BESIII和CEPC的粒子鉴别

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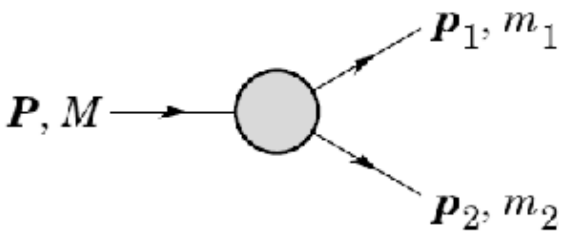
内容

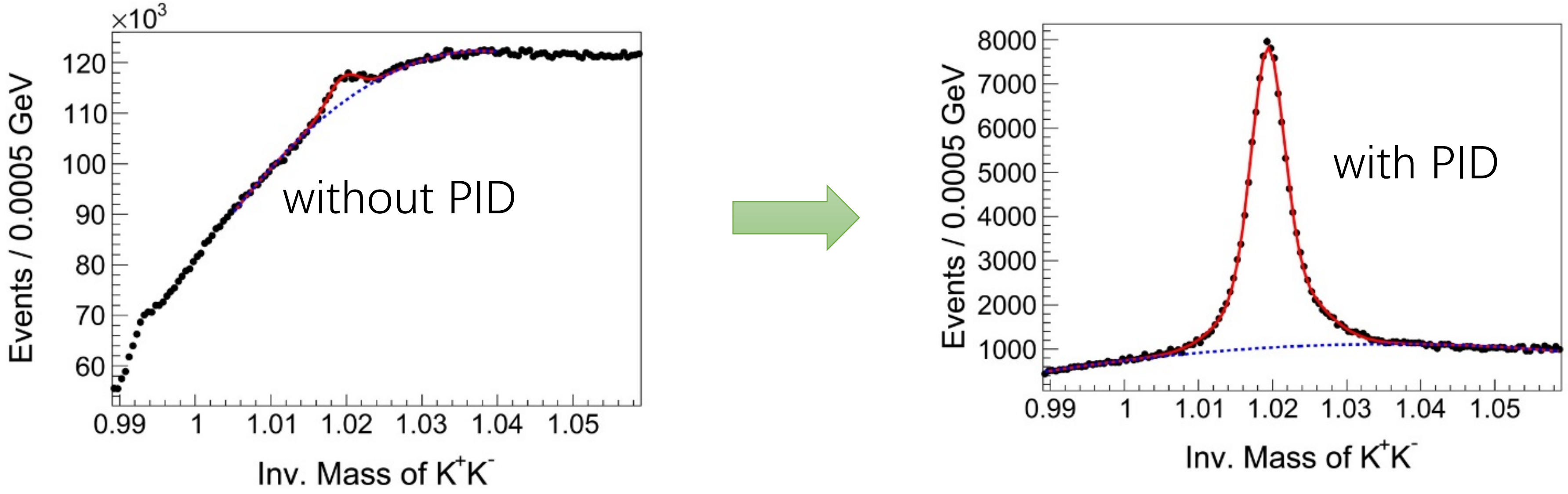
- 粒子鉴别介绍
- BESIII粒子鉴别
- CEPC粒子鉴别
- 总结

为什么要做粒子鉴别（PID）

- 两个粒子的不变质量：$M^2 = m_1^2 + m_2^2 + 2(E_1E_2 - p_1p_2cos\theta)$



$\phi \to K^+K^-$不变质量的比较 (数据中 Inclusive $\phi \to K^+K^-$)



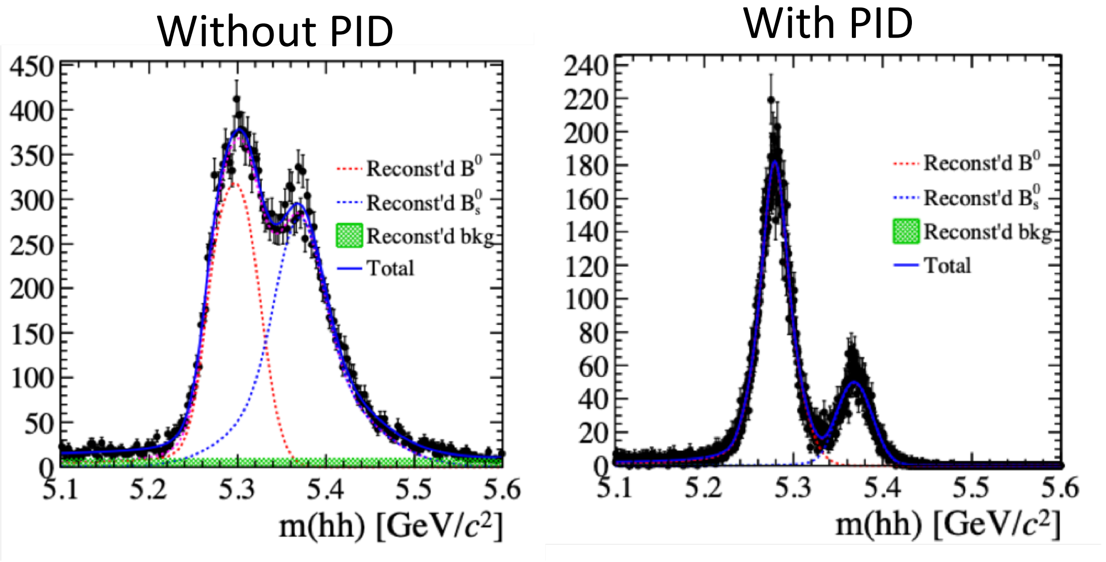
PID in future lepton collider experiments

- Particle identification is essential for flavor physics and jet study
  - Reduce combination background
  - Improve mass resolution
  - Improve jet energy resolution
  - Benefit flavor tagging

Example of the impact of PID in heavy flavor decay reconstruction

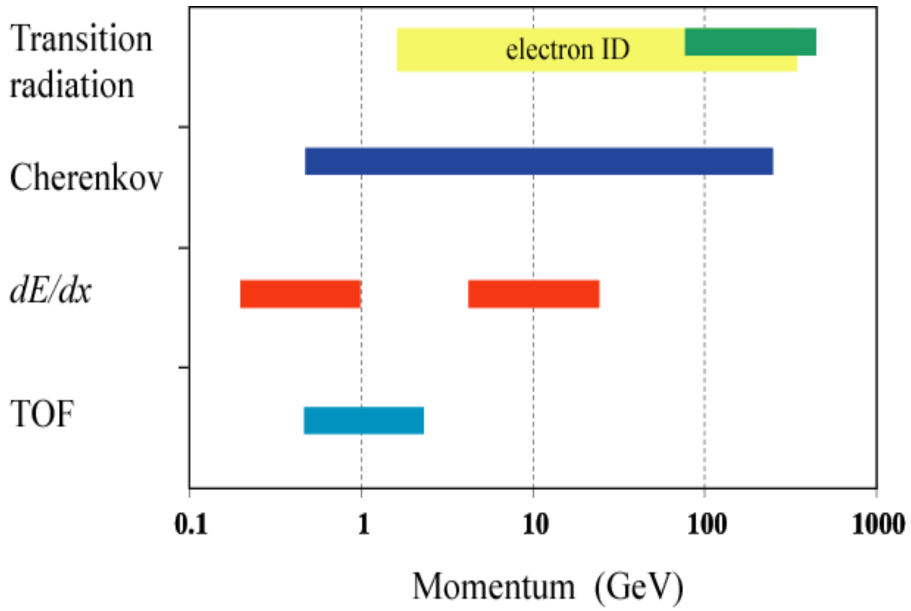
Disentangle the various $B_s^0(B^0) \to h^- h^+$ in same topology final-states.

Simulation at CEPC



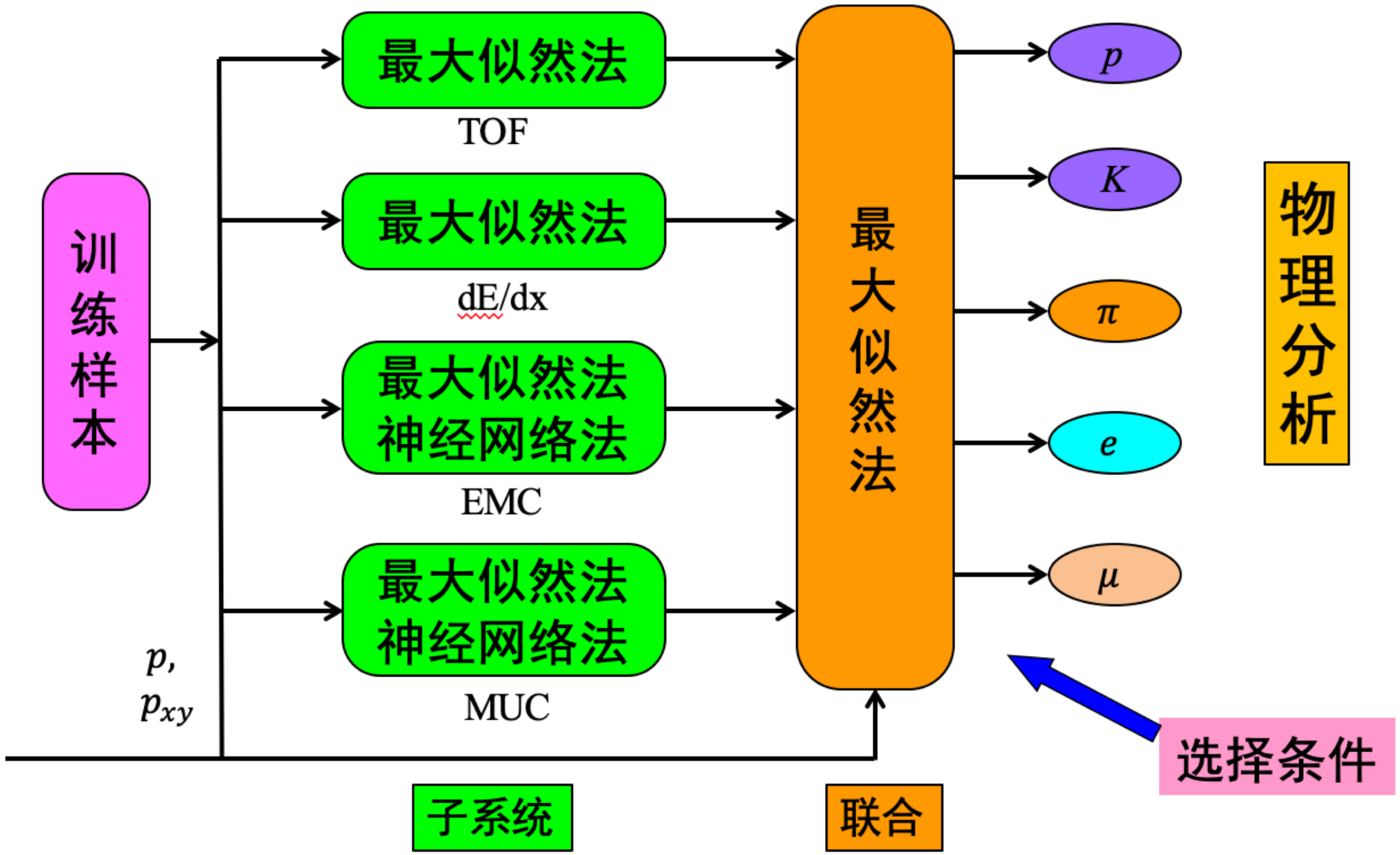
粒子鉴别技术

- 电离能损(dE/dx)测量： 气体探测器（漂移室 或 TPC）
- 飞行时间（TOF）探测：闪烁体或MRPC
- 切伦科夫（Cherenkov）探测器
- 穿越辐射（Transition Radiation）探测器



