GEM and Tracking:
Lessons from SBS and R&D on MPGDs

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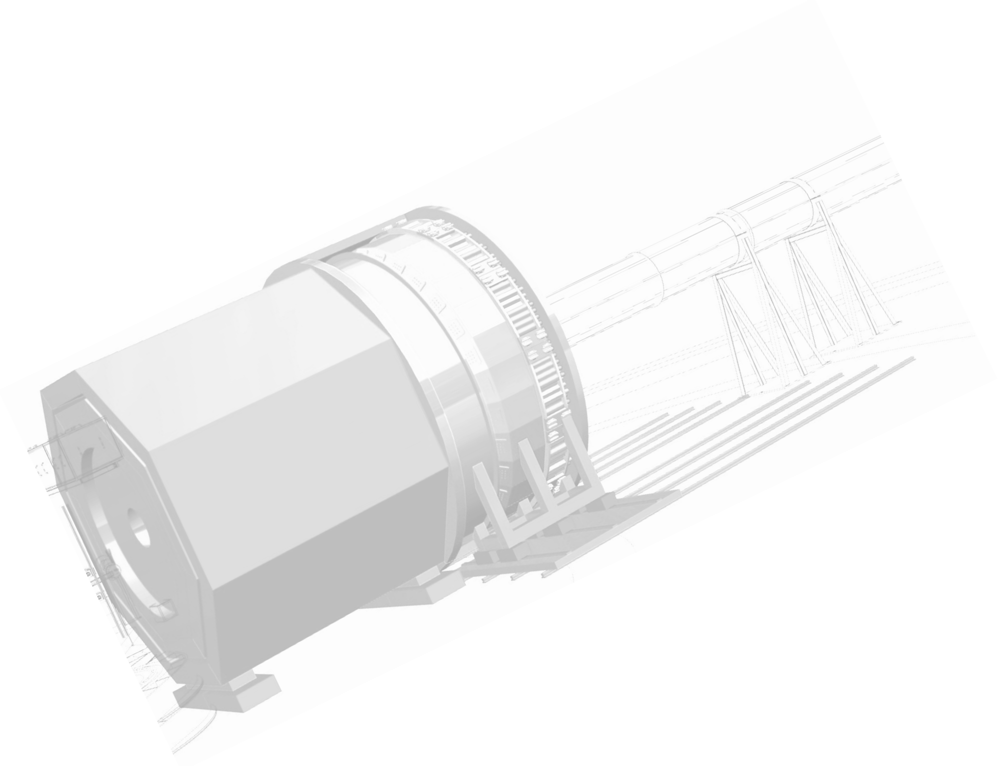
ON BEHALF OF THE GAS DETECTOR DEVELOPMENT GROUP AT UVA

9 JANUARY 2025

SoLID GEM and Tracker

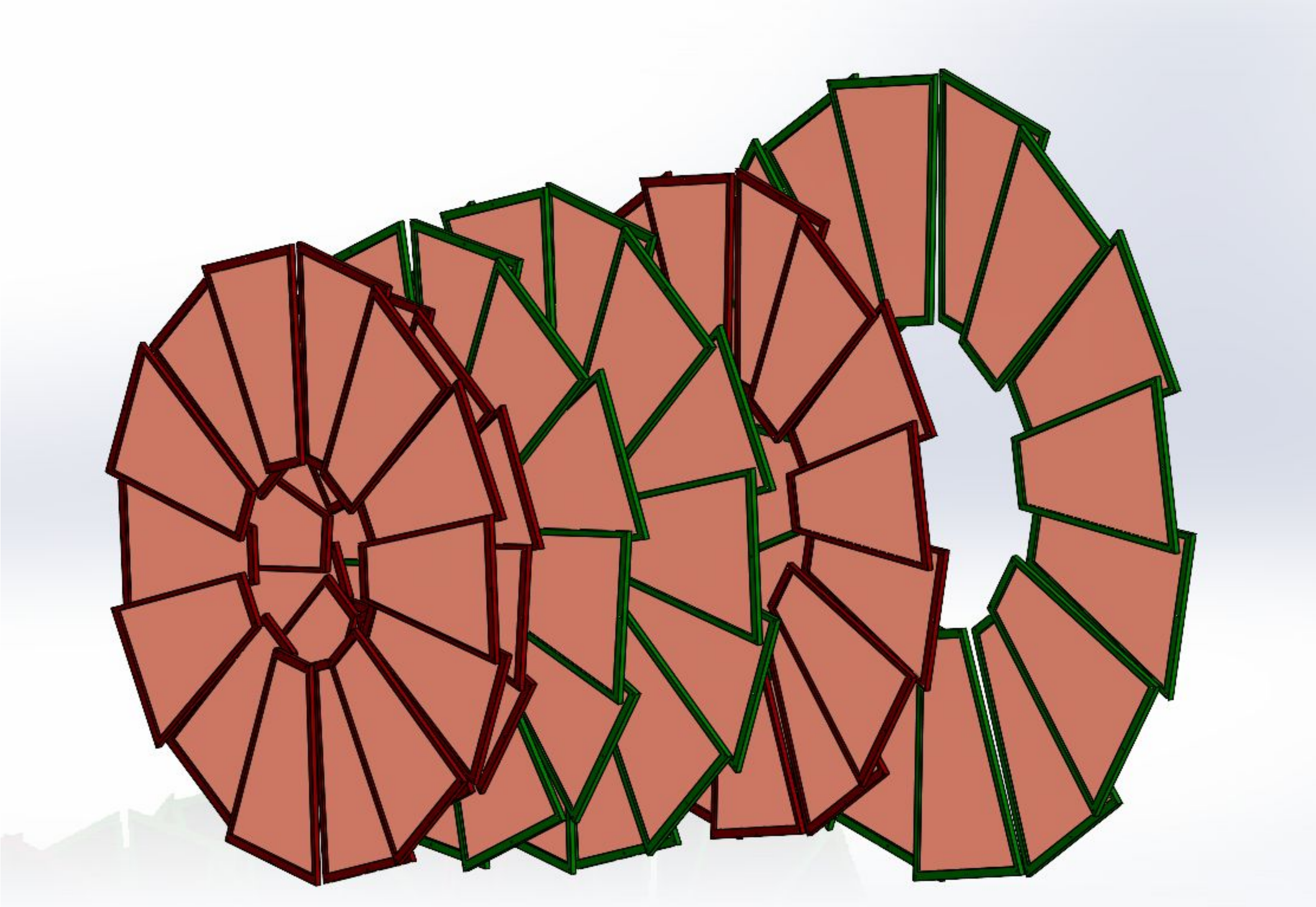
Outline

- SoLID GEM Overview
- Lessons Learned from SBS GEM Trackers
- Lessons Learned from R&D on MPGDs
  - R&D on Thin-Gap Triple GEM for EIC
  - R&D on Large-area µRWELL for CLAS12



GEM Overview for SIDIS

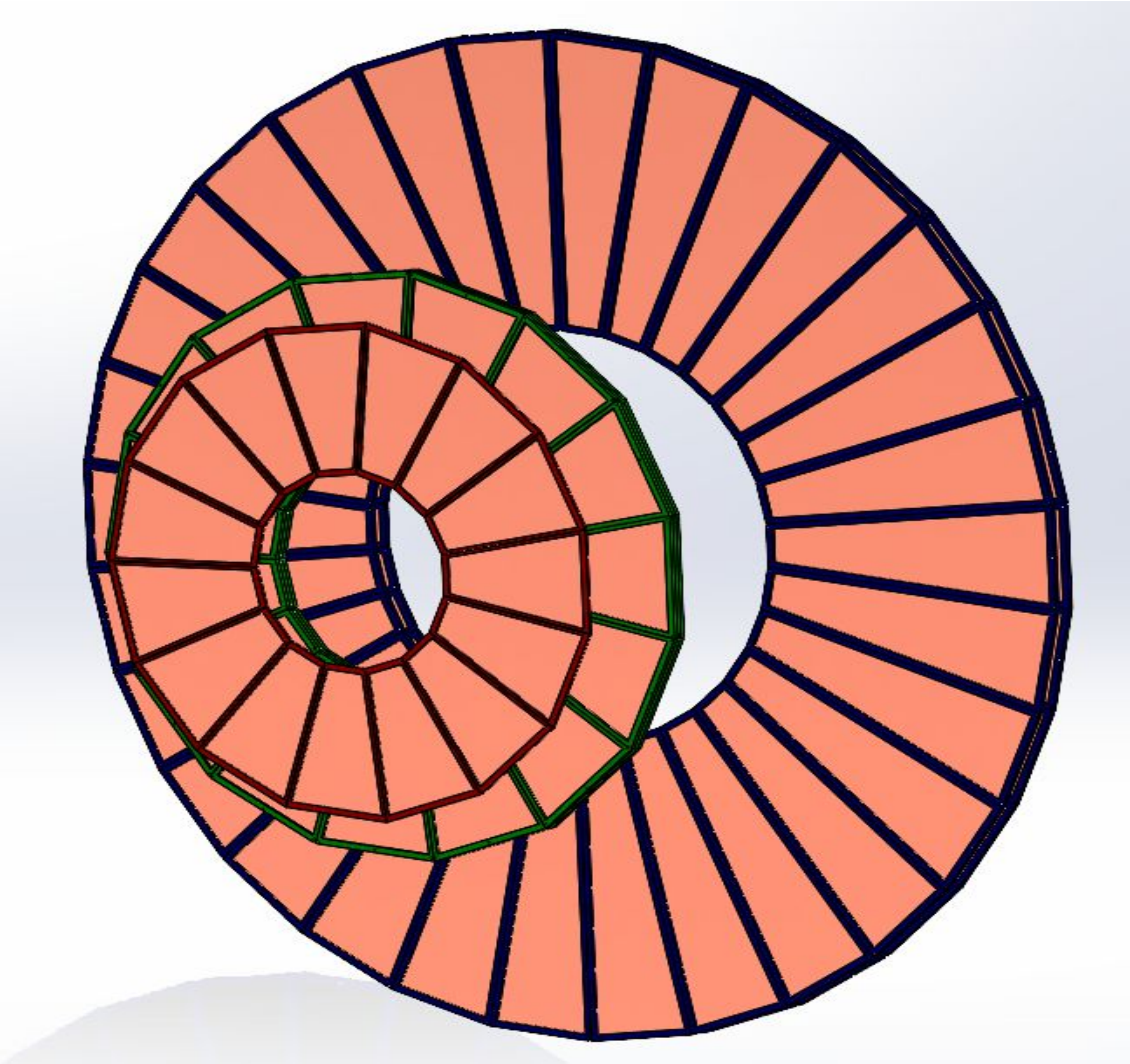
Plane	Z (cm)	R_I (cm)	R_O (cm)	Length (cm)
1	-175	36	87	51
2	-150	21	98	77
3	-119	25	112	87
4	-68	32	135	103
5	5	42	100	58
6	92	55	123	68



- ➔ Under optimization process:
  - ◆ GEM plane locations
  - ◆ Sizes of GEM modules
- ➔ Total active area ~ 21 m^2

GEM Overview for PVDIS

Location	Z (cm)	R_{min} (cm)	R_{max} (cm)
1	157.5	51	118
2	185.5	62	136
3	190	65	140
4	306	111	221
5	315	115	228
Total			



- ➔ Finalizing how many SIDIS GEMs could be used for PVDIS
- ➔ Total active area ~ 37 m^2

SoLID GEM Requirements

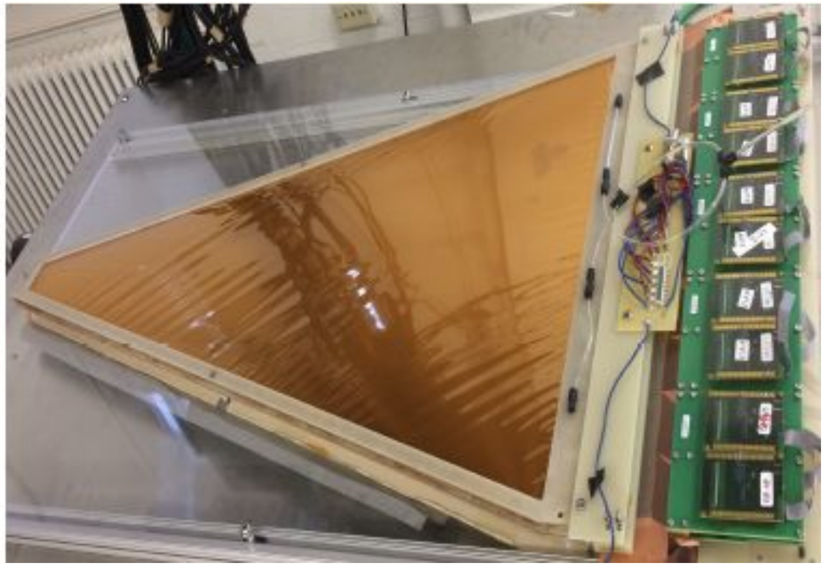
➔ Modules with a trapezoidal geometry

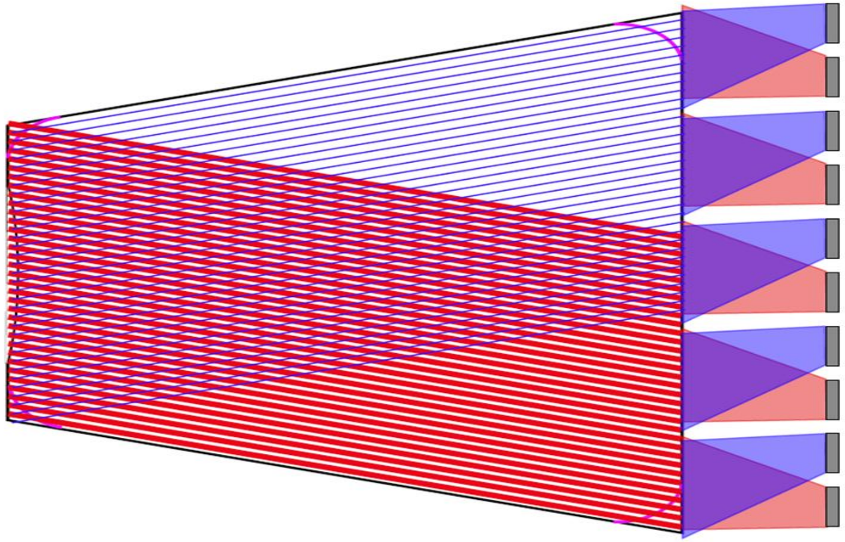
- ◆ **Narrow side frames to minimize material thickness in active area**

➔ Overall GEM-module efficiency: 92%

➔ Position resolution

- ◆ 100 µm (1 mm) in azimuthal (radial) direction.
- ◆ 2D U-V readout with 12° or 24° stereo angle between strips
- ◆ 400 µm (600 µm) strip pitch for layers 1-3 (5-6)
- ◆ The high occupancy at layer #1: split each readout strip into two channels

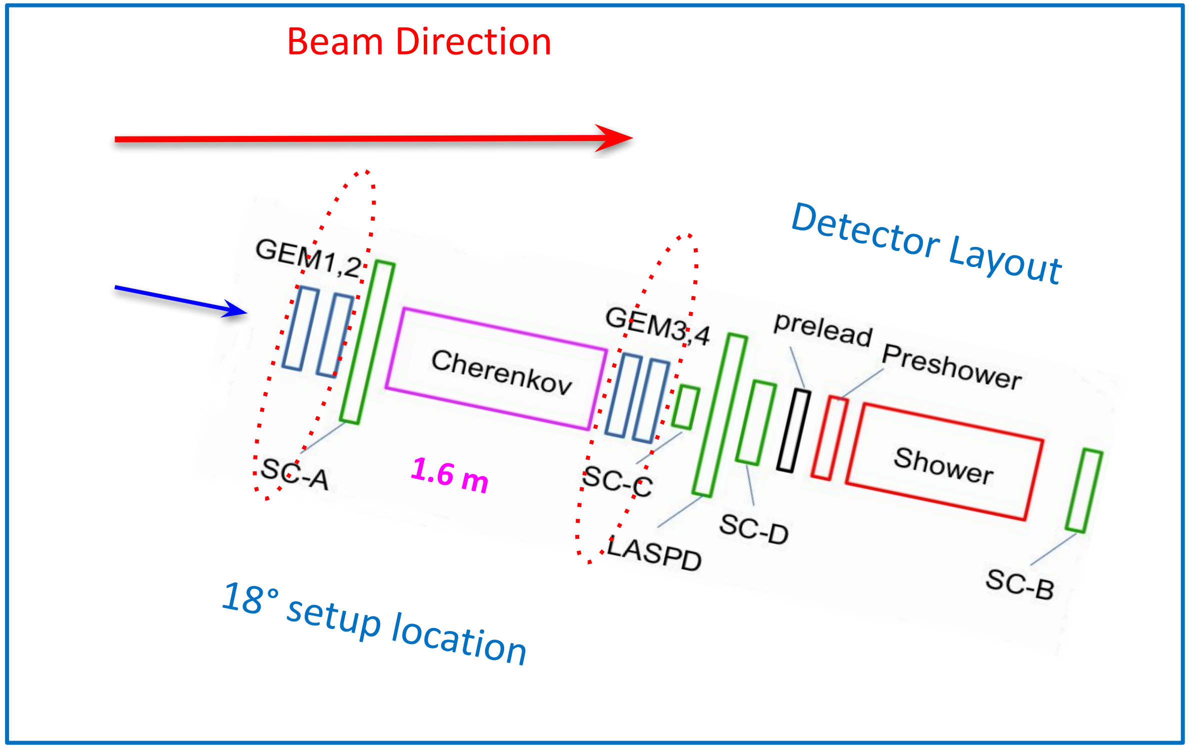




Hall C Beam Test

Beam test setup

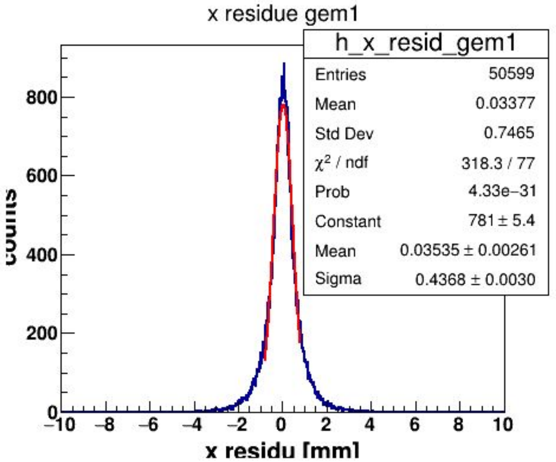
- Front to back: GEM1+2, SC-A, Cer, GEM3+4, SC-C, LASPD, Preshower, Shower, SC-B
- Two test conditions: 7° and 18°
- GEM (1+2)and GEM (3+4) separation: 1.6 m

