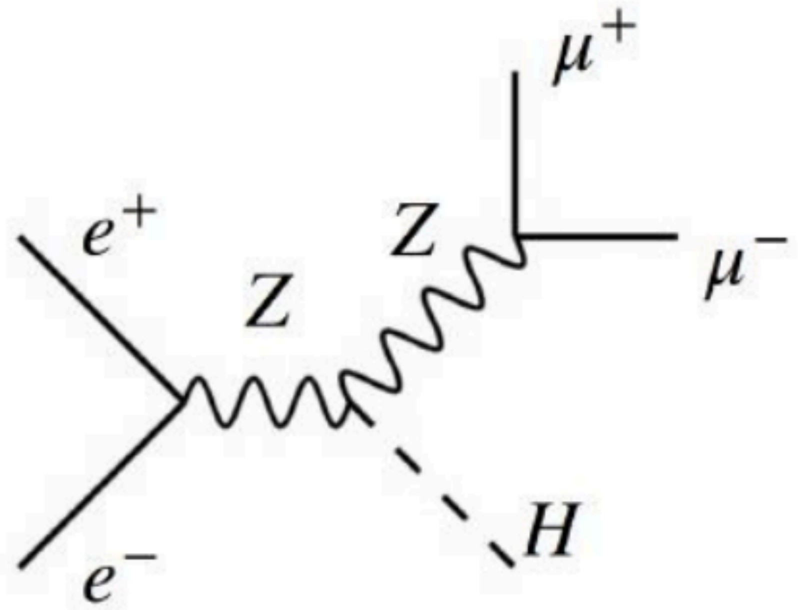
Straw tracker for FCC-ee experiments

Kevin Nelson
USFCC meeting
17 October 2024

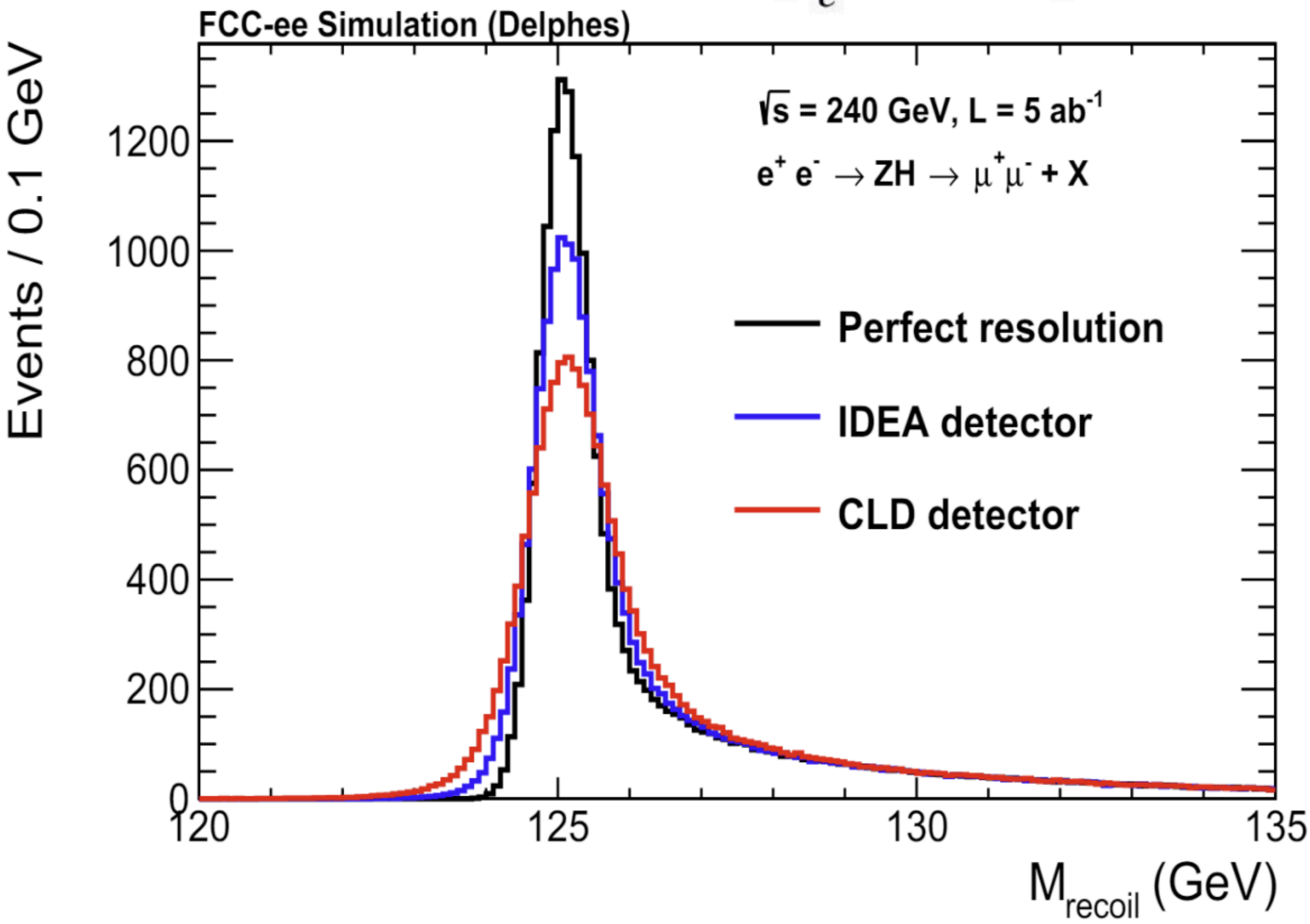
Introduction

- **Momentum resolution is an important requirement for the FCC-ee tracker**

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



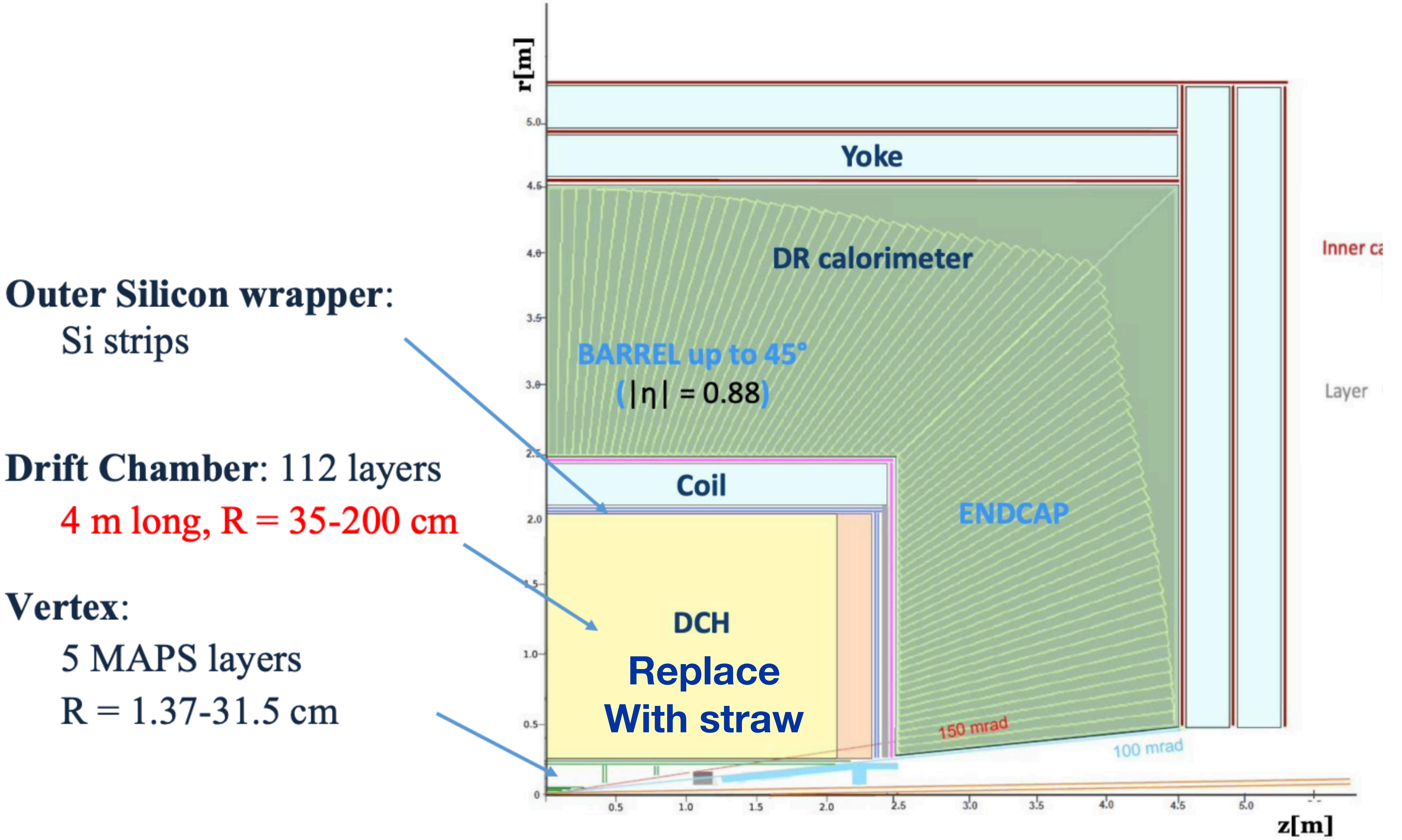
- **Sensitivity dominated by the $Z \rightarrow \mu\mu$ channel**
- **Require the track momentum resolution should not be worse than the beam energy spread (~0.16% at 240 GeV)**
  - σ_{p_T}/p_T ~0.2% at 45 GeV
  - A factor of 5-10 better than the current ATLAS and CMS inner trackers
- **Current proposals for FCC-ee experiment inner tracker:**
  - CLD: full silicon pixel+strip (TPC under consideration)
  - IDEA/ALLEGRO: silicon pixel + Drift chamber + outer silicon wrapper
- **We propose a straw tracker concept in place of drift chamber:**
  - Pixel + **Straw tracker** + Silicon wrapper



Straw tracker: detector concept

- **We propose a straw tracker (combined with pixel + silicon wrapper) for an FCC-ee inner tracker:**
  - Length 4-5m
  - O(100) layers
  - Straw diameters 1-1.5 cm
  - Single straw resolution 100-120 μm
  - 1.2% X_0 in straw tracker
  - Detector optimization ongoing.

- **Discussed today:**
  - Geant4/dd4hep simulation
  - Garfield gas simulation
  - Test beam studies
  - Cosmic-ray studies
  - Recent FCC straw tracker workshop



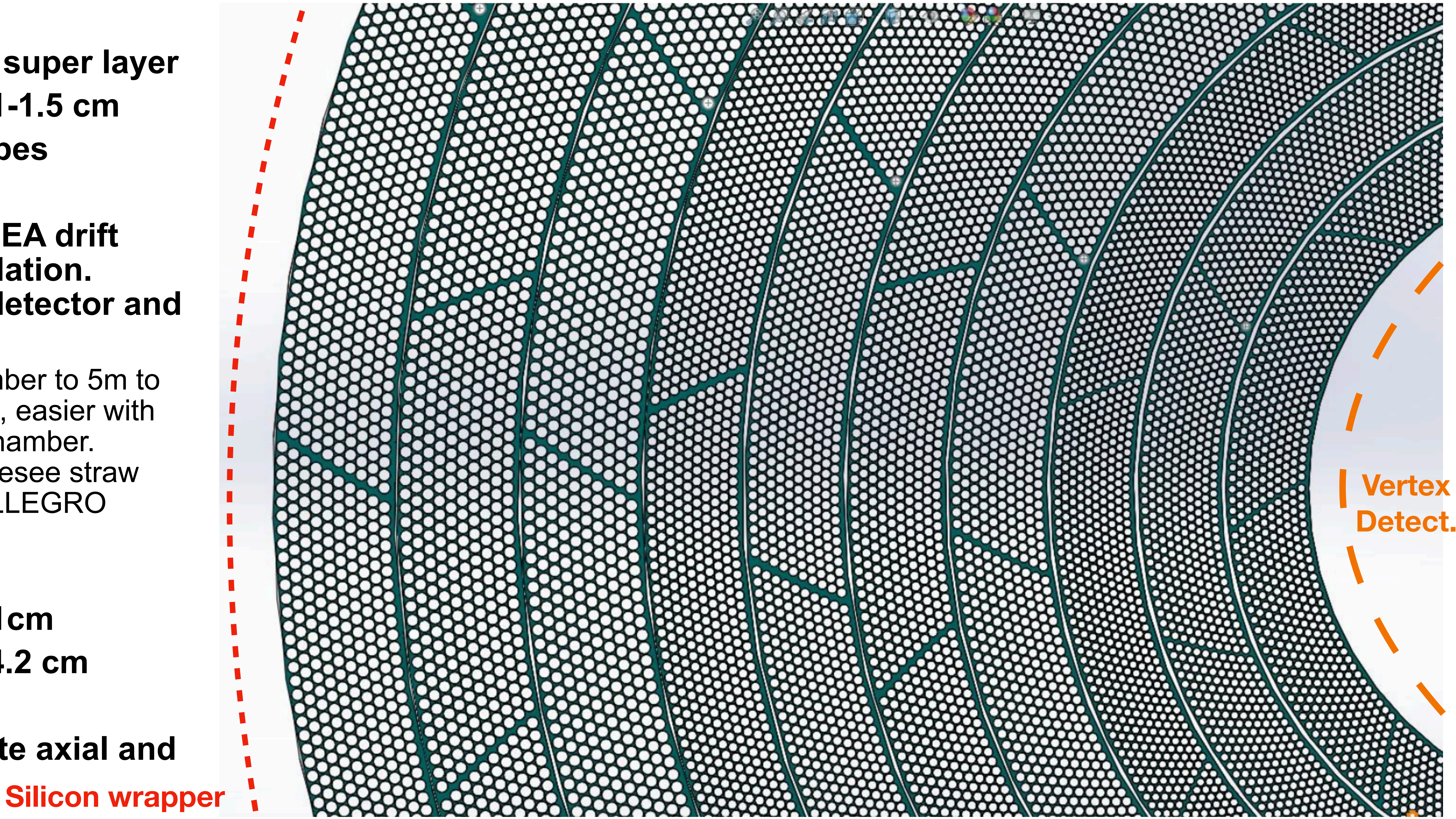
Straw tube layout: the WIP detector concept

- **10 super layers**
- **10 sublayers per super layer**
- **Diameter varies 1-1.5 cm**
- **Order 100,000 tubes**

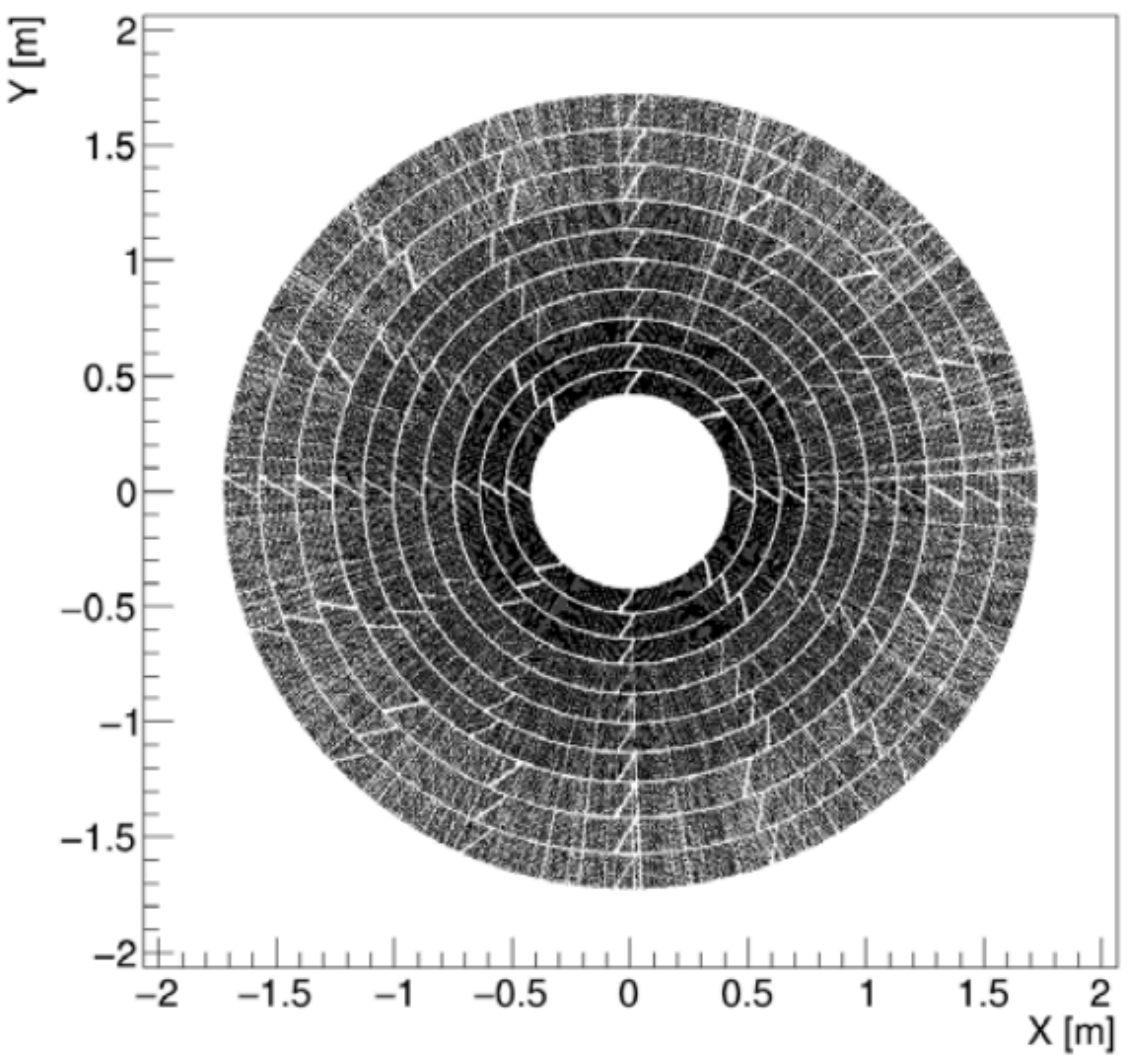
- **Put in place of IDEA drift chamber in simulation. Between vertex detector and silicon wrapper**
  - Can extend chamber to 5m to match ALLEGRO, easier with straw than drift chamber. Eventually we foresee straw may be part of ALLEGRO concept.

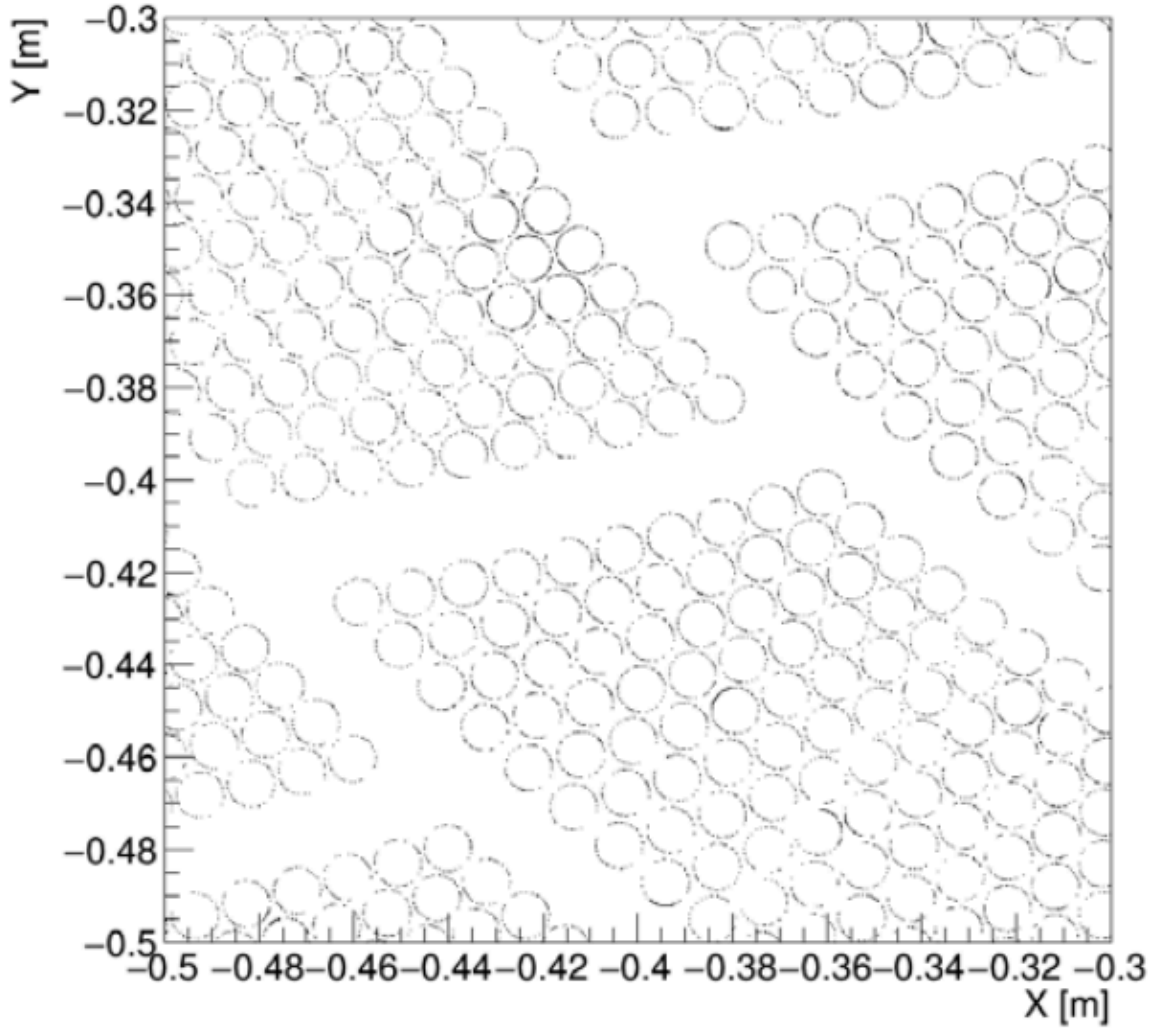
- **Inner radius: 35.1cm**
- **Outer radius: 184.2 cm**

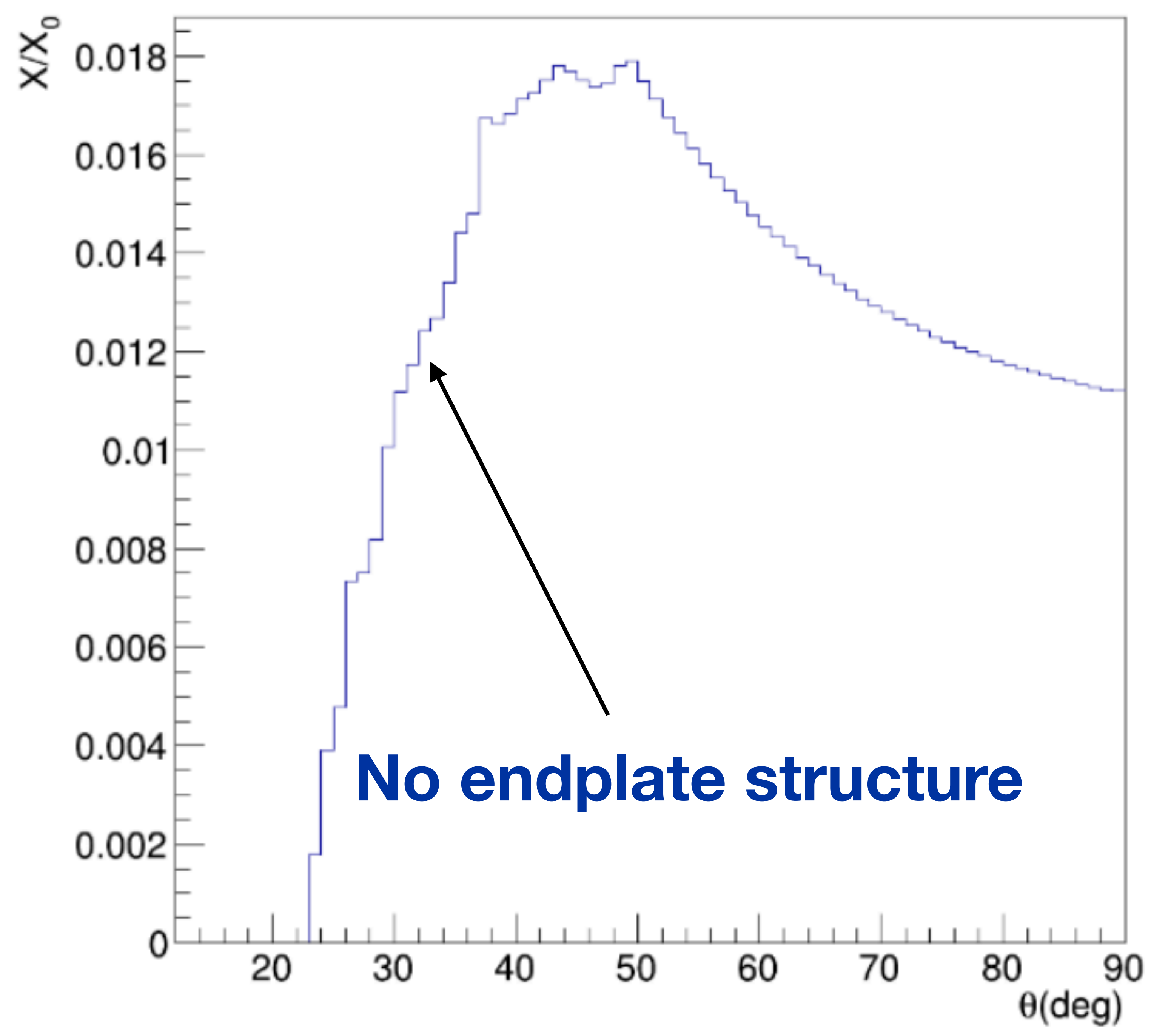
- **Option to alternate axial and stereo layers**



Dd4hep simulation





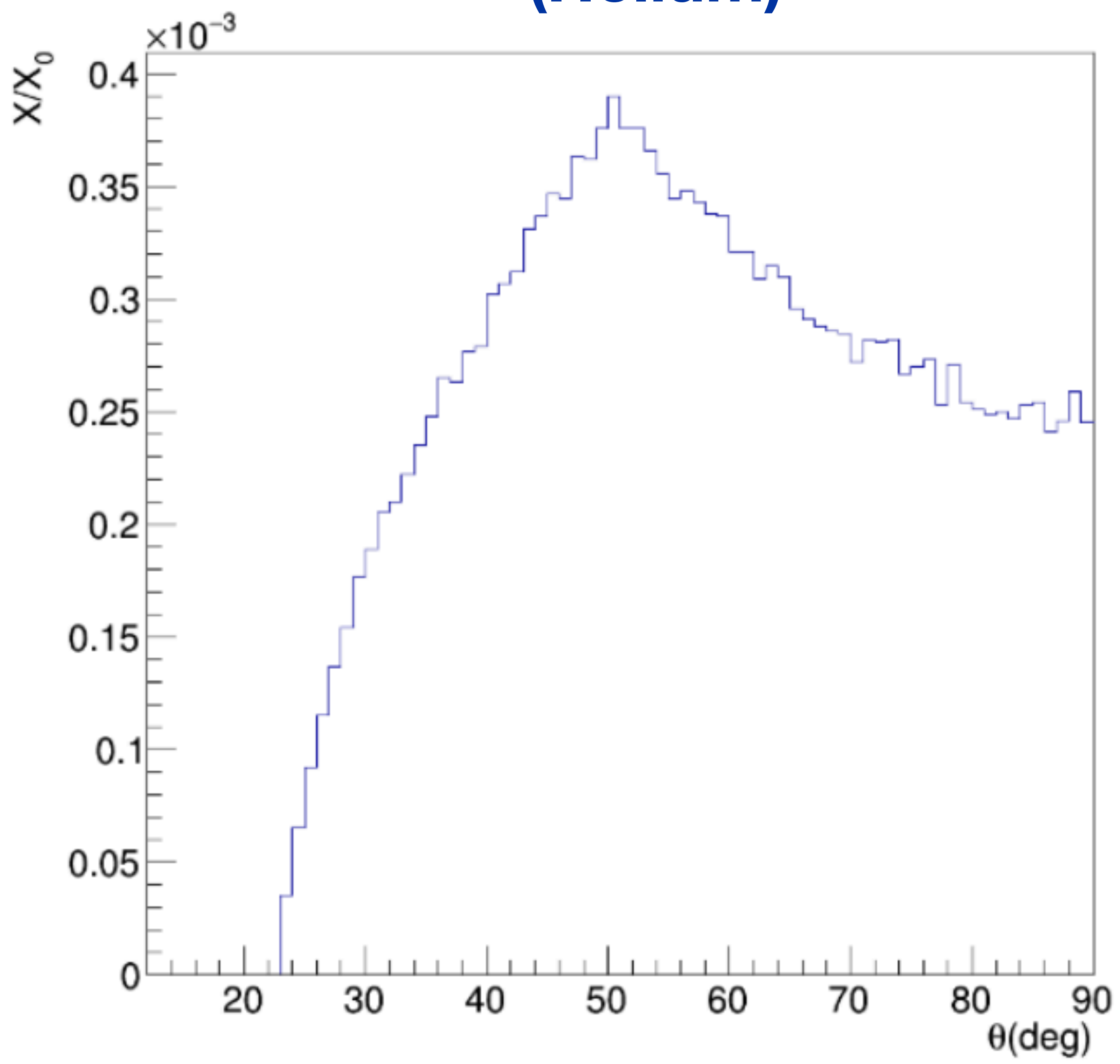


- **The straw tracker has modular design. Nominal geometry:**
  - 12 micron thick mylar layer
  - 50 microns Aluminium coating
  - Wire: 20 microns diameter Tungsten
  - No endplate structure added yet. Study $\theta = 90^o$

Material budget

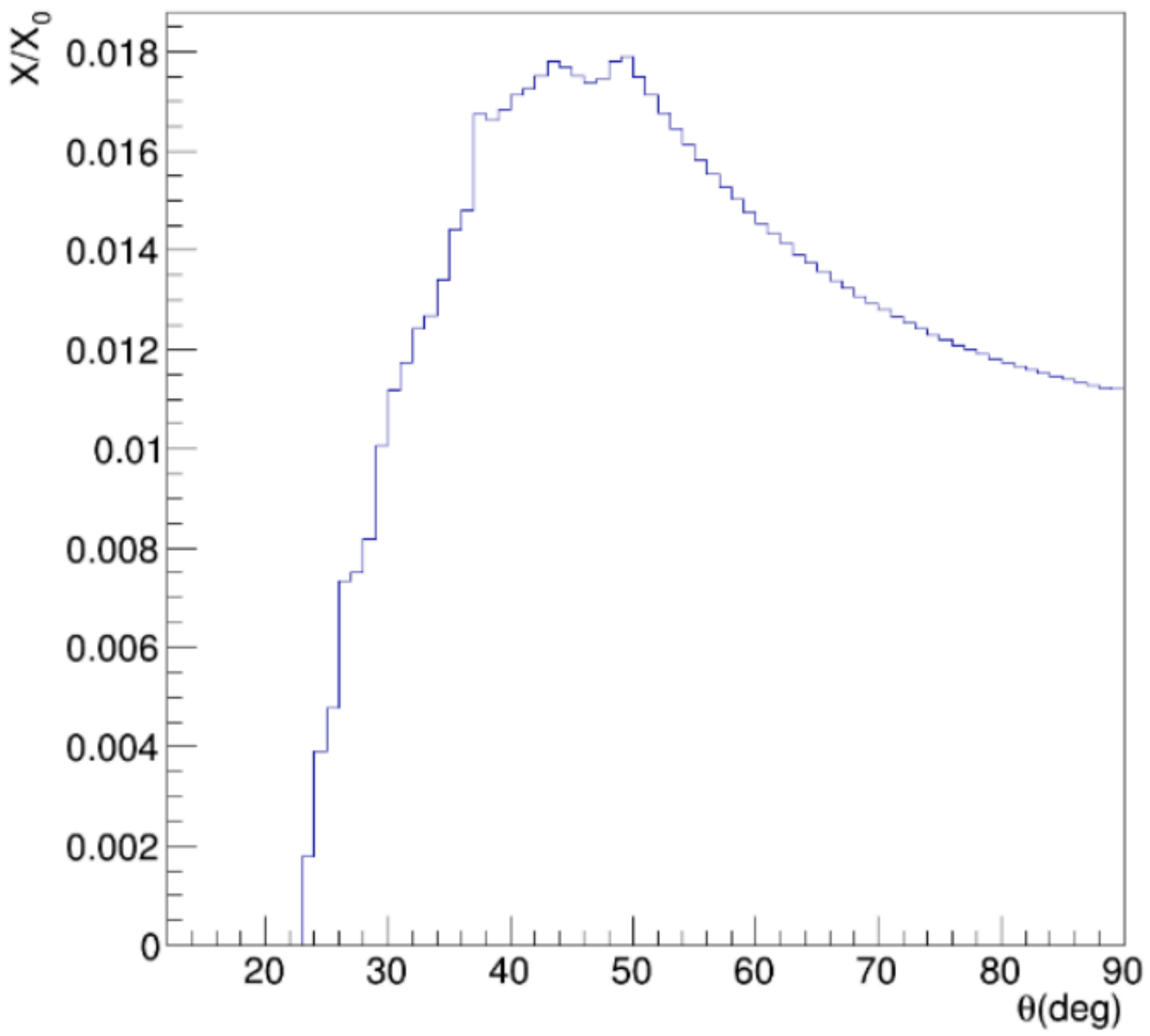
- **Material budget breakdown for individual components**
- **Negligible contribution from Helium and Aluminum coating. Mostly from Mylar wall.**
  - Air between tubes also considered. No glue: we anticipate ultrasonic welding technique.

(Helium)



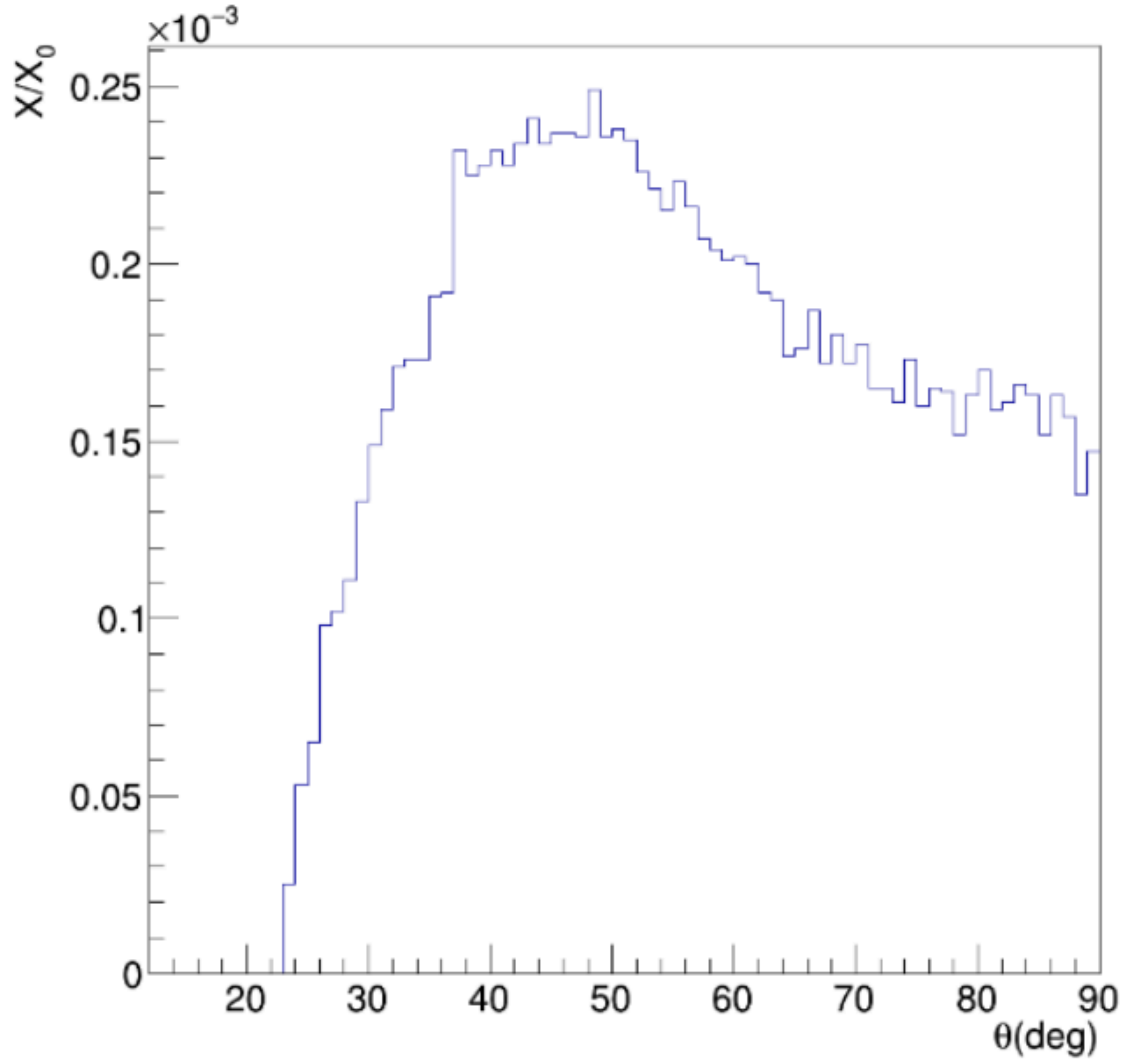
He

(12 micron Mylar wall)



Mylar

(50 nm Al coating)



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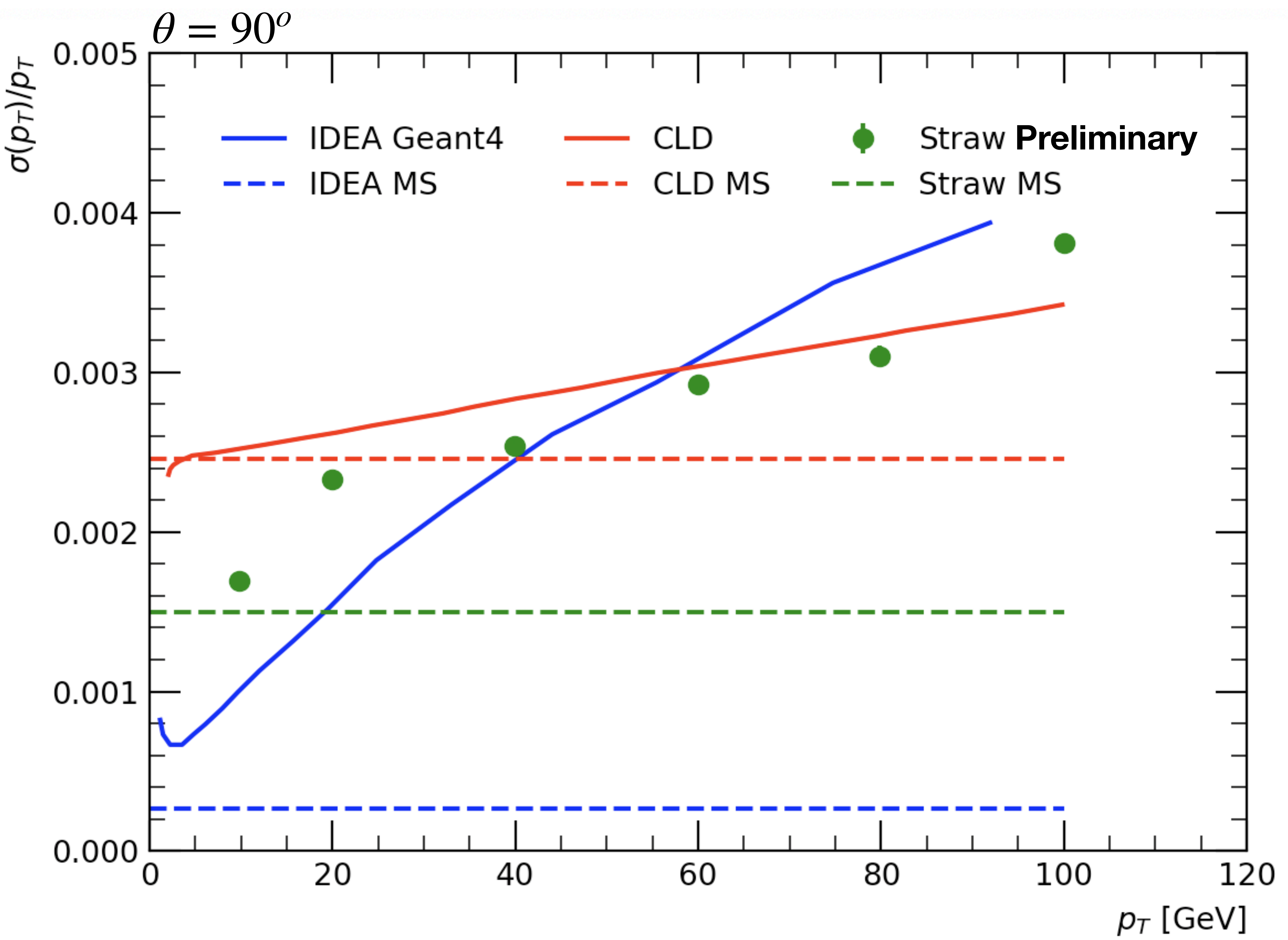
Tracking results

