Straw Tracker Development for FCC-ee

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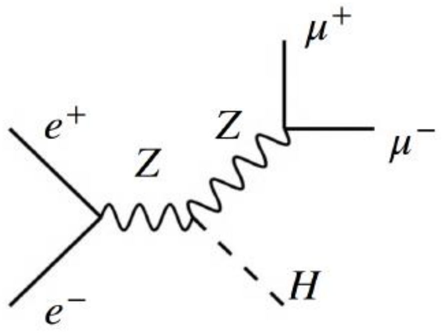
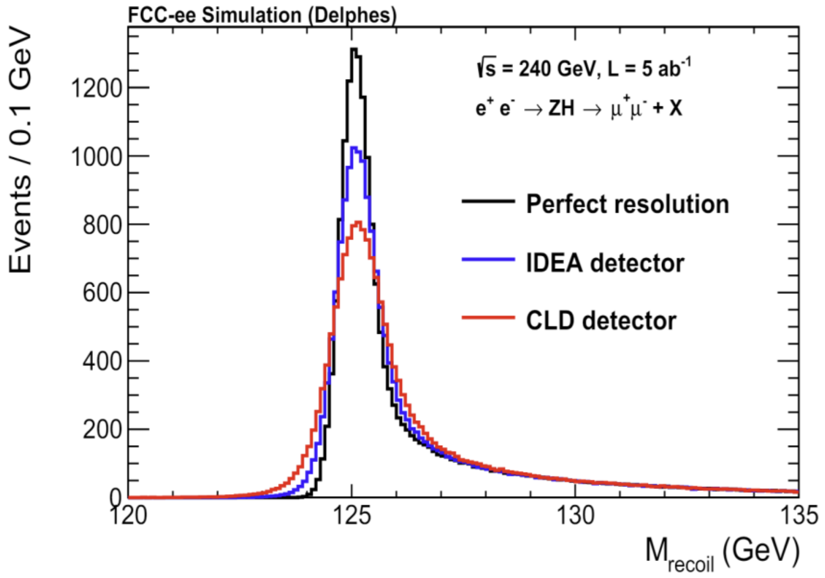
FCC-ee Tracker Requirements

- **Requires track momentum resolution ~0.2% at 45 GeV**
  - 5-10x better than current ATLAS and CMS inner tracker resolutions at the same energy
  - Needed to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section

$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

  - Momentum resolution should not be worse than beam energy spread (~0.16% at 240 GeV)
- **PID capabilities for a wide momentum range**
  - >3σ π/K separation from O(100) MeV to O(40) GeV
- Two proposed approaches:
  - Silicone only tracker+ specific PID detector (CLD)
  - pixel detector + **gaseous tracker** + silicon wrapper (IDEA with open drift chamber as the gaseous tracker)





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Straw Tracker Proposal

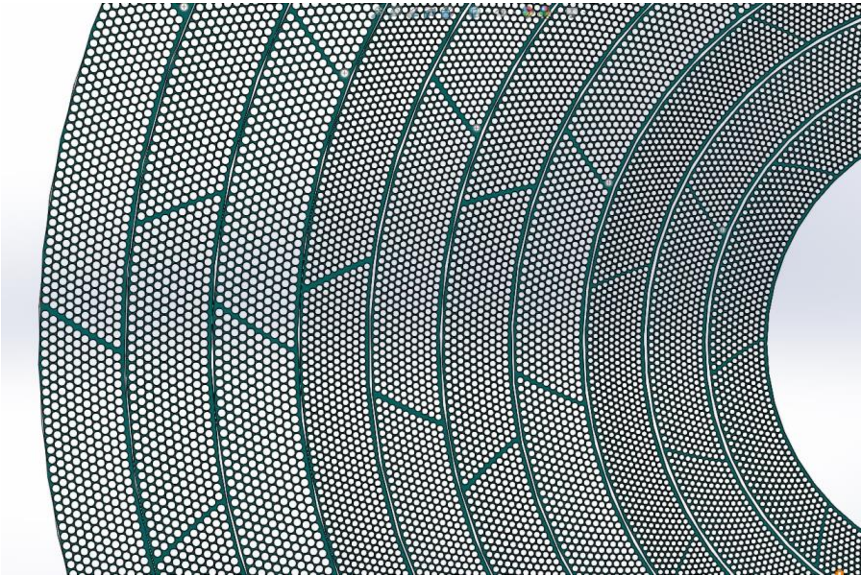
We propose to build a thin-wall straw tracker for FCC-ee

- 12 µm thin Mylar film straws with gold/copper coating
- 20 µm diameter Tungsten wire
- Filled with He-isobutane gas mixture
- Single hit resolution: 100 µm

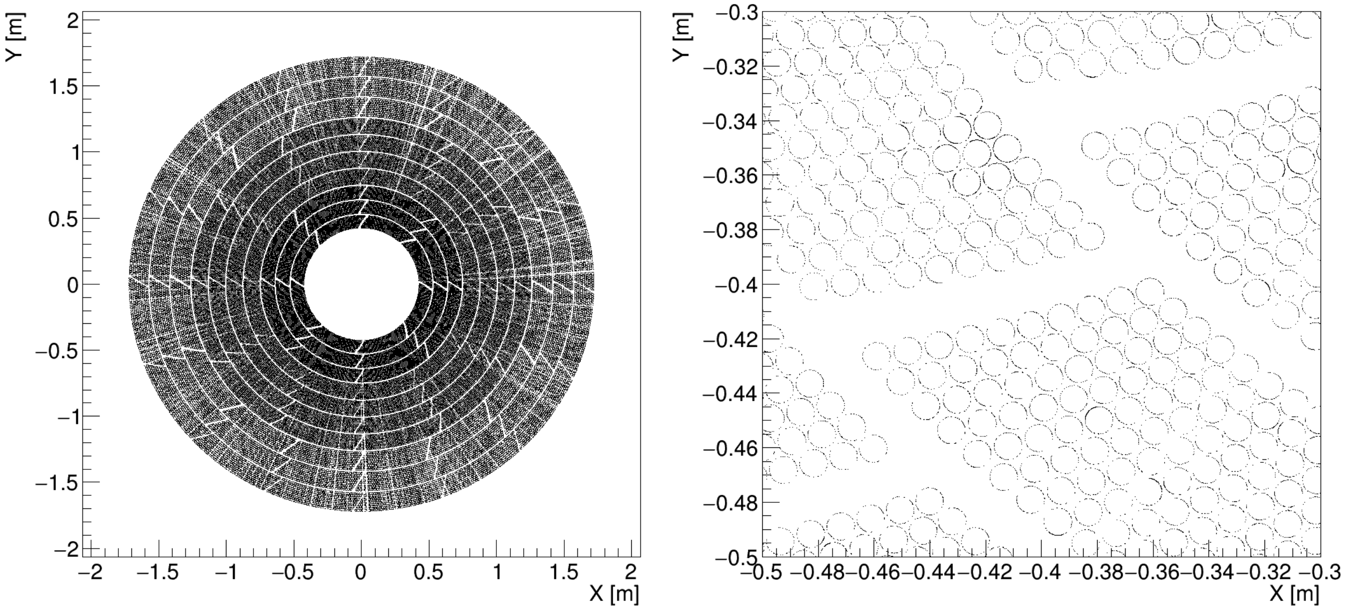
Benefits

- Low material budget
- Straw tubes are independent
- Great adaptability in design, construction, and operation
- PID with dN/dX

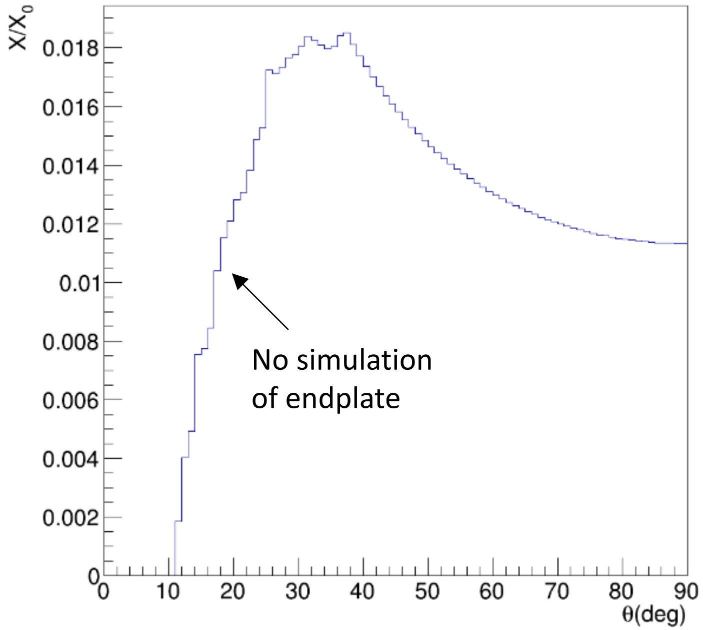
Example layout:
Radius coverage: 31.1 cm to 184.2 cm
Length: 4.0-5.5 mm
Tube diameter: 1.0-2.0 cm
Stereo angle: 2-5°
10 multilayers, 10 straw layers each
~60,000 total straws



