Drift Chamber with Cluster Counting for CEPC

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March 13, 2024

LCTPC Collaboration Meeting

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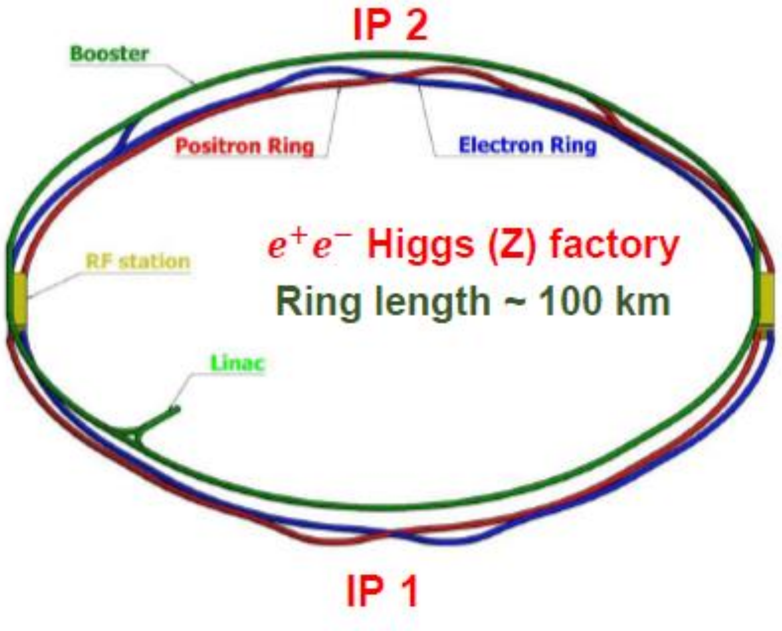
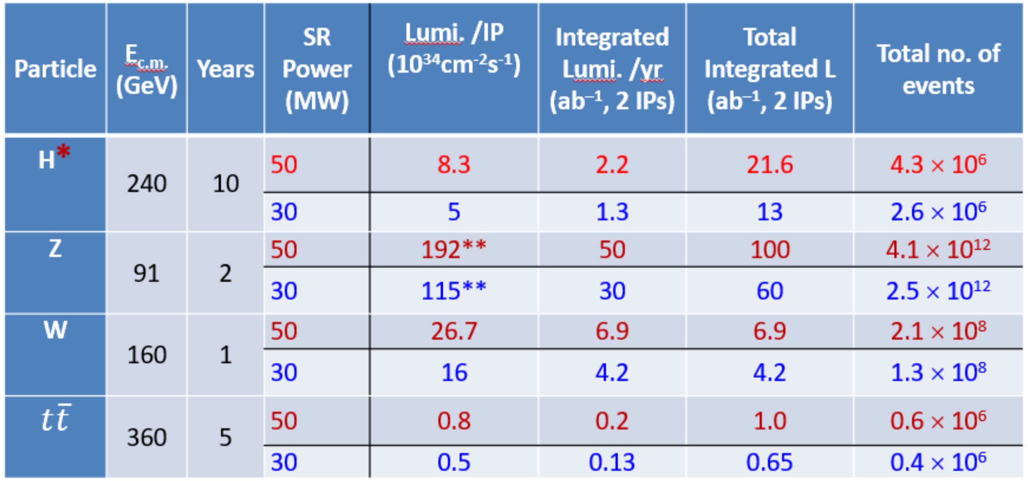
Outline

- Introduction
- Detector design and performance
- Prototype experiments
- 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.





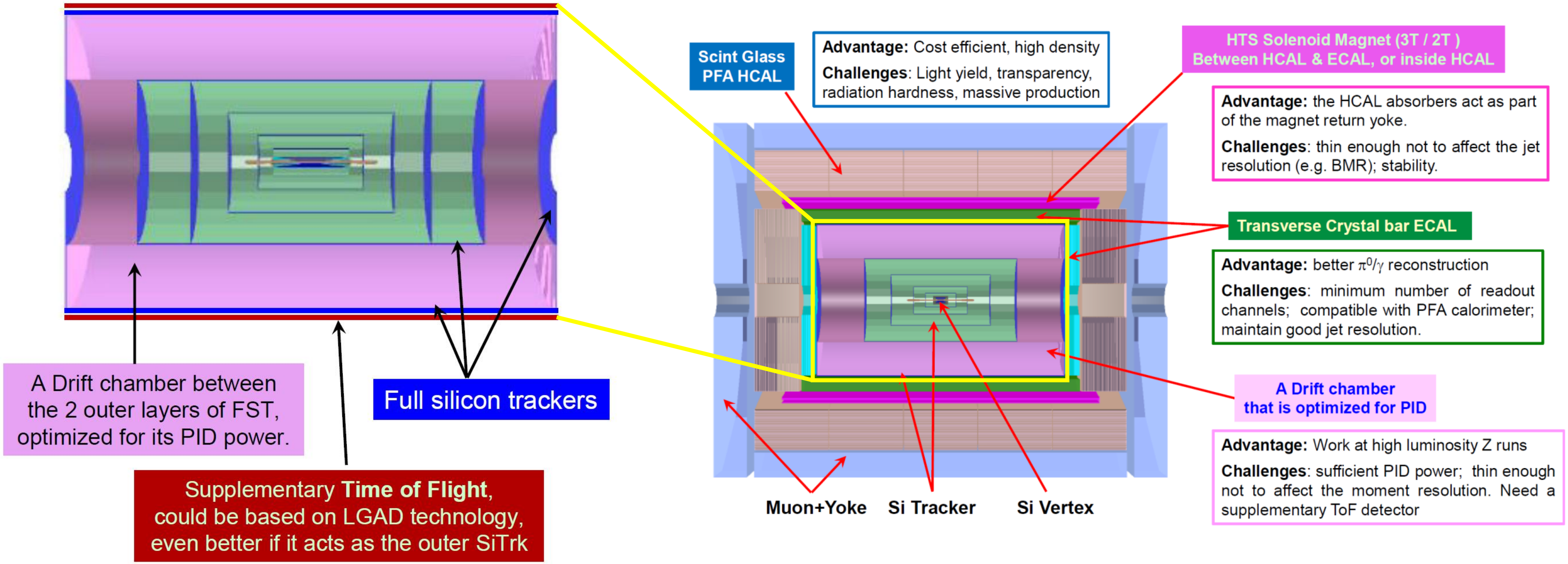
Particle	$E_{c.m.}$ (GeV)	Years	SR Power (MW)	Lumi. /IP (10^{34}cm^{-2}s^{-1})	Integrated Lumi. /yr (ab^{-1}, 2 IPs)	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of events
H*	240	10	50	8.3	2.2	21.6	4.3×10^6
			30	5	1.3	13	2.6×10^6
Z	91	2	50	192**	50	100	4.1×10^{12}
			30	115**	30	60	2.5×10^{12}
W	160	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.

CEPC 4th concept detector



Scint Glass PFA HCAL

Advantage: Cost efficient, high density

Challenges: Light yield, transparency, radiation hardness, massive production

HTS Solenoid Magnet (3T / 2T)
Between HCAL & ECAL, or inside HCAL

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution. Need a supplementary ToF detector

A Drift chamber between the 2 outer layers of FST, optimized for its PID power.

Full silicon trackers

Supplementary **Time of Flight**, could be based on LGAD technology, even better if it acts as the outer SiTrk

A drift chamber with cluster counting technique to provide PID

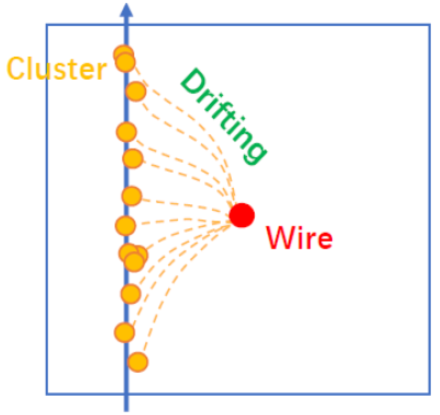
Cluster counting in gaseous detectors

- **Cluster counting:** Measure individual ionization clusters instead of dE/dx, could significantly reduce the uncertainty

- **In time**
  - Time measurement in small drift cells of DC
  - Challenging of fast-shaping electronics (~ns needed)
  - De-couple the charge collection from the cluster counting altogether
  - →optical, with ~(sub) ns continuous readout sensors

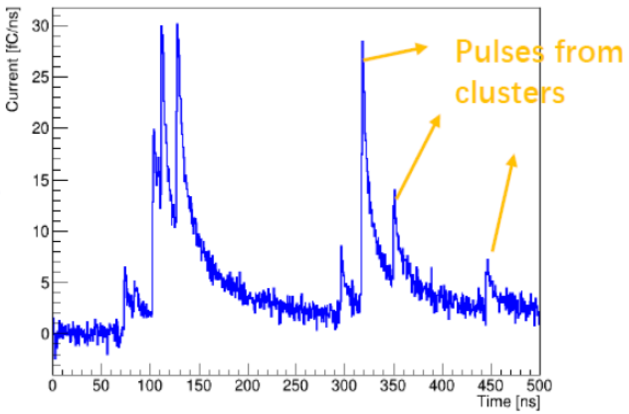
- **In space**
  - Resolve clusters in space by high granularity TPC
  - Challenging of the low power consumption electronics (>40 mV/fC needed at 2000 of gas gain)
  - Pixelated readout – high granularity
  - →the reasonable pixilation reveals the underlying cluster structure in 3D chamber

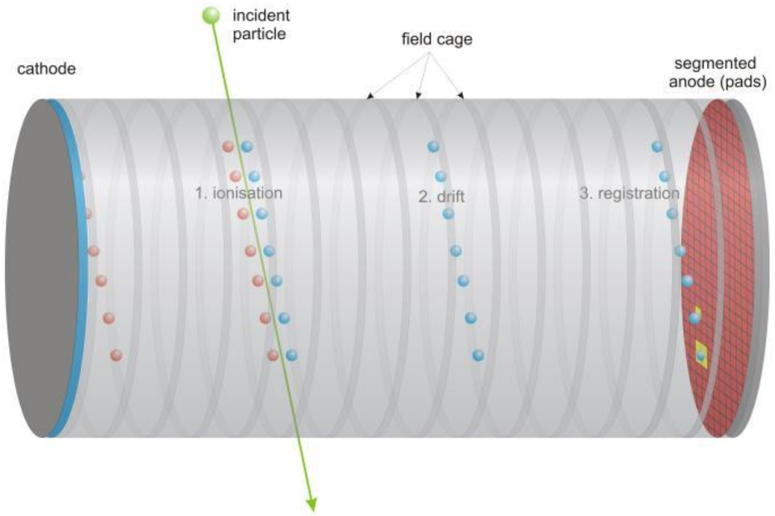
DC cell



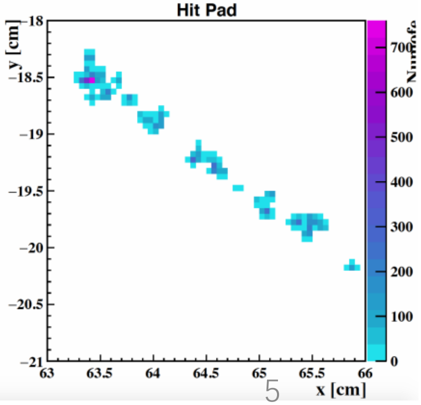
(for demonstration)

