MOLLER Overview

Measurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction

Brynne Blaikie
University of Manitoba

on behalf of the MOLLER Collaboration

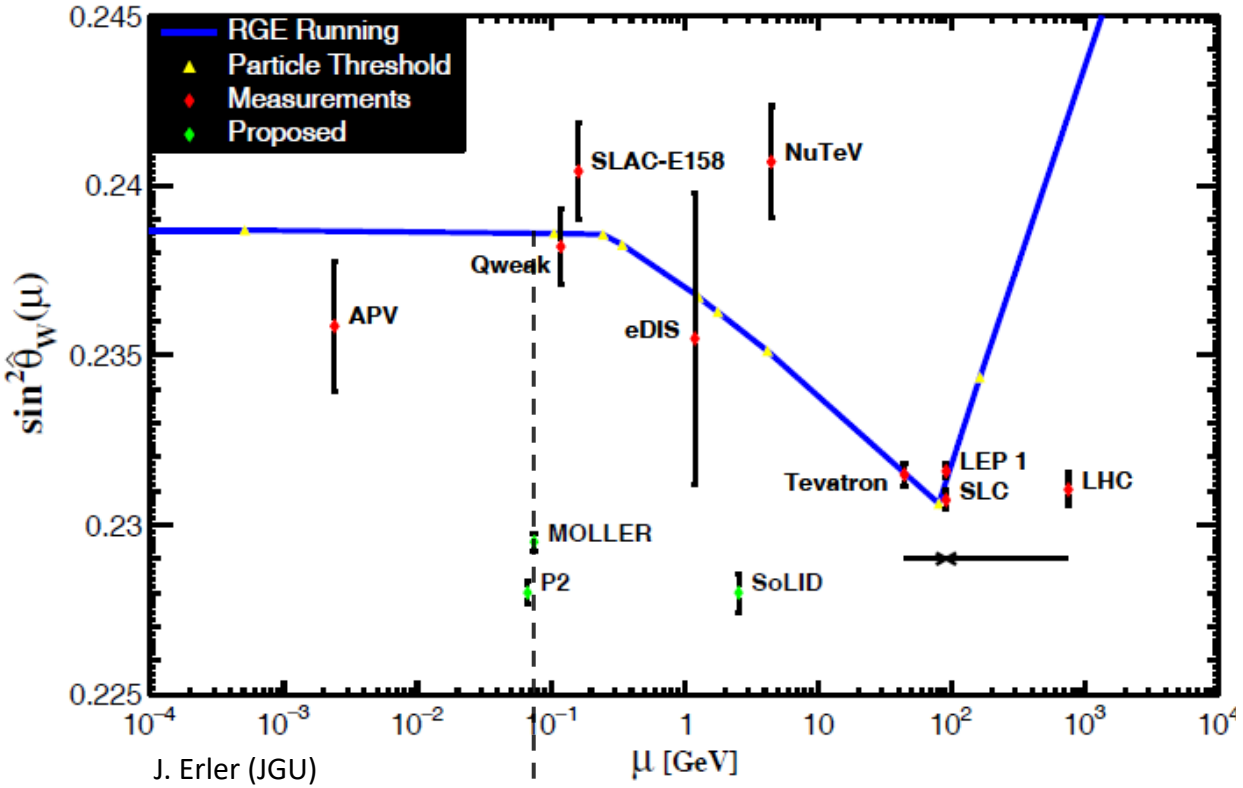
Weak Mixing Angle
Møller Scattering and A_{PV}
MOLLER Parameters
MOLLER Subsystems
- Target
- Spectrometers & Collimation
- Detectors
- Integrating Electronics

Hall A/C Summer Collaboration Meeting
17 June 2026

Motivation – Weak Mixing Angle

Probing the electroweak sector of the Standard Model

$\sin^2\theta_W$ "running" with interaction energy due to varying radiative corrections



J. Erler (JGU)

describes the mixing of

SU(2) with coupling constant g
U(1) with coupling constant g'

$$sin^2(\hat{\theta}_W) = \frac{g^2}{g^2 + g'^2}$$

Significance of MOLLER Results:

Disagrees with Standard Model?

➡ BSM evidence for new particles

Agrees with Standard Model?

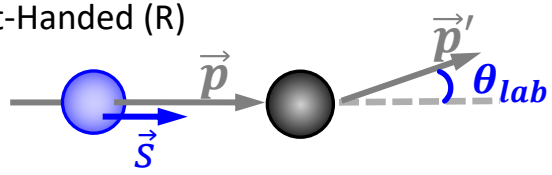
➡ low Q^2 constrains new physics at multi-TeV scale

MOLLER will determine $\sin^2\theta_W$ at average $Q^2 = 0.0056\ \mathrm{GeV}^2$ using **parity-violating electron scattering**

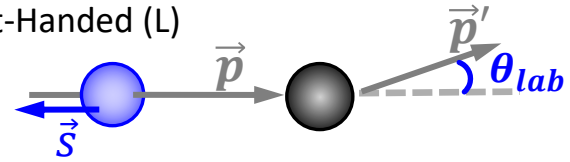
Method – Parity-Violating Electron Scattering

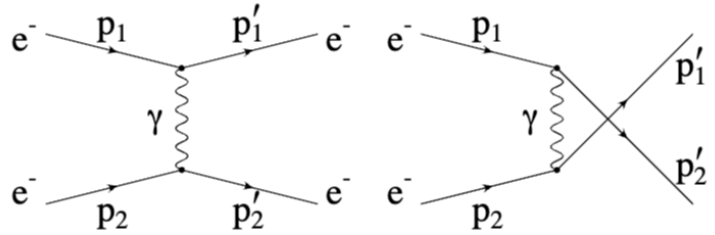
Møller Scattering of longitudinally polarized electrons from unpolarized target electrons:

Right-Handed (R)

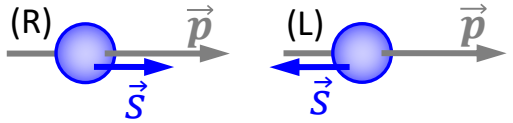


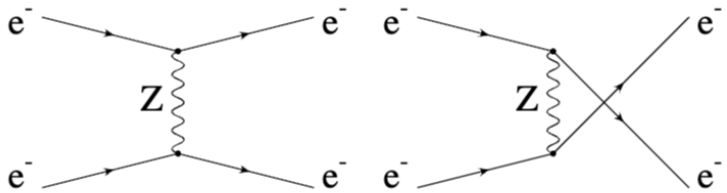
Left-Handed (L)



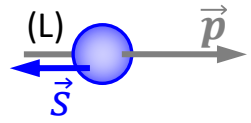


Electromagnetic Interaction: conserves parity

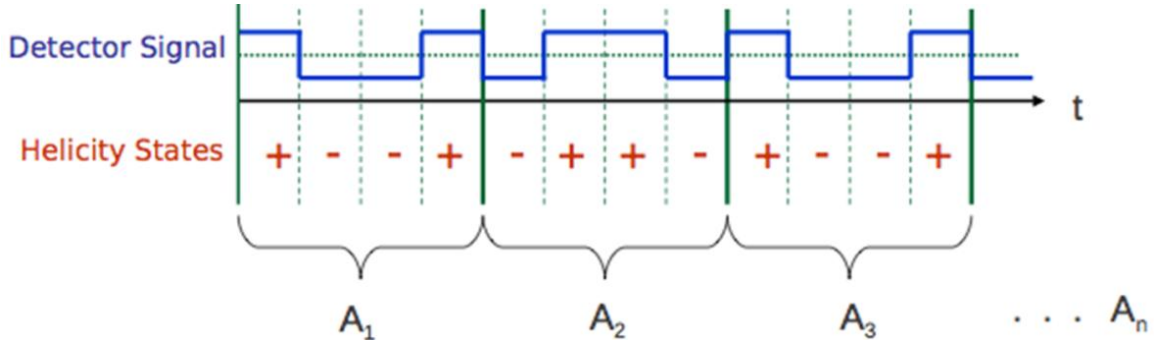




Weak Interaction: **violates parity**



Measure fractional rate difference (asymmetry) between flipping helicities:



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = m_e E \frac{G_F}{\pi\alpha\sqrt{2}} \frac{4sin^2\theta_{cm}}{(3 + cos^2\theta_{cm})^2} Q_W^e$$

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

***Really Challenging:** PVES asymmetries are ~10^{-6} to 10^{-9}

→ Requires high luminosity and high precision

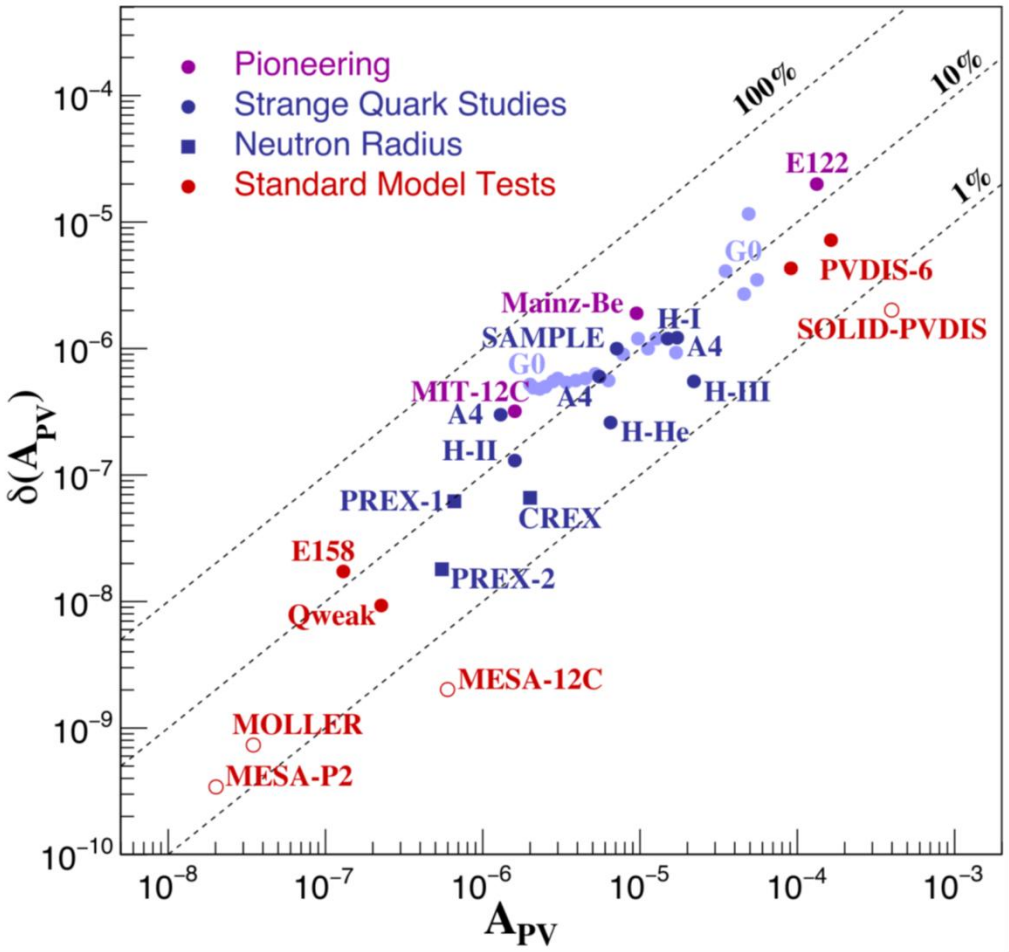
MOLLER Nominal Parameters

Key Design Parameters and Goals:

- $\mathcal{L} = 3 \times 10^{39}\ cm^{-2} \cdot s^{-1}$
- $P_{beam} \geq 90 \pm 0.5\ \%$
- $E_{beam} = 11\ GeV$
- $I_{beam} = 65\ \mu A$

- rapid helicity flip (1.92 kHz), high beam stability
- high precision polarimetry
- high power LH_2 target
- large acceptance
- systematic uncertainty control
- 344 PAC days = 8256 hours = 3 - 4 calendar years