GEANT Simulations: Material Effects



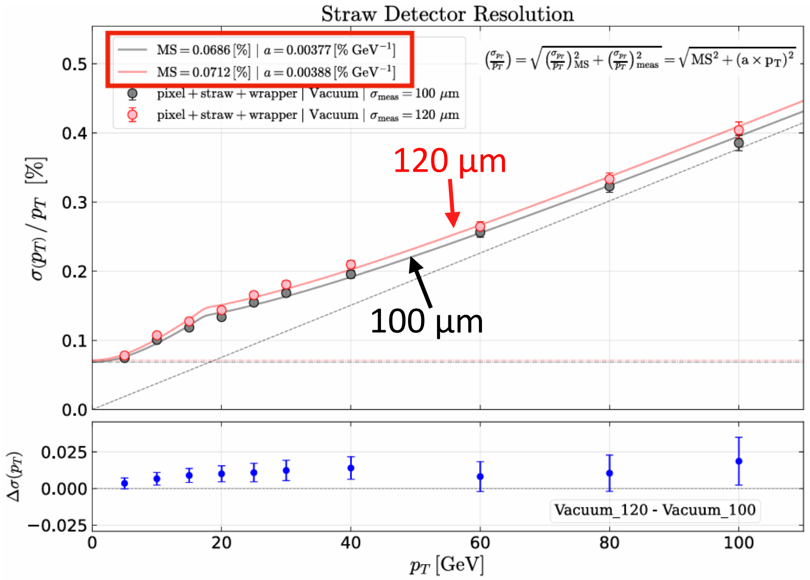
GEANT simulated hits for 5000 muons with p_T=20 GeV



For 100 layers with 12 μm thickness,
~3.7 mm Mylar in total, **~1.2% X_0 at $\theta = 90°$**

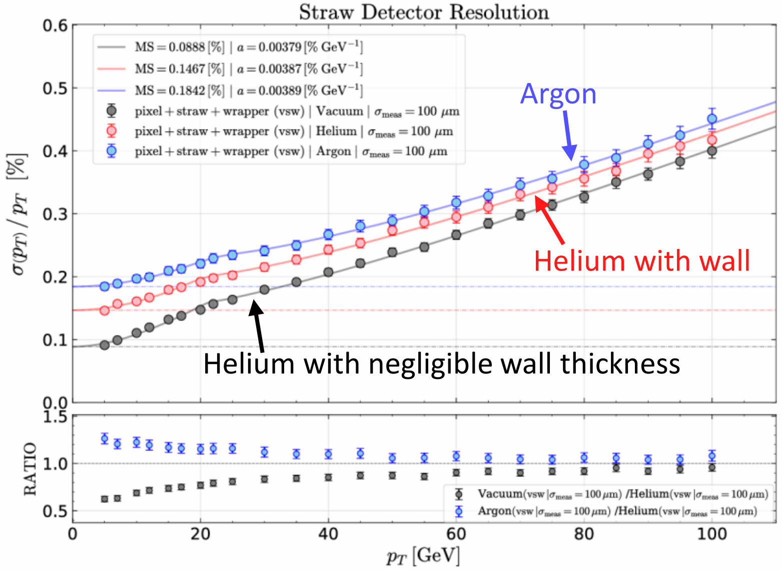
X_0 dominated by Mylar wall, negligible contributions from gas and coating material
→ **minimal material is crucial!**

GEANT Simulations: Momentum Resolution Studies



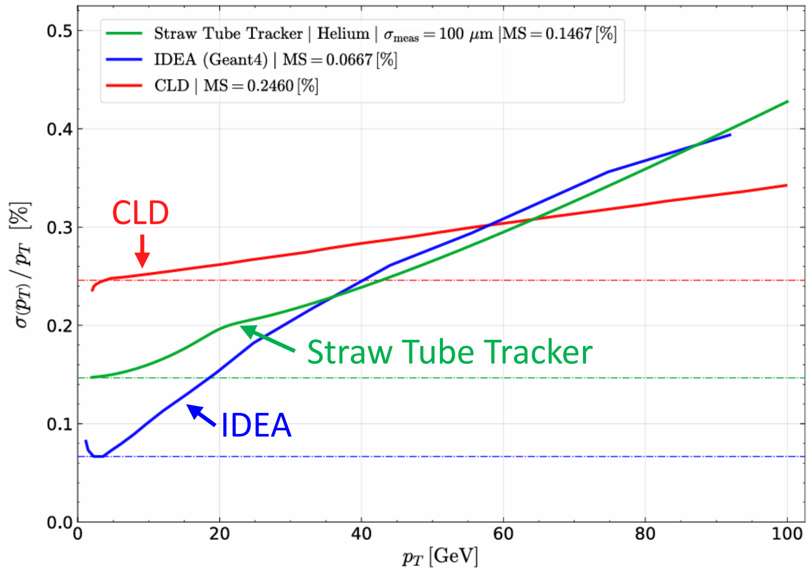
Effects of single hit resolution

$$\left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{MS}} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{\mathrm{meas}}} = \sqrt{\mathrm{MS}^2 + (a \times p_T)^2}$$



Impact of different gases:

- Helium with negligible wall thickness
- Helium with wall
- Argon



Comparison with CLD and IDEA

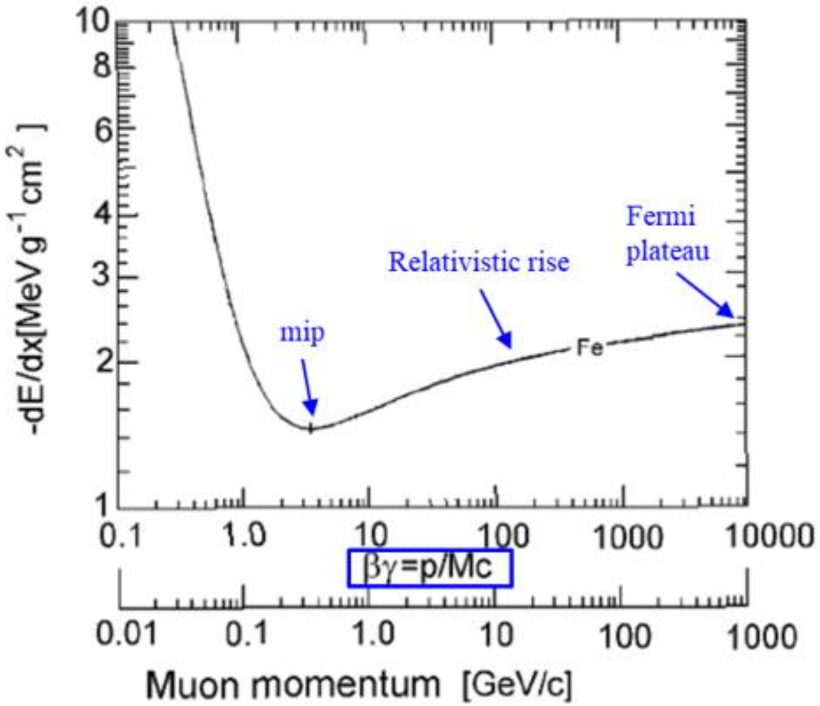
Traditional dE/dX Method

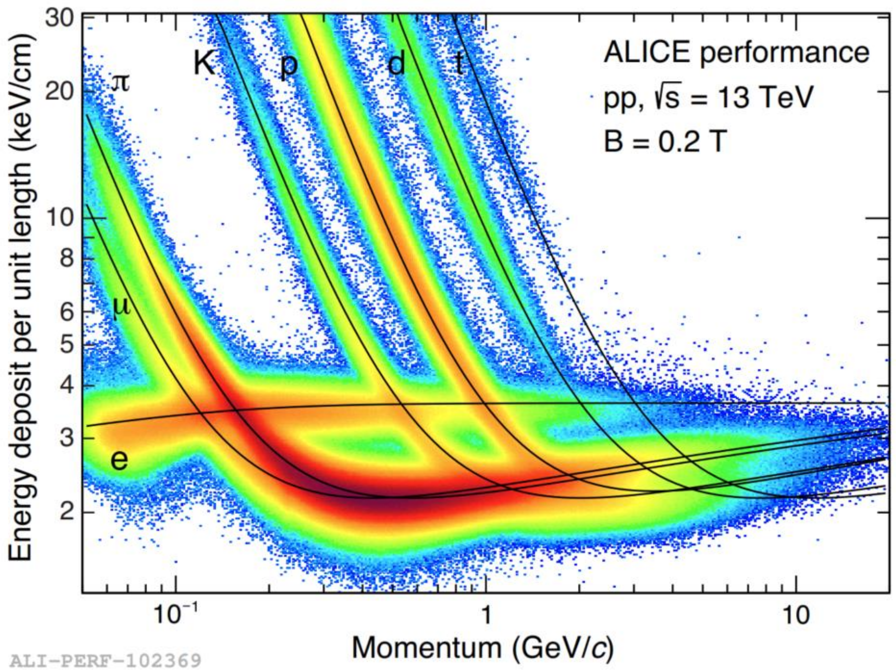
Gaseous detectors are known for good PID though dE/dX

