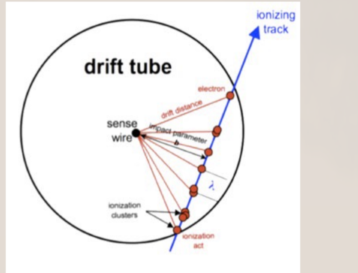
Enhancing Particle Identification for Future Circular Collider Experiments using Cluster Counting Technique

W. Elmetenawee[1,*], M. Abbrescia[1,2], M. Anwar[3], A. Corvaglia[4], N. De Filippis[1,3], F. De Santis[4,5], E. Gorini[4,5], F. Grancagnolo[4], F. G Gravili[4,5], M. Louka, A. Miccoli[4], M. Panareo[4,5], M. Primavera[4], F. M. Procacci[1,2], A. Ventura[4,5]

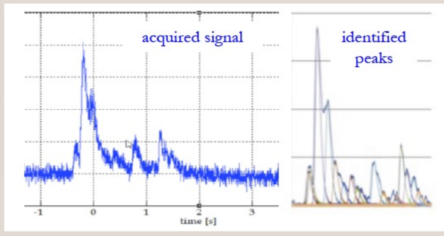
[1]INFN di Bari, [2]Universit`a di Bari, [3]Politecnico di Bari, [4]INFN di Lecce, [5]Università del Salento

A Cluster Counting Technique

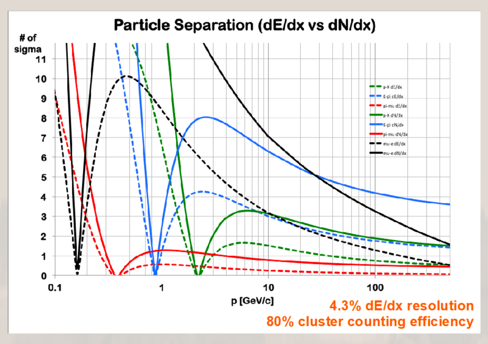
➢Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.



➢By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.). with a better resolution w.r.t the dE/dx method.



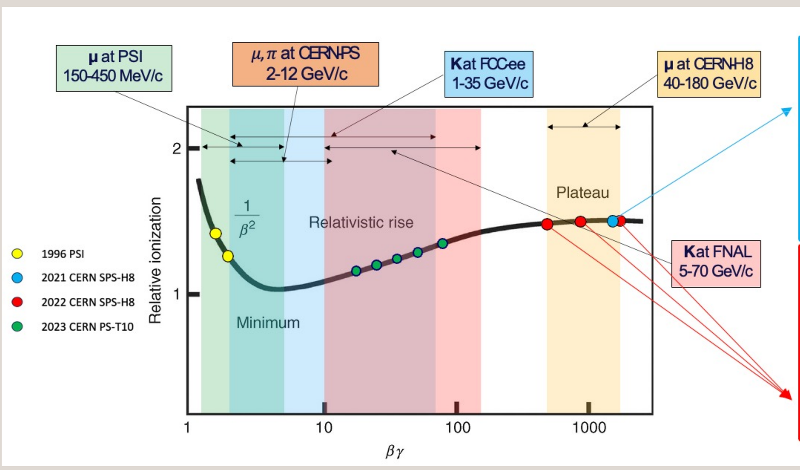
➢Analytic calculations: Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines).

