Summary of PID in the gaseous detectors

Huirong Qi, Linghui Wu

Many thanks for all contributions in the CEPC Workshop 2022
Many thanks for all VTX/TRK conveners of Wei Wei, Zhijun Liang, Harald
Many thanks for some inputs from Manqi Ruan, Gang Li, Zhi Deng, Zhiyang Yuan, Yue Chang, Liwen Yu
Yiming Li, Guang Zhao, Jianbei Liu, Zhujun Fang, Peter Kuilt, Uli, Bohdan, Franco…

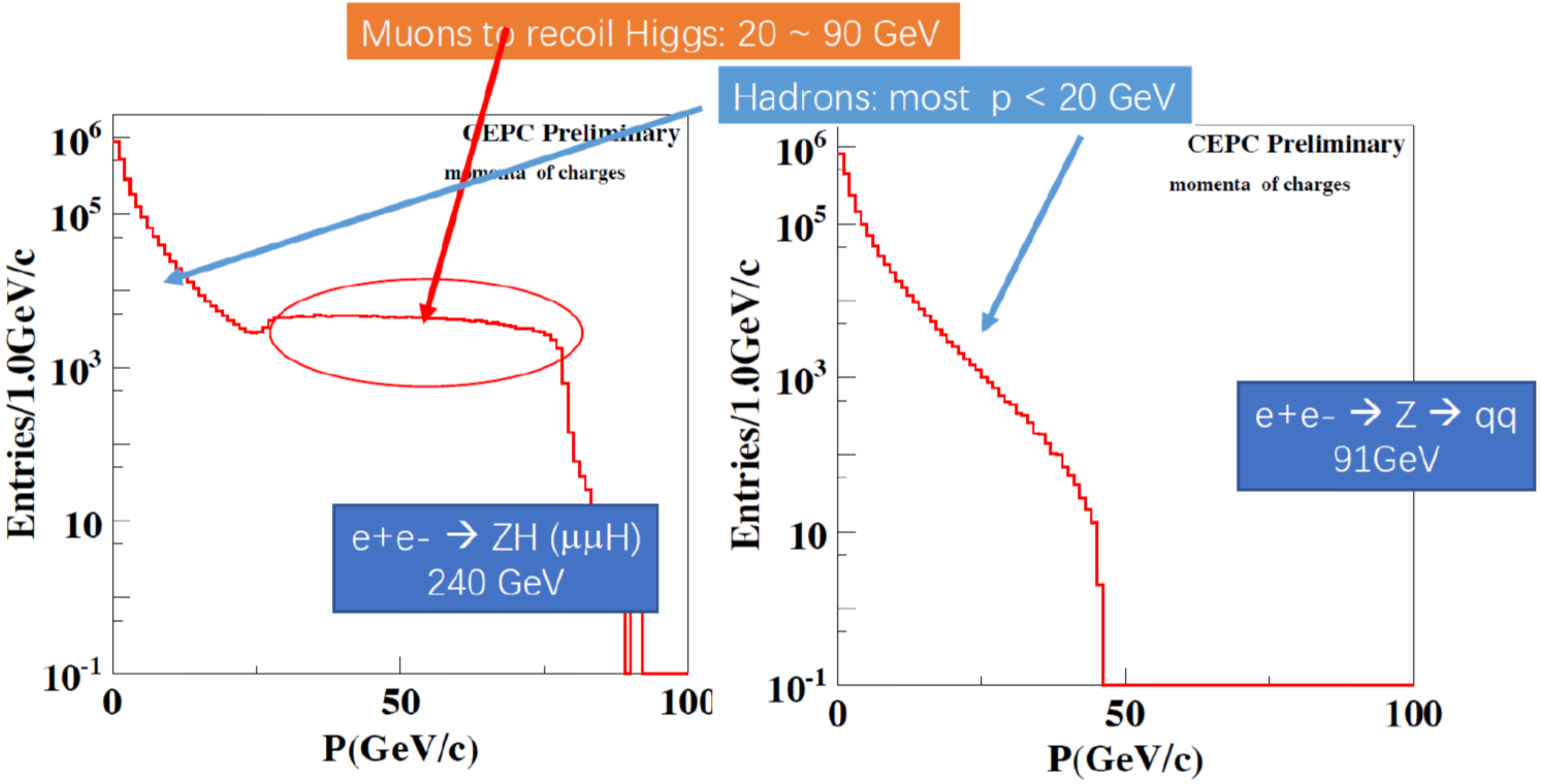
CEPC Physics and Detector regular meeting, June 1, 2022

Content

We just focus on the talks in CEPC workshop and some considerations.

- Overview of PID in the gaseous detector
- Prospects and discussions
  - In Time - Cluster counting in DC
  - In Space – Cluster counting in TPC
  - Low material budget uRWELL detector

Physics requirements: hadron momenta



- Most hadrons from Higgs/Z pole data are below 20 GeV/c
- The drift chamber should have sufficient PID separation power for hadrons < 20 GeV/c

Overview of PID in the gaseous detector

7 talks = 3DCs + 3 TPCs + uRWELL

11:00 - 12:40 Parallel-1 VTX/TRK

Zoom link

Conveners: Prof. 梁志均 LIANG Zhijun, Harald Fox (Lancaster University), Dr. Huirong Qi (Institute Physics, CAS)

Location: Main Building (A623)

11:00 **CEPC vertex detector R & D global overview** *20'*
Speaker: Prof. Zhijun Liang (IHEP)
Material: **Slides**

11:20 **CEPC vertex detector technology overview** *20'*
Speaker: Ying ZHANG (IHEP)
Material: **Slides**

11:40 **Status of TPC detector R&D for CEPC** *20'*
Speaker: Dr. Huirong Qi (Institute of High Energy Physics, CAS)
Material: **Slides**

12:00 **Low power consumption ASIC readout R&D for TPC** *20'*
Speaker: Dr. 智 邓 (清华大学)
Material: **Slides**

12:20 **μRWELL-based cylindrical tracker for the next generation colliders** *20'*
Speaker: Zhujun Fang (USTC)
Material: **Slides**

16:00 - 17:45 Parallel 6 VTX/TRK

Zoom link

Conveners: Prof. 梁志均 LIANG Zhijun, Harald Fox (Lancaster University), Dr. Huirong Qi (Institute Physics, CAS), Mr. Wei WEI (高能所)

Location: Main Building (A623)

16:00 **Drift chamber R&D for CEPC** *20'*
Speaker: Francesco Grancagnolo (INFN-Lecce)
Material: **Slides**

16:20 **bent CMOS sensor R & D for next-generation vertex detector** *20'*
Speaker: Magnus Mager (C)
Material: **Slides**

16:40 **Upate pixelated TPC technology R&D** *20'*
Speaker: Peter Kluit (N)
Material: **Slides**

17:00 **Silicon track detector R&D for CEPC** *20'*
Speaker: Fergus Wilson (STFC Rutherford Appleton Laboratory)
Material: **Slides**

14:00 - 15:30 Parallel 5 Performance & Soft

Zoom link

Conveners: Dr. Weidong Li (高能所), Dr. Linghui Wu (IHEP), Dr. Sheng-Sen Sun (Institute

14:40 **Study of Cluster Counting for CEPC drift chamber** *20'*
Speaker: Guang ZHAO (IHEP)
Material: **Slides**

15:00 **PID with Gaseous Tracking and Fast Timing** *20'*
Speaker: Bohdan Dudar (DESY)
Material: **Slides**

dE/dx and dN/dx

- **dN_{cl}/dx** resolution is potentially better than **dE/dx**.
- Cluster counting requires the fast electronics and sophisticated counting algorithms, or alternative readout methods.
- It has the potential of being less dependent on other parameters – however certain gasses (He, Ne) are better suited than others (Ar) due to their primary ionization characteristics

$$\sigma \sim (\delta \cdot L)^{-0.5} = \sqrt{N_{cl}}$$

- In cluster-counting mode there is a clear statistical advantage, even taking into account a cluster identification efficiency. There is the potential of better resolution by at least a factor 2 (theoretically)
- The relativistic rise is flattened out by a strict primary cluster count

  → a hybrid approach (dE/dx + dN/dx) may be better suited long drift lengths (long. diffusion + attachment) tend to de-cluster the primary ionization.
- Potential source of systematics should be considered too.
- Optimize the gas for longitudinal diffusion
  - Future DCs may applied
  - TPCs may hit intrinsic limitations

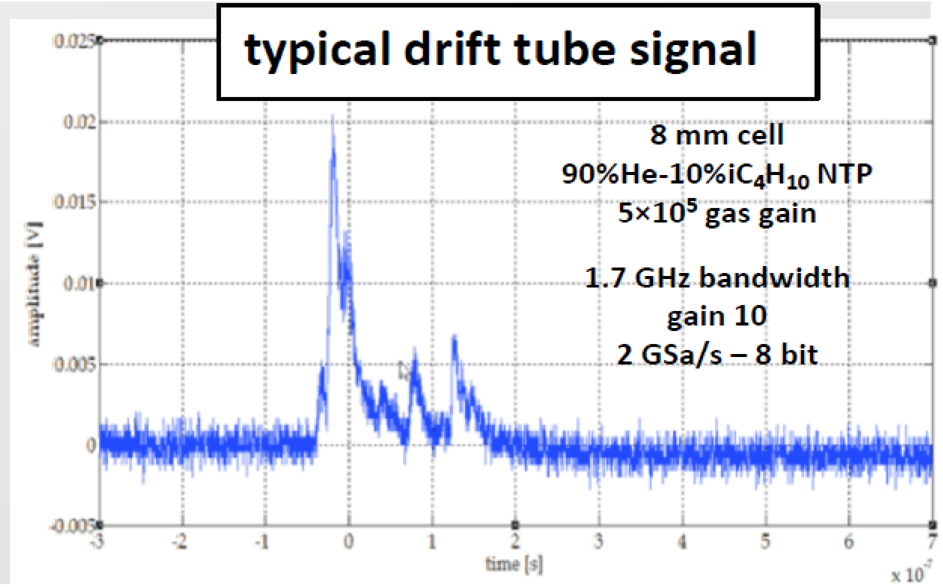
How to identify the clusters and achieve dN/dx ?