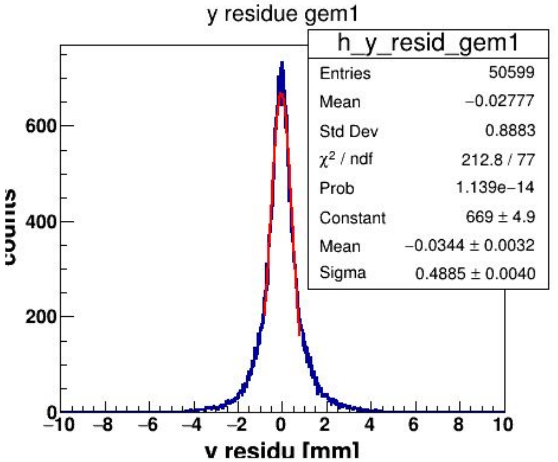


Tracking and spatial resolution

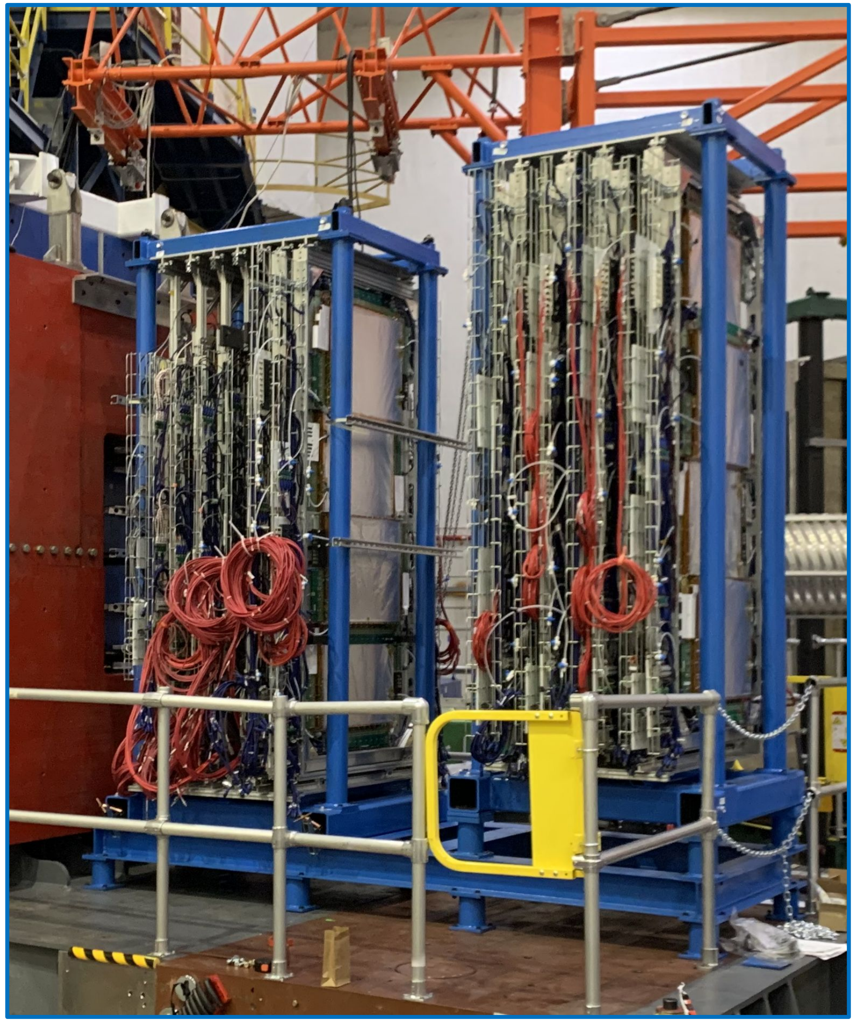
- Raw occupancy is much higher than projected for SoLID experiments
  - 40% on the front layers, 10% on the back layers
- Tested both SBS tracking algorithm and Millipede algorithm
- Residue standard deviation after alignment: 500 µm
- **High occupancy, No optics, No Survey Data =>**

  How reliable is this result?





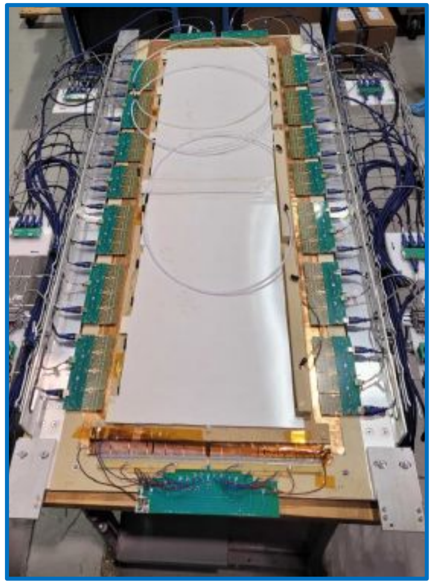
SBS GEM Tracker Overview



- Sixteen (16) layers of SBS GEM installed in experiments:
  - Forty 60 x 50 cm^2 GEM modules in 10 layers - 36 modules in beam
  - Six 150 x 40 cm^2 large GEM modules - All six modules in beam

60 x 200 cm^2 (four modules)

40 x 150 cm^2 (single module)

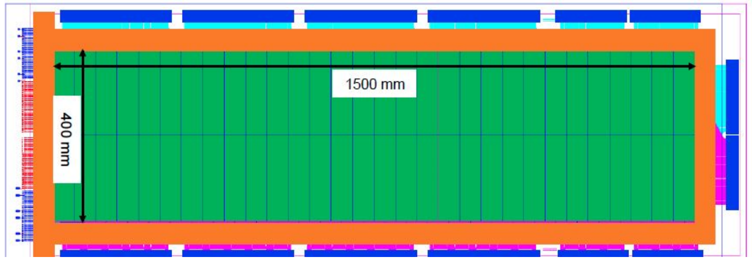


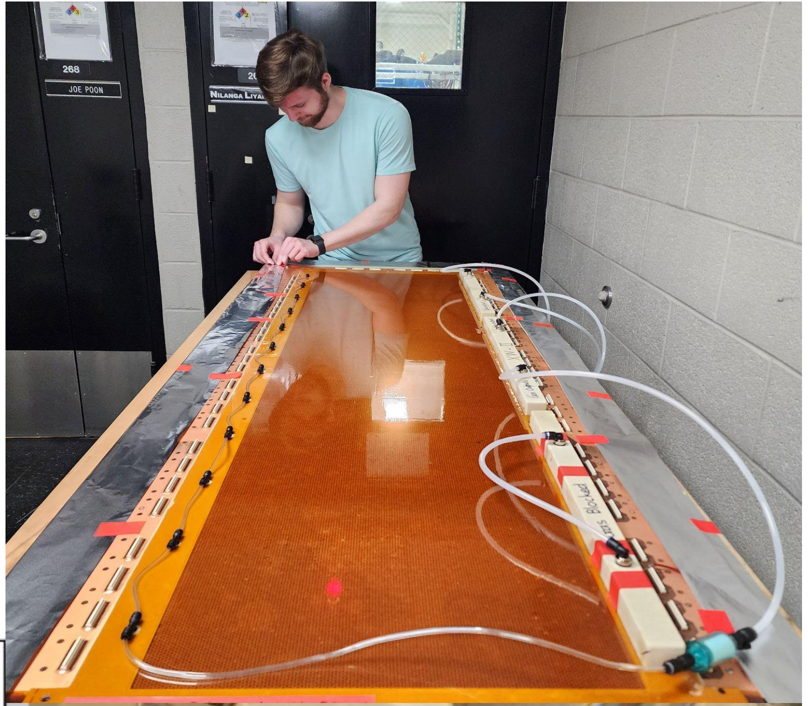
- **SBS GEM trackers have been running above 18 months in GMn, nTPE, GEn-II, and GEn-RP experiments**

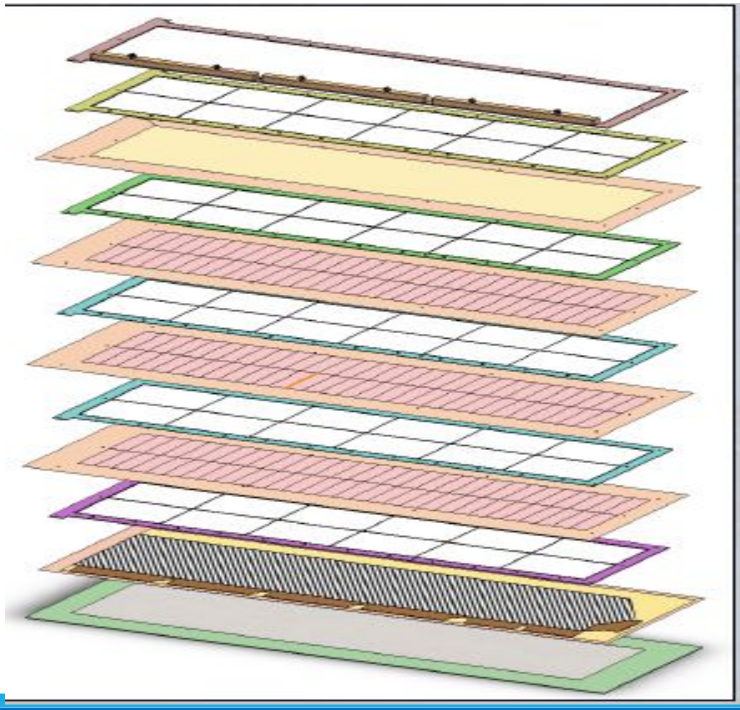
Experiences from SBS GEM Tracker

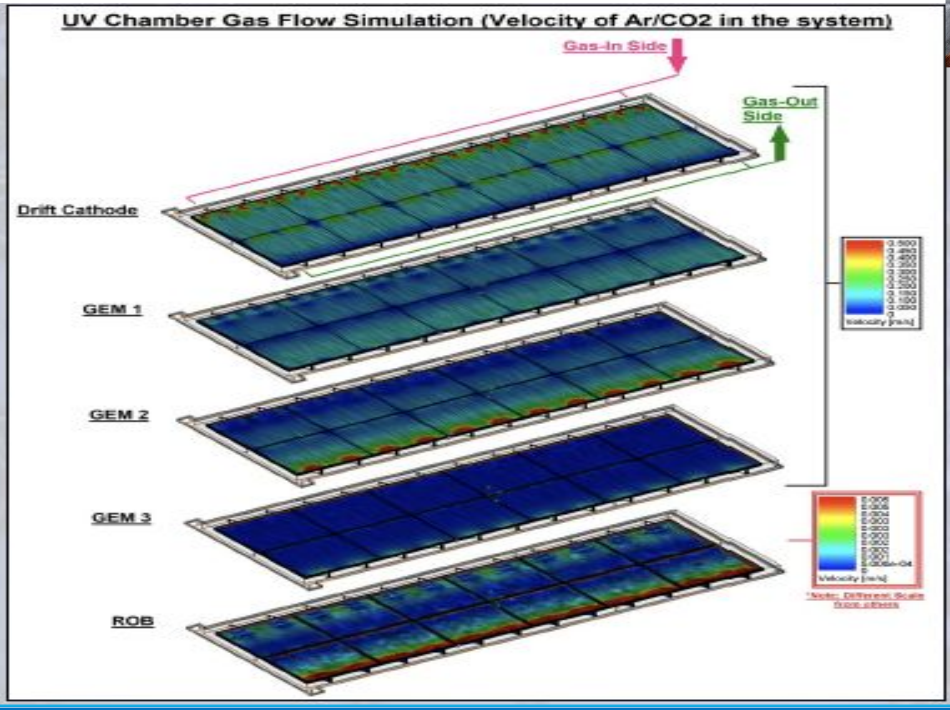
Large GEM Construction

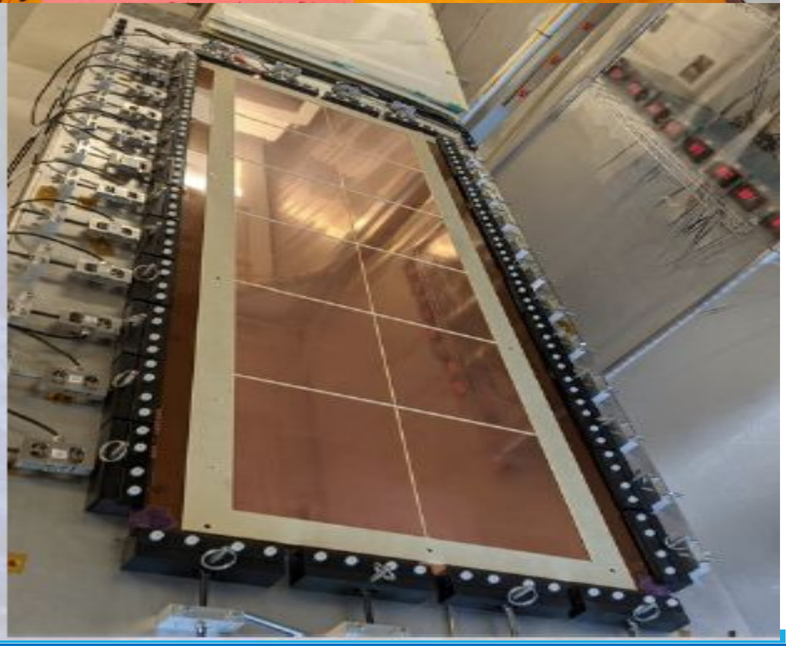
- **Active areas larger than the largest SoLID GEM detectors needed**
- All six large GEM have performed exceptionally well in beam





