A straw tracker for FCC-ee Experiment

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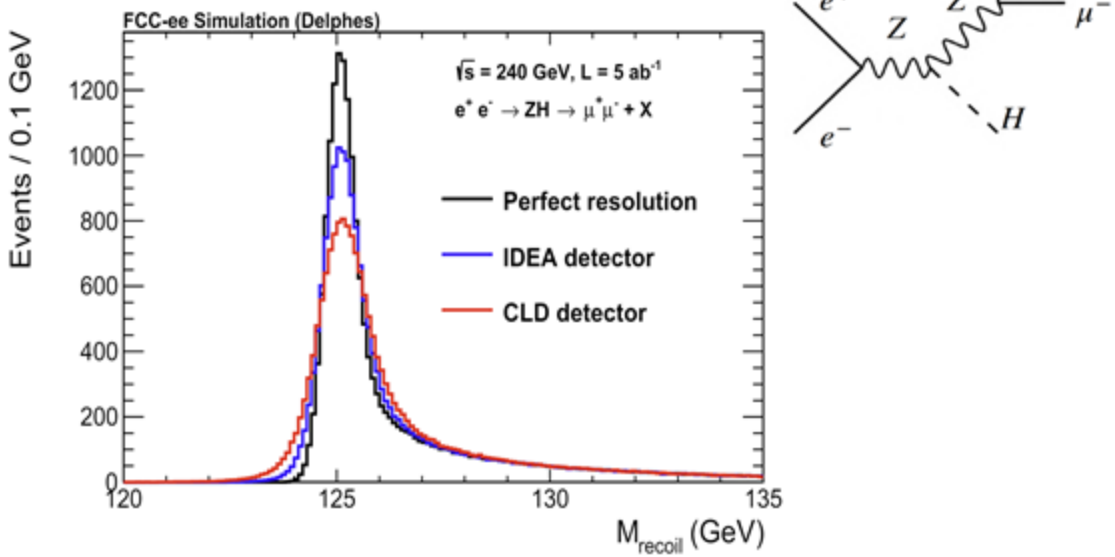
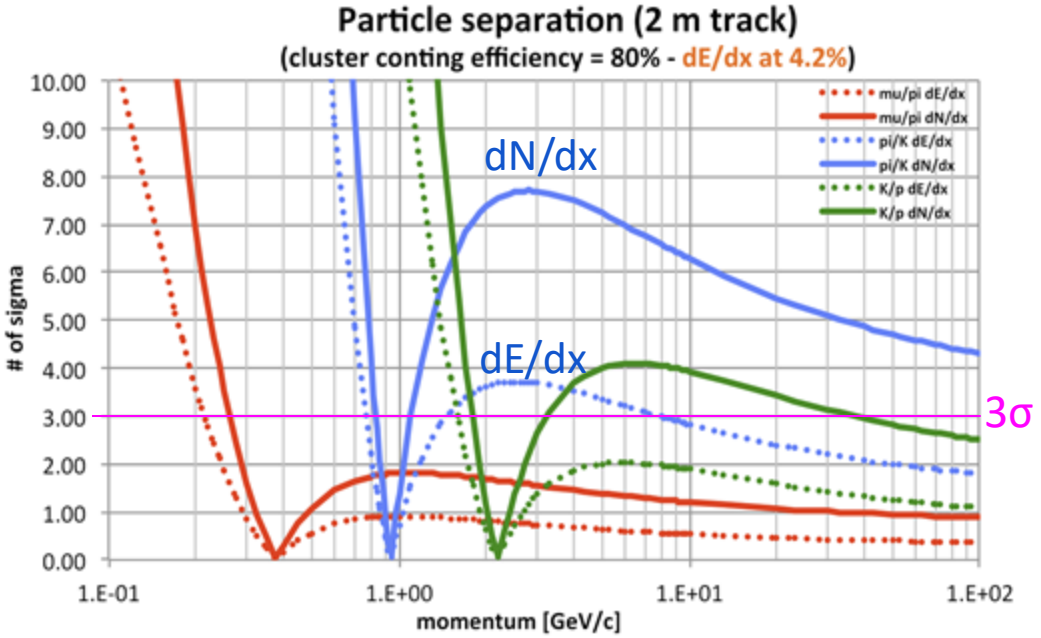
Requirements for the FCC-ee inner tracker

- **Excellent momentum resolution for charged particles**
  - Important to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section measurements

$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

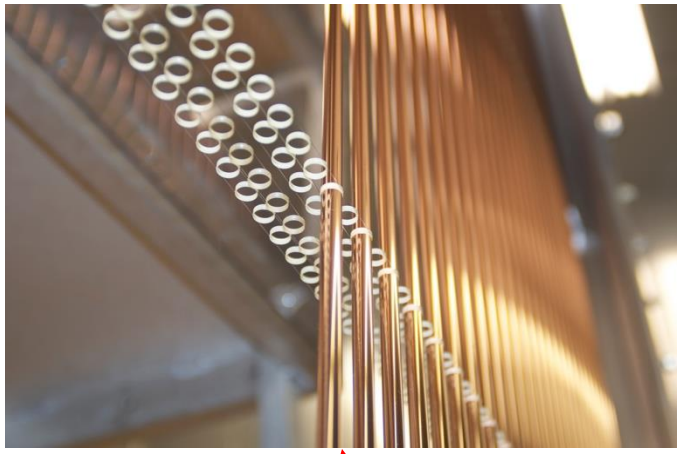
  - Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)
    - - $\sigma(p_T)/p_T$ ~ 0.1-0.2% at 45 GeV
    - - a factor of 5~10 better than the ATLAS and CMS inner tracker momentum resolution at 45 GeV
  - A transparent tracker is crucial
- **Excellent PID capabilities for a wide momentum range**
- **Current Proposed approaches:**
  - CLD: silicon only tracker + specific PID detector (or silicon tracker + TPC)
  - IDEA: pixel detector + gaseous tracker +silicon wrapper

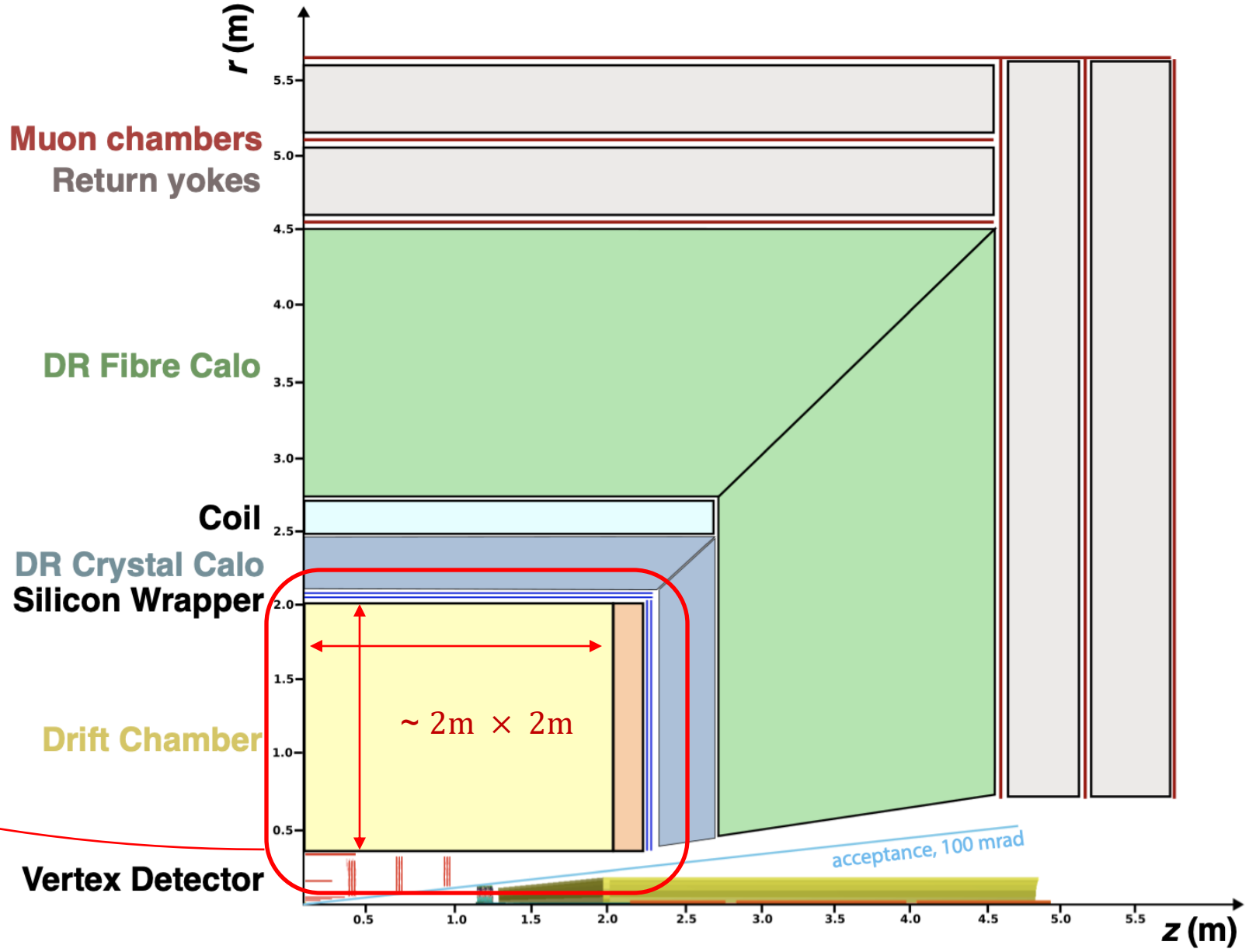




IDEA layout

Straw Tracker





A straw tracker proposal

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

- 12 μm thickness metalized Mylar film straws
- 20 μm diameter Tungsten wire
- Filled with He-isobutane gas mixture
- Single hit resolution: 100 μm

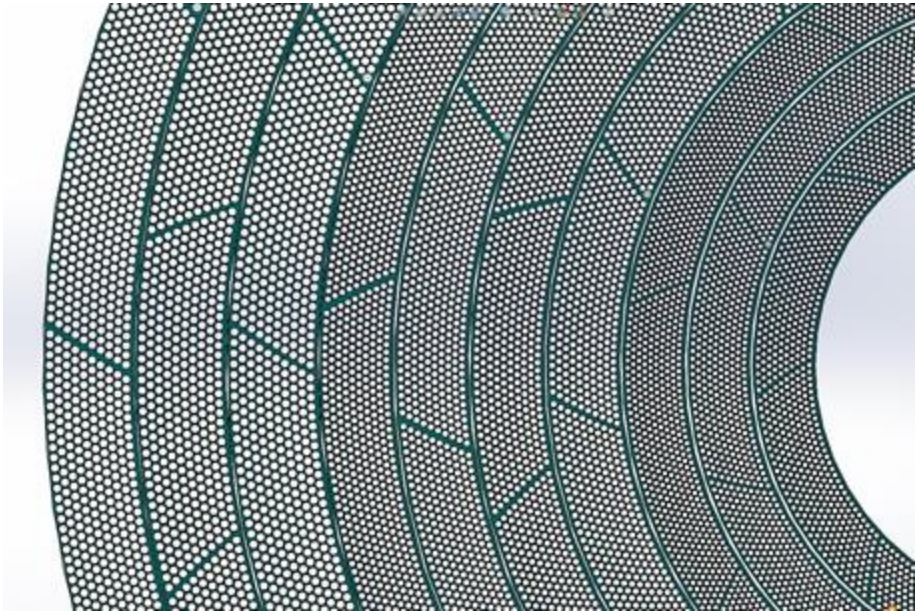
Straw trackers are robust and could provide high performance for tracking and PID

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

Challenges:

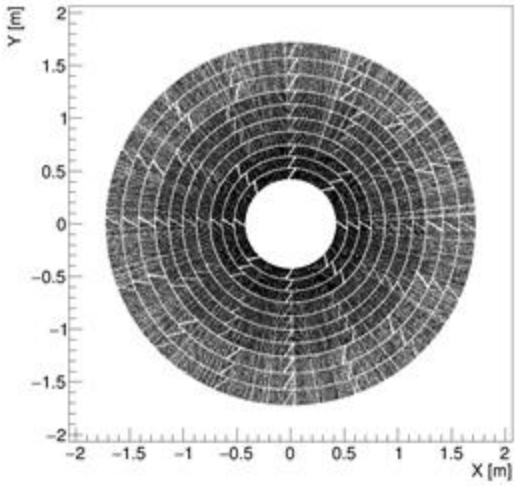
- Control material budget
- Produce thin-wall straws with high yield rates
- Straw assembly and mechanical support for 4-5 m long straws

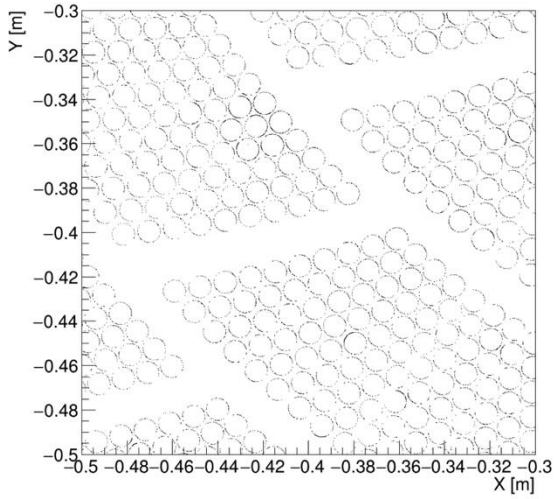
An example layout:
O(60k) straws, coverage: R between 0.3-1.8 m and a length of 4-5 m
Diameters 1.0 - 1.5 cm. 10 superlayers (each 10 layers), Stereo angle: 2-5 degrees

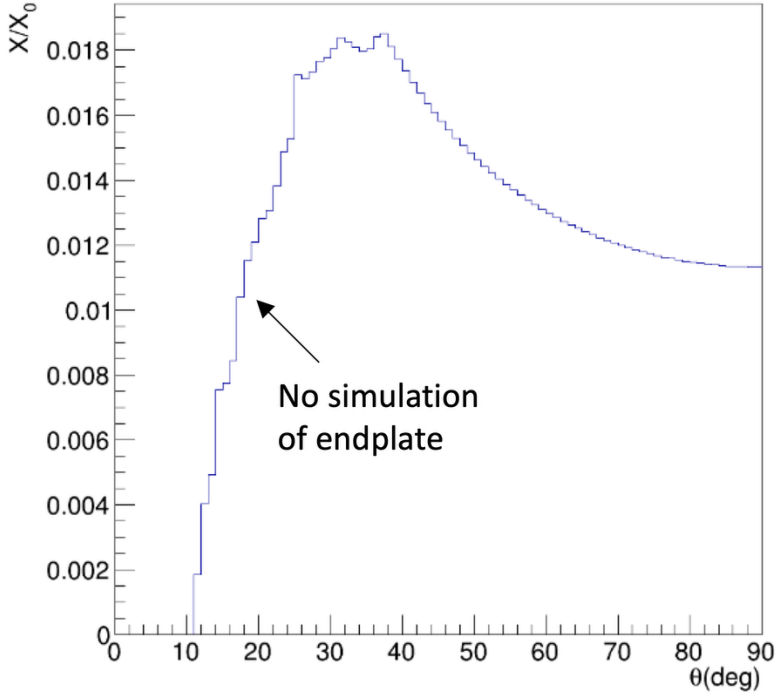


GEANT Simulations: Material Effects

- GEANT-simulated single muons
- On average about 80 hits per track
- For 100 layers with 12 μm thickness,~3.7 mm Mylar in total**, ~1.2%** X_0 **at** $\boldsymbol{\theta = 90°}$
- X_0 dominated by Mylar wall, negligible contributions from gas and coating material



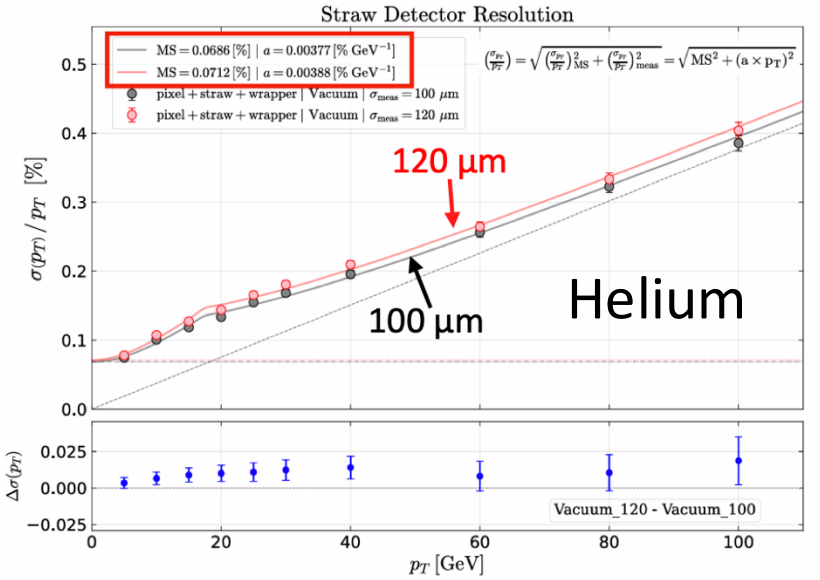




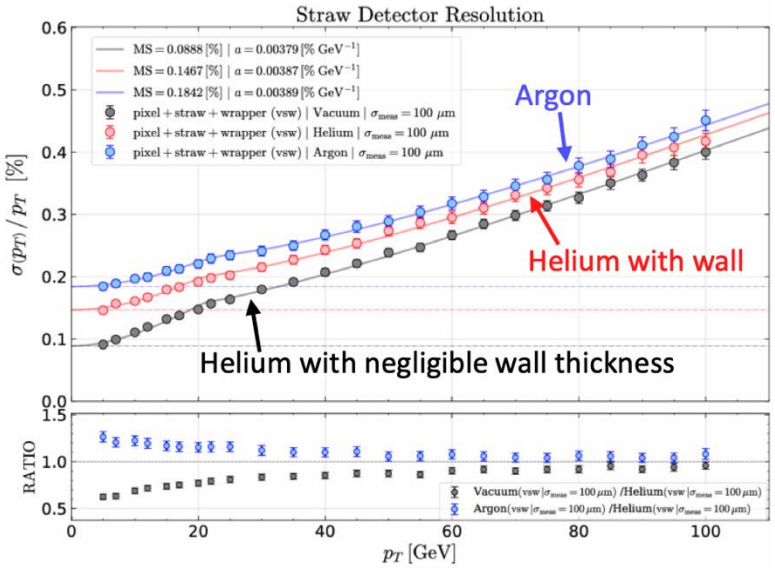
GEANT simulated hits for 5000 muons with $P_T = 20$ GeV

GEANT Simulations: Momentum resolution

- GEANT-simulated single muons: hits are then smeared and fitted with a python track fitting algorithm
- On average about 80 hits per track
- Momentum resolution determined assuming no material for the straw tube wall, using Helium or Argon gas

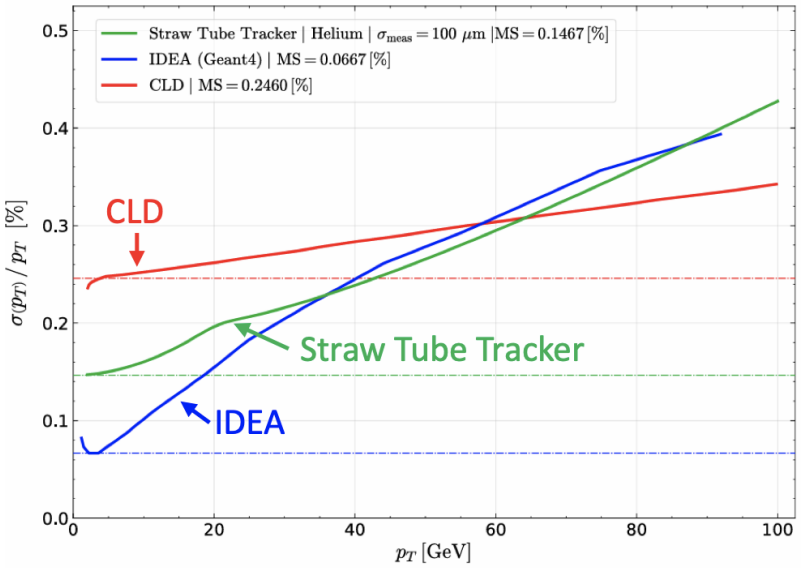


Momentum resolution for different single hit resolutions



Impact of different gases:
- Helium with negligible wall thickness
- Helium with wall
- Argon

IDEA plot taken from De Filippis's talk at the Michigan straw tracker workshop



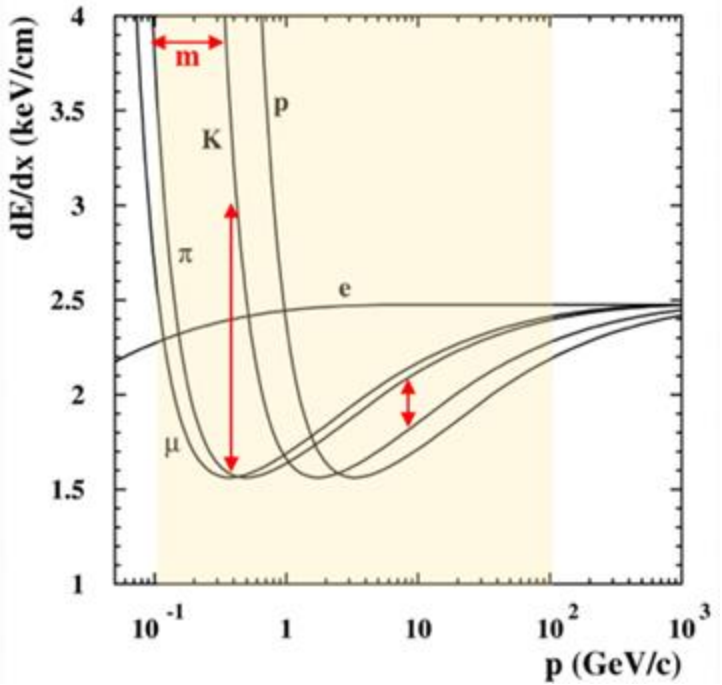
Comparison with CLD and IDEA

These resolutions are calculated based on different assumptions and should be viewed with a grain of salt (for example r=0.3-1.8 m for the straw tracker, and r=0.35-2 m for the IDEA drift chamber)

Particle identification: dE/dX and dN/dX

Important to have >3σ π/K separation over a wide momentum range from O(100 MeV) to O(40 GeV) for many Higgs and flavor physics studies.

