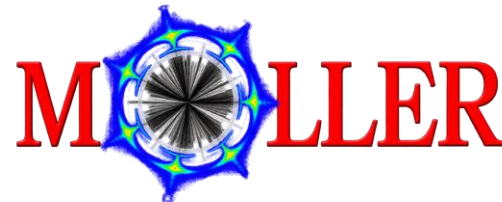


Commissioning and Performance Studies of the GEM Tracking System for the MOLLER Experiment at Jefferson Lab

Vimukthi Haththotuwa Gamage

University of Virginia

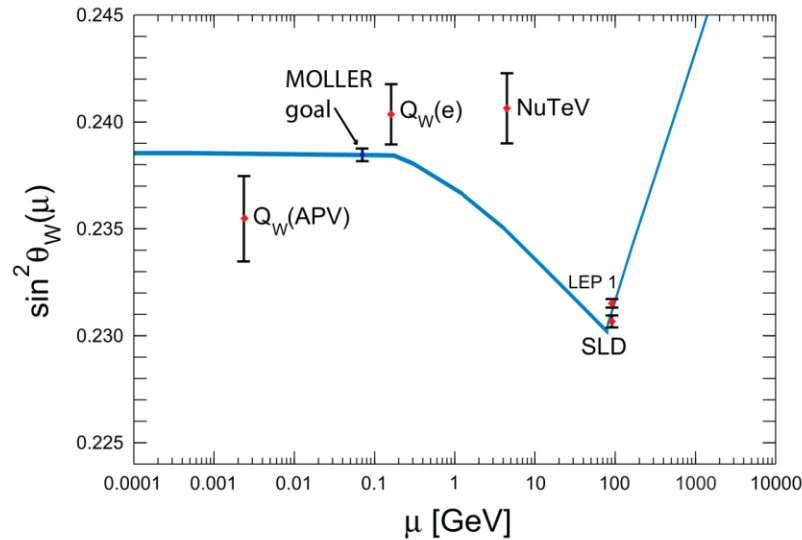
On behalf of UVA MPGD Group and MOLLER Collaboration



Overview

- MOLLER Experiment
 - Physics Motivation
 - Experimental Method
- Tracking System
- Commissioning and Performance studies

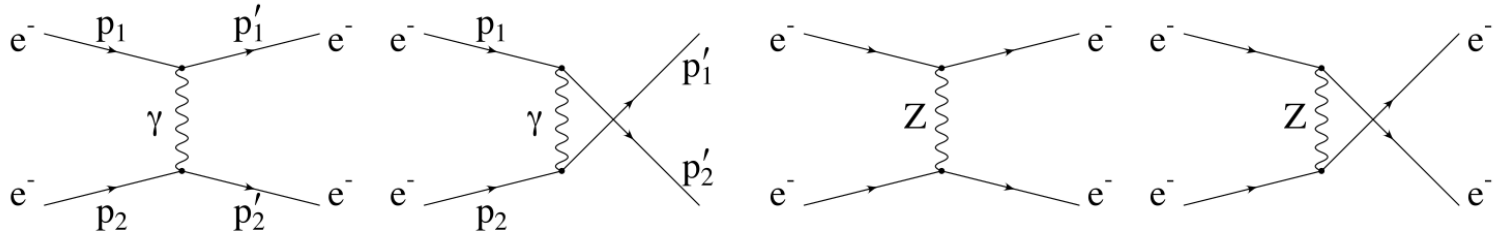
MOLLER Experiment : Physics Motivation



Proposed MOLLER measurement

$$A_{pv} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{mG_F}{\sqrt{2}\pi\alpha} \frac{4E \sin^2 \theta}{(3 + \cos^2 \theta)^2} Q_W^e$$

$$Q_W^e = 1 - 4 \sin^2 \theta_W$$



Feynman diagrams for Moller scattering at tree level

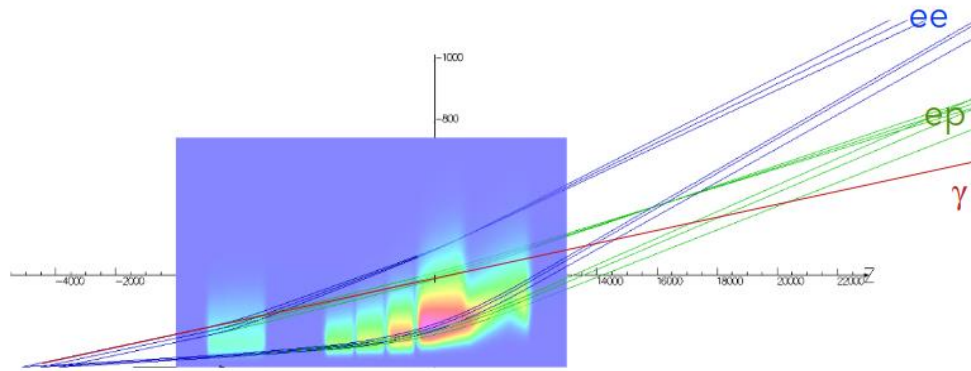
Physics Motivation

- Precision measurement of the parity-violating asymmetry, A_{PV} , in Moller scattering
- Use A_{PV} to extract weak charge of the electron, Q_W^e , and thus the weak mixing angle
- Test the Standard Model at low momentum
- Search for signature of physics beyond the Standard Model through deviations from the predicted asymmetry

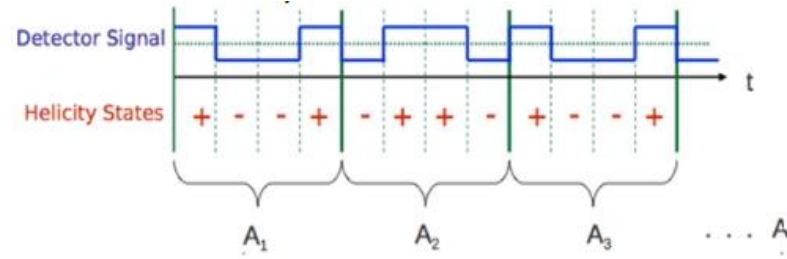
Goals

- Measure the parity-violating asymmetry with unprecedented precision
- Achieve ~2.4% relative precision on the weak charge of the electron
- Provide sensitivity to new physics at multi-TeV energy scales

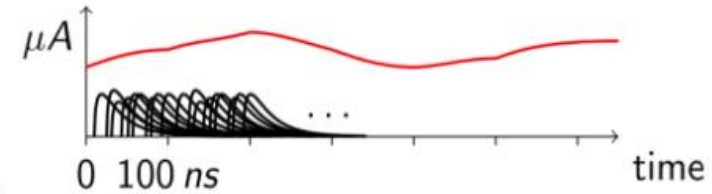
MOLLER Experiment : Experimental Method



Azimuthal field separates ee, ep, and photons at detector plane



Rapid measurement over helicity reversals to cancel noise

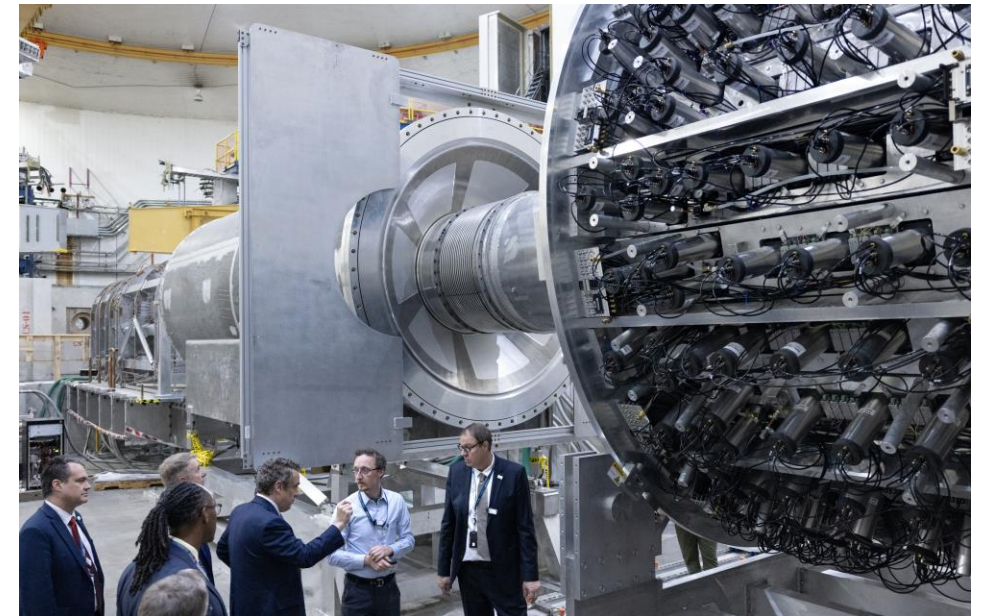
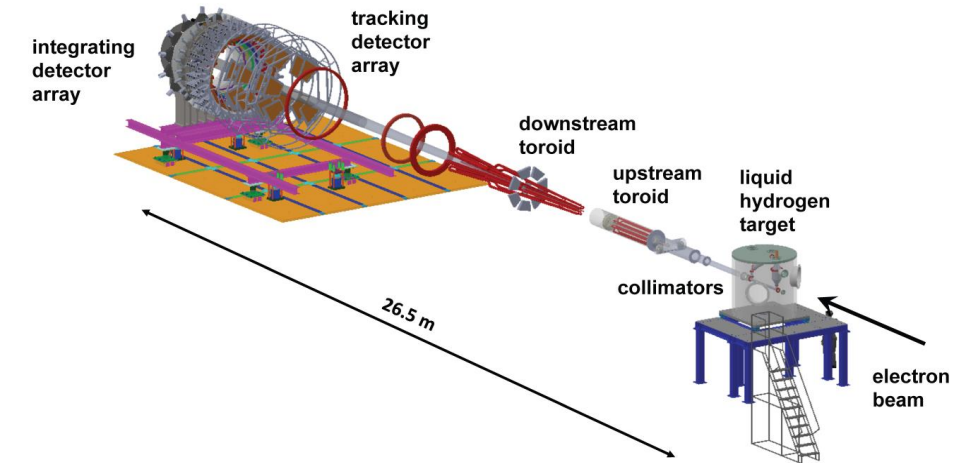


Integration of analog detector current

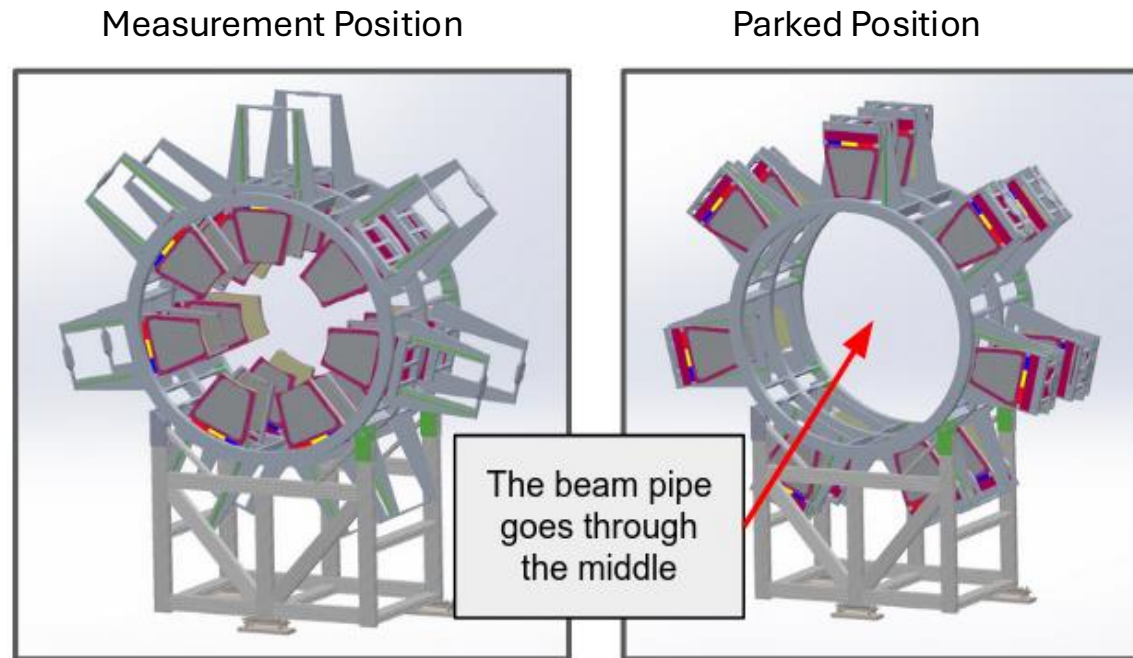
- Longitudinally polarized electron beam with rapid helicity flip from CEBAF
 - $E_{\text{beam}} = 11 \text{ GeV}$, $I_{\text{beam}} = 65 \text{ } \mu\text{A}$, $f_{\text{flip}} = 1.92 \text{ kHz}$
- Beam electrons are scattered off liquid H_2 target
 - $L_{\text{target}} = 125 \text{ cm}$, $P_{20\text{K}} = 35 \text{ psia}$, $\text{Luminosity} = 2.4 \times 10^{39} \text{ cm}^{-2}\text{s}^{-1}$
- MOLLER electrons are deflected to the main detector (**integrating mode**) by the spectrometer
 - **Rate $\sim 130 \text{ GHz}$**
- Measure the integrated flux for each helicity to obtain the raw asymmetry