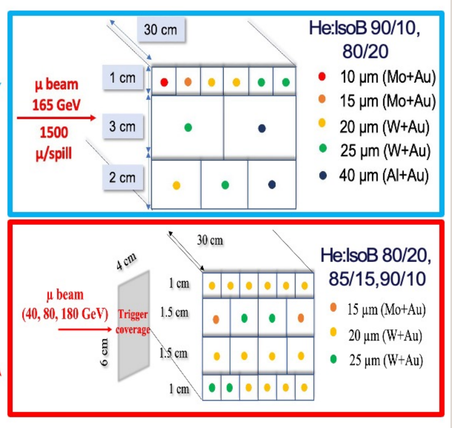


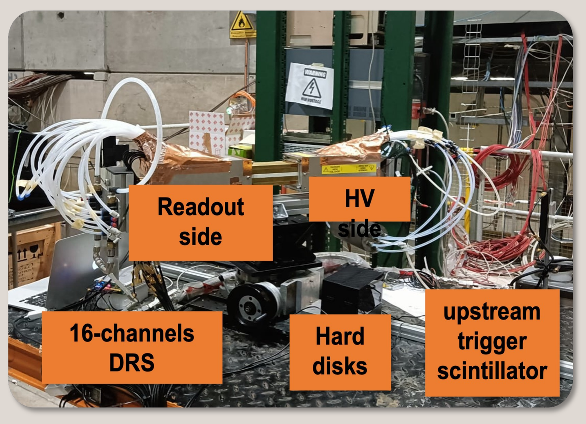
B Beam Test setup & goals

➢Beam tests to experimentally assess and optimize the performance of the cluster counting/timing techniques.

- Two muon beam tests performed at CERN H8(βγ > 400) in Nov. 2021 and July 2022.
- Two muon beam tests performed at CERN T10 in Jul 2023 and Jul 2024 using μ beam (1-12 GeV).
- Another test is planed to be done at FNAL-MT6 with π and K ($\beta\gamma$ = 10−140) to fully exploit the relativistic rise.







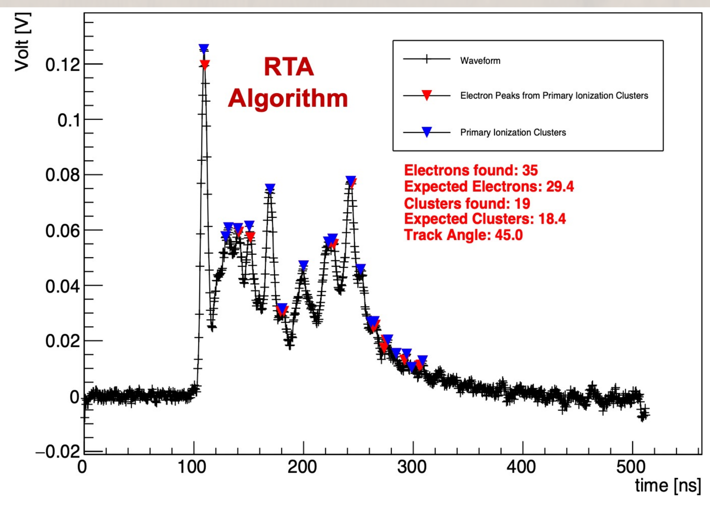
C Electron-peaks finding algorithms

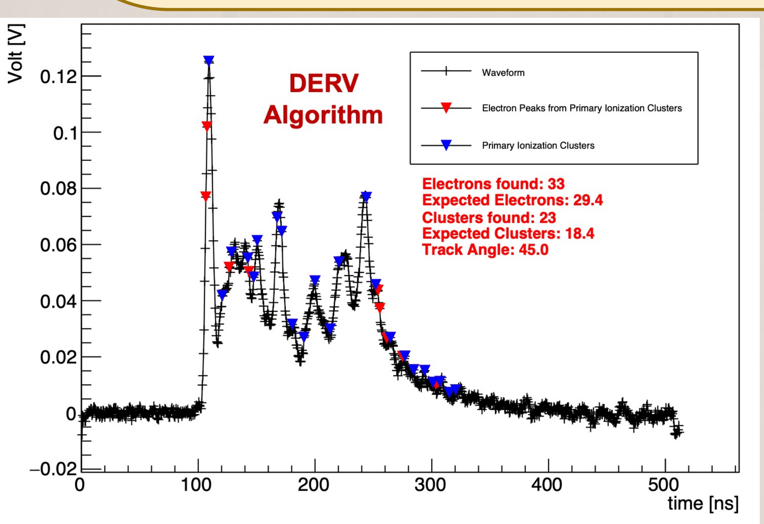
Running Template Algorithm (RTA)