Expect 10-15% difference between pi/K dE/dX distribution above a few GeV, important to have good dE/dX resolution

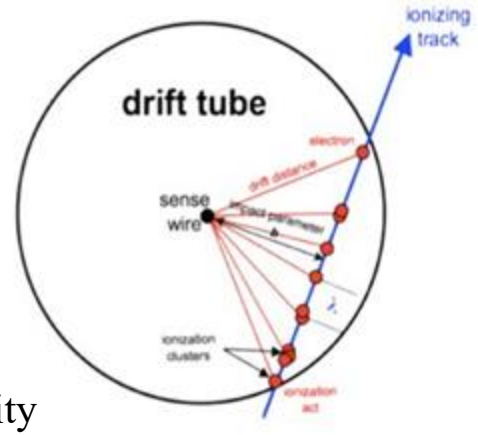


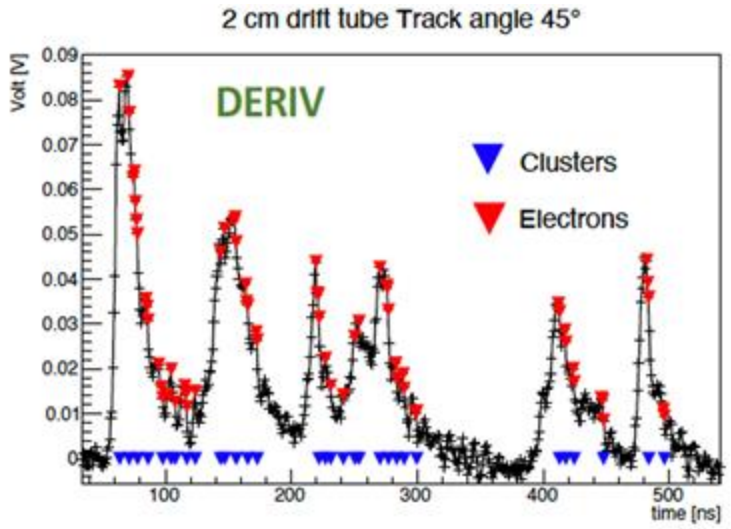
Truncated mean (dE/dX):

- 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: $\sigma = 0.41 \times n^{-0.46} \times (\tau p)^{-0.32}$ for Argon (τp in unit of cm bar)
- $\sigma = 4.5\%$ assuming $n = 120$ and $\tau p = 1$ cm bar

Counting clusters (dN/dX):

- 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 previous experiments have implemented this technique and used it online yet
- Some test beam studies performed by the drift chamber community





N. De Filippis, Detector concept meeting Nov 2023

Challenges on dN/dX

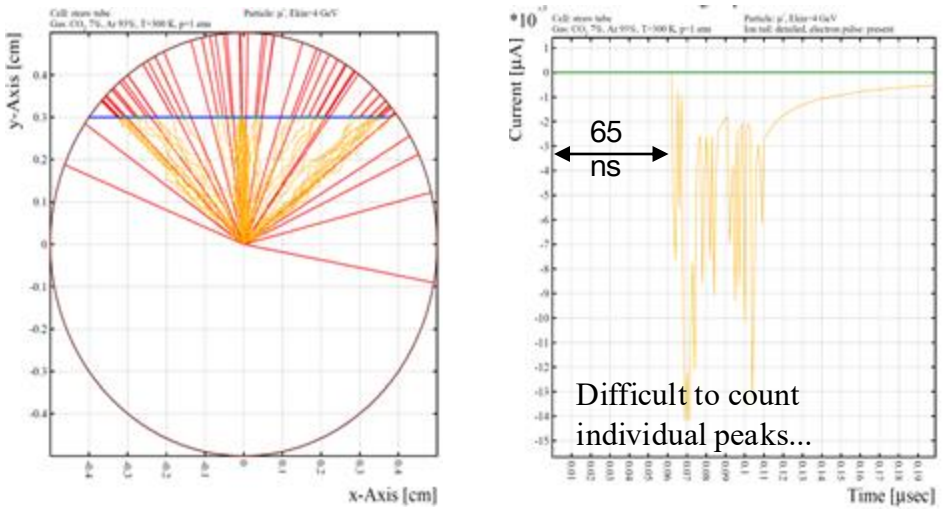
Garfield++ simulation for Helium-based and Argon-based gas mixtures

- Ar-based gas: high ionization density (~40/cm) and 50 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~5 ns
- He-based gas: lower ionization density (~10/cm) and 30 mm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~15 ns
- Many clusters will only have one electron-ion pair, however, there are also a few clusters with many electron-ion pairs
- On average, slightly more than two electron-ion pairs produced per primary cluster

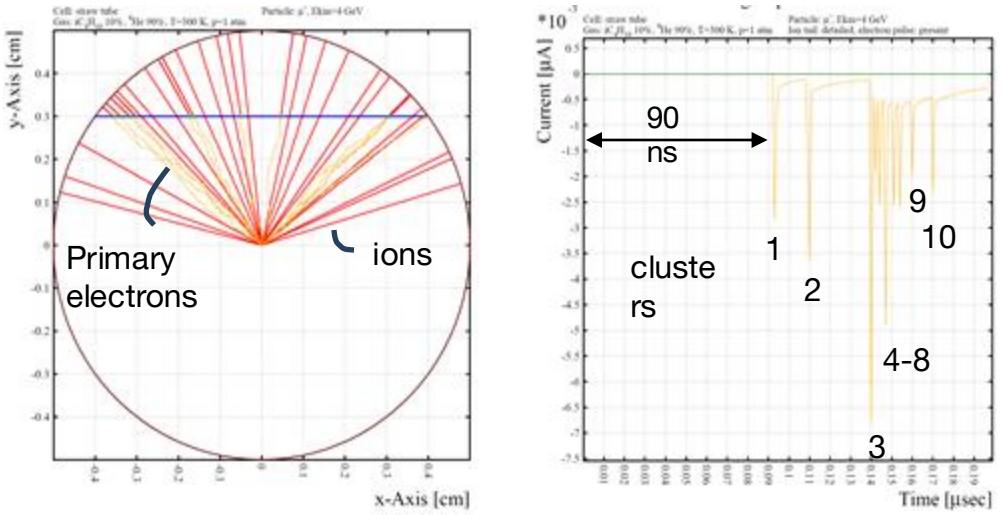
Need to have large amplification, fast and low noise front-end electronics, waveform digitization, and fast algorithm to identify clusters

Upenn + Michigan + UT Austin: Working on a proposal to develop a prototype of frontend electronics

- Besides this digital approach, we are also investigating an analog approach to find out electron peaks
- Benefit: low power consumption and small data rate



$Ar:CO_2$ (93:7) 1bar

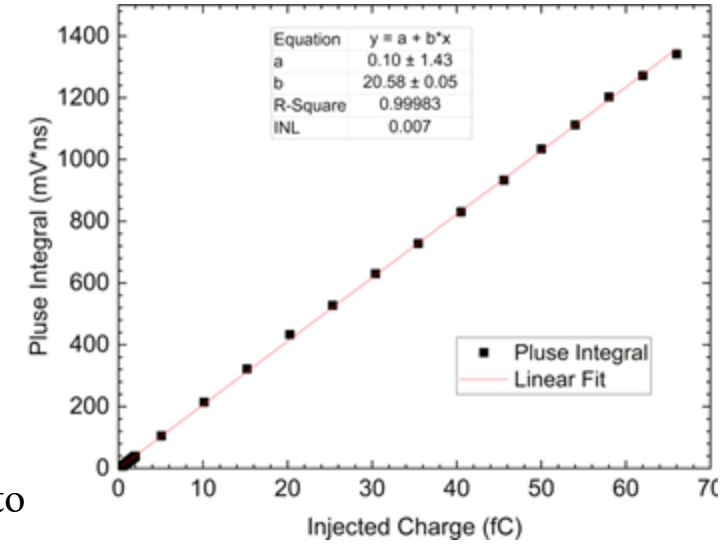


$He:iC_4H_{10}$ (90:10) 1bar

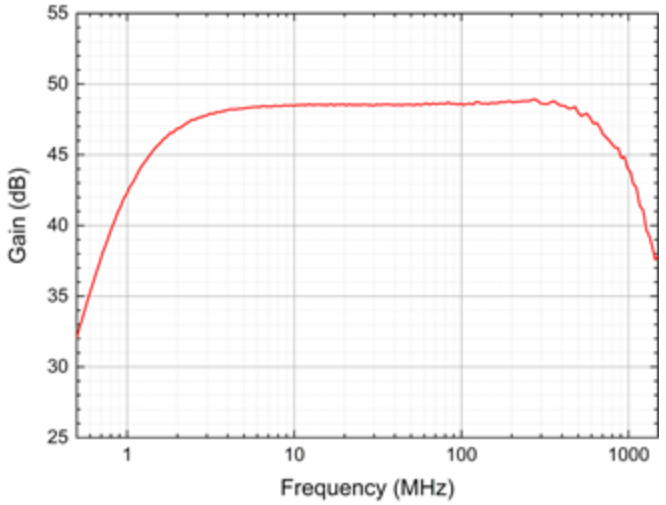
5mm radius tube with 1 bar and 1kV simulated here

New Fast Amplification board

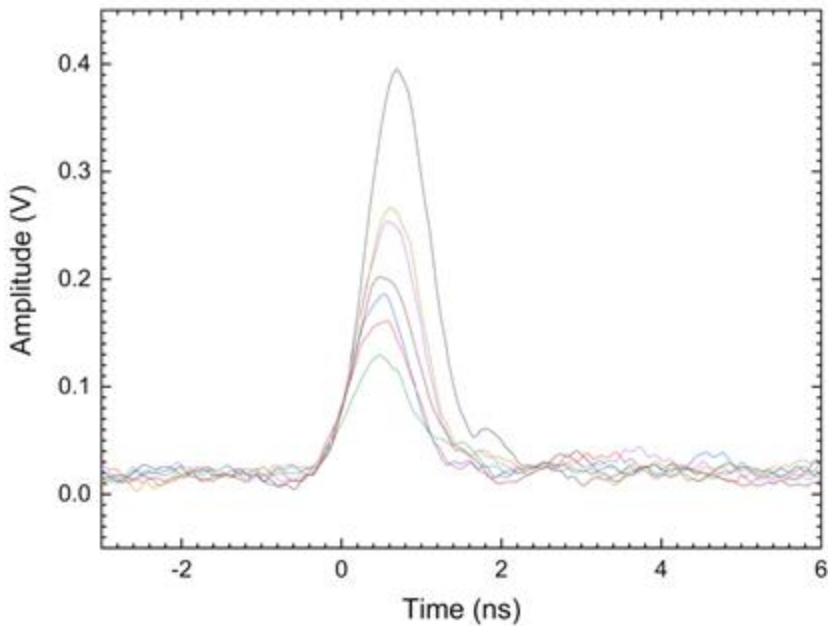
- The amplification board needs to provide another amplification factor of O(10^2) and needs to be fast
- A new frontend board designed and produced
  - Read out 8 channels per board
  - Waveforms will be recorded by the CAEN DRS4 waveform digitizers, most readout firmware/software developed
  - Mounted on the sMDT mini-chambers (8 are available) to perform dN/dX studies using cosmic rays in the lab and test beams at CERN