MOLLER Experiment : Experimental Setup

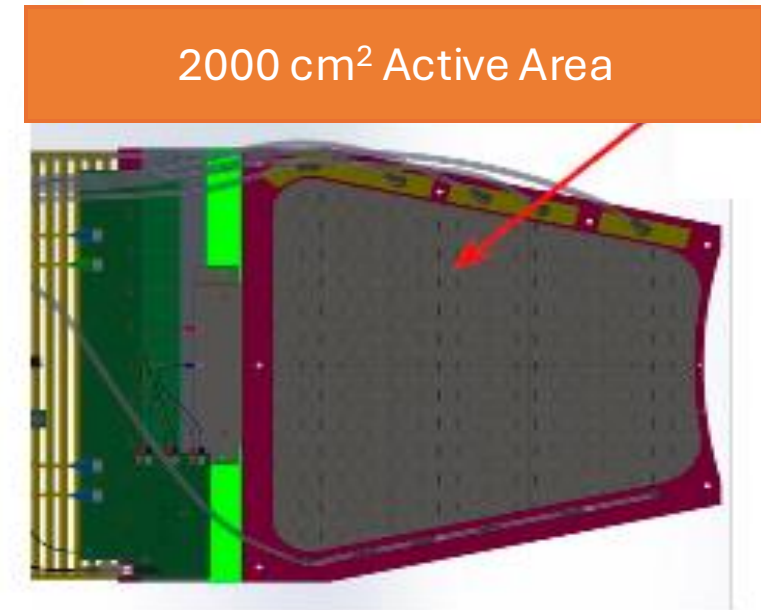
- Polarized Beam
- Target System
- Collimators and Spectrometer
- Main Detector
- Auxiliary Detectors
- Showermax
- Pion Detector System
- Data Acquisition



Tracking System



Rotating tracking system



MOLLER GEM in the mounting structure

- Consist of four Gas Electron Multiplier (GEM) Detector planes, each with seven GEM modules of 2000 cm² active area
- Operate in **counting mode** during dedicated low beam-current runs for calibration and kinematic verification
- Removed from the immediate path of the scattered flux during the full beam-current operation in the **integrating mode** to avoid radiation damage

Motivation, Goals and Measurements

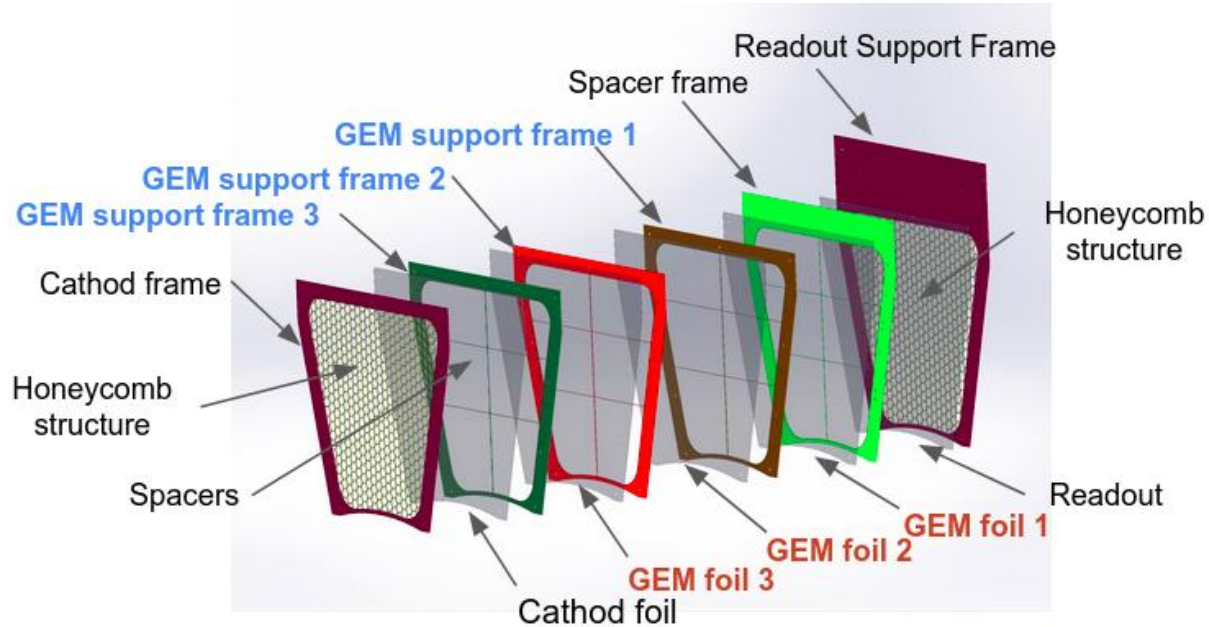
Motivation and Goals

- Reconstruct scattered electron trajectories to determine the experimental acceptance
- Map focal-plane coordinates and track angles to target kinematic variables
- Validate the spectrometer optics and Monte Carlo simulations
- Identify contributions from elastic electron-proton scattering and other backgrounds
- Determine the acceptance-averaged kinematic factor (target uncertainty below 0.5%)

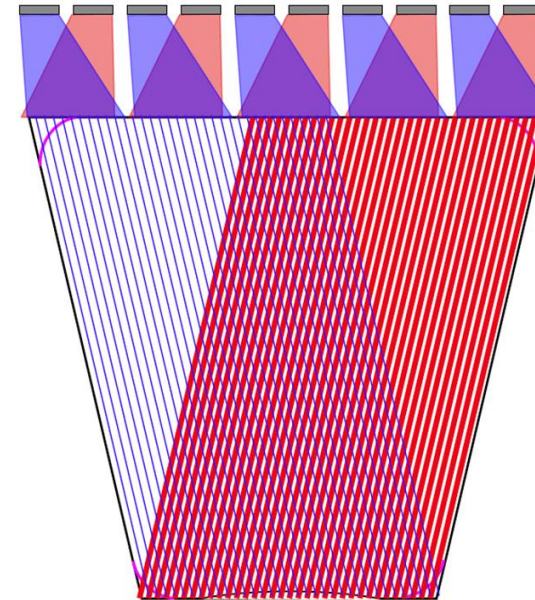
Measurements

- Dedicated low-current measurements using GEM detectors in the active position
- Event-by-event reconstruction of scattered electron trajectories
- Determine position and angular distributions at the detector planes
- Reconstruct target kinematics using the spectrometer optics model
- Compare measured distributions with Monte Carlo simulations
- Optimize detector operating conditions and reconstruction efficiency

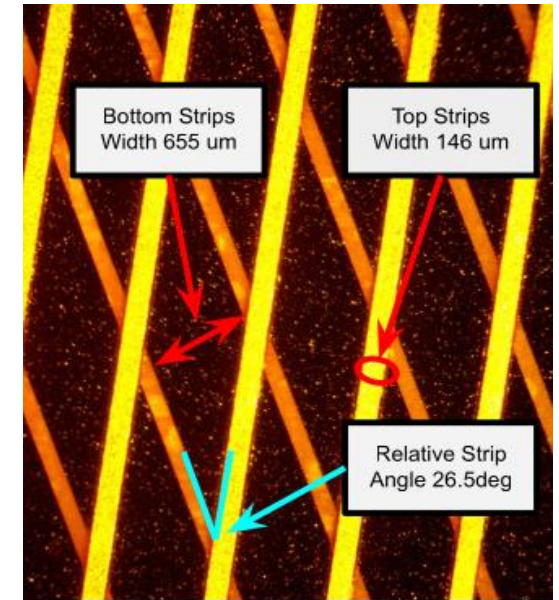
GEMs in the MOLLER Experiment



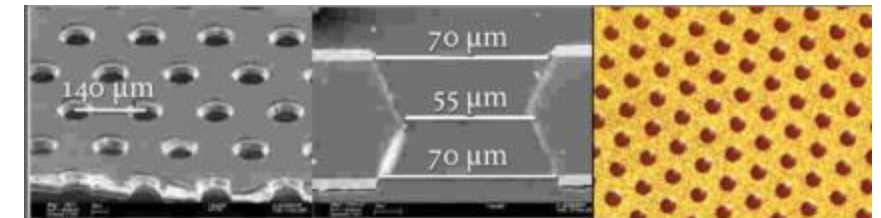
Exploded view of the MOLLER GEM * design by Bhashitha Dharmasena



MOLLER GEM readout

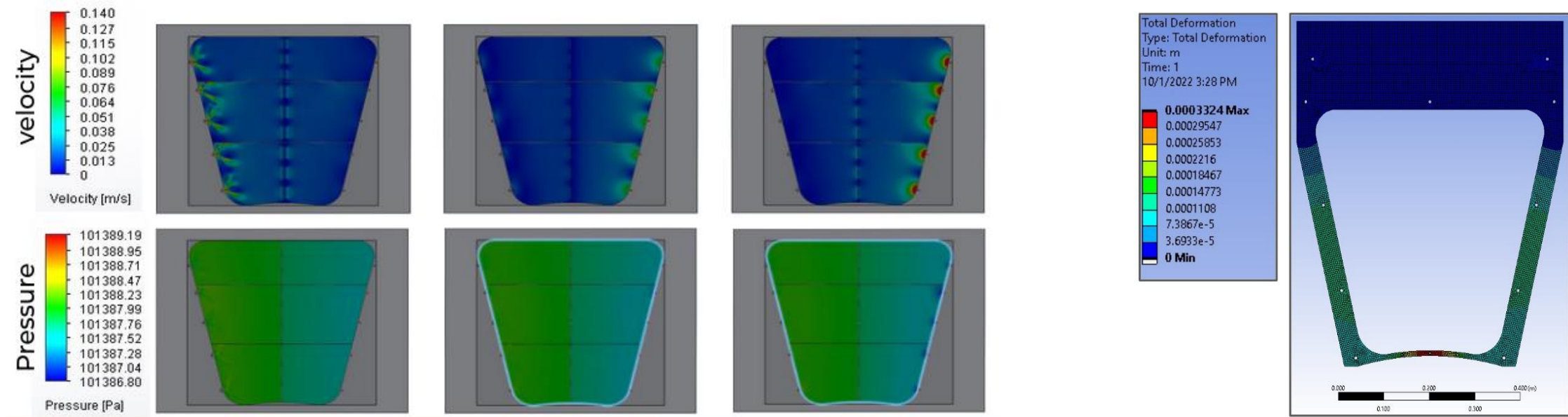


- Trapezoidal shape design with thing curved edges : operated near the beam pipe
- Each GEM foil consists of 20 individual sectors
- UV-readout with 10 APV25 cards
- Detector production : UVA and SBU shared responsibility
- This talk primarily focus on the studies done at UVA



MOLLER GEM Foil

Mechanical Design



CFD and FEA simulations for gas flow (left) and foil stress (right) *simulations by Bhashitha Dharmasena

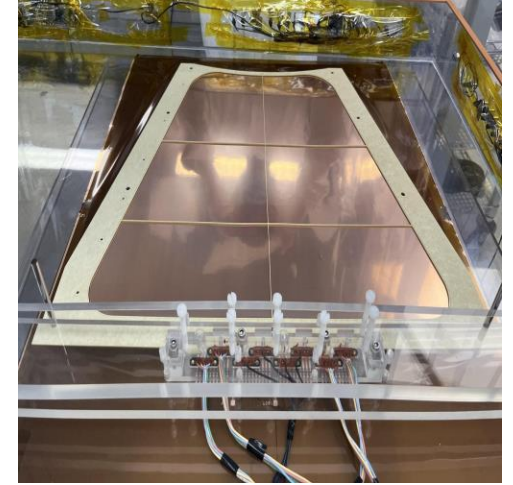
- Deflection of the module is under 3 safety factors when subjected to foil stress
- Honeycomb structures add lateral strength
- Five gas inputs and five outputs with oval smooth-edged gas pockets
- Consistent gas flow inside the detector : pressure buildups avoided

