A straw tracker for FCC-ee

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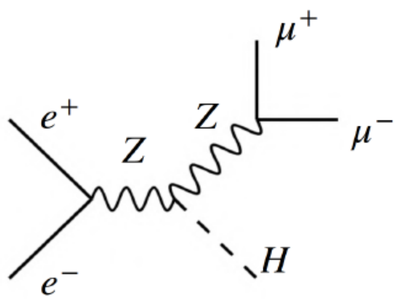
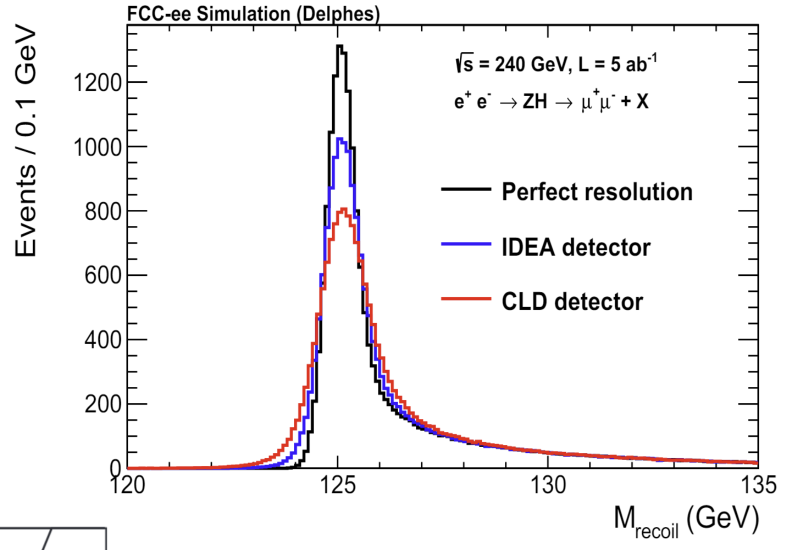
Requirement for the FCC-ee tracker

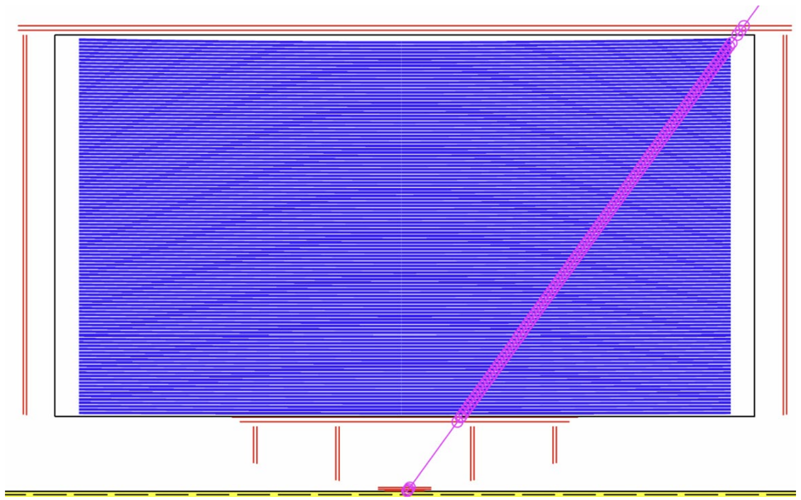
- Excellent momentum resolution for charged particles is critical for the FCC-ee physics program
  - Important to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section measurements

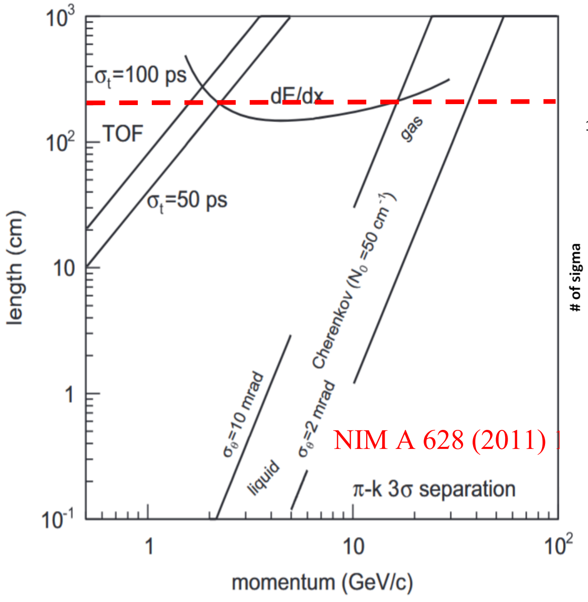
$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

  - Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)
    - $\sigma(p_T)/p_T$ ~ 0.2% at 45 GeV
    - a factor of 5~10 better than the current ATLAS and CMS inner tracker momentum resolution at 45 GeV
  - A transparent tracker is crucial
- Excellent PID capabilities for a wide momentum range
- O(100) hits per track will be important for pattern recognition and long-live particle search

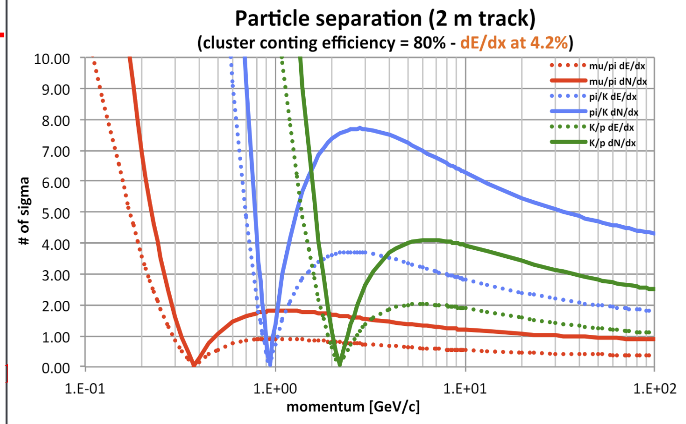








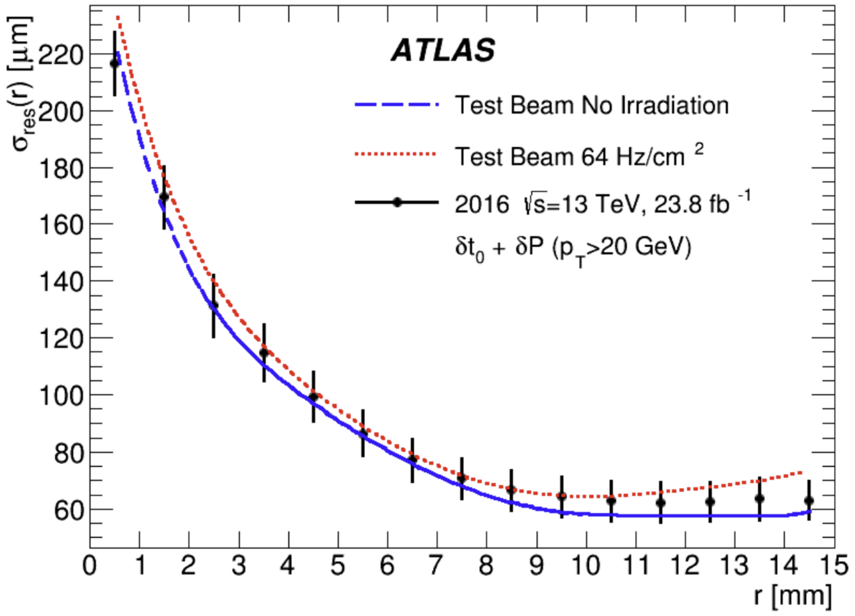
Length of a tracker system needed to achieve a 3σ π-K separation



Benefits of a straw tracker

Straw trackers are robust and could provide high performance for tracking and PID (Compared to the drift chamber):

- Each straw is a single unit, if a sense wire is broken, the channel can be easily removed
- Charges produced in one single straw will remain in that unit
- The electric field is radial symmetric; the resolution is independent of a particle's incident angle, no need to incorporate angular correction factors → better single hit resolution
- Straws with different radii can be used in different regions to optimize hit occupancy and channel counting
    - Larger radius straws → better hit resolution
    - Larger radius straws → less number of straws → less material
- Relatively low wire density: <1 wire/cm^2 (40~60k straws)
- Optimize the gas mixture to improve the PID capability
- Different gas mixtures may be used at the same time
- Flexible layouts for central and endcap regions
- Simpler endplate structure