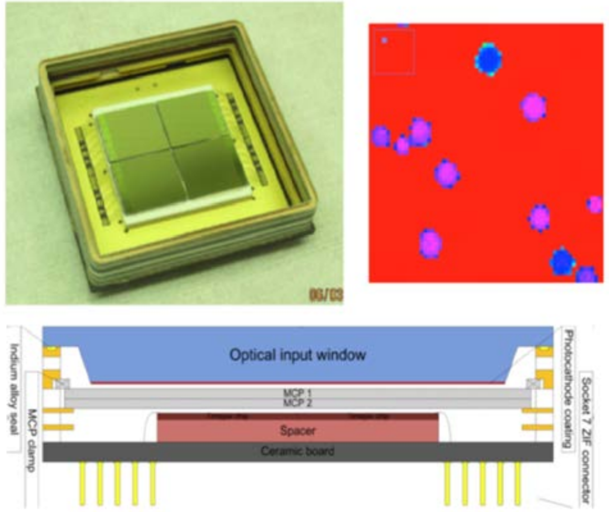
In Time

- Challenging of the fast-shaping electronics (~ ns needed)
- De-couple the charge collection from the cluster counting altogether
- → optical, with ~(sub)ns continuous readout sensors

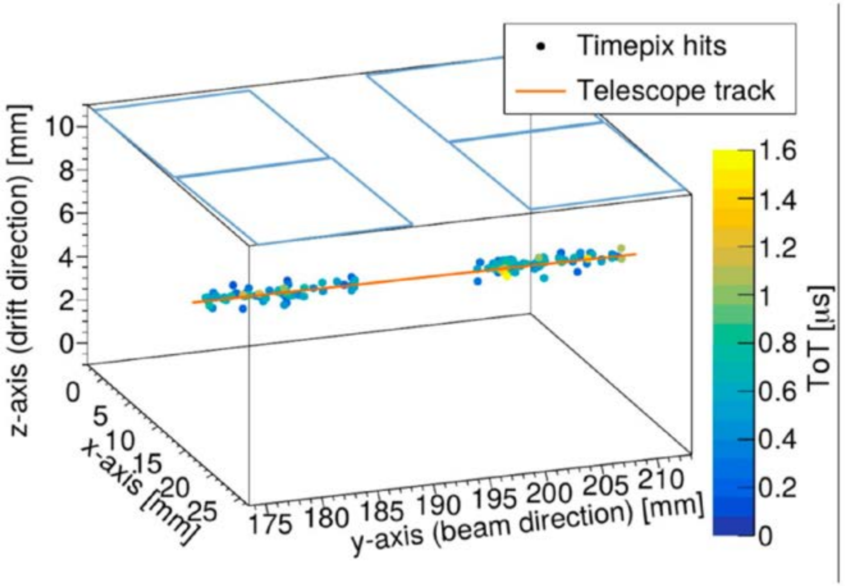
In Space

- Challenging of the low power consumption electronics (>40mV/fC needed at 2000 of gas gain)
- Pixelated readout
- → the reasonable pixilation reveals the underlying cluster structure in 3D chamber





J Vallerga et al 2014 JINST 9 C05055



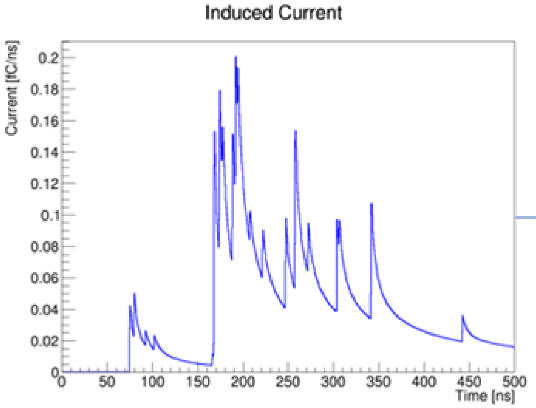
- Simulation and experimental studies on DC

Simulation of Cluster counting in DC (4th concept in CEPC)

- Waveform-based simulation

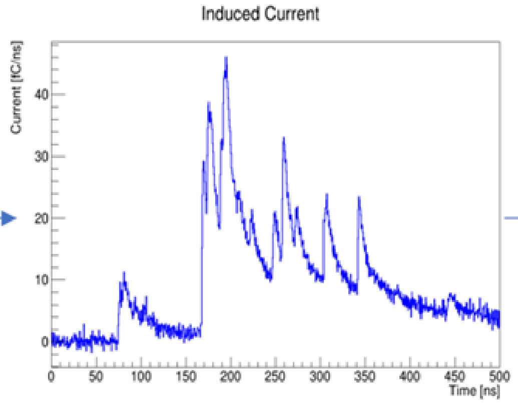
Guang Zhao (IHEP)

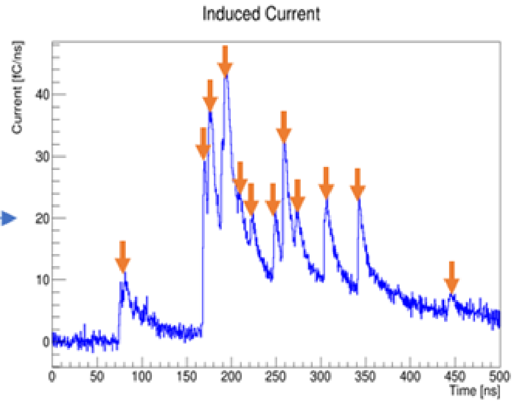
Induced current



Electronics

Realistic waveform





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

Electronics:
- Preamplifier
- Noises
- ADC

Peak finding algorithm:
- Second derivative

Garfield++ simulation

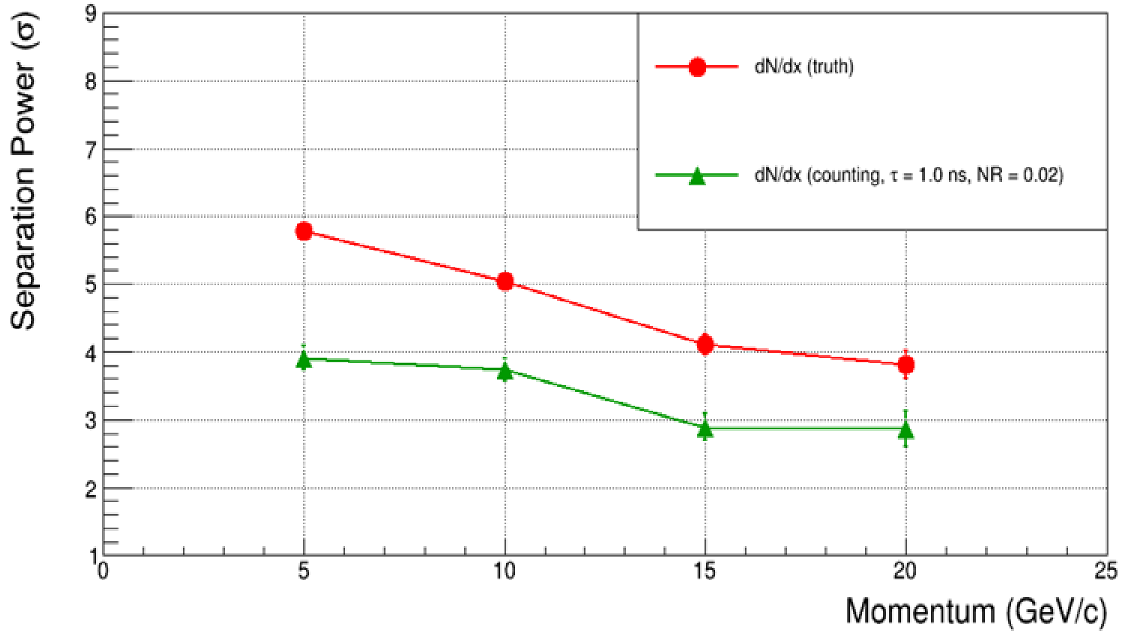
Digitization

Reconstruction

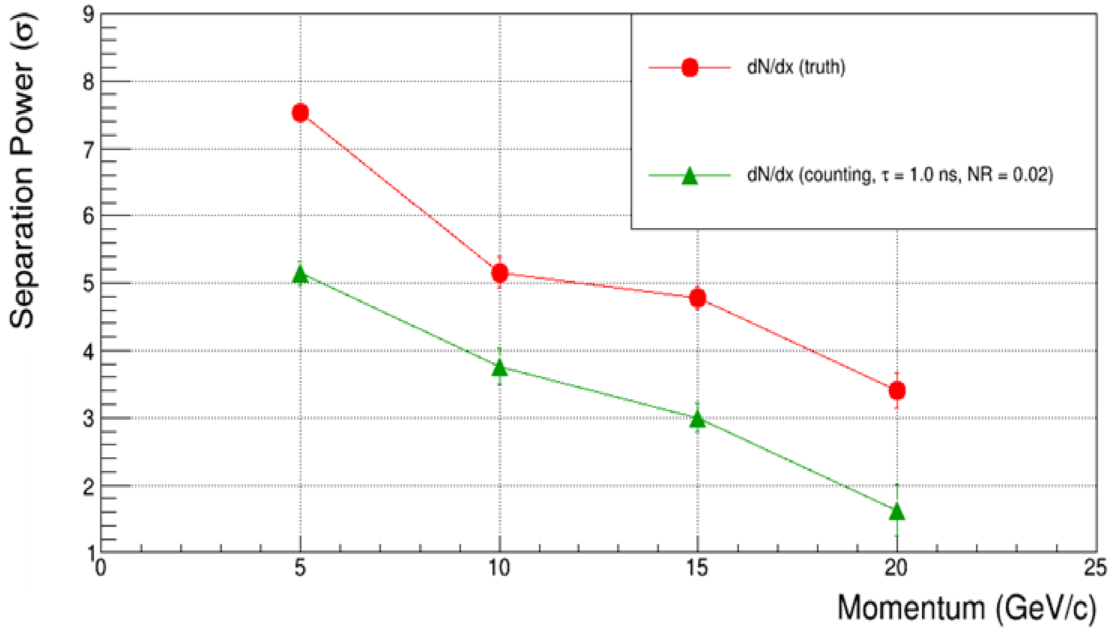
K/π separation for gas mixtures

Guang Zhao (IHEP)

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



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



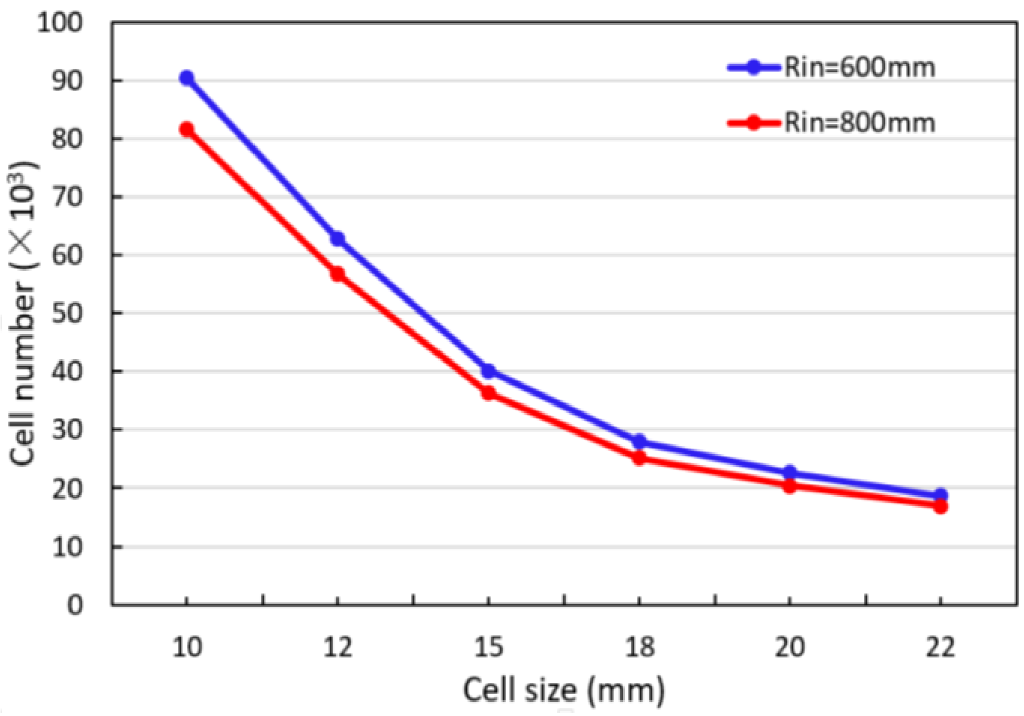
- He 90% + iC_4H_{10} 10% has better K/pi separation for high momentum
- He 80% + iC_4H_{10} 20% has better K/pi separation for low momentum
- PID in low momentum region can be covered by timing detector ➔ **He 90% is favored**