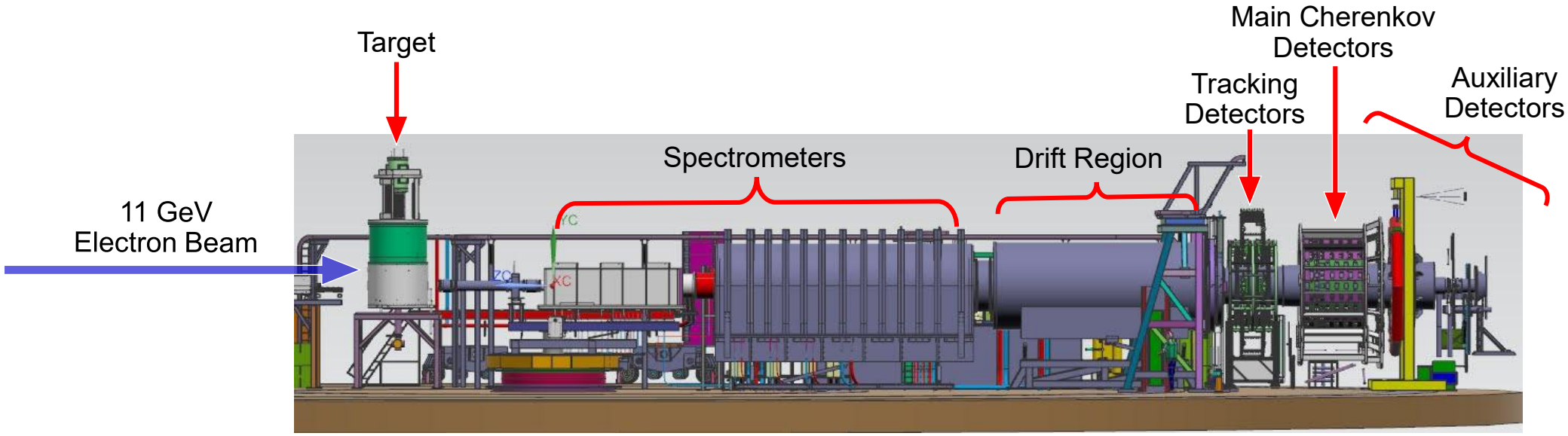
A_{PV} predicted to be $\approx$ 33 ppb



MOLLER Goal:

$$\delta A_{PV} = 0.8\ \text{ppb} \qquad \Rightarrow \Delta Q_W^e = 2.4\% \qquad \Rightarrow \Delta \sin^2\theta_W = 0.1\%$$

MOLLER Subsystems



Target System – LH2

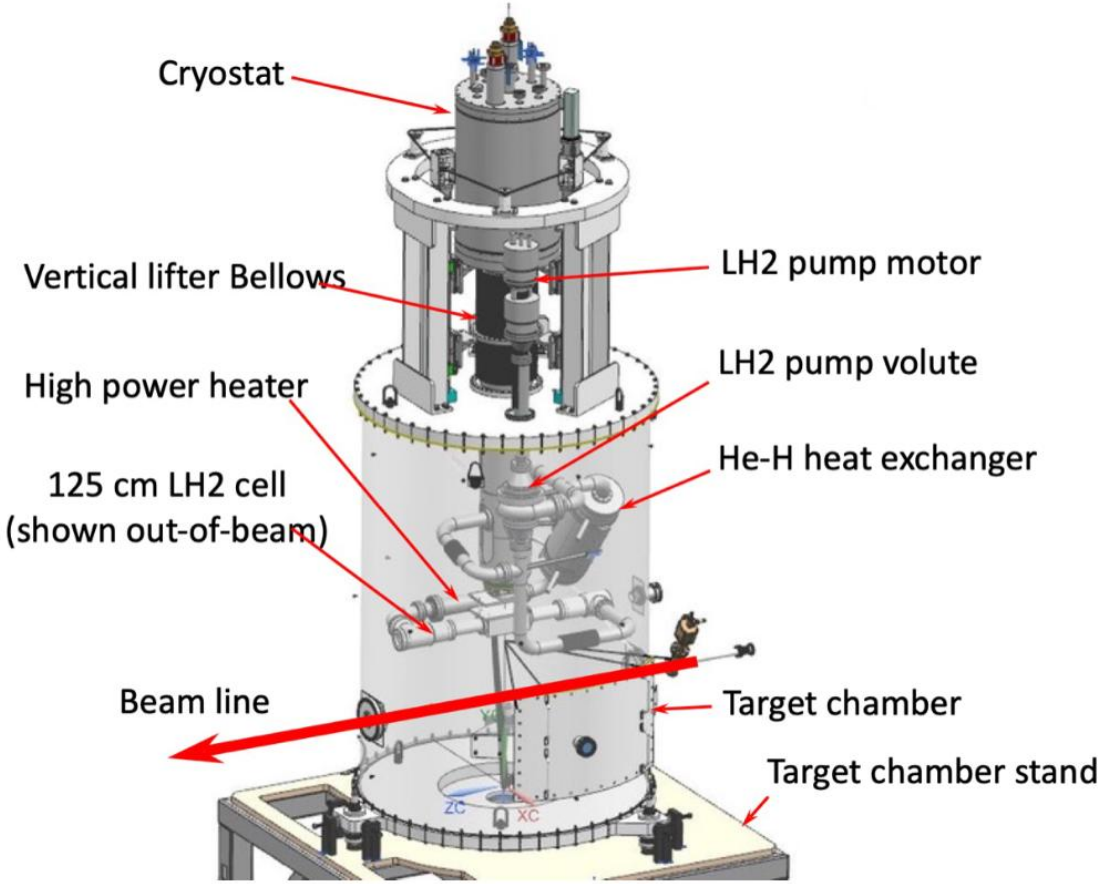
Requirements:

- Minimize target density fluctuations
- Maximize luminosity

Specs:

- 125 cm long LH_2 target
- 4 kW total power

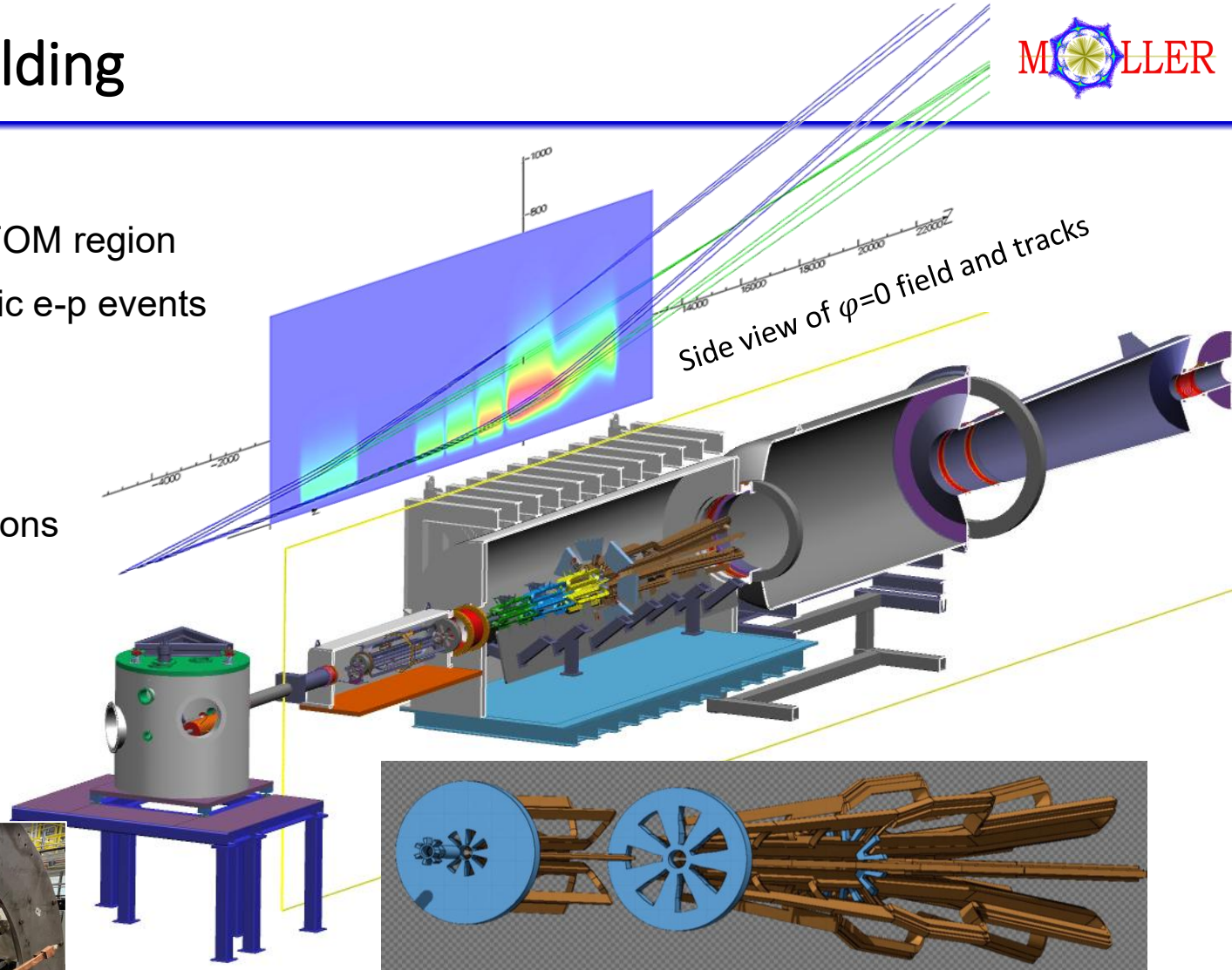
highest power LH2 target !!

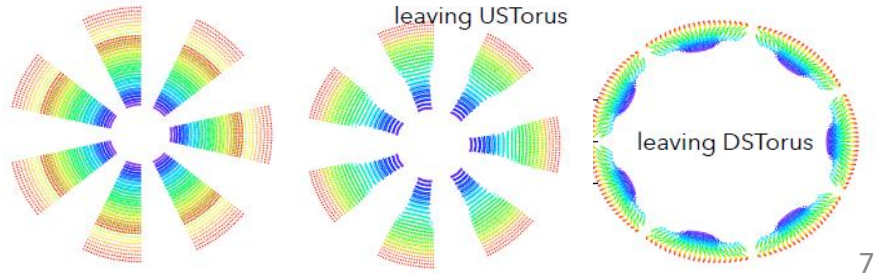


Spectrometer, Collimation, and Shielding

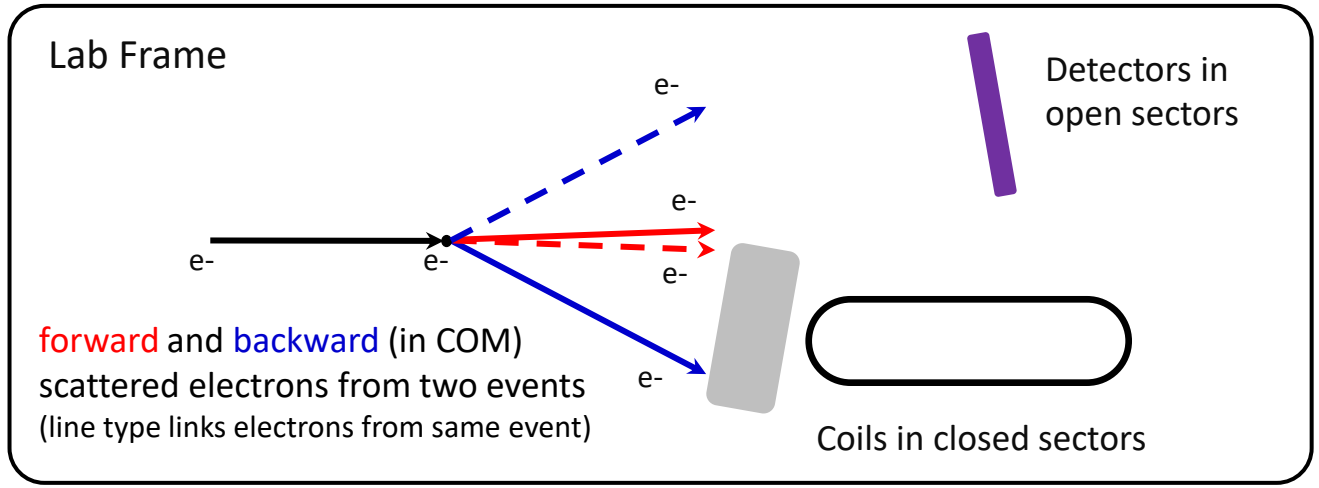
5 toroidal magnets with 7-fold symmetry

- **full azimuthal acceptance** of Møller events in high FOM region
- **separation of Møller events** from elastic and inelastic e-p events
- precise collimation
  - remove line-of-sight between target and detectors
  - "2-bounce" to minimize backgrounds
- channel for degraded beam and bremsstrahlung photons to beam dump

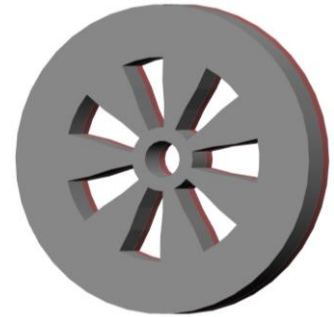




100% Azimuthal Acceptance



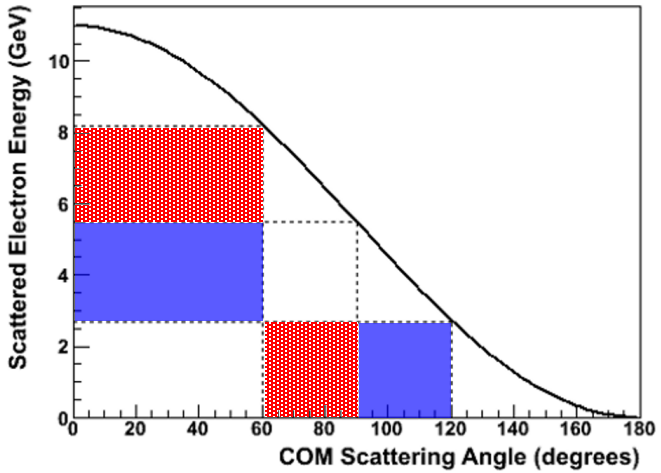
Any odd number of coils will allow for 100% φ acceptance

