Overview of Upcoming MOLLER Experiment at Jefferson Lab

HUONG NGUYEN

UNIVERSITY OF VIRGINIA

ON BEHALF OF THE MOLLER COLLABORATION

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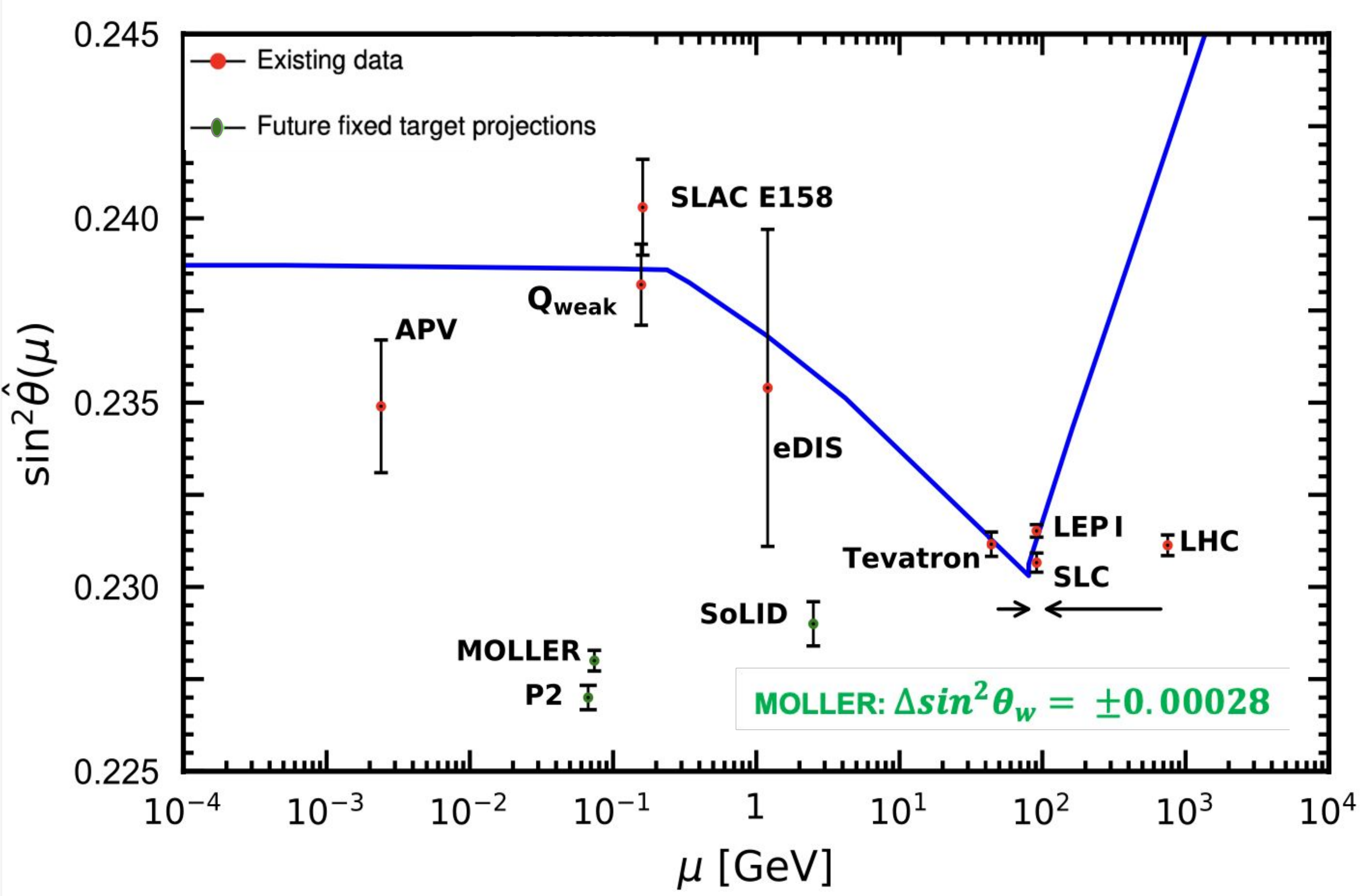
Overview of MOLLER Experiment at Jefferson Lab

Outline

- **MOLLER**: **M**easurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction
- The Physics Goals & Experimental Method
- Key Features of MOLLER Apparatus
- MOLLER Schedule & Outlook

The Main Objective of MOLLER Experiment

Precision determination of electroweak mixing angle at low energy ($Q^2 \ll MZ$)



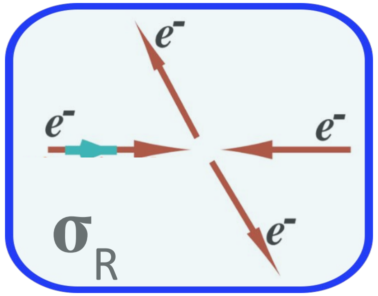
- Running weak mixing angle in the MS-bar scheme

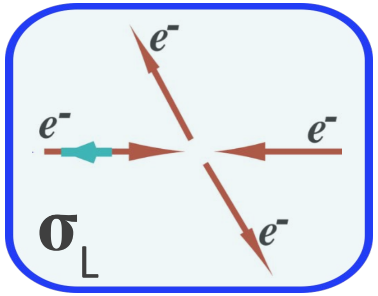
- Precision examination of the electron's weak charge through the measurement of parity violating (PV) asymmetry at low momentum transfer
  - + Helping to resolve differences between previous measurements of $\sin^2\theta_W$ or find interesting new effects
  - + Indirect search for new dynamics beyond the Standard Model with unique sensitivity to TeV scale physics

The MOLLER Observable

Parity- violating asymmetry A_{PV} in Møller Scattering

- Asymmetry in cross-section of electrons with helicity ±1/2 scattered off unpolarized electron





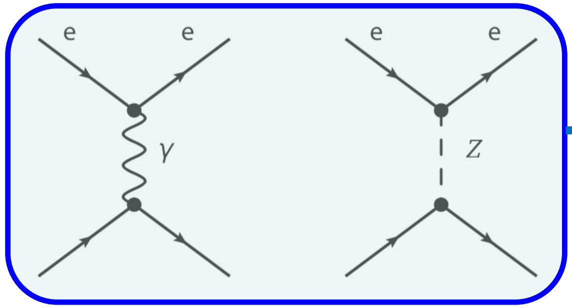
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

➔ Incident beam is longitudinally polarized

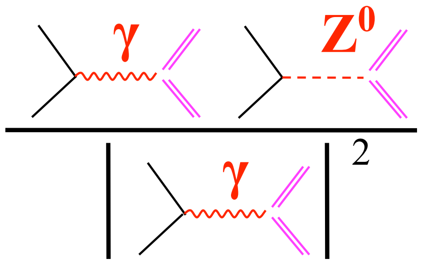
➔ Change sign of longitudinal polarization

➔ Measure fractional rate difference

- **A_{PV}** is determined from interference between the exchange of photon and a Z-boson in scattering



$$\sigma = \left|\mathcal{M}_\gamma + \mathcal{M}_Z\right|^2$$



$$A_{PV} \sim \frac{(\gamma \text{ diagram})(Z^0 \text{ diagram})}{\left|(\gamma \text{ diagram})\right|^2} \propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

- **Weak mixing angle θ_W**

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

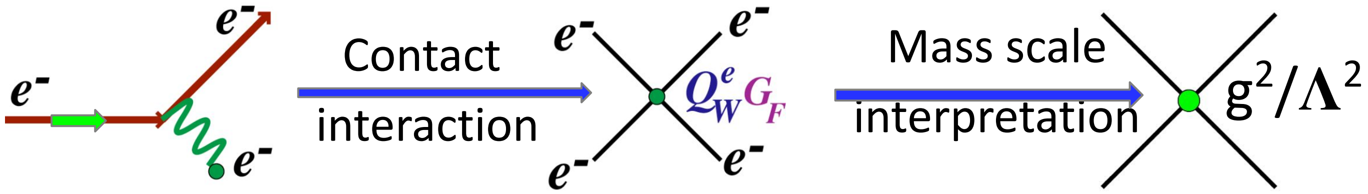
MOLLER Physics Reach

Probe Physics at multi-TeV scale via A_{PV} precise measurement

- MOLLER is optimized for ultra-high precision measurement of A_{PV} at low energy:
  - Momentum transfer: **$Q^2 = 5.8 \times 10^{-3}$ GeV^2**
  - Projected A_{PV} at MOLLER's kinematics: **A_{PV} ~ 32 ppb ; ΔA_{PV} ~ 0.8 ppb**

- MOLLER offers an unique new physics reach
  - Exploits pure Leptonic weak neutral current interaction at low Q^2
  - Theoretical prediction can be calculated accurately with negligible uncertainty from hadronic physics