BESIII粒子鉴别

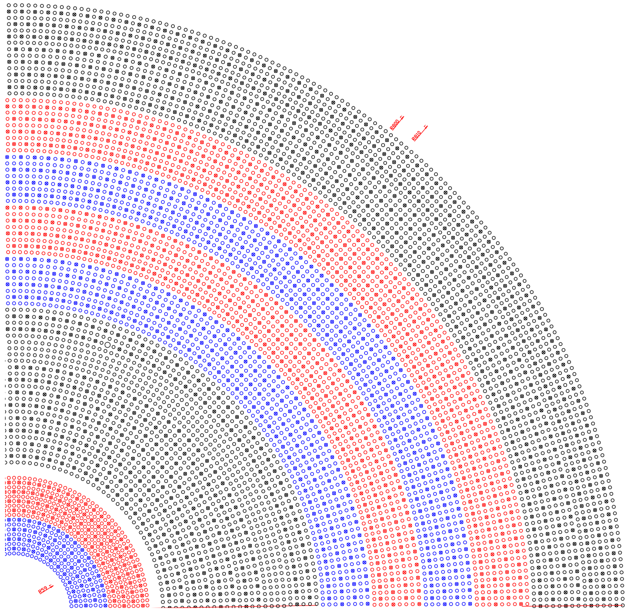
BESIII粒子鉴别算法

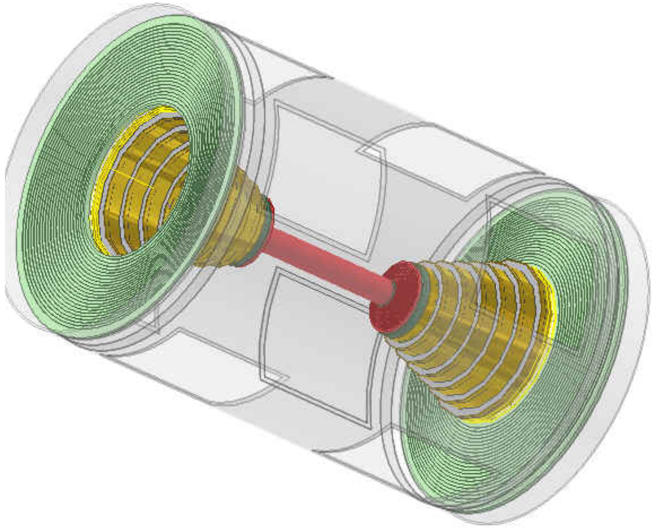


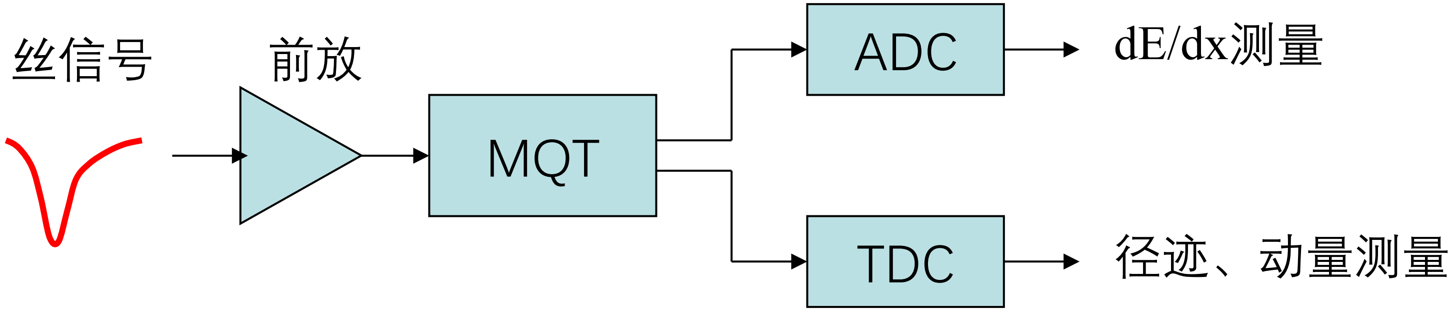
- 软件算法稳定运行十余年

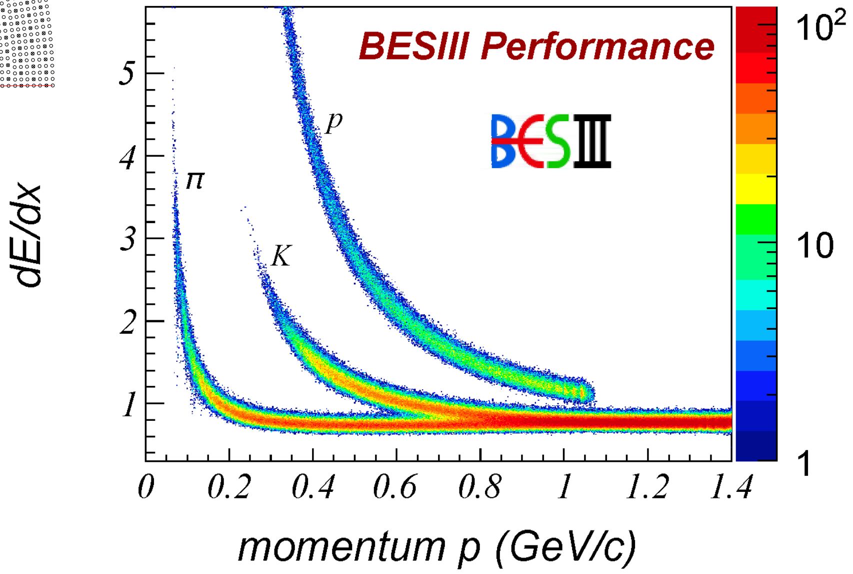
漂移室电离能损(dE/dx)测量

- 43 sense wire layers group to 11 super-layers
- End-plates :ladder shape
- cosθ from -0.93 to 0.93
- Small cell geometry
- 6796 sense wires (axial and stereo type)









dE/dx重建

MDC径迹重建

↓

对Q进行各种修正 →

- 路径长度修正
- Run by run增益修正
- 单丝增益修正
- 漂移距离-入射角修正
- 饱和效应修正

↓

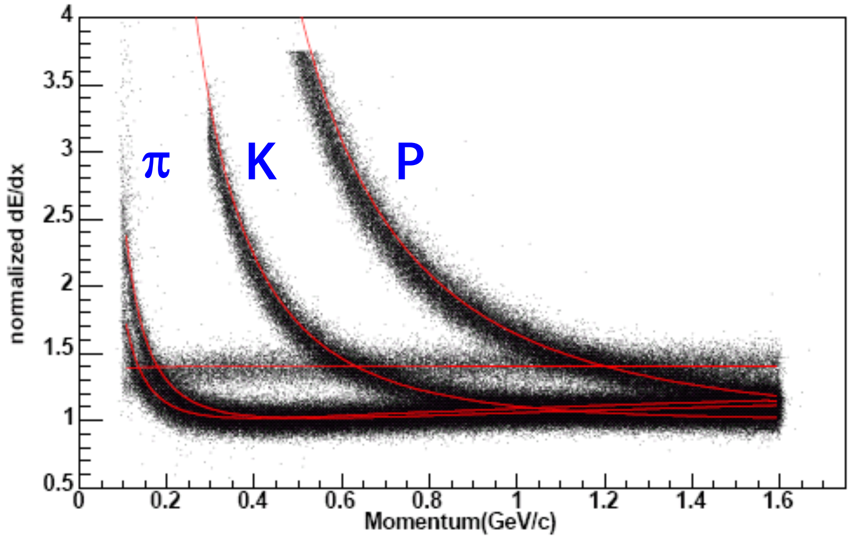
截断平均

↓

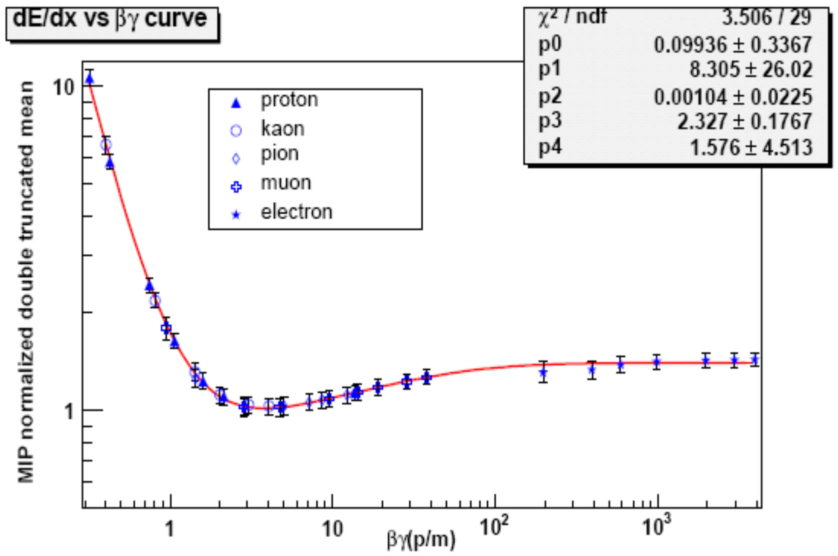
$$\chi = \frac{dE/dx(\text{测量})\text{-}dE/dx(\text{期望})}{\sigma(dE/dx)}$$