- **Using preliminary Geant4 IDEA simulation for comparison**
  - From: Nicola's talk, slide 42
  - We believe significant material was omitted for the analytical calculation (see backup)
  - Used 100 μm drift chamber resolution. We aren't sure about their assumptions for pixel, wrapper.
- **Assumptions on resolution for straw:**
  - Vertex pixel=5 μm
  - Straw=120 μm
  - Silicon wrapper=15 μm
- **Material included:**
  - From IDEA: Beampipe, vertex detector, silicon wrapper
  - From straw: wire, Helium gas, Mylar (12μm walls), air between tubes (total 1.2% X_0)
  - Using IDEA v03 concept from dd4hep, simply comment out drift chamber and replace with straw
- **Straw fully competitive with drift chamber**



MS contributions are from analytical calculation

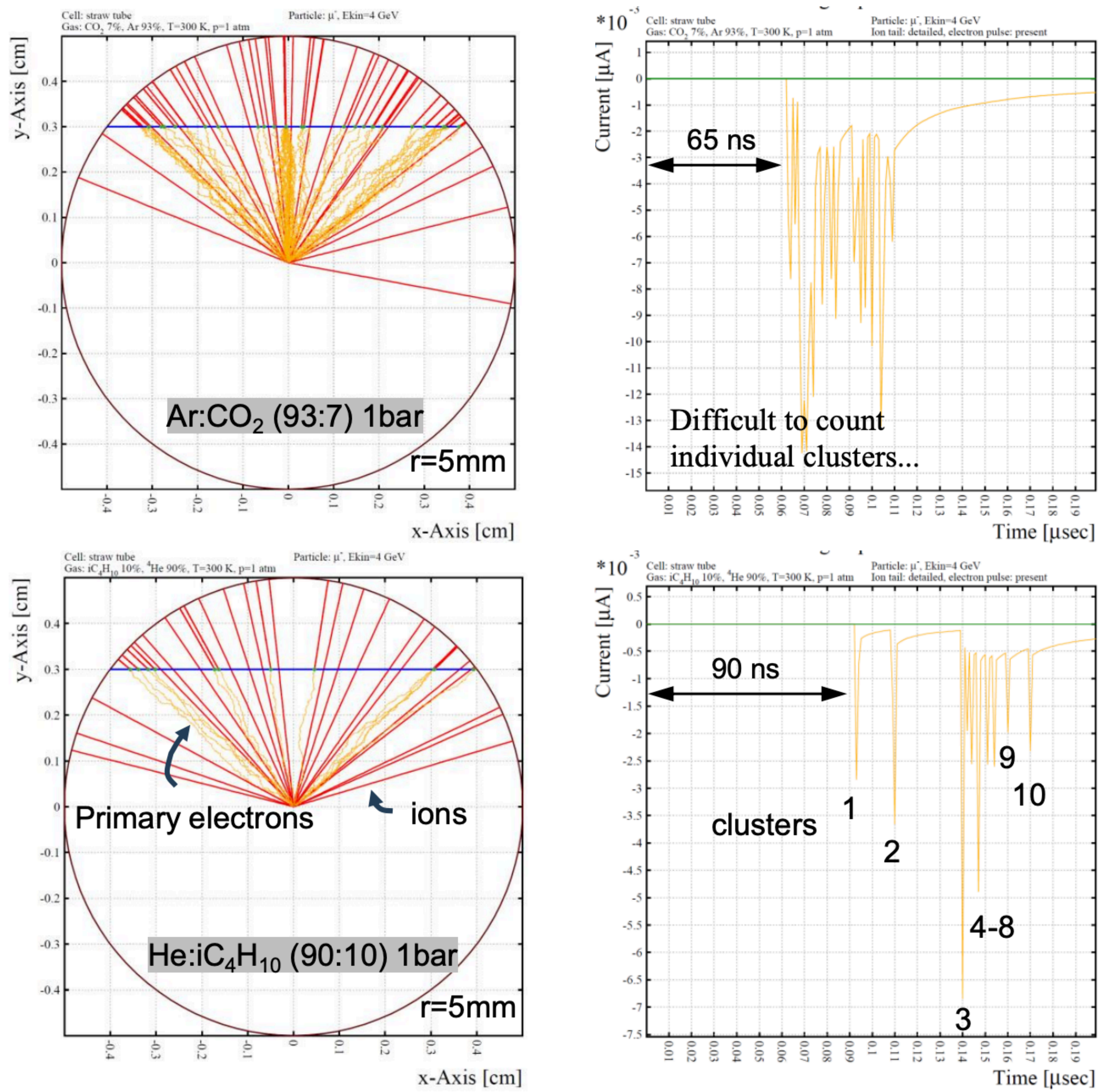
Simulation in different gas mixtures

- **Need to pay attention to the balance between timing resolution and transverse diffusion**

- **Ar-based gas:** high ionization density (~40 clusters/cm) and moderate electron drift velocity 50 μm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~5 ns.

- **He-based gas:** lower ionization density (~15 clusters/cm) and 30 μm/ns (@E~2kV/cm). Mean cluster arrival time separation: ~15 ns.

- Plots are meant to visualize the cluster separation. See backup for drift time spectra. Maximum drift time usually between 100-300 ns



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

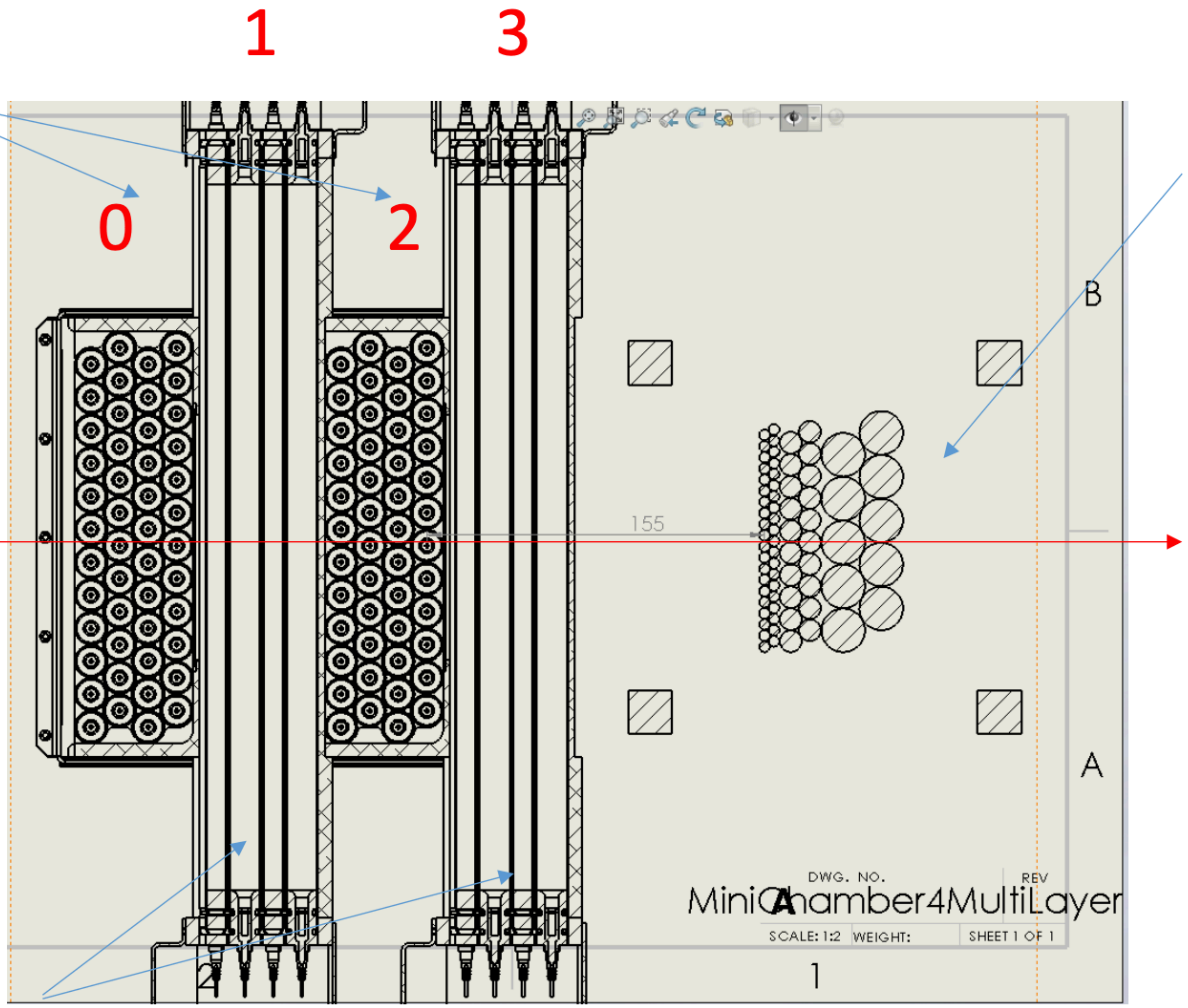
Straw tube test studies

- **Two ongoing experimental studies:**
  - Test beam at CERN:
    - Using ATLAS MDT readout electronics (does not record full waveform).
      - Can study resolution, wire centering, dE/dx study via Wilkinson ADC or ToT mode
  - Cosmic-ray study in Ann Arbor:
    - Using oscilloscope to read waveform from straw
      - Can study dN/dx method due to full waveform (eventually need read-out electronics with waveform digitization)
      - Need 100x gain on top of HV gas gain

Test Beam Studies (CERN)

Setup from top view

Two vertical sMDT chambers 0 & 2 (parallel with straws, measuring the X position)



Beam direction (Z direction)

Straws:
18 tubes are connected to the sMDT DAQ (TDC 8, Channel 6--23)

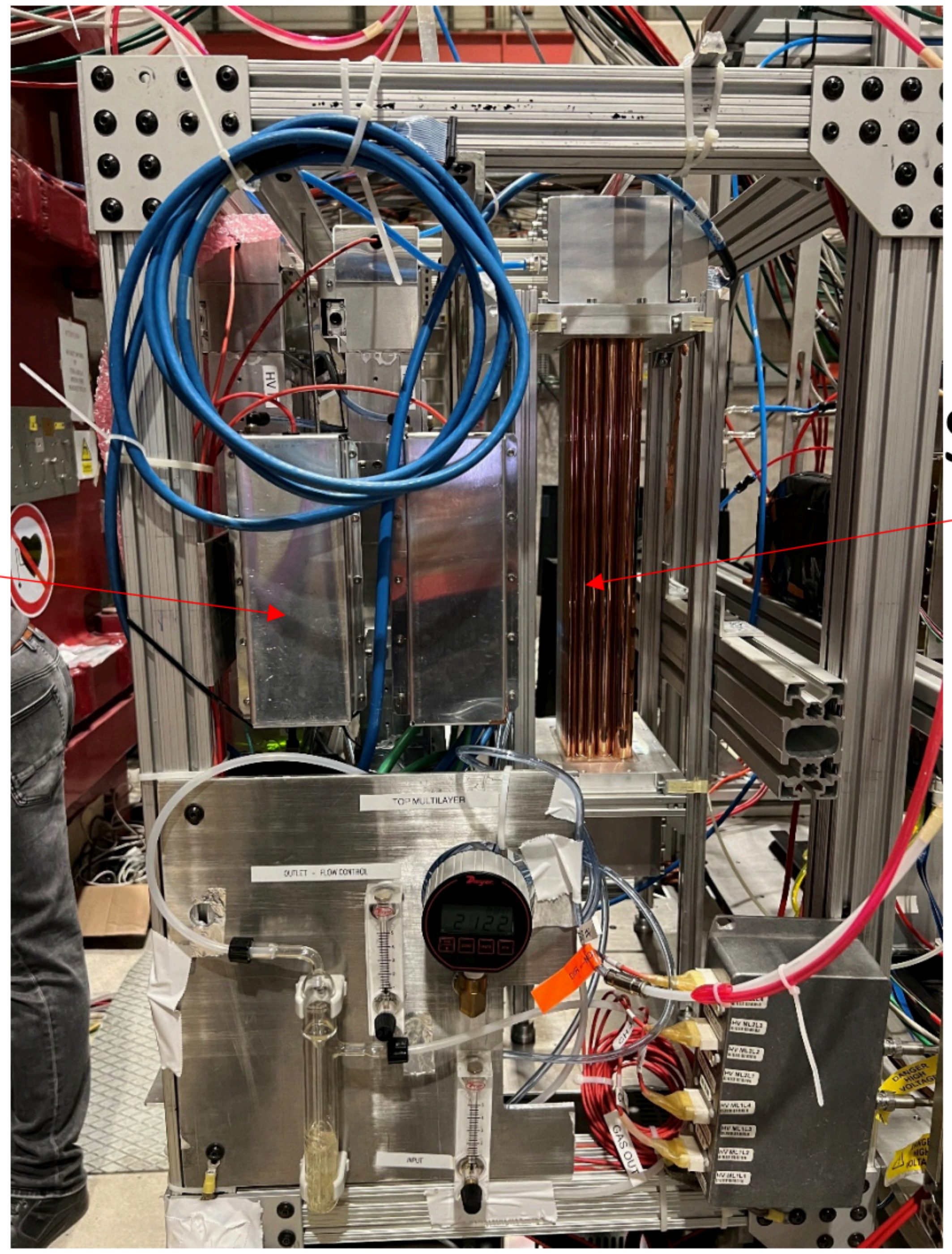
- 5 mm tubes with HV 1450 V
- 10 mm tubes with HV 1750 V
- Nominal threshold: -28 mV (~3.1 fC)
- 70% Ar, 30% CO2 at 2 bar

Two horizontal sMDT chambers 1 & 3 (orthogonal to straws, measuring the Y position)

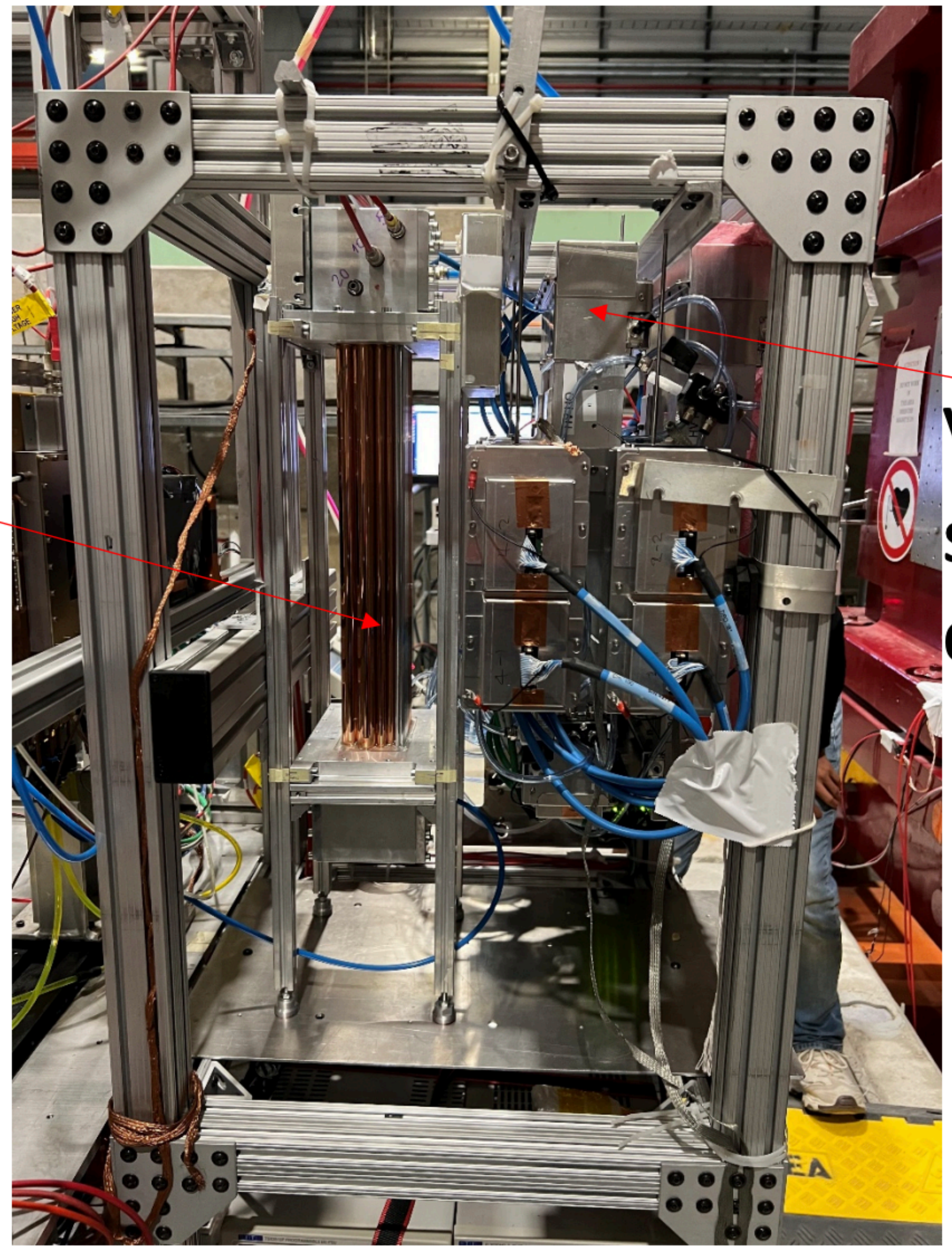
sMDT tubes with HV 2730 V
93% Ar, 7% CO2 at 3 bar

- **Compare ADC spectra and time spectra (ADC in "Wilkinson ADC" mode. More in backup.)**
  - For most of the straw tubes, longer drift time -> larger ADC

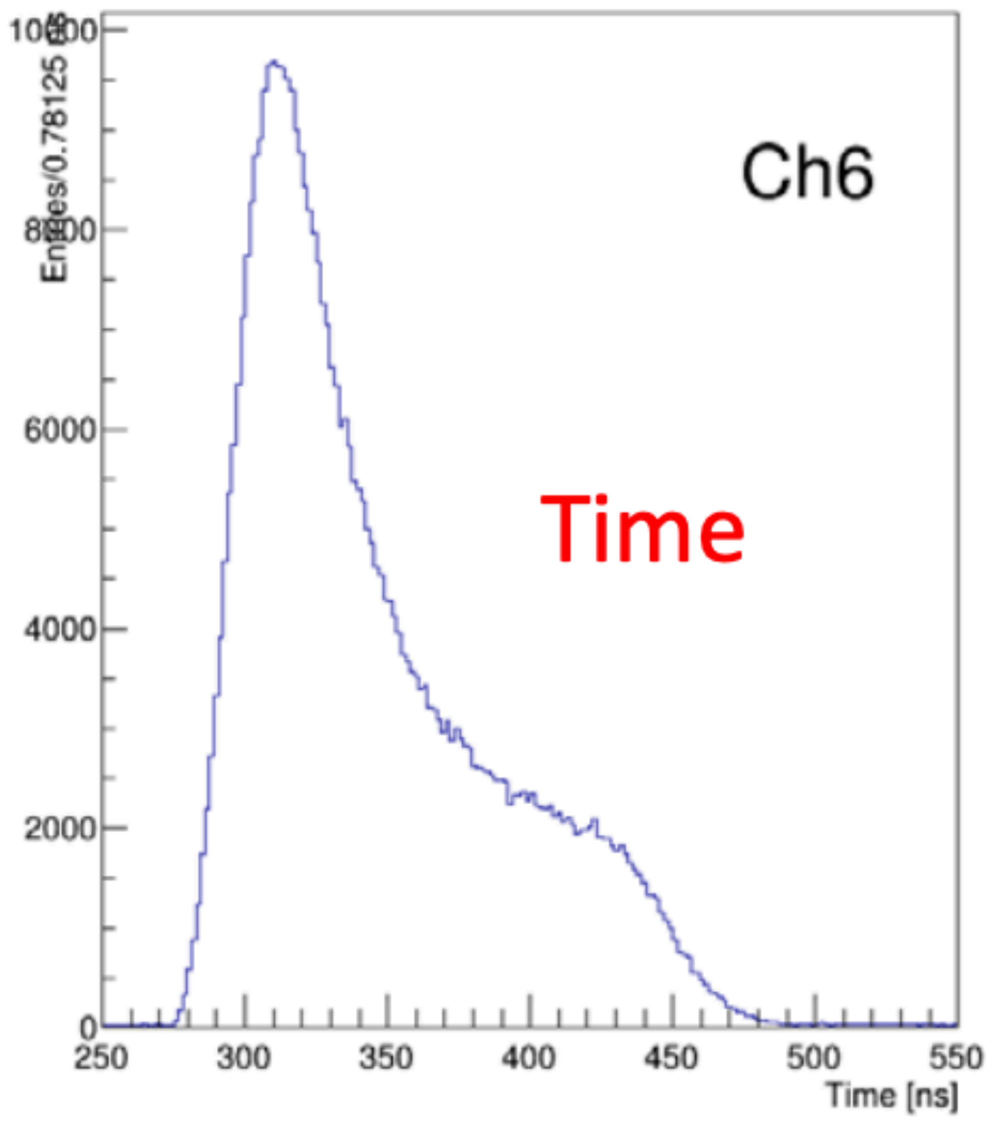
Horizontal sMDT chambers

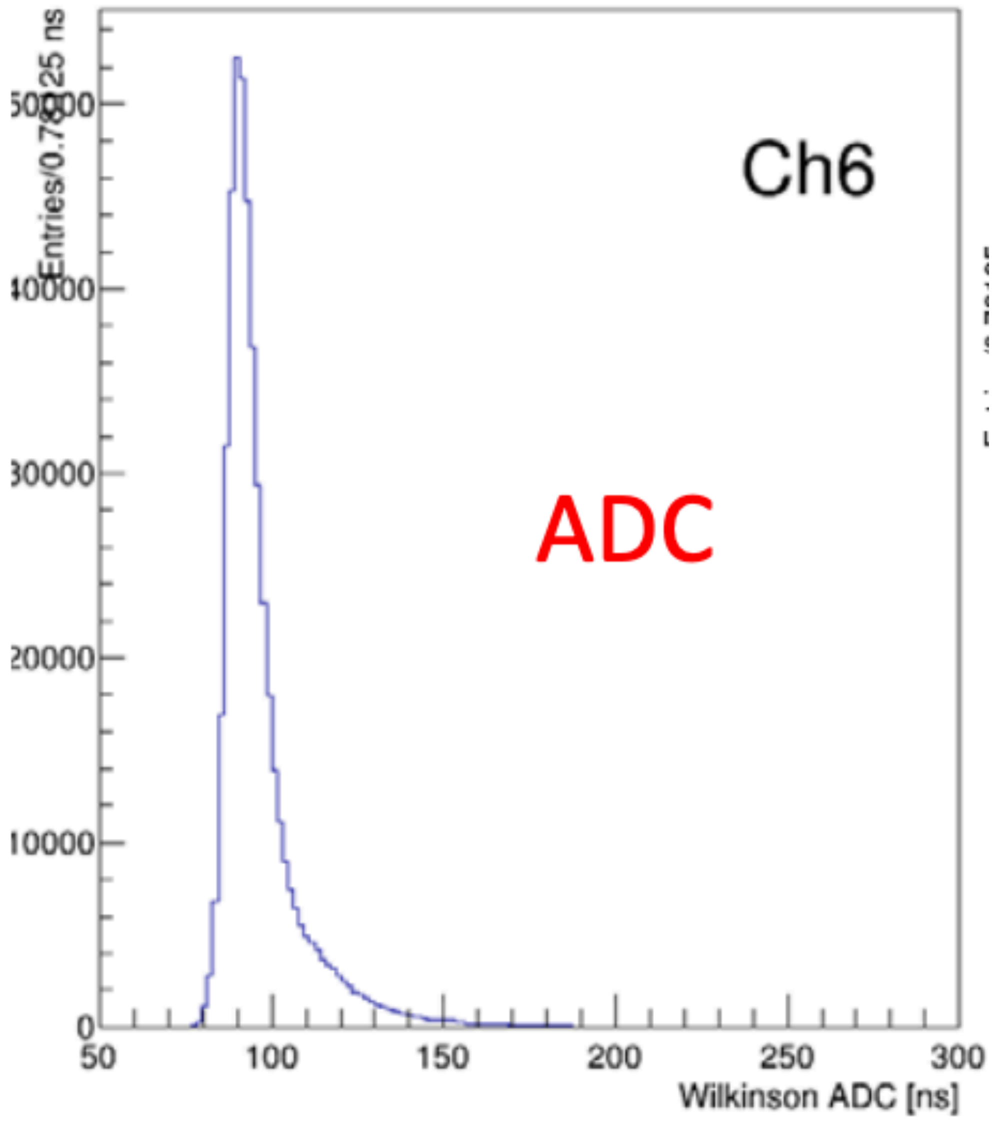


Straws



Vertical sMDT chambers



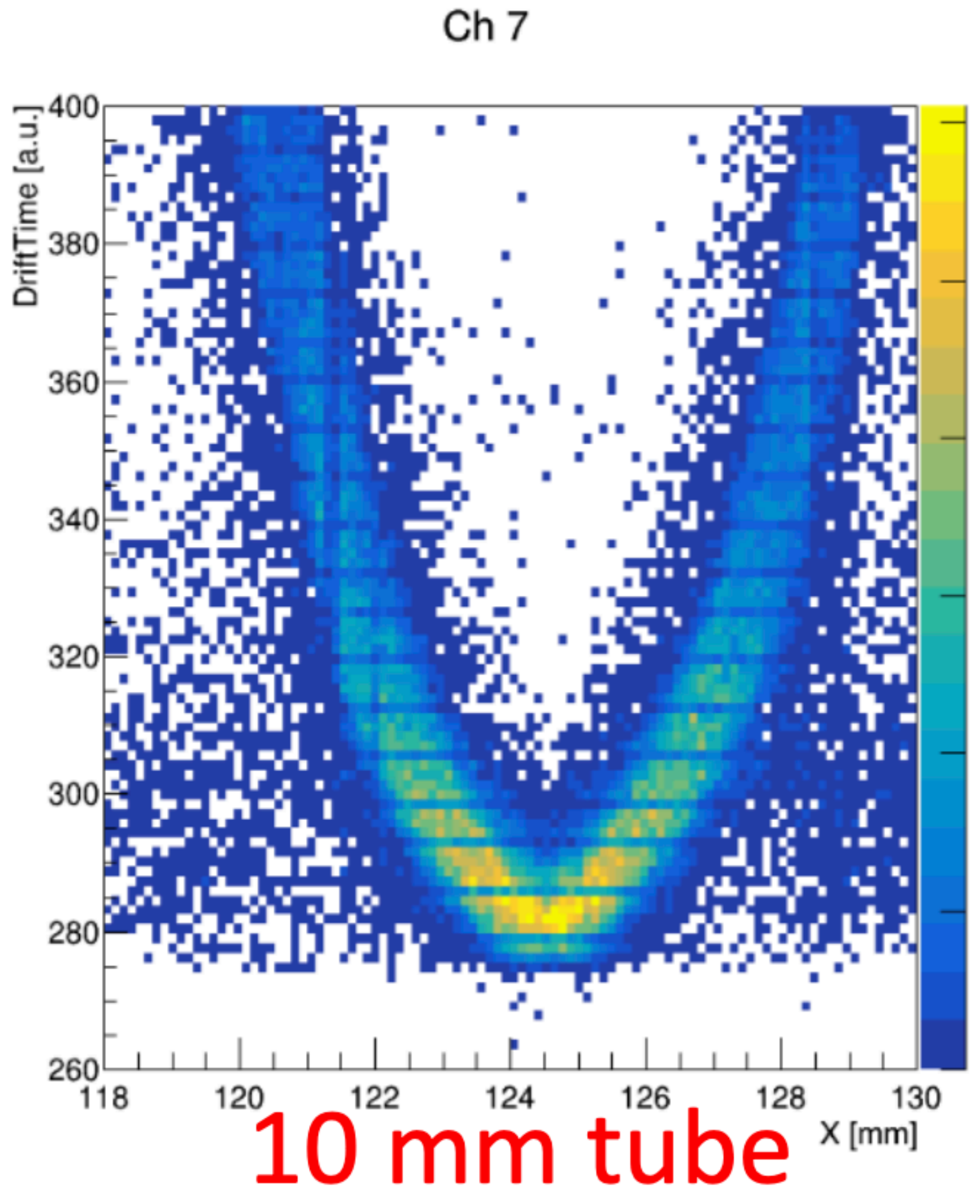


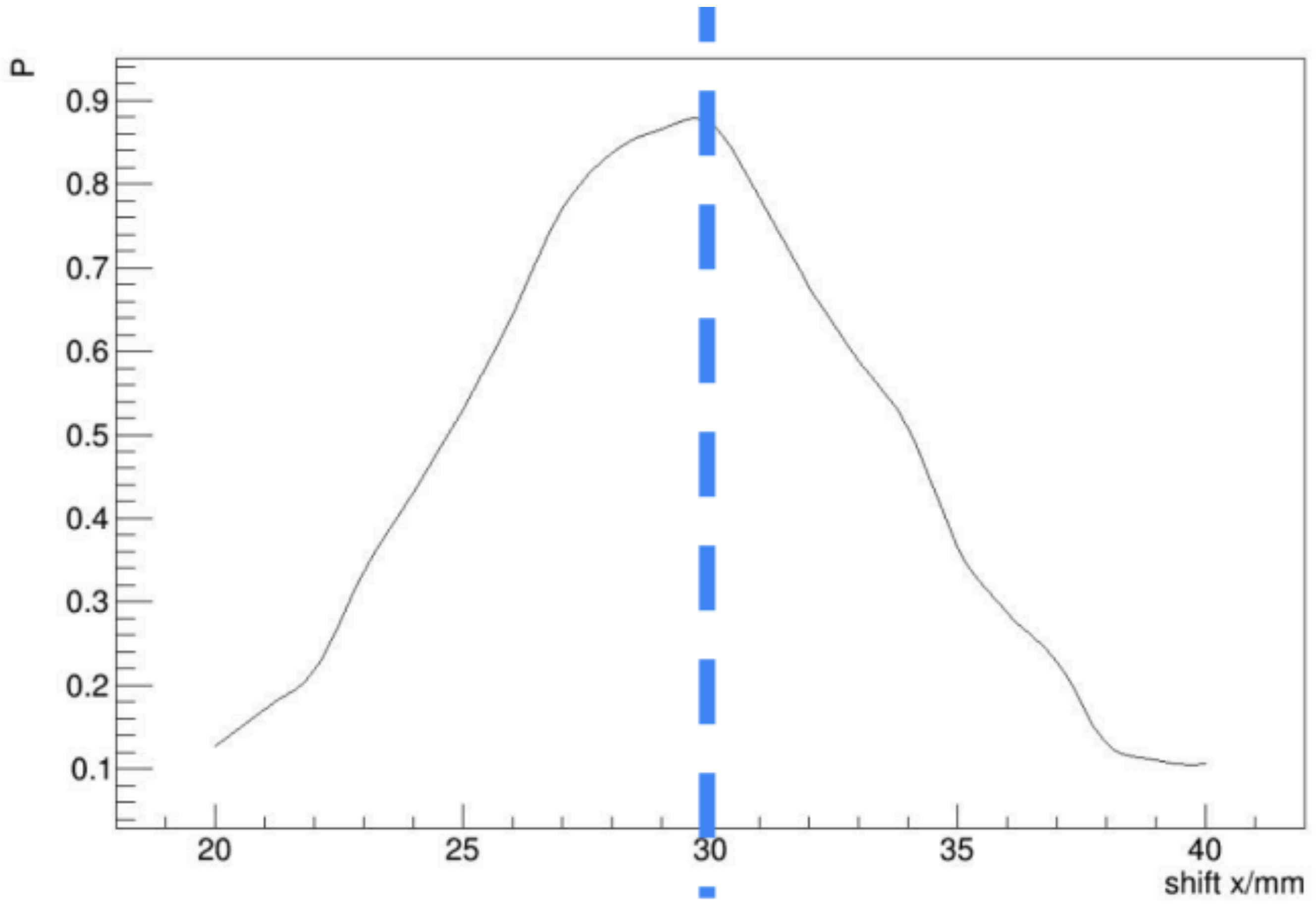
Straw alignment

- Use sMDT tracker to predict the muon track in 3D.
- Start with a nominal alignment and calculate the efficiency of the straw:

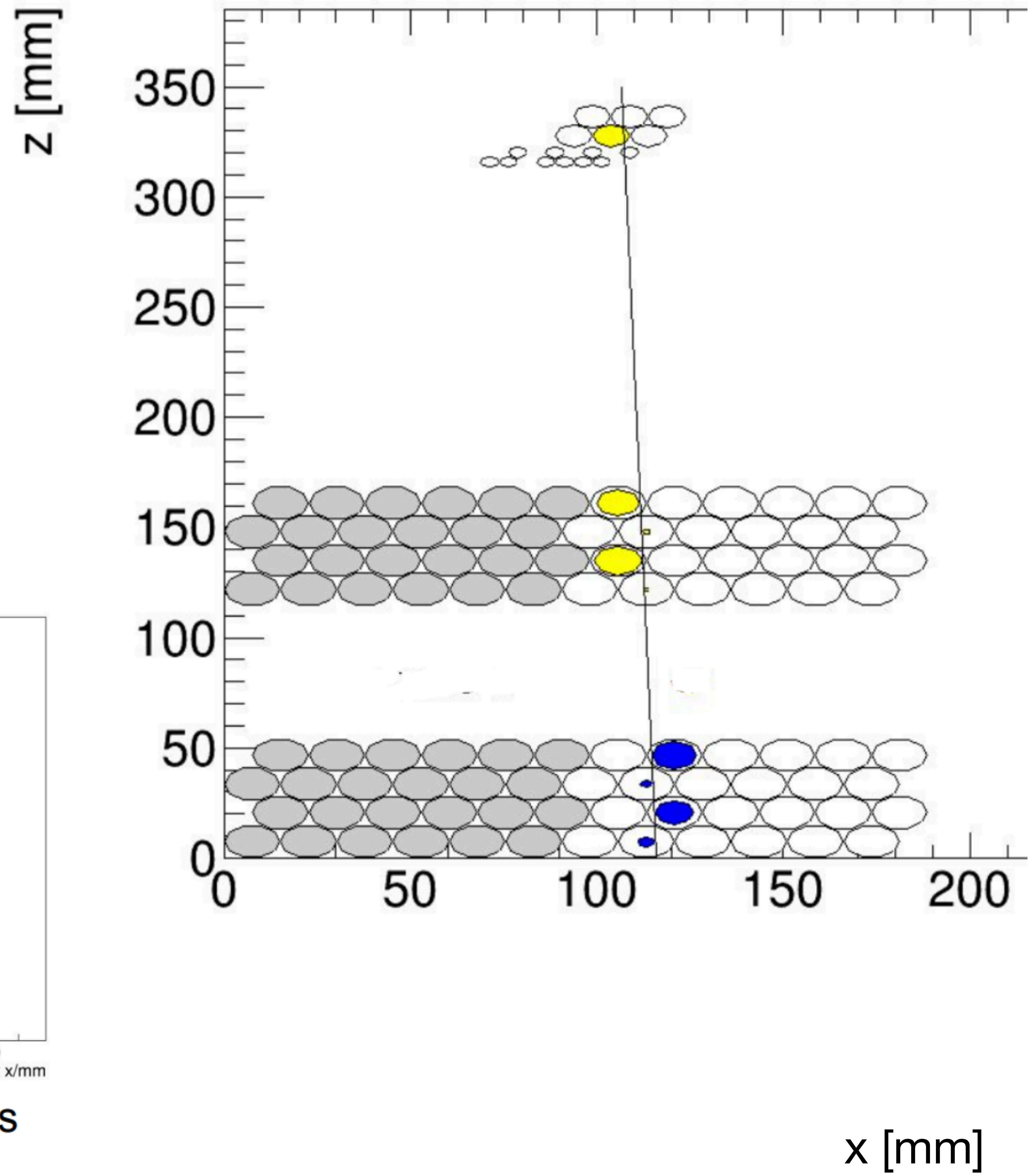
$$\epsilon = P(\text{hit on straw tube} \mid \text{sMDT track through straw tube})$$

- Adjust position of the straw to maximize the efficiency
- ~90% efficiency in 10/16 tubes