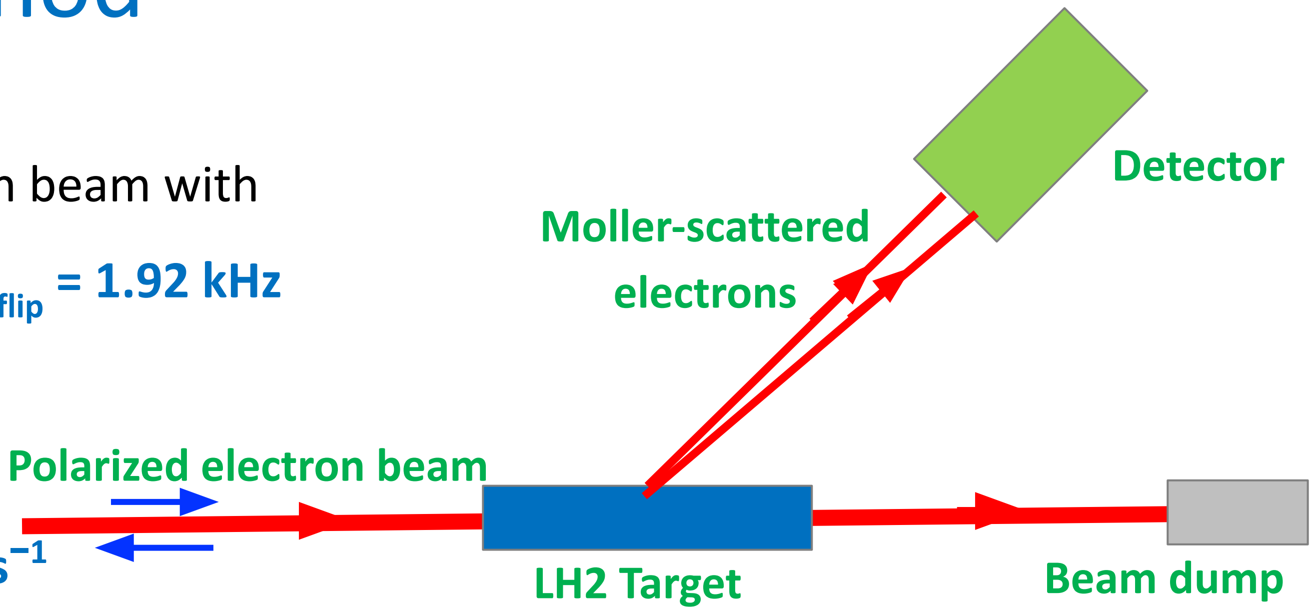
- Sensitive to interaction amplitudes as small as $1.5 \times 10^{-3} \times G_F$
- Extend the reach for new dynamics beyond SM to mass scale **Λ/g ~7.5 TeV**



MOLLER Experimental Method

Measurement principle

- CEBAF provides a longitudinally polarized electron beam with helicity rapidly flipped: E_b= 11 GeV, I_b = 65 µA, f_{flip} = 1.92 kHz
- Polarized beam electrons impinge on unpolarized LH2 target oriented along the beam direction: L_{taget} = 125 cm, P_{20K}= 35 psia, $\mathscr{L}$ = 2.4 x 10^{39} cm^{-2} s^{-1}



- Moller-scattered electrons are deflected from background by spectrometer system and focused onto integrating detector system at expected rate R ~ 130 GHz
- Measure Integrated flux of Møller-scattered electrons during each period of the left- and right-handed beam helicities to evaluate scattering asymmetry for each pair of helicity windows:

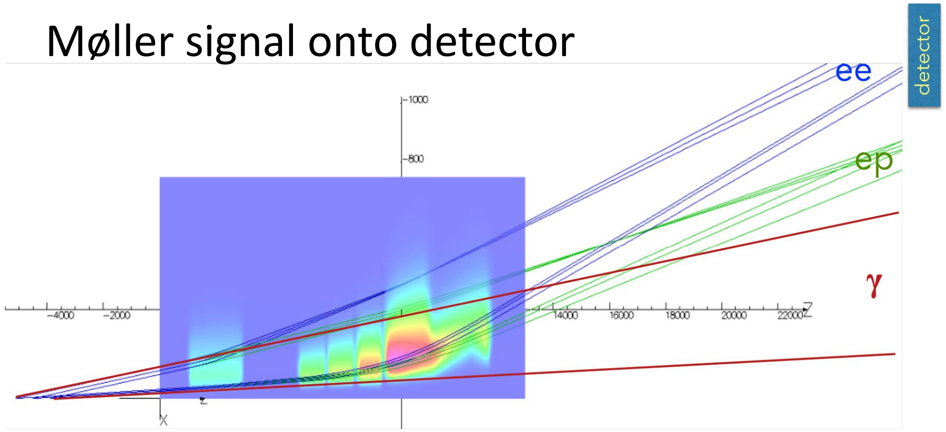
$$A_i^{raw} \equiv \left(\frac{F_R - F_L}{F_R + F_L}\right)_i \simeq \left(\frac{\Delta F}{2F}\right)_i.$$

➔ A_{PV} is extracted from the average measured asymmetry, with corrections applied to account for experimental effects

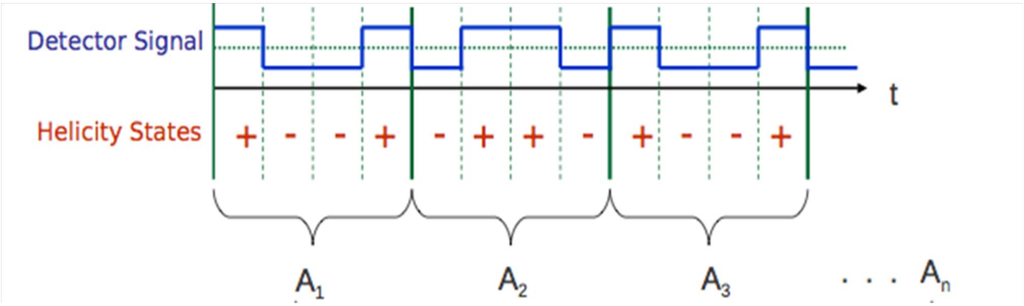
MOLLER Experimental Method

Flux integration technique for A_{PV} measurement

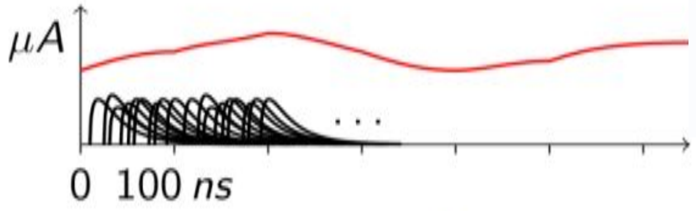
- Map E-θ correlation to focus Møller signal onto detector



- Rapid measurement over helicity reversals



- Integration of analog detector current

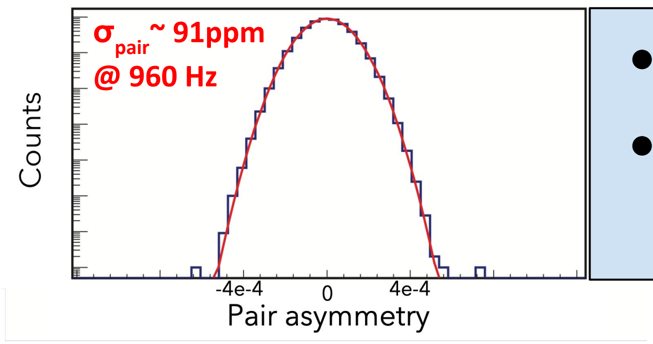


$$A_i^{\text{raw}} \equiv \left(\frac{F_R - F_L}{F_R + F_L}\right)_i \simeq \left(\frac{\Delta F}{2F}\right)_i$$

- Correct raw measured asymmetry for the experimental conditions changing rapidly :

$$\left(A_{cxpt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

- **Pulse-pair asymmetry distribution A_{expt}**



- Central value reflects A_{phys}
- σ_{pair} is parameter that determine statistical error

Critical Factors in MOLLER Experimental Design

- **Experimental design driven by the precision goals for measuring expected A_{PV} ~ 32 ppb:**
  - 2% statistical & 1% systematic uncertainty

- **High luminosity and acceptance** *Møller Rate ~ 130 GHz*
  - High intensity and polarization beam:
    65 μA beam current at 11 GeV with 90% polarization
  - 125cm long LH2 target
  - Full azimuthal acceptance with θ_{lab} ~ 5 - 20 mrad

- **Controlling Systematic Uncertainty**
  - Acceptance/Optics calibration
  - Monitoring sources of background
  - Beam monitoring, control and calibration
  - Polarimetry & "spin reversal" tool

