Drift Chamber with Cluster Counting for the CEPC 4th Concept

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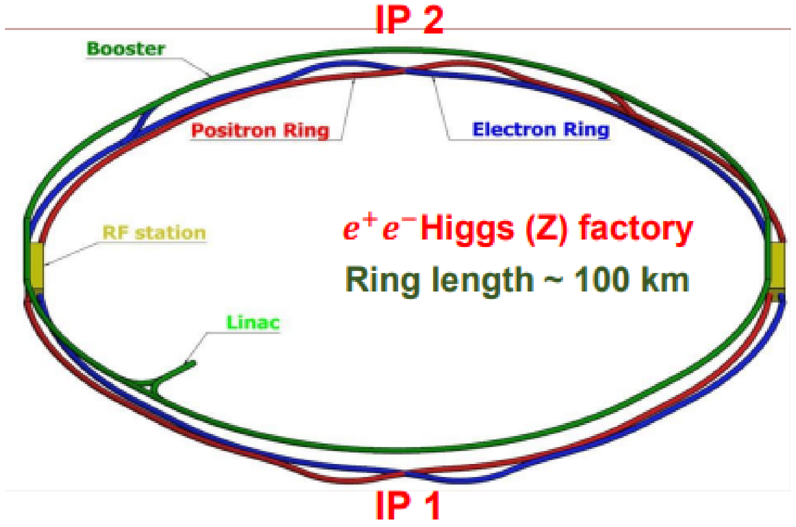
Outline

- **Part 1: Baseline simulation study**

- **Part 2: Recent feasibility studies**
  - Reconstruction algorithm with deep learning
  - Prototype experiment and mechanical studies
  - Physics study with Delphes

Physics programs 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	4.3×10^6
			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.

- 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.
  - …

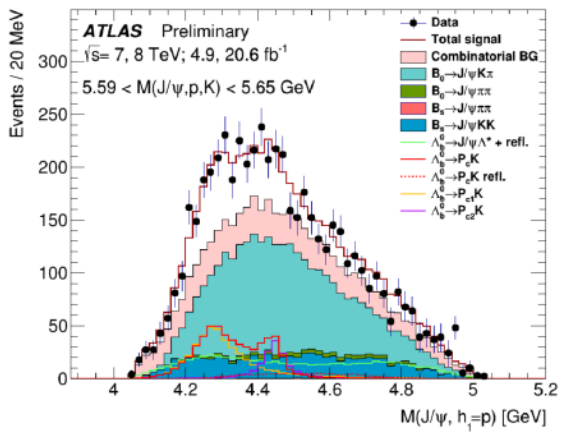
Particle identification

- **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
  - …

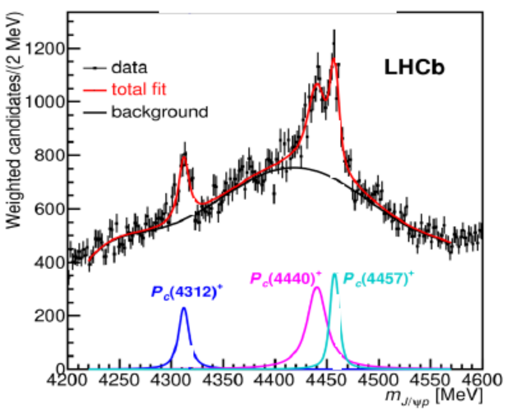
Pentaquark search in $\Lambda_b \to J/\Psi p K$

Without PID

[ATLAS-CONF-2019-048]

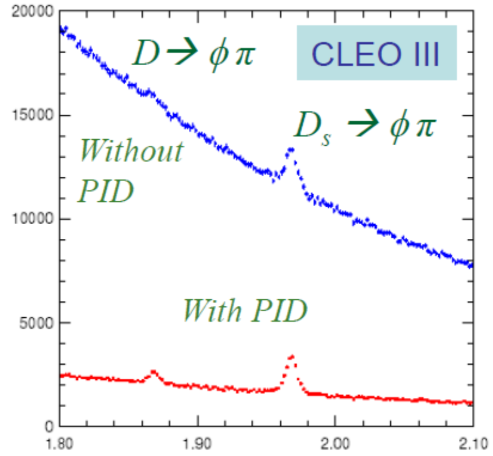


With PID ~ no background



[LHCb, PRL 122 (2019) 222001]

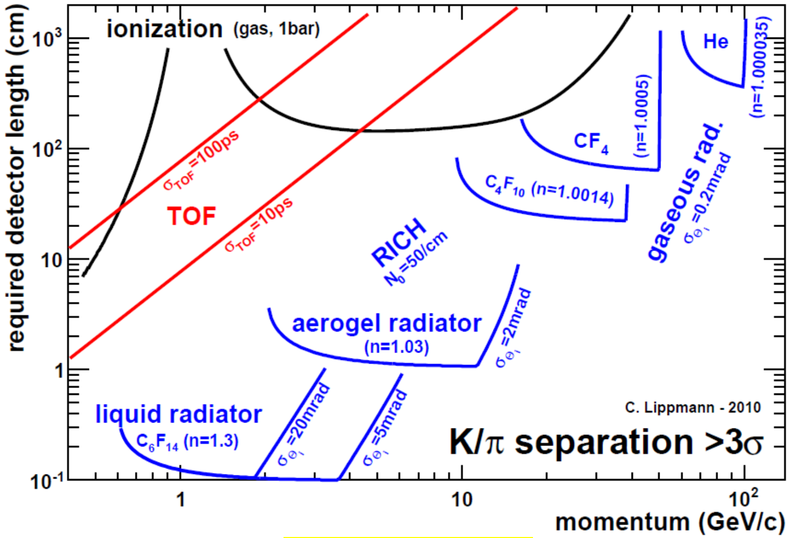
$D_{(s)} \to \phi\pi$



* Figures from Guy Wilkinson's slides

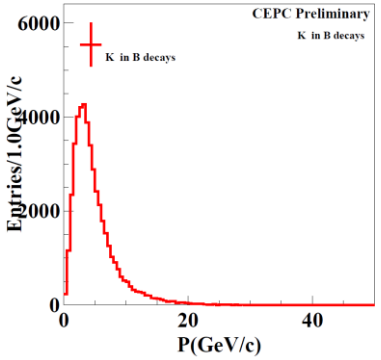
PID detector system

- **A gaseous tracking detector is favored because**
  - Additional to tracking, the gaseous detector can also provide PID with ionization measurement “for almost free”
  - The PID power of a gaseous detector can cover the hadron momenta range of interest for CEPC (< 20 GeV)
  - NOTE: There is always a “blind spot” at low momentum, which needs to be fixed by a supplementary timing detector
- **Proposed PID detectors: DC + thin supplementary ToF**

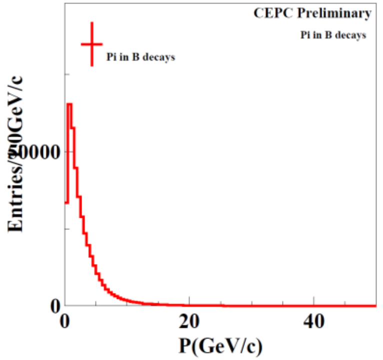


arXiv:1101.3276v4

K in B decays

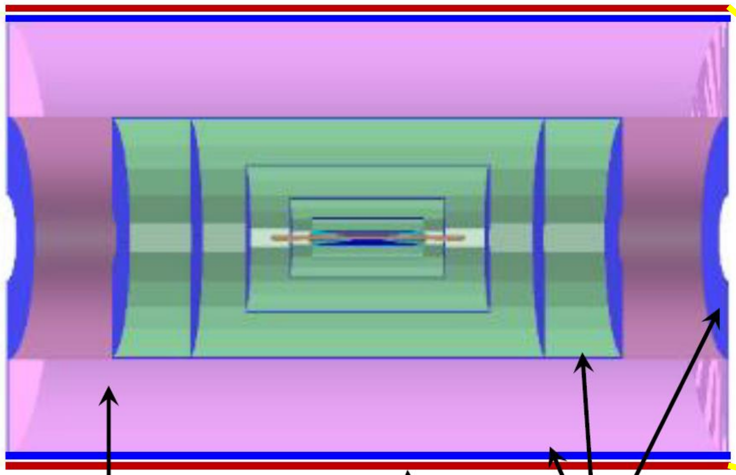


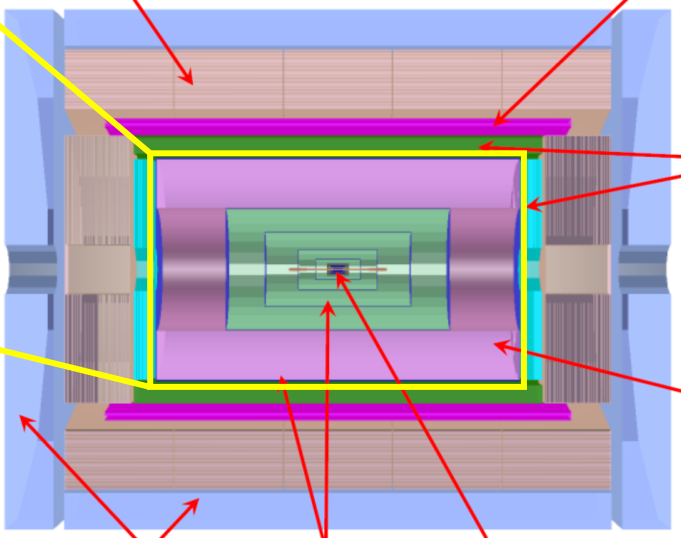
π in B decays



Most K/pi momentum < 20 GeV/c

CEPC 4th concept detector



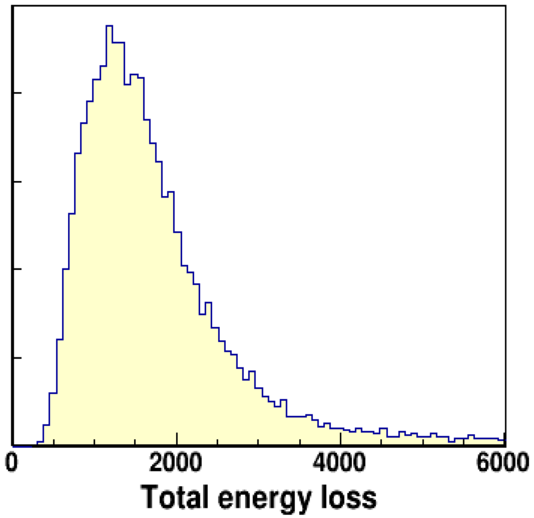


Preliminary PID requirement: >2σ K/π separation for 20 GeV/c tracks

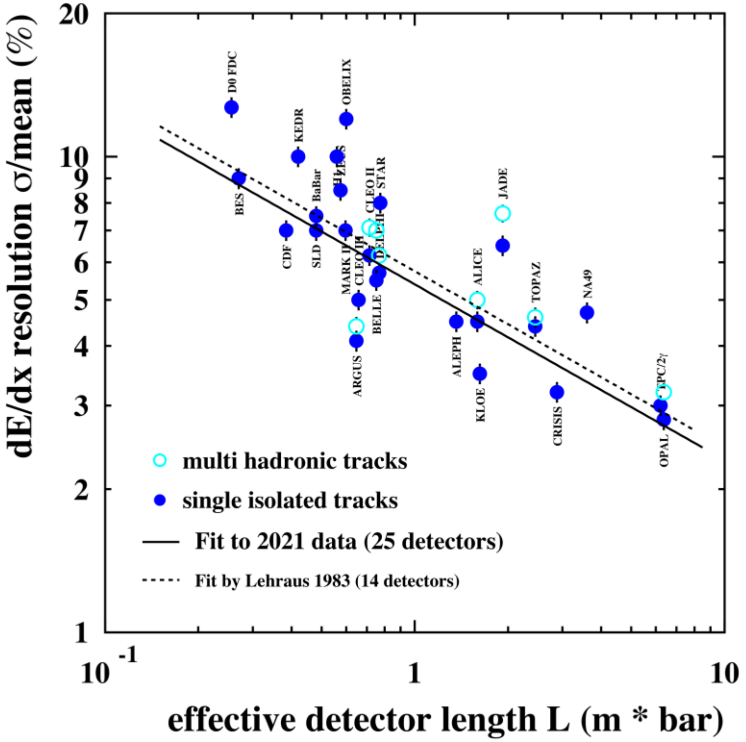
Energy loss measurement: dE/dx

- 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*



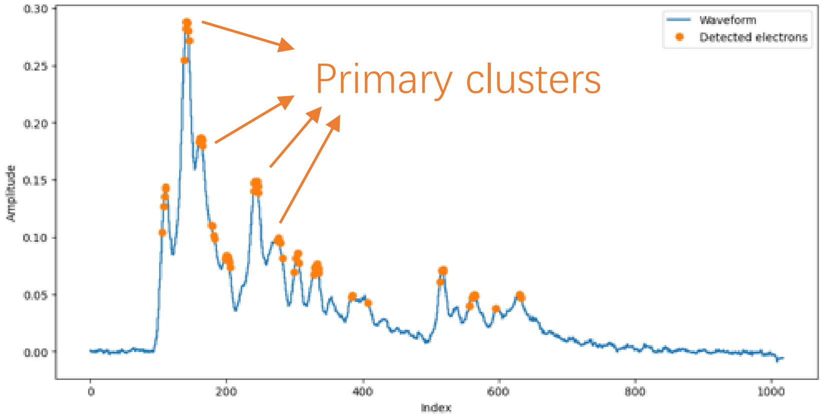
- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** $* L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** $* L^{-0.37}$ (%)
- **No significant improvement in the past 40 years**