Induced current

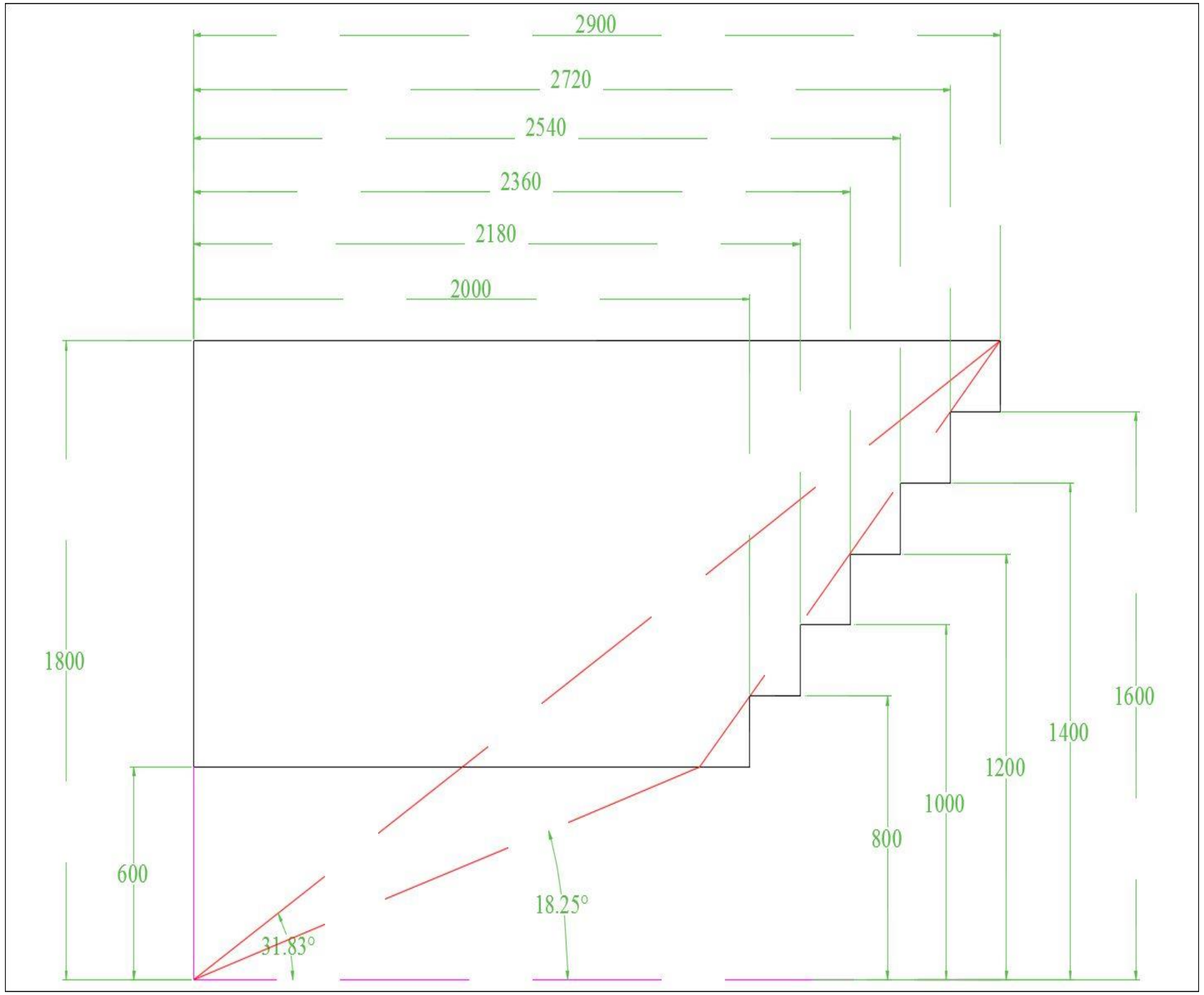


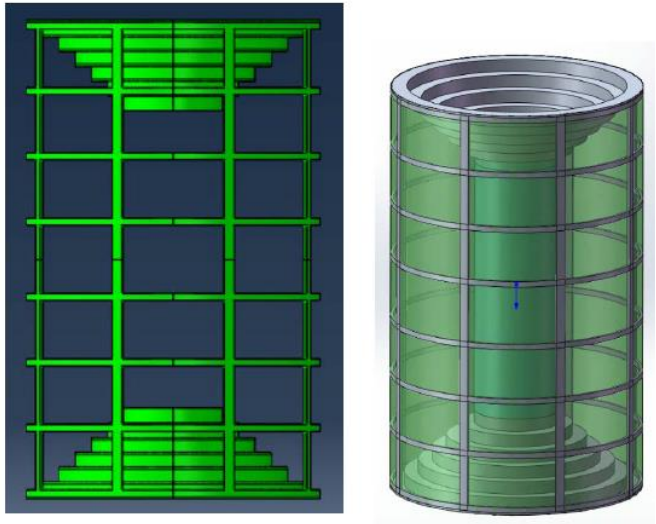


Readout



Preliminary DC layout





- Full length: 5800 mm
- Barrel coverage: |cosθ| < 0.85
- Radius: 600 – 1800 mm
- Support: 8x8 carbon fibre frame
- Endcap: 25 mm Al plate

Challenges for DC with CC

- **Challenges for cluster counting**
  - Detector design: Detector layout, cell size, working gas with low drift velocity, low ionization density, low diffusion and low cluster size
  - Fast electronics: Bandwidth > 1 GHz, gain > 10, sampling rate > 1.5 GS/s, bit resolution > 12 bit

➢ **Detector optimization**
➢ **Prototype experiments**

- Reconstruction: Efficient primary clusters detection from waveforms in high pile-up and noisy environments

➢ **Deep learning algorithm**

- **Challenges for large volume DC**
  - Electrostatic stability: L ~ 6m, need wire material studies

➢ **Finite element analysis**

- Data reduction: ~1 TB/s (Z-pole), need online data reduction
- Power consumption/cooling design

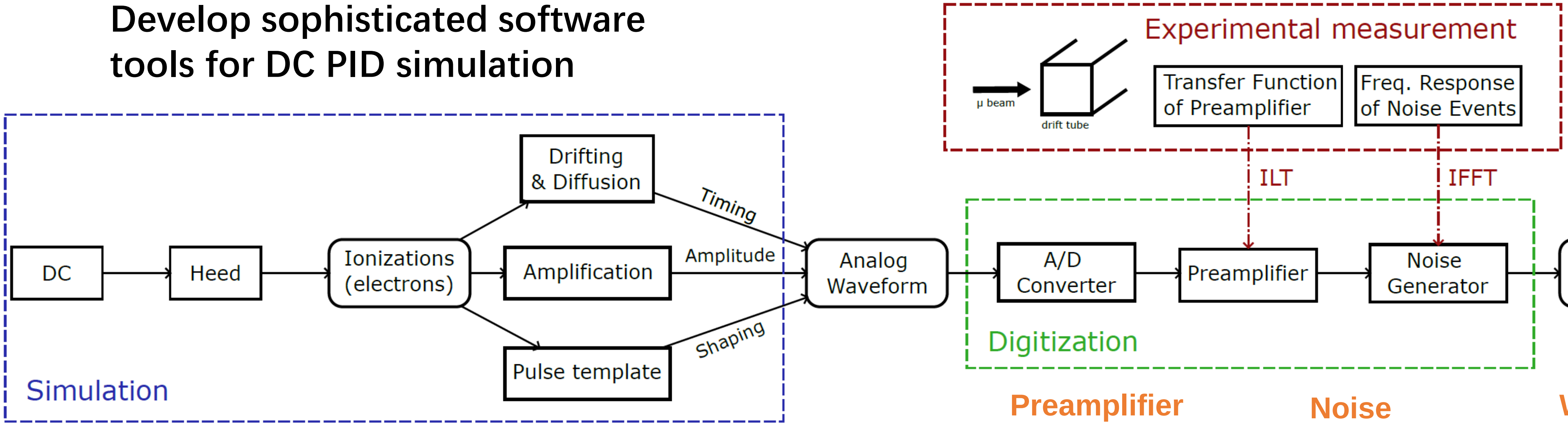
• **Need to do**

Detector design and performance

- Simulation
- Reconstruction
- Mechanics

Waveform-based simulation

Develop sophisticated software tools for DC PID simulation



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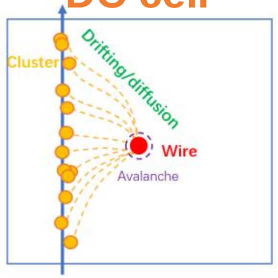
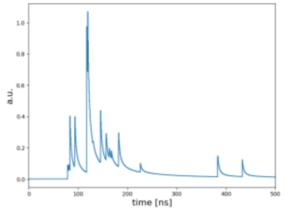
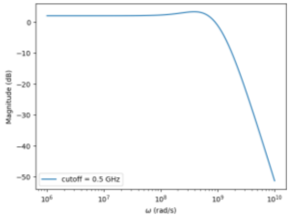
DC cell