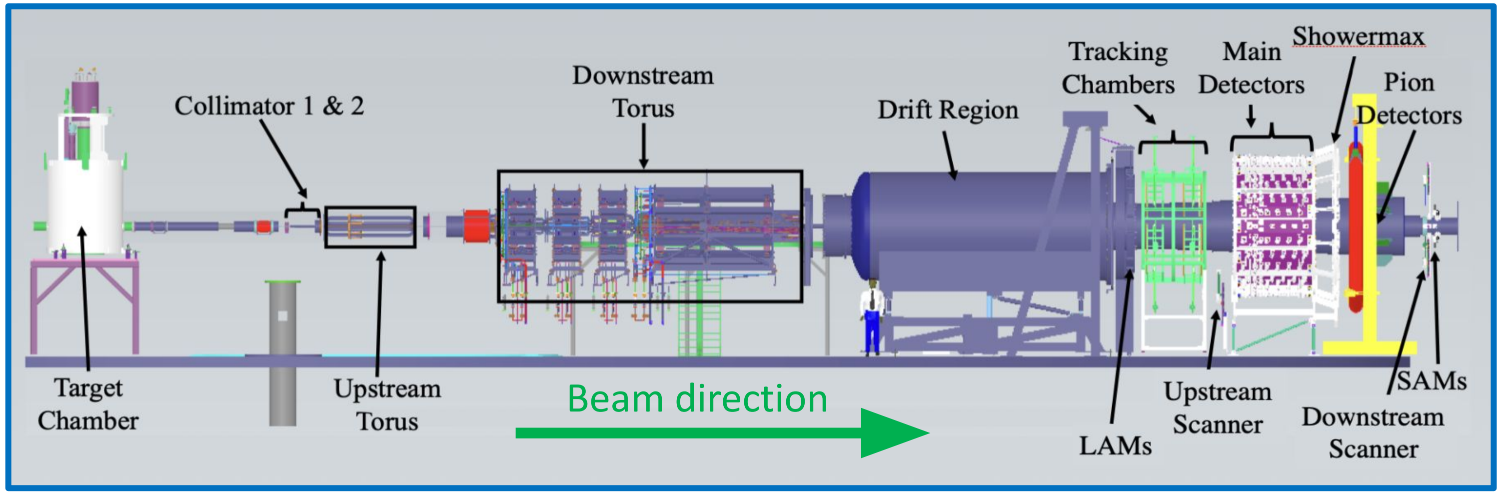
- **Control noise** *91 ppm at 960 Hz*
  - Stable beam and target
  - Rapid beam helicity flip
  - Precision monitoring and calibration
  - Low noise detectors and R/O electronics

- **Integrate time** *344 beam days*
  - Radiation resistance for materials and electronics

- **MOLLER at JLab**
  - JLab has 25 years of high precision PVES experiments
  - MOLLER collaboration: 40+years of experience with E158, Qweak, PREX/CREX

MOLLER Apparatus Overview

- **Target System**:
  - Liquid hydrogen target for production run
  - Solid targets for calibration
- **Spectrometer System**
  - Collimators
  - 7-fold symmetric toroidal magnet system
- **Main Integrating Detectors :** Main system to handle the primary asymmetry measurement



- **Tracking Detectors:** Provides the diagnostic power for calibration; GEM tracking planes covering the full relevant polar and azimuthal ranges.
- **Auxiliary detectors :** Cross-check Møller flux measurement; measure pion backgrounds; Monitor beam or other background asymmetries.
- **Polarized Beam, Monitoring and Diagnostics:** keep total asymmetry correction close the goal for statistical precision
- **Polarimetry:** Use two polarimeters to X-checked measurement of beam polarization at 0.4% precision
- **DAQ and Trigger:** supports both counting & integrating modes for detector systems & beam diagnostic monitors

MOLLER Operational Parameters & Run Phases

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
$\theta_{\rm CM}$	50°-130°
$\theta_{\rm lab}$	0.26°-1.2°
$\langle Q^2 \rangle$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$2.4 \cdot 10^{39}$
σ [μbarn]	≈ 60
Møller Rate @ 65 μA [GHz]	≈ 134
Statistical Width(1.92 kHz flip) [ppm/pair]	≈ 91
Target Raster Size [mm $\times$ mm]	5×5
Production running time	344 PAC-days = 8256 hours
ΔA_{raw} [ppb]	≈ 0.54
Background Fraction	≈ 0.10
$P_{\rm B}$	$\approx 90\%$
$\langle A_{PV} \rangle$ [ppb]	≈ 32
$\Delta A_{stat}/\langle A_{expt} \rangle$	2.1%
$\delta(\sin^2 \theta_W)_{stat}$	0.00023

- **MOLLER targeted three run phases**

Run	PAC Days	Calendar Weeks	
Period	(prod)	(prod)	(calib)
I	14	5	6
II	95	27	3
III	235	56	4
Total	344	88	13

- Allow time for improving hardware & fix problems uncovered during calibration
- Opportunity to improve calibration and refine run planning

MOLLER Projected Precision of A_{PV} Measurement

Statistical uncertainty

- Statistical power of A_{PV} measurement:
  - Based on precision of measurements made with a pair of integration periods σ_{pair}
  - Statistical uncertainty estimate for measured asymmetry:

$$\sigma_{A_{expt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}}$$

- A_{pv} statistical uncertainty
  - Correct $\sigma_{A_{expt}}$ for experimental effects to translate it to statistical uncertainty on A_{PV}

- Projected contributions to σ_{pair} at 1920 Hz helicity reversal rate

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	$\sim$ **82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

$$\frac{\sigma_{expt}}{A_{expt}} = 2.1\ (\%) \rightarrow \frac{\delta_{PV}}{A_{PV}} = 2.4\ (\%)$$

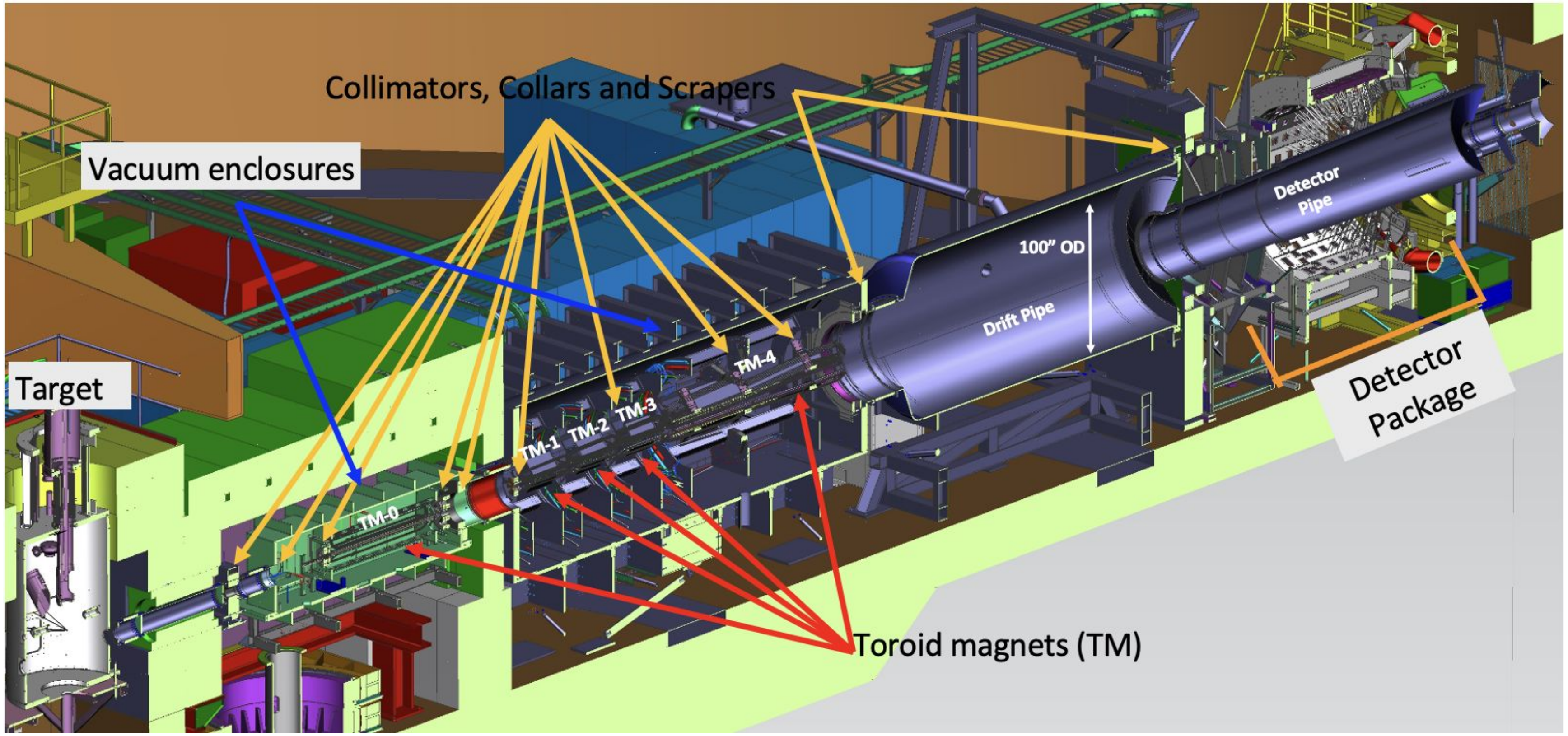
MOLLER Projected Precision of A_{PV} Measurement