- ➢ Defines an electron pulse template with exponential rise/fall
- ➢ Digitized to match the data sampling rate
- ➢ Scans waveform using a sliding window
- ➢ Compares template to data and applies a threshold to find peaks
- ➢ Subtracts found peaks and repeats until no new peaks are detected

Derivative Algorithm (DERIV)

- ➢ Computes first and second derivatives using amplitude averaged over twice the timing resolution.
- ➢ At the peak candidate position:
  - Derivatives must be smaller than the signal-related r.m.s.
  - Derivatives must increase before and decrease after the peak
  - Amplitude must be greater than the r.m.s.
  - Amplitude difference with neighboring points must also exceed the r.m.s.



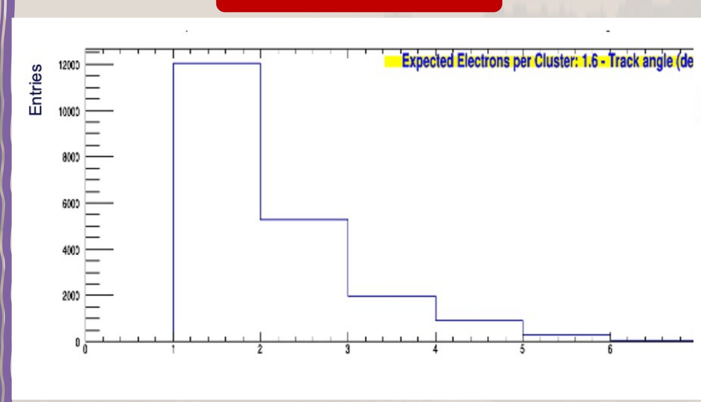


D Reconstruction of Primary Ionization Clusters

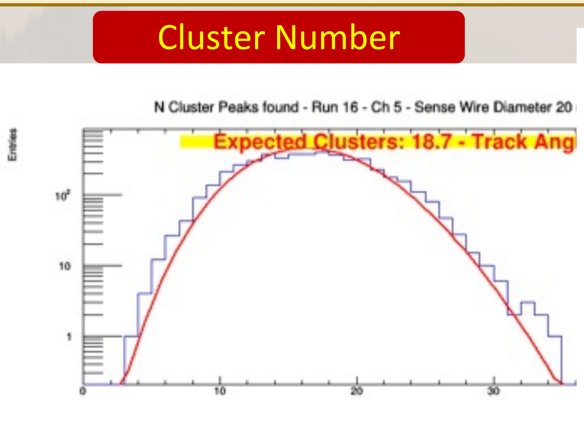
Clusterization algorithm

- ➢Merges nearby electron peaks to avoid overcounting fake electrons.
- ➢Peaks close in time, within the expected electron diffusion window (∝ √t, gas-dependent), are treated as one ionization cluster.
- ➢Each cluster counts the number of merged electrons.
- ➢Cluster position and amplitude taken from the highest peak.
- ➢Number of clusters follows a Poisson distribution.