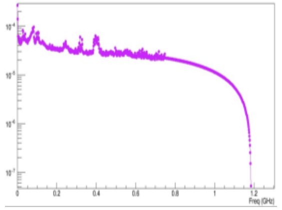
Induced signal



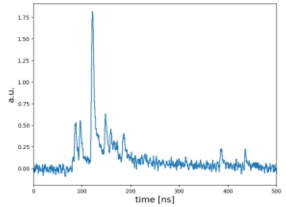
Preamplifier



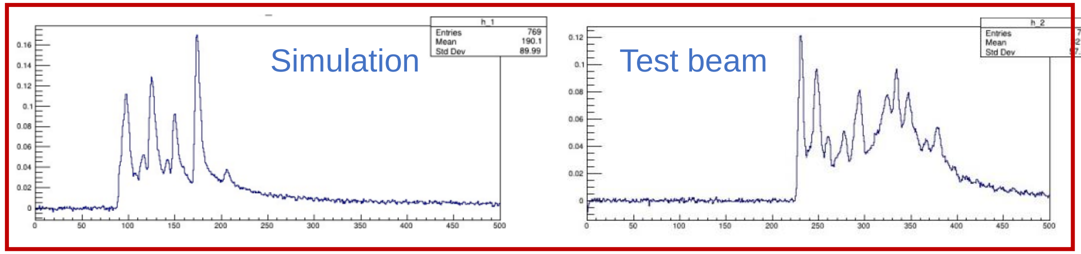
Noise



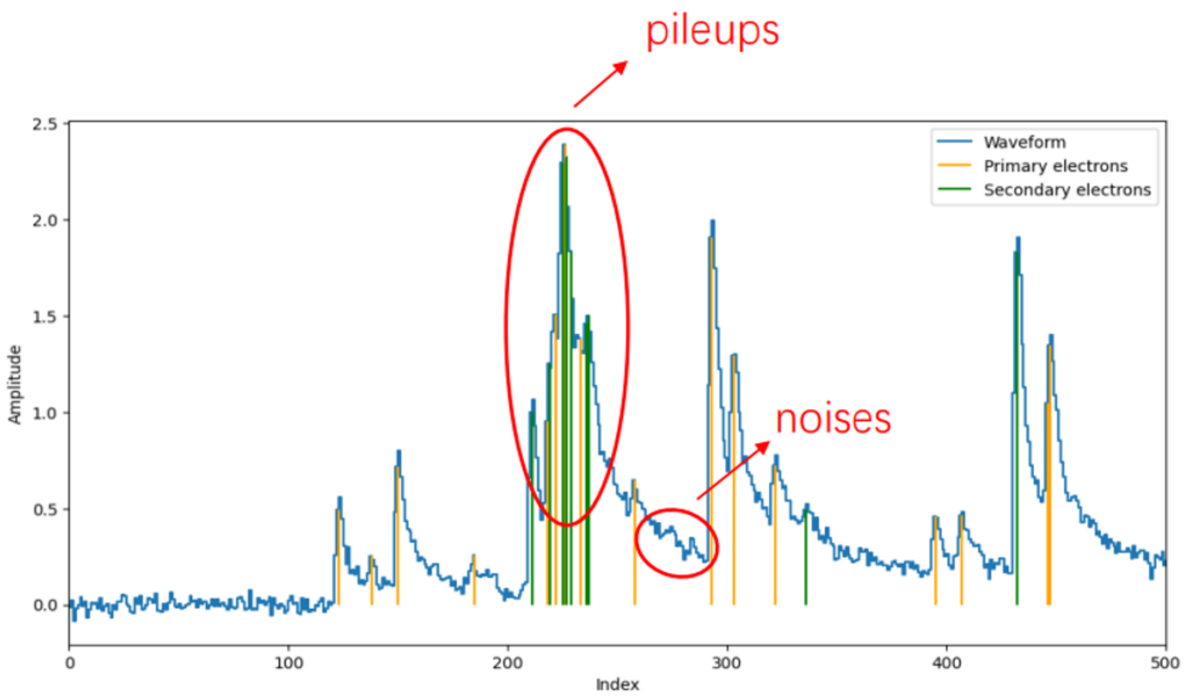
Waveform



Tuned MC is comparable to data



Traditional reconstruction algorithm



Simulated waveform of a DC cell. Orange lines are primary electrons. Green lines are secondary electrons.

Reconstruction: Each primary and secondary electrons forms a peak in the waveform. Need to determine the # of primary peaks.

Peak finding: Detect all electron peaks

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

Clusterization: Merge electrons to form clusters

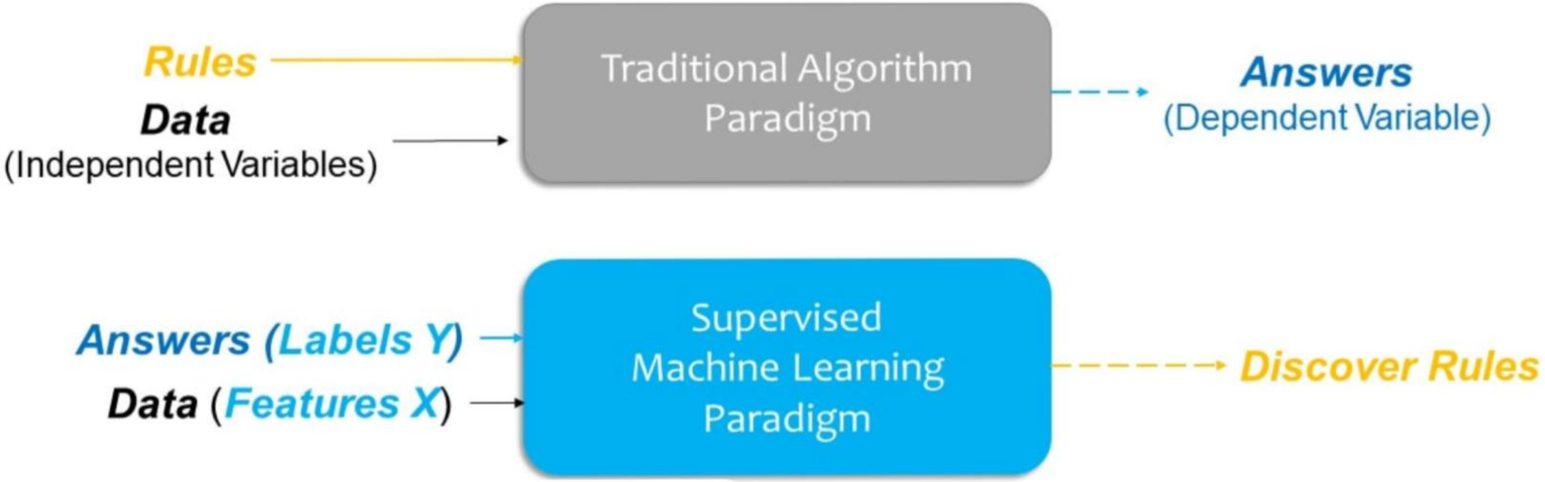
- Merge peaks within $[0, t_{cut})$
- The t_{cut} is related to diffusion

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

Deep learning reconstruction algorithm

- **Traditional algorithm:**
  - Use partial information of the raw waveform
  - Require human input prior knowledge

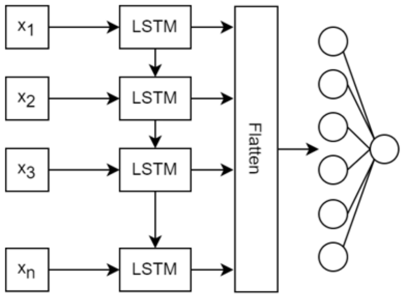
- **Supervised learning could be more powerful** because
  - make full use of the waveform information
  - automatically learn characteristics of signals and noises from large labeled samples



Supervised model for simulated samples

Peak finding with LSTM

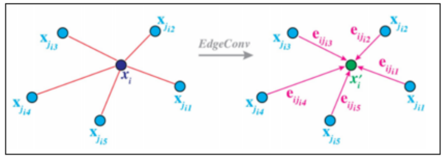
Why LSTM? ➔ Waveforms are time series



- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

Clusterization with DGCNN

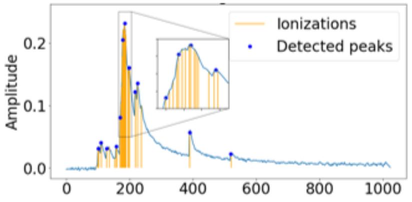
Why DGCNN? ➔ Locality of the electrons from the same primary cluster, perform massage passing through neighbor nodes in GNN



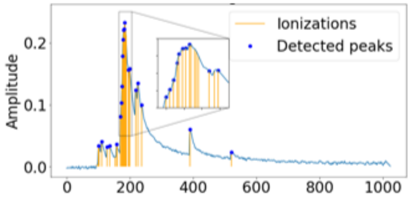
arXiv: 1801.07829

- Architecture: DGCNN (GNN-based)
- Method: Binary classification of primary and secondary electrons

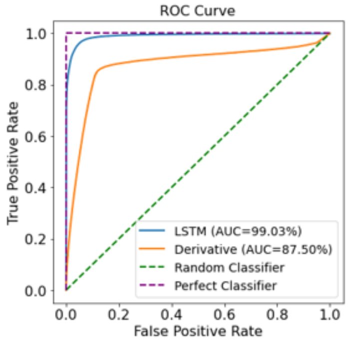
Derivative-based method

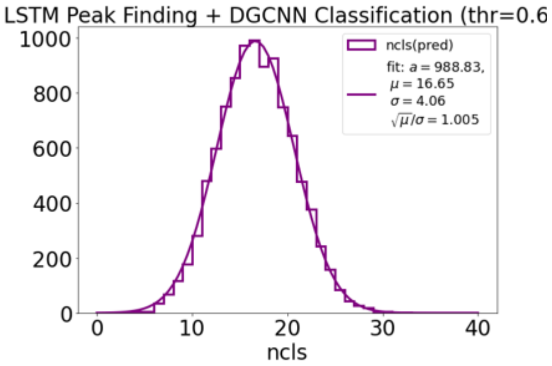


LSTM

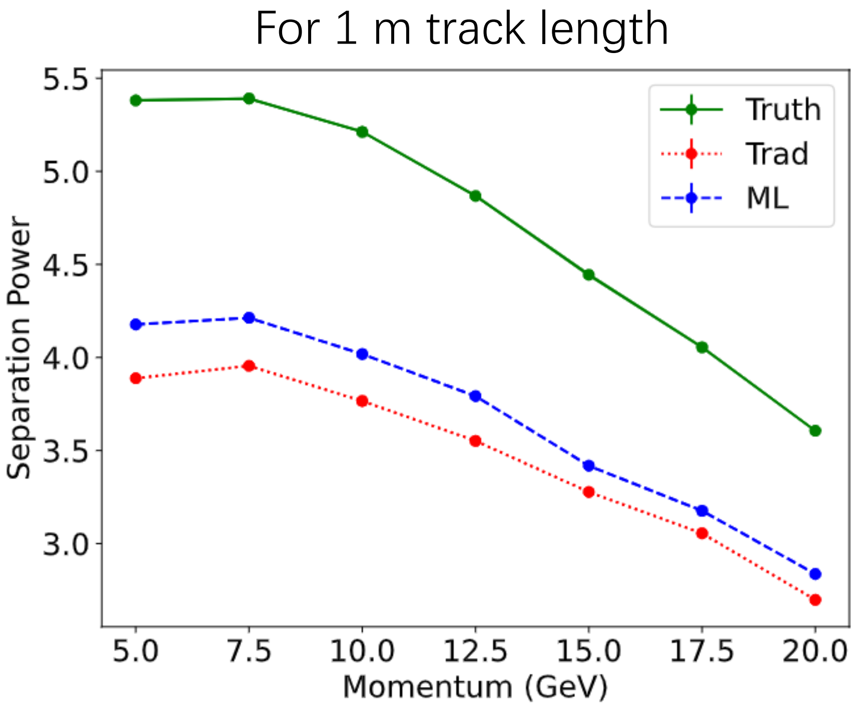


Peak finding: ML is better than derivative-based method





Peak finding + Clusterization: Very well Poisson-like distribution



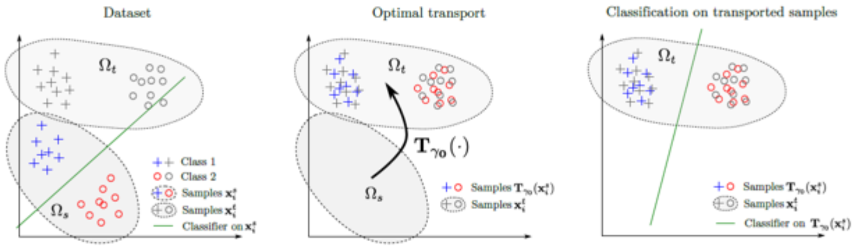
~10% improvement on K/π separation power with ML (equivalent to a detector with 20% larger radius)

Domain adaptation model for data samples

Main challenges:

- Discrepancies between data and MC
- Lack of labels in experimental data

→ **Domain adaptation**



Align data/MC samples with Optimal Transport

Loss for labeled samples in source domain

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

Loss for labeled samples in target domain (THIS WORK)

Cost of feature differences between source and target

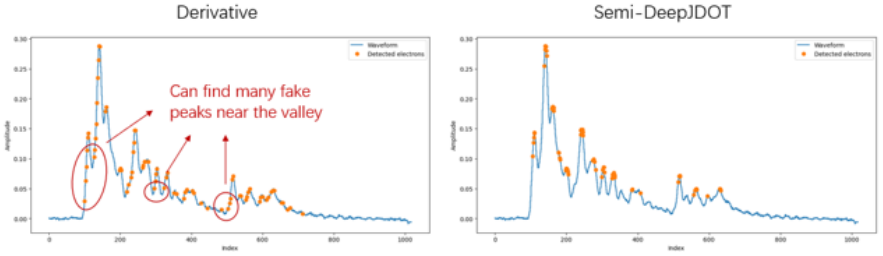
Cost of 'label' differences between source and target

Cost of joint feature-label distribution for OT

Semi-supervised implementation our work

2

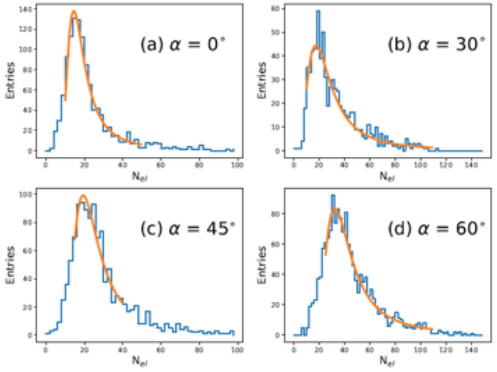
Single-waveform results between derivative alg. and DL alg.

