A muon System Made of Drift Tubes and Scintillator Strips For FCC -ee

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Group expressed interests:
Michigan, Brookhaven, Fermilab, SLAC, Michigan State University, Sezione di Roma

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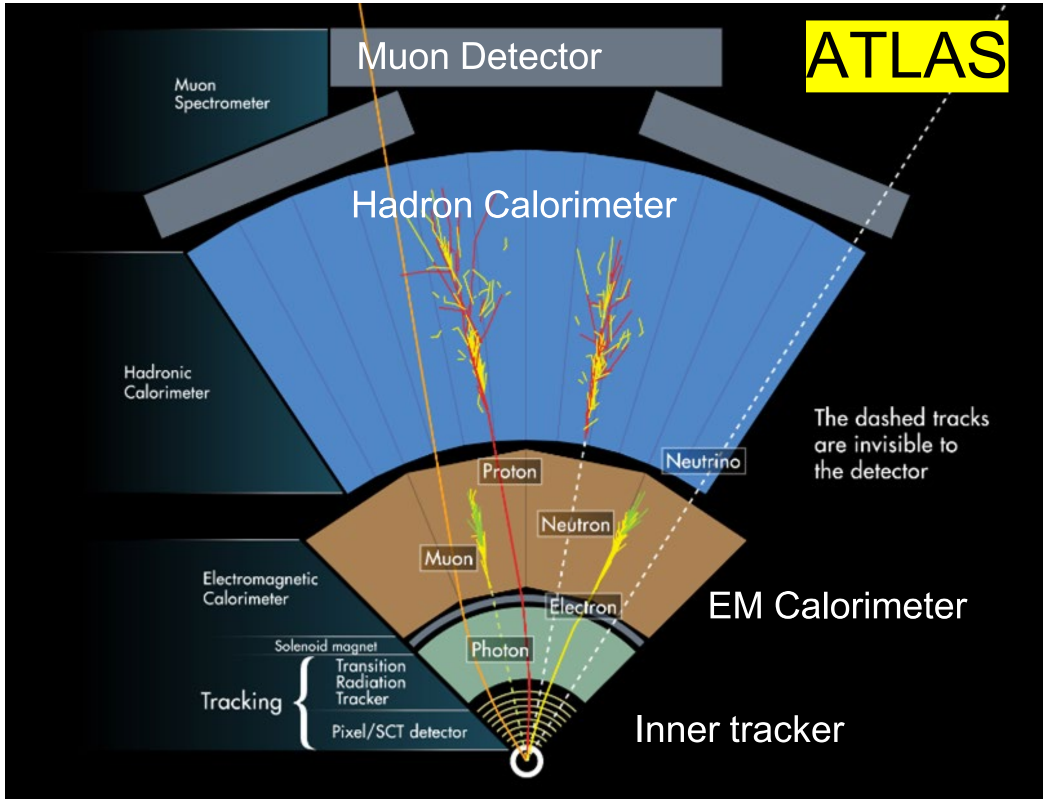
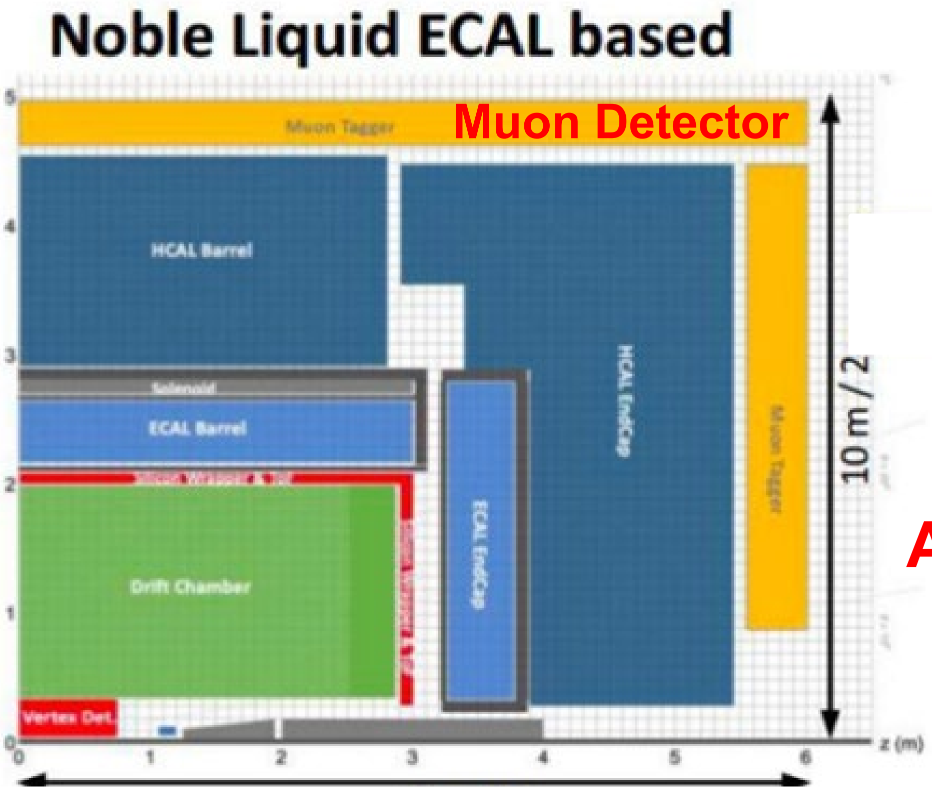
Muon system in colliding beam experiments





FCC-ee detector concept

ALLEGRO

Muon identification (tagging) and independent triggering

- Tracking system, the outmost part of a detector (large volume)
- Muon filter: reject hadronic particle punch through

Building for discovery

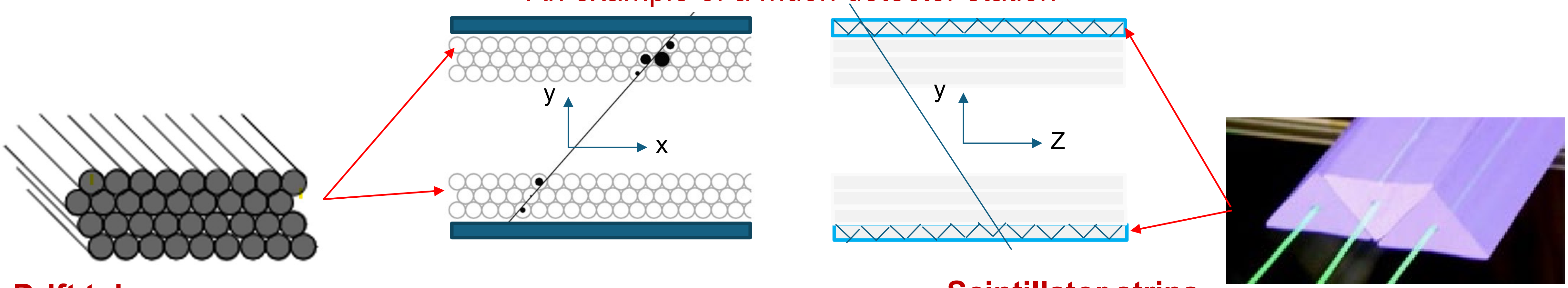
- Reconstruction of decay vertices of long-lived particles
- Time-of-flight information for detecting massive stable particles

FCCee Muon System Design Considerations

We propose a system with drift tubes and scintillator strips to satisfy the requirements

- **Cost-effective:** Inexpensive to construct and with a low channel count
- **Robust:** Reliable and robust to operate for long term
- **High precision:** Precision position measurements from **drift tubes**
- **Fast:** Fast timing information from **scintillator strips**

An example of a muon detector station



Drift tube area

spatial measurements with a resolution of **σ_{xy}~100μm per tube**

- Reconstruction of track segments,
- Reconstruction of decay vertices of long-lived particles

Scintillator strips

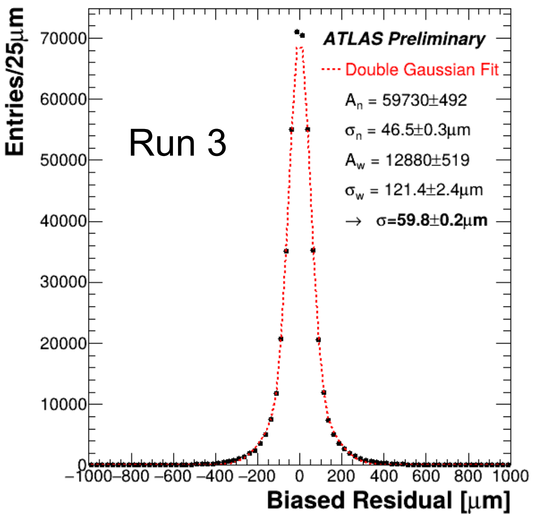
with **σ_z~1mm** and **σ_t~200ps**

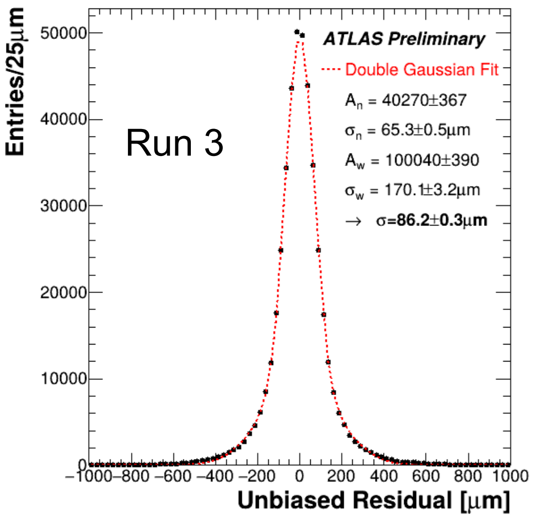
- Triggers
- Momentum measurement with multiple stations
- Time-of-flight (TOF) information for massive stable particles

Drift Tube and Scintillator Strip Performance

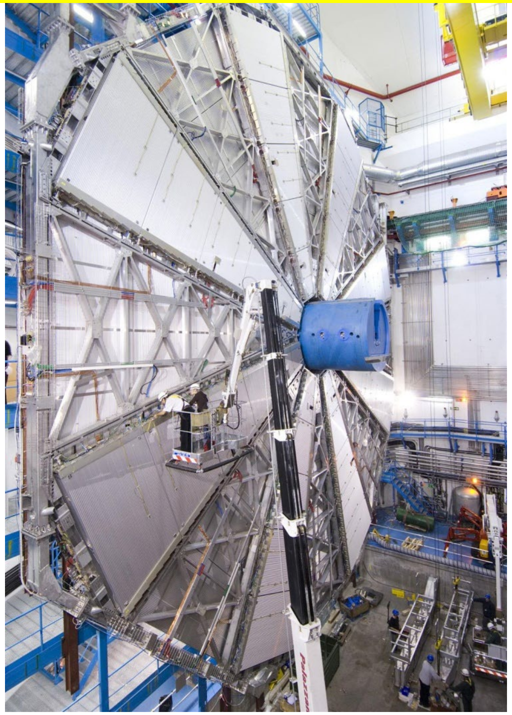
Excellent performance of ATLAS Precision drift tube muon detector

- ✓ Momentum scale accurate to 0.1%
- ✓ Resolution reached design goal: ~80 μm per tube
- ✓ TDAQ efficiency close to 100%
- ✓ 99.7% fully functional after 15 years operations at the LHC





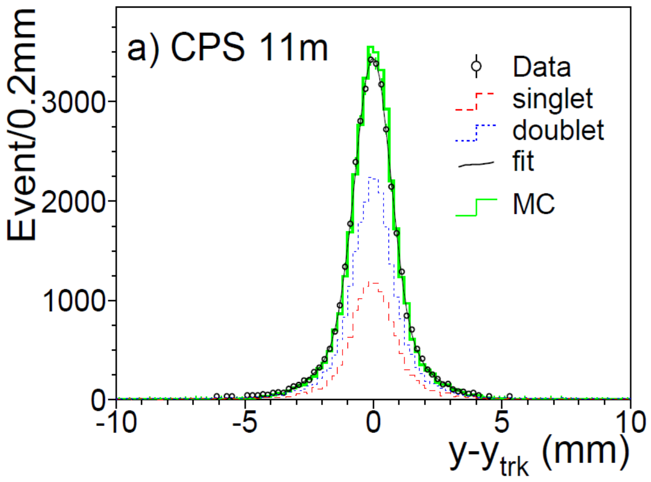
ATLAS muon detector: Big-Wheel



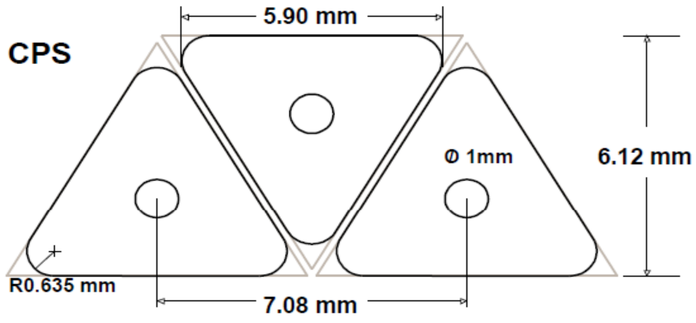
D0 experiment used extruded scintillator strips from Fermilab, with holes in the middle to house Wave Length Shifting (WLS) fibers.
Visible Light Photon Counters (VLPCs) were used as photodetectors

Now, SiPMs have better specs than the VLPCs and are faster, should improve the performance! Readout both ends for TOF information.

Sci. strips for the D0



NIM A 378 (1996) 131
arXiv:hep-ex/0007026



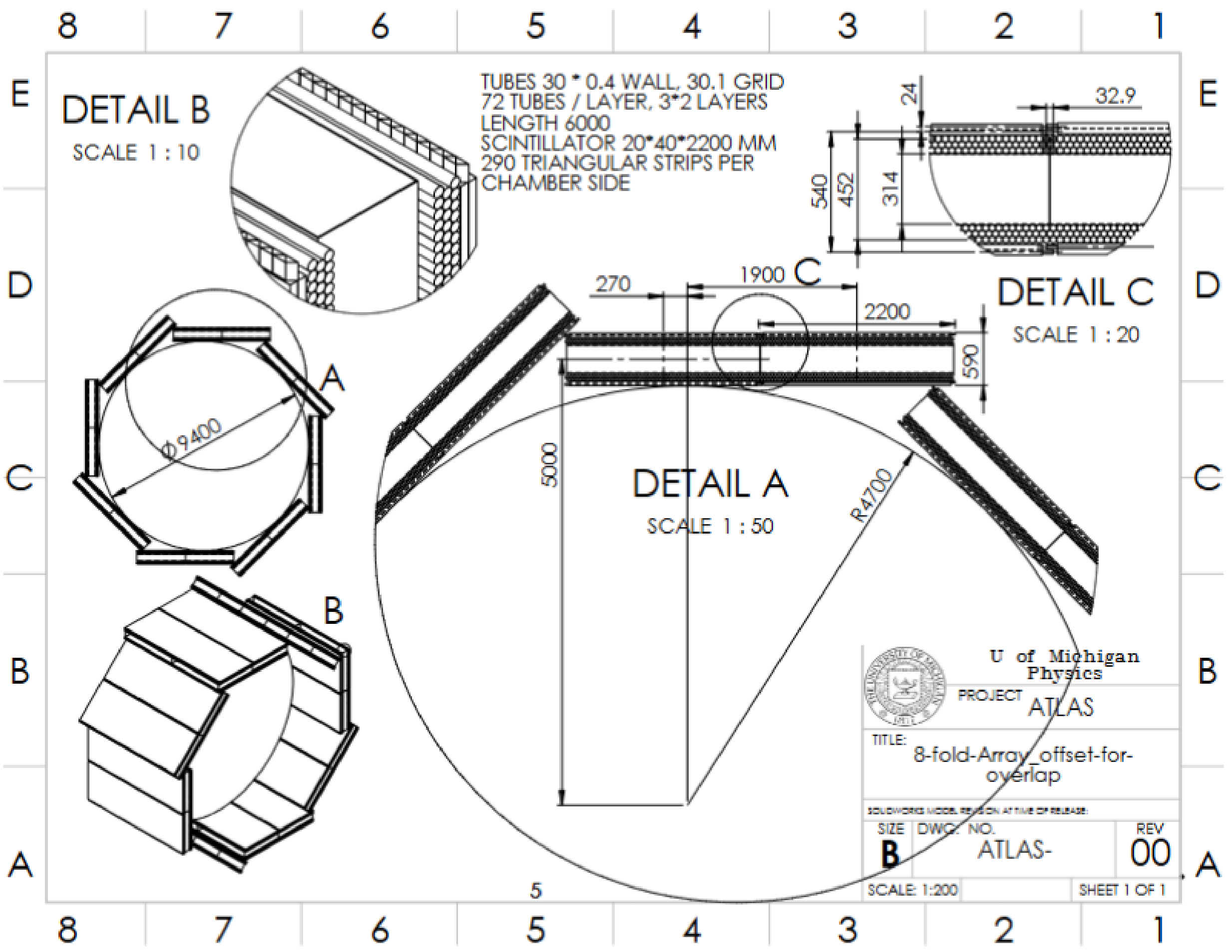
resolution of ~8% of the strip base width

Detector Layout Study with ALLEGRO Concept

Key parameters of the muon detector

Component	Parameters
Drift-tube	Length: 6000 mm Outer Diameter: 30.0 mm Gas Material: Ar:CO_2 (93%:7%) Wall Thickness: 0.4 mm Wall Material: Aluminum Wire Diameter: 35 μm Wire Material: Tungsten Configuration: 72 tubes/layer, 6 layers/module
Scintillator	Length: 2200 mm Cross-section: Triangular (40 × 20 mm) Scintillator Material: Polystyrene plastic Configuration: 290 strips per chamber side
Module Gap	Spacer thickness: 314 mm