- dE/dX: ionization energy loss per unit length

Limitations of dE/dX

- Energy loss fluctuations in Landau distribution
- Resolution is sensitive to gas gain fluctuations





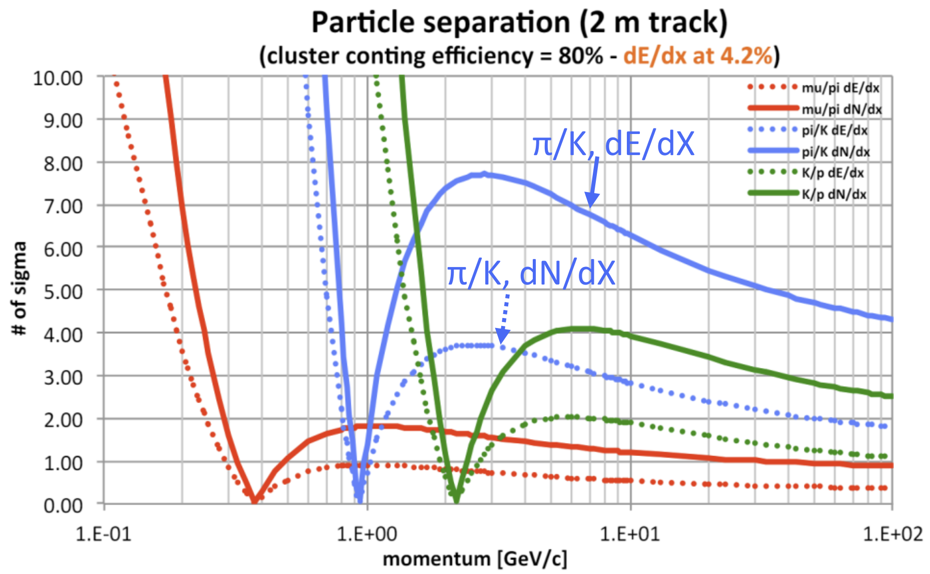
Cluster Counting Method (dN/dX)

Instead, count number of primary ionization clusters per unit length

Improves resolution

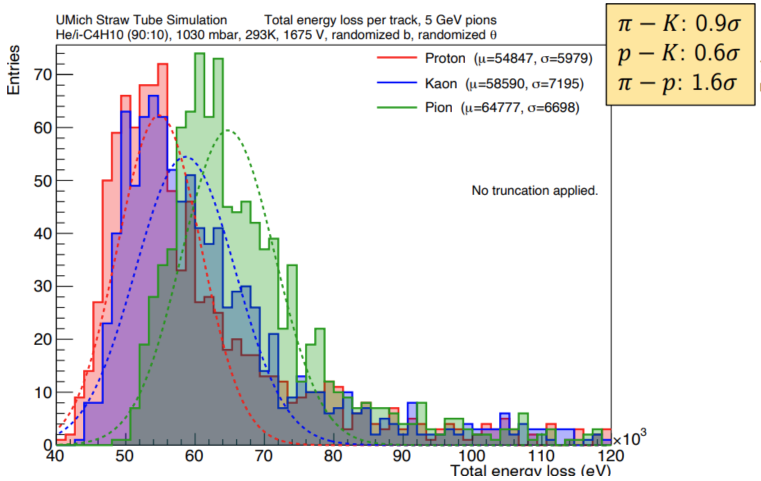
- e.g. (top right plot) For a 2-meter gas track at 1 bar with 20 clusters/cm (N_p=4000), resolution is $1/\sqrt{N_p}$~1.6% vs 4.2% for dE/dX

No previous experiments have implemented this technique!

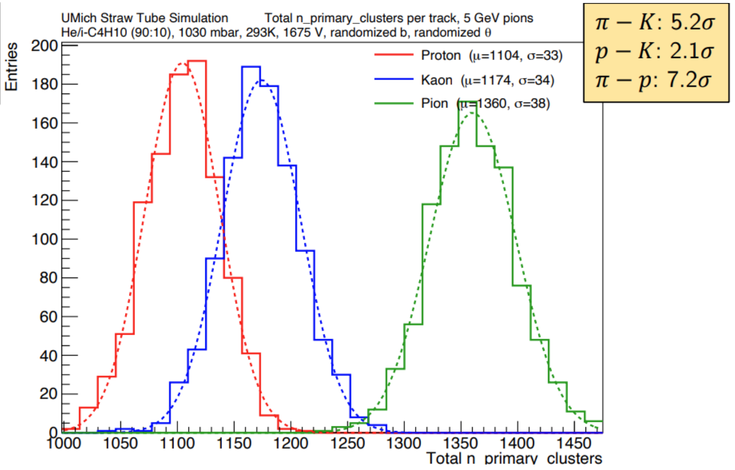


Bethe-Bloch predictions

Garfield++ Simulations:



dE/dX: Ionization energy loss for pion, kaon, and proton tracks with a path length of 107 cm



dN/dX: Number of primary clusters produced by pion, kaon, and proton tracks with a path length of 107 cm

Cluster Counting Method (dN/dX)

Instead, count number of primary ionization clusters per unit length

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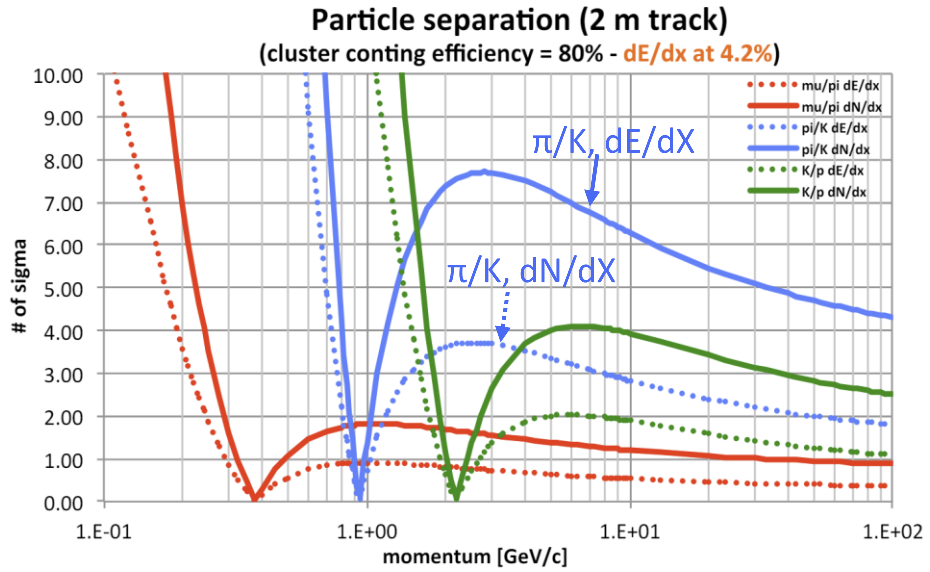
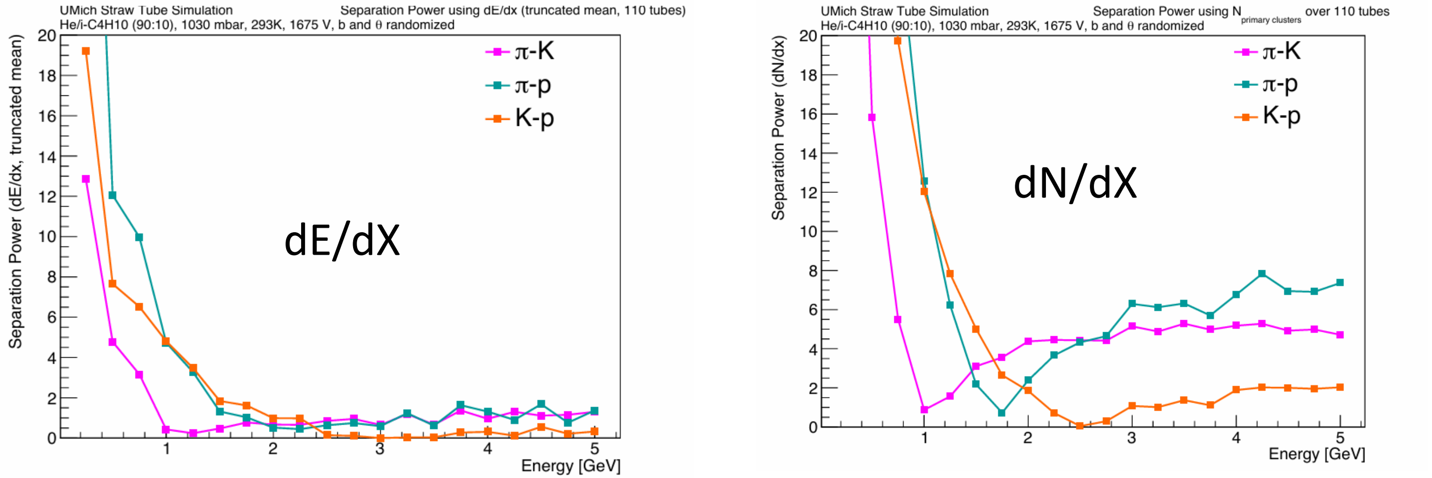