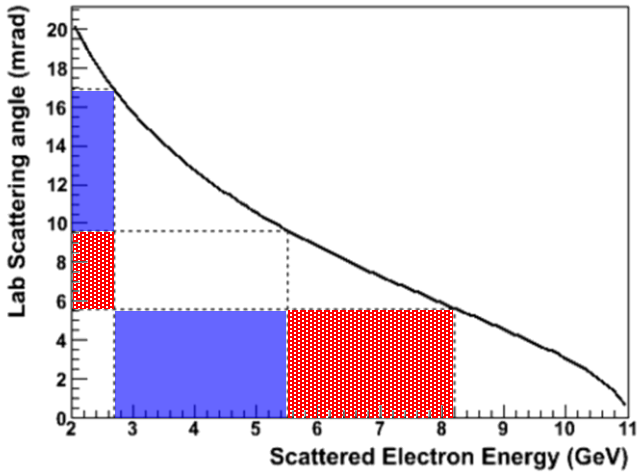


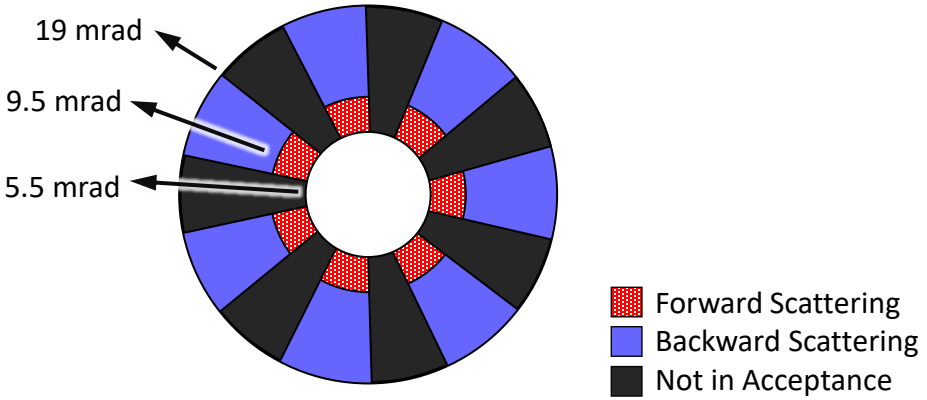
acceptance defining Coll.2
5 m downstream of target

$$60^\circ \leq \theta_{COM} \leq 120^\circ$$

$$2.75 \leq E_{scat} \leq 8.25\ GeV$$





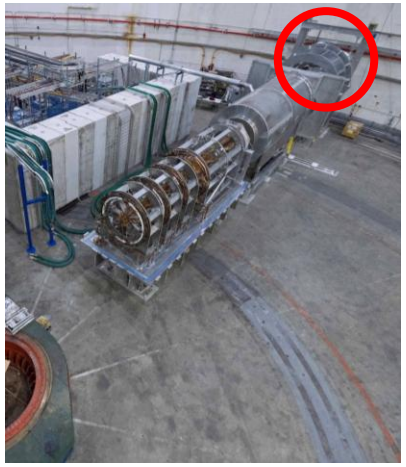


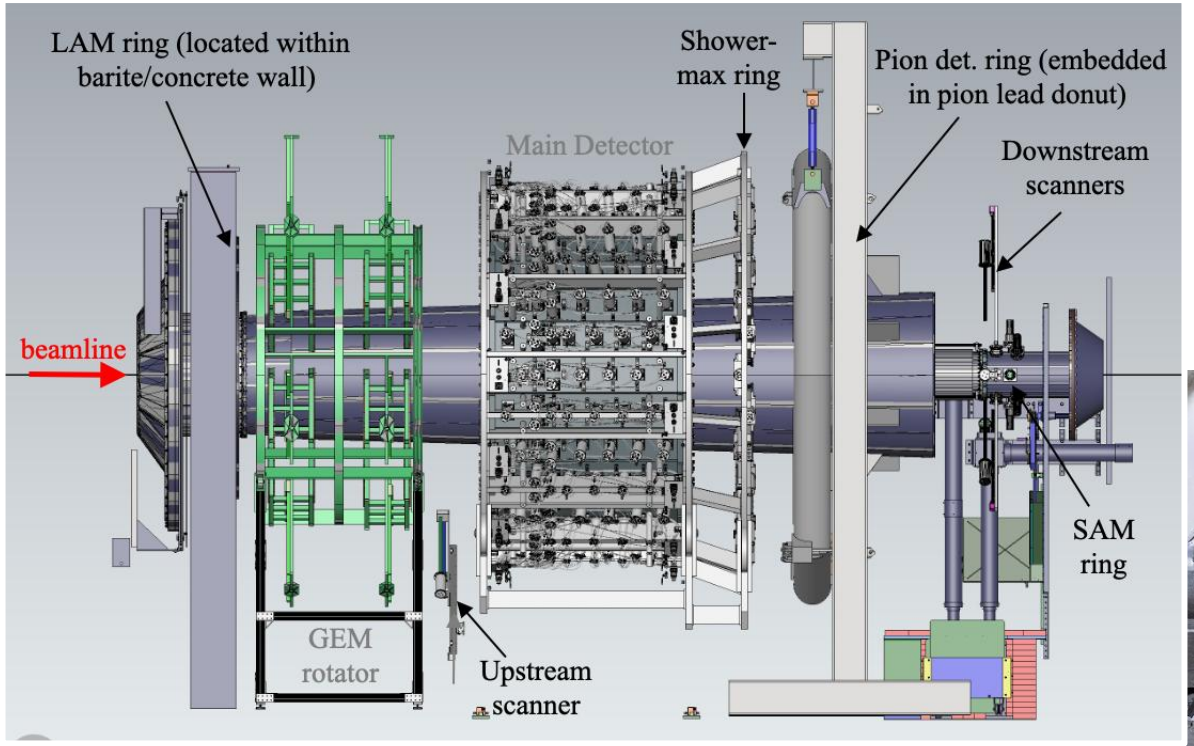
Detector Overview

Integrating (current mode) detectors: asymmetry measurements in both signal and background, beam and target monitoring

Tracking (counting mode) detectors: spectrometer calibration, electron scattering angle distribution and background measurements

- GEMs and Scintillators
- Shower-max
- Pion Detectors
- Scattered Beam Monitors
  - Large Angle Monitors
  - Small Angle Monitors
  - Diffuse Beam Monitors
- Scanners
  - Upstream Scanners
  - Downstream Scanners
- HVMAPS
- Main Cherenkov Detectors

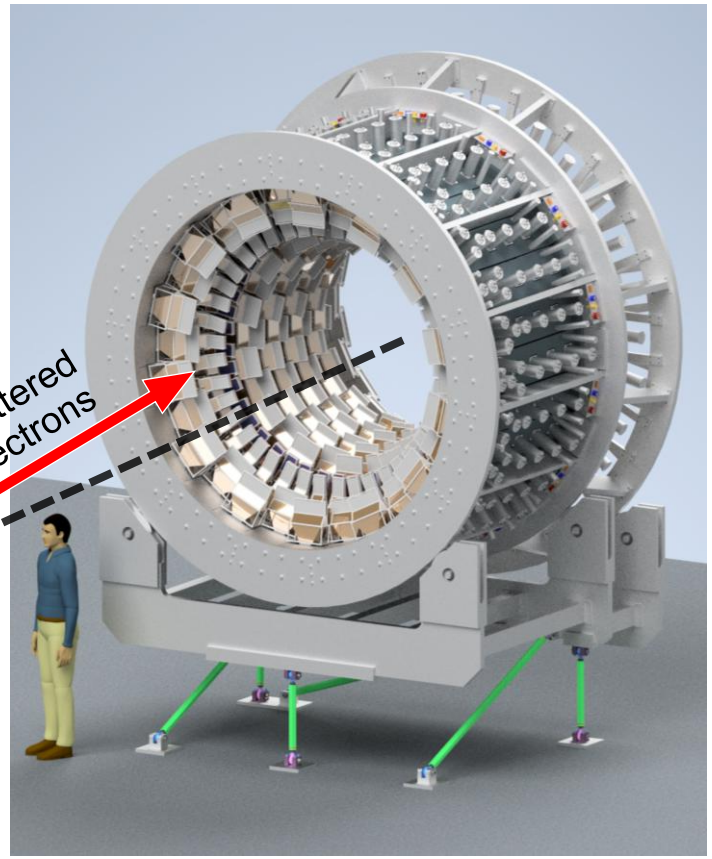


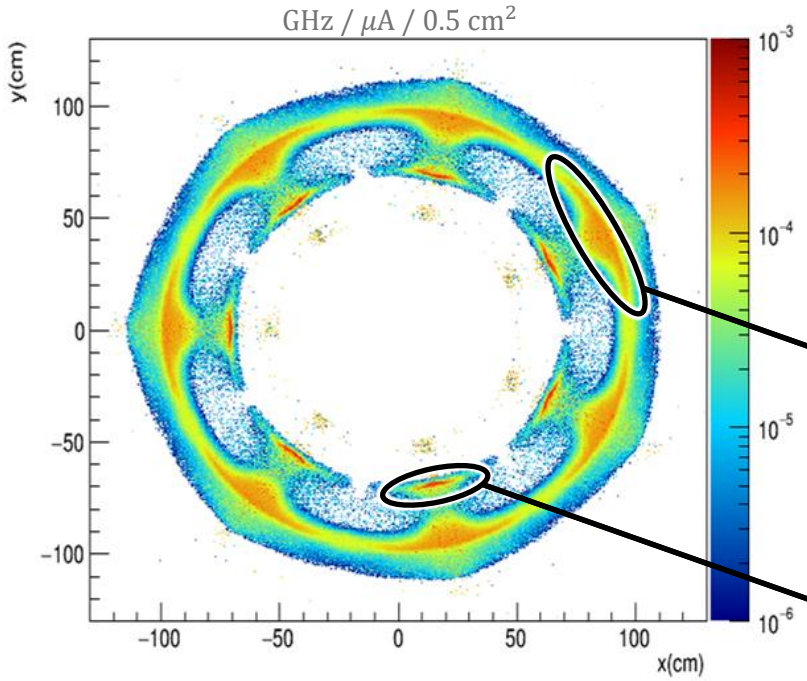


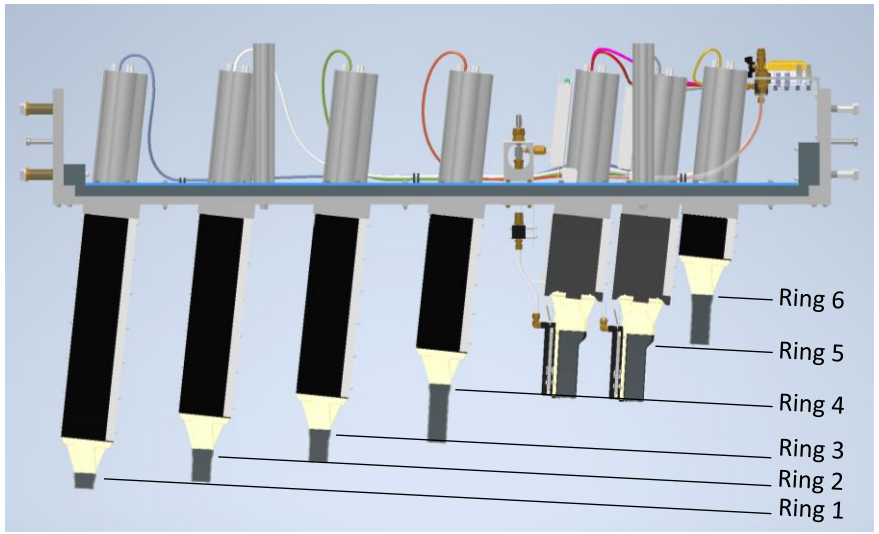
Main Cherenkov Detector Array

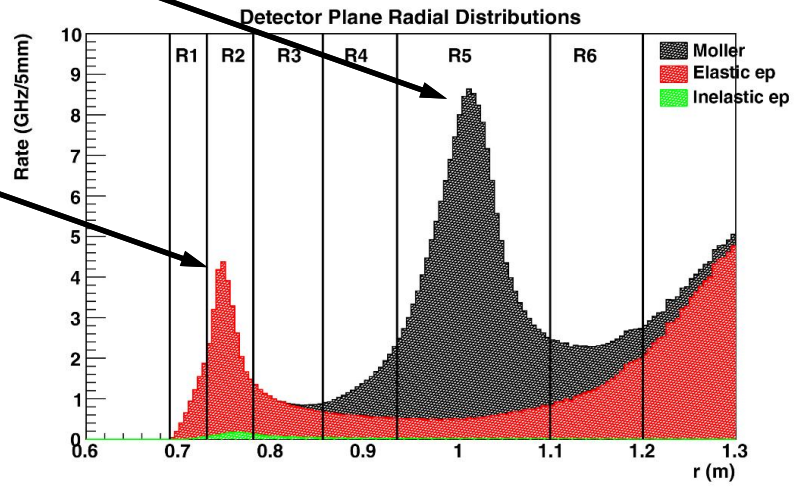
224 fused silica Cherenkov detectors

- Radially split into 6 Rings
- Azimuthally split into 28 Segments
- Remote switching between integration and event modes