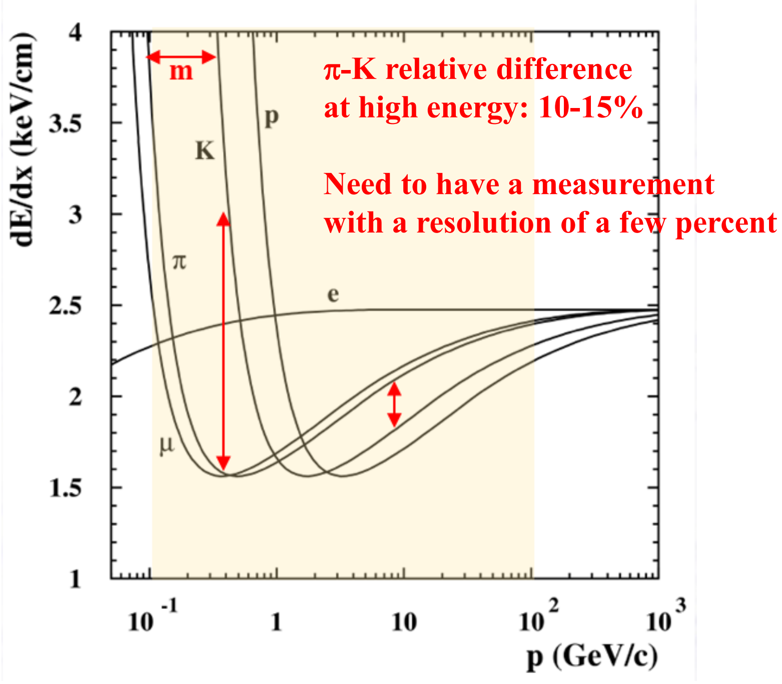


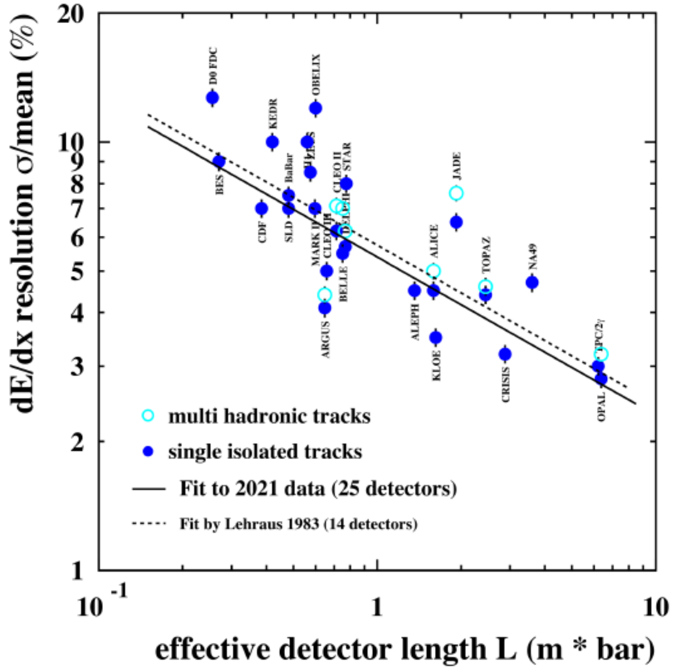
ATLAS MDT position resolution vs radius
arXiv: 1906.12226

Challenges:

- More material budget
- Produce thin-wall aluminum-coated straws with high yield rates
- Straw assembly and mechanical support for 4-5 m long straws

PID using the energy loss



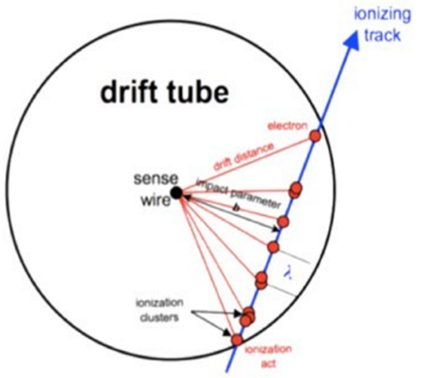


Truncated mean (dE/dX):

- Remove 20-60% of events with large momentum transfer
- The resolution depends on sample length τ, gas pressure p, number of samples n, and the gas composition
- Empirical parameterization of resolution: **$\sigma = 0.41\times n^{-0.46} \times (\tau p)^{-0.32}$** for Argon ($\tau p$ in unit of cm bar)
- σ = 4.5% assuming n = 120 and τp = 1 cm bar (σ = 3.2% if τp = 3 cm bar)

PID by counting clusters

- **Counting clusters (dN/dX):** count number of primary clusters produced along the track path
- Estimated the resolution to be **$\sigma = 1/\sqrt{N_{clusters}}$**
  - With n = 120 and 15 clusters per sample → σ = 2.3%
  - σ = 2.6% even if we have a cluster-finding efficiency of 80%
  - Roughly a factor of 2 better than the dE/dX method
- No experiments have implemented this method and used it online yet
  - Need to have fast frontend electronics and process the waveform
  - Fast algorithms to identify clusters
- Lots of studies performed by the MEG-II and DCH communities
  - Muon test beams at CERN (4-12 GeV and 165/180 GeV)



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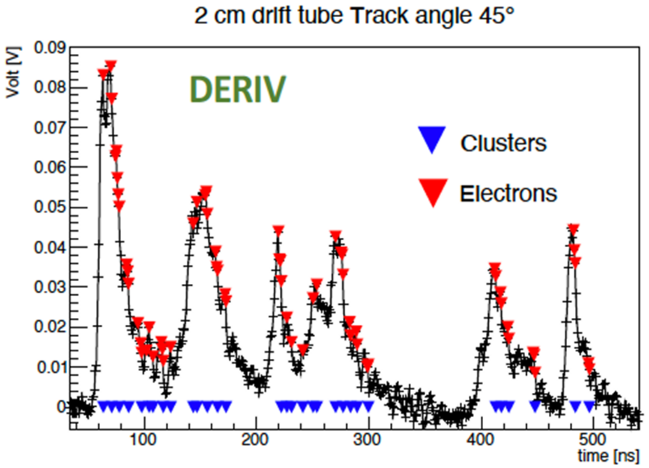
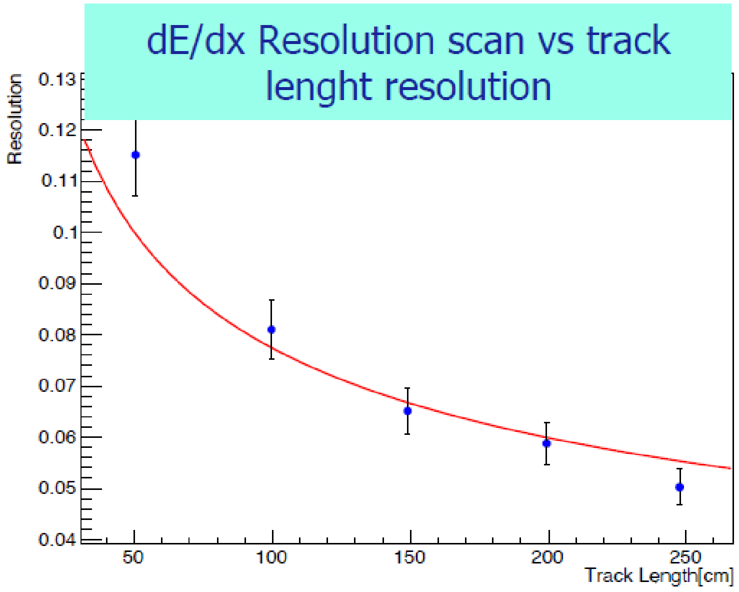
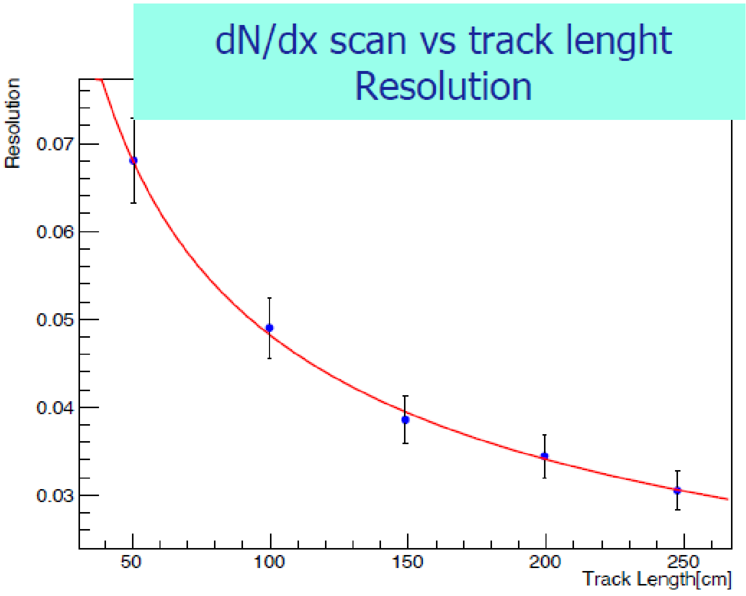