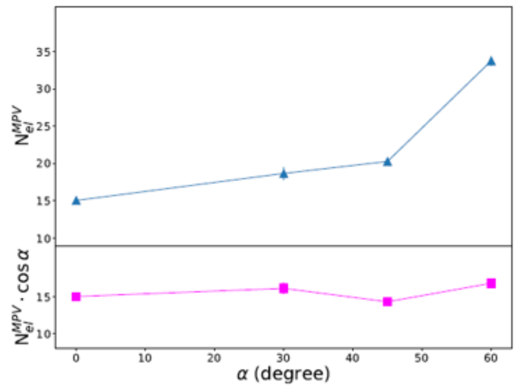


Note: Require similar efficiency for both cases

DL algorithm is more powerful to discriminate signals and noises

Multi-waveform results for samples in different angles





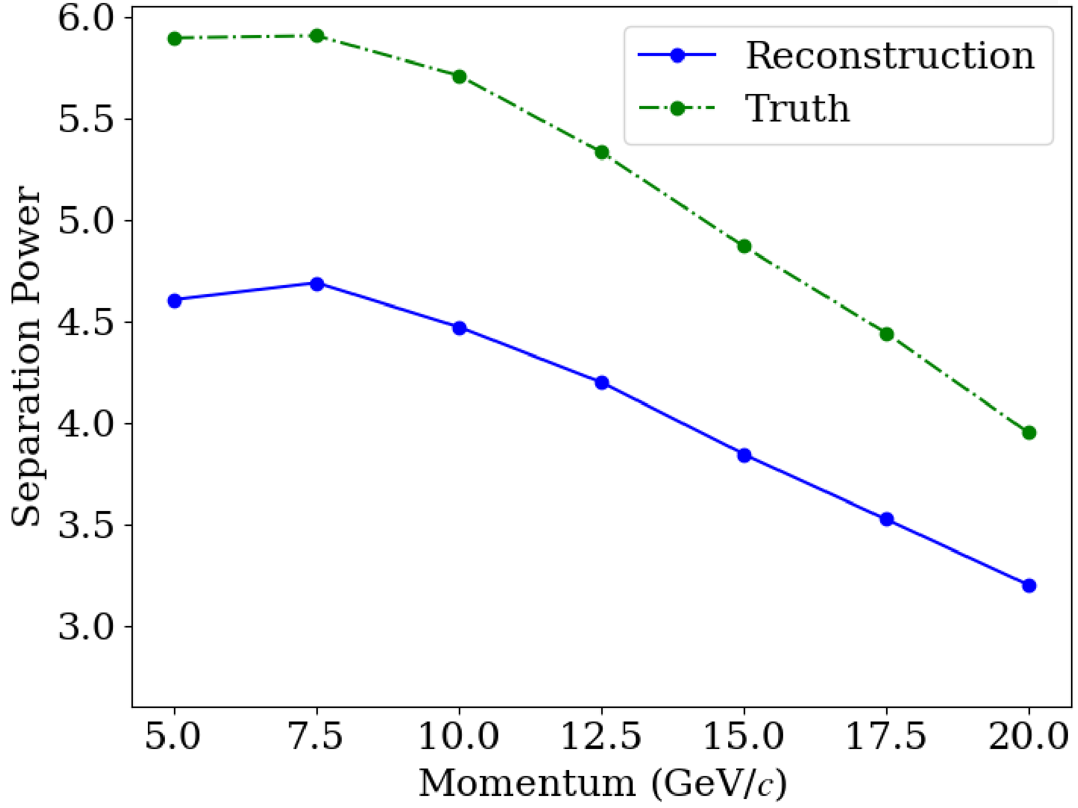
Scale w.r.t. track length

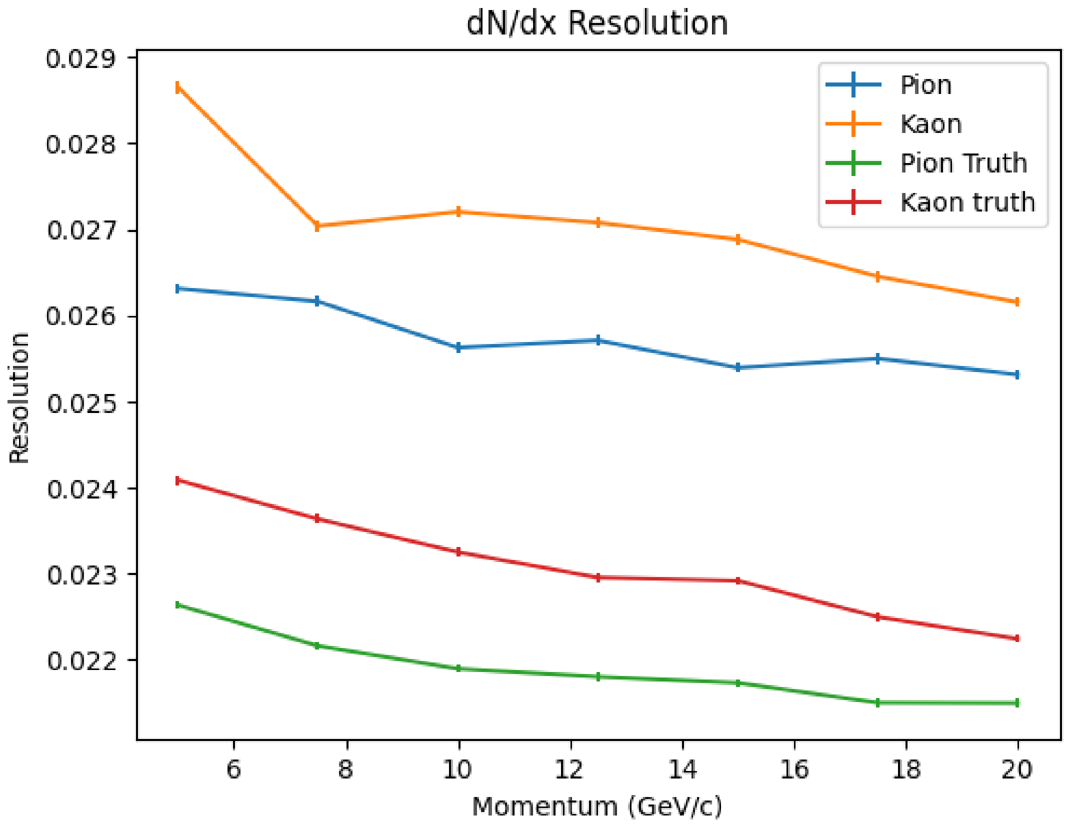
25

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

PID performance

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





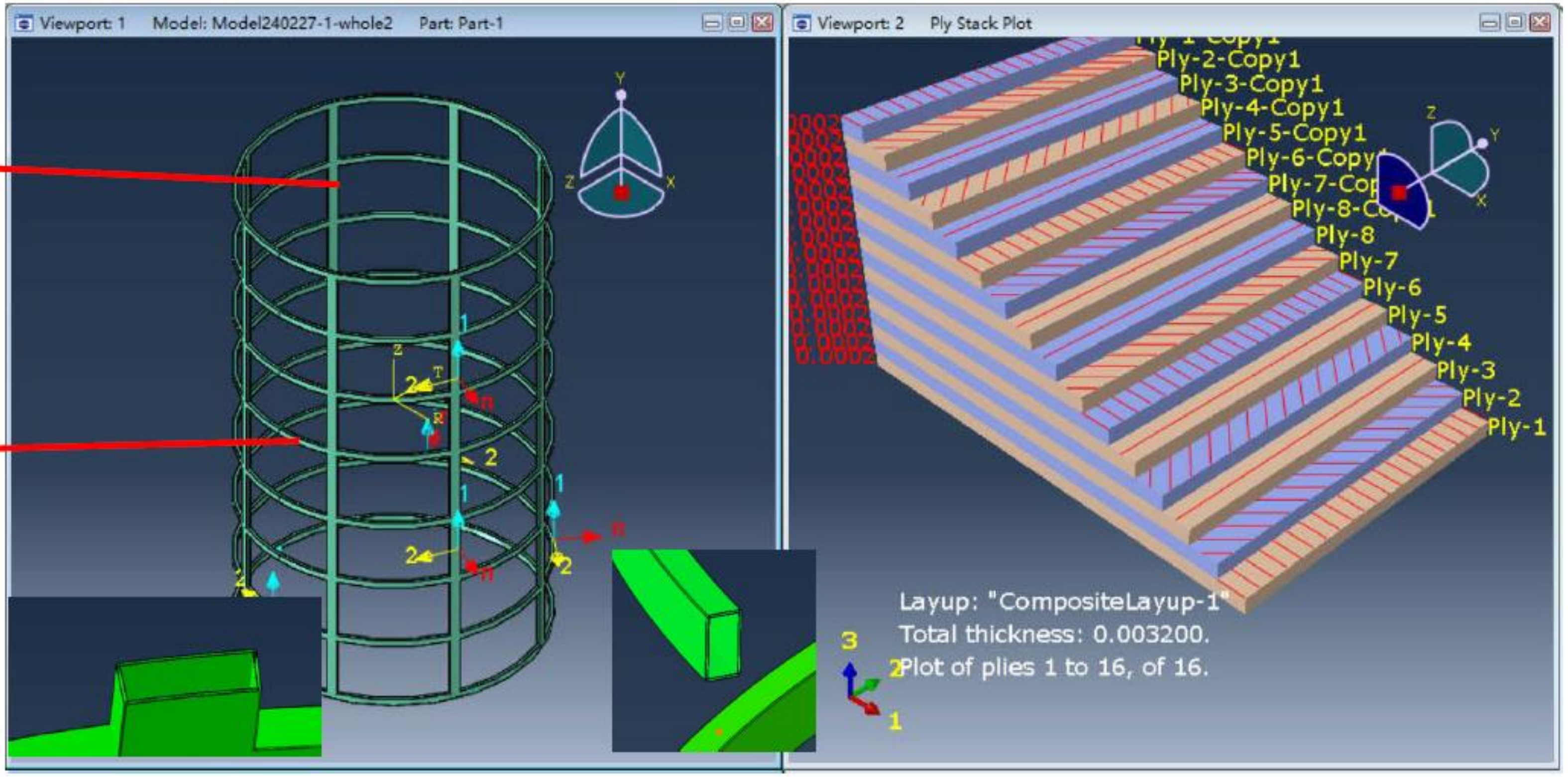
For 1.2 m track length (cosθ = 0)

- K/pi separation = 3.1 σ @ 20 GeV/c
- Resolution < 3% for K/π momentum > 5 GeV/c

Support structure design

竖梁
复合材料：
125*40mm，
壁厚3.2mm
总重：78kg

环梁
复合材料：
80*40mm
壁厚3.2mm
总重：111kg



Layup: "CompositeLayup-1"
Total thickness: 0.003200.
Plot of plies 1 to 16, of 16.