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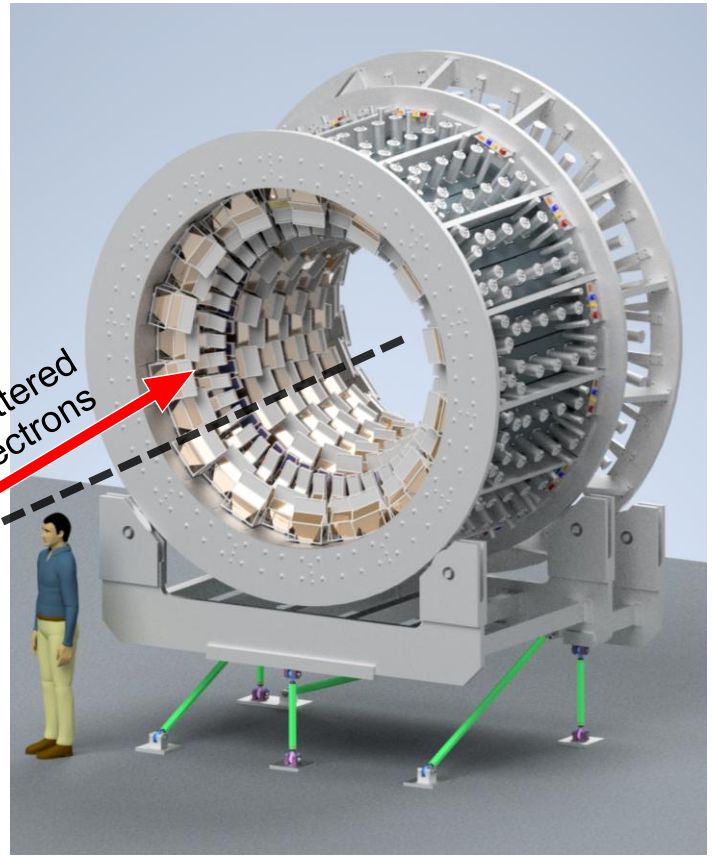

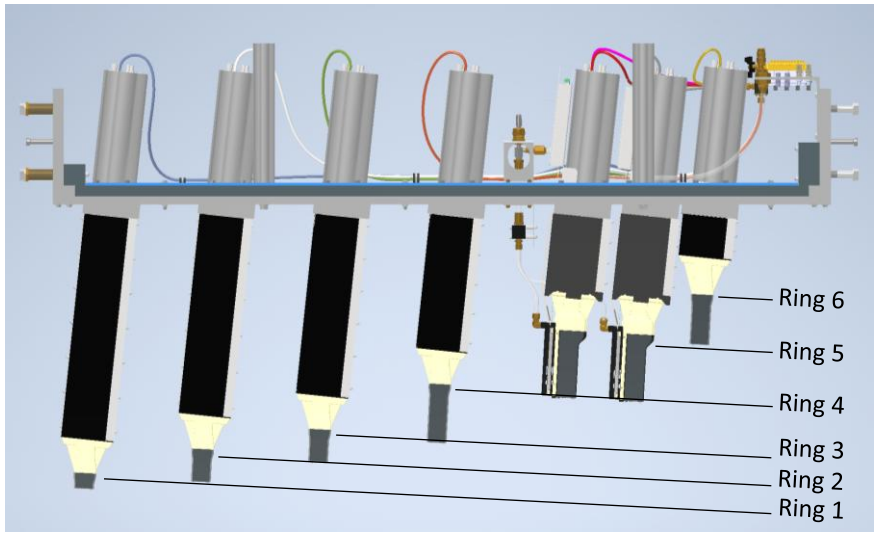

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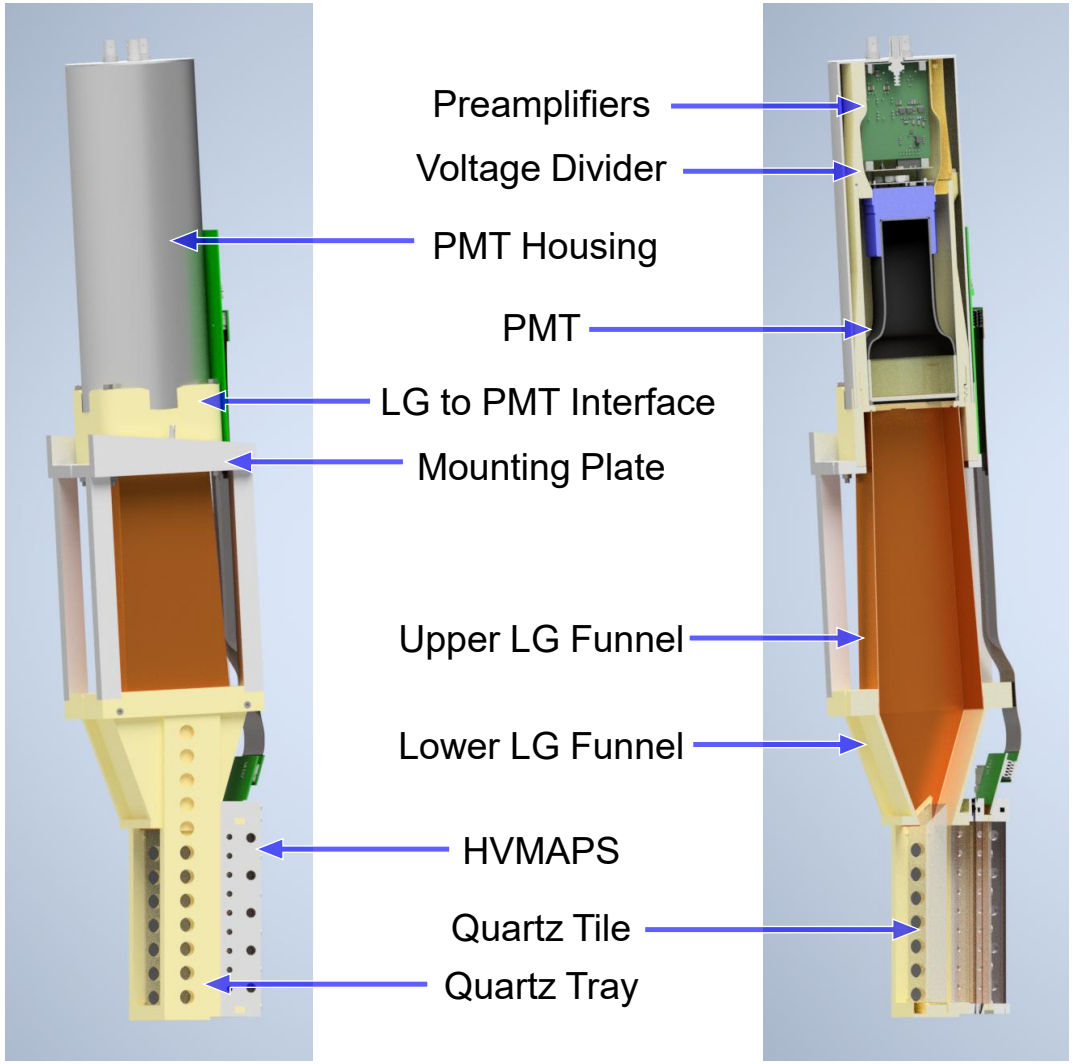
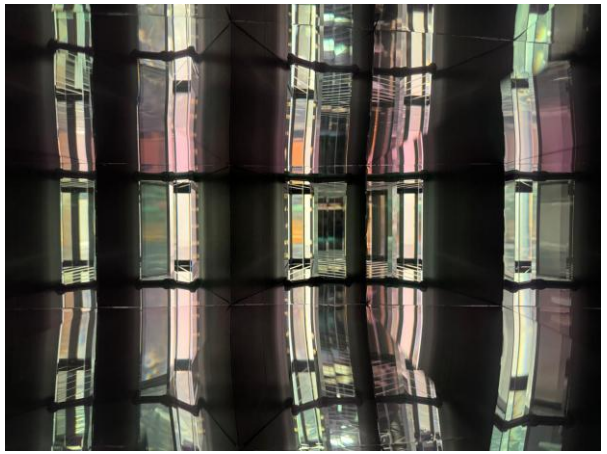
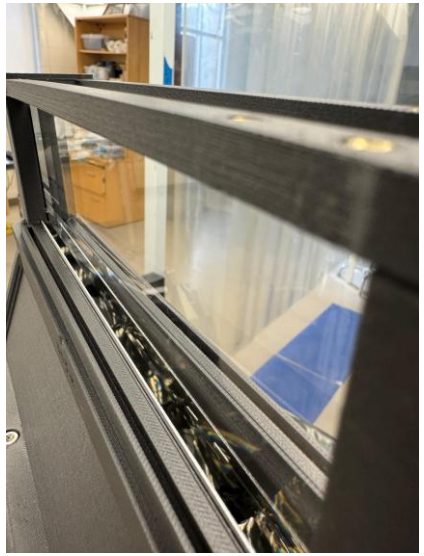
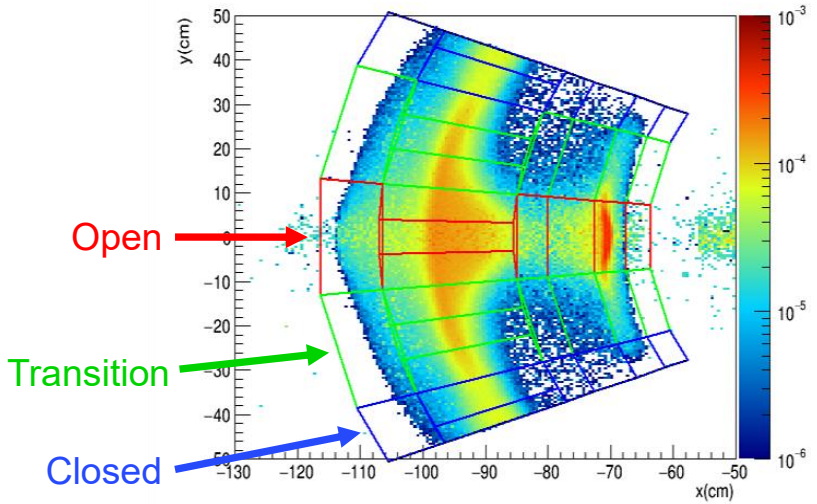




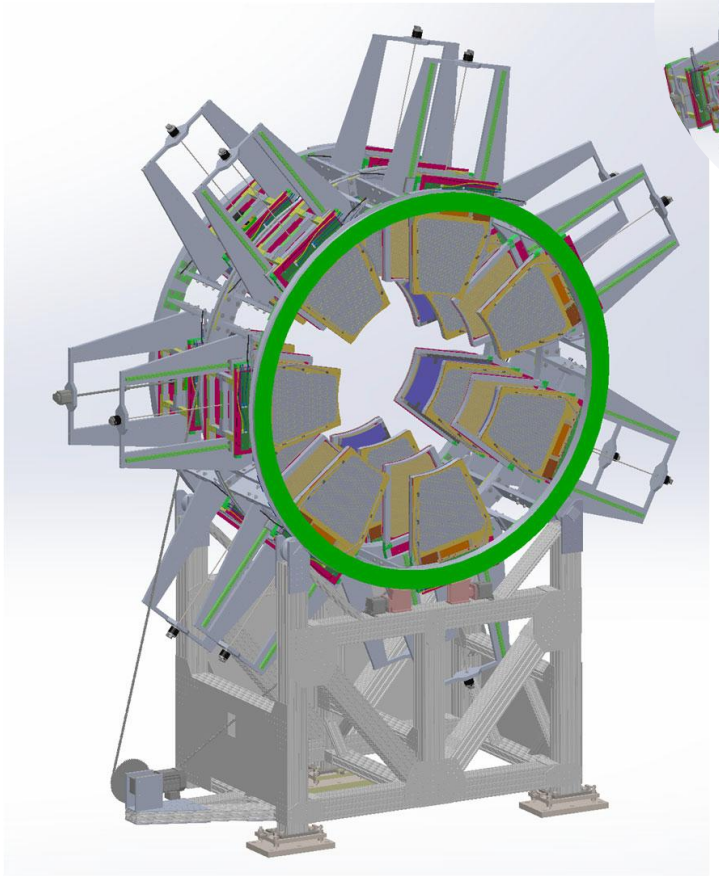


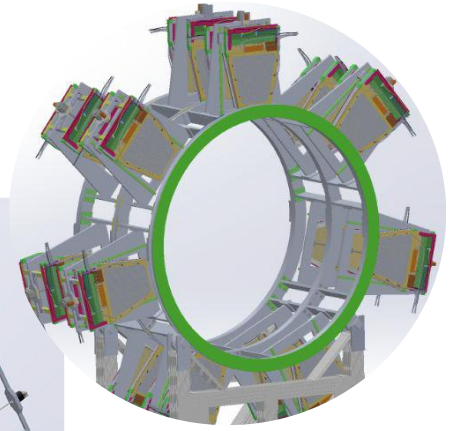


Tracking – GEM Rotator

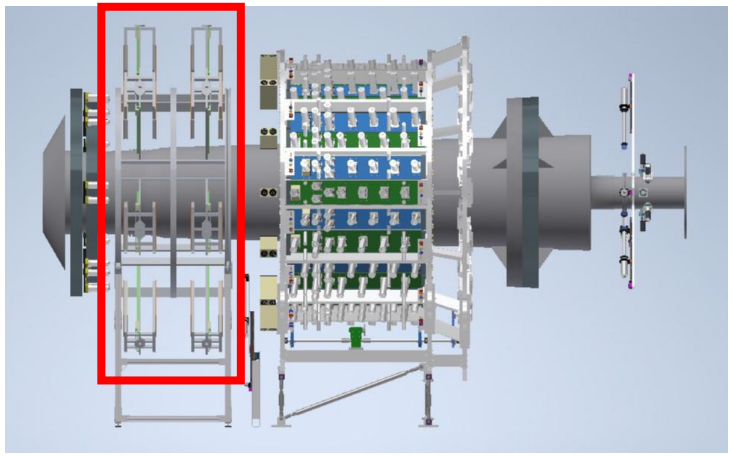
Counting Mode Measurements: backgrounds, kinematics, spectrometer diagnostics, calibration