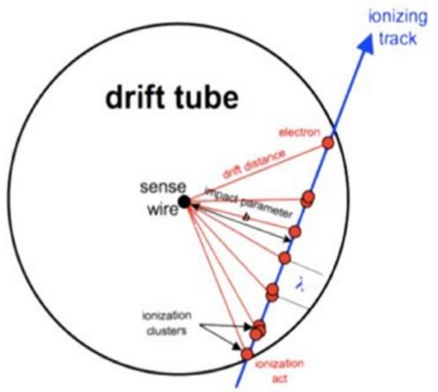
Bethe-Bloch predictions

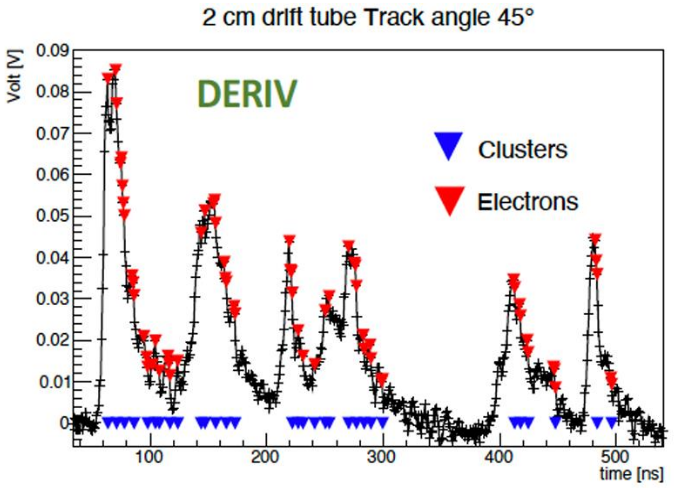


Garfield++ simulation of separation power with He-isobutane at 1 bar

dN/dX Challenges

- Single electron resolution
  - 90% of clusters contain only one electron. Even with gas gain ~10^5, collecting signal is <1 fC due to attenuation → requiring large amplification and low-noise electronics





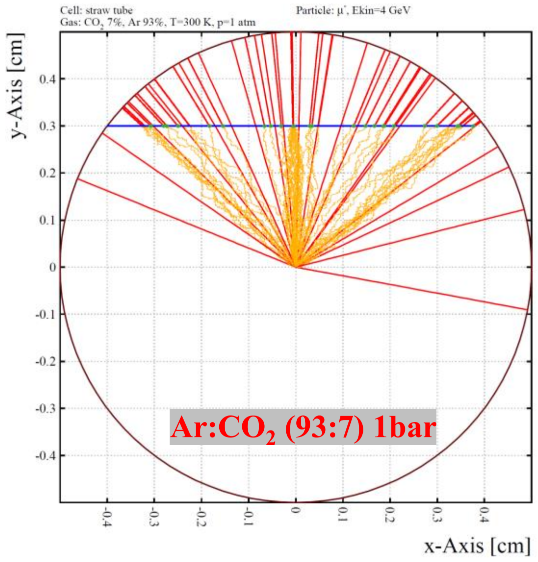
N. De Filippis

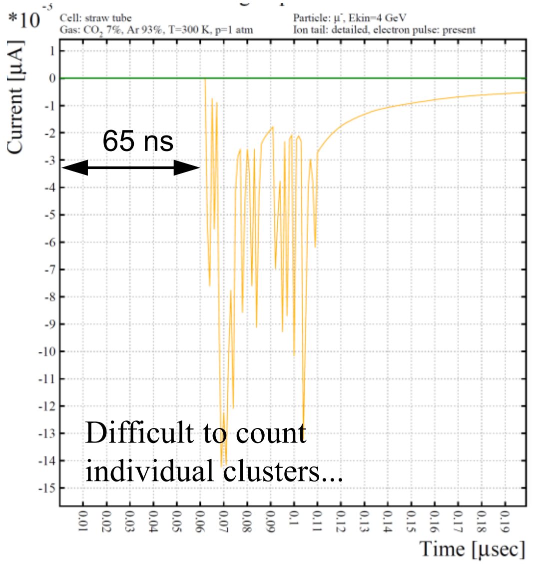
- Timing optimization
  - balancing sufficient resolution to separate nearby primary clusters while not over-resolving secondaries from the same cluster → gas mixture studies
- Waveform digitization
  - need to capture full waveforms at 1 ns resolution over hundreds of ns → fast digitizer
- Data volume
  - digitizing every waveform from O(60,000 channels) is nonrealistic → need fast peak-finding and cluster-finding algorithms implemented in hardware
- Noise suppression

Gas Mixture Studies

Choice of gas mixture important for optimizing dN/dX

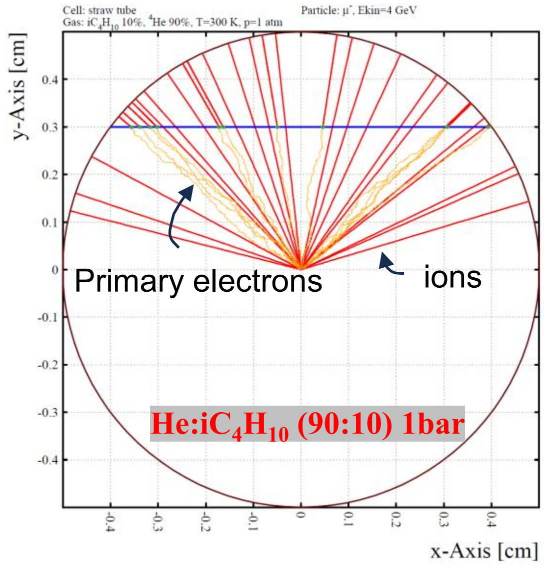
Needs high primary ionization density, low diffusion, wide cluster separation