- Carbon fiber frame structure, including 8 longitudinal hollow beams and 8 annular hollow beams
- Thickness of inner CF cylinder: 200 μm/layer * 16 layers = 3.2 mm
- Effective outer CF frame structure: 1.8 mm
- Thickness of end Al plate: 25 mm

Wire tensions

	cell number /step	length	single sense wire tension(g)	Single field wire tension(g)	total tension /step (kg)
	2684	4000	43.29	66.52	651.78
	3452	4360	51.43	79.03	995.95
	4220	4720	60.28	92.62	1426.88
	4988	5080	69.82	107.29	1953.63
	5756	5440	80.07	123.03	2585.27
	6524	5800	91.02	139.85	3330.85
total	27623				10944

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:

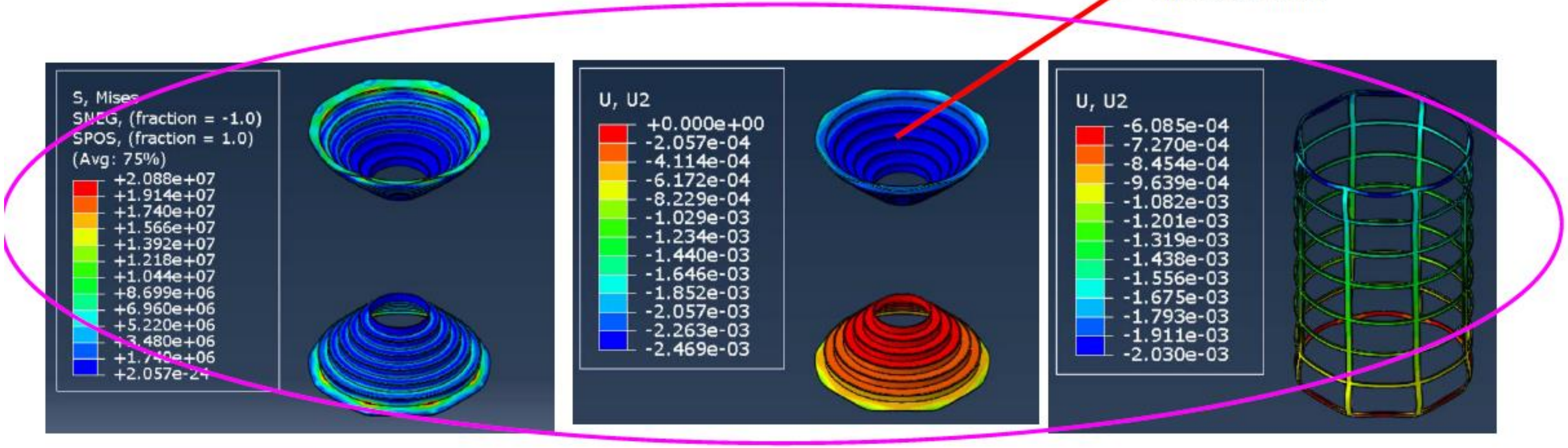
$$T > \left(\frac{VLC}{d}\right)^2/(4\pi\varepsilon_0)$$

Finite element analysis

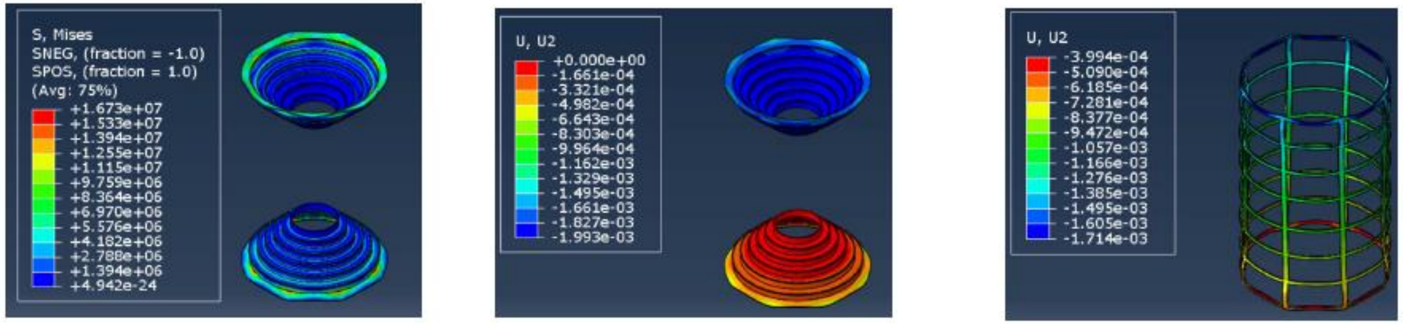
25 mm endcap thickness:

- Max. stress: 20.9 MPa
- Deformation: 2.5 mm for endcap, 1.4 mm for CF frame

端面板拉力+轴向自重荷载：



端面板厚度25mm，应力20.9MPa，变形2.5mm，框架变形1.4mm



端面板厚度30mm，应力16.7MPa，变形2.0mm，框架变形1.3mm

Summary of DC performance

	Higgs	Z-pole
B-field (T)	3	2
Performance		
material budget barrel (X0)	1.14%	1.14%
material budget endcap (X0)	28%	28%
Npoints per full track	66	66
point resolution in rϕ (μm)	100	100
point resolution in rz (μm)	2000	2000
momentum resolution normalised: $\sigma(1/pT) = a \pm b/pT$	$2.1\times10^{-5} \pm 0.77\times10^{-3}/pT$	$3.2\times10^{-5} \pm 1.16\times10^{-3}/pT$
a (1/GeV)	2.1×10^{-5}	3.2×10^{-5}
b	0.77×10^{-3}	1.16×10^{-3}
K/π separation power @ 20GeV	3.1 σ	3.1 σ
Hit rate (maximum)		70.4kHz/cell
Occupancy (maximum)		10.6%

Prototype experiments

- Test beam
- β source

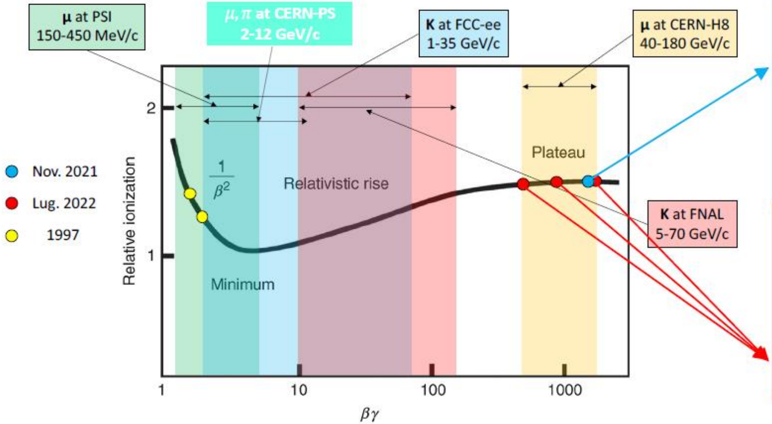
Test beam experiments at CERN

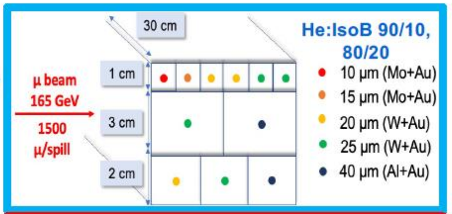
Beam tests organized by INFN group (leaded by Franco Grancagnolo and Nicola De Filippis):

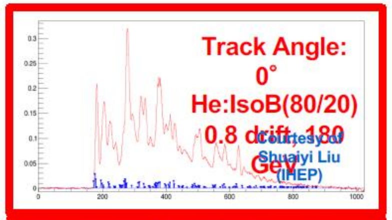
- Two muon beam tests performed at CERN-H8 (βγ>400) in Nov. 2021 and July 2022.
- A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN.
- Ultimate test in 2024 with π and K (βγ = 10-14) to fully exploit the relativistic rise.

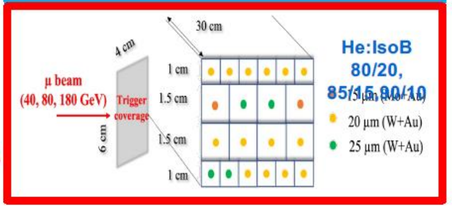
Contributions from IHEP group:

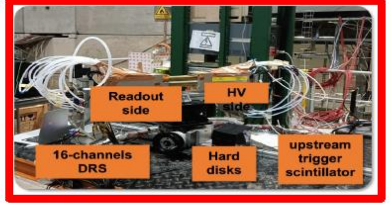
- Participate data taking and collaboratively analyze the test beam data
- **Develop the deep learning reconstruction algorithm**