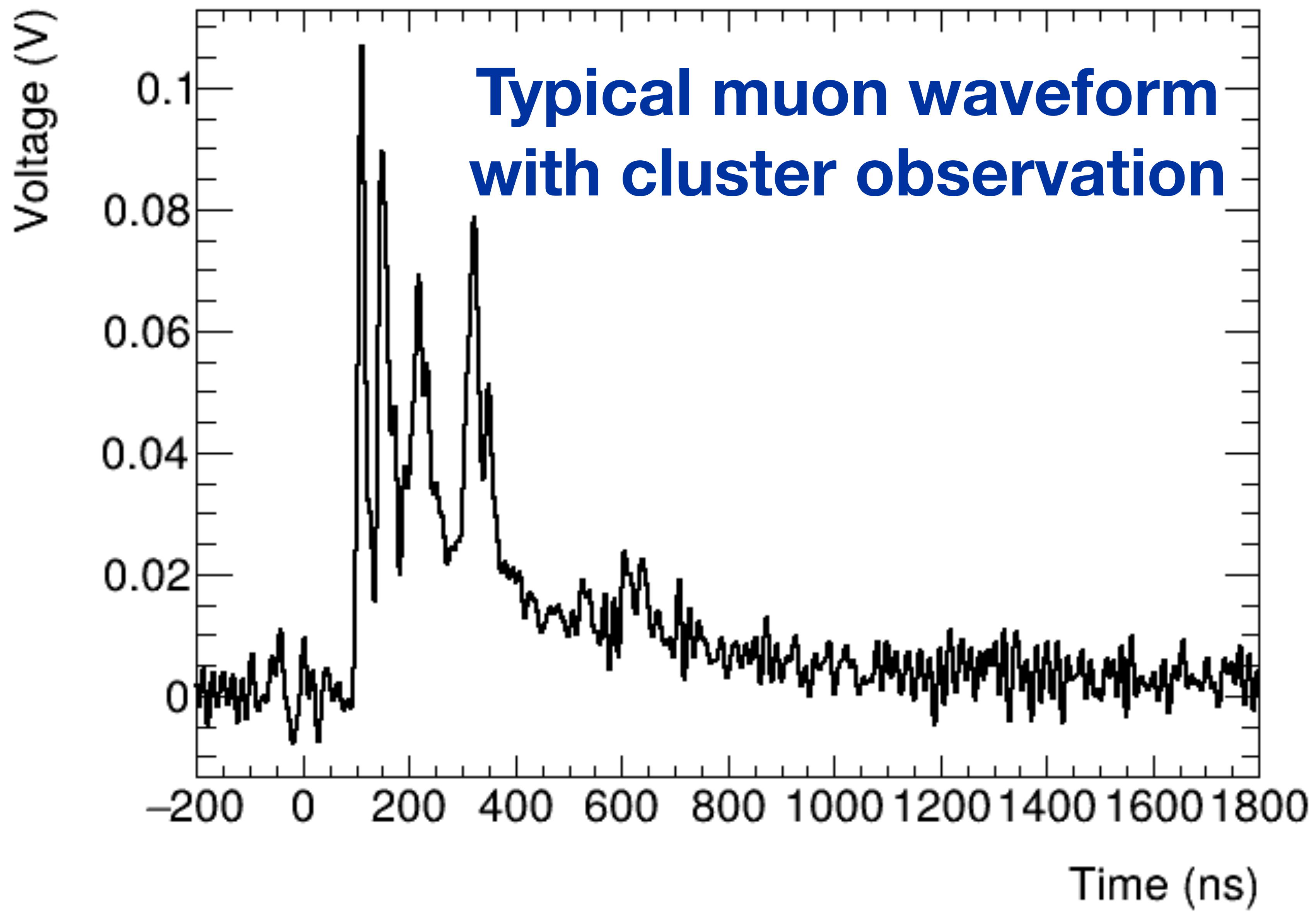


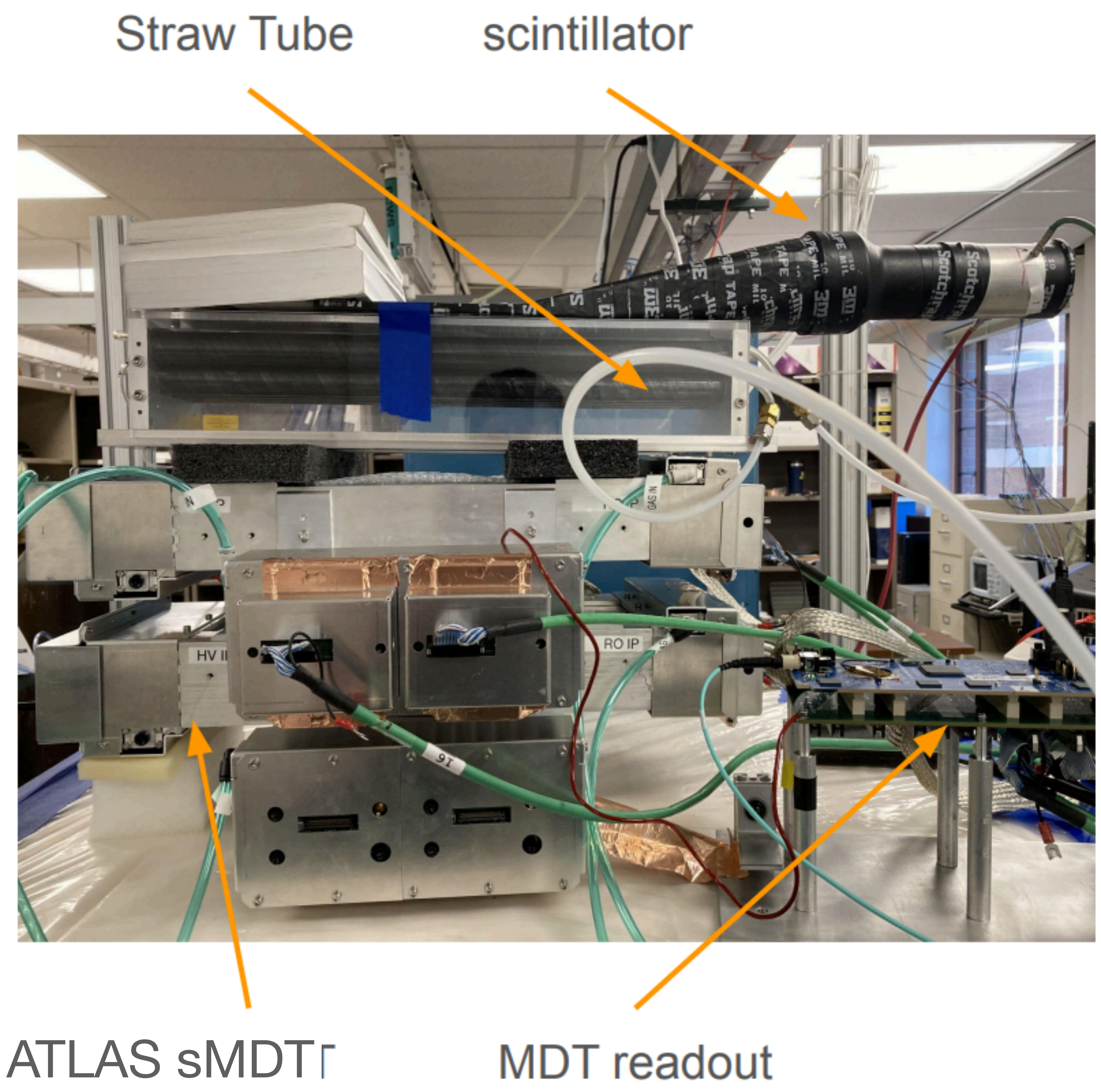
Maximum efficiency corresponds to the best alignment



Cosmic studies (Ann Arbor)

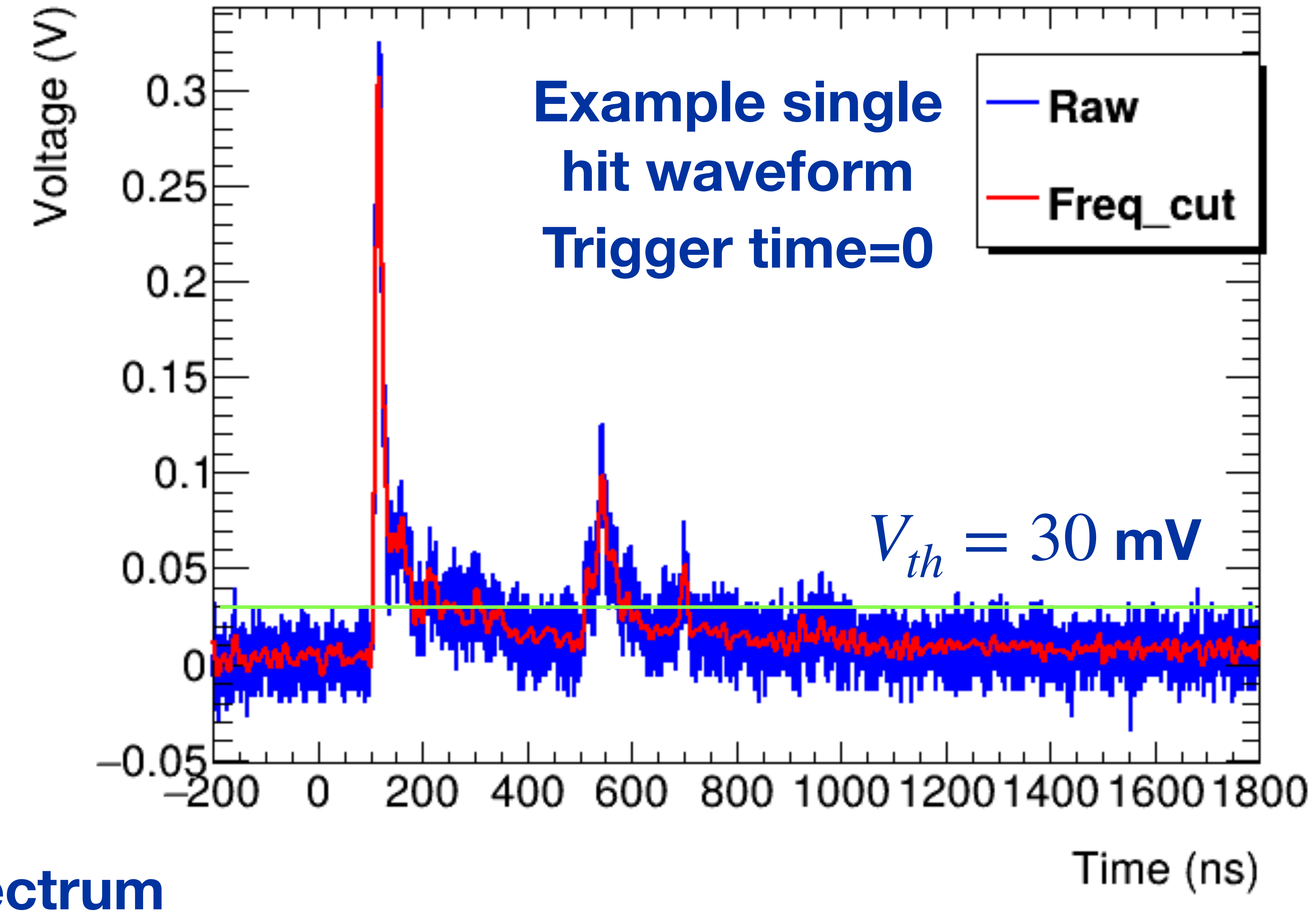
- **A cosmic-ray test setup in Ann Arbor**
- **Using ATLAS drift tubes to reconstruct track in 3D.**
  2 tracking planes with perpendicular sets of drift tubes.
  - Same sMDT set up as used in test beam studies at CERN.
- **Experimental setup:**
  - Straw tube HV=1750 V, diameter=2.5cm, Ar:CO2 (93:7) at 1.1 bar
  - ATLAS sMDT HV=2730 V, diameter=1.5cm, Ar:CO2 (93:7) at 3 bar
  - Scintillator size: 20x20 cm
  - 2 straw tubes are read out



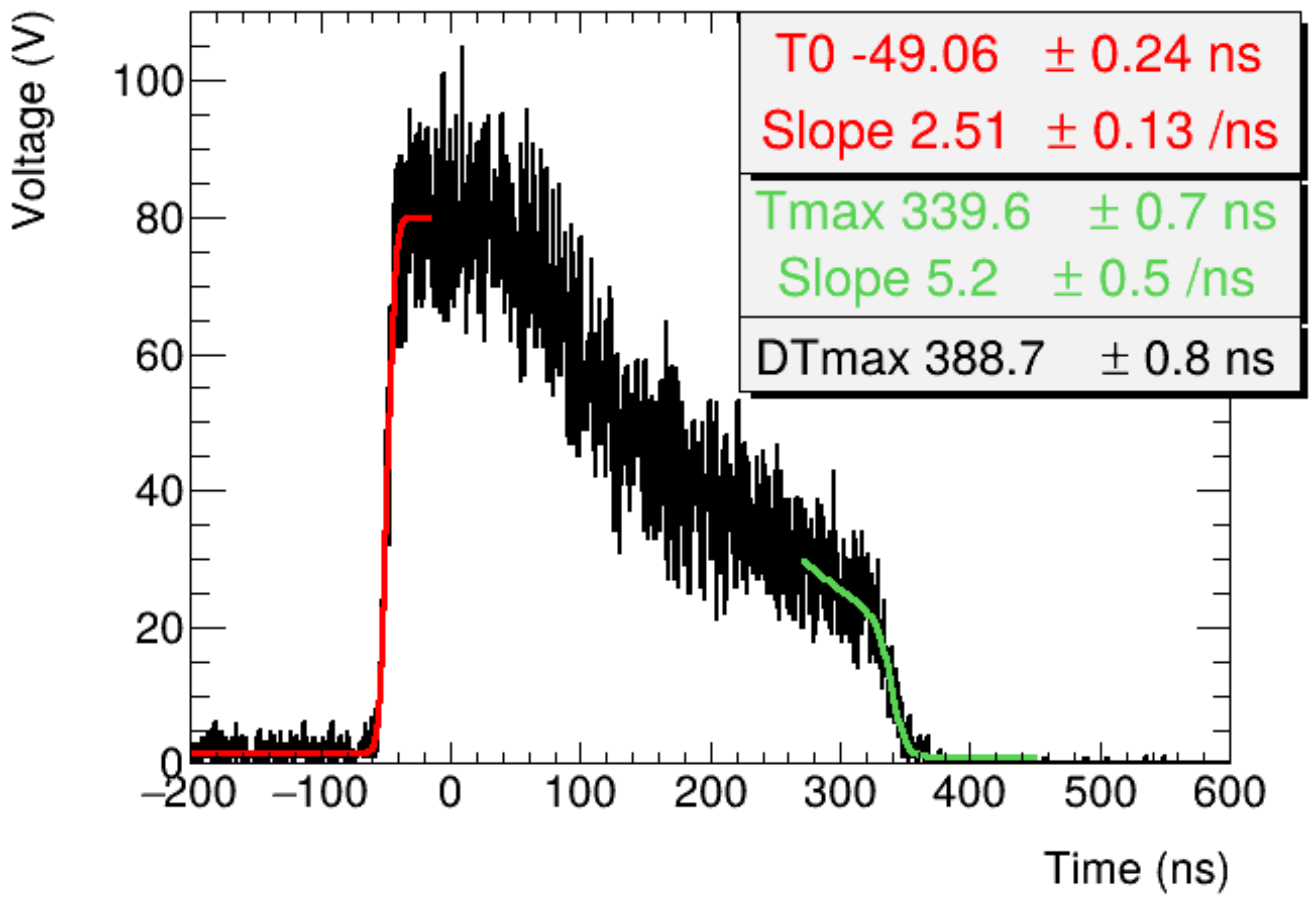


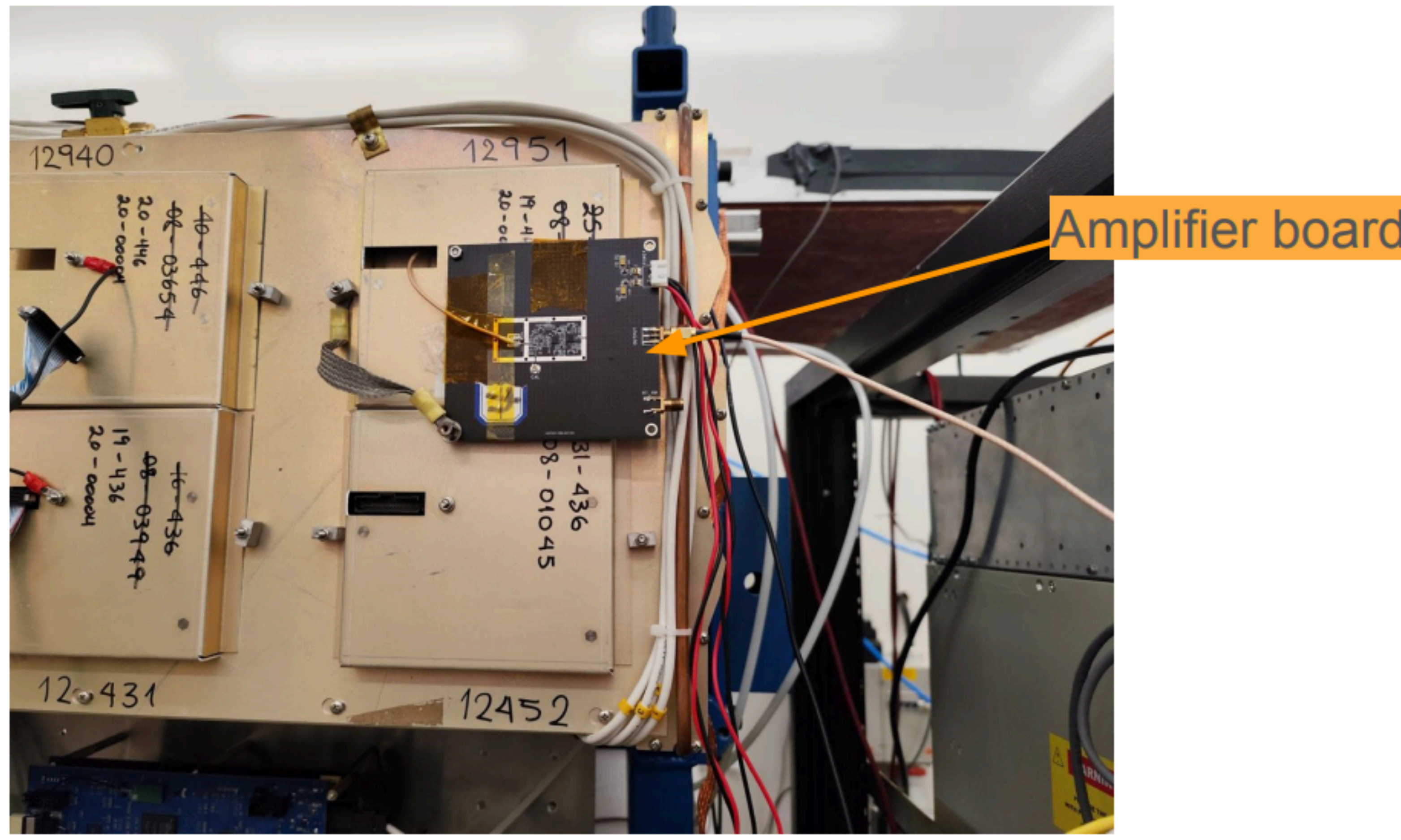
Drift time spectrum

- **Filtering removes noise, allowing low threshold voltage**
- **Drift time is calculated from the first leading edge crossing the threshold voltage.**
- **Drift time spectrum is well behaved.**
- **Plan to modify HGTD amplifier board**
  - Create new board to mount on straw prototypes and use CAEN digitizer board to read out all waveforms.
- **Further test beam plans:**
  - Fermilab (requested for May 2025)
  - CERN sometime 2025



Straw tube drift time spectrum





Additional 100x amplification needed

Straw tracker workshop

- **A successful workshop was organized earlier this week in Ann Arbor**
- **~35 participants from 20 institutions**
  - ~15 remote participants
- **Jianming will summarize further at detector concept meeting**
  - https://indico.cern.ch/event/1463707/ (Monday 10am EST)

Why a straw tracker workshop?

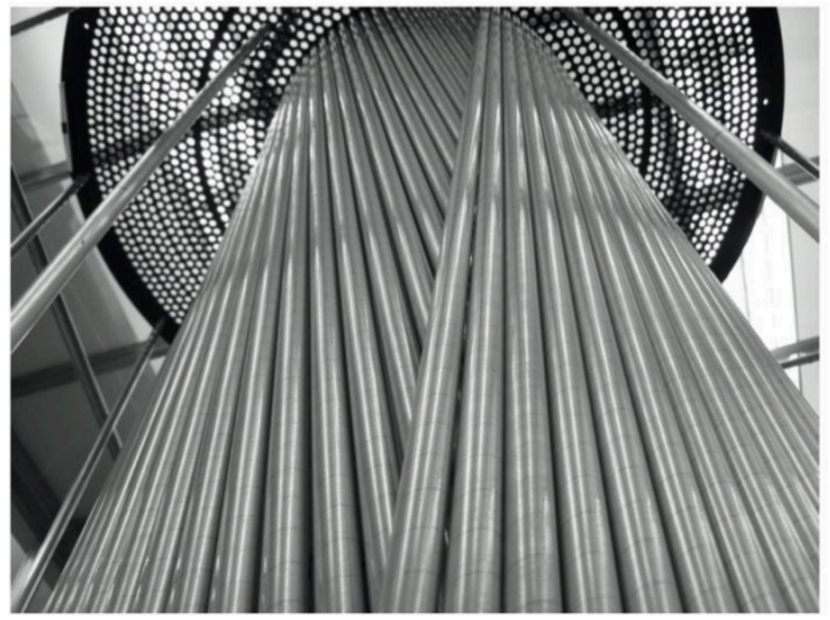
This workshop intends to bring together experts and interested parties to investigate the feasibility of incorporating a straw tracker into the inner detector. The topics for the workshop will encompass reviews of existing straw trackers and their latest developments, the requirements for a Higgs factory, critical R&D issues, as well as potential layouts for an inner detector that includes a straw tracker.

- **Straw trackers have been used for more than 30 years by many HEP experiments, why do we still need R&D for FCC-ee experiments?**
  - New technology to make a thin-wall straw (down to 12 microns) with ultra-sonic welding method (not yet available in the US)
  - Building a straw tracker with much larger volume is extremely challenging, needs a lot of engineering and prototyping
  - Using a straw tracker for particle ID will need new electronics development, ML technology for dN/dx measurement

Straw tracker workshop

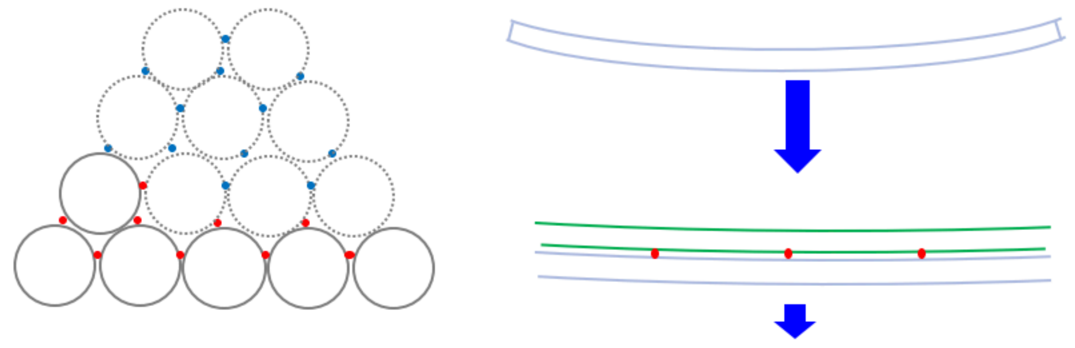
- **Many different experiments represented**
  - ATLAS, PANDA, Mu2e, GlueX, NA62, SHiP, DUNE
- **Many participants specialized in production of straw tubes**
- **Lots of experience on straw production, assembly, operation and frontend electronics presented**

GlueX straw tracker

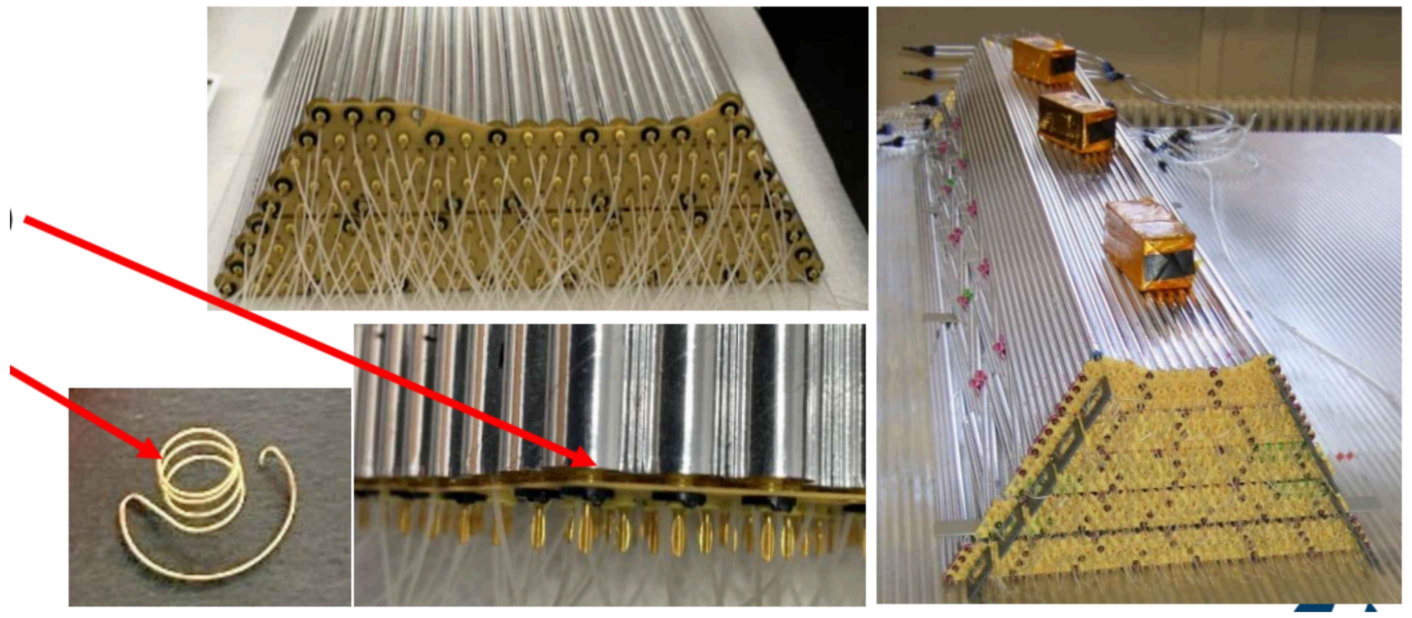


Self-supporting straw layers

- glue straws in planar layers with minimal gap together
- reference profile plates define exact straw-straw distance
- pressurized modules show high rigidity



Close-packed, dot-glued straw layers sustain wire tension and reduce bending.



3× 3kg Pb bricks on top of hexagon modules.

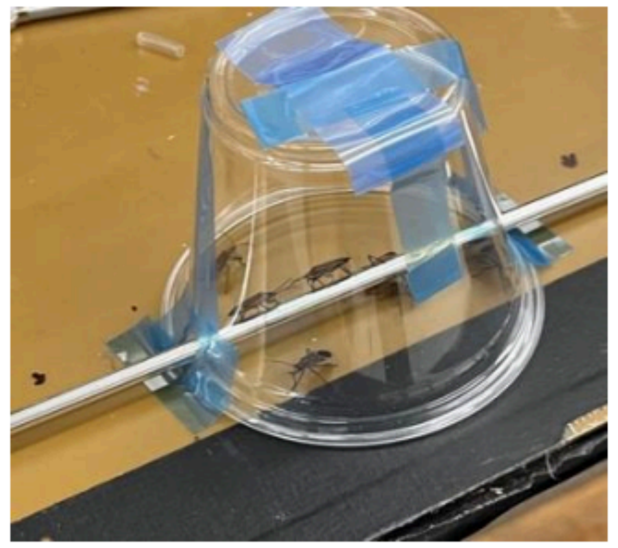
R&D on self-supporting straw

Actual bugs bite holes in Mu2e straw

An investigation found the cause.

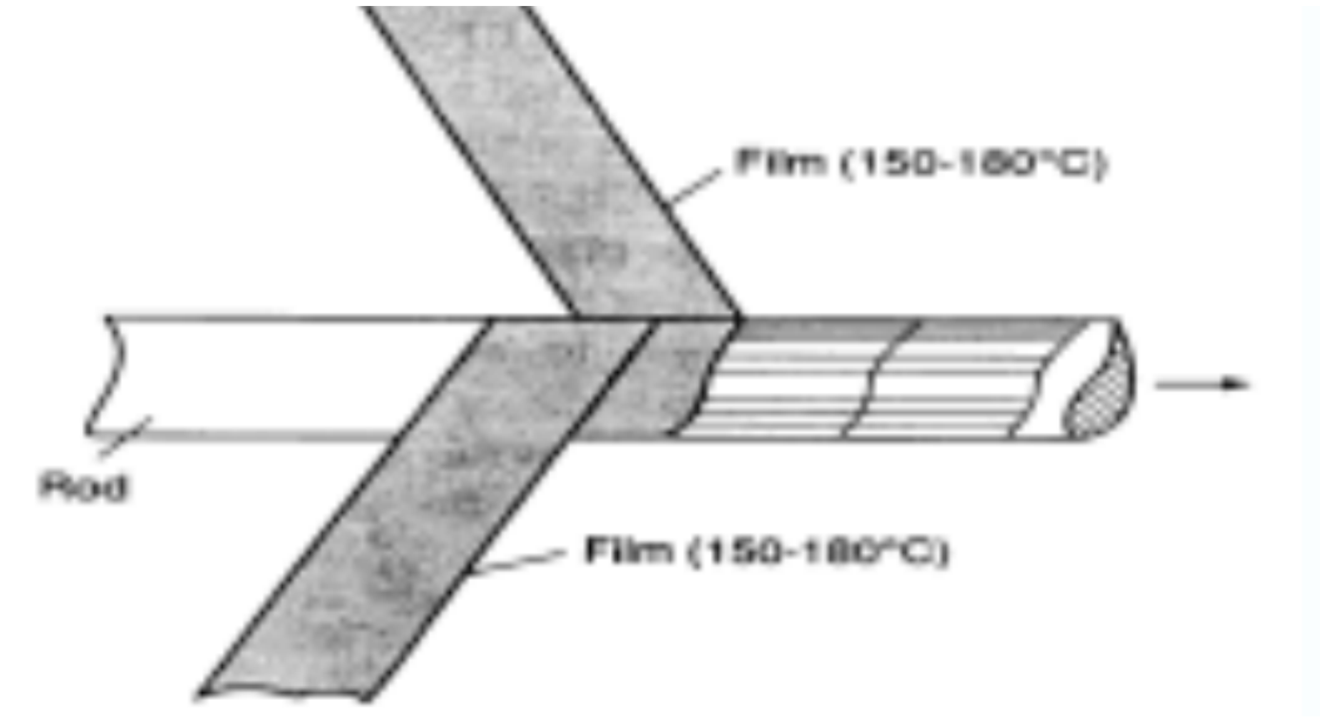
Actual Bug

Boxelder bugs found in the assembly cleanroom

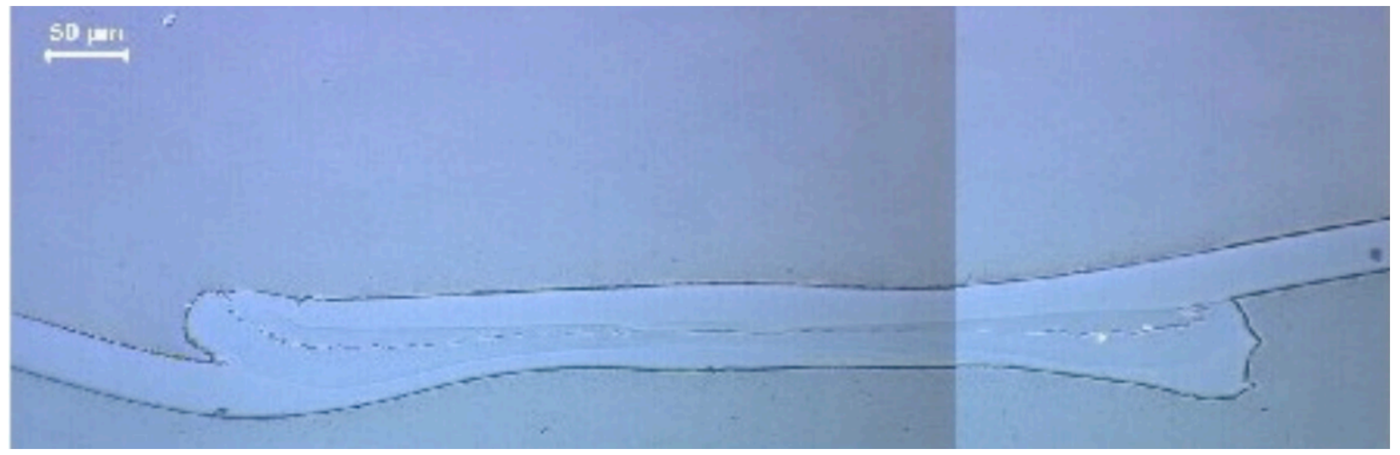


Trapped the bugs to show they could cause hole in straws

Straw used in many experiments



Straw winding



Straw welding

Straw winding

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

Straw welding

- NA62
- COMET
- SHiP
- DUNE
- SPD NICA
- ,,

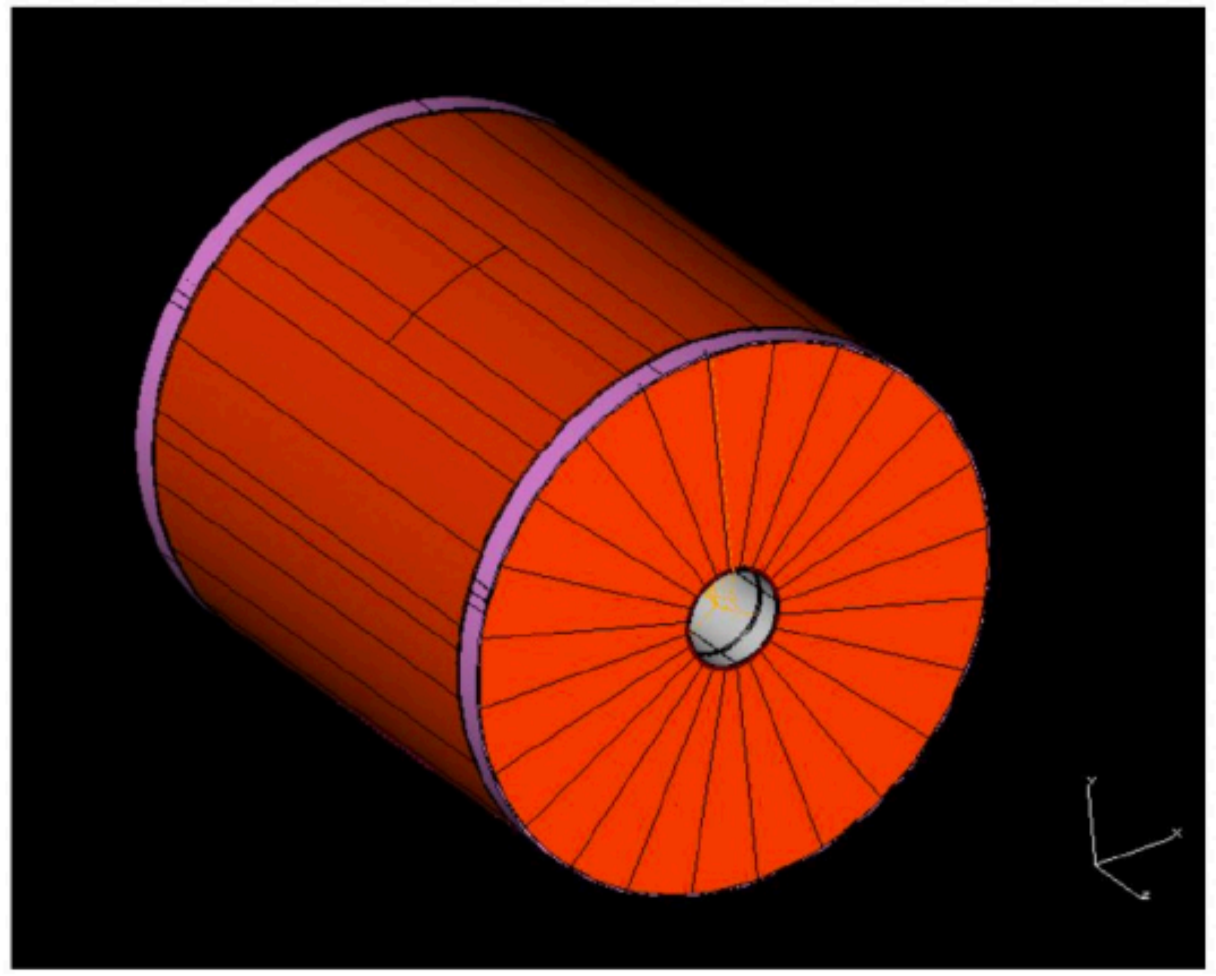
red color- straw tracker created with our participation

See Temur's talk

Straw tracker workshop

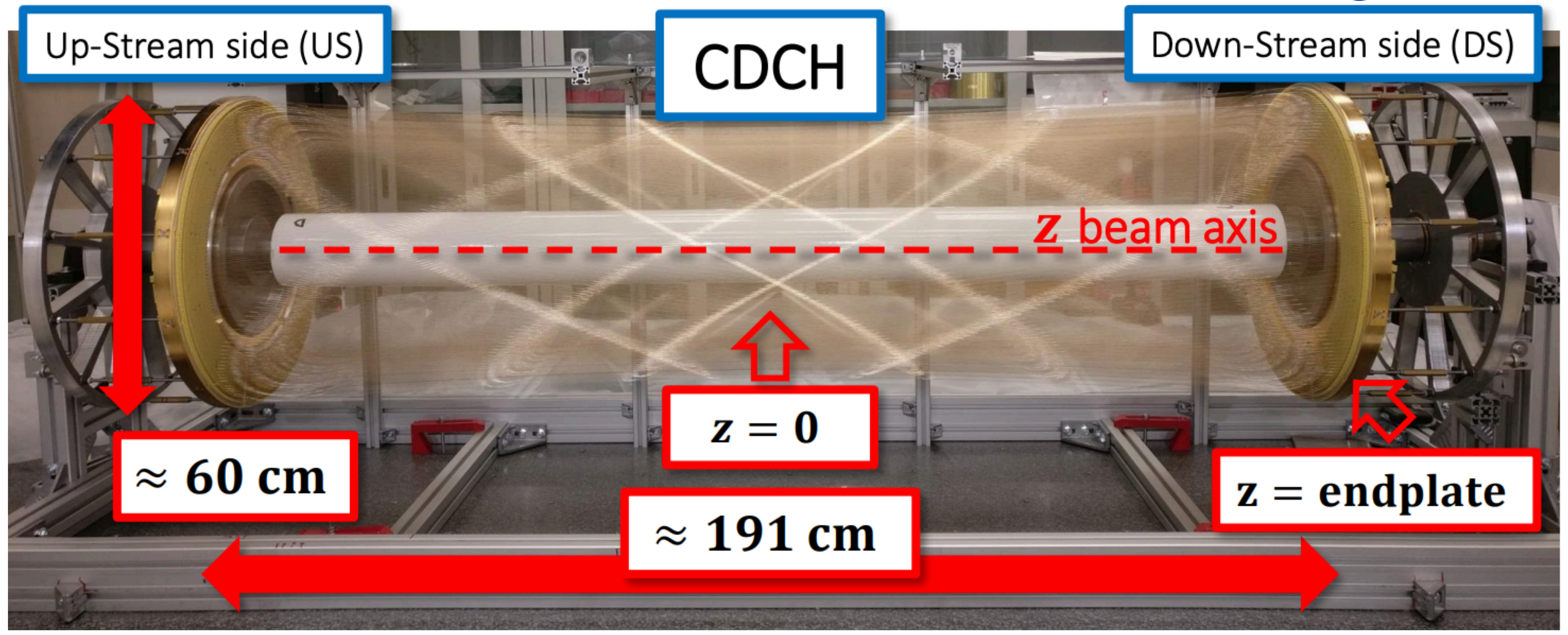
- **Drift chamber experts also well represented**