Engineering Drawing



GEANT4 Simulation of Muon System

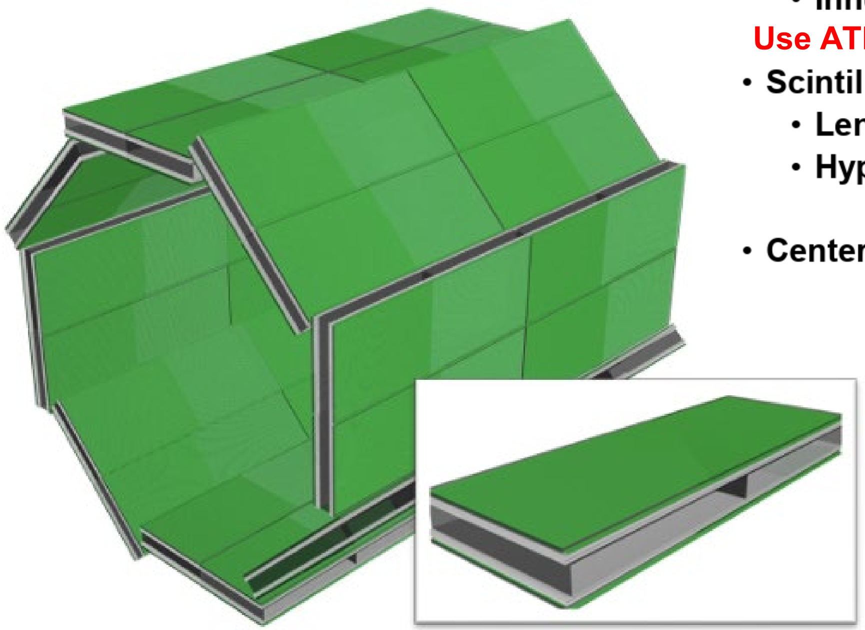
Geometry in DD4hep

- Geometric acceptance > 98% with the layout of the muon system
- Can extend to multiple stations

- **Muon System**
  - Barrel

- Main parameters
  - Tube
    - Length 6000mm
    - Outer diameter 30mm
    - Inner diameter 29.2mm

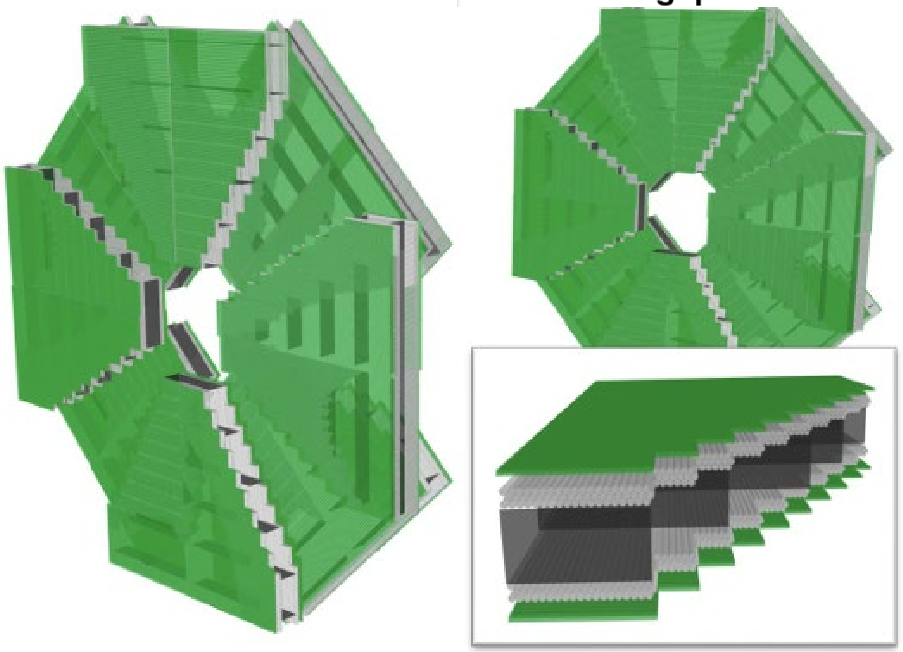
  Use ATLAS BOL MDT as a model
  - Scintillator
    - Length 2200mm
    - Hypotenuse 40mm
  - Center gap thickness 317mm



Muon Barrel (module)

- **Muon System**
  - EndCap

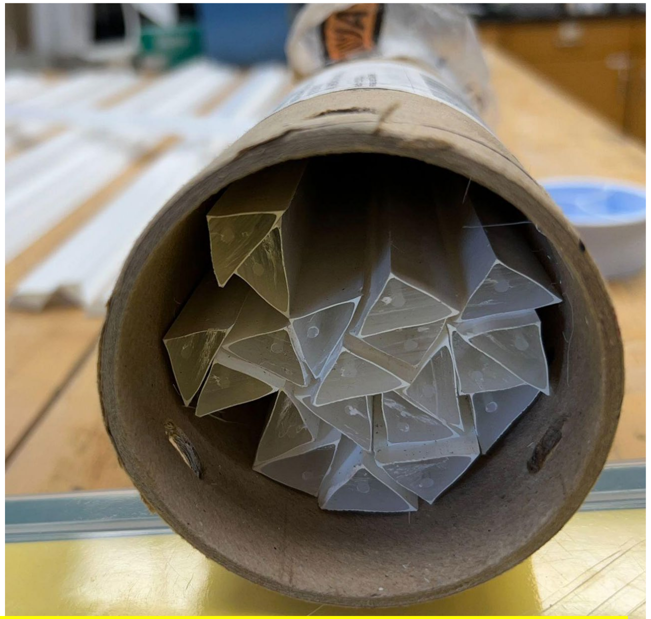
- Main parameters
  - Tube
    - Length 1000~3700mm
    - Outer diameter 30mm
    - Inner diameter 29.2mm
  - Scintillator
    - Length 586~2170mm
    - Hypotenuse 40mm
  - Center gap thickness 300mm



Muon EndCap (module)

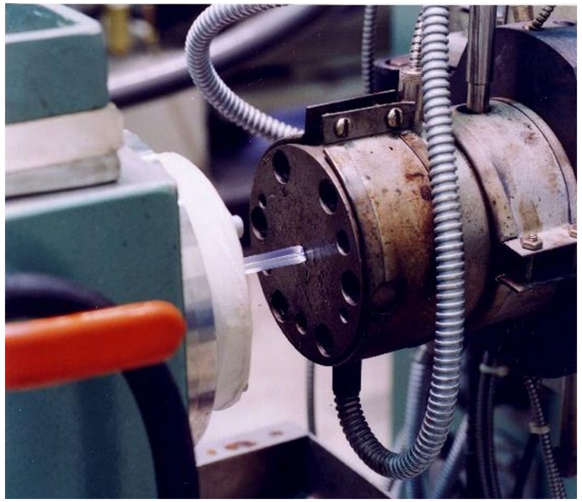
Scintillator Strip Production at Fermilab

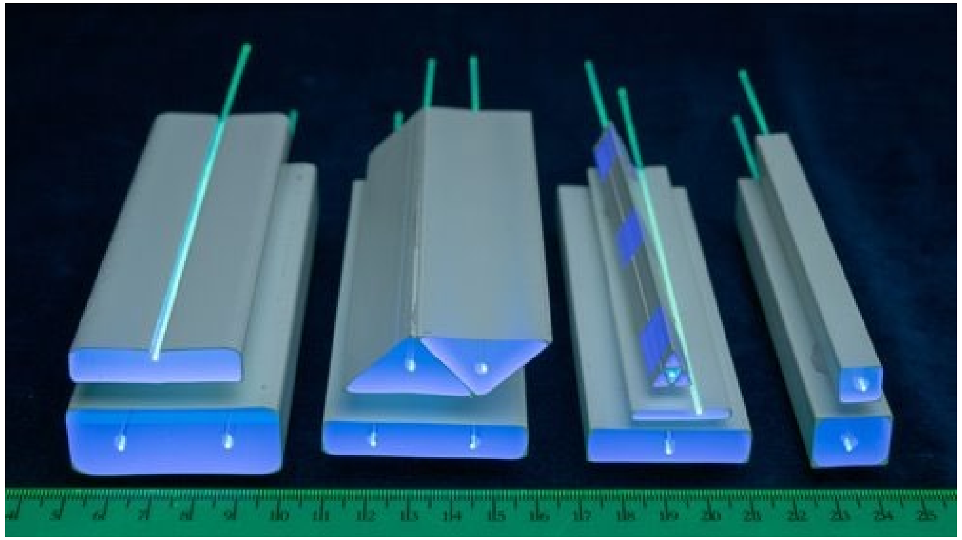
- Fermilab scintillator strip production facility is unique worldwide: high quality, low cost!
- We visited Fermilab twice to learn how to build the strip detector and obtained more than 100 triangular strips to build multiple small scintillator strip prototypes at UM.



Triangular Strips brought back from Fermilab to UM to make prototypes

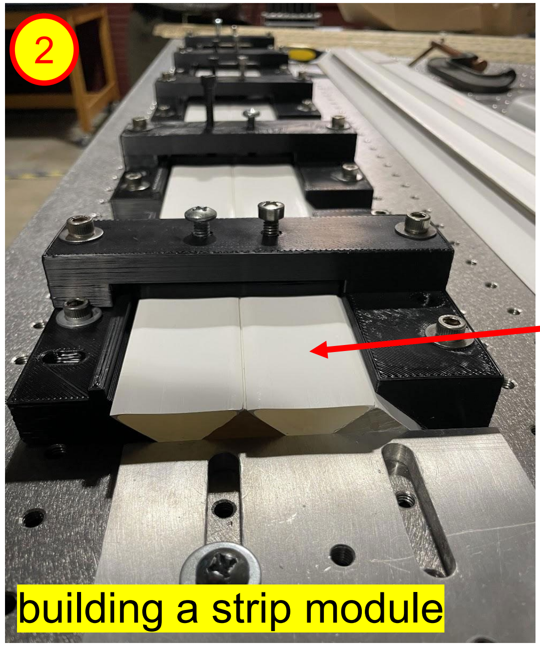
Fermilab Scintillator Extruder System



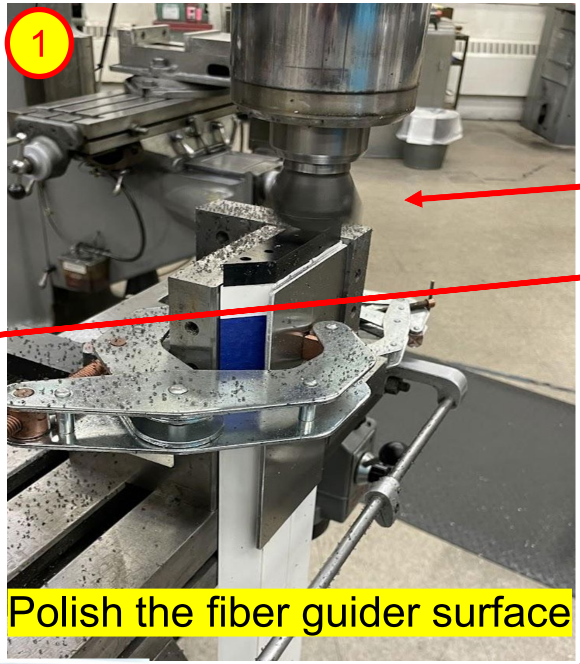


Scintillator Strip Detector Construction at UM

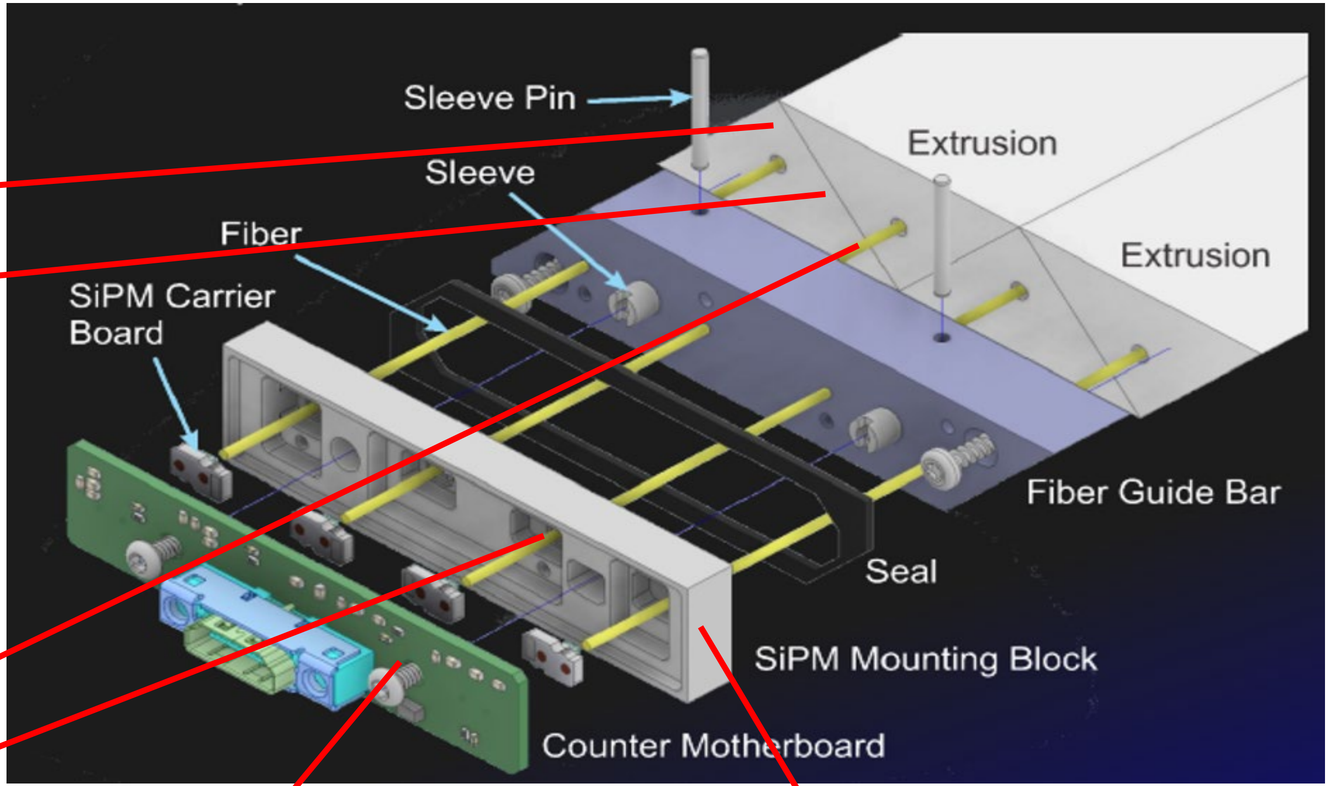
Triangular scintillator strips: 4 cm base, 2 cm height, and 1 m long, from Fermilab, **WLS fibers**: Kuraray YS-2M and YS-4M, 1.5mm diameters; **Hamamatsu S13360-3075PE SiPMs** on both ends.



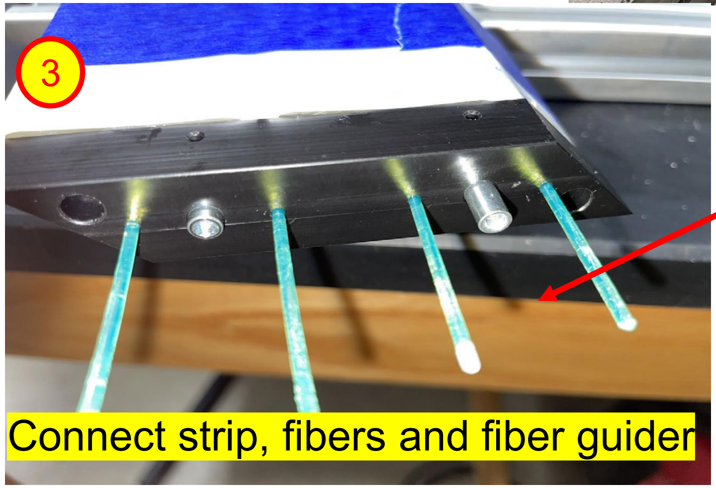
building a strip module



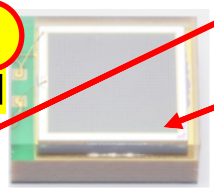
Polish the fiber guider surface



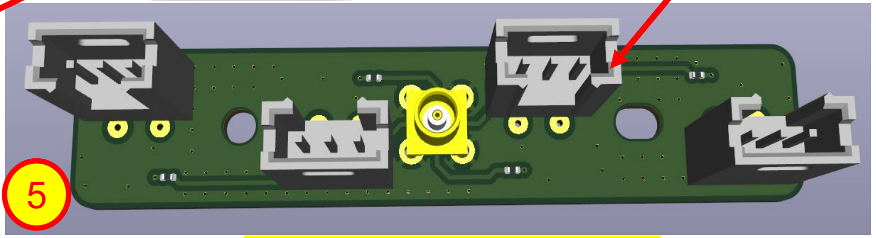
https://arxiv.org/abs/2202.08184



Connect strip, fibers and fiber guider



SiPM



RO PCB Motherboard

SiPM holder

Scintillator Strip Detector Prototype and DAQ System

- Built 2 scintillator strip prototypes: each contains 8 strips, SiPMs on both ends shipped to CERN for test beam studies, and 1 module (4 strips) at UM for cosmic ray test,
- Use CAEN DT5202 for SiPM bias voltage and signal readout:
  - Based on Citiroc ASICs: Preamplifier, a Slow Shaper with peak sensing detector, and a Fast Shaper followed by a discriminator.
  - ADC to digitizer peak; FPGA based TDC for time measurement.
  - Dual range low gain and high gain for peak finding;
  - 0.5 ns LSB, 0.25 ns resolution for Time-of-Arrival (TOA) and Time-over-Threshold (TOT) measurements.

