# Status of the straw tracker development

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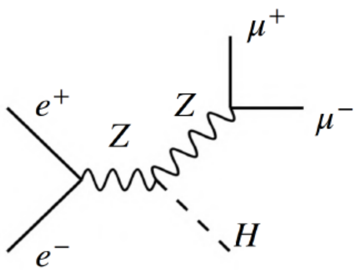
# Requirements for the FCC-ee tracker

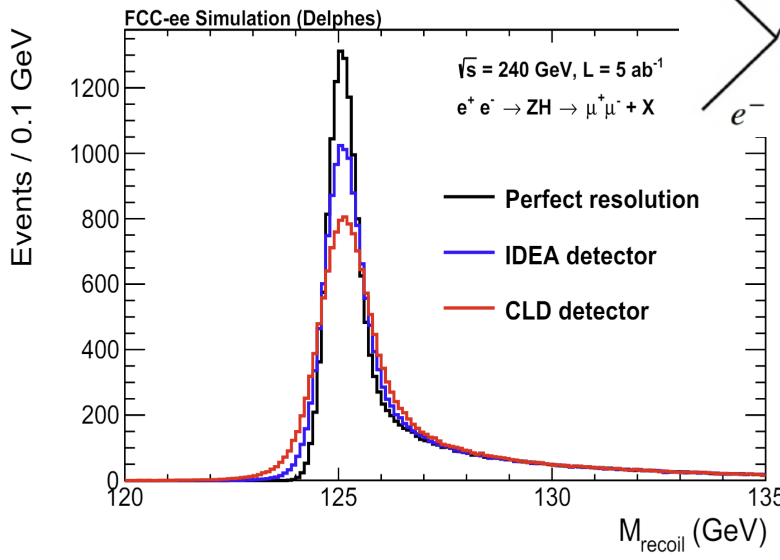
- Excellent momentum resolution for charged particles is critical for the FCC-ee physics program
  - Important to reconstruct the recoil mass distribution for the Higgs mass and ZH cross section measurements

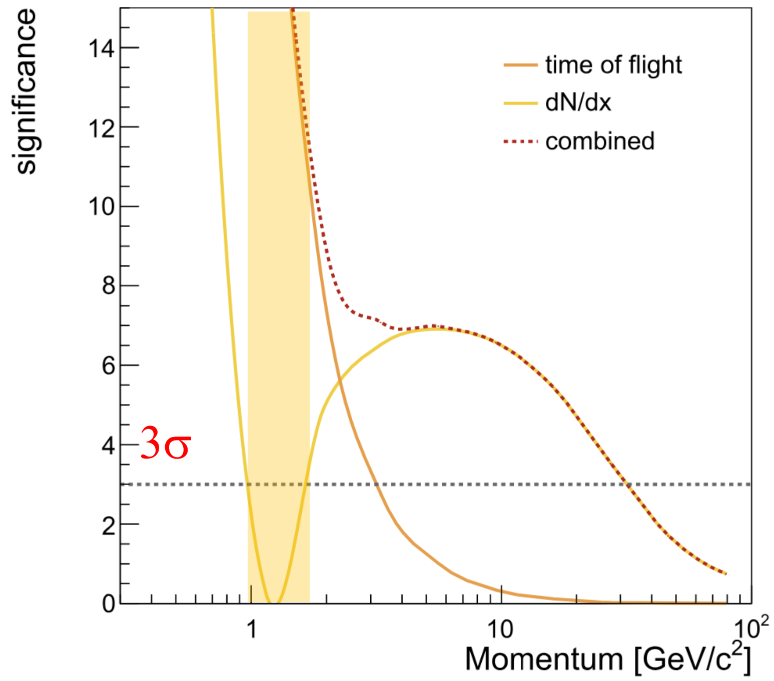
$$M_{recoil}^2 = (\sqrt{s} - E_{l\bar{l}})^2 - p_{l\bar{l}}^2 = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^2$$

  - Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)
    - $\sigma(p_T)/p_T \sim$ 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 from O(100 MeV) to O(40 GeV), important for many B, Higgs, and electroweak physics studies

A hybrid silicon + gaseous tracker is an excellent choice, especially for PID and pattern recognition

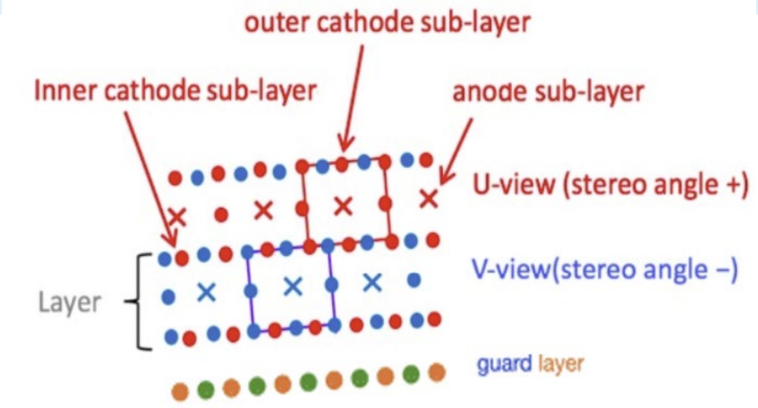


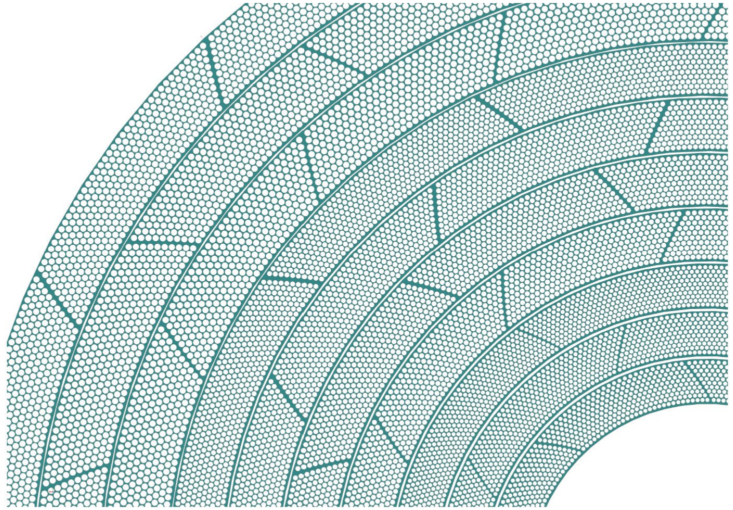
# Drift chamber

- A unique-volume, high granularity, full stereo, low mass, and cylindrical chamber
- $R_{in}$=0.35 m and $R_{out}$=2 m, length L=4m
- 12-14.5 mm wide square cells, drift time up to 400 ns
- 112 co-axial layers at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors
- 343,968 wires in total:
  - Sense wires: 20 μm diameter W(Au) → 56,448 wires
  - Field wires: 40 μm diameter Al(Ag) → 229,056 wires
  - Ground wires: 50 μm diameter Al(Ag) → 58,464 wires
- 5:1 field-to-sense wire ratio → uniform equipotential surface
- $\sigma_{xy} \sim 100$ μm, $\sigma_z \sim 1$ mm
- Operating gas: He:i$C_4H_{10}$ (90:10)
- Advantages: lower material budget, large path length and easy to calculate
- Challenges: small margins on the wire tensions, ~10 tons of forces on the two endplates, …

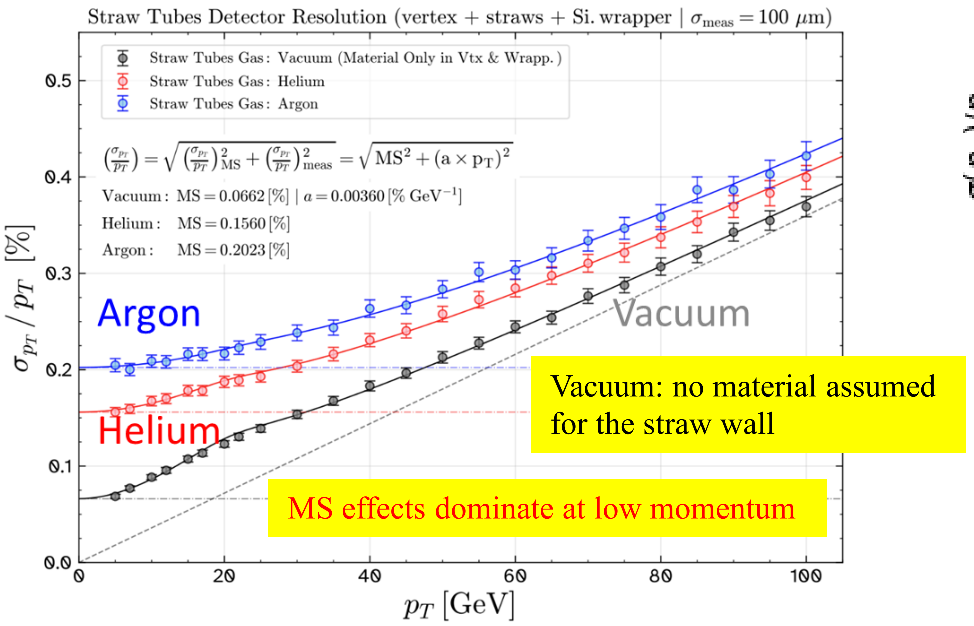


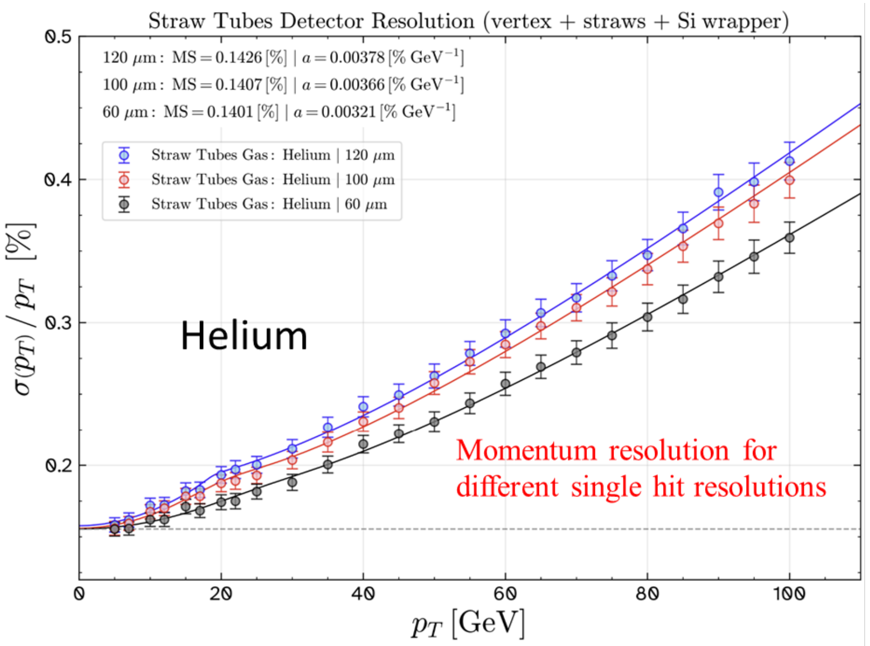

# Straw chamber

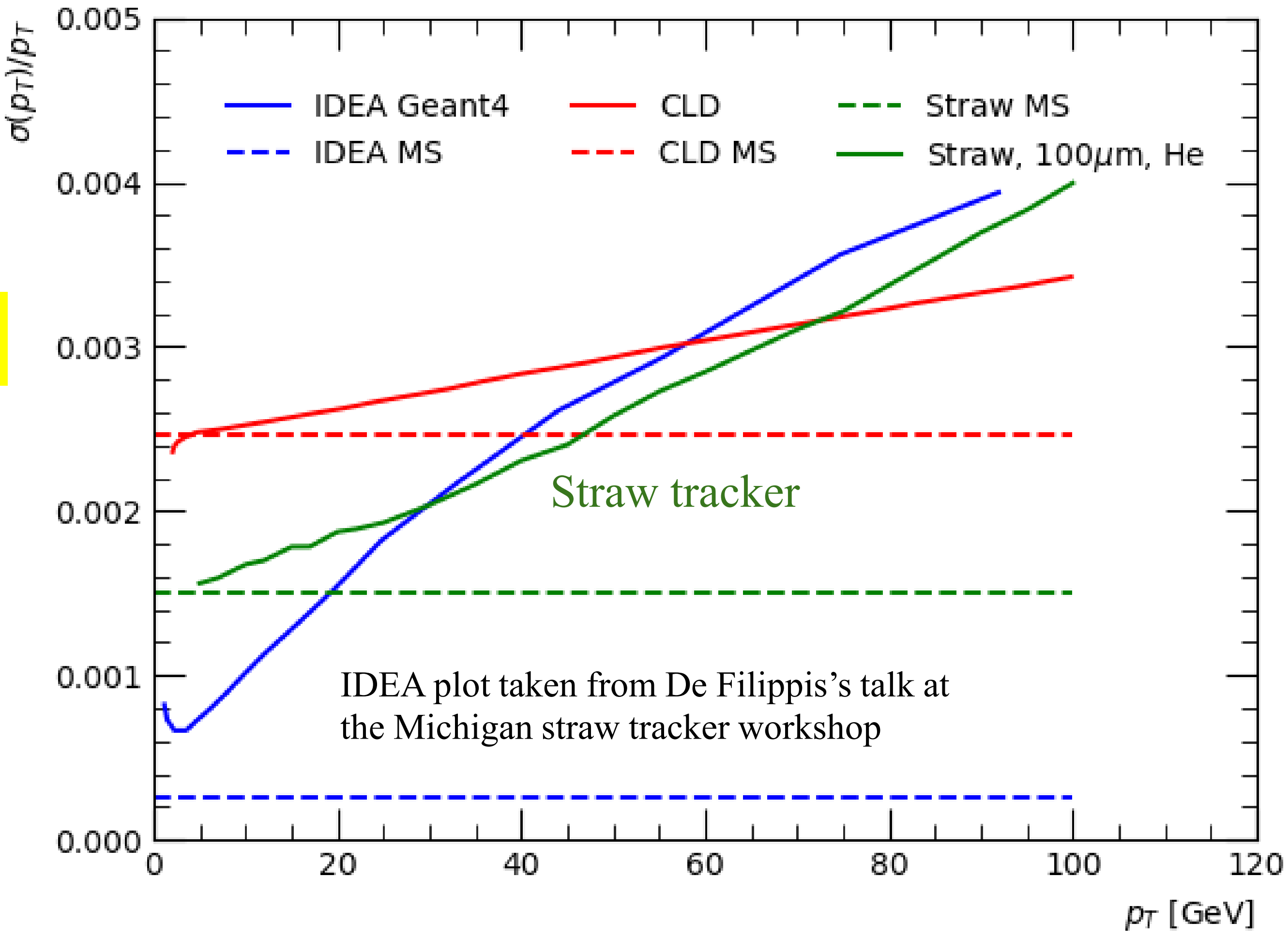
- Thin-walled straw tubes made of metallized Mylar film using spiral winding or ultrasonic welding
- One example detector layout (proposed in 2024):
  - 12 μm-thick Mylar film
  - $R_{in}$=0.3 m, $R_{out}$=1.8 m, L=4-5 m
  - Diameter 1 – 1.5 cm
  - 10 superlayers with 10 sublayers each
  - Stereo angle: 2 – 5 degrees
  - O(60k) straws
- $\sigma_{xy} \sim 100$ μm, $\sigma_z \sim 1$ mm
- Operating gas: He:i$C_4H_{10}$ (90:10)
- Advantages: low wire density, a single unit for each straw, radially symmetric electric field
- Challenges: thin tube production, support for long wires/tubes, …