- Finding electron peaks
- Clustering electrons to clusters





IDEA test beam results

(some) Past, current and future straw trackers

Winding

- ATLAS
- LHCb
- PANDA
- CBM
- COMPASS
- Mu2e
- NA64
- SVD-2
- GLUEX
- COZY-TOF
- …

Ultrasonic welding

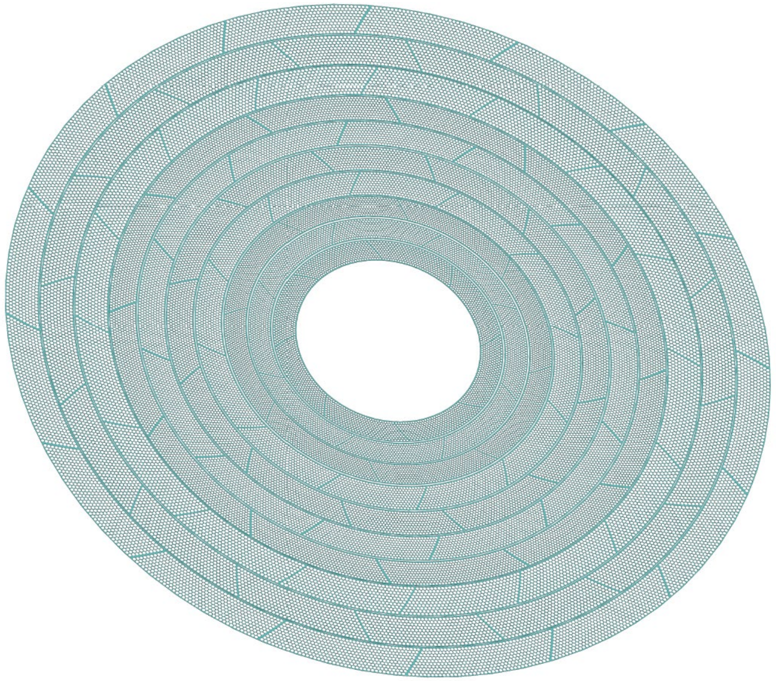
- NA62
- COMET
- SHiP
- DUNE
- SPD NICA
- …

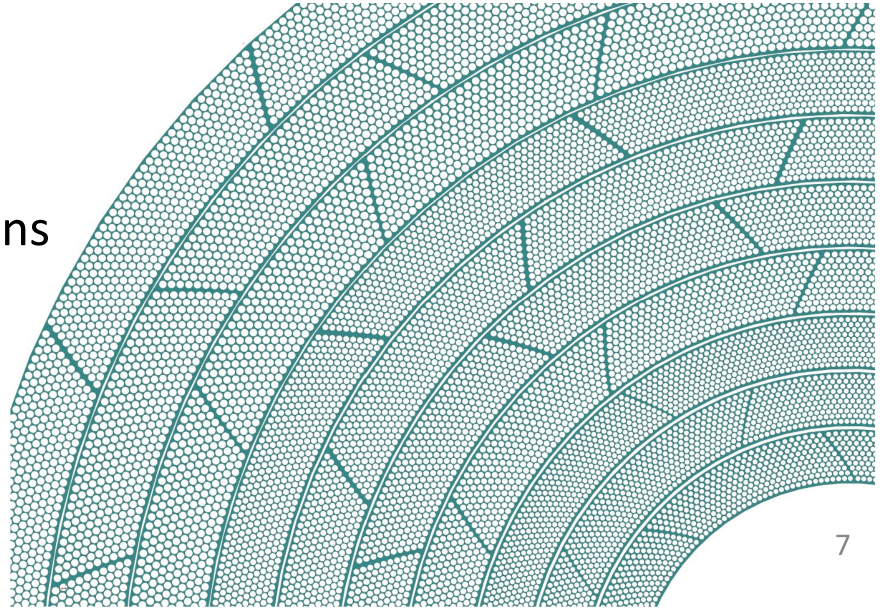
Mu2e: two layers of 6-um Mylar film + 3 um adhesive, max length: 1.2 m, 23k straws

DUNE: 19 um-thick Mylar film, max length: 3.75 m, 219k straws

Straw Chamber Proposal (example)

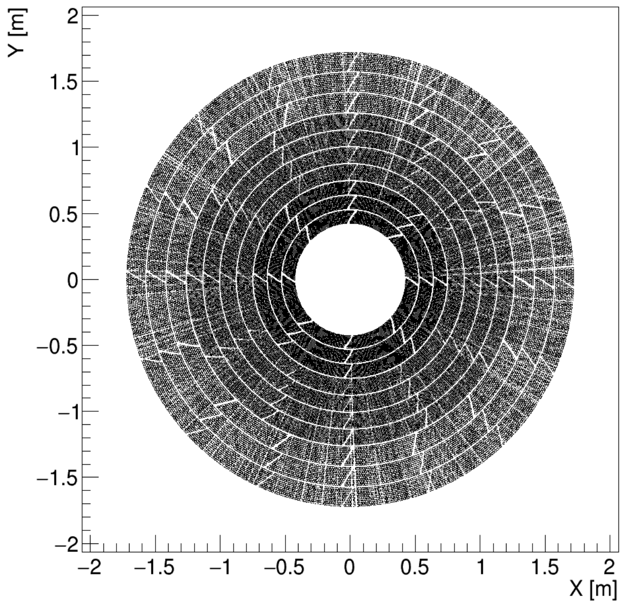
- Dimensions: 4-5 m long, 30 cm to 1.8 m radius
- Material budget (~1.2% X_0 assuming 100 layers of 12-µm thick Mylar film for barrel, no estimation for forward yet)
- Geometry layout
  - 12 µm Mylar wall thickness with Tungsten-Re wires
  - Straw radius from 1 cm to 1.5 cm
  - 10 superlayers with 10 sublayers each
  - A few degree (2^0-6^0) for stereo angles (A-U-V)
- In total ~60k straws
- Potential operating gas mixture: He+iC_4H_{10} (90:10)
  - 1.5 m of Ar → 1.5% X_0
  - Could consider to use He and Ar in different detector regions
- Overall expected resolution: σ_{xy} ~ 120 µm and σ_z ~ 1 mm

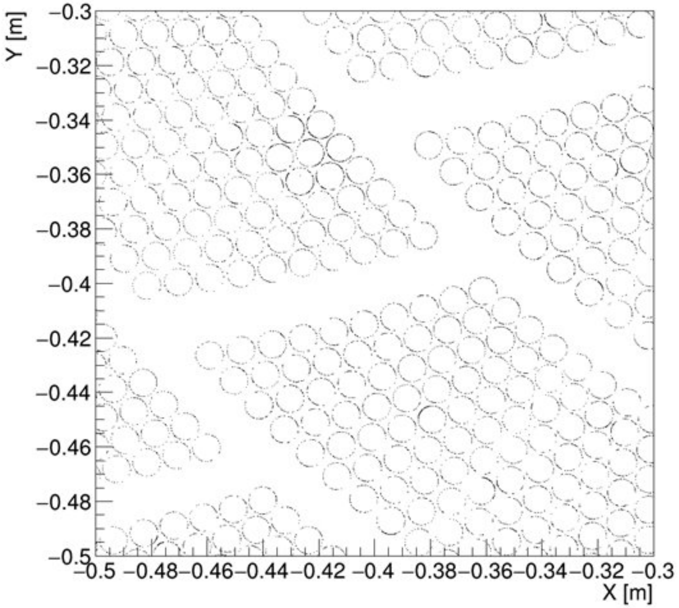




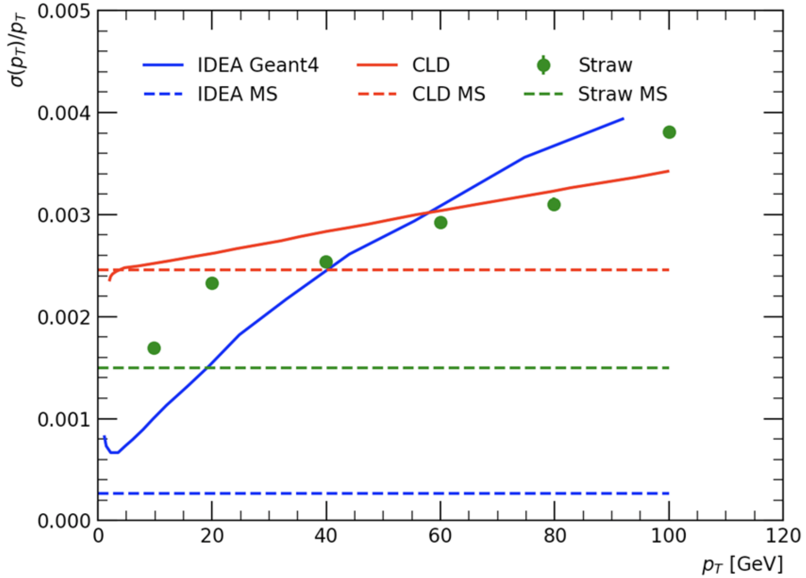
Simulation with GEANT

- Implemented a geometry inside GEANT, 1.35% X_0 for 100 layers of straws with a wall thickness of 12 μm
- 0.05 μm Aluminum coating on the inner wall
- Sense wire: radius of 10 μm Tungsten
- Endplate supporting structure could be similar to DCH
- Momentum resolution studies with a simple python track fitting program with MS effects included
  - Straw tube resolution: 120 μm
  - Pixel resolution: 5 μm
  - Silicon wrapper resolution: 15 μm
  - Ongoing work with the actual track fitting with ACTS