Systematic Uncertainties

- Projected leading systematic uncertainties on A_{PV}
- The ultimate uncertainties to be achieved progressively with operational experience

Error Source	Fractional Error (%)	
	Run 1	Ultimate
Statistical	**11.4**	**2.1**
Absolute Norm. of the Kinematic Factor	3	0.5
Beam (second moment)	2	0.4
Beam polarization	1	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \rightarrow (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \rightarrow e + Al(+\gamma)$	0.3	0.15
Transverse polarization	2	0.2
Neutral background (soft photons, neutrons)	0.5	0.1
Linearity	0.1	0.1
Total systematic	**5.5**	**1.1**

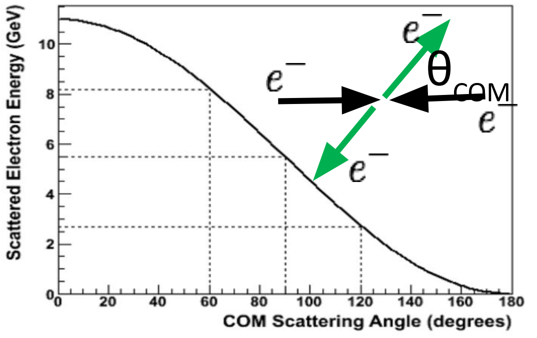
MOLLER Spectrometer Cutaway

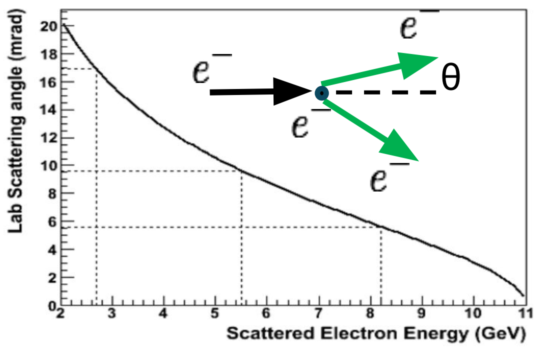


- Collimators to define the acceptance and to reject scattering from the exhaust beam
- Five toroidal magnets with 7-fold symmetry to focus Møller scattered electrons & reject backgrounds

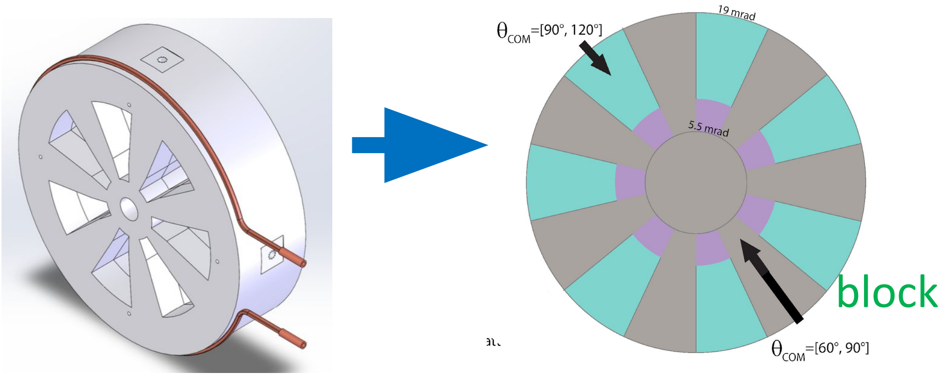
MOLLER Spectrometer Design

- **Acceptance collimators**
  - Collimates exhaust beam
  - FOM optimized for: $\theta_{COM} = 90^o \pm 30^o$

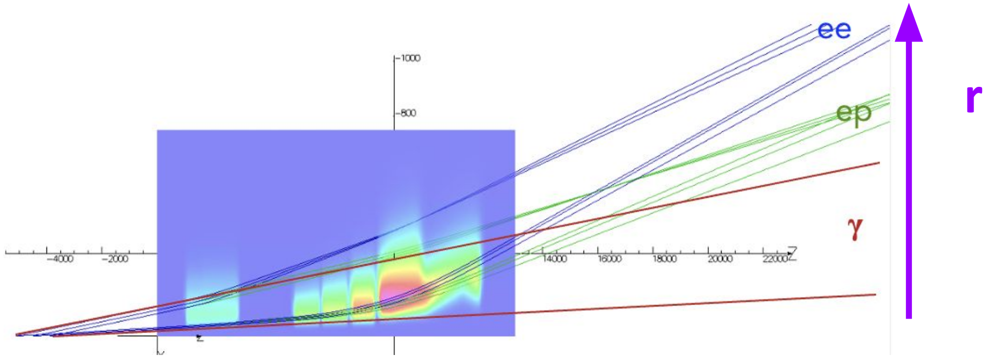


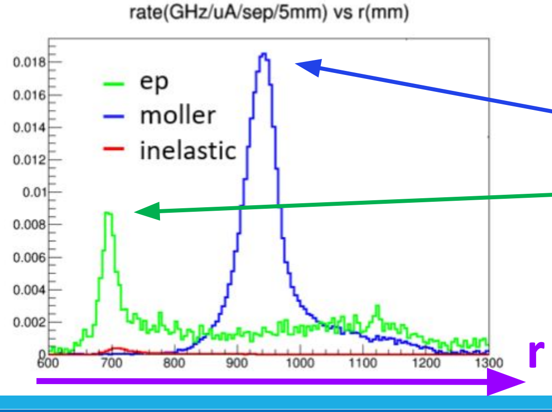


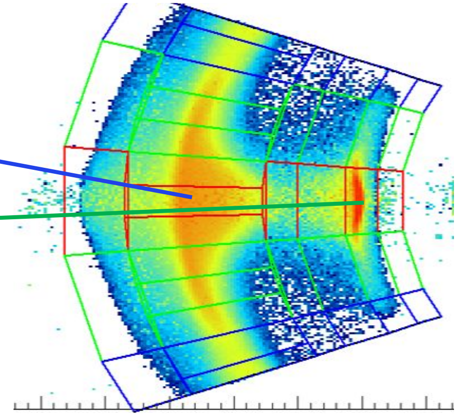
- Select scattered electron: θ_{lab} = 5 – 18 mrad
- Select either forward or backward Møller scattered electron ➡️ **Blocks 50% of azimuth**



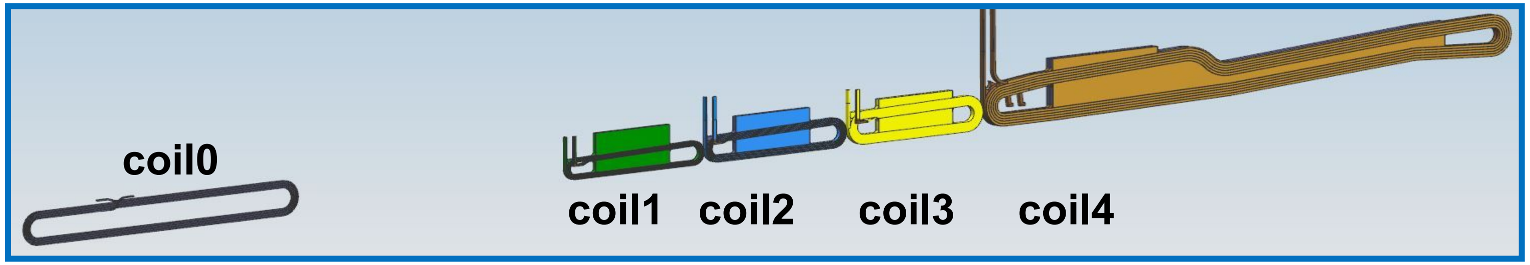
- **Azimuthal field from toroidal magnet separates e-e, e-p elastic, ep-inelastic at detector plane**