Charge Gain: 20.58 mV/fC

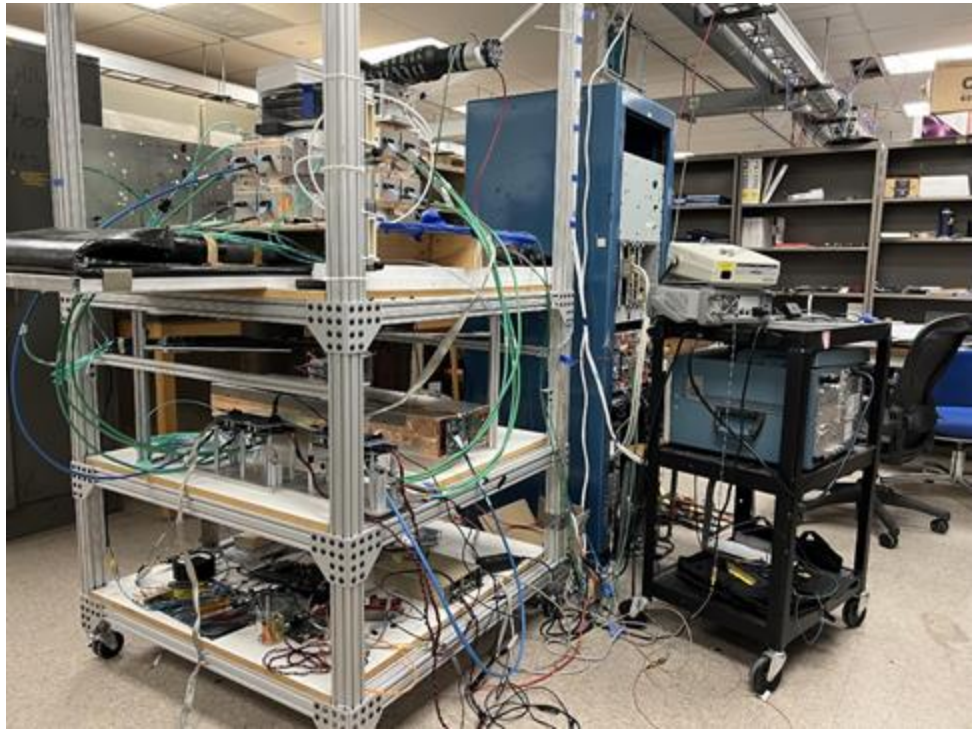


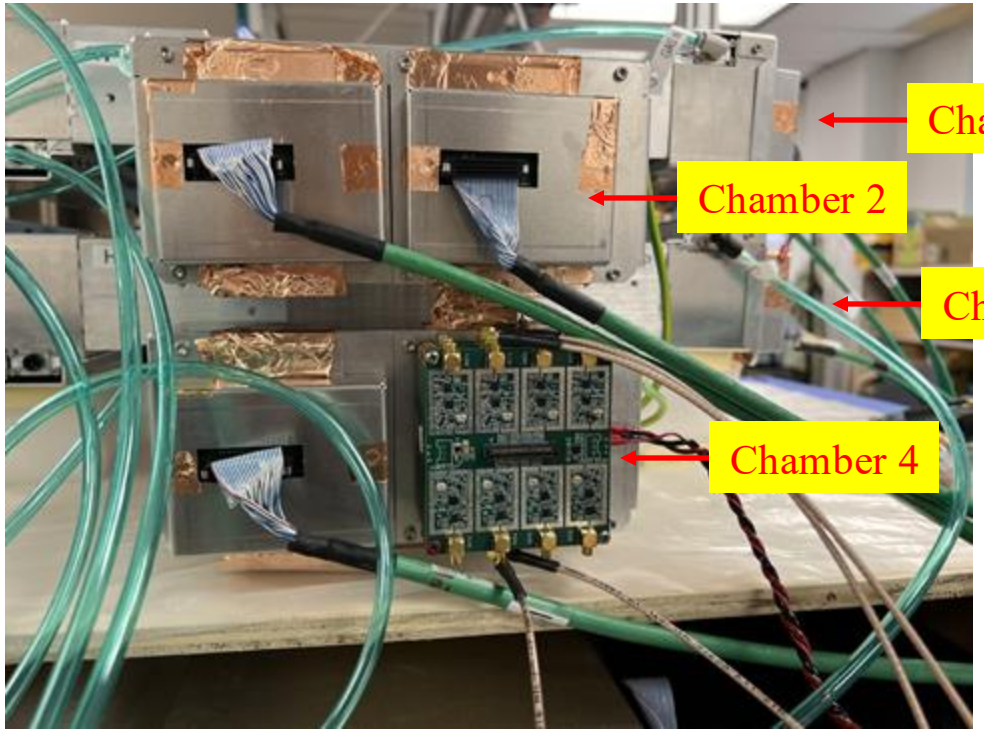
-3 dB Bandwidth: 1.5-872 MHz



Amplifier output of a fast delta-like signal

Cosmic Ray Test Setup at Michigan

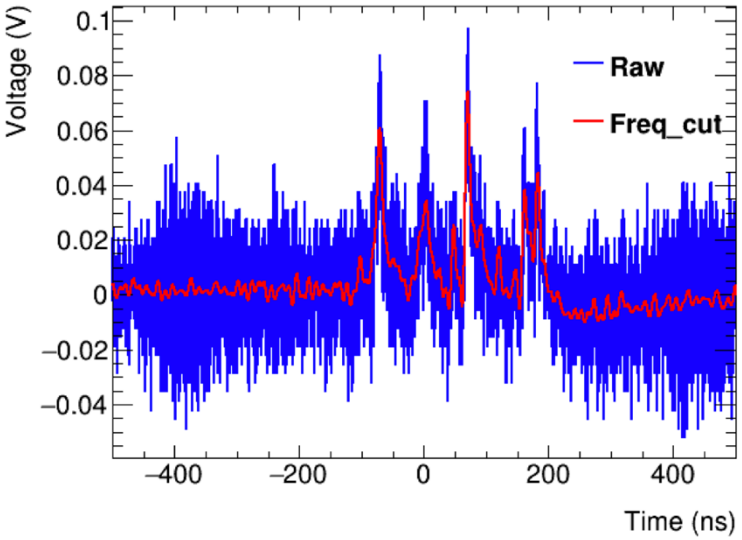


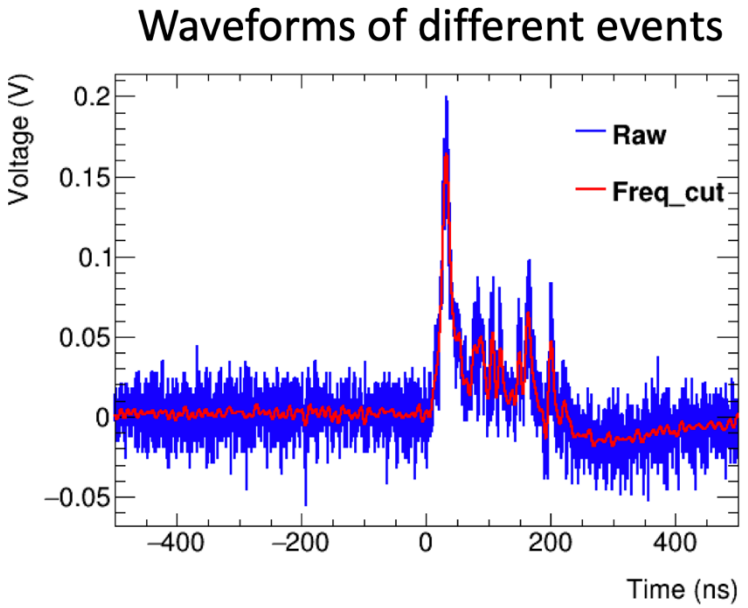


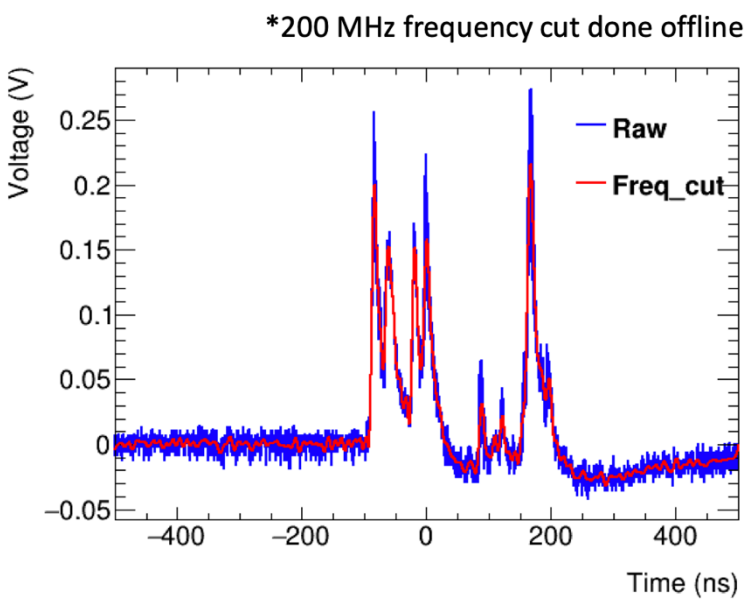
- A scintillator is used to trigger on cosmic muon events
- Four sMDT chambers (1.5 cm diameter tube, 50 μm diameter wire, four layers each with a resolution of ~100 um per tube) perpendicular to each other
- Three chambers will be read out using the ATLAS electronics and will determine the muon direction and calculate the path length (dX)
- One chamber will be read out using the new amplification board and oscilloscope to record all waveforms for offline analysis to find dN
- Cosmic ray studies in the lab to determine number of primary clusters per cm

Cosmic Ray Test Results with He-based gas

- Use the new amplifier to record raw cosmic ray waveforms from the sMDT tracker. These waveforms will be used to develop dN/dX algorithms for PID.
- Larger noise observed and need to apply a low pass filter to reduce noise
- A derivative method is used for peak finding.



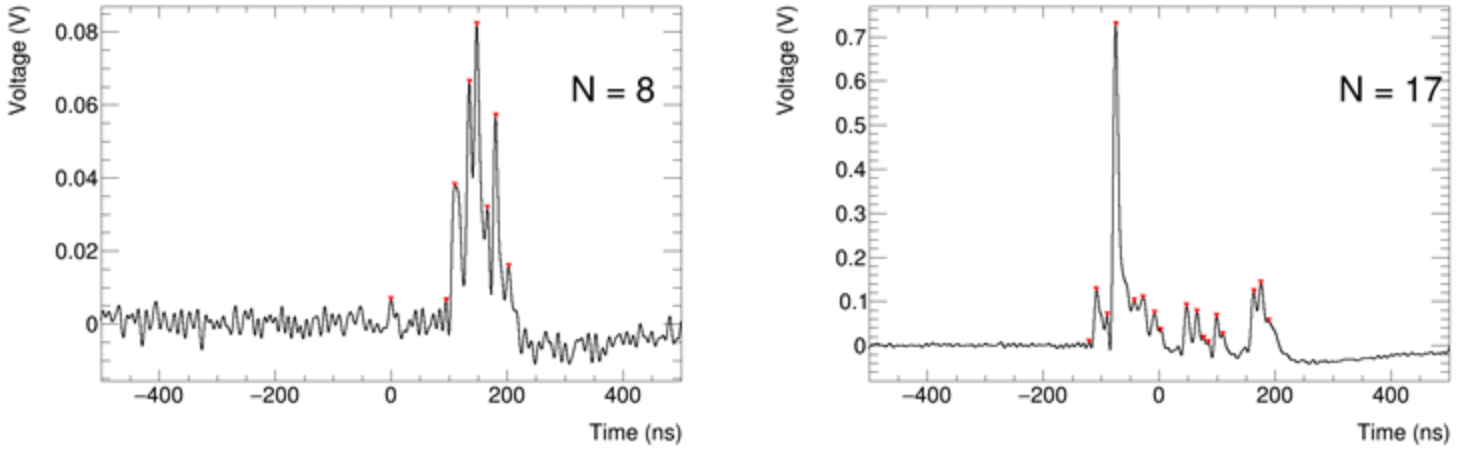




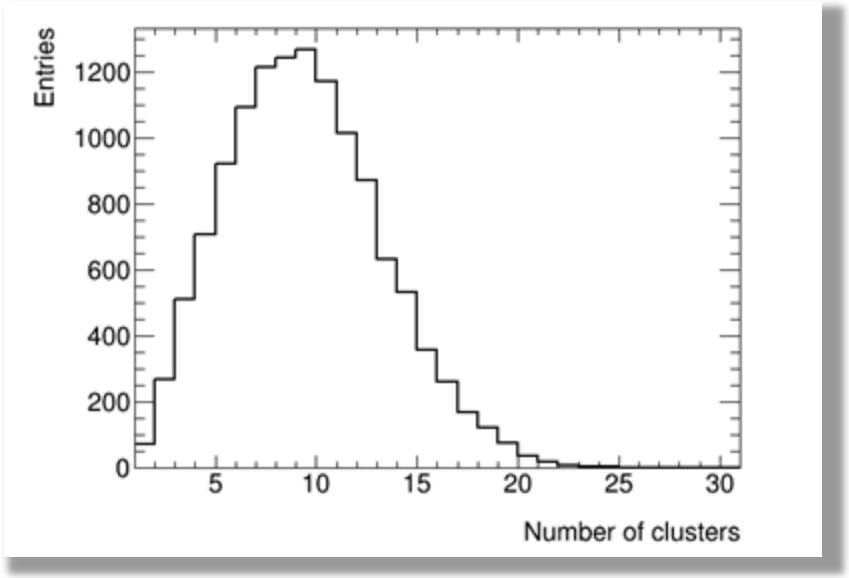
Cosmic Ray Test Results with He-based gas