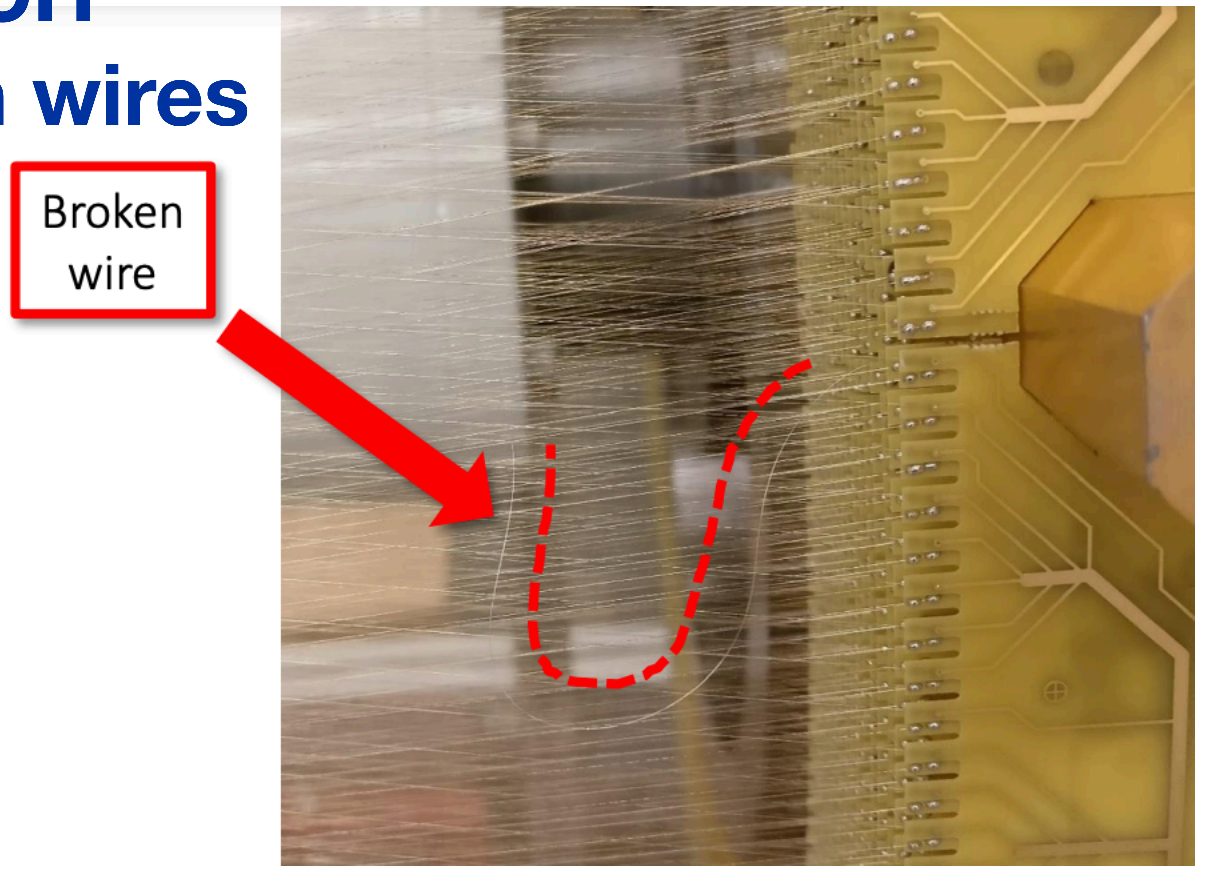
IDEA Drift Chamber



Plan to start the construction of a DCH prototype full lenght, three sectors

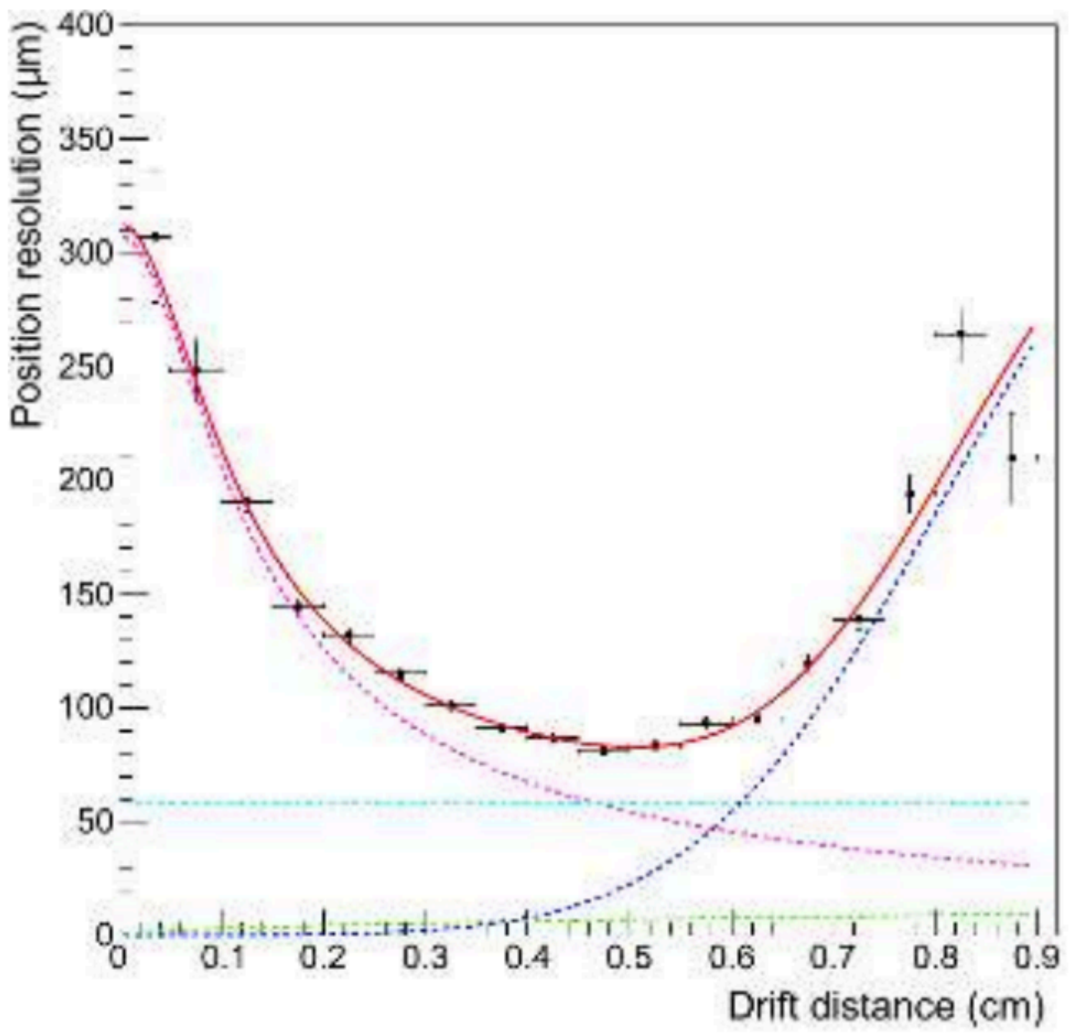
MEG II DCH
Fixing broken wires





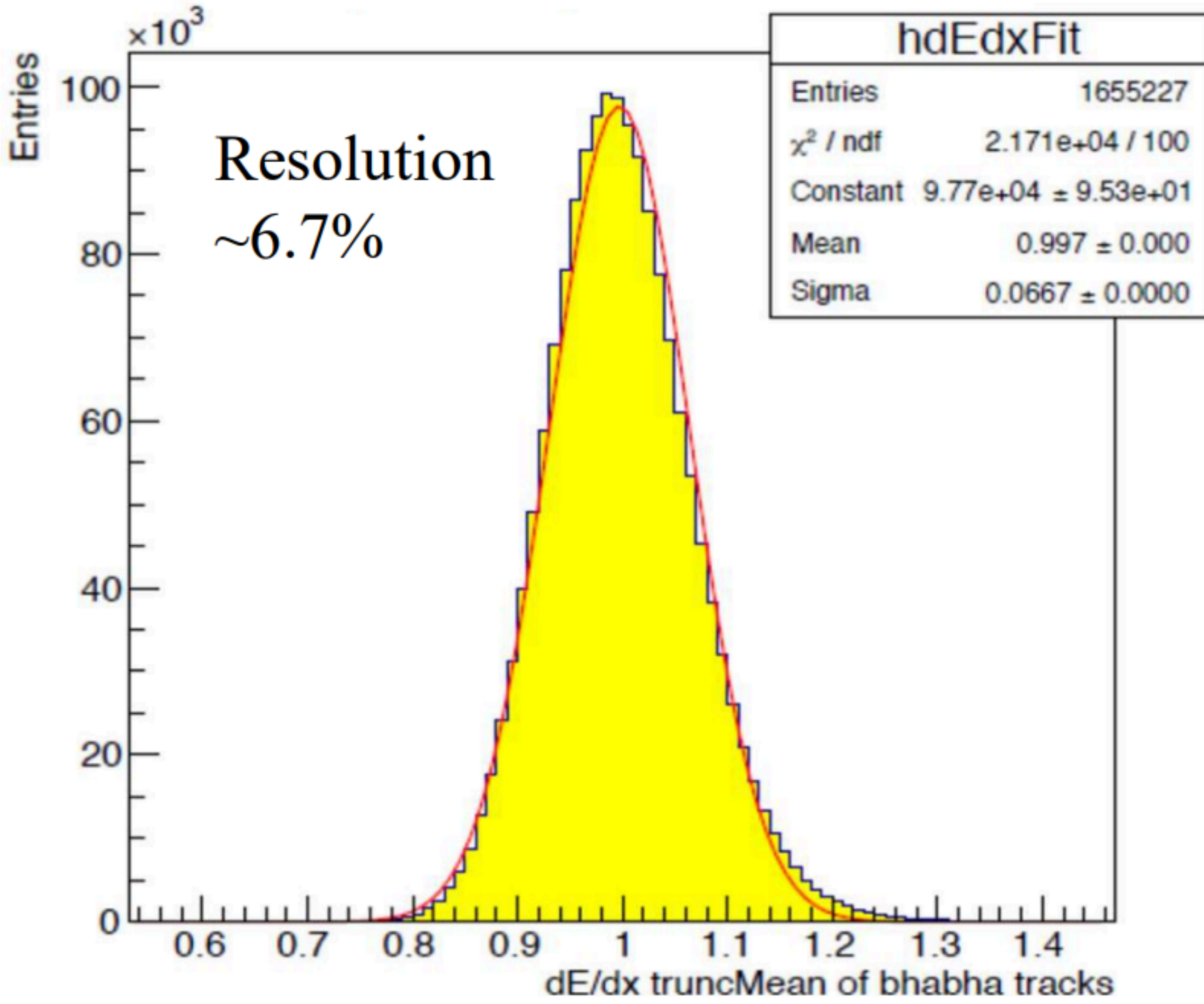
Belle-II Drift chamber

Position resolution



Belle-II
Truncated dE/dx method

Bhabha events



Conclusion

- **Significant interest from the community as showcased in the recent workshop**
  - Michigan, MPI, MSU, UMass-Amherst, Tufts, Harvard, UCI
  - Meetings will be organized by Junjie (Michigan) and Oliver (MPI) and George (BNL).
  - All are welcome to join the growing community!

- **Synergy with drift chamber:**
  - Gas, simulation, electronics
  - Significant contributions from drift chamber experts at the straw tracker workshop

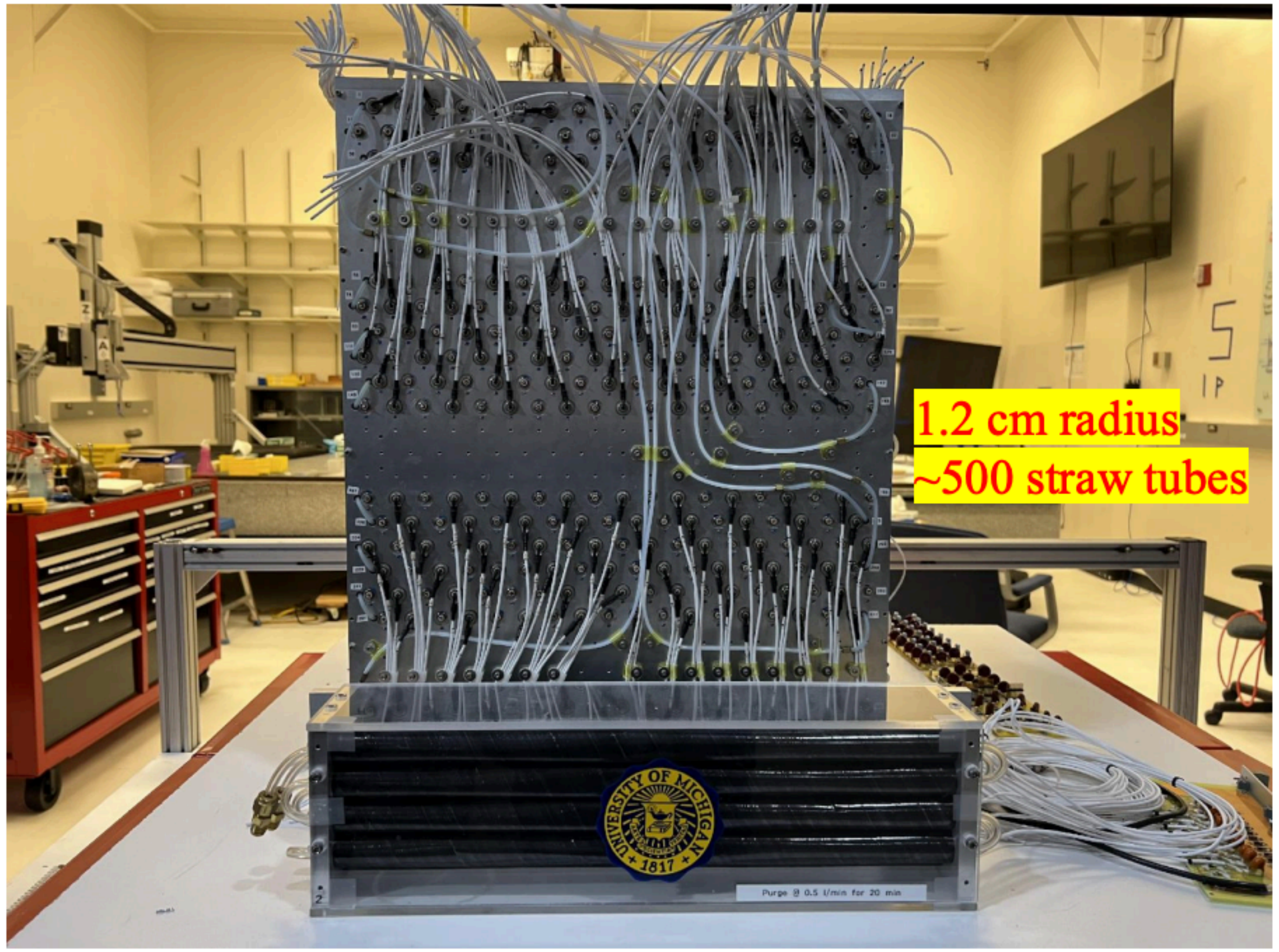
- **Work currently underway:**
  - dd4hep/Geant4 simulation, Garfield simulation, test beam, cosmic-ray studies

- **Next steps:**
  - Add stereo angle in dd4hep geometry, study performance outside of only $\theta = 90^o$, optimize layout
  - Continue Garfield simulation and study PID prospects in different gasses
  - Build new prototype with ~25 straws
  - Modify amplifier and use CAEN waveform digitizer to record waveforms. Develop fast algorithms for cluster finding.
  - With new prototype and readout electronics, perform test beam and cosmic ray studies through 2025

Backup

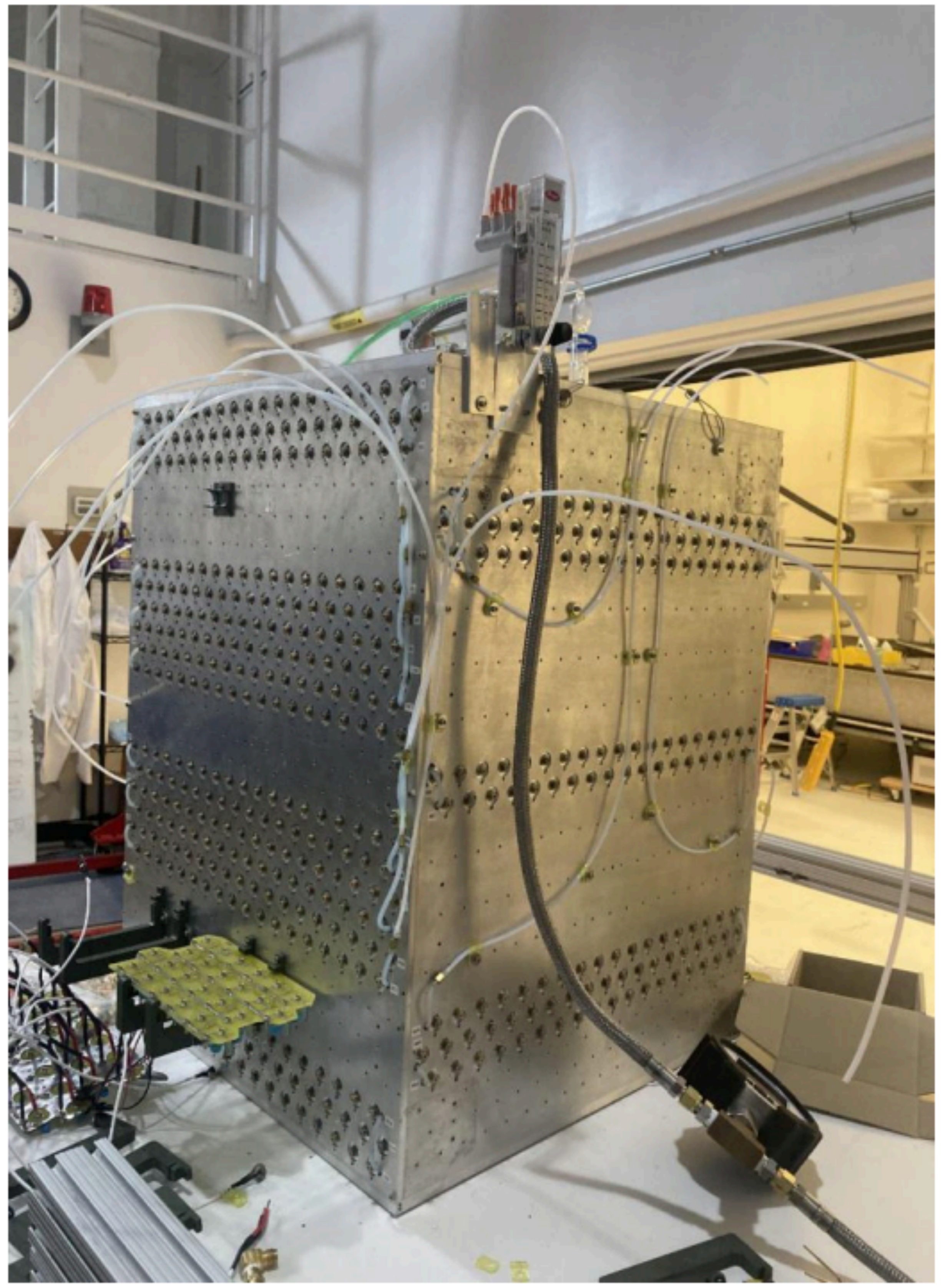
Straw tracker at Michigan

Straw tracker at Michigan



A straw tracker at the UM ATLAS muon detector construction lab

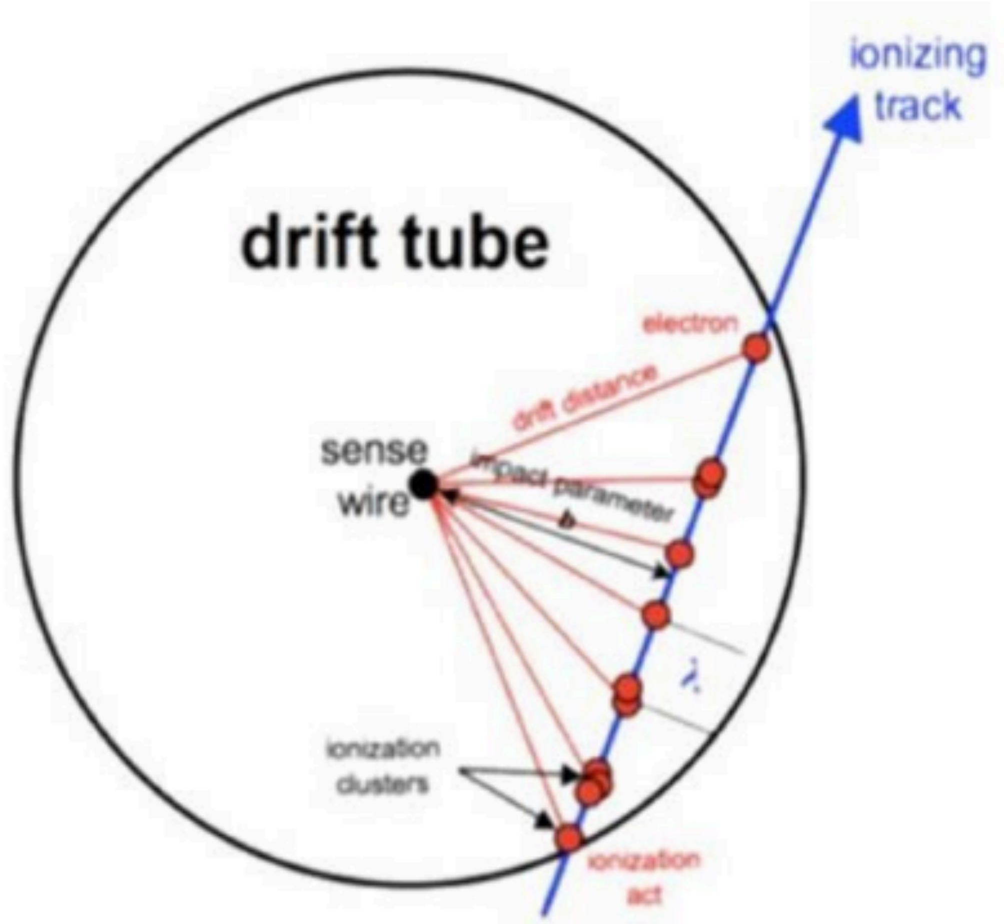
MPI plans to build a straw tracker this fall also



- Only three wires shorten
- Gas flow tested for all straws
- Cables remade so that they can be inserted into the ATLAS MDT hedgehog cards
- MDT mezz, CSM and miniDAQ system ready
- Cosmic ray studies and potential test beam studies at Fermilab

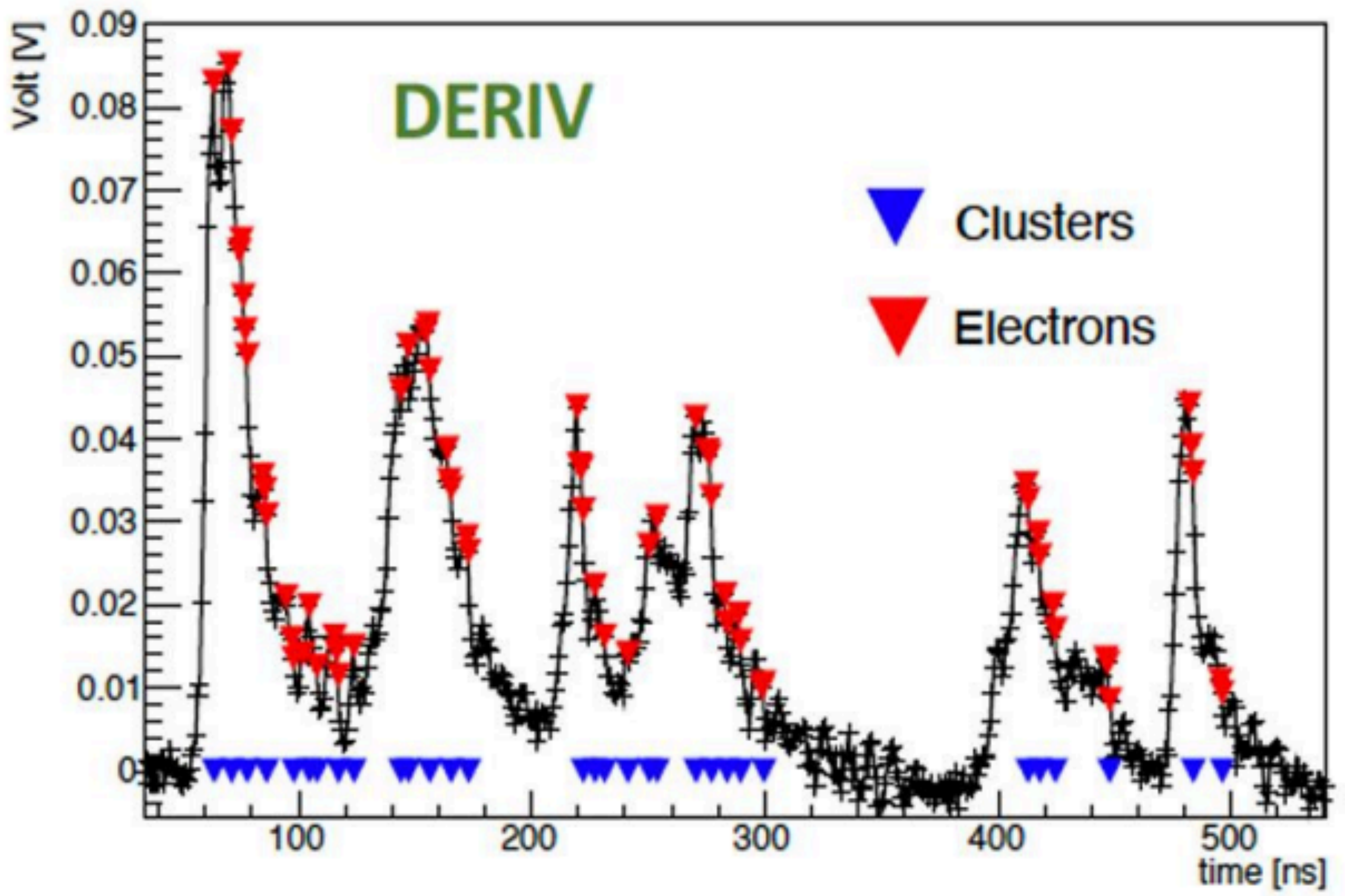
Cluster counting (dN/dx)

- Count number of clusters produced along the track path
- Estimate the resolution to be $\sigma = N_{clusters}^{-0.5}$
  - With n=120 and 15 clusters per sample, then we have $N_{clusters}$=1800 and σ = 2.3%
  - If we assume a cluster-finding efficiency of 80%, we will have σ = 2.6%
  - Roughly ×2 better than the truncated mean method
  - Not a single experiment has implemented this method and used it online yet
  - Lots of studies performed by the IDEA community



N. De Filippis

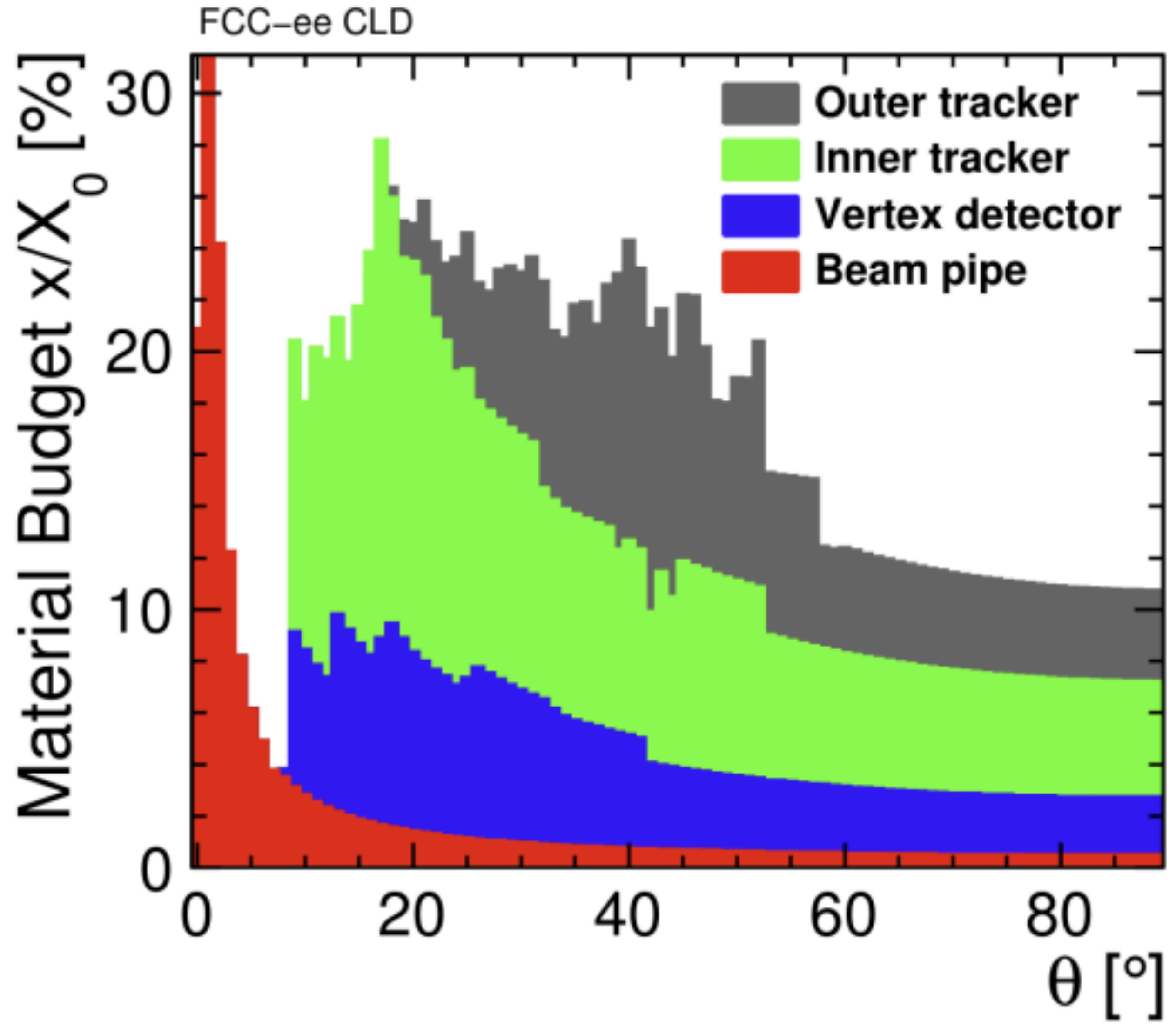
2 cm drift tube Track angle 45°



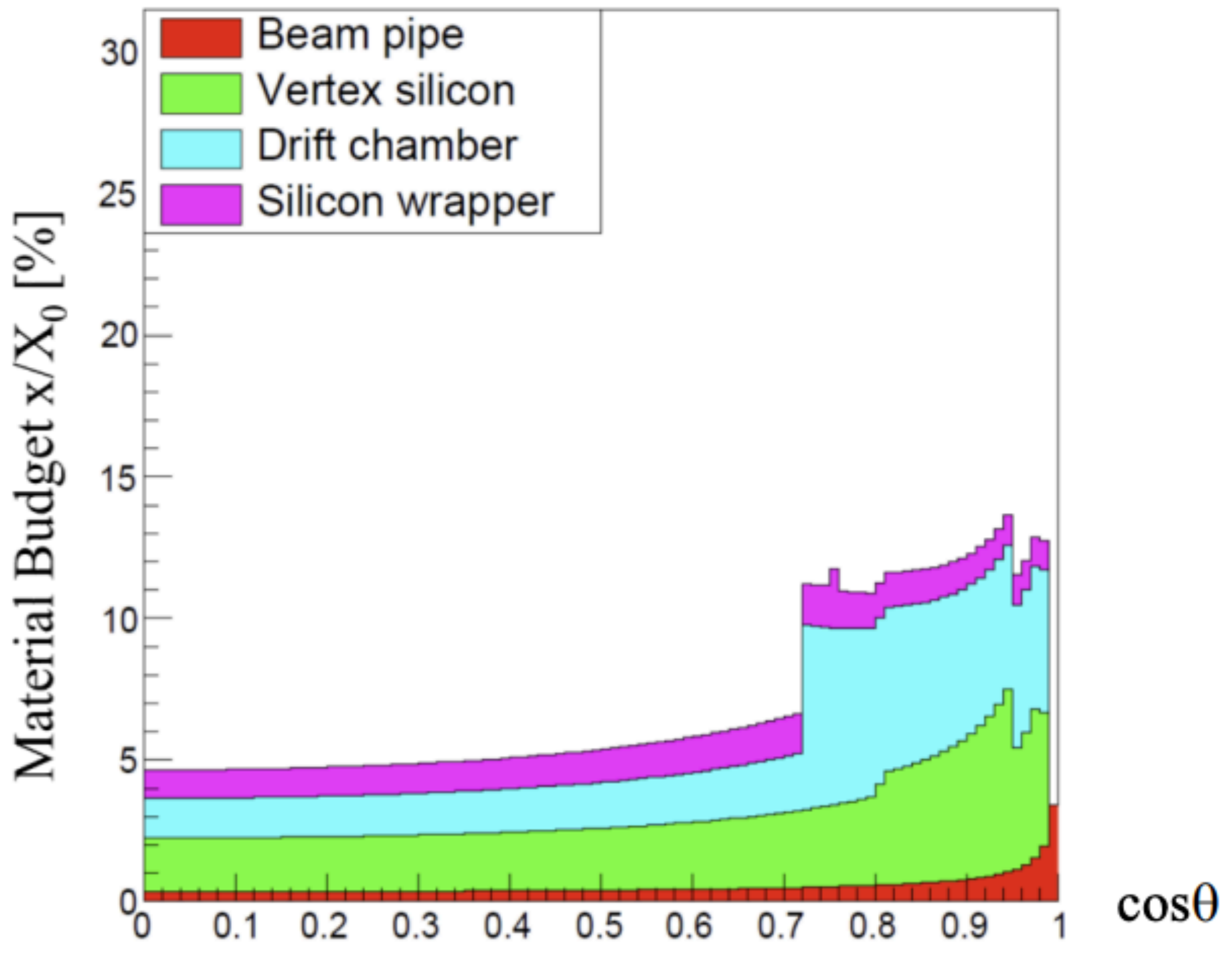
- Finding electron peaks
- Clustering electrons to clusters

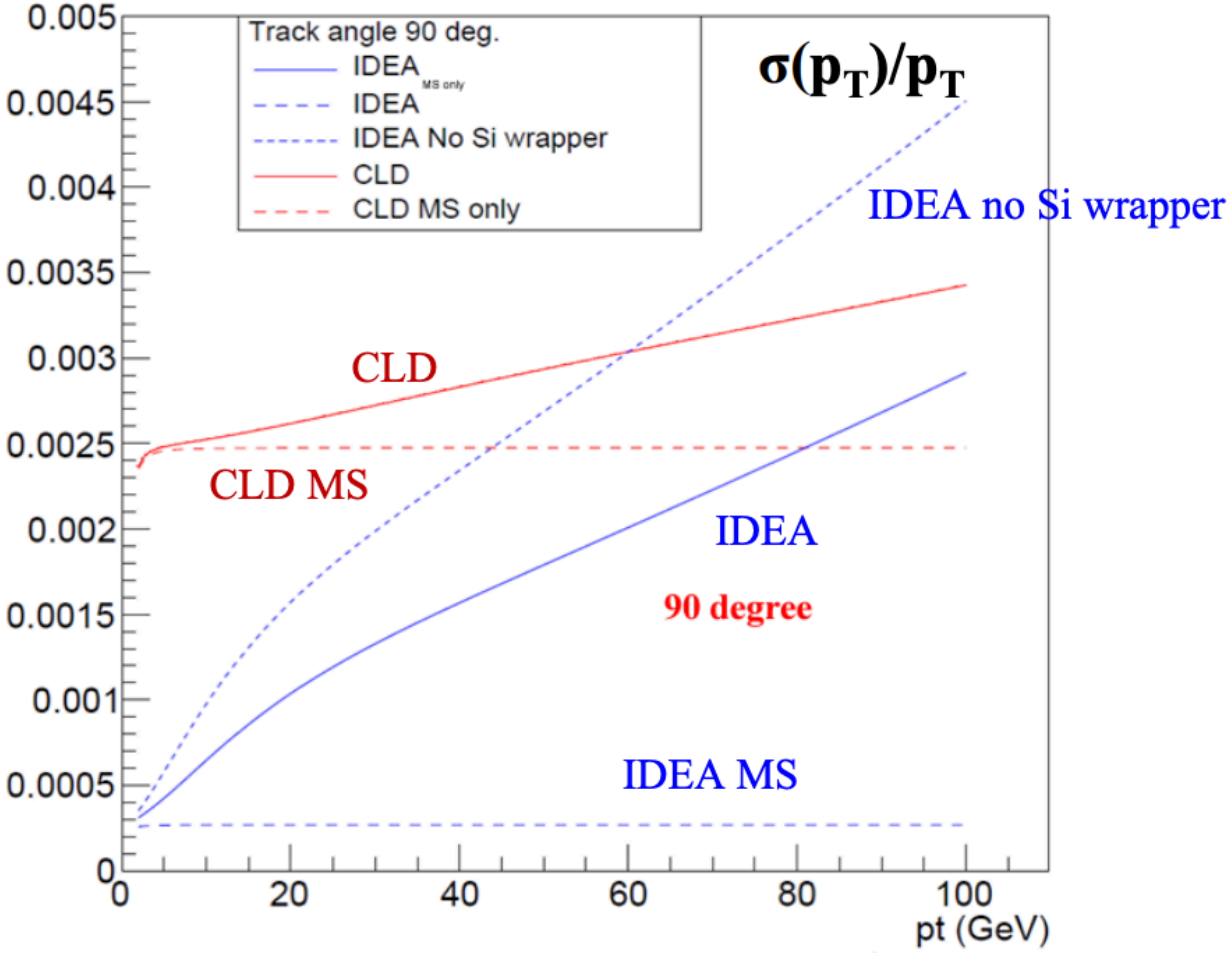
CLD and IDEA concepts

CLD



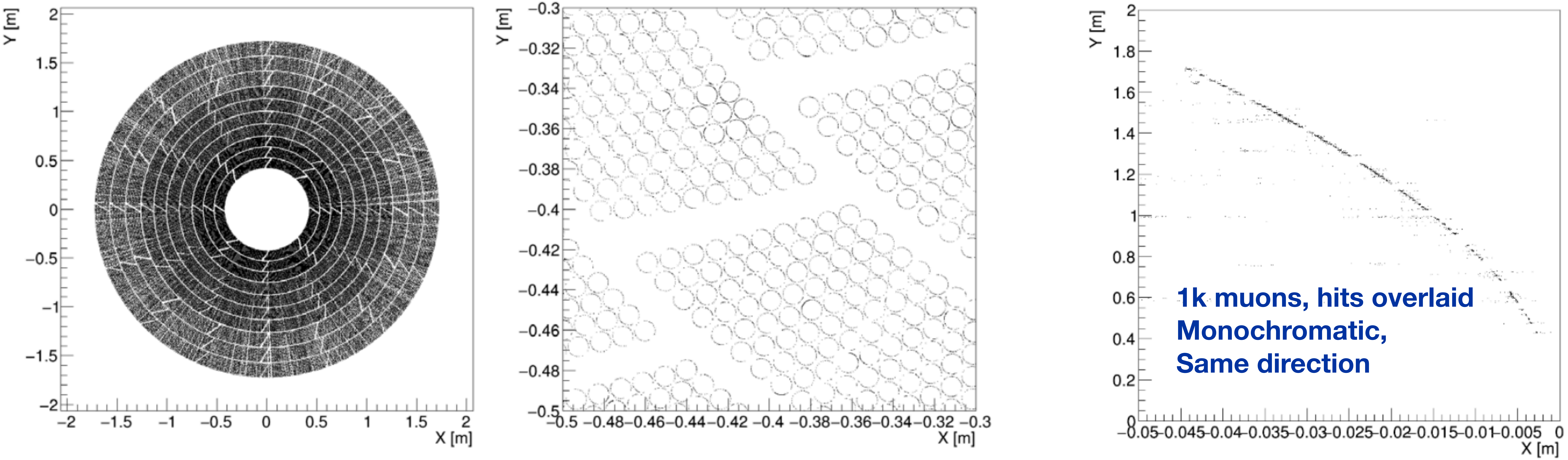
IDEA





Transparent tracker is the key for the momentum resolution
But material budget is not the only parameter that determines the inner tracker's momentum resolution

Dd4hep simulation



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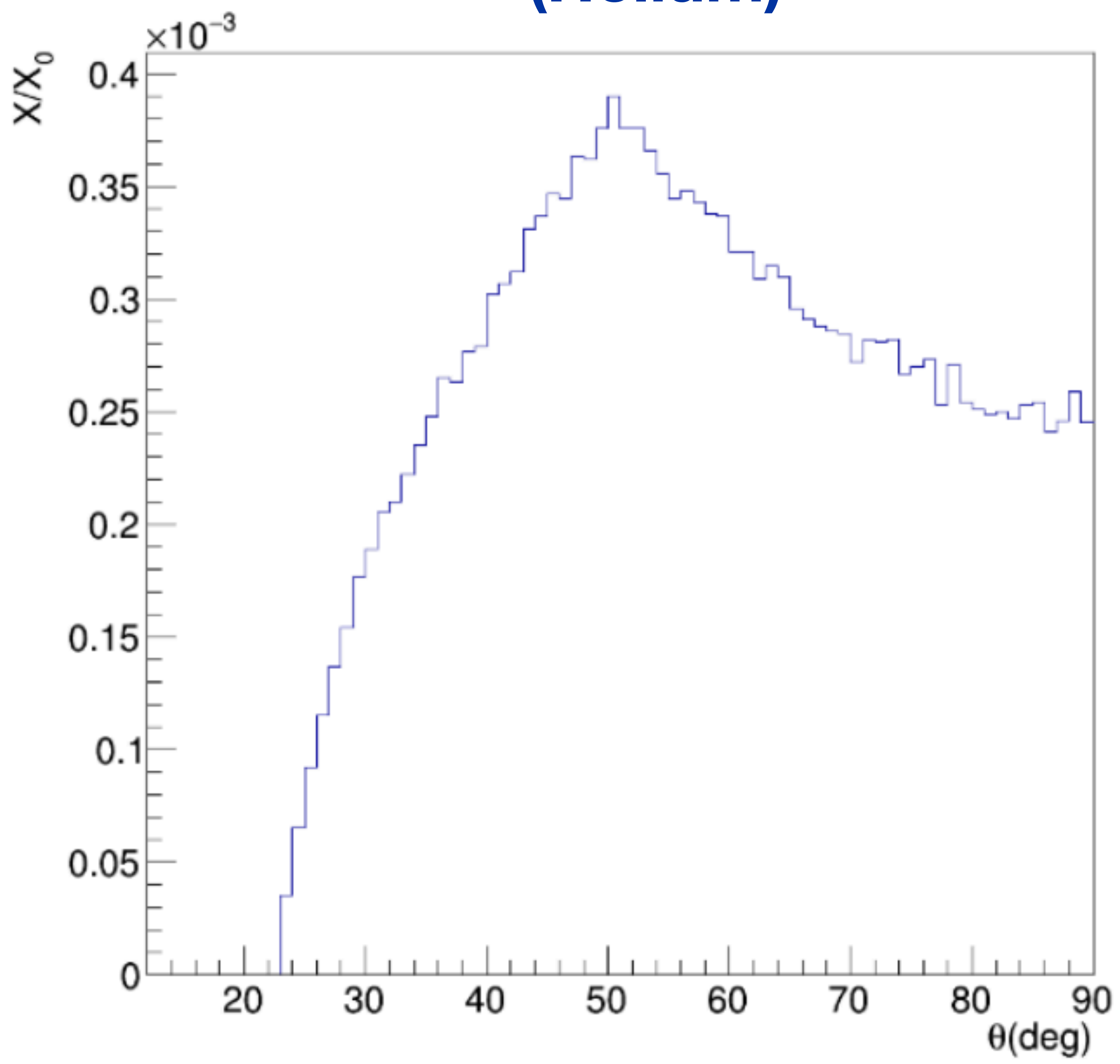
  - 12 micron thick mylar layer
  - Tube size varies for each multilayer. 10 multilayers total. 10 layers per multilayer.