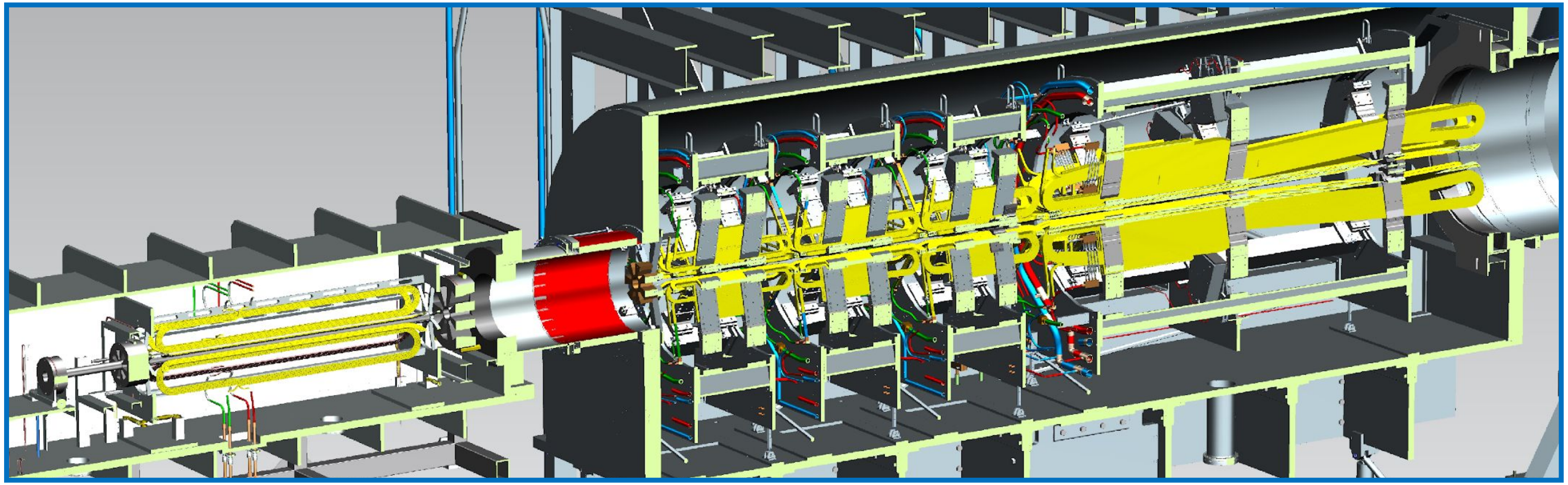






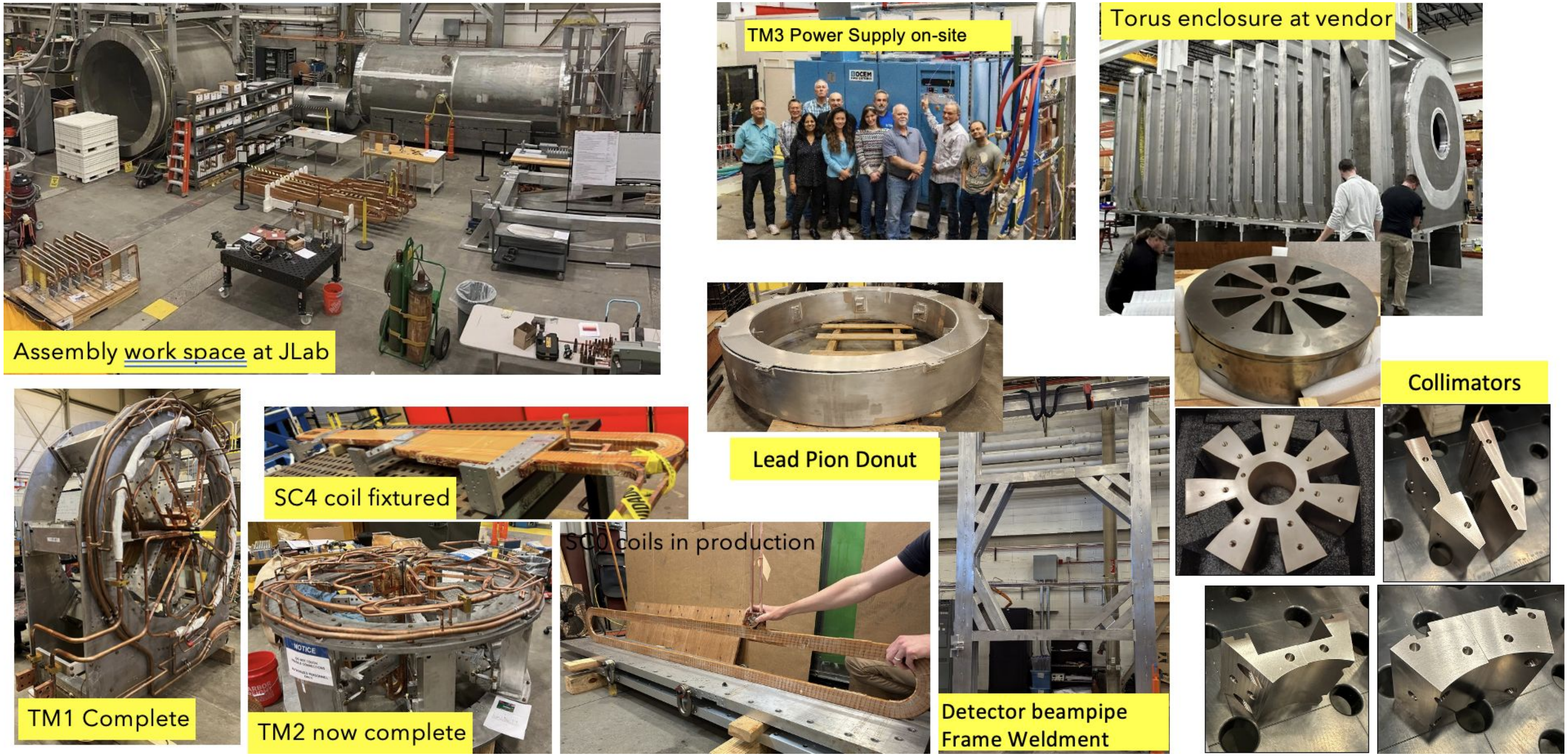
MOLLER Spectrometer Magnetic Design





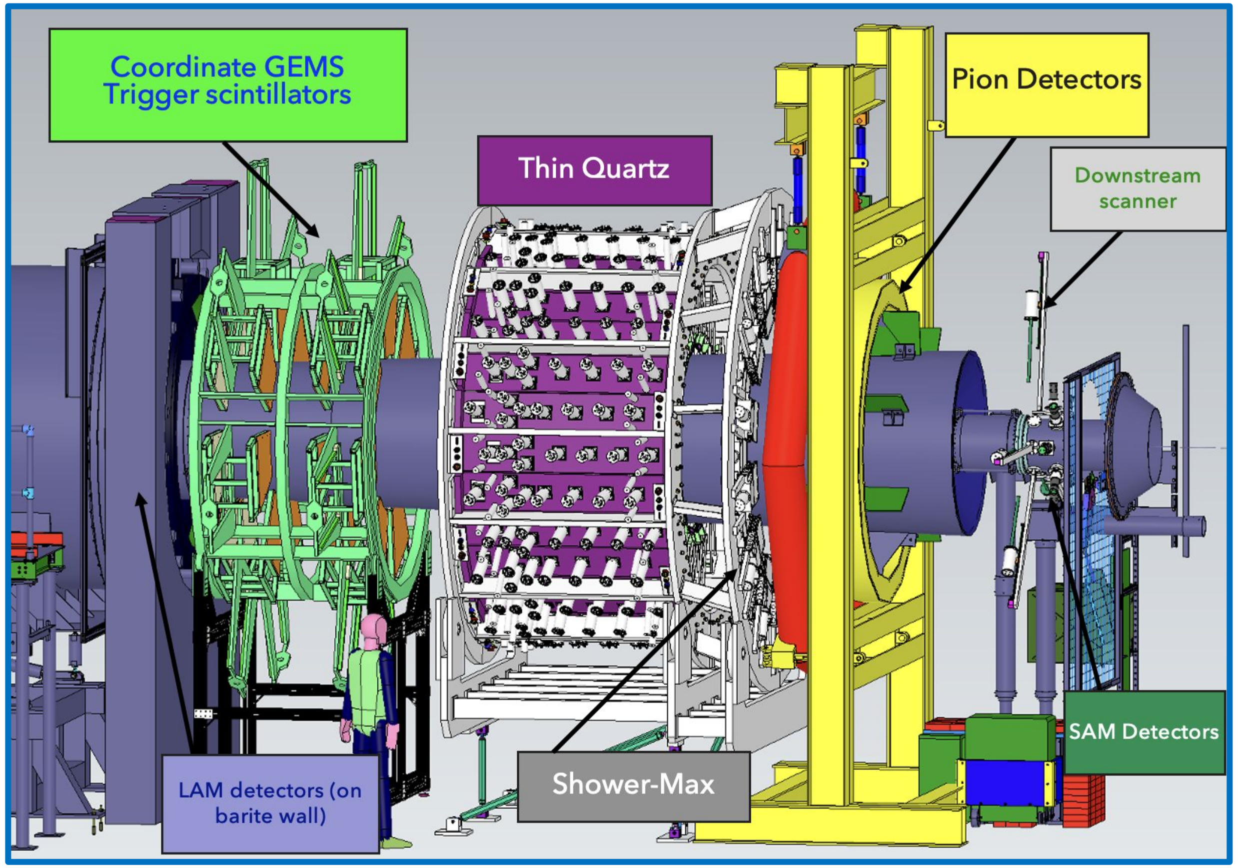
- Optimized for azimuthal acceptance to focus electrons with small scattering angles corresponding momentum range $3 \lesssim E' \lesssim 8$ GeV from a long (125 cm) target

