Drift Chamber with Cluster Counting Techniques for CEPC

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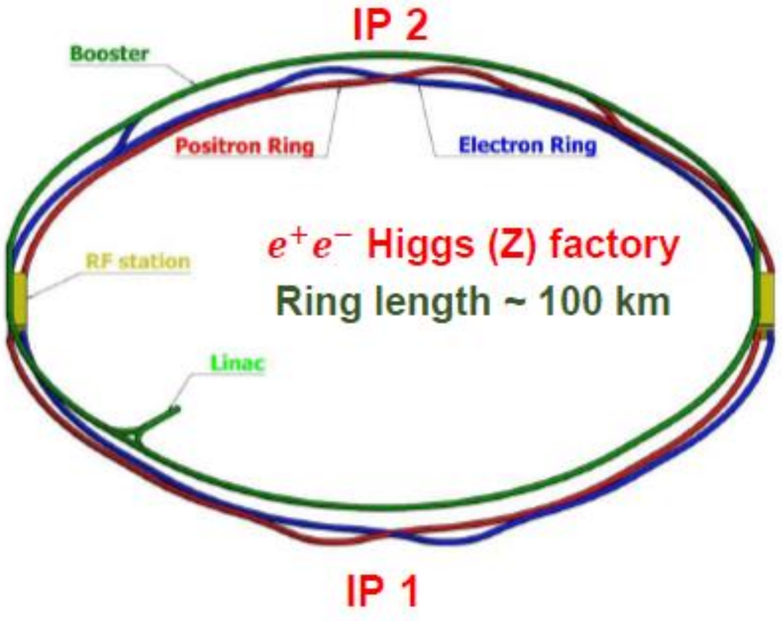
Outline

- **Introduction**
- **CEPC drift chamber R & D**
  - Simulation study
  - Prototype test
  - Mechanical design
  - Electronics scheme
- **Summary**

The Circular Electron Positron Collider

- The CEPC was proposed in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as an e^+e^- Higgs / Z Factory.
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.
- It is possible to upgrade to a pp collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



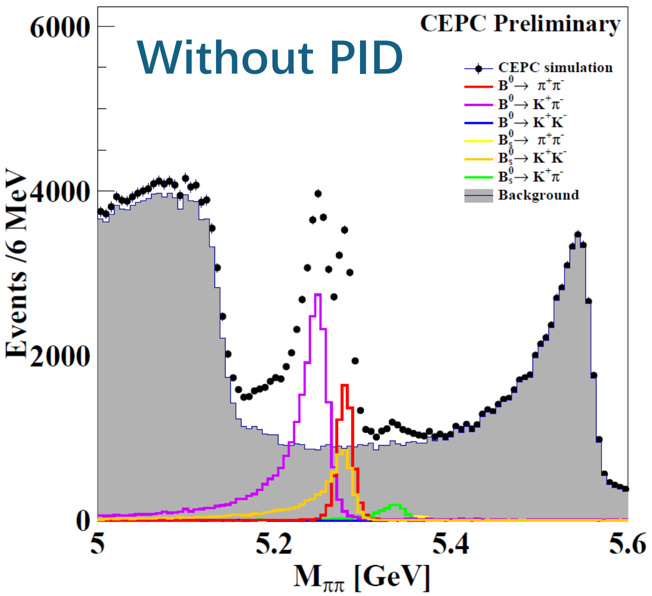
Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP ($10^{34}cm^{-2}s^{-1}$)	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W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

* 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.

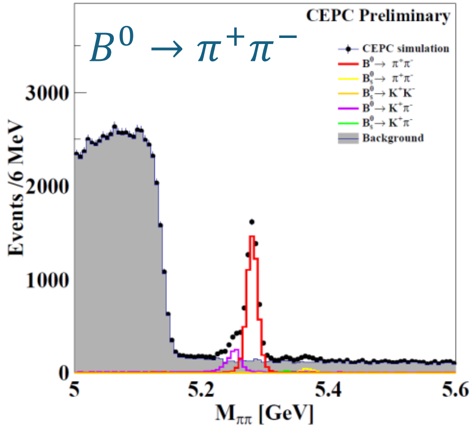
Particle identification

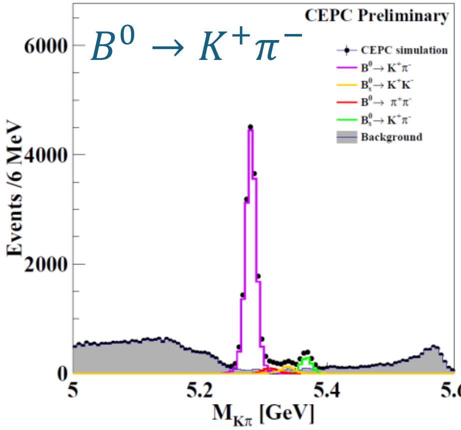
- **PID is essential for CEPC, especially for flavor physics**
  - Suppressing combinatorics
  - Distinguishing between same topology final-states
  - Adding valuable additional information for flavor tagging of jets
  - …

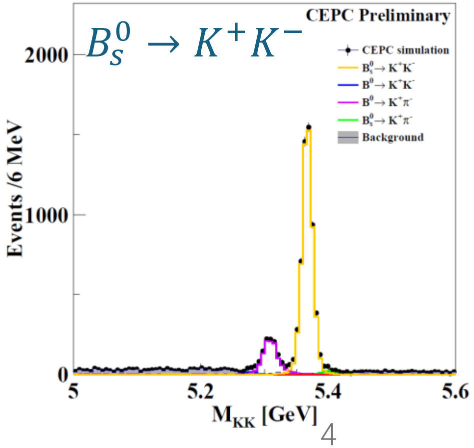
Benchmark channel:
$\mathbf{B^0_{(s)} \to h^+h'^-}$