Assembly and Testing

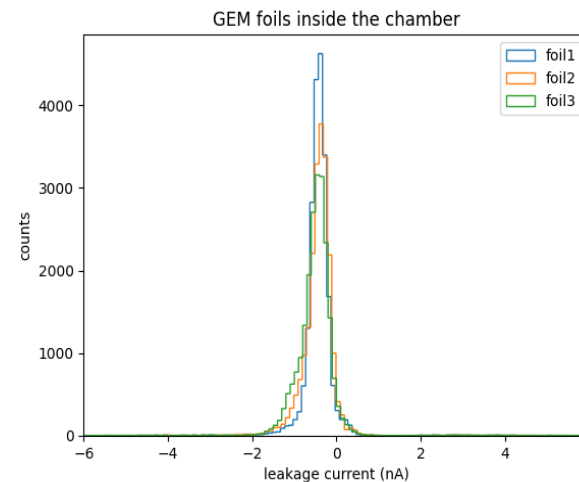
- Preparation of frames (sanding, washing, and varnishing)
- Stretching and gluing foils on the frames
- High voltage sector testing : repeated for raw, framed, and chambered foils
- Module assembly from the bottom readout support and sealing after assembly
- Completion of gas fixtures and high voltage distribution



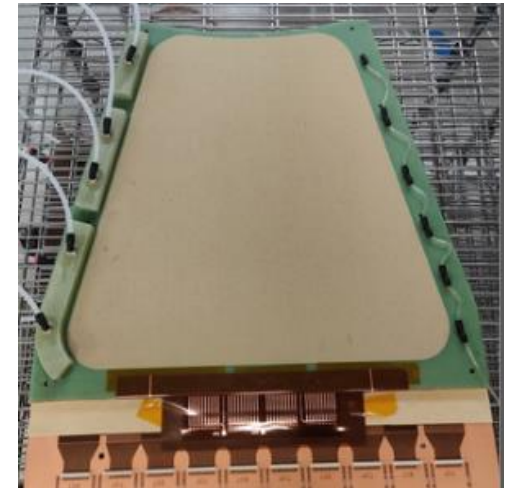
Varnished frames



HV sector testing

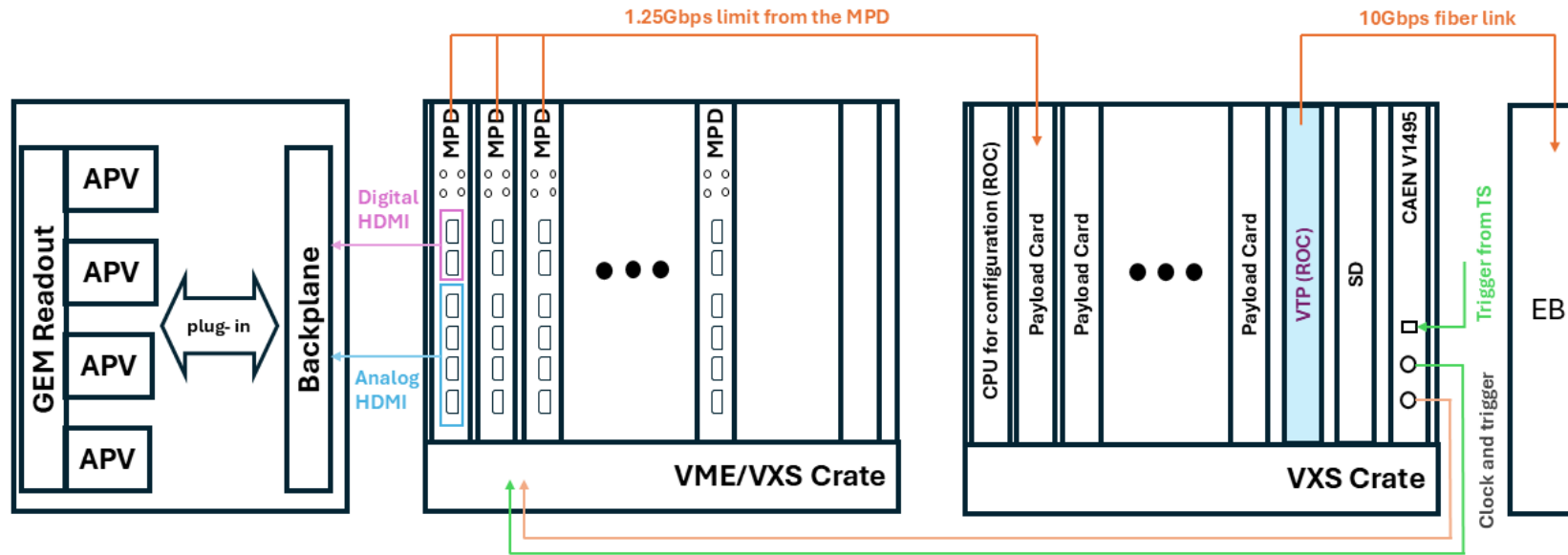


Leakage current distributions



Completed module

Readout and DAQ



Simplified diagram of the GEM DAQ

- APV25 provides analog signal sampling and multiplexed readout
- MPD electronics digitize and process the APV25 signals
- VTP-based readout integrated with the CODA data acquisition system
- Online processing includes pedestal and common mode subtraction, and zero suppression
- Offline processing includes cluster and track reconstruction

Noise and Mitigation

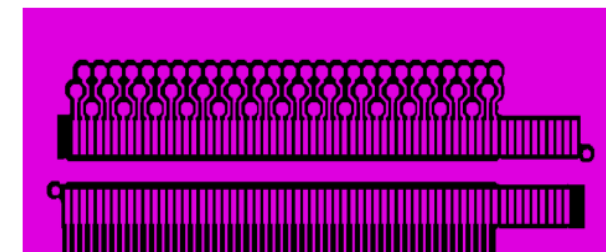
Noise Source

- Electronic noise from front-end electronics and readout channels.
- Common-mode fluctuations affecting groups of APV25 channels.
- Pickup from grounding, power distribution, and external electronics.
- Noisy or unstable channels affecting cluster reconstruction.

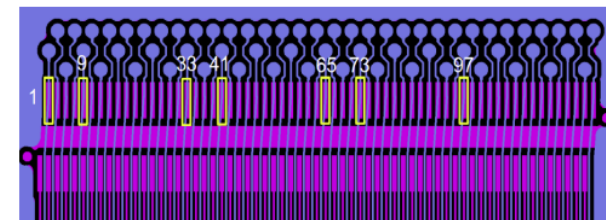
Noise Mitigation

- Channel-by-channel pedestal calibration.
- Event-by-event common-mode correction.
- Identification and masking of noisy channels.
- RF cage shielding for the detector
- Optimization of grounding and electrical connections.

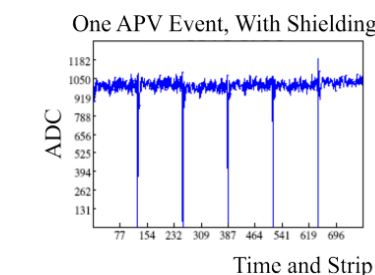
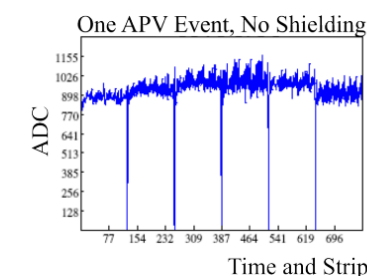
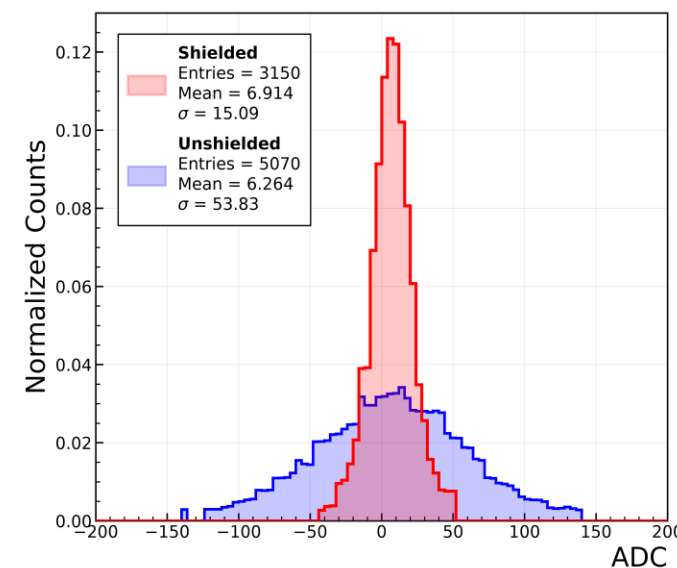
MOLLER shielding design and work led by brynna Moran



Prototype design



Production design



Common mode improvements from shielding in SBS

Cosmic Stack

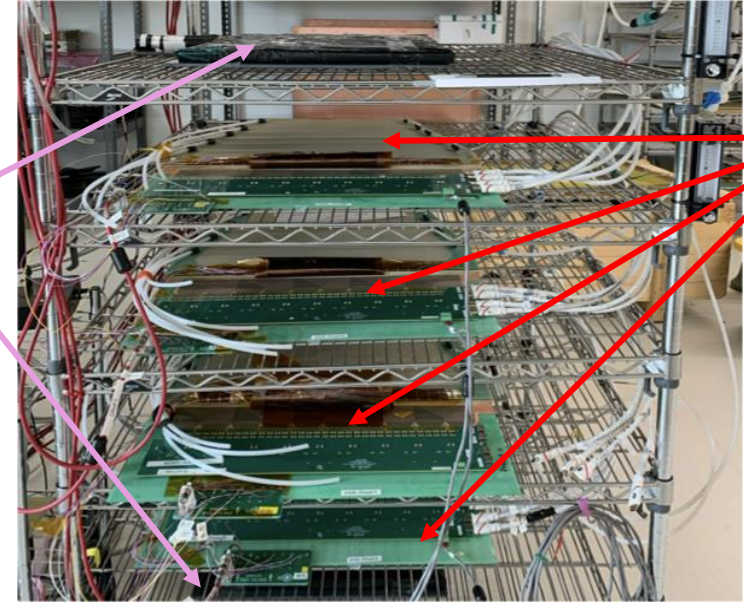
Cosmic-Ray Tracking Setup

- Four-plane GEM tracking telescope with scintillator coincidence triggering.
- APV25 front-end electronics with MPD/VTP readout and CODA DAQ.
- Individual high-voltage control using WIENER/CAEN supplies.
- Dedicated cosmic-ray data taking for detector commissioning.
- Reconstruction and performance studies using moller-counting and mpd_gem_view_ssp.

Commissioning Objectives

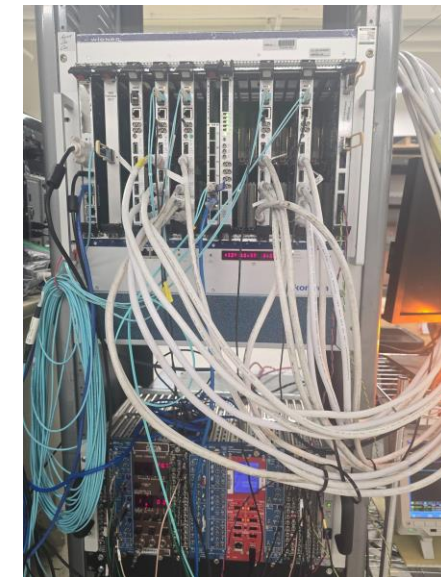
- Validate readout and detector operation
- Establish stable high-voltage operating conditions
- Evaluate cluster reconstruction and hit efficiency
- Characterize spatial resolution and tracking performance