# Momentum resolution



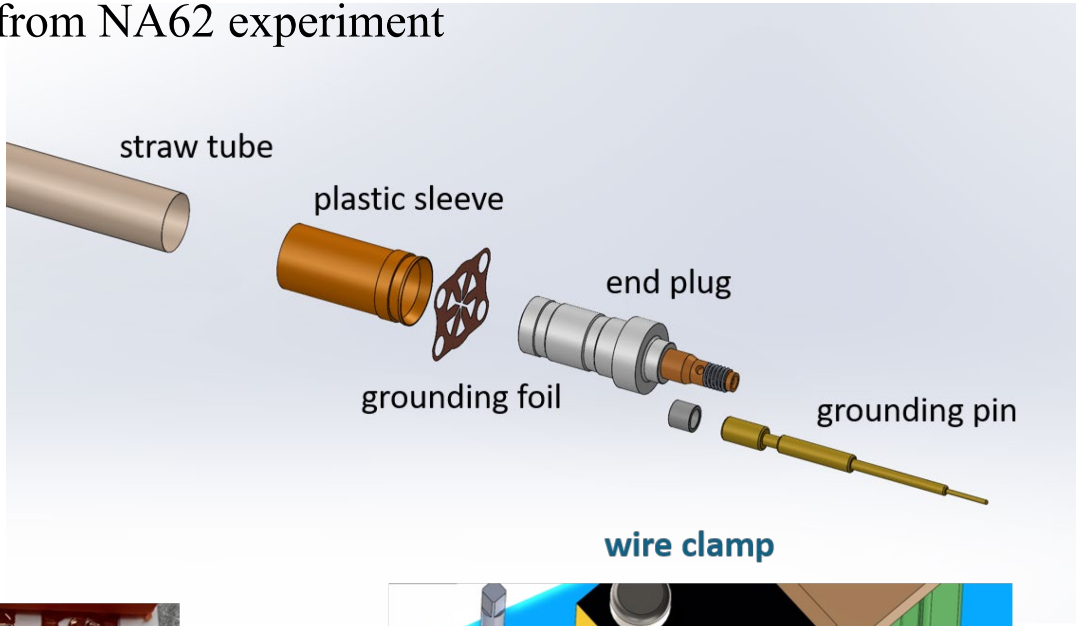



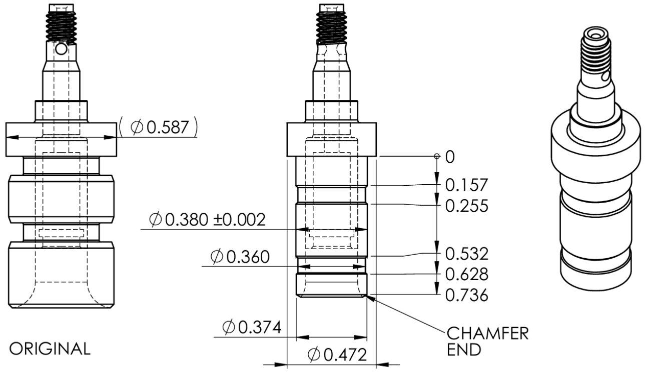

These resolutions are calculated based on different assumptions and should be viewed with a grain of salt (for example r=0.3-1.8 m for the straw tracker, and r=0.35-2 m for the IDEA drift chamber)

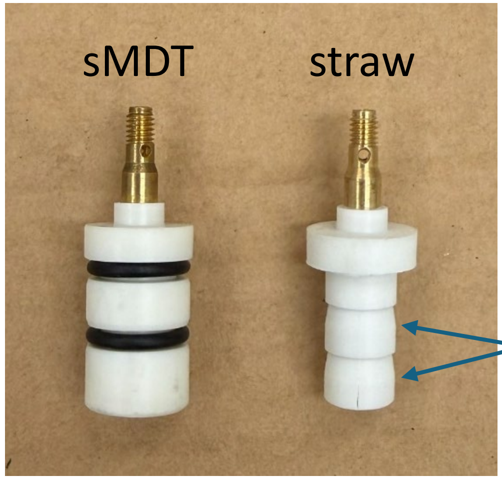
# Straw tube

- Building 24 straw prototype using ultrasonic welding straw tubes from NA62 experiment
  - material: 20 nm Au, 50 nm Cu, 36 μm PET
  - length = 0.5 m, diameter = 1 cm, wire diameter = 50 μm
- Adapt to the existing sMDT design and infrastructure at Michigan



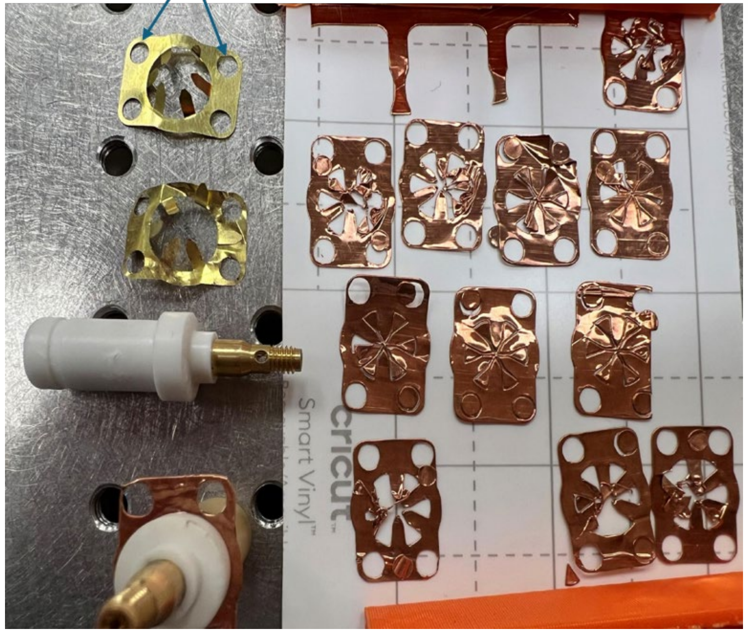

## Modified end plugs

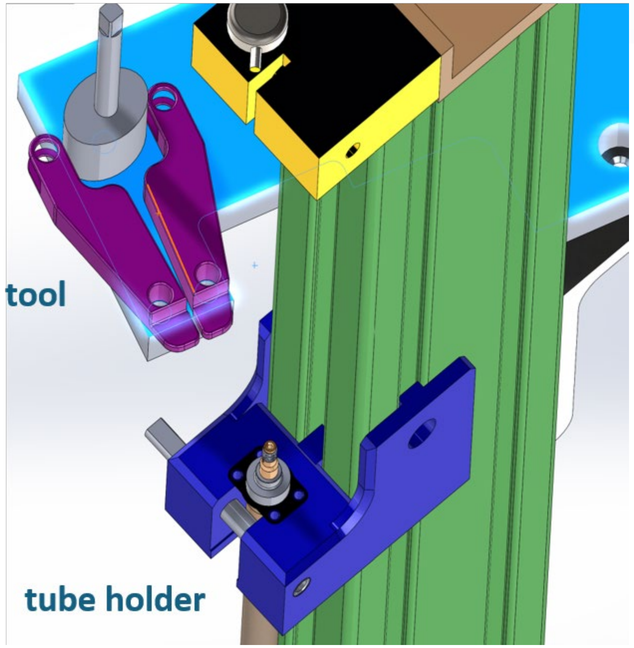


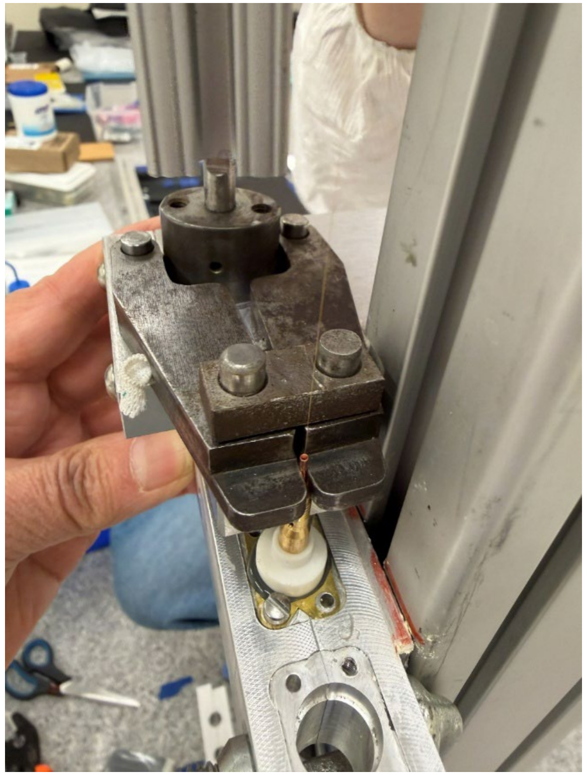

2 grooves for glue to create gas seal (vs O-rings for sMDT)

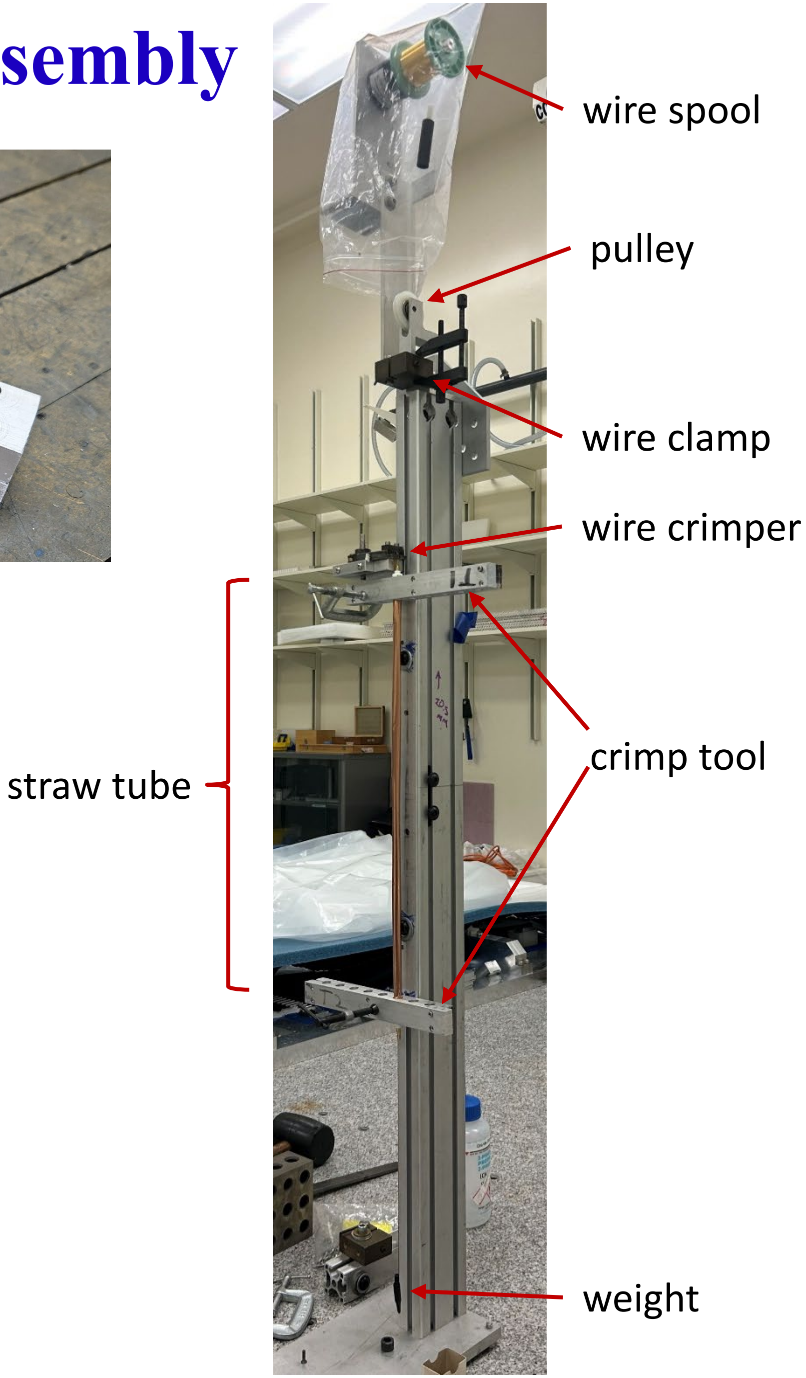
Holes for securing foil orientation with screws