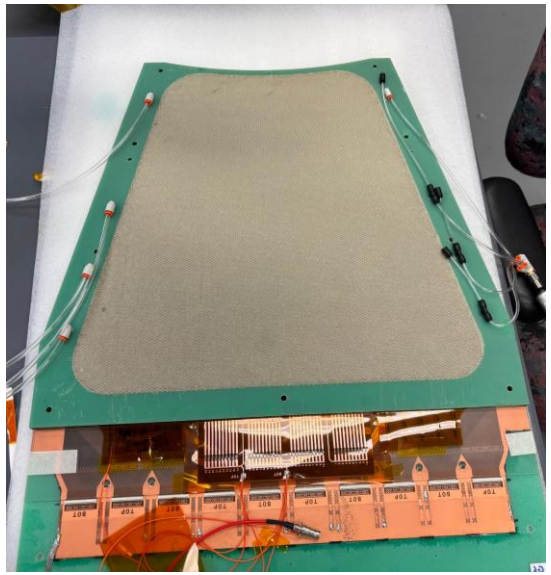
- 28 (4 layers x7) GEM modules
- 14 (2 layers x7) trigger scintillators

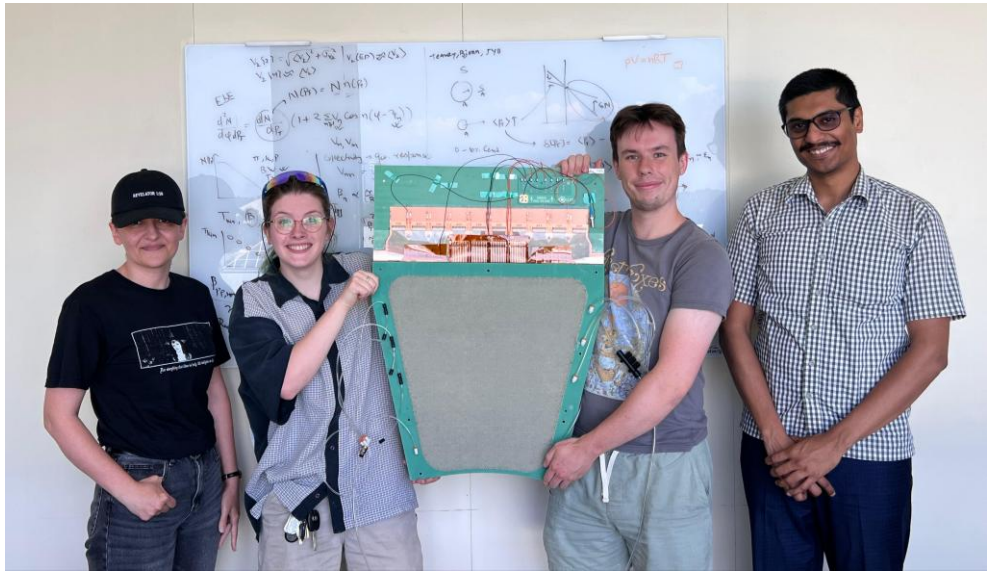




radial extraction during high beam current !





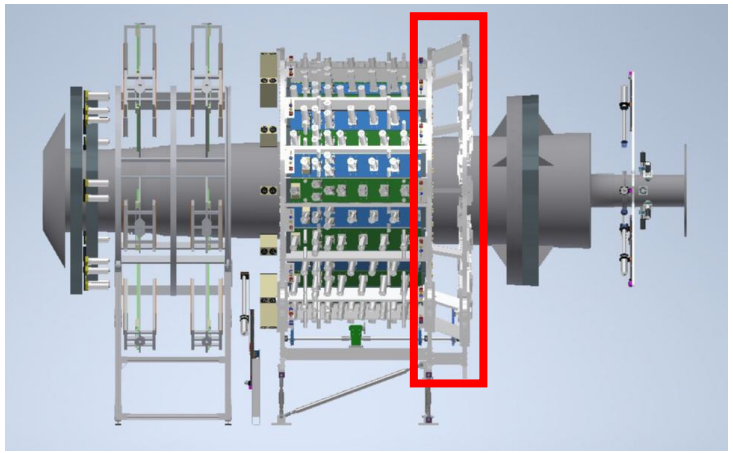


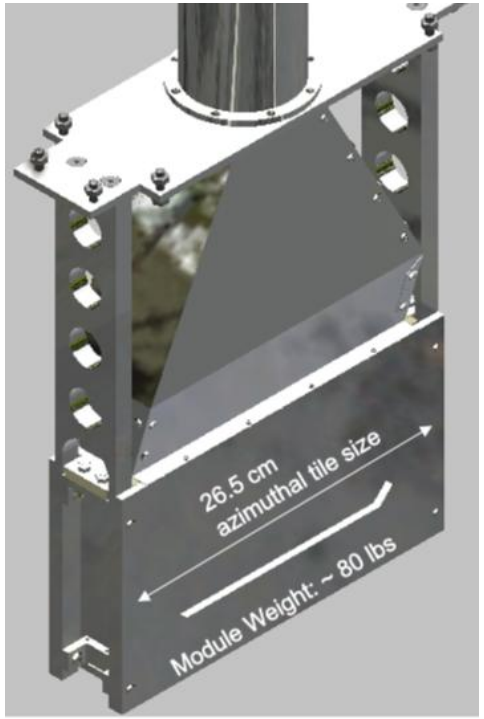
J. Shirk (Stony Brook)

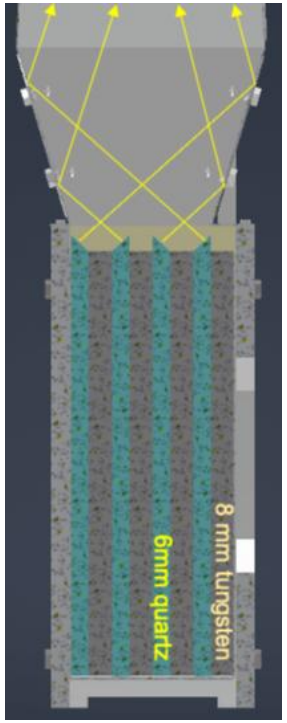
Shower-max

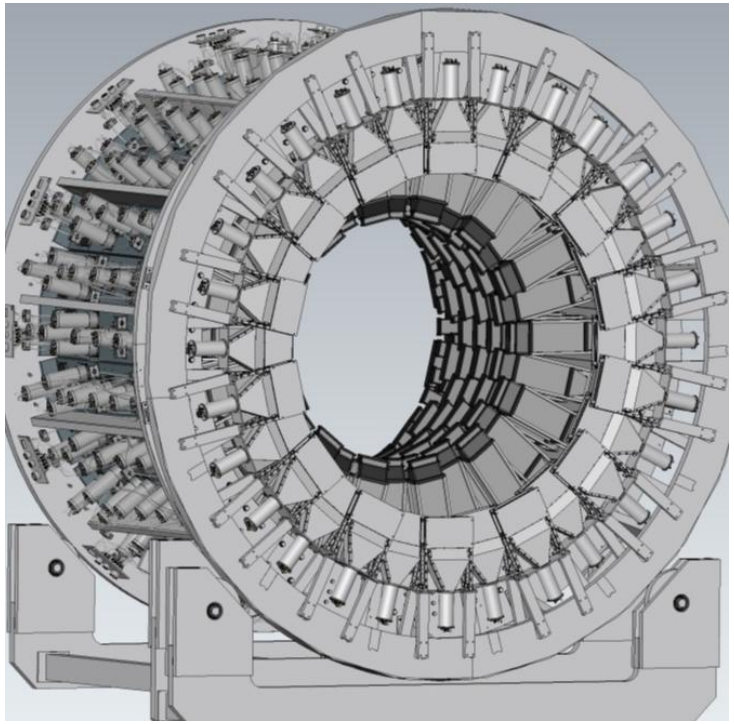
Goal: Second, independent measurement of Møller peak

- 28 electromagnetic sampling calorimeters
  - higher E – samples more
  - lower E – samples less
- layered quartz and tungsten