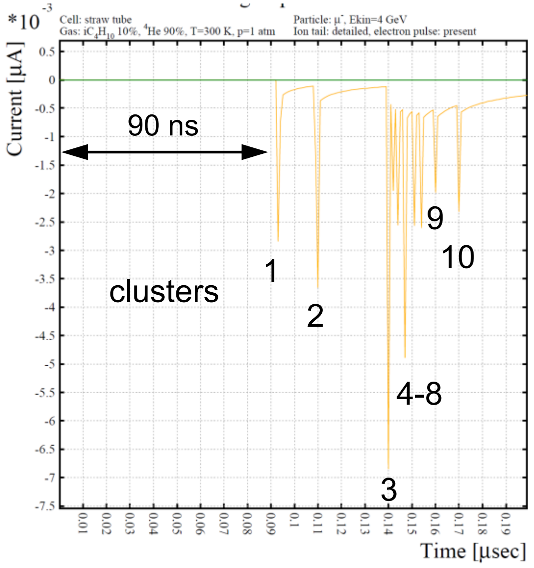




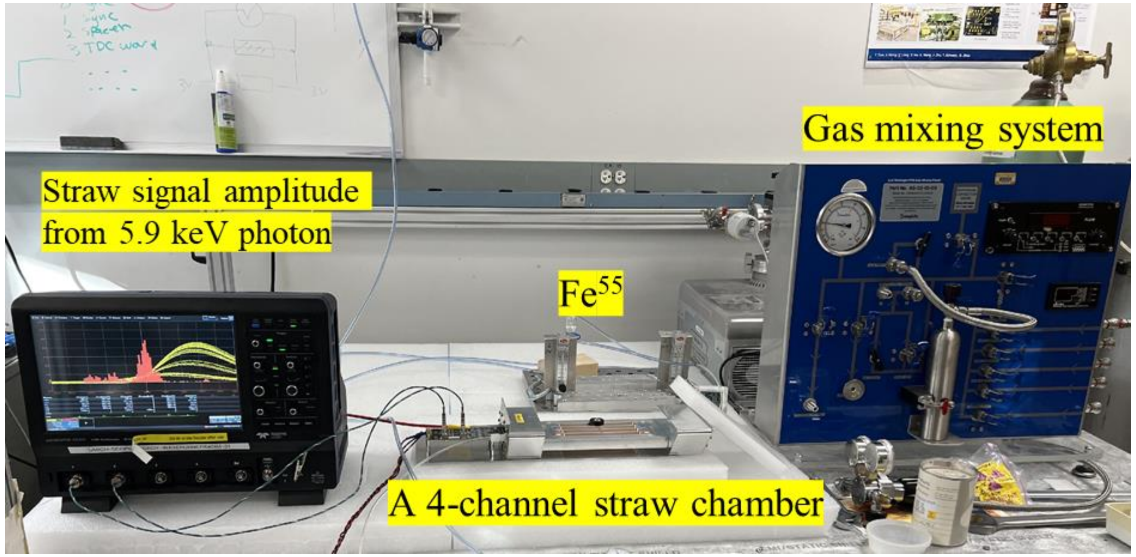
Simulations with Garfield++ show

- **Ar/CO2**: higher cluster density (~40/cm) but shorter cluster separation (~2-3 ns)
- **He-isobutane:** lower cluster density (~10/cm) but longer cluster separation (~7-45 ns)

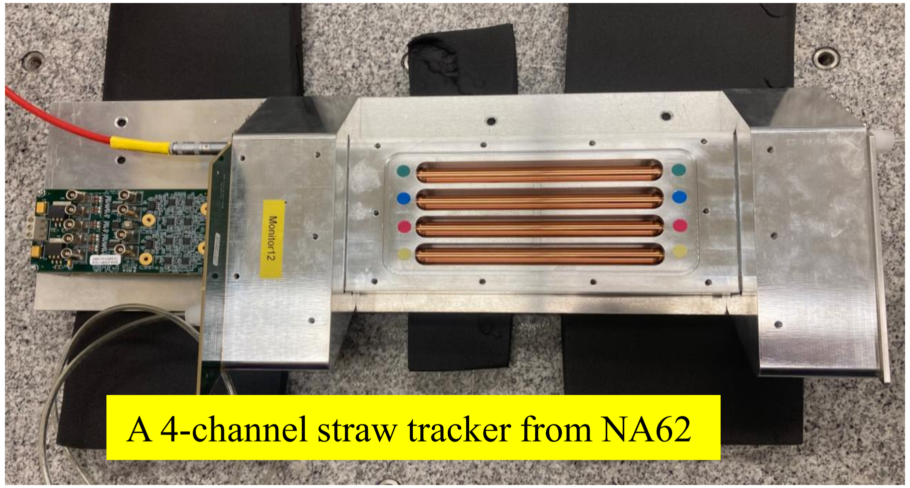


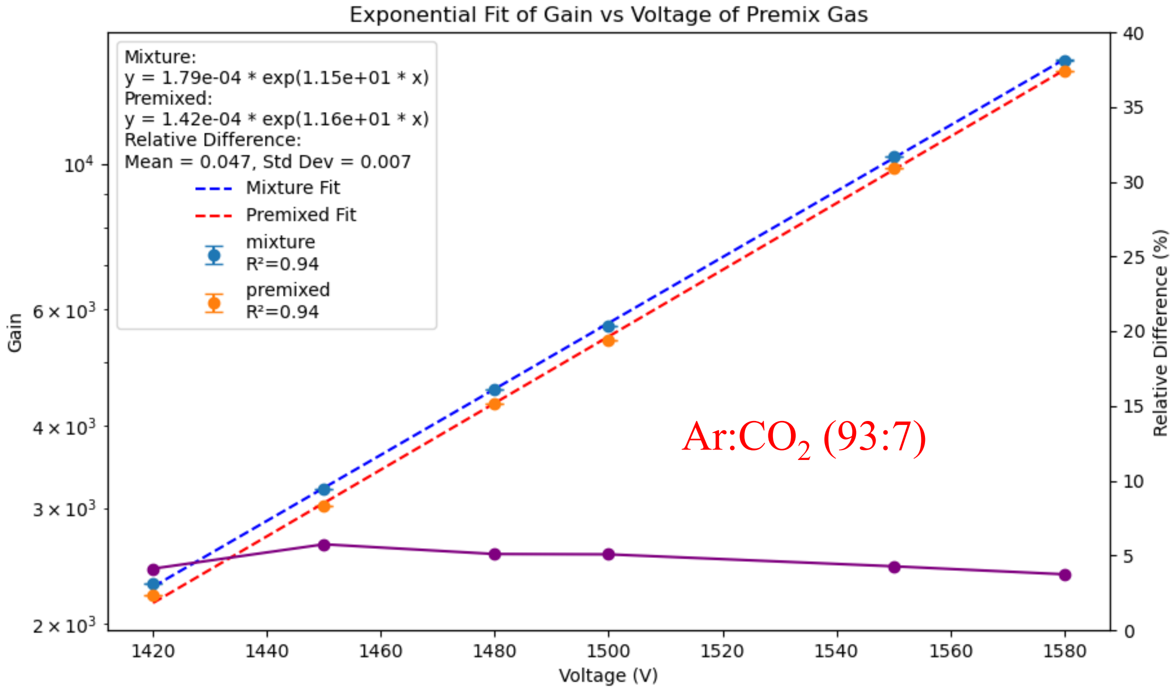


Gas Mixing System at Michigan



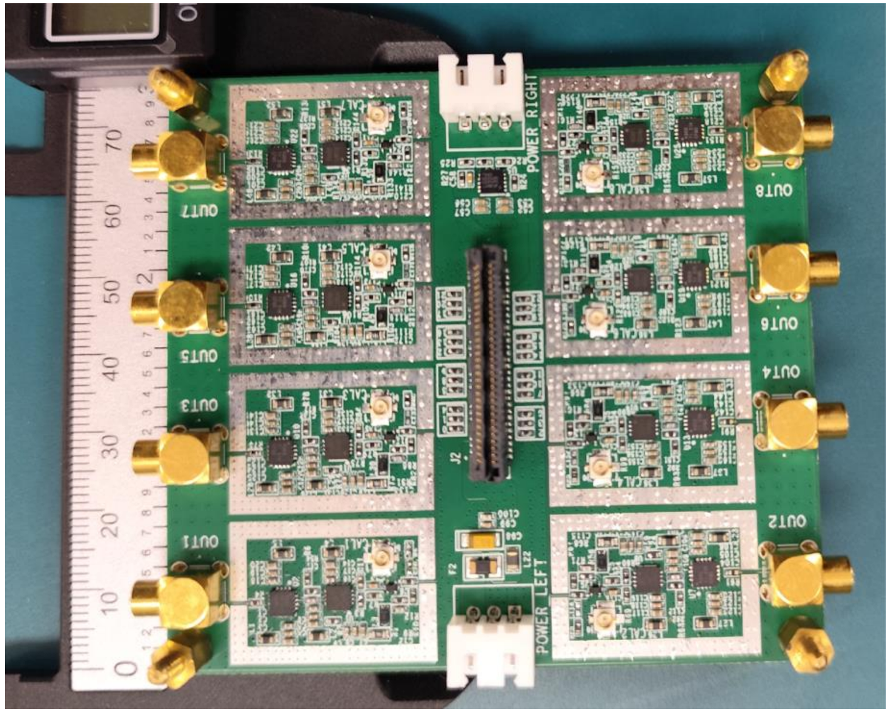
- System can mix up to 4 different gases
- Straw tracker used for gas gain studies
- Needs upgrade to mix He with liquified Iso