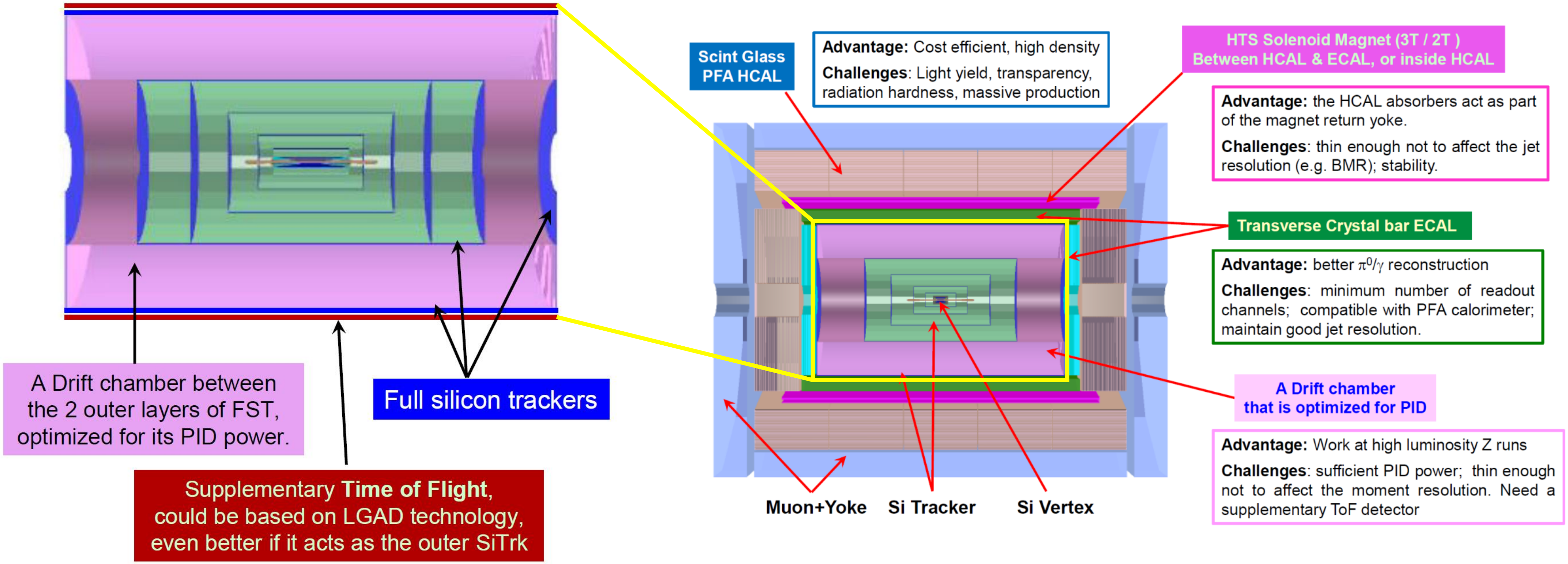
With PID







CEPC 4th concept detector

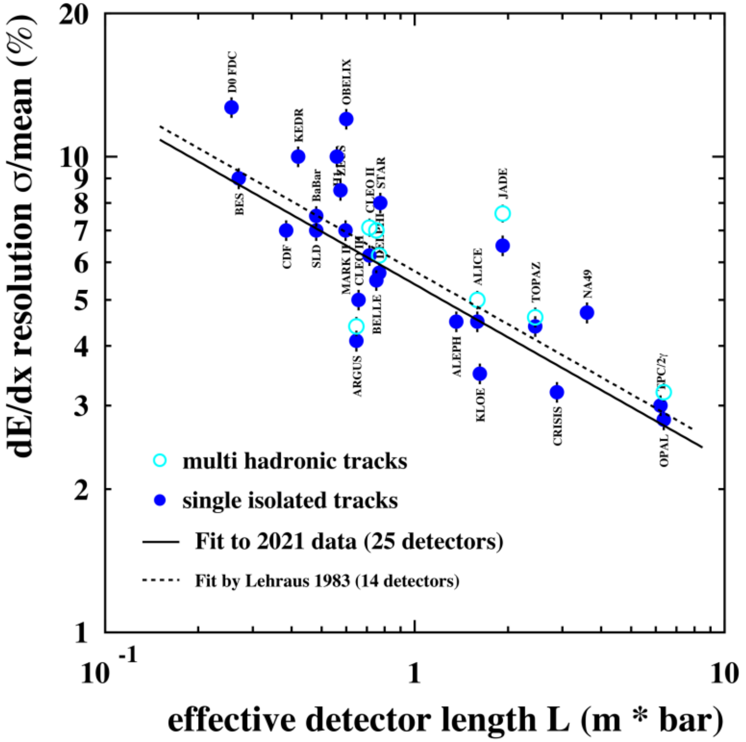


A drift chamber with cluster counting (dN/dx) is one of the gaseous detector options

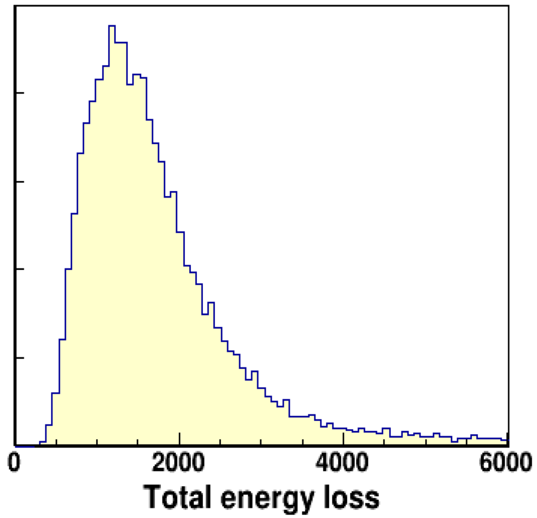
Energy loss measurement: dE/dx

- **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 …

"Lehraus" Plot 2021*



Integrated charge



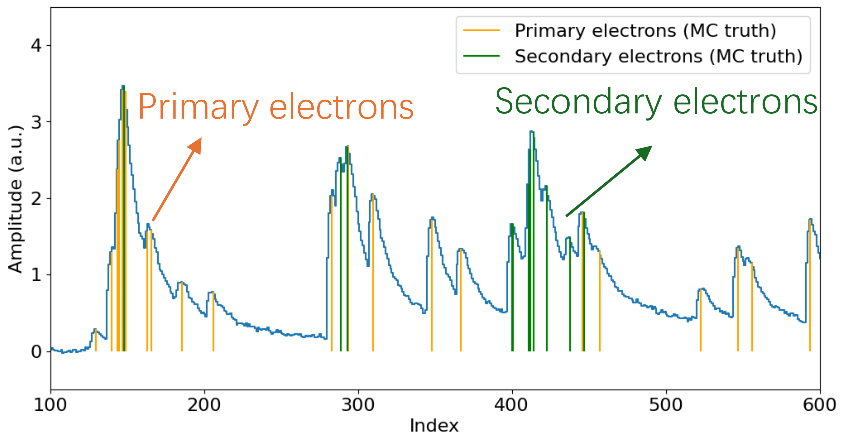
- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** ∗ $L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** ∗ $L^{-0.37}$ (%)
- **No significant improvement in the past 40 years**

* From Michael Hauschild's talk @ RD51 workshop

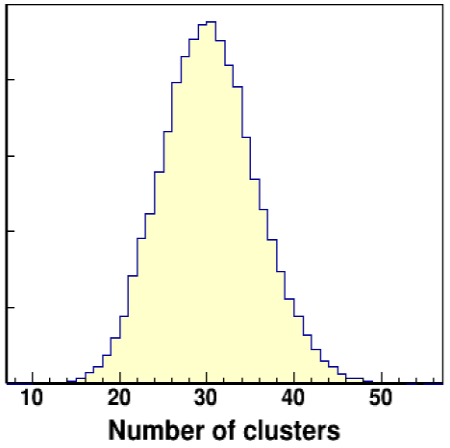
Cluster counting measurement (dN/dx)

- **Alternatively, counting primary clusters**
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - **Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx**

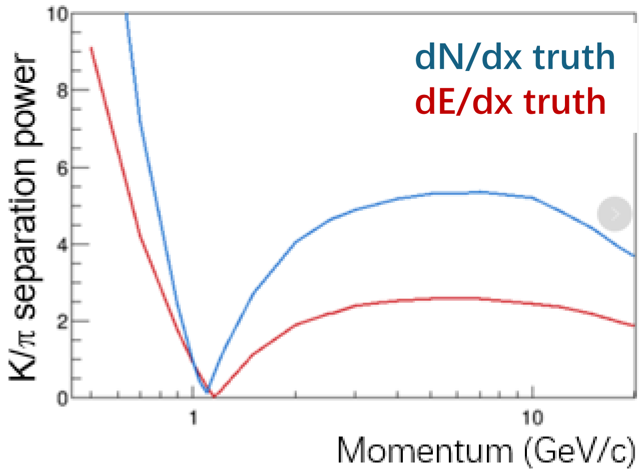
Waveform



Counting clusters



K/π separation power
dN/dx vs dE/dx

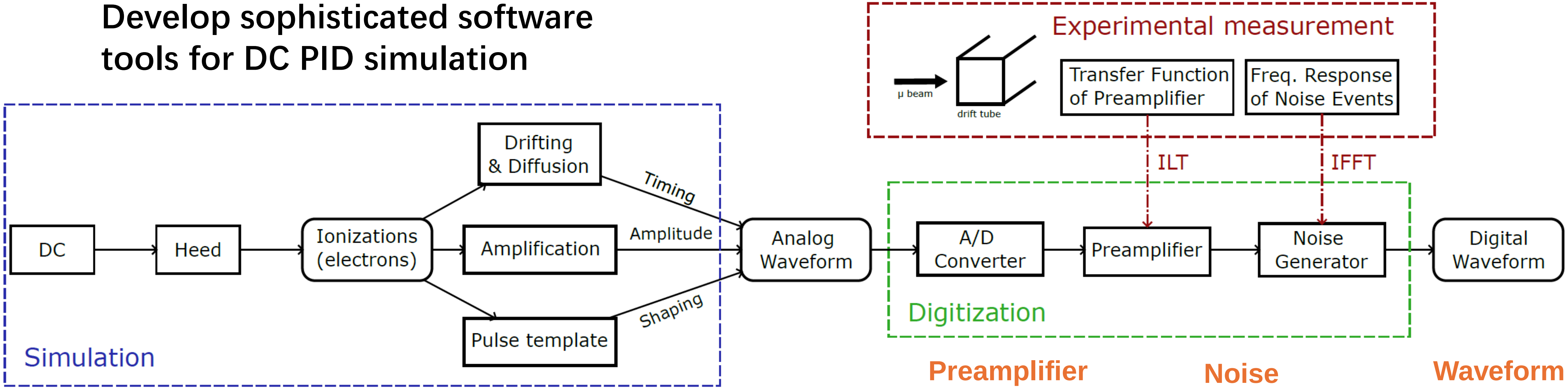


Require fast electronics and sophisticated counting algorithm to count the number of **primary electrons**

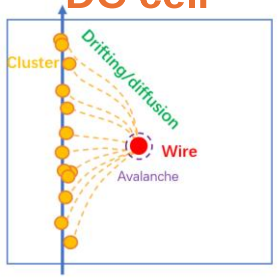
dN/dx is extremely powerful, proposed in ILC, FCC-ee, CEPC

Waveform-based simulation

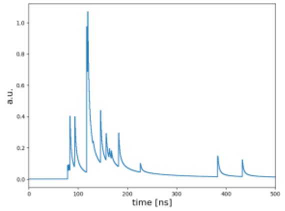
Develop sophisticated software tools for DC PID simulation