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

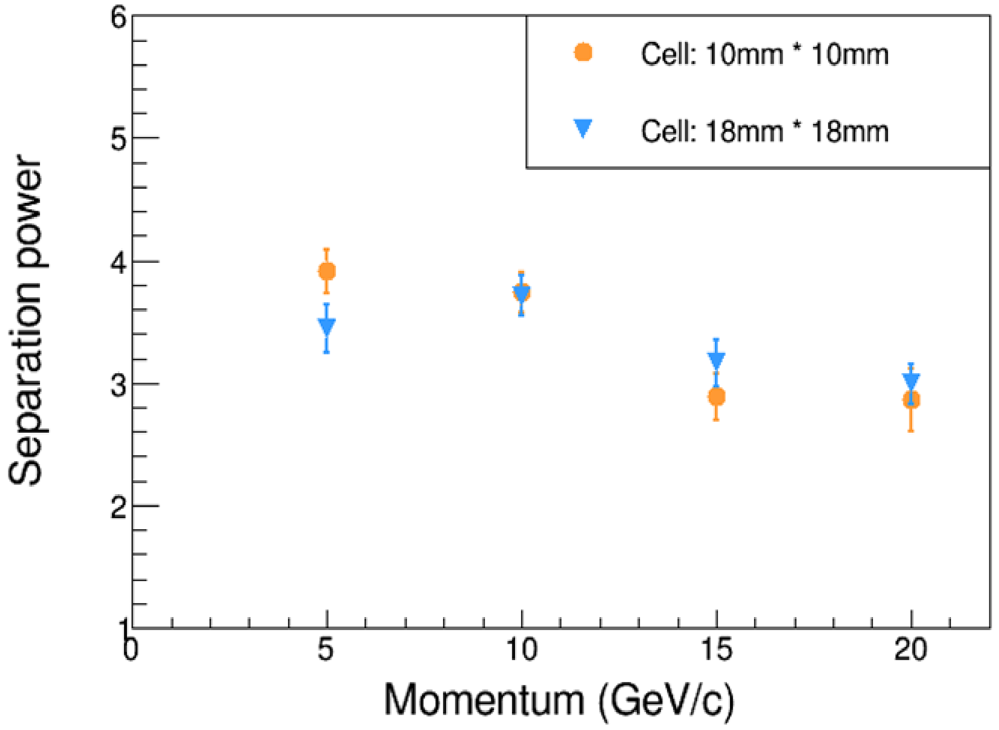
Study of cell size

Guang Zhao (IHEP)

# of cells vs. cell size



Comparison of K/π separation power

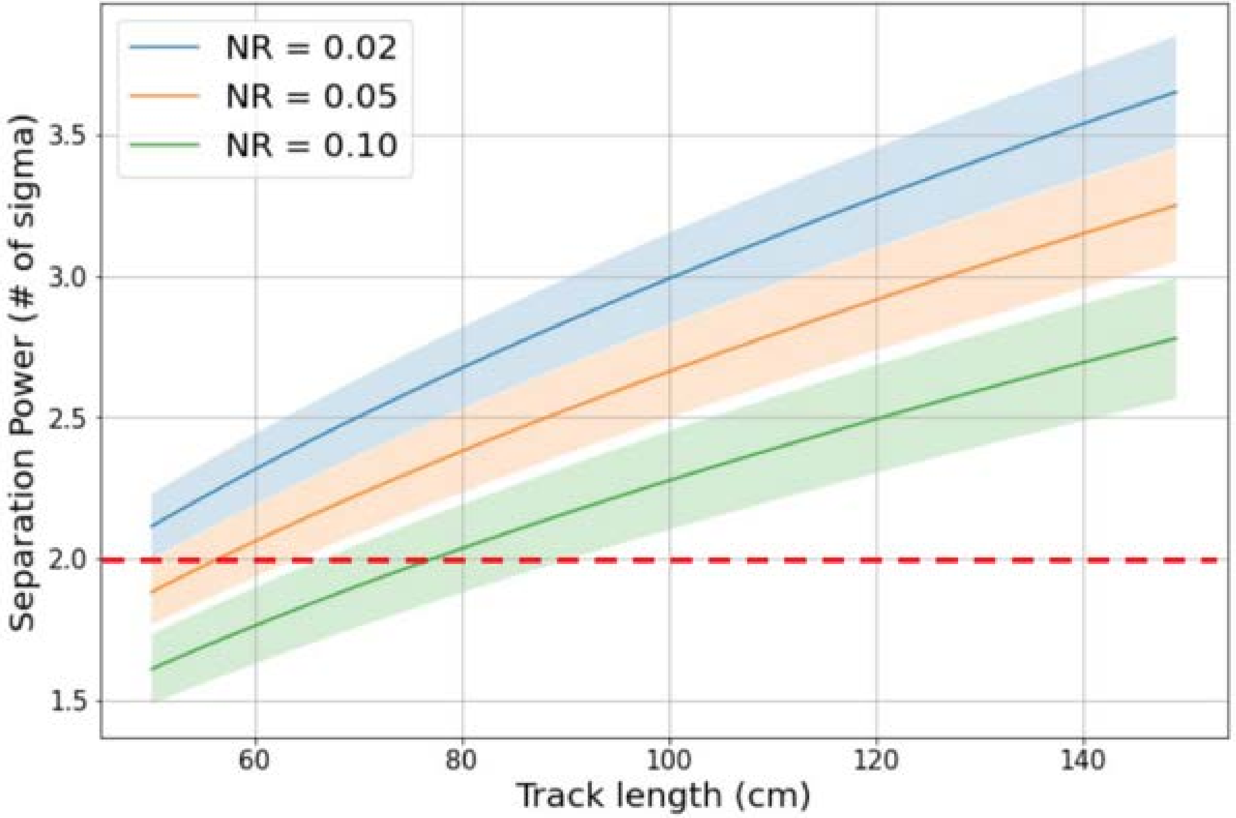


- **Cell size cannot affect PID significantly**
- **Cell size = 18 x 18 mm is better for mechanical structure**

Simulation of Cluster counting in DC (4th concept in CEPC)

Guang Zhao (IHEP)

- Waveform-based simulation
- Simulation gives us the suggested parameters of DC
  - Gas mixtures: 90% He + 10% C_4H_{10}
  - Cell size: 1.8 cm × 1.8 cm
  - Thickness of DC: < 100 cm (2σ K/π separation @ 20 GeV/c)



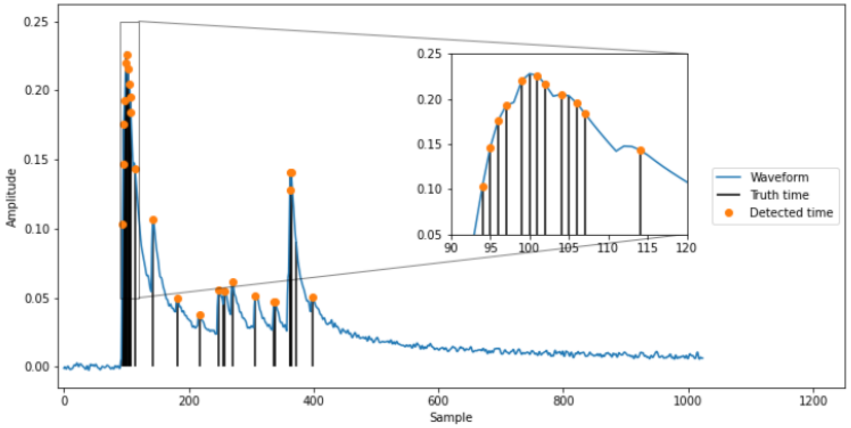
The resolution scales with $L^{-0.5}$

Outlook

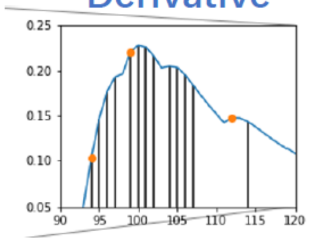
Guang Zhao (IHEP)

- **Study the PID requirement from physics channels**
  - Physics input to constrain the detector parameters
  - Delphes fast simulation is ongoing
- **More effective peak finding algorithm**
  - An algorithm using deep learning is being developed. Preliminary study shows promising results

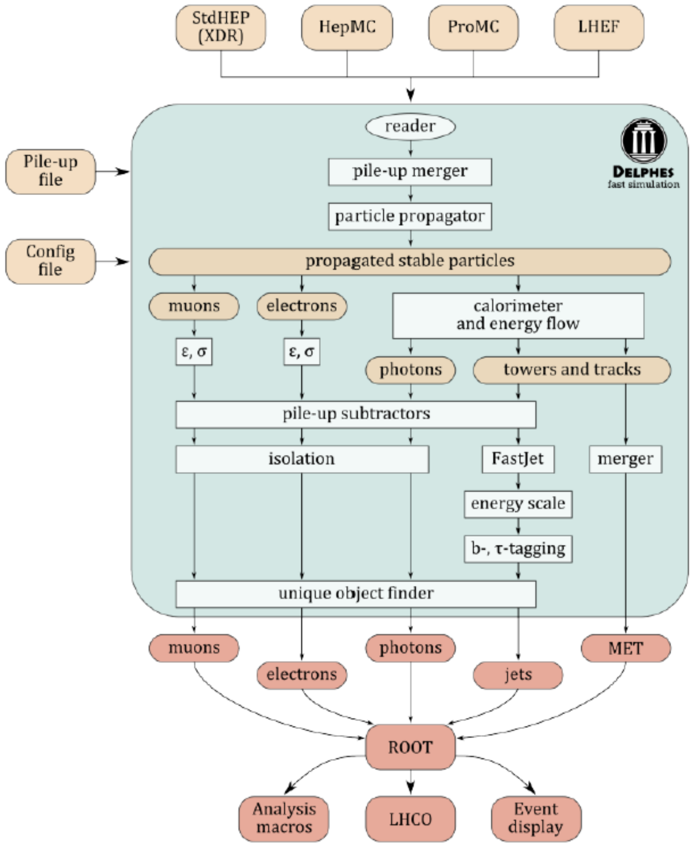
Deep Learning



Derivative



Delphes

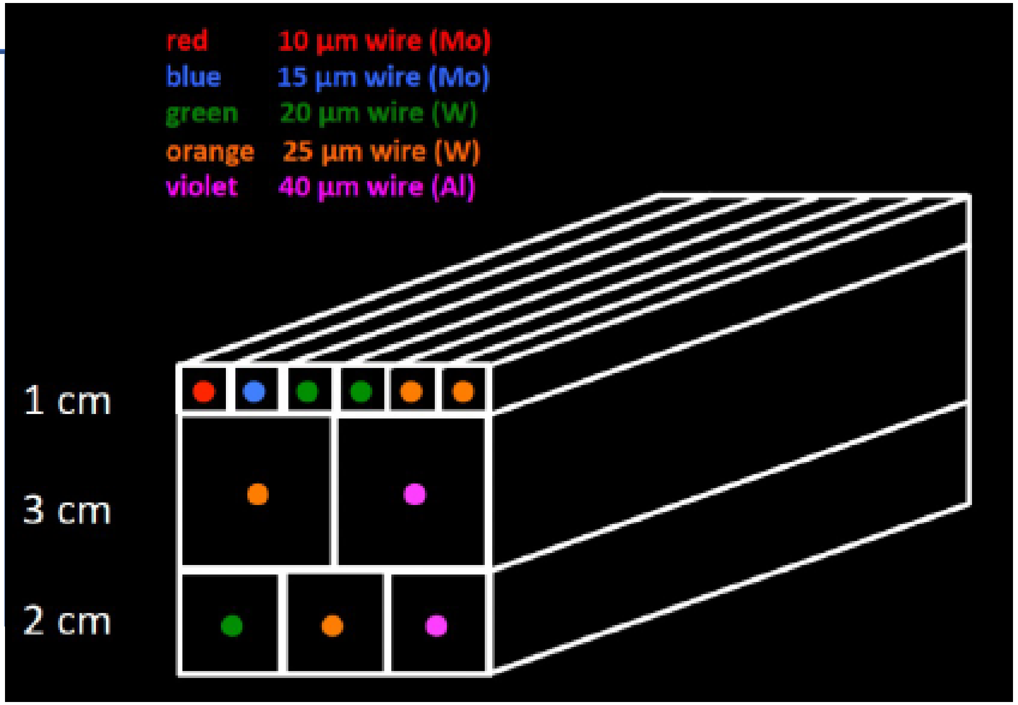


Experimental studies of Cluster counting on DC

- Offline analysis on November test beam data taken with 165 GeV/c muons beams from 11st November, 2021
- Dealing with 11 drift tubes having cell sizes of 1-cm, 2-cm and 3-cm