Trigger
Scintillators



GEMs

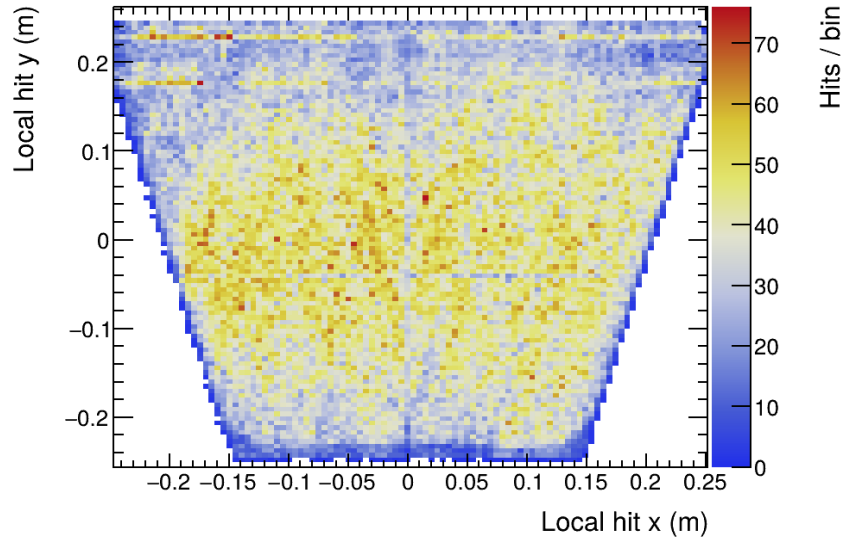
GEM stack



DAQ crate

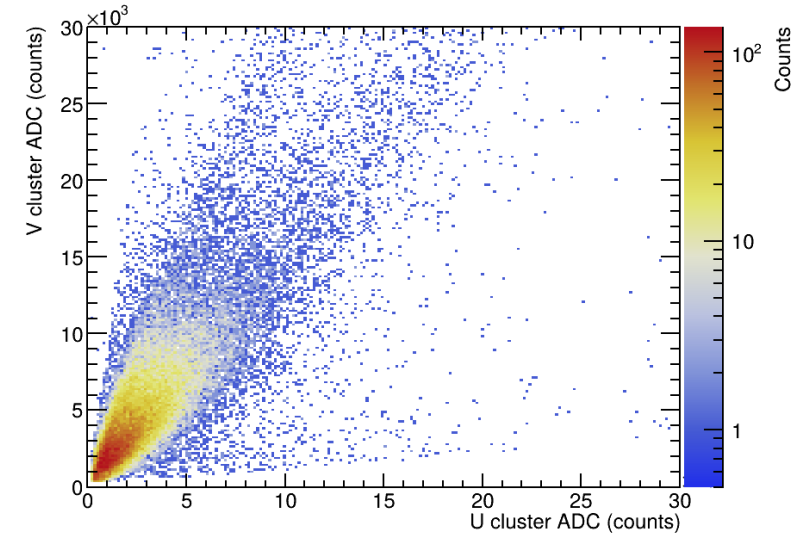
Commissioning

Reconstructed 2D hits (no track cut) | Module 3



Reconstructed 2D hit distribution

U-V cluster ADC correlation | Module 3

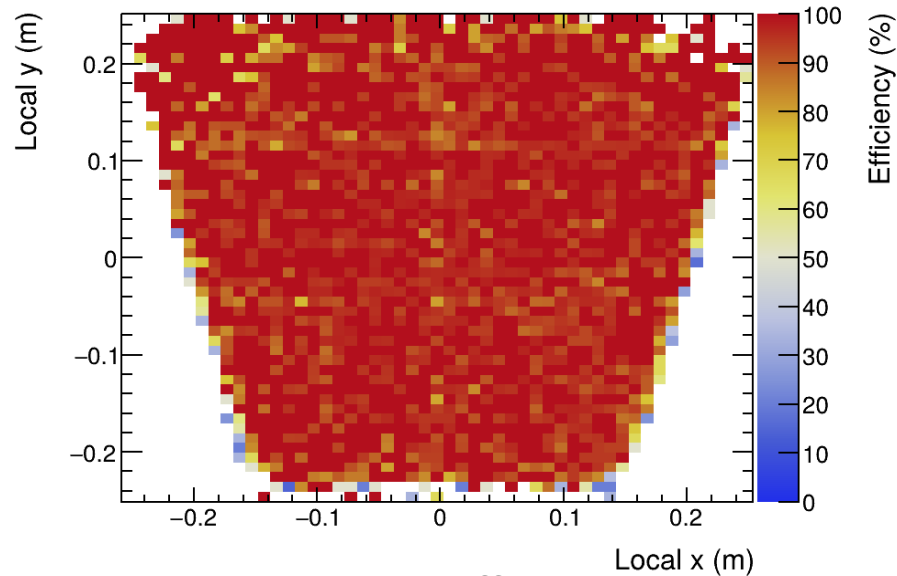


U/V cluster ADC correlation

- Successful reconstruction of two-dimensional GEM hit distributions.
- Reconstructed hit map reproduces the expected trapezoidal detector geometry.
- Correlated U/V cluster signals provide a consistency check for two-dimensional hit reconstruction.
- Cosmic-ray data used to validate detector response and clustering algorithms

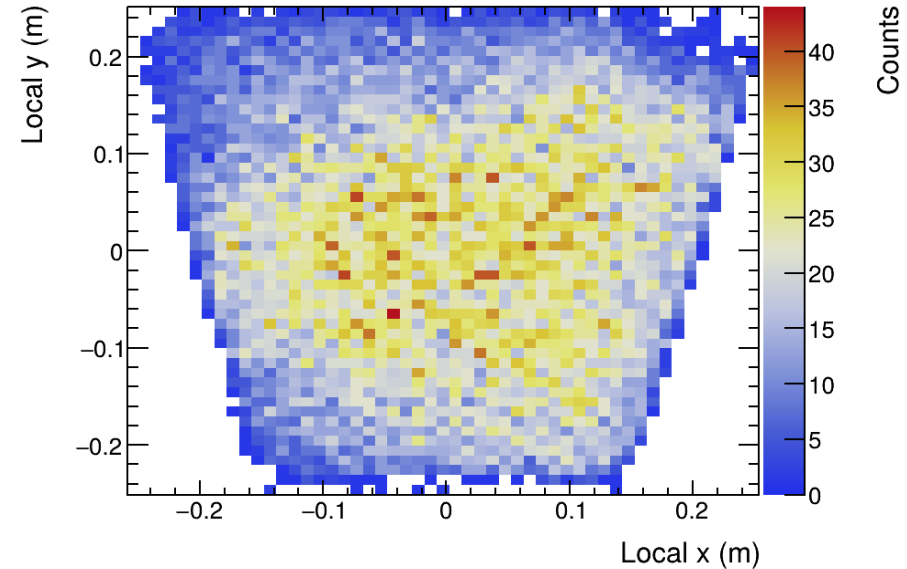
Performance : Efficiency

Track-based efficiency | Module 3



Track-based efficiency map

Detected hits on good tracks | Module 3



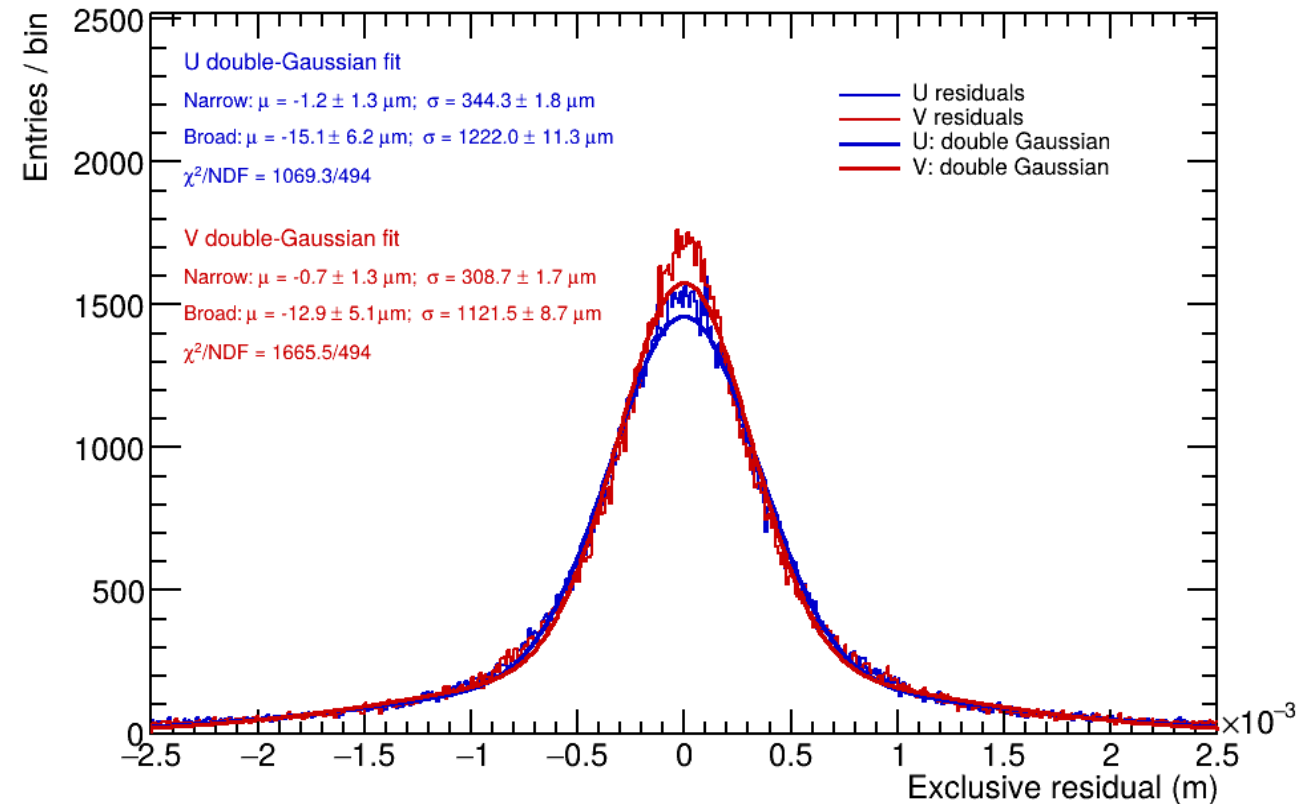
Detected hits on good tracks

- Detector efficiency evaluated using reconstructed cosmic-ray tracks.
- Tracks reconstructed without the detector under evaluation to avoid selection bias.
- Expected hit positions compared with reconstructed clusters.
- Spatial efficiency maps used to investigate detector uniformity.
- High efficiency observed across most of the active detector area.

Performance : Tracking Residuals

- Exclusive residuals calculated by excluding the detector under evaluation from the track fit.
- Reconstructed hit positions compared with track projections.
- Residual distributions characterized using two-Gaussian fits.
- Narrow Gaussian component describes the core tracking response.
- Broader component accounts for non-Gaussian tails and additional reconstruction effects.

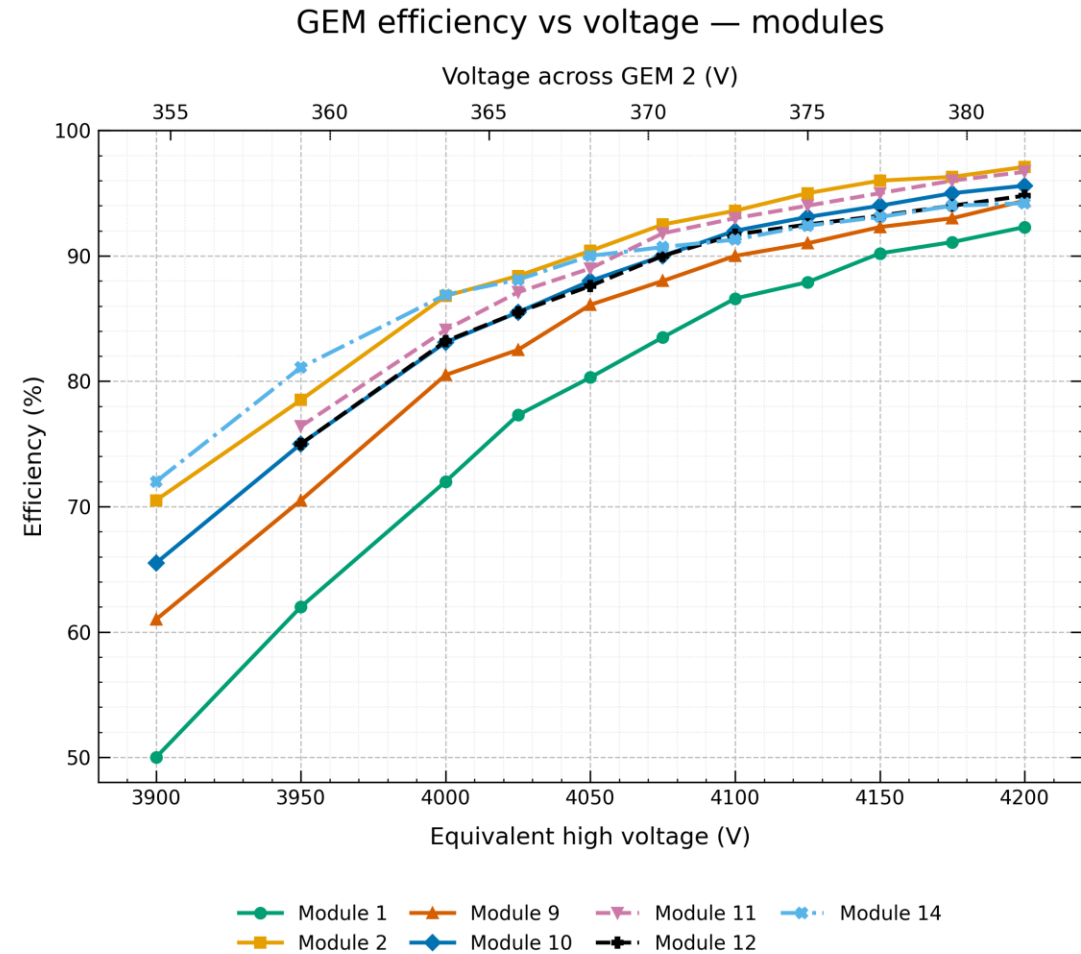
Exclusive track residuals: two-Gaussian fits