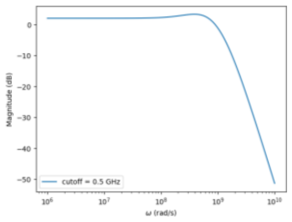
DC cell



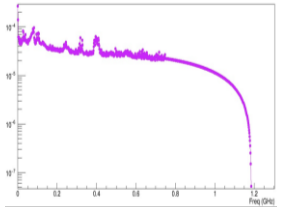
Induced signal



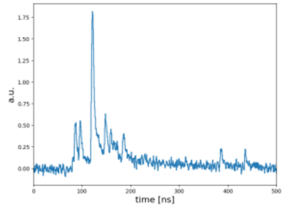
Preamplifier



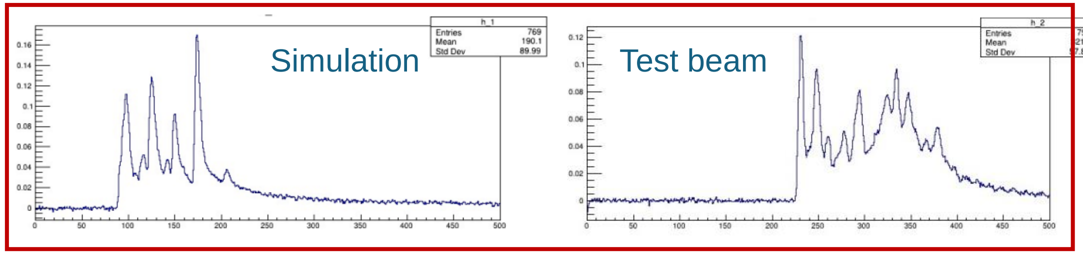
Noise



Waveform

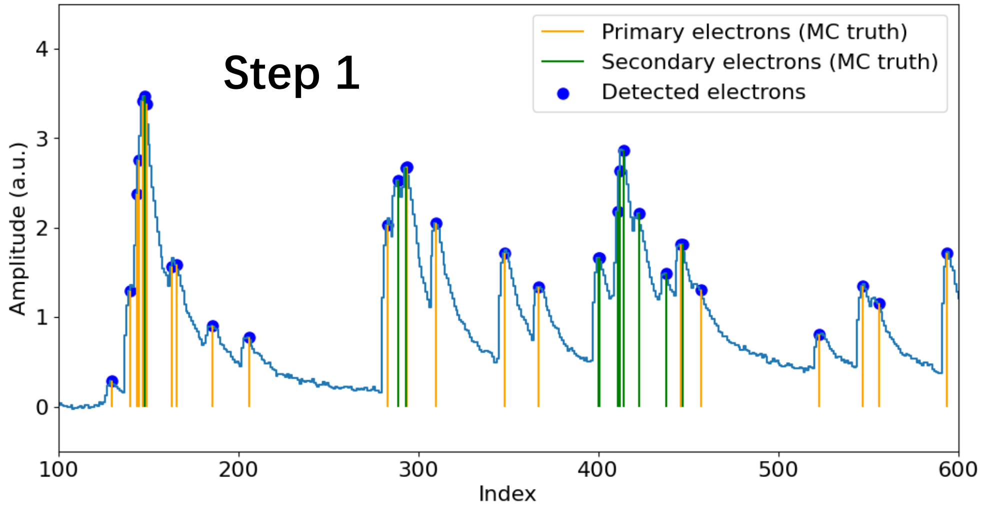


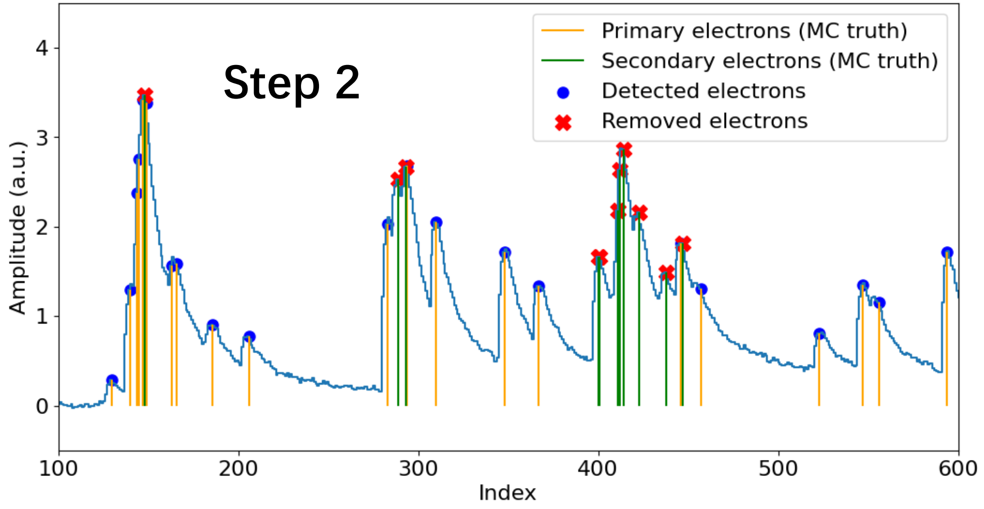
Tuned MC is comparable to data



arXiv: 2402.16493

dN/dx reconstruction with supervised learning





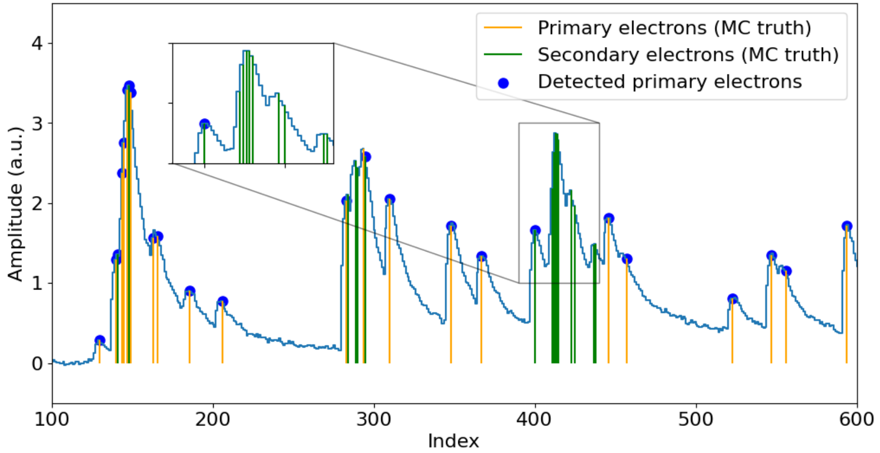
Reconstruction task: Determine the number of **primary electrons** in the waveform

2-step machine learning algorithm:

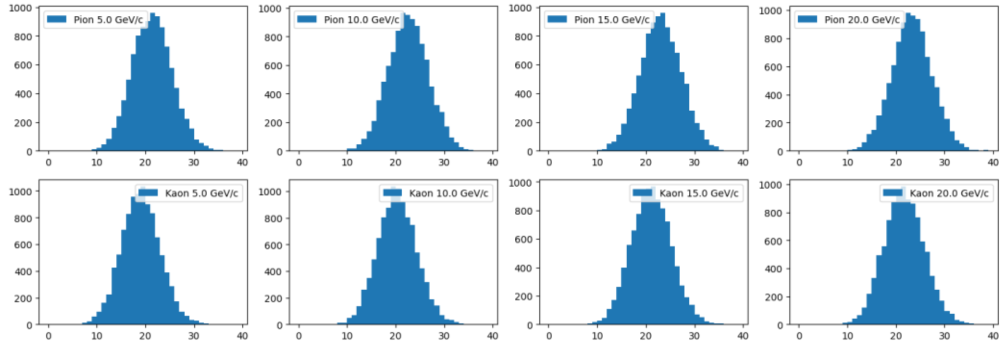
- **Peak finding by LSTM:**
  - Detect peaks from both primary and secondary electrons
- **Clusterization by DGCNN:**
  - Remove secondary electrons from the detected peaks in step 1