* From Michael Hauschild's talk @ RD51 workshop

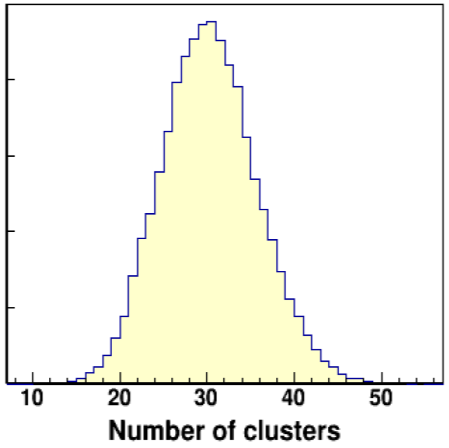
Cluster counting measurement: dN/dx

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

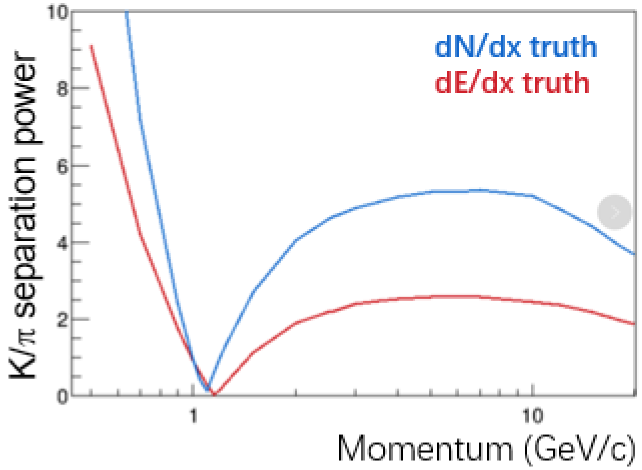
Waveform



Counting clusters



K/π separation power
dN/dx vs dE/dx



Require fast electronics and sophisticated counting algorithm

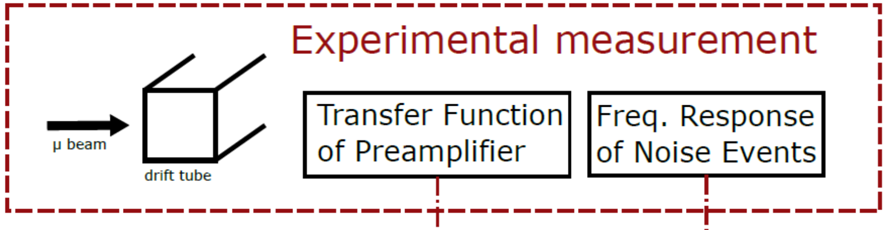
CC is extremely powerful, proposed in ILC, FCC-ee, CEPC

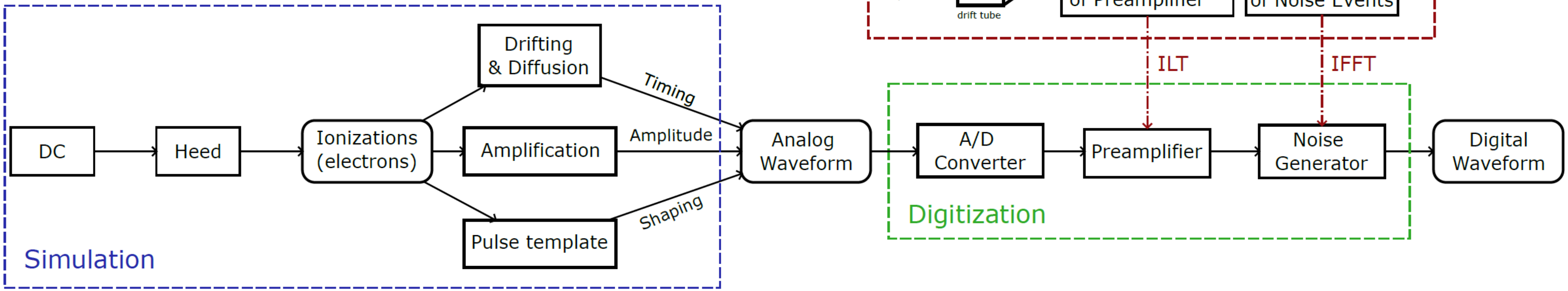
Baseline simulation study

PID, tracking and mechanicals

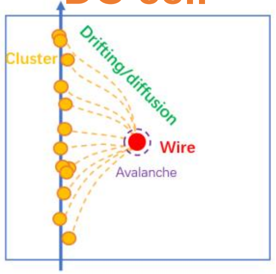
Waveform-based full simulation

Develop sophisticated software tools for DC PID simulation

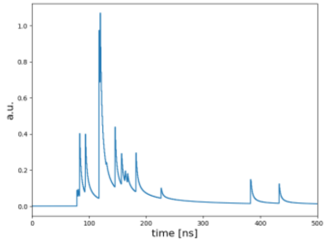




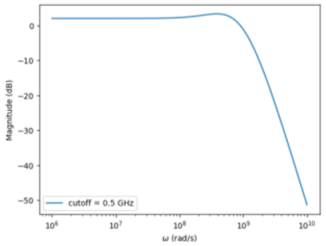
DC cell



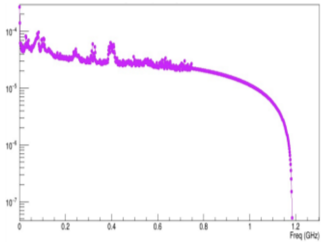
Induced signal



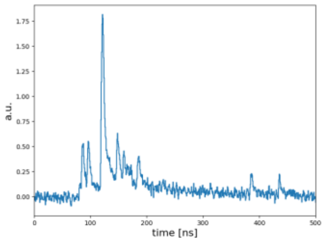
Preamplifier



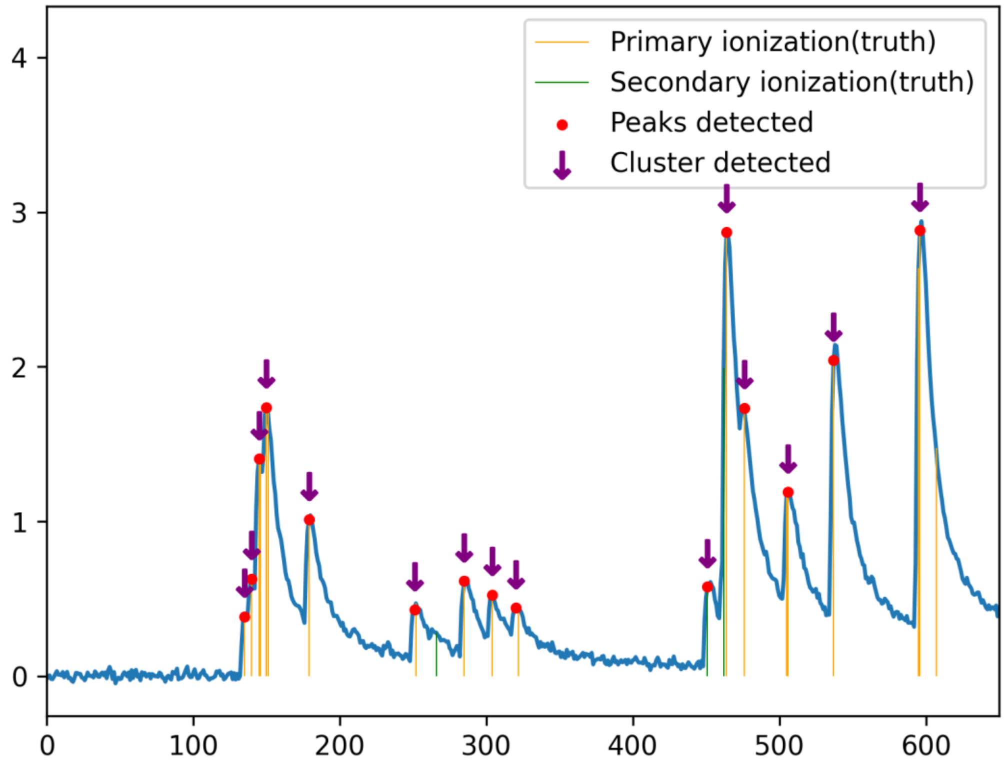
Noise



Waveform



Reconstruction algorithm



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

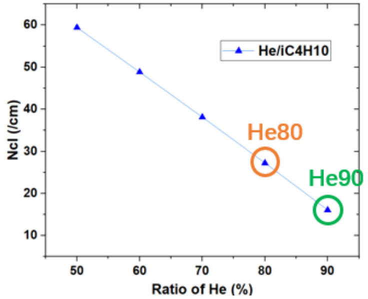
Optimization

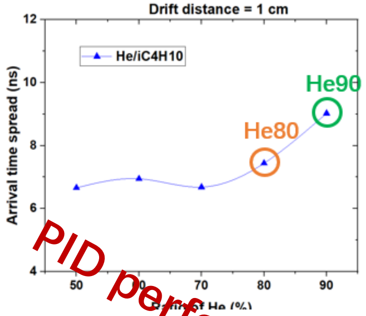
- **Figure of merit**
  - PID performance: K/pi separation power $n = |\mu_\pi - \mu_K| / (\sigma_\pi + \sigma_K) x2$ (Waveform sim.)
  - Tracking resolution: $\sigma(1/p_t)$, $\sigma(d_0)$ (Fast tracking)
  - Mechanical stability (FEM)

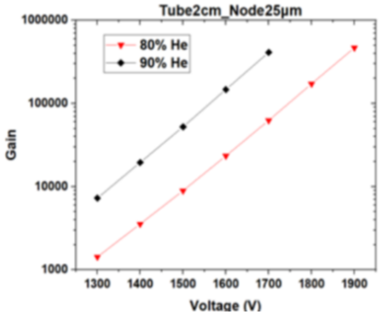
- **Parameters**
  - Gas mixture
  - Cell size
  - Detector thickness
  - Mechanical structures

Optimization (cont.)