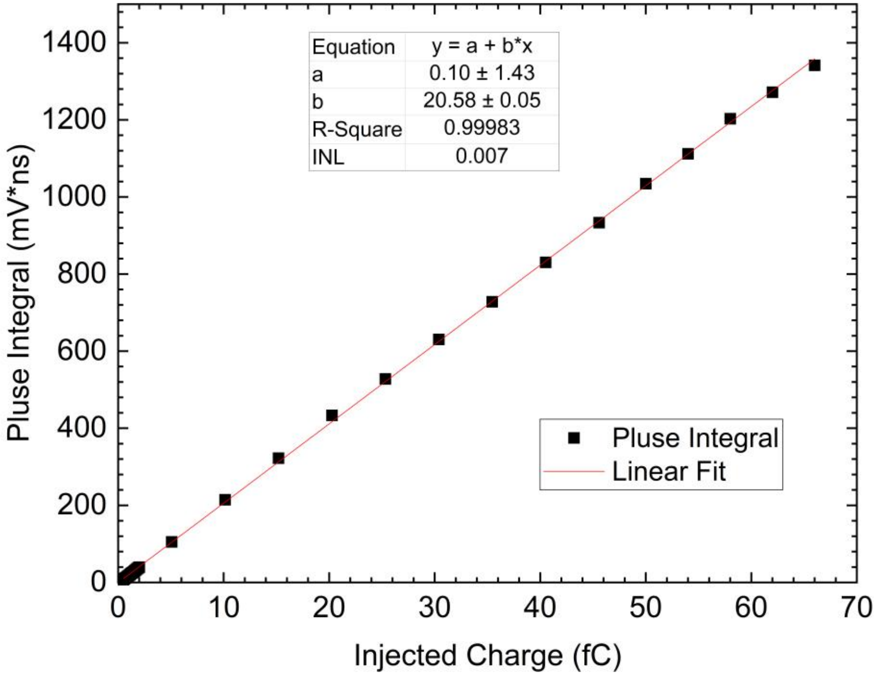




New Fast Amplification Board

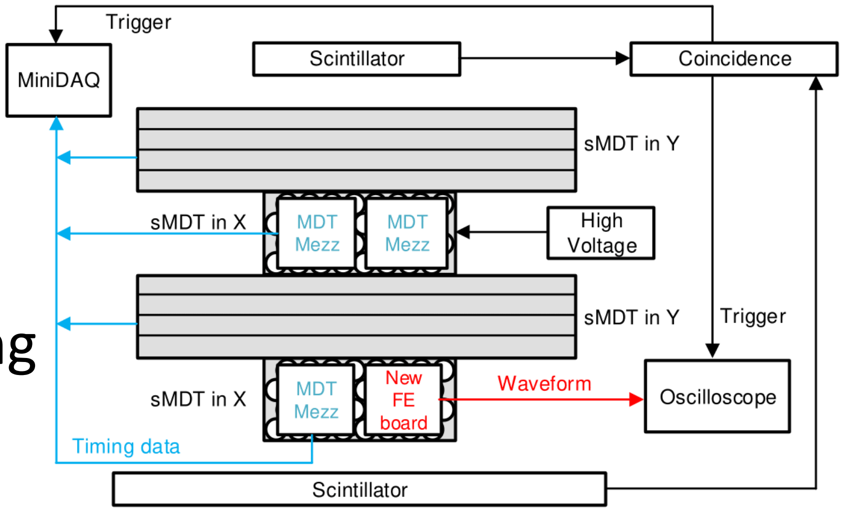
- 8-channel front-end fast amplification board with O(100) gain has been designed and produced
- Purpose: need to record full waveforms and enough amplification to detect single electron
- Waveforms will be recorded by CAEN DRS4 waveform digitizers, but oscilloscope is used for testing
- Customized Faraday Cages to cover each channel
- Mounted an sMDT mini-chambers (8) to perform dN/dX studies using cosmic rays in the lab and test beams at CERN

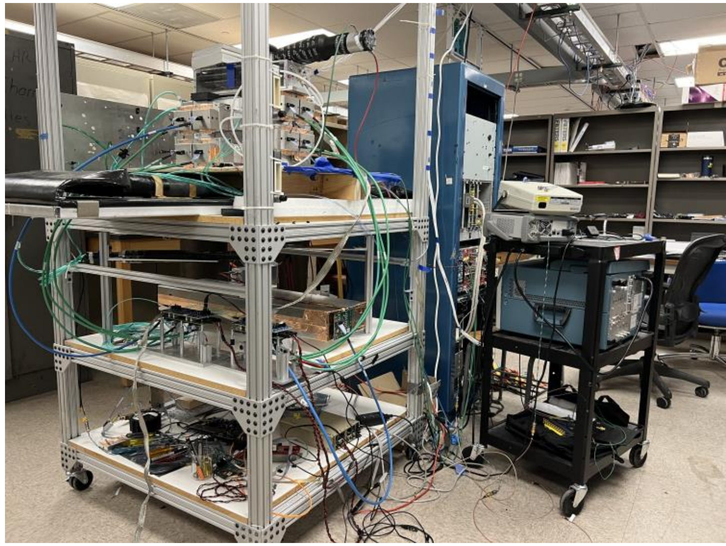


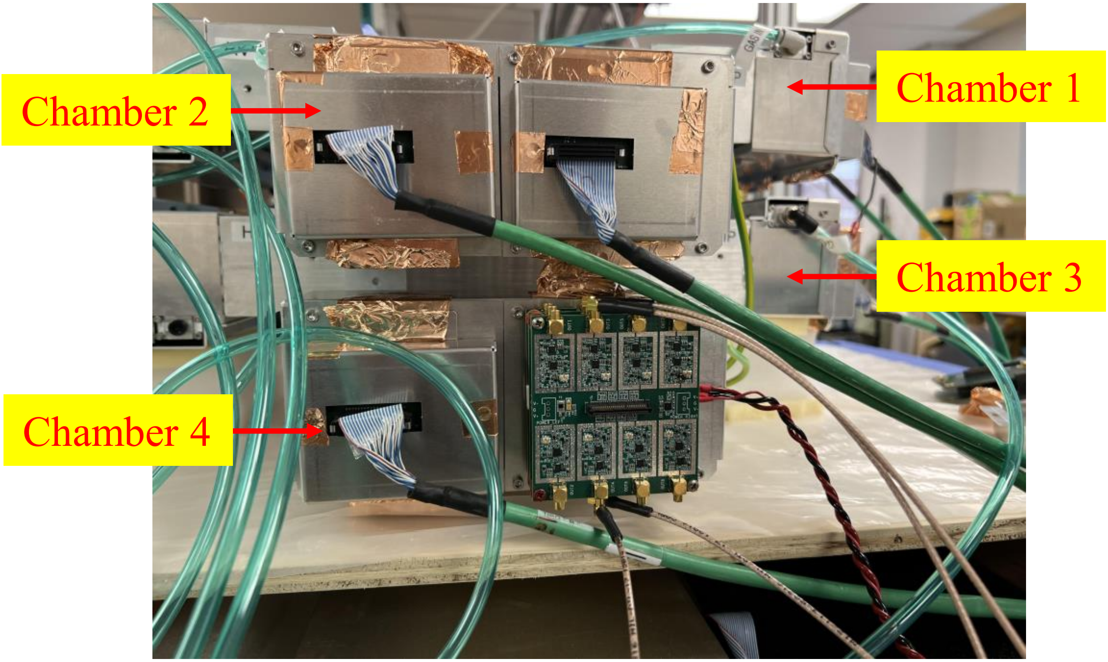


Setup at Michigan

- Scintillator trigger counter
- Four sMDT chambers arranged perpendicularly, each comprising four layers of 1.5cm diameter drift tubes with single-tube resolution of 100 um.
- Three chambers read out using ATLAS electronics to reconstruct muon tracks and calculate their path length
- One chamber read out with the new amplification board and an oscilloscope to record waveforms for offline cluster-counting analysis.