PID performances with supervised models

Detected primary electrons from a waveform

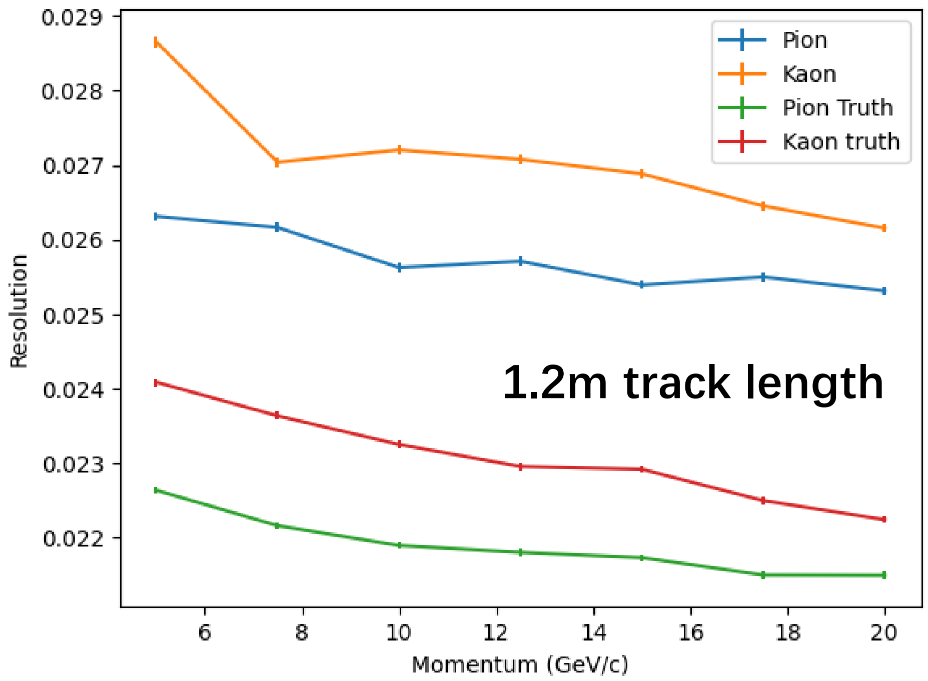


Reconstructed # of clusters distributions



The reconstructed n_{cls} distributions are very well Gaussian-like

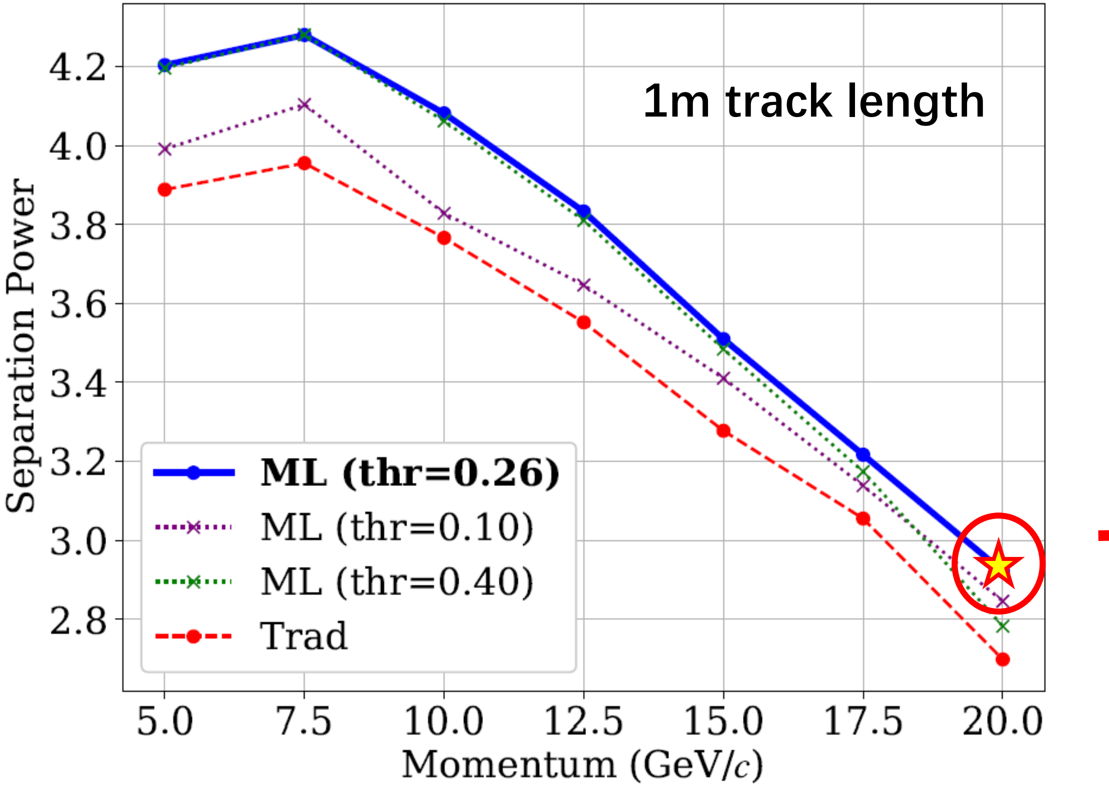
dN/dx resolution



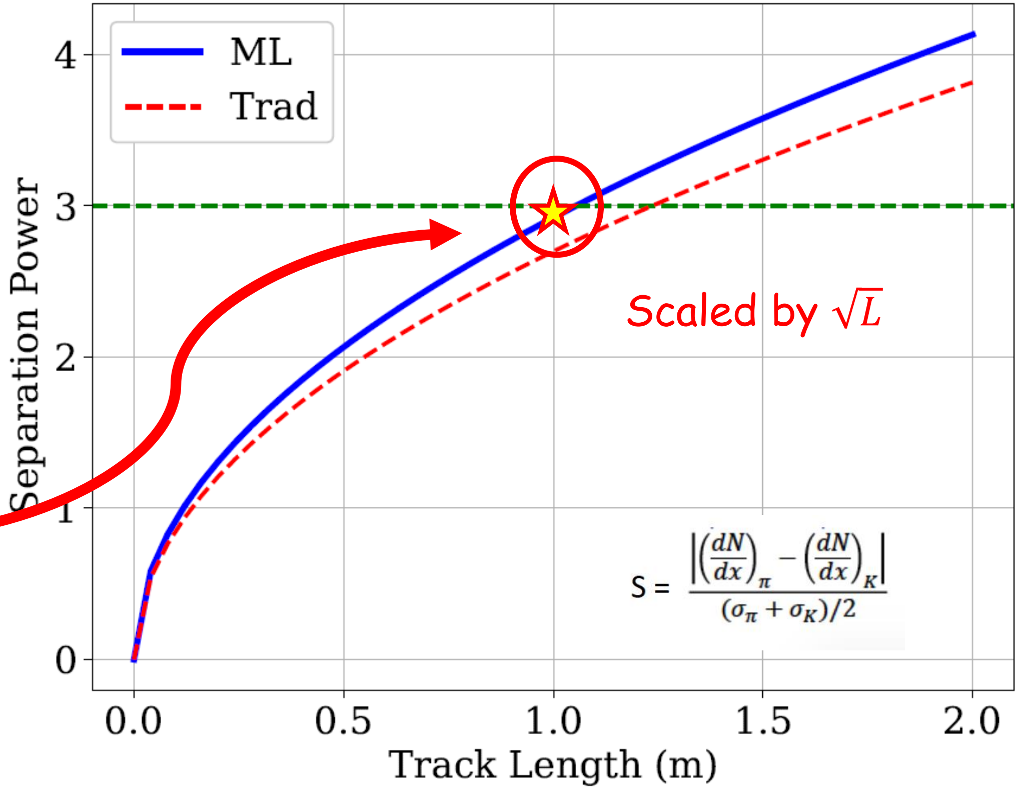
dN/dx resolutions for high momenta pions/kaons are < 3%， which are much better than typical dE/dx ~5%

PID performances with supervised models (II)