DT5202 unit

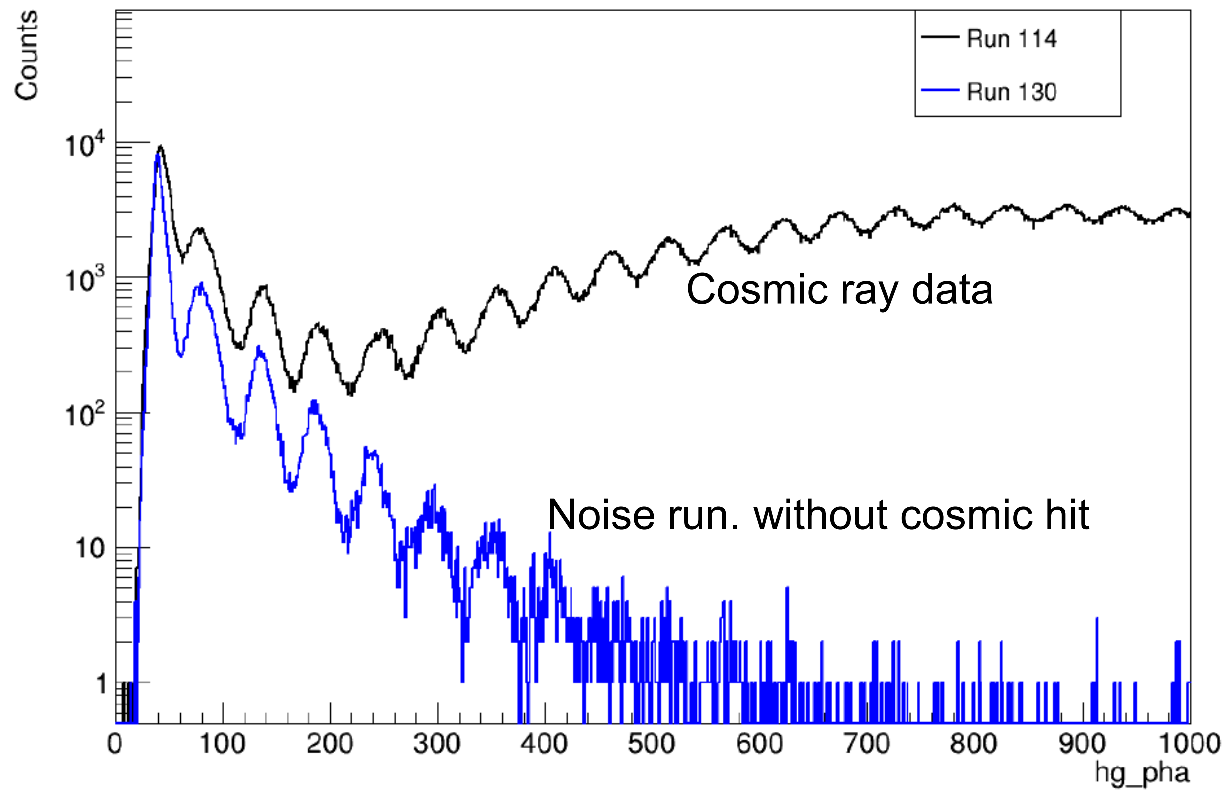
Apply optical grease on the SiPM window for better coupling

Two Scintillator Strip Detector Prototypes
- Each contains 2 quartic-strips modules (total of 8 single strips);
- SiPM readout on both ends.

Cosmic Ray Studies at Michigan

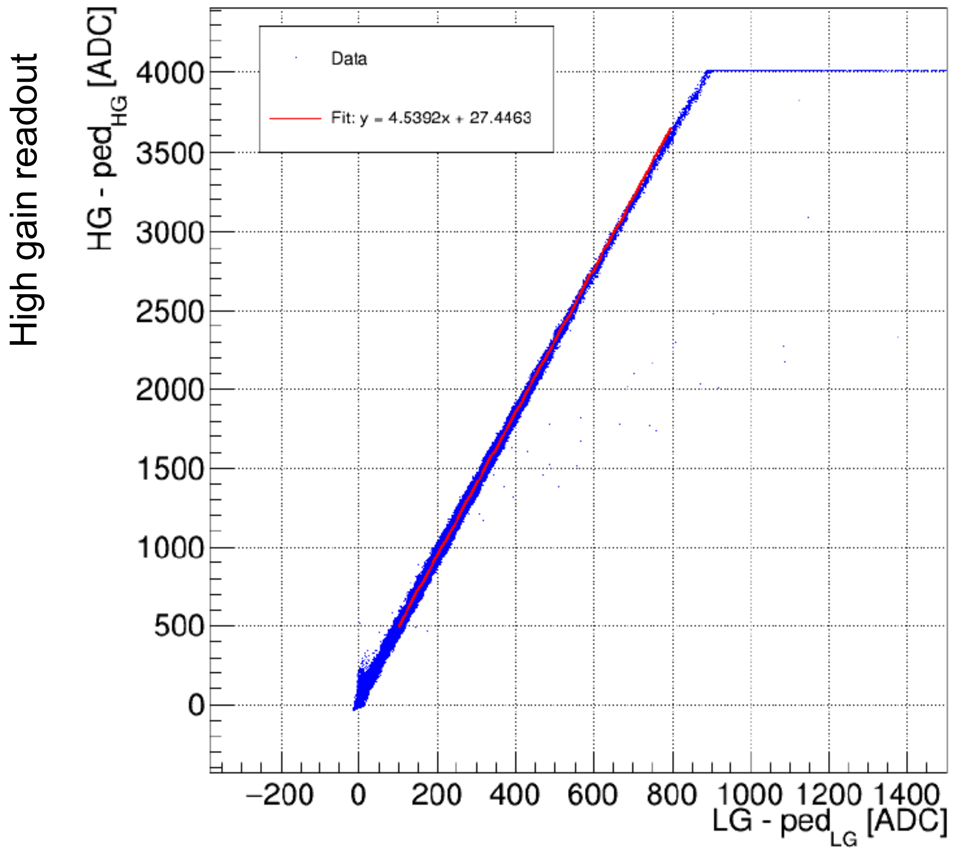
CAEN module with two 32-channel Citiroc ASICs, with both high and low gain readouts. High Gain for single PE calibration, and low gain for MIP measurement

Calibrate using single PE peaks in the high gain readout



High gain readout

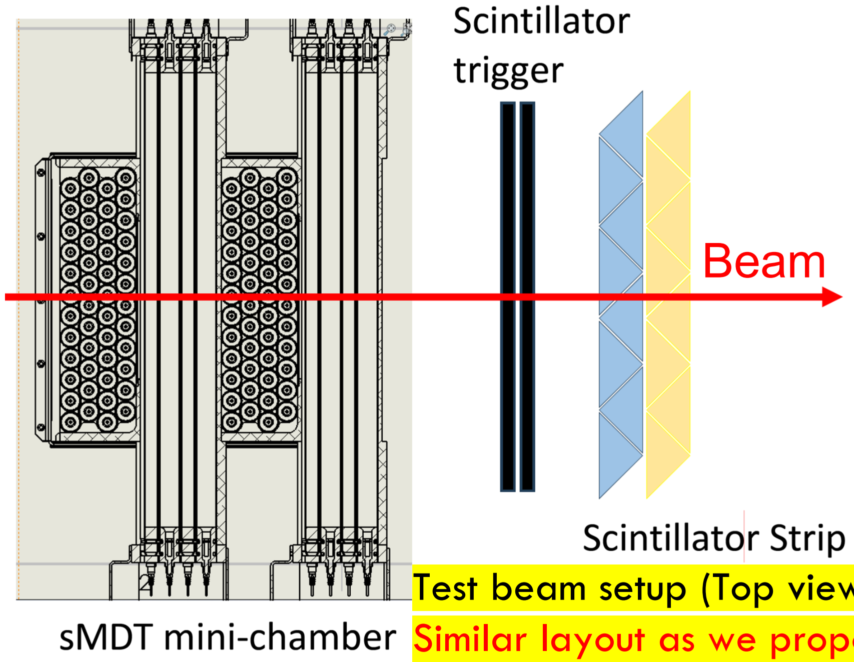
Calibration: High gain vs. Low gain readout



Low gain readout

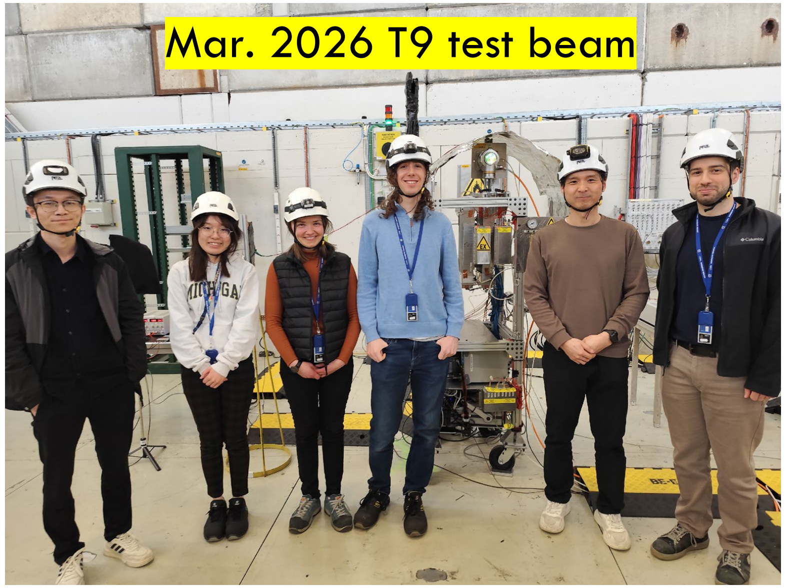
Test Beam Campaign at CERN

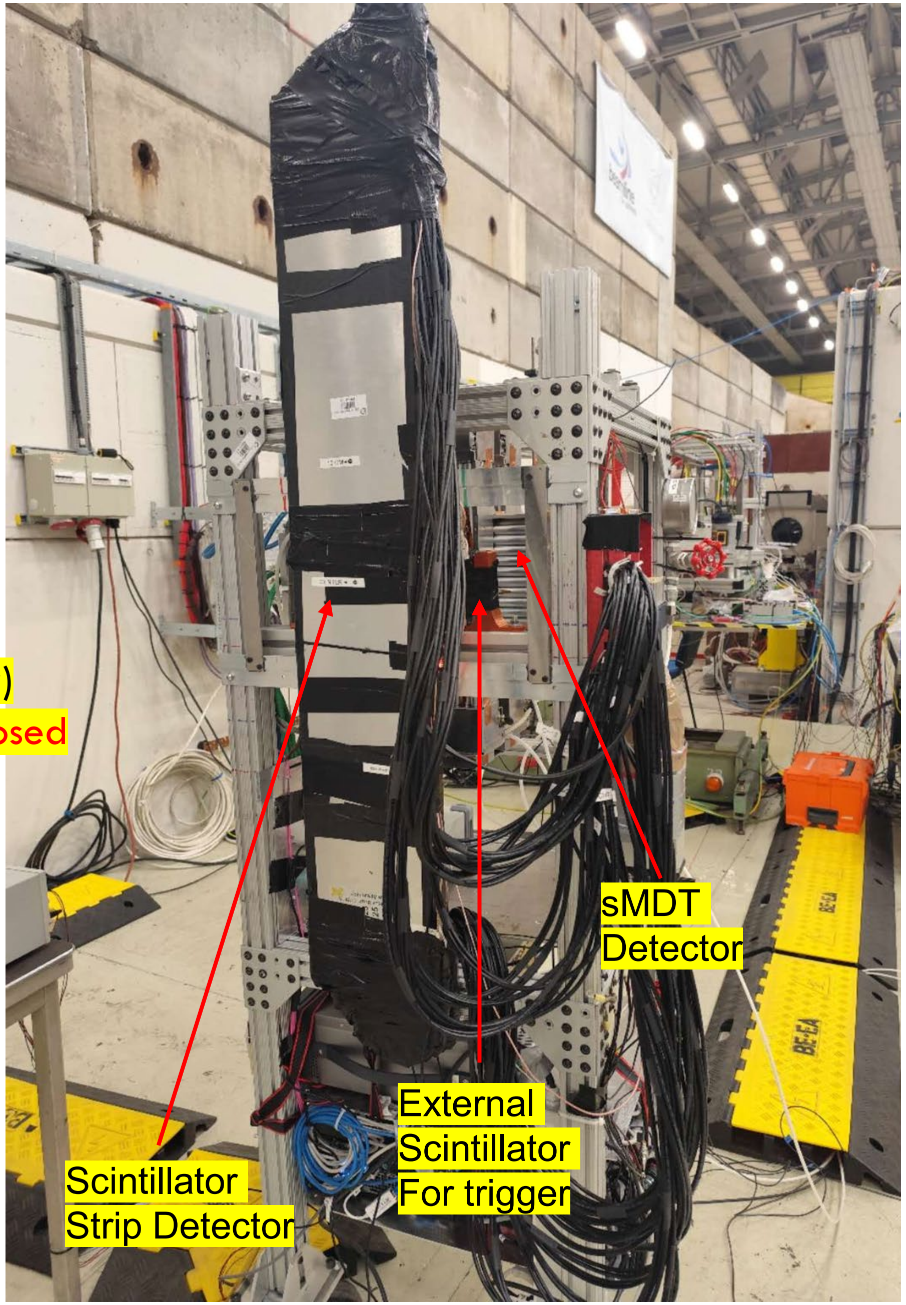
- Joined two test beam campaigns at CERN PS T9 to verify the performance of the scintillator strips with 10 Gev Hadron beam.
- Mini-sMDT chambers provide 3D reference tracks. Using 3-bar 93:7 Ar:CO_2 gas mixture and +2730 V HV. ATLAS MDT electronics readout.
- Overall synchronization efficiency is 95-99%.



Test beam setup (Top view)

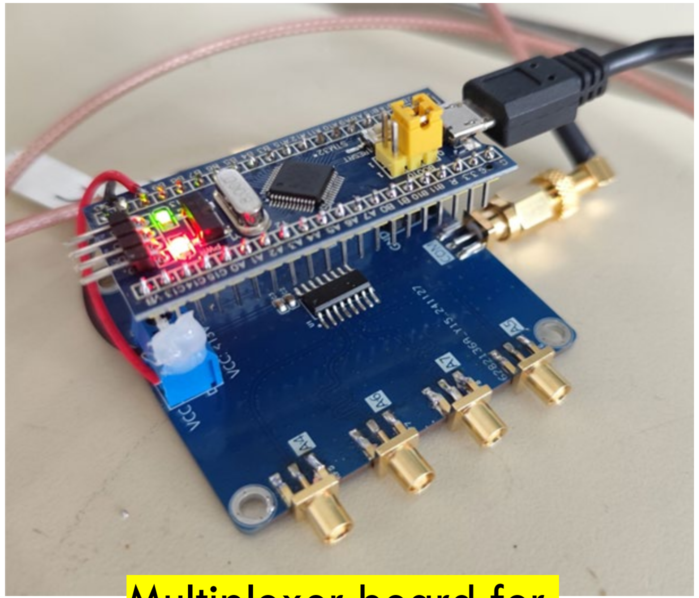
Similar layout as we proposed



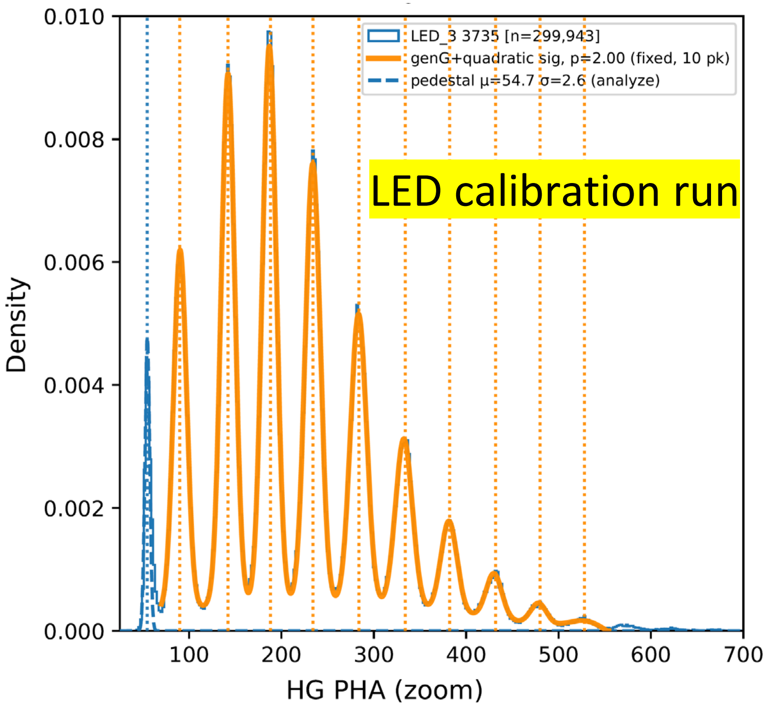


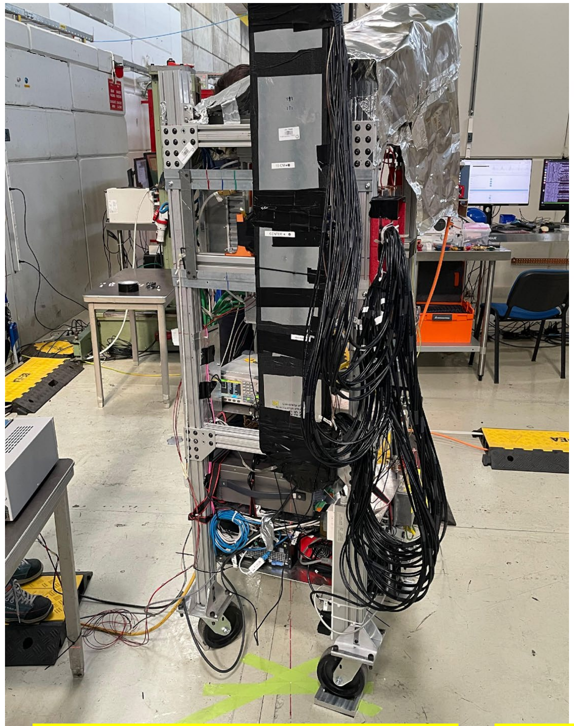
Test Beam Campaign at CERN

- Position scan
  - 8 different points along the strip
  - 7 different points across different strips at center (A group) and 25 cm away from center (F group)
  - ~30 degree tilted for A0/A1/A2
- External scintillator trigger as default; Self-trigger for A&B groups
- Threshold scan at A0/A1/A2
- LED calibration run and noise run for each movement