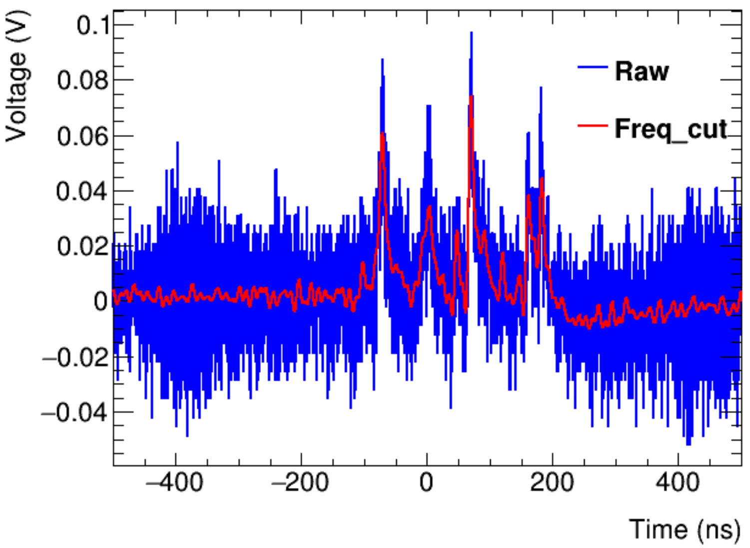


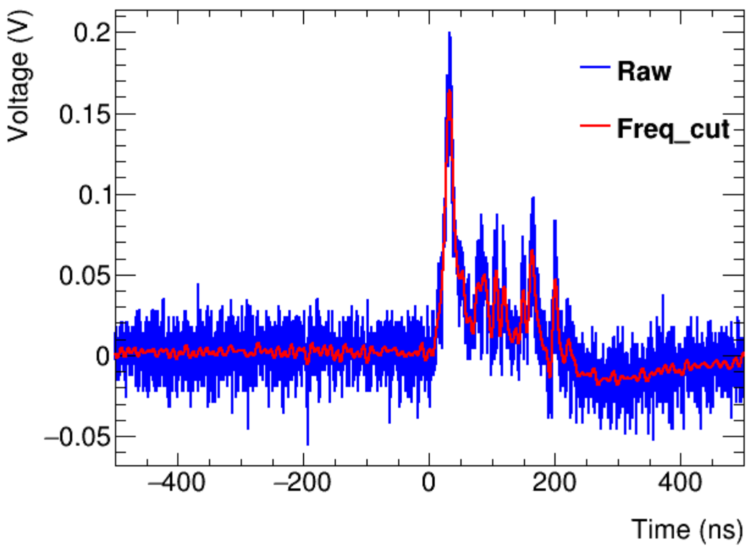


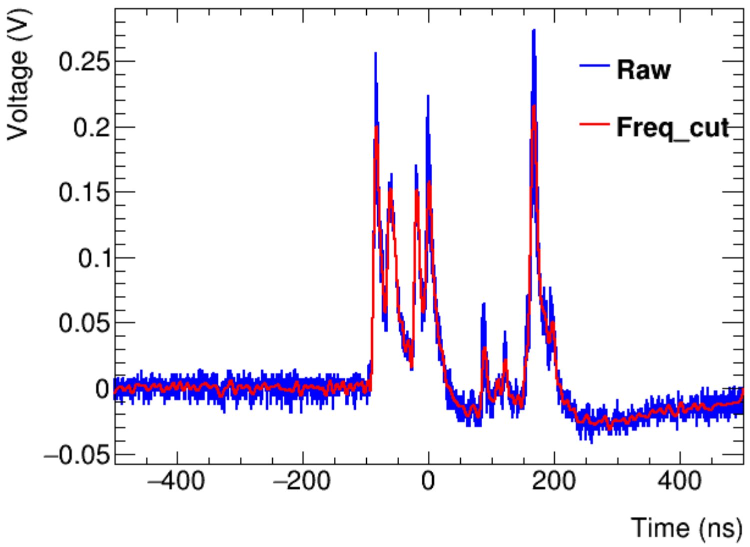
Preliminary Cosmic Ray Studies

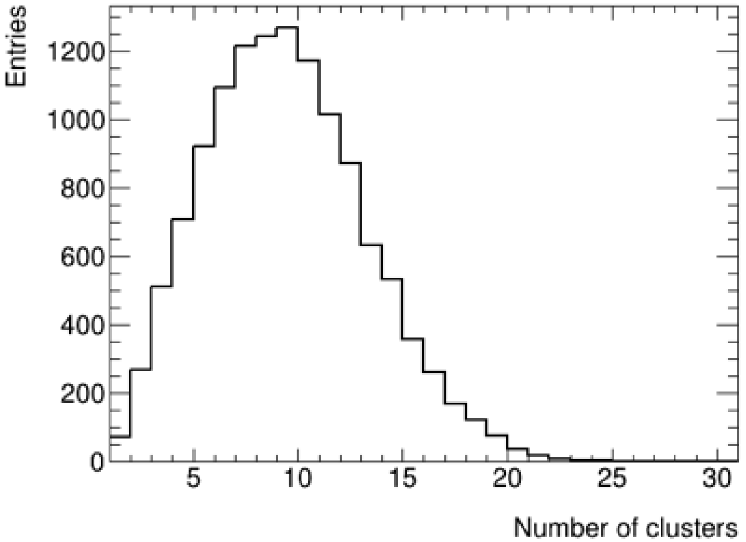
Waveforms of different events

*200 MHz frequency cut done offline







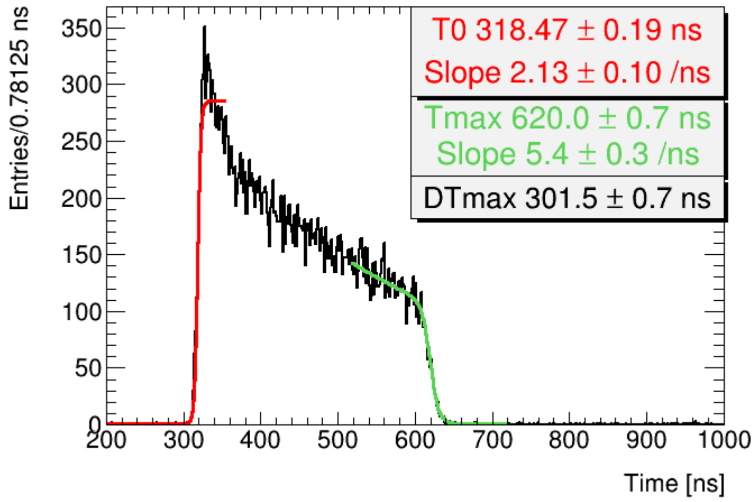


Tasks

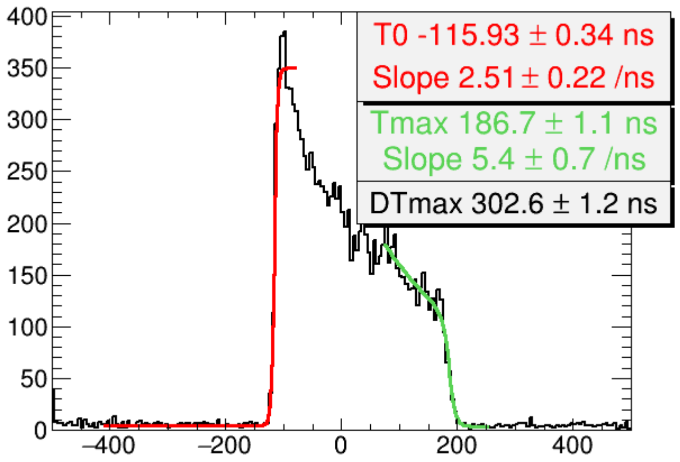
- Reliably distinguish between primary and secondary clusters
- Understand efficiency for detecting primary clusters
- Develop AI/ML algorithm for online cluster counting

Cosmic Ray Studies

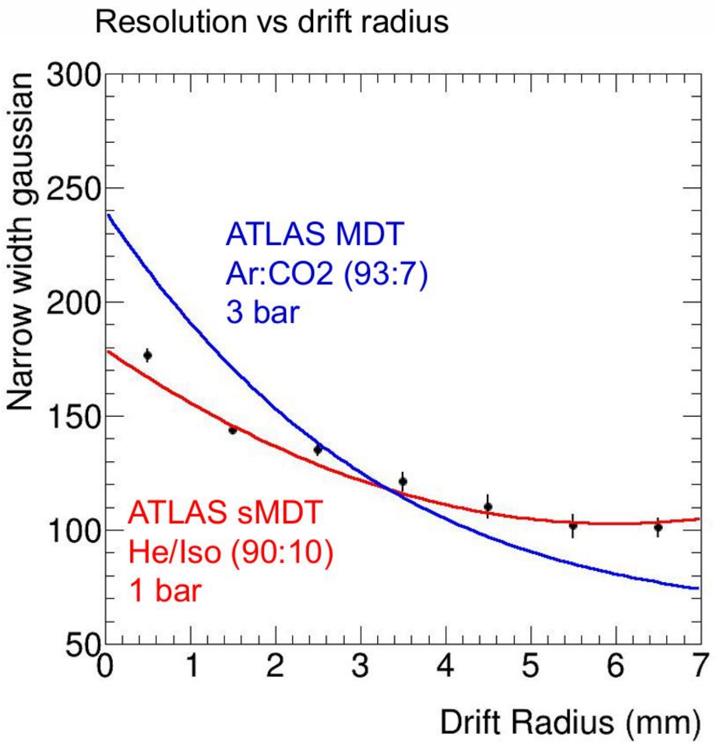
- Observed similar drift time for both readout
- Approaching target resolution of 100 µm