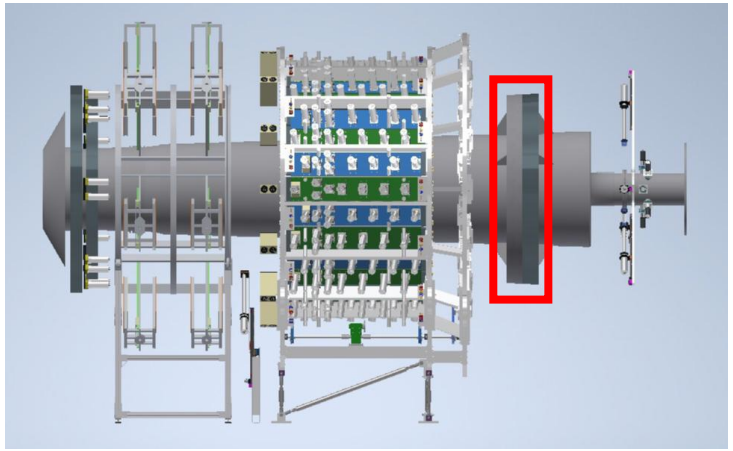


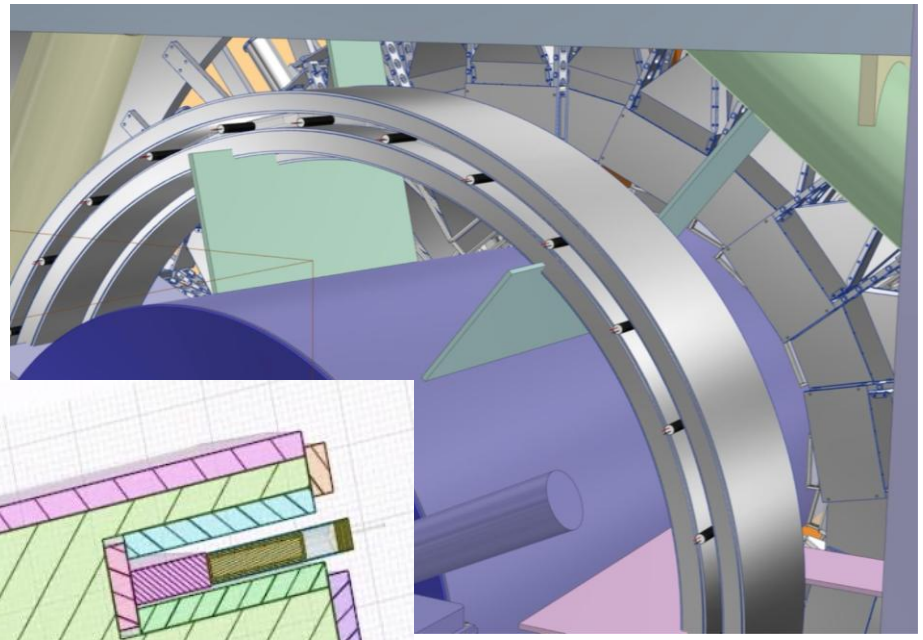


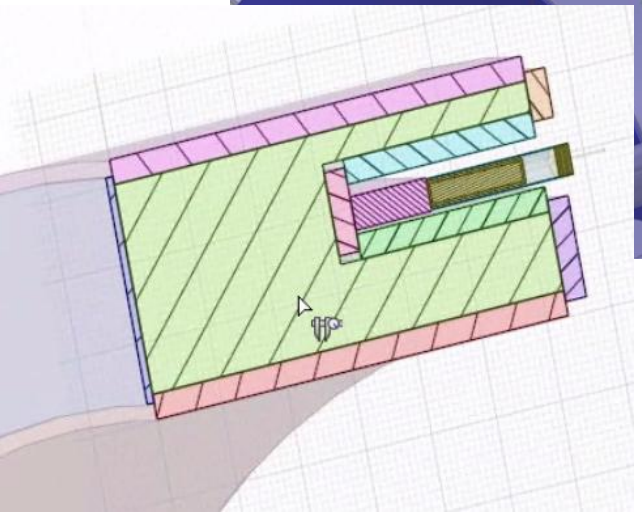
Pion Detectors

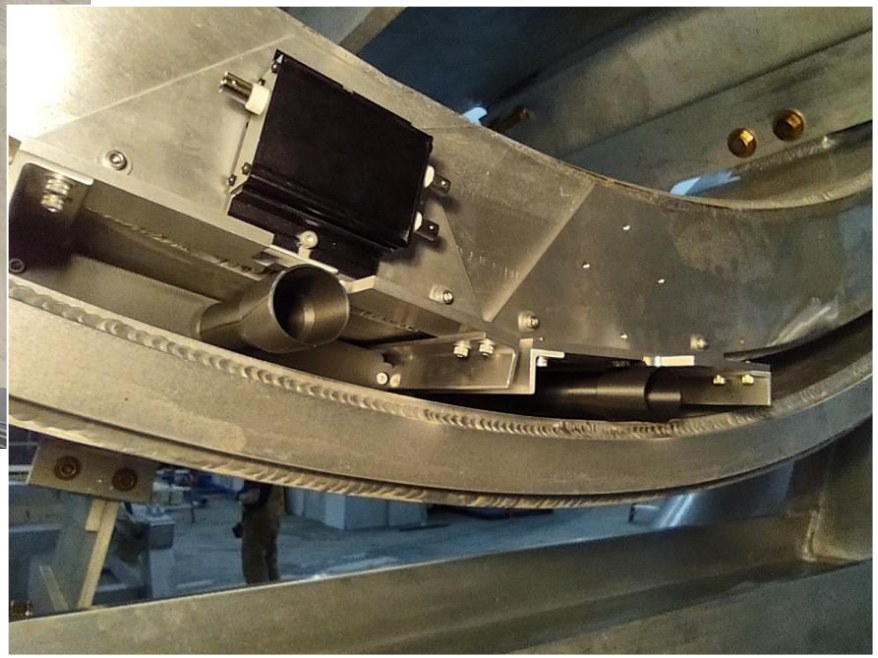
Goal: Quantify pion background contamination in Møller signal asymmetries

- 28 acrylic Cherenkov detectors
- encased in Pb donut, downstream of shower-max detectors to suppress Møller electrons by > 10^3









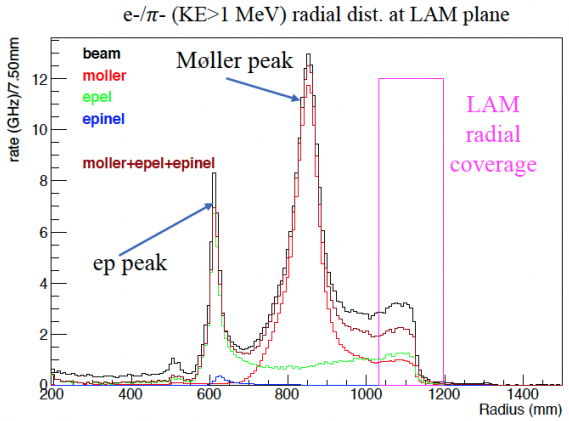
D. Armstrong (W&M)

Scattered Beam Monitors

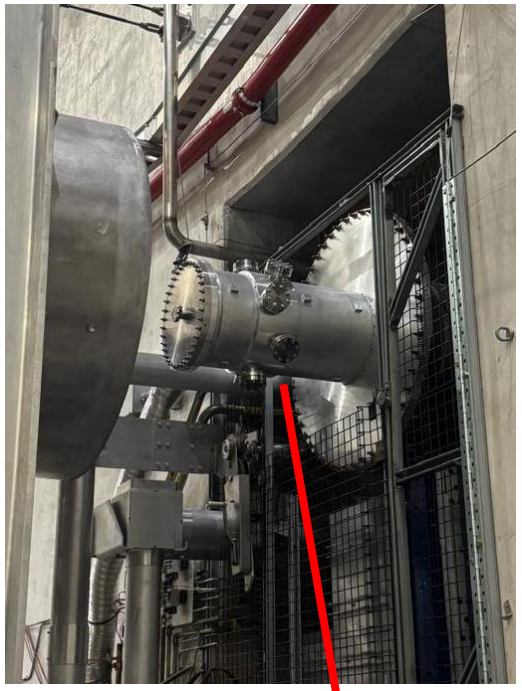
Goal: Monitor for false asymmetries

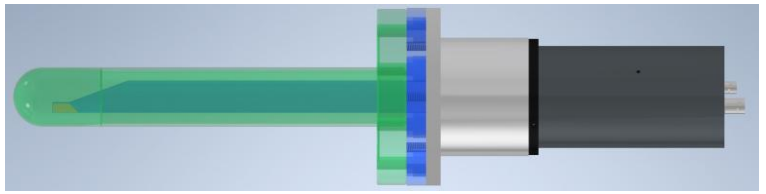
7 Large Angle Monitors (LAMs)

rate dominated by e-p elastic tail

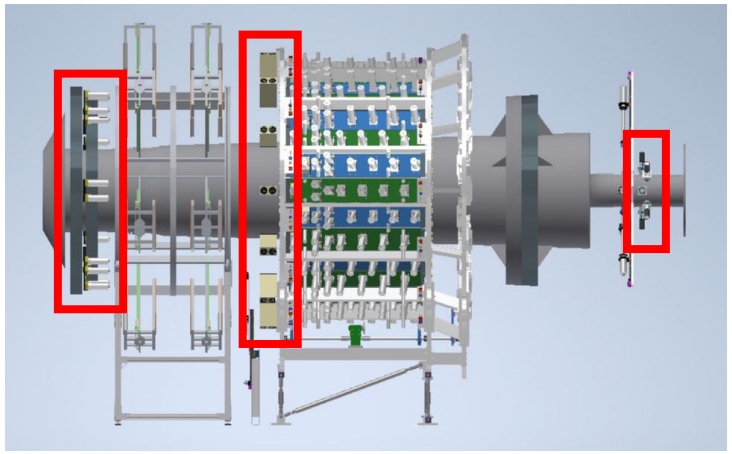


14 Diffuse Beam Monitors (DBMs)





8 Small Angle Monitors (SAMs)

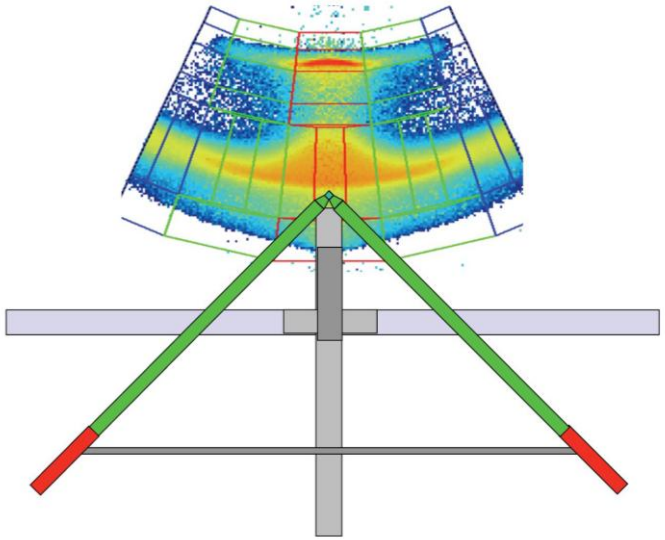


D. Valmassei (VTech)

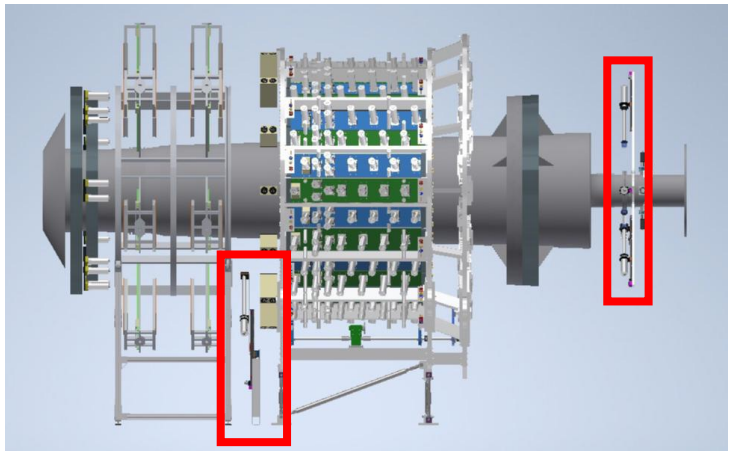
Scanner Detectors

Goal: Create rate distribution maps of scattered flux

- 4 Downstream Scanners
  - 4x 1D radial scanning for integration mode, magnet off
- 1 Upstream Scanner
  - 2D scanning for scattered rate dist. in one sector
    - integration and counting mode
    - verify both currents same distribution
    - monitor stability of kinematics and backgrounds
    - full scan complete in < 1 hour

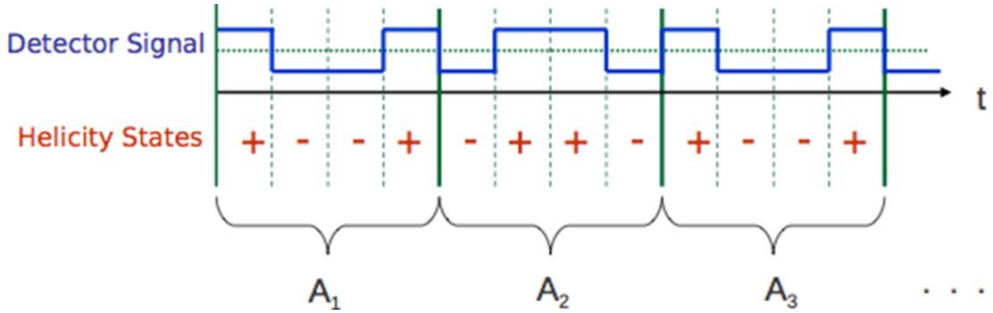


D. Valmassei (VTech)



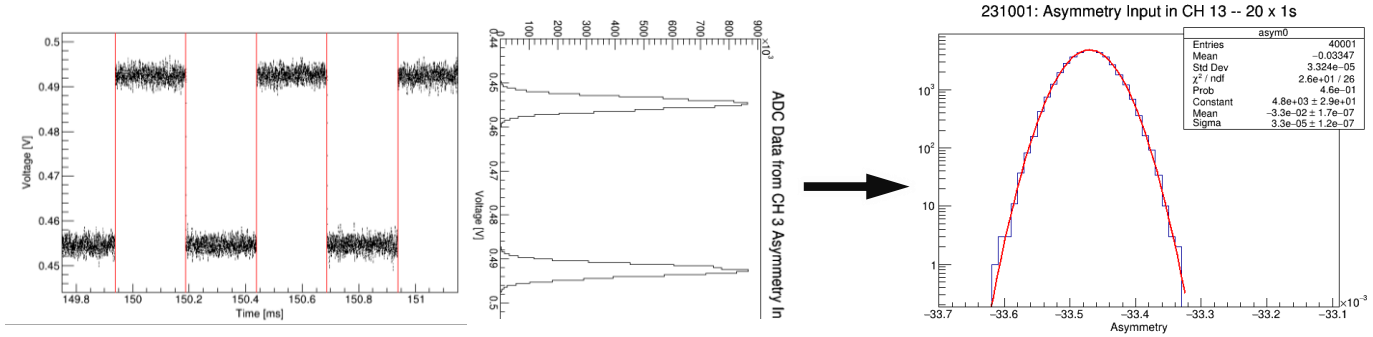
Integrating MOLLER Analog-to-Digital Converter (ADC)

Flux Integration over each helicity window from light collected in Cherenkov detectors.