K/π separation power vs. momentum



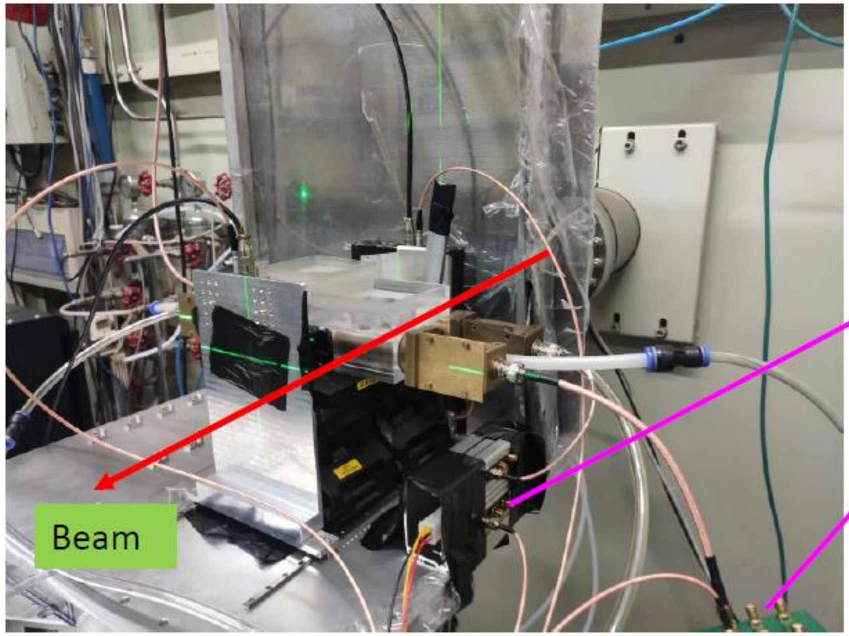
K/π separation power @ 20 GeV/c

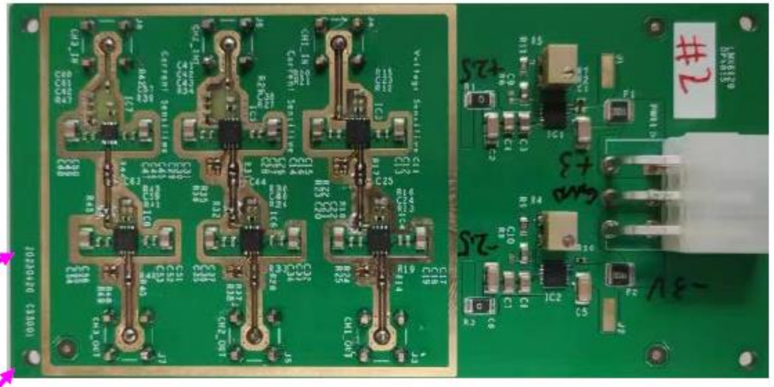


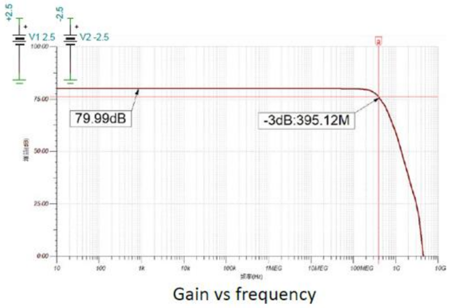
~10% improvement for ML (equivalent to a detector with 20% larger radius)

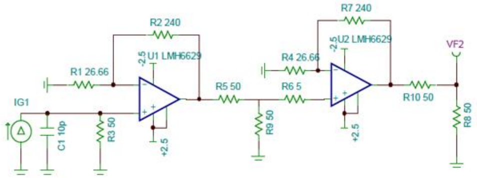
Could achieve 3σ for 1m track length. For 1.2m track length (current CEPC baseline), the separation is 3.2σ

Test beam with detector prototype (IHEP)

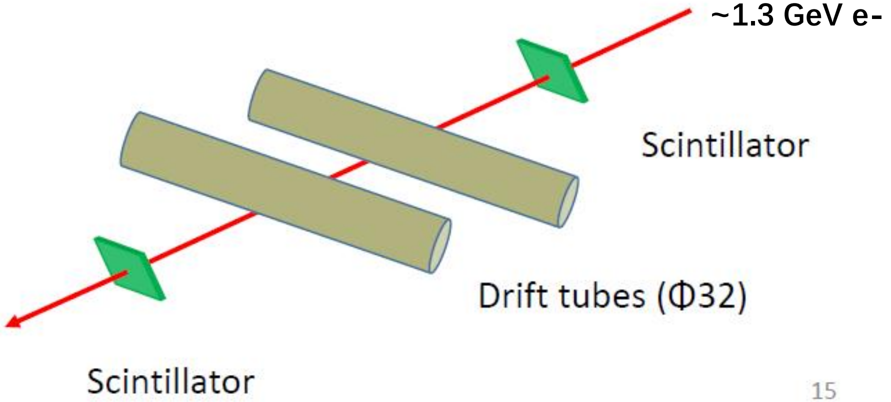








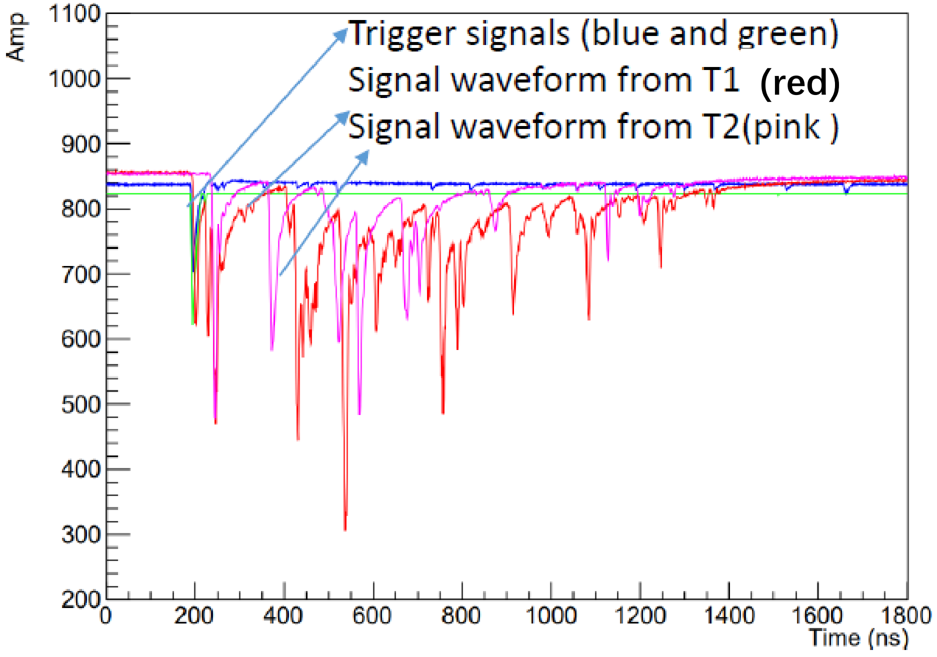
- Two drift tubes + preamps + ADC (1GHz)
- The system was tested with electron beam at IHEP

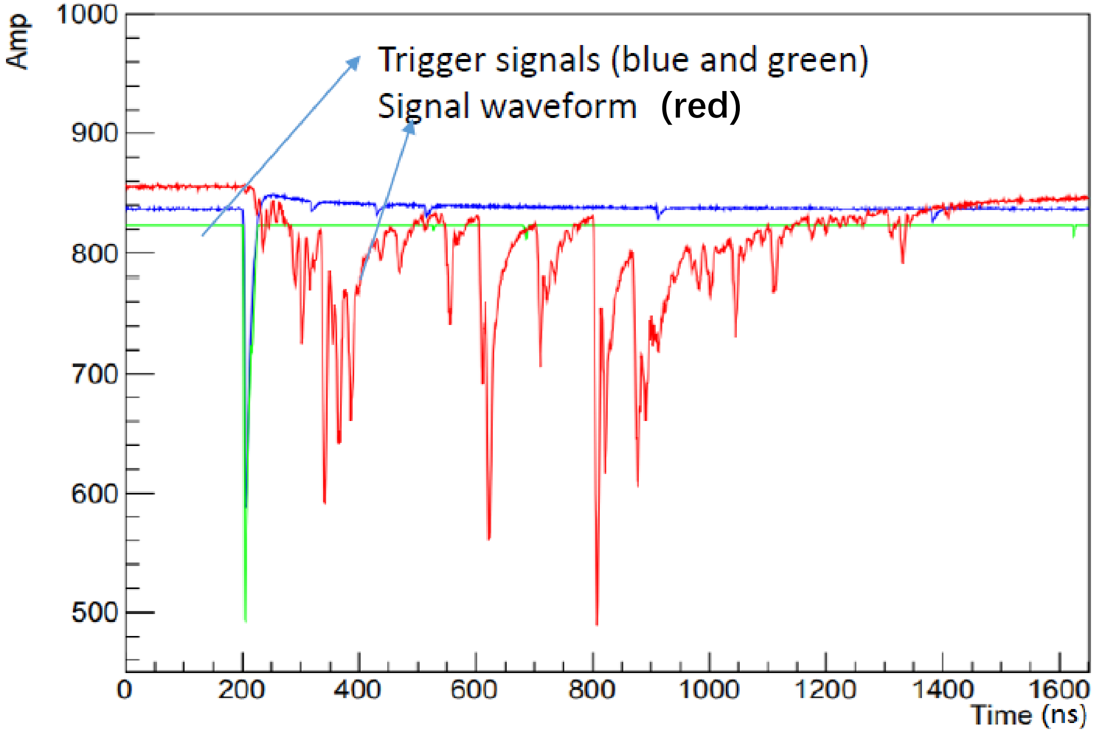


High bandwidth current sensitive preamplifiers based on LMH6629 have been designed and developed

Typical collected waveforms

- He: iC_4H_{10} = 90 : 10
- Digitizer: DT5751
  - Sampling rate: 1GHz
  - Four channels, two for scintillators, two for drift tubes