MOLLER Spectrometer Construction



MOLLER Detector Package

- **Detector readout modes :**
  - Current mode: for asymmetry measurement at high rate
  - Counting mode: for calibration & bkgs study at low rate

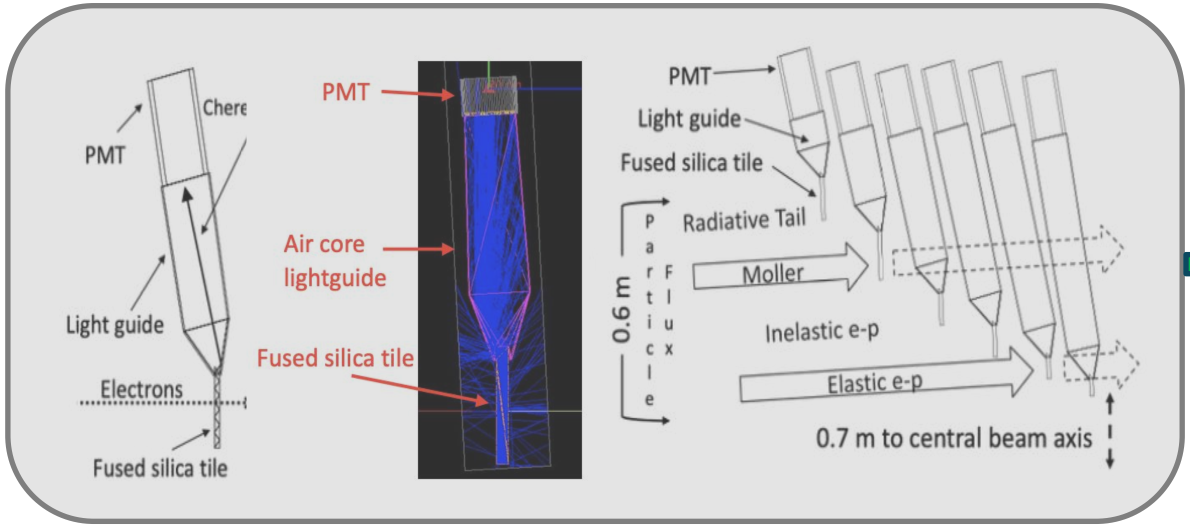


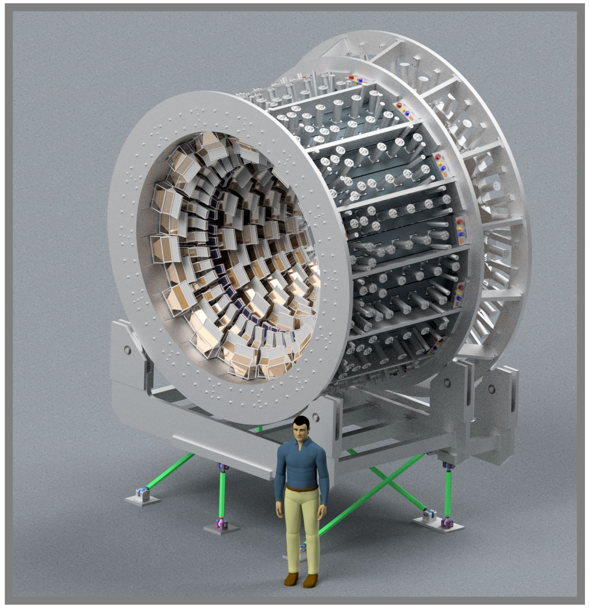
- **Main integrating detector : "Thin Quartz"**
  - Radially and azimuthally segmented to optimize Møller signal resolution & quantify background contributions
  - Operate in both current & counting modes

- **Tracking detector**
  - Read out in counting mode
  - Consists of GEM planes & trigger scintillators
  - Provides diagnostic power to calibrate spectrometer optic & acceptance and verify response function of Quartz detector

- **Auxiliary Detectors**

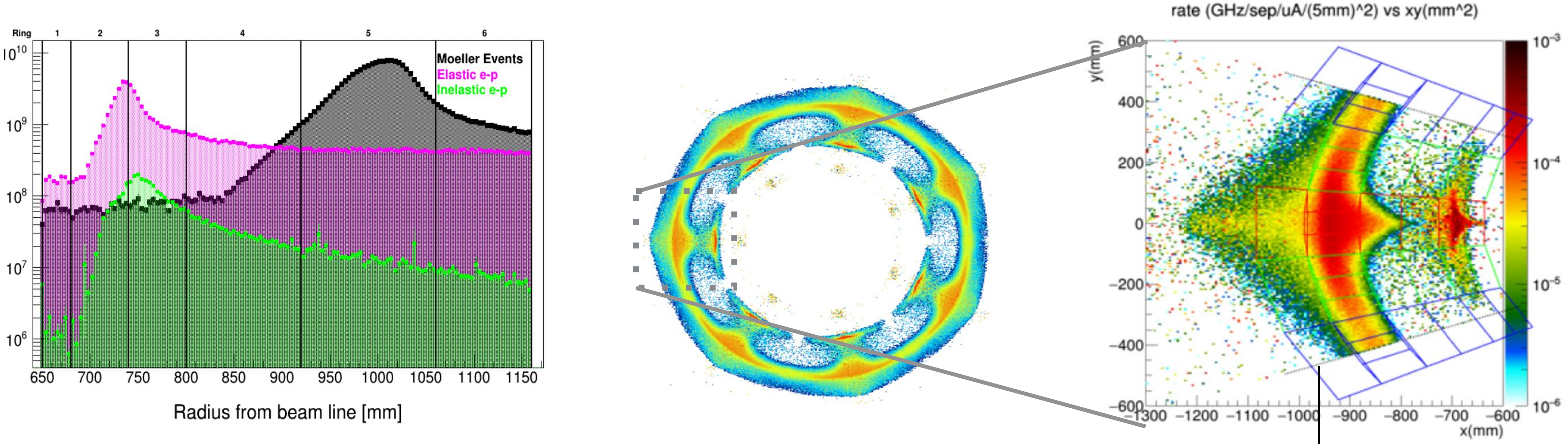
MOLLER Main Integrating Detector





- Each element comprises quartz Cherenkov radiators ,light guide and PMT
- Require both radial and azimuthal segmentation to follow kinematic separation created by spectrometer
- Radial segmentation into six rings: Møller peak centered in Ring 5 & e-p peak found in Ring 2
- Ring 5 is azimuthally segmented into 84 elements

Capturing the Scattered Flux at Main Detector

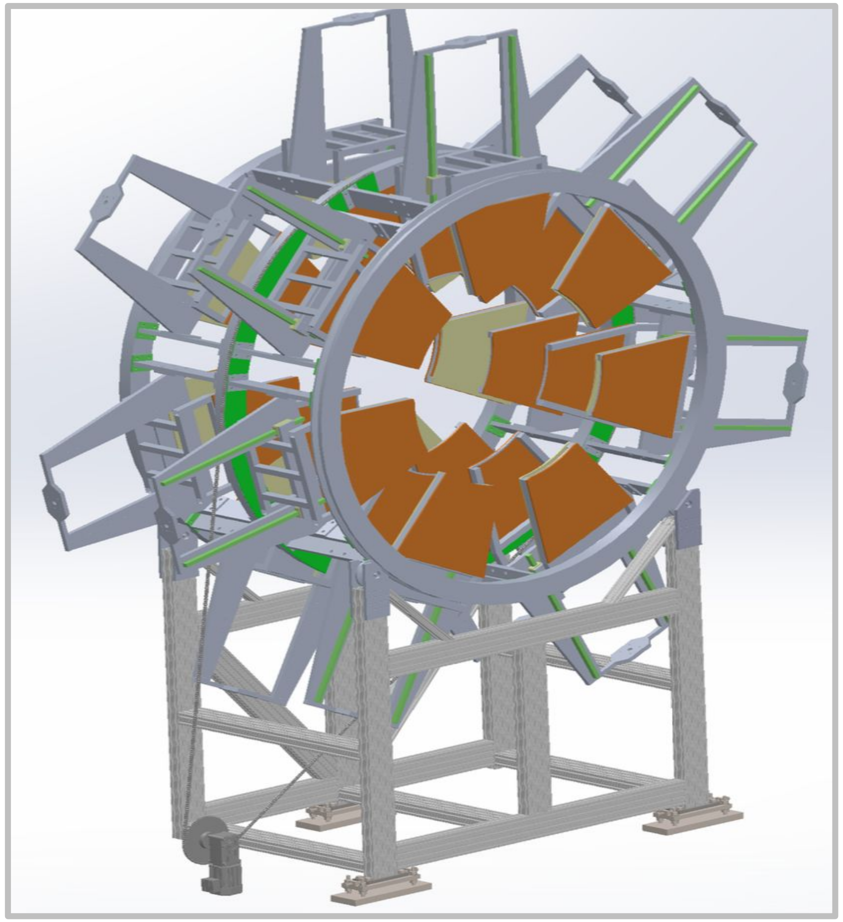


- Segmentation of the main detector plane enables azimuthal and radial binning

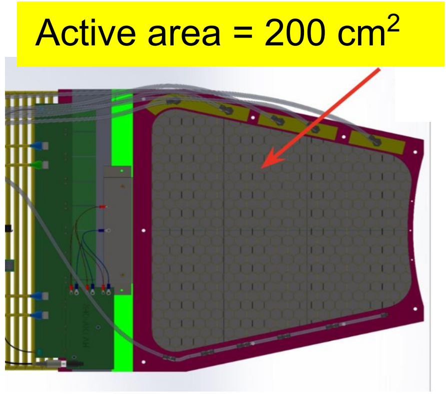
  → allowing deconvolution of the asymmetries from the various background processes
- The rate at the Møller peak is significantly higher than the average rate (1 MHz/mm^2 vs. 50 kHz/mm^2)
- Calibration with tracking detectors at low beam current and continuous monitoring of detector asymmetry widths during normal operation will improve magnetic field modelling

  → more accurate rate distributions.