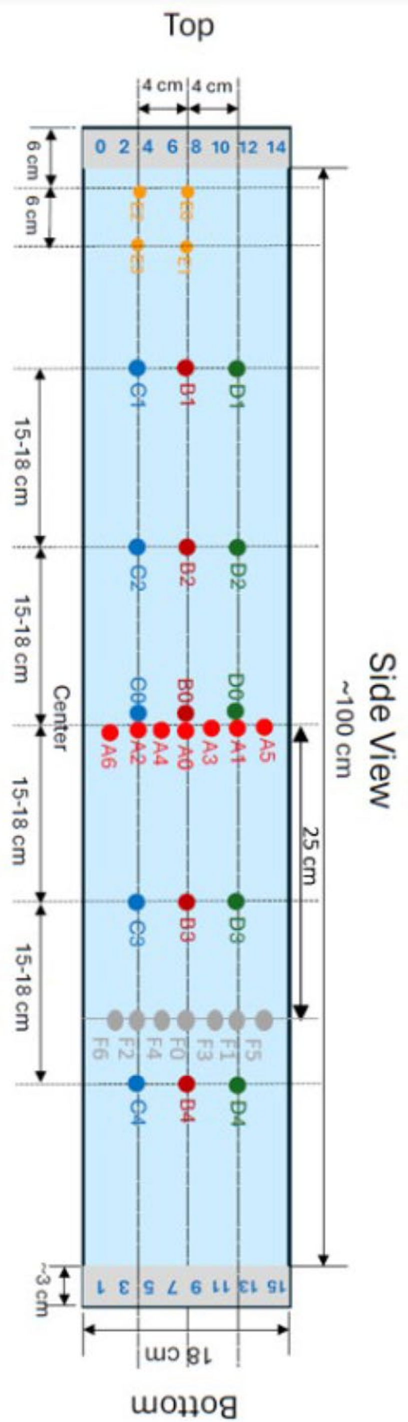


Multiplexer board for automatic LED calibration scan

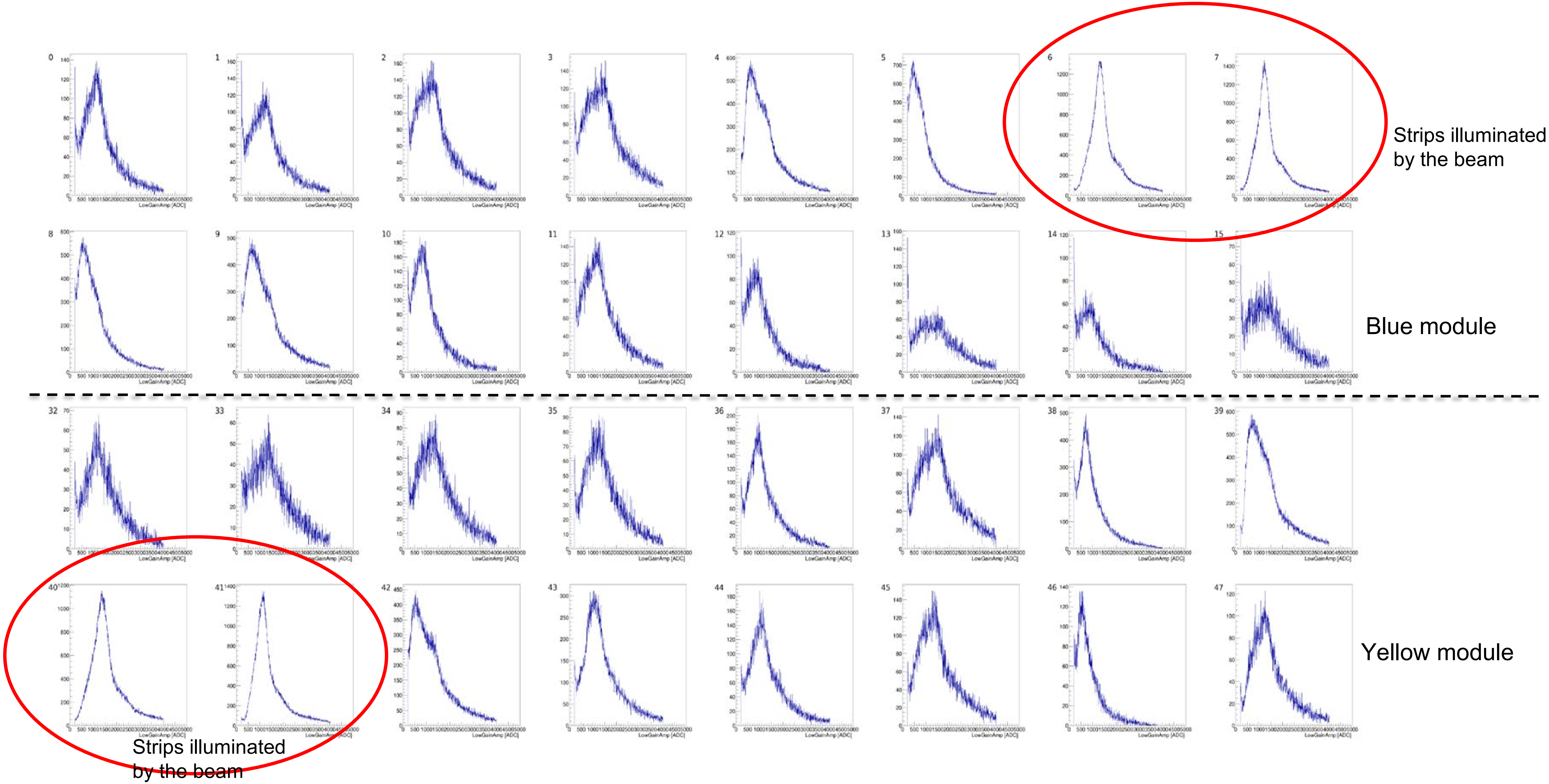




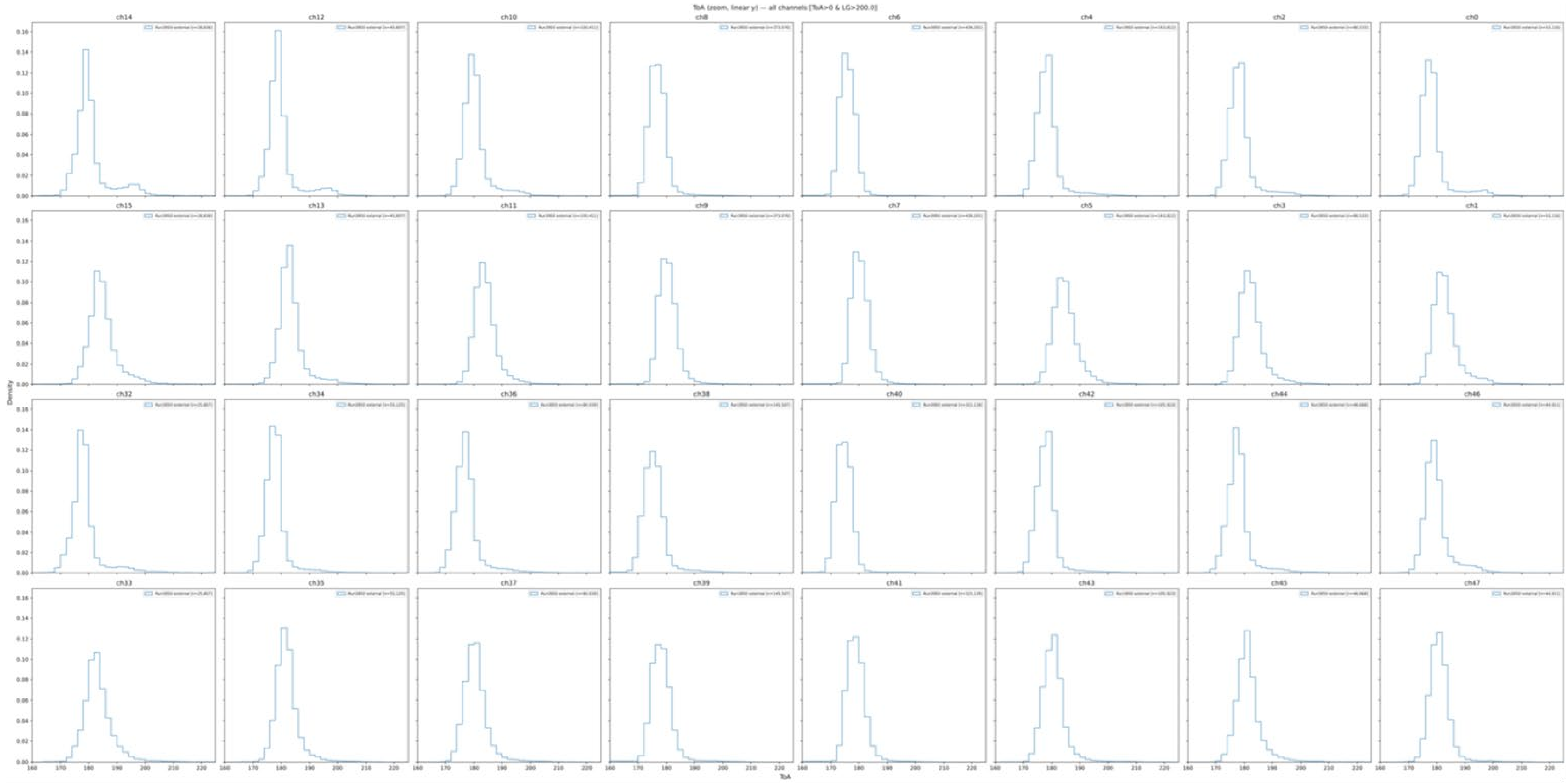
Tilted the detector by $\pm 30°$ to the beam line



Raw ADC Spectra from Low Gain Readouts for all 32 channels



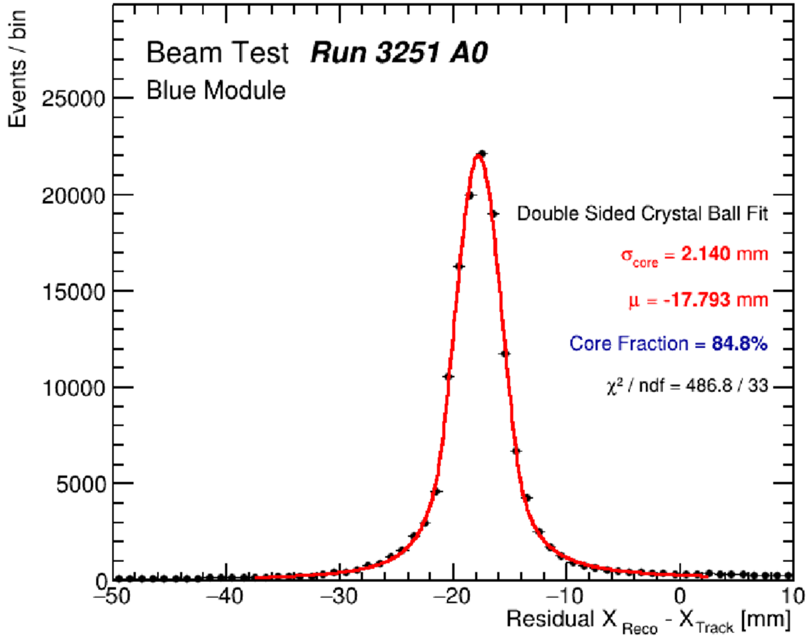
TOA distribution across channels



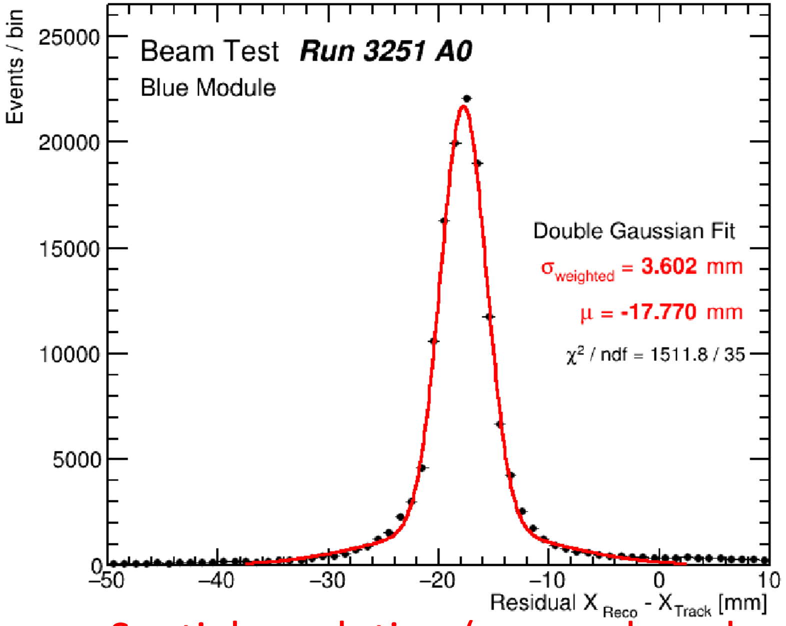
Mar 2026, position at B1, LG-PA, using external trigger, deadtime=4000 ns

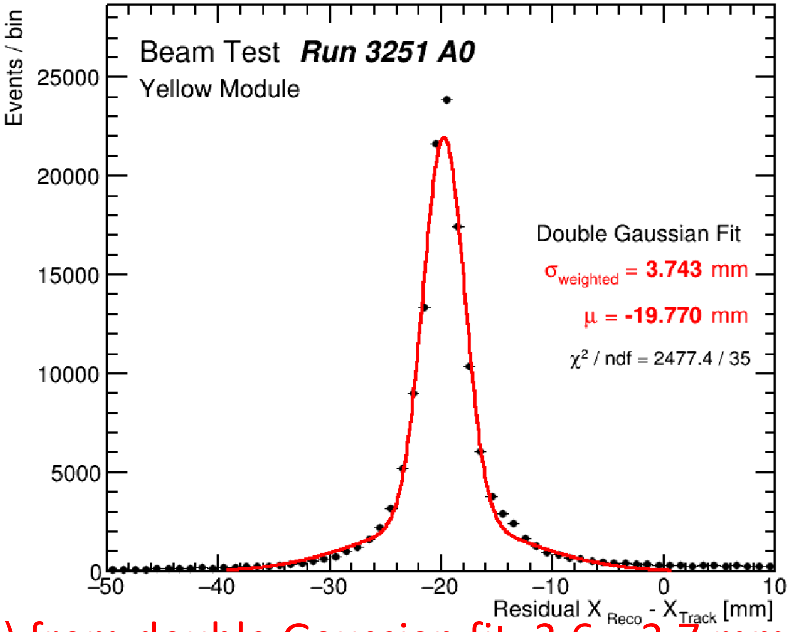
Preliminary Test Beam Results

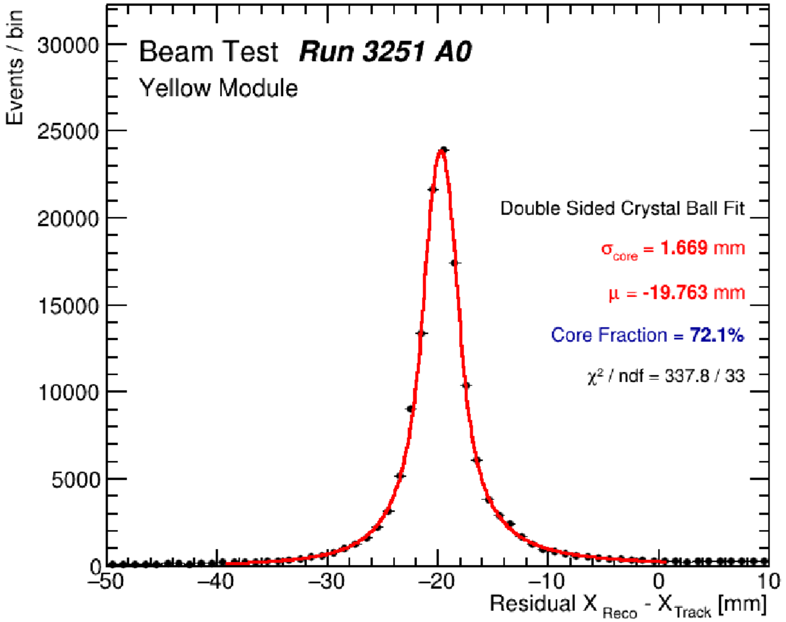
- **Cross-Strip spatial resolution** study (Nov 2025 test beam data)
  - Reference tracking collection.
  - PE calibration with position from sMDT and was compared to the centroid of the scintillator strip charge HG/LG
- Spatial resolution (core): 1.7 – 2.1 mm (see plots right)
- Spatial resolution (one end readout) from double Gaussian fit: 3.6 – 3.7 mm (including the tail contributions) → see plots below.
- 2026 test beam: With better calibration method and equal cable lengths to improve the resolution.