Tasks

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



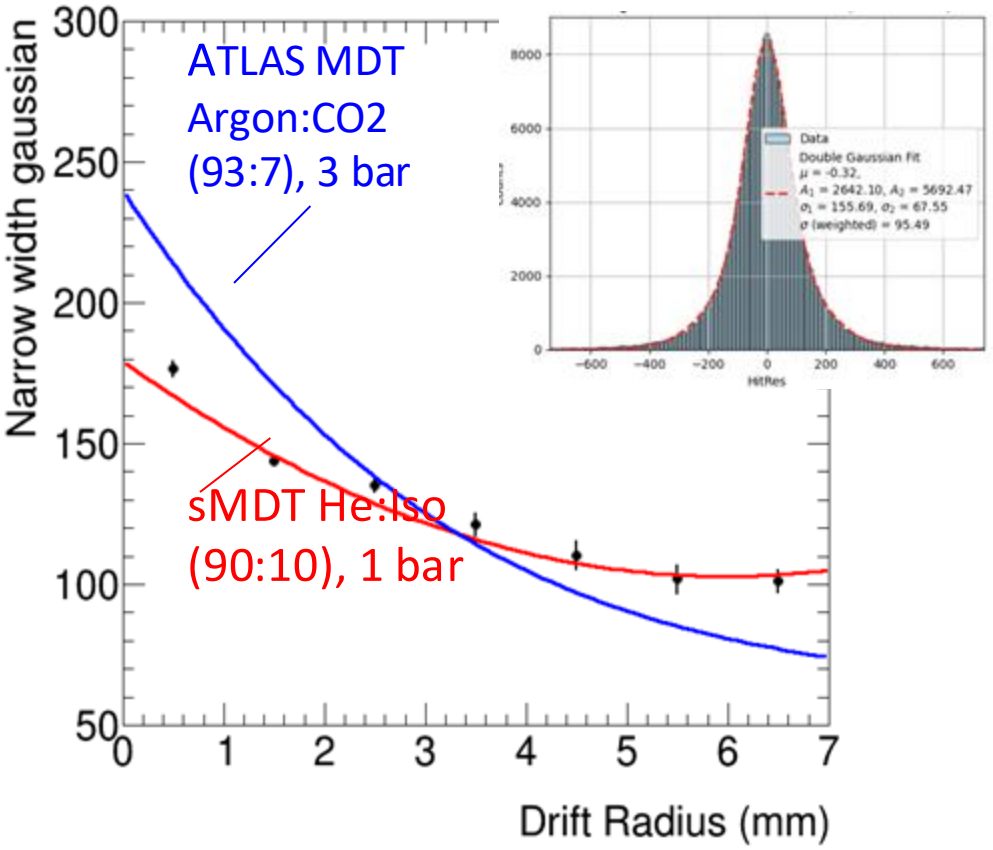
Peaks counting



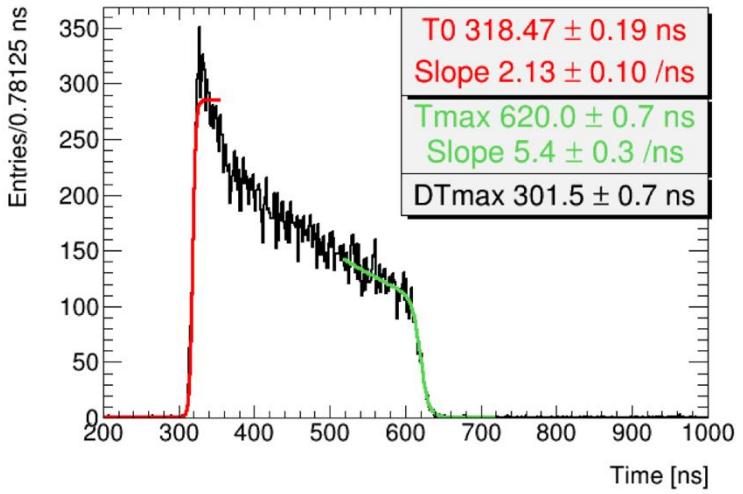
Number of peaks distribution

Cosmic Ray Test Results with He-based gas

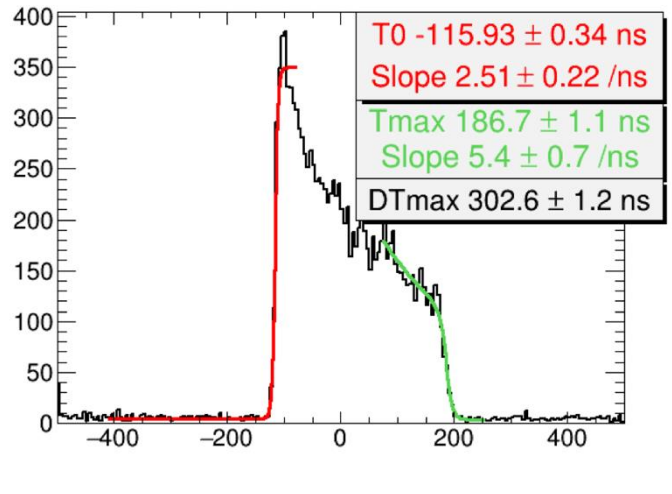
- Study He-based gas detector tracking resolution with sMDT tracker (σ~125 μm)
- Observed similar drift time for both readout



Helium:Isobutane (90:10) gas mixture resolution vs drift radius. Single tube resolution = 125 μm

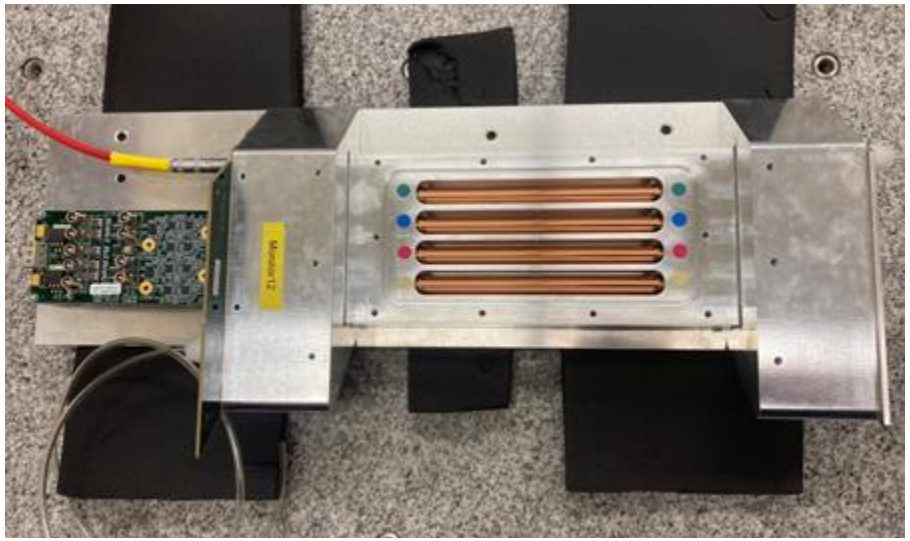


Drift Time spectrum with ATLAS sMDT electronics



Drift Time spectrum by waveform recording

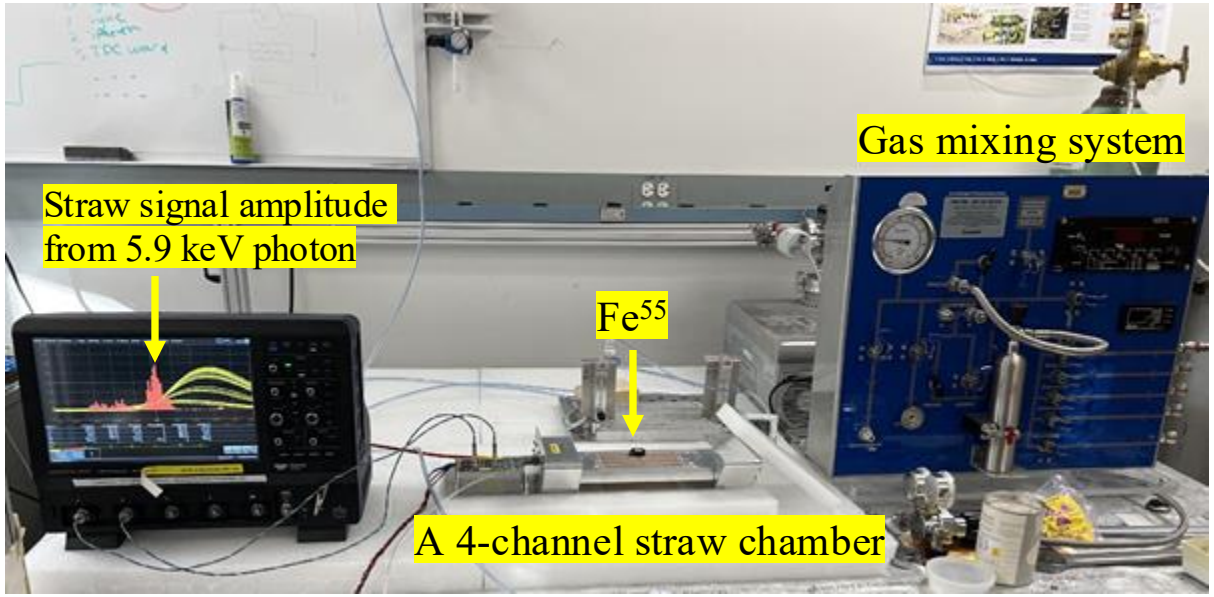
Gas mixture studies

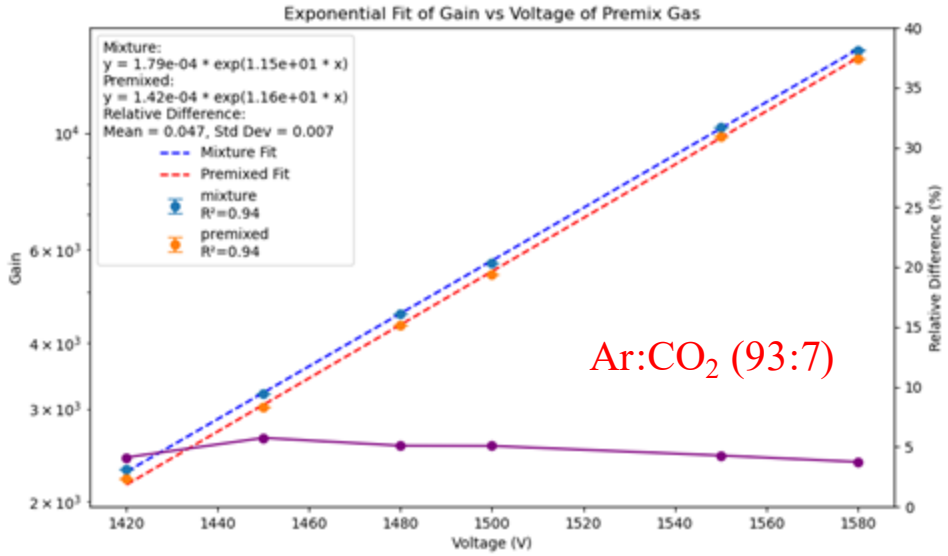


A 4-channel straw tracker from NA62

- Try different gas mixture to optimize for both momentum resolution and PID detection
- Argon based gas is good for momentum resolution, and He based gas is favorable to measure dN/dx
- For different gas we also need to determine the gain and the working point
- Need upgrade to mix He with liquified Isobutane

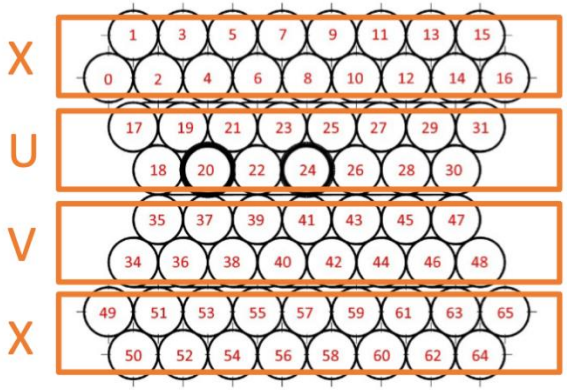
- More details will be discussed in the muon detector talk.
  "A High-Precision, Fast, Robust, and Cost-Effective Muon Detector for the FCC-ee"