Francesco Grancagnolo (INFN)

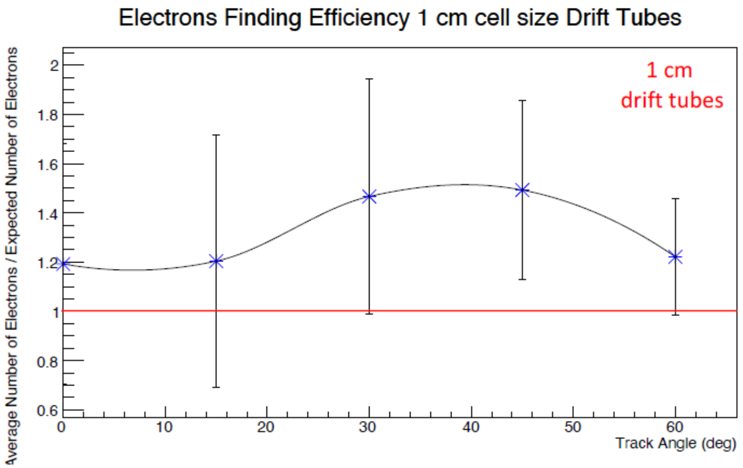
- **Channels 4,5,6,7,8,9** are the 6 Drift Tubes of 1 cm cell size respectively:
  - Channel 4 with a wire diameter of 10 micrometer
  - Channel 5 with a wire diameter of 15 micrometer
  - Channel 6 and 7 with a wire diameter of 20 micrometer
  - Channel 8 and 9 with a wire diameter of 25 micrometer
- **Channels 10,11,12** are the 3 Drift Tubes of 2 cm cell size respectively:
  - Channel 10 with a wire diameter of 20 micrometer
  - Channel 11 with a wire diameter of 25 micrometer
  - Channel 12 with a wire diameter of 40 micrometer

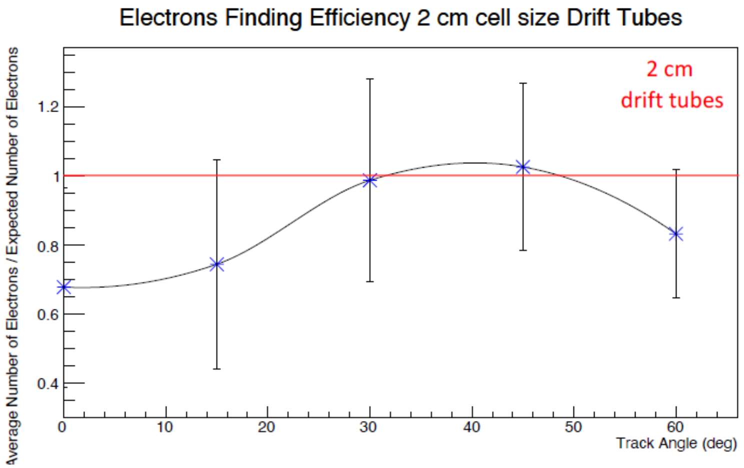


Cluster counting and electron peaks counting

Electron peaks counting

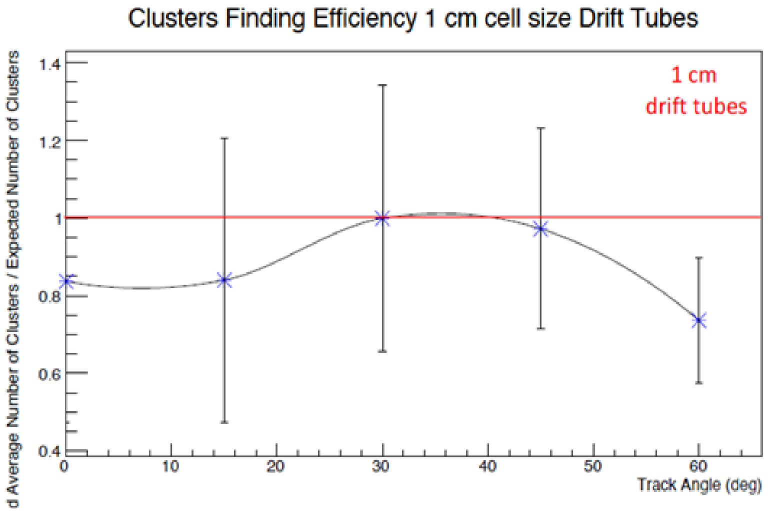
Francesco Grancagnolo (INFN)

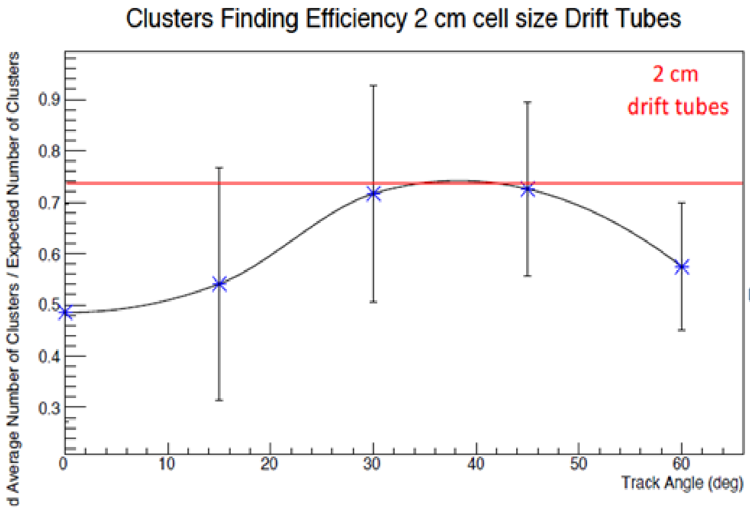




- Electrons **overcounting** due to fake electron peaks in adjacent bins (easily corrected in the clusterization algorithm)
- **Inefficiency** for 2 cm drift tubes under investigation
- **Undercounting** for $\alpha < 30°$ due to space charge effects
- **Undercounting** for $\alpha > 45°$ due to high electron peaks density (average 5 bins at 60°) → **real inefficiency** (can be corrected)

Cluster counting





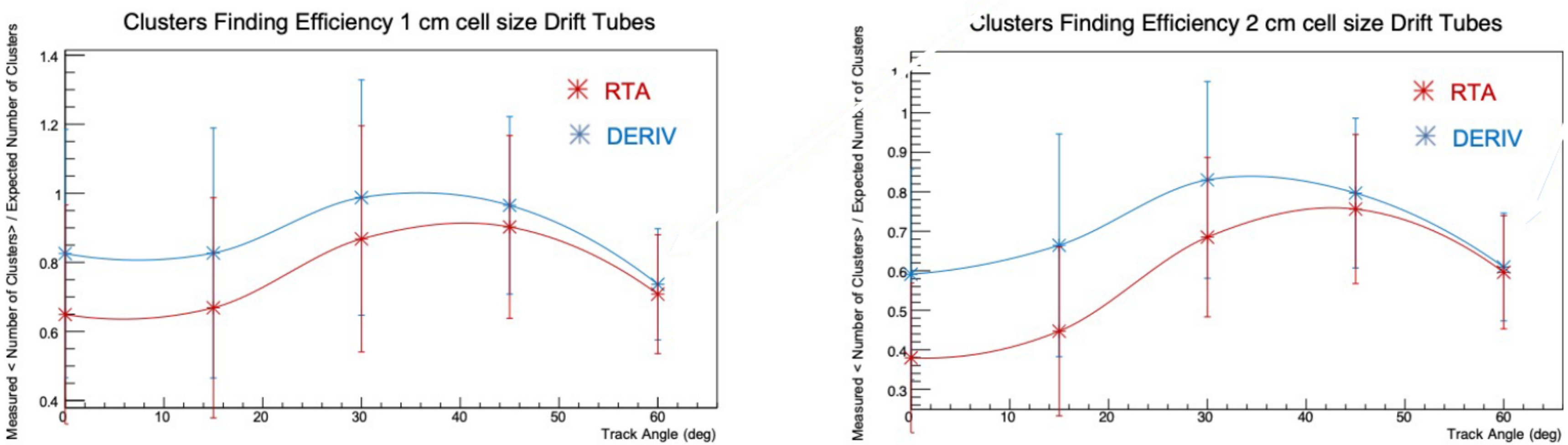
- Same effects seen in the electron peaks counting (**space charge** and high **electron peaks density)**
- **Full efficiency** and **Poisson distribution** for 1 cm drift tubes
- **25-30% average inefficiency** for 2 cm drift tubes (electron inefficiency)
- **Inefficiency** may be cured by increasing the sampling rate (more bins per peak)

Conclusions + plan

- Evidence of space-charge effects and indication of space-charge dimension (essential for simulating in a realistic way the drift chamber behavior beyond Garfield++)
- The time spread of the last cluster is distributed as expected, allowing for an event time stamping at the Z-pole at the level of 1 ns.
- Next step will be the experimental measurement of the cluster density and cluster size distributions over the relativistic rise region, which will begin this coming summer at CERN H8.

Francesco Grancagnolo (INFN)

Comparison between RTA and DERIV



- **preliminary** performance comparison
- both algorithms are quite simple from the computational point of view and have few parameters to be optimized
- both algorithms can be easily implemented in FPGA's
- new, orthogonal algorithms (Guang NN attempt) are very welcome

- Simulation and experimental studies on TPC

Simulation of PID with gaseous tracking and timing in ILD

- dE/dx reconstruction inside TPC
- dE/dx and cluster counting for ILD
- Time of Flight particle ID and V0 finder

Bohdan Dudar (DESY)

TPC in the ILD Geant4 simulation:
Gas: Ar-CH_4-CO_2 mixture (93%/5%/2%)
Segmentation: 220 radial hits with a 6 mm step

Compute_dEdxProcessor

1. Calculates dE/dx per hit

$$\left(\frac{dE}{dx}\right)_{hit} = \frac{\text{sum(gas ionisation from Geant4)}}{\text{distance to the previous hit}}$$

2. Calculates truncated mean <dE/dx> per track

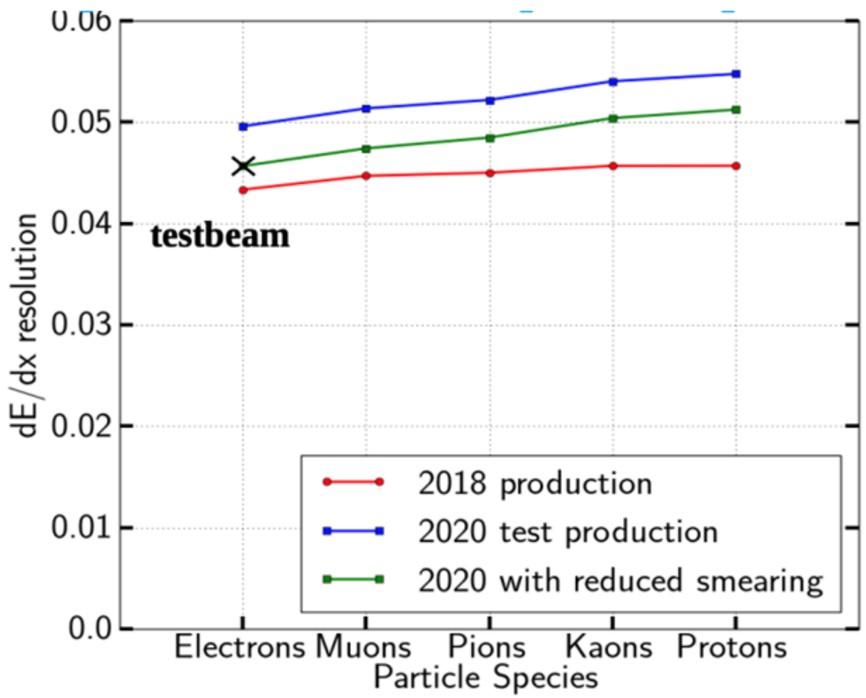
$$\left\langle \frac{dE}{dx} \right\rangle_{track} = \begin{matrix}\text{take all hits associated with a track} \\ \text{reject 30\% hits with the highest dE/dx} \\ \text{reject 8\% hits with the lowest dE/dx}\end{matrix}$$