- Clear electron peaks: ~ns risetime

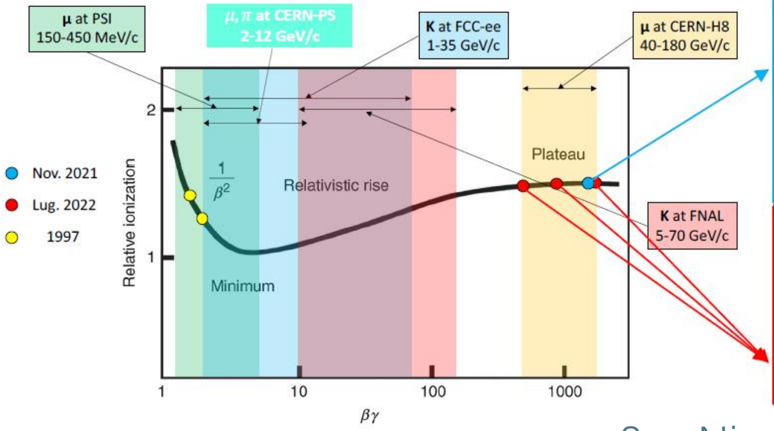
Test beam experiments at CERN

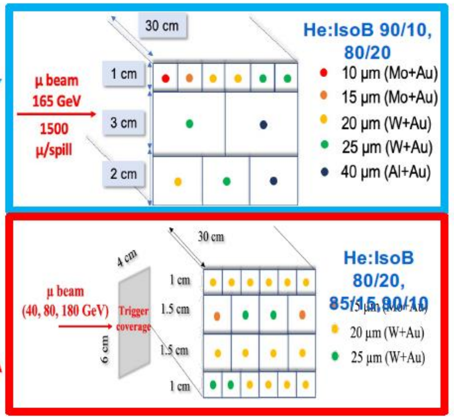
Beam tests organized by INFN group (leaded by Franco Grancagnolo and Nicola De Filippis):

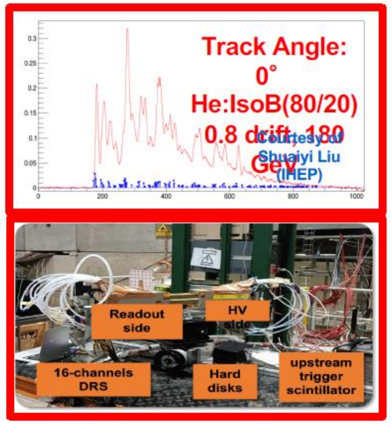
- Two muon beam tests performed at CERN-H8 (βγ>400) in Nov. 2021 and July 2022.
- A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN.
- Test beam at CERN in 2024 is ongoing.

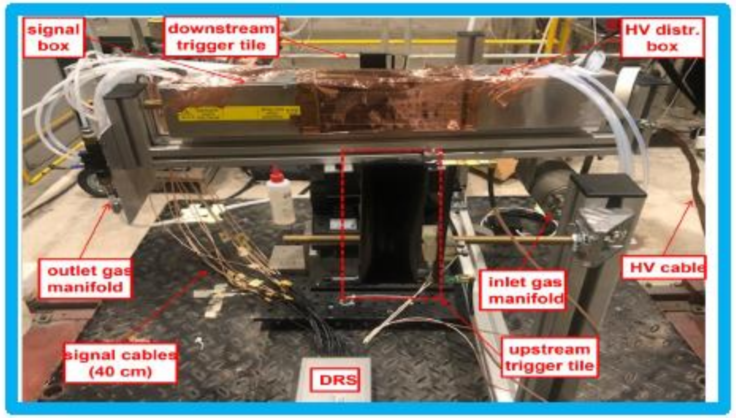
Contributions from IHEP group:

- Participate data taking and collaboratively analyze the test beam data
- **Develop the deep learning reconstruction algorithm**









See Nicola De Filippis's talk at the CEPC Workshop for details

dN/dx reconstruction with domain adaptation

Computer Physics Communications 300, 109208 (2024)

Loss for labeled samples in source domain

$$\min_{f,g}\left[\sum_{i=1}^{m} L_s\left(y_i^s, f(g(x_i^s))\right) + \frac{1}{m_l}\sum_{i=1}^{m_l} L_t\left(y_i^{t,l}, f\left(g(x_i^{t,l})\right)\right) + \min_{\gamma\in\Delta}\sum_{i,j}^{m}\gamma_{ij}\left(\alpha\|g(x_i^s)-g(x_j^t)\|^2 + \lambda_t L_t\left(y_i^s, f\left(g(x_j^t)\right)\right)\right)\right]$$

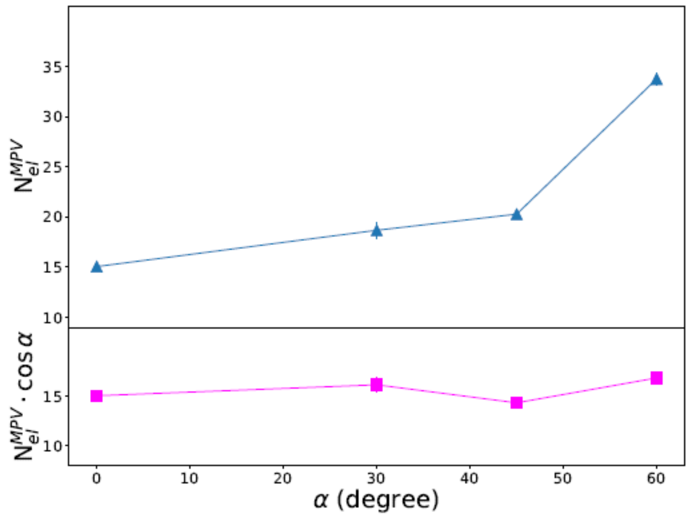
Loss for labeled samples in target domain (THIS WORK)

Cost of feature differences between source and target

Cost of 'label' differences between source and target

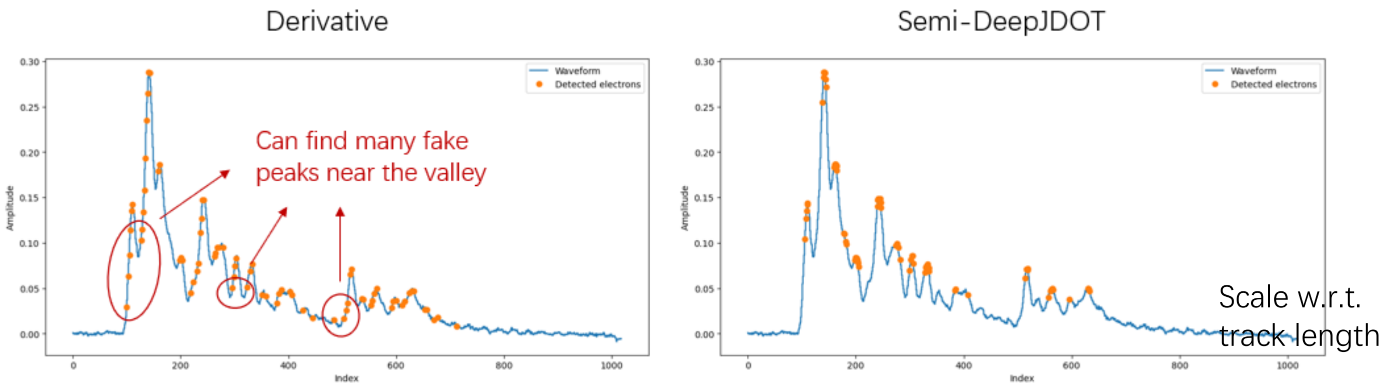
Cost of joint feature-label distribution for OT

Semi-supervised domain adaptation



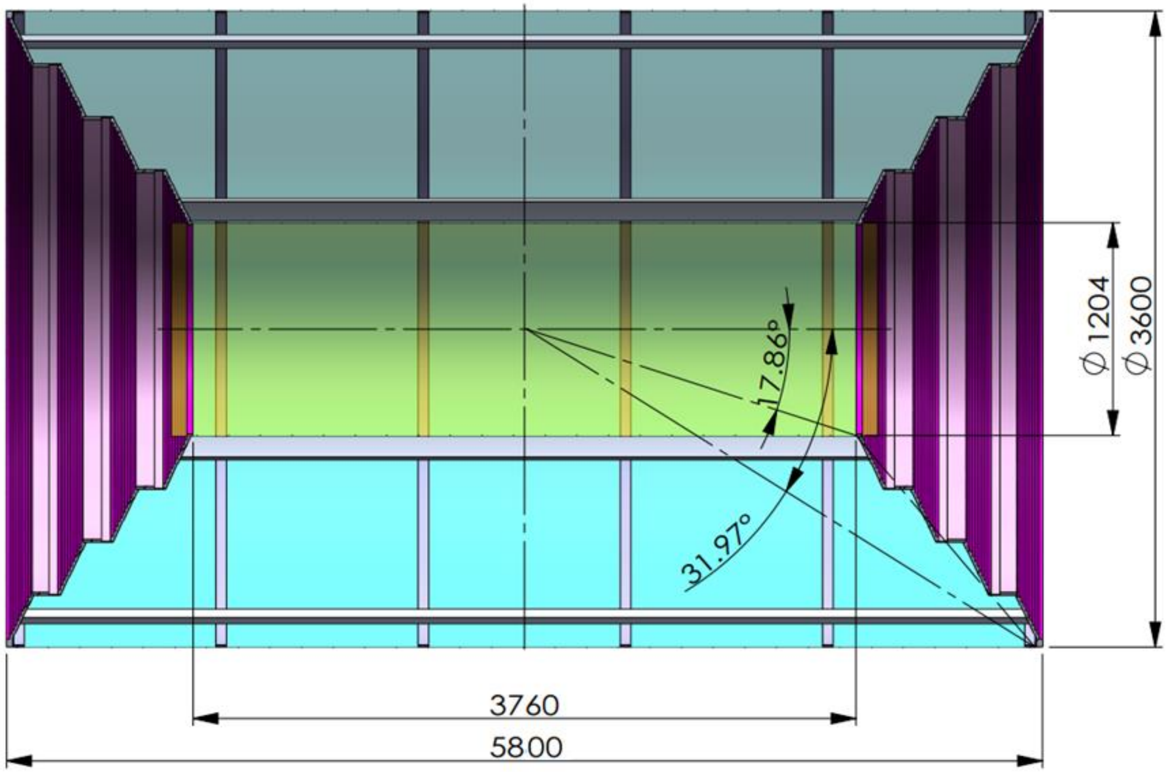
ML algorithm is stable w.r.t. track length

Single-waveform results between derivative alg. and DL alg.