- 计算不同粒子假设下的χ，用于粒子鉴别

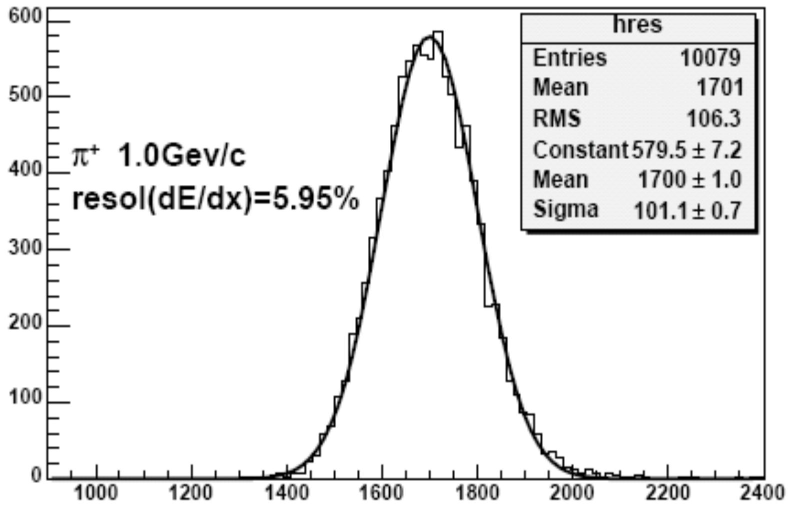
dE/dx性能



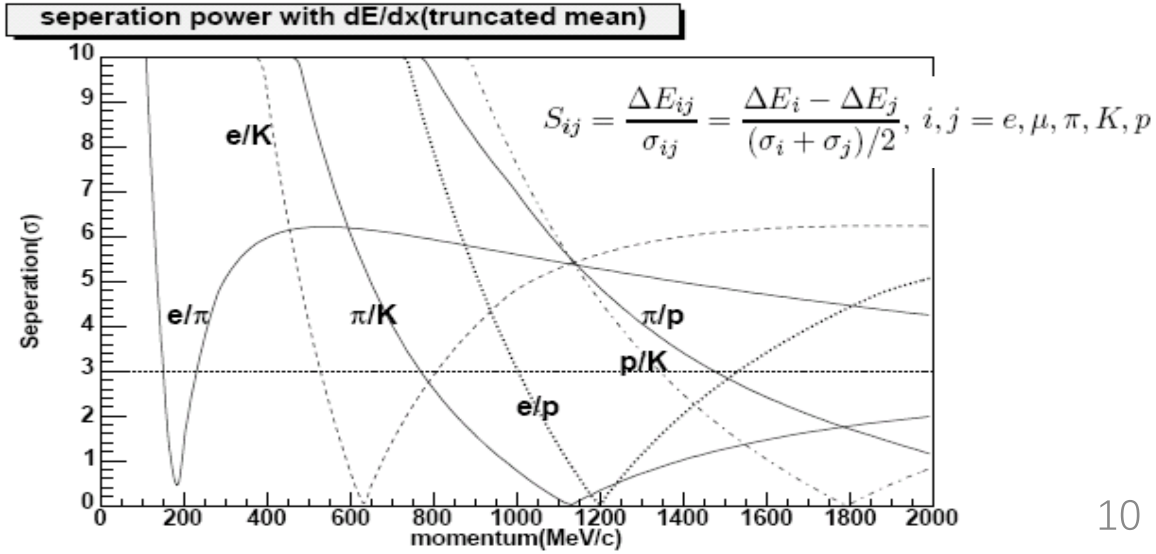
π
K
P
normalized dE/dx
Momentum(GeV/c)



dE/dx vs βγ curve
χ² / ndf 3.506 / 29
p0 0.09936 ± 0.3367
p1 8.305 ± 26.02
p2 0.00104 ± 0.0225
p3 2.327 ± 0.1767
p4 1.576 ± 4.513
proton
kaon
pion
muon
electron
MIP normalized double truncated mean
βγ(p/m)



hres
Entries 10079
Mean 1701
RMS 106.3
Constant 579.5 ± 7.2
Mean 1700 ± 1.0
Sigma 101.1 ± 0.7
π⁺ 1.0Gev/c
resol(dE/dx)=5.95%



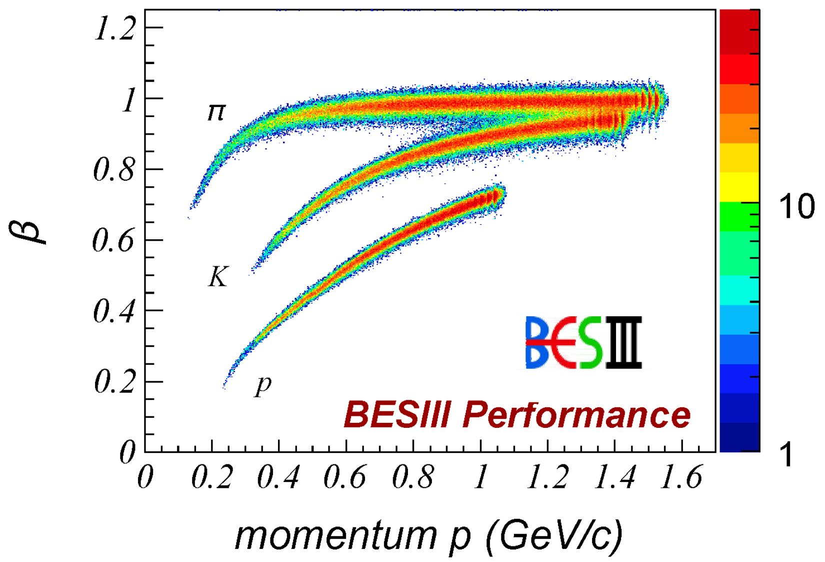
seperation power with dE/dx(truncated mean)
$S_{ij} = \frac{\Delta E_{ij}}{\sigma_{ij}} = \frac{\Delta E_i - \Delta E_j}{(\sigma_i + \sigma_j)/2}, \ i,j = e, \mu, \pi, K, p$
e/K
e/π
π/K
π/p
p/K
e/p
Seperation(σ)
momentum(MeV/c)

飞行时间(TOF)测量

- 飞行时间探测器是通过测量带电粒子的飞行时间，结合径迹探测器测量的粒子的动量和飞行径迹长度，得到粒子的质量，实现粒子鉴别。

$$\beta = \frac{v}{c} = \frac{L}{c \cdot t} \qquad \beta = \frac{p \cdot c}{E} = \frac{1}{\sqrt{\left(\frac{m \cdot c}{p}\right)^2 + 1}} \qquad m = \frac{p}{c}\sqrt{\left(\frac{c \cdot t}{L}\right)^2 - 1}$$

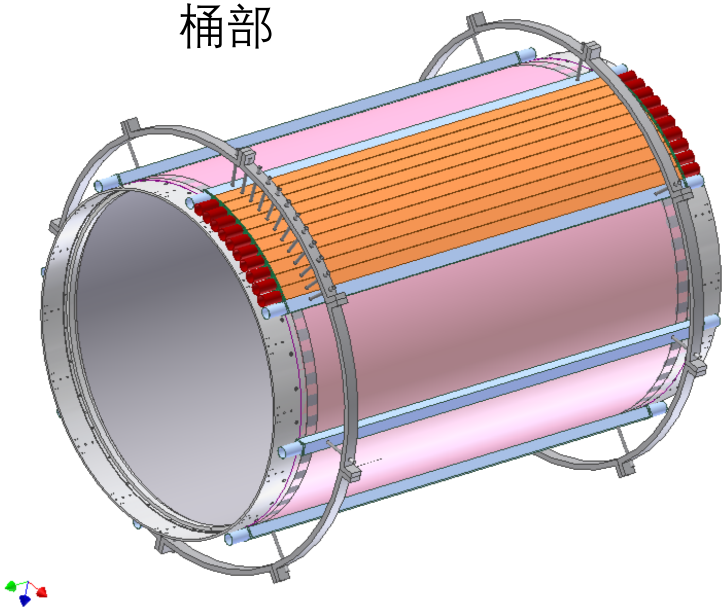
- 动量-速度法
- 动量$p \uparrow$，$v \rightarrow c$，$\beta \rightarrow 1$