the core has a resolution 1.7~2.1mm



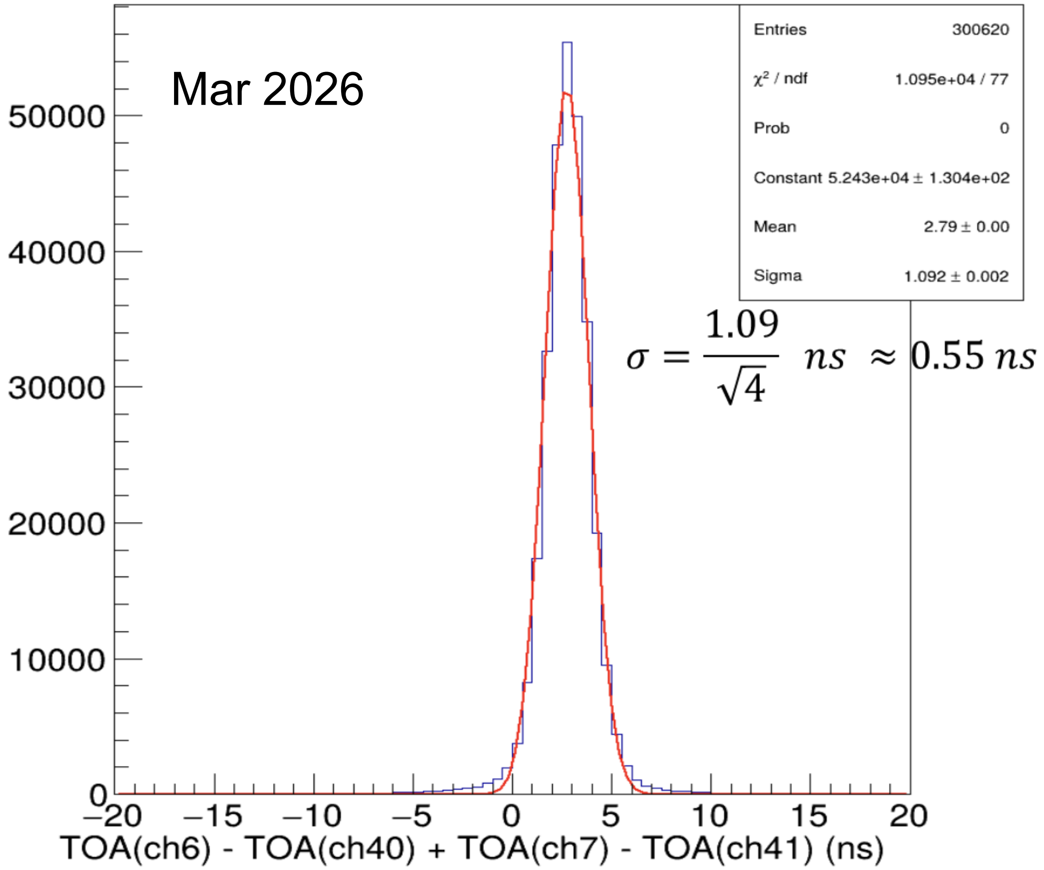


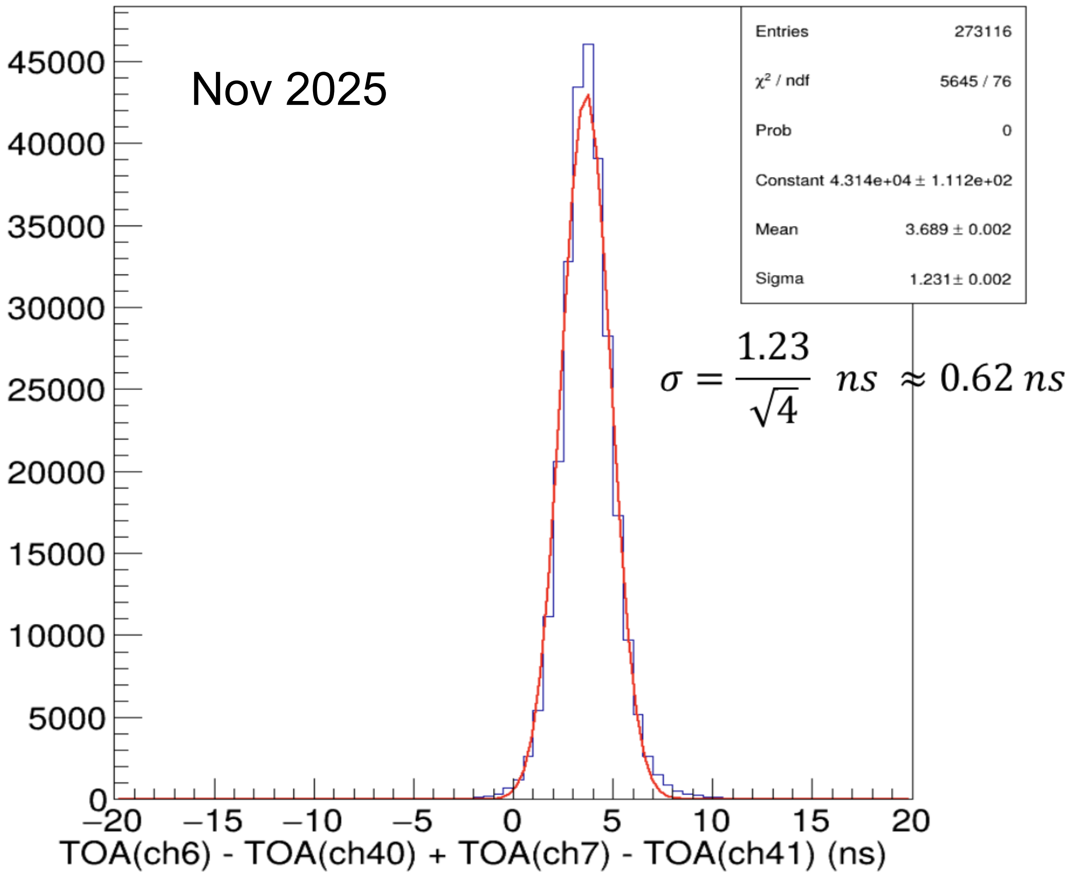


Spatial resolution (one end readout) from double Gaussian fit: 3.6 – 3.7 mm

Preliminary Test Beam Results

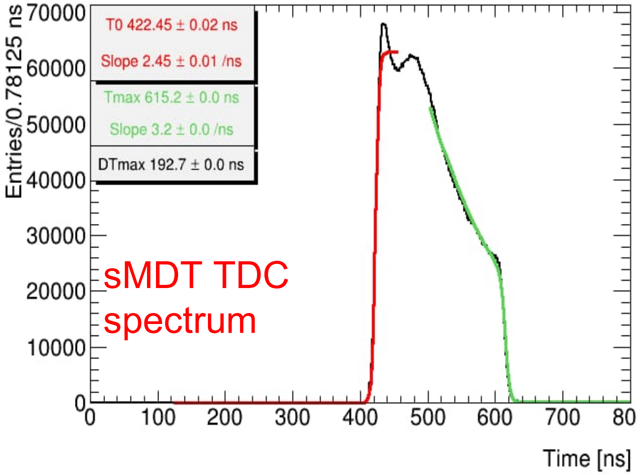
- **Single channel time resolution** from Mar 26 was 0.55 ns
- Resolution from Nov 25 of the same position calculated with the same channels was 0.62 ns.
- The intrinsic time resolution of CAEN DT5202 was measured to be around 280 ps. We still have a large room to improve: time slew correction, calibration, reference track, etc.

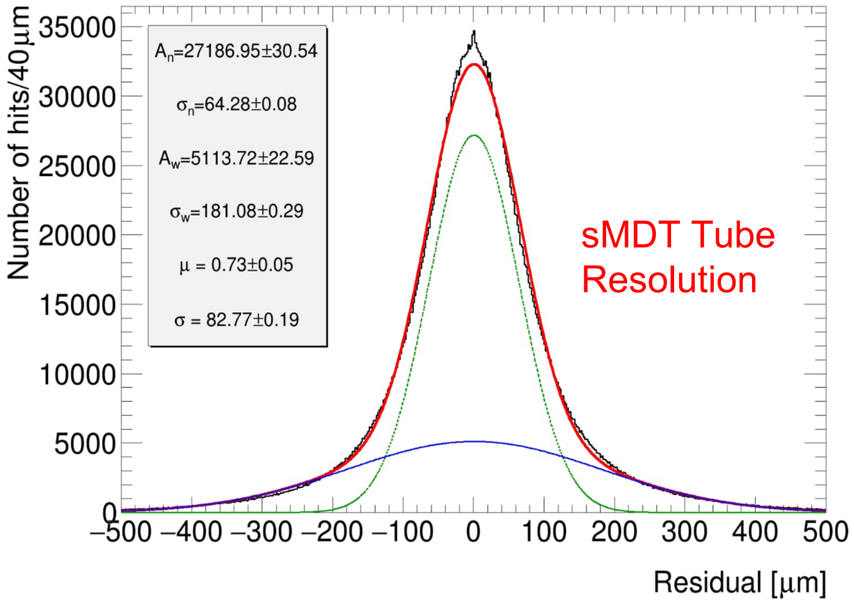


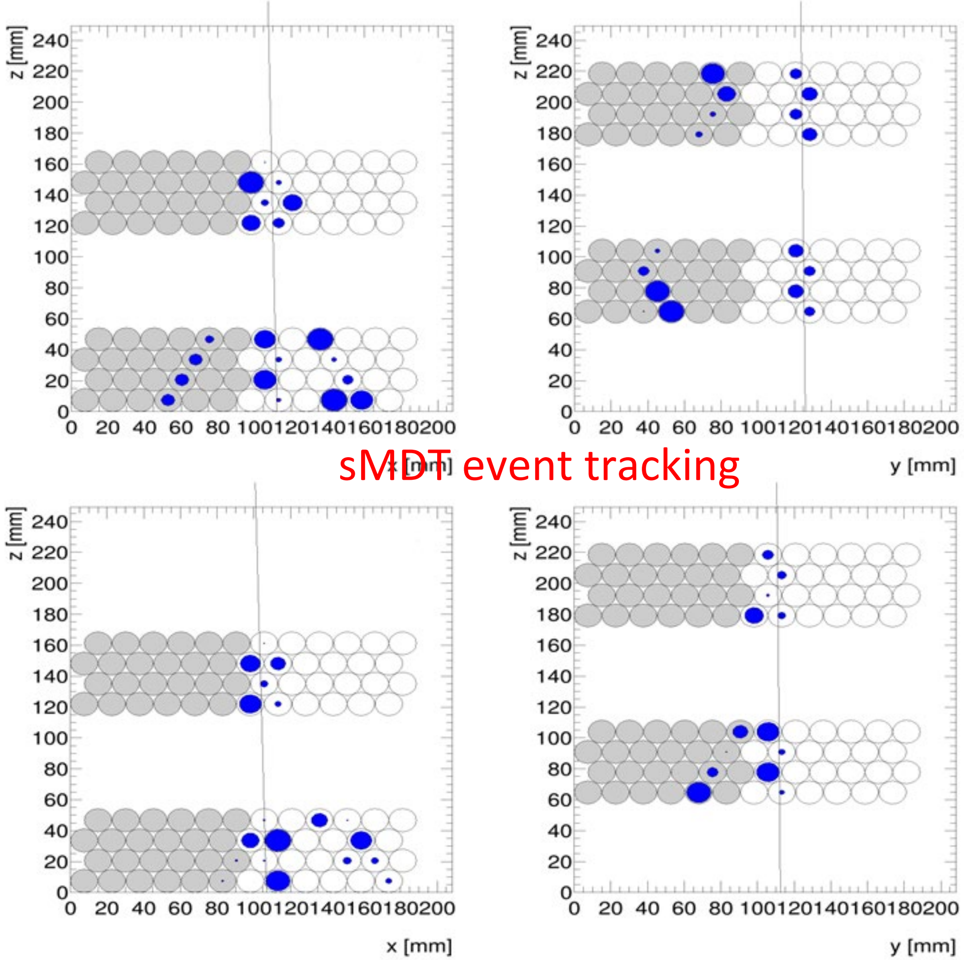


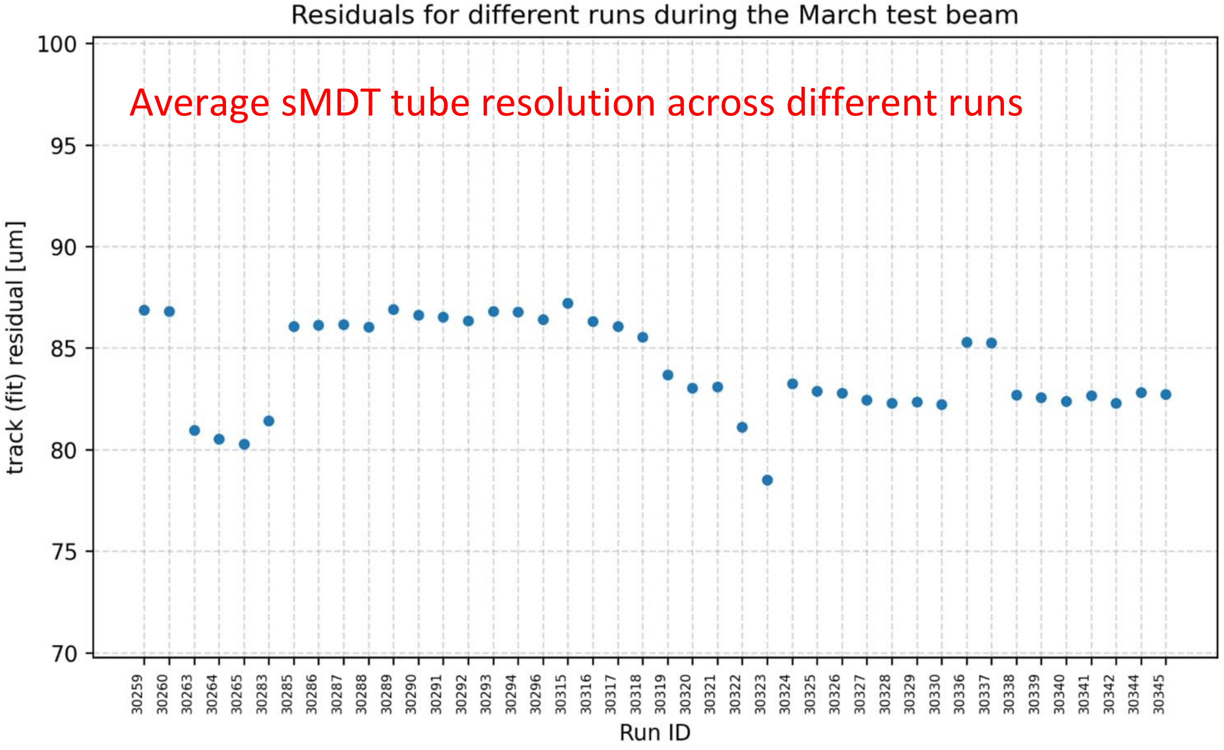
Preliminary Test Beam Results

- sMDT chambers used in the test beam can provide 3D tracking;
- **Average sMDT tube resolution ~85 µm**









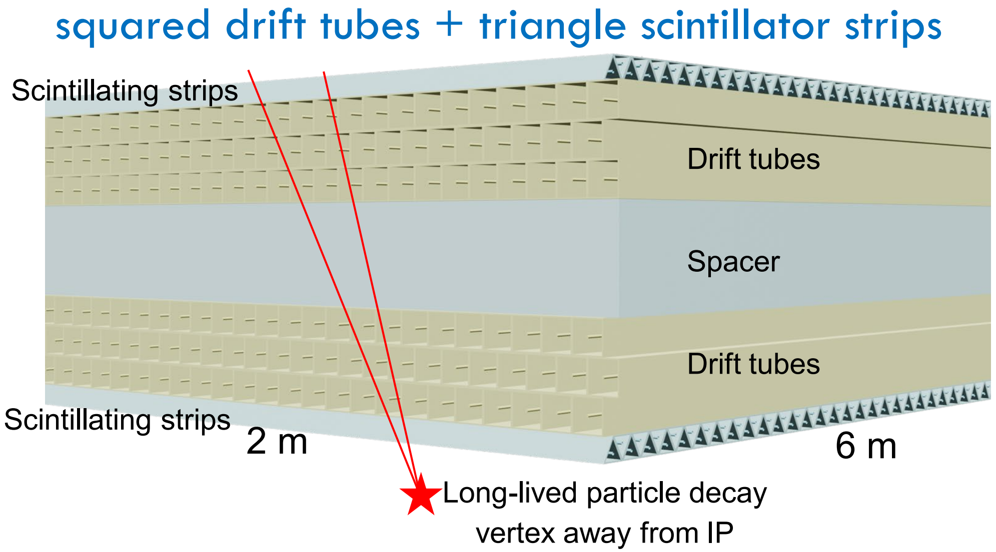
On-going/Planned Test -beam Data Analysis

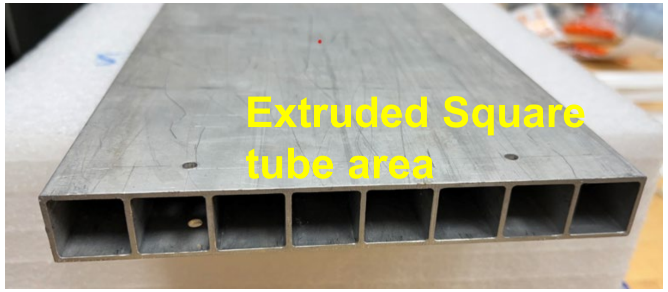
Lots of work to do on data analysis:

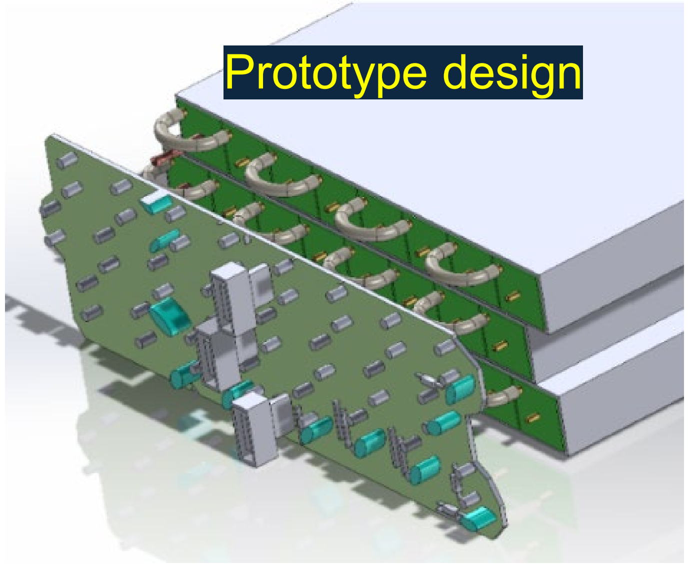
- Charge Particle **Track Reconstruction**
- sMDT and SCNT-strip **DAQ event synchronization** and sMDT reference tracker for SCNT-strip in sMDT coordinate system
- **SCNT Strip calibrations**: AIMING all channels with same gains
- SCNT-strip Precision **position measurements and efficiency** determinations strip by strip
- SCNT-strip **time measurements and efficiency** determinations strip by strip
- SCNT-strip **2nd coordinator along SCNT-strip** by using charge and time separately and efficiency determinations strip by strip
- SCNT-strip **signal attenuation studies** strip by strip
- SCNT-strip **trigger studies**
- SCNT-strip **GEANT4 simulation**