Calculate Asymmetry from adjacent data window pairs.

$$A_i = \left(\frac{F_R - F_L}{F_R + F_L}\right)_i \cong \left(\frac{\Delta F}{2F}\right)_i$$

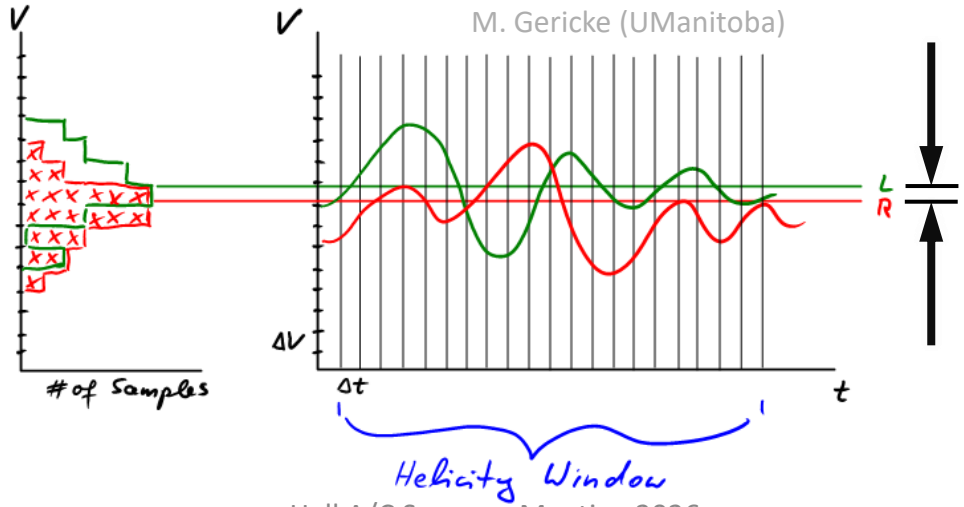


Selected ADC Specs:

18 bit, 15 Msps ($\Delta t \sim 68$ ns)

$\pm 4.096\ V$ dynamic range

ADC amplitude resolution:
$\Delta V \simeq 4V/2^{17} \simeq 32\ \mu V$



33 ppb asymmetry:
$\Delta V \simeq 0.12\ \mu V$ @ $2V$

Massively over-sample within each helicity window

Thank You

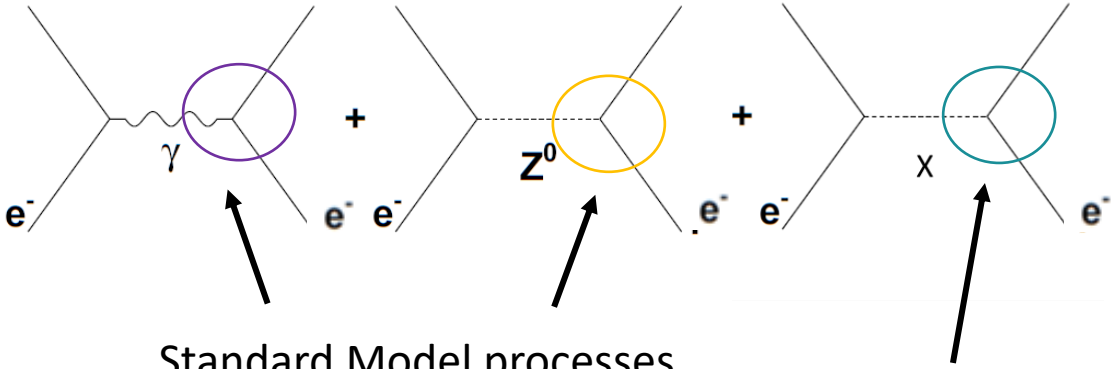
Appendix

Nominal Parameters

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
θ_{CM}	50°-130°
θ_{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_{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

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

Future Impact: BSM or High Energy Constraints



Standard Model processes

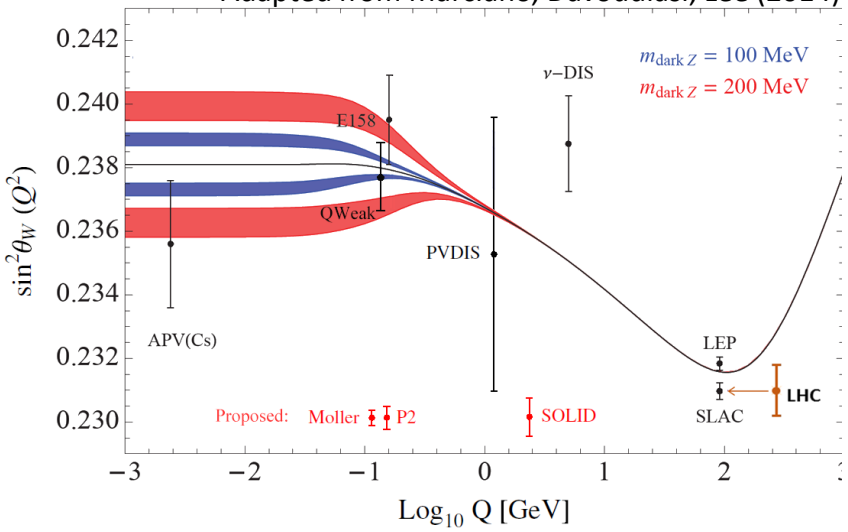
Standard Model Test
possible new exchange particle X

$Q^2 \to 0$
measure coupling of new physics to electrons

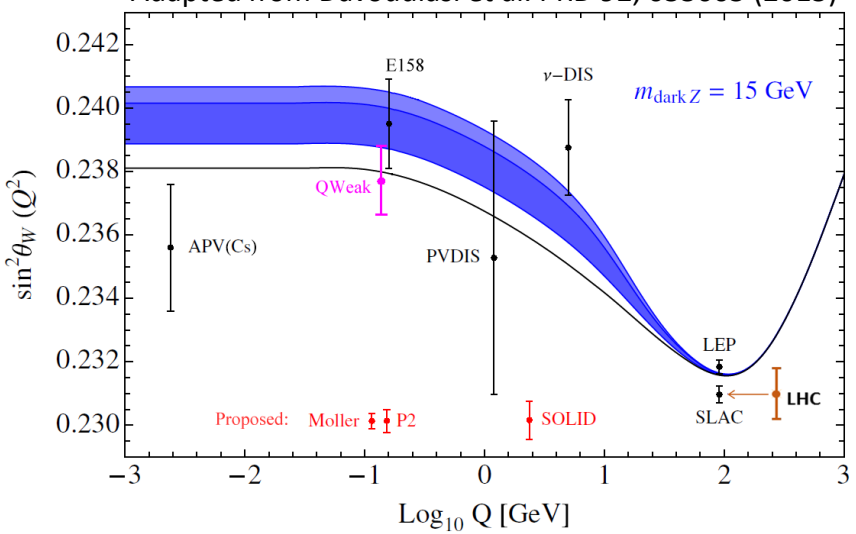
Possible BSM sensitivities:

- massive $\boldsymbol{Z'}$ boson interactions
- dark photon / $\boldsymbol{MeV}$ level $\boldsymbol{Z}$
- new parity violating interactions
- lepton compositeness ($\boldsymbol{47\ TeV}$)

Adapted from Marciano, Davoudiasl, Lee (2014)



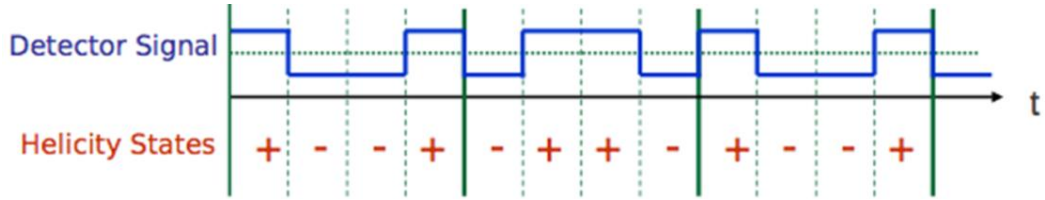
Adapted from Davoudiasl et al. PRD 92, 055005 (2015)

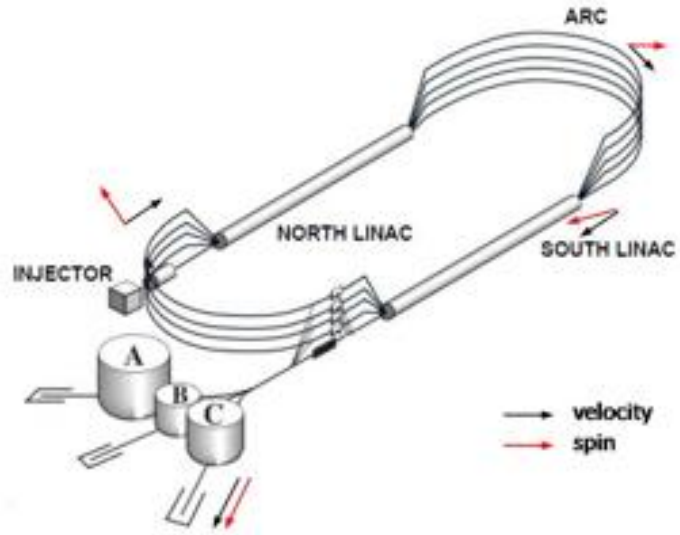


- observe dark Z as shift in $\sin^2\theta_W$
- effect dependent on mass of dark Z

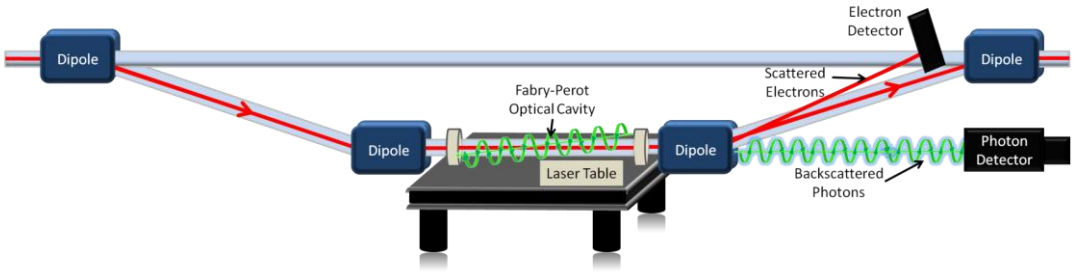
Electron Beam and Polarimetry

- 11 GeV longitudinally polarized $P_{beam} \geq 90 \pm 0.5\ \%$
- 1920 Hz fast helicity reversal rate
  - pseudo-random pattern

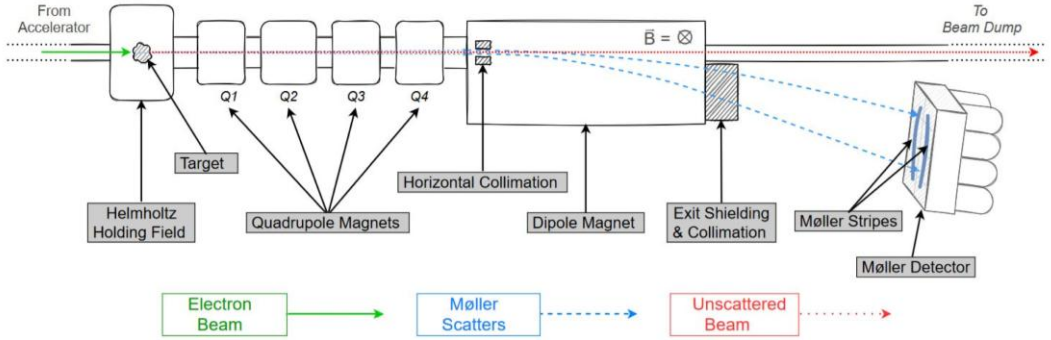




Compton Polarimeter: continuous at production beam current

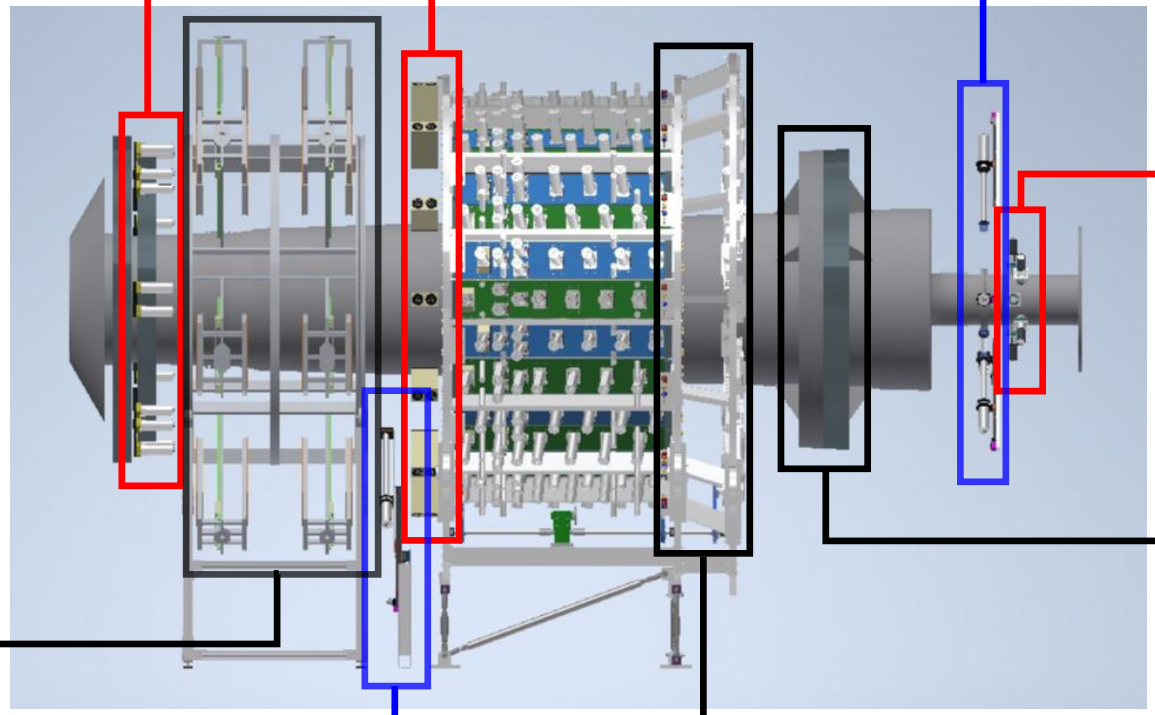


Møller Polarimeter: invasive at low beam current



Tracking System & Auxiliary Detectors

Scattered Beam Monitors: monitoring for false asymmetries



Scanners: scattered flux maps

GEM Rotator: tracking system

- 28 (4 layers x7) GEMs
- 14 (2 layers x7) Scintillators

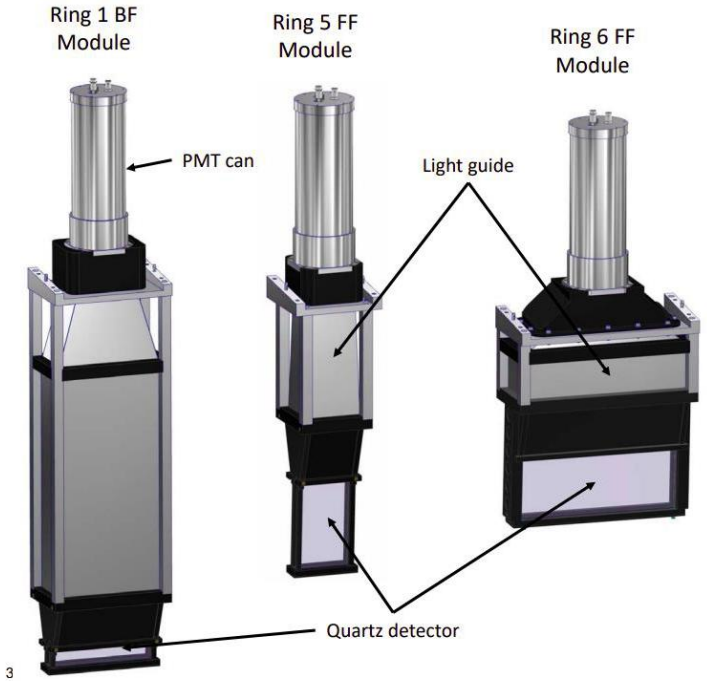
Shower-max: second, independent measurement of Møller peak

