

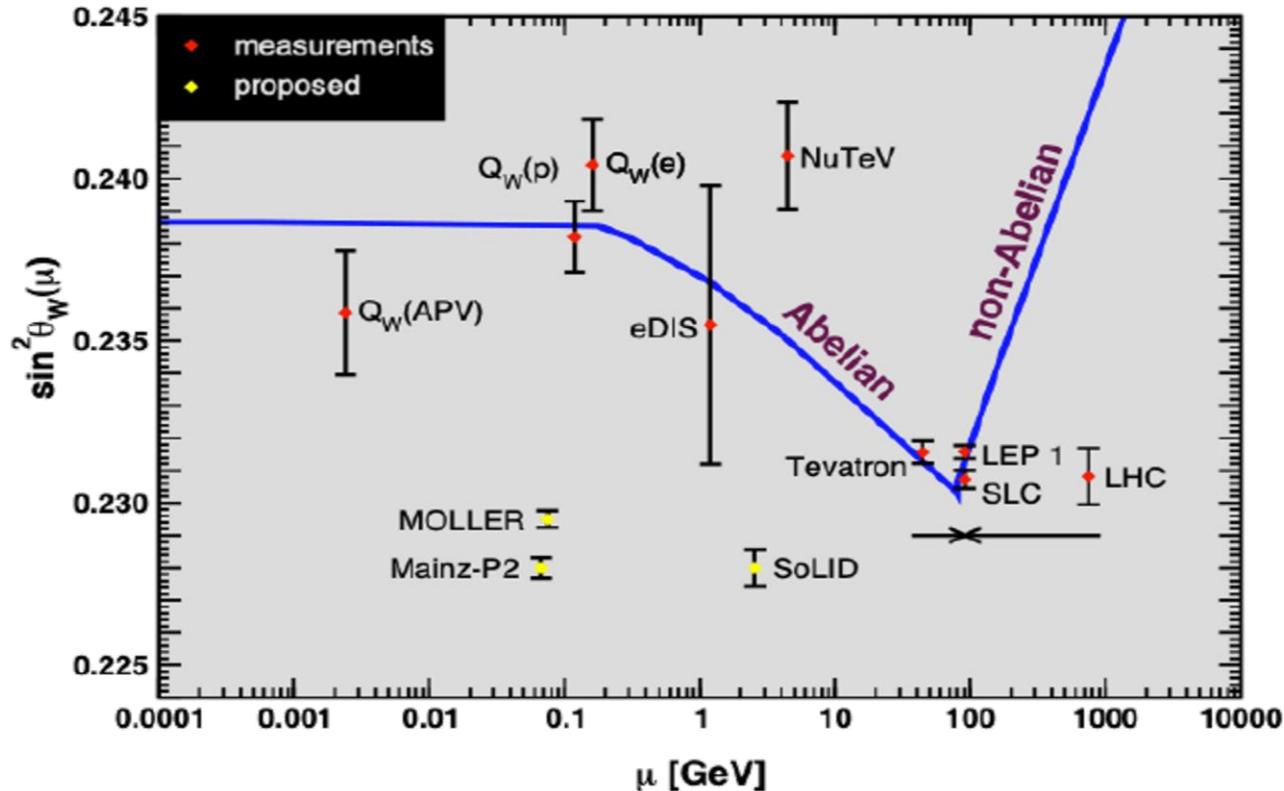
# The MOLLER Experiment: Probing Electroweak Dynamics via Parity-Violating Electron Scattering

Brynne Blaikie  
University of Manitoba

- Motivation
- Methods
- MOLLER Apparatus
- MOLLER Subsystems
  - Target
  - Spectrometers
  - Auxiliary Detectors
  - Main Detectors
  - Data Acquisition



←  $\sin^2 \theta_W$  “running” with interaction energy due to varying radiative corrections →



## Significance of MOLLER Results:

Disagrees with Standard Model?