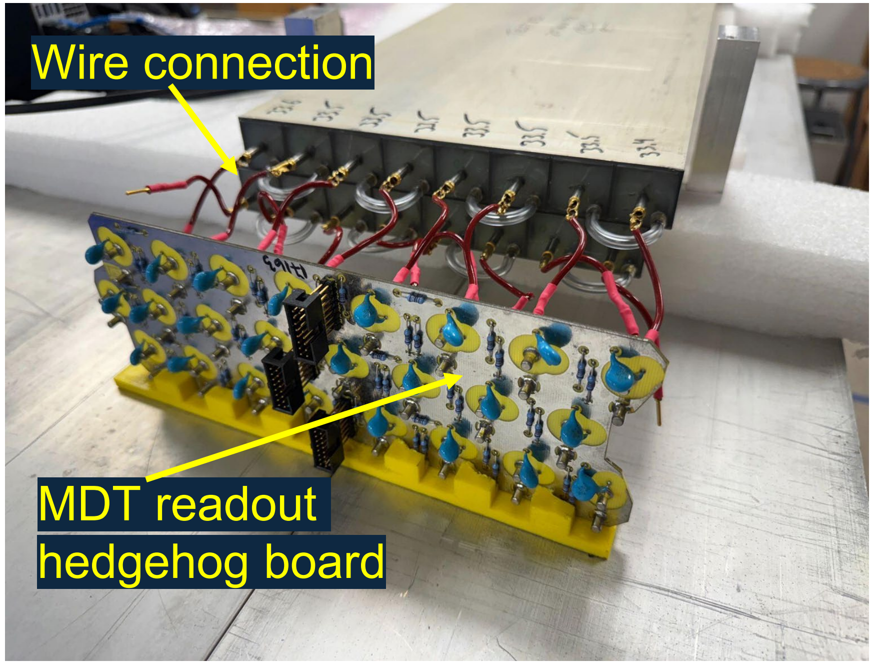
R&D: Squared Drift Tube Chamber Prototype

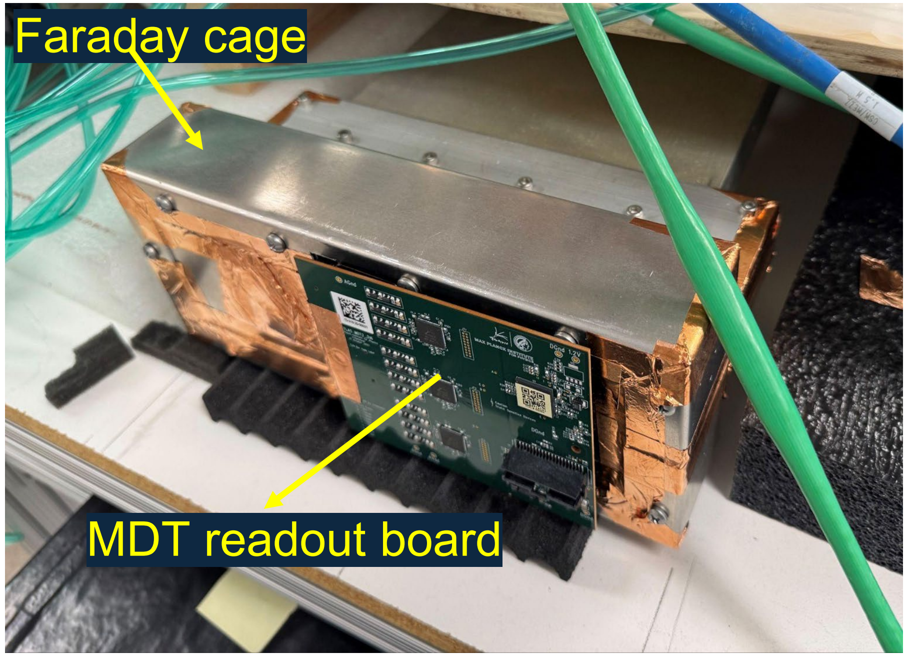
- One possible optimization is to use **square tubes** (e.g., 1-inch square tubes), which can **reduce costs by a factor of 5** compared to round tubes, while also simplifying chamber construction.
- Prototype was constructed. Further R&D is needed to evaluate the performance of square drift tubes.

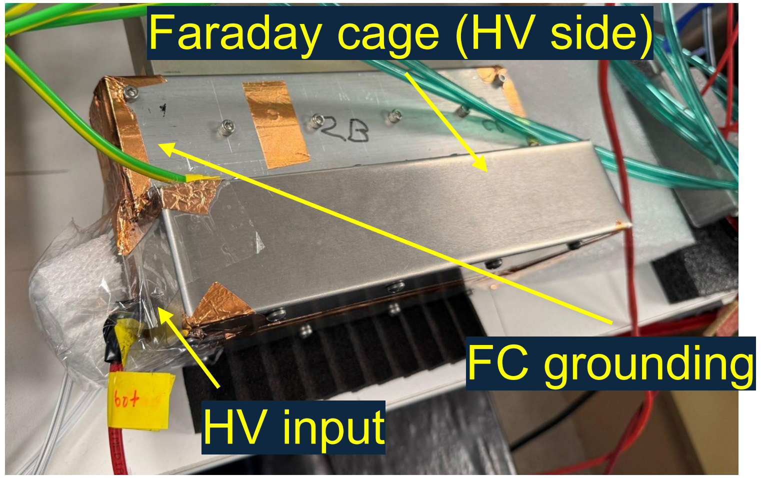








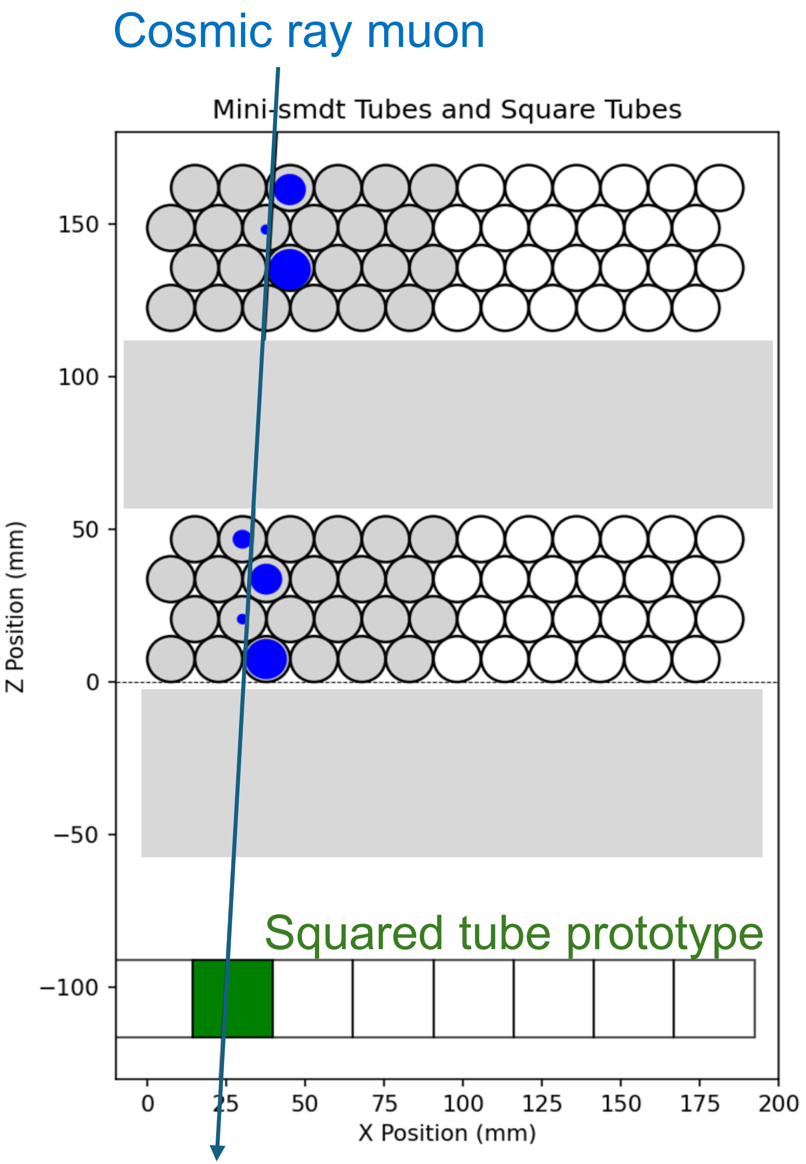


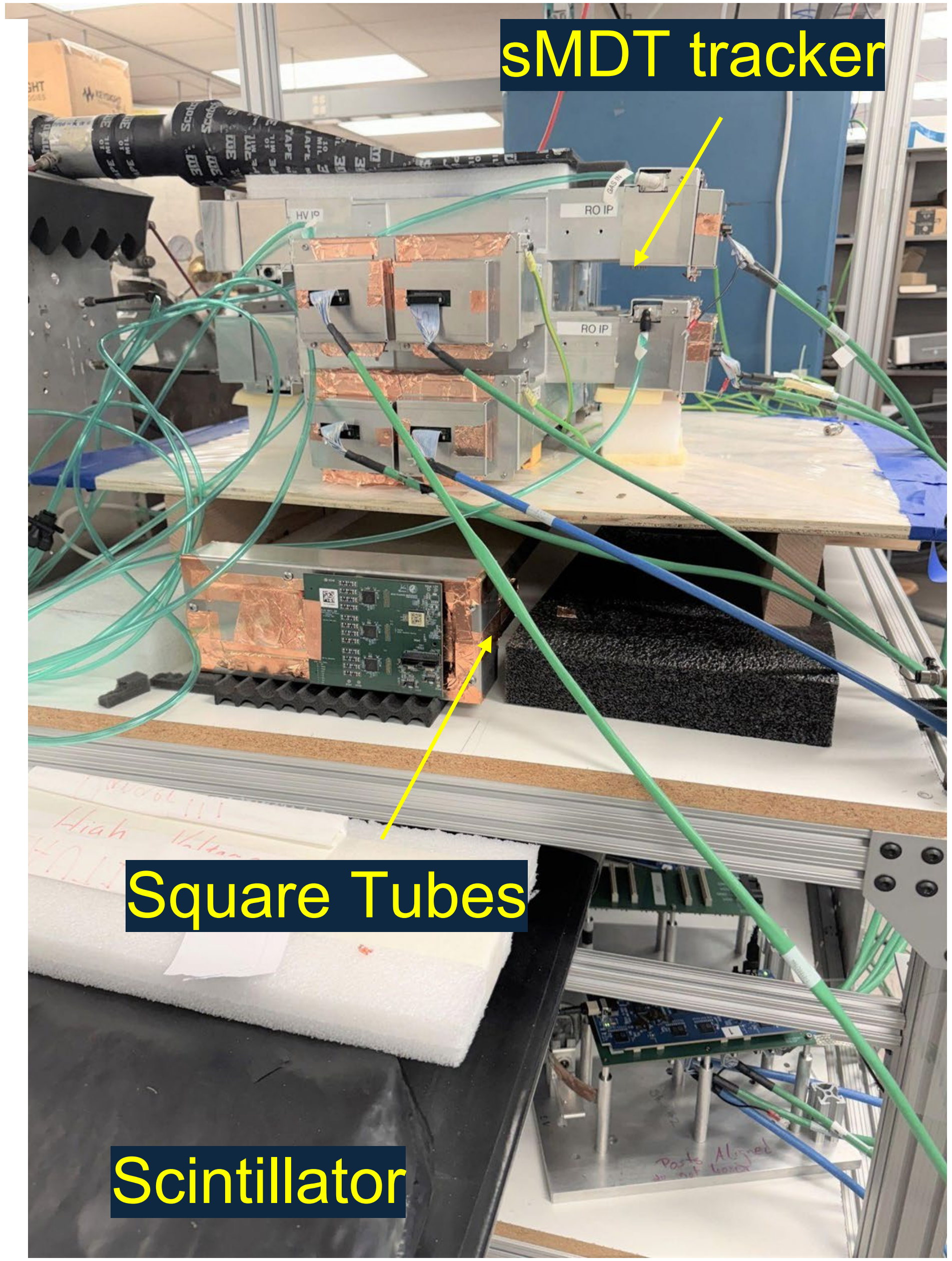


Cosmic Ray Test Station at University of Michigan

We use ATLAS sMDT as a 3D reference tracker to study performance of the square tube :

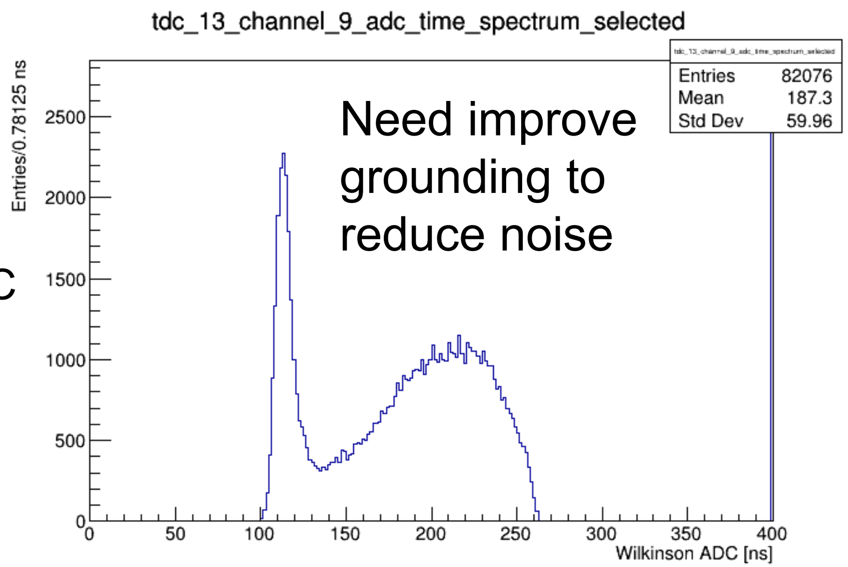
- 4-layer sMDT tubes (15 mm diameter, 34 cm length)
- 2 multi-layers in X and 2 in Y to form a tracker
- spatial resolution of ~100 µm per tube

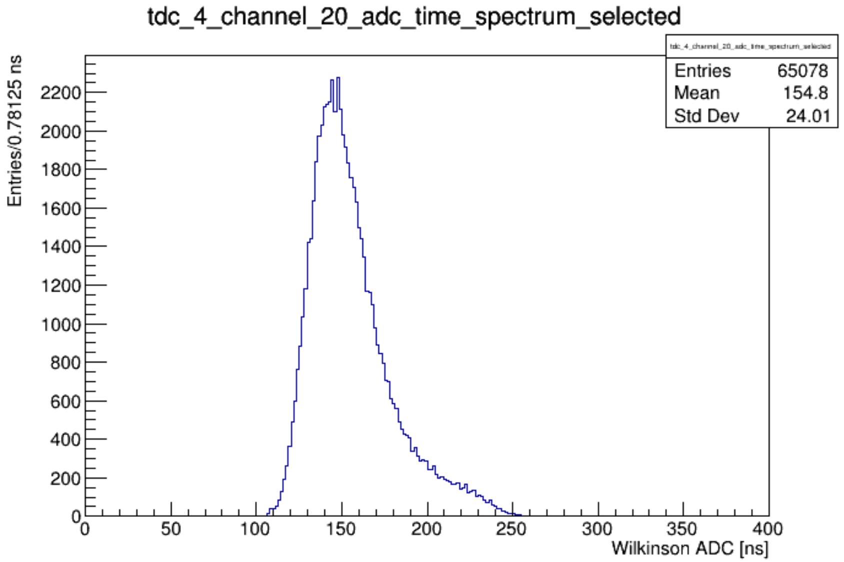




Square-tube ADC and Drift time (TDC) spectra

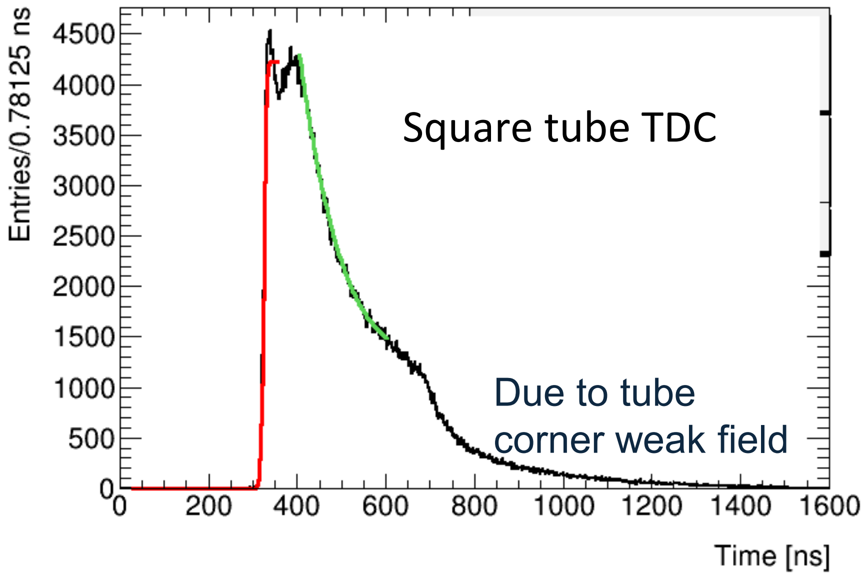
Square tube ADC
Ar:CO_2 93:7,
1.65 bar, 2176 V