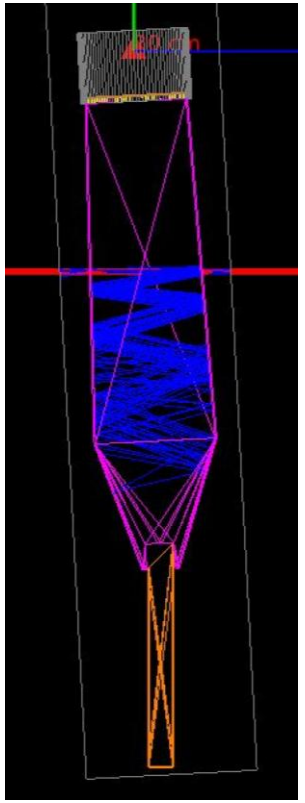
- 28 electromagnetic sampling calorimeters

Pion Donut: quantifies pion background

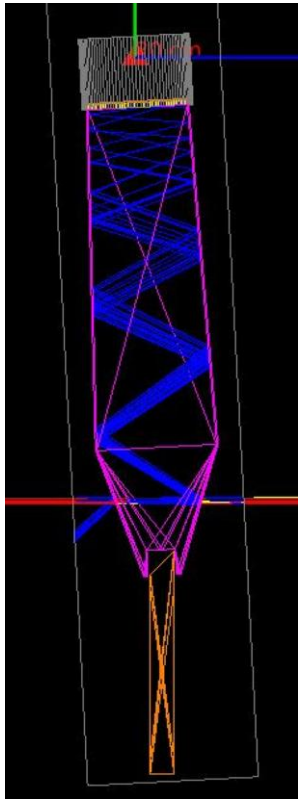
- 28 acrylic Cerenkov detectors

Main Detector Elements

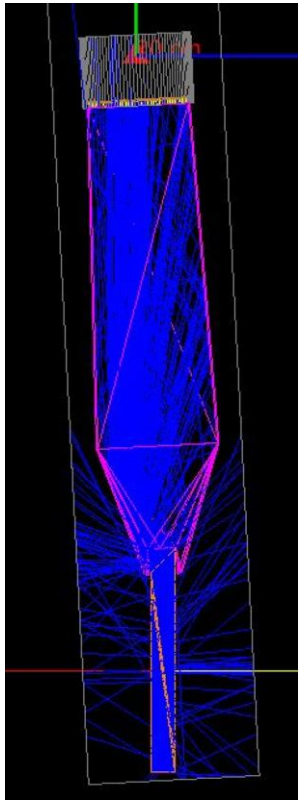




Upper guide events



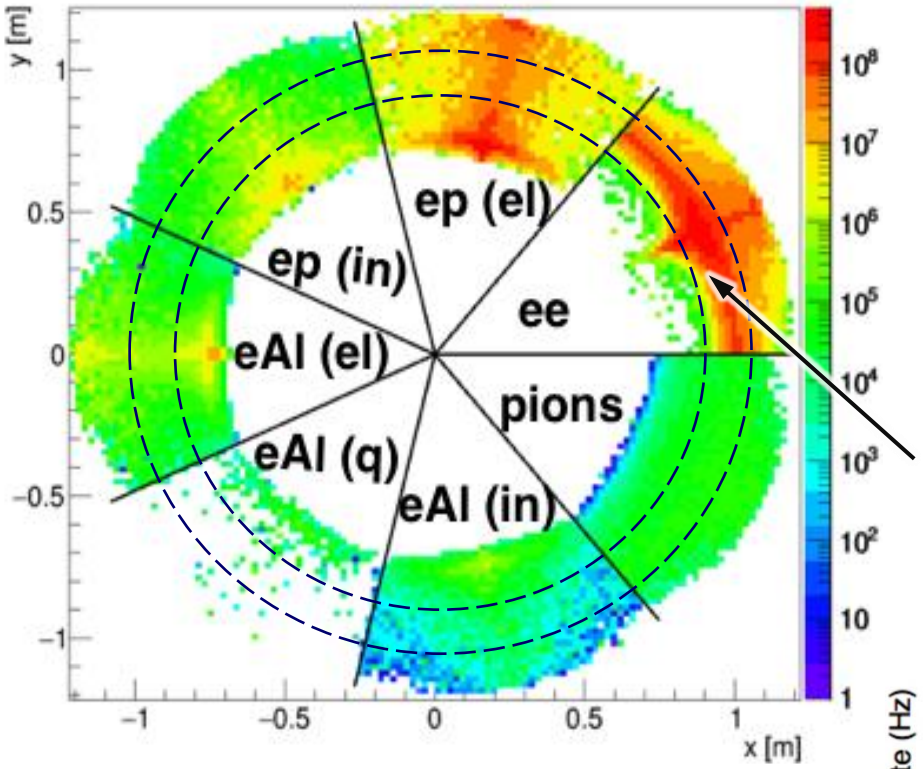
Lower guide events



Quartz events

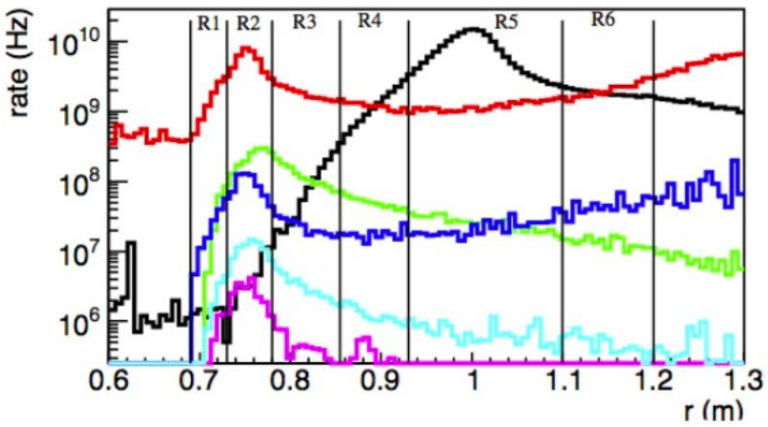
Irreducible Backgrounds

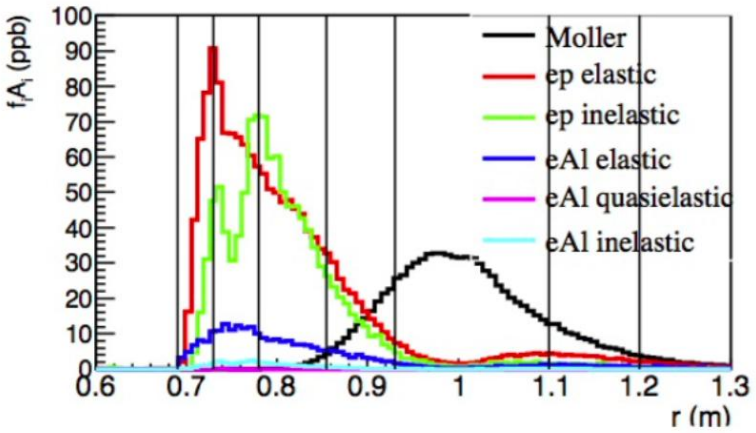
Signal and Background Distributions



Ring 5

- combination radial + azimuthal binning measures distribution of backgrounds for deconvolution from Møller signal
- background scattering processes may match energy-angle of Møller scattering

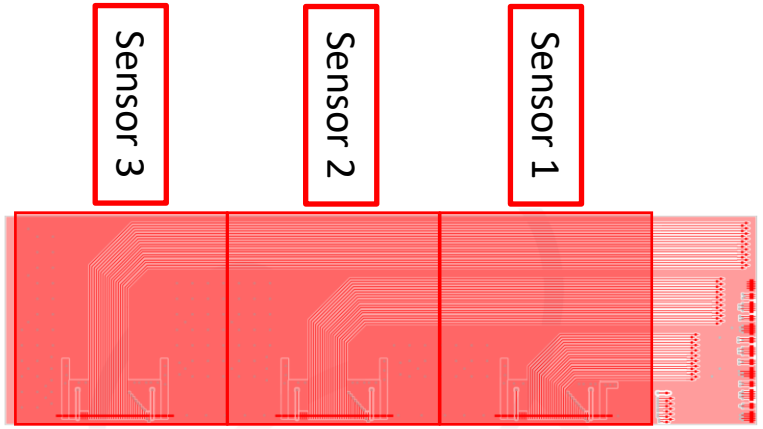


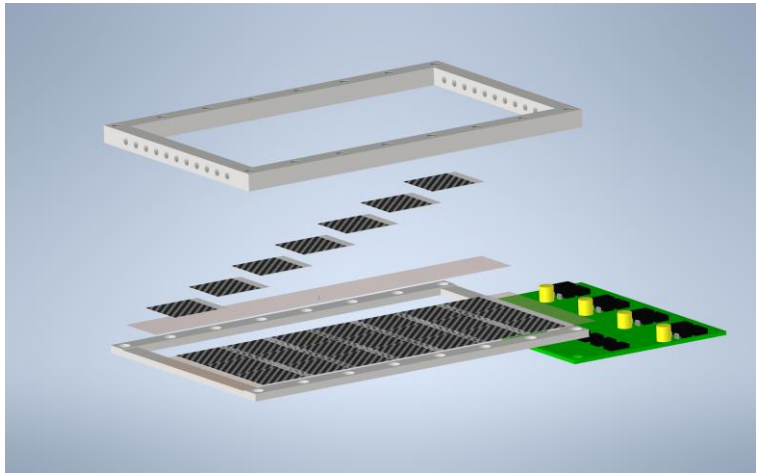


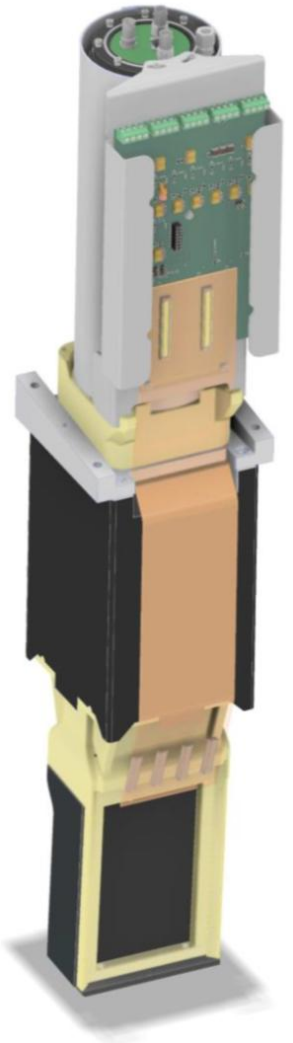
HVMAPS

High Voltage Monolithic Active Pixel Sensors

- active pixel size: 80 x 80 um^2
  - readout electronics, filters, amplifiers all integrated into chip
- overall detectable region size: 2 x 2 cm^2
- timing resolutions: 16 ns
- peak detection rate: 30 MHz







Ring 5

- 7 chips bonded to a flex-print
- 4 strips per quartz tile
- 28 HVMAPS placed behind
- map scattered electron profile
- diagnostic purposes
- HVMAPS glued & wire-bonded to Kapton flex-print w signal and power traces

$$R = 2.2 \times 10^{-4} \times 70/25 \simeq 600\ kHz/mm^2 \quad \Longrightarrow \quad \simeq 4\ kHz/pixel$$