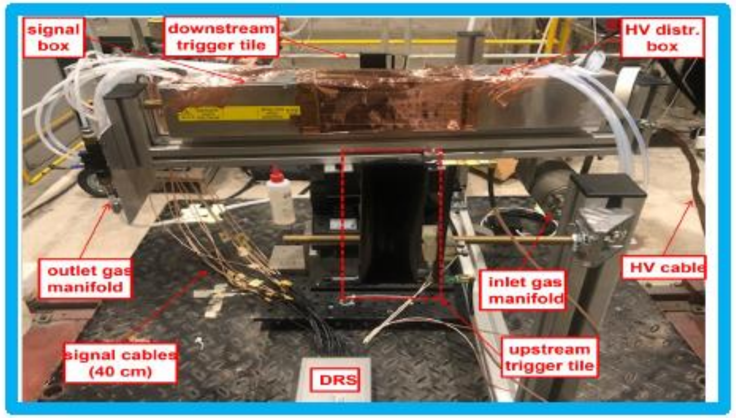










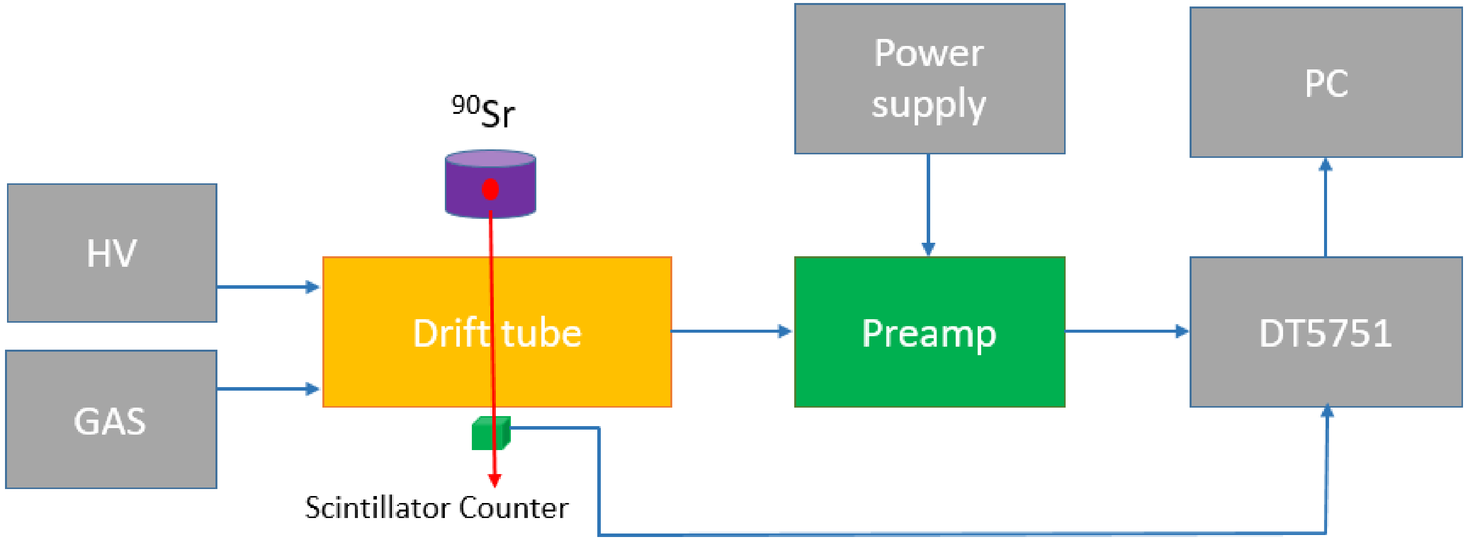


See Nicola De Filippis's talk at the CEPC Workshop for details

Prototype experiment at IHEP

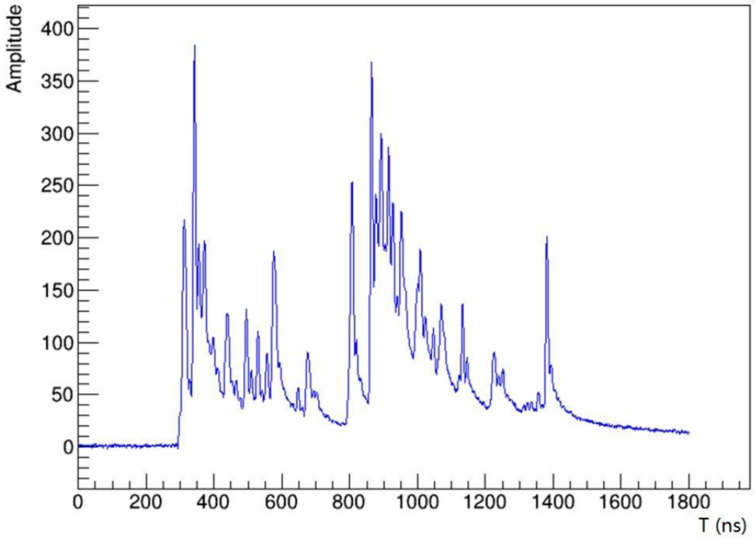
Also done the test beam at BEPC2 with 1.3 GeV electron beams. Analysis ongoing.

Experiment layout



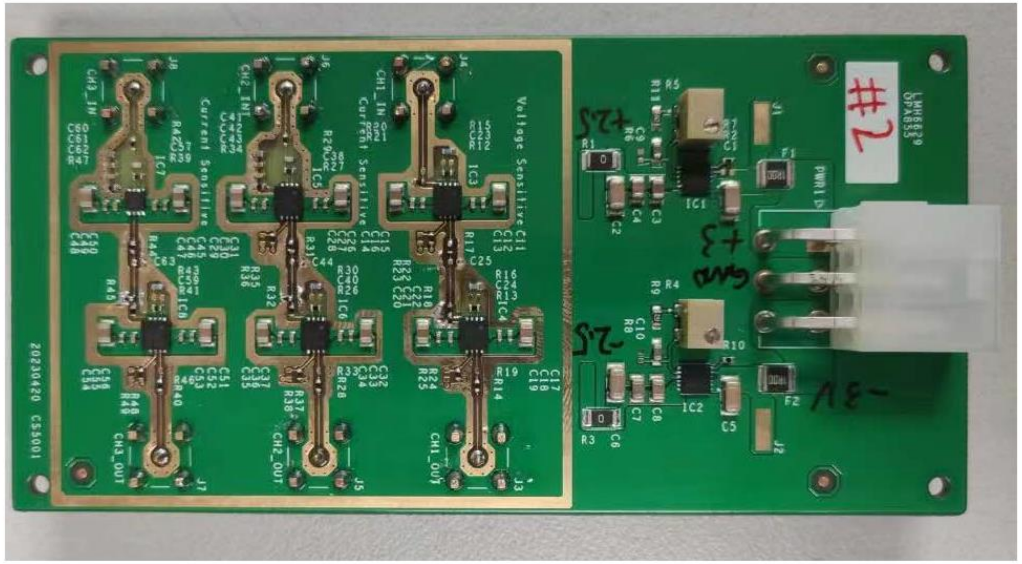
- Diameter of the tube: 30 mm
- Working gas: He/iC_4H_{10}=90:10

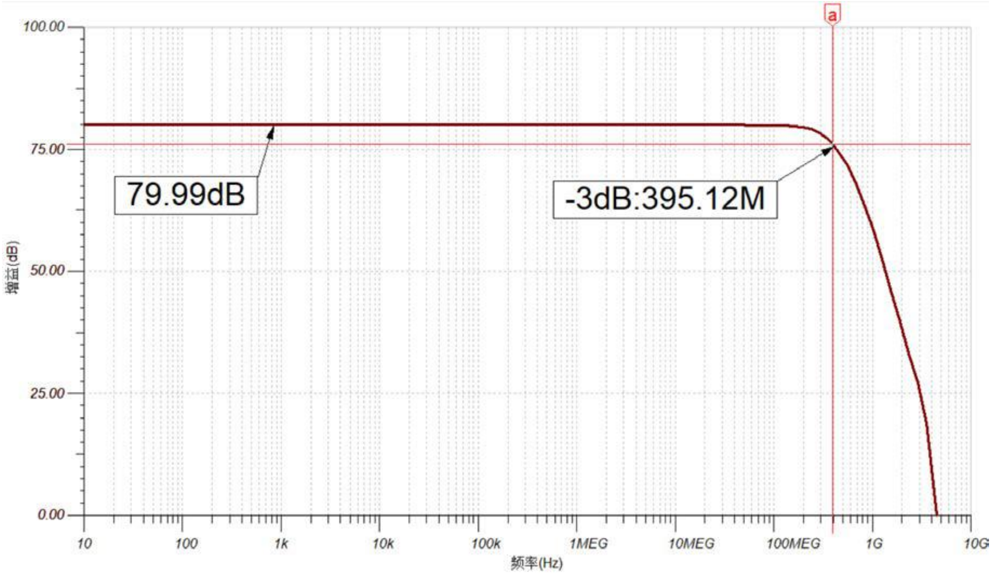
Waveform with Sr-90 β source

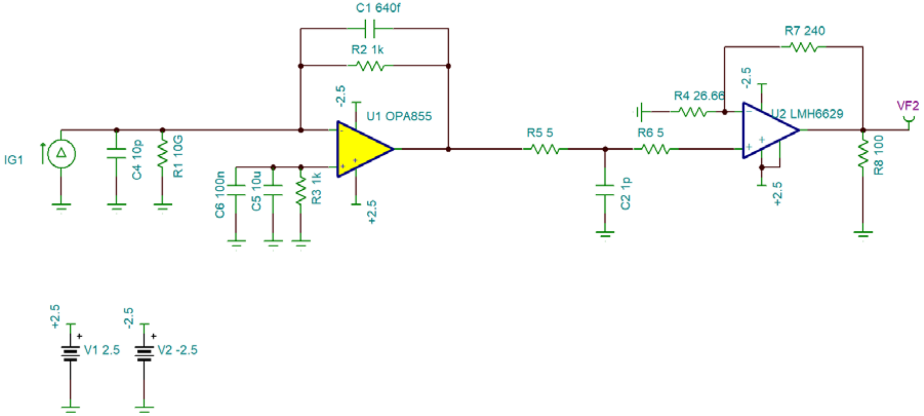


CC signal observed with
- **low noise**
- **high bandwidth**
- **fast risetime: ~ns**

Electronics development







- High bandwidth current sensitive preamplifiers based on LMH6629 have been designed and developed
- Tested with detector prototype and digitizer (DT5751) with 1 GHz sampling rate

Summary

- **Preliminary DC design**
  - PID performance: >3σ K/π separation at 20 GeV/c for 1.2 m track length
  - Mechanical stability: Stable with FEM simulations
- **Reconstruction**
  - 10% improvement on K/π separation for supervised model
  - Domain adaption model for experimental data
- **Experiments**
  - Fast electronics development and prototype test at IHEP: observe CC signals
  - International collaboration on test beam experiments

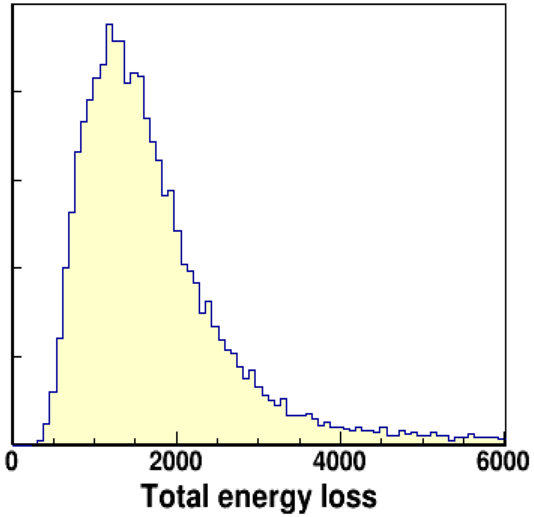
- **Plans**
  - Fine detector optimization
  - Optimize deep learning algorithm and FPGA implementation
  - Electronics developments and experiments
  - Mechanical design and tests
  - Physics benchmarks