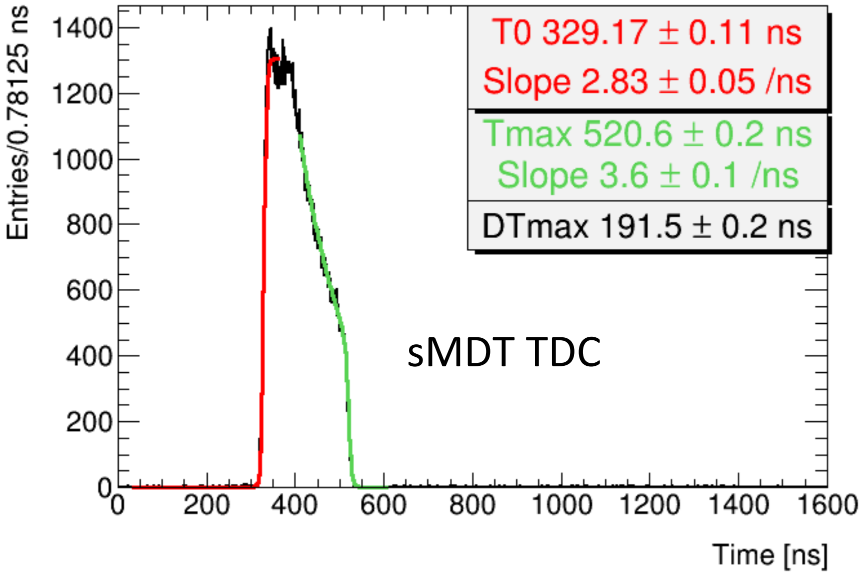




sMDT ADC
Ar:CO_2 93:7,
3 bar, 2730 V

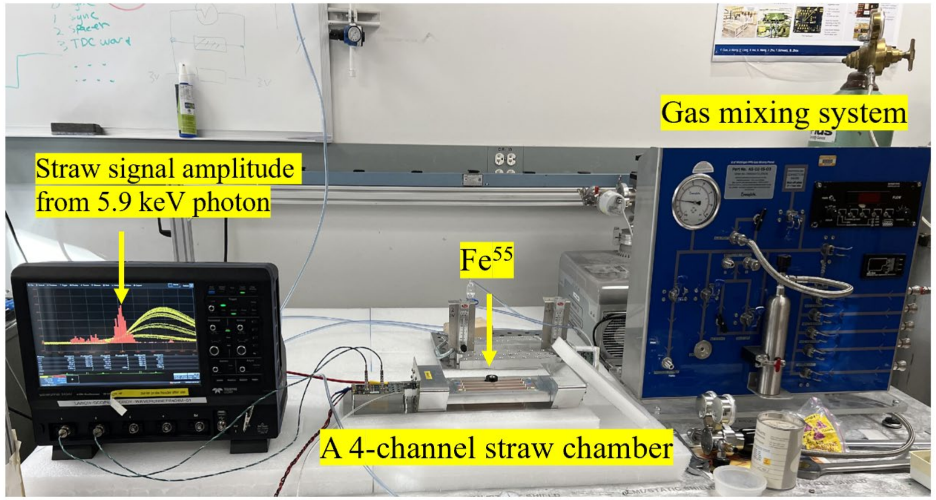
Require
detailed
calibration



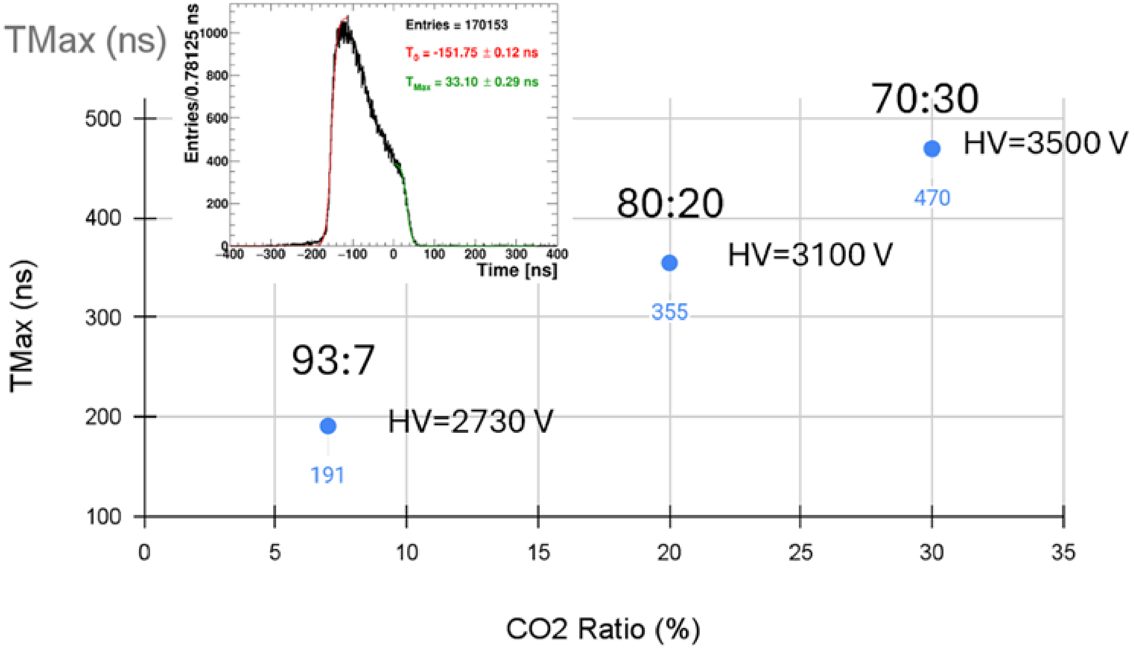


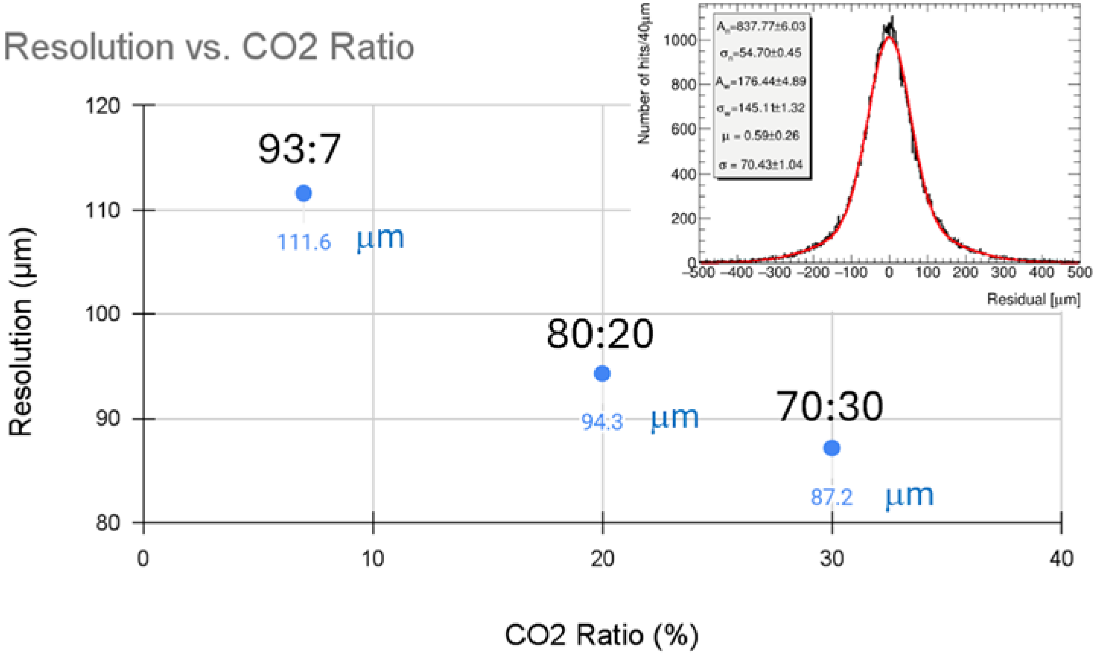
Study of Drift Gas Mixture

- Build and test/calibrate a gas mixture system. Study the gas gain with a small straw chamber using ^{55}Fe. sMDT chambers are used to study the tracking performance
- Using ATLAS sMDT muon chambers to study the drift time and resolution at pressure = 3 bar: More CO_2 component, longer drift times, and better tracking resolution
- Search for new environmentally friendly gas mixtures



$$gain = \frac{output\ charge}{input\ charge} = \frac{(mean\ pulse\ height/2mV)\ fC \times 10^{15}}{No.\ of\ primary\ electrons \times e\ C}$$



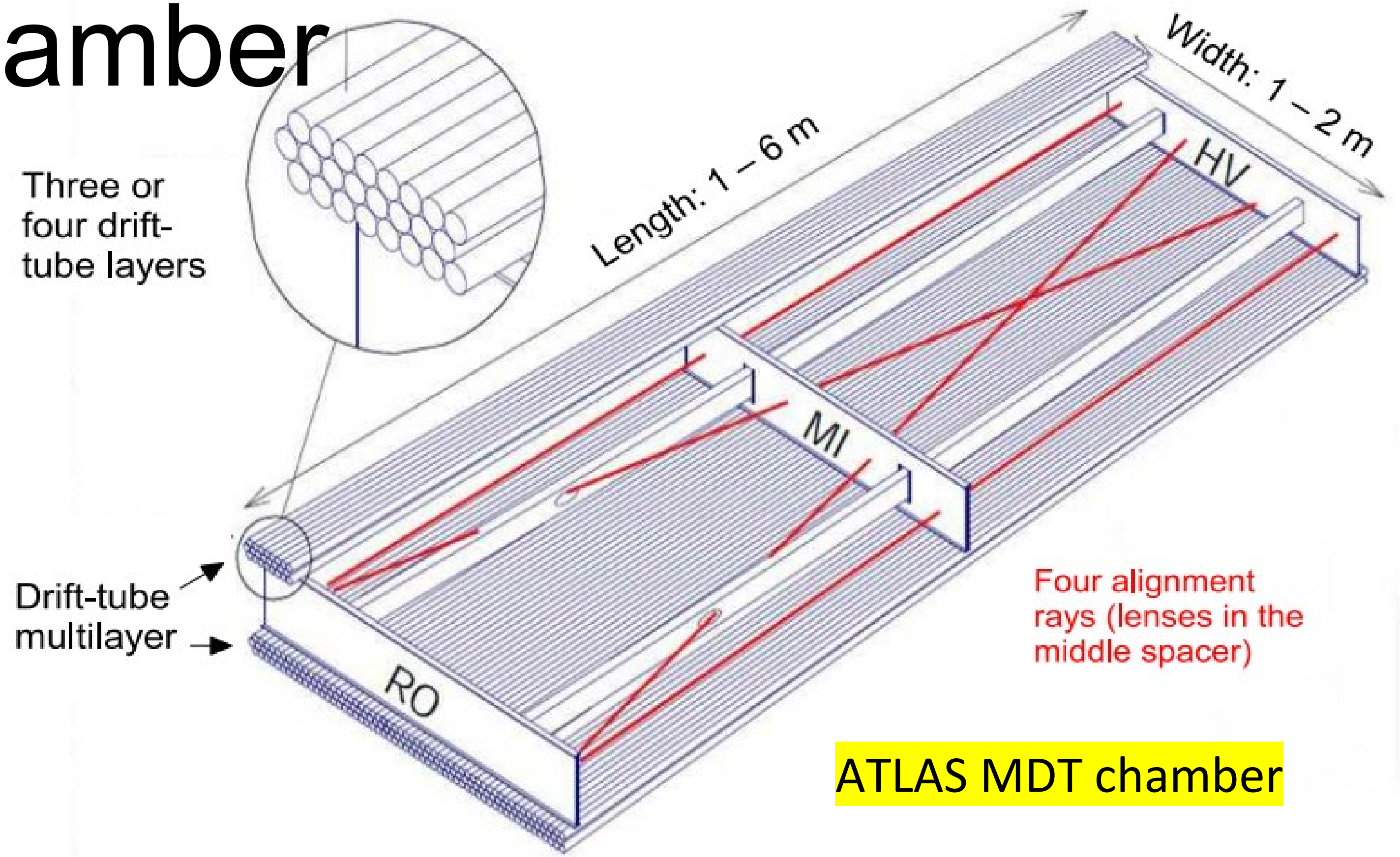


Summary

- A combination of drift tubes and scintillators for a muon system is a **high precision, fast timing, robust, and cost-effective** option to meet the muon detection requirements at FCC-ee
- **On going R&D:**
  - ❖ GEANT4 simulation with ALLEGRO detector concept design
  - ❖ Scintillator strip detector prototype built with SiPMs on both ends, using CAEN Module as Readout:
    - Test beam in Nov. 2025 and Mar. 2026 at CERN PS T9;
    - sMDT provides better than 100 um 3D tracking resolution;
    - Good data quality, preliminary results show good performance;
    - Intensive data analysis are ongoing/planned.
  - ❖ Square drift tube prototype, much cheaper than ATLAS round tubes, is built and used ATLAS MDT electronics for readout
    - Develop method to reduce the noise of the squared tube chamber
    - Develop techniques for calibration of the squared tube chamber to improve the resolution
  - ❖ Gas mixture system has been built and calibrated to study the drift gas mixture

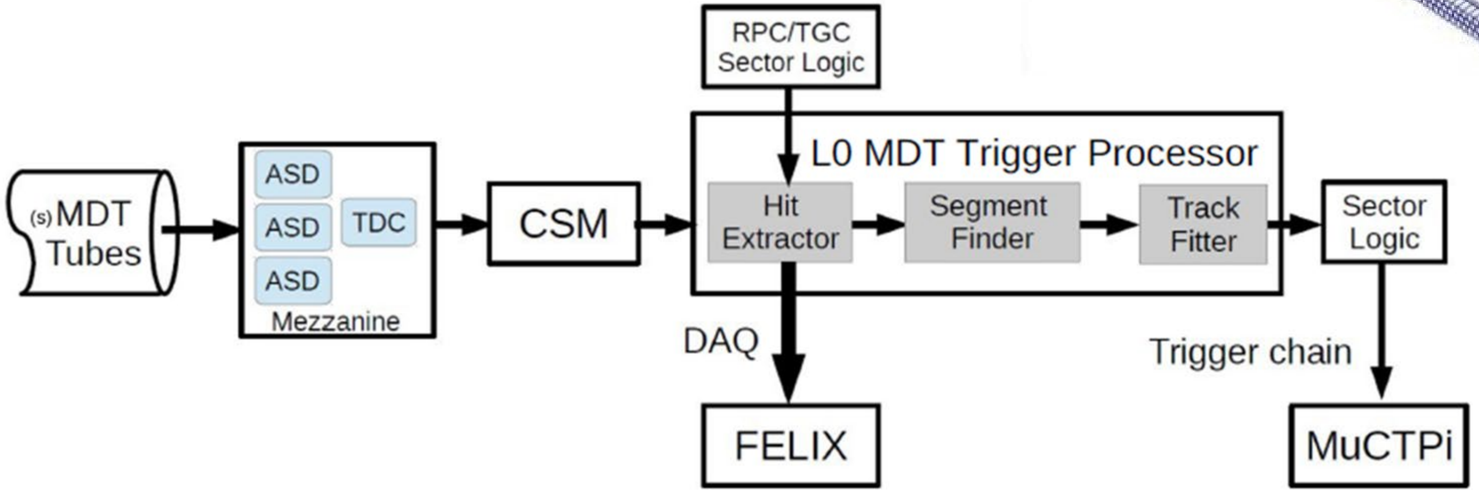
Backup

ATLAS (s)MDT chamber



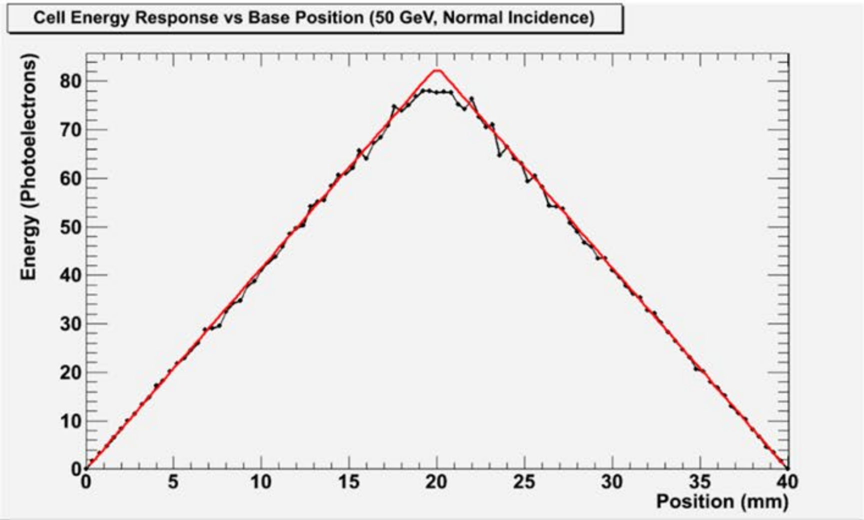
ATLAS MDT chamber

MDT readout electronics



Vernier Effect

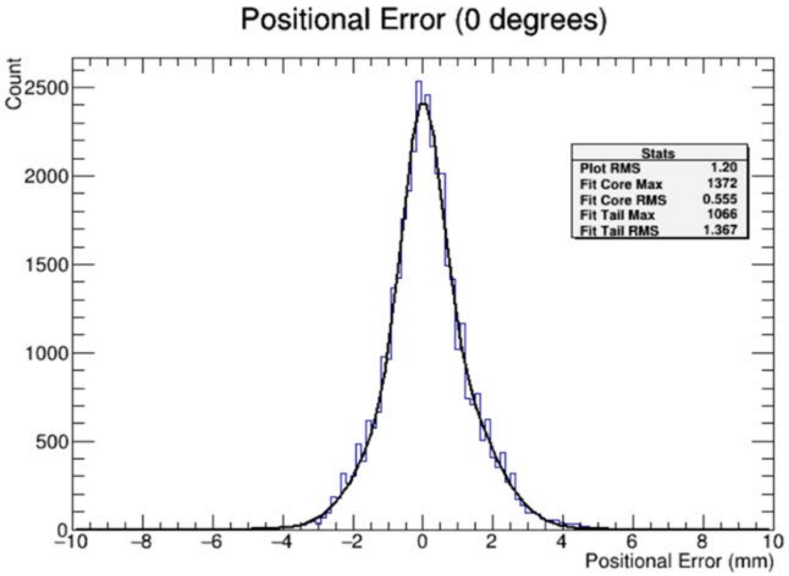
Triangular geometry allows for reconstruction of perpendicular tracks to ~1mrad angular resolution and ~1mm spatial resolution



Vernier Angular RMS Table (milliradians)