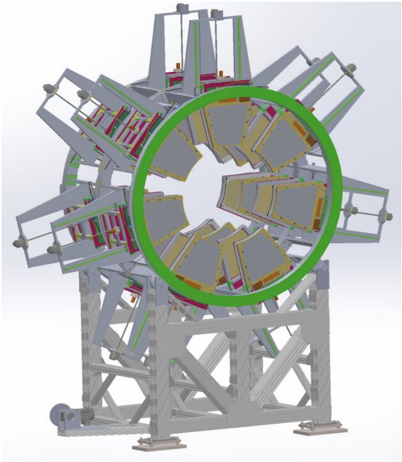
MOLLER GEM Tracking System



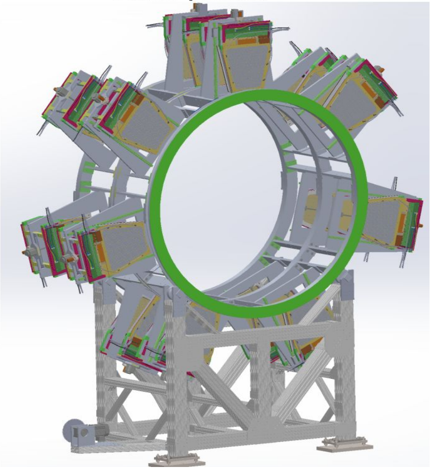
- Consist of four Gas Electron Multiplier (GEM) planes & each plane has seven GEM modules of $200cm^2$ active area
- Operate in counting mode during dedicated low beam-current runs for calibration and kinematic verification
- Being removed from the immediate path of the scattered flux during full beam-current runs to avoid radiation damages