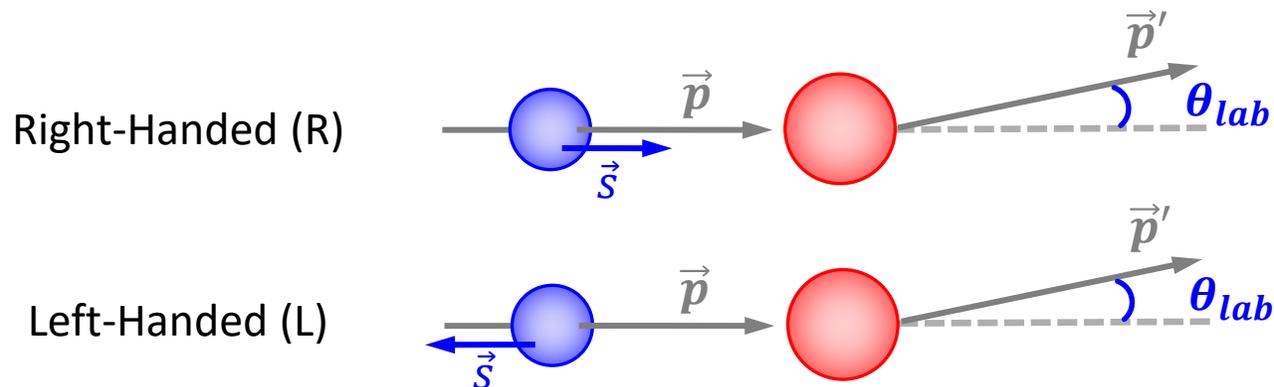
➔ BSM evidence for new particles

Agrees with Standard Model?

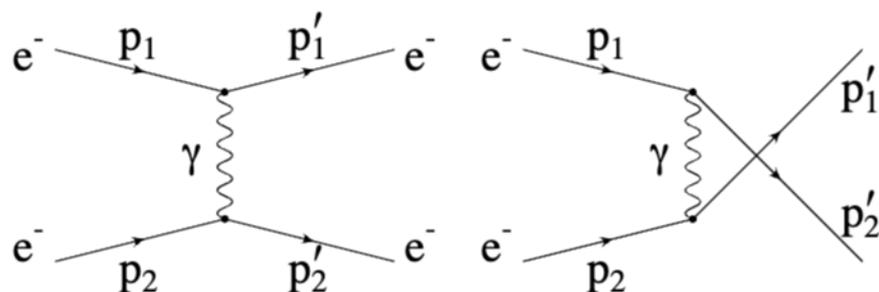
➔ low  $Q^2$  indirectly probes new physics at multi-TeV scale

# Method – Parity-Violating Electron Scattering (PVES)

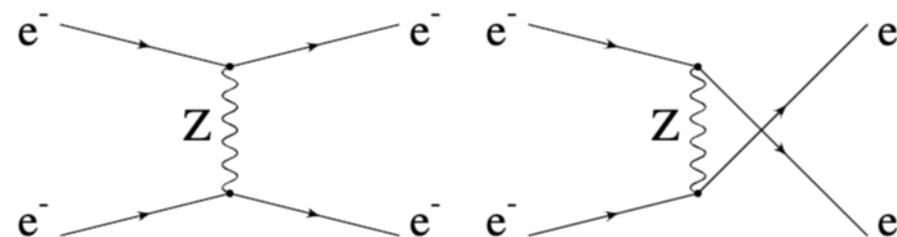
**Møller Scattering:** longitudinally polarized electrons incident on unpolarized target electrons