3. Smears $\langle dE/dx \rangle_{track}$ to match LCTPC test beam results

https://arxiv.org/abs/1801.04499

International Large Detector

dE/dx resolution difference became more prominent between particle species

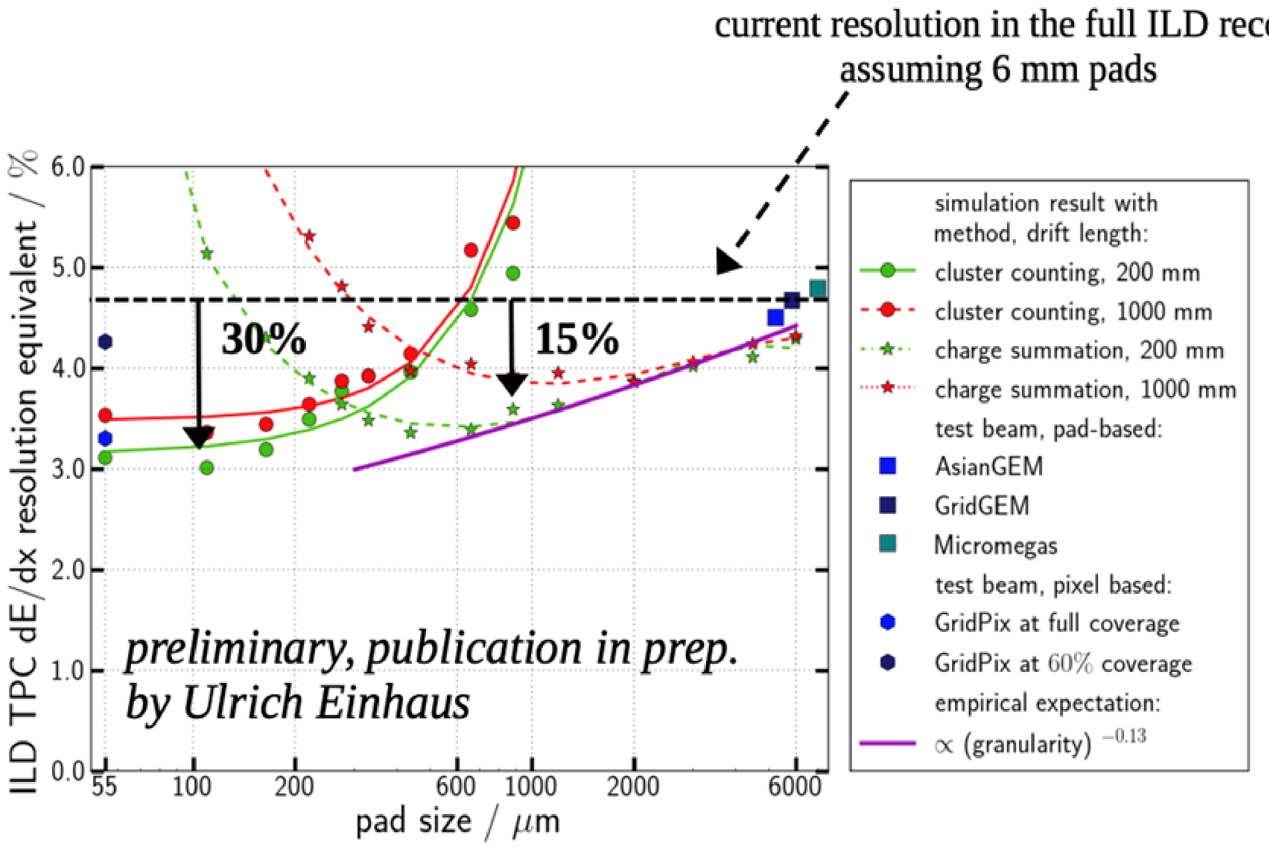


note[1]: currently, not all track hits are used, but only hits from the first half circle
note[2]: smearing accounts for N_{hits} and θ_{track} correlations
note[3]: for overlapping tracks hits are merged

Cluster Counting / Charge summation / Granularity

Bohdan Dudar (DESY)

- Current full ILD reconstruction: 6 mm pads → ~4.6 % dE/dx resolution
- 6 mm → 1 mm: 15% improved resolution via charge summation (dE/dx)
- 6 mm → 0.1 mm: 30% improved resolution via cluster counting (dN/dx)

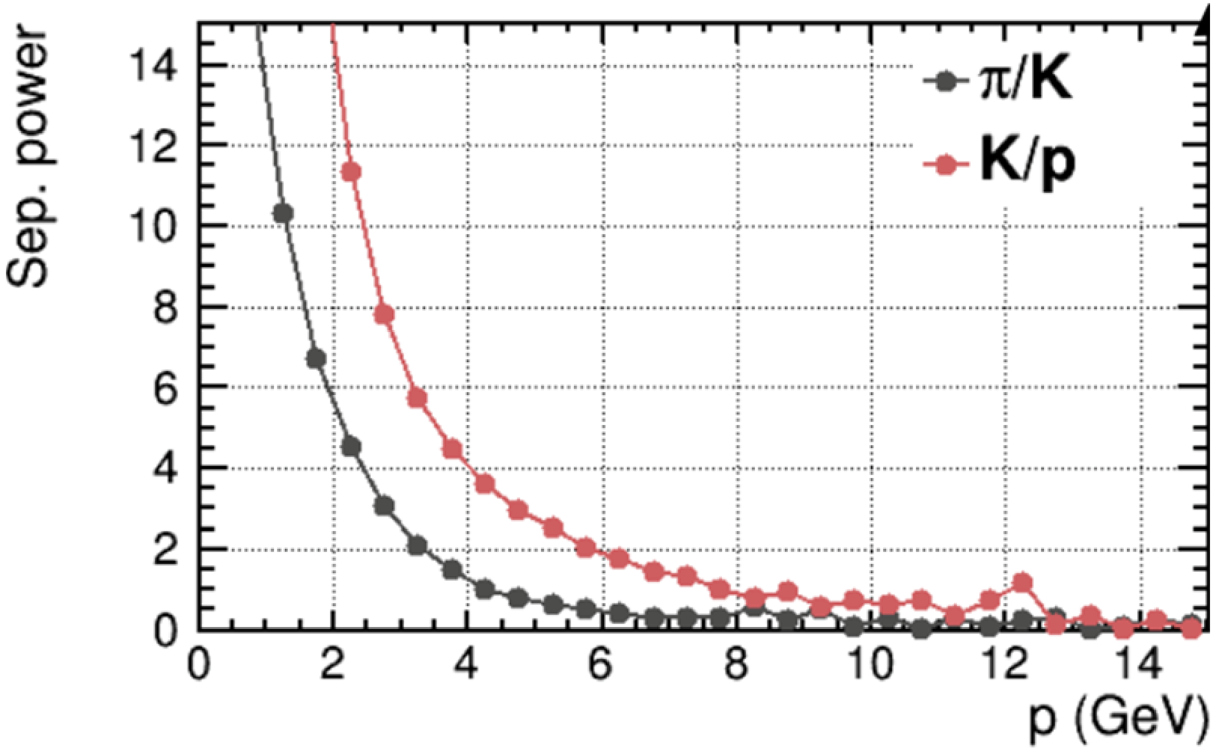


Changing granularity might stop working at very low pad sizes, due to a very distorted pad geometry

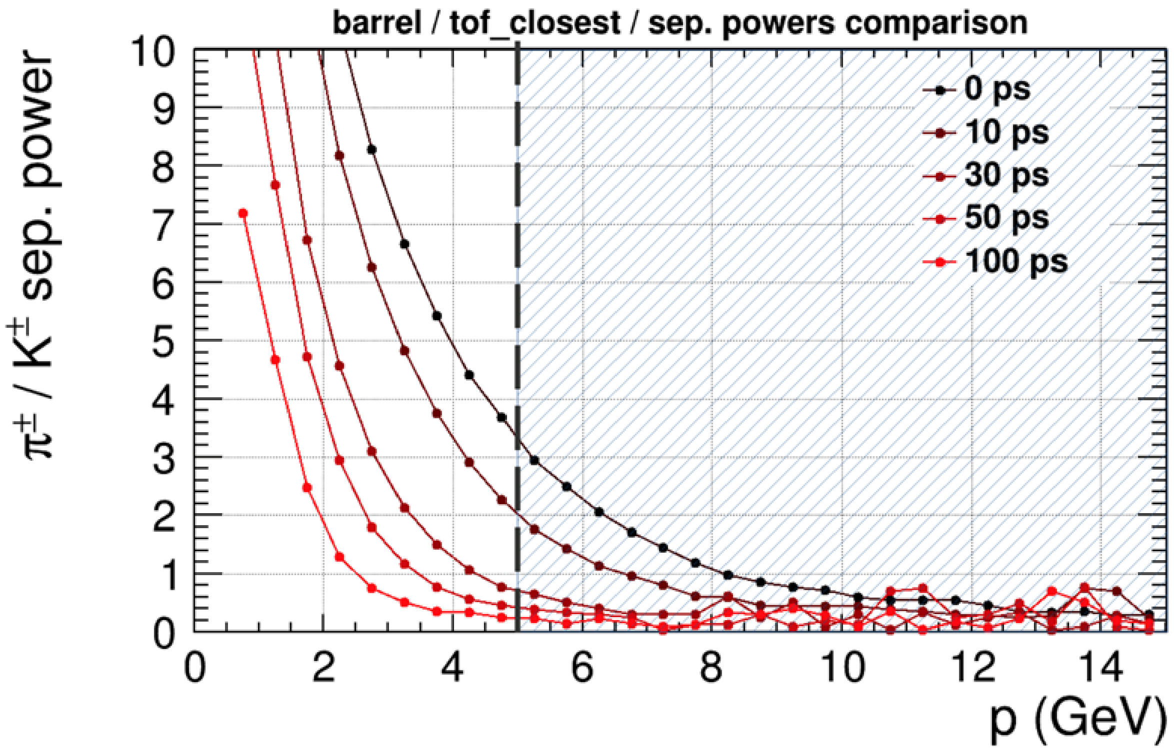
Time of Flight particle ID

Bohdan Dudar (DESY)

Separation power vs p
(only barrel / 30 ps TOF resolution)