Material budget

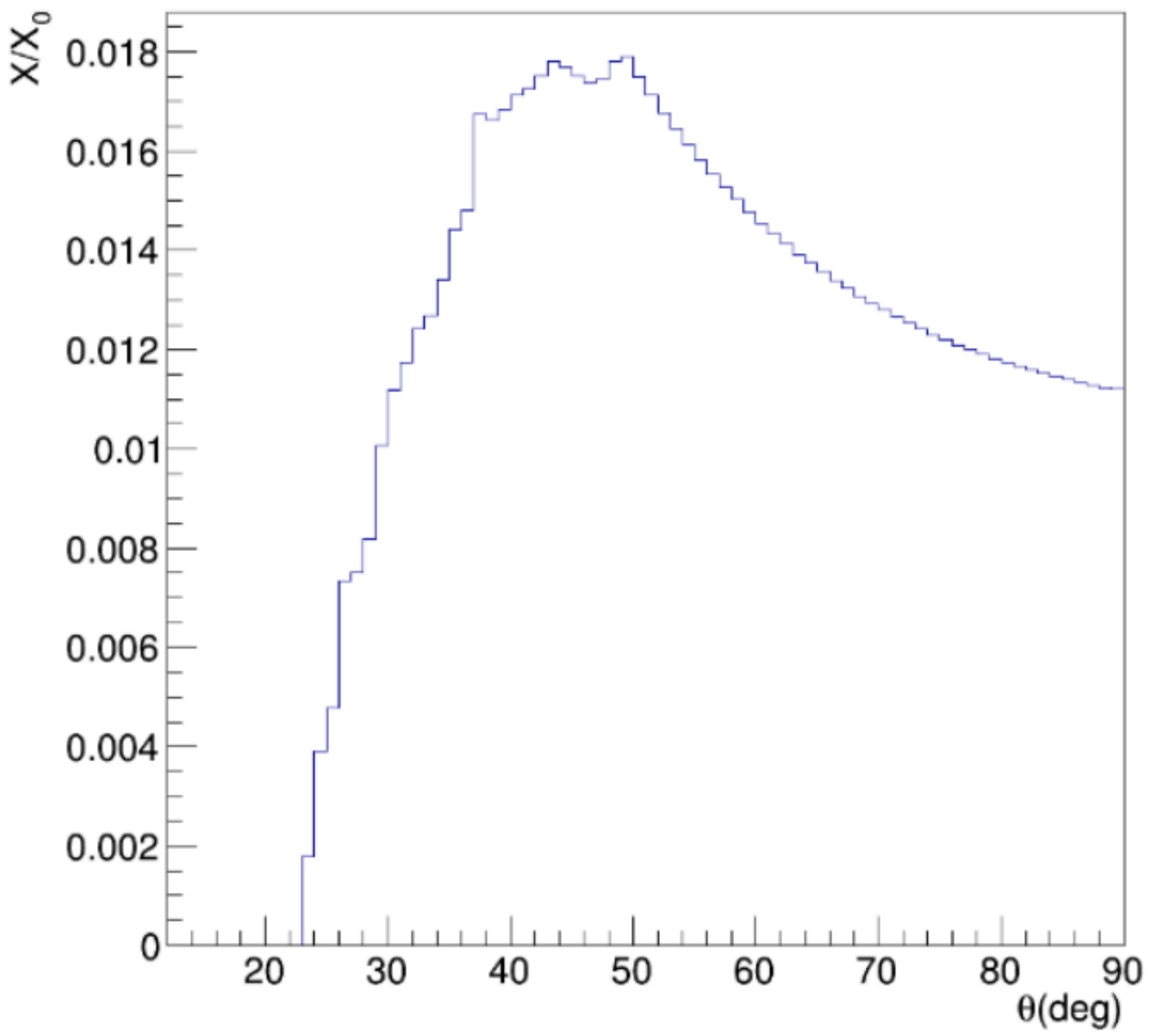
- **Material budget breakdown for individual components**
- **Negligible contribution from Helium and Aluminum coating. Mostly from Mylar wall.**

(Helium)



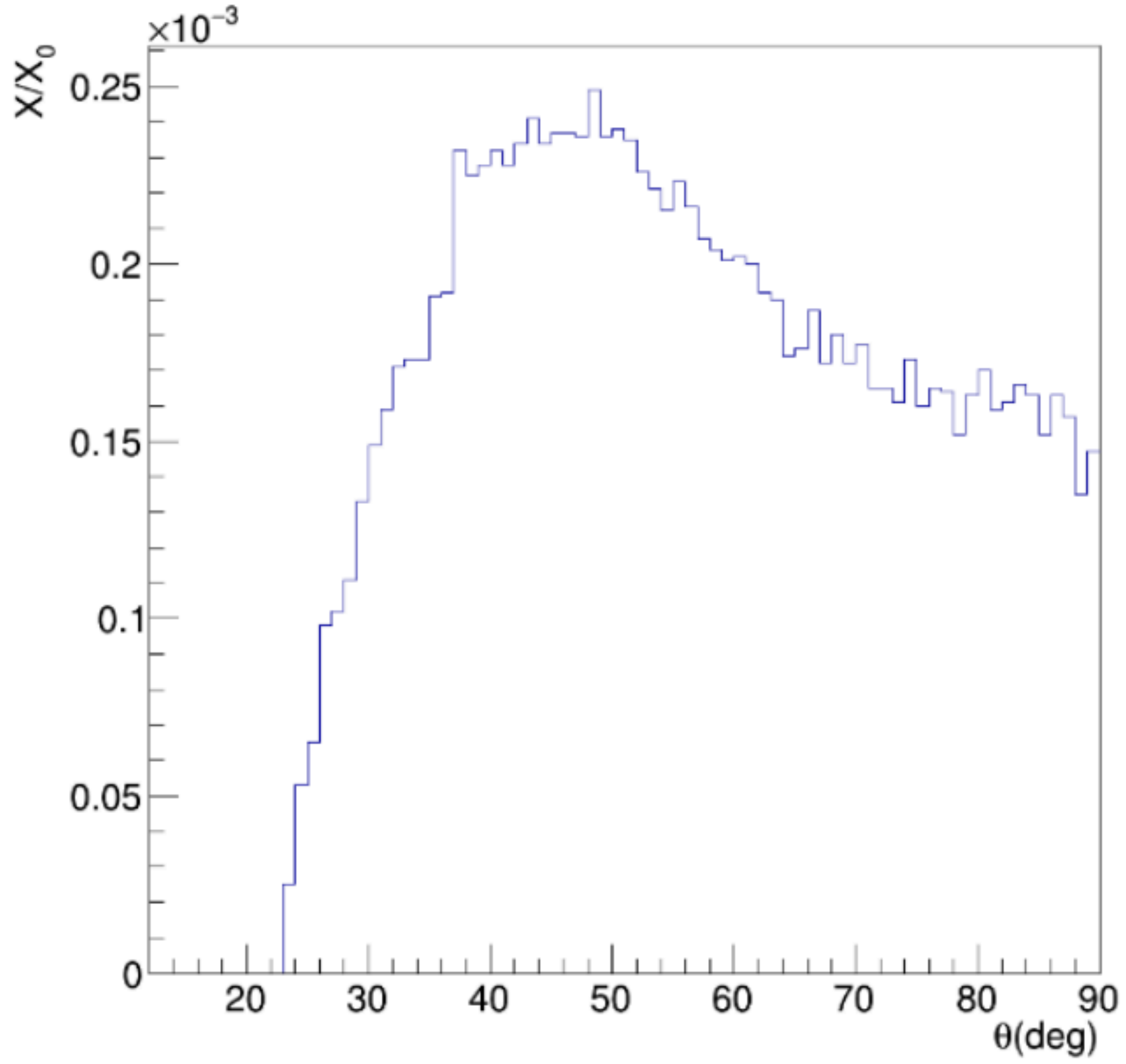
He

(12 micron Mylar wall)



Mylar

(50 nm Al coating)



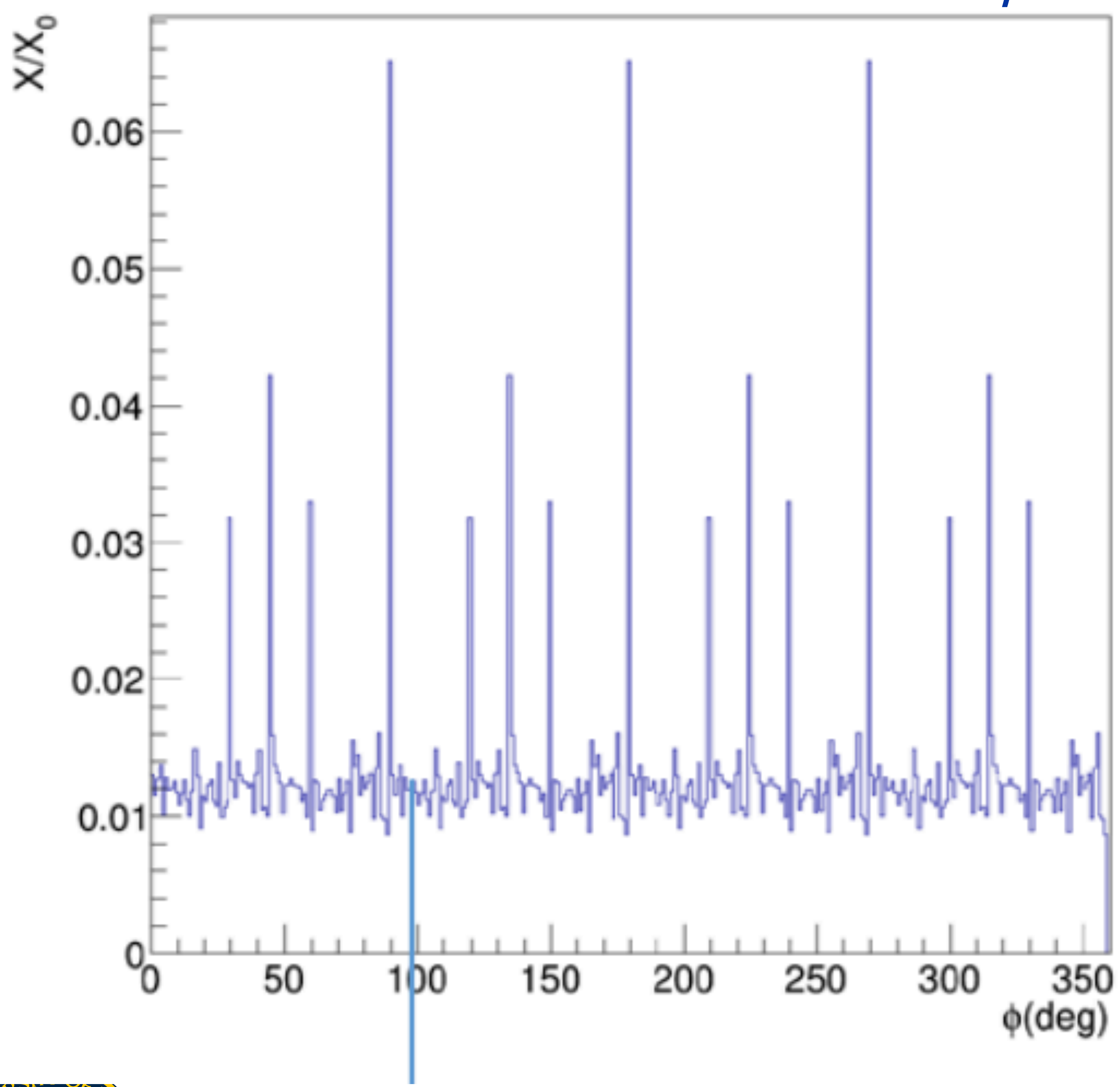
Al

Material budget

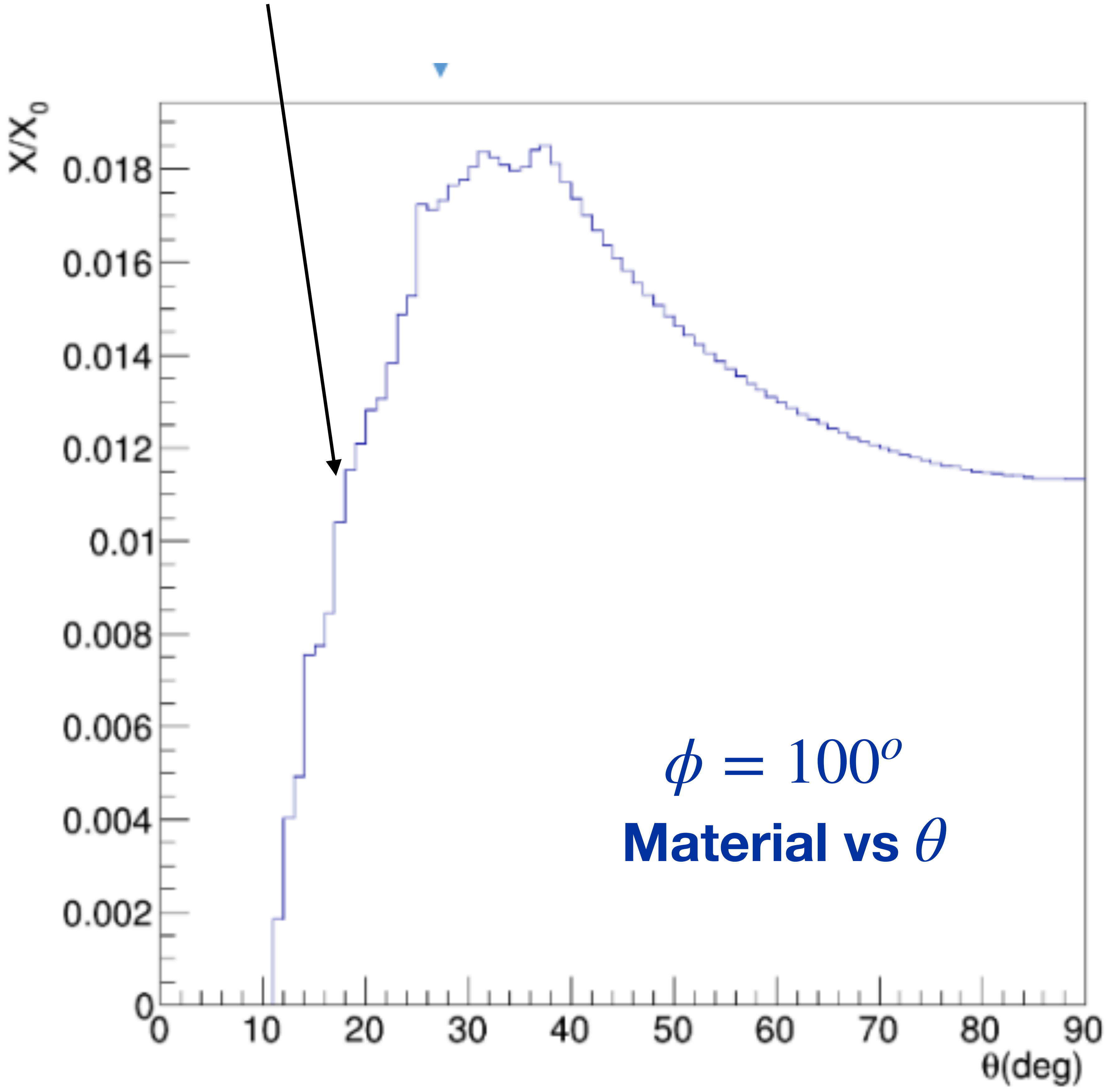
- **Nominal geometry as described has 1.2% radiation length at $\theta = 90^o$**
- **Spikes are from events where the muon passes through the Tungsten wire**
- **Note: no endplate simulation**

$\theta = 90^o$

Material vs ϕ



No endplate simulation



$\phi = 100^o$

Material vs θ

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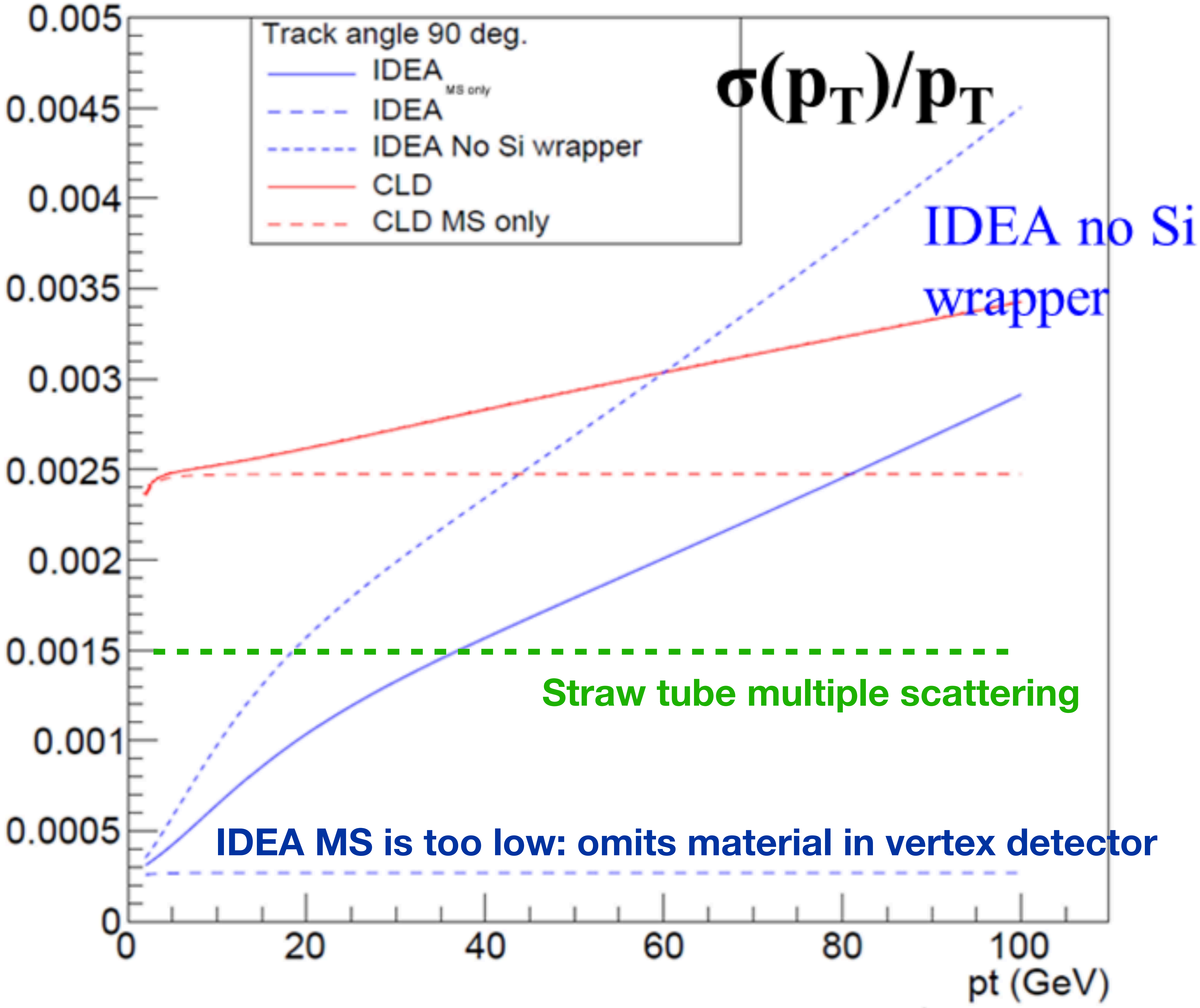
Comparison with other detector concepts

- **Showing CLD and IDEA concepts along with our concept: IDEA but with drift chamber replaced with straw tracker**

- **Theoretical calculation of multiple scattering**
  - Assuming relatively even material per layer
  - Assuming relativistic muons ($\beta = 1$)

$$\left(\frac{\sigma_{p_T}}{p_T}\right)_{\textbf{scat}} = \frac{0.0136}{0.3 L_p B}\sqrt{x/X_0} = 0.15\,\%$$

  - Depending on number of straw tubes this could change by 20-30%. Probably not lower than 0.1%



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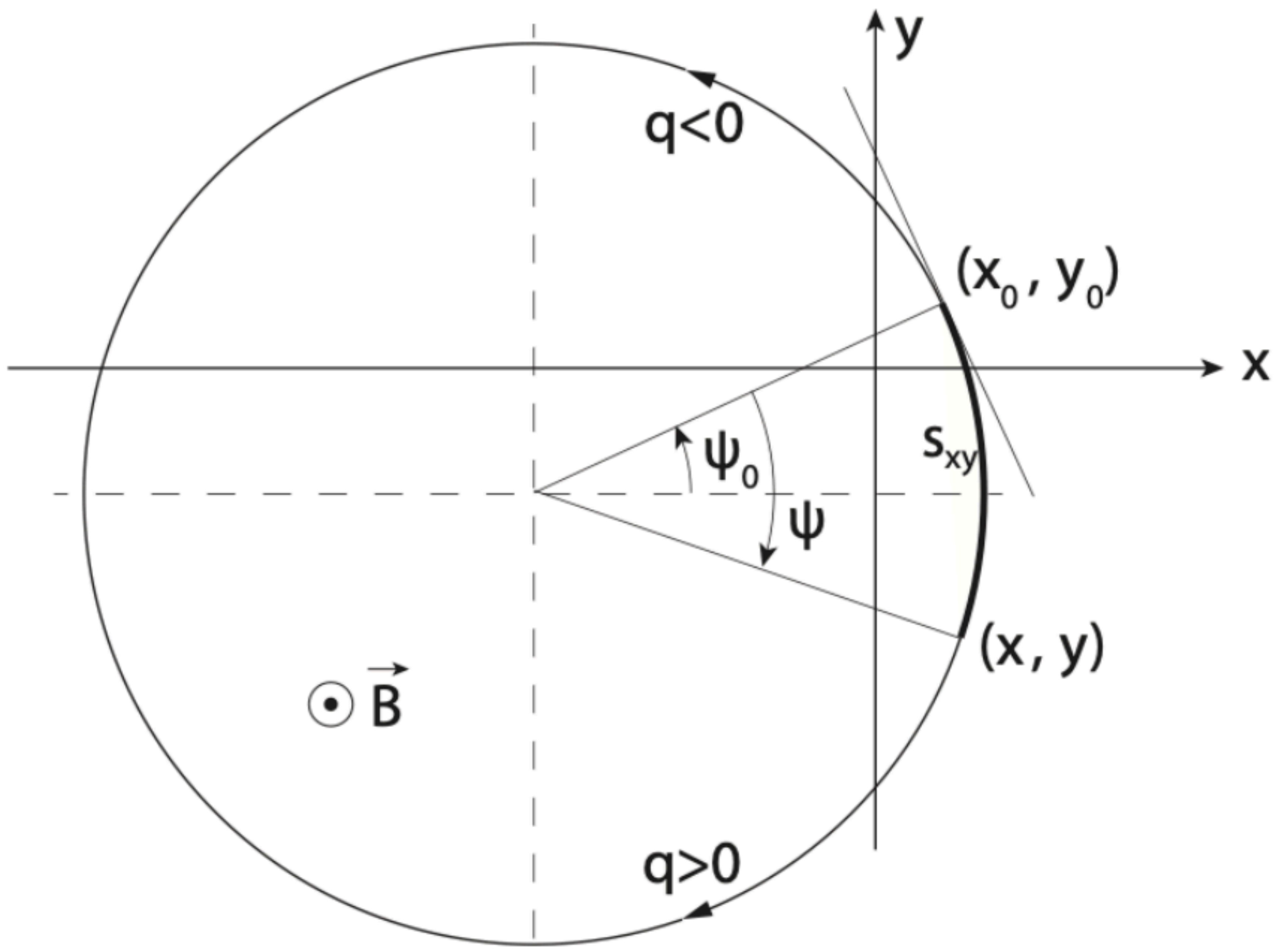
Tracking

- **The simplified simulation we developed performs tracking in 2D**
  - Simulate monochromatic muons initially pointed in the positive y dir.
  - Vary muon energy to measure resolution as a function of p_T at $\theta = 90^o$
- **Rather than 6 parameters only 4 are required**
  - (x_0, y_0) initial position
  - Initial p_T
  - Initial angle ψ_0
  - Excluded for 2D tracking: z_0, θ
- **Intrinsic detector resolution:**
  - Smear truth hits (from Geant4) in various detector subsystems by gaussian distributions:
    - Straw tube: 120 microns
    - Pixel: 5 microns
    - Silicon wrapper: 15 microns



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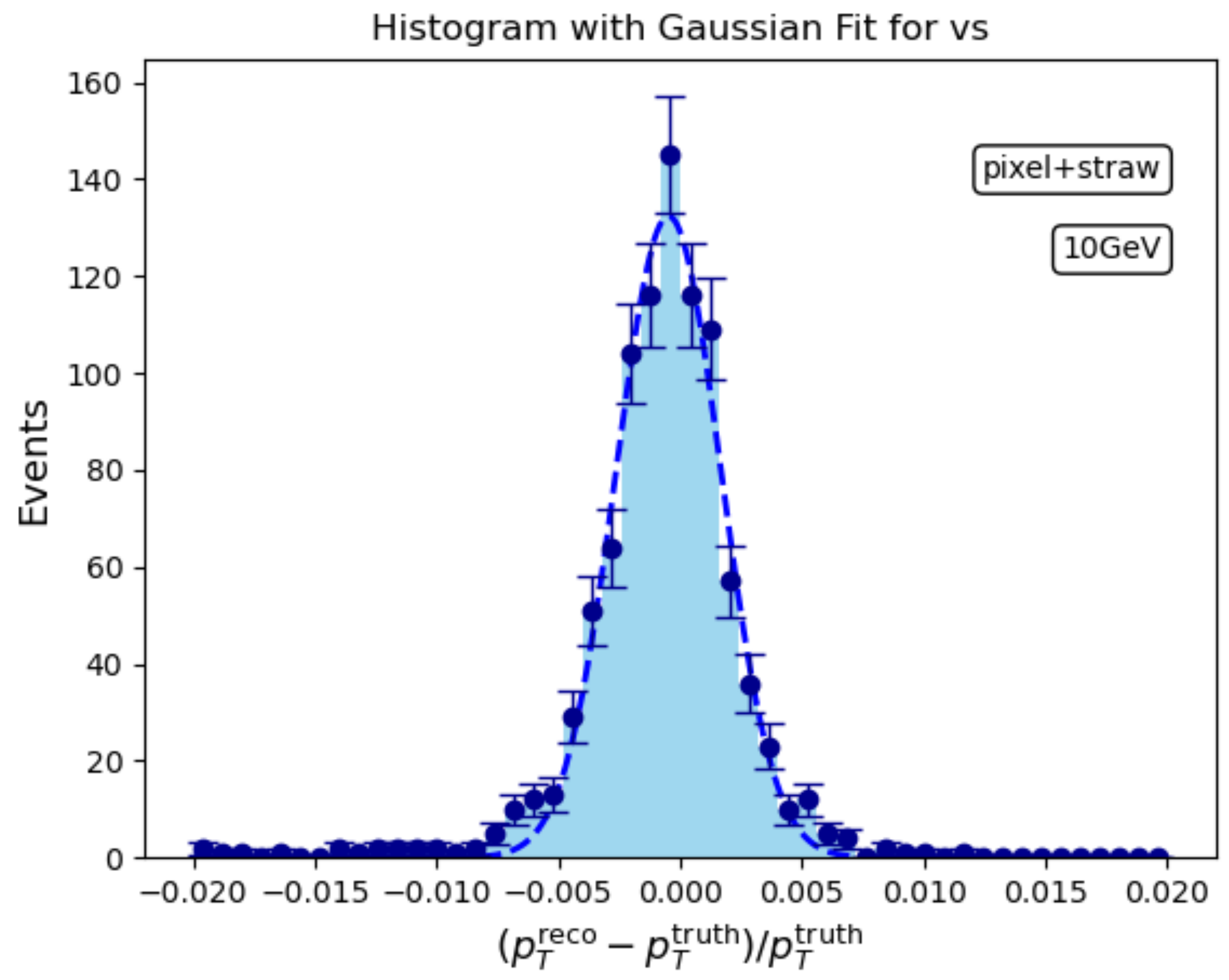
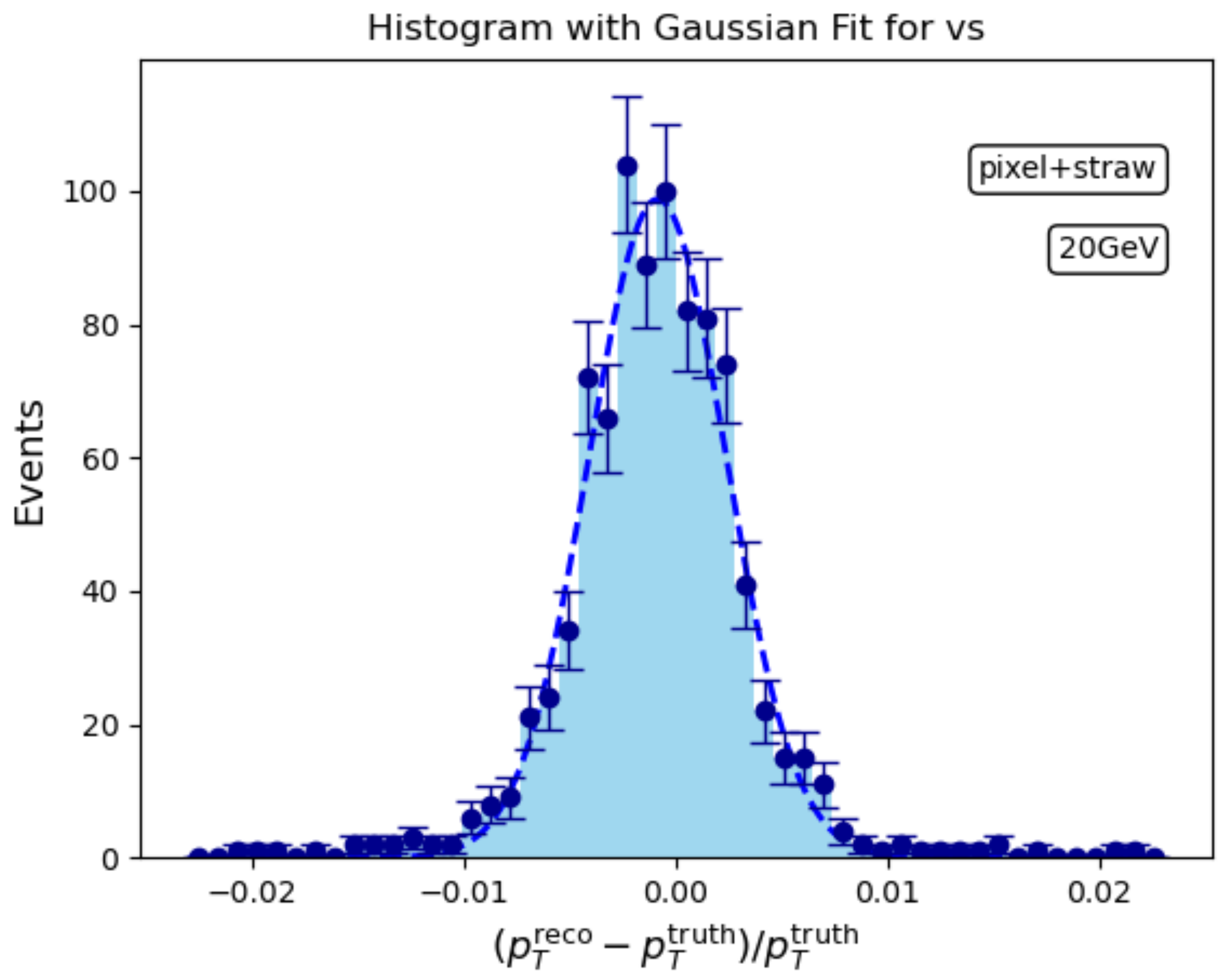
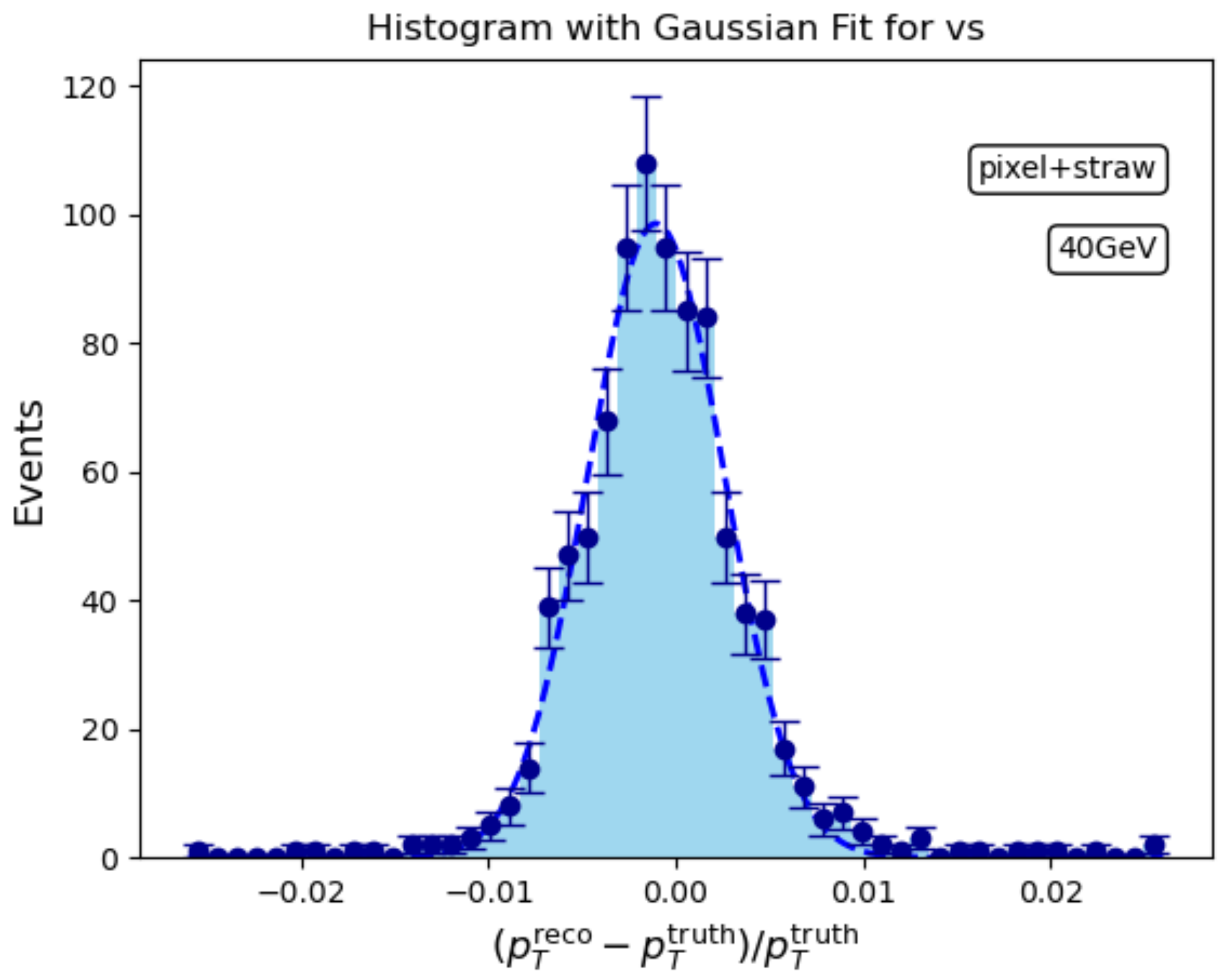
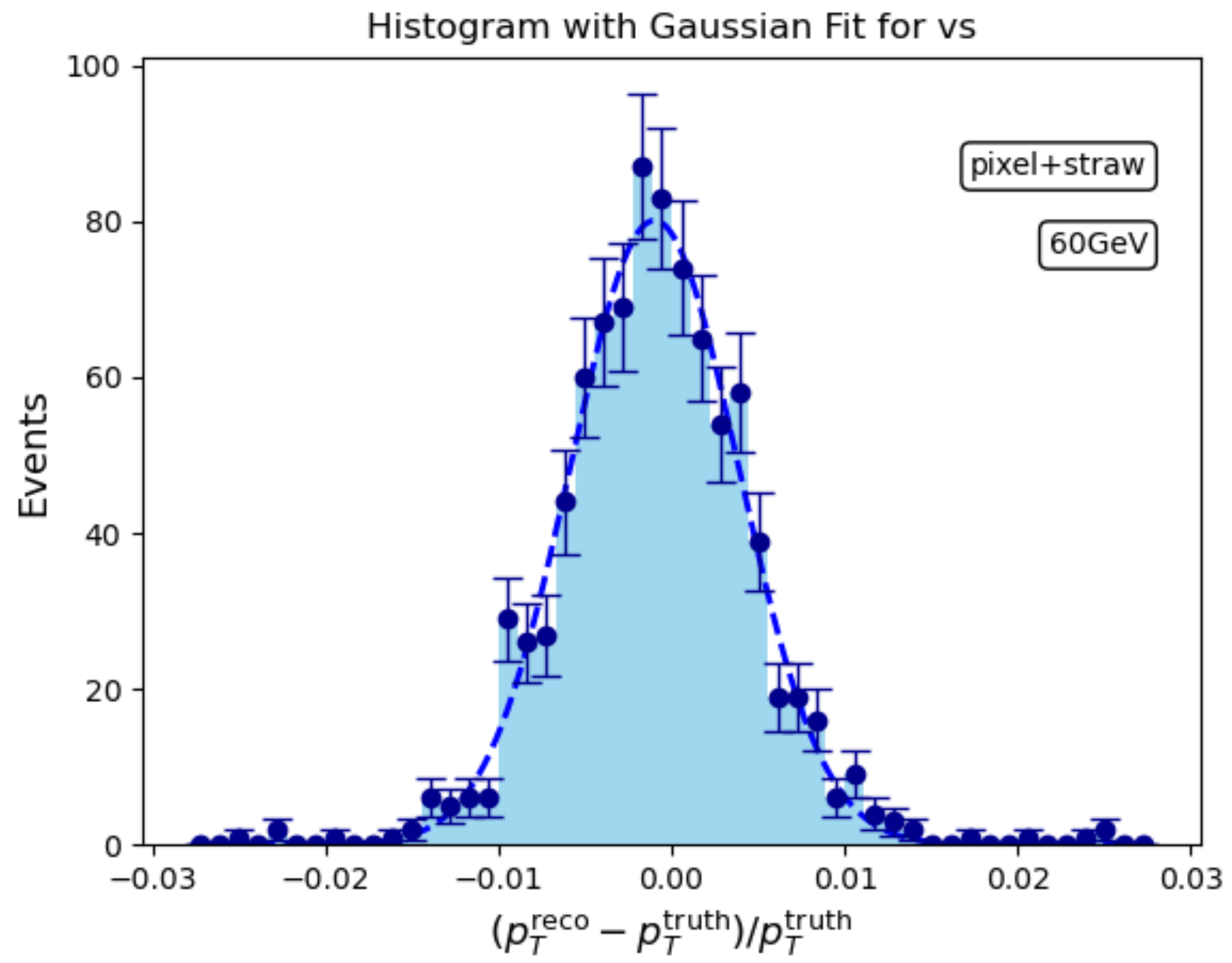
Tracking results