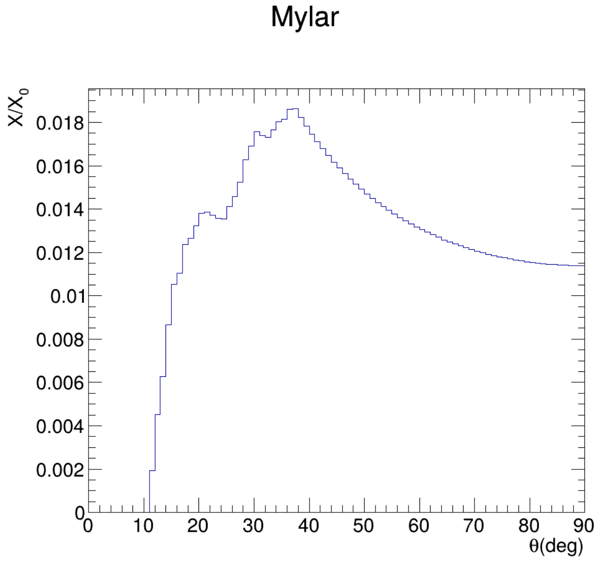
GEANT implementation
Hits from 5000 muons



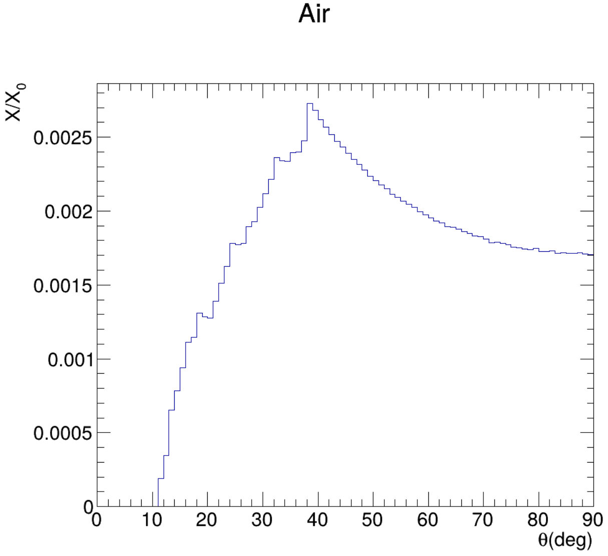
These resolutions are likely calculated based on different assumptions and should be viewed with a grain of salt.
(for example, the radius coverage of straws is from 0.3 m to 1.8 m)

Material budget

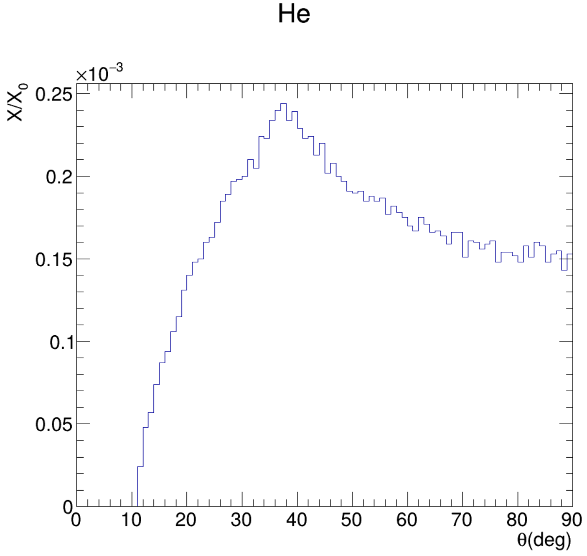
Using the GEANT simulation to collect the material inside the detector from the detailed geometry. (~1.35% X_0 at $\theta = 90°$, not including any mechanical structure. Mainly contributed by the mylar walls)



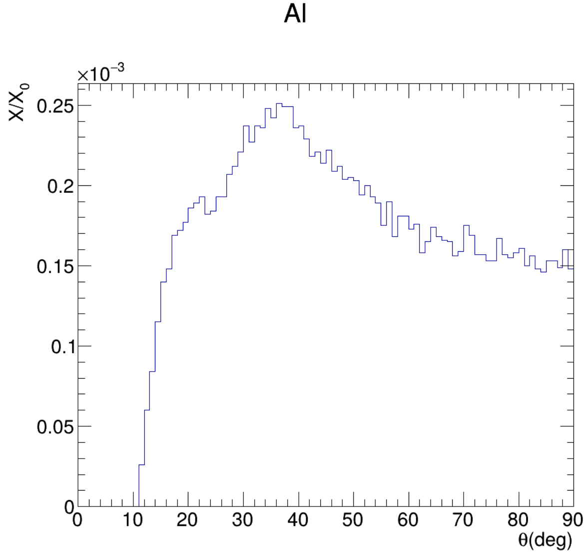
Mylar wall (12 μm)



Gap-filled air



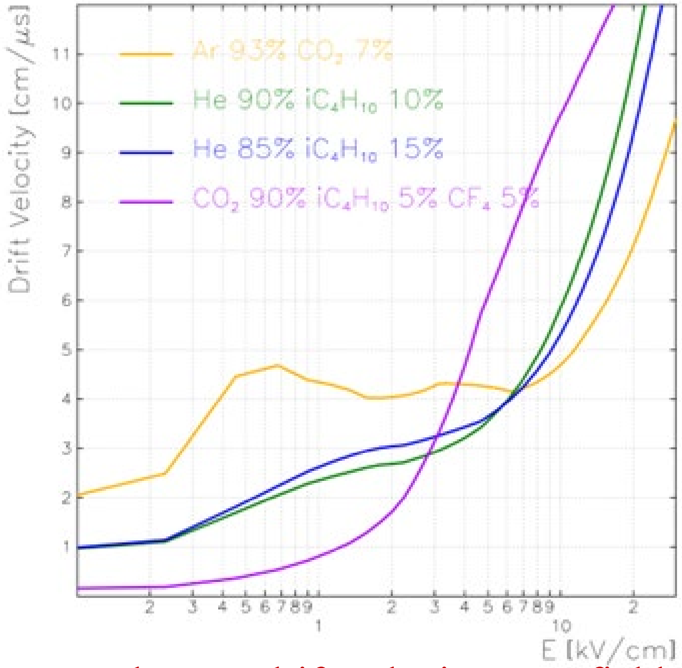
Helium gas



Aluminum coating (50 nm)