Separation power vs TOF resolution



dE/dx + TOF PID + ongoing

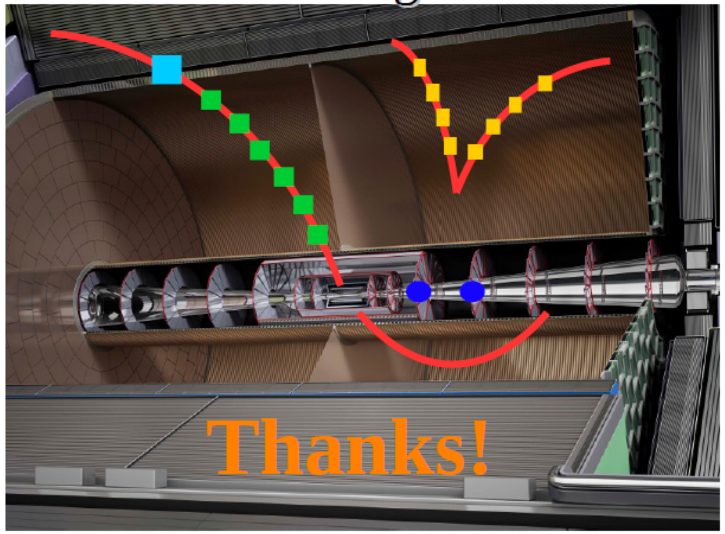
- Many active developments have happened over the recent years (despite Covid) showing a great TPC particle ID capabilities
- dE/dx PID is already very robust, but still has a room to improve resolution beyond current 4.6%
- TOF PID is very recent and develops very fast, showing excellent PID below 5 GeV complementing dE/dx in a dip

Still many things are planned and ongoing:

- Make fully robust likelihood PID processor: dE/dx+TOF+shower shapes+etc.
- Simulate realistic digitizer in the ECAL for TOF measurement, not only earliest MC contribution, but full threshold behaviour.
- Explicitly show TOF particle ID benefits for physics analyses
- Full assessment of V_0 finder and its relation to LCFIPlus vertexing/V_0s planned for this year

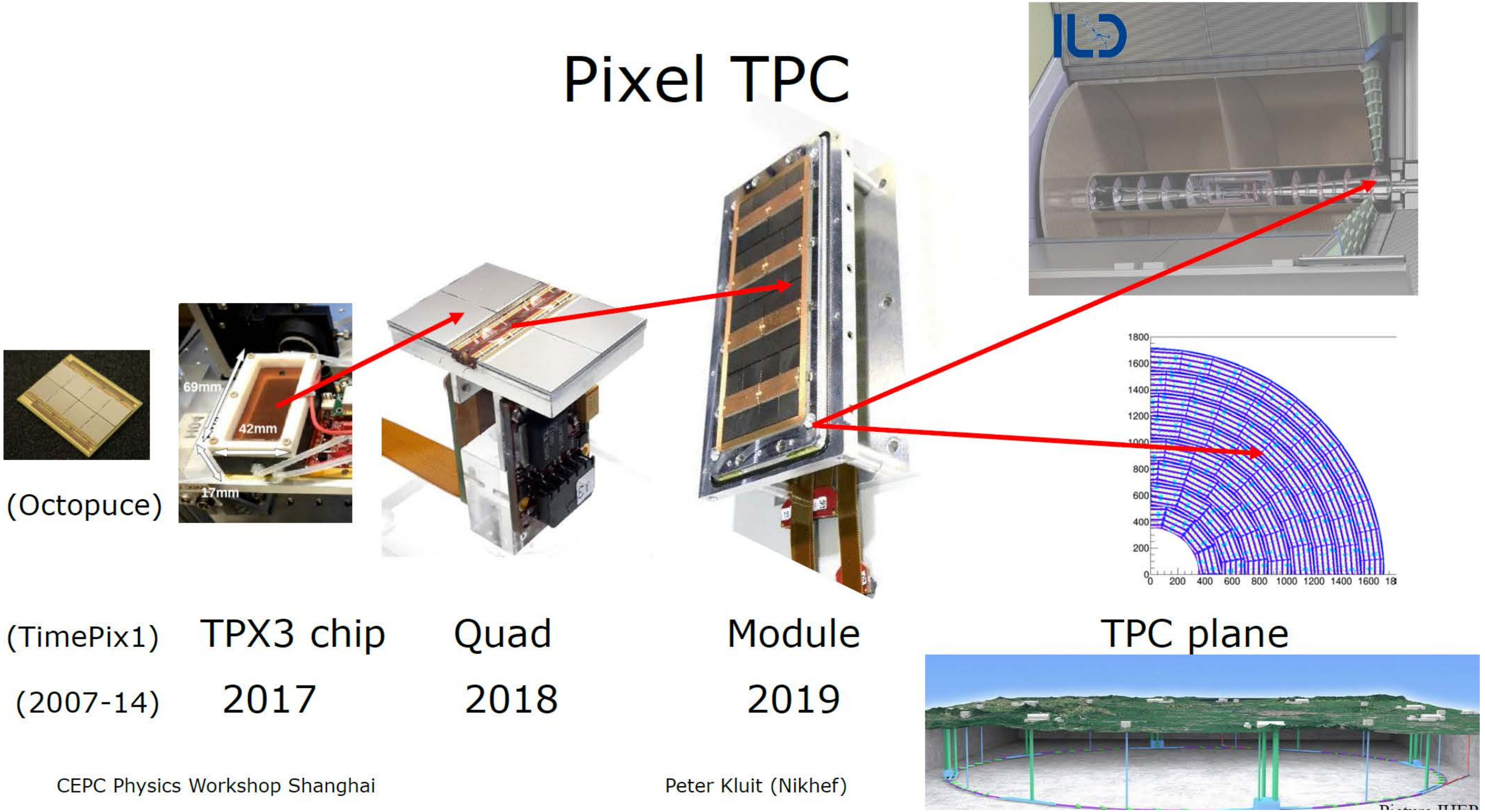
Bohdan Dudar (DESY)

International Large Detector



Pixelated TPC technology R&D

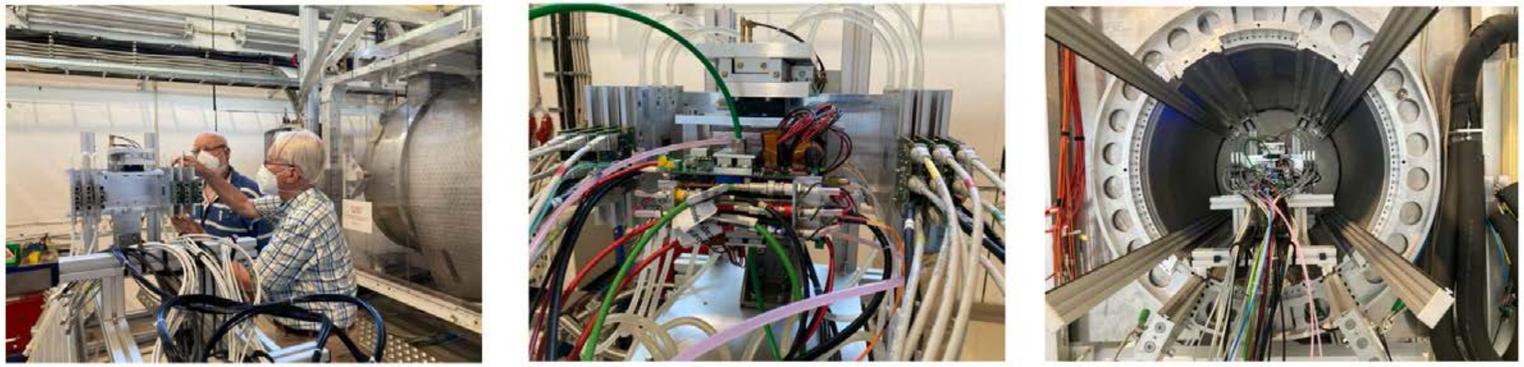
Peter (NIKHEF)



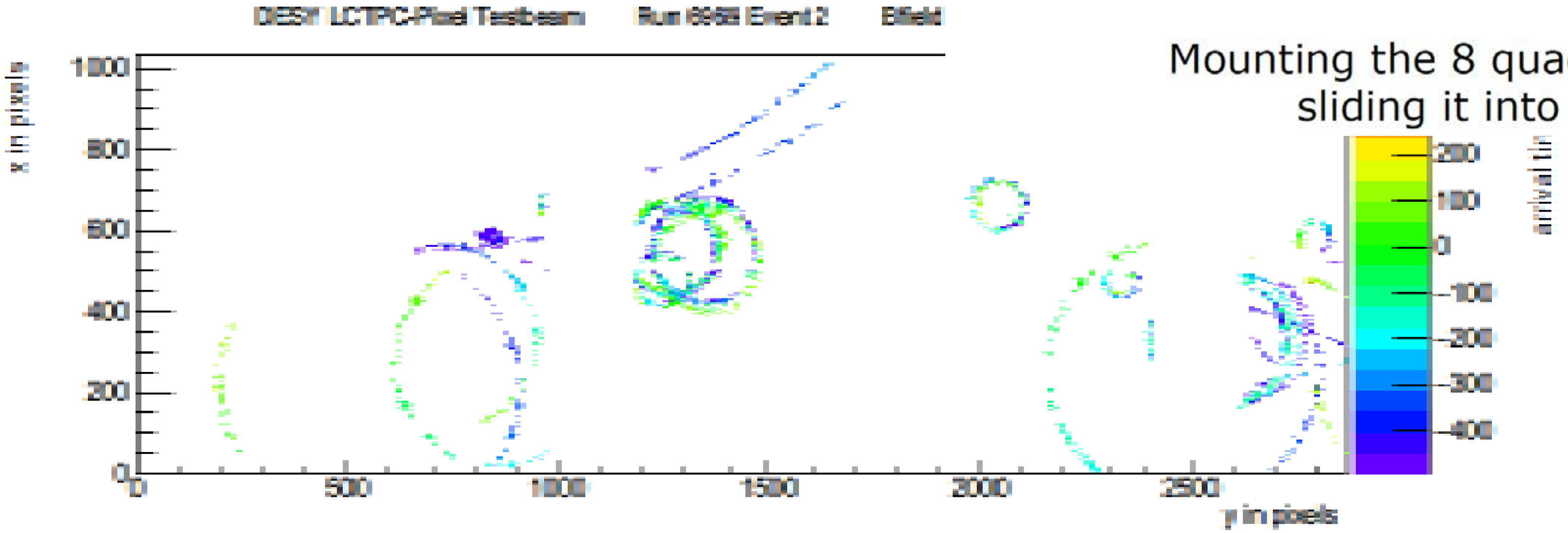
Pixelated TPC technology R&D

Peter (NIKHEF)

- High statistics data taken with different B fields
- A beautiful data set and we look forward to study further the performance (resolutions and deformations) σ_{xy}<250 μm and σ_z<425 μm (mean drift distance of 6.4 mm)
- Opportunity to exploit pixel TPC high precision tracking and particle identification with dE/dx using single electrons



Mounting the 8 quad module between the silicon planes sliding it into the 1 T PCMAG solenoid



DESY test beam June 2021

Conclusion and plan

Peter (NIKHEF)