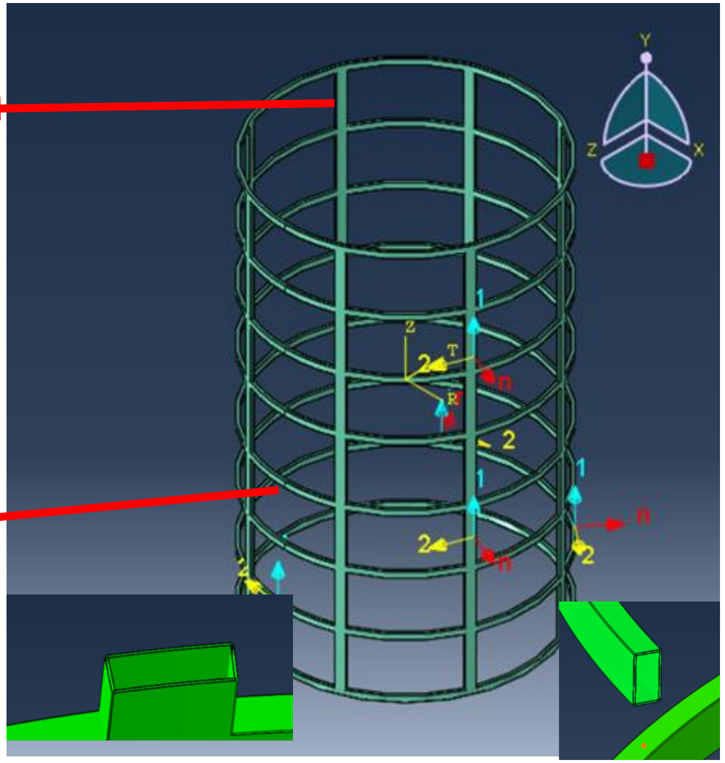
ML algorithm is more powerful to discriminate signals and noises

Overall mechanical design



Cross section of longitudinal HB : 80mm*40mm, thickness: 3.2mm

Cross section of annular HB : 40*10mm Thickness: 3.2mm



CF frame structure: 8 longitudinal hollow beams + 8 annular hollow beams + inner CF cylinder and outer CF cylinder

- Length: 5800 mm
- Outer diameter: 3600 mm; Inner diameter: 1200 mm
- Thickness of each end plate: 20 mm, weight: 880 kg

Wire tensions

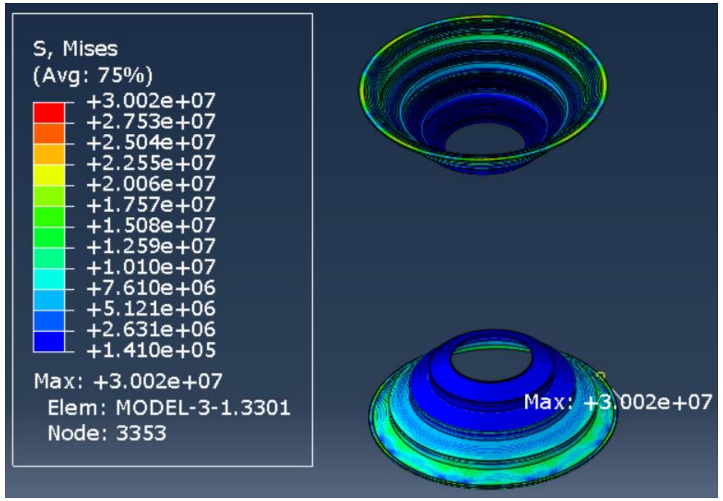
	Cell number/step	Average length (mm)	Single sense wire tension (g)	Single field wire tension (g)	total tension/step (kg)
step1	9172	5668	86.92	133.56	4472.08
step2	7528	5122	70.98	109.07	2997.38
step3	5845	4526	55.43	85.16	1817.14
step4	3939	3928	41.75	64.14	922.46
total	26483				10209

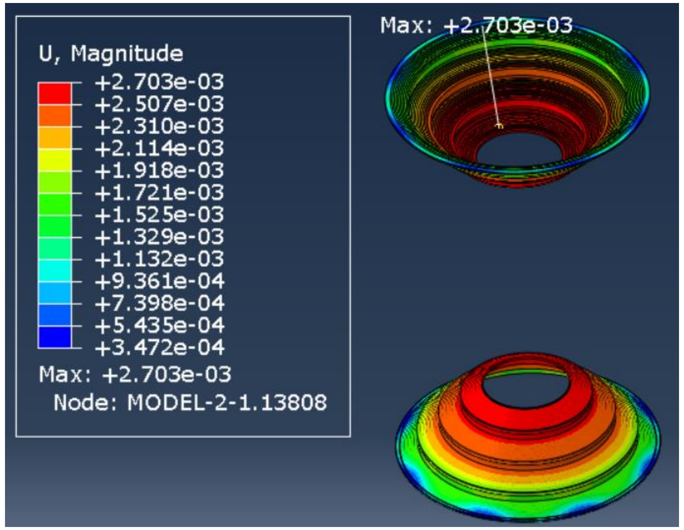
Diameter of field wire (Al coated with Au) : 60µm
Diameter of sense wire (W coated with Au): 20µm
Sag = 280 µm

Meet requirements of stability condition:

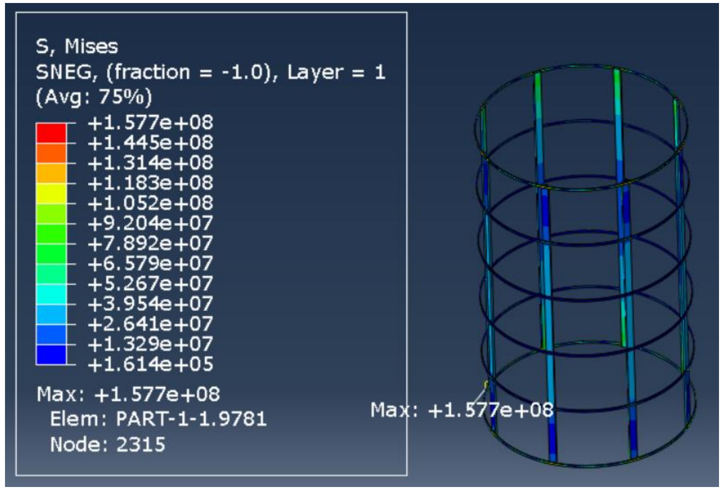
$$T > \left(\frac{VLC}{d}\right)^2 / (4\pi\varepsilon_0)$$

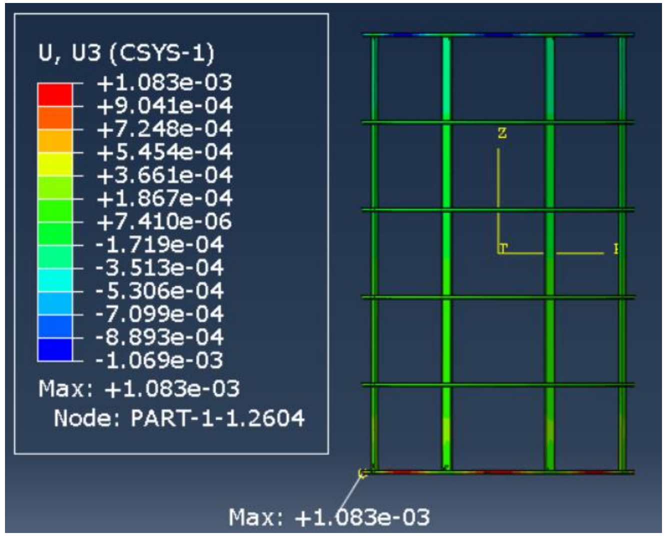
Finite element analysis





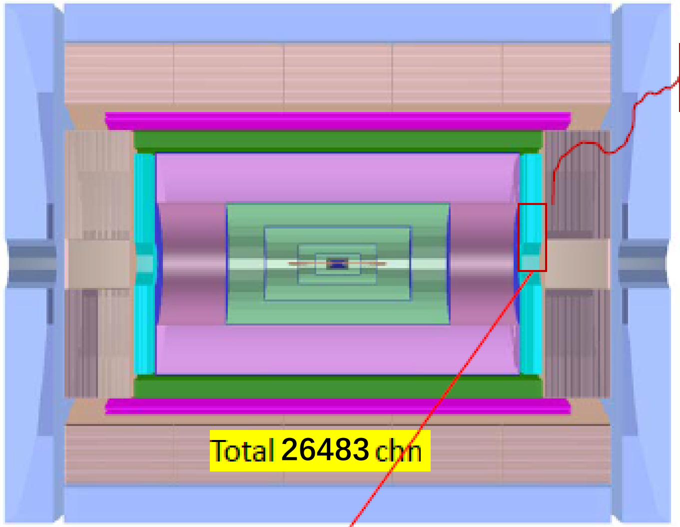
- Max Mises stress of End plate : 30MPa
- Endplate deformation 2.7mm