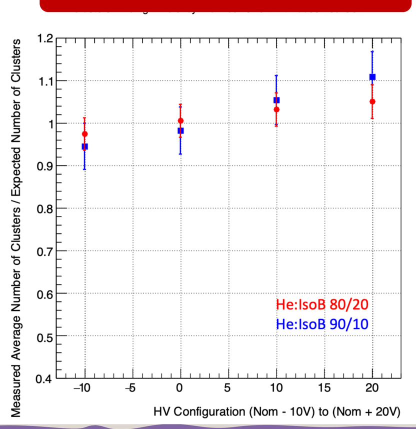
Cluster Size



Cluster Number



HV scan



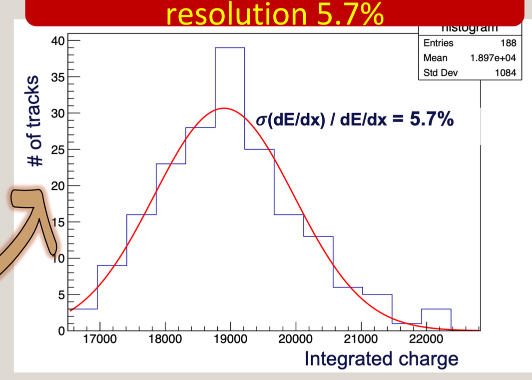
E Comparative Analysis of dE/dx and dN/dx Resolution

➢Compares two methods using identical particle tracks:
- ✓ dE/dx – energy loss per unit length
- ✓ dN/dx – ionization cluster density

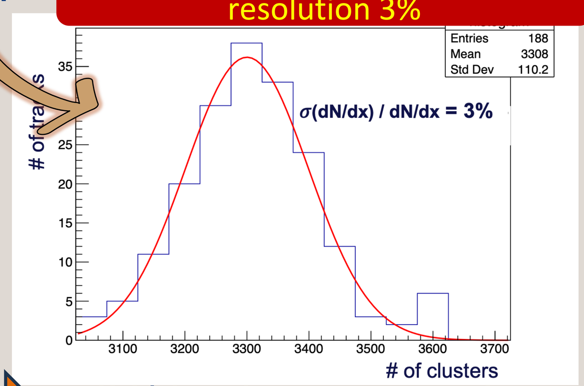
➢ dE/dx uses charge deposits along the track
- Follows a Landau distribution with large fluctuations.
- Truncated mean (removing top 20% charges) improves stability.

➢ dN/dx uses RTA + clusterization to count ionization clusters

@2m long track we have dE/dx resolution 5.7%

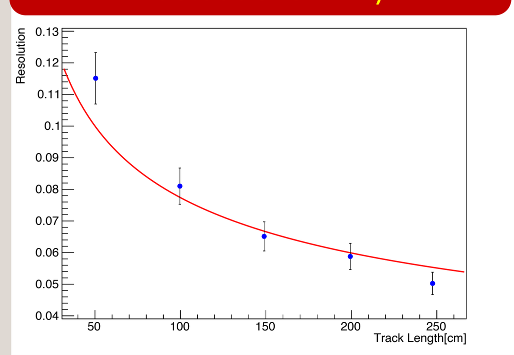


@2m long track we have NE/dx resolution 3%

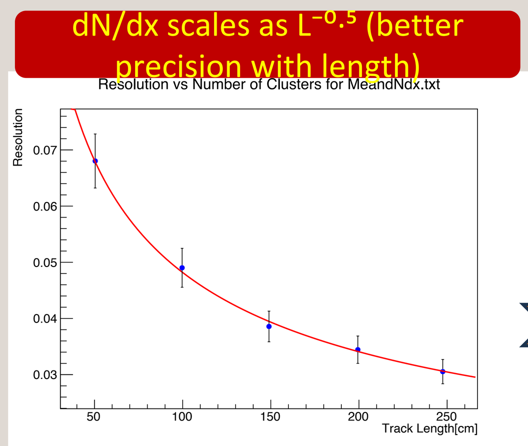


Resolution vs. track length:

dE/dx scales as $L^{-0.37}$ (Landau fluctuations limit)



dN/dx scales as $L^{-0.5}$ (better precision with length)