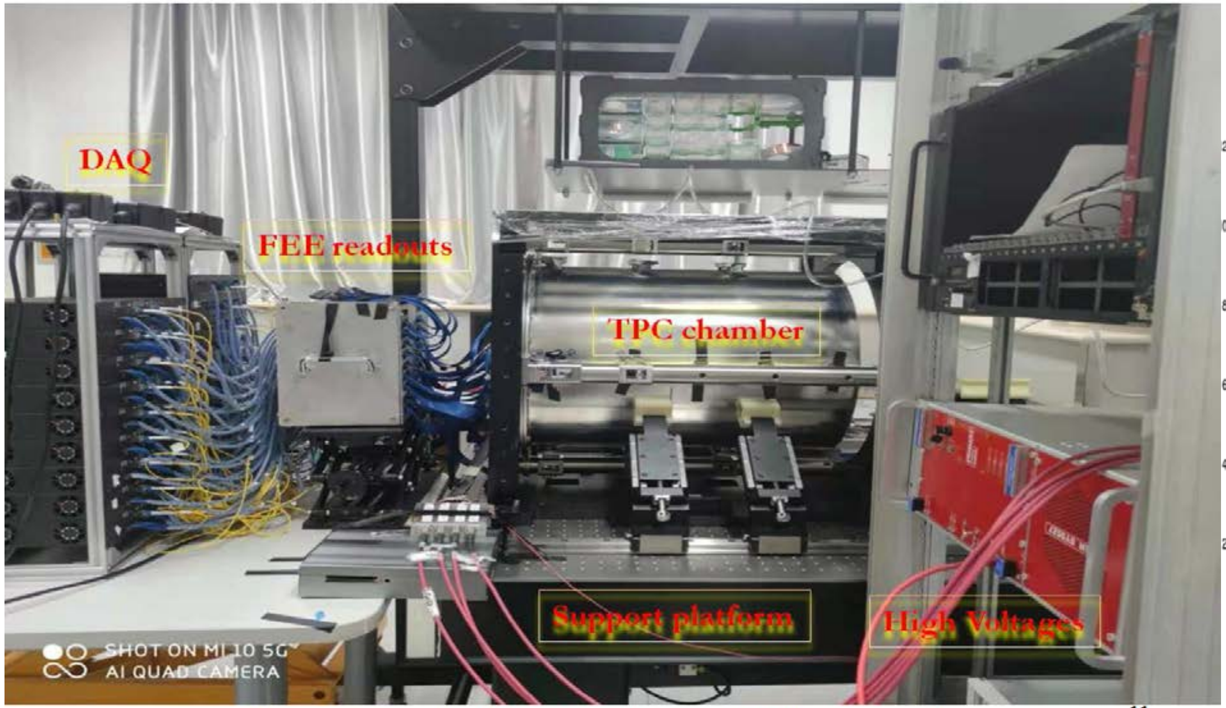
- A single chip GridPix detector was reliably operated in a test beam in 2017
  - Single electron detection => the resolution is primarily limited by diffusion
  - Systematic uncertainties are low: < 10 μm in the pixel xy plane
  - dE/dx resolution for a 1 m track is 4.1%
- A Quad detector was designed and the results from the 2018 test beam presented
  - Small edge deformations at the boundary between two chips are observed
    - added guard wires to the module to obtain a homogeneous field
  - After correcting the edges, deformations in the transverse plane shown to be < 15 μm
- An 8-Quad module has been designed with guard wires
  - Deformations in the transverse plane for one quad are shown to be < 15 μm
- Test beam data taken at DESY in 2021: first results on precision tracking presented
- A pixel TPC has become a realistic viable option for experiments
  - High precision tracking in the transverse and longitudinal planes, dE/dx by electron and cluster counting, excellent two track resolution, digital readout that can deal with high rates
  - A double grid will allow to reduce the Ion back flow distortions substantially

TPC technology R&D for CEPC

Huirong (IHEP)

- Studies have been done using the different active area of the hybrid TPC detector modules
- Validated IBF×Gain using the TPC detector module
- A laser TPC prototype has been successfully developed and studied at IHEP in the last 6 years. Ion backflow can be reduced to 1 level at gain 2000.

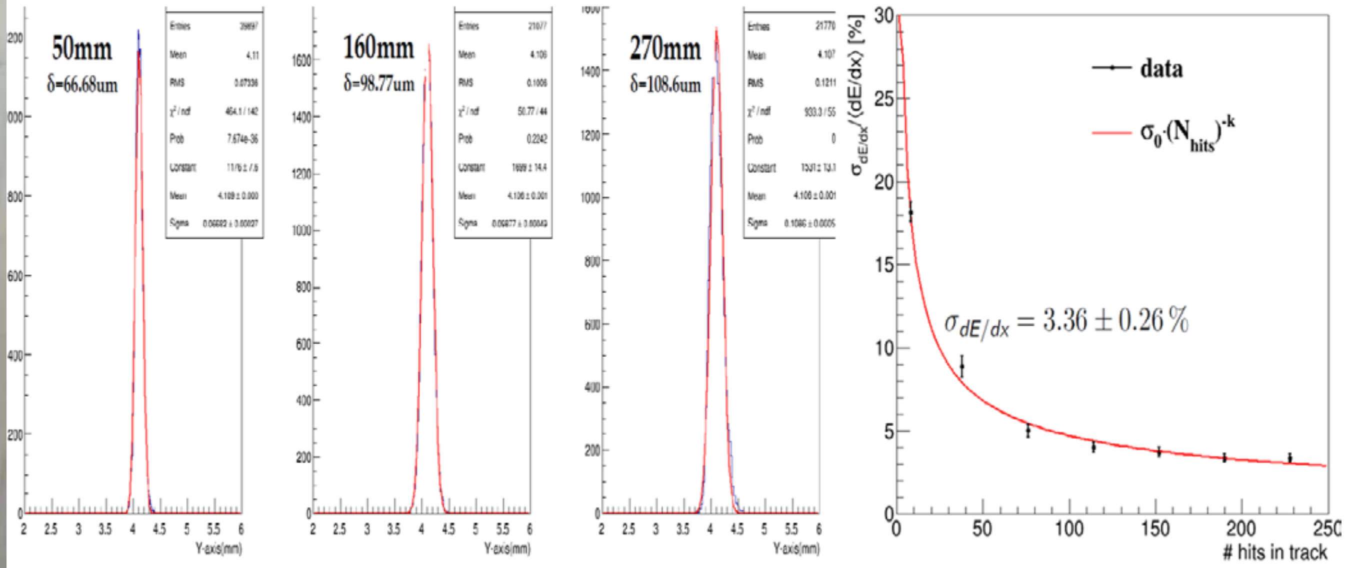
- Successfully to develop the TPC prototype integrated 42 UV laser tracks
- Spatial resolution, dE/dx resolution achieved with the pseudo-tracks (DONE)



TPC prototype R&D using 266nm UV laser tracks

11

- Spatial resolution can reach to about 100um along the drift length of the TPC prototype and it can meet the physics requirement of CEPC
- Pseudo-tracks with 220 layers (same as the actual size of CEPC detector concept) and dE/dx can reach to 3.36 ± 0.26%



Results of the spatial resolution and dE/dx

TPC prototype plan

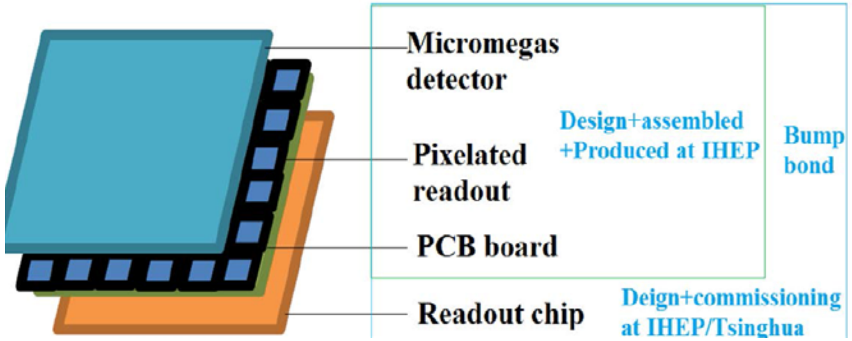
- R&D plan will mainly focus on making pixelated TPC prototype working
- Improve the laser track resolution and cluster size
- Improved dE/dx with dN/dx

Huirong (IHEP)

Prototype plan #1

- **Realization of pixelated technology collaborated with Tsinghua**

Bump bond pixelated readout with Micromegas detector	Module size	To be addressed by R&D
• **≥300um×300um** • Developed the readout chip by Deng Zhi (Tsinghua) • Developed the Micromegas detector sensor at IHEP • Development of the new module and prototype	1-2 cm^2	• Research on pixelated readout technology realization • Optimization of cluster profile and pad size • Study of the ‘dN_{cl}+dx’
	100 cm^2	• Study the distortion using UV laser tracks and UV lamp to create ions disk • In-situ calibration with UV Laser system • Study of the ‘$dE/dx+dN_{cl}/dx$’



Tsinghua University
University

20

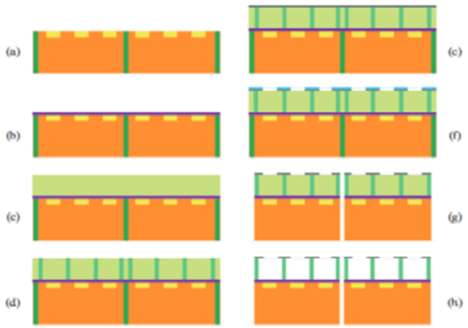
Prototype plan #2

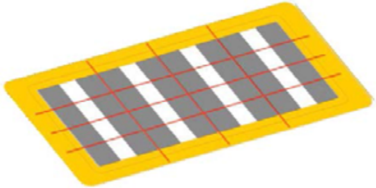
- **Realization of pixelated technology using GridPix chip collaborated Bonn**
  - **110um×110um and smaller**
  - Design the different readout pixelated size
  - Collaborated with Bonn University to produce the new prototype (Peter, Jan and Jochen from Bonn)
  - Study using UV laser tracks

University of Bonn
University

Production of GridPixes

a) Cleaning
b) Deposition of Protection layer
c) SU-8 covering
d) Exposure with mask
e) Aluminium layer is deposited
f) Another layer of photoresist is applied, exposer with a mask creates a hole pattern, and the holes are chemically etched
g) The wafer is diced
h) The unexposed SU-8 is resolved





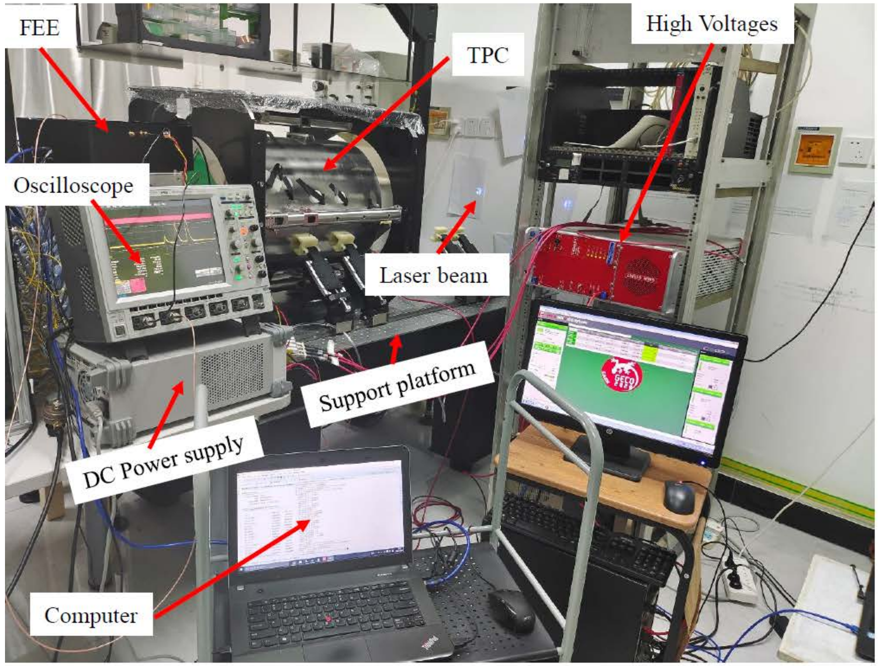
21

TPC ASCI readout R&D

- WASA V1: 16 channel AFE+ADC+LVDS data output
- The Power consumption: AFE in 1.4 mW/ch and ADC in 1 mW/ch
- Tested with TPC detector at IHEP:OK, more tests with more readout ongoing