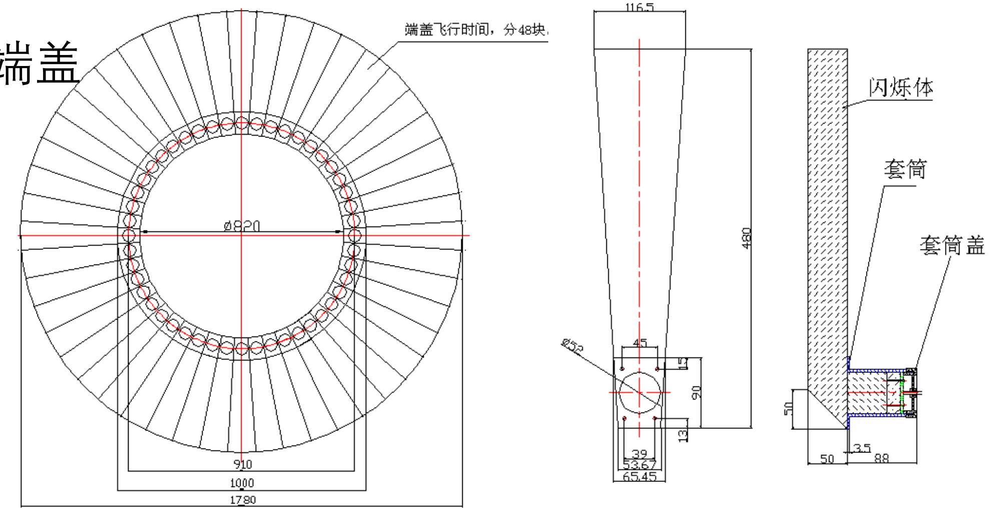
TOF探测器

- 塑料闪烁体+光电倍增管
- 桶部双层：BC408
- 旧端盖单层：扇形BC404
- 新端盖：多气隙电阻性板室（MRPC）

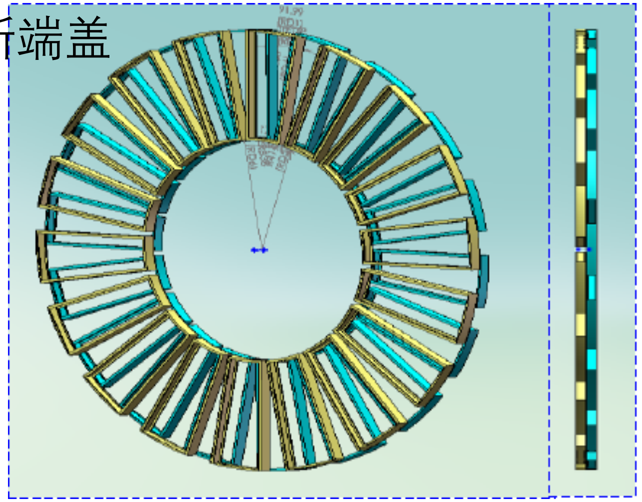
桶部

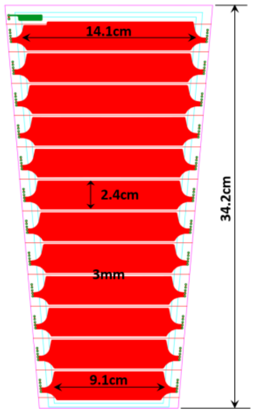


旧端盖



新端盖



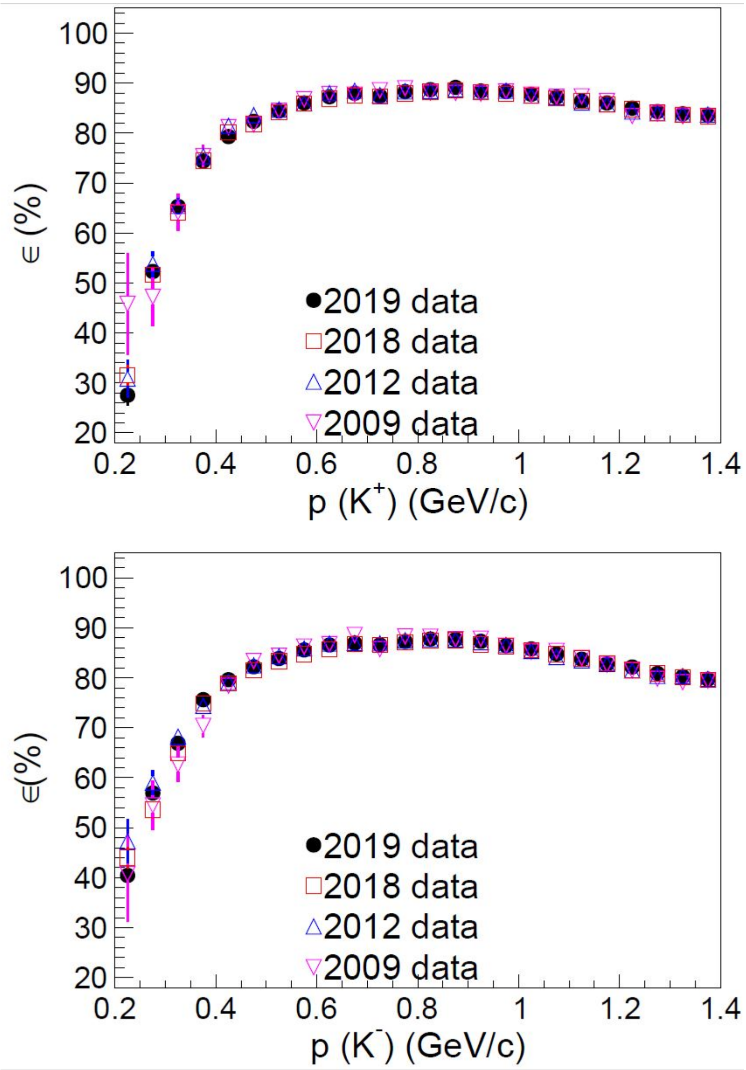


TOF粒子鉴别性能

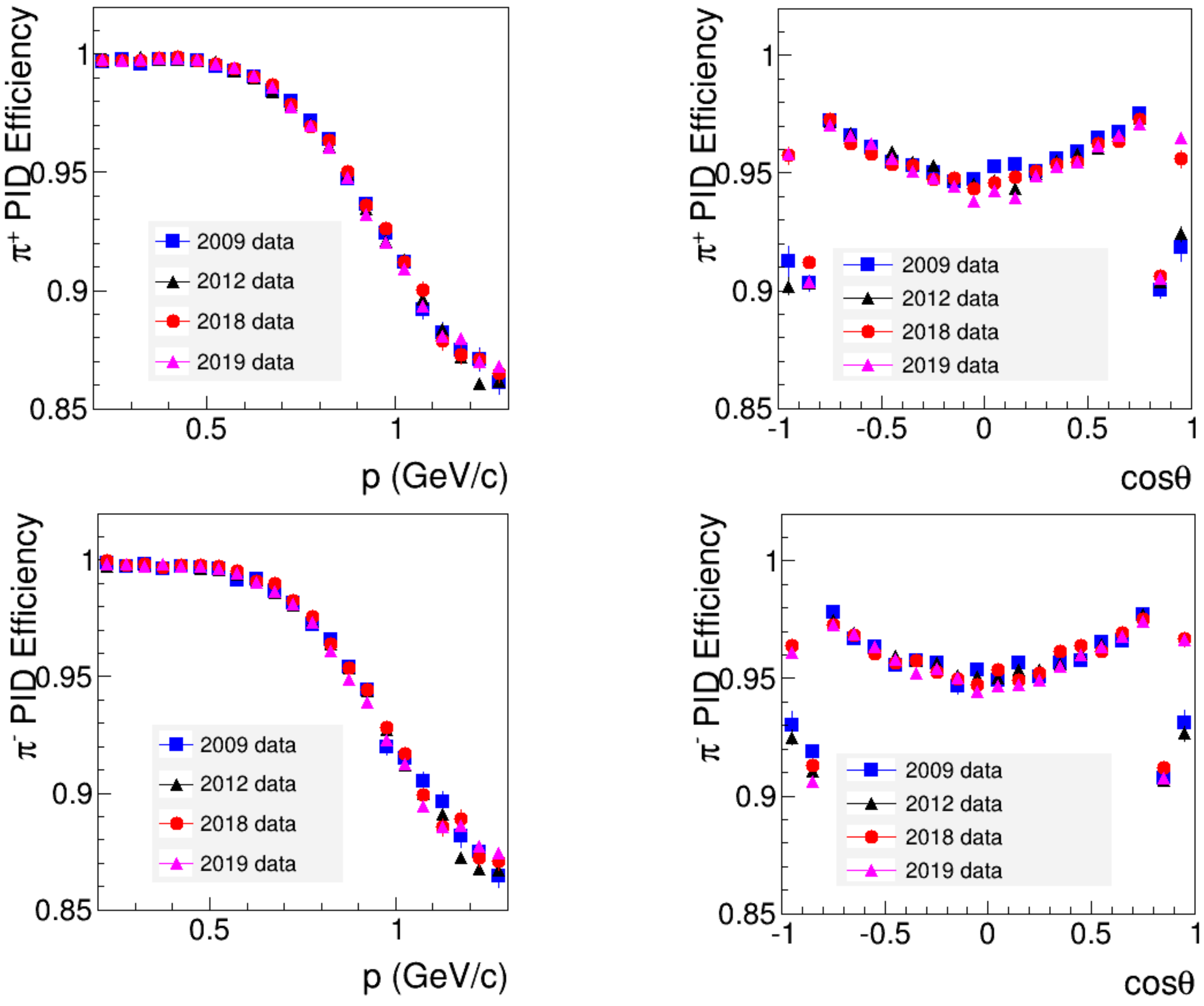
- 粒子鉴别通过比较测量时间与预期时间差

$$\chi = \frac{\Delta t}{\sigma} = \frac{t_{measure} - t^{i}_{predict}}{\sigma}$$

时间分辨（ps）	
桶部	68
旧端盖	98
新端盖	60



Pion PID效率 (dE/dx + TOF)



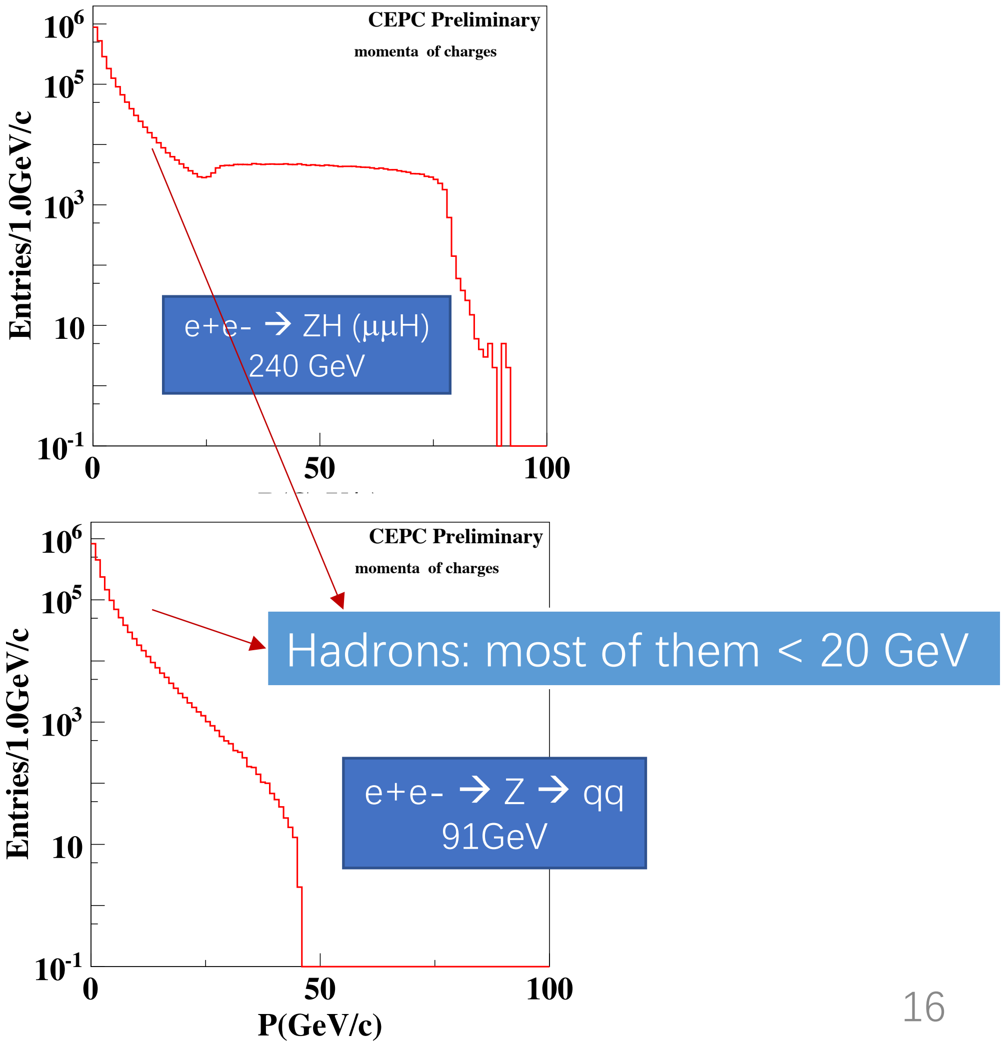
Liu Fang's talk
(https://indico.ihep.ac.cn/event/11535/)

CEPC粒子鉴别

物理研究对PID的需求

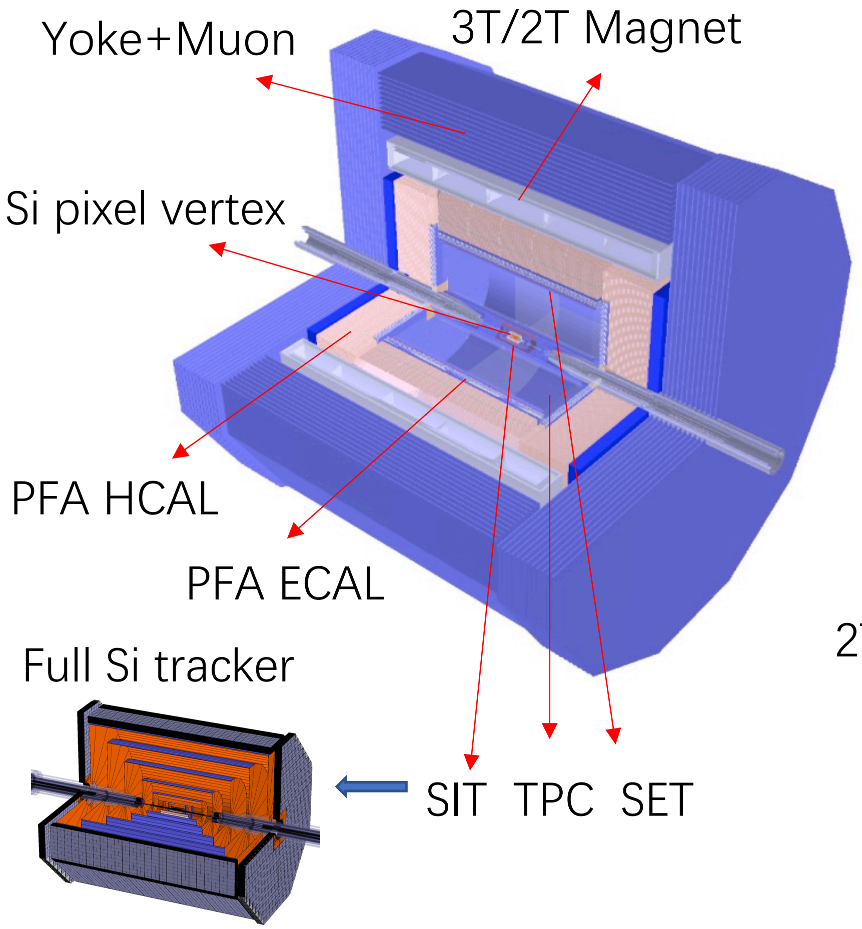
Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) =$ $2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} =$ $5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E =$ $\frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Flavor physics ⇒ Excellent PID, better than 2σ separation of π/K at momentum up to ~20 GeV.