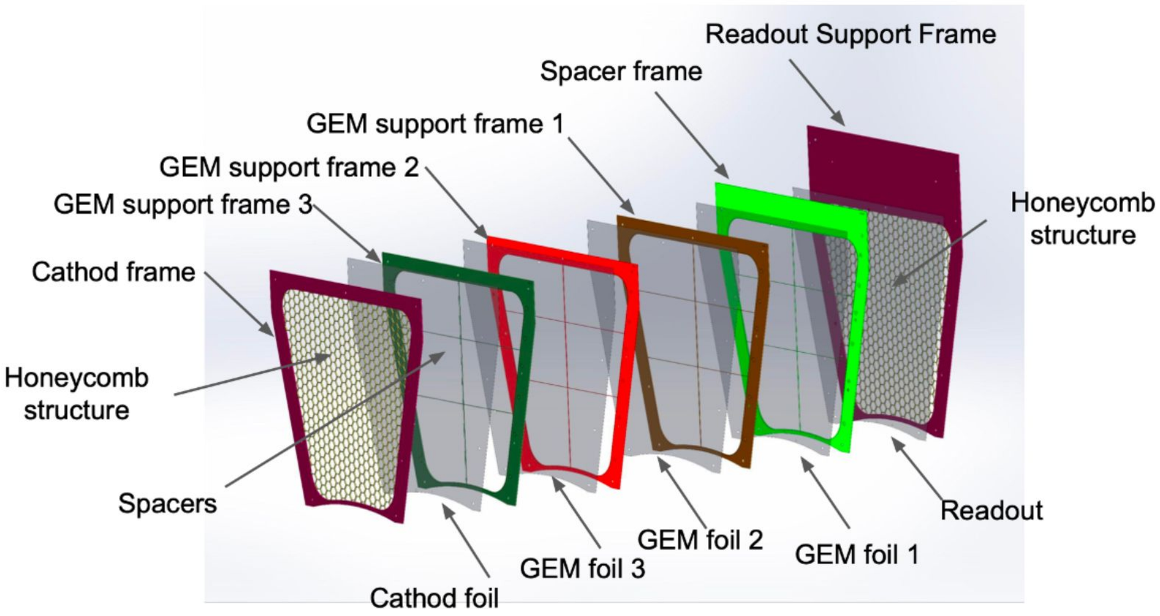
Measurement position

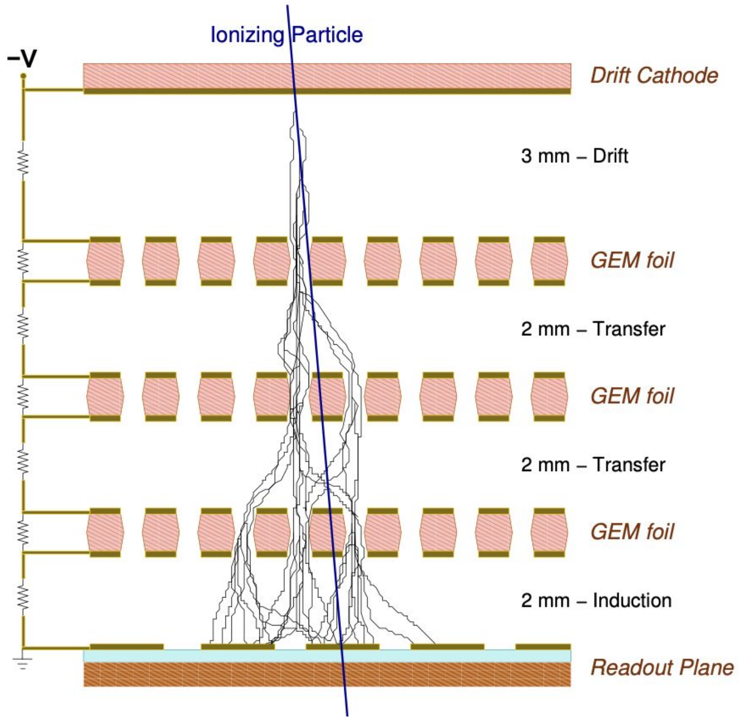


Parked position



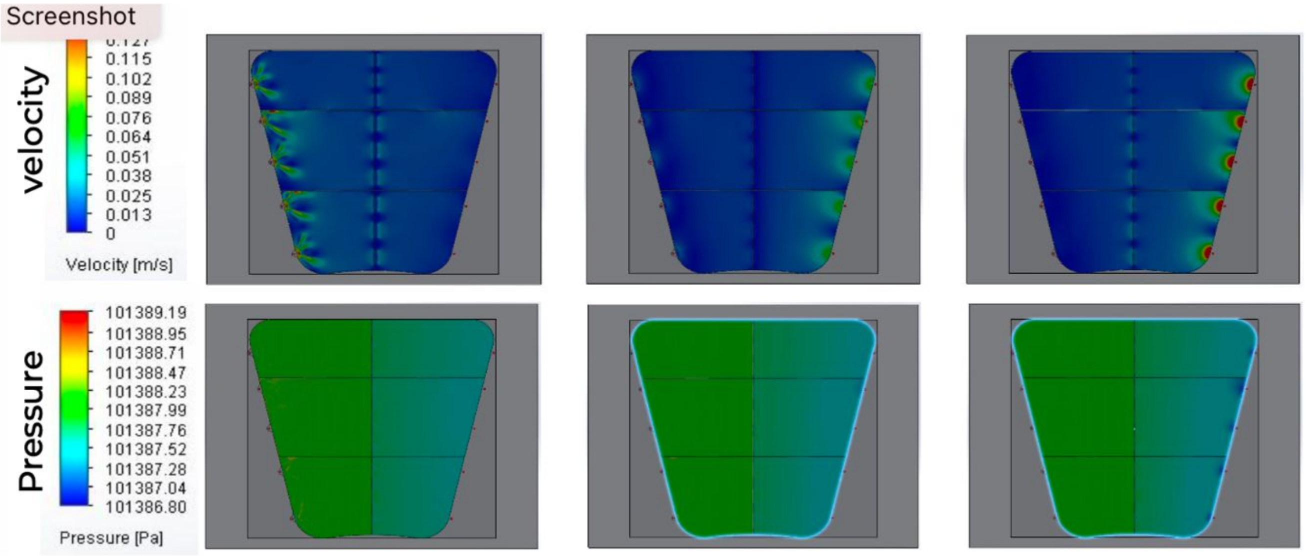
GEM Module Design

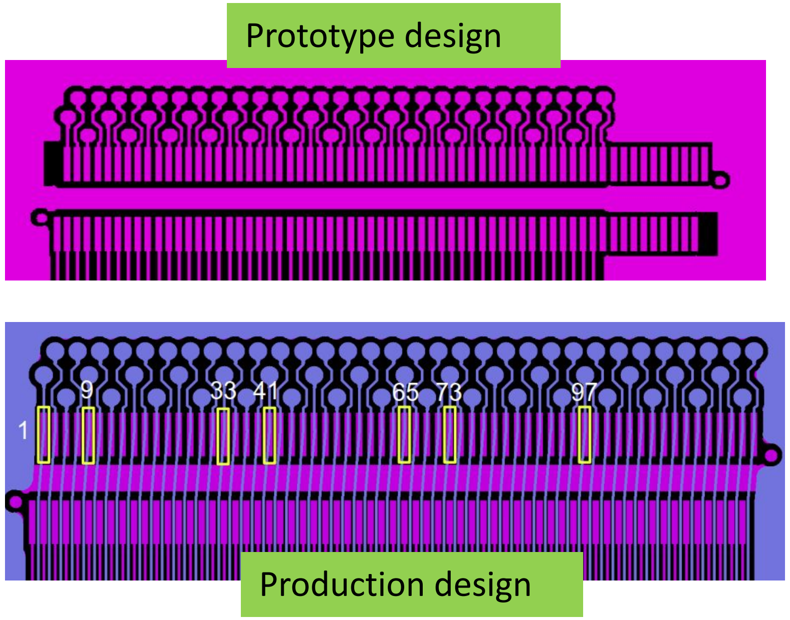




- GEM Design for MOLLER builds on recent experience with triple-GEM detectors for SBS tracking system at JLab
- High flux capability, good position resolution
- Thin curved inner-edge allows GEM active area getting closer to beam pipe to cover full acceptance

GEM Module Gas Simulation & Noise Suppression



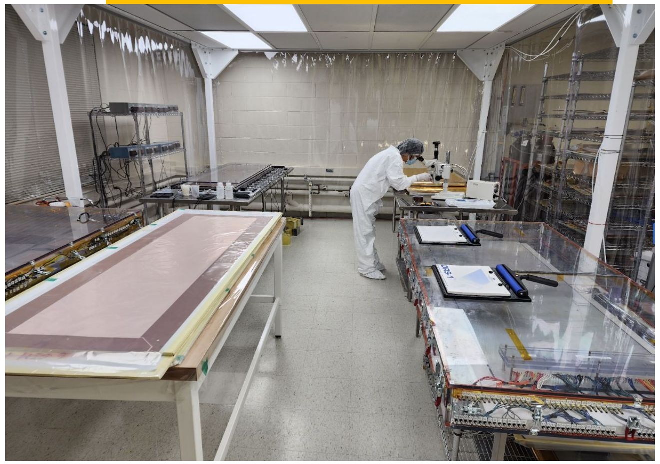


- Consistent gas flow is achieved inside the detector
- Ensure uniform gain & efficiency
- Avoid pressure buildups inside the

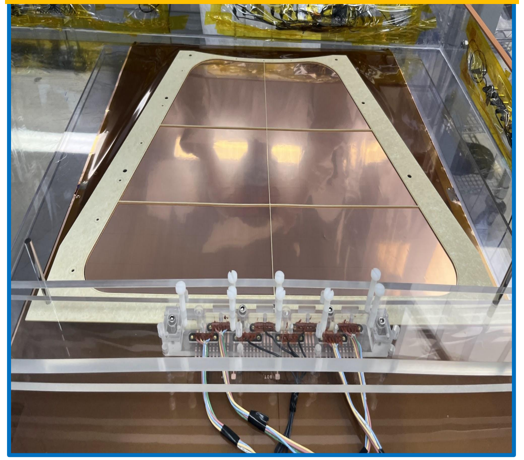
- Observed higher noise levels on the first 7 APV channels due to crosstalk from APV header
- Redesign readout board so that the noisy channels are not connected to a detector readout strip.

MOLLER Tracking Detector: Construction & Testing

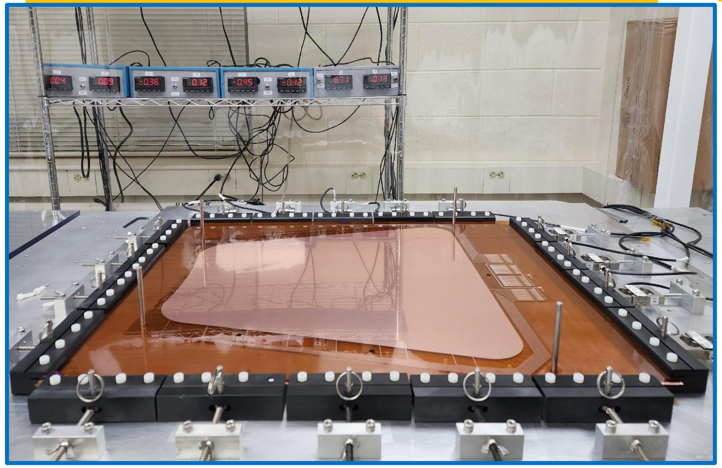
Uva Cleanroom



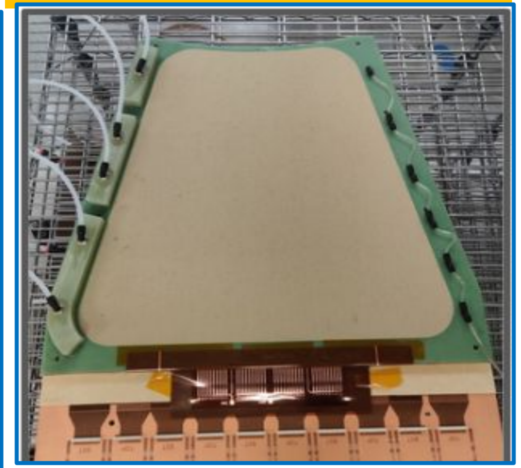
GEM foil quality control

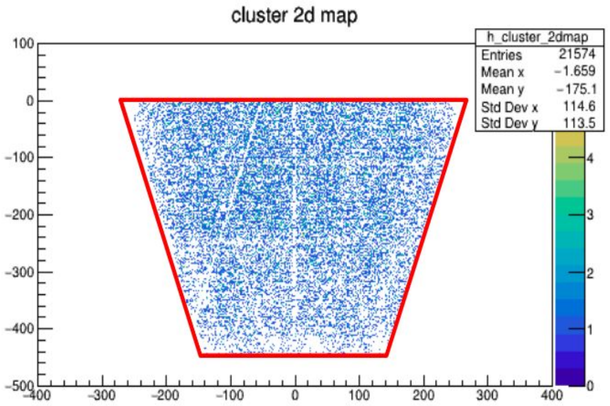


Stretching GEM foil for assembly

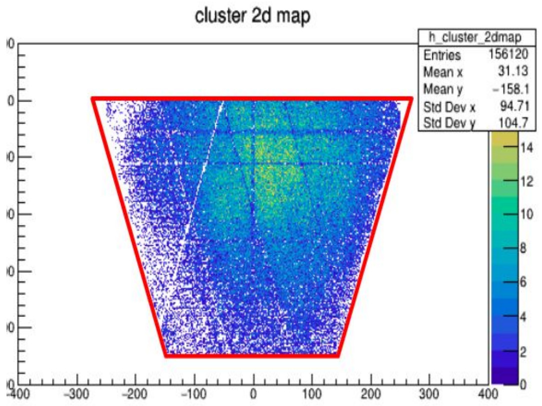


Completed GEM module





Cosmic 2D Cluster Distribution



X-Ray 2D Cluster Distribution

- One prototype and 28 production modules
- Optimized GEM design for MOLLER
- Modules are tested with X-Ray & Cosmic
  - X-Ray test: confirm working sectors and R/O functionality
  - Cosmic test: confirm the gain uniformity & eficiency

MOLLER Status & Outlook

- MOLLER has great potential to make significant physics impacts
- Engineering Design complete: final technical design report is public
- Acquisitions ongoing and Construction has begun
- Installation: 2025-2026
- Commissioning: Early 2027
- Physics Analysis through 2029 and beyond
- Incoming MOLLER activities of UVA Detectors Lab:
  - Installation and Commissioning Tracking detector
  - Join collaboration efforts on running experiment and performing physics analysis
  - **Looking for two (2)Graduate Students and (1) Postdoc to join our team!**

Thank you for your attention!

CONTACT: HTN3R@VIRGINIA.EDU