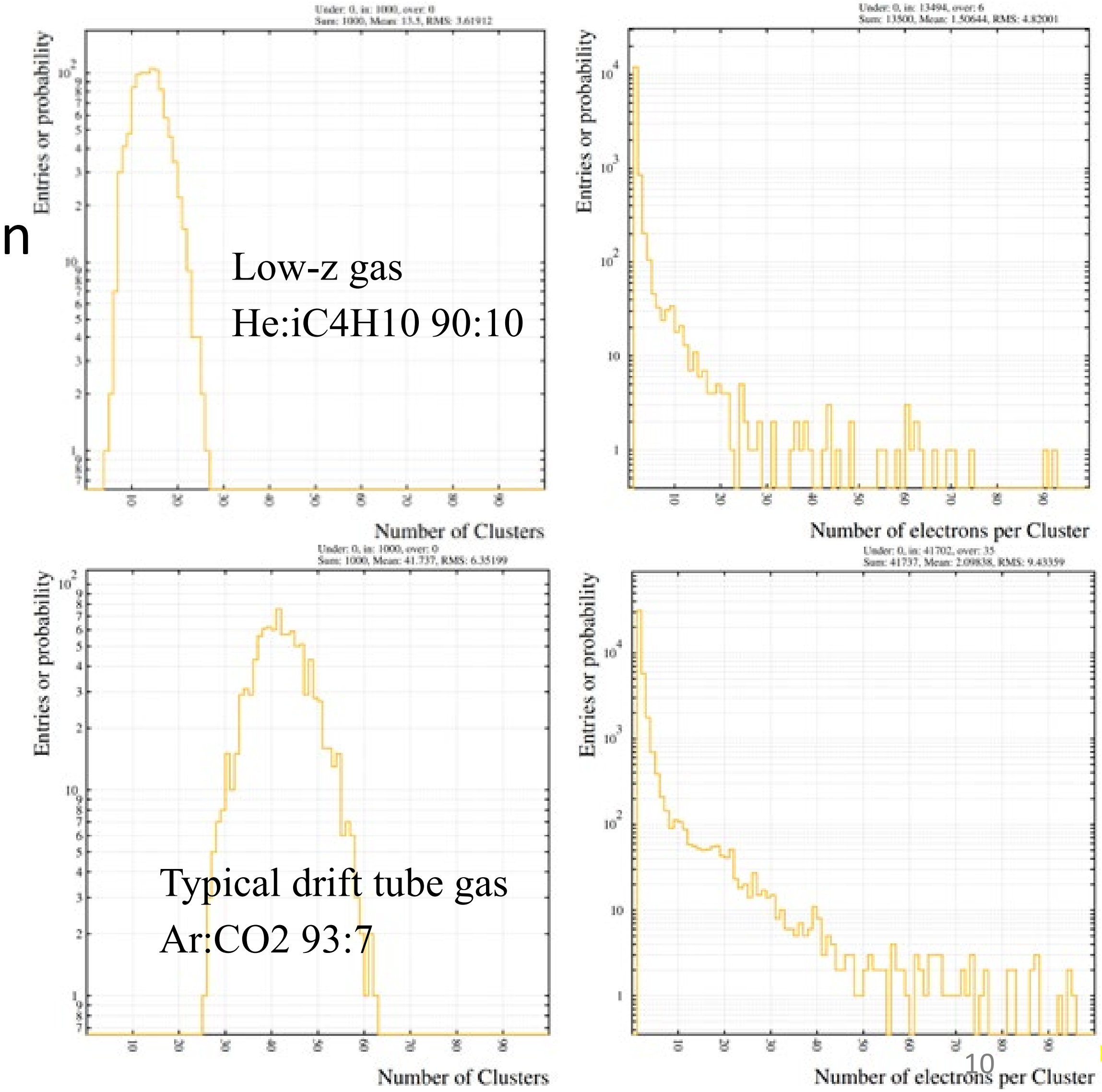
Gas simulation with Garfield

- Ongoing Garfield simulation:
  - Ionization statistics in several gas mixtures
  - Electron and ion transportation properties
  - Signal induction and timing structure
- Provide essential inputs for the gas optimization and dE/dx(dN/dx) measurement for PID



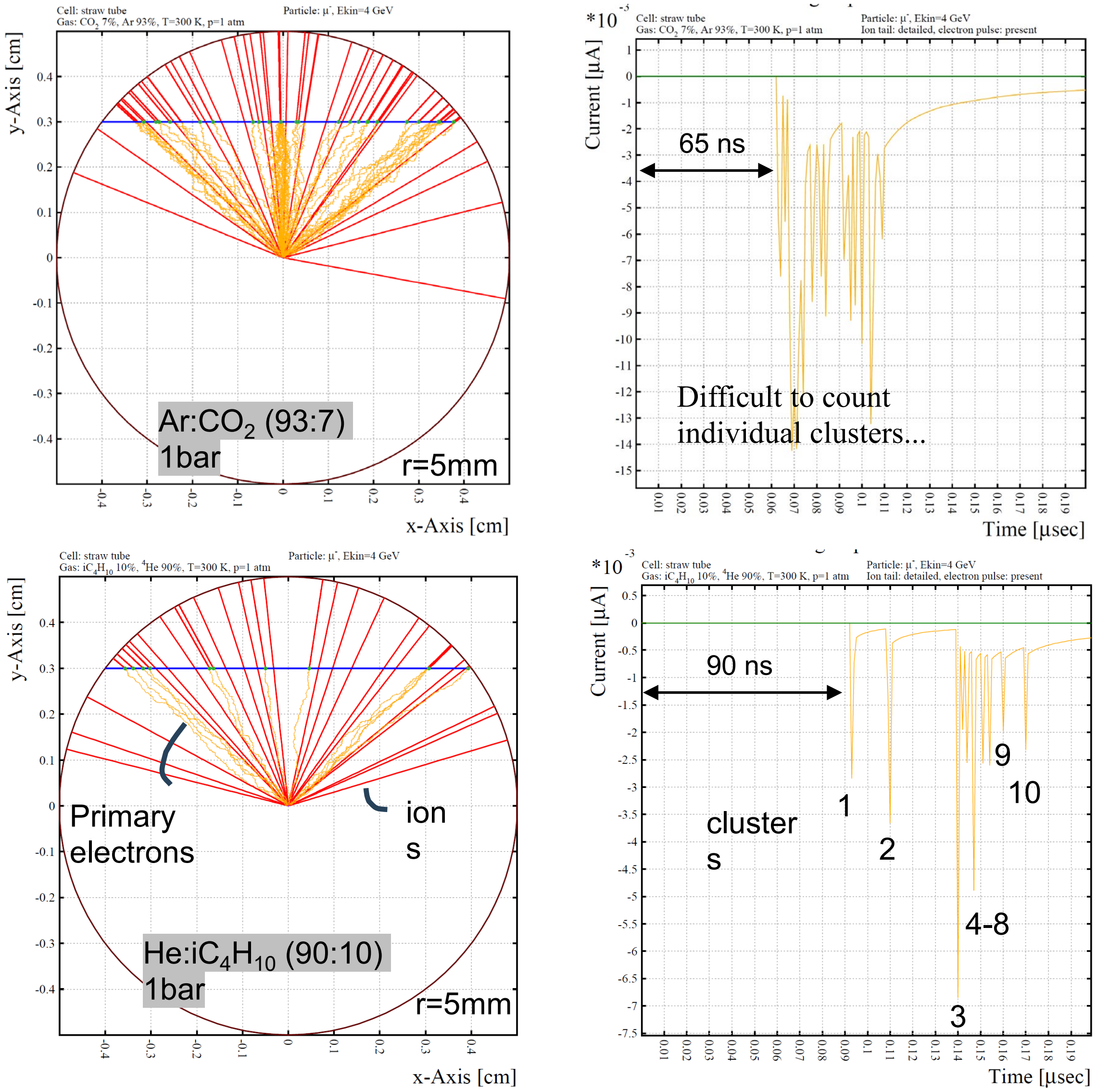
Electron drift velocity vs. e-field

Simulated primary ionization cluster number (left) and size (right) for 4 GeV muon in a 10 mm-diameter straw



Simulation of signals in different gas mixtures

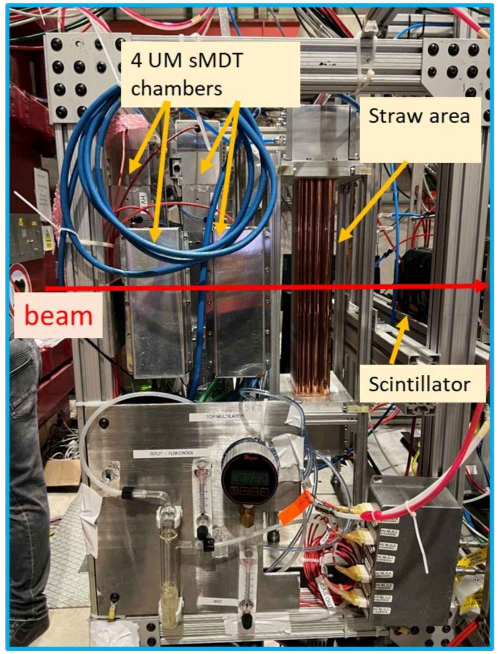
- dN/dx expected to improve dE/dx PID based on traditional charge measurements
- Ar-based gas: high ionization density (~40/cm) and moderate electron drift velocity 50 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~5ns
- He-based gas: lower ionization density (~20/cm) and 30 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~15ns