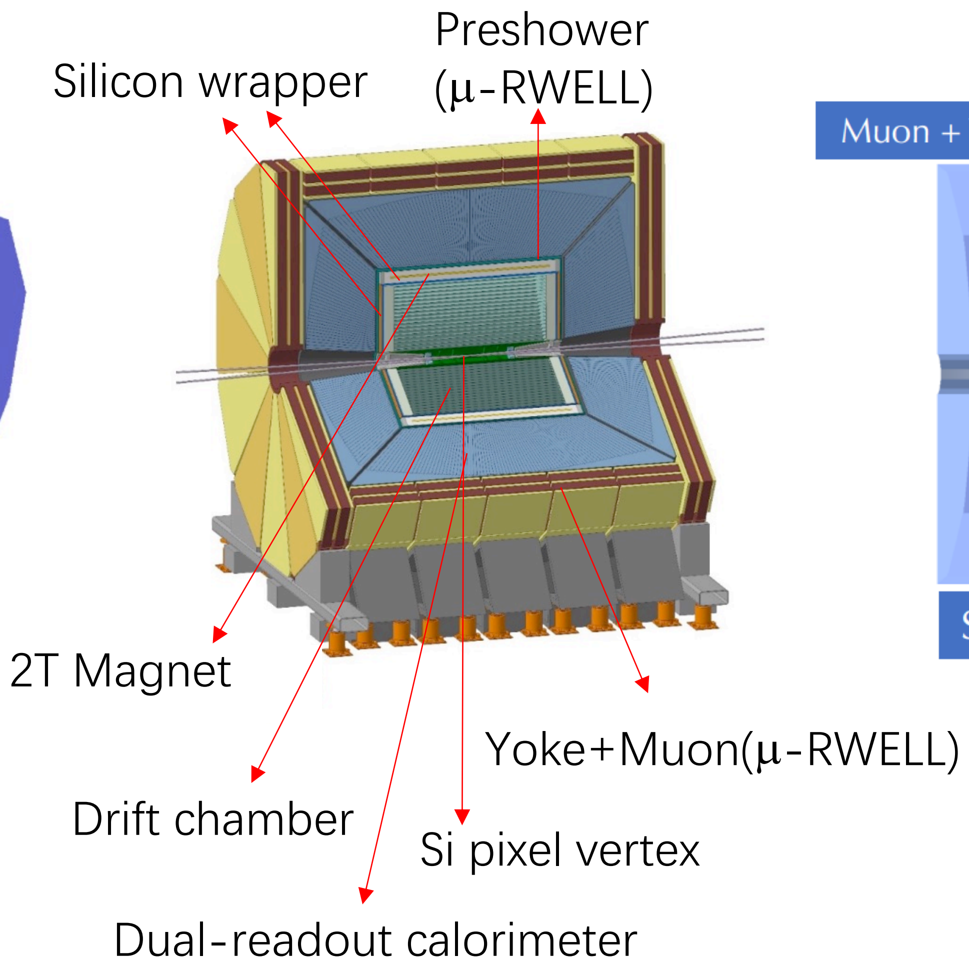


CEPC探测器

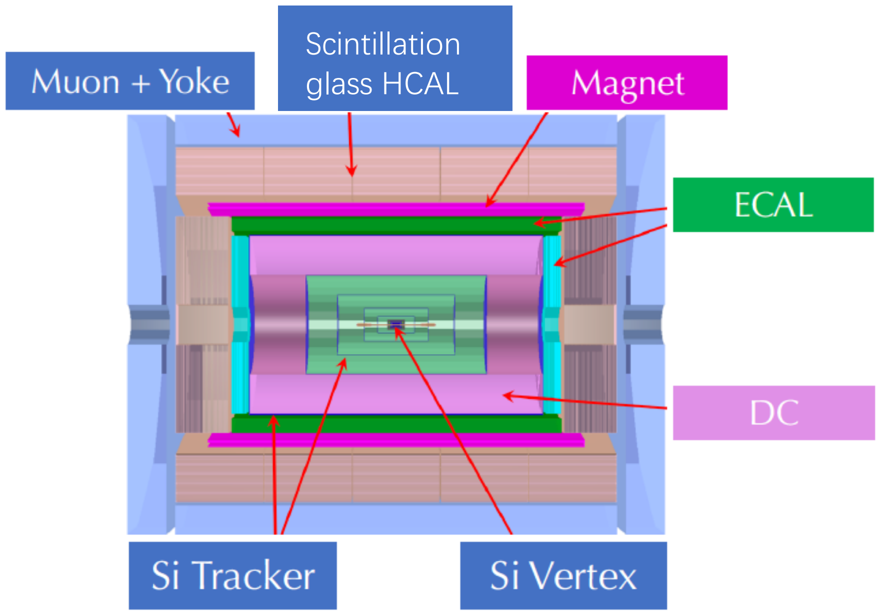
CDR



IDEA

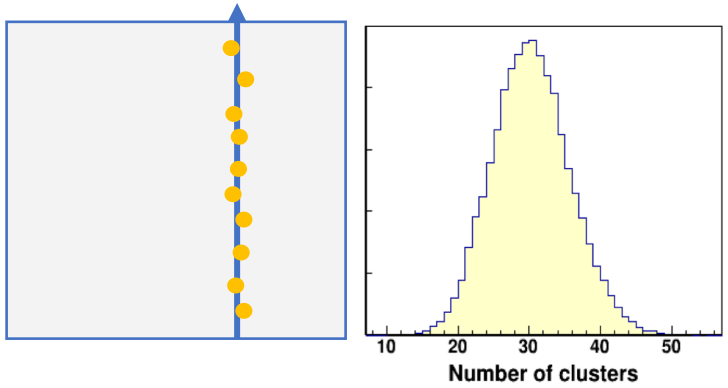


4^{th} conceptual

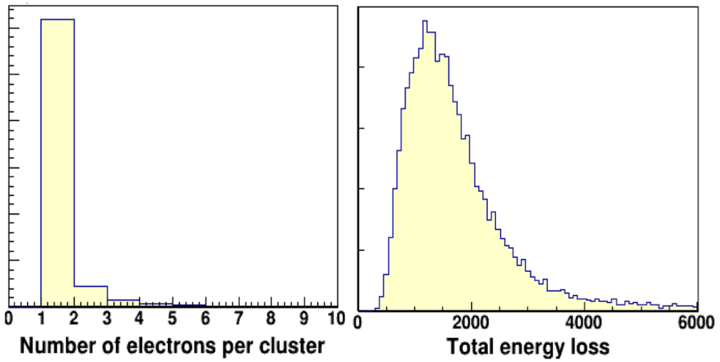


气体探测器（TPC或DC）的电离测量

初级电离
(Primary ionization)



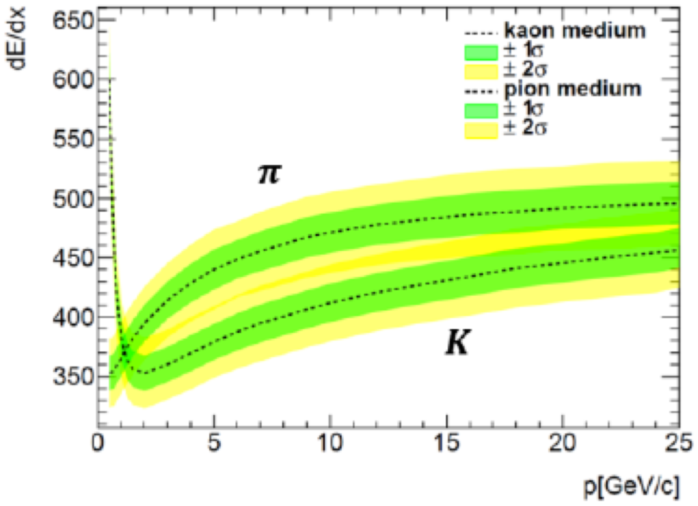
次级电离
(Secondary ionization)



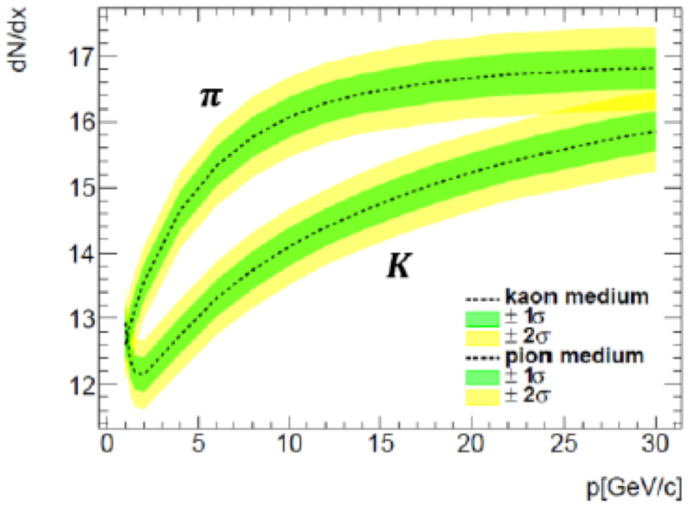
- 电离能损测量: Energy loss per unit length (dE/dx), Landau distribution, large fluctuation
- 电离计数技术 (cluster counting): Number of primary ionization clusters per unit length (dN/dx), Poisson distribution, small fluctuation → cluster counting technique