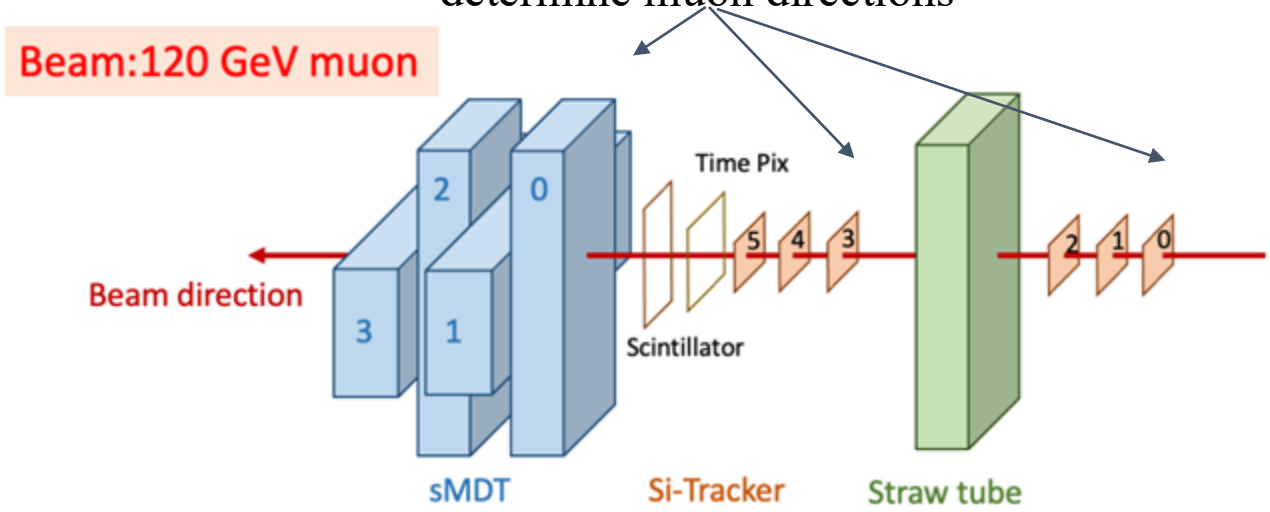


Test Beam Studies: Setup

- Performed test beam studies with Temur's group at CERN SPS/PS facility from 2024/09 to 2024/10
- Straw information:
  - Tube-wall 36 μm coated with 20 nm gold and 70 nm copper
  - Central wire diameter: 30 μm
  - Two planes of X (vertical tubes), two planes of U (2° stereo angle), two planes of V (−2° stereo angle), and two other planes of X
- Si-tracker has an acceptance of 20 mm×10 mm, provide tracks with a resolution ~5 μm



Silicon and sMDT chambers used to determine muon directions



Test Beam Studies: Results

Single tube spatial resolution

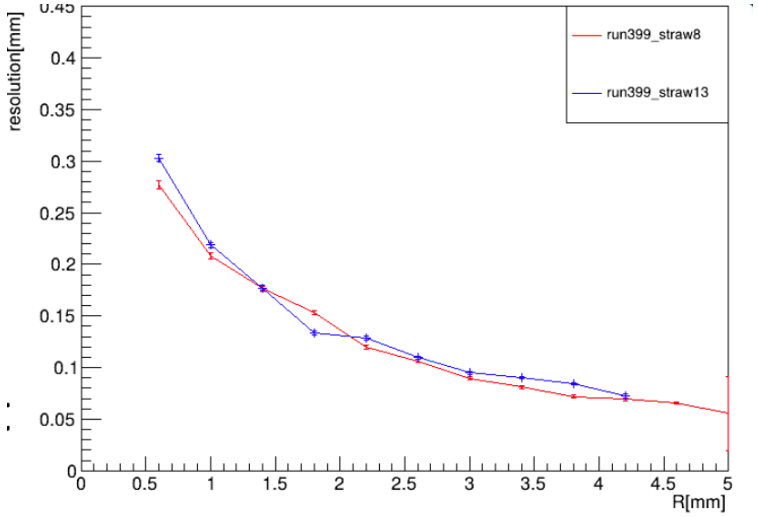
- Extract the R-T function from the silicon tracker measurement
- Predict the hit position using straw tubes' readout
- Combine hits from the silicon tracker and straw tubes in track fit to obtain straw resolution
- Resolution can reach ~100 μm

Efficiency

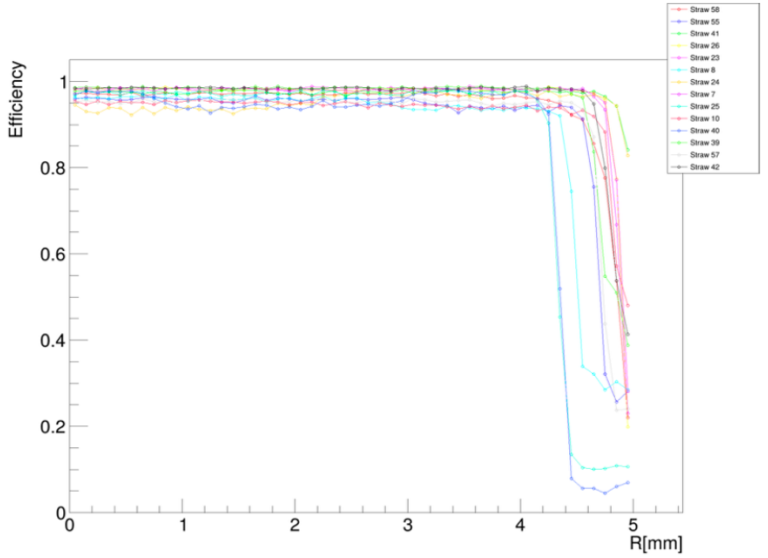
- Efficiency is uniform across different tubes, vary from 94%~98%

Second coordinate resolution

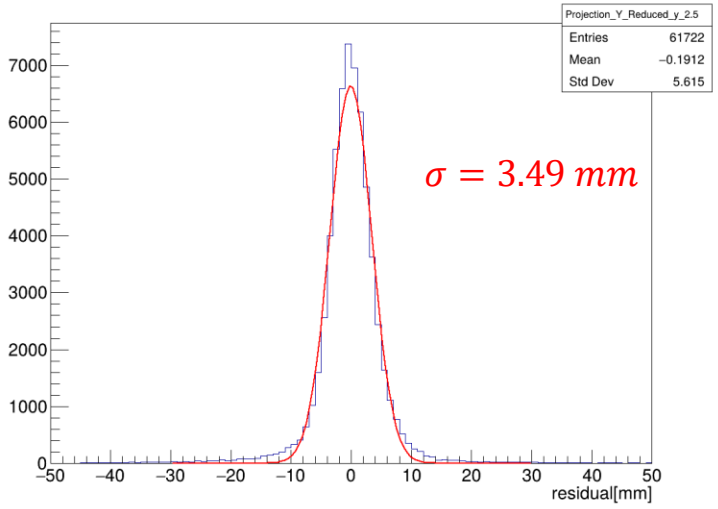
- 3D track reconstruction using hits from X/U/V layers
- Best resolution of ~ 3.5 mm



Resolution's relation with radius
(select 2 tubes in different layer)



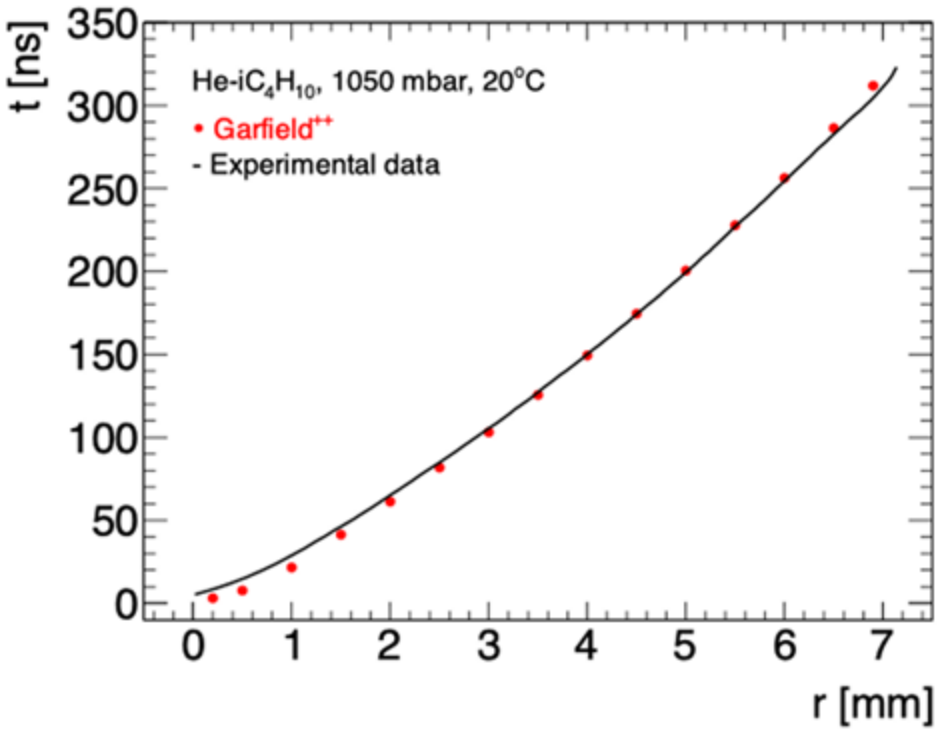
Efficiency's relation with radius

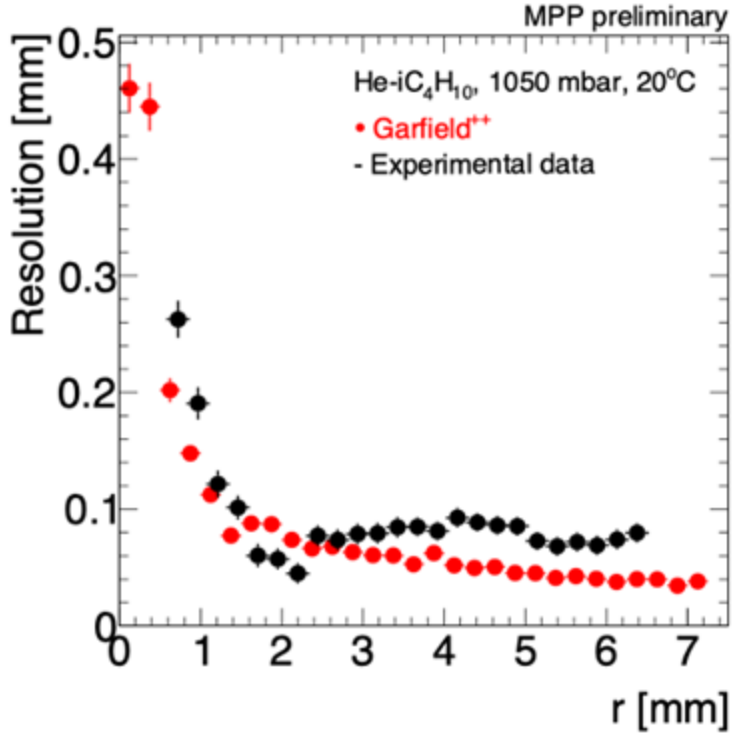


Distribution of 2nd coordinate difference
measured by straw and SI-tracker

Cosmic Ray Studies with Helium gas mixture

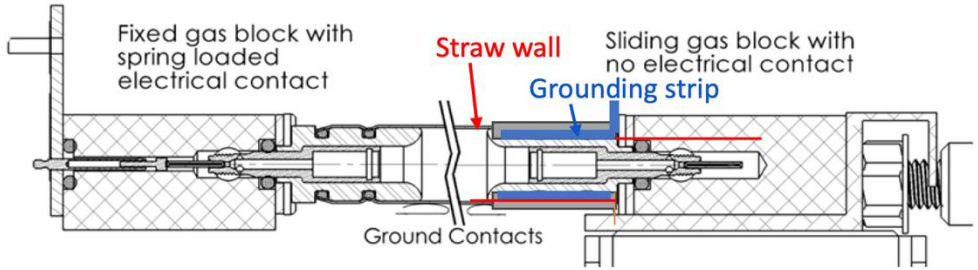
- MPI performed Garfield simulation for He-isobutane and measured the single hit resolution using cosmic muons