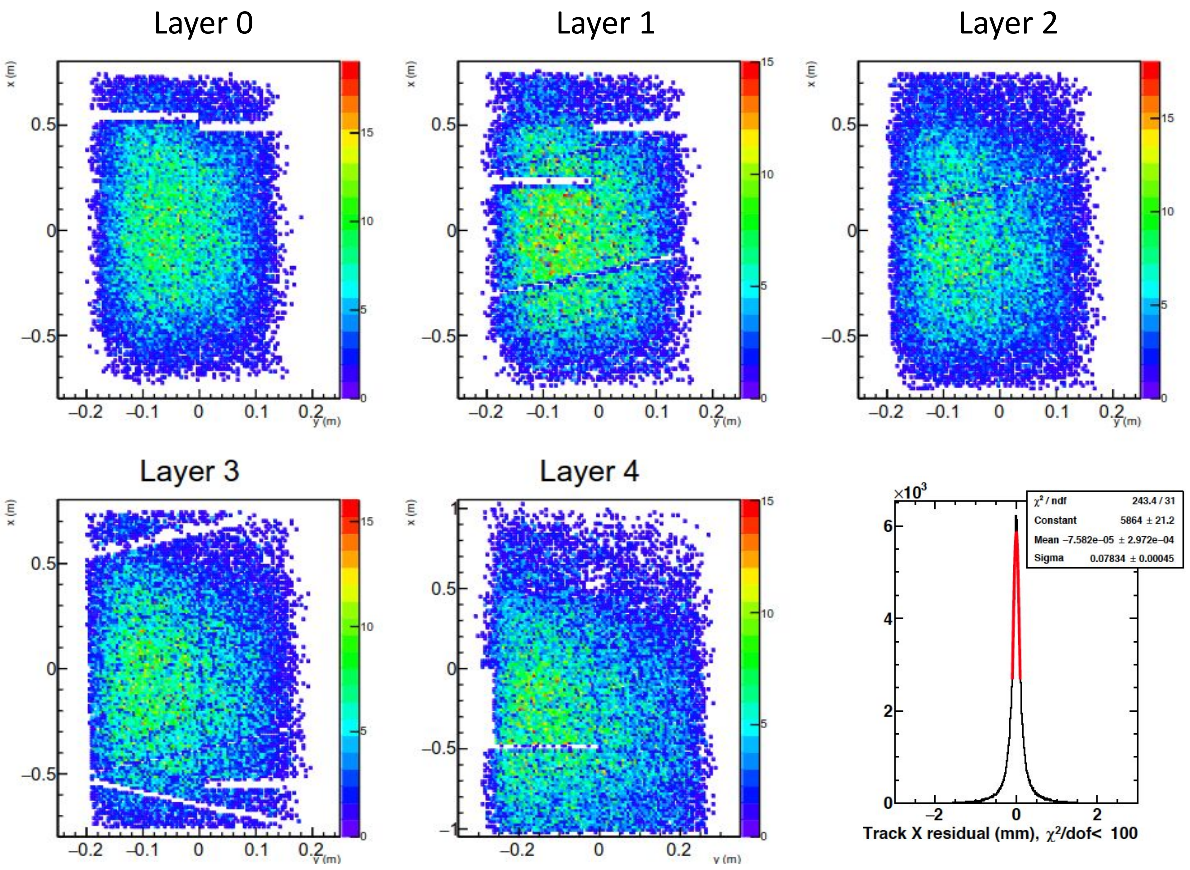






Experiences from SBS GEM Tracker

GEM Operation at Luminosity Exceeding SoLID Requirements



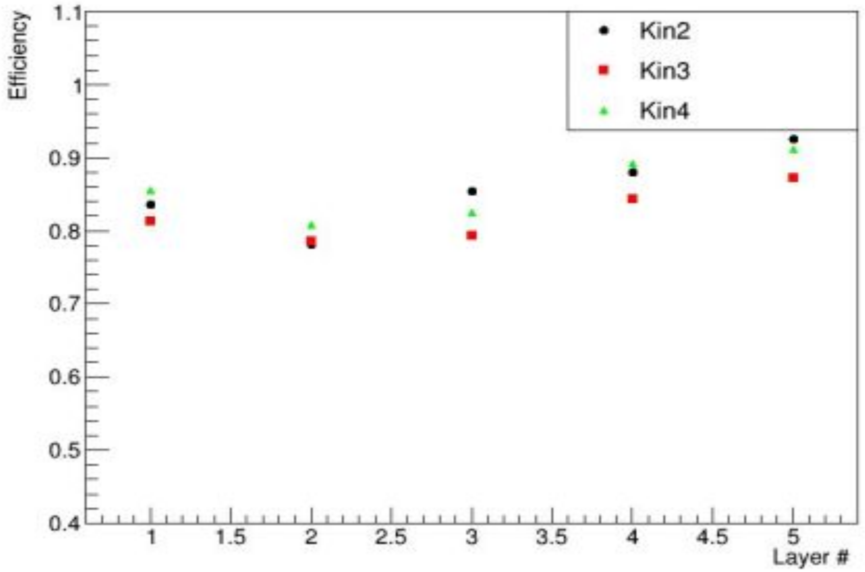
GEn-II: Electron Arm tracking hit map

- ❖ **GEn-II experiment:**
  - ➢ Up to 45 uA on 60 cm ^{3}He target
  - ➢ **Luminosity ~ 5 x proposed SoLID ^{3}He SIDIS**
- ❖ **GMn experiment:**
  - ➢ Stable running with 12 uA beam on 15 cm LD2 target (test runs up to 36 uA)
  - ➢ **Luminosity ~ 3 x proposed SoLID PVDIS**
- ❖ **SBS GEM performance**
  - ➢ **HV stable operation**
  - ➢ Robust under harsh conditions
  - ➢ No radiation damage observed
  - ➢ No detector aging effects observed
  - ➢ **Spatial resolution ~ 70 um** for tracks perpendicular to detector.

Experiences from SBS GEM Tracker

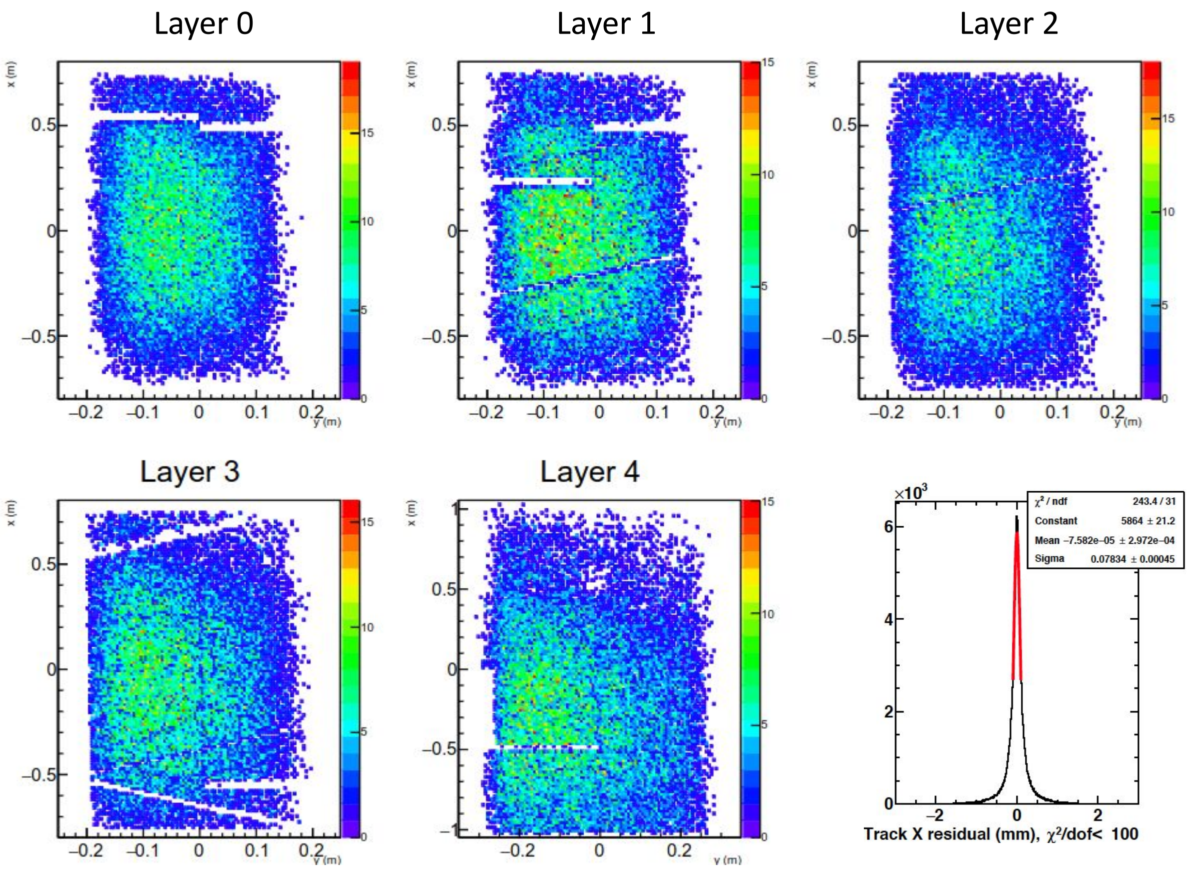
GEM/Tracking Performance at Luminosity Exceeding SoLID Requirements

❖ **GEn-II:** Electron Arm Tracking efficiency for each layer



- Tracking efficiency for each layer > 80%
- **Overall tracking efficiency >97%**
- A few dead areas caused by dead high voltage sectors and faulty electronics

❖ **GEn-II:** Electron Arm Tracking hit map



Experiences from SBS GEM Tracker

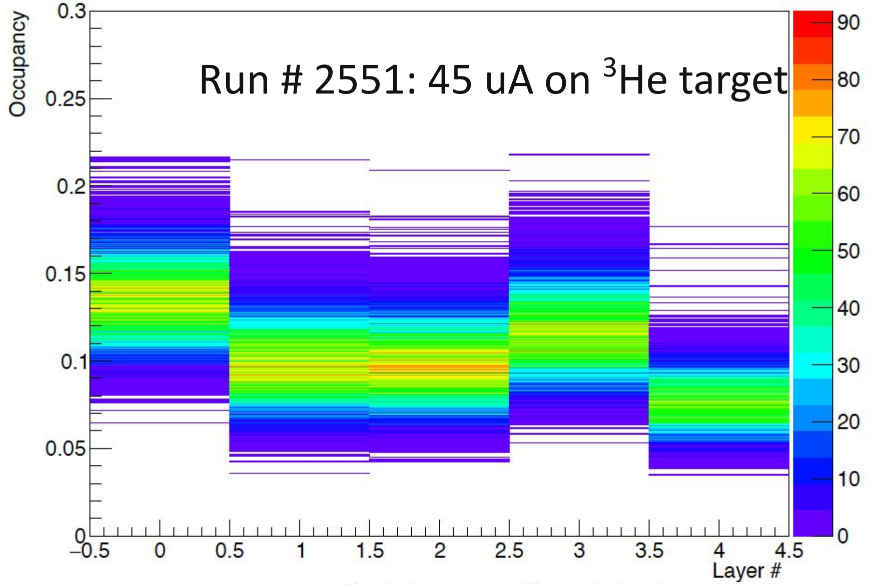
GEM Occupancy at Luminosity Exceeding SoLID Requirements

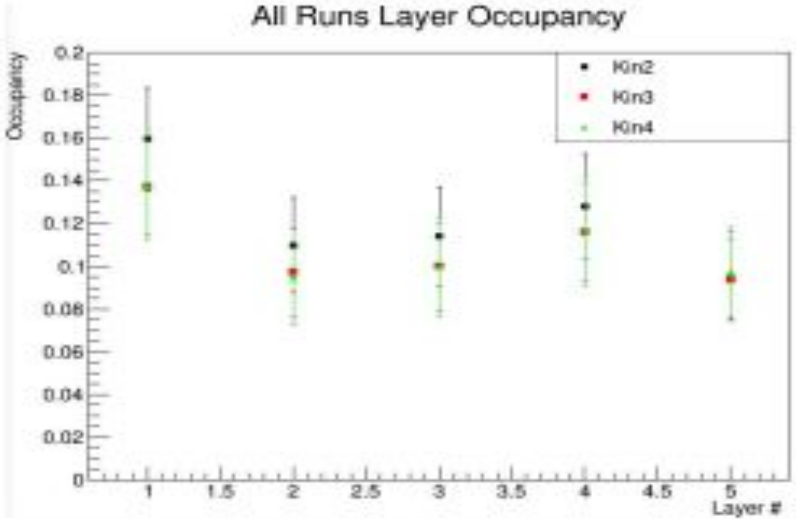
PVDIS: Projected GEM Occupancies

PVDIS GEM occupancies		
Plane	Total strip number (u+v) per sector	Raw Occupancy (%)
1	1156	4.48
2	1374	2.55
3	1374	2.21
4	2287	0.82
5	2350	0.75

- SBS GEM reached occupancy as high as 15%
- SBS already achieved occupancy higher than occupancies projected for PVDIS and SIDIS

GEn-II: Electron Arm GEM Occupancies

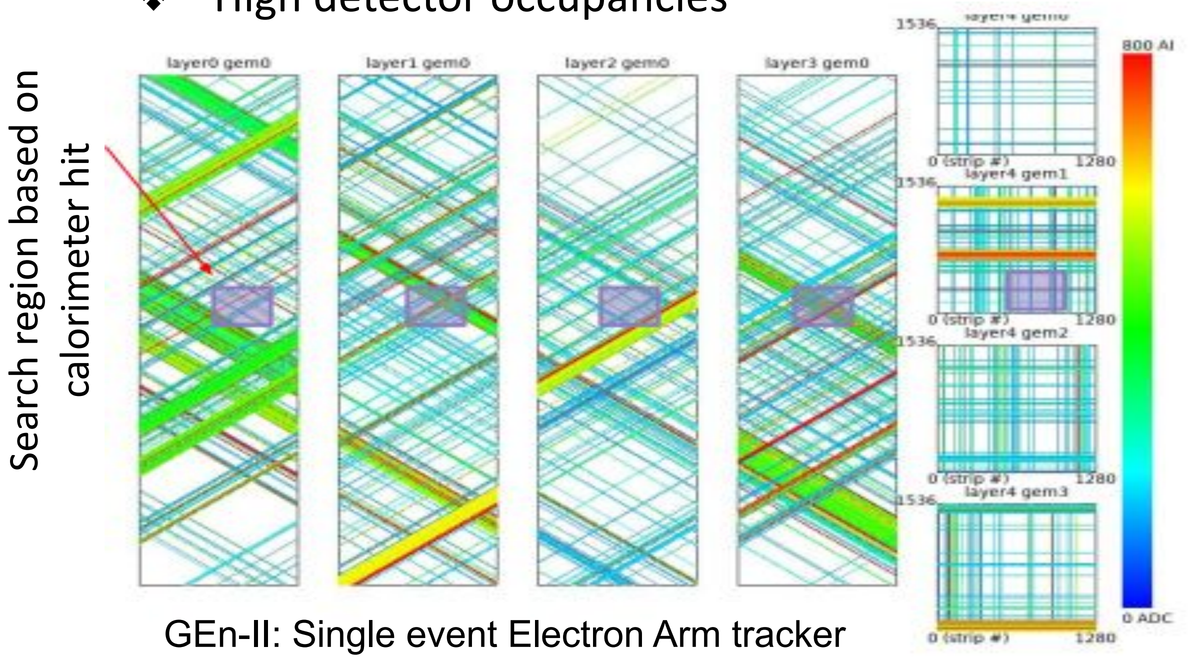




Lessons Learned from SBS GEM Tracker

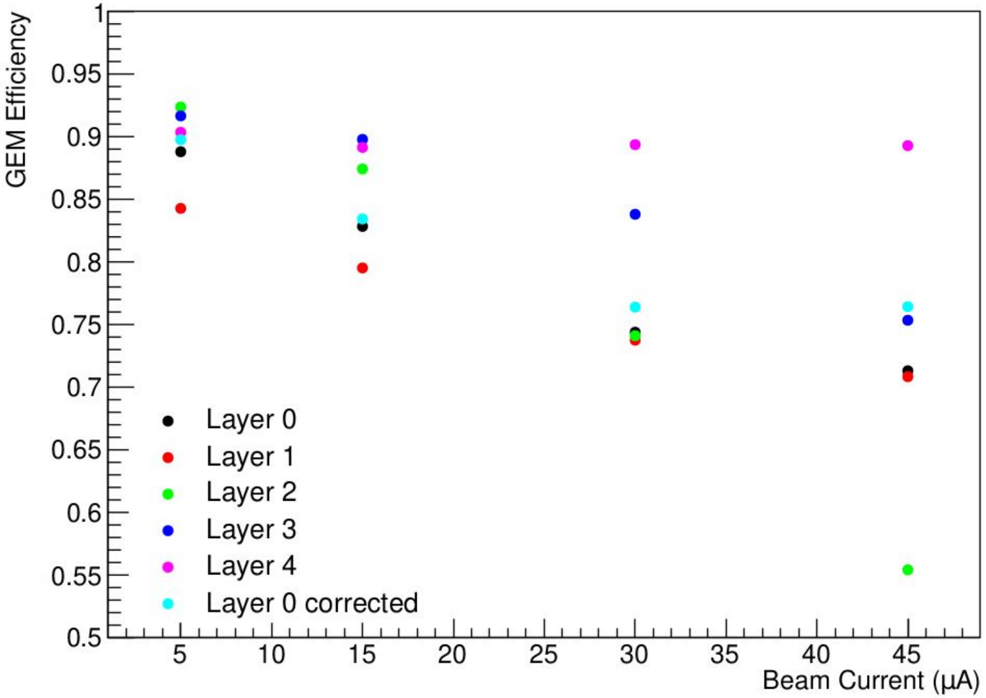
High Rate Challenge for Tracking

- ❖ High detector occupancies



GEn-II: Single event Electron Arm tracker

- ❖ Tracking efficiency drops as rate increases

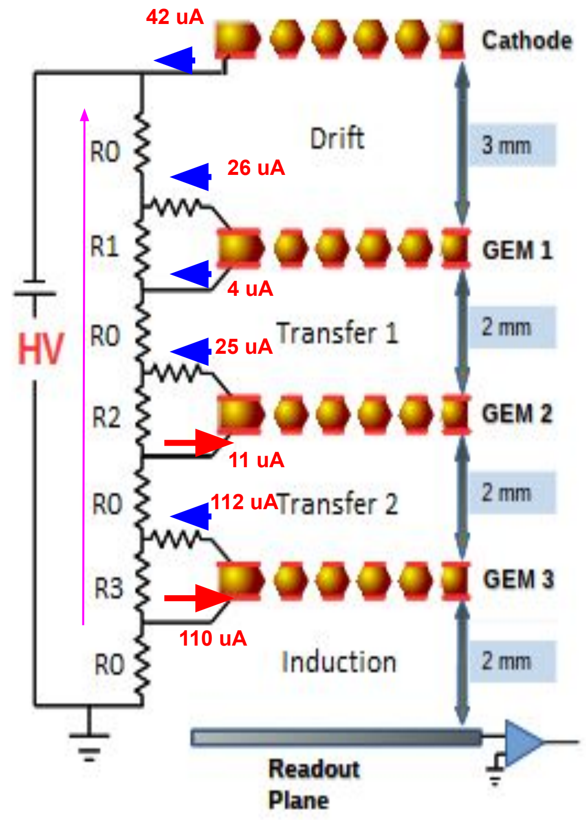


- ❖ **High rate conditions lead to:**
  - ➢ High detector occupancy→ Large number of 2D hit combinations →**Increase difficulty in track finding**
  - ➢ Drop voltage on GEM protective resistors →Lower the field strength in GEM holes →**Lower GEM gain**