dE/dx vs dN/dx

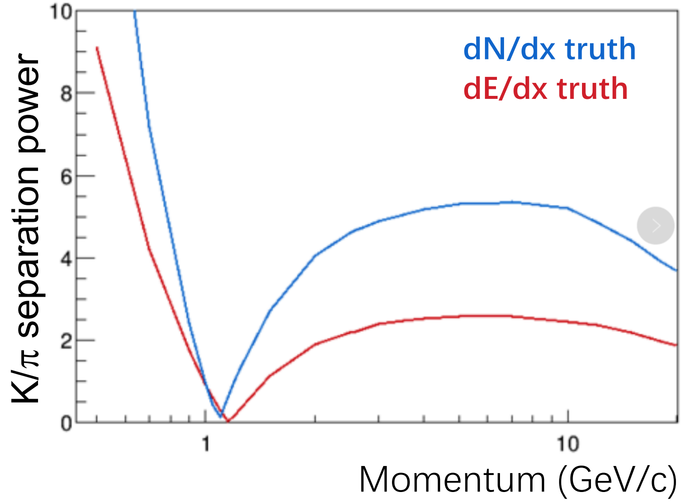
dE/dx



dN/dx



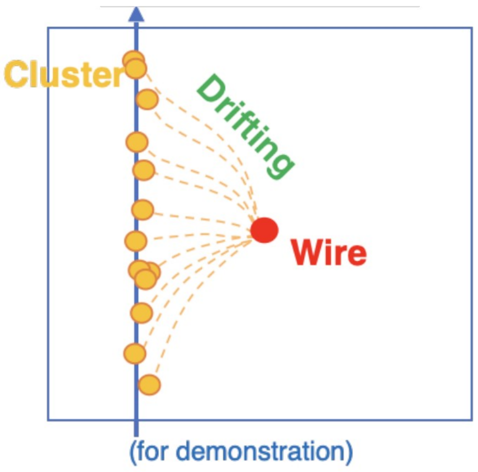
K/π separation power
dN/dx vs dE/dx

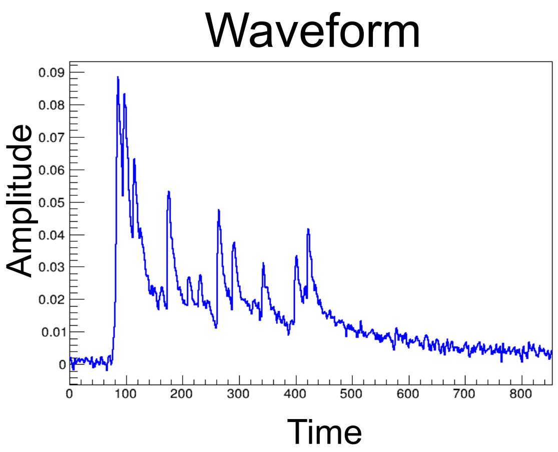


- 与传统的dE/dx方法相比，dN/dx测量预期将显著提高PID性能，也将有利于进一步提高空间分辨、区分来自不同径迹的hit时间

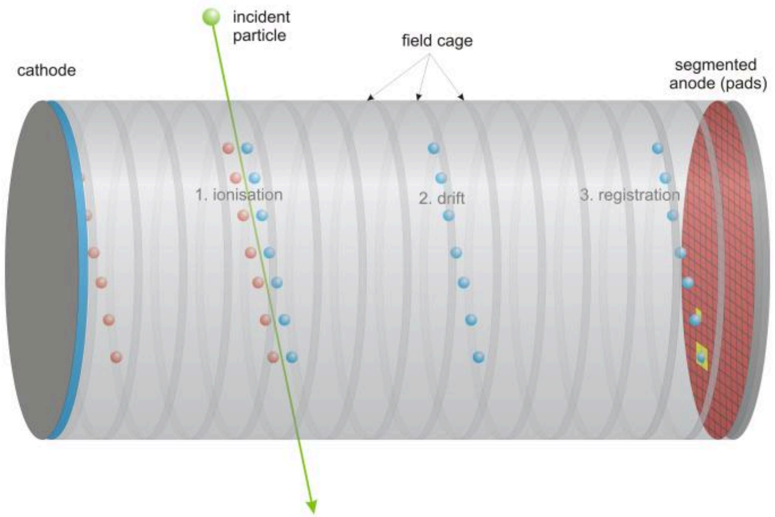
dN/dx测量：漂移室(DC) vs TPC

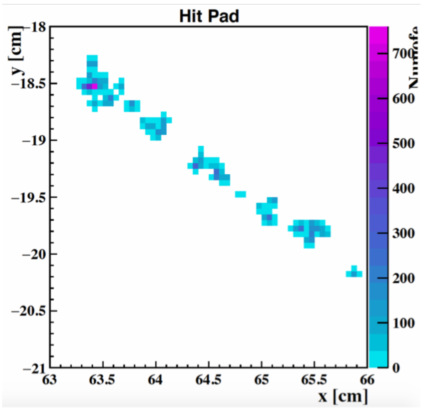
漂移室





TPC



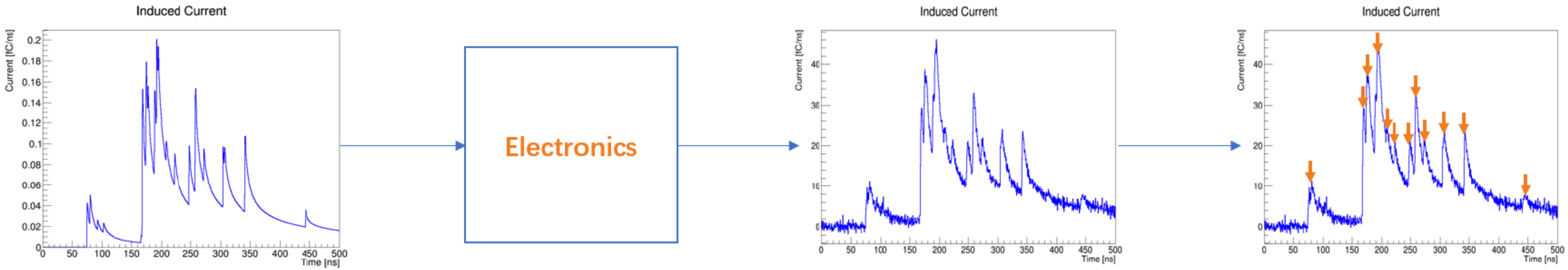


- 特点：时间谱寻峰
- 关键技术：
  - 高采样率、低噪声的读出电子学
  - 高性能寻峰算法

- 特点：空间的cluster寻找
- 关键技术：
  - 像素读出（读出通道数↑、功耗↑）
  - 高性能cluster重建

漂移室dN/dx模拟研究

Induced current　　　　Realistic waveform



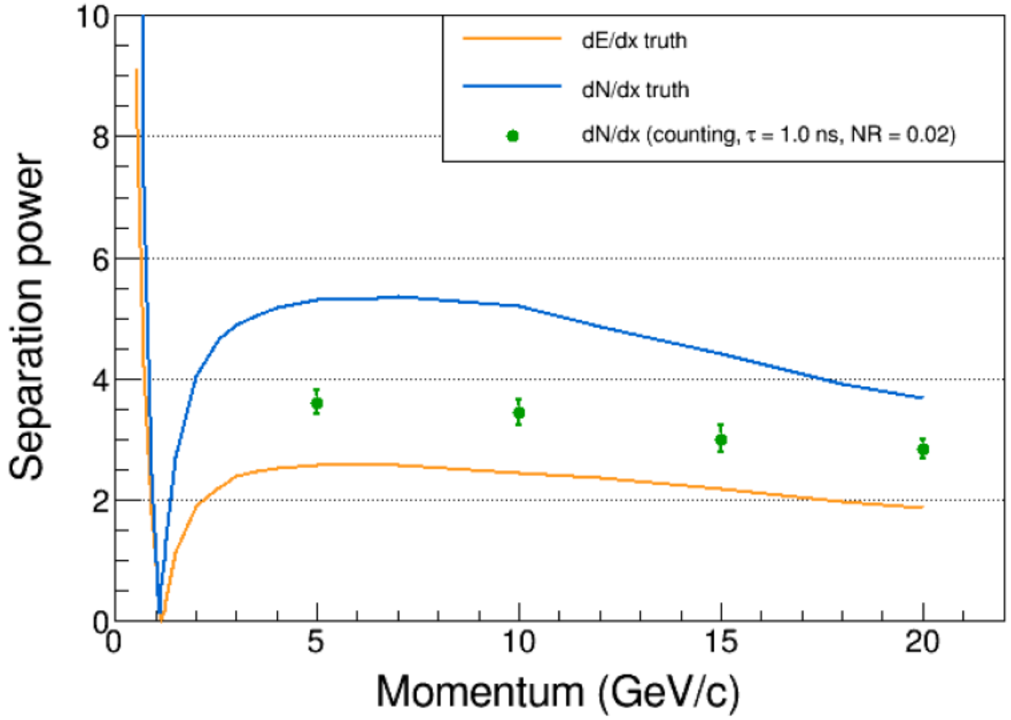
Signal generator (Garfield++):
- Heed: ionization process
- Magboltz: gas properties (drift/diffusion)

Electronics:
- Preamplifier
- Noises
- ADC

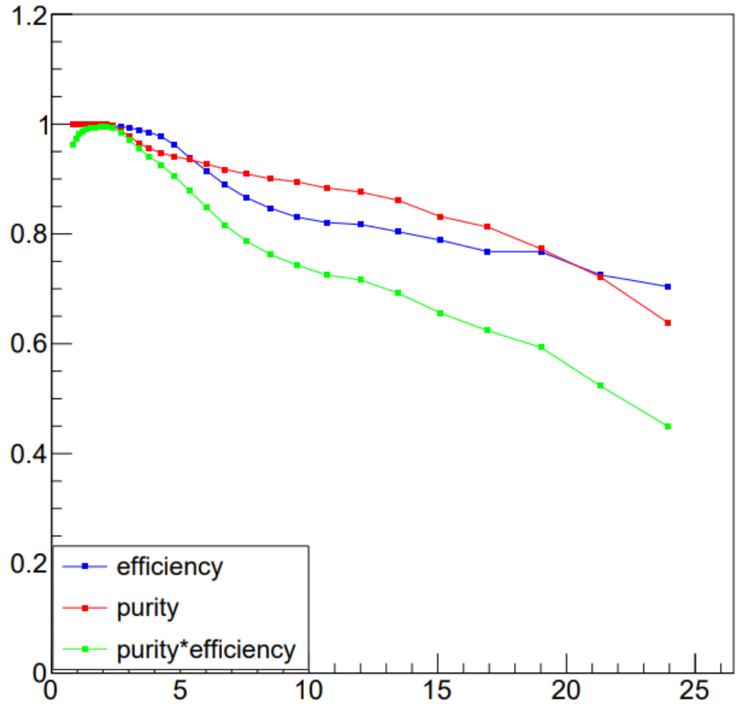
Peak finding algorithm:
- 微分算法
- 机器学习算法
- 反卷积
- CWT

模拟研究初步结果

K/π separation power
(Full simulation, L=1m)



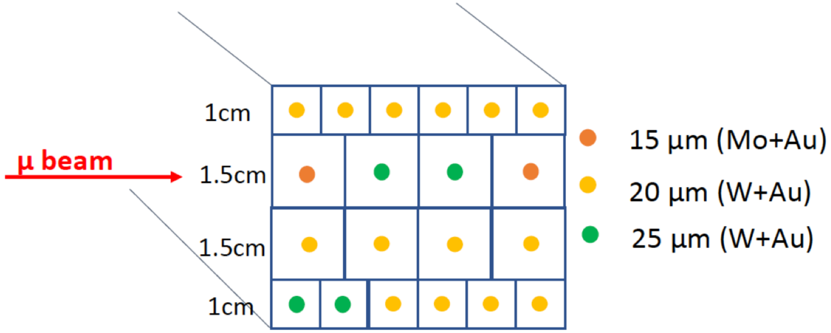
Kaon efficiency and purity
(dN/dx+TOF, with Delphes)