Exclusive tracking residuals

Performance : Plateau Studies

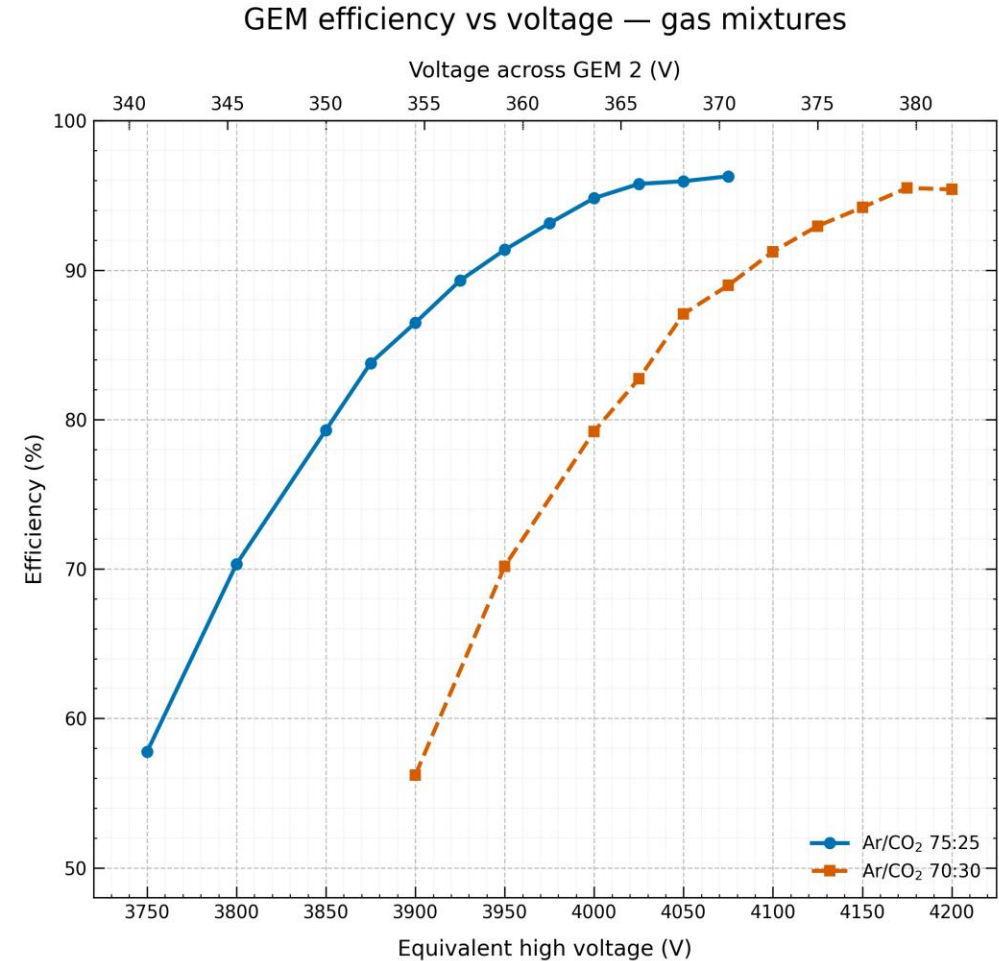
- Detector efficiency measured as a function of applied high voltage with ArCO₂ (70:30) gas mixture
- Efficiency increases with voltage as the gas amplification improves
- Most tested modules approach a high-efficiency region at elevated voltages
- Module-to-module variations observed in the voltage dependence
- Results guide the selection of stable operating conditions



Track based efficiency for a set of modules

Performance : Gas Ratio Studies

- Detector efficiency measured for two gas mixtures ArCO_2 (70:30) and ArCO_2 (75:25)
- Detector operated at ArCO_2 (75:25) reached the plateau at a significantly lower voltage
- One mixture achieves comparable efficiency at a lower applied voltage
- Both mixtures approach high efficiency within the measured voltage range
- Results inform the choice of gas mixture and operating voltage



Track based efficiency for two gas mixtures

Summary and Outlook

Summary

- Four-plane GEM cosmic-ray tracking setup established for detector commissioning.
- Two-dimensional hit and track reconstruction demonstrated.
- Track-based efficiency and residual studies used to characterize detector performance.
- High-voltage and gas-mixture scans performed to investigate operating conditions.

Outlook

- Complete characterizing and optimizing operating parameters: November 2026
- Integrating and commissioning MOLLER tracking system in the experimental Hall: November 2026 - Spring 2027
- Physics data taking with GEM tracking in experimental Hall: Summer 2027

Acknowledgment

- UVA detector group
 - Prof. Nilanga Liyanage, Prof. Huong Nguyen, brynna Moran, Bhashitha Dharmasena, Jacob McMurtry, Vidura Vishvanath, Nithaya Kularathne
- SBU detector group
- MOLLER Collaboration
- Jefferson Lab Hall A Staff
- US Department of Energy Office of Science

Thank You

Supplemental

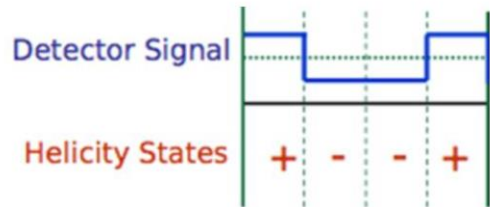
(From Kate Evans)

Polarized Beam

Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab

Voltage applied to Pockels cell affects polarization of laser light used to generate polarized electron beam.

Need to minimize Helicity-Correlated-Beam-Asymmetries (HCBA)



Beam expectations:

- 11 GeV
- $65 \mu\text{A}$
- 90% longitudinal polarization
- 1.92 kHz helicity flip rate
 - Sequence of 32 states
- $5 \times 5 \text{ mm}^2$ raster



In experimental
Hall A

Polarized Beam

Beam Property	Cumulative Helicity Correlation (full data set)
Intensity	$< 10 \text{ ppb}$
Energy	$< 1.4 \text{ ppb}$
Position	$< 0.6 \times 10^{-9} \text{ m}$
Angle	$< 0.12 \times 10^{-9} \text{ radian}$
Spot-size	$< 10^{-5}$

Hall A uses Moller and Compton polarimetry to make precise beam polarization measurements.



In experimental
Hall A

Target System

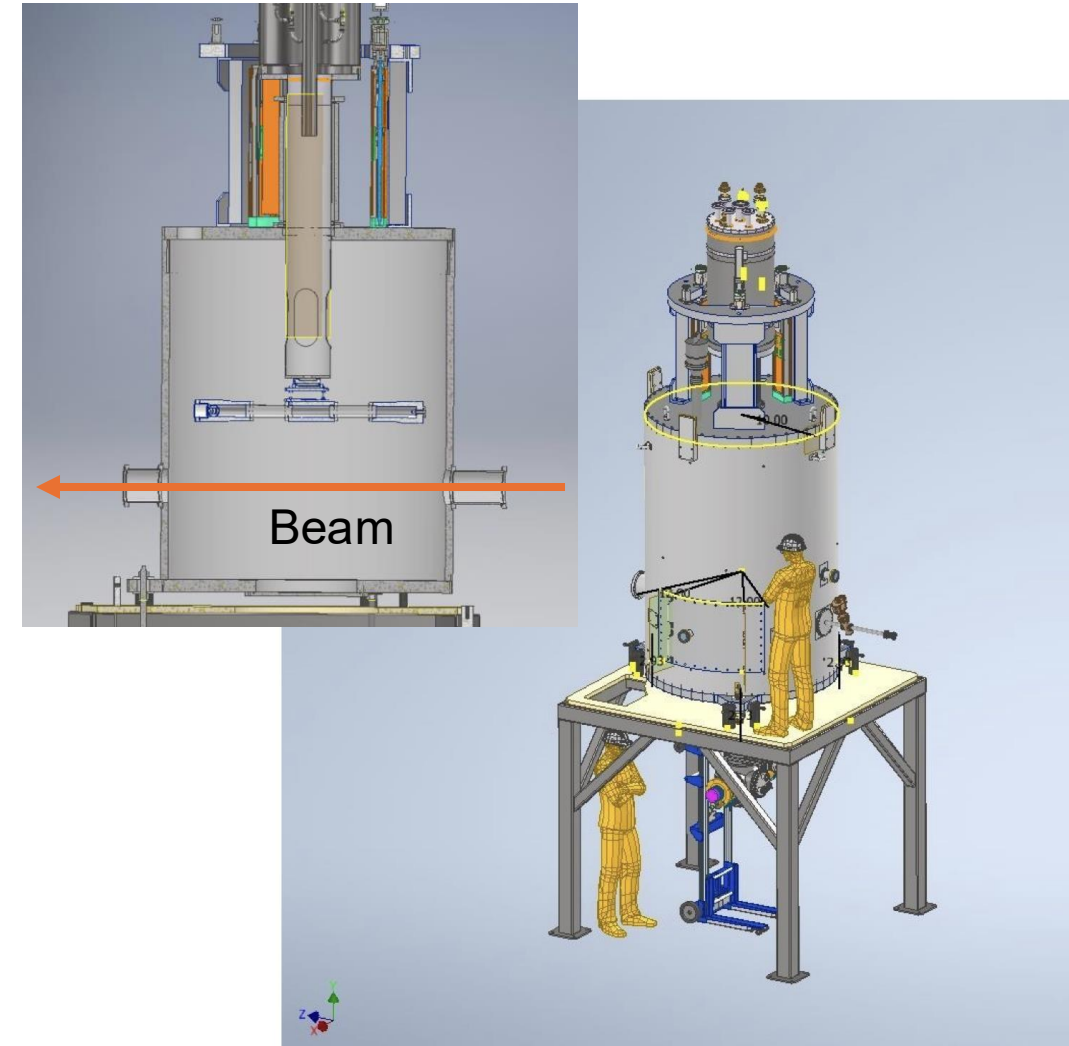
Main experiment target:

- Liquid hydrogen
- 125 cm long
- Designed using computational fluid dynamics (CFD)

Requirements:

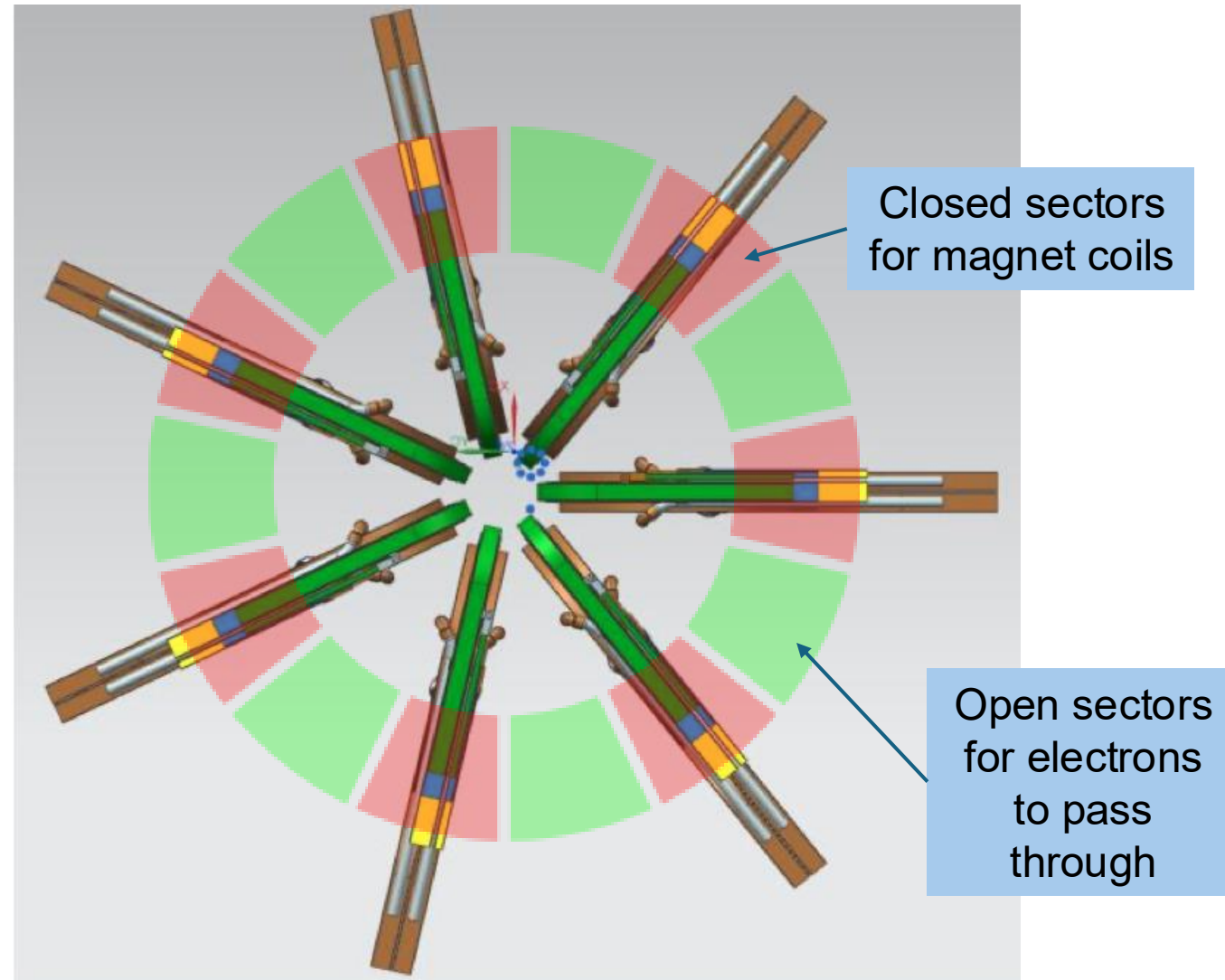
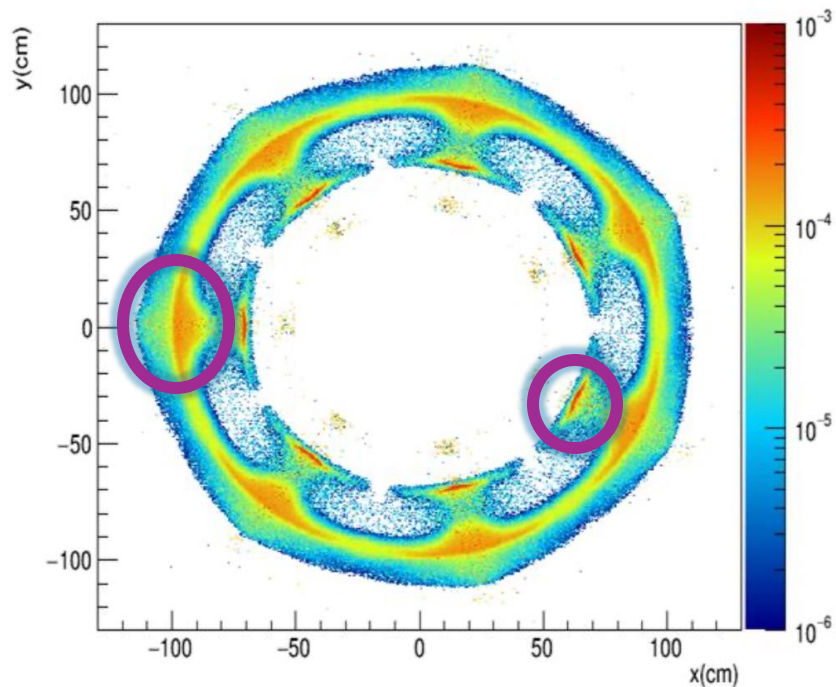
- Maximal luminosity
- Minimal density fluctuations (<30 ppm)

Cell Thickness	8.9 g/cm ²
Cell Acceptance	2 π , 12 mrad
Pressure	35 psia
Temperature	20 K
Al Windows in Beam	<0.25 mm
LH ₂ Pump Rate	<25 l/s
Power	4.5 kW



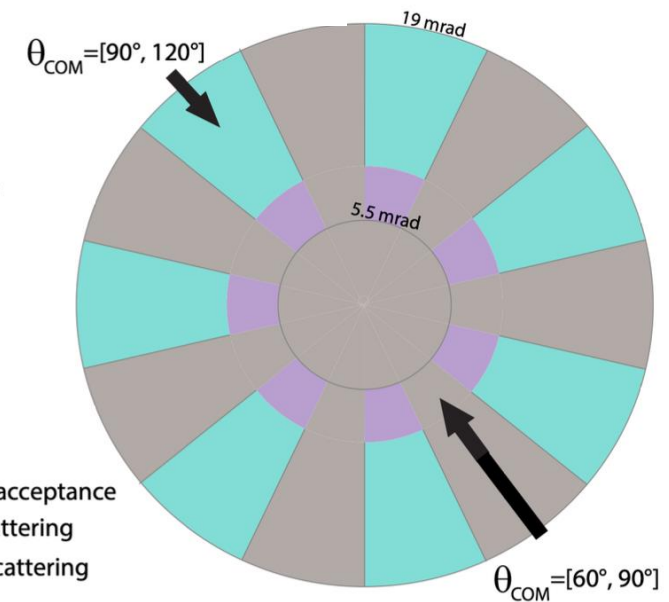
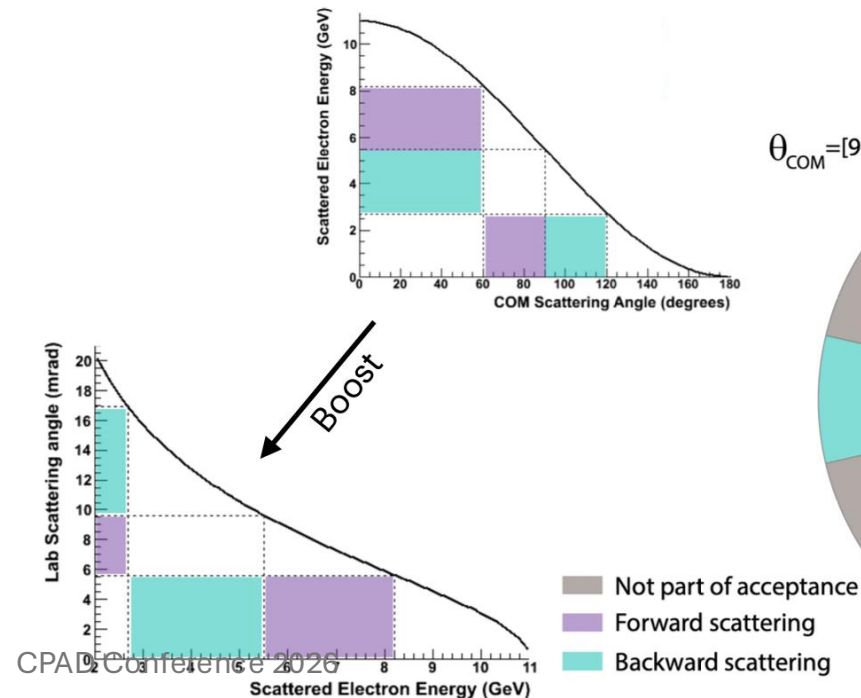
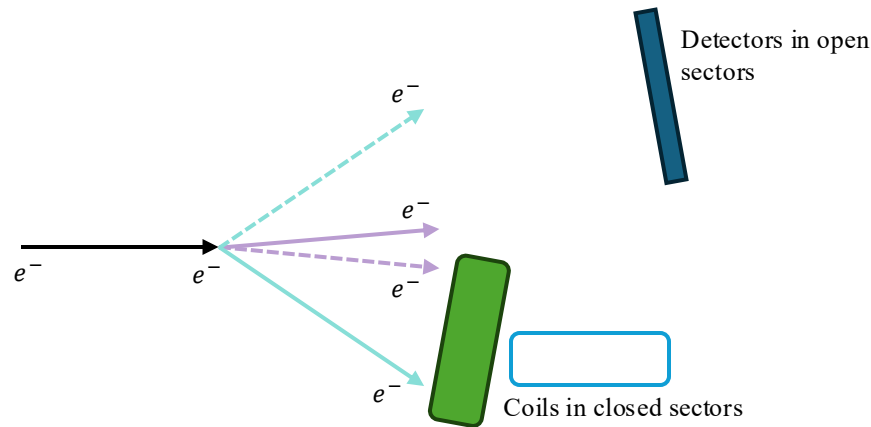
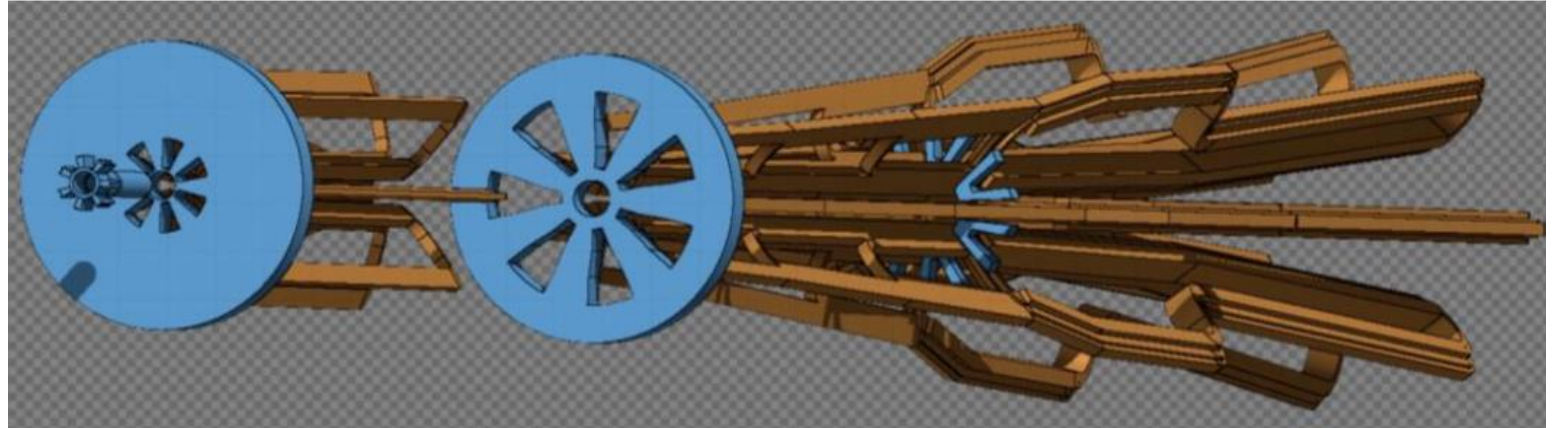
7-Fold Symmetry

- Open, closed, and transition sectors
- Azimuthal defocusing due to toroidal B-field spreads scattered electrons across entire azimuth