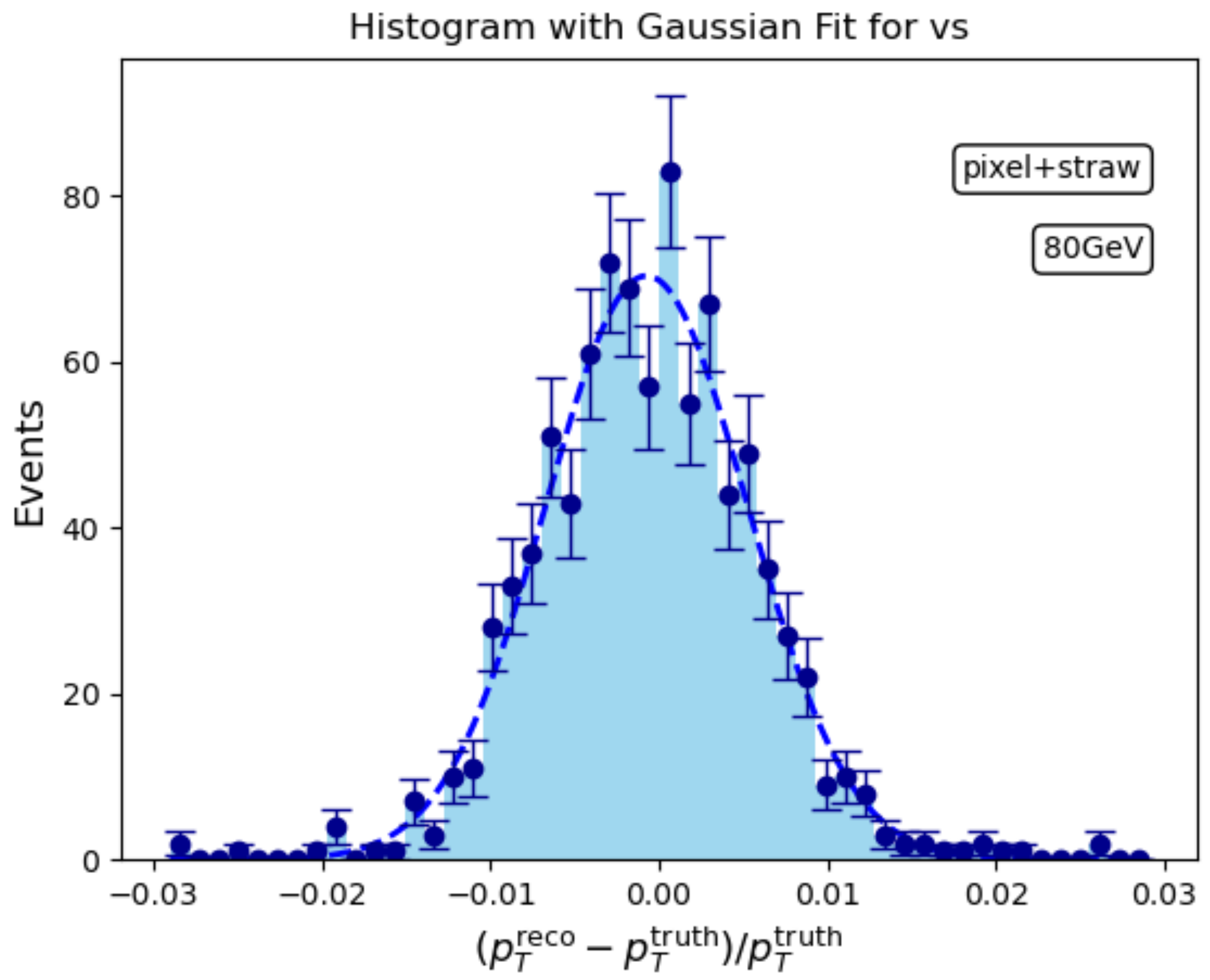
- **Configuration using vertex detector + straw tubes (exclude silicon wrapper)**
- **Individual gaussian fit validation shown. Each histogram is 1000 monochromatic muons**

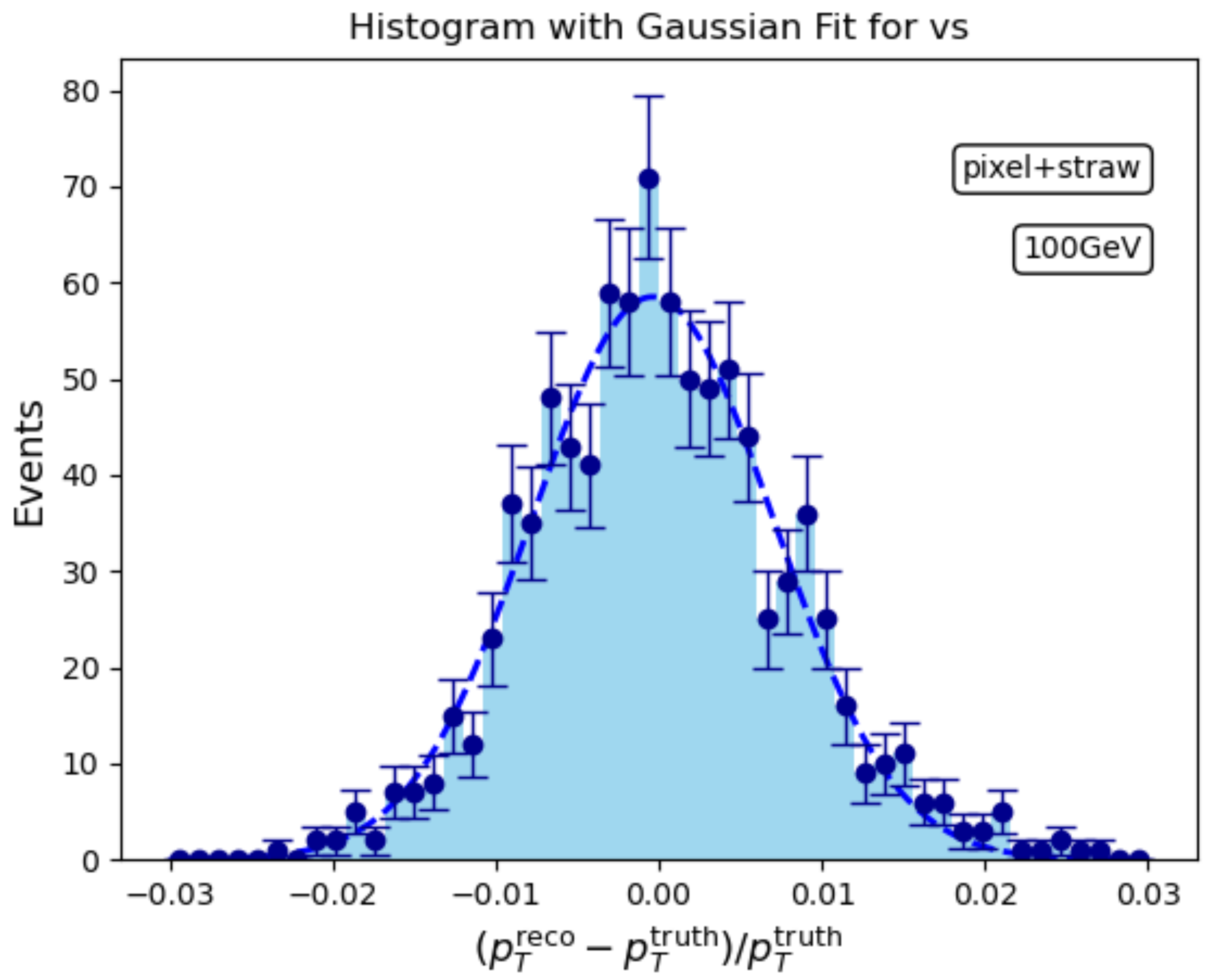






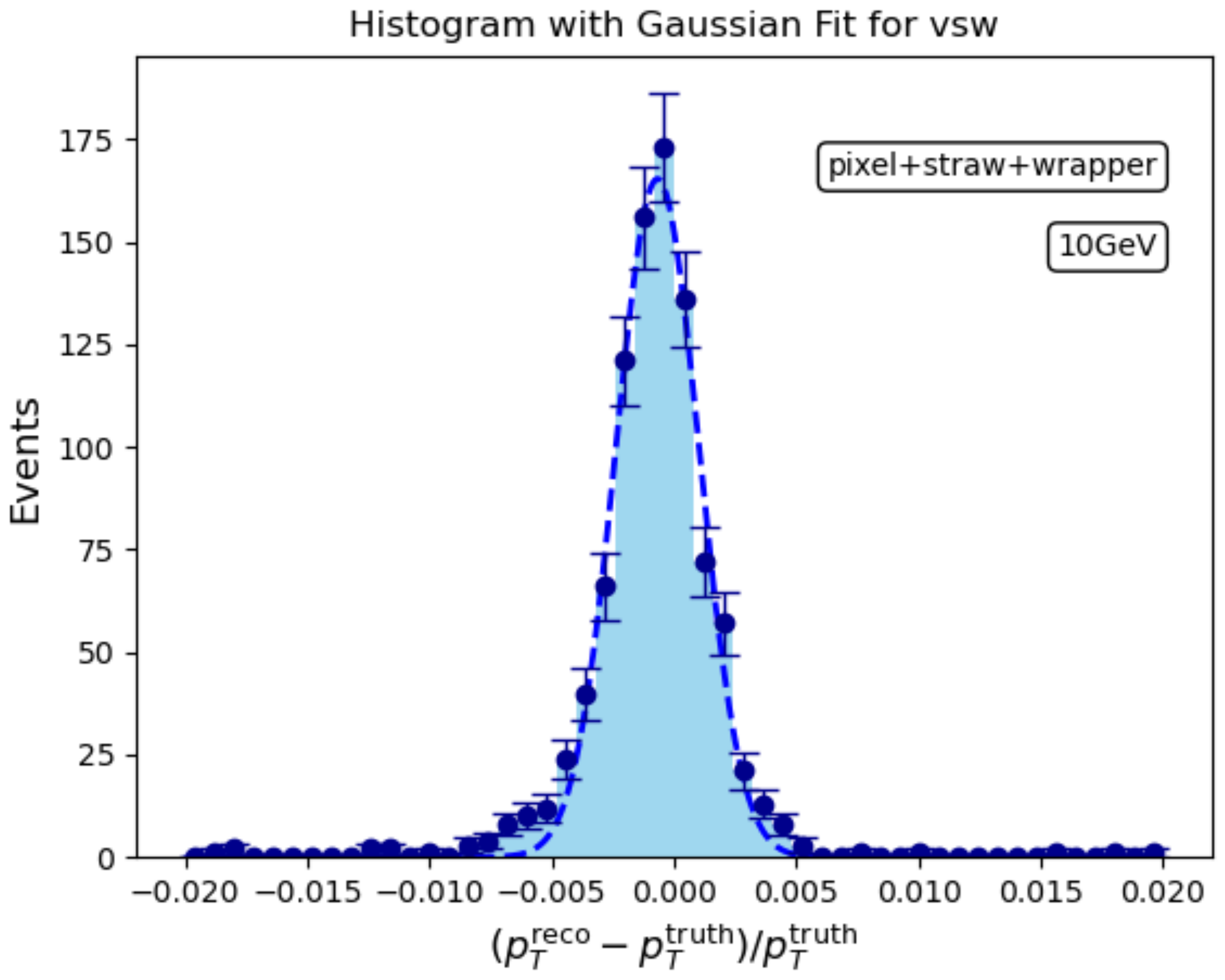


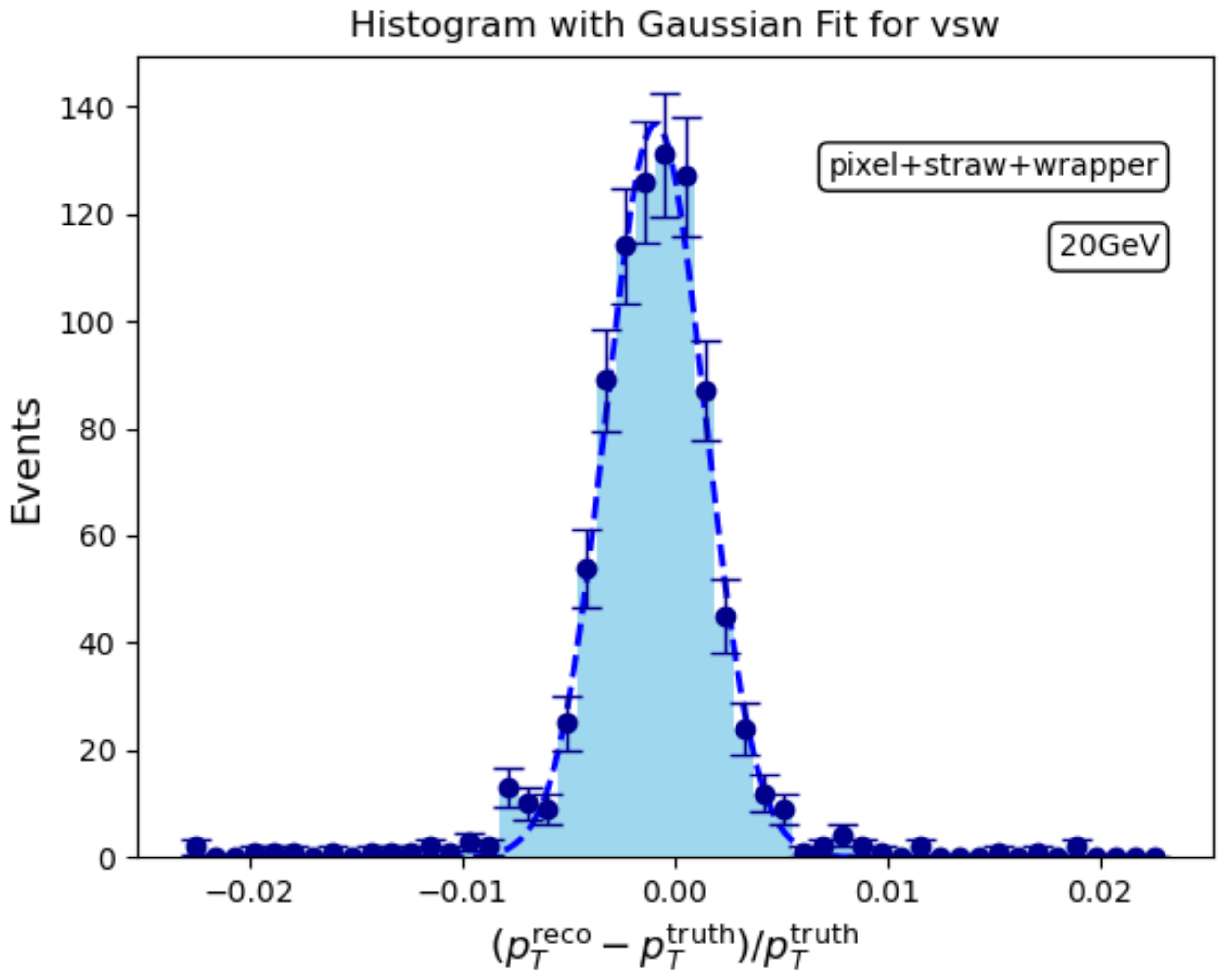


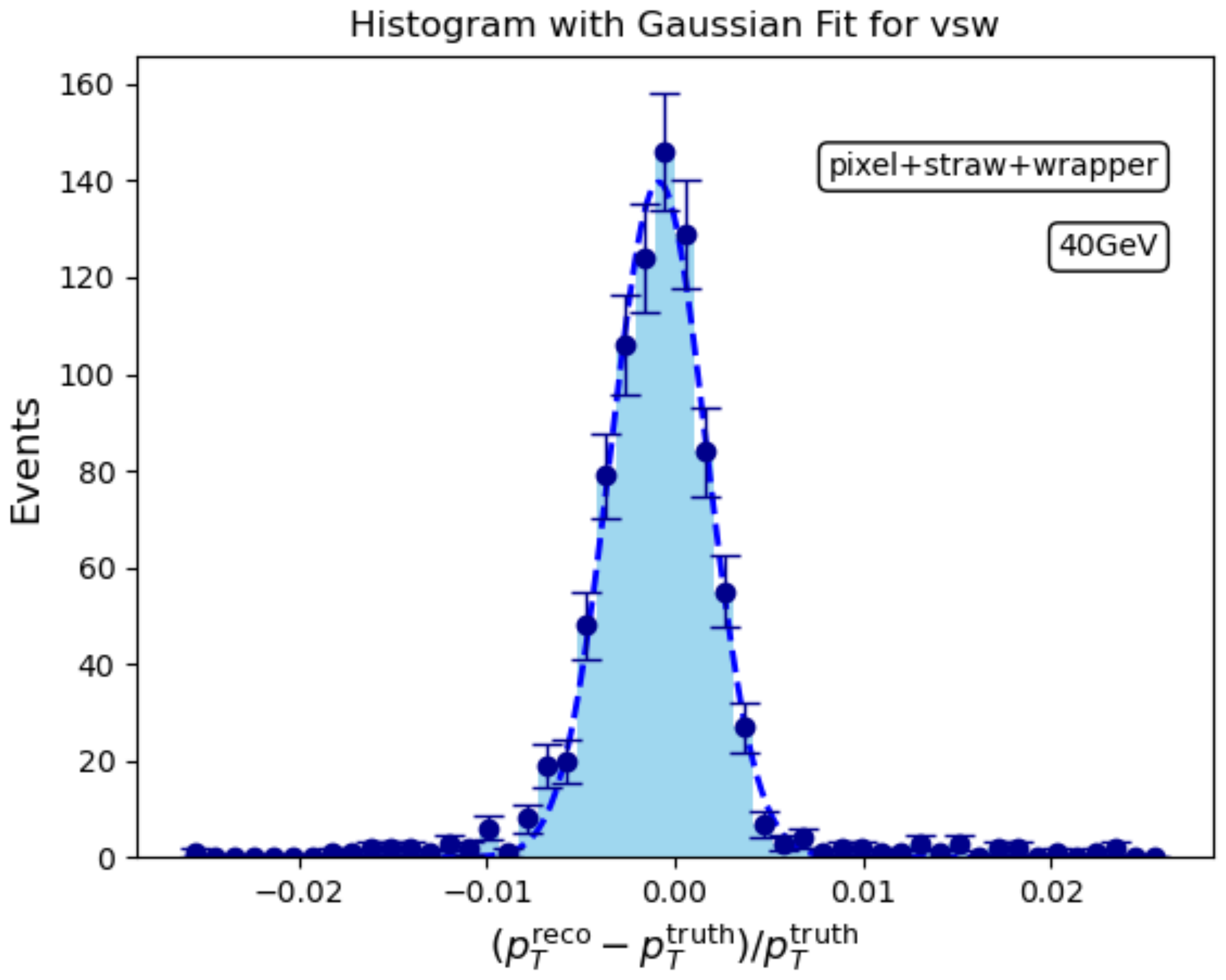


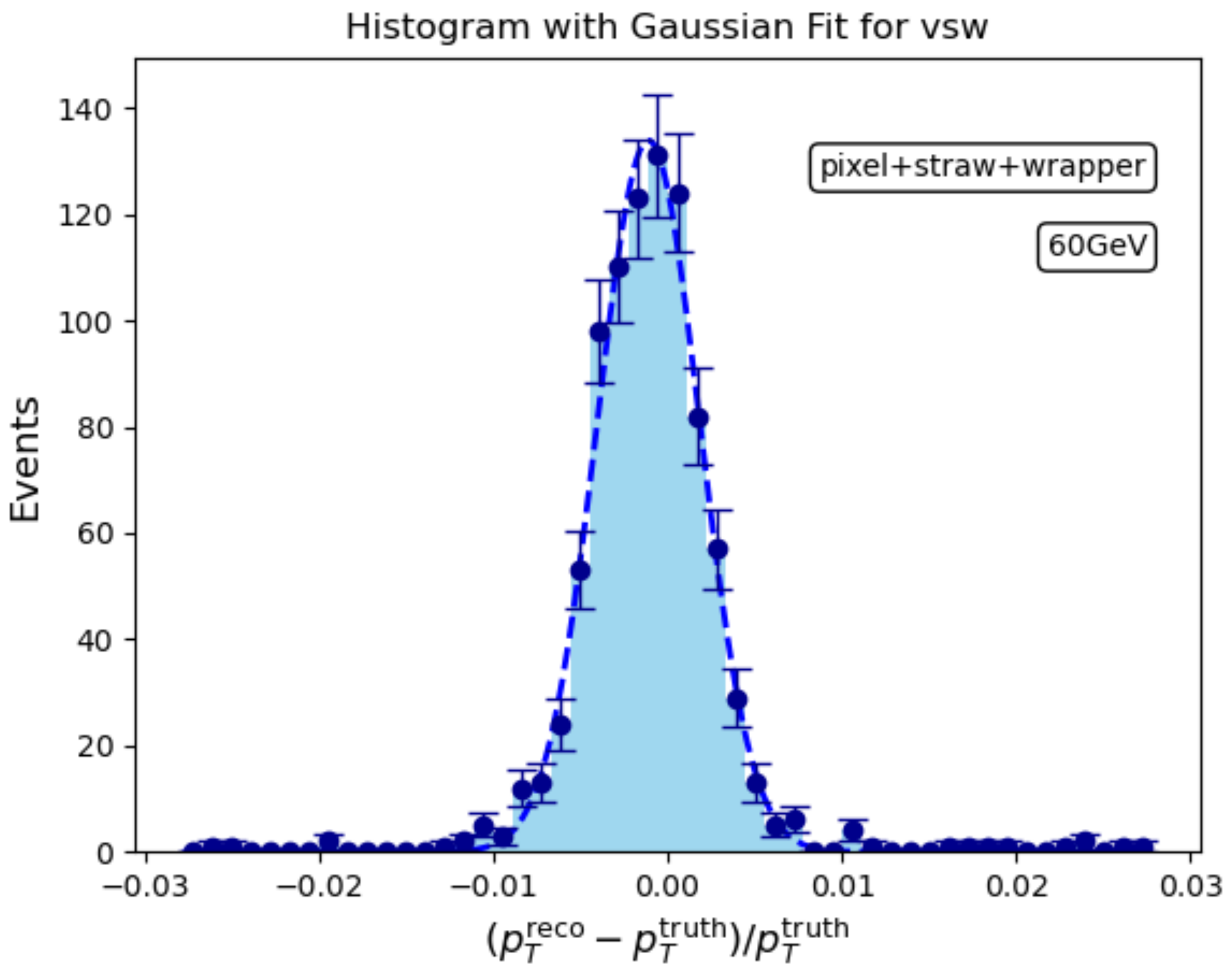
Tracking results

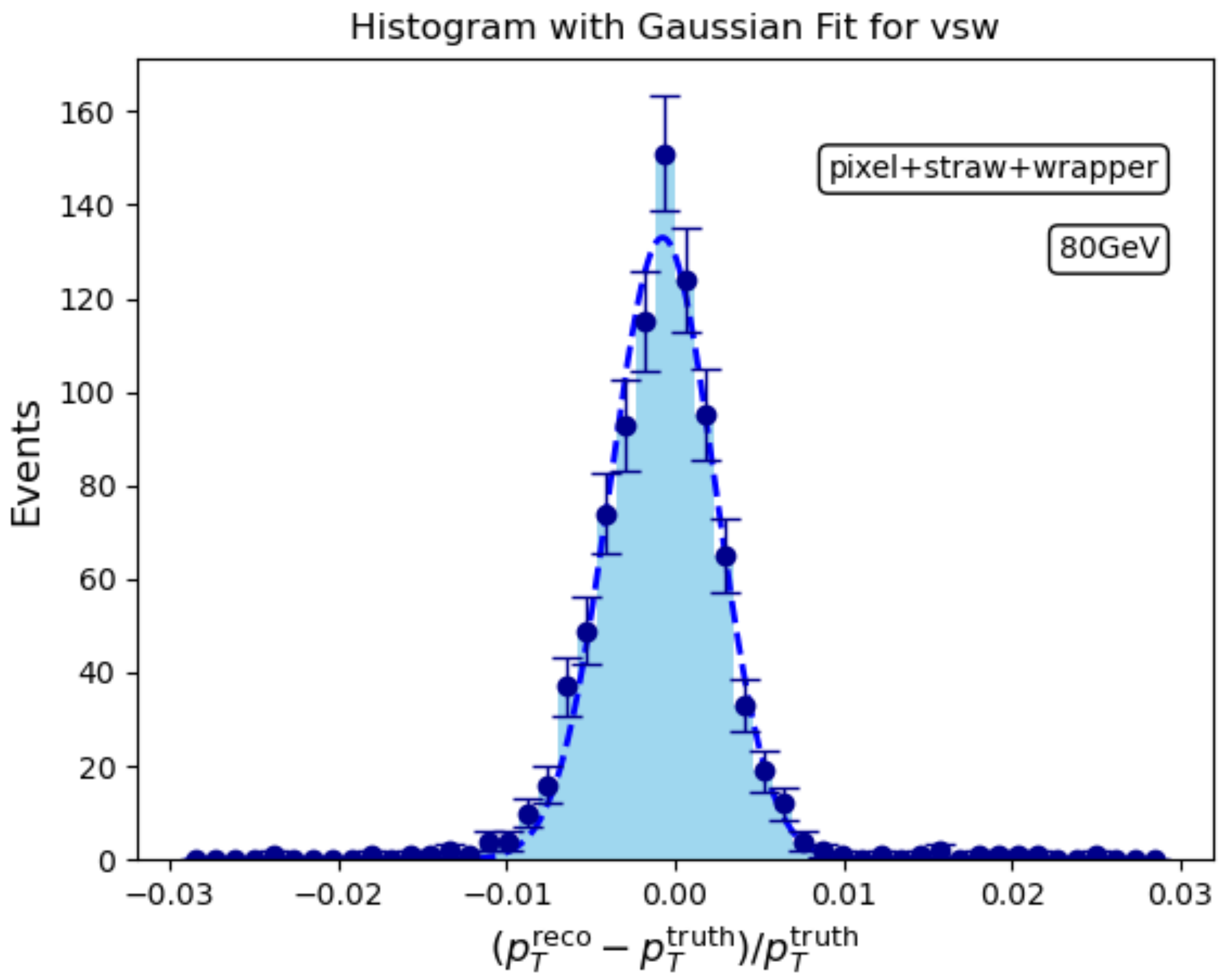
- **Configuration using vertex detector + straw tubes + silicon wrapper**
- **Individual gaussian fit validation shown. Each histogram is 1000 monochromatic muons**

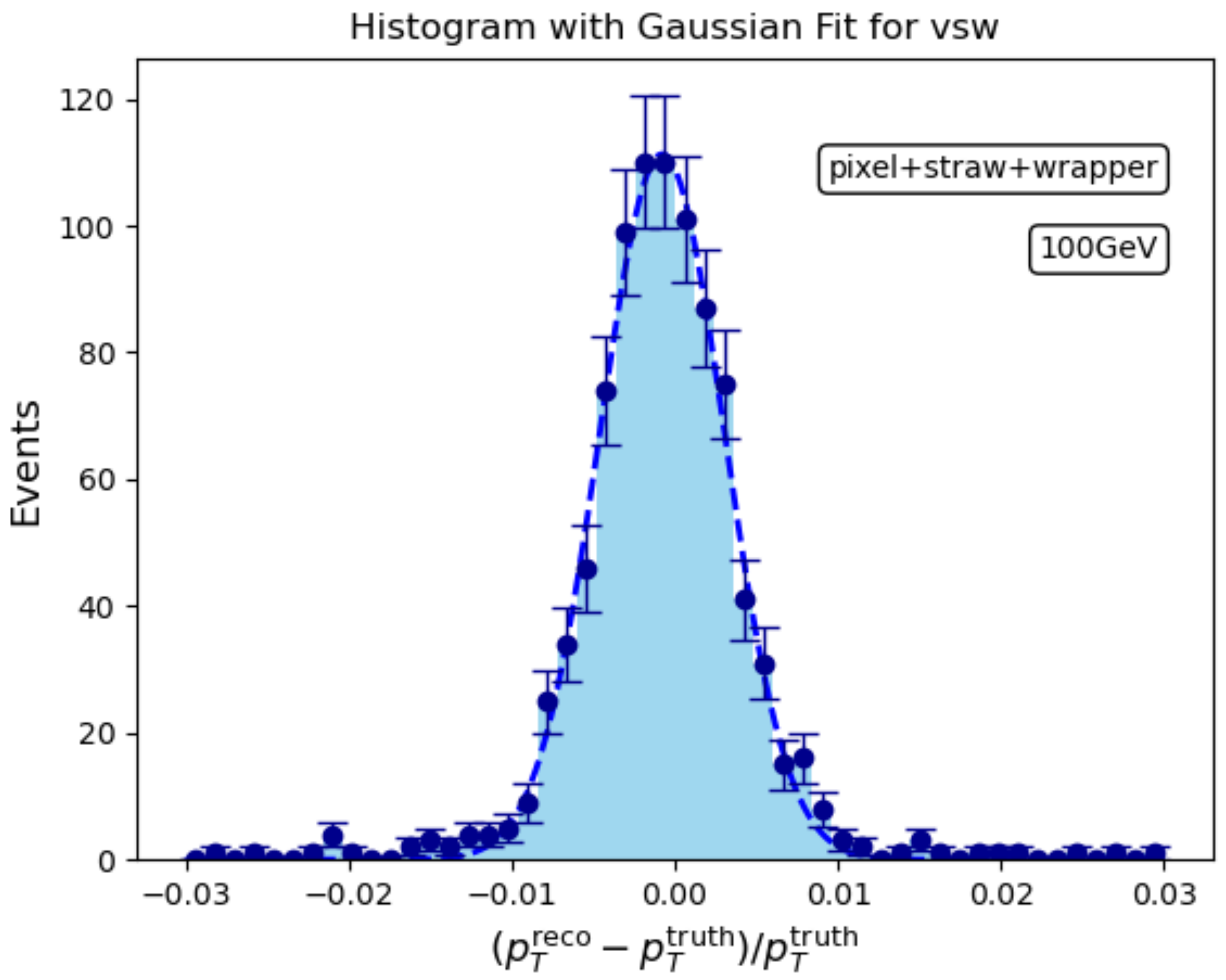






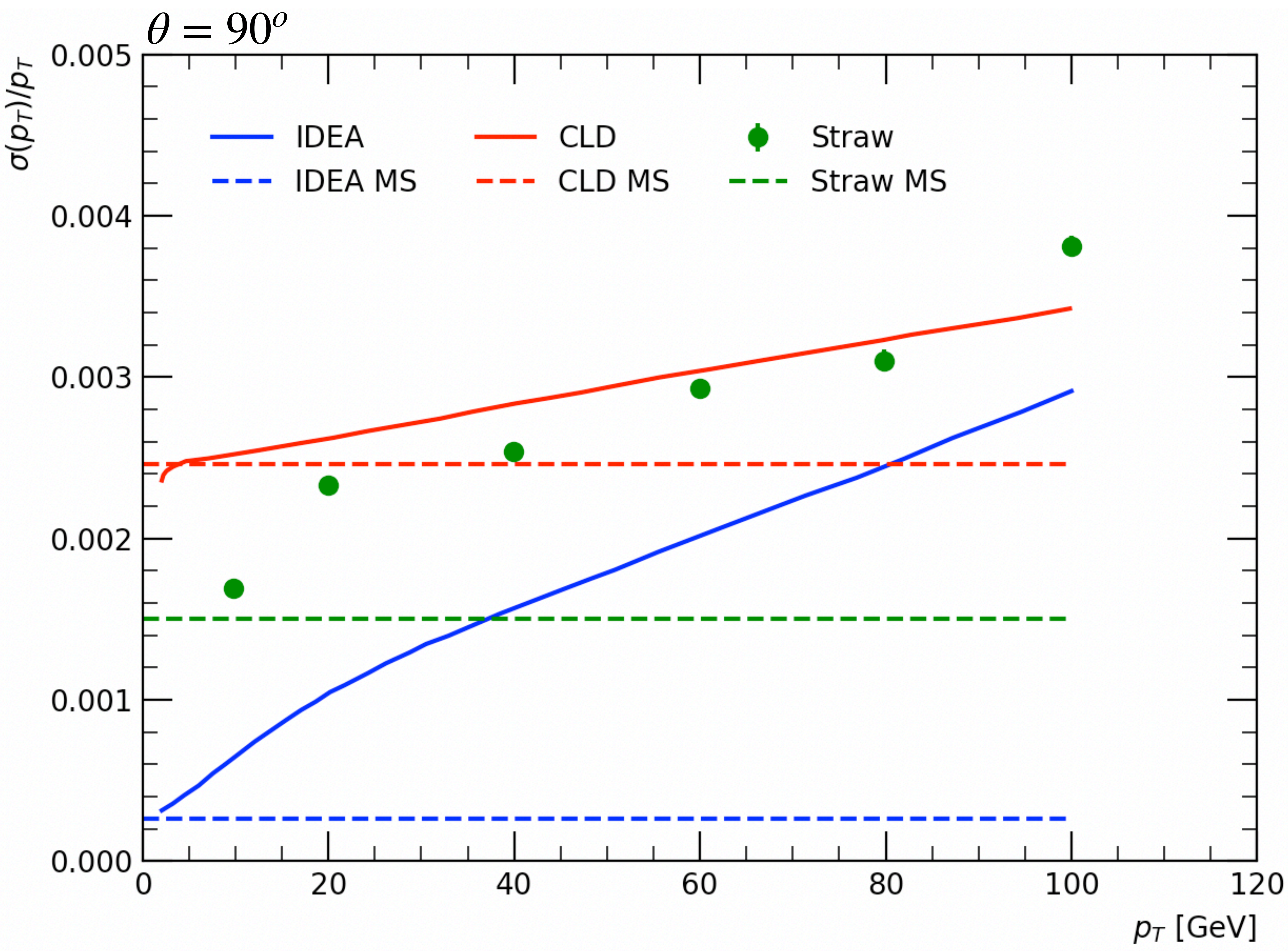






Tracking results

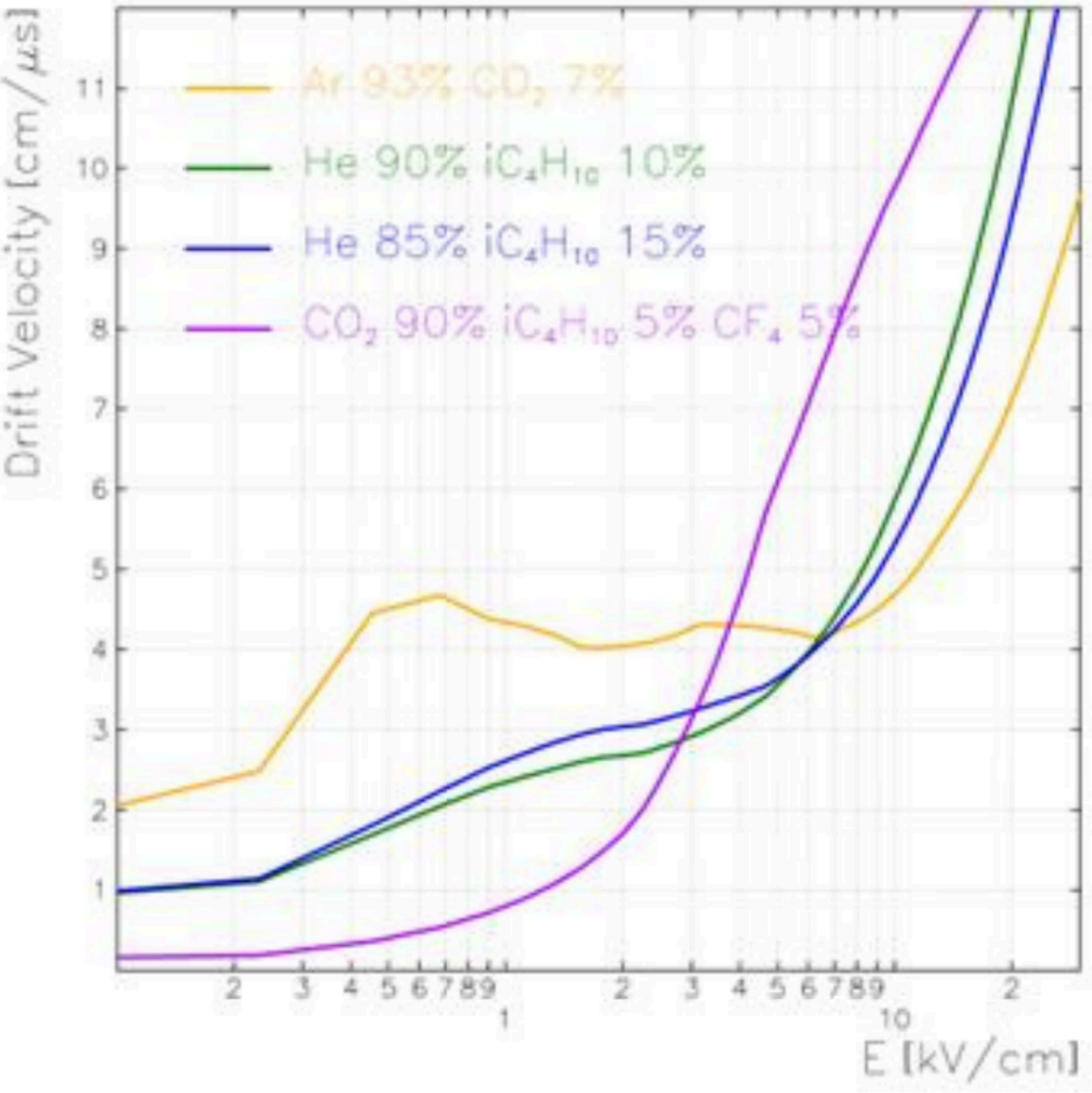
- **Compare straw tube to other detector concepts**
- **There are (tiny) error bars on the straw points from the statistical error on the gaussian fit. No other sources of error considered.**
- **Straw MS is from analytical calculation. MS included in simulation.**
- **Straw tube geometry is not yet optimized!**
- **Assumptions on resolution:**
  - Vertex pixel=5 μm
  - Straw=120 μm
  - Silicon wrapper=15 μm