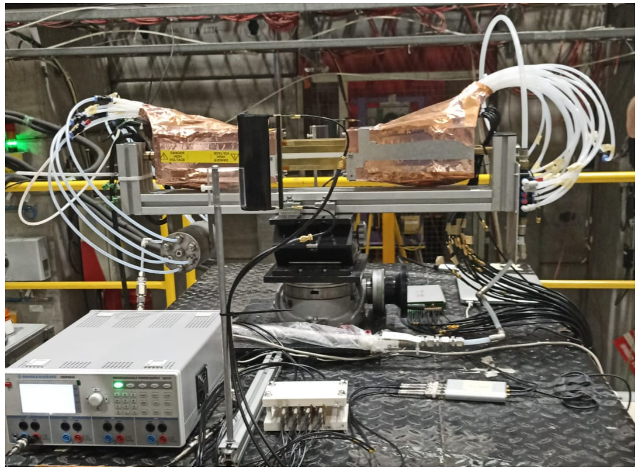


K/π separation power at 20 GeV/c is around 3σ

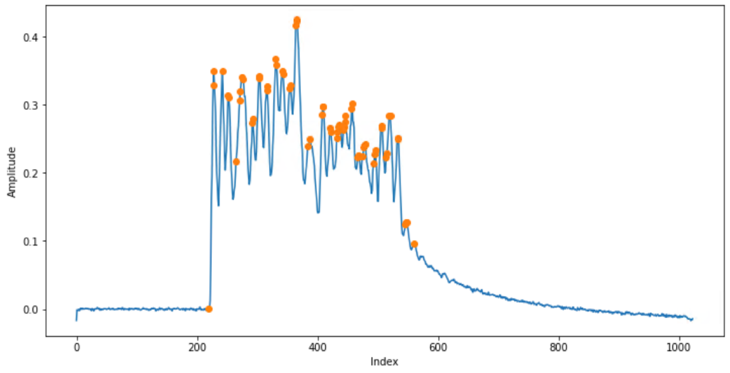
初步的束流测试

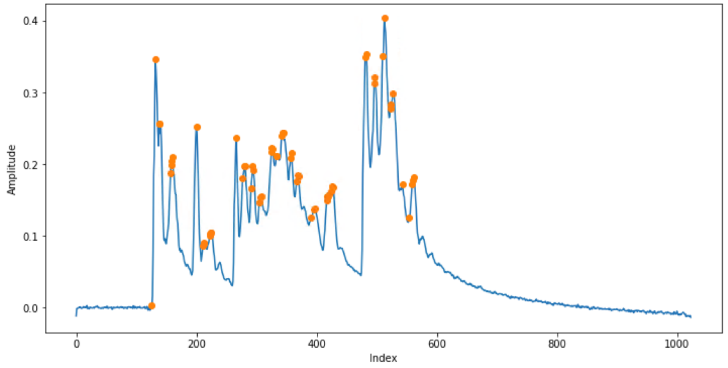
- Beam tests organized by INFN group
- Cooperation between INFN and IHEP on data analysis is ongoing





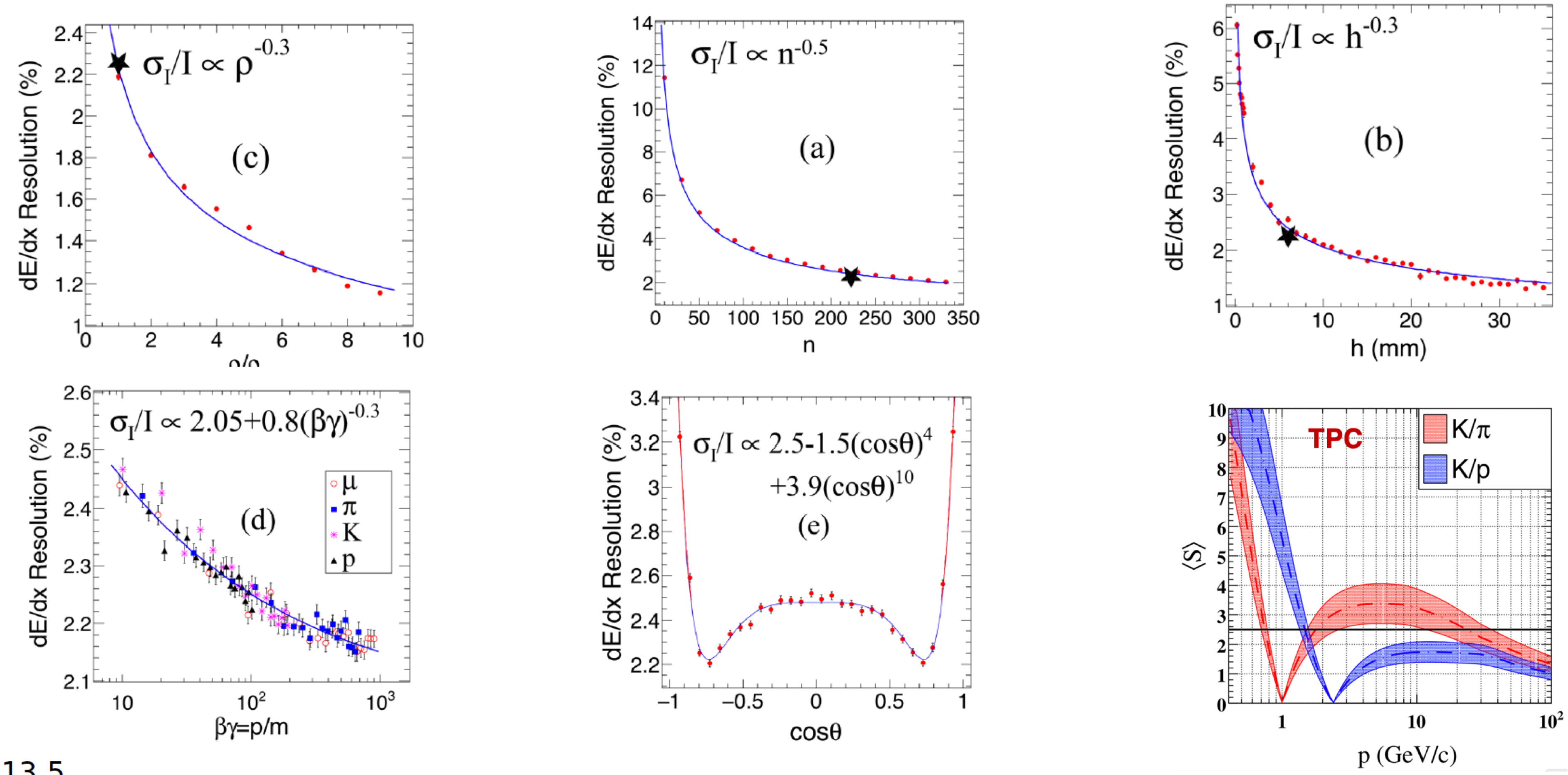
机器学习寻峰算法初步尝试





TPC dE/dx性能模拟

dE/dx分辨（CDR设计，基于Geant4）



$$\sigma_I/I = \frac{13.5}{n^{0.5}\cdot(h\rho)^{0.3}}\left[2.05+0.8(\beta\gamma)^{-0.3}\right]\times\left[2.5-1.5(cos\Theta)^4+3.9(cos\Theta)^{10}\right]$$

https://doi.org/10.1140/epjc/s1 … 03-3

Microsoft Word

TPC PID性能模拟结果

$$S_{AB} = \frac{|t_A - t_B|}{\sqrt{2}\cdot\sigma_{TOF}}$$

$$S_{AB} = \frac{|dE/dx_A - dE/dx_B|}{\sqrt{\sigma_A^2 + \sigma_B^2}}$$

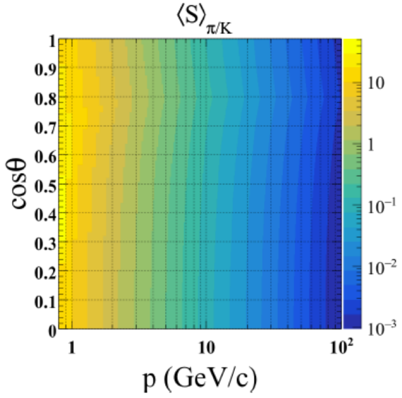
combine

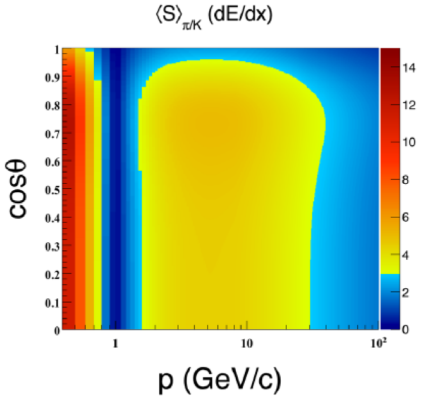
TOF

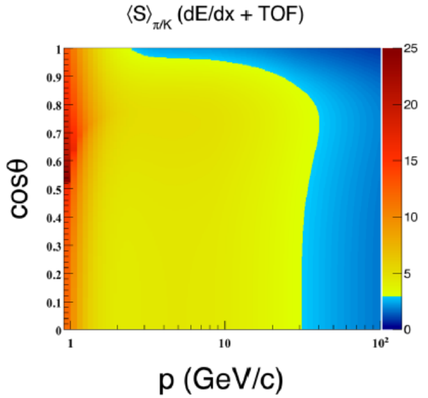
dE/dx

$$\sqrt{S_{dE/dx}^2 + S_{TOF}^2}$$

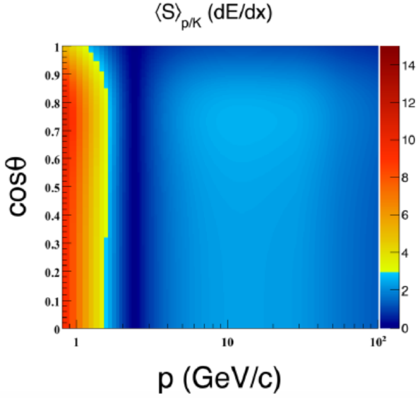
π/K

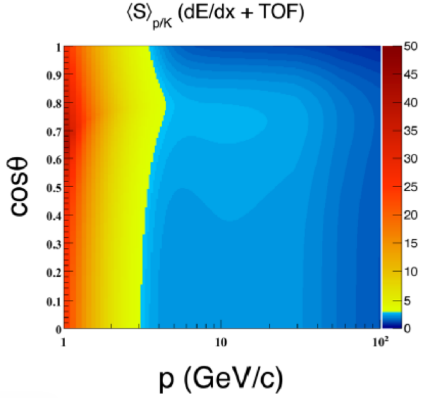






proton/K



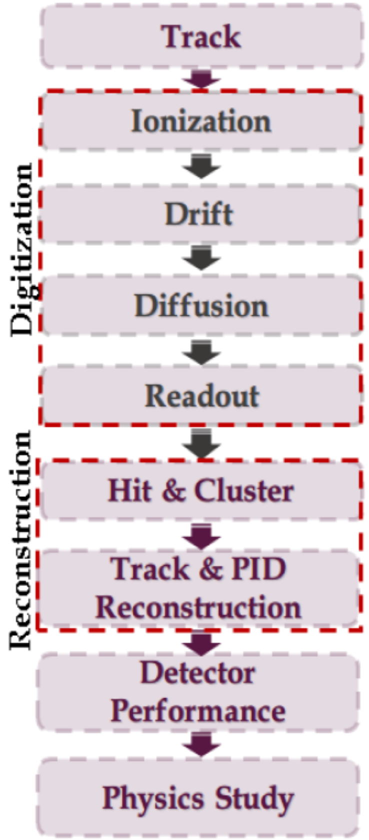


https://arxiv.org/abs/2209.14486 (accepted by NIMA)