Lessons Learned from SBS GEM Tracker

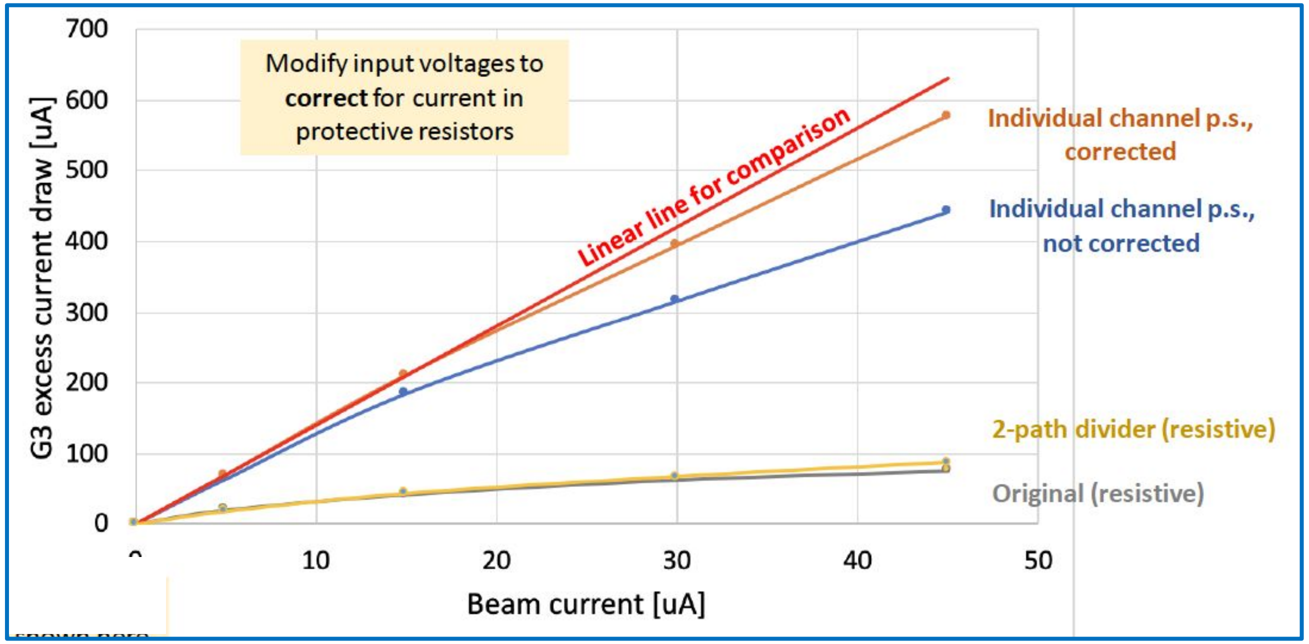
Individual Power Channels to maintain GEM gain in High Rates

❖ **Remove resistive HD dividers**



❖ **Use a parallel power supply to individually power the GEM electrodes**

- ➢ Applied HV correction to compensate the voltage drop on protective resistors
- ➢ Restore the field strength in GEM holes →restore GEM gain
- ➢ Tested during the GEn-II, use for GEn-RP, GEp-V, LAD

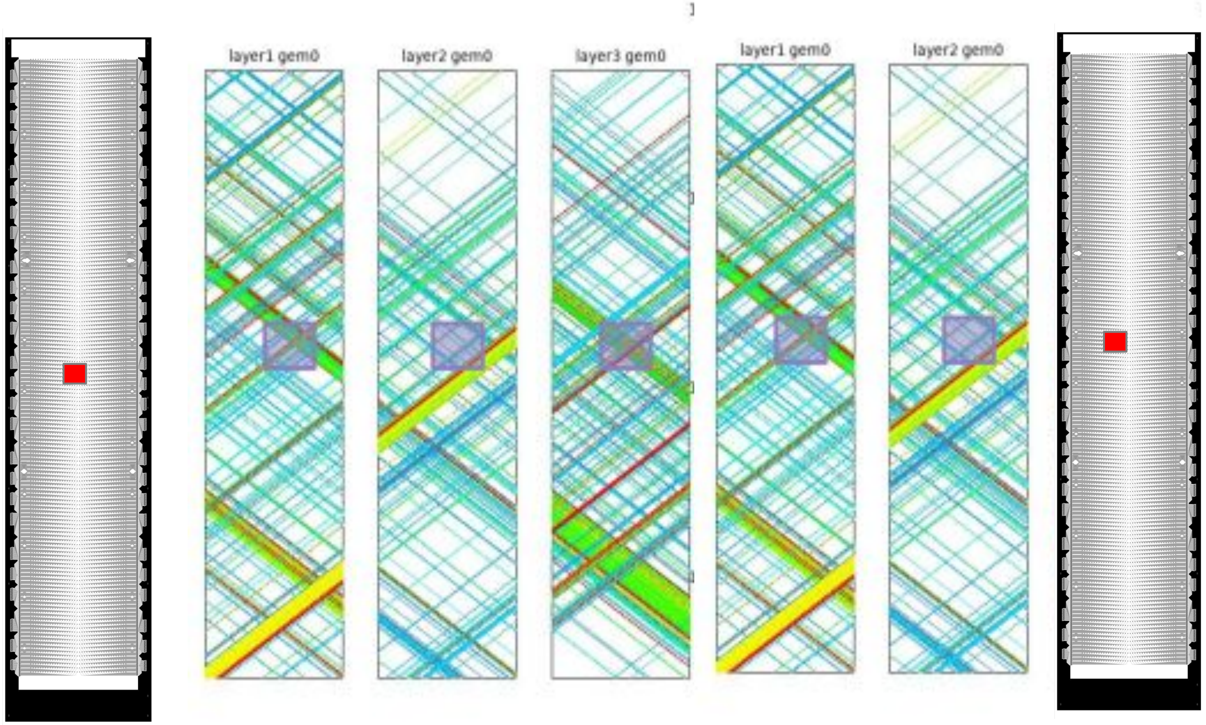


GEM gain vs. Luminosity with different HV configurations

Lessons Learned from SBS GEM Tracker

Improving track reconstruction by adding two Pixel GEM layers

- Placing two pixel-GEM layers at the front and back of SBS front-tracker

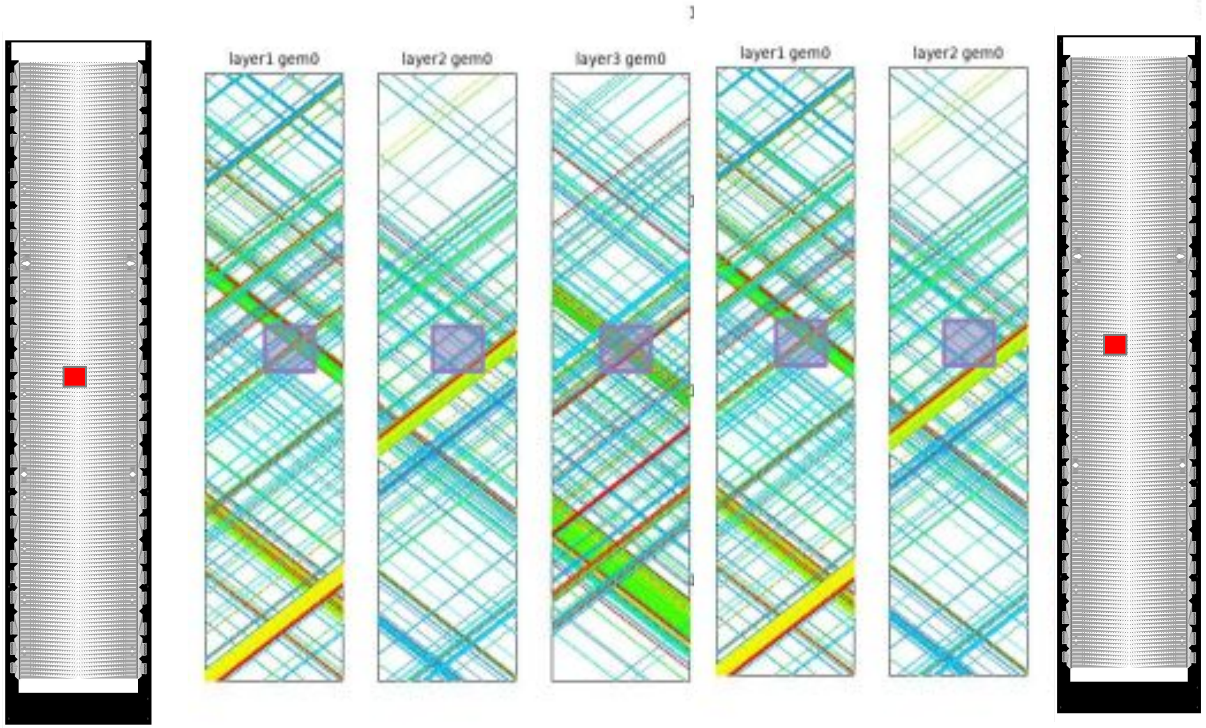


- **Pixel GEM layers:**
  - Triple-GEM amplification
  - **Pixel readout: 9 x 9 mm^2**
  - Active area 40 x 150 cm^2
- **Add two Pixel-GEM layers to SBS tracker system:**
  - Conversion hits resulting photon bkg → increase occupancy
  - Apply coincidence condition between two pixel layers → resolve tracking ambiguities caused by uncorrelated bkg hits
  - Narrowing down the search area for hits in the subsequent 2D-strip-readout → Accelerate track-finding process under SBS condition

Lessons Learned from SBS GEM Tracker

Improving track reconstruction by adding two Pixel GEM layers

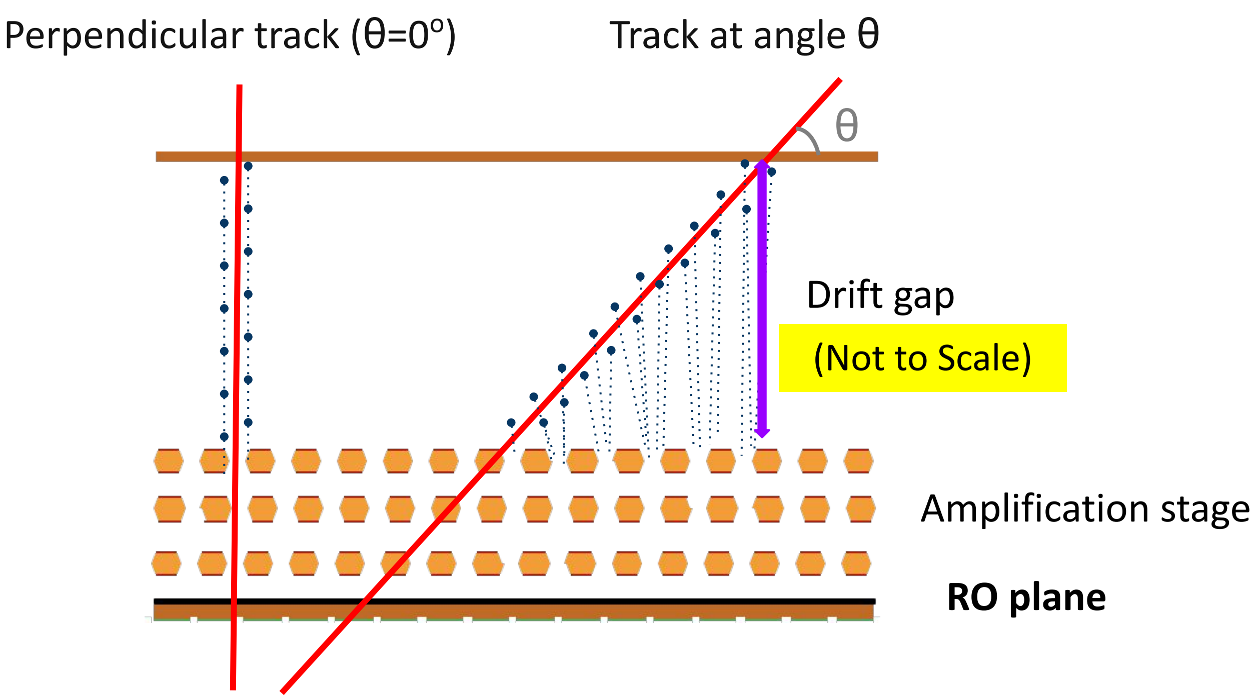
- ❖ Placing two pixel-GEM layers at the front and back of SBS front-tracker



- ❖ **SBS tracker:**
  - ➢ Procurement of components for two Pixel layers are underway (CERN)
  - ➢ Aim to install them and use during the SBS GEp experimen
- ❖ **Adding pixel chambers to SoLID tracker?**
  - ➢ Clean up most of the random hits and select mostly the high energy tracks.
  - ➢ Enhancing the performance of track reconstruction
  - ➢ Needs evaluation with simulations

Lesson Learned from GEM R&D for EIC

Tracking at Large Incident Angles

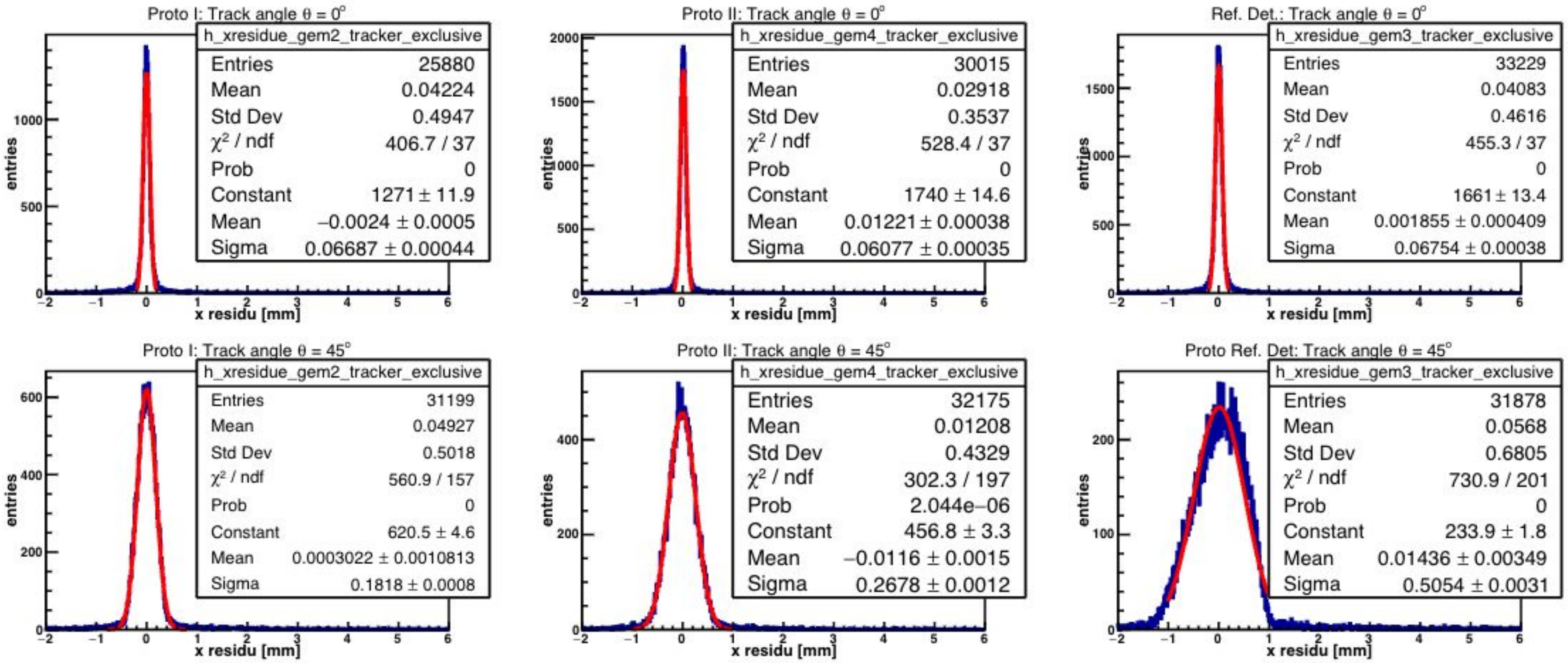


- Spatial resolution for small angle tracks determined by RO structure
  - For perpendicular track: σ ≅ 70 μm
- **Deterioration in the spatial resolution growing with the track angle**
- At large track angles, spatial resolution no longer determined by the RO structure but the drift path that particle traverses before reaching the amplification stage
- **Reduce drift gap to circumvents dependence of spatial resolution on track angle**