Electromagnetic Interaction: conserves parity



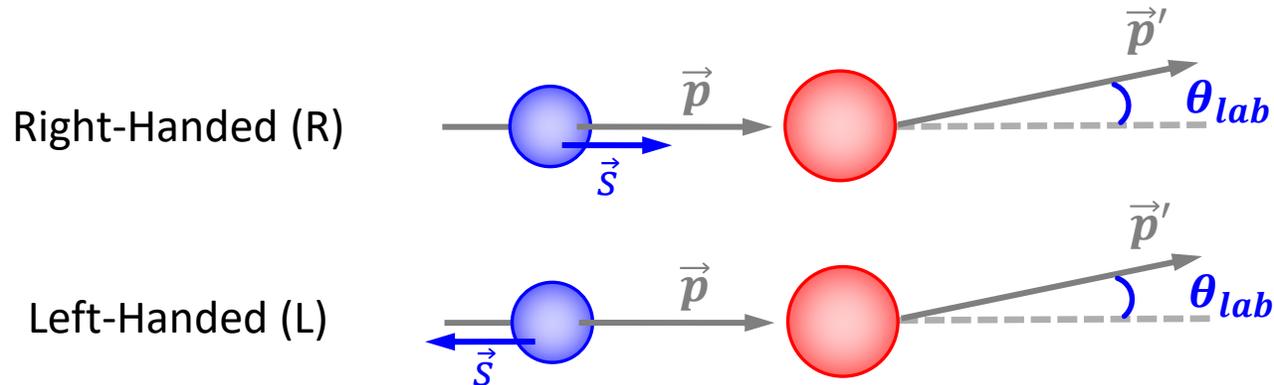
Weak Interaction: **does not conserve parity**



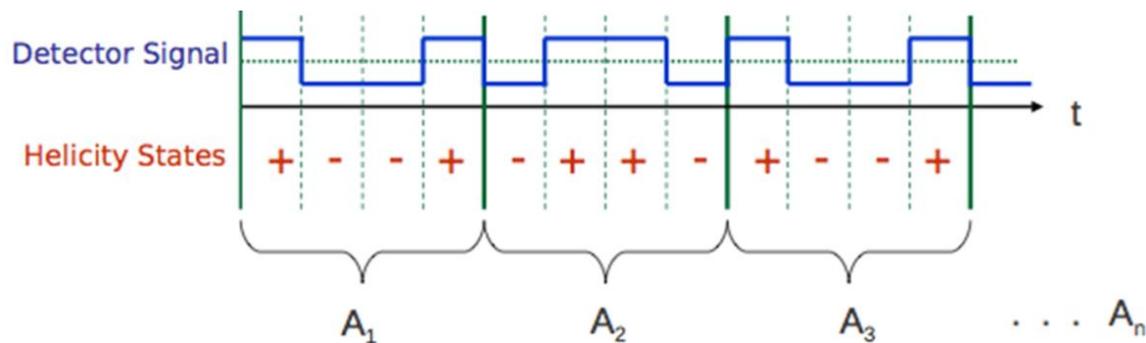
➡ really cares about the “handedness” of the electrons

# Method – Parity-Violating Electron Scattering (PVES)

**Møller Scattering:** longitudinally polarized electrons incident on unpolarized target electrons



Measure **fractional rate difference** in Møller scattering:



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

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

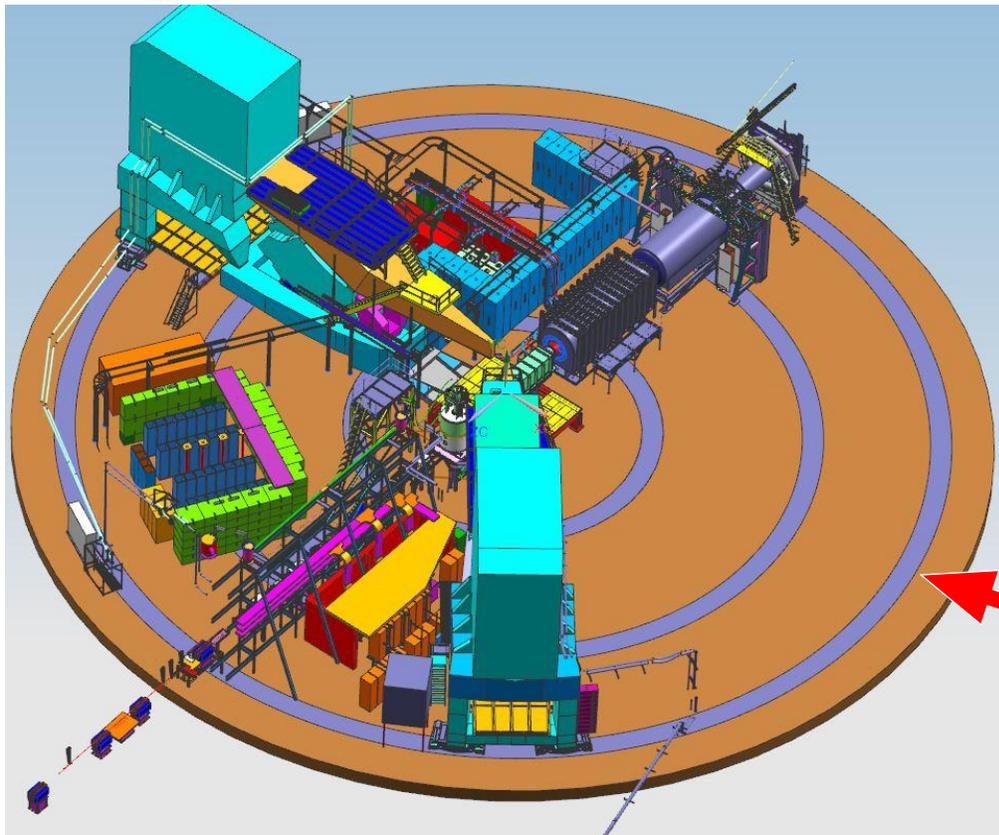
**\*Really Challenging:** PVES asymmetries are  $\sim 10^{-6}$  to  $10^{-9}$

➔ Requires high luminosity and high precision

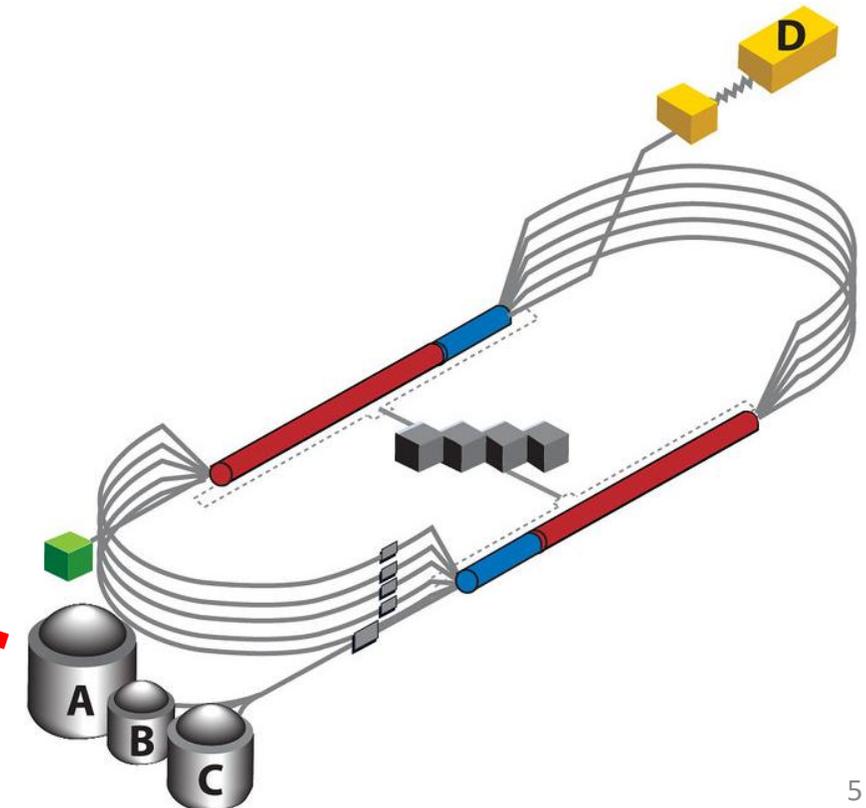
# Thomas Jefferson National Accelerator Facility

- located in Newport News, VA
- best parity quality beam in the world
- rapid helicity flip (1.92 kHz), high beam stability

$$P_{beam} \geq 90 \pm 0.5 \%, \quad E_{beam} = 11 \text{ GeV}, \quad I