Backup

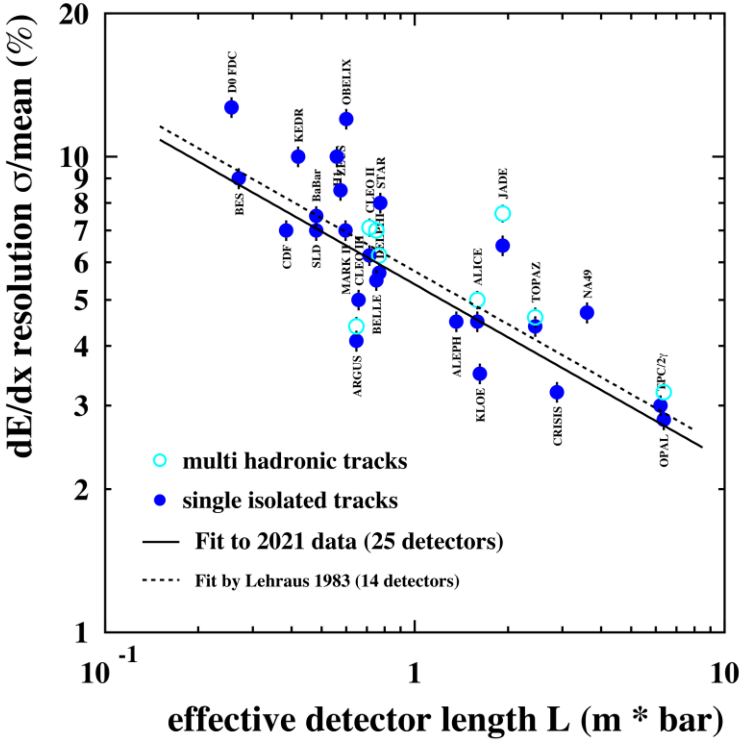
Energy loss measurement: dE/dx

- **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*



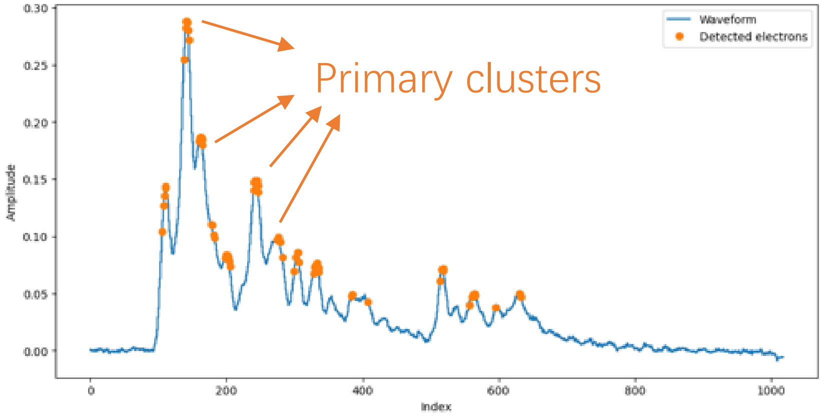
- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** $* L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** $* L^{-0.37}$ (%)
- **No significant improvement in the past 40 years**

* From Michael Hauschild's talk @ RD51 workshop

Cluster counting by time

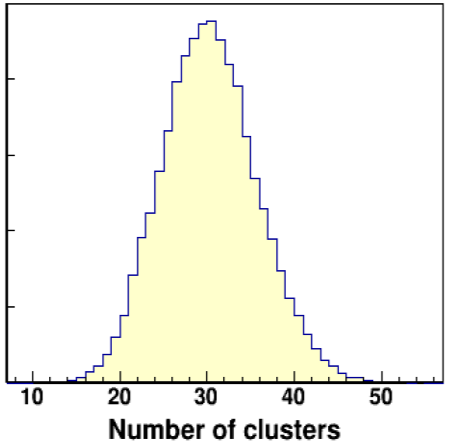
- **Alternatively, counting primary clusters**
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - **Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx**

Waveform

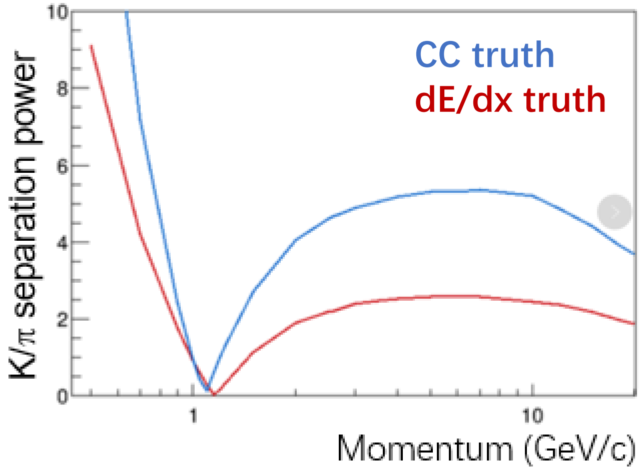


Require fast electronics and sophisticated counting algorithm

Counting clusters



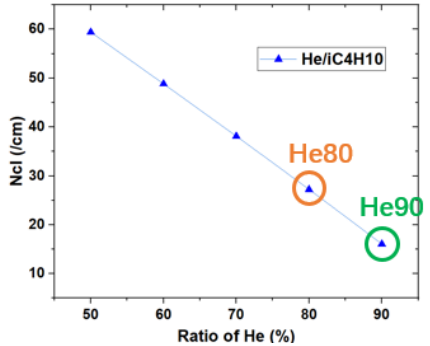
K/π separation power
CC vs dE/dx

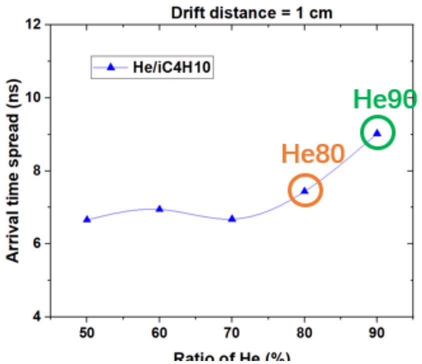


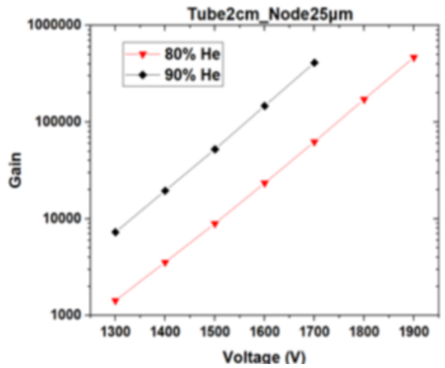
CC is extremely powerful, proposed in ILC, FCC-ee, CEPC

Gas mixture

- Gas mixture choice: He + C_4H_{10}



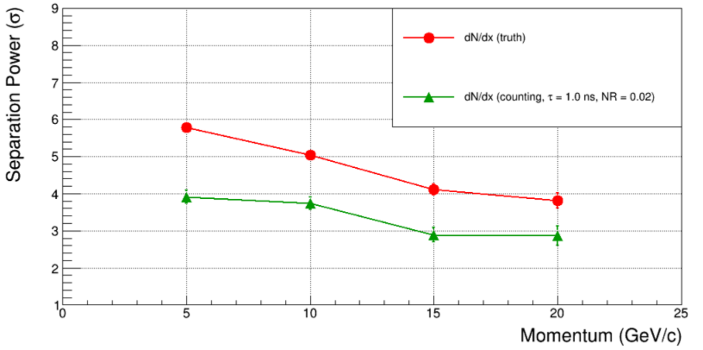




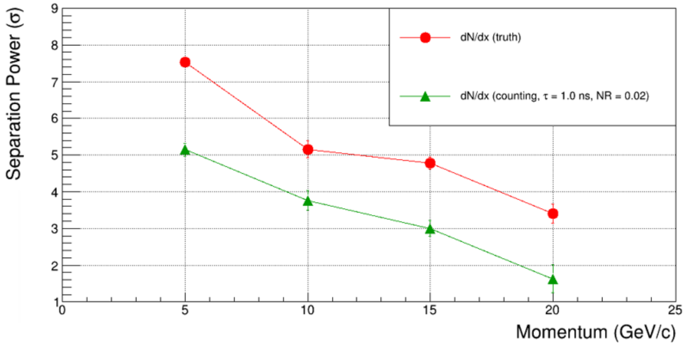
Gas property for CC:

- Small ρ_{cl} ➔ less statistics, large time separation
- Slow v_d ➔ large time separation
- Small σ_d ➔ less likely double-counting

He 90% + iC_4H_{10} 10%, L = 1m, NR = 0.02，1x1cm cell

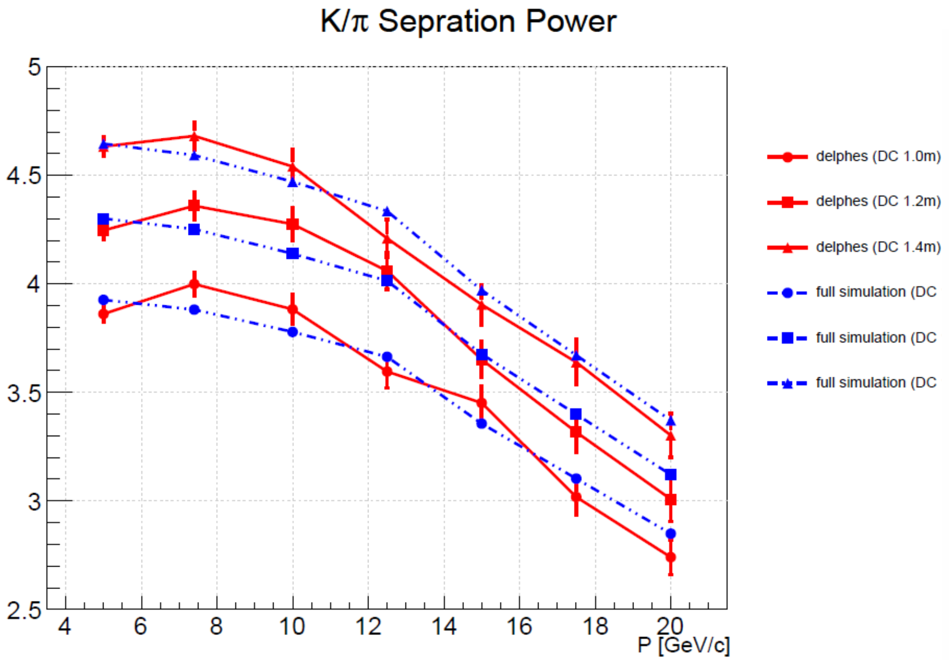


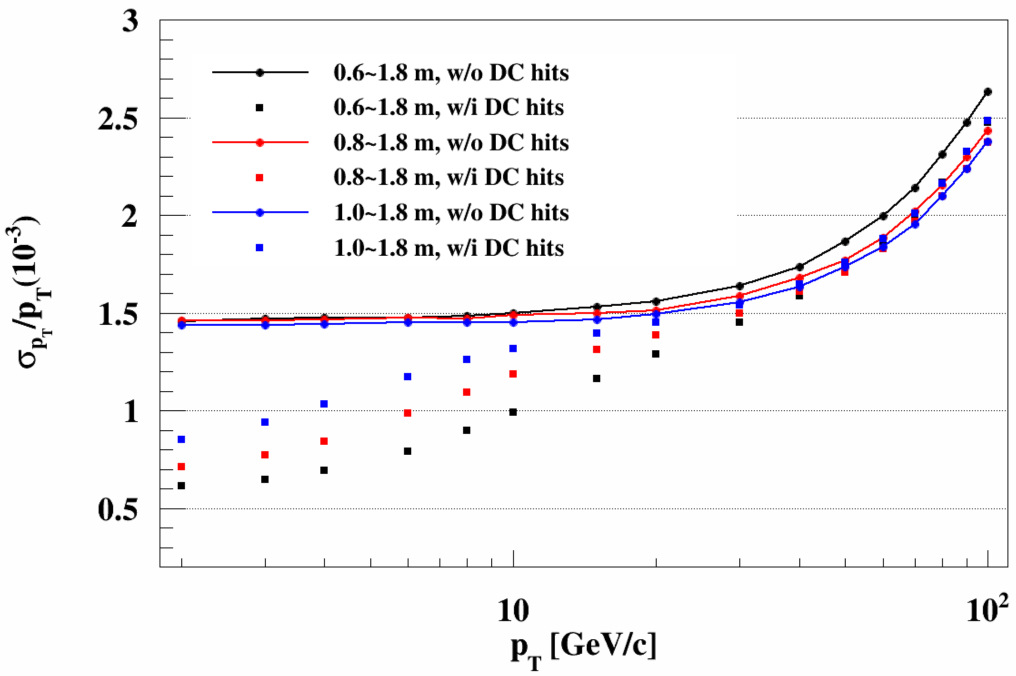
He 80% + iC_4H_{10} 20%, L = 1m, NR = 0.02, 1x1cm cell