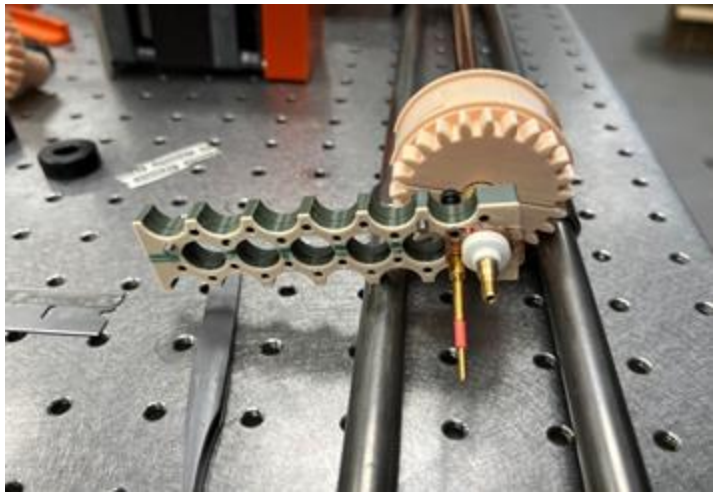


Straw Chamber Prototype Construction

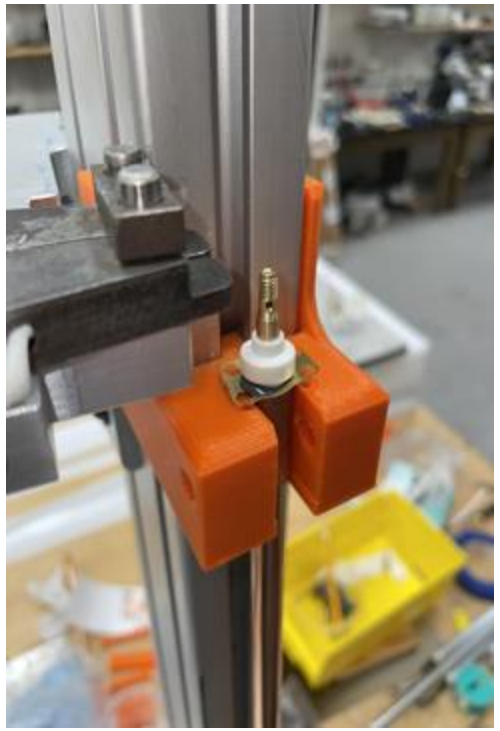
- Plan to construct a prototype chamber consisting of 24 straws, each 50 cm in length, building on our extensive experience with the construction of ATLAS sMDT chambers
  - Utilize ATLAS sMDT HV boards and readout electronics
  - Modify the sMDT end plug, develop new endplate support structures and new 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

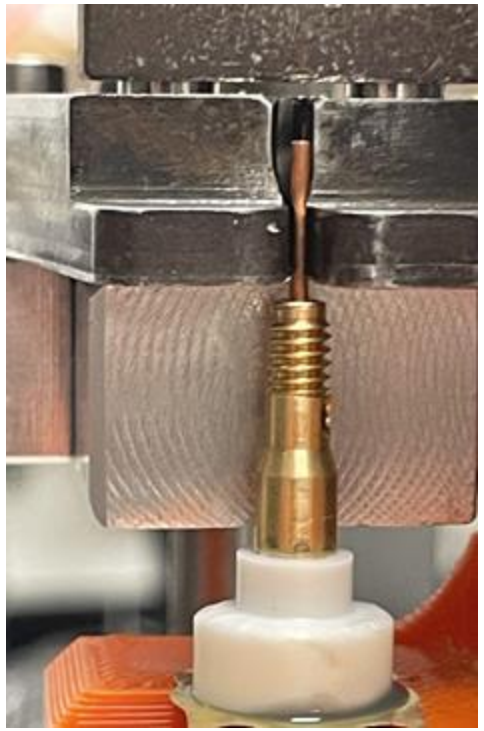


50 cm long straw tubes



Straw tube assembly





Wire the tube

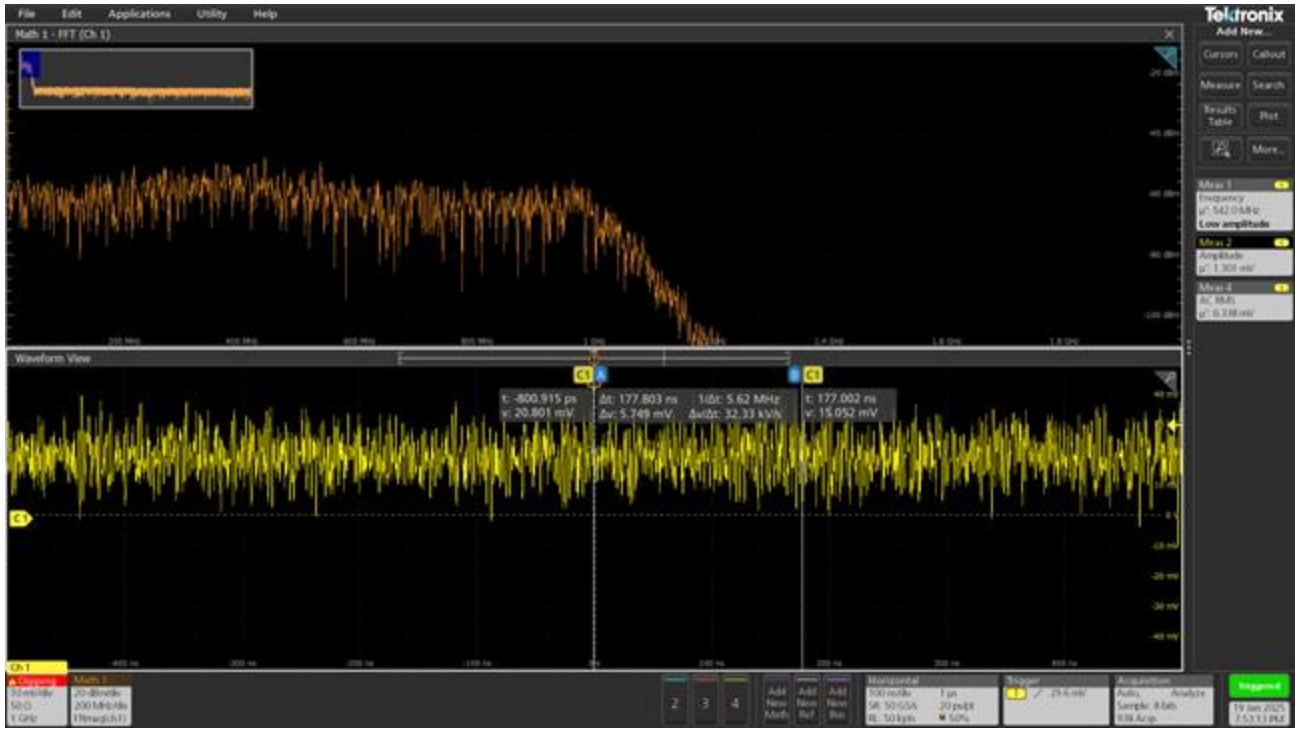
Summary

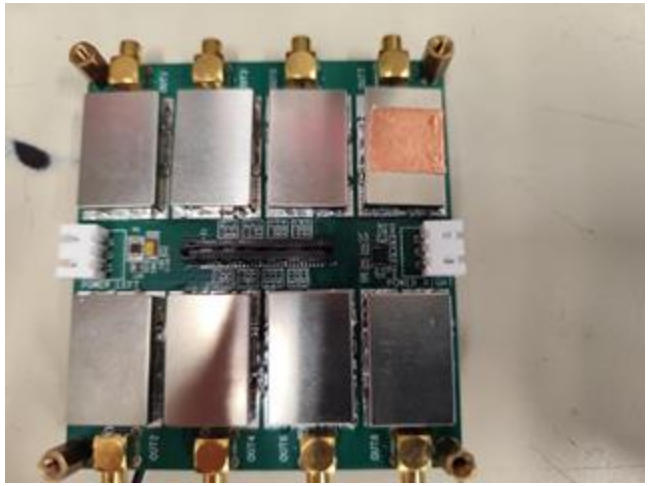
- Preliminary studies of the straw tracker with dN/dX and tracking performance indicate promising performance that meets FCC-ee demands.
- Much ongoing R&D studies: simulation work, gas mixture system, dN/dX, straw production and assembly, readout electronics, mechanical structure...
- Significant progress made 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!

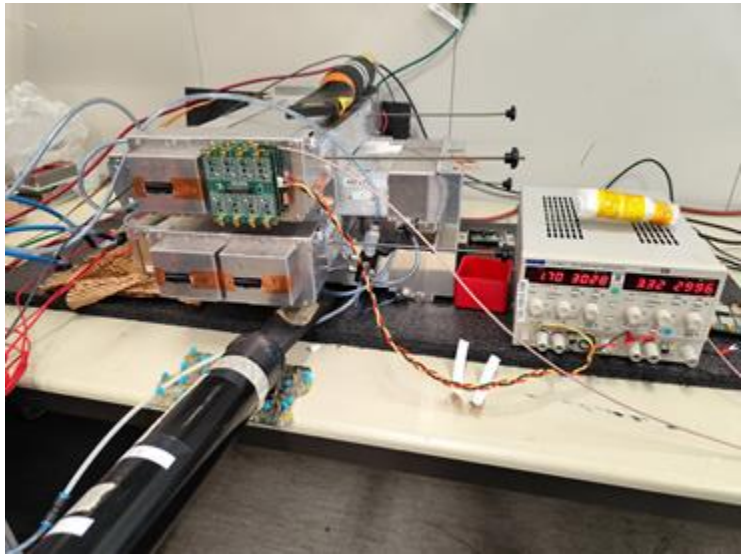
Back up

New amplification board

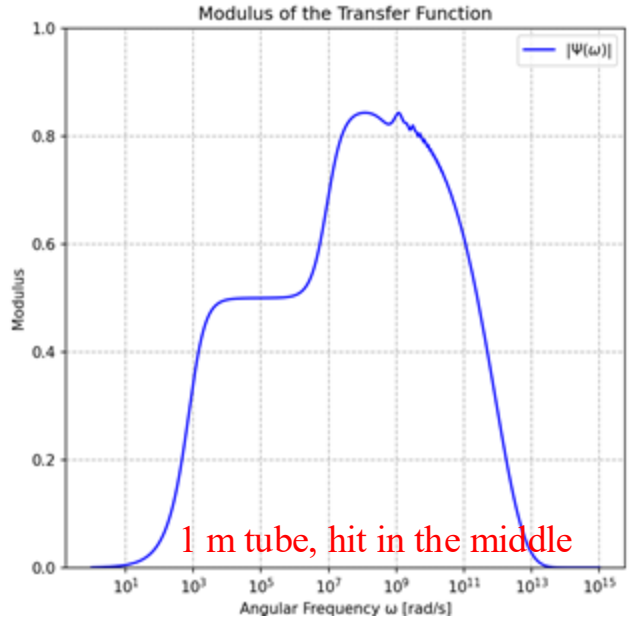
- Each board has 8 channels, by soldering different input resistors and then stacking 3 boards together, can read out 24 channels
- Protection circuit on RO HH, removed it from the amplification board
- Add a Pole-Zero cancellation circuit between 2nd and 3rd stages to reduce undershoots
- Customized Faraday Cages to cover each channel
- RMS noise around 6.38 mV (input floating, NO FC), bandwidth ~1 GHz
- Input a 2.5-mV pulse, output pulse 1.08 V, Gain: 427 V/V