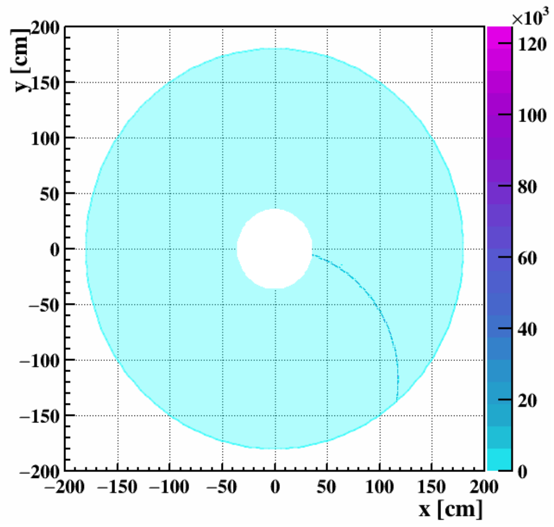
TPC dN/dx测量

- All detailed simulation **starting** at IHEP using Garfied++ and Geant4
  - Setup the new simulation framework
  - TPC detecror module simulated **under 2T and T2K gas** from CEPC CDR

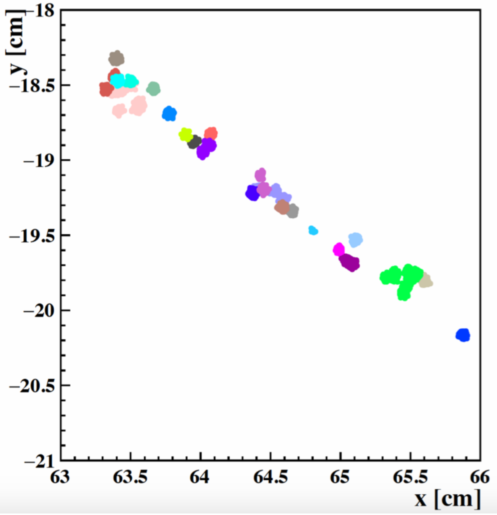
模拟研究刚开始



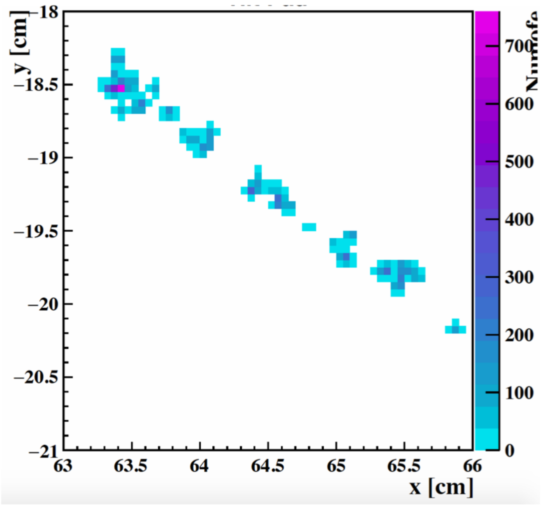
Track



Cluster (truth)



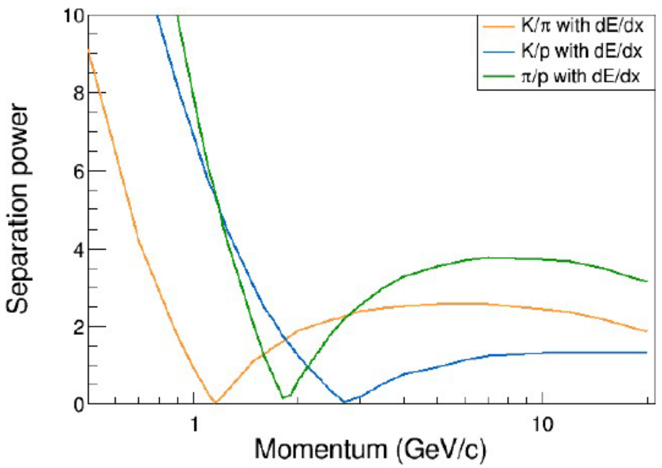
Pad 读出



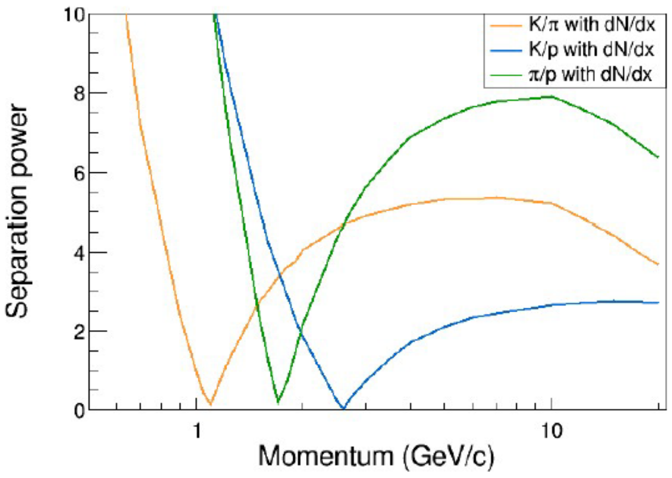
Timing detector

- Complementary to gas detector
  → 0-4GeV for K/pi separation, 0-8GeV for K/p separation

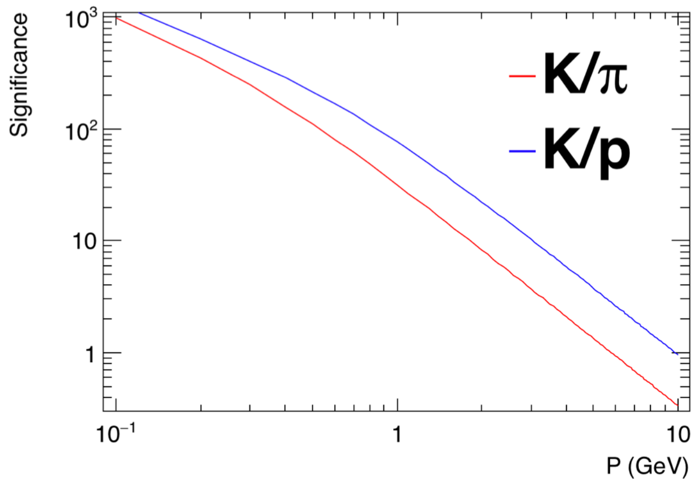
dE/dx



dN/dx



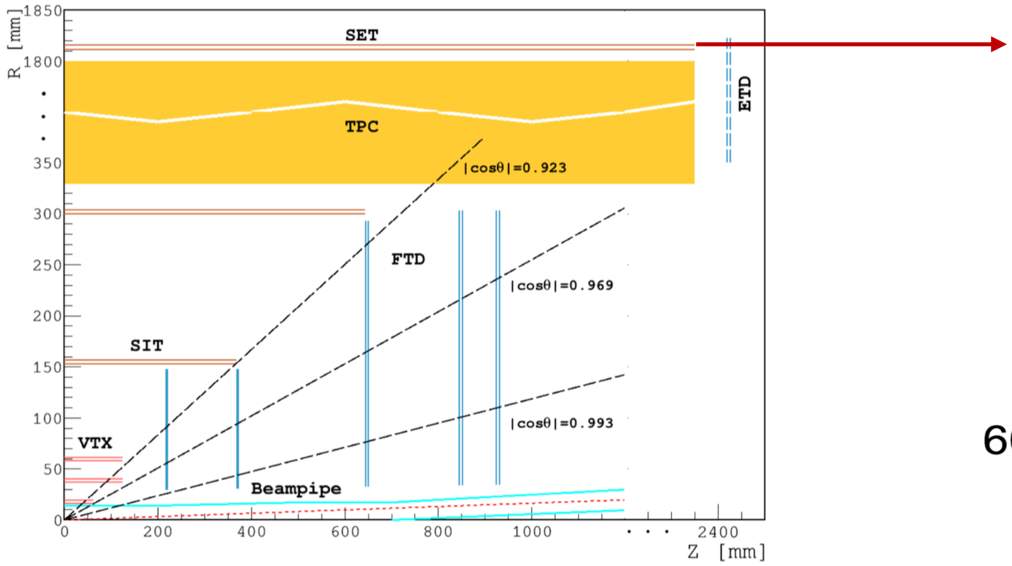
TOF



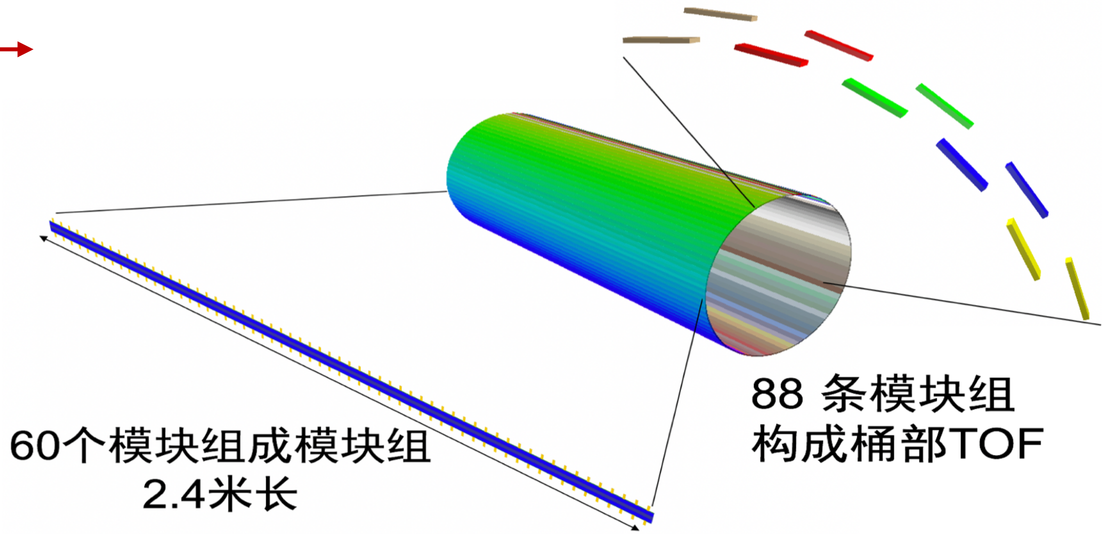
CEPC timing detector (concept)

- Timing detector: Between tracker and calorimeter
  → Close to SET tracker, Radius ~1.8m
- Target time resolution: 20 pico-second(ps)
- Area of detector (Barrel : 50m^2 , Endcap 20m^2)

Baseline detector concept in CDR



桶部 Low-Gain-Avalanche-detector (LGAD)



总结

- BESIII带电强子鉴别：dE/dx + TOF
  - 软件算法稳定运行十余年
- CEPC
  - 基于TPC或DC的dN/dx测量，与dE/dx相比预期将有更好的PID性能
  - 基于LGAD的TOF测量
  - 研究计划
    - dN/dx方法的性能研究及实验验证
    - 4th conceptual探测器端盖设计
    - 切伦科夫探测技术研究