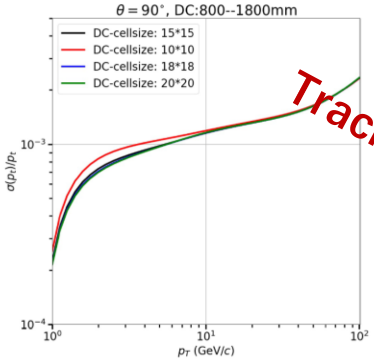
- Gas mixture choice: He + C_4H_{10}

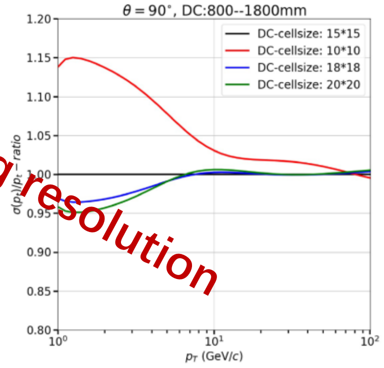






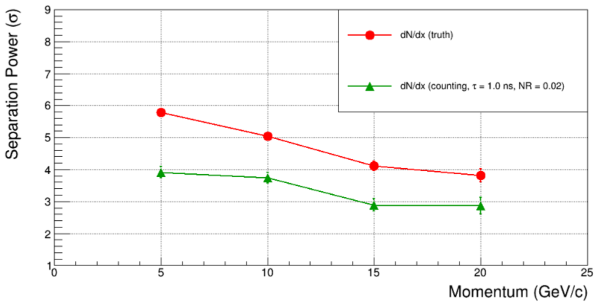
PID performance



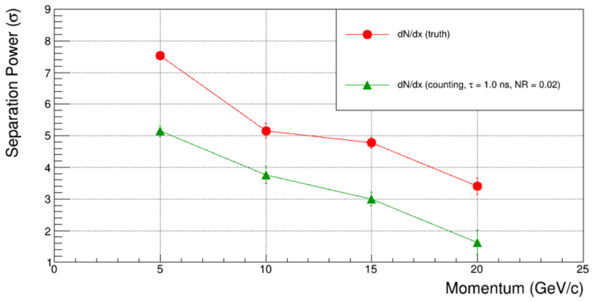


Tracking resolution

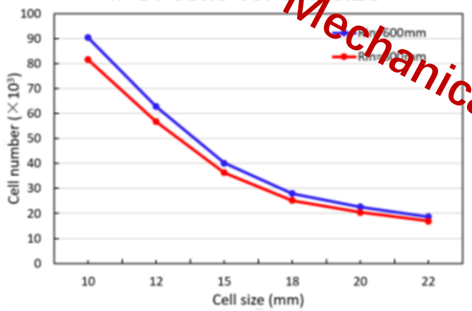
He 90% + iC_4H_{10} 10%, L = 1m, NR = 0.02， 1x1cm cell



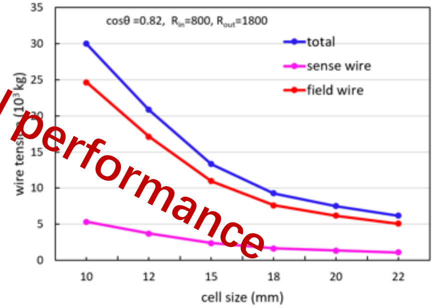
He 80% + iC_4H_{10} 20%, L = 1m, NR = 0.02, 1x1cm cell



\# of cells vs. cell size



wire tension vs. cell size

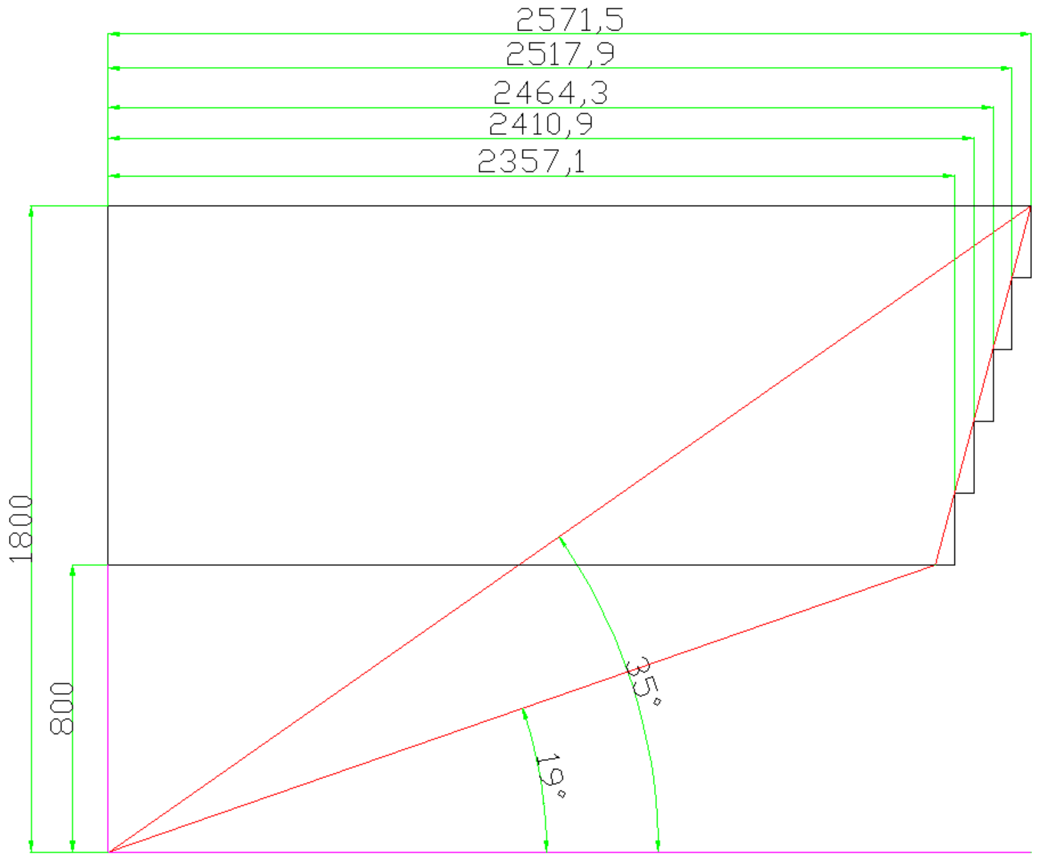


Mechanical performance

DC baseline design

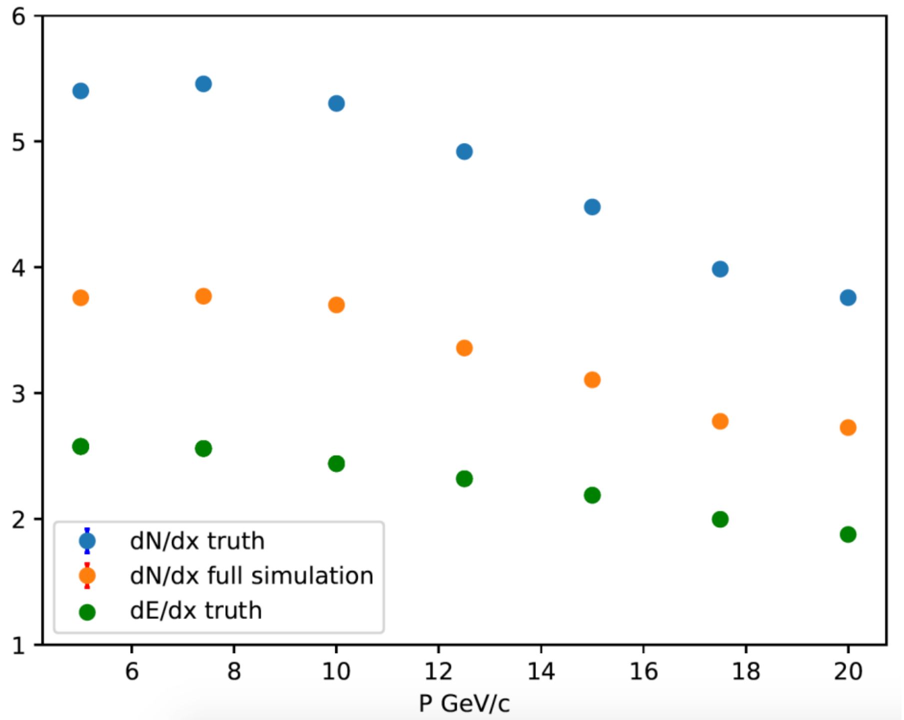
Optimized DC Parameters

DC 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/iC_4H_{10}=90:10

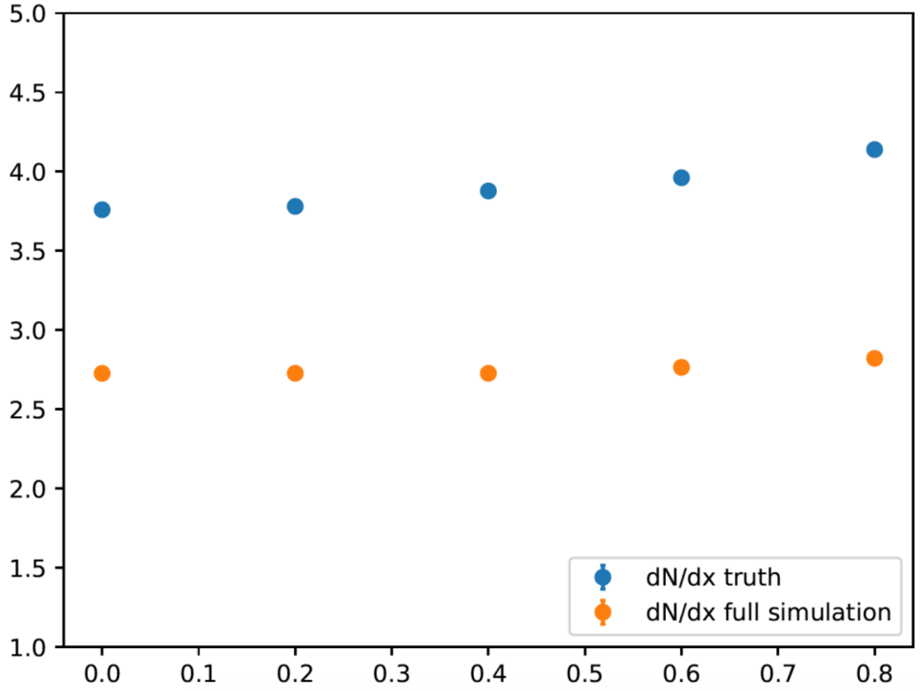


PID performance

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)

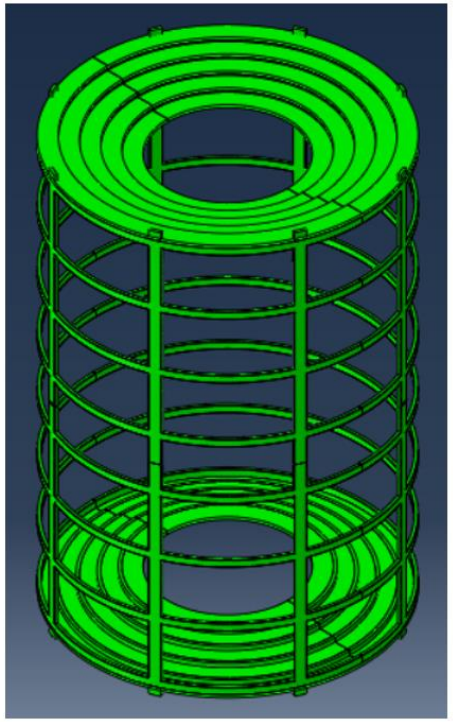
Mechanicals: Wire tension

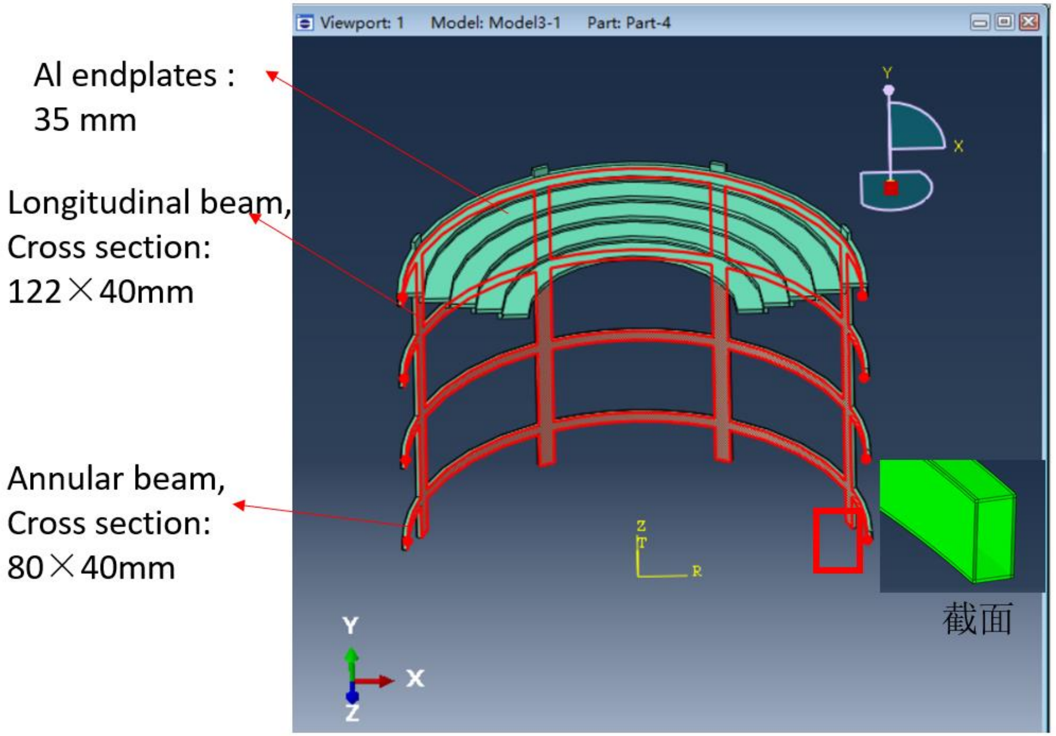
- ✓ Diameter of field wire (Al coated with Au) : 60 µm
- ✓ Diameter of sense wire (W coated with Au): 20 µm
- ✓ Sag = 280 µm