- **He 90% + iC_4H_{10} 10% is better for high momentum**

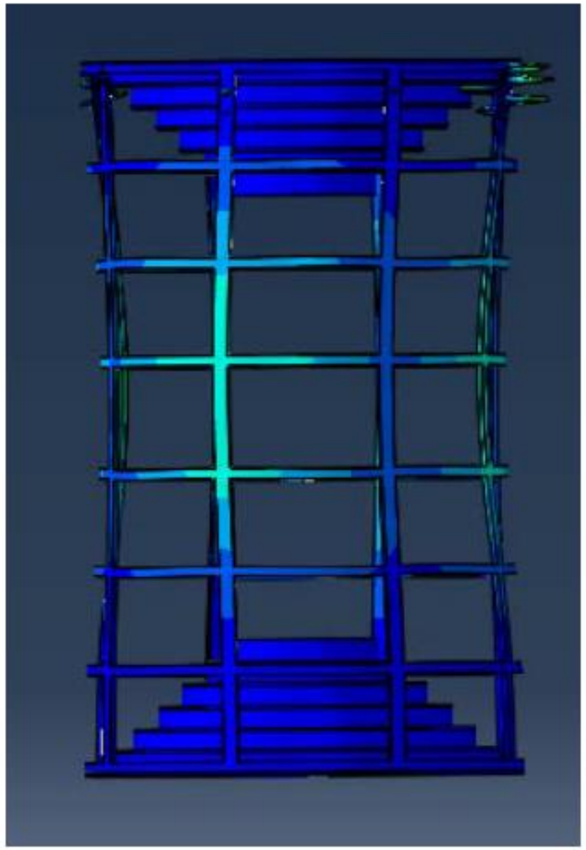
Inner radius



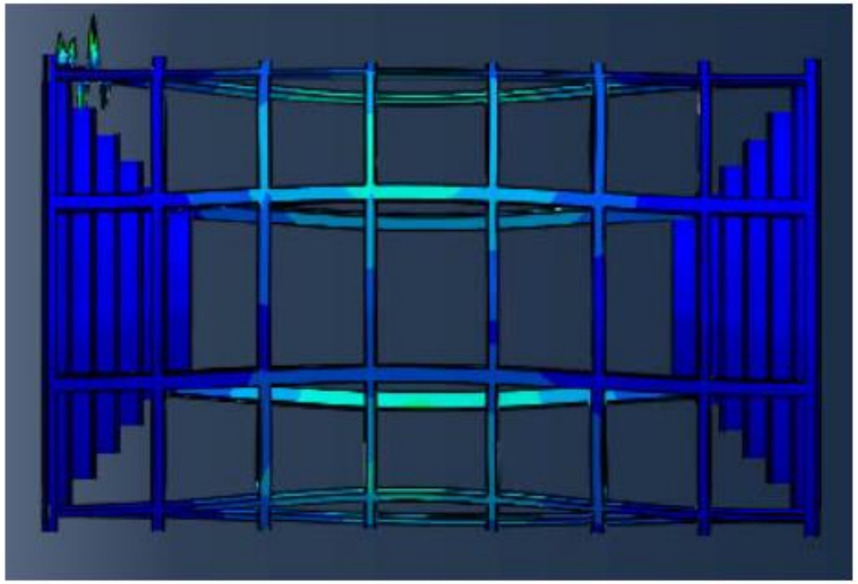


- Large thickness is better for PID ➔ From 2.8σ to 3.1σ even 3.3σ @ 20 GeV/c
- Smaller inner radius is better for tracking resolution, but more challenge on engineering and more beam backgrounds

Tensile load on support structures



竖直方向自重，
失稳系数~12



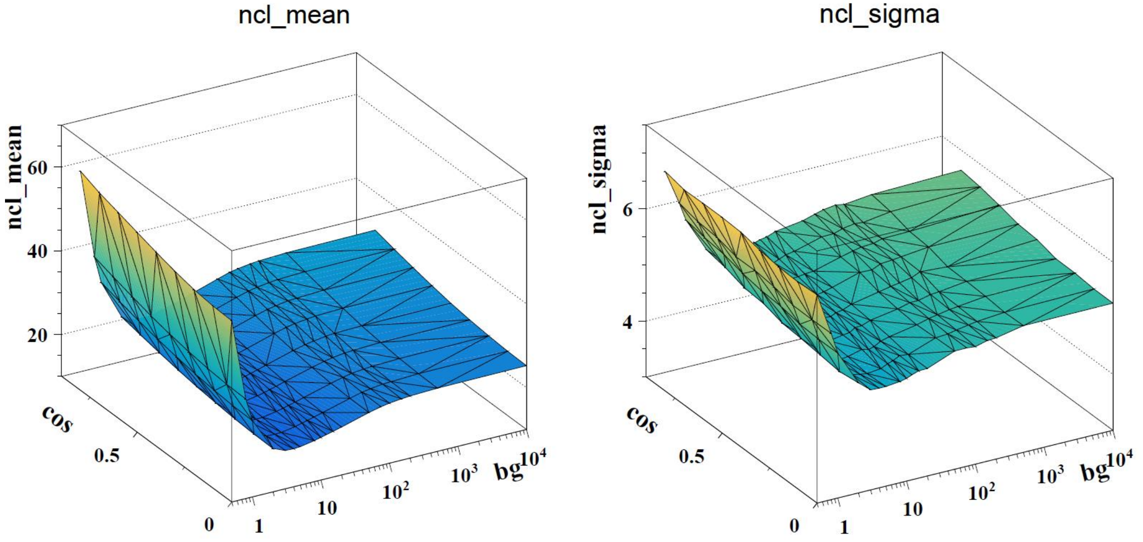
水平方向自重，
失稳系数~14

线性失稳就具有10倍以上
安全系数。

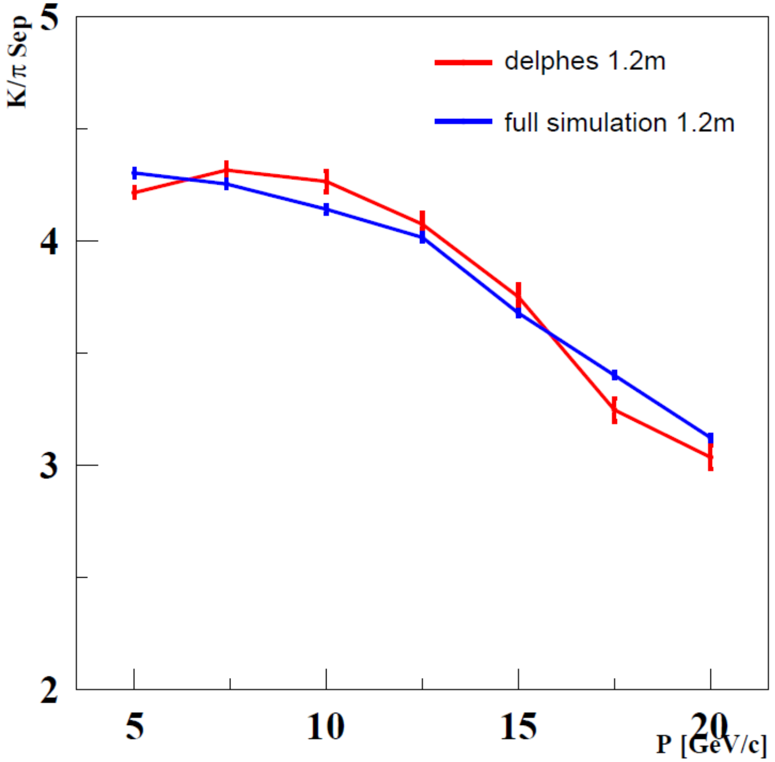
(buckling factor)

Physics study with Delphes

- **Delphes: A C++ framework, performing a fast multipurpose detector response simulation**
  - $10^2 \sim 10^3$ faster than the fully GEANT-based simulations
  - Sufficient and widely used for phenomenological studies
- **Develop dedicated PID modules (CC and TOF) and perform quick physics studies**



K/π separation power

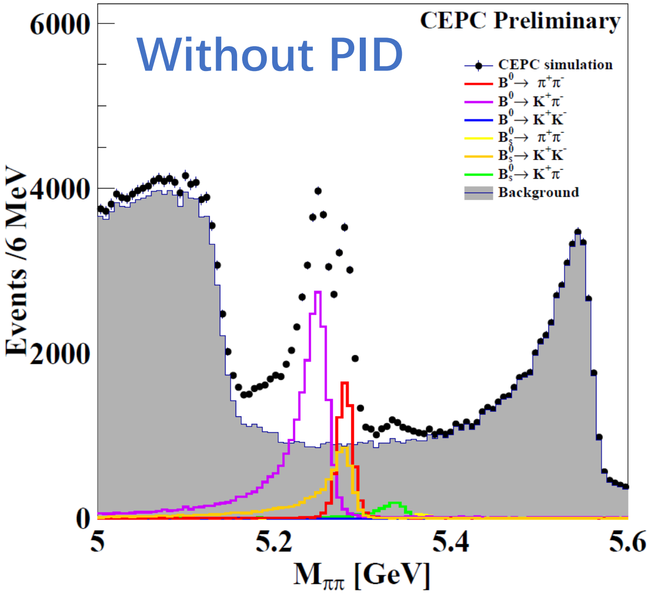


Good consistent to full simulation

Study of $\mathbf{B^0_{(s)} \to h^+h'^-}$

- **Motivation**
  - Rich physics programs in $\mathrm{B^0_{(s)} \to h^+h'^-}$ decays
    - Time-dependent asymmetry, direct CP violation, lifetime measurement, …
  - Good test bed to study impact of PID in flavor physics
  - Explore physics potential of Tera-Z

- Significantly improved SNR with PID
- More detailed studies ongoing



With PID