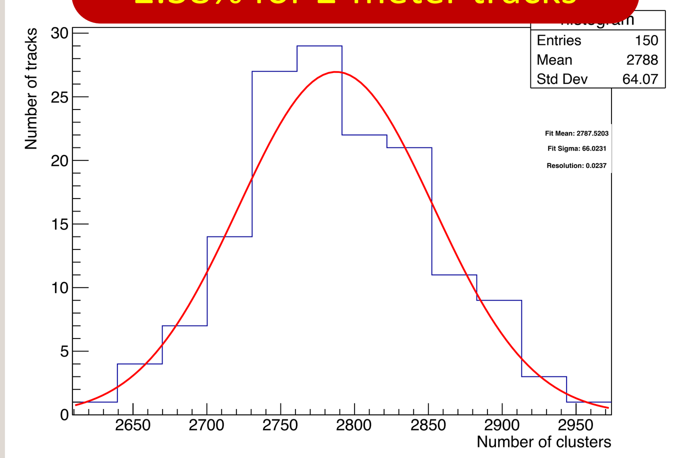
dN/dx shows superior resolution and scaling behavior

F Improved dN/dx Resolution with Waveform Cleaning and Physical Corrections

Waveform Cleaning for Improved dN/dx Resolution:

- ➢ Applied cleaning criteria to reject distorted or incomplete waveforms
- ➢ Required cluster time span to stay within a physically reasonable range
- ➢ Suppressed tracks with wide or noisy signals

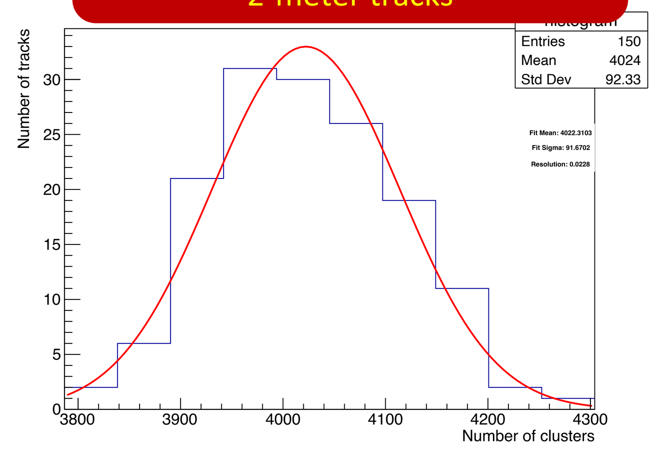
Resulted in improved dN/dx resolution: from 3.00% to 2.38% for 2-meter tracks



Correction for Recombination and Attachment Effects

- ➢ Ionization electrons can be lost due to recombination or attachment during drift
- ➢ Applied a time-based correction to compensate for cluster loss:
  - Derived from the trend of cluster count vs. time
  - Used 2D histograms (clusters vs. time)
  - Fitted time profiles with a linear (first-order) function
- ➢ Correction applied event-by-event to account for spatial variations

Resulted in improved dN/dx resolution: from 2.38% to 2.28% for 2-meter tracks



G Conclusions

The cluster counting technique offers a significant advancement in particle identification, supported by both analytical studies and simulations. The development of the DERIV and RTA algorithms enabled accurate electron peak detection, with performance validated using test beam data. Resolution studies showed that the dN/dx method achieves a resolution 2.5 times better than the traditional dE/dx approach, matching theoretical expectations. These results highlight the strong potential of cluster counting for future detector technologies.

H References

[1] G. Cataldi, F. Grancagnolo and S. Spagnolo, Cluster counting in helium based gas mixtures, Nuclear Instruments and Methods in Physics Research 386 (1997) 458.

[2] W. Elmetenawee and et al, Advancing Particle Identification in Helium-Based Drift Chambers: A Cluster Counting Technique Study through Beam Tests. PoS ICHEP2024 (2025), 1067.

[3] I. Lehraus and et al, Particle identification by dE/dx sampling in high pressure drift detectors, Nucl. Instr. Meth. 196 ((1982) 361) .

EPS-HEP 2025, 6-11 Jul, Marseille, France

*email address: Walaa.Elmetenawee@ba.infn.it

Poster ID#798