- **SoLID: Need detector optimization to reach the required spatial resolution for the range of angles: 8° →35° ?**

Lessons Learned from GEM R&D for EIC

Spatial Resolution of Thin-Gap Triple-GEM at Large Tracking Angles

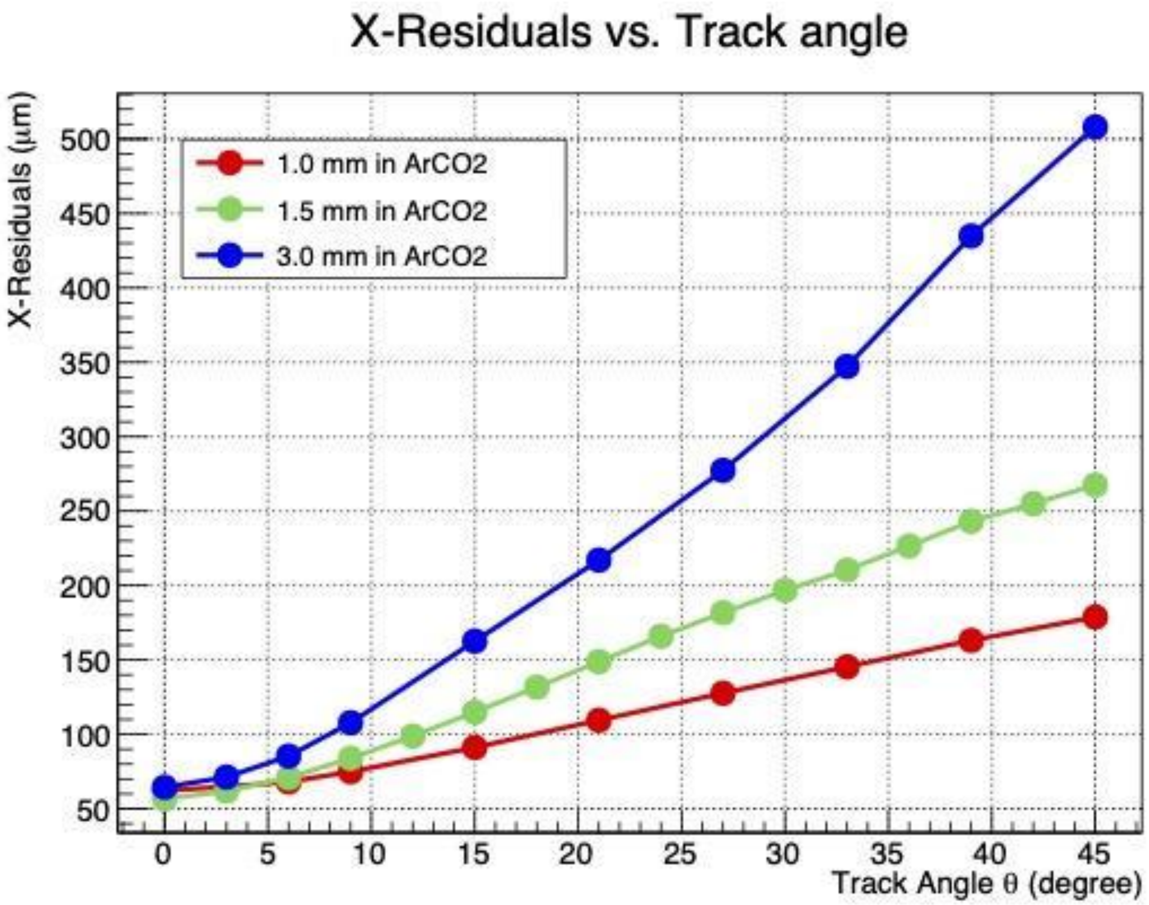


Drift Gap	1.0 mm	1.5 mm	3.0 mm
Spatial resolution @ 0°	66 мm	67 мm	67 мm
Spatial resolution @ 45°	182 мm	268 мm	505 мm

Lessons Learned from GEM R&D for EIC

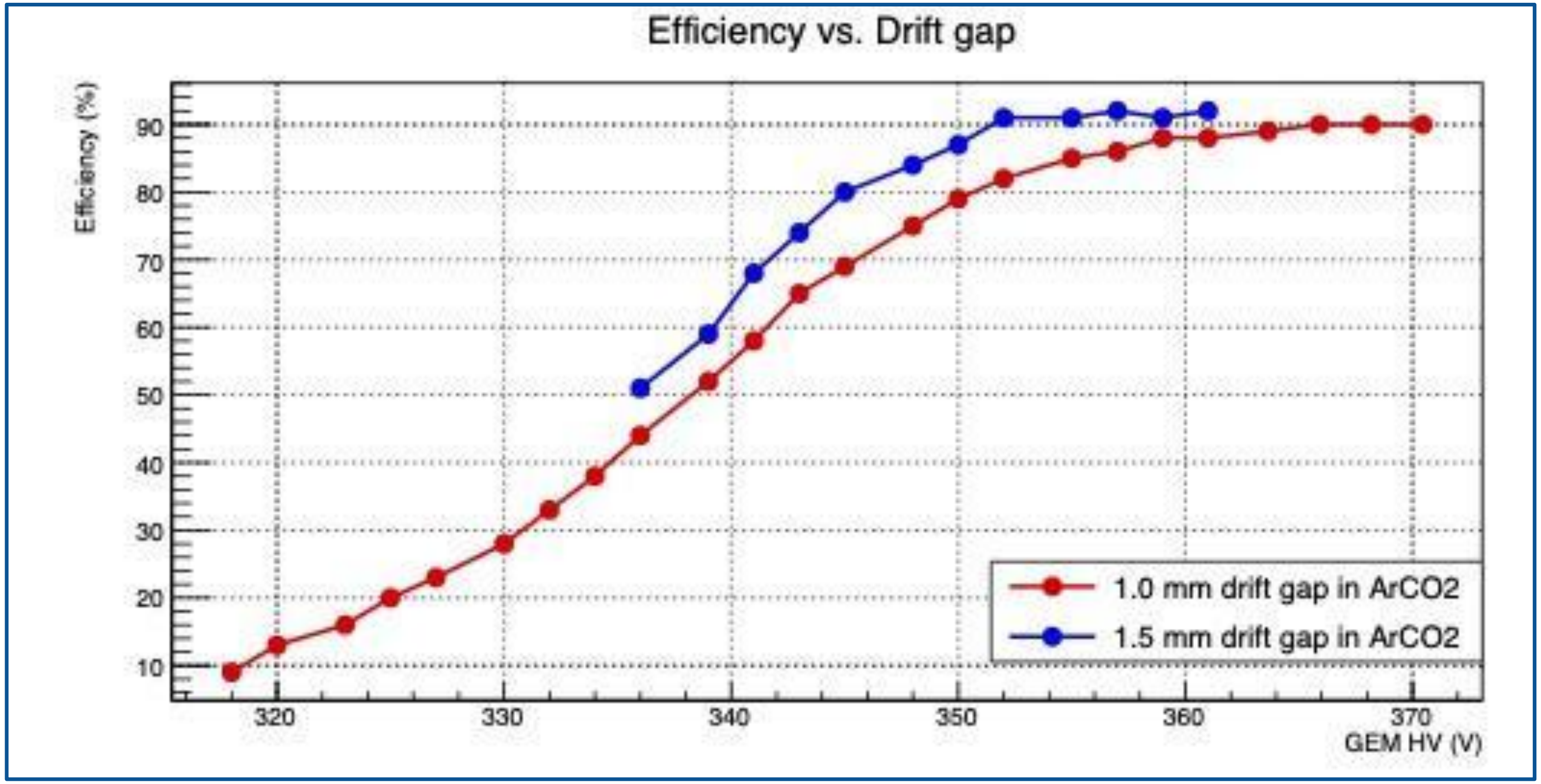
Spatial Resolution of Thin-Gap Triple-GEM at Large Tracking Angles

- With a standard 3 mm drift gap, significant deterioration in spatial resolution begins with a track angle as small as $\theta = 10^o$
- Spatial resolution at track angle **θ = 27°**
  - 3.0 mm driff gap: **~ 277 µm**
  - 1.5 mm drift gap: **~ 180 µm**
  - 1.0 mm drift gap: **~ 127 µm**
- **SoLID: Need to reduce the drift gap?**



Lessons Learned from GEM R&D for EIC

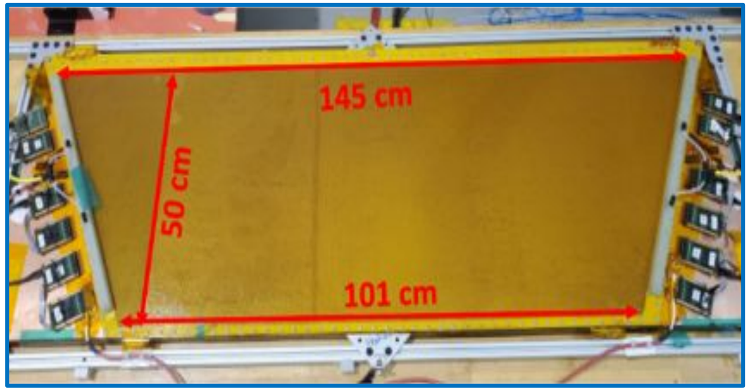
Efficiency of Thin-Gap Triple-GEM with Perpendicular Track

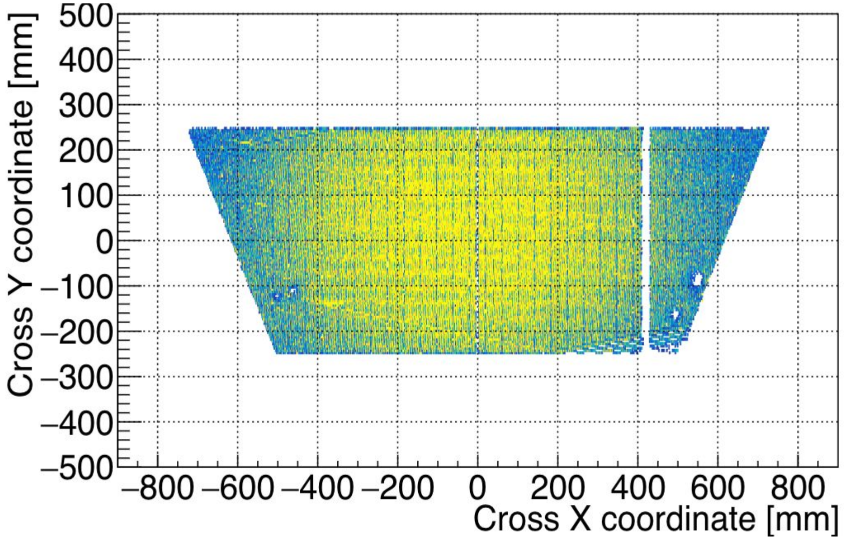


- ❖ Detector having **<u>1.5 mm drift gap</u>** achieves efficiency of 92% in $ArCO_2$ (80%/20%) gas mixture

Experience from R&D on Large-area µRWELL for CLAS12

Large µRWELL Construction & Operation





(Plot from Rafayel Paremuzyan)

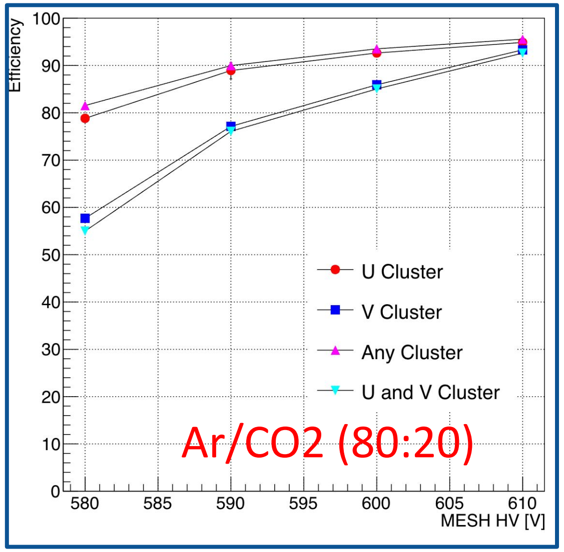
- Detector construction is much simpler compared to GEMs
  - Large-area honeycombs supporting µRWELL and cathode were made at UVa by vacuum gluing technique
  - Assembly time: 5 days vs. 21 days ⟶ Reduce the complexity of building a large number of detectors
  - Much less frames ⟶significantly reduce the material within the active area
  - Robust detector (reopened in 2024 to change component)
- Lower production costs
- 98% of the detector active area is functional
- The dead area caused by dust/contamination deposited on the amplification well is negligible (compared to the entire sector of 10 cm² for GEM)

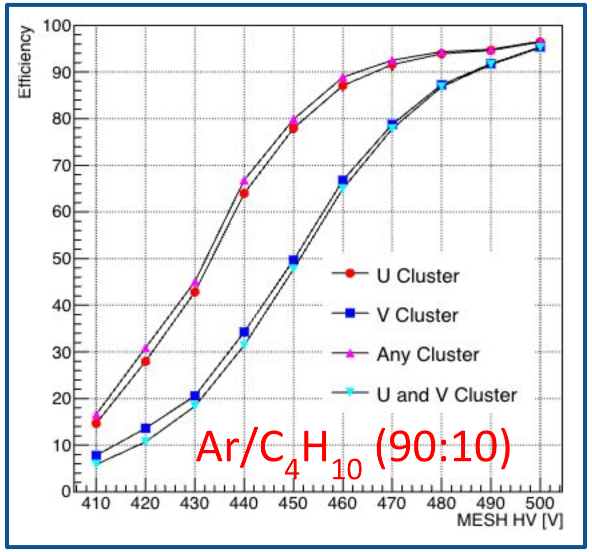
Lessons Learned from R&D on Large-area µRWELL for CLAS12

Optimizing Operating Gas mixture and Detector Structure

- Detection efficiency of the bottom readout layer is significantly lower than top readout layer
  - Due to lower gain on the bottom RO layer
  - Reducing detector overall efficiency
  - Solution: build a pair of 1D detectors facing each other; each 1D readout layer oriented in the U (or V)direction and has its own µRWELL amplification stage

Plots from Rafayel Paremuzyan





- Optimization of operating gases
  - Ar/CO_2 (80%/20%): Amplification HV needed to be pushed to 600 to reach the efficiency of 90%
  - Ar/C_4H_{10} (90%/10%): Detector reached 90% efficiency comfortably at 490 V => Operated much more stably
  - Further optimization with gas ratio in Ar/C_4H_{10}

Conclusions

- SBS runs demonstrate that the requirements for SoLID tracking can be achieved with GEMs
- Adding pixel-GEM layers could improve the performance of track reconstruction
- Need to optimization of drift gap to enhance detector spatial resolution, efficiency, & stability
- µRWELL has the potential to lower the cost, reduce fabrication complexity & material budget
- Needs evaluation with simulations!
- Pre-R&D is needed to evaluate!