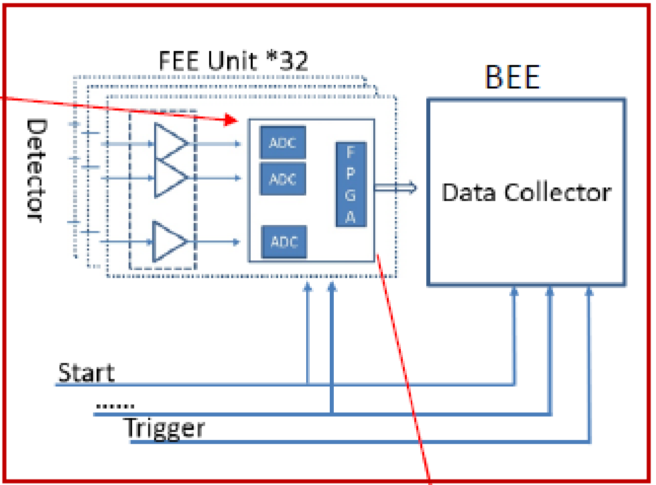




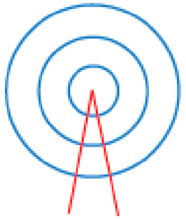
- Max Mises stress of CF frame : 235MPa
- CF frame deformation 1.1mm

Global design of Elec-TDAQ system

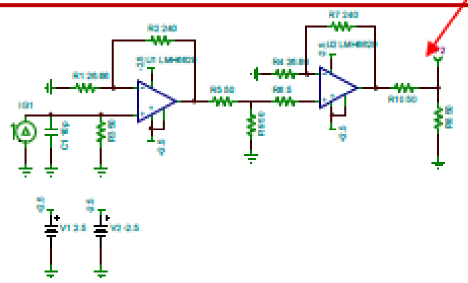




FEE 2: Non-Radiation-hardness FEE with ADC and FPGA



12 chn
Grp by sector

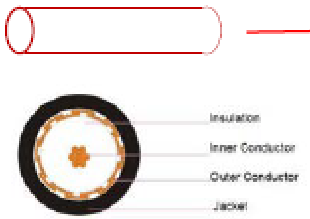


High Bandwidth Preamp
100mW/ch -> 2.7kW in total

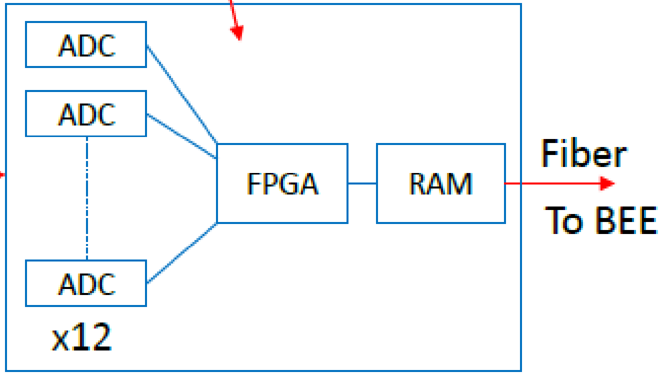
1.4kW for each end plate, air cooling is OK
no additional material bufget

FEE 1: Radiation hardness FEE with preamplifier

x12



Analog signal on Cable
2.8mm per co-ax
12 signals + 1 Power
3dB attenuation @ 280MHz



ADC @1.3Gsps, 12bit

Summary of DC parameters

R extension	600-1800mm
Length of outermost wires（cosθ=0.85）	5800mm
Thickness of inner CF cylinder: (for gas tightness, no load)	200µm (0.08% X_0)
Thickness of outer CF cylinder: (for gas tightness, no load)	300µm (0.13% X_0)
Outer CF frame structure:	Equivalent CF thickness: 1.8 mm (0.77% X_0)
Thickness of end Al plate:	20mm / 25mm (22.5X_0 / 28% X_0)
Cell size:	~ 18 mm × 18 mm
Cell number	26483
Diameter of field wire (Al coated with Au)	60µm
Diameter of sense wire (W coated with Au)	20µm
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10
Gas + wire material	0.16% X_0

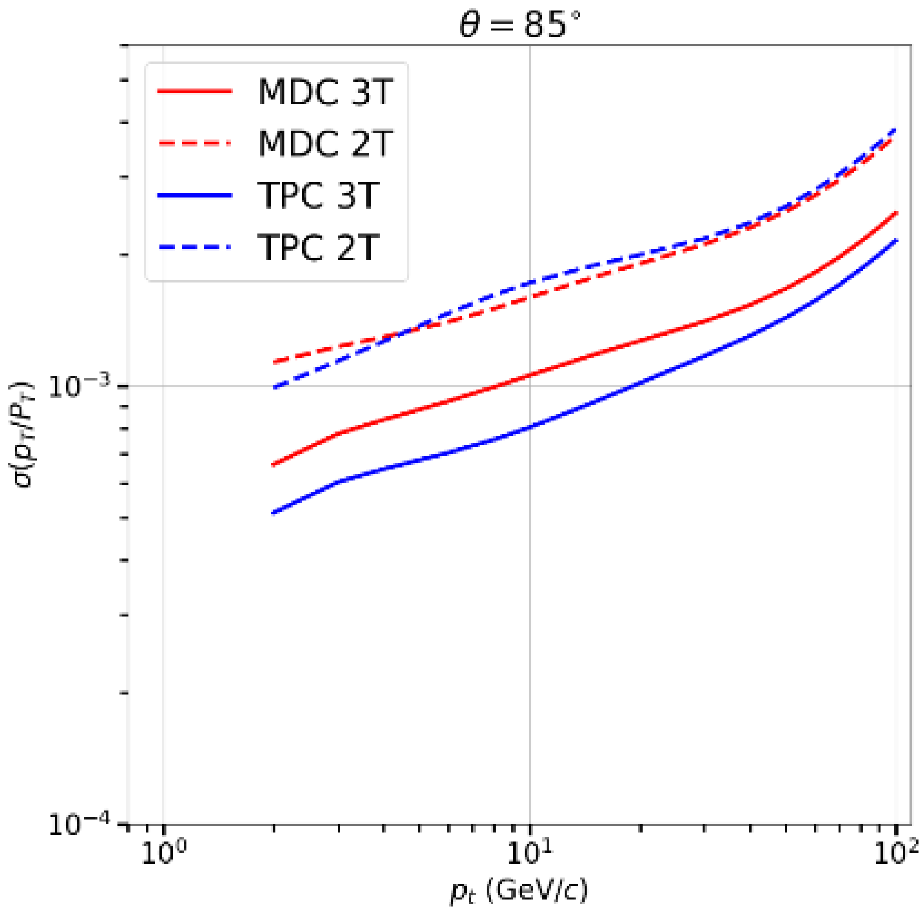
Summary

- **R & D progress of the CEPC drift chamber**
  - PID performance: >3σ K/π separation at 20 GeV/c for 1.2 m track length
  - dN/dx reconstruction with deep learning shows promising performance for simulation and testbeam data
  - Fast electronics is under development. Preliminary analysis with the testbeam validates the electronics and the feasibility of dN/dx measurement
  - Preliminary mechanical design and FEA show a stable structure
  - Global electronics scheme is reasonable

- **Plans**
  - Fine detector optimization
  - Optimize deep learning algorithm and FPGA implementation
  - Prototyping and testing with full-length cells (mechanics, manufacturing, testing)

Backup

Momentum resolution



$$\sigma\left(\frac{1}{p_t}\right) = a \pm \frac{b}{p_t}$$

	Higgs	Z-pole
a (1/GeV)	2.1×10^{-5}	3.2×10^{-5}
b	0.77×10^{-3}	1.16×10^{-3}