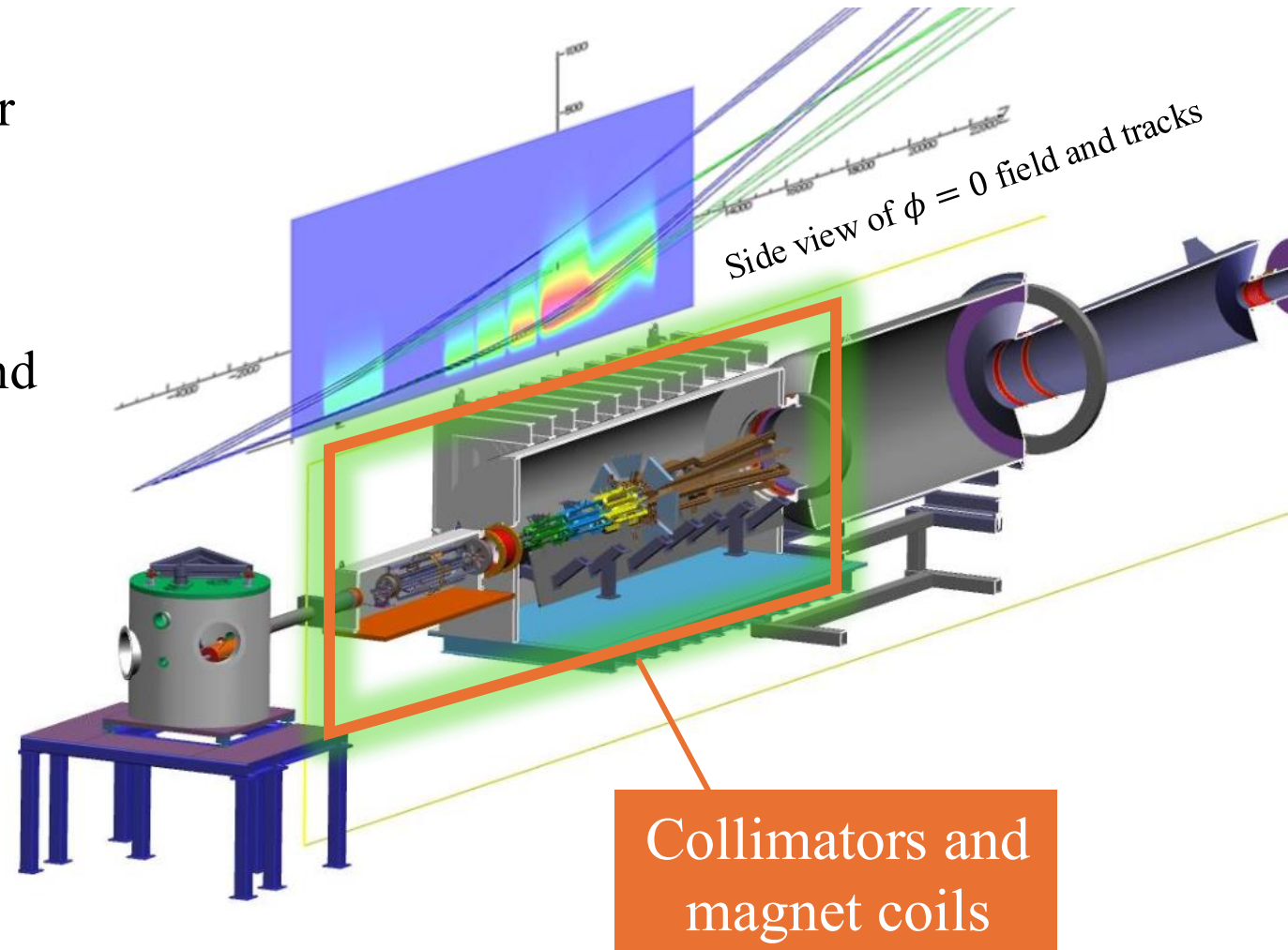
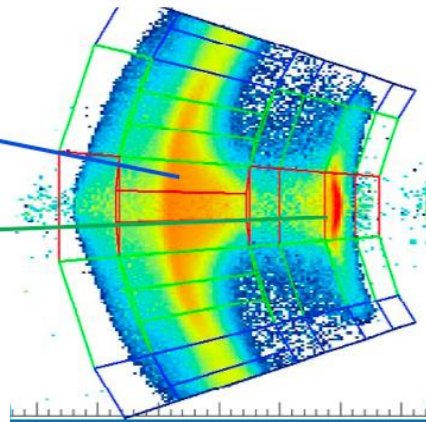
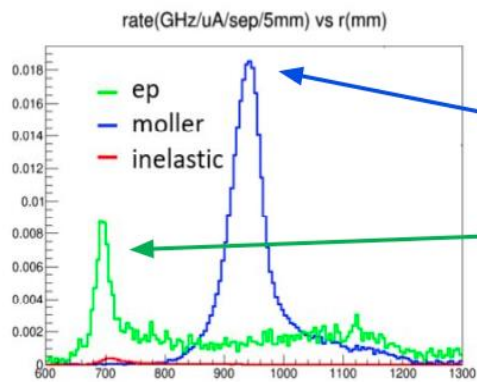
Shielding Collimators

- Clean up stray beam
- Shield toroidal coils
- 2-bounce system
- Select scattered electrons
 - $5 < \theta_{lab} < 20$ mrad
- Block 50% of azimuth
 - Only count one electron from each scattered pair

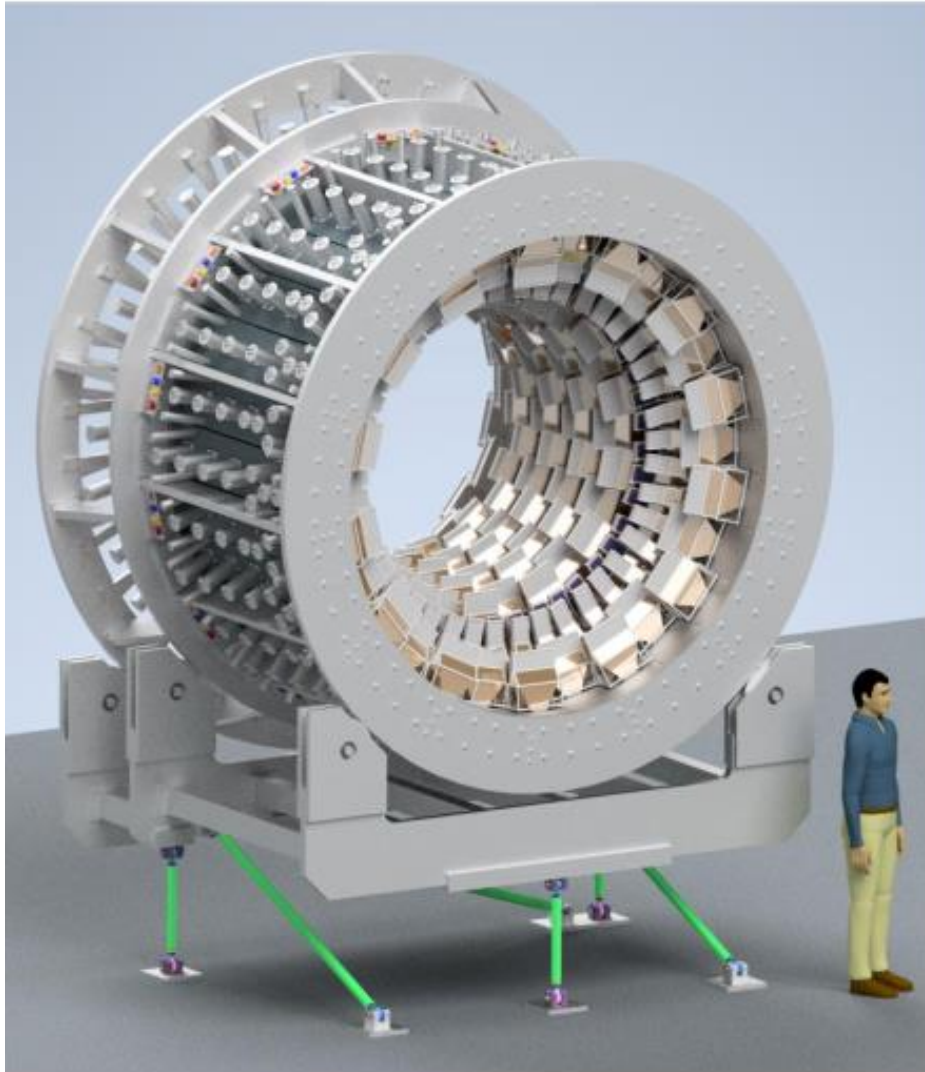


Spectrometer

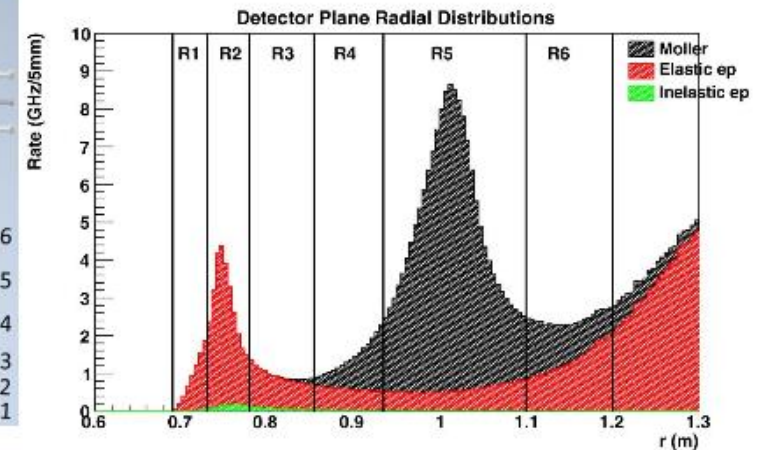
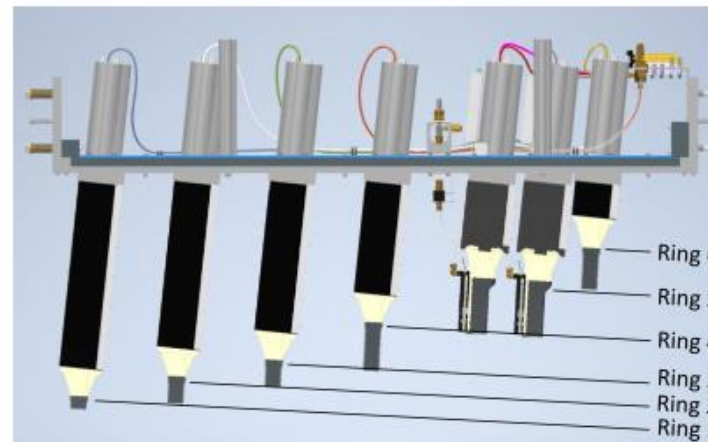
- Two sets of toroidal magnets
- Separate scattered electrons based on their processes
- Focus Møller electrons onto small radial region
- Main sources of background are elastic and inelastic eP events



Main Detector

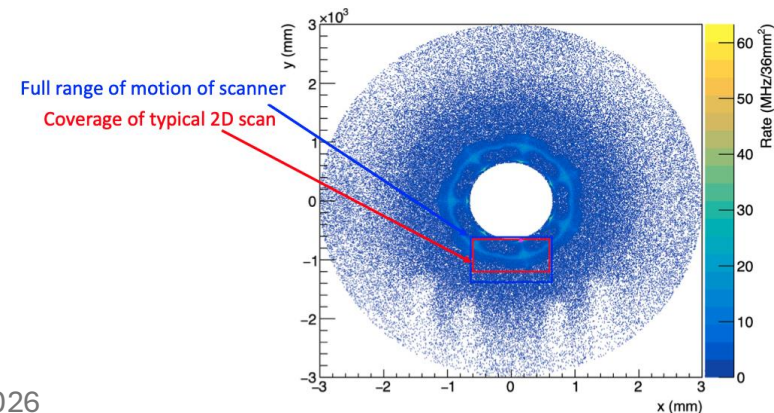
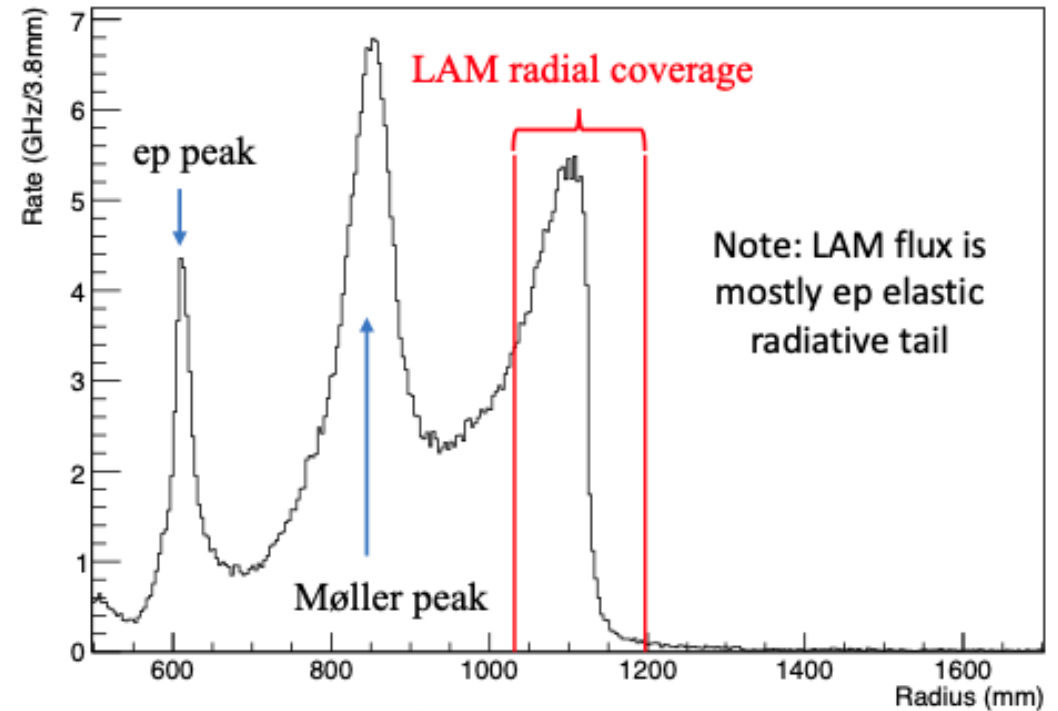


- 224 detectors split into 6 radially separated rings
 - Radiation hard fused-silica Cherenkov detectors with radial and azimuthal segmentation
- Møller electrons are focused on Ring 5