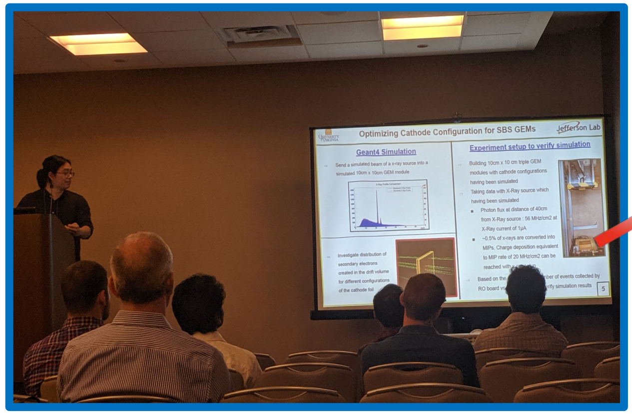
Future perspectives

- Finalize prototype designs
- Make plans for building and testing prototypes
- Explore possibilities for uRwell for lower exposure layers
    - Interface with Hall B, JLab-EIC, & LHCb -Frascati

UVa GEM Fabrication and R&D Program

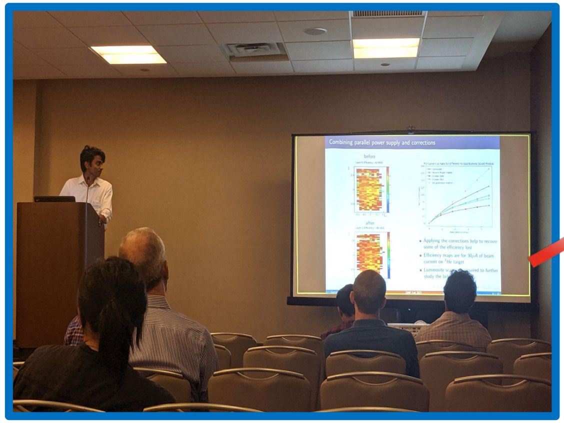
Research Capabilities

Simulation & Validation

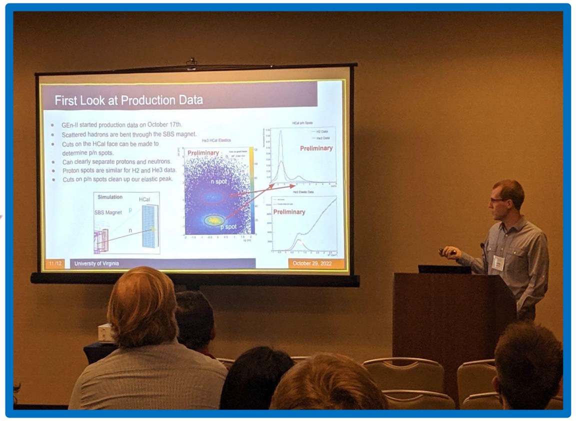


Design & Construction

Characterize & Commision



Data & Physics Analysis



Group Members

- Prof. Nilanga Liyanage
- Dr. Huong Nguyen
- Dr. Asard Amedh
- Seven (7) Ph.D. Students
- Two (2) Undergrad RA
- Two (2) Technicians

Thank you for your attention!

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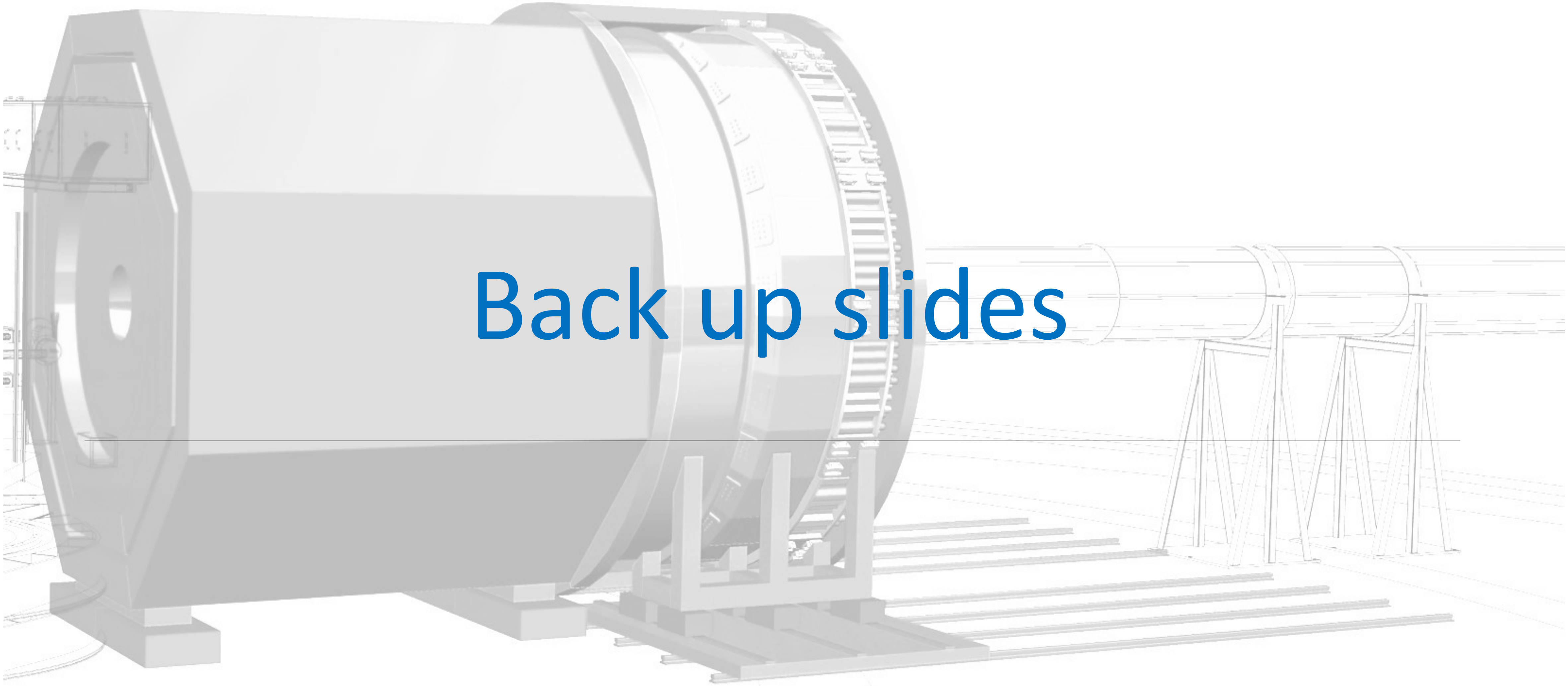
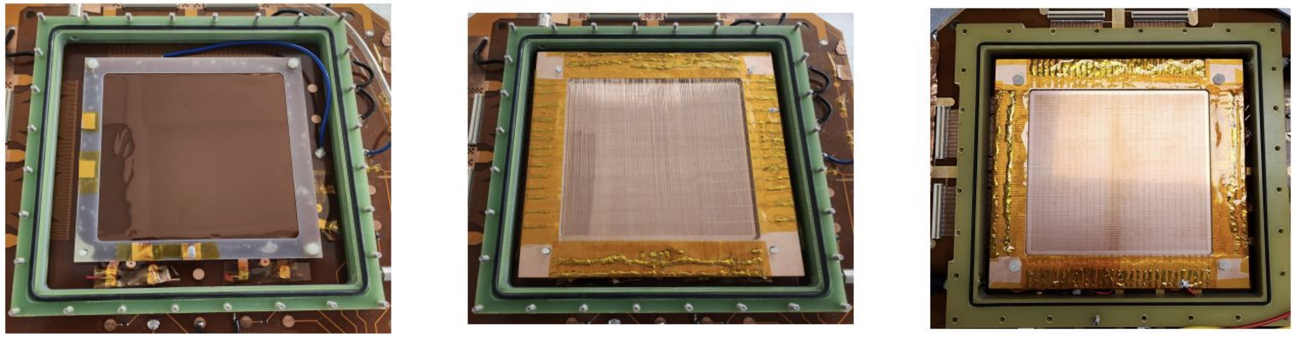
Back up slides



Design and Fabrication of Thin-gap Triple-GEM Prototypes

- **Motivations to reduce drift gap:**
  - Circumvents dependence of spatial resolution on track angle & lessens the effect of magnetic field
- **Investigations:**
  - Performance of triple-GEM detectors at large acceptance with different drift gaps
  - Optimize performance of detectors with different gas mixtures to recover efficiency
  - Explore different cathode structures to maintain stability of thin-gap detectors
- **Design and fabrication of 6 prototypes:**
  - Three prototypes (10cm x 10 cm) having the same structure, different drift gap 1.0, 1.5, 3.0 mm
  - Three prototypes having the same drift gap, different cathode structures

	Cathode	Drift Gap	Tested at FNAL in June 2023
Proto I	Copper-Kapton foil	1.0 mm	ArCO2, HV & Angle Scan
Proto II	Copper-Kapton foil	1.5 mm	ArCO2 & KrCO2 HV & Angle Scan
Proto III	Copper-Kapton foil	3.0 mm	ArCO2, Angle Scan
Proto IV	400 µm-pitch fine Copper wire	1.5 mm	ArCO2, HV & Angle Scan
Proto V	800 µm-pitch fine Copper wire	1.5 mm	ArCO2, HV & Angle Scan



(a) (b) (c)

(a) Cu-Kapton Cathode (b) 400 µm wire-pitch cathode (c) 800 µm wire-pitch

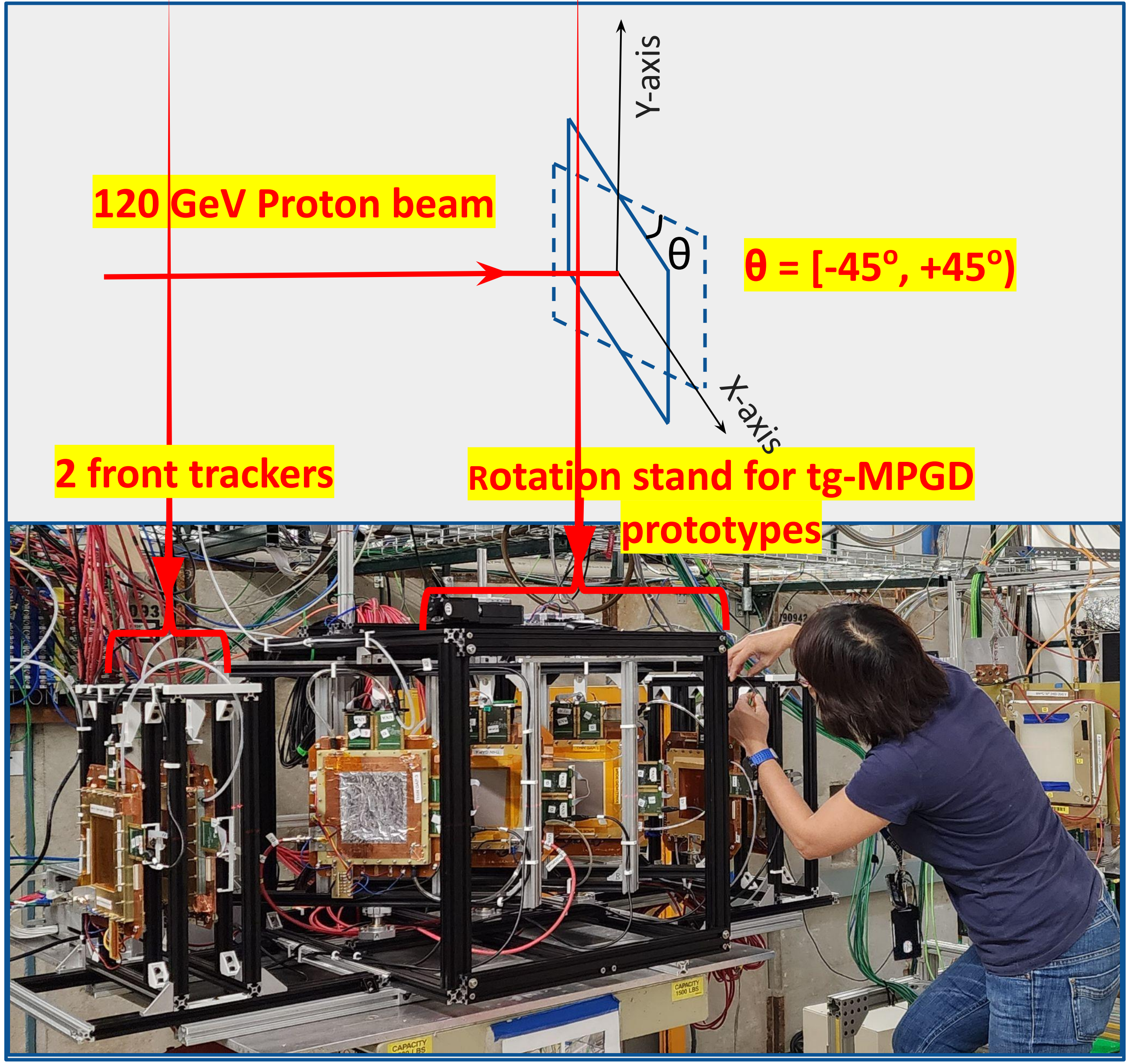
FermiLab Beam Test Setup for Spatial Resolution Study

Setup for spatial resolution study:

- Setup for spatial resolution studies was designed and built by K. Gnanvo and J. Lee (JLab)
- 4 trackers: 2 trackers upstream and 2 trackers downstream
- A rotation stand placed in the middle allows to test up to 3 prototypes at the time
- Rotation stand rotates the X-Y plane by an angle θ ➡ x-spatial resolution will be affected the most as θ increases

Investigate spatial resolution with track angle spanning from 0° to 45° for :

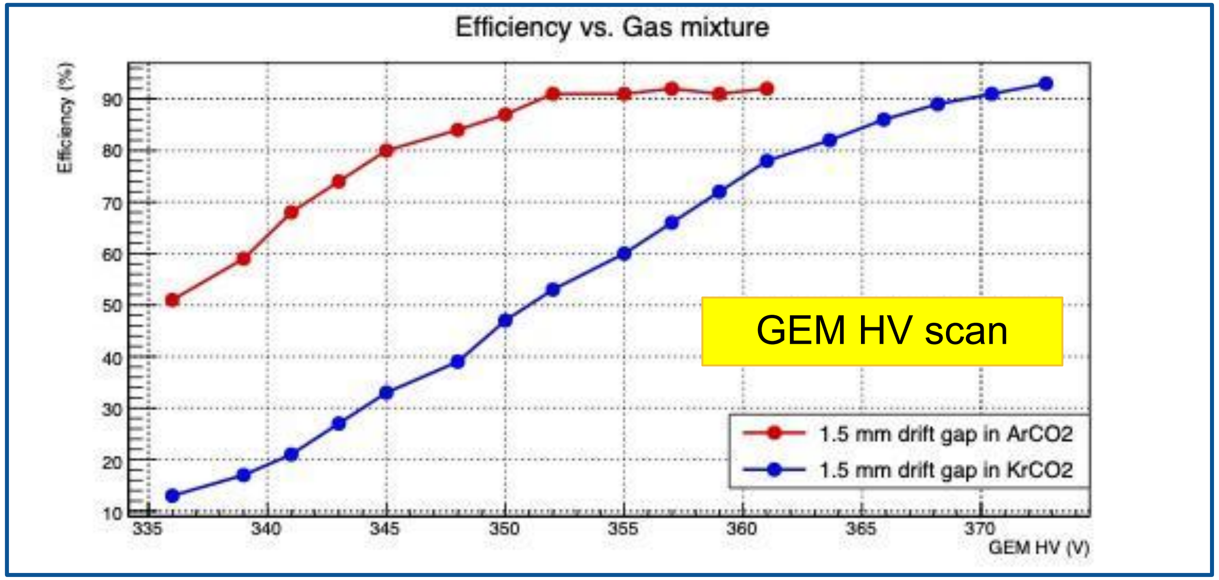
- Same prototype in different gas mixtures ($KrCO_2$ & $ArCO_2$)
- Prototypes with different drift gaps & cathode structure



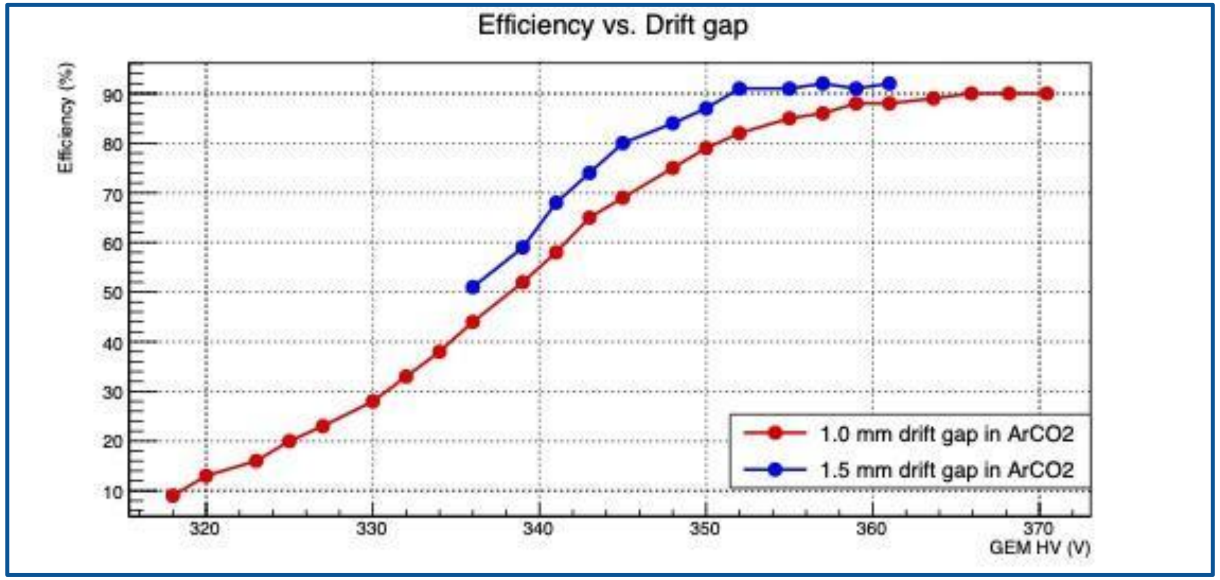
Efficiency Study of the Thin-Gap Triple-GEM Detectors