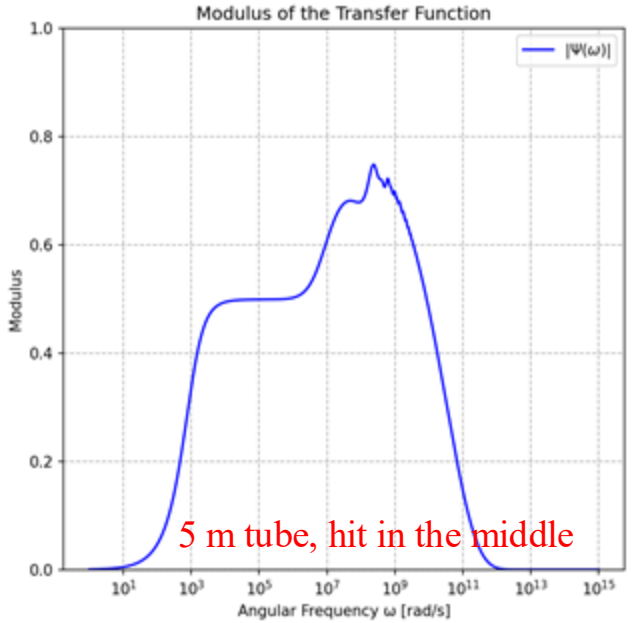


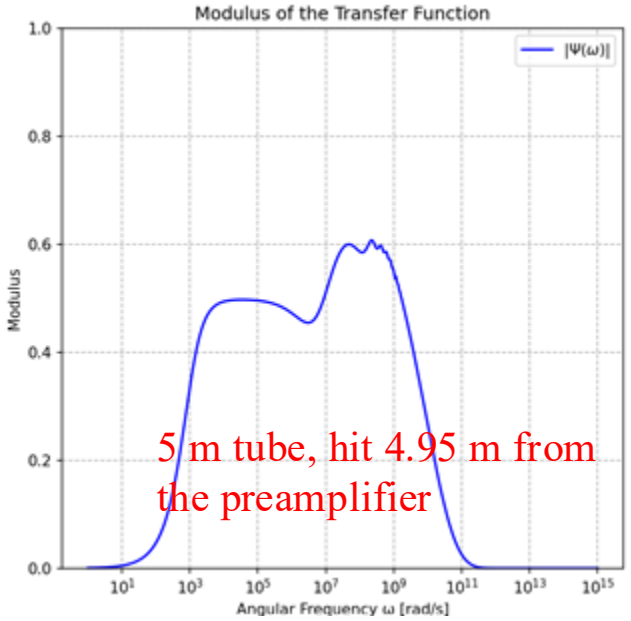


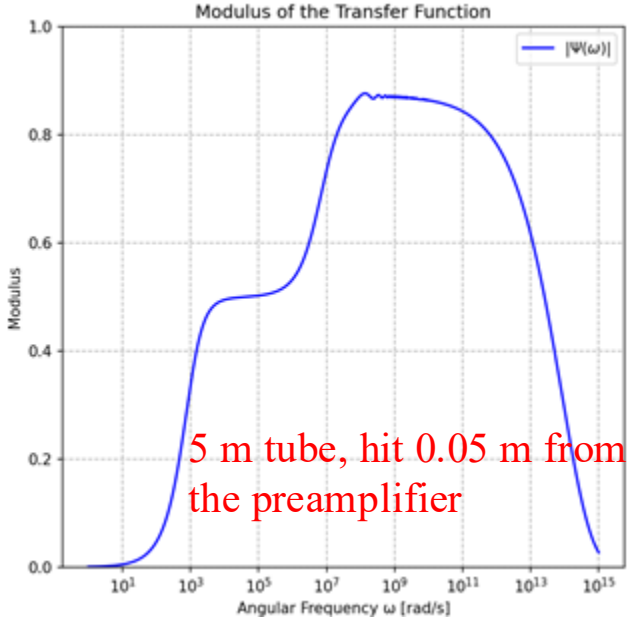


Understanding the detector and electronics signal



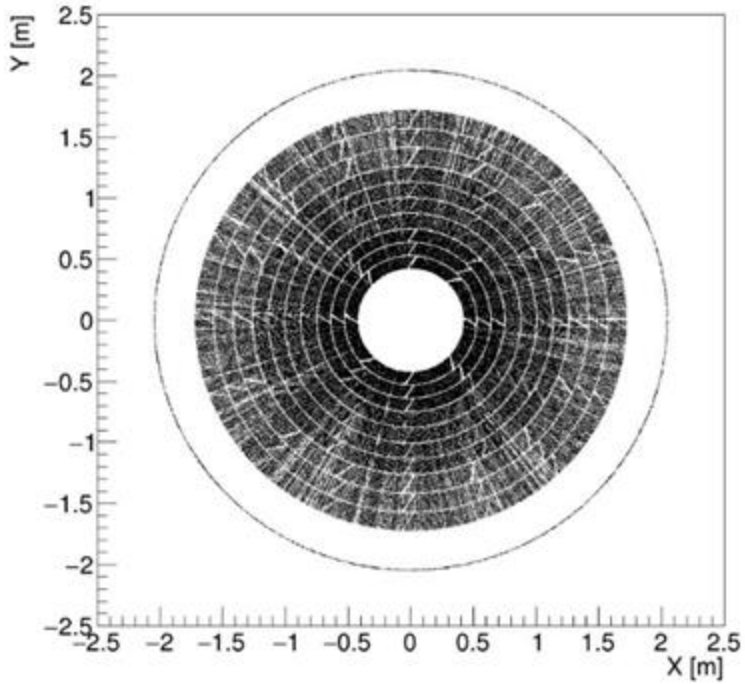






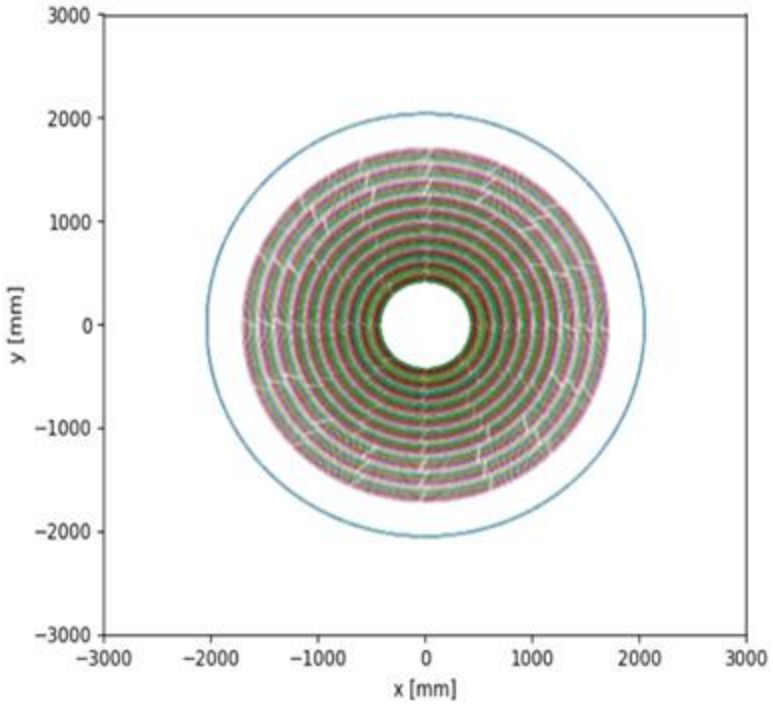
A Common Tracking Software (ACTS)

- Using A Common Tracking Software (ACTS) to study the tracking performance with the straw tracker
  - A tracking geometry description which can be constructed manually or from TGeo and DD4hep input
  - Implementations of common algorithms for track propagation and fitting, like Kalman Filter
- Translated geometry from DD4hep to ACTS
  - Complete Geant4 description in the DD4hep geometry contains not only the sensitive detector (Helium, silicon) but also passive elements (Mylar wall, sense wire, etc.)
  - To improve the speed, sensitive parts are kept in the ACTS geometry with passive parts removed or simplified
- Material mapping and the implementation of the track fitting is on going



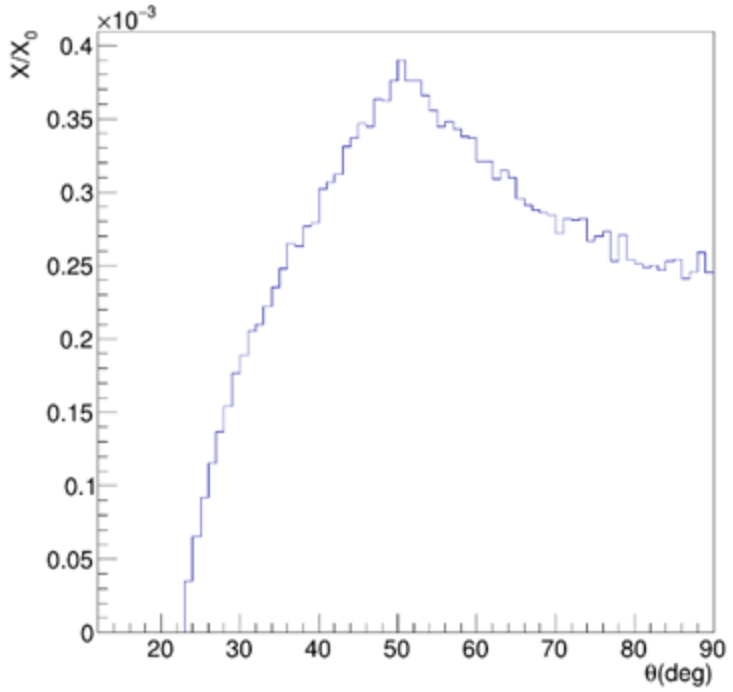
DD4hep geometry: .xml, .cpp

ROOT geometry (TGeo): .root

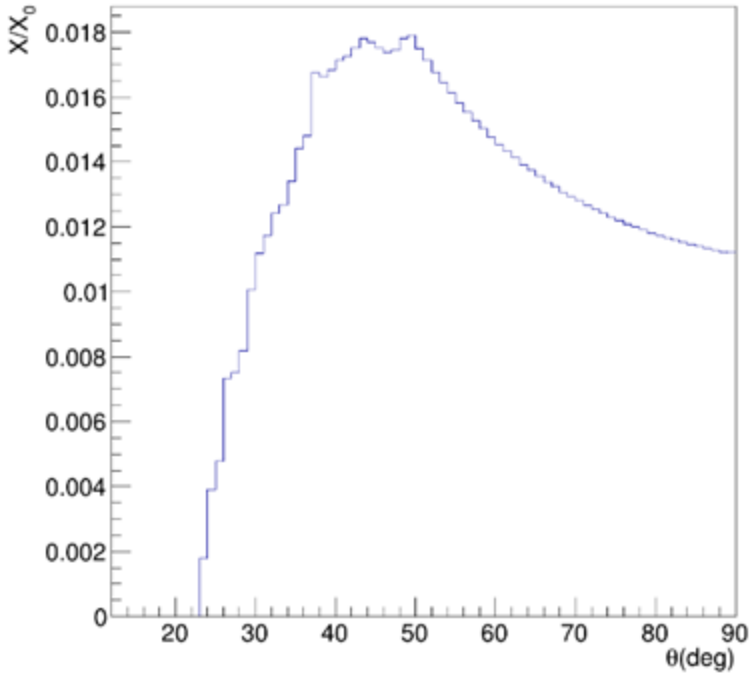


ACTS geometry: .json

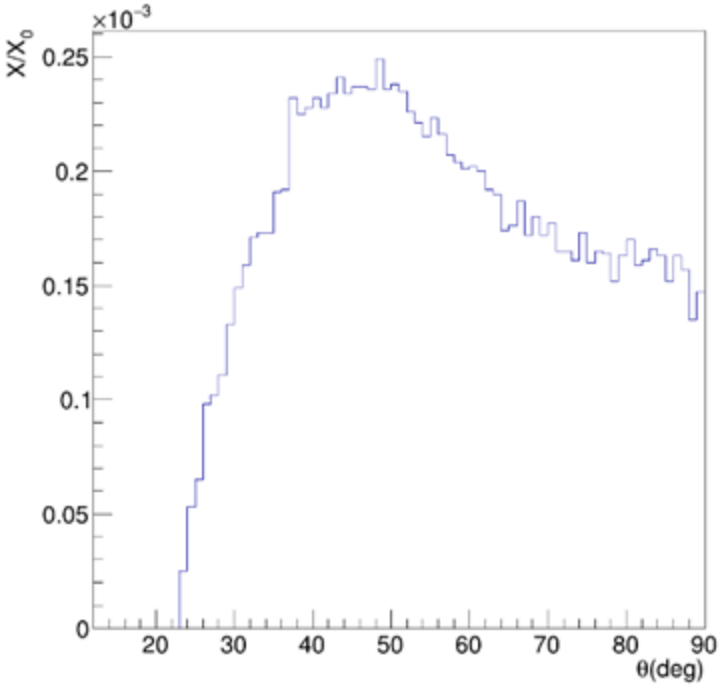
Material budget from the GEANT simulation



He



Mylar



Al