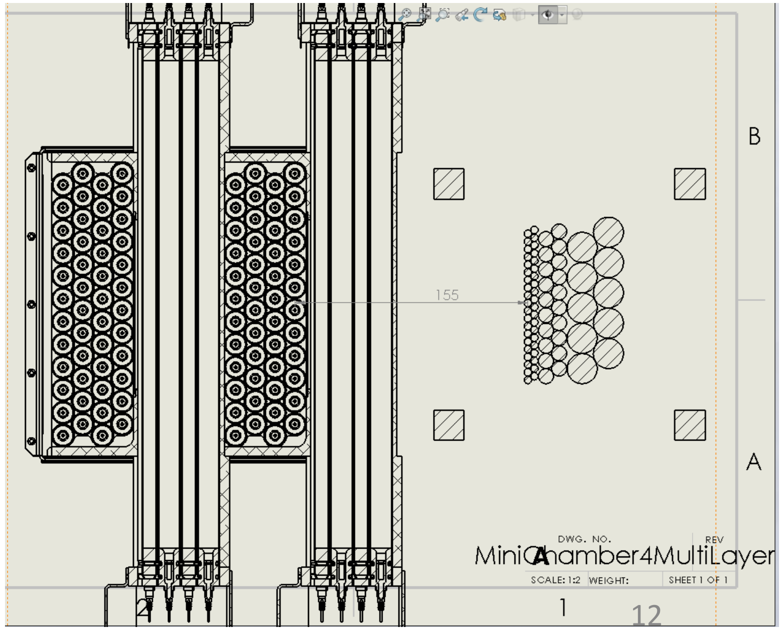


5mm radius tube with 1 bar and 1kV simulated here

Test beam at CERN

- Performed test beam studies with Temur's group at CERN SPS/PS facility from 2024/09 to 2024/10
- Study the time spectrum and spatial resolution of straw tubes at different working conditions.
- The UM team provided:
  - sMDT telescope with total 16 tube layers (assembled in 4 mini-chambers, each with 4-layers, two in X and two in Y directions).
  - Front-end electronics mezzanine with TDC resolution of 0.78 ns
  - MiniDAQ system capable to handle 100 kHz trigger rate and readout 500 channels
  - Online monitoring
  - Offline data analysis

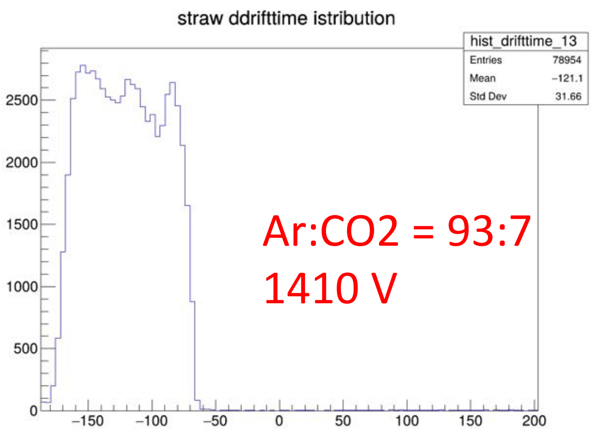


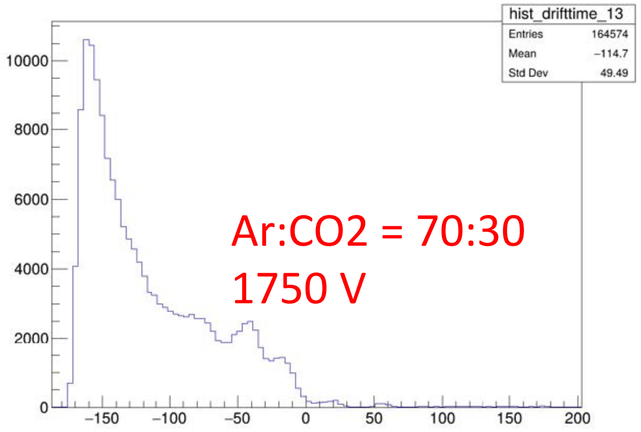


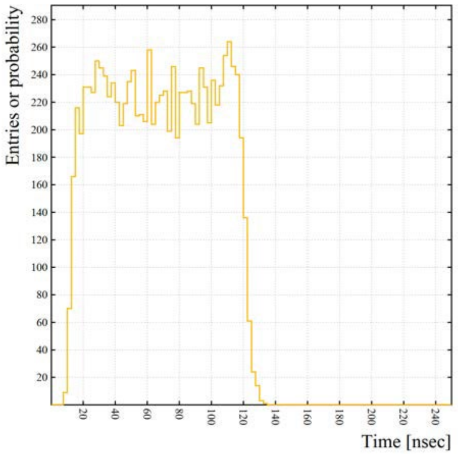
Straw performance from test beam

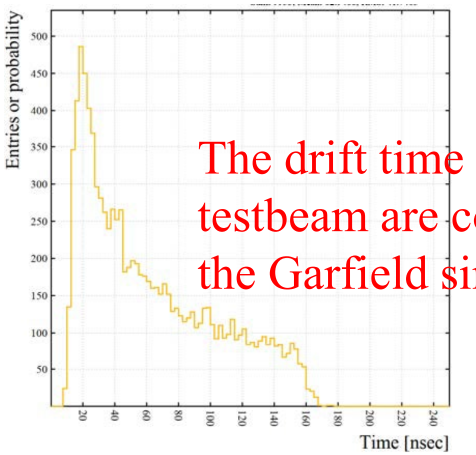
Straw information:

- Tube-wall 36 µm coated with 20 nm gold and 70 nm copper
- Central wire diameter 30 um

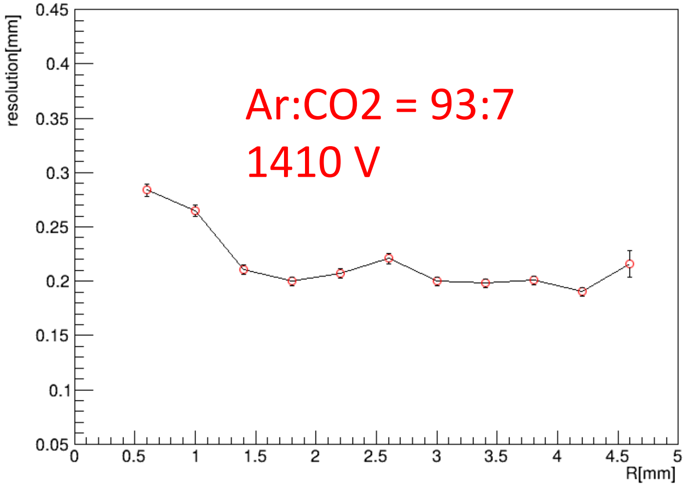


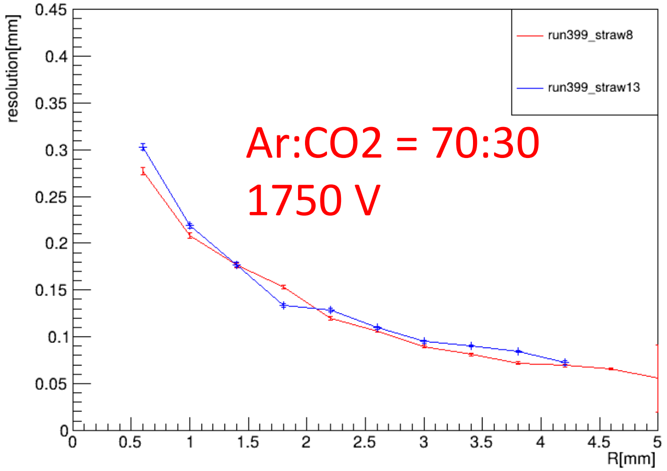






The drift time spectra from testbeam are consistent with the Garfield simulation



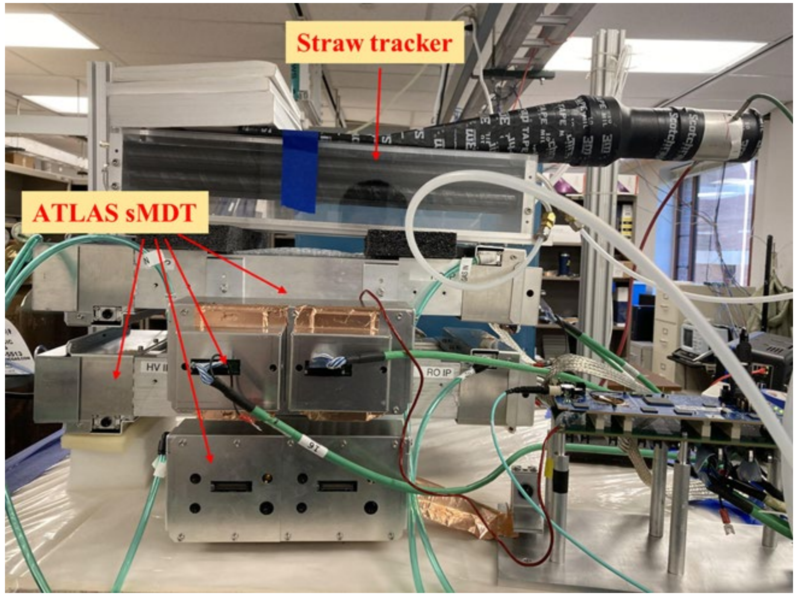


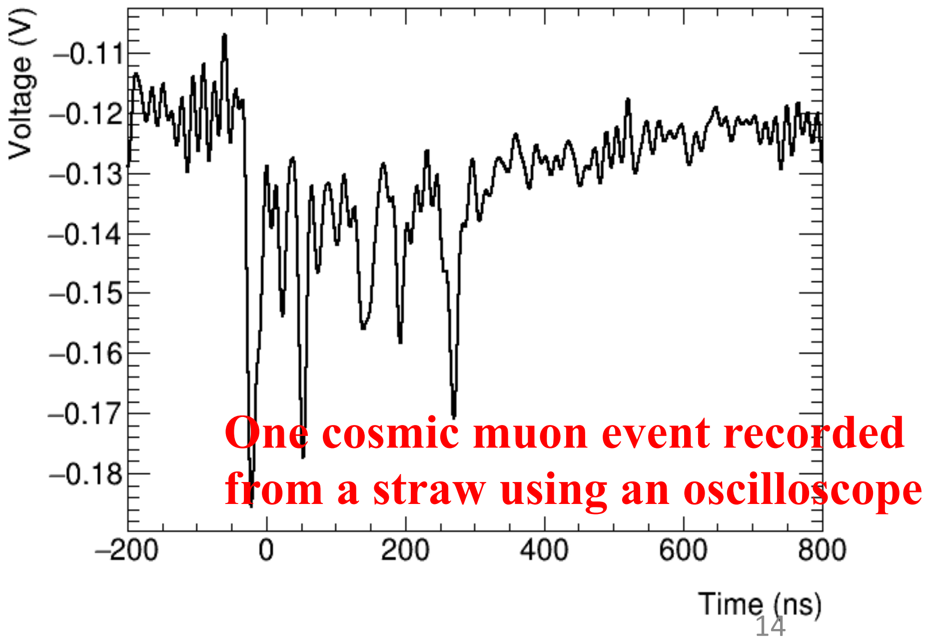
The spatial resolution is promising with the (Ar:CO2 70:30) gas mixture, which reaches ~100 µm on the tube edge

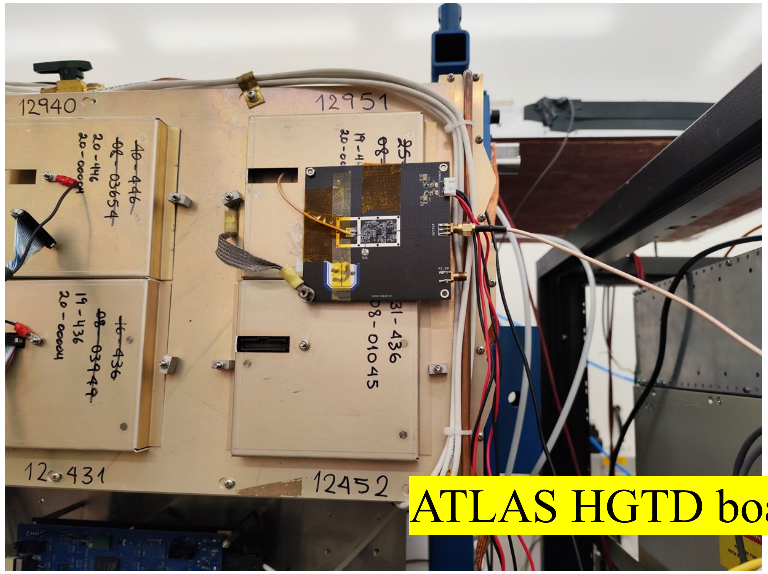
Ongoing cosmic ray test

Raw signal amplification and waveform digitization

- Need to have enough frontend amplification to detect signals from single electrons
- Need to have the entire waveform to first find electron peaks and then apply clustering algorithm to reconstruct primary clusters produced
- Large noises due to the long cable from the straw to the NIM amplifier (the setup at Michigan)
- Modify an ATLAS HGTD board. The new board can be directly plug into the ATLAS sMDT chamber



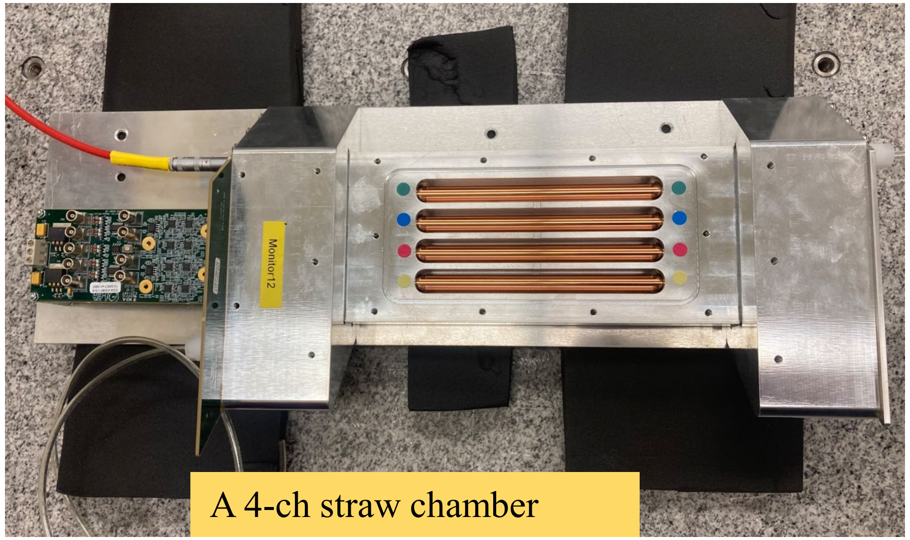




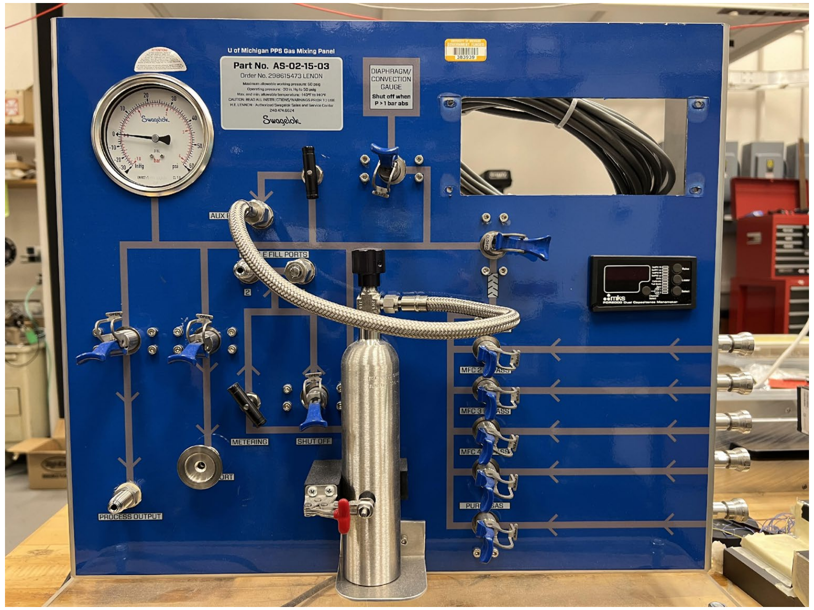
ATLAS HGTD board

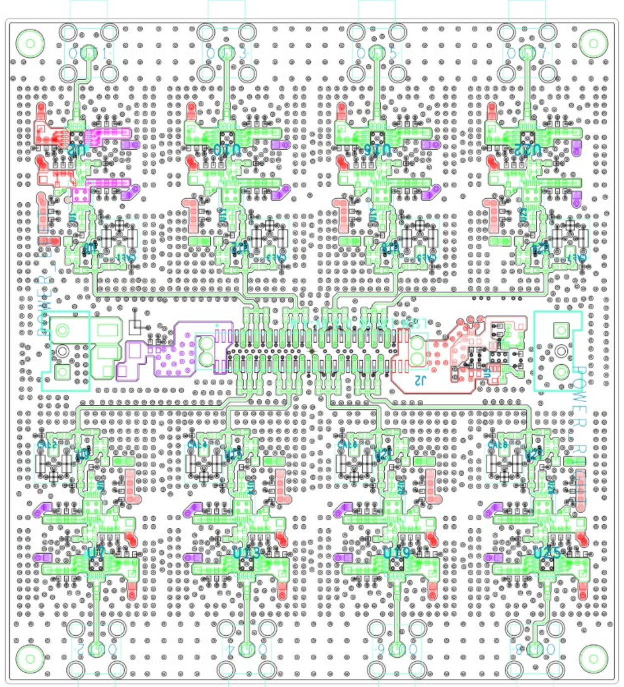
Plans

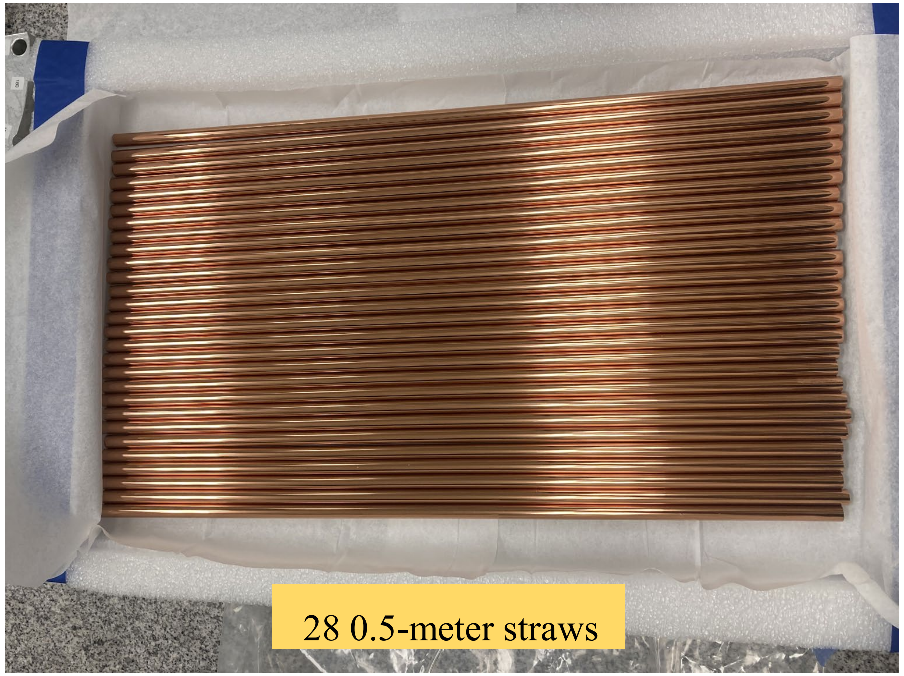
- Detector layout and optimization
- Track reconstruction (ACTS) and momentum resolution studies
- A 4-ch straw chamber from NA62 for gas and gain studies
- Build a prototype chamber using ~25 straws
- Calibration of the gas system
- dN/dX studies for PID:
  - Garfield++ simulation to understand primary and secondary clusters
  - Develop peak-finding and cluster-finding algorithms
  - New amplification boards designed and produced, plan to test them on sMDT chambers, CAEN waveform digitization boards will be used for the readout
  - Cosmic ray studies first, test beam at CERN



A 4-ch straw chamber






28 0.5-meter straws

Summary

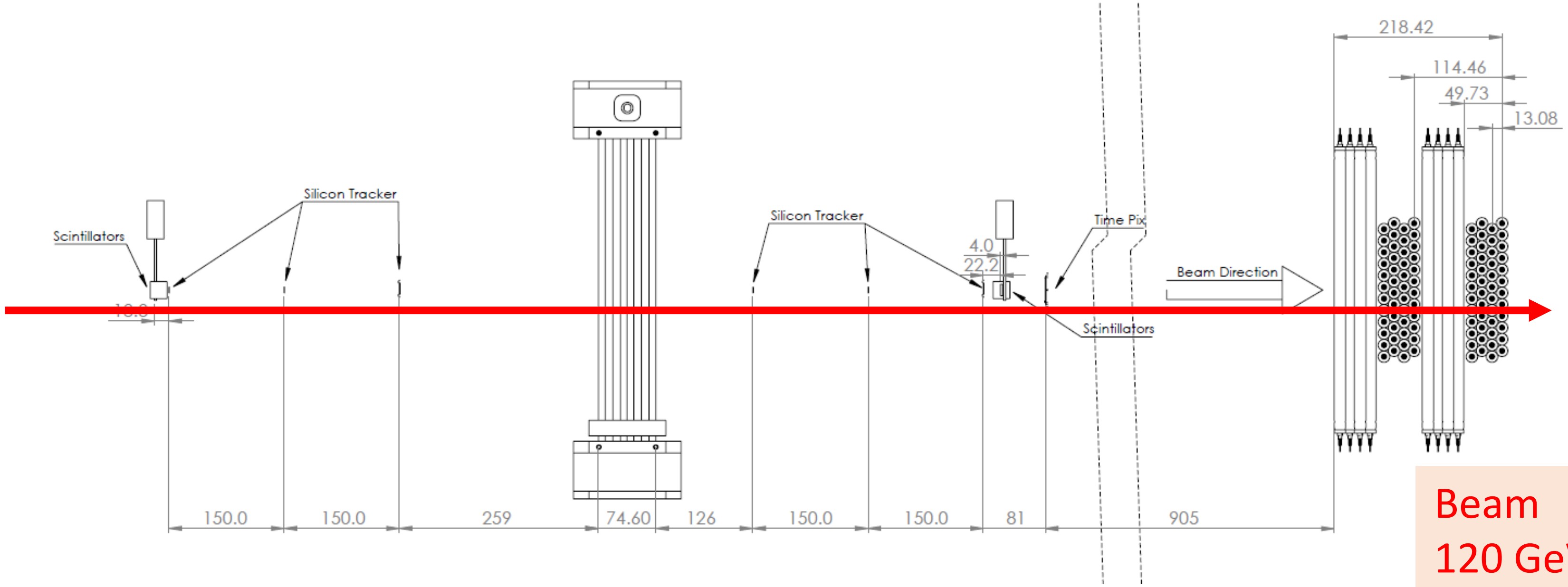
- A straw tracker could be a good option for FCC-ee experiments
  - Reasonable material budget (~1.35% X_0 for ~100 layers with wall-thickness of 12 µm)
  - Straws with 12-19 µm-thick wall (ultrasonic welding) and 3.5 (×2) µm-thick wall (winding) are available
  - Will have another 10+ years for industry to improve the yield for straws with wall thinner than 15 µm and develop even thinner straws
  - Could use >4 m straws to extend the tracker volume
- Mature technology, robust and can achieve high performance for tracking and particle identification
- DRD1 WP3 Project A "Straw and Drift tube development for future collider experiments", Oliver Kortner (MPI) and Junjie Zhu (Michigan) are coordinators
- Participating institutions include MPI, Michigan, UMass-Amherst, Tufts, Harvard, MSU, UCI, Duke and UT Austin
- Close collaboration with people working on the DCH, straw production companies, and other experiments using straws
- Synergies with almost all drift chamber studies: gas, front-end electronics, dE/dx(dN/dx) etc.

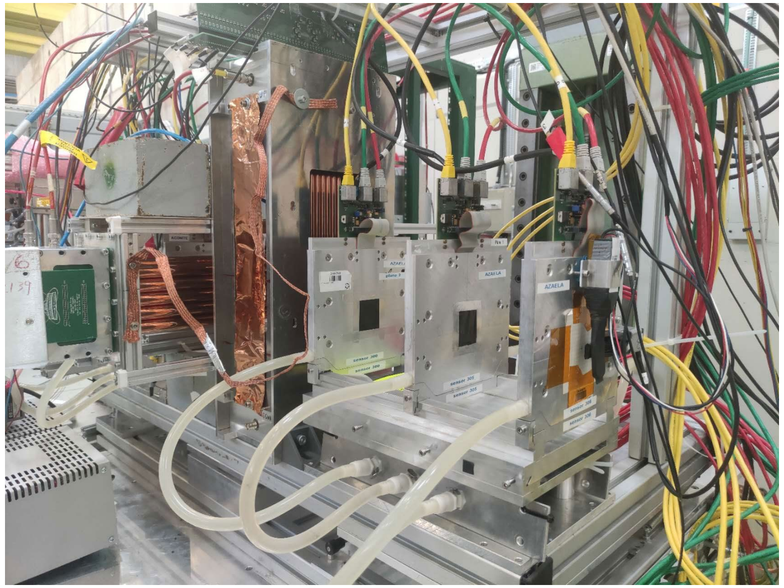
Thank you!

Back up

Test beam setup

Straw array





Beam
120 GeV
muon

- sMDT and straws read out by MiniDAQ
- Si-tracker read out by a different DAQ (Requiring synchronization with MiniDAQ)
  - 6 pixel detector planes of MIMOSA 26 sensors (20 × 10 mm)
  - 1 plane of FEI4 (20 × 20 mm), provide trigger (Large time fluctuation ~25 ns. Introduce a digitized scintillator signal as time reference)

Straw performance