Preliminary results from ongoing analysis of June 2023 Fermilab test beam data

- **Efficiency vs. Gas mixture study:**



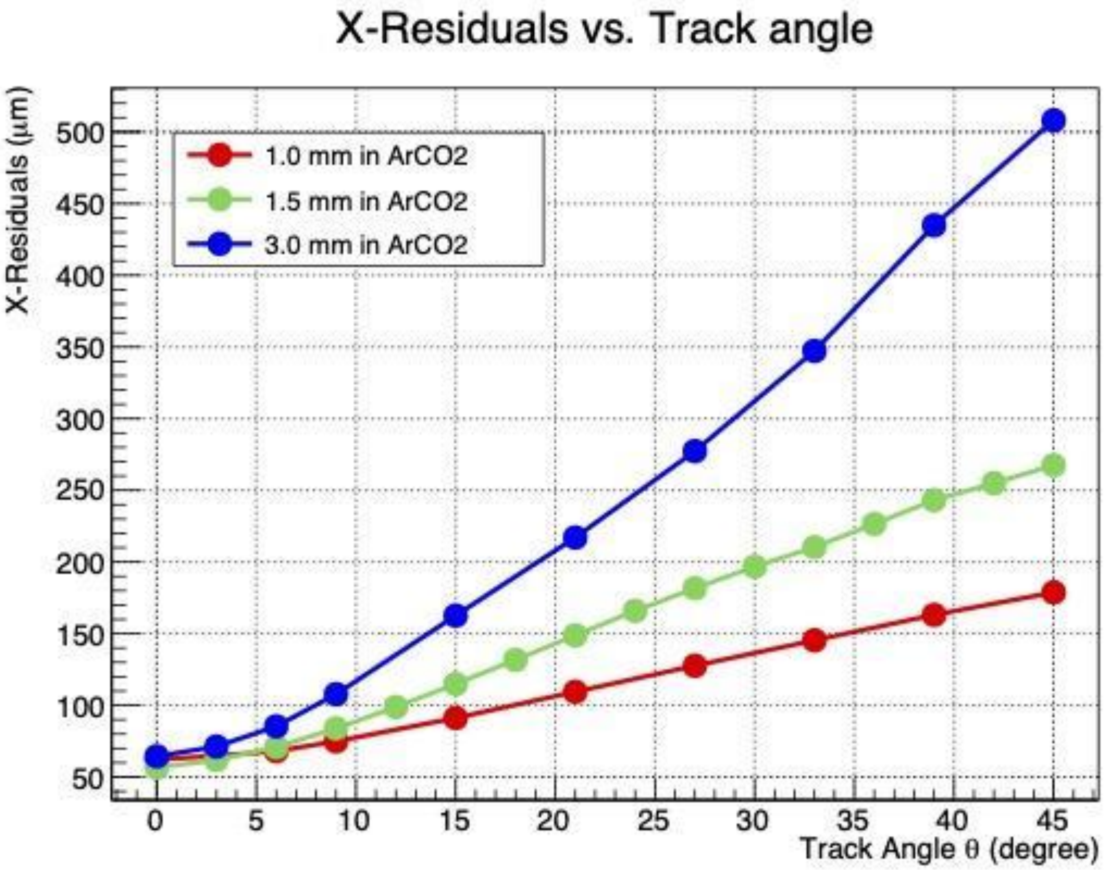
- **Efficiency vs. Drift Gap study:**

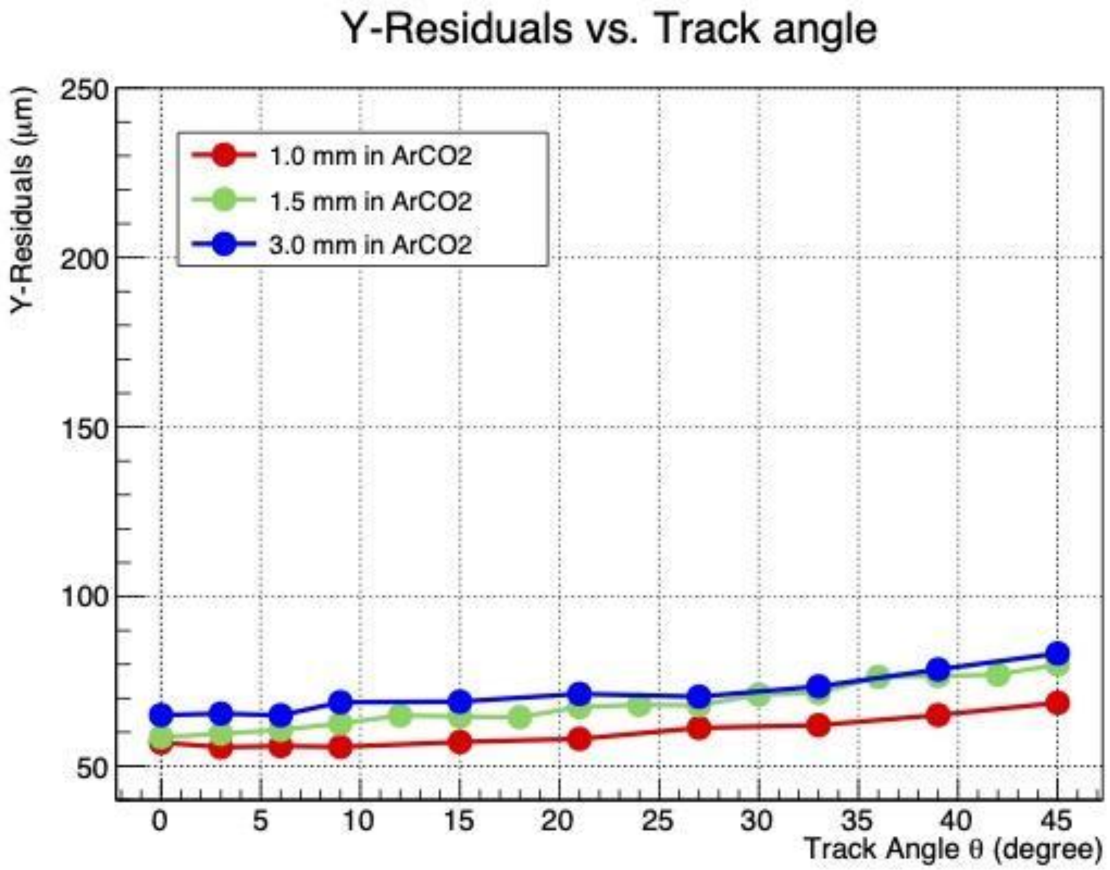


- Efficiency of **1.5 mm drift gap detector** vs. HV applied to GEM foil with 2 different gas mixtures KrCO2 and ArCO2
- **1.5 mm drift gap detector** reaches 93% efficiency in ArCO2 at HV GEM significantly lower than in KrCO2 **(355V vs. 390V)**

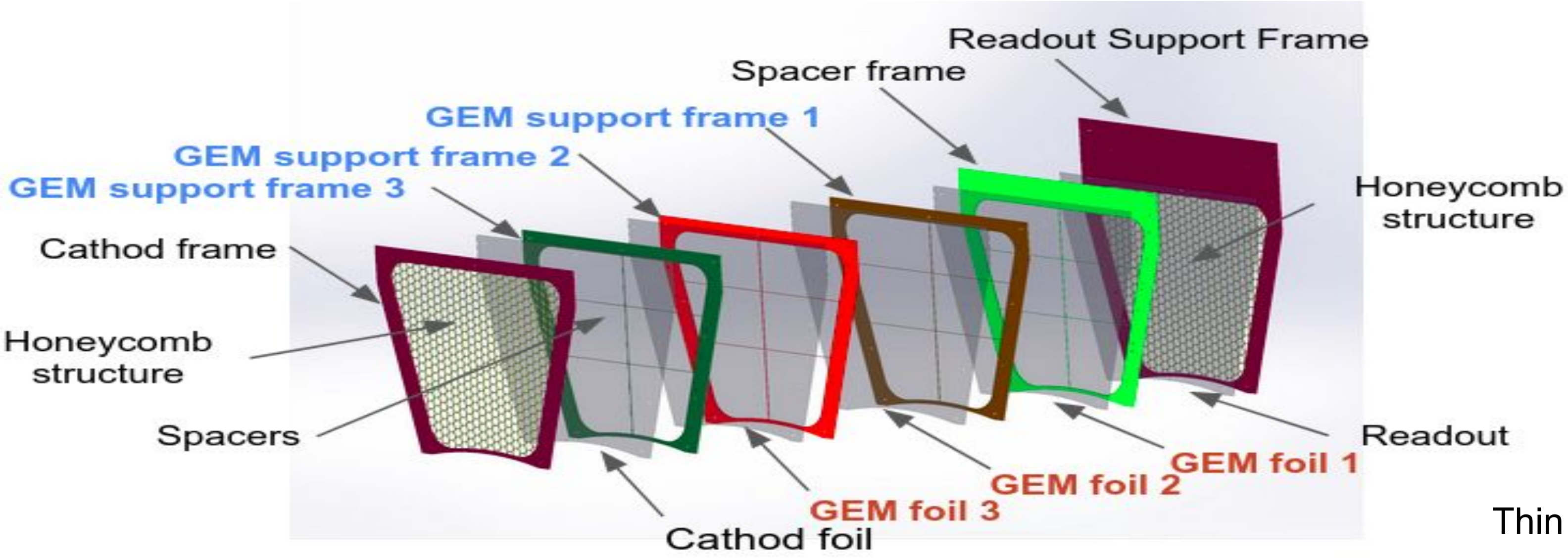
⇨ In optimized ArCO2 (80%/20%) gas mixture, a detector having **1.0 mm drift gap** achieves efficiency of 90%.

- **Spatial resolution vs. track angle studies**

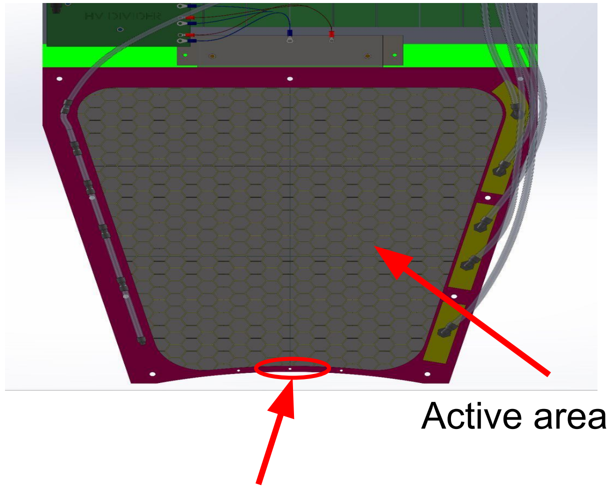




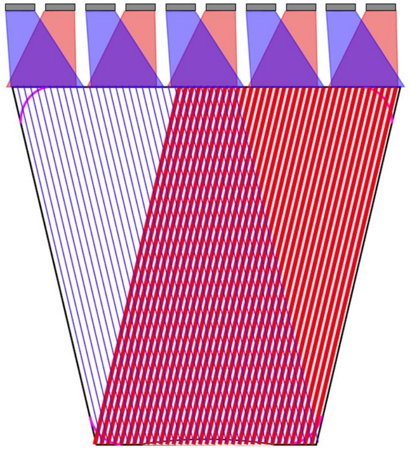
Design of GEM Module for MOLLER



Exploded View of Basic Components



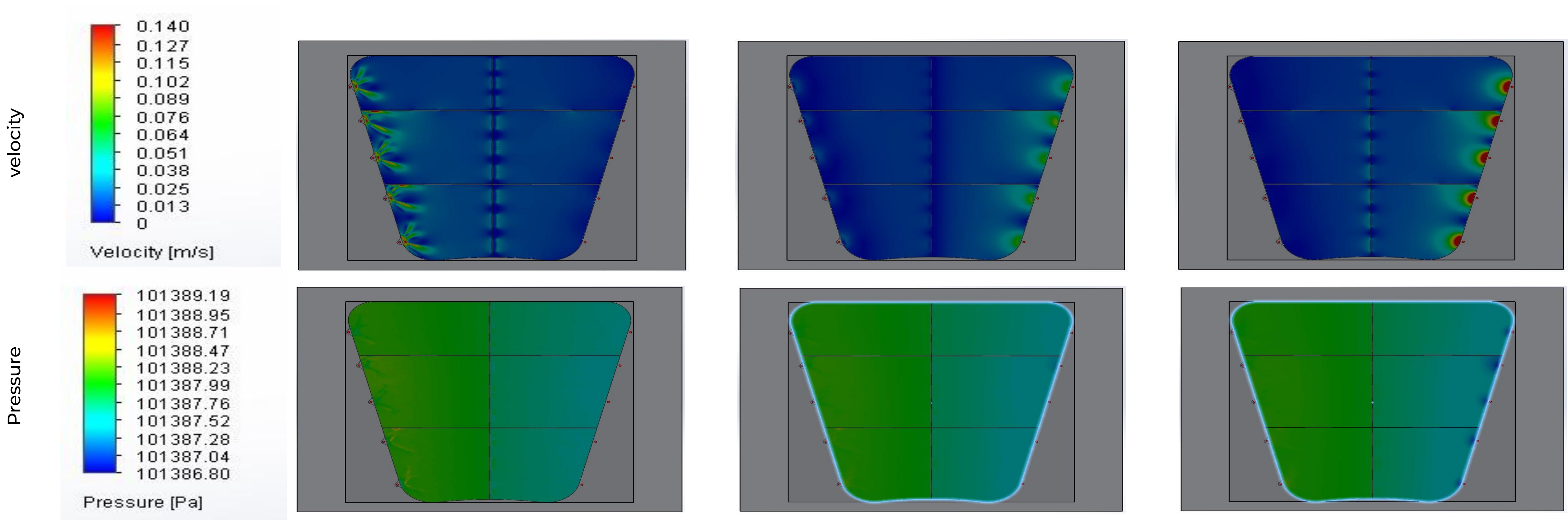
Thin **curved** edge that goes very close to the beam pipe



Specifications of MOLLER Triple-GEM Module

- ⇨ Trapezoidal shape design with thin curved edge allow detectors to be operated near the beam pipe
- ⇨ Module is 2700 cm^2 in size with active area of ~ 2000 cm^2
- ⇨ Each GEM foil consists of 20 individual sectors
- ⇨ UV-readout with ten (10) APV25 cards

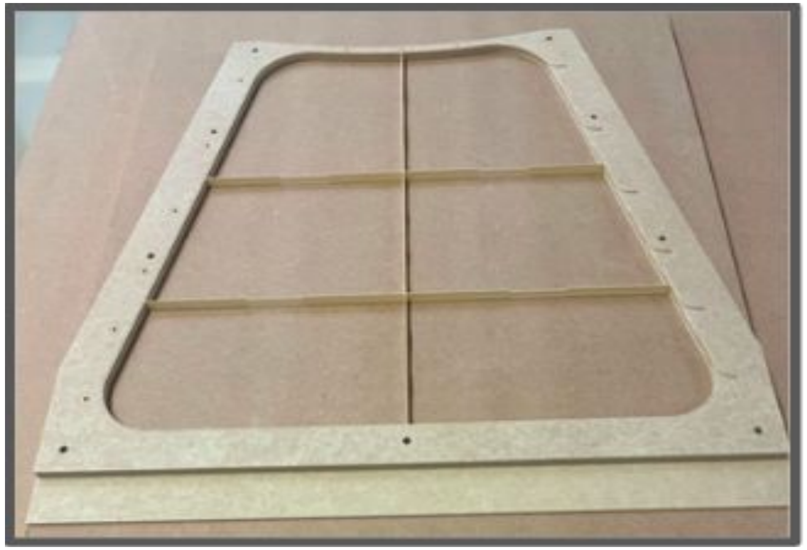
Gas Flowing Simulations of MOLLER GEM Module



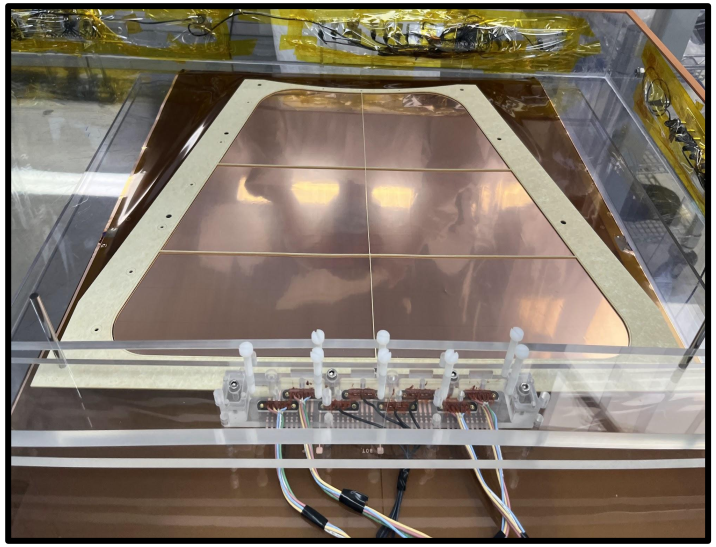
- Five (5) gas inputs and five (gas) outputs with oval smooth-edged gas pockets
- Consistent gas flow is achieved inside the detector
- Avoid pressure buildups inside the module