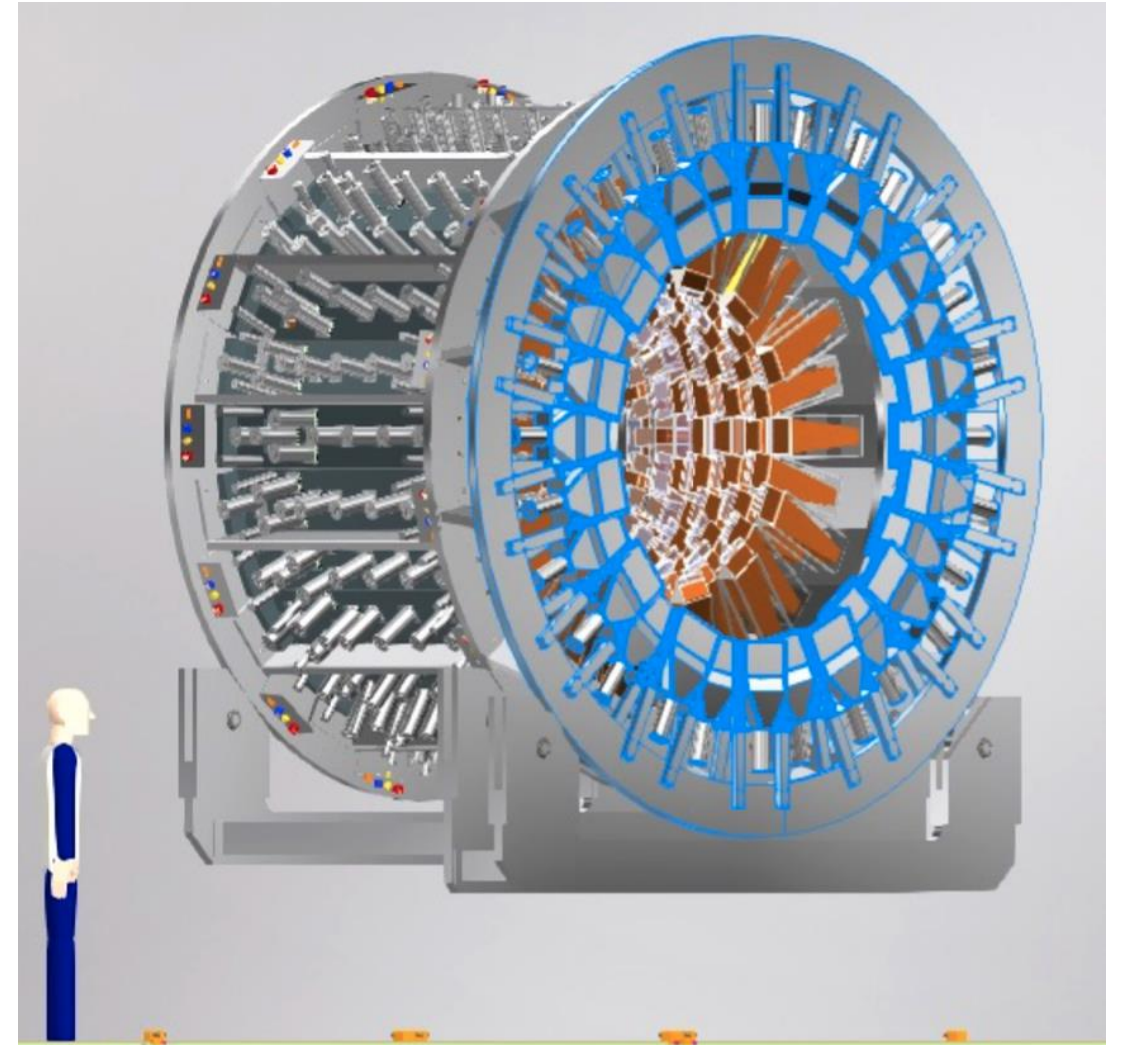
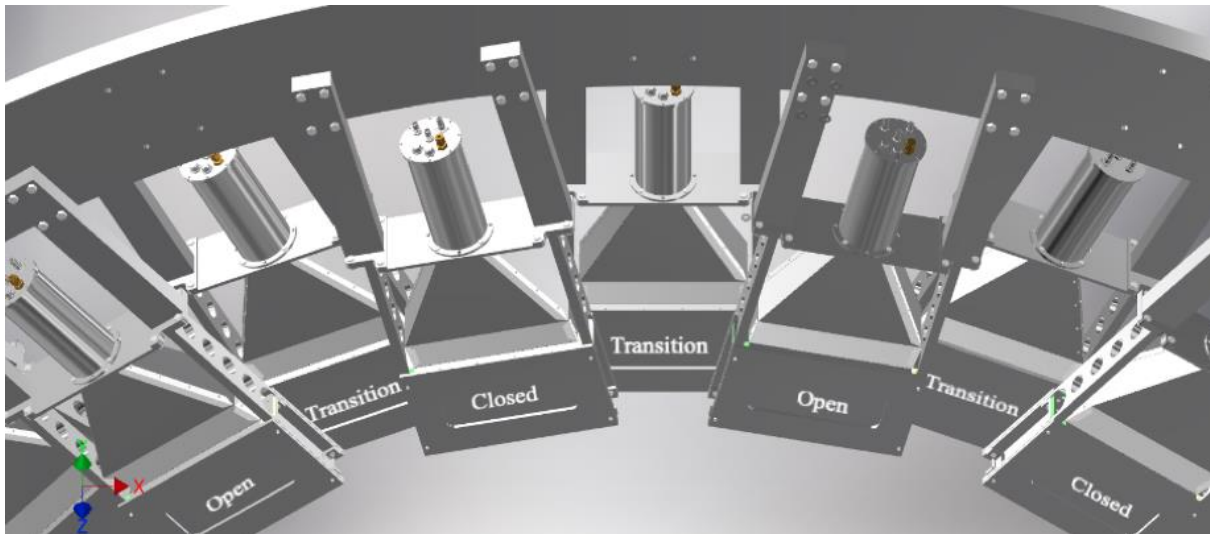
Auxiliary Detectors

- Extra detector systems to monitor potential false asymmetries
- Scattered Beam Monitors
 - Large Angle Monitors
 - Small Angle Monitors
 - Diffuse Beam Monitors
- Downstream and Upstream Scanners
 - Confirm rate for tracking system
 - Monitor scattered flux distribution during production data-taking
 - Verify alignment of the primary acceptance defining collimator

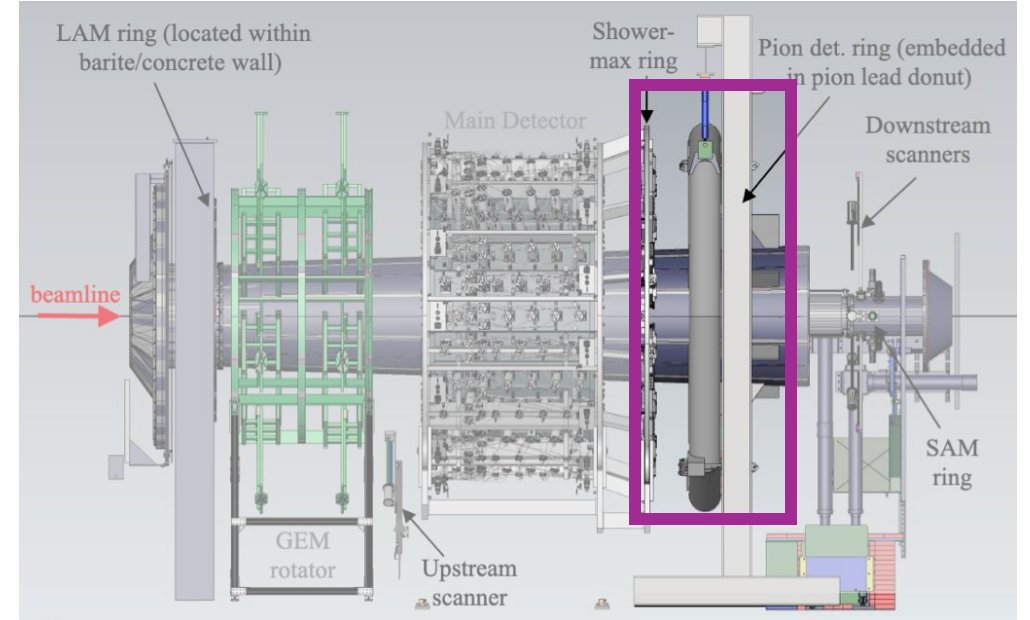
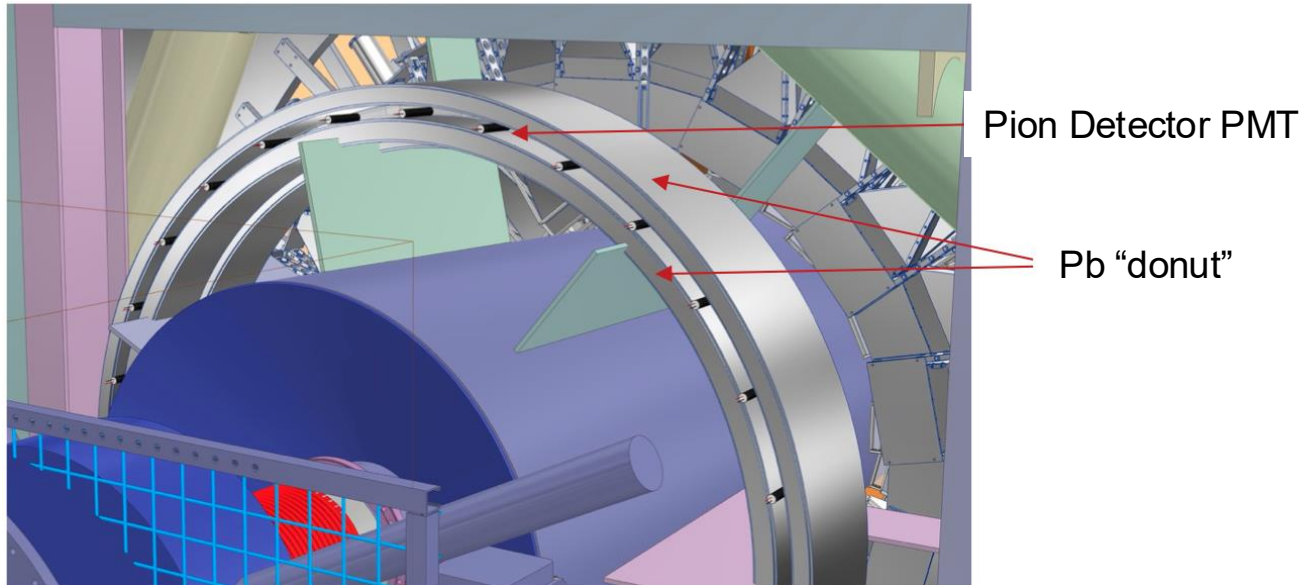


Showermax

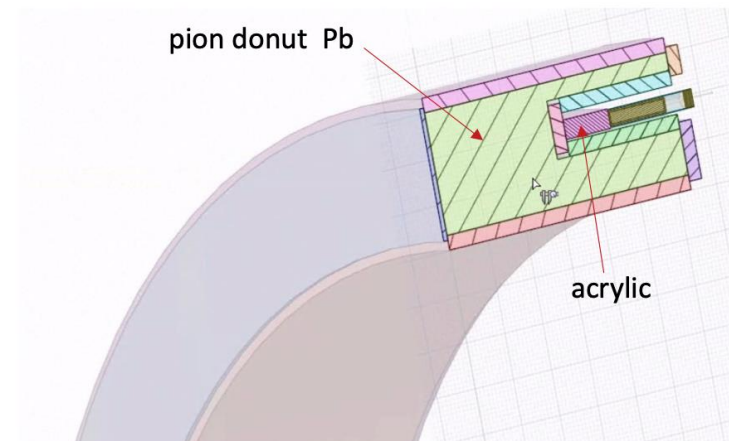
- Provide additional complimentary measurement of Møller signal seen by Ring 5
- Less sensitivity to hadronic background
- Electromagnetic sampling quartz-tungsten calorimeter
- Modules cover open, closed, and transition sectors



Pion Detector System



- Measure pion flux to correct for background asymmetry
- 28 identical acrylic Cherenkov detectors
 - Encased in a Pb "donut" to suppress Møller electrons
 - Showermax + Pb "donut" = $45X_0$



DAQ

Integrating Mode

- Signals are integrated over “helicity window”
- Used with full beam current
- Electron rates in Ring 5 can reach 1 MHz/mm²
- Rate of detected Møller events can be up to **135 GHz**

Counting Mode

- Used for the Tracking System and calibration
- Low rates allow for individual event counting
- Maximum triggered event rate ~5 kHz
- Observe each individual event