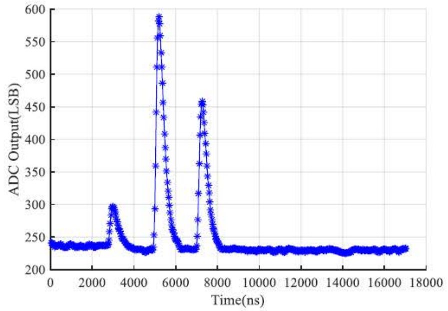
Deng Zhi (Tsinghua)

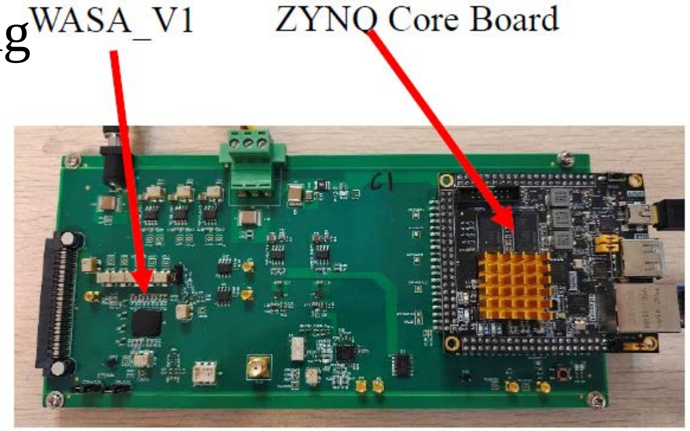
Test Results: Laser Tracks

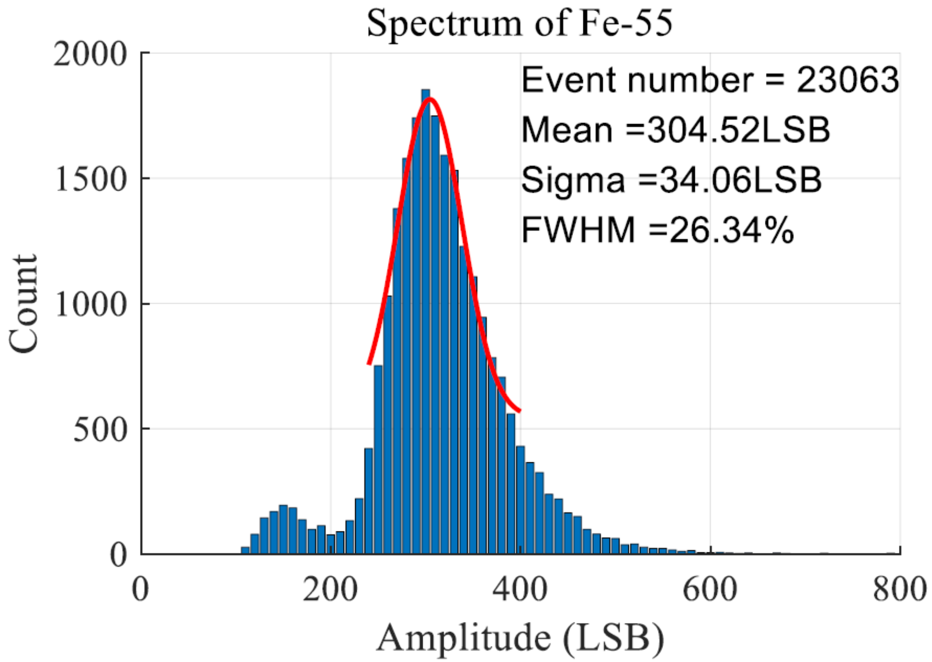


TPC Work Conditions：

- GEM: 280 V
- Drift Field: 9000 V/50 cm = 180 V/cm
- Gas: Ar/CF_4/iC_4H_{10} 95/3/2 (T2K)
- Laser: 7.2 mJ @20 Hz
- Sampling Rate： 30 MS/s



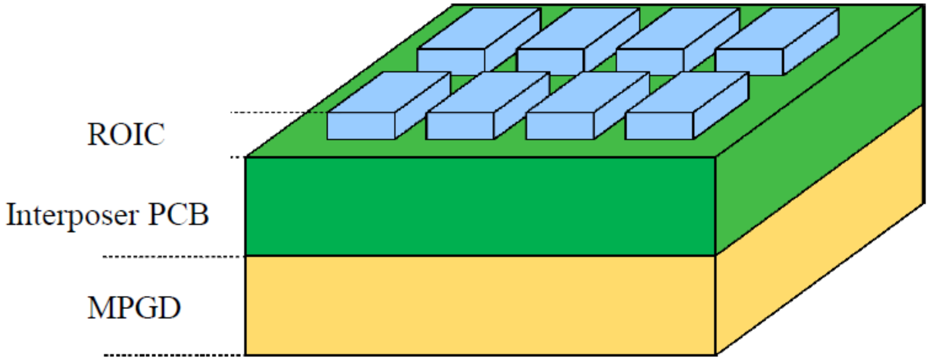


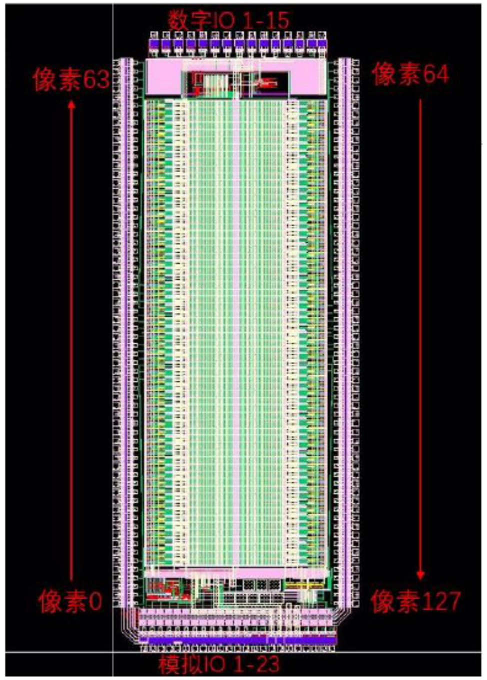


ASCI readout R&D onging

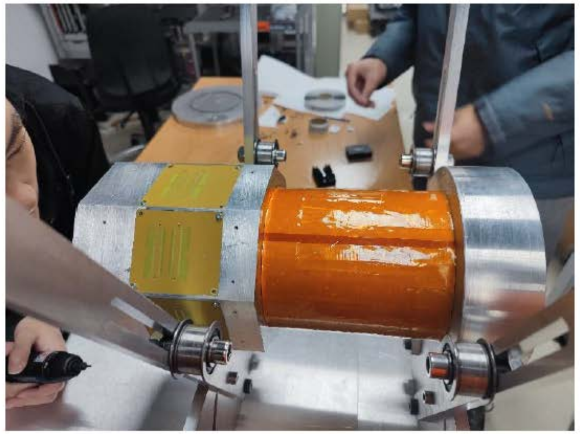
Deng Zhi (Tsinghua)

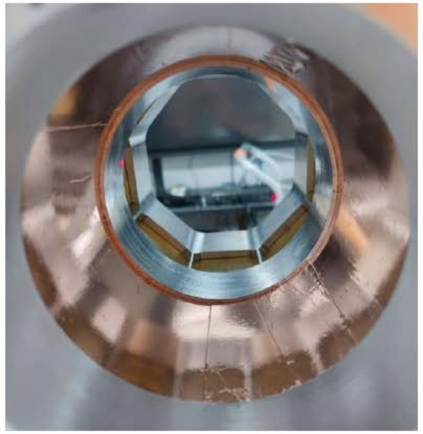
- Large Pixel Readout
  - 1mm x 6 mm → 0.3~0.5 mm pixel
  - Higher precision, higher rate
  - Potential for dN/dx
- Concept Design
  - ROIC +Interposer PCB as RDL
  - High metal coverage, 4-side buttable
  - Low power Energy/Timing measurement ASIC
    - ~100 e noise
    - 5 ns drift time resolution
    - <100 mW/cm2





- Simulation and experimental studies on uRWELL





Fang Zhujun(USTC)

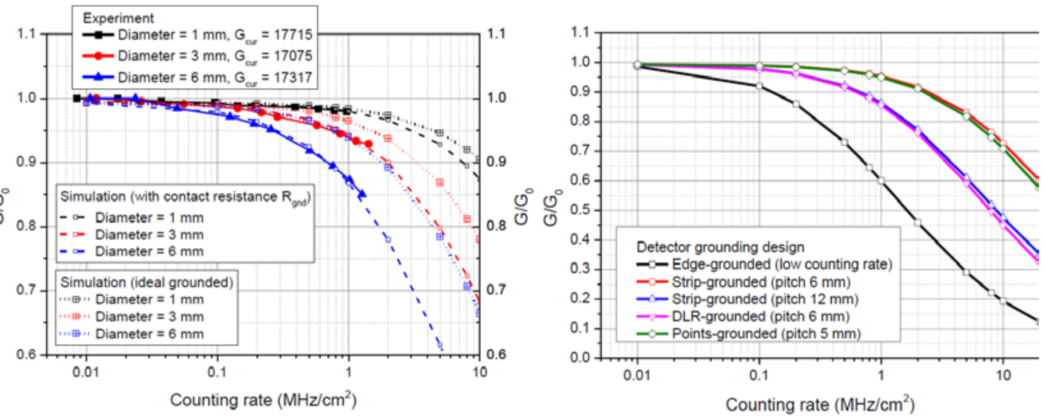
Low material budget

High counting rate capability

Large detection area with acceptable cost

Experiments show a good match with the simulation result

Optimize the fast grounding design of µRWELL, for better counting rate capability



Z. Fang, *et al.*, Simulation and optimization of a fast grounding design for micro-pattern gas detectors with a resistive layer, *NIMA*, 2022

1. µRWELL-based detector could used in the next generation colliders.
2. A cylindrical detector is studied:
   - Suppressing budget to approximately 0.25% X/X_0 per layer.
   - Optimizing mechanical structure and µRWELL film designs.
   - Promoting counting rate capability and spatial resolution.
3. In this step, the simulated spatial resolution of approximately 100 µm and 400 µm in rφ and z direction, respectively.

uRWELL for next generation collider

Fang Zhujun(USTC)

Inner tube: tradeoff between material budget and structural strength

(Key point: adhesion, substrate, manufacturing technologies)

μRWELL film: FPCB technologies

Structure	Material	Thickness (cm)	Material budget (X/X_0)
Inner tube	Aluminum (X_0=8.897 cm)	0.001	**0.011%**
	Polyimide (X_0=28.57 cm)	0.01	**0.035%**
	Aramid honeycomb/Rohacell foam (X_0≈267 cm)	0.2	**0.075%**
Gas Volume	Argon-based gas mixture (X_0=11760 cm)	0.5	0.0043%
Outer tube (μRWELL film)	Aluminum (X_0=8.897 cm)	0.0015	0.017%
	Polyimide (X_0=28.57 cm)	0.03	0.106%
	DLC (X_0=12.13 cm)	0.0001	0.00082%
Total			**0.249%**

- Low material budget realization
- Mechanical structure optimization
- μRWELL film optimization
- Counting rate capability optimization
- Spatial resolution performance

Conclusion

- Classical PID with dE/dx by charge measurement established since many decades at large detectors
  - dE/dx resolution depends on track length and gas pressure
- Cluster Counting promises up to ~3x better dE/dx resolution (~2x better separation power)
  - in time (small drift cells) , needs very fast electronics
  - in space (TPC + pixelated endplates) , needs good cluster finding algorithm
- Cluster Counting can be complementary to classical dE/dx by the spread charge
  - Many groups focus on it and ongoing for CEPC, FCC-ee …
- In my view, ‘Real’ new ideas need and beyond.

Many thanks!