GEM Quality Control and Assembling

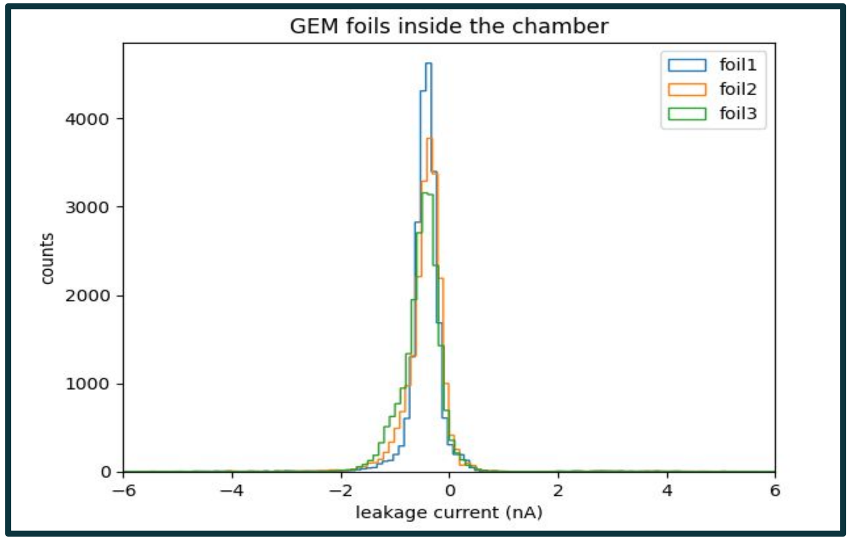
- ⇨ Preparation of frames (sanding, washing & varnishing)
- ⇨ Stretching and gluing GEM foils on the prepared frames
- ⇨ High voltage sector test is repeated on Raw, Framed & Chambered GEM foils
- ⇨ Assembling the module starting from the bottom readout support and sealing the assembled detector
- ⇨ Connecting gas fixtures and completing the high voltage distribution



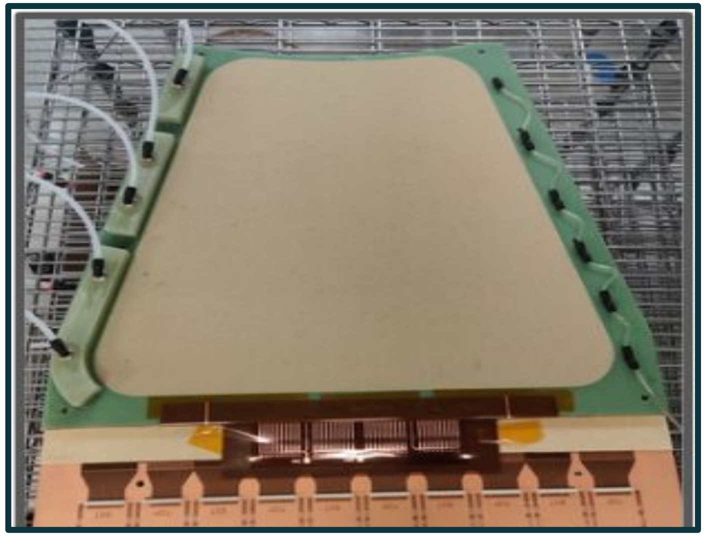
Preparing frames



HV GEM sector test



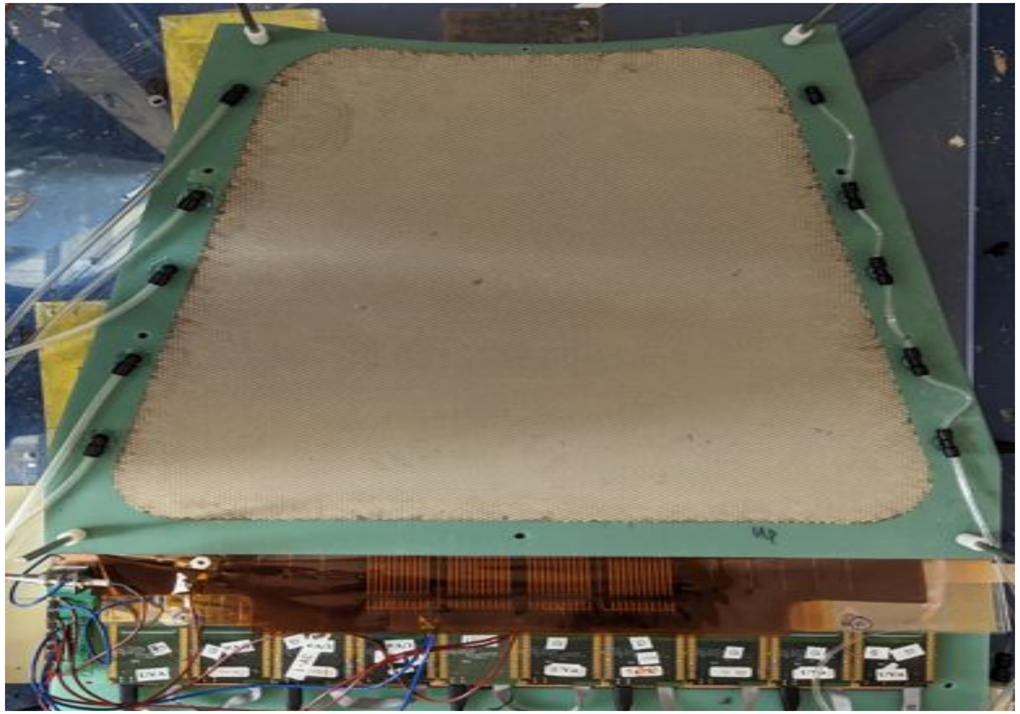
GEM leaked current distribution

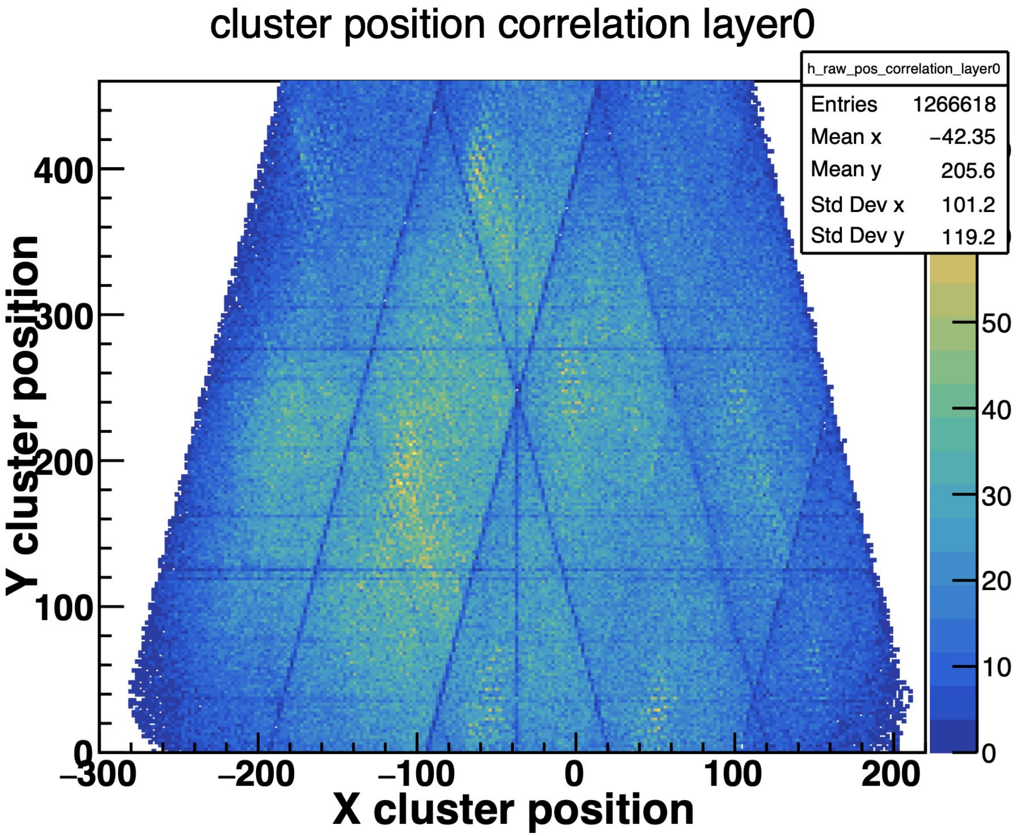


Completed module

X-Ray data with SRS Readout

- Random trigger was used for x-ray test, hit counts more sensitive to strip noise – reason we see less counts on the edges of each APV for data taken with SRS

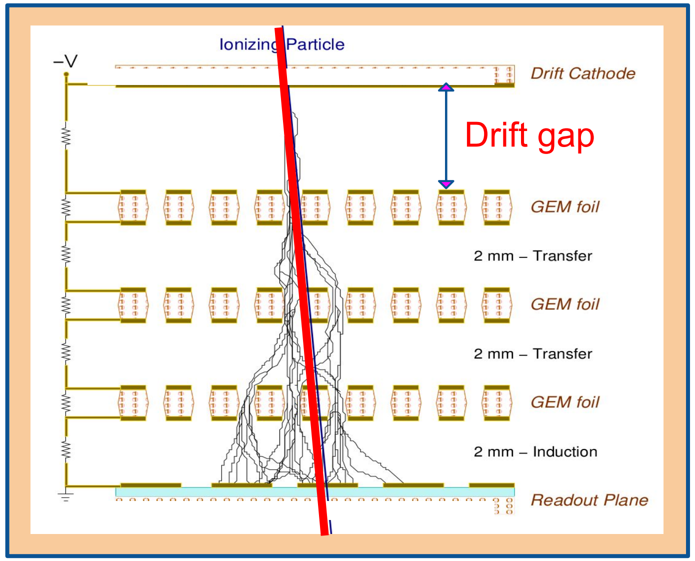




UVa GEM Fabrication and R&D Program

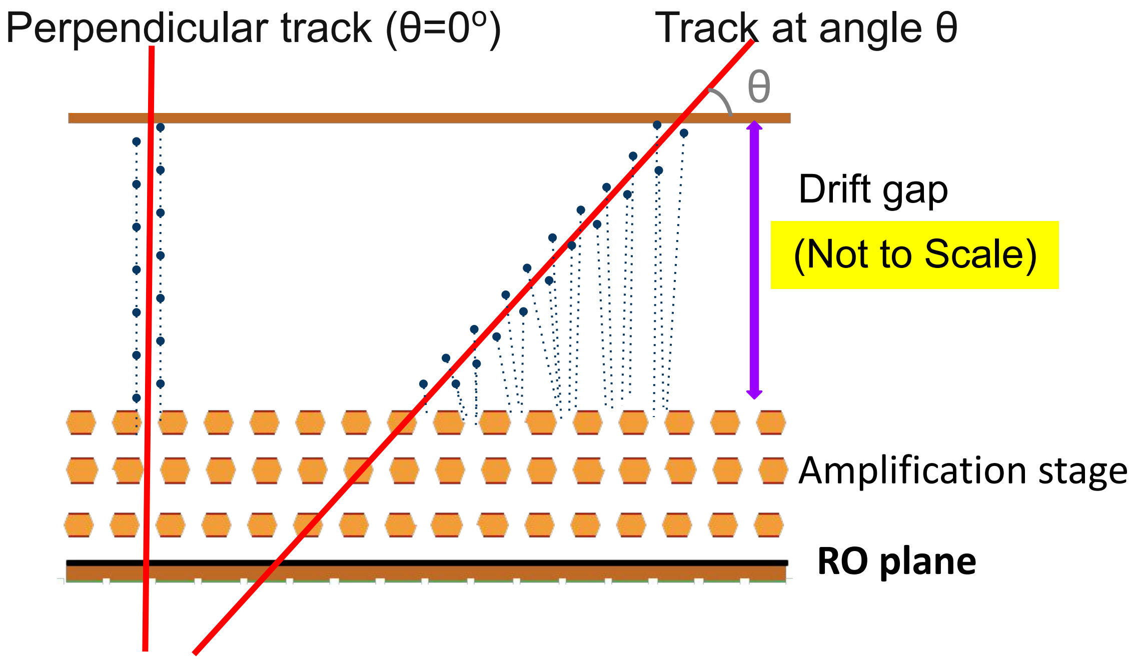
Thin-Gap Triple-GEM at Large Tracking Angles

- ❑ Triple-GEM detectors at small track angle



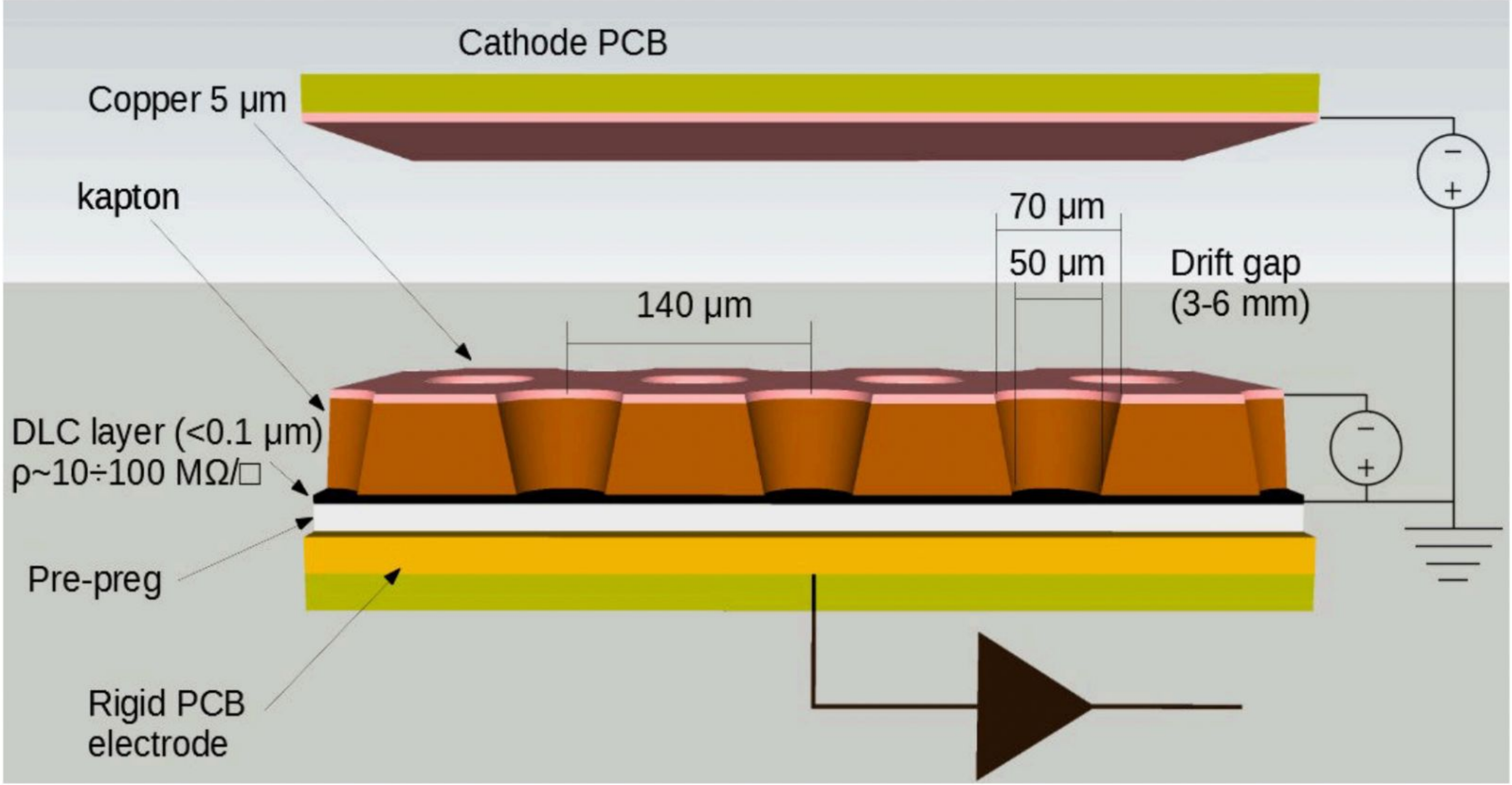
- ❖ Standard 3mm drift gap
- ❖ Spatial resolution for small angle tracks determined by RO structure
- ❖ For perpendicular track: σ ≅ 70 µm

- ❑ Triple-GEM detectors at large track angle



- ❖ Deterioration in the spatial resolution growing with the track angle
- ❖ Spatial resolution no longer determined by the RO structure but the drift path that particle traverses before reaching the amplification stage
- ❖ Reduce drift gap to circumvents dependence of spatial resolution on track angle

The µ-RWELL



Cathode PCB
Copper 5 µm
kapton
70 µm
50 µm
Drift gap
(3-6 mm)
140 µm
DLC layer (<0.1 µm)
ρ~10÷100 MΩ/□
Pre-preg
Rigid PCB
electrode