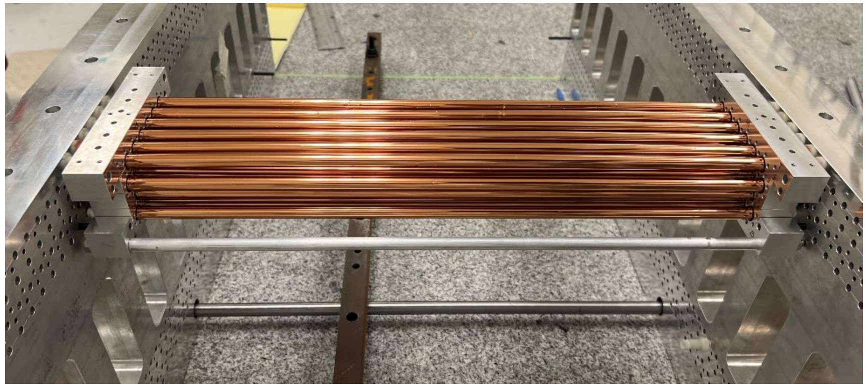


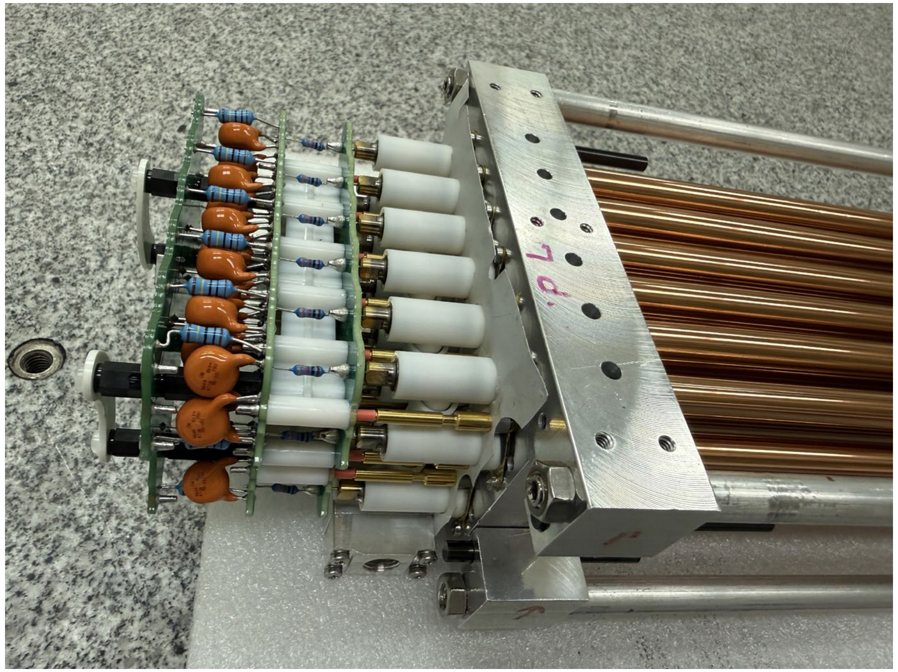
# Tube and chamber assembly



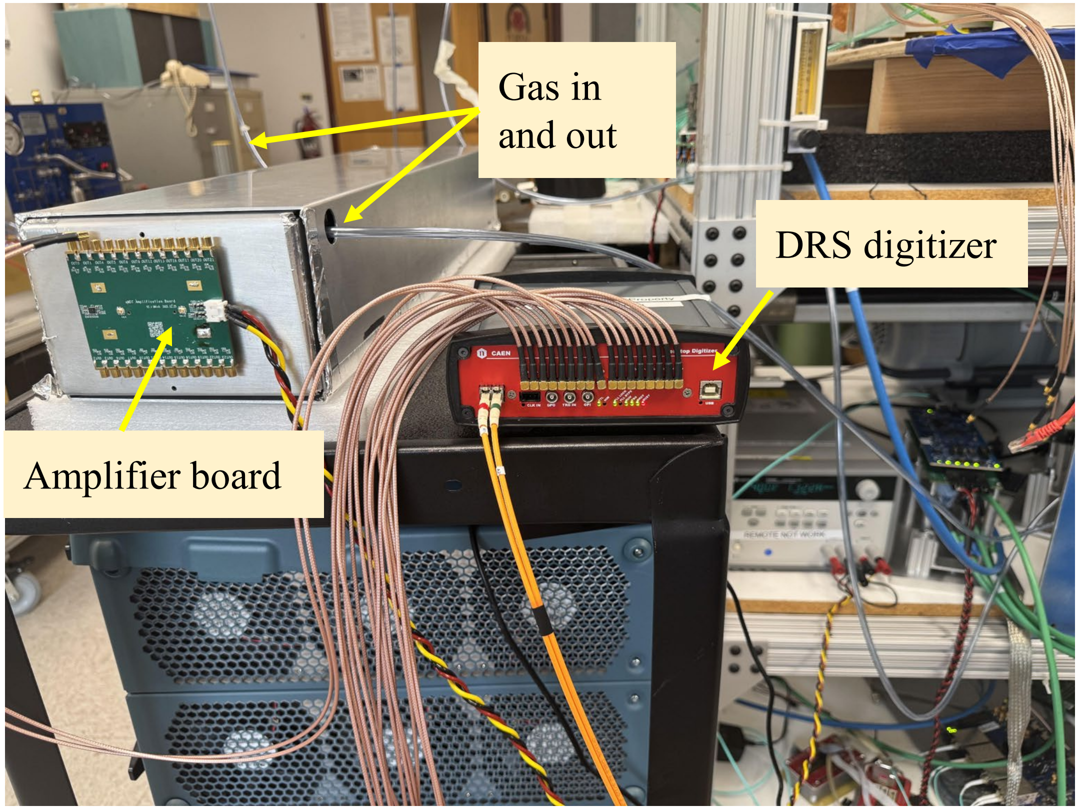


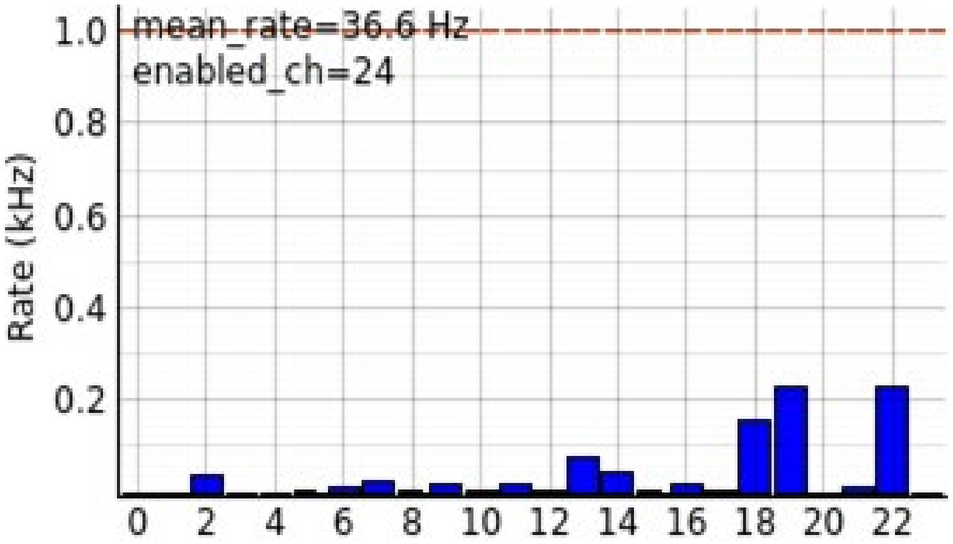



Maintaining precise mechanical alignment for each tube is crucial for achieving a spatial resolution of 100 μm



# Faraday cage and noise studies



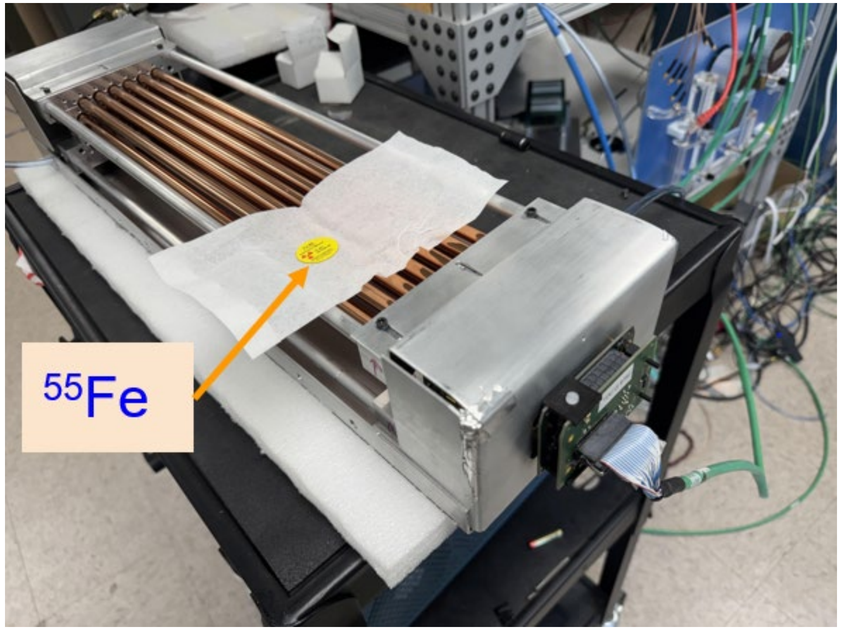



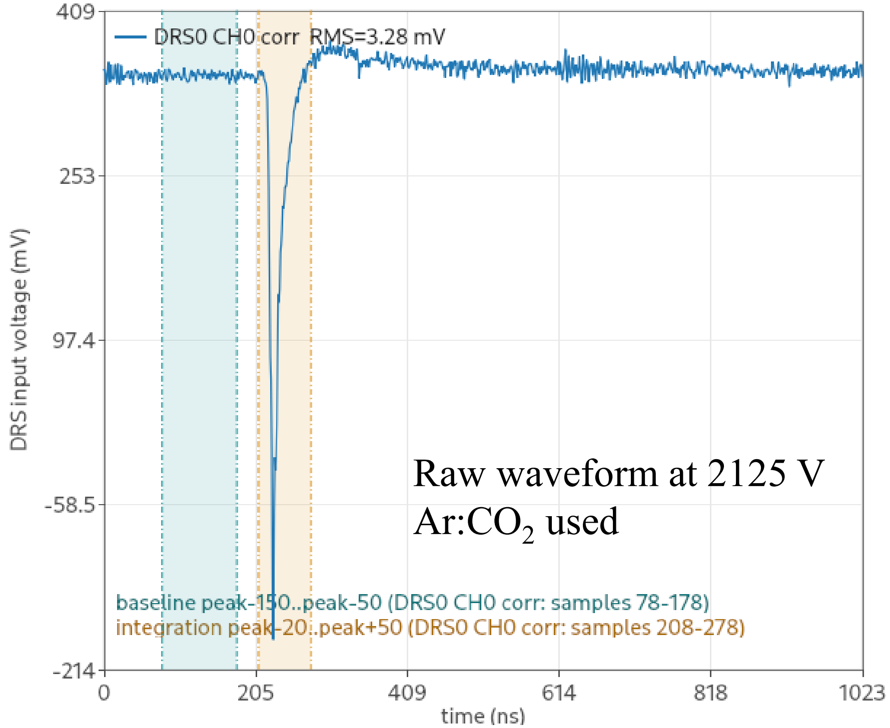

HV=1700 V and p=1.08 bar Ar:$CO_2$ (93:7)

Noise is measured with the ASD threshold set to 39 mV using the ATLAS MDT electronics

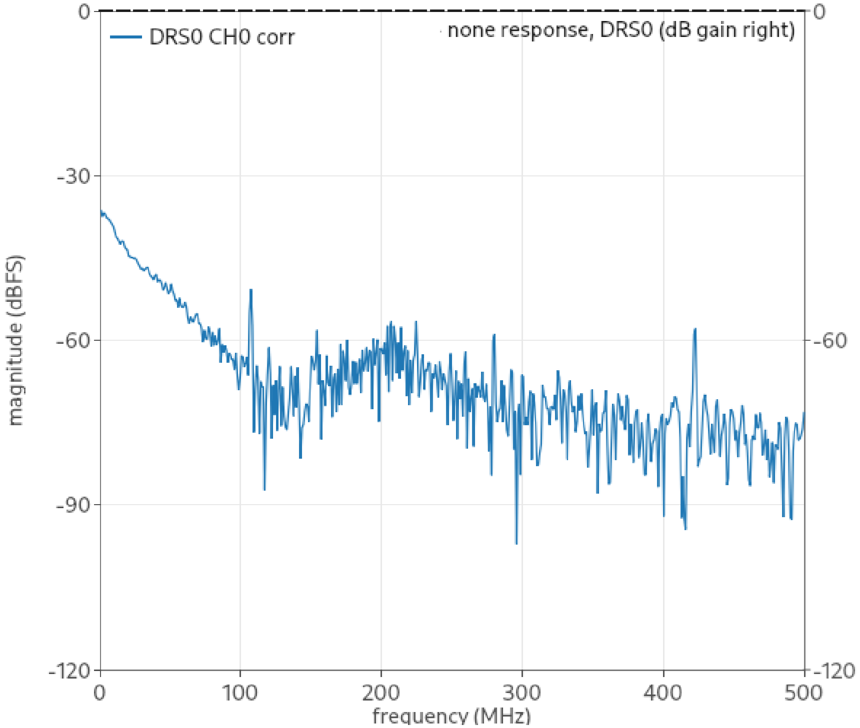
# Gas gain studies

- Need to run the system with a gas gain of 1-2×$10^5$
- Due to the thin wall of the straw tracker, a $Fe^{55}$ source can be used to study the gas gain as a function of the high voltage applied
- About 210 primary electrons produced with a 5.9 keV $Fe^{55}$ X-ray photon



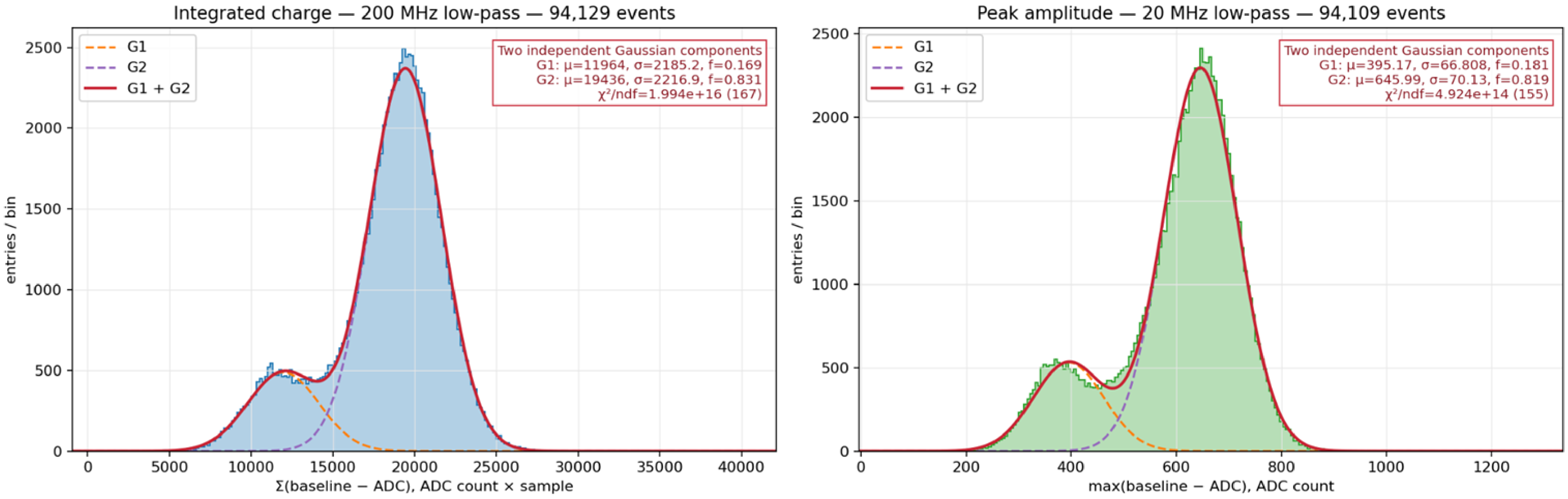




Raw waveform at 2125 V
Ar:$CO_2$ used



# Gas gain studies

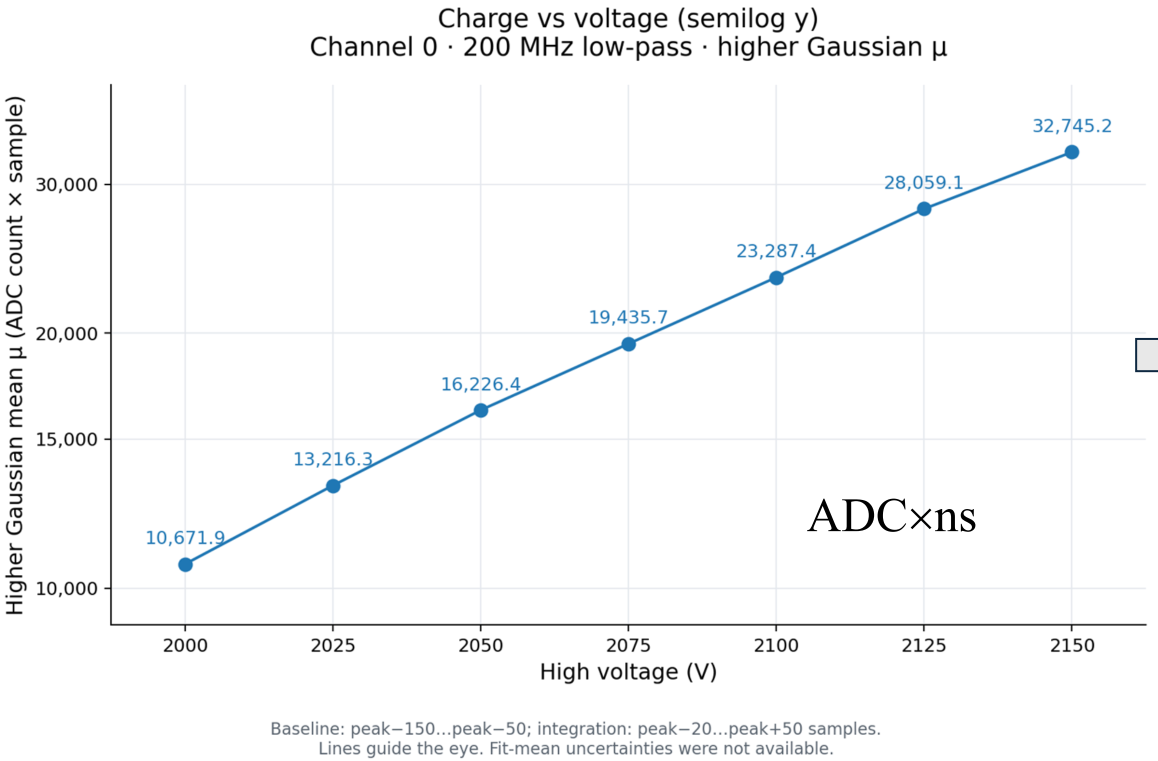
- High voltage is scanned from 2000 V to 2150 V for Ar:$CO_2$ 70:30 gas mixture with p=1.030 bar
- A 200 MHz low pass filter is applied for charge integrating

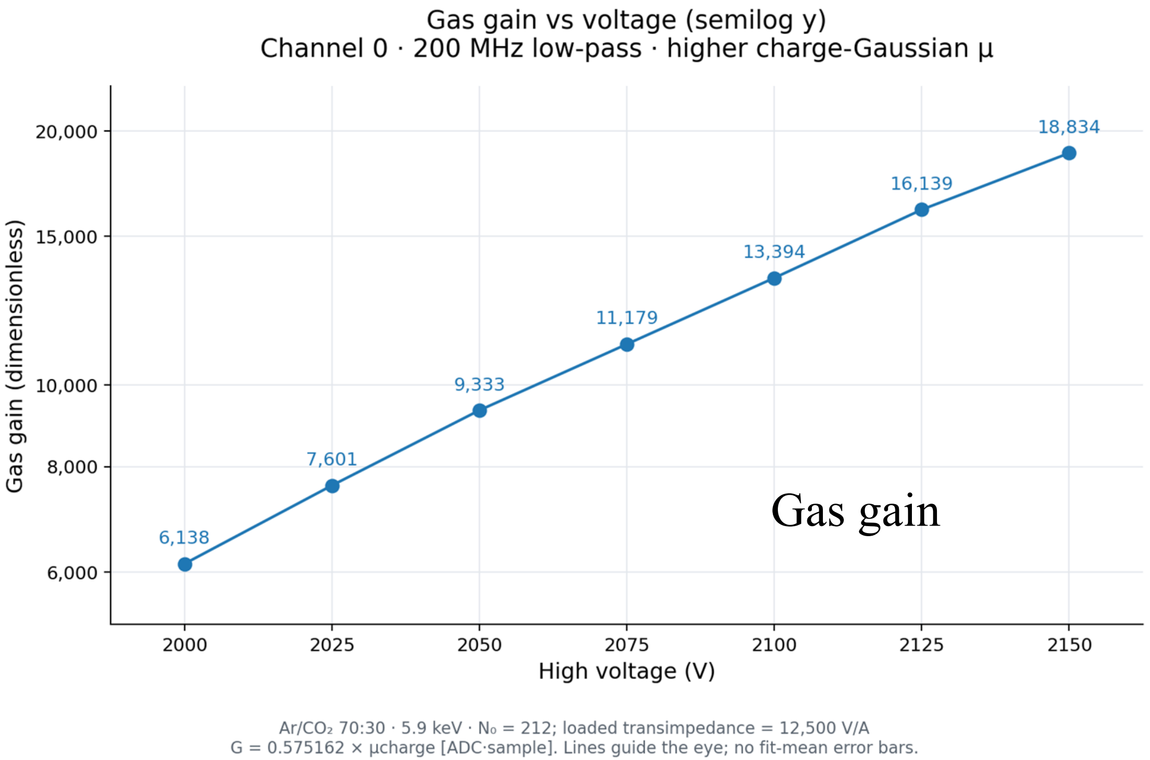



Main peak caused by 5.9 keV photons for both charge and peak measurements (HV = 2075 V)

# HV scan

- Gas gain Diethorn equation $G(V) = \exp\left[\frac{V \ln 2}{\Delta V \ \ln(b/a)} \ln\left(\frac{V}{aE_{\min} \ln(b/a)}\right)\right]$
- A convenient local approximation is $G(V) \approx G(V_0)e^{k(V-V_0)}$
- Gas gain = Integrated area / ($Z_t \times N_0 \times e$), with amplifier board $Z_t$ = 12500 V/A, $N_0$ = 212 p.e
- The test results show a linear relationship between gas gain and the applied voltage in semi log scale

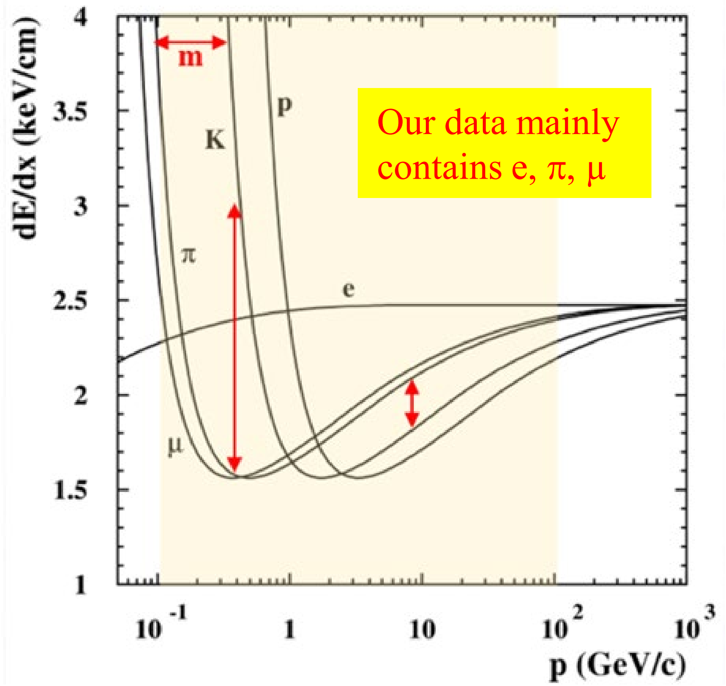


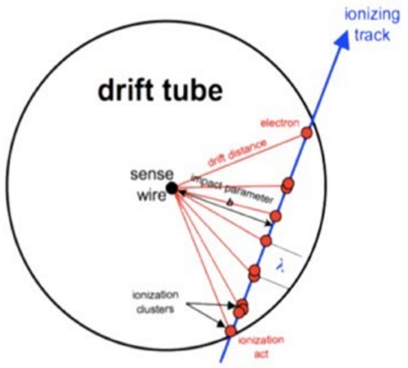



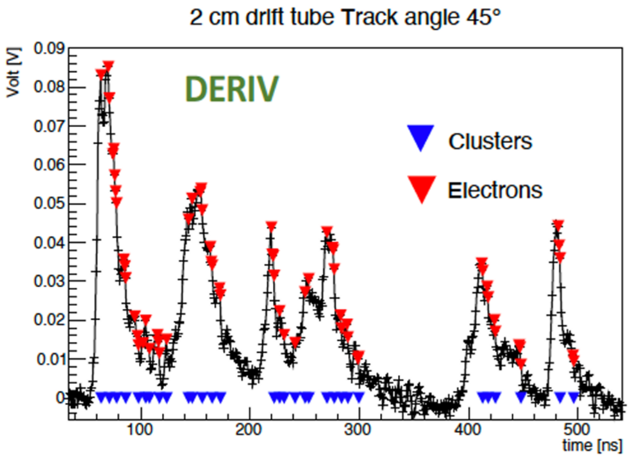

Spent >5 months to prepare tools to build a straw tracker and ~2 months to have the Faraday design ready and built last week. More studies are ongoing to measure gas gain with He:isobutane and spatial resolution studies using cosmic muons

# Particle identification: dE/dX and dN/dX

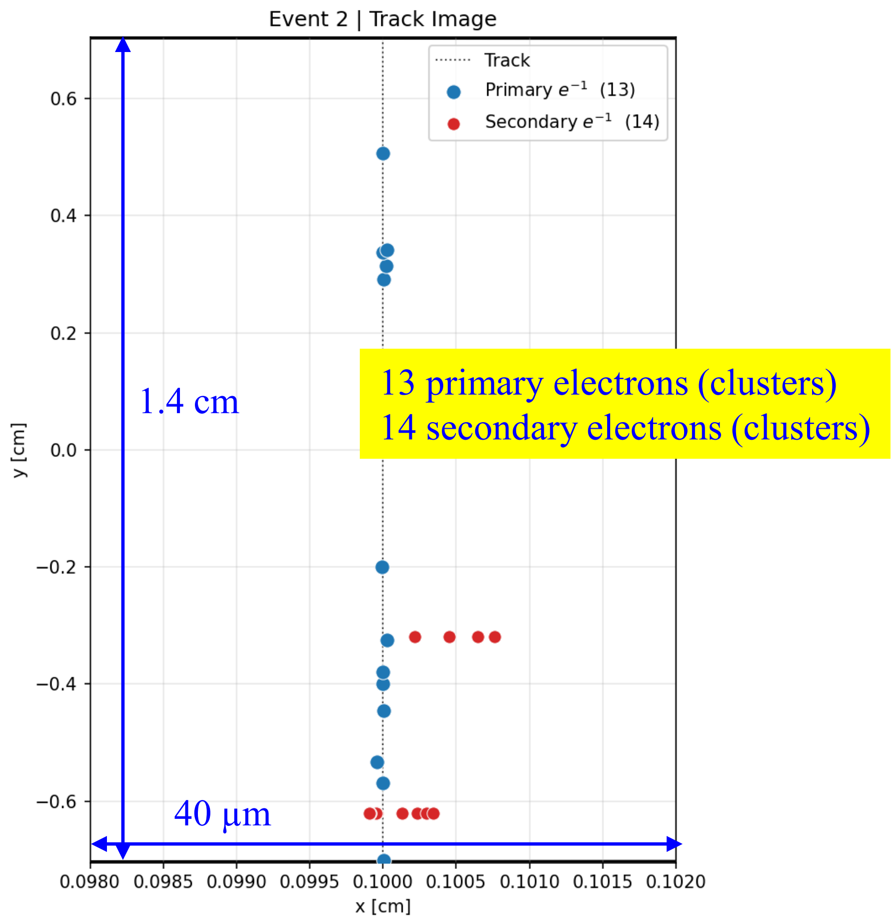
- Important to have good PID capabilities for an FCC-ee tracker
  - Overall we want to have >3σ π/K separation over a wide momentum range from O(100 MeV) to O(40 GeV)
  - π-K relative difference at ~10 GeV: 10-15%, need to have a measurement with a resolution of ~2-3%
- Truncated mean (dE/dX):
  - Remove 20-60% of events with large momentum transfer
  - The resolution depends on sample length $\tau$, gas pressure $p$, number of samples $n$, and the gas composition
  - Empirical parameterization: $\boldsymbol{\sigma=0.41\times n^{-0.46}\times(\tau p)^{-0.32}}$ from Argon ($\tau p$ in unit of cm bar)
  - $\sigma$=4.5% assuming n=120 and $\tau$p=1 cm bar
- Cluster counting (dN/dX):
  - Counting number of primary clusters produced
  - Estimated the resolution to be $\boldsymbol{\sigma=1/\sqrt{N_{clusters}}}$
  - $\sigma$=2.6% with a cluster-finding efficiency of 80% for 2 m path length
  - Roughly a factor of 2 better than the dE/dX method
- Very challenging and no previous collider experiments have implemented this technique
- Muon test beam studies at different energies done by the IDEA drift chamber community (arXiv:2509.21883)

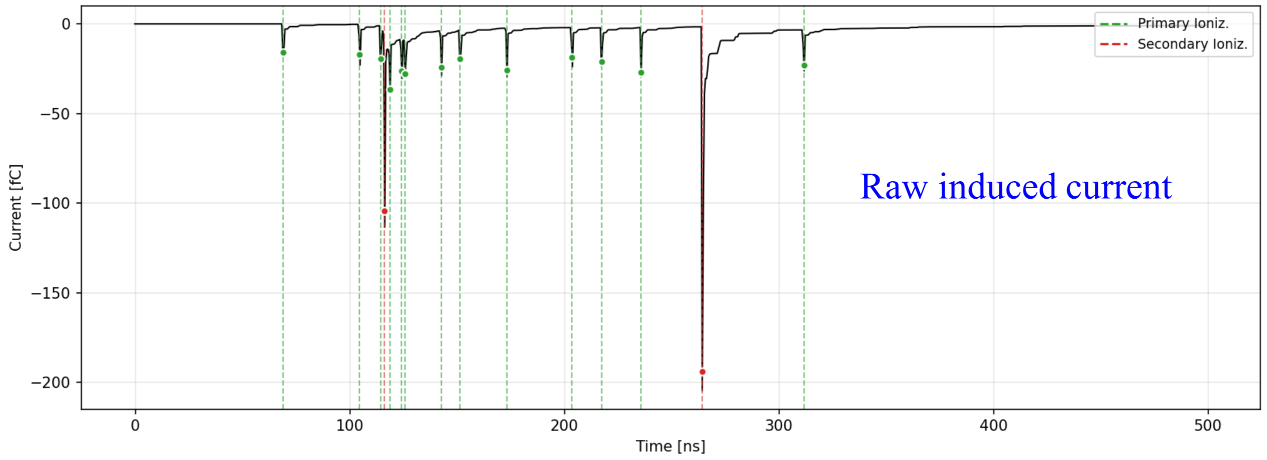


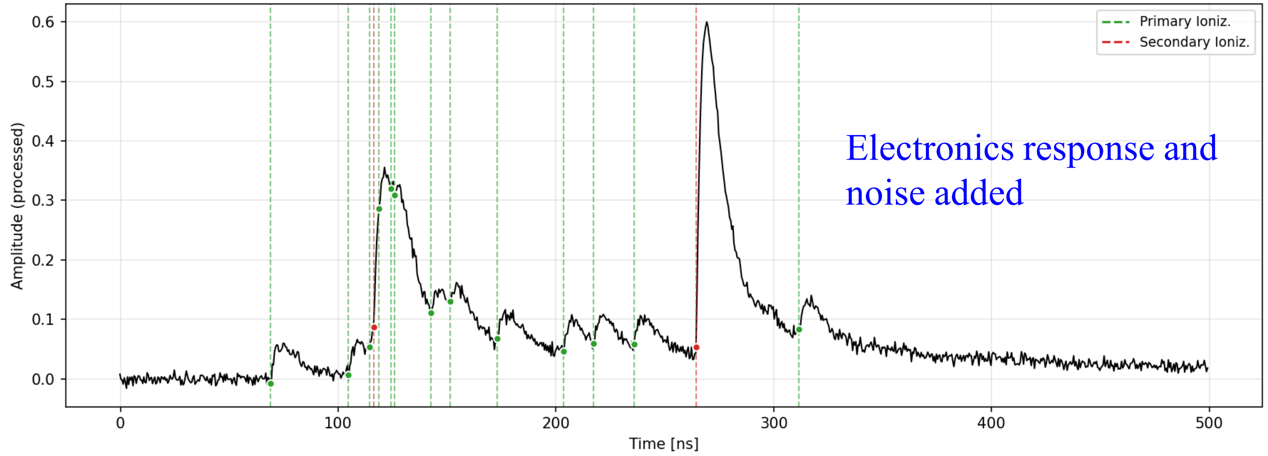



# Ionization and induced current formation



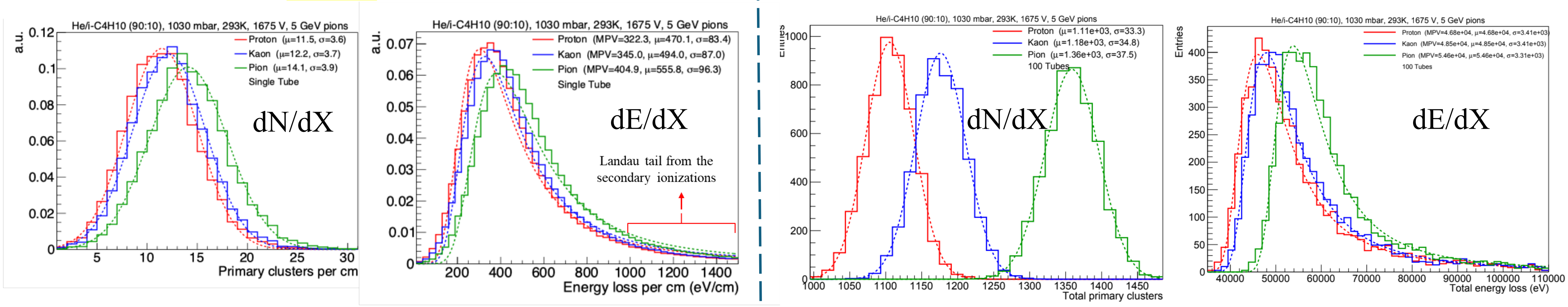

- On average 10-20 primary clusters per cm for He:i$C_4H_{10}$
- Secondary clusters mainly come from high-energy δ electrons
- On average similar numbers of primary and secondary clusters
- Important to count primary (not secondary) clusters

# Challenges on dN/dX

- Large signal amplification: ~1 fC or less induced charge due to a single electron with a gas gain of $10^5$
- Low noise front-end electronics: < ~0.2 fC noise RMS
- Good separation of primary and secondary clusters
- Fast front-end electronics: ~1 GHz sampling for waveform digitization
- Need to have a long path length
- Fast and efficient online algorithms to effectively identify primary clusters and reduce data throughput
- Low power consumption for front-end electronics (maybe also need to consider analog peak-finding algorithms on FE)

1 tube

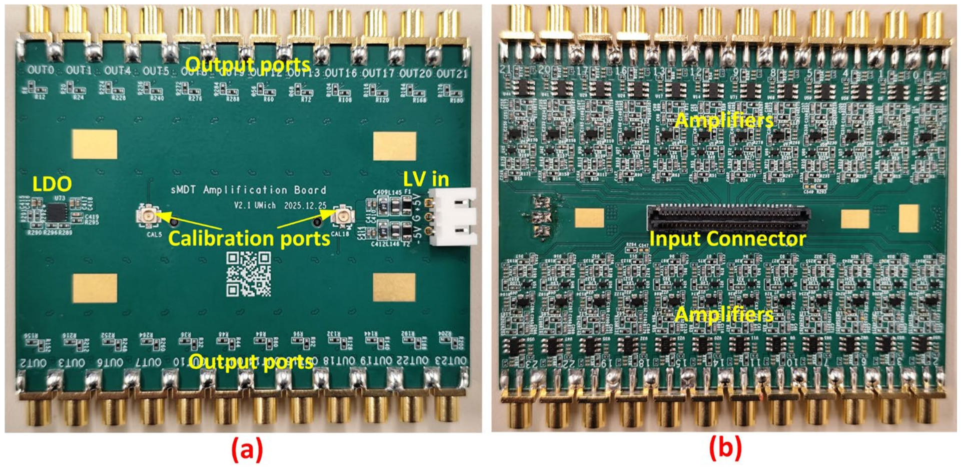
100 tubes

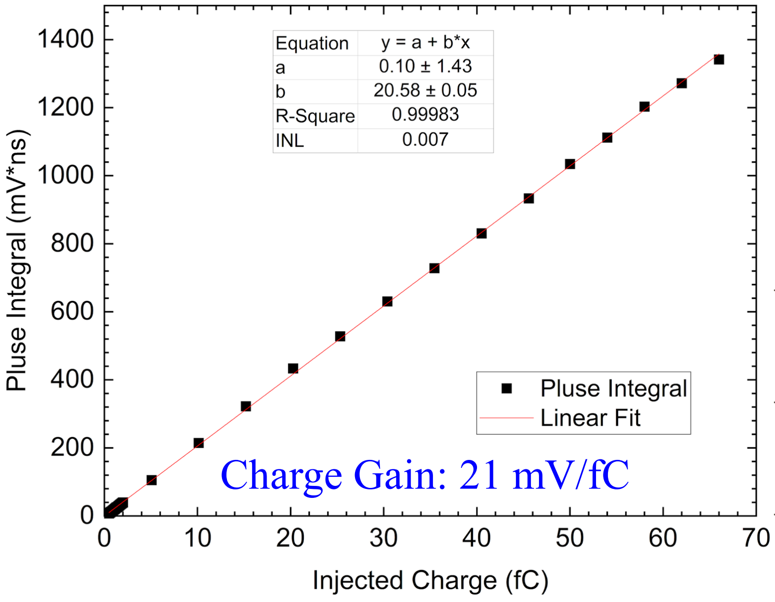


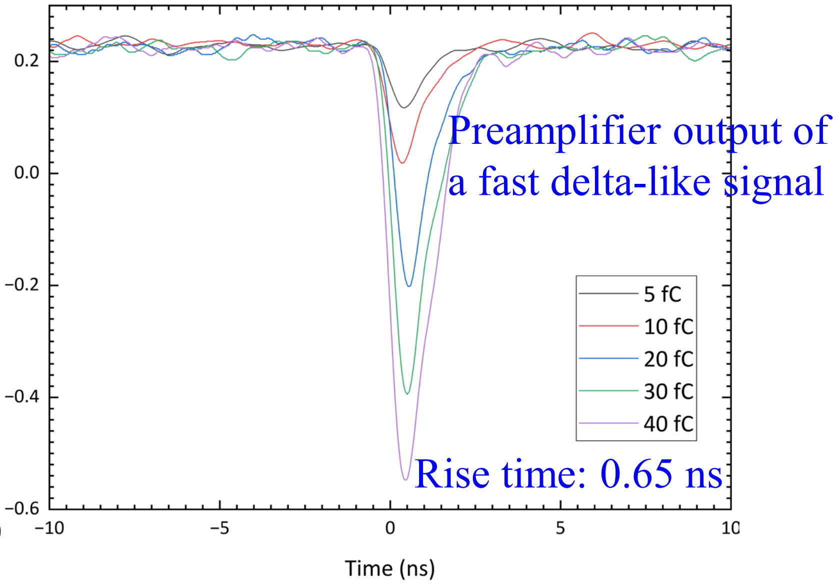

Garfield simulation with 5 GeV protons, kaons, and pions

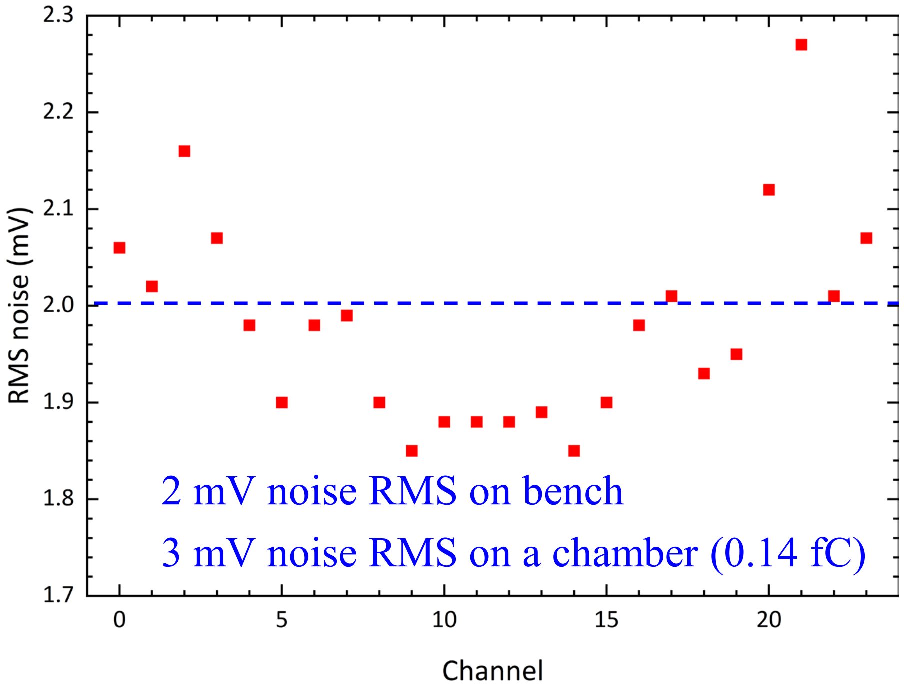
# Amplifier board

- Use four 4-layer ATLAS aluminum sMDT chambers (effective diameter: 1.4 cm) for dN/dX studies with test beams and cosmic rays
- A new amplifier board has been designed and fabricated to amplify detector signals
  - Three-stage amplification and a pole-zero cancellation
  - Read out 24 channels per board
  - Waveform recorded by DRS4 waveform digitizers

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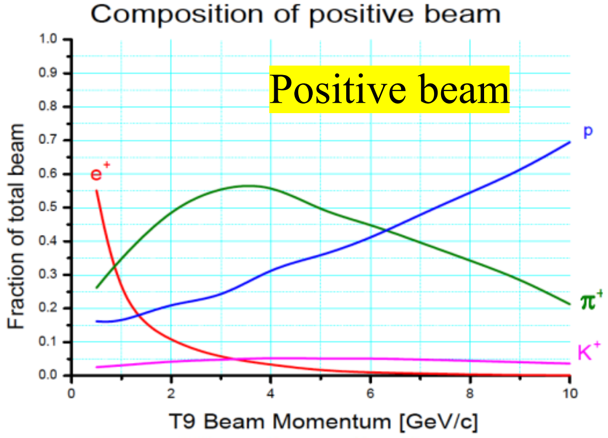
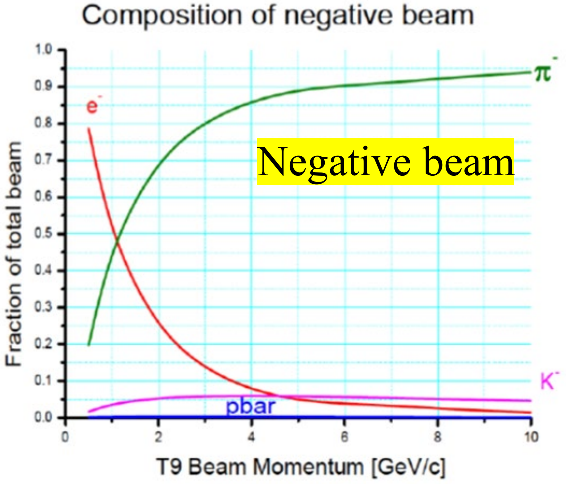
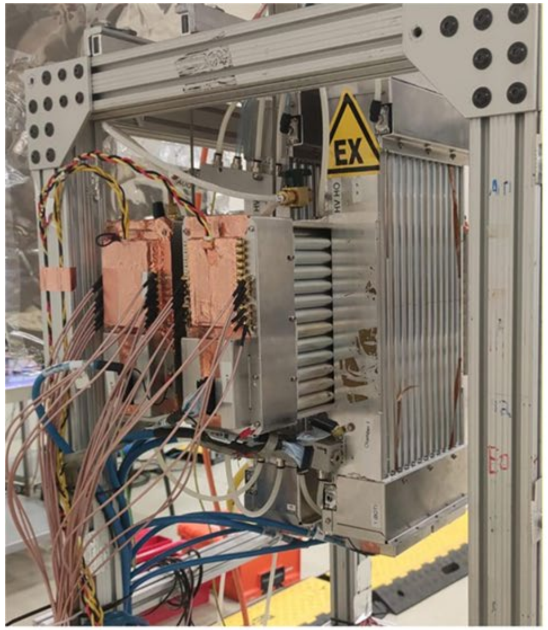
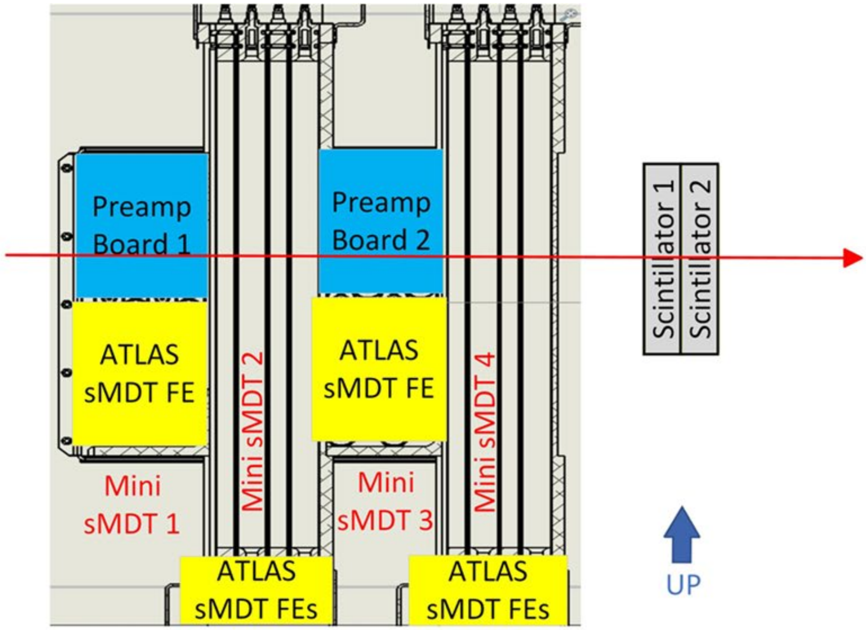
# Test beam studies at CERN T9

- Test beam studies at CERN's T9 beamline:
  - Nov 2025 (positive beam) with the older version of the amplifier board
  - March 2026 (negative beam) with the new version of the amplifier board
- Four sMDT chambers were used, two with ATLAS MDT electronics, and two with amplifier + waveform digitizers
- He:i$C_4H_{10}$ (90:10) used but only at 0.97 bar and 1.15 bar due to safety reasons
- Data taken with 1/2/5/10 GeV mixed hadron beam and 1/2/5 GeV electron/positron beam
- A Cherenkov counter is used to identify electrons/positrons



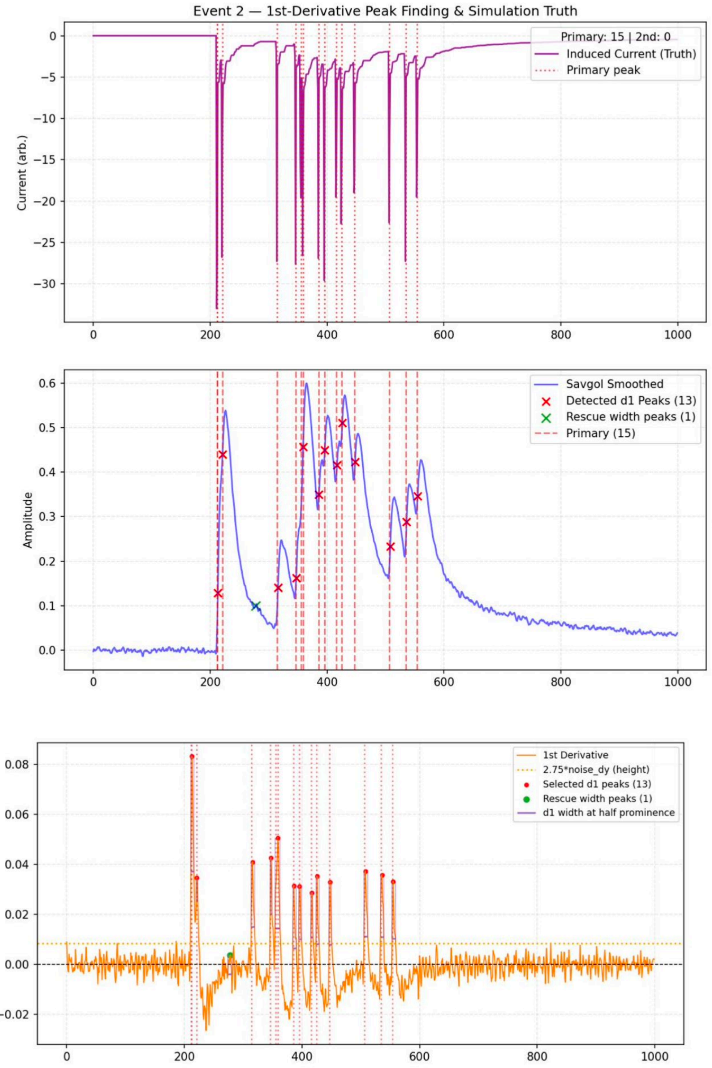



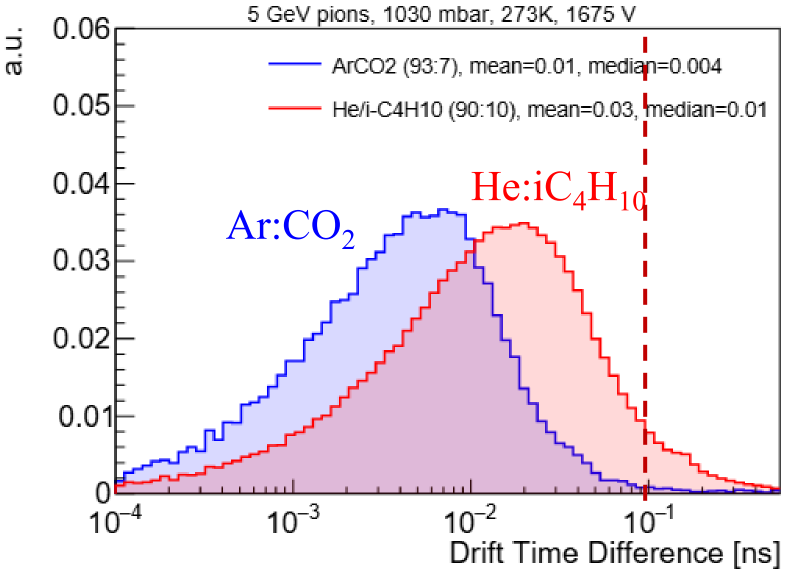



# Peak-finding algorithm based on 1st order derivative (dN)

- A more complete report can be found at FCC-ee Detector Concepts Meeting at https://indico.cern.ch/event/1664040/
- We have further improved the peak-finding algorithm in this past summer
- A peak is counted when:
  - Algorithm is firstly developed on simulated waveforms, and then updated using real waveforms from Test Beam
  - No peak-merging algorithm developed so far → one peak is one cluster in our studies right now, but given the timing resolution we have, the peak-merging probability is likely small
  - Challenge: different noise performance and electronics response in experiment and simulation

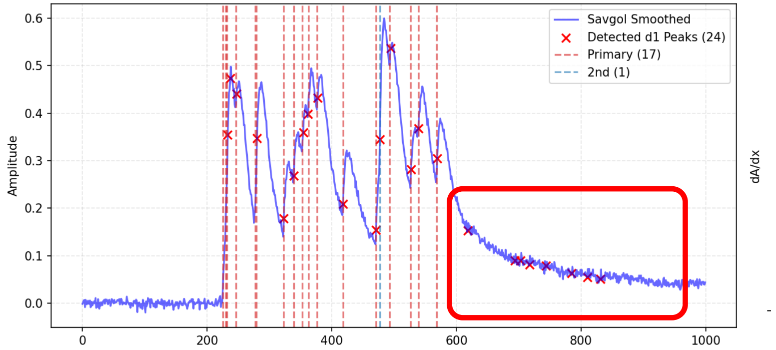


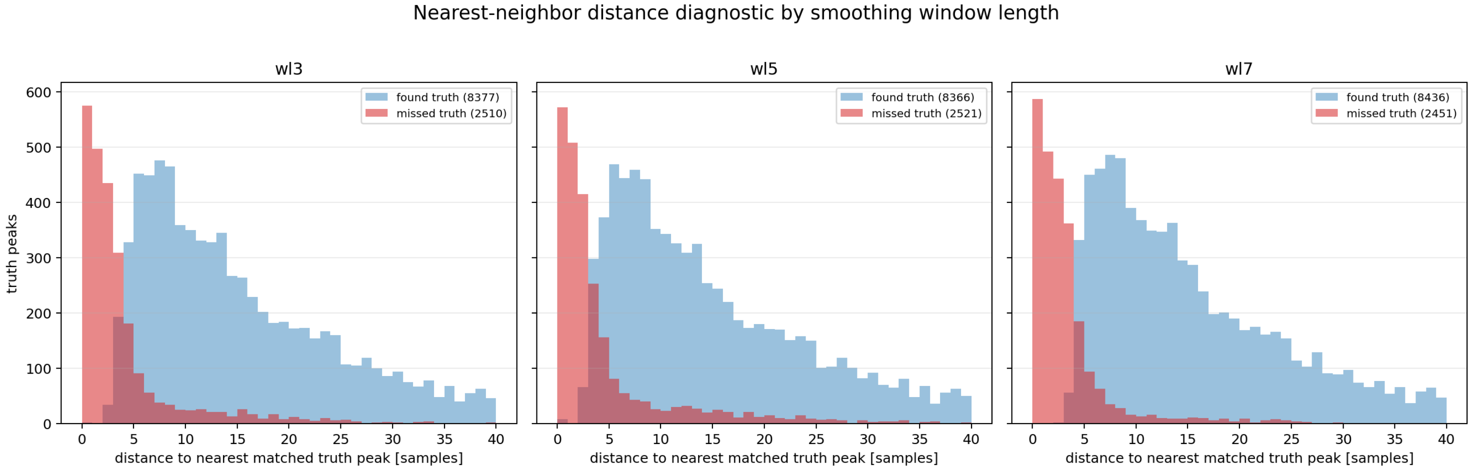

Garfield simulation of time difference between primary and their secondary clusters

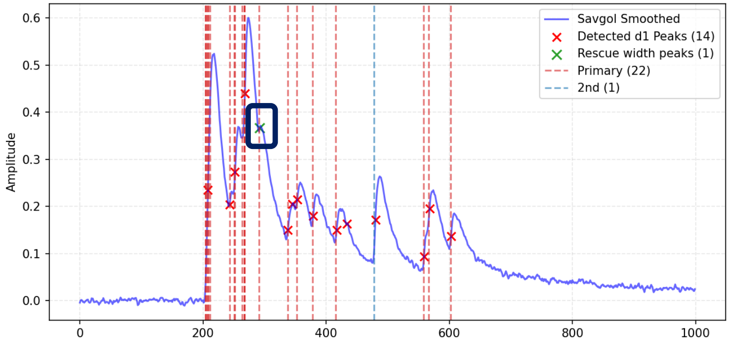
# Peak-finding algorithm based on 1$^{st}$ order derivative (dN)

- **Methodology:**
  - smooth waveform: Savitzky – Golay Filter, smooth window length (wl) selection needs to be carefully studied
  - Find positive 1$^{st}$ derivative peaks as candidates.
  - topology cuts: 1$^{st}$ derivative peak prominence & amplitude
  - Amplitude check: Amplitude peaks have delay compared with 1$^{st}$ derivative peak
  - tail veto: reject noise peak after the last high peak with tighter requirements.
  - rescue selection: fail height →pass shape → pass amplitude → count as rescued
- Observed an efficiency of ~80% and purity of 95% using simulated waveforms




**Noise peaks with no tail veto**



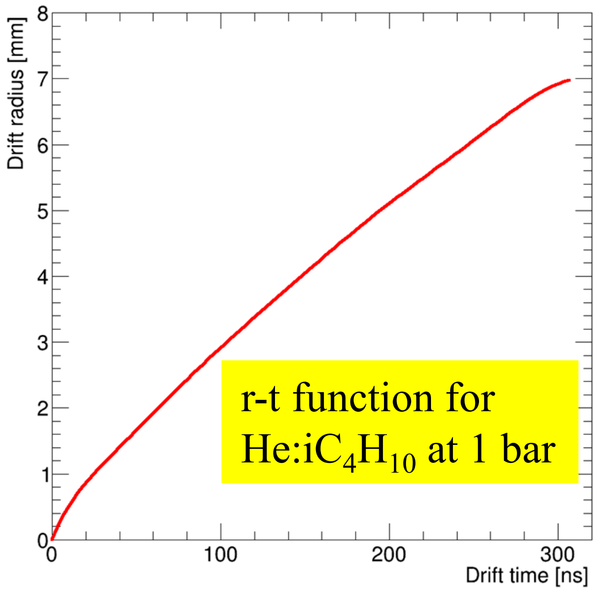



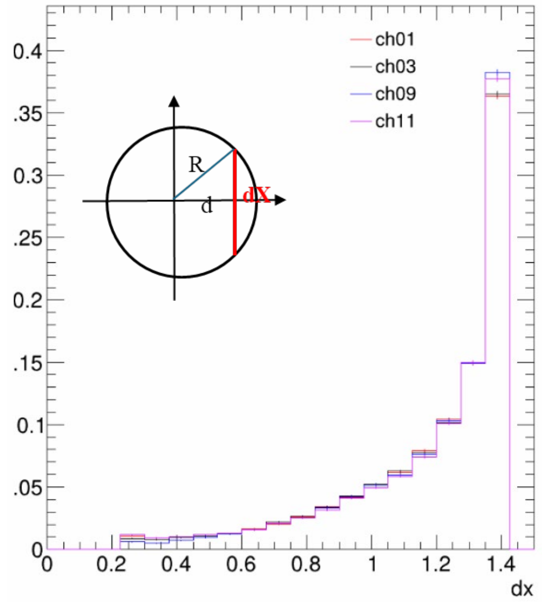

**Small nearest-neighbor distance highlights close clusters / pile-up; wl controls the resolution-noise tradeoff.**

**Rescue peak example**

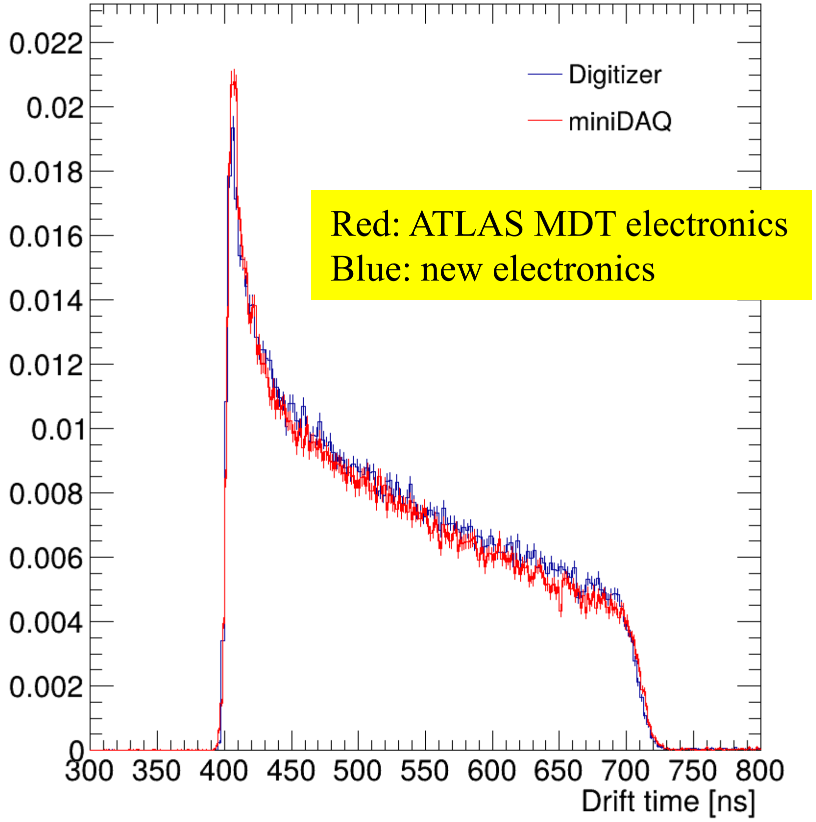
# Path length (dX)

- A drift tube measures the drift time (wrt a reference time, often provided by a trigger device)
- Use the measured r-t function to determine the drift radius (d)
- Path length is calculated as $dX = 2\sqrt{R^2 - d^2}$

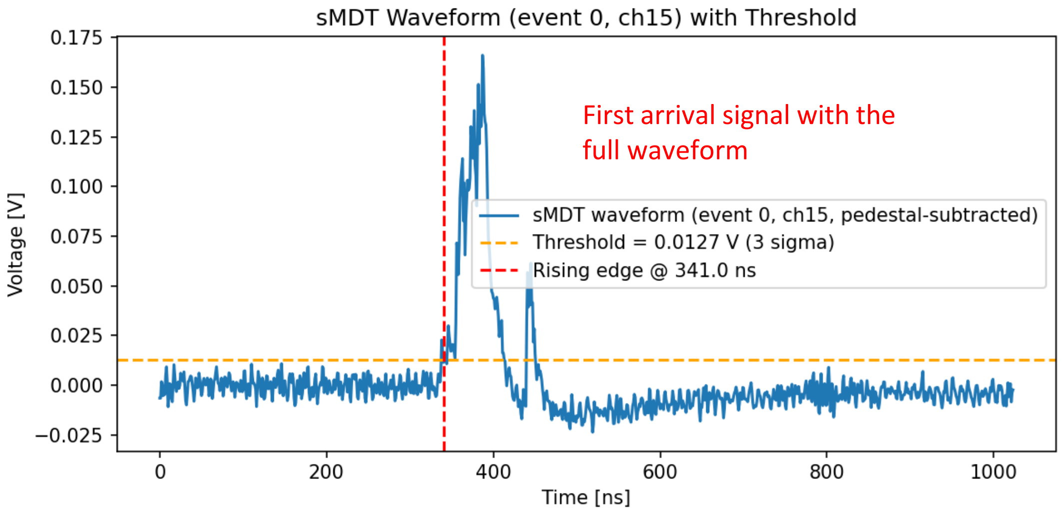


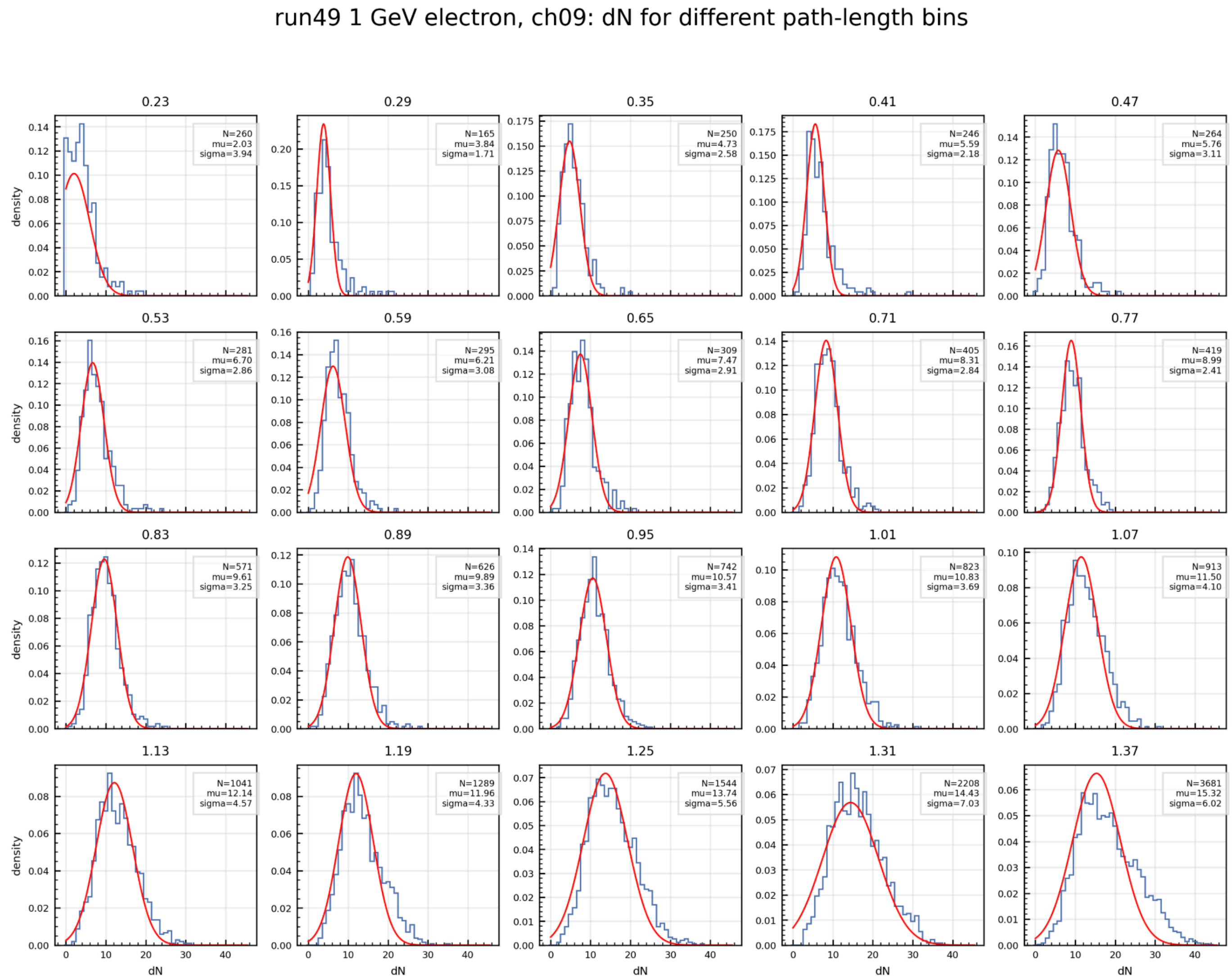

97% of uniformly-distributed tracks with a path length >0.3 cm for a tube with a diameter of 1.4 cm



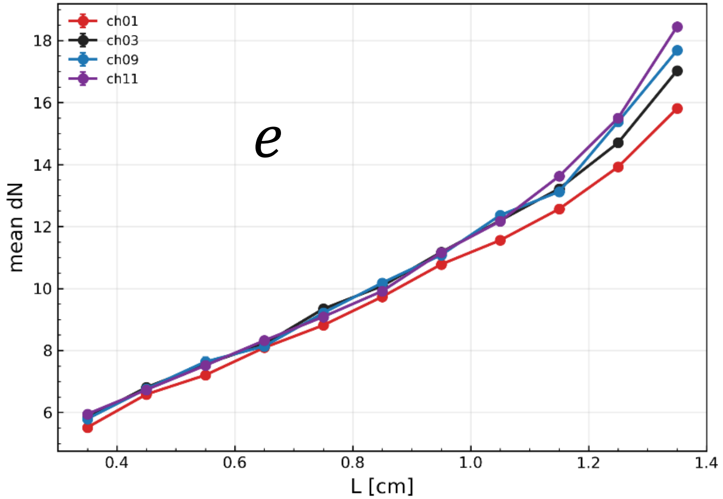

Drift time spectrum using the ATLAS MDT electronics (only detect the first arrival hit) and new electronics (full waveform digitization)

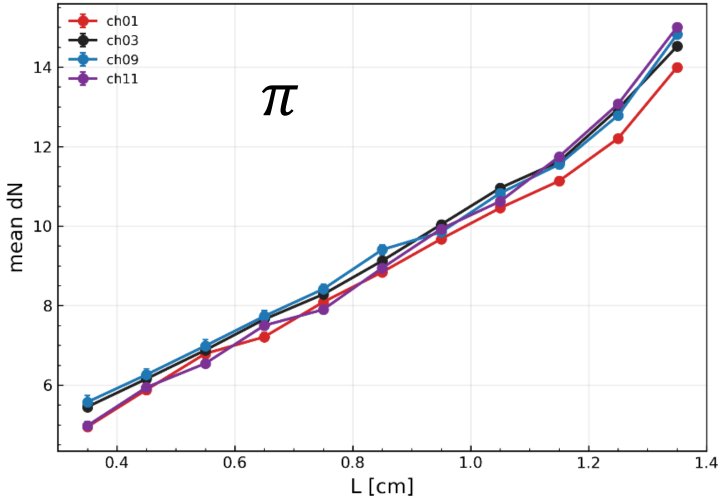


# Preliminary dN/dX results (1 GeV, e/π beam)



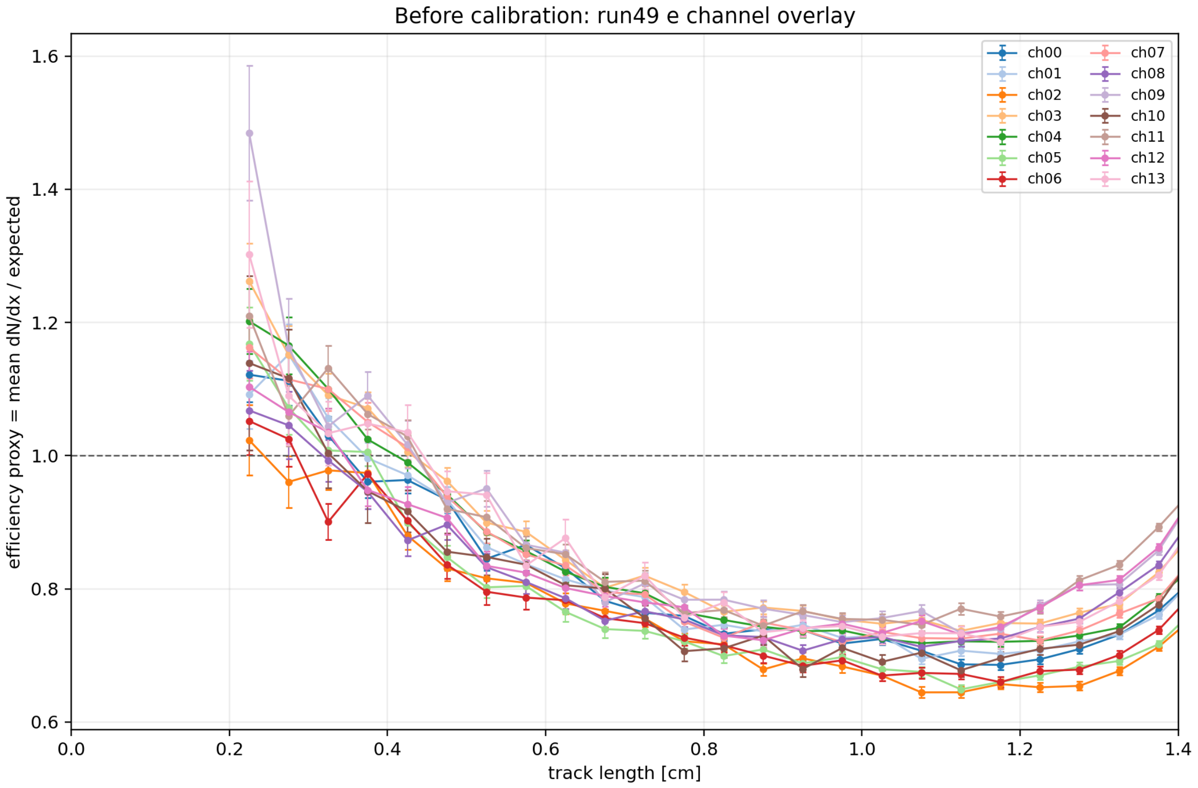

dN for different dX values

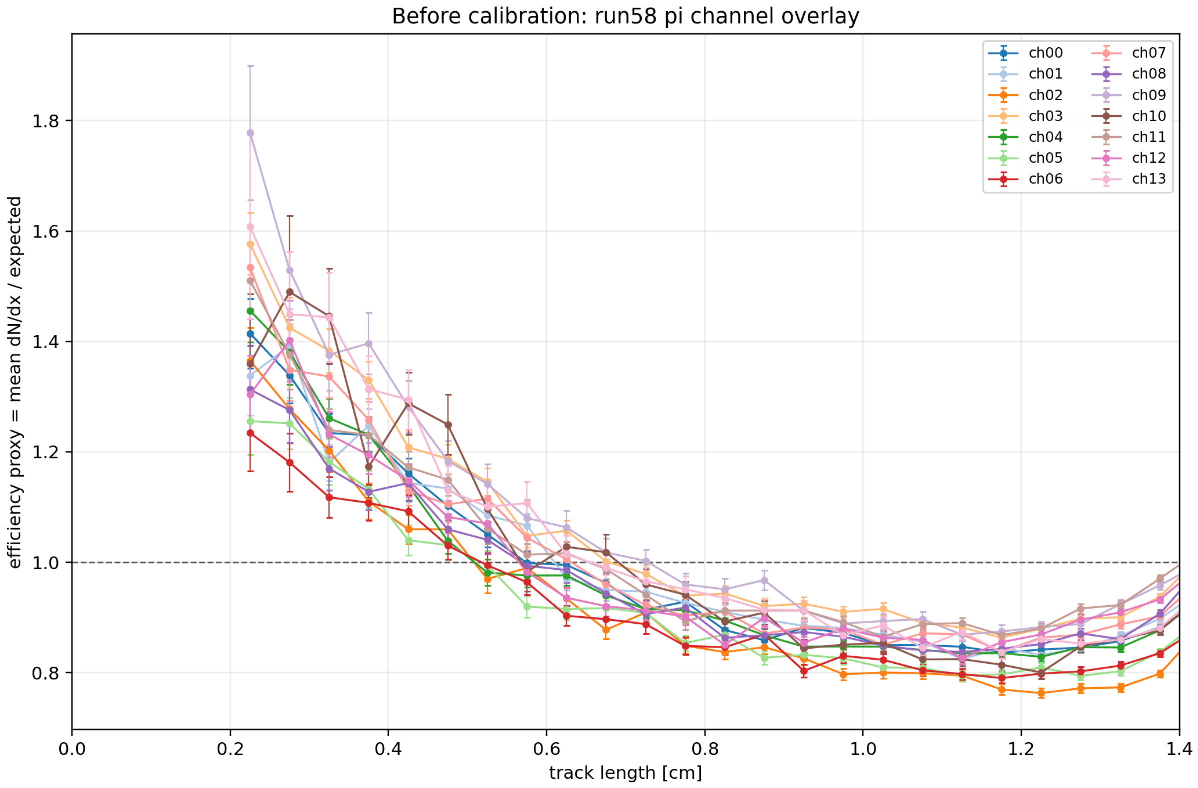



Non-zero dN for dX=0

# Efficiency vs path length

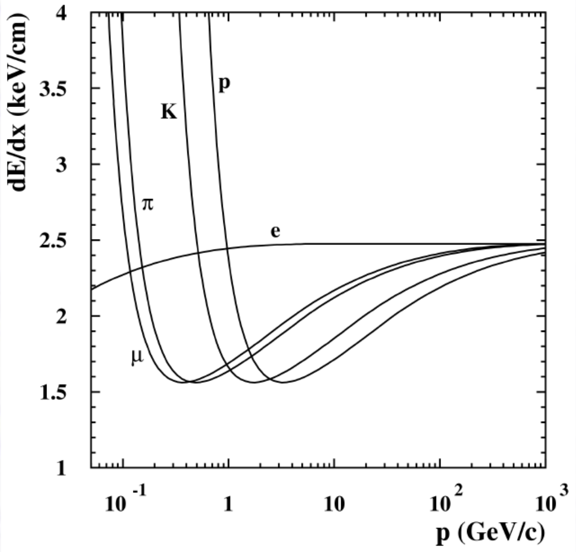


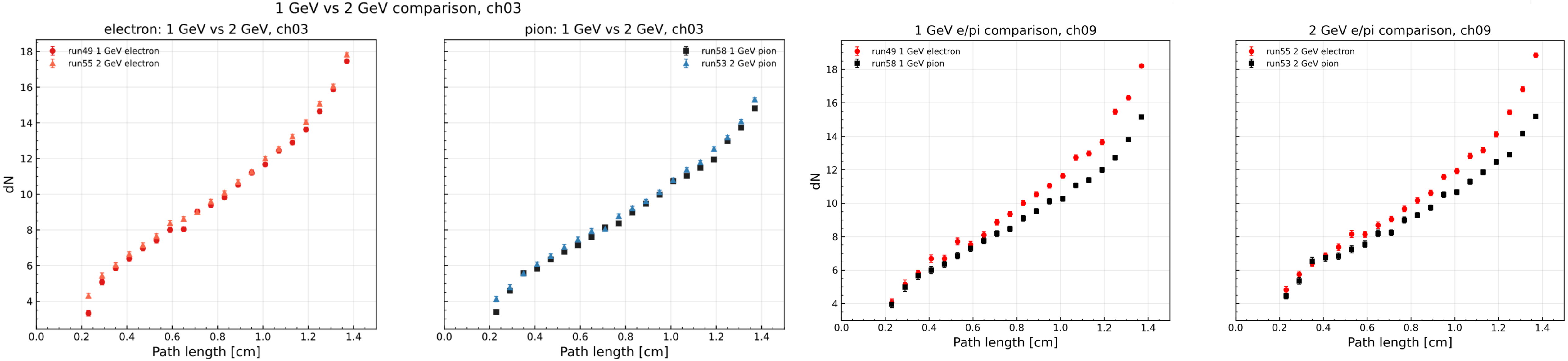




With the simulated number of clusters as the denominator

# Preliminary dN/dX results

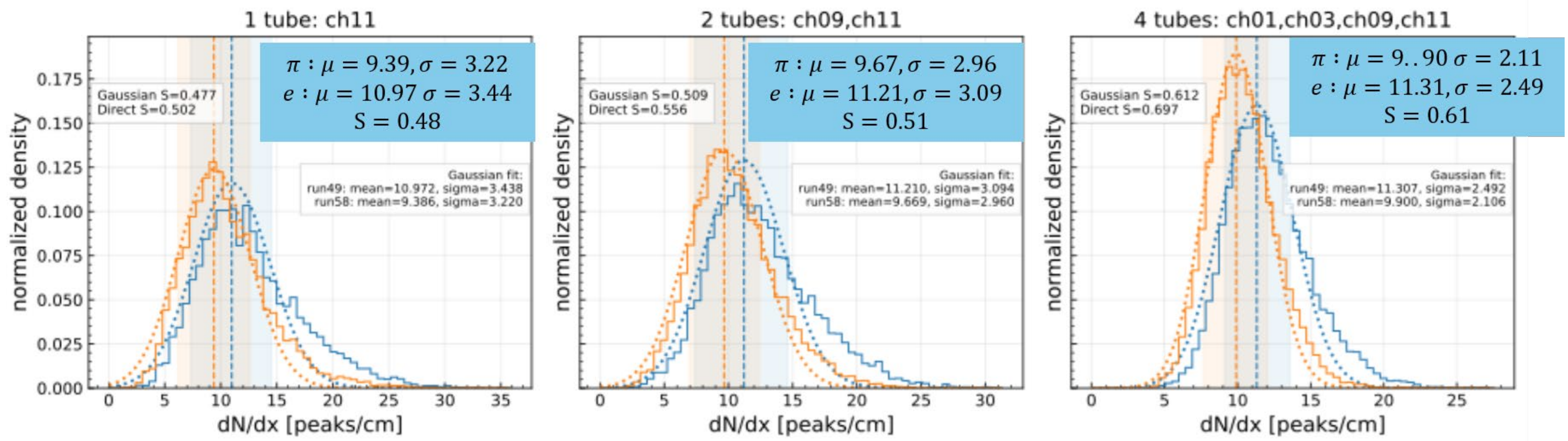
- The same peak-finding algorithm is applied to all runs and channels
- $dN$ is the number of reconstructed waveform peaks
- Track length is obtained from the drift-time and RT reconstruction
- No cluster-finding efficiency correction is applied



# Preliminary dN/dX results

- Tracks hit by more tubes will have smaller sigma values
- Mean value changes due to no calibration among tubes
- A gaussian fit was performed to calculate the separation power:
  - $S = \frac{|\mu_1 - \mu_2|}{(\sigma_1 + \sigma_2)/2}$



# Conclusions

- Built a 24-channel straw chamber, good results for noise performance and gas leakage rate, working on gas gain studies using a $Fe^{55}$ radiative source and position resolution studies using cosmic muons
- Developed a new amplification board and a readout system (amplifier+DRS4) to amplify the detector signals and perform waveform digitization
- Performed test beam studies at CERN's T9 beamline
  - Positive and negative beams
  - Hadron beams: 1/2/5/10 GeV and electron/positron beams: 1/2/5 GeV
  - $He{:}iC_4H_{10}$ (90:10) used at ~1 bar
- Lots of data taken and data analysis still ongoing
- Some preliminary results shown today, more studies to be done