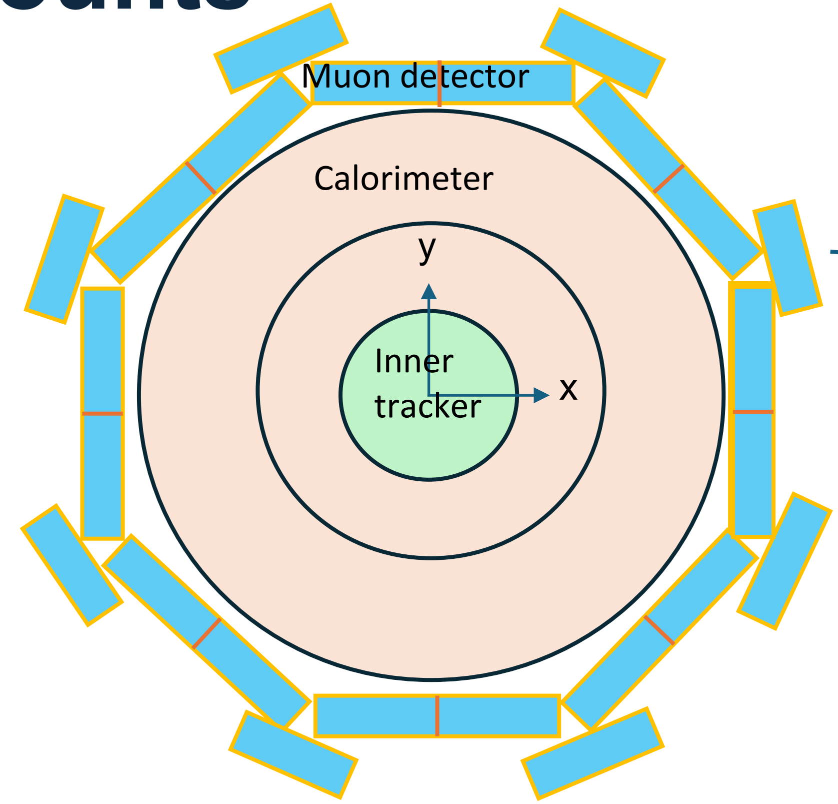
Angle (degrees)

Muon Energy (GeV)	0	5	10	15	20	25	30	35	40	45
5	1.482	1.454	1.458	1.533	1.552	1.622	1.611	1.628	1.633	1.661
10	0.993	0.967	0.989	1.026	1.037	1.055	1.044	1.035	1.009	0.960
15	0.889	0.857	0.884	0.934	0.930	0.953	0.943	0.925	0.874	0.812
20	0.860	0.815	0.867	0.895	0.915	0.921	0.914	0.892	0.829	0.764
30	0.815	0.801	0.835	0.849	0.869	0.898	0.874	0.845	0.801	0.735
40	0.805	0.808	0.829	0.850	0.867	0.893	0.877	0.837	0.784	0.723
50	0.802	0.782	0.842	0.848	0.849	0.885	0.873	0.846	0.790	0.713
75	0.800	0.791	0.839	0.843	0.846	0.881	0.881	0.825	0.767	0.700
100	0.802	0.812	0.835	0.846	0.827	0.879	0.891	0.813	0.768	0.716
150	0.808	0.795	0.830	0.851	0.862	0.881	0.878	0.817	0.777	0.721

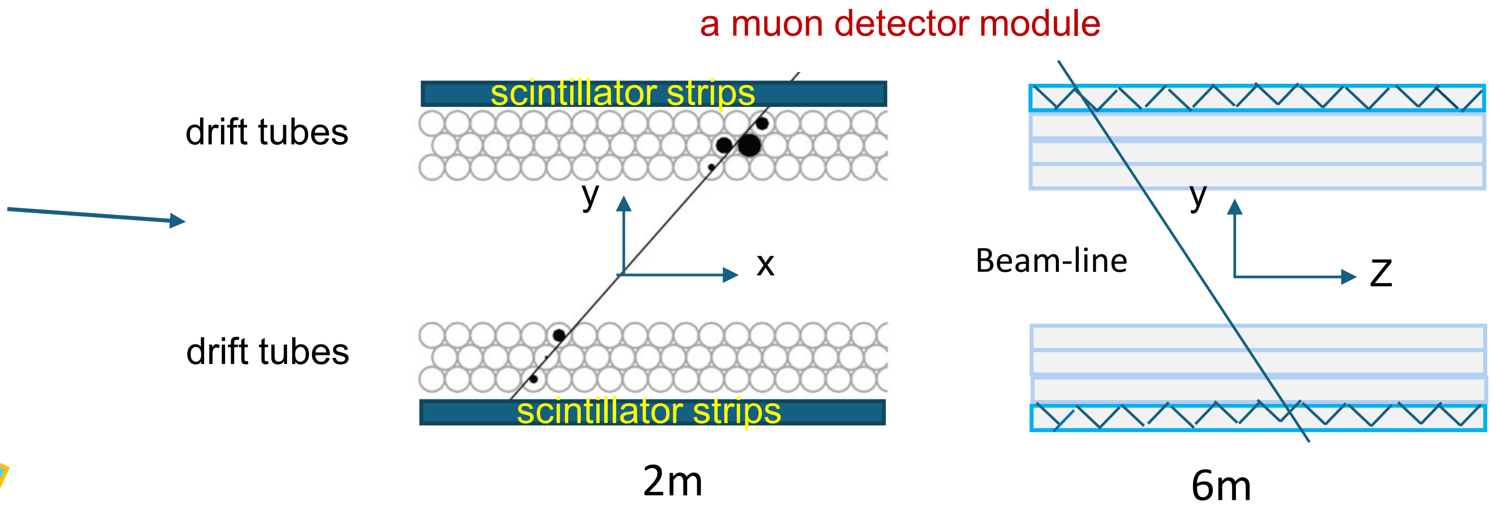


[Exploring the great pyramid: detector TDR]

Possible Barrel Muon Detector Layout & Channel Counts



Solenoid central magnet



Using ATLAS BOL chamber as an example:

Each module of muon chamber size: 2m x 6m

Number of chambers in barrel: (8x3)x2 = 48

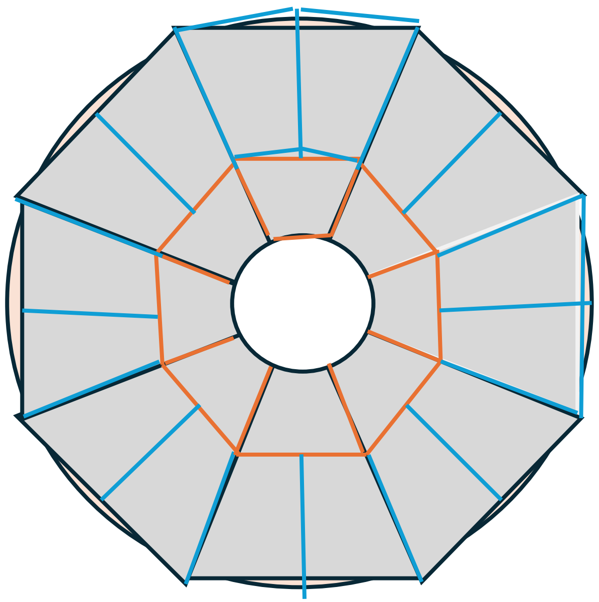
Ref: Num. of ATLAS BOL chambers: 96

Each module consists of
384 drift tubes of diameter=1.5cm, 64 tubes/layer
Arranged in two multi-layers with a spacer of 35 cm
Total number of drift tubes: (384x3x8x2)=**18432**

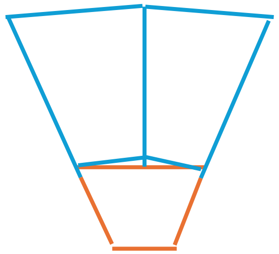
Number of scintillator strips:
(300x2)x2=1200 4m-long scintillator strips / wider chamber
Total 1200x8 = **9600** 4m-long strips + **9600** 2m-long strips

Endcap muon system layout and channel counts

- **The end-cap chamber design will depend on the magnet configuration**
- **Assume solenoid central magnet, the end-cap field lines have larger components perpendicular to the beam line**



Schech of the endcap big-wheel of the muon system



Each sector consisting of 3 chambers:
Lower chamber: R = 1.0 - 2.5 m
Top chambers (2): R = 2.5 – 4.5 m

Drift tube wire perpendicular to the beam line
Scintillator strips perpendicular to tubes, and beam line

Three tube layers: 408 tubes/small-chamber
708 tubes/large-chambers
Total number of tubes for 2 end-caps: **17,856**
Total number of scintillator strips for 2 end-caps: **6000**

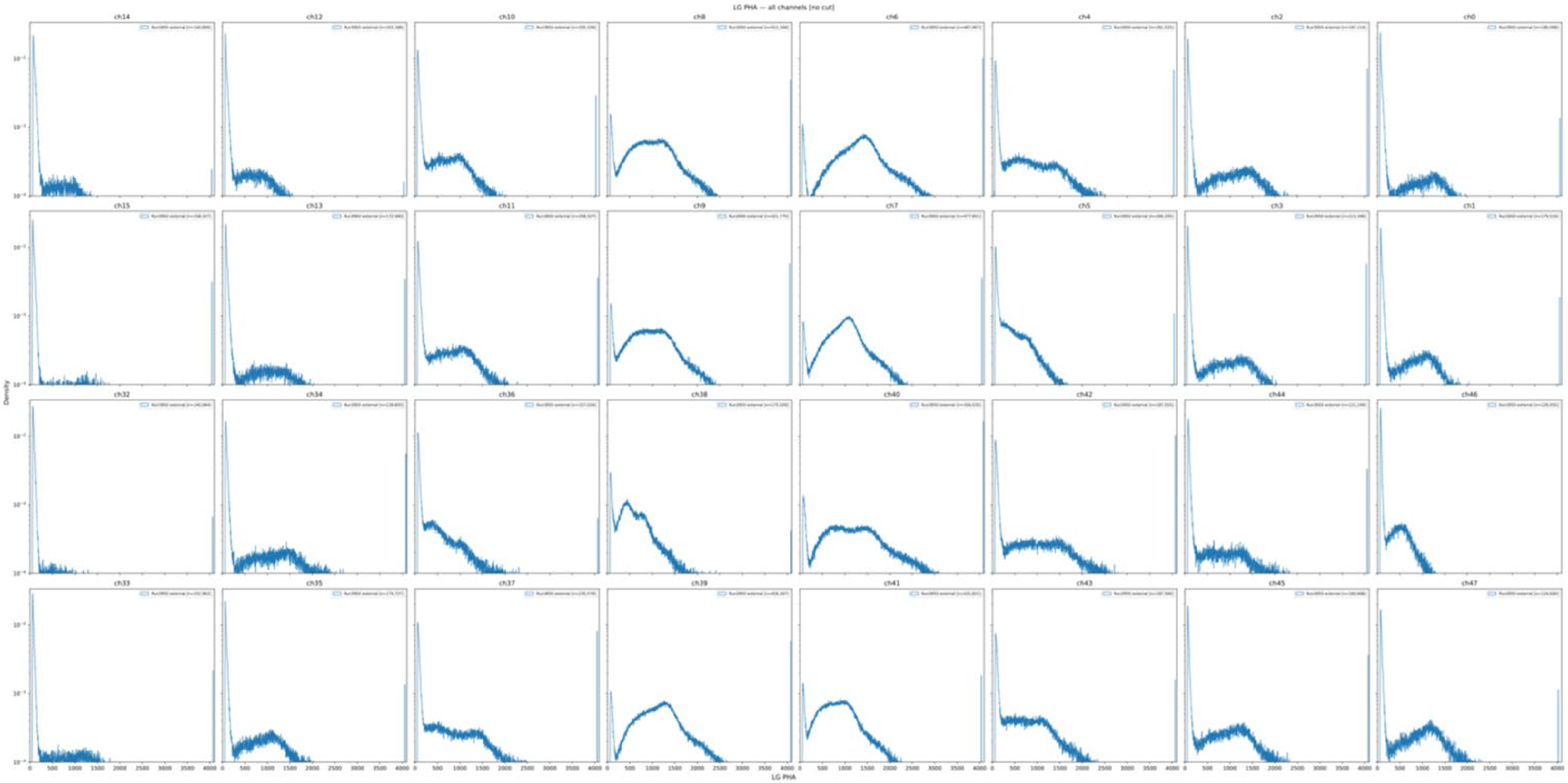
Total number of drift tubes (3 cm in diameter) for barrel + endcaps of the muon system: **36,288**

Total number of scintillation strips (2 cm base): **25,200**

Total readout channels for the proposed muon system: 61,488

Test Beam online DQ Check

LG amplitude across channels



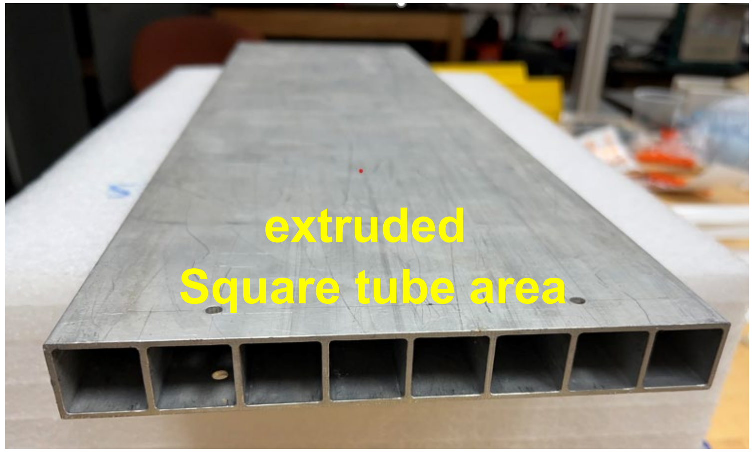
Mar 2026, B1, LG-PA, external trigger, deadtime=4000

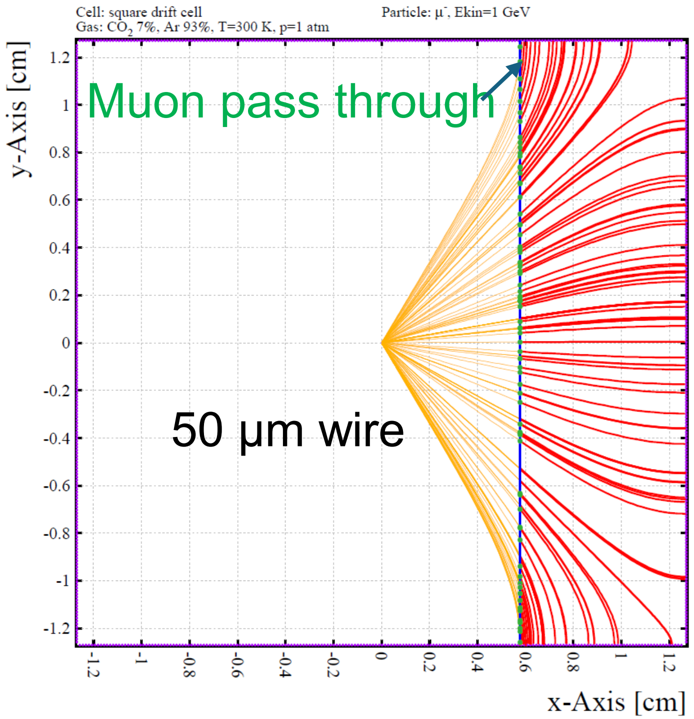
Beam Hit Positions

R&D: build and test squared tube prototype

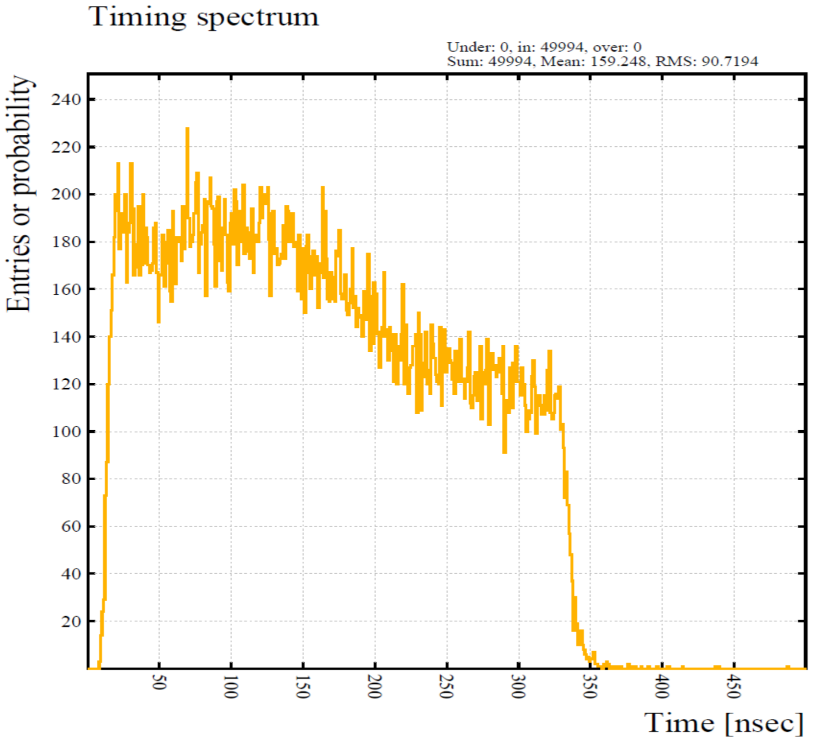
Garfield simulation of the square tube electric properties

1 inch square-tube simulation Ar:CO_2 93:7, 1 atm, 1650 V

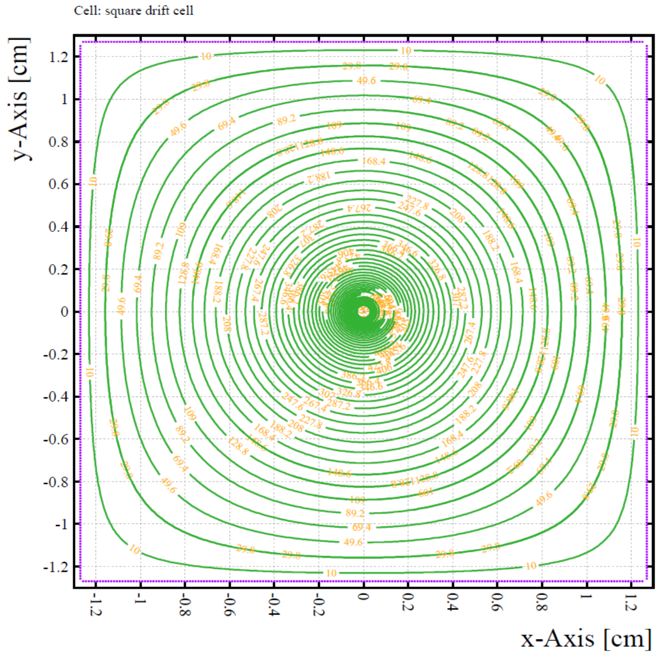




Ionized electrons along the muon track drift to wire



Drift time spectrum



E-field potential contour