Drift Time spectrum with ATLAS sMDT electronics

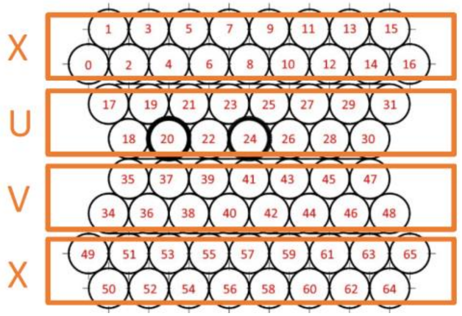


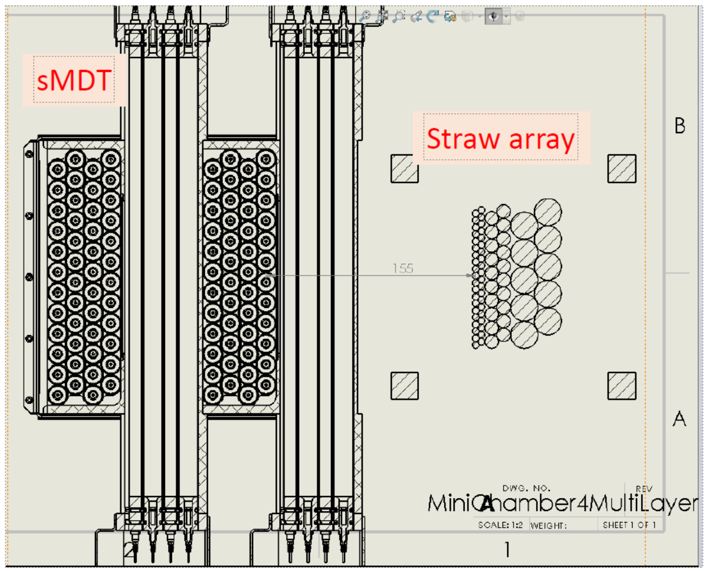
Drift Time spectrum by waveform recording



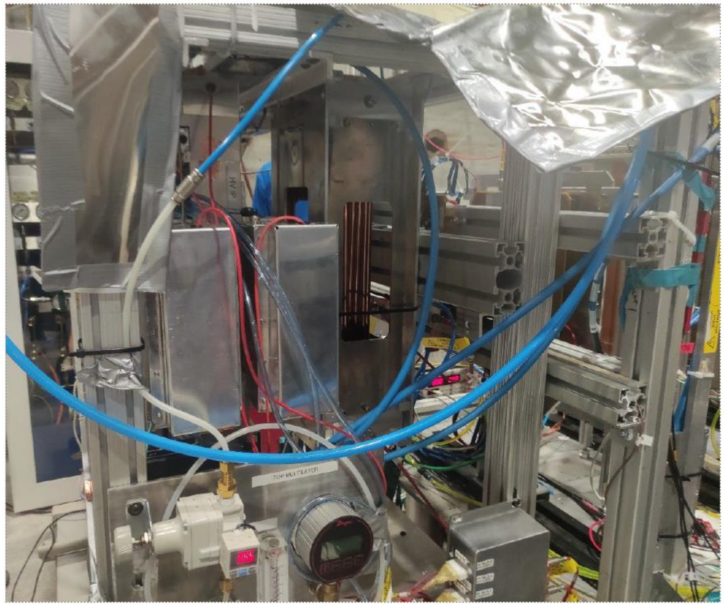
Note: drift tubes can be used for resolution studies and dN/dX studies

Test Beam Studies



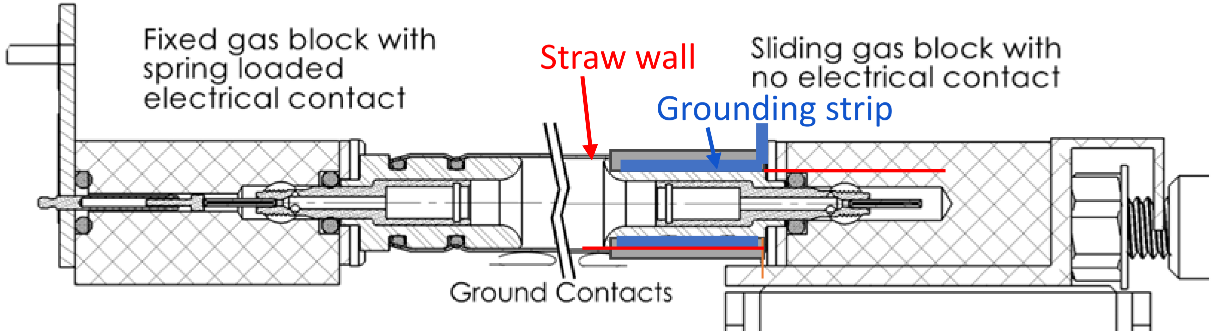


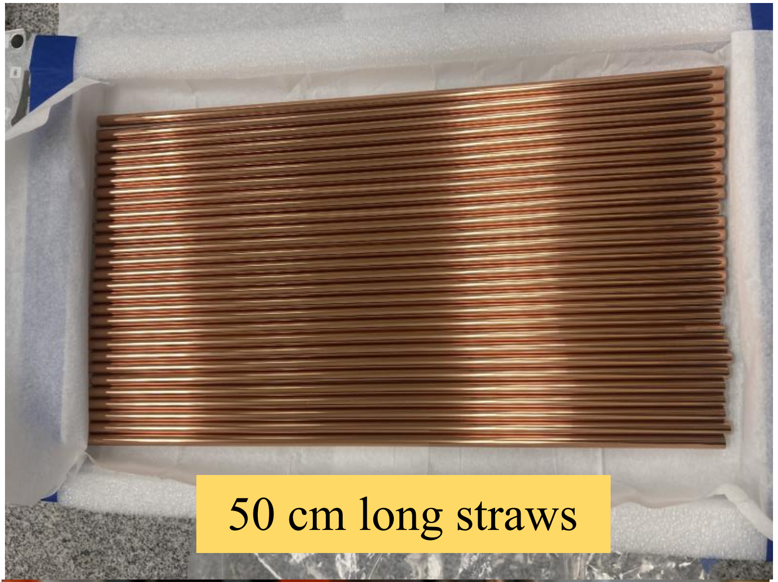
- Ongoing test beam studies with 150 GeV muons at CERN
- 4 sMDT chambers and 8 layers of straw tubes (4 X, 2 U, and 2 V)
- Due to leakage of gas distribution panel and safety concerns, He-isobutane was not allowed → using 70:30 Ar:CO2 at 1 bar
- Single-hit resolution = 104 μm
- Single waveform recorded for 24 channels (1 GHz sampling rate, ~3 kHz trigger rate)
- Similer drift time observed using the recorded waveform and using ATLAS electronics
- Plan to use He-isobutane for November's test beam runs at T9



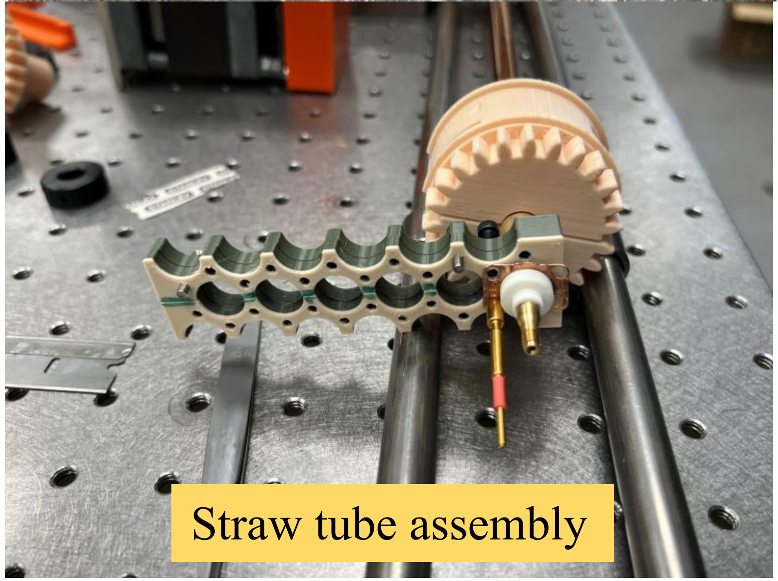
Straw Chamber Prototype Development

- Plan to construct a prototype chamber consisting of 24 straws, each 50 cm in length, building on our extensive experience with the construction of ATLAS sMDT chambers
  - Utilize ATLAS sMDT HV boards and readout electronics
  - Modify the sMDT end plug, develop new endplate support structures and new grounding scheme
  - Define the wiring procedure and design the gas distribution system
- Serve as a pilot project to establish construction methods for long straw chamber construction and to carry out performance studies





50 cm long straws



Straw tube assembly

Summary

- Preliminary studies of the straw tracker with dN/dX indicate promising performance that meets FCC-ee demands.
- Much ongoing R&D studies: simulation work, gas mixture system, dN/dX, straw production and assembly, readout electronics, mechanical structure...
- Significant progress at Michigan and MPI with many US institutions expressing interest in contributing.
- DRD1 WP3 Project A “Straw and Drift tube development for future collider experiments”, Oliver Kortner (MPI) and Junjie Zhu (Michigan) are coordinators.
- Please reach out if interested!