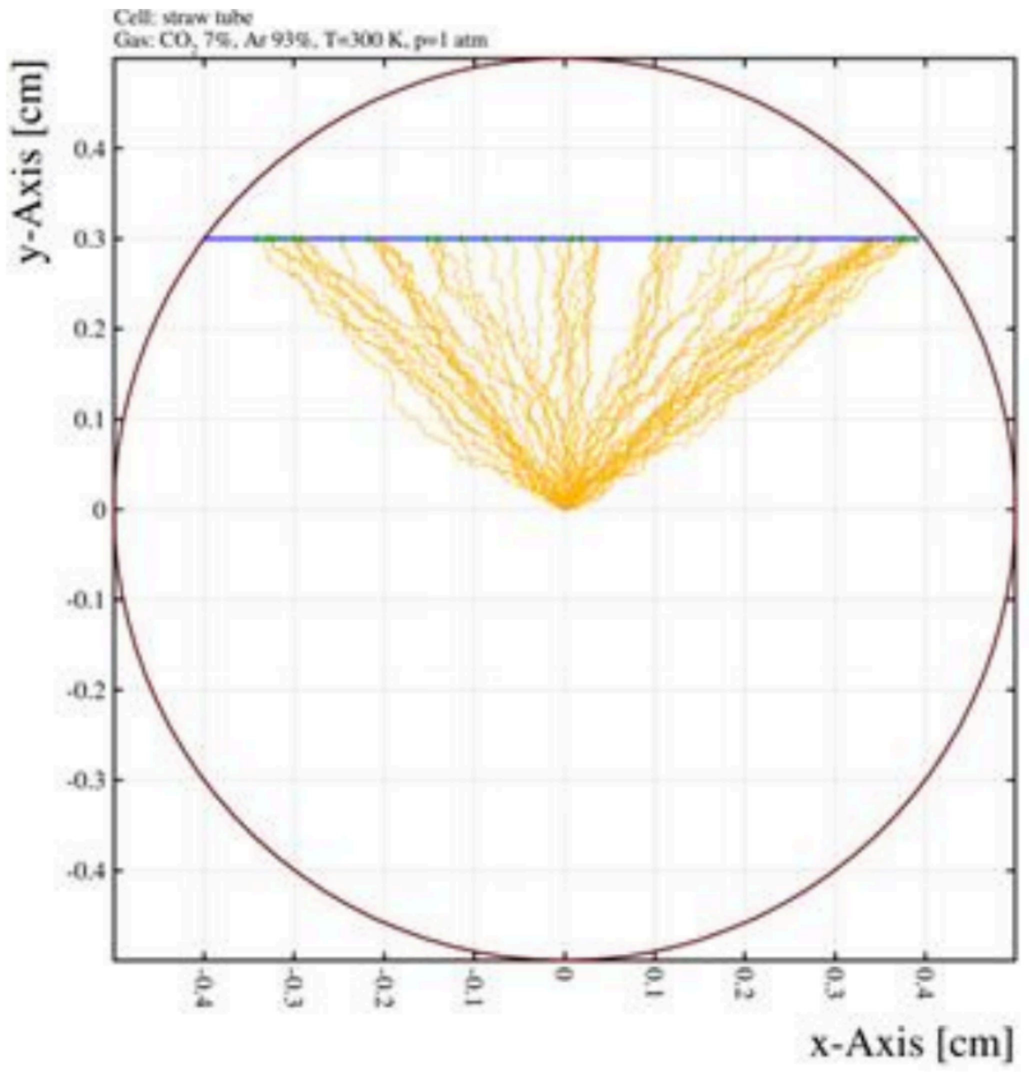
Gas simulation with Garfield

- **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**
- **1.5 meters of Argon = 1.5%** X_0

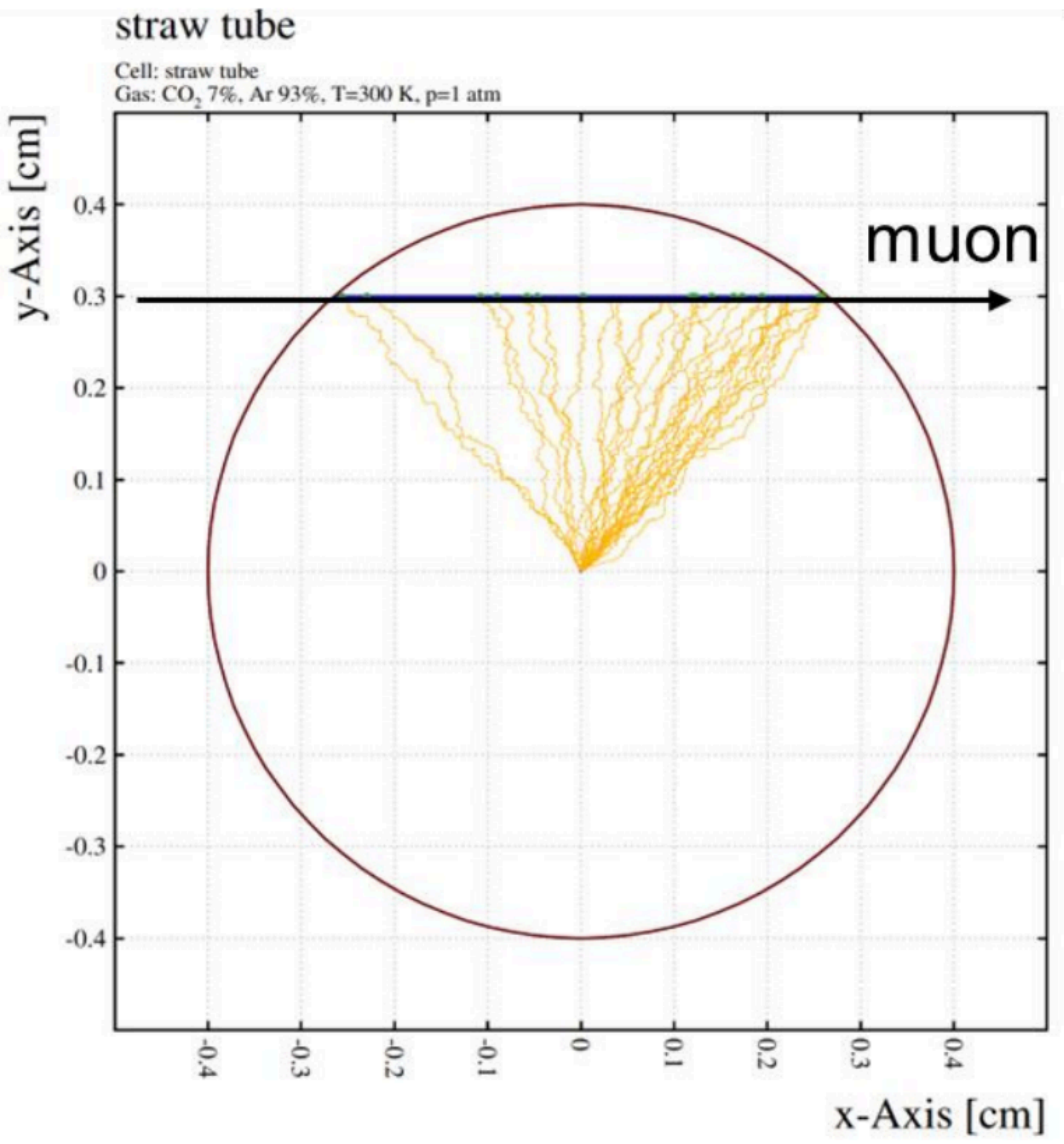


Electron drift velocity vs. e-field

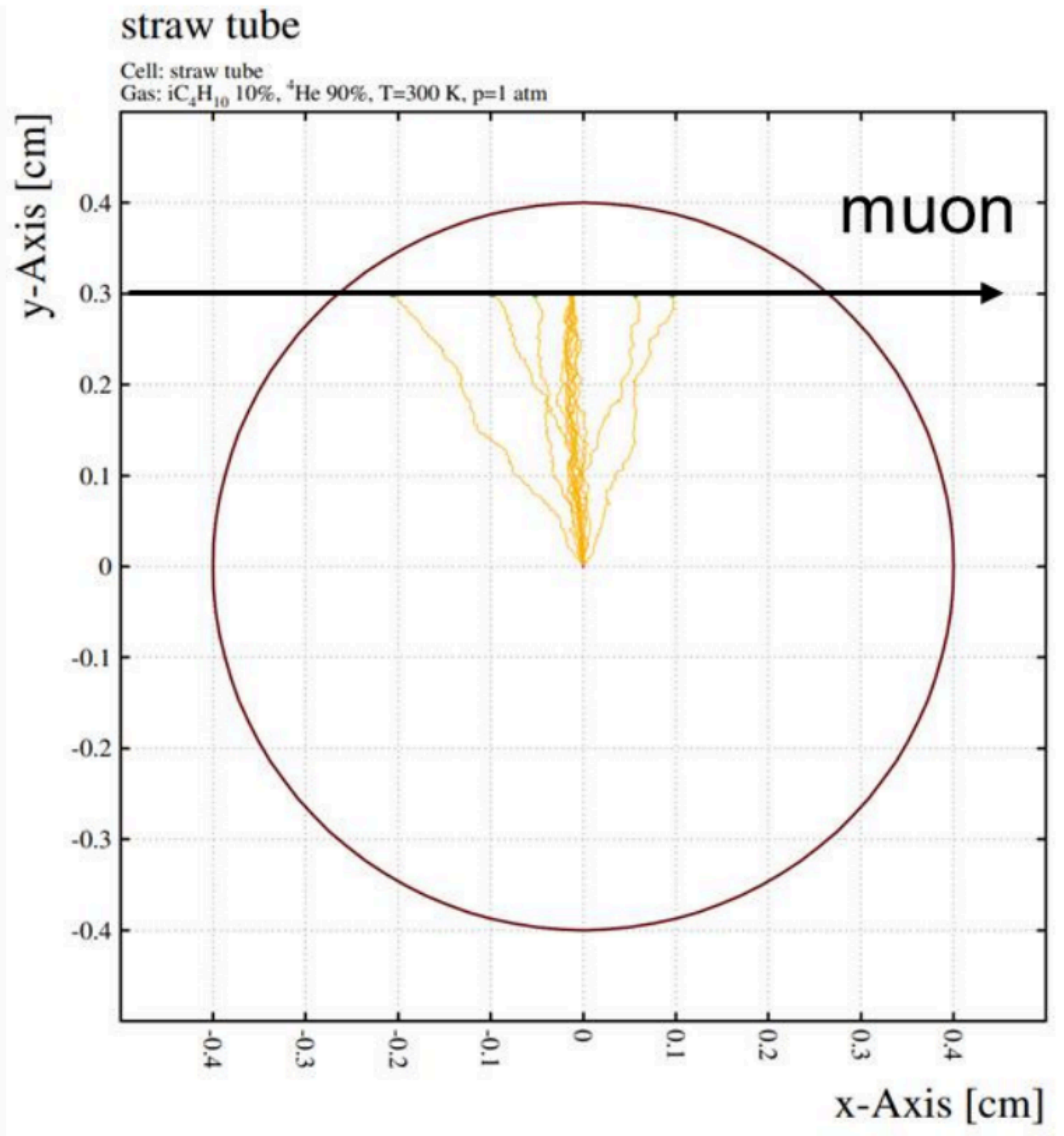


Simulated ionizations created by a muon track and primary electron drift towards wire

Typical drift tube gas
Ar-93-CO2-7

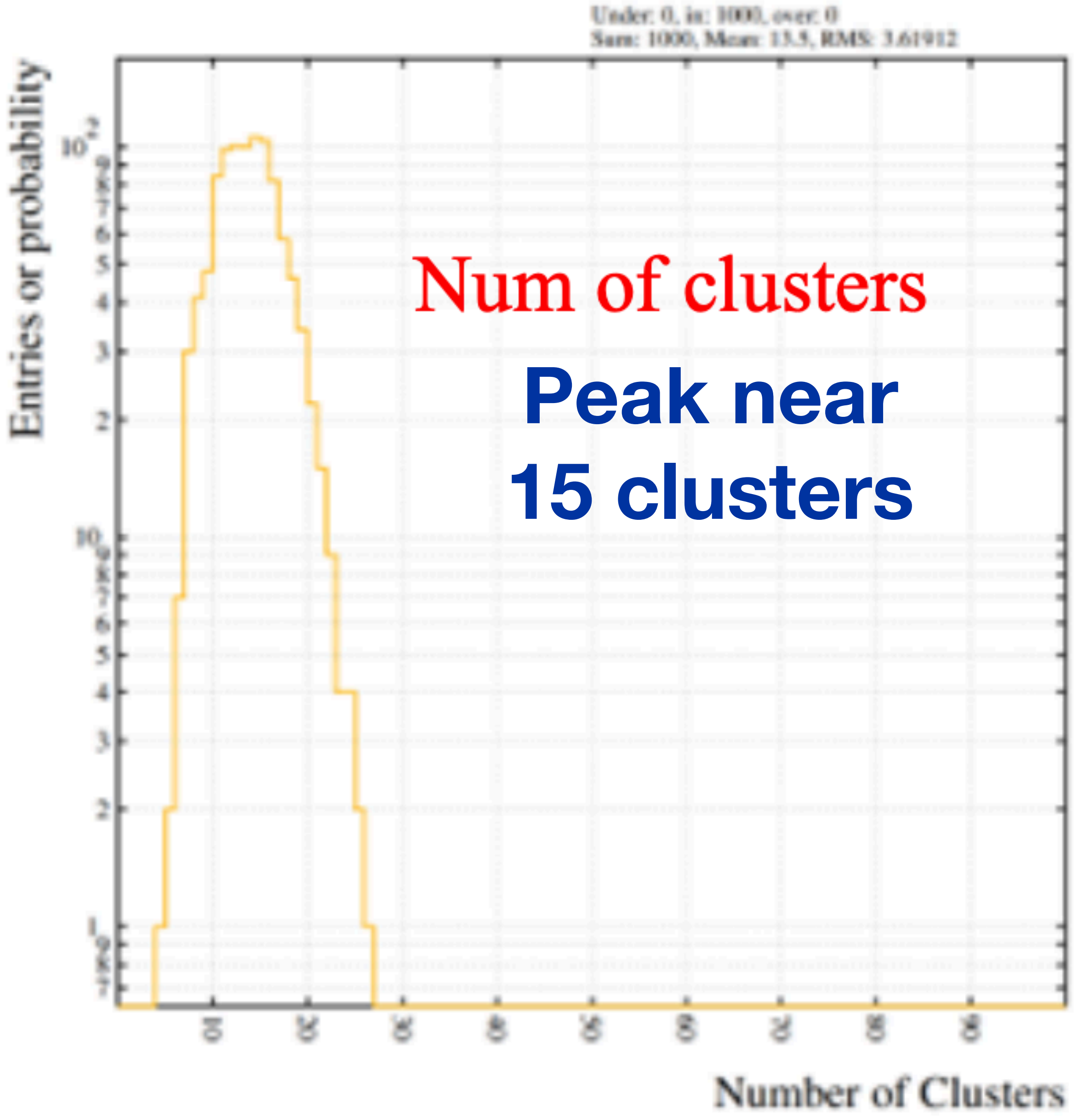


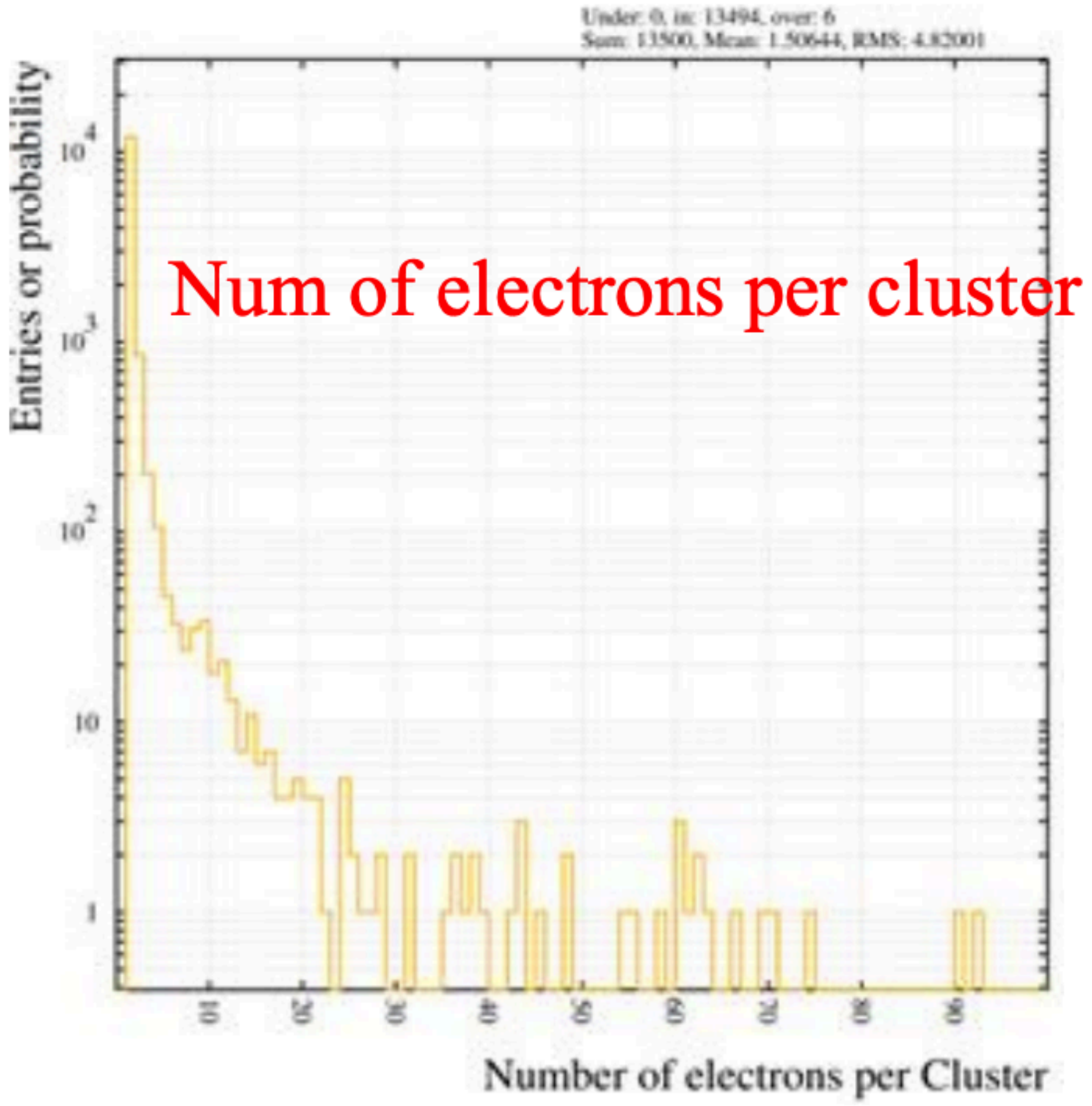
Low-z gas
He-90-iC4H10-10



Gas simulation with Garfield

Low-z gas
He-90-iC4H10-10



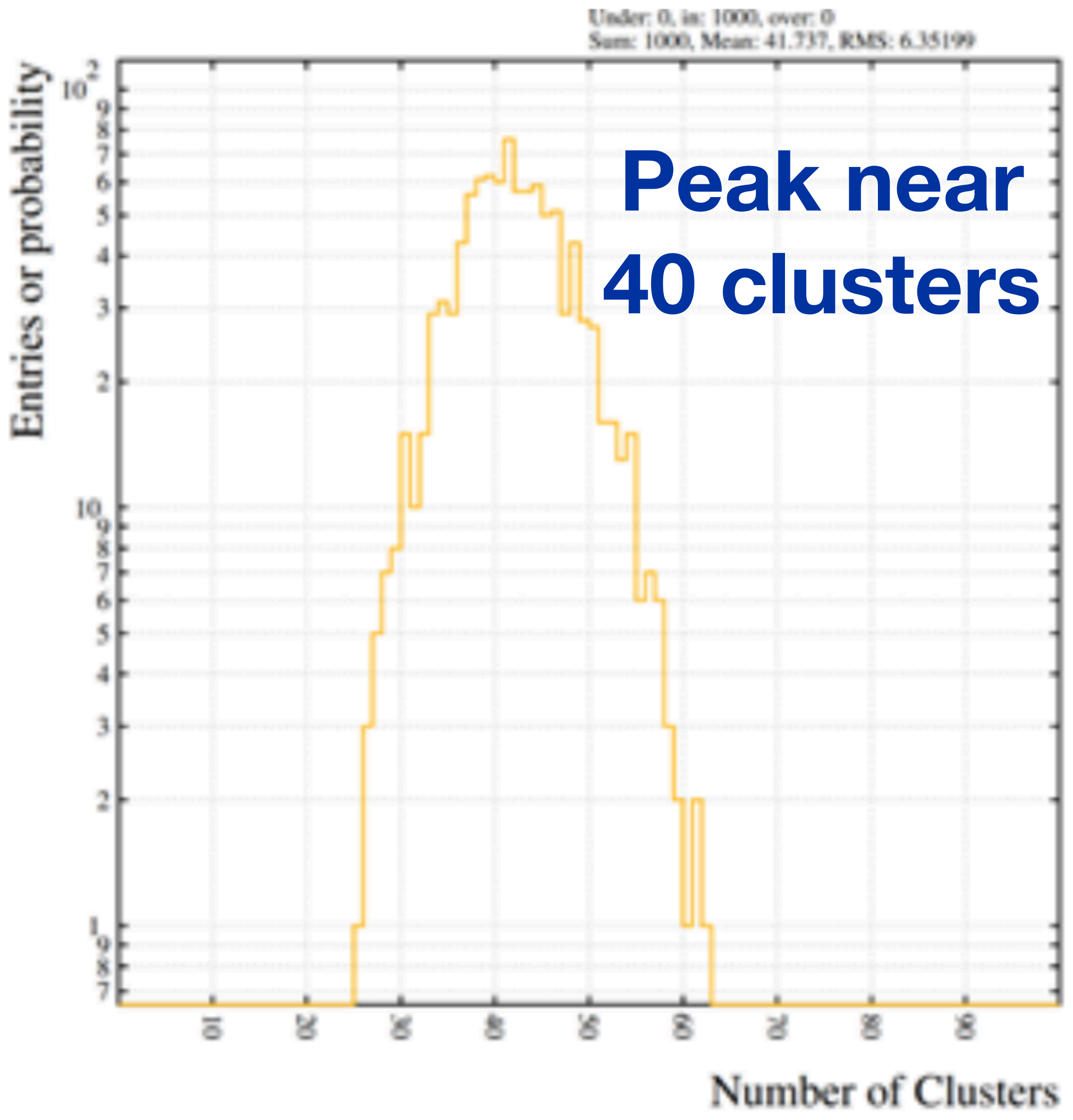


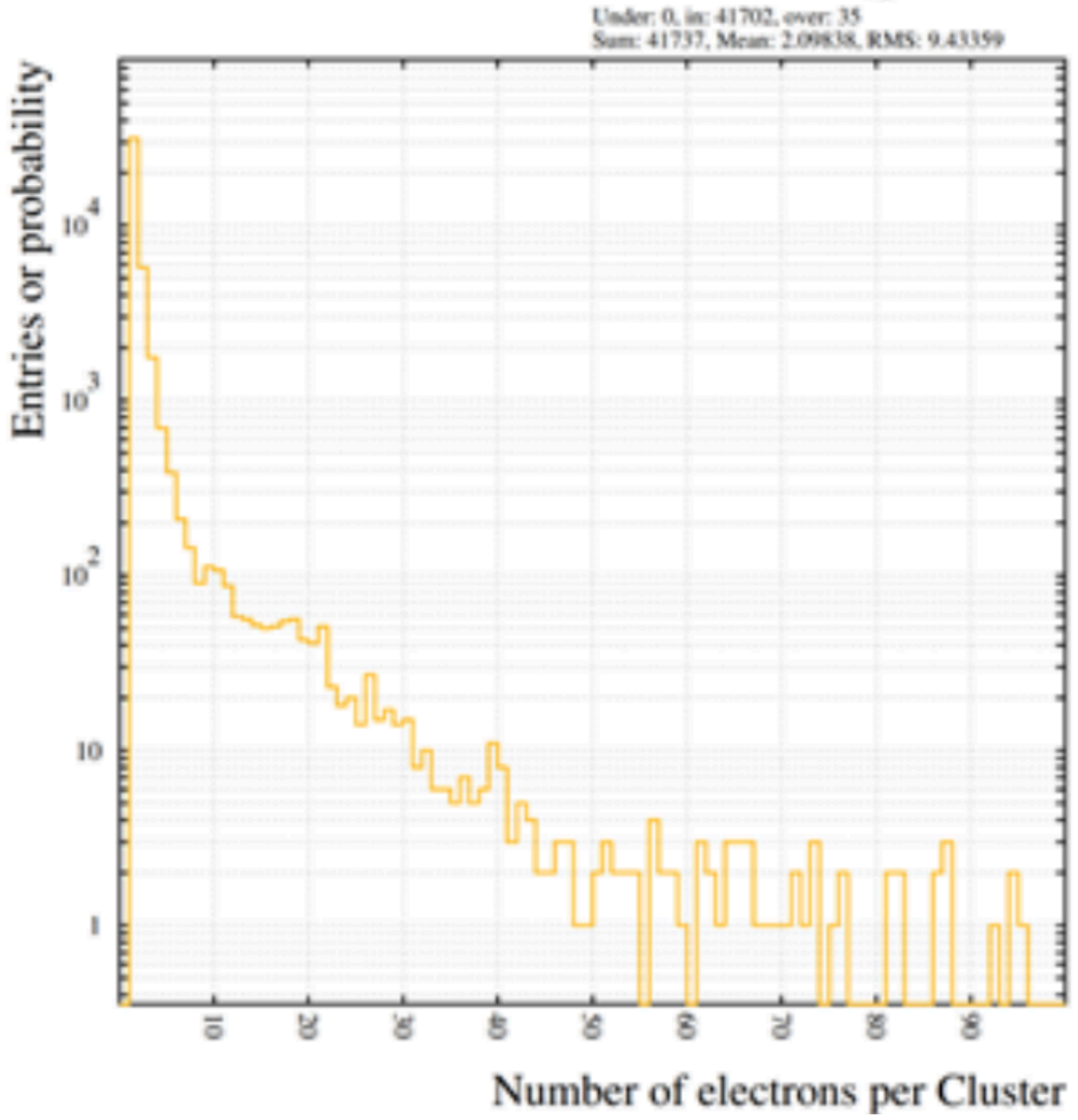
Simulation done for 4 GeV muon
in a 10 mm-diameter straw

k	CH_4	Ar	He	CO_2
1	78.6	65.6	76.60	72.50
2	12.0	15.0	12.50	14.00
3	3.4	6.4	4.60	4.20
4	1.6	3.5	2.0	2.20
5	0.95	2.25	1.2	1.40
6	0.60	1.55	0.75	1.00
7	0.44	1.05	0.50	0.75
8	0.34	0.81	0.36	0.55
9	0.27	0.61	0.25	0.46
10	0.21	0.49	0.19	0.38
11	0.17	0.39	0.14	0.34
12	0.13	0.30	0.10	0.28
13	0.10	0.25	0.08	0.24
14	0.08	0.20	0.06	0.20
15	0.06	0.16	0.048	0.16
16	(0.050)	0.12	(0.043)	0.12
17	(0.042)	0.095	(0.038)	0.09
18	(0.037)	0.075	(0.034)	(0.064)
19	(0.033)	(0.063)	(0.030)	(0.048)
≥20	$(11.9/k^2)$	$(21.6/k^2)$	$(10.9/k^2)$	$(14.9/k^2)$

Num of electrons
generated per cluster

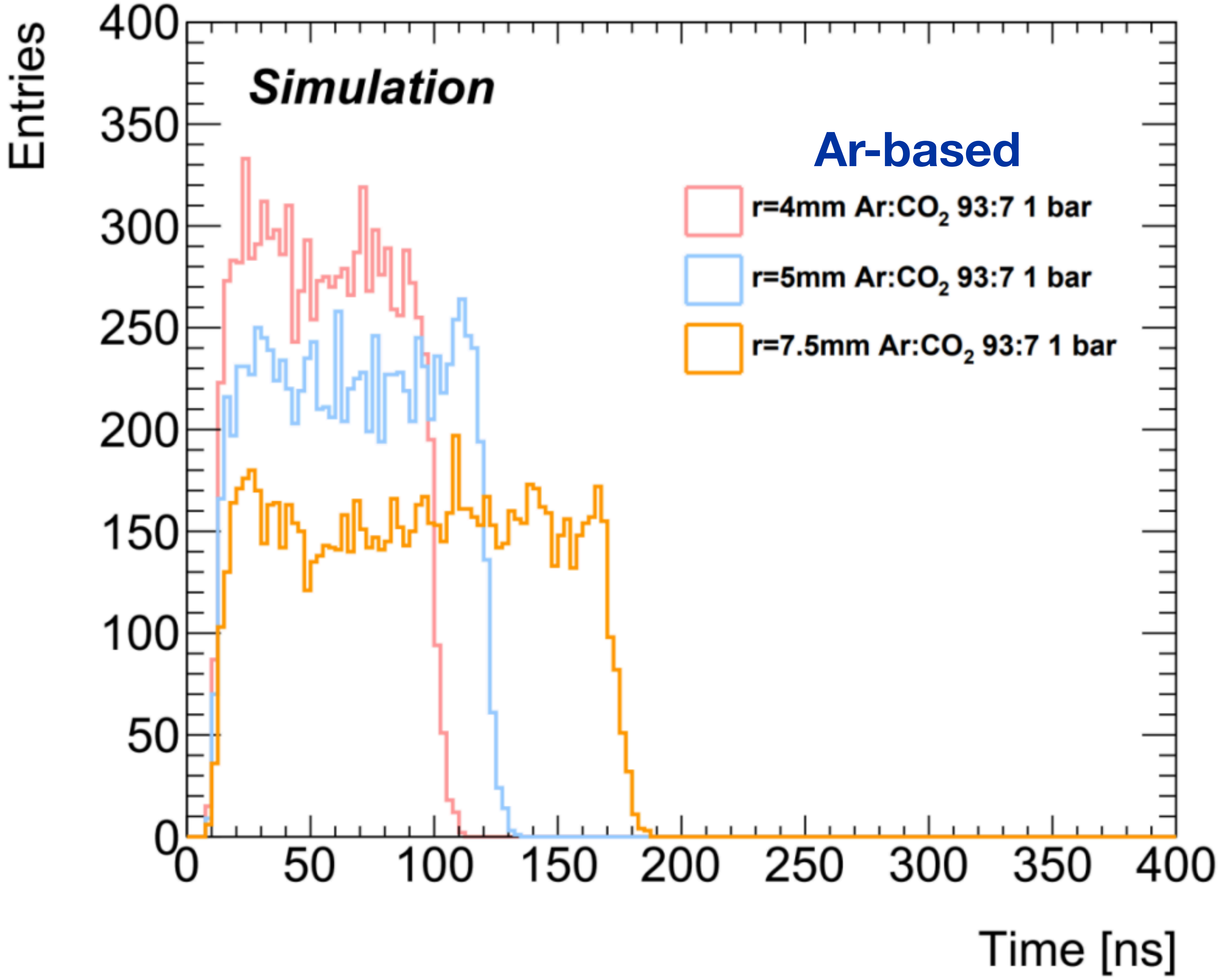
Typical drift tube gas
Ar-93-CO2-7

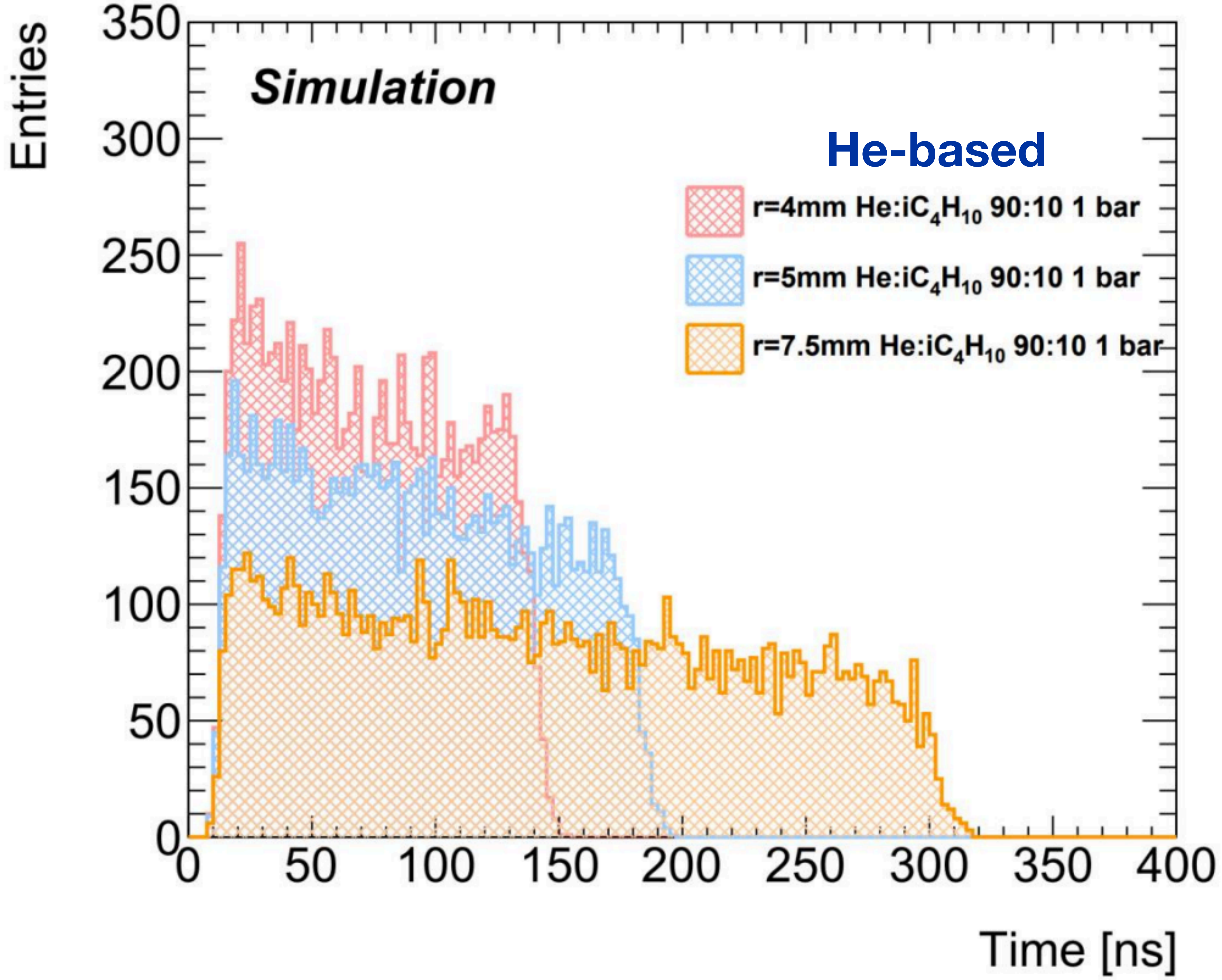




Simulation of the drift time spectrum

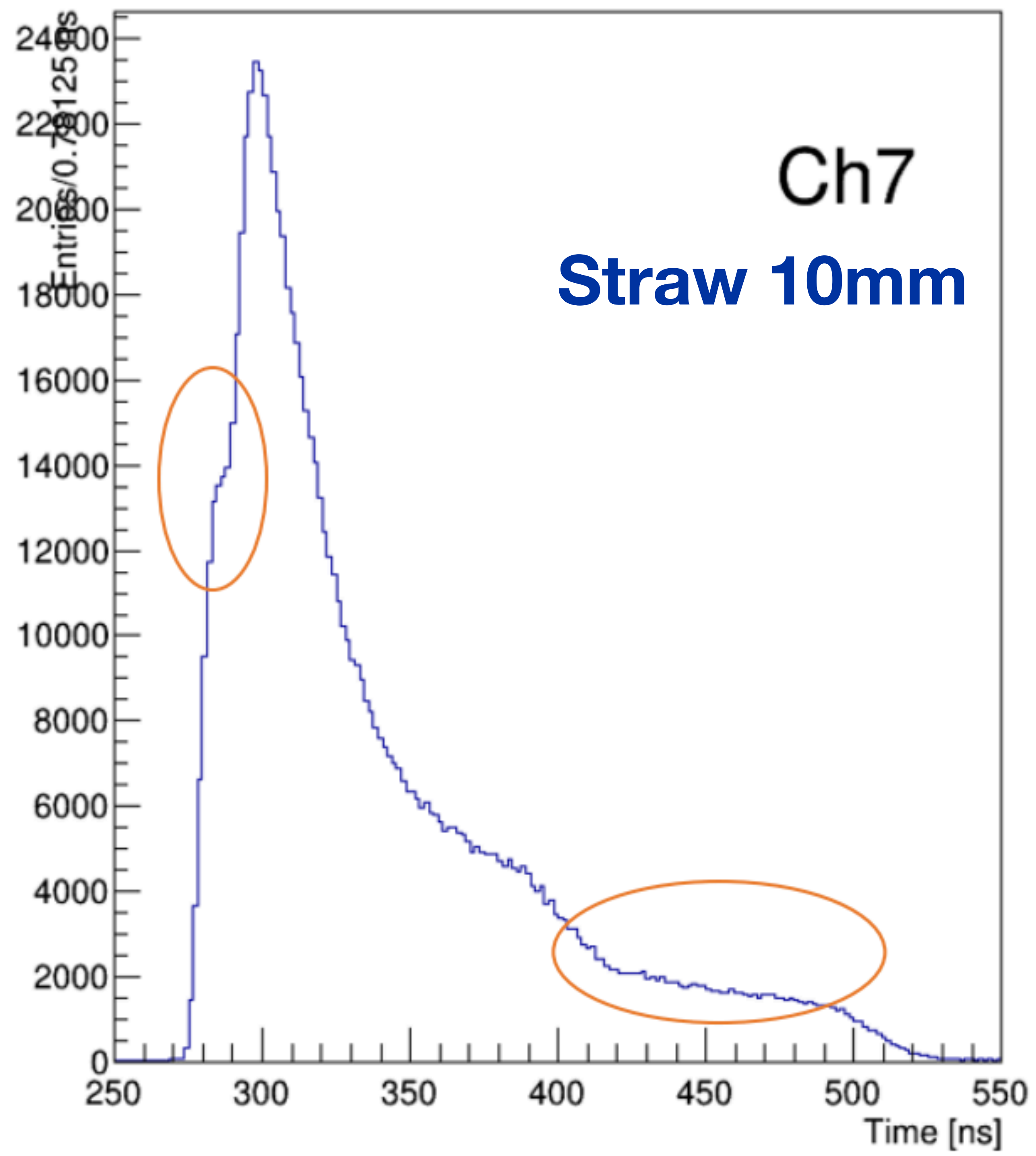
- **Simulation of the straw tube drift time spectrum (convolution of earliest cluster arrival time and the amplifier response)**
  - Drift time spans 100-300 ns, comparable to ATLAS monitored drift tubes
  - ~50% longer drift time in He-based gas compared with Ar-based gas (1 bar)
  - Drift time depends on the straw radius, gas pressure, and high voltage applied