Step	cell number /step	length	single sense wire tension (g)	Single field wire tension (g)	total tension /step (kg)
1	3417	4715	60.15	92.42	1153.08
2	4185	4822	62.91	96.66	1477.02
3	4953	4929	65.74	101.00	1826.47
4	5721	5036	68.62	105.44	2202.24
5	6489	5143	71.57	109.96	2605.11
total	**24766**				**9263.92**

Meet requirements of stability condition: $T > (\frac{VLC}{d})^2/(4\pi\varepsilon_0)$

Mechanicals: Support structures





- Carbon fiber frame structure, including 8 longitudinal hollow beams and 8 annular hollow beams
- Thickness of inner CF cylinder: 200 μm/layer
- Effective outer CF frame structure: 1.63 mm
- Thickness of end Al plate: 35 mm

- **Mises stress: 70 MPa**
- **Principal stress: 33 Mpa**
- **Deformation: 0.8 mm**
- **Buckling coefficient: 17.2**

Mechanicals are generally stable

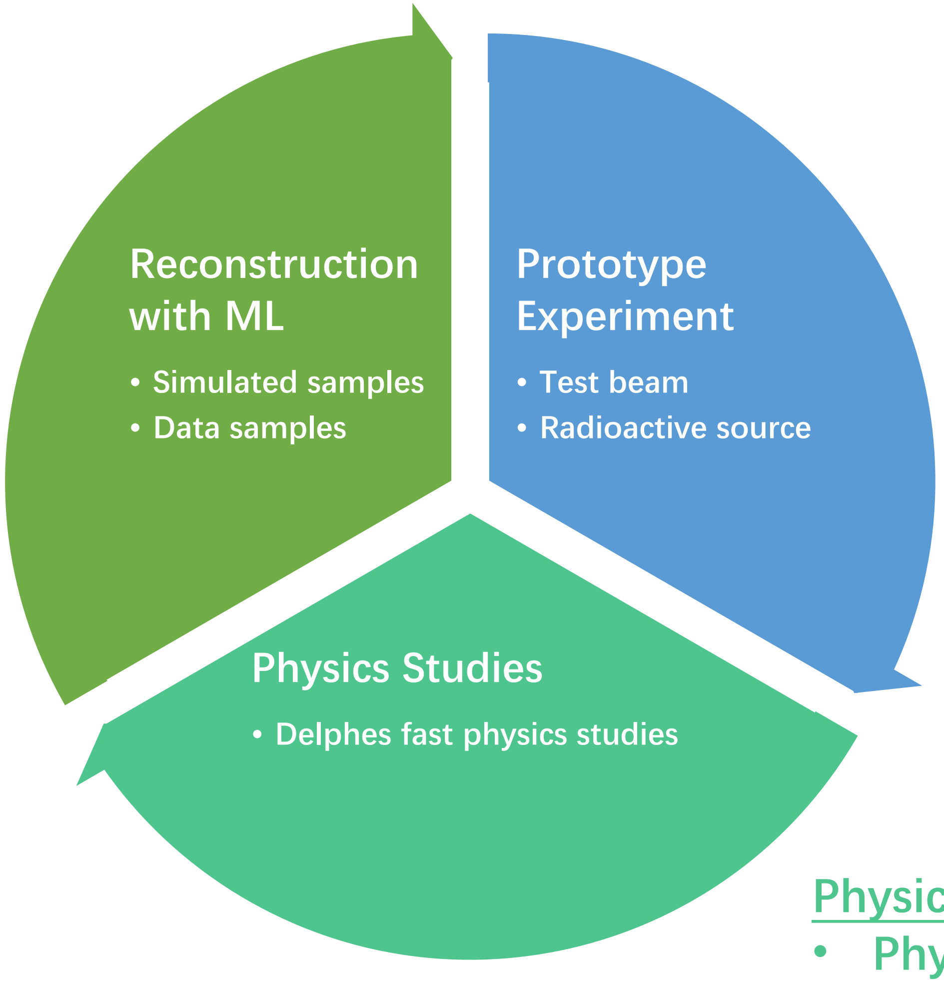
Recent feasibility studies

ML reconstruction, prototype experiments and physics studies

Recent 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

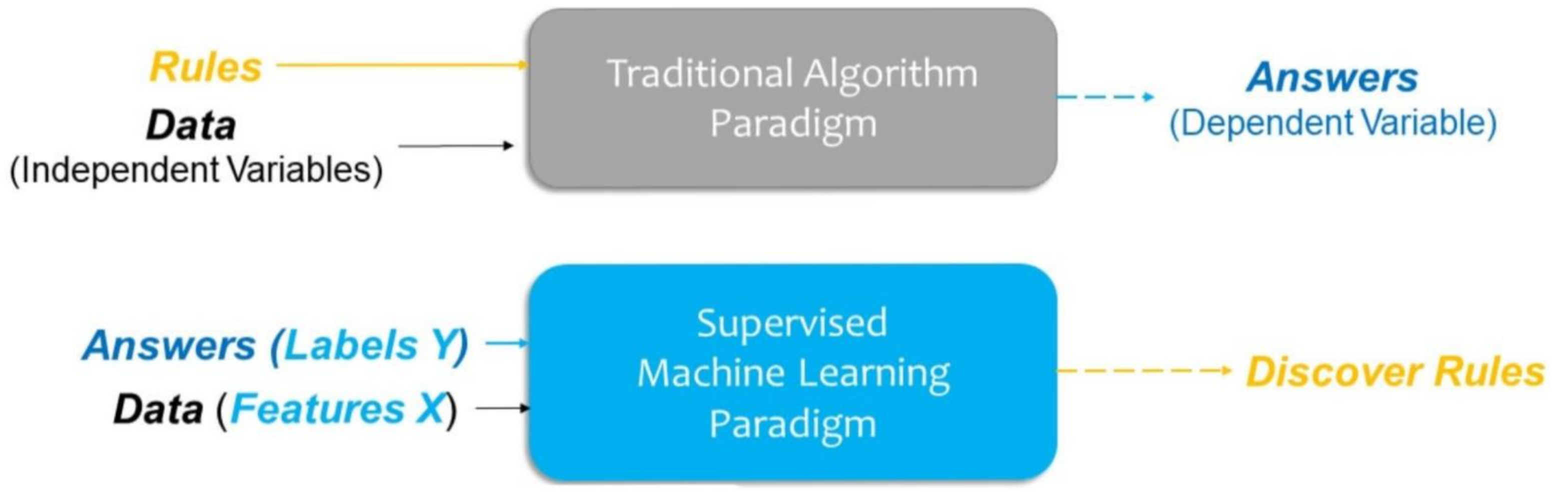


Physics performances:
- Physics benchmarks to evaluate CC technique

Reconstruction algorithm with ML

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

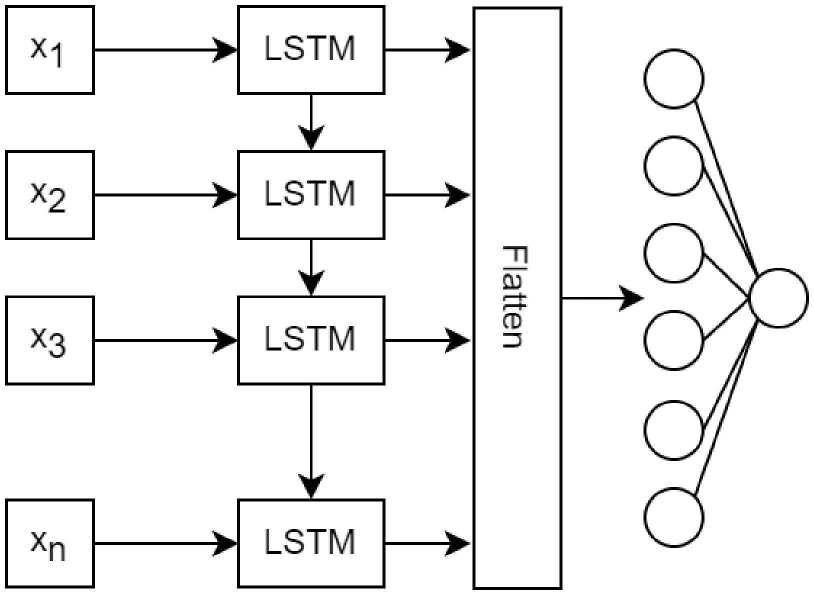
- **Supervised learning could be more powerful** because
  - make full use of the waveform information
  - automatically learn characteristics of signals and noises from large labeled samples



Supervised model for simulated samples

Peak finding with LSTM

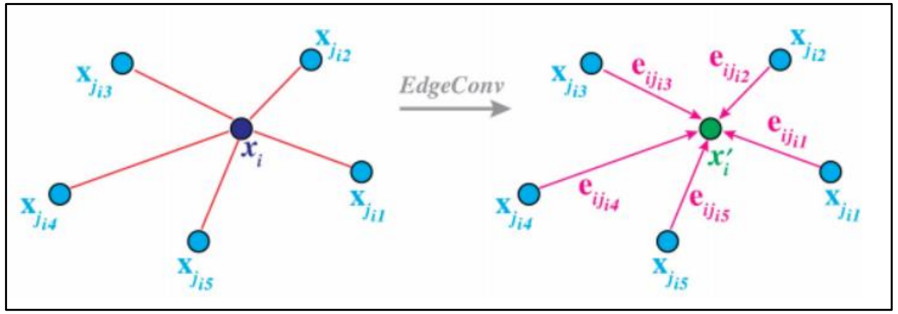
Why LSTM? ➔ Waveforms are time series



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

Clusterization with DGCNN

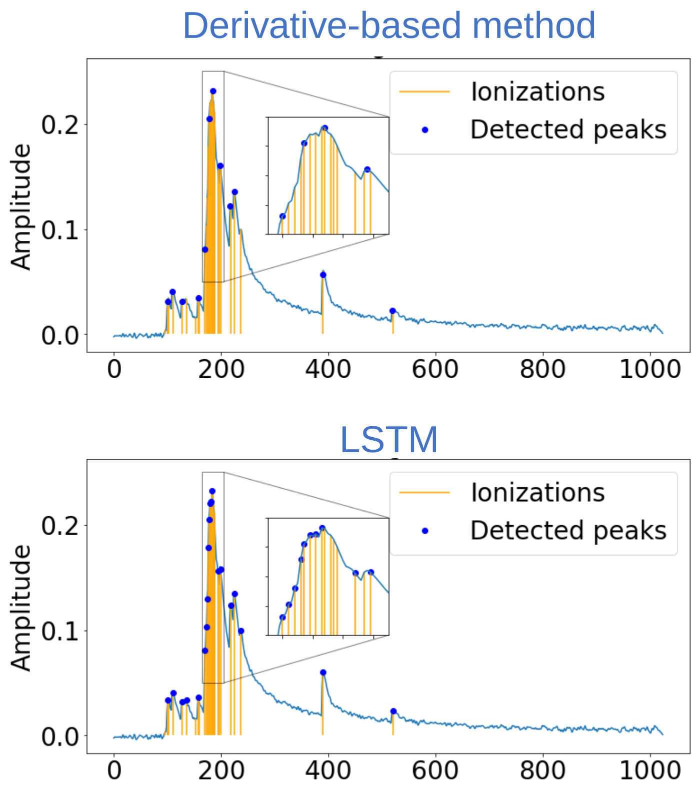
Why DGCNN? ➔ Locality of the electrons from the same primary cluster, perform massage passing through neighbor nodes in GNN

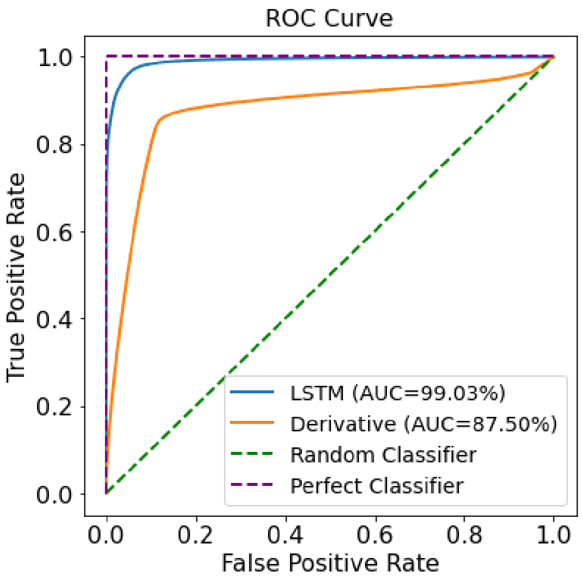


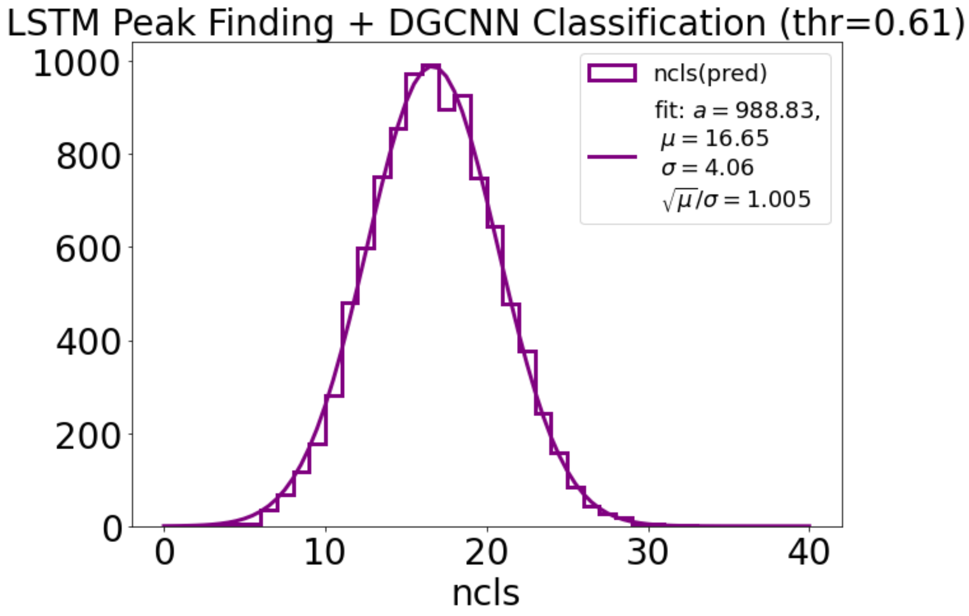
arXiv: 1801.07829

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

Reconstruction results



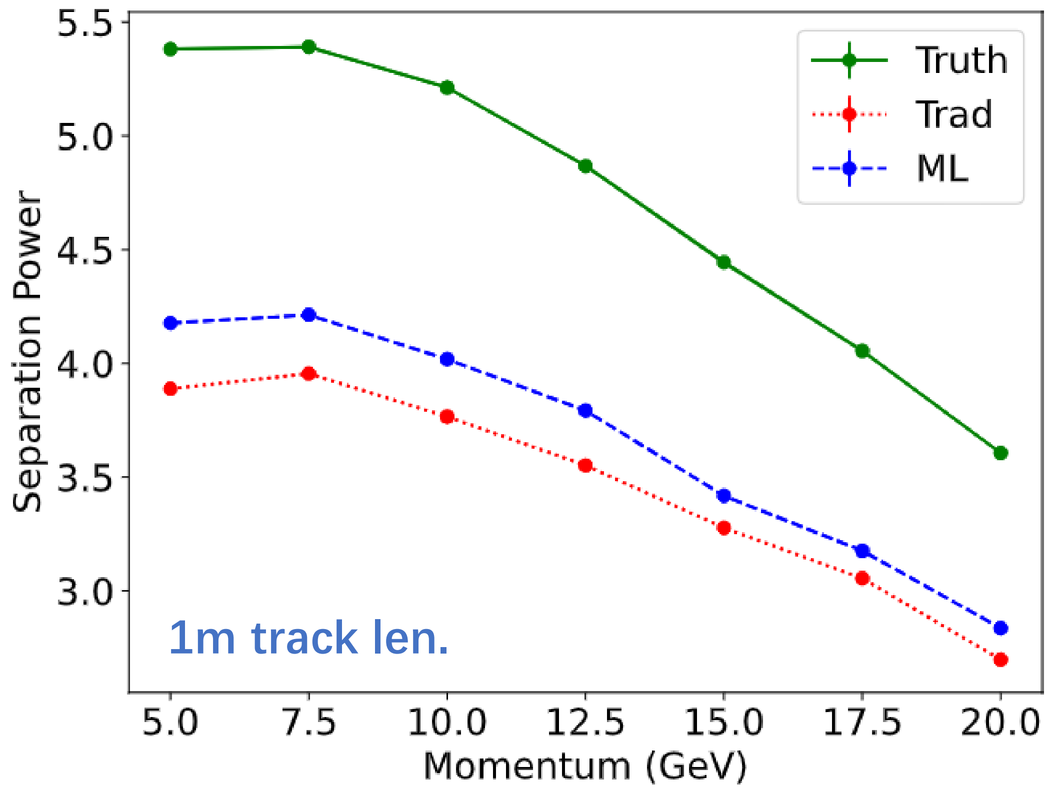




Peak finding: ML is better than derivative-based method

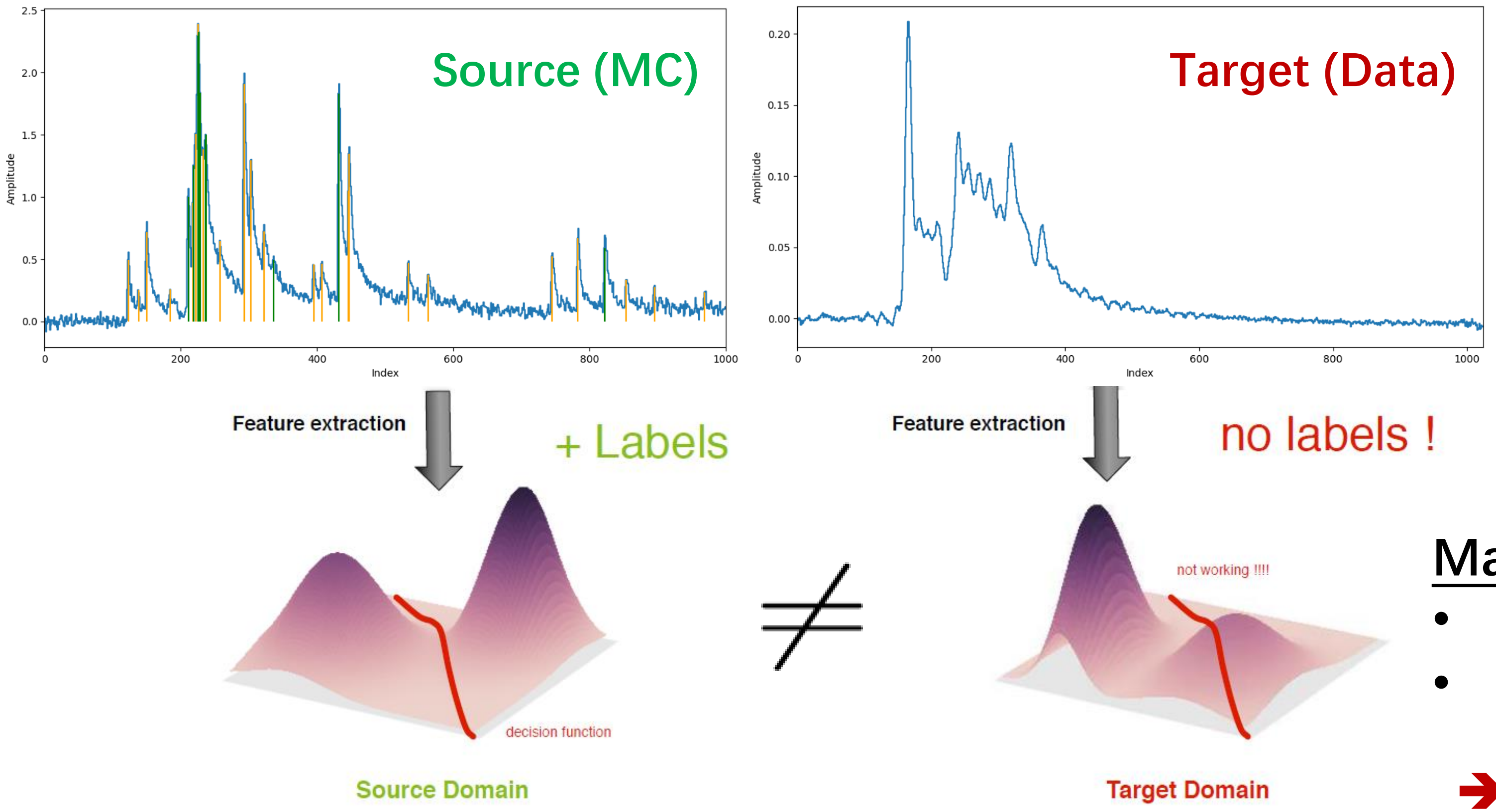
Peak finding + Clusterization: Very well Poisson-like distribution

PID performances with supervised models



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

Challenge of ML algorithm on experimental data samples

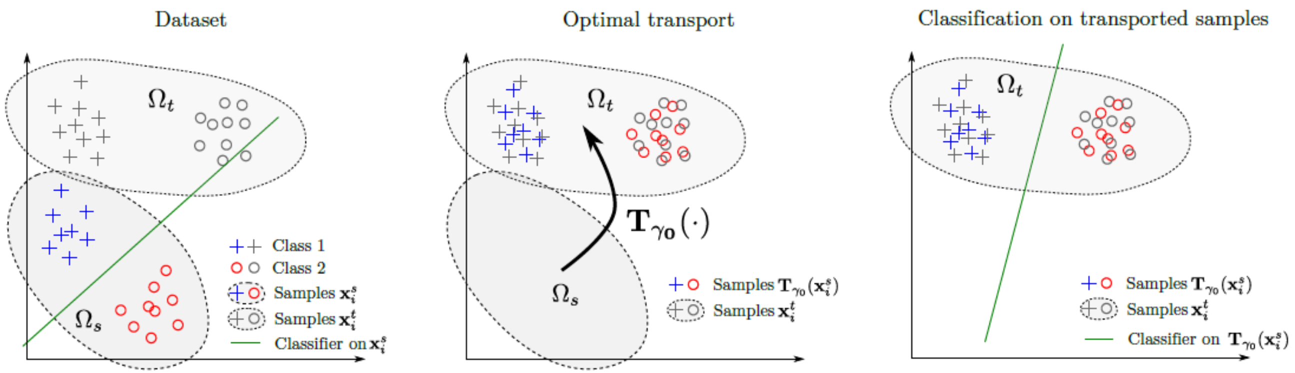


Main challenges:

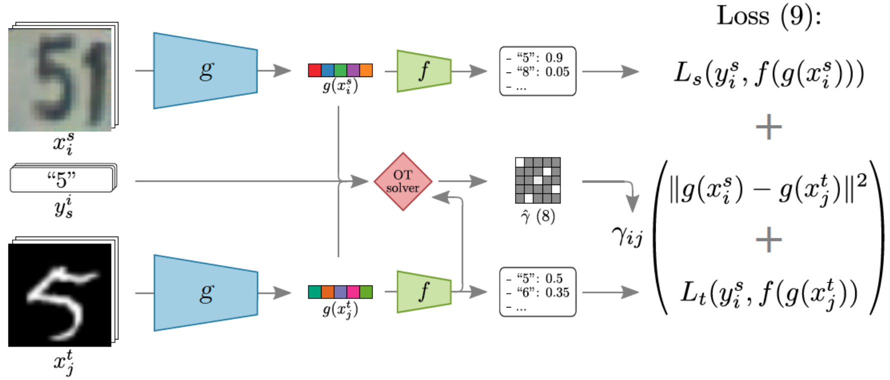
- Discrepancies between data and MC
- Lack of labels in experimental data

➔ **Cannot directly apply the supervised model trained by simulated samples**

Semi-supervised domain adaptation



Align data/MC samples with Optimal Transport



Original work by Damodaran, et al. (arXiv: 1803.10081)

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)

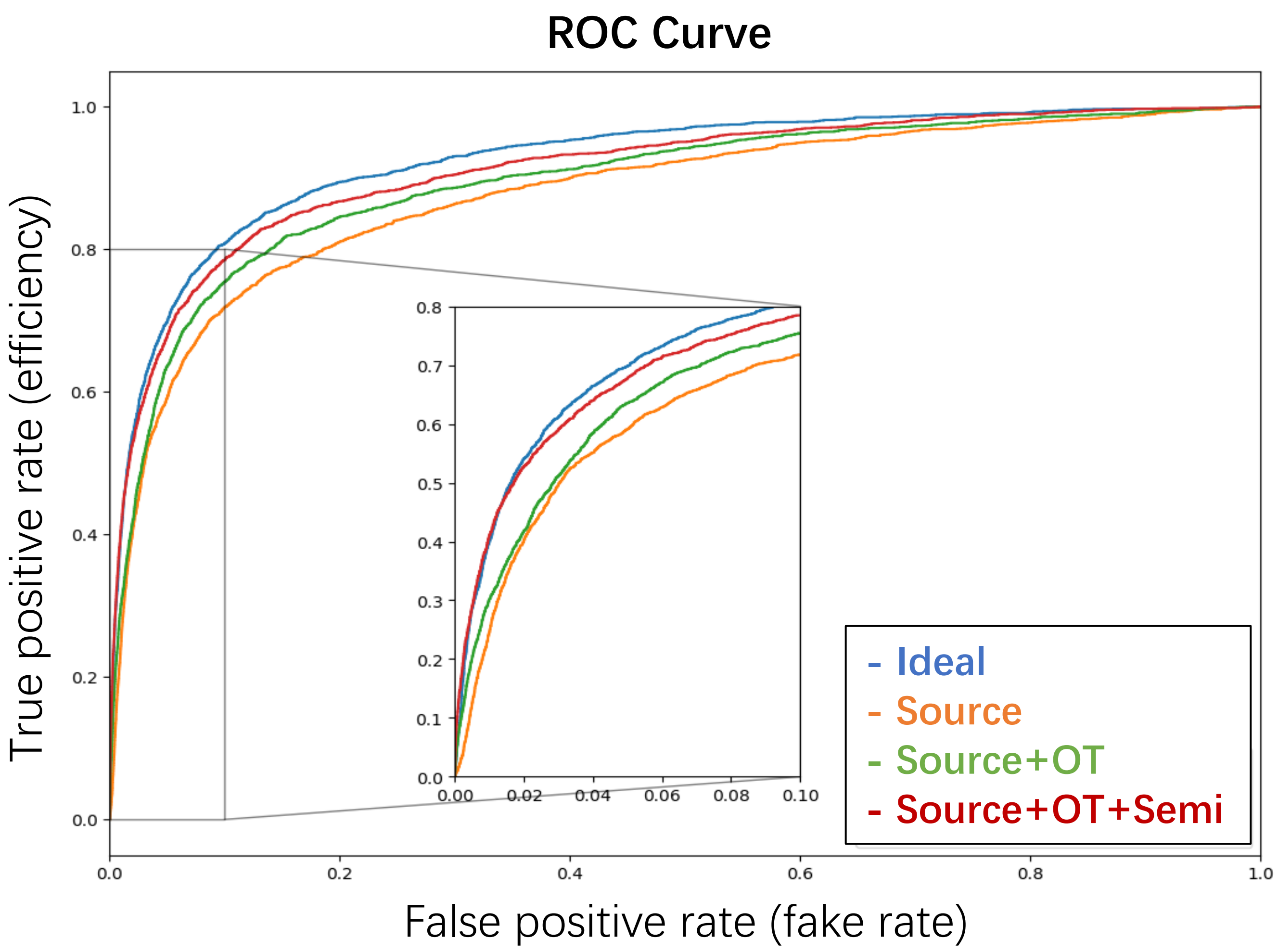
Cost of feature differences between source and target

Cost of ‘label’ differences between source and target

Cost of joint feature-label distribution for OT

Semi-supervised implementation in our work

Numeric experiment



Numeric experiment with pseudo data:

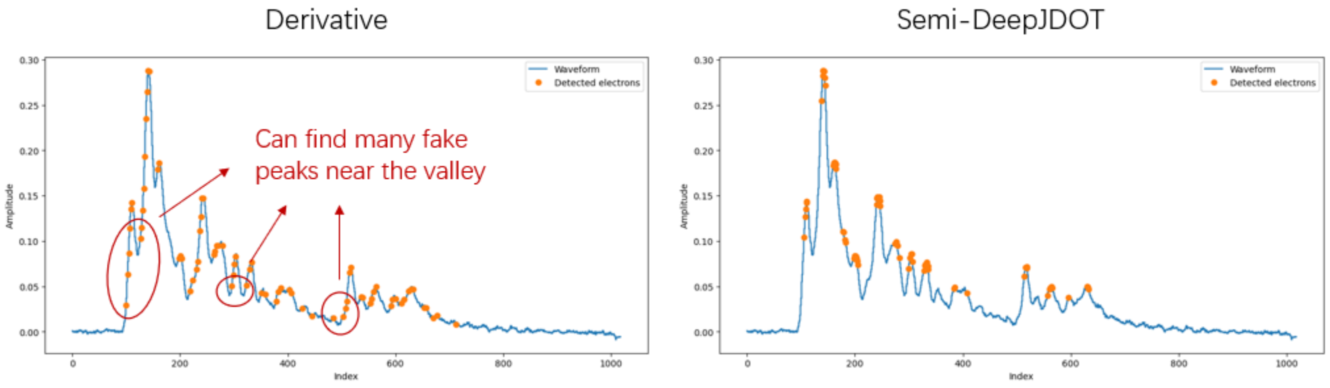
- Use labels in pseudo data to evaluate

Model	AUC	pAUC (FPR<0.1)
Ideal (supervised)	0.926	0.812
Source (baseline)	0.878	0.749
Source + OT	0.895	0.769
Source + OT + Semi (Semi-supervised DA)	0.912	0.793

Validation: Performance of Semi-DeepJDOT model is very close to the ideal model (supervised model)

Peak finding for test beam data

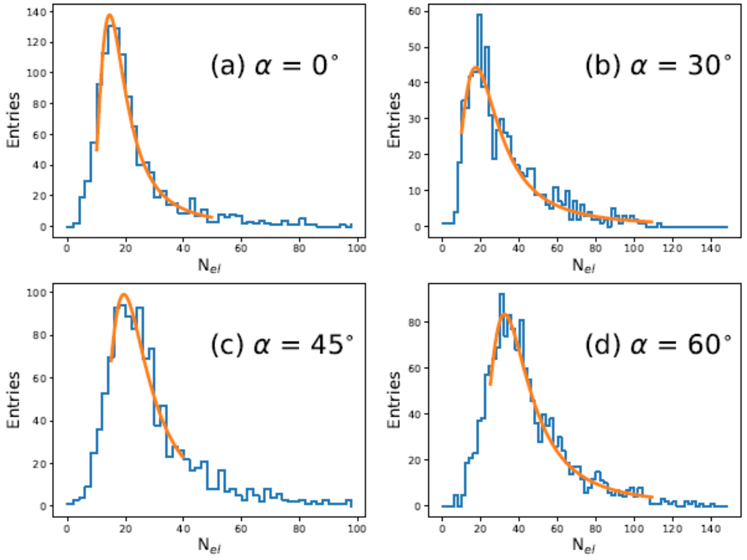
Single-waveform results between derivative alg. and DL alg.

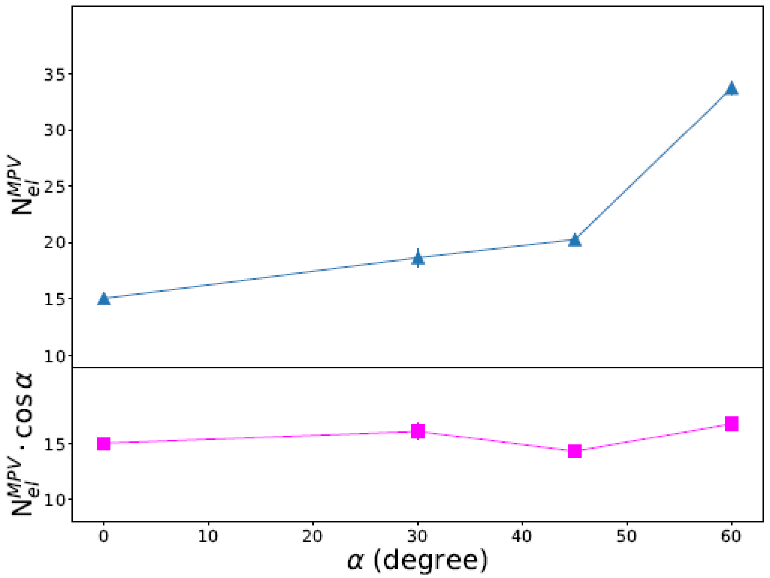


Note: Require similar efficiency for both cases

DL algorithm is more powerful to discriminate signals and noises

Multi-waveform results for samples in different angles





Scale w.r.t. track length

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

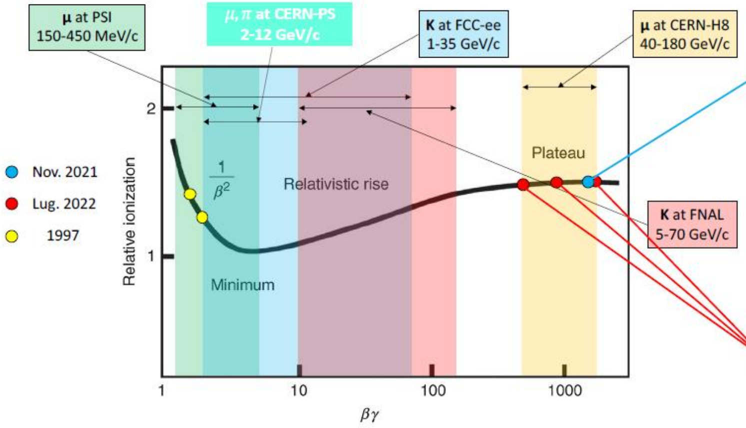
Prototype experiment with test beam

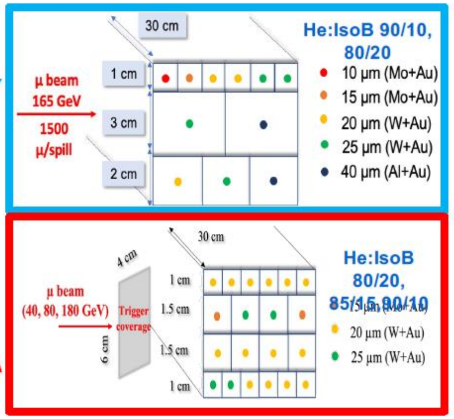
Beam tests organized by INFN group:

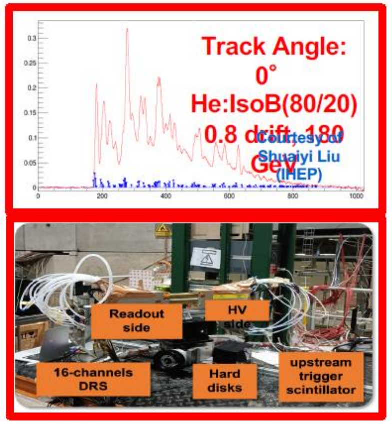
- Two muon beam tests performed at CERN-H8 (βγ>400) in Nov. 2021 and July 2022.
- A muon beam test (from 4 to 12 GeV/c) in 2023 performed at CERN.
- Ultimate test at FNAL-MT6 in 2024 with π and K (βγ = 10-14) to fully exploit the relativistic rise.

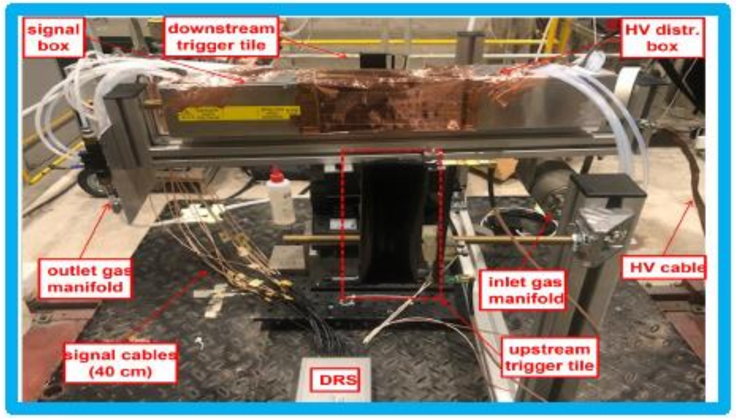
Contributions from IHEP group:

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





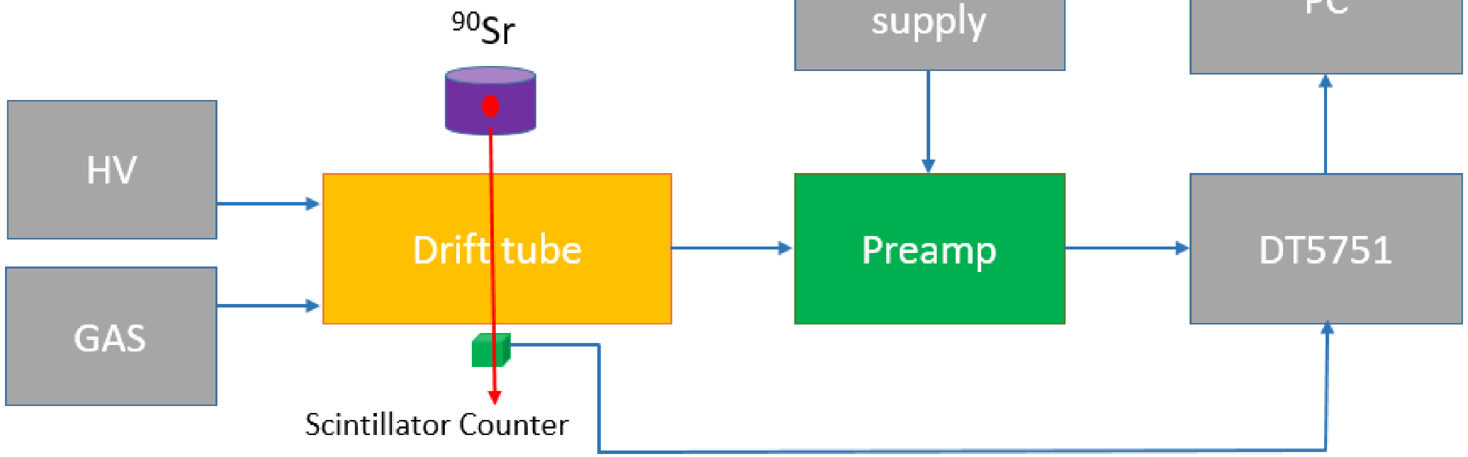




See Nicola De Filippis's talk at the CEPC Workshop for details

Prototype experiment with radioactive source

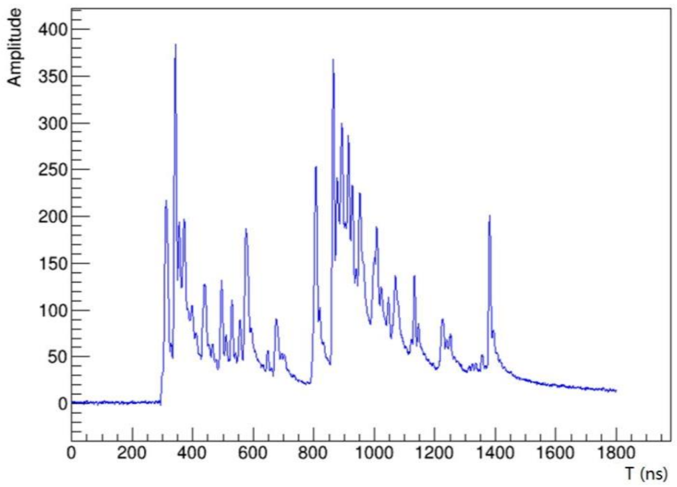
Experiment layout



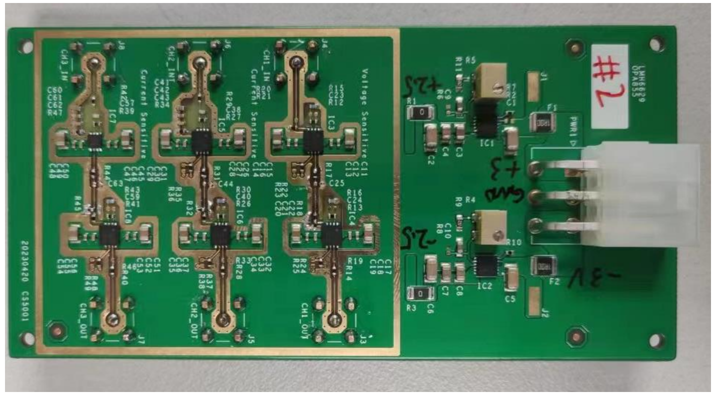
- Diameter of the tube: 30 mm
- Working gas: He/iC_4H_{10}=90:10

See Mingyi's talk

Waveform with Sr-90 β source



Preamplifier

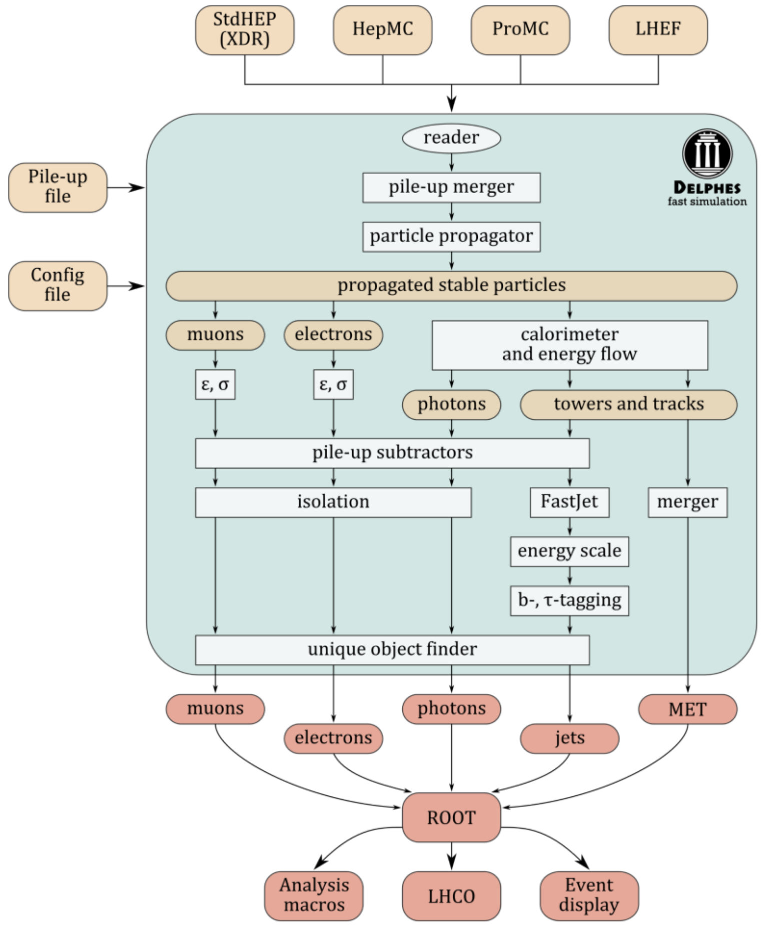


- Bandwidth ~1GHz
- ADC sampling rate 1GHz

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

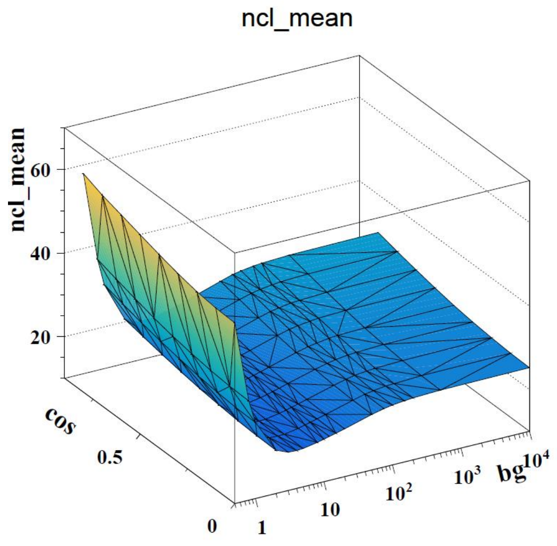
- **Develop dedicated PID modules (dN/dx and TOF) and perform quick physics studies**

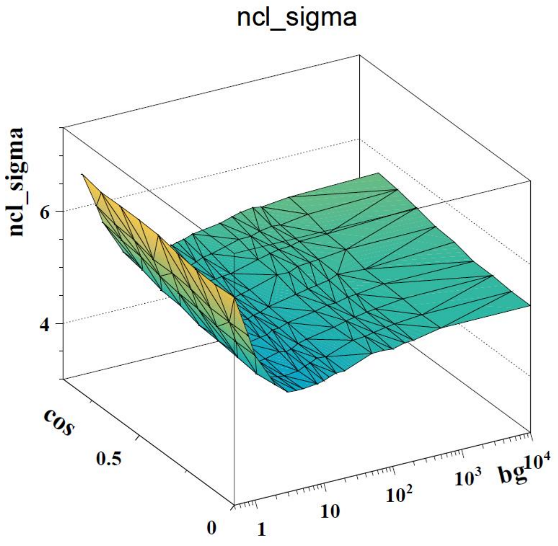


J. High Energ. Phys. **2014**, 57 (2014)

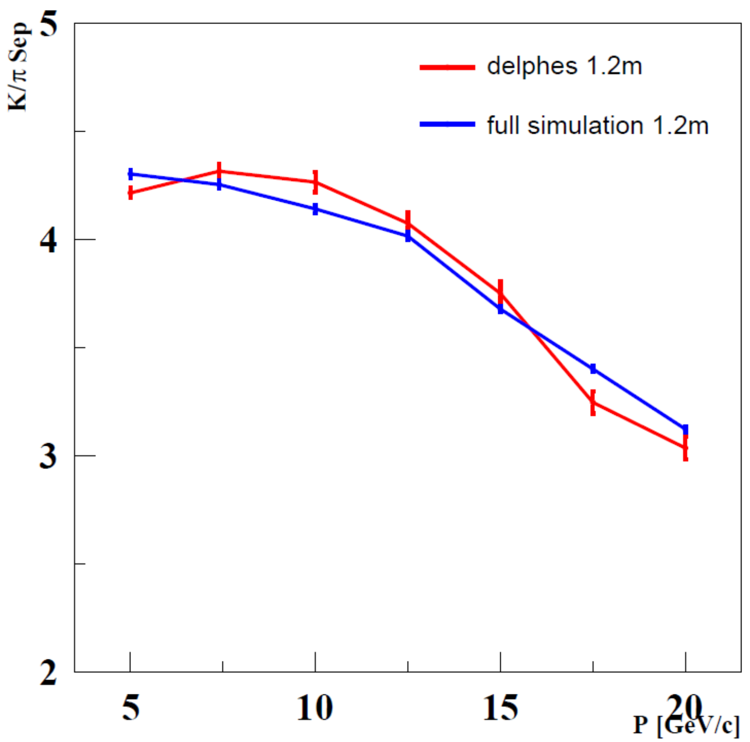
PID modules implementation

- **dN/dx parameterization from full simulation**
  - dN/dx_{mean} vs. $\beta\gamma$ and $\cos\theta$
  - dN/dx_{sigma} vs. $\beta\gamma$ and $\cos\theta$
- **TOF parameterization by assuming a resolution of 30 ps**





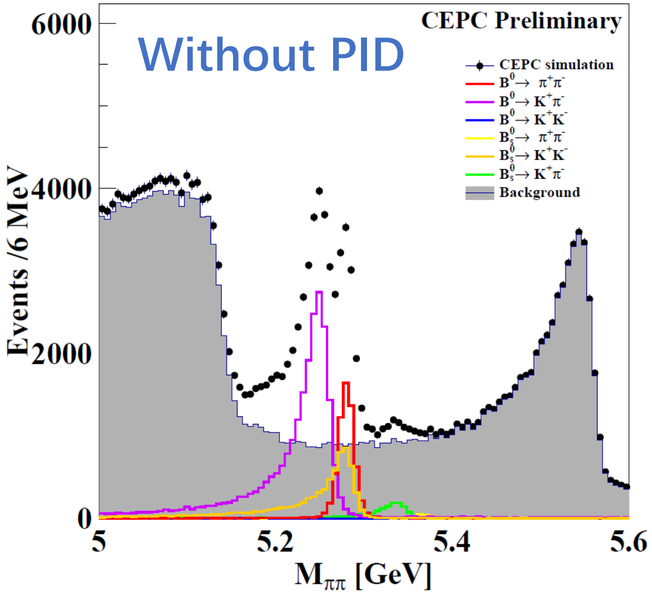
K/π separation power



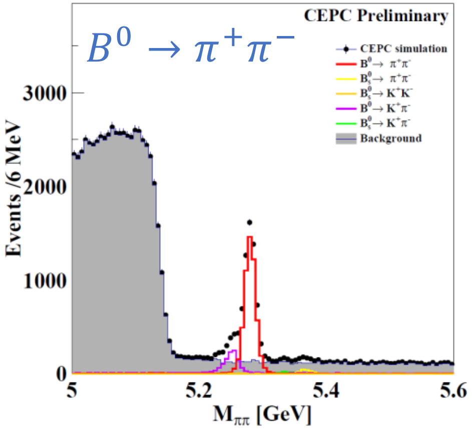
Good consistent to full simulation

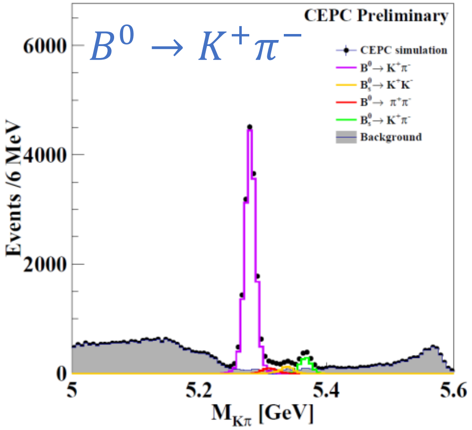
Study of $\mathbf{B^0_{(s)} \to h^+h'^-}$

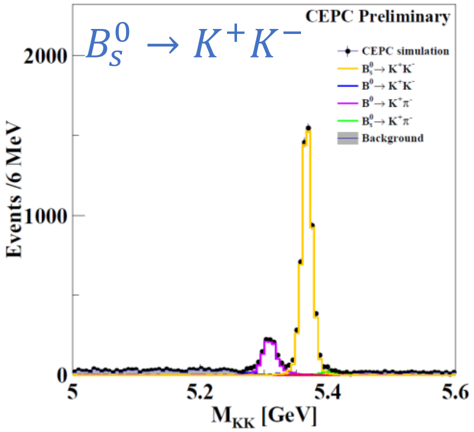
- **Motivation**
  - Rich physics programs in $B^0_{(s)} \to h^+h'^-$ decays
    - Time-dependent asymmetry, direct CP violation, lifetime measurement, …
  - Good test bed to study impact of PID in flavor physics
  - Explore physics potential of Tera-Z



With PID







- **Significantly improved SNR with PID**
- **More detailed studies ongoing**

Summary

- **Baseline DC design with full simulation**
  - PID performance: Close to 3σ K/π separation at 20 GeV/c for 1m track length
  - Mechanical stability: Stable with FEM simulations

- **Recent efforts on cluster counting feasibility**
  - Deep learning algorithms: Models for both simulated and experimental samples, outperform traditional algorithms
  - Prototype experiment: Improved setup and new preamplifier, show potential for cluster counting; Collaboration on beam tests
  - Delphes fast simulation: PID performance consistent to full simulation, improved signal sensitivity with PID in physics channels

- **Future works**
  - Further optimize the design
  - Optimize deep learning algorithm, prepare papers
  - Test beam data analysis
  - More prototype experiments

Backup

Requirements of detector and key technologies

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu\text{m}$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1\times10^{-3}}{p\times\sin^{3/2}\theta}(\text{GeV}^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 2%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(\text{GeV})}$ Granularity $\sim 2 \times 2 \times 2\ \text{cm}^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field $2-3$ T Material budget $< 1.5X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(\text{GeV})}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(\text{GeV})}$

Analytical tracking resolution calculation

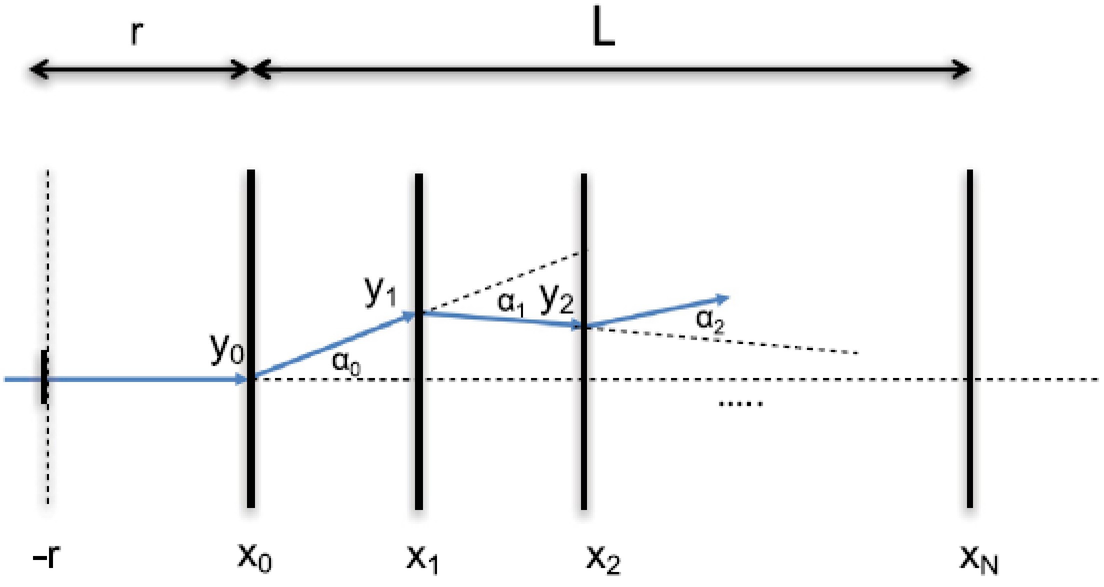


Fig. 2. Effect of multiple scattering in the different detector planes.

Covariance calculation considered position resolution and multiple scattering

Least square: $\chi^2 = (\boldsymbol{y} - \boldsymbol{Ga})^T \boldsymbol{C_y^{-1}} (\boldsymbol{y} - \boldsymbol{Ga})$

Covariance of 5-parameters : $\boldsymbol{C_a} = \left(\boldsymbol{G^T C_y^{-1} G}\right)^{-1}$

$$\boldsymbol{G_{mn}} = \frac{\partial F(a, x_n)}{\partial a_m}$$

Helix:

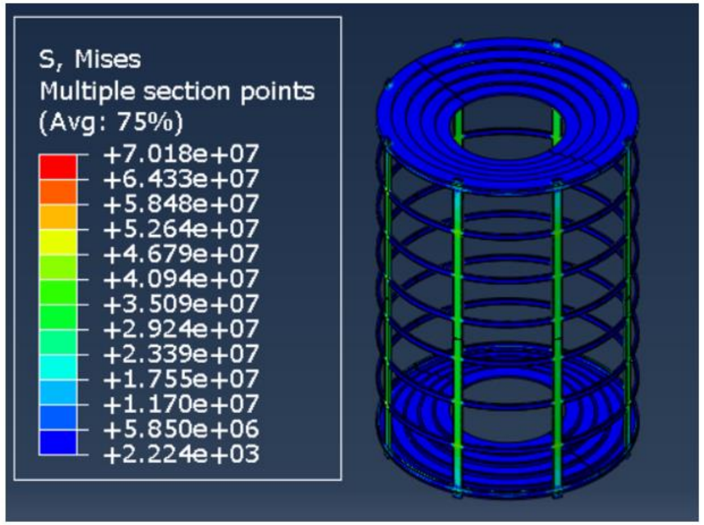
$$x = d_0 \cos\phi + R[\cos\phi - \cos(\phi + \varphi)]$$

$$y = d_0 \sin\phi + R[\sin\phi - \sin(\phi + \varphi)]$$

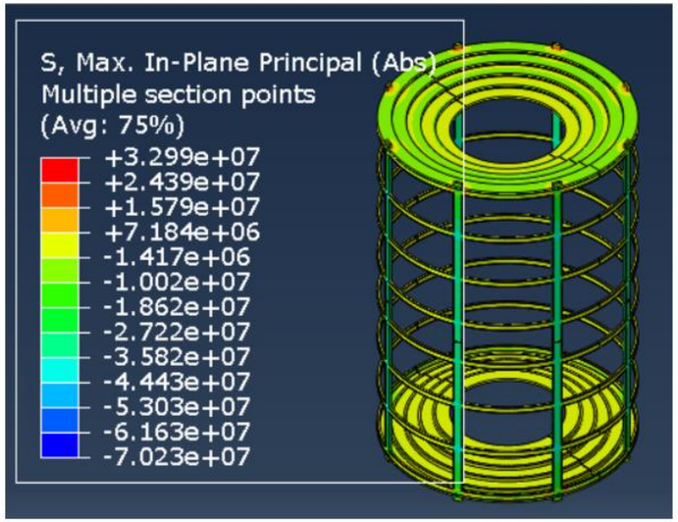
$$z = z_0 - R\tan\lambda \cdot \varphi$$

Ref : Nuclear Inst. and Methods in Physics Research, A 910 (2018) 127–132

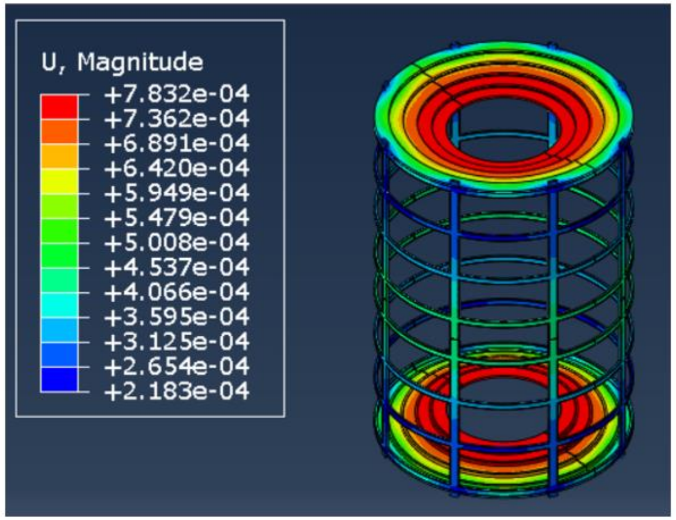
Mechanical study: stability



Mises stress



Principle stress



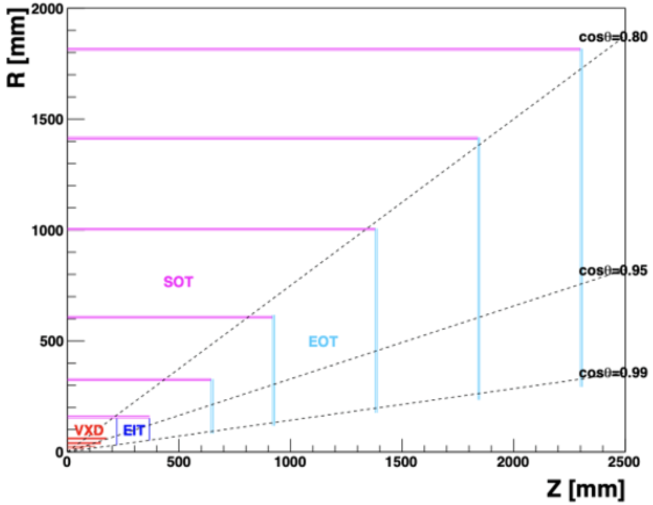
Deformation

Finite element model——wire tension + weight loads
(supported by eight blocks at each endplate)

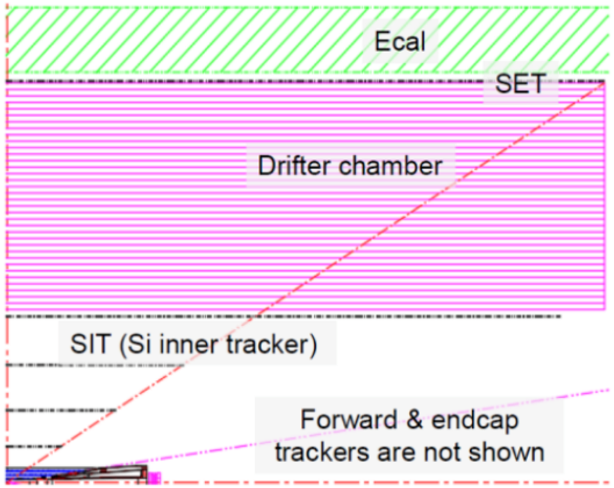
Mises stress: 70MPa
Principal stress : 33MPa
Deformation: 0.8mm
Buckling coefficient: 17.2 , it is safe

The support structure is stable, and the deformation is acceptable

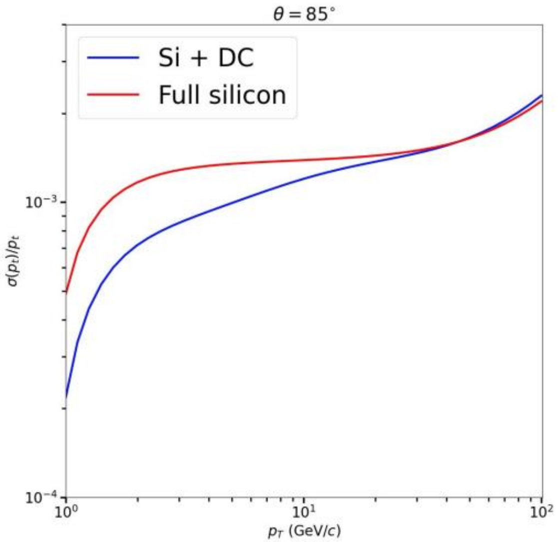
Momentum resolution



Full Silicon Tracker (FST) from CDR



Si + DC



Momentum resolution in low momentum range is benefited with Si+DC