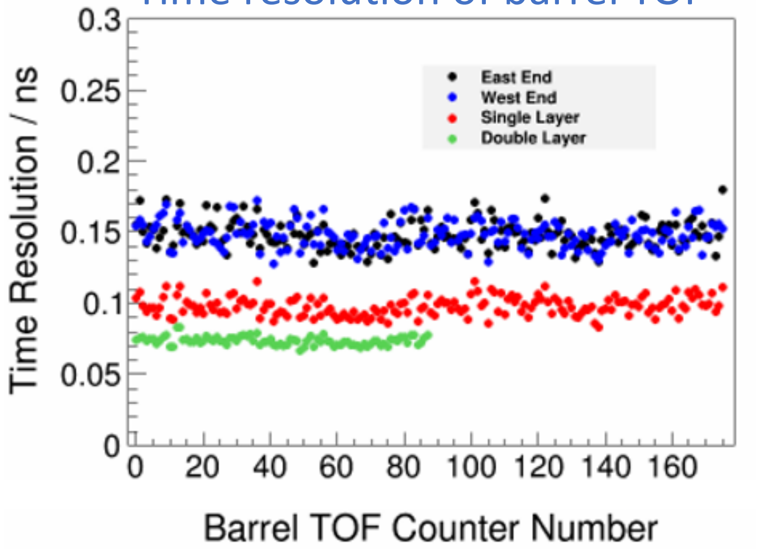

Endcap after upgrade



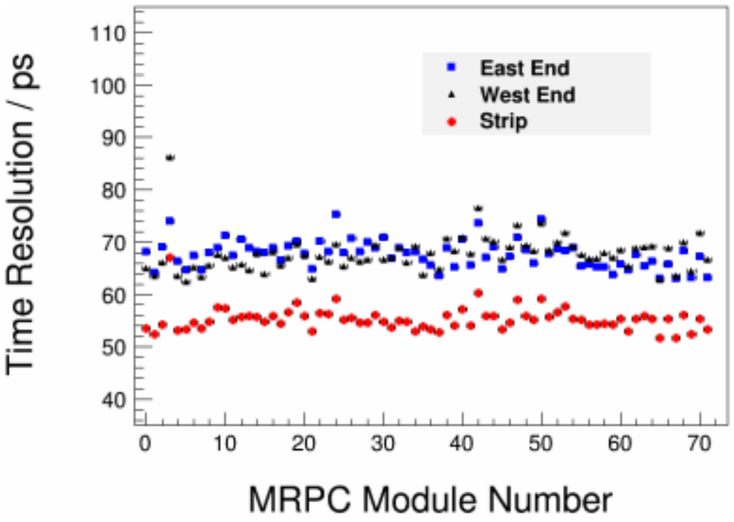
# TOF performance

| Time resolution （ps） | |
|---|---|
| Barrel | 68 |
| Endcap (before upgrade) | 98 |
| Endcap (after upgrade) | 60 |

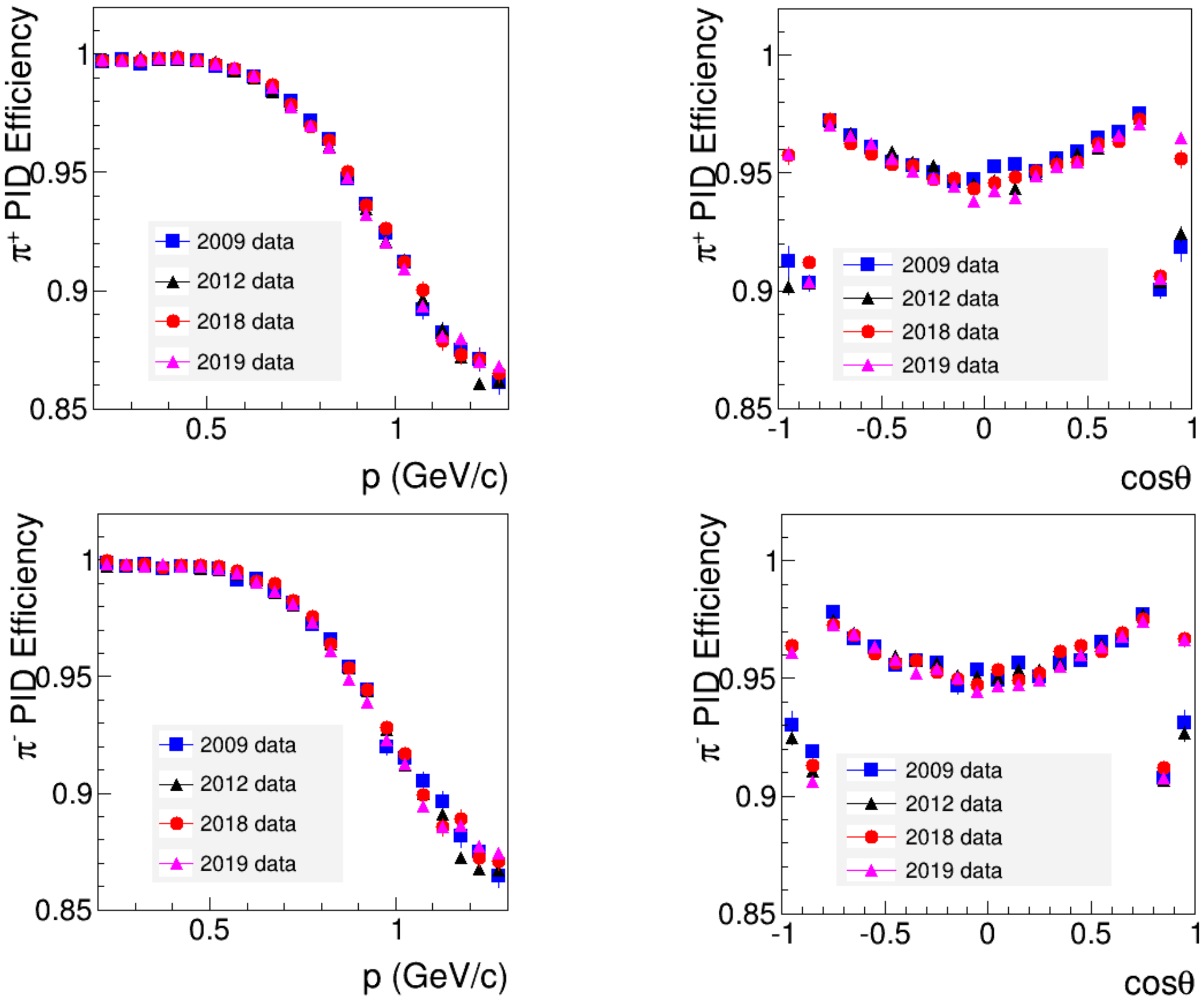
Time resolution of barrel TOF




Time resolution of MRPC



# Pion PID efficiency (dE/dx + TOF)



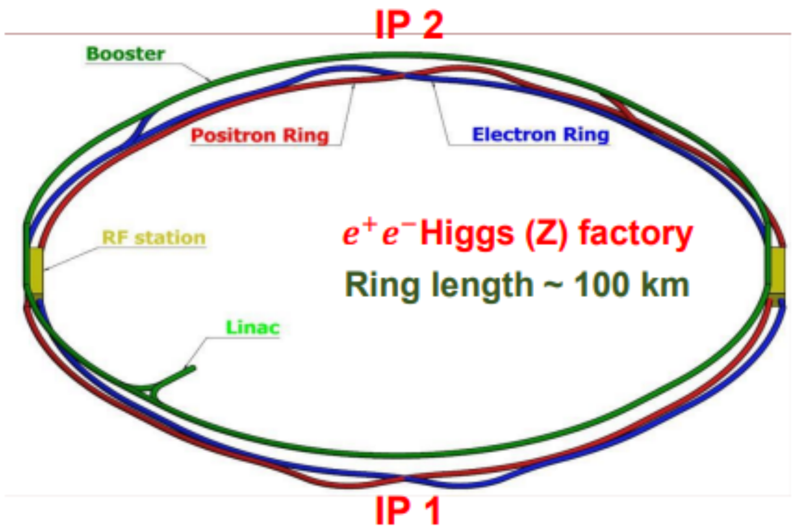

Liu Fang's talk
(https://indico.ihep.ac.cn/event/11535/)

# PID of CEPC

Guang Zhao, Linghui Wu, Mingyi Dong, Gang Li, Zhefei Tian,
Zhenyu Zhang, Xu Gao, Shuaiyi Liu, Shengsen Sun

# Physics study at CEPC

- The CEPC aims to start operation in 2030's, as a Higgs (Z) factory in China. The plan is to operate
  - Above **ZH** threshold ($\sqrt{s}$ ~ 240 GeV) for 7 years.
  - Around and at the **Z** pole for 2 years.
  - Around and above **W⁺W⁻** threshold for 1 year.
  - It is upgradeable to run at the $t\bar{t}$ threshold.
- Possible *pp* collider (SppC) of $\sqrt{s}$ ~ 50–100 TeV in the future.

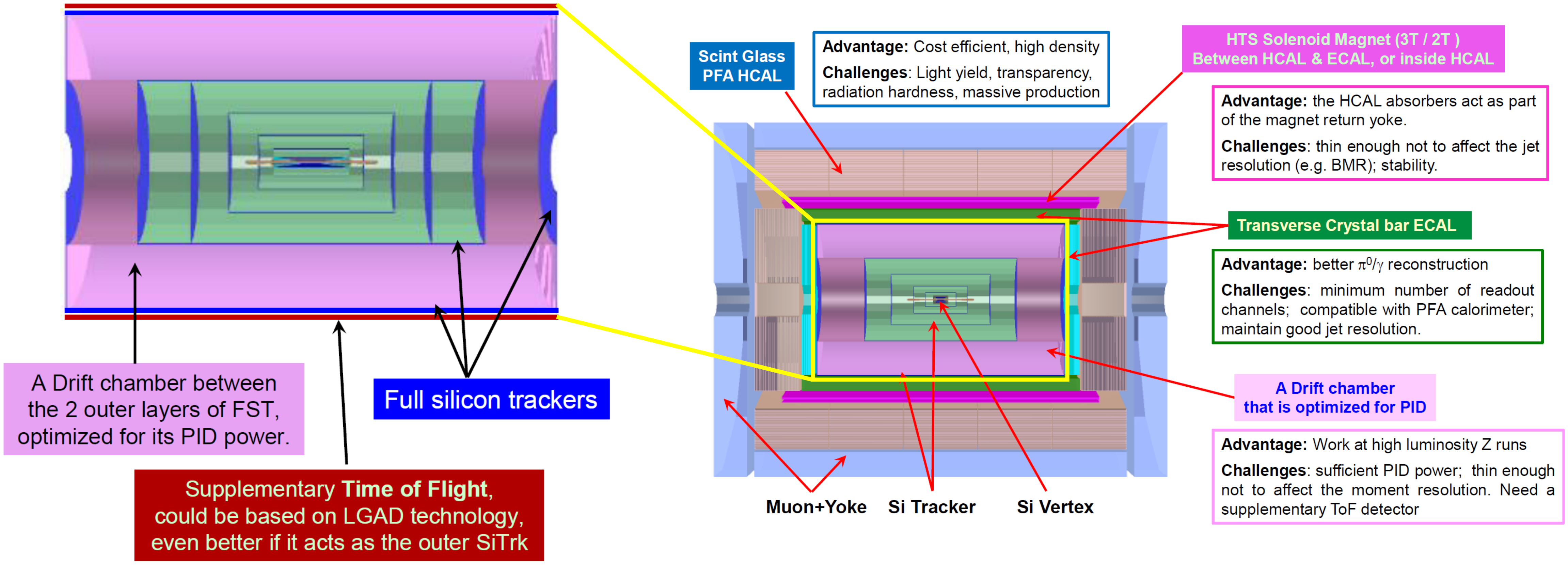



| Particle | $E_{c.m.}$ (GeV) | Years | SR Power (MW) | Lumi. /IP ($10^{34}cm^{-2}s^{-1}$) | Integrated Lumi. /yr ($ab^{-1}$, 2 IPs) | Total Integrated L ($ab^{-1}$, 2 IPs) | Total no. of events |
|---|---|---|---|---|---|---|---|
| H* | 240 | 10 | 50 | 8.3 | 2.2 | 21.6 | $4.3 \times 10^6$ |
| | | | 30 | 5 | 1.3 | 13 | $2.6 \times 10^6$ |
| Z | 91 | 2 | 50 | 192** | 50 | 100 | $4.1 \times 10^{12}$ |
| | | | 30 | 115** | 30 | 60 | $2.5 \times 10^{12}$ |
| W | 160 | 1 | 50 | 26.7 | 6.9 | 6.9 | $2.1 \times 10^8$ |
| | | | 30 | 16 | 4.2 | 4.2 | $1.3 \times 10^8$ |
| $t\bar{t}$ | 360 | 5 | 50 | 0.8 | 0.2 | 1.0 | $0.6 \times 10^6$ |
| | | | 30 | 0.5 | 0.13 | 0.65 | $0.4 \times 10^6$ |

* Higgs is the top priority. The CEPC will commence its operation with a focus on Higgs.
** Detector solenoid field is 2 Tesla during Z operation, 3Tesla for all other energies.
*** Calculated using 3,600 hours per year for data collection.

- The large samples from 2 IPs: **$10^6$** Higgs, **$10^{12}$** Z, **$10^8$** W bosons, provide a unique opportunity for
  - High precision Higgs, EW measurements,
  - Study of flavor physics (b, c, tau) and QCD,
  - Probe physics beyond the standard model.
  - …

# CEPC $4^{th}$ concept detector

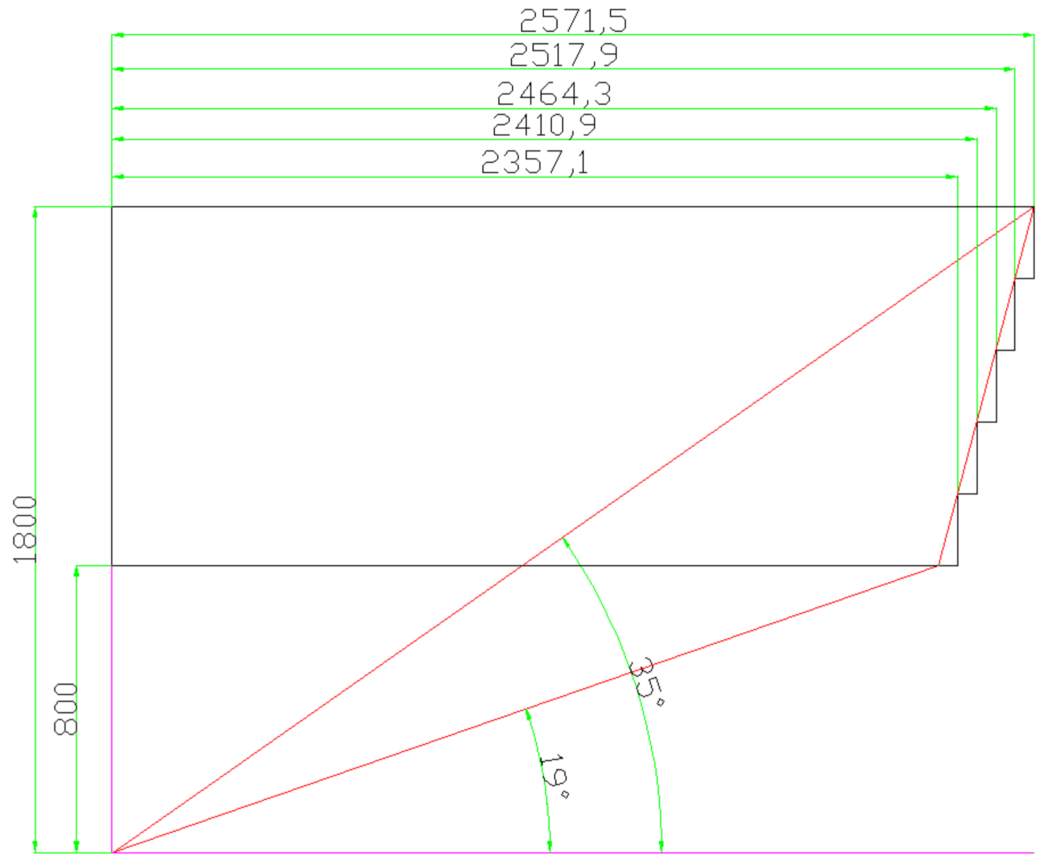



**Preliminary PID requirement: >2σ K/π separation for 20 GeV/c tracks**

# Preliminary DC design

### Preliminary parameters

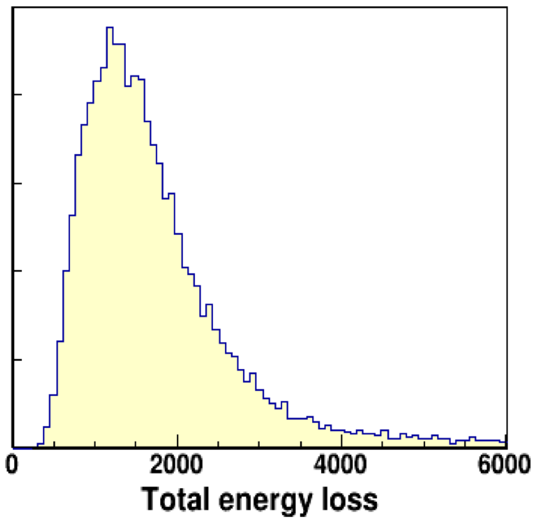
| | |
|---|---|
| Radius extension | 800-1800 mm |
| Length of outermost wires （cosθ=0.82） | 5143 mm |
| Thickness of inner CF cylinder | 200 μm |
| Outer CF frame structure | Equivalent CF thickness: 1.63 mm |
| Thickness of end Al plate | 35 mm |
| Cell size | 18 mm × 18 mm |
| # of cells | 24766 |
| Ratio of field wires to sense wires | 3:1 |
| Gas mixture | He/i$C_4H_{10}$=90:10 |



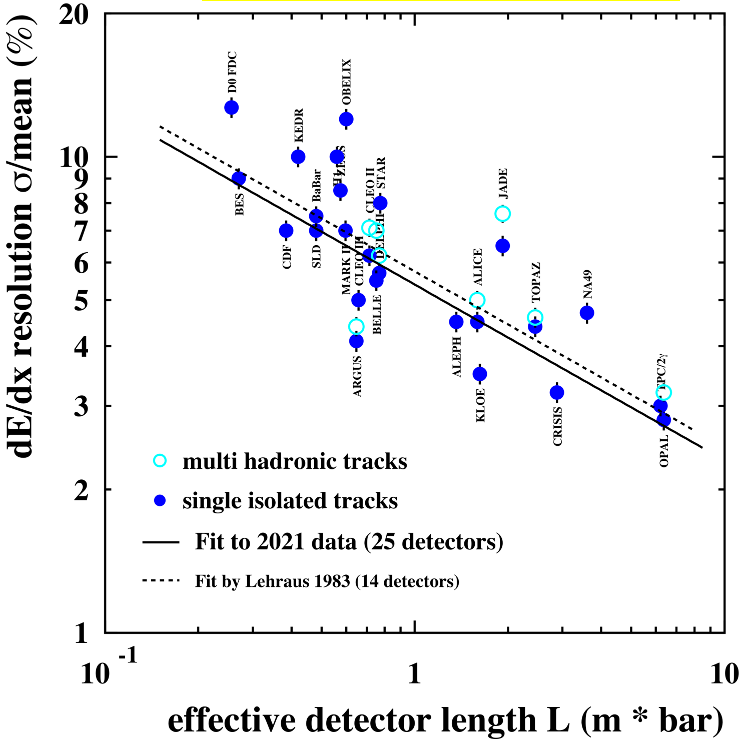
# Energy loss measurement: dE/dx

- Main mechanism: Ionization of charged tracks
- Traditional method: Total energy loss (dE/dx)
  - Landau distribution due to secondary ionizations
  - Large fluctuation from many sources: energy loss, amplification …

Integrated charge




"Lehraus" Plot 2021*



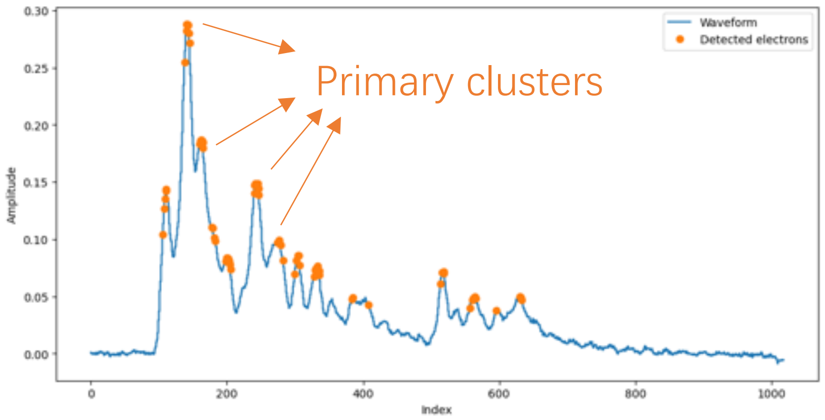

- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** * $L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** * $L^{-0.37}$ (%)
- **No significant improvement in the past 40 years**

* From Michael Hauschild's talk @ RD51 workshop

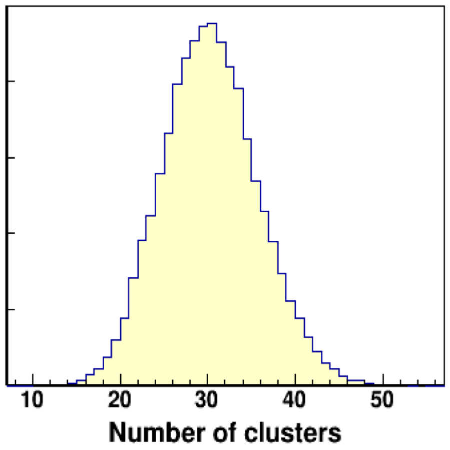
# Cluster counting measurement: dN/dx

- Alternative method: Counting primary clusters (dN/dx)
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - **Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx**

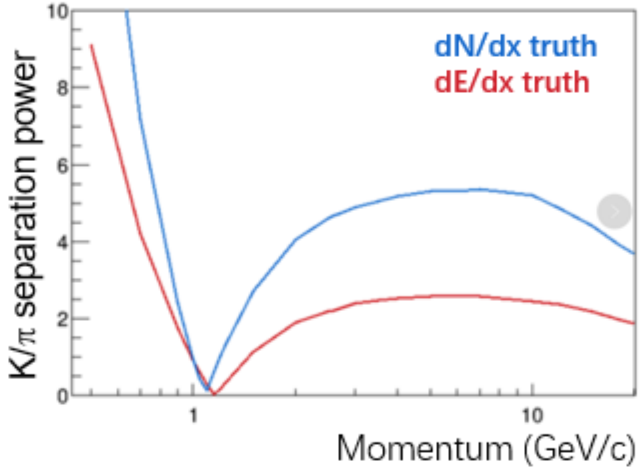
**Waveform**




**Counting clusters**




K/π separation power
dN/dx vs dE/dx



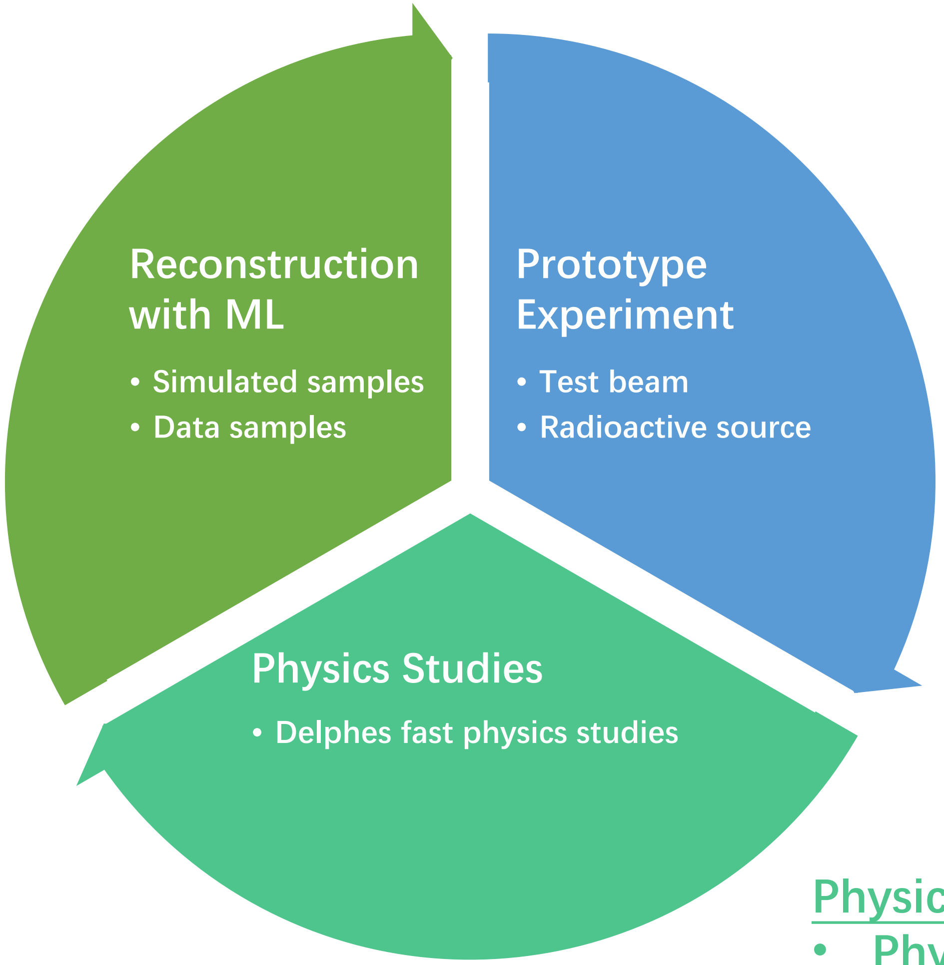

Require fast electronics and sophisticated counting algorithm

**dN/dx is extremely powerful, proposed in ILC, FCC-ee, CEPC**

# Feasibility studies

**Software challenges:**

- Efficient algorithm to count clusters in high noise-levels and pile-ups




**Hardware challenges:**

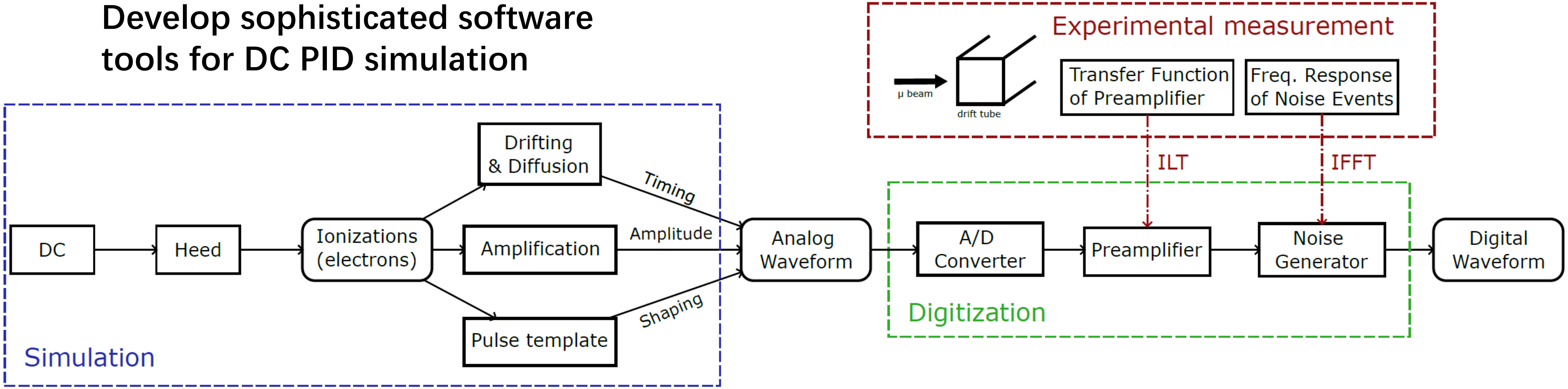
- Large volume detector design
- Fast front-end electronics
- Efficient data preprocessing

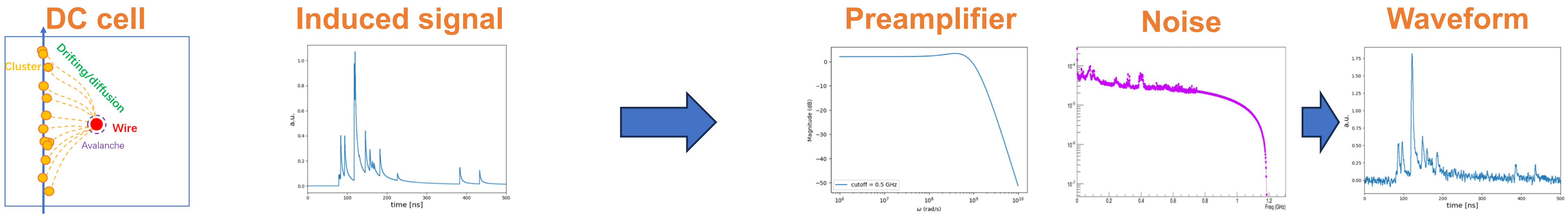
**Physics performances:**

- Physics benchmarks to evaluate CC technique

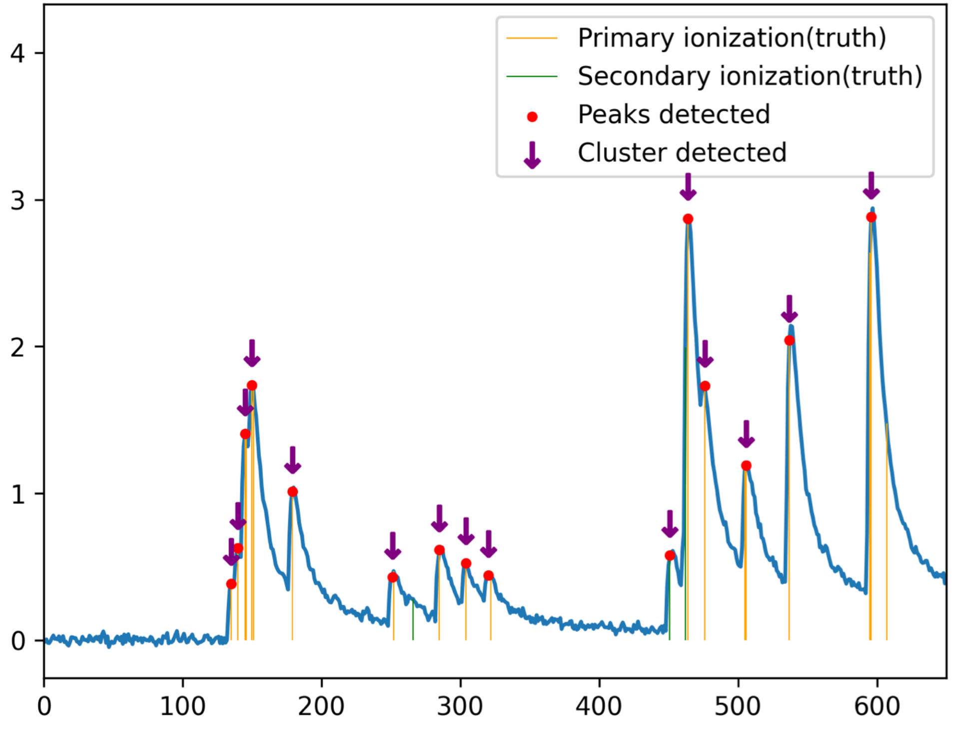
# Waveform-based full simulation

**Develop sophisticated software tools for DC PID simulation**



# Reconstruction algorithm (traditional method)




**Peak finding: Detect all electron peaks**

- Taking 1st and 2nd order derivatives
- Peak detection by threshold passing

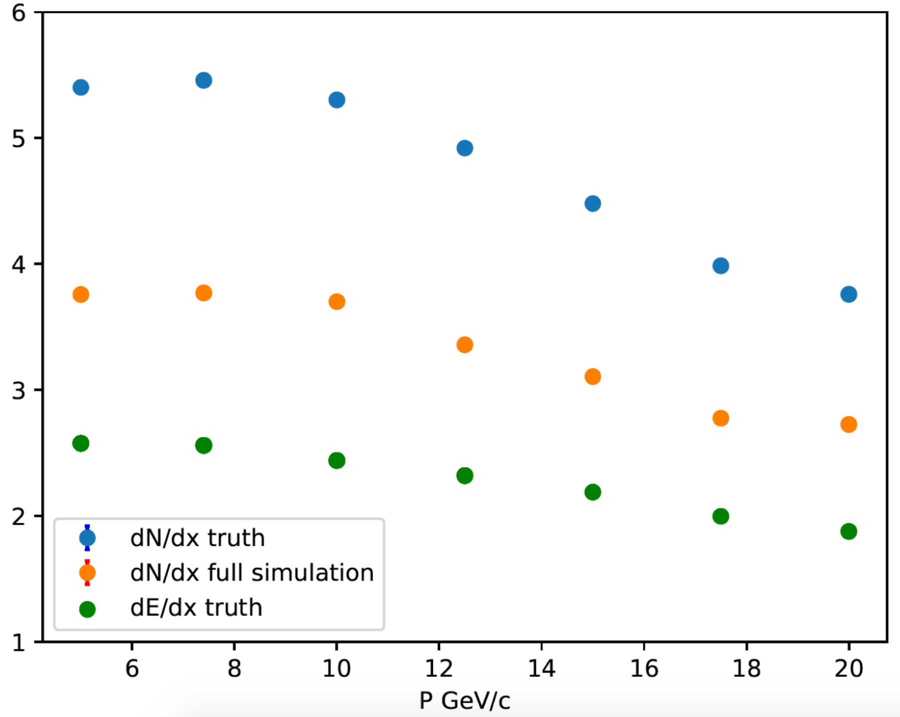
**Clusterization: Peak merge to form clusters**

- Merge peaks within $[0, t_{cut})$
- The $t_{cut}$ is related to diffusion

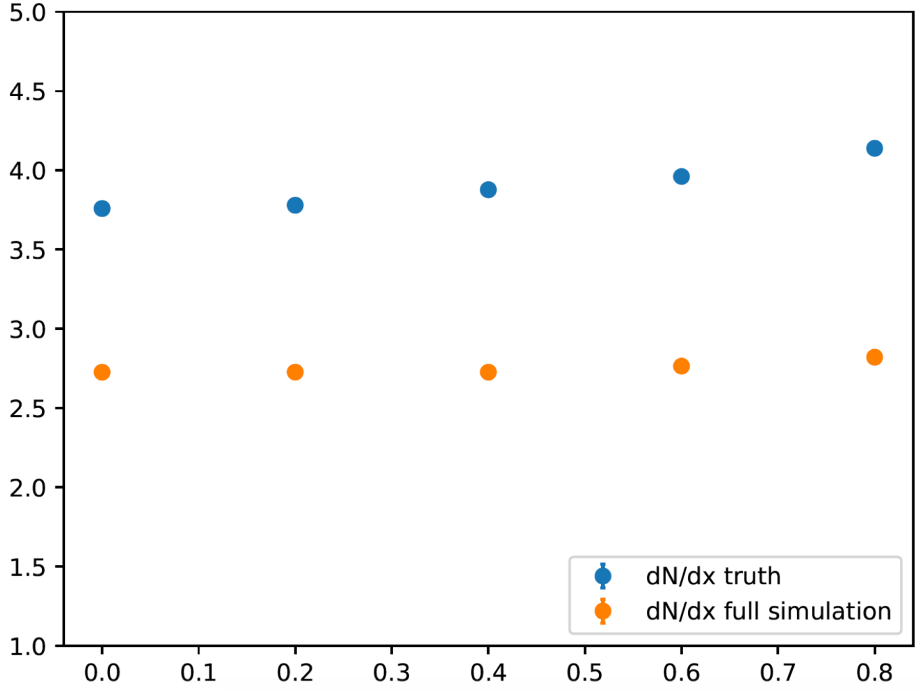
- Pros: Fast and easy to implement
- Cons: Suboptimal efficiency for highly pile-up and noisy waveforms

# PID performance

## K/π separation power vs P (1m track length, cosθ=0)




## K/π separation power vs cosθ (P=20GeV/c)




Separation power

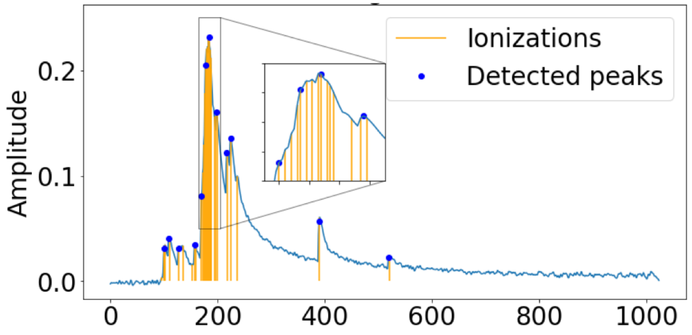
$$S = \frac{\left|\left(\frac{dN}{dx}\right)_\pi - \left(\frac{dN}{dx}\right)_K\right|}{(\sigma_\pi + \sigma_K)/2}$$

**2σ K/π separation for 20 GeV/c tracks could be achieved (preliminary)**

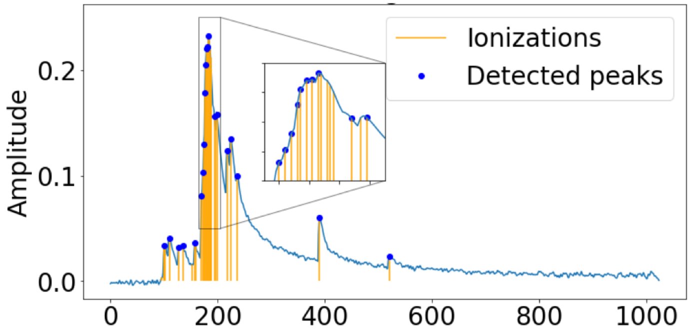
# Reconstruction algorithm with ML

- Algorithm with deep learning developed
  - Peak finding with LSTM
  - Clusterization with DGCNN

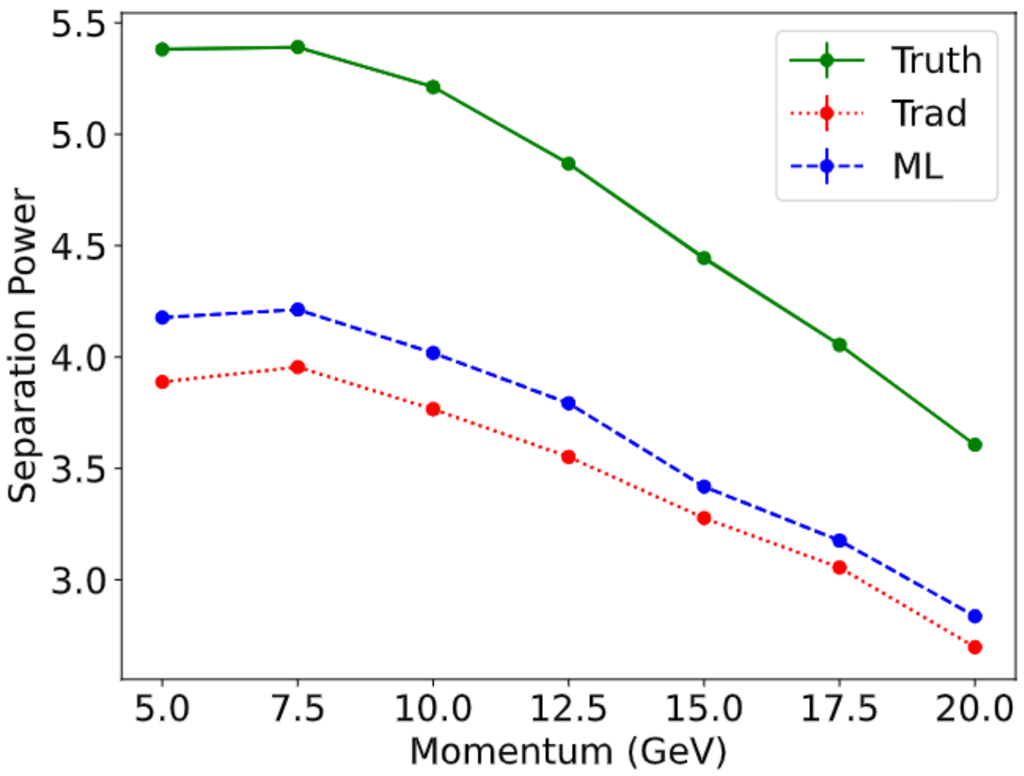
Derivative-based method




LSTM

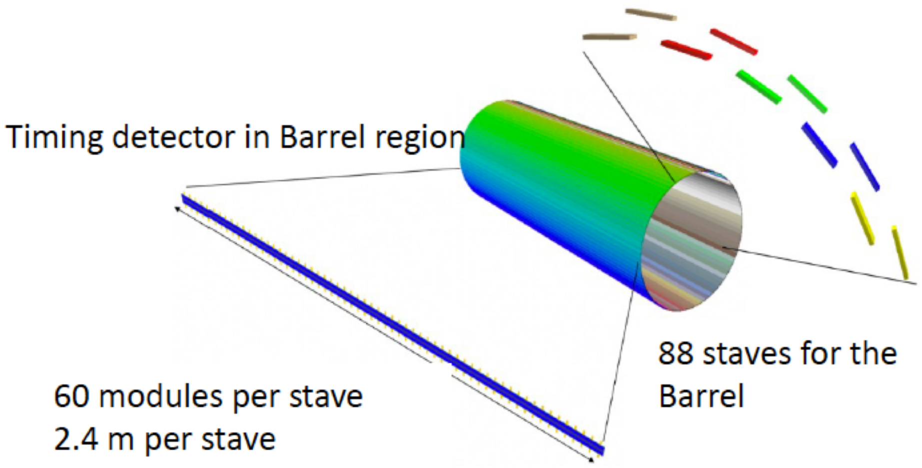



Separation power (~10% improvement with ML)



# CEPC timing detector: Concept

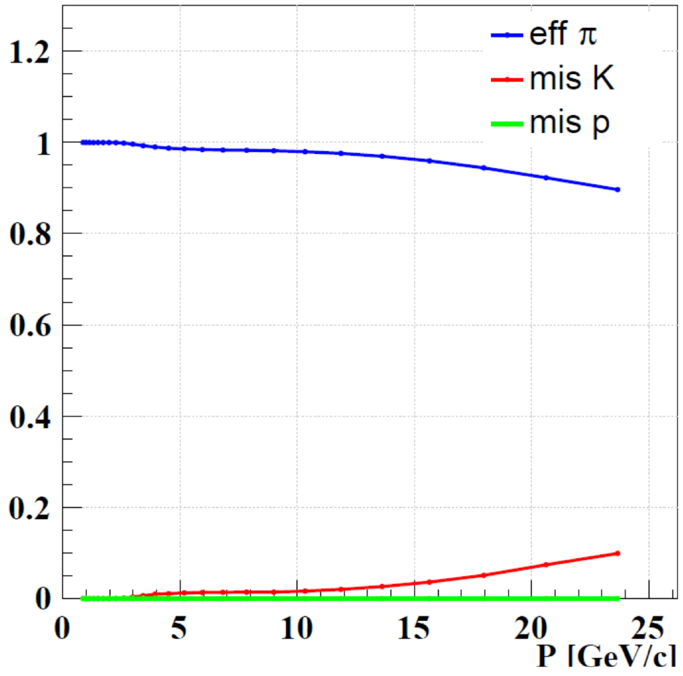
- Time of flight detector based on LGAD (EIC proposed LGAD-based TOF detector )
  - Area of detector ( Barrel : 50 $m^2$ , Endcap 20 $m^2$ ), ~ $10^6$ channels
  - Strip-like sensor ( each strip: 4cm × 0.1 cm)
  - Should be part of SET (silicon wrapper layer outside TPC or drift chamber)
    - Serve as Timing detector and part of the tracker
    - Timing resolution: 30-50 ps
    - Spatial resolution: ~ 10 µm



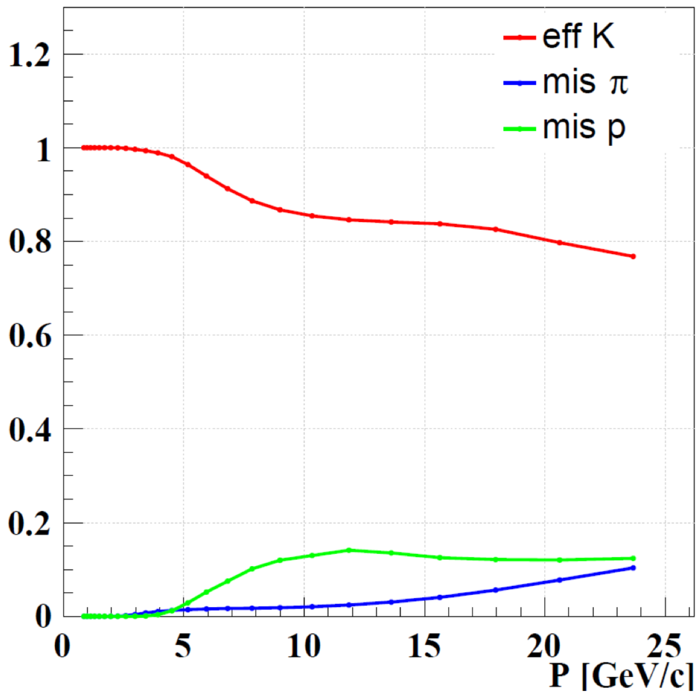

Tianyuan's talk
https://indico.ihep.ac.cn/event/19316

# Preliminary results of PID efficiency (dN/dx + TOF)

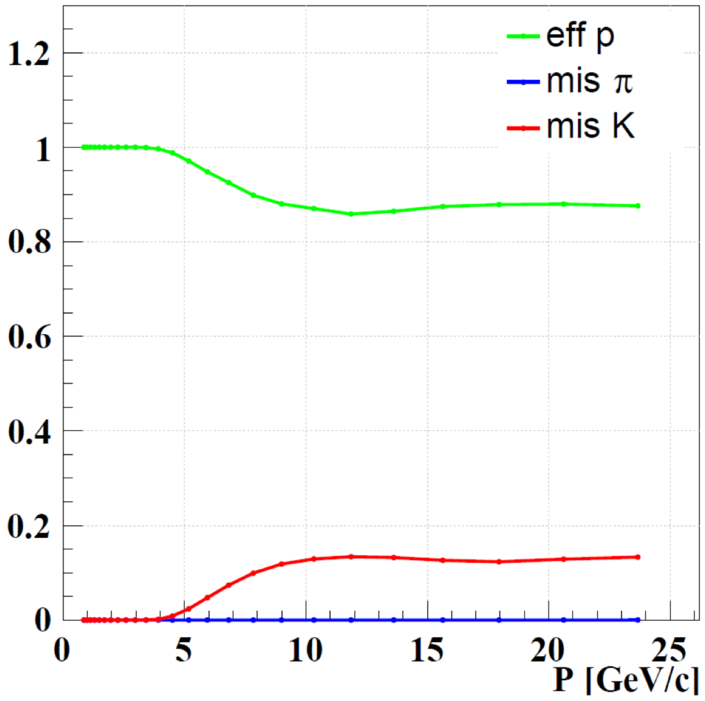
$\pi$




$K$




$p$



# Summary

- PID of BESIII
  - dE/dx with MDC + TOF
  - Good performance and running stably for more than ten years
- PID of CEPC
  - dN/dx in gaseous detector + TOF with LGAD
  - Simulation study of the drift chamber shows dN/dx can provide better PID capability than dE/dx method
  - Lots of work ongoing

*Thanks!*