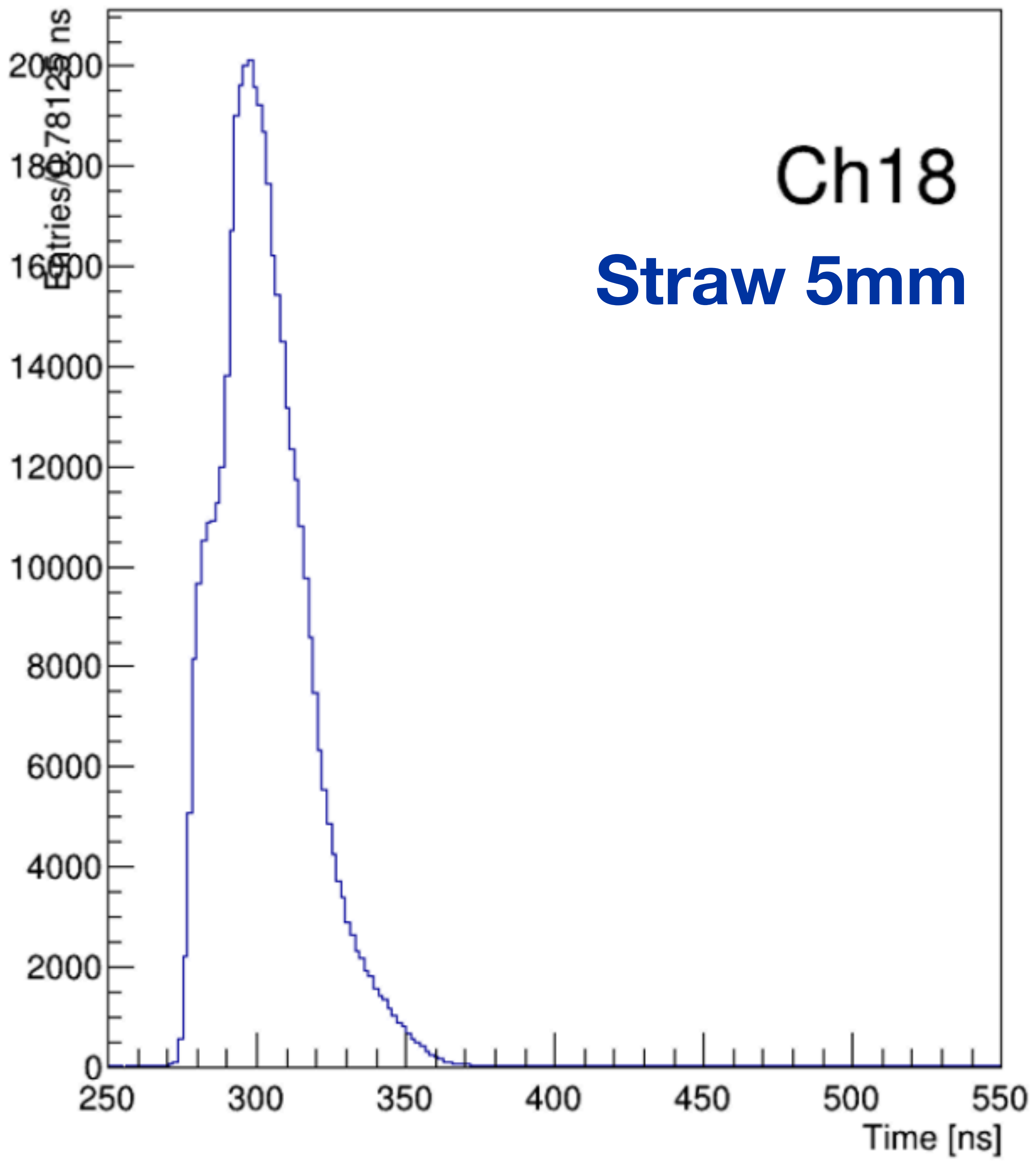


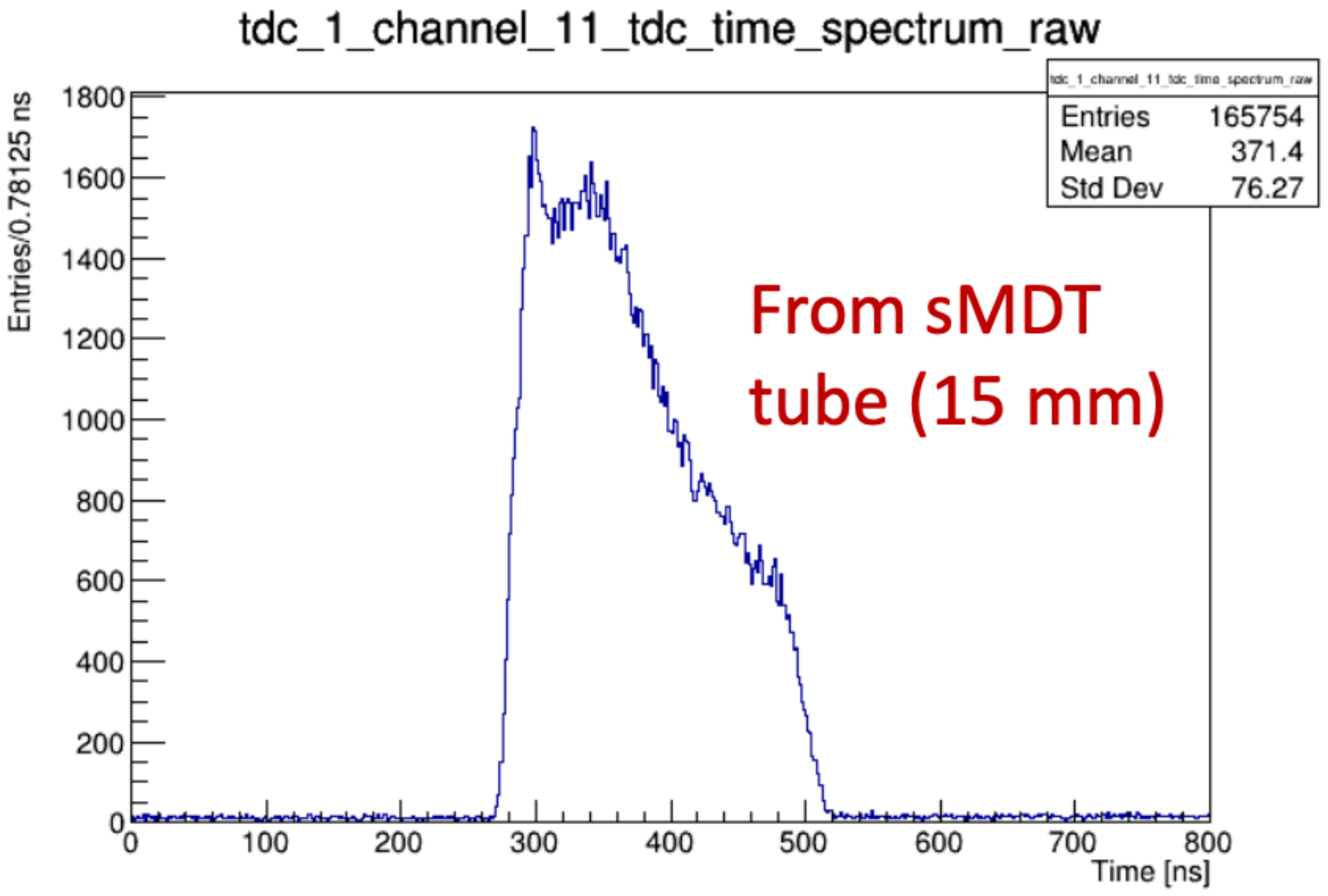


Straw drift time spectra

- **Two typical straw time spectra (more spectra in backup)**
  - Ch7 is a 10mm tube and Ch18 is a 5mm tube (diameter)
  - Additional steps in the leading and falling edges of Ch7:
    - Sense wire is not located at the tube center







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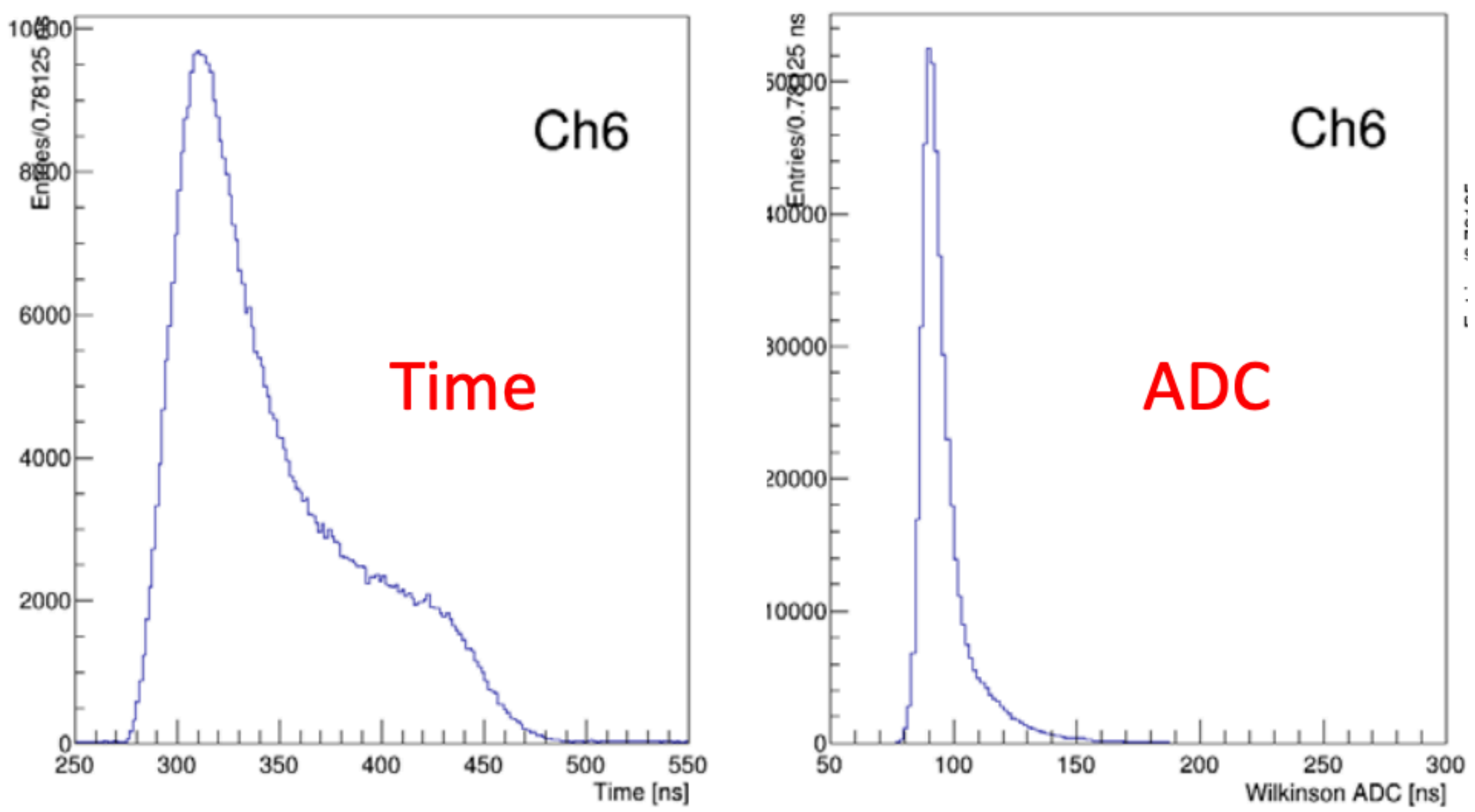
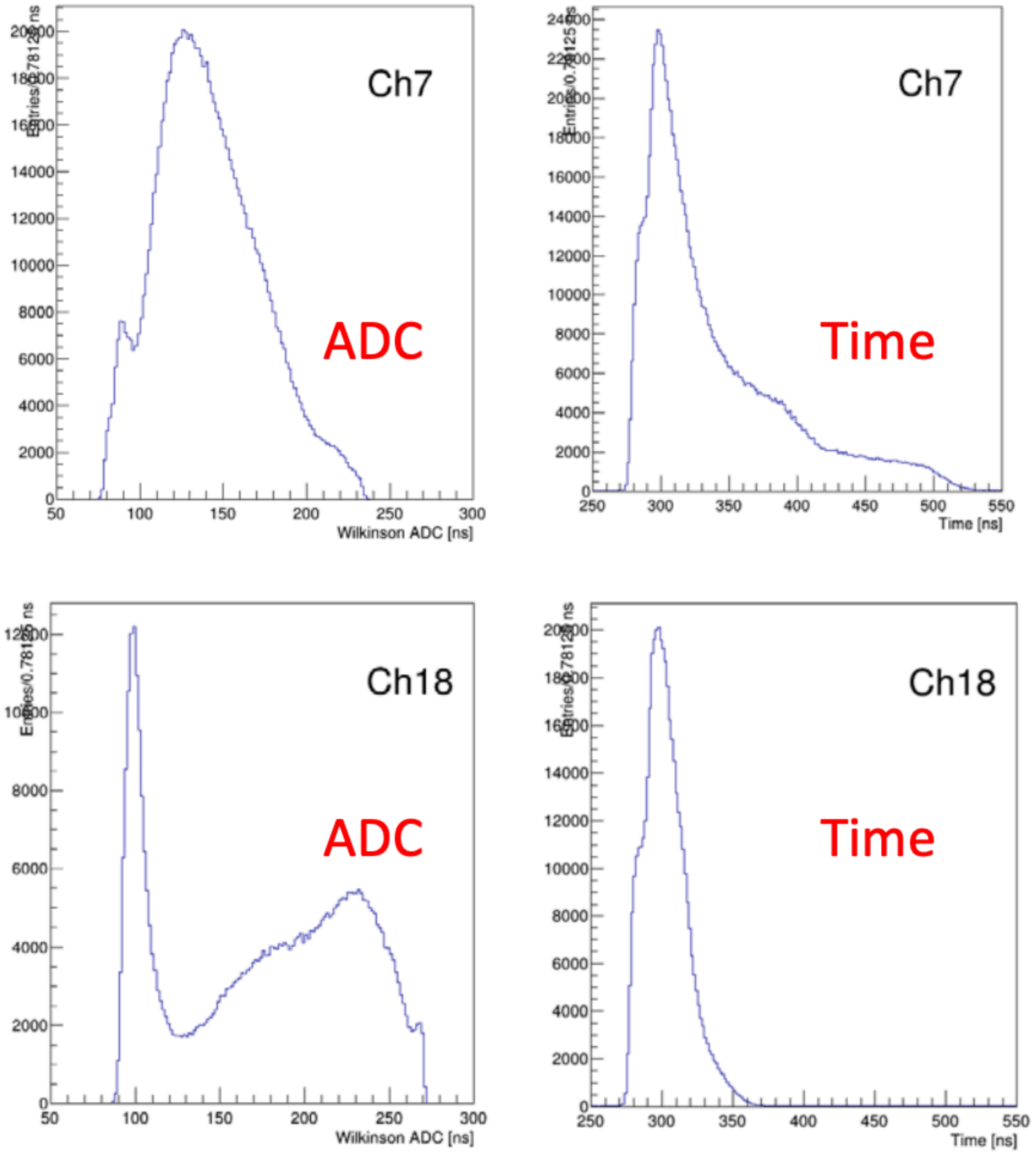
Straw ADC spectra

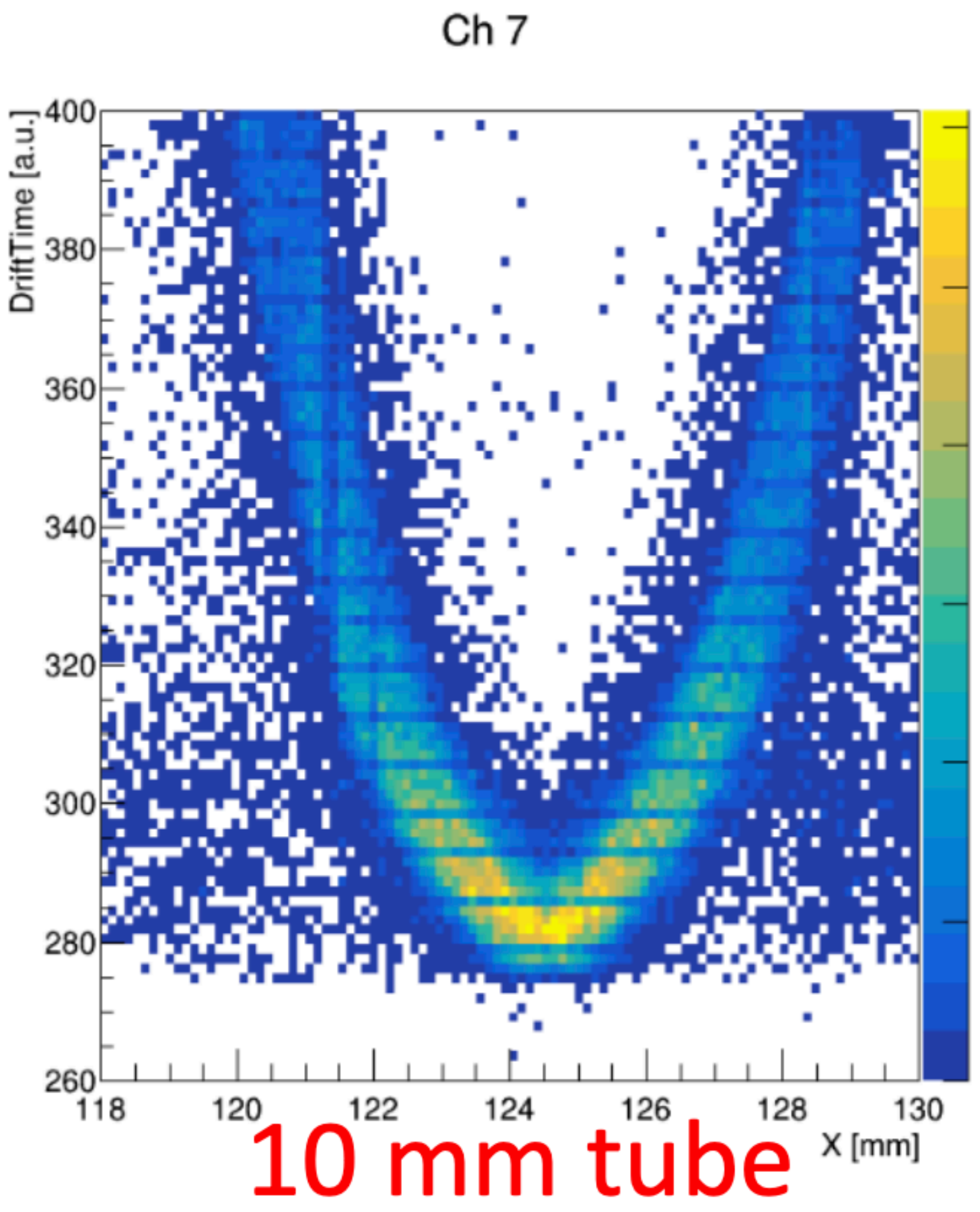
- **Compare ADC spectra and time spectra (ADC in "Wilkinson ADC" mode. More in backup.)**
  - For most of the straw tubes, longer drift time -> larger ADC
- **Short drift time events may also have large ADC**
- **Weird Ch6: longer drift time but small ADC**

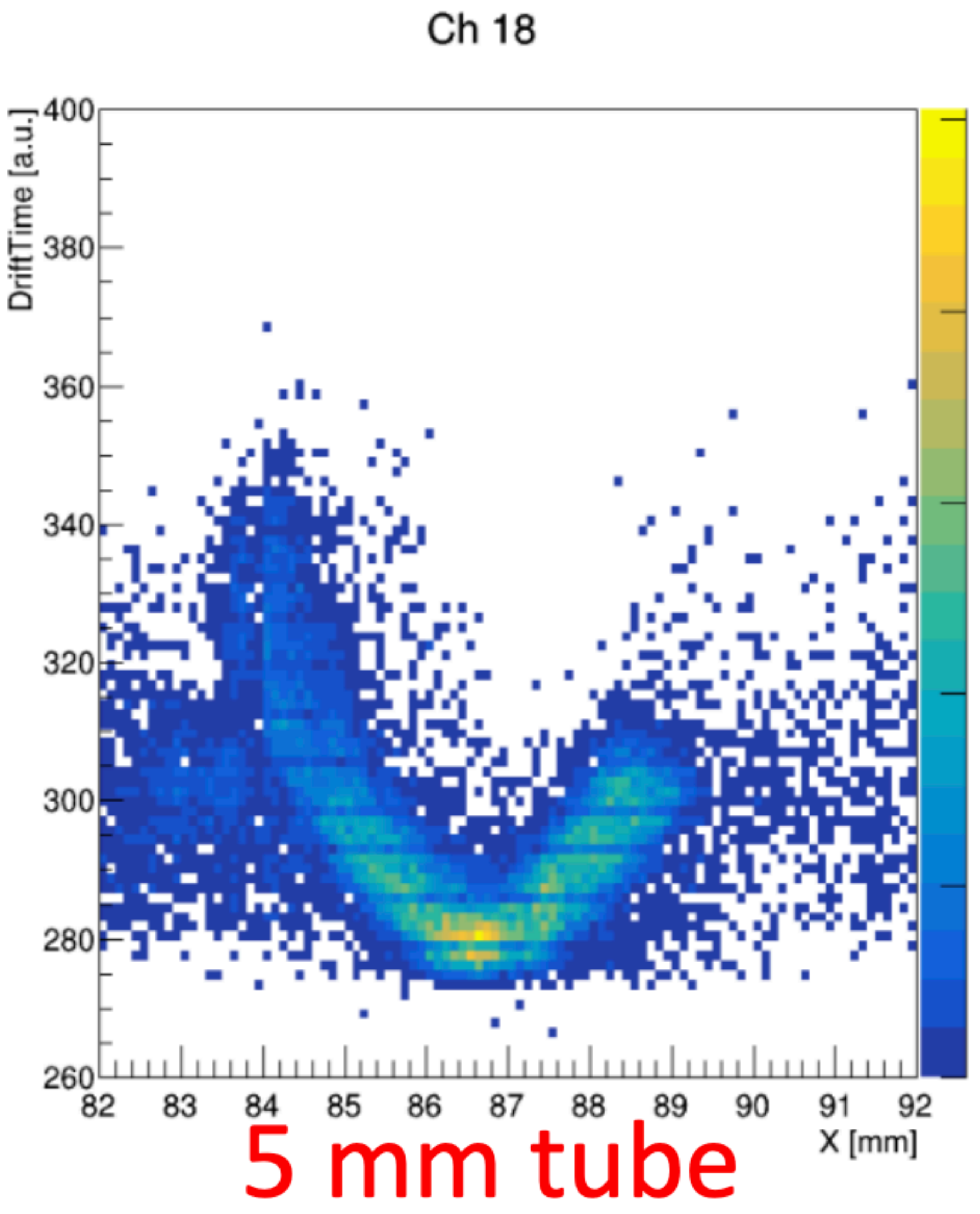




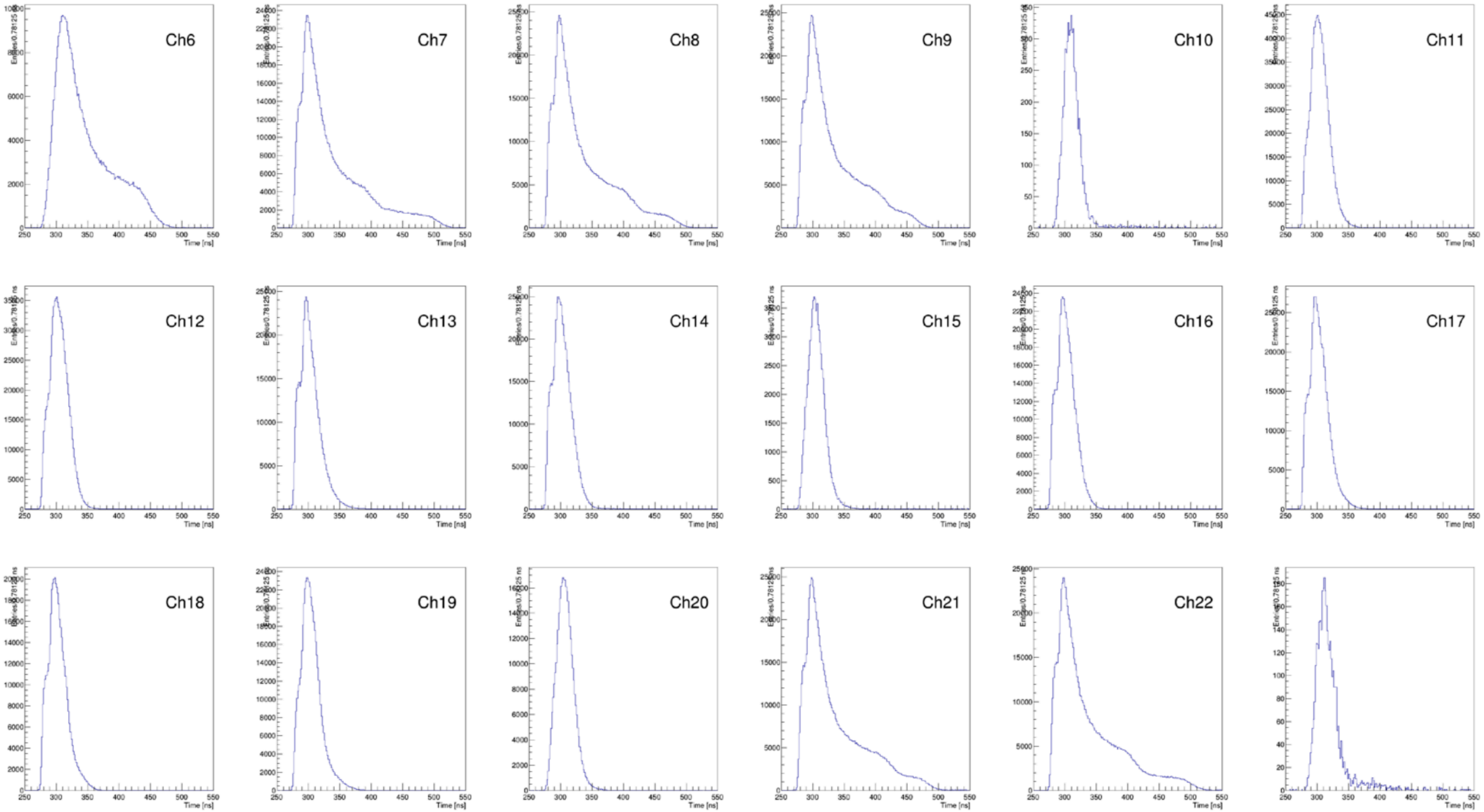
Straw alignment

- **Alignment between straws and sMDT tracker in progress.**
- **Extrapolate sMDT track to straws and extract the x position on the straws**
- **Compare x position to drift time to measure straw position. Also gives a sense of the r(t) relation.**

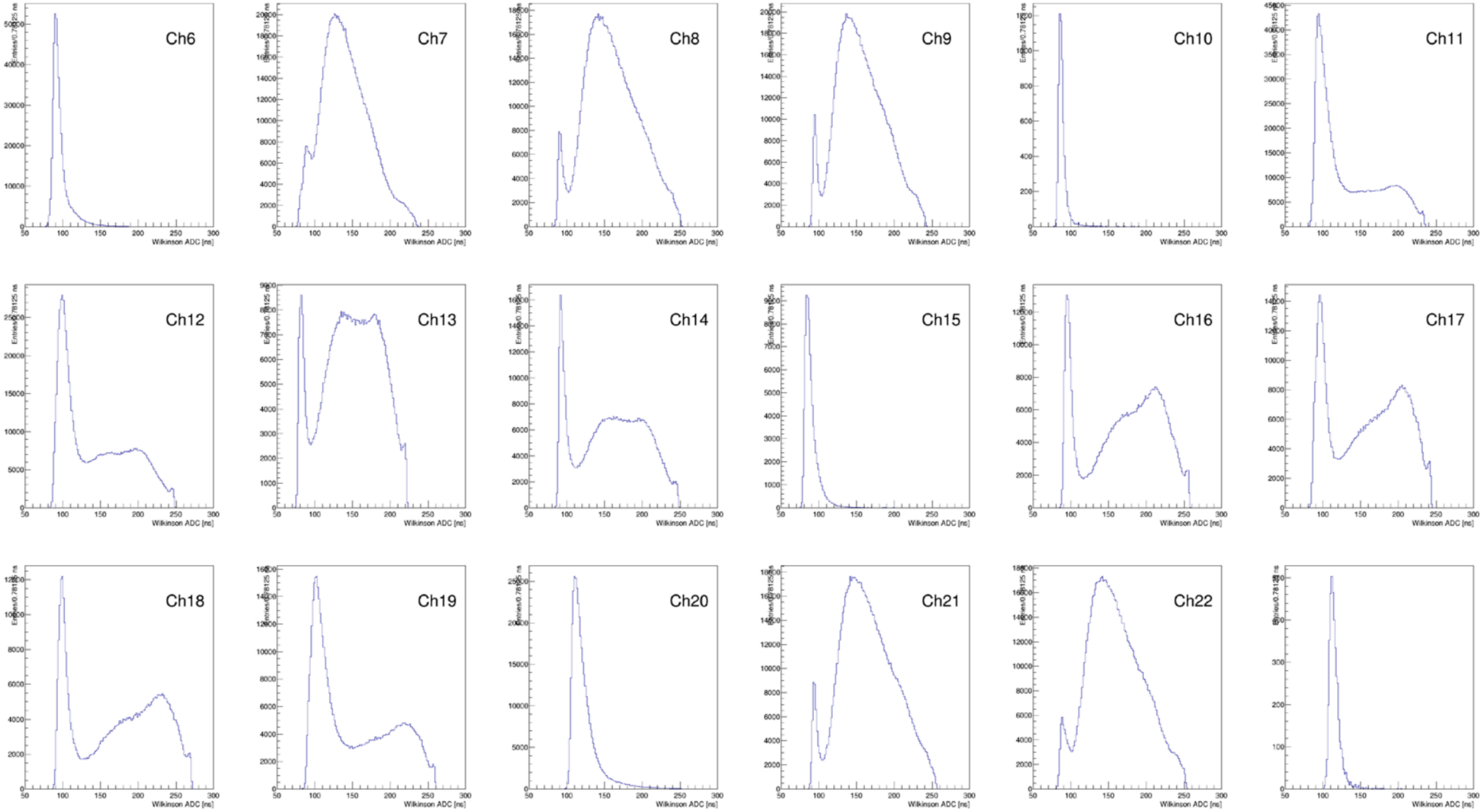




Time spectra of straw



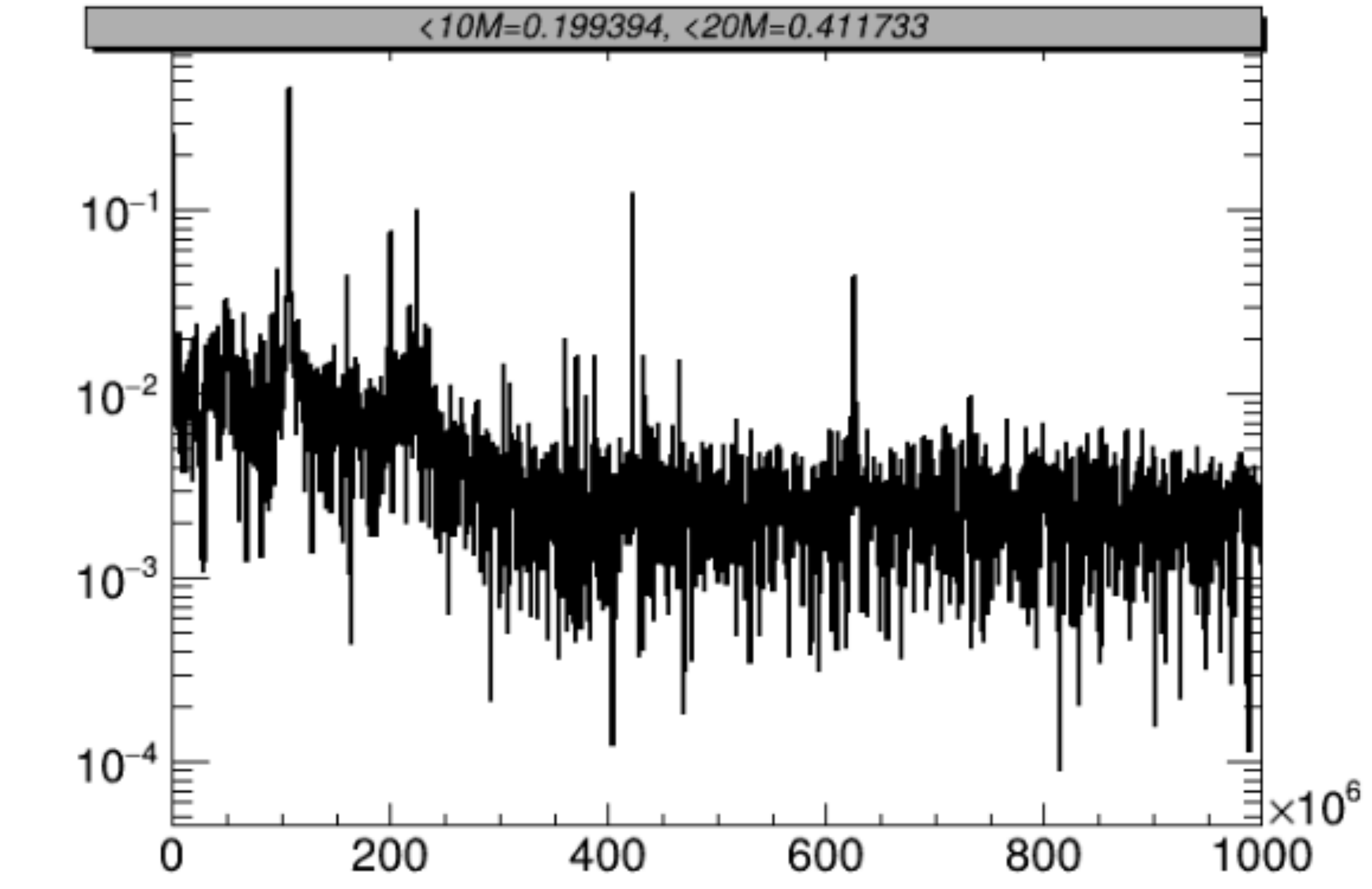
ADC spectra of straw



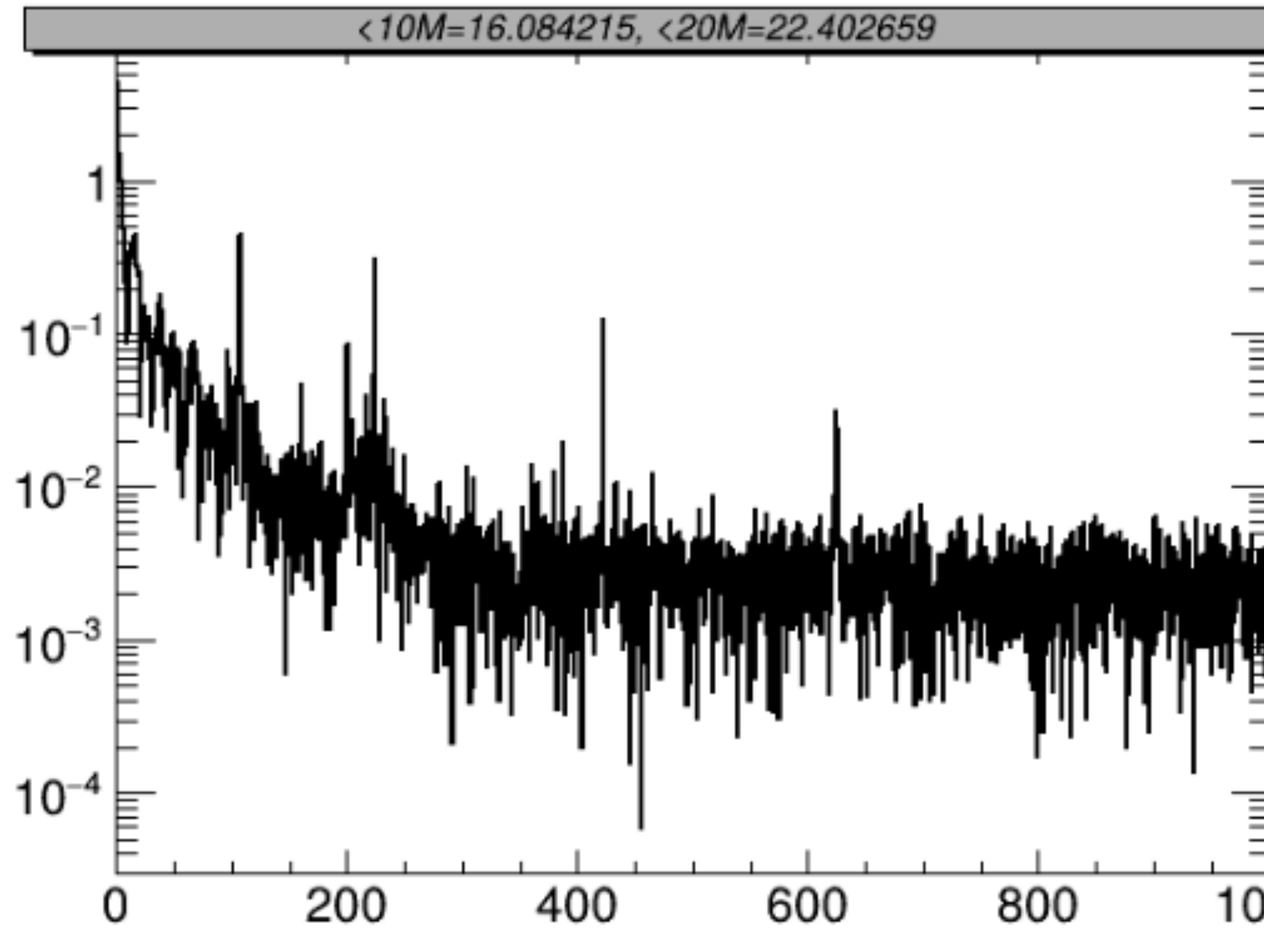
Waveform filtering

- **Low frequency components consistent with muon signal.**
- **Remove high frequency noise with FFT and frequency cut**

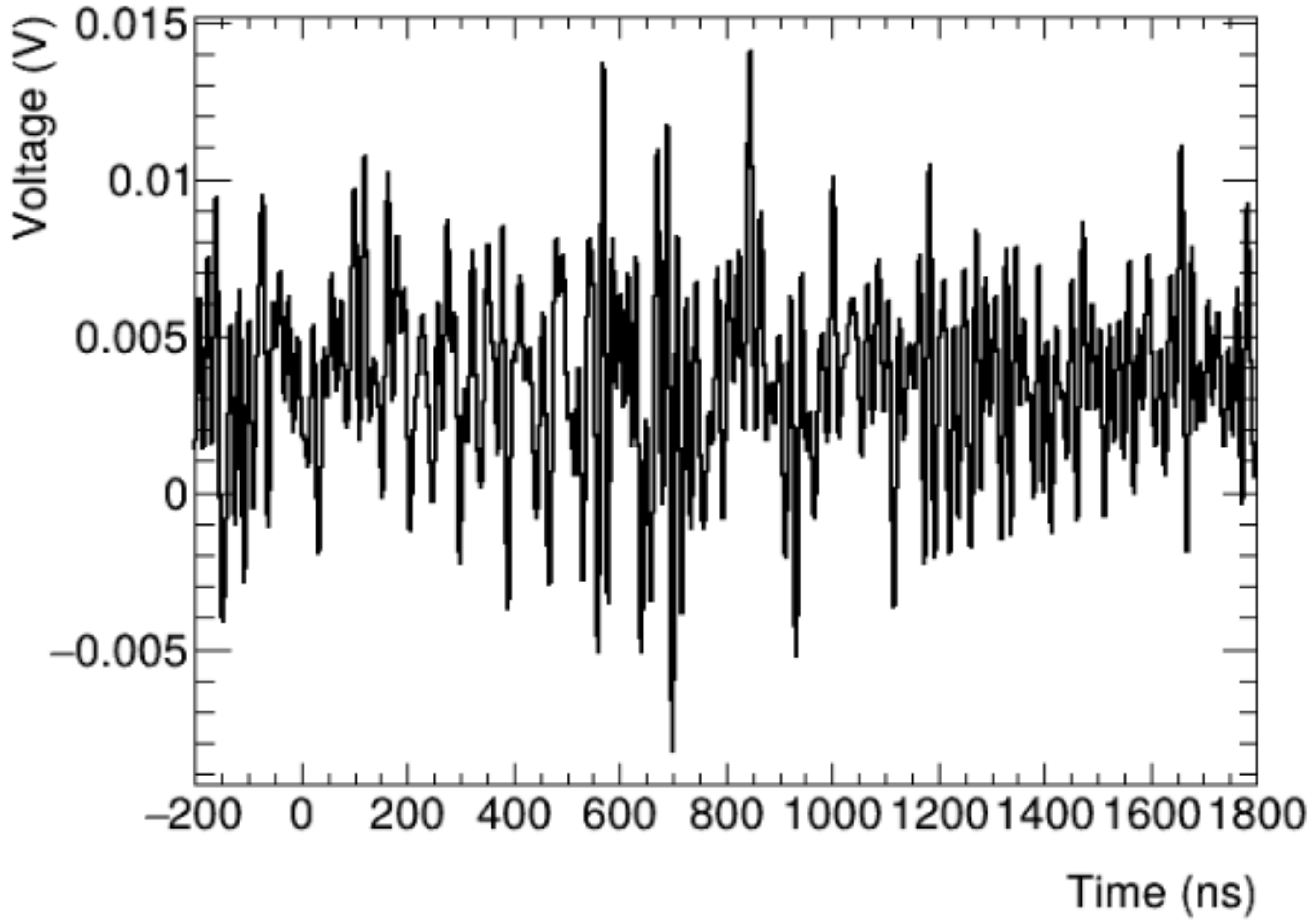
Noise FFT



Muon FFT



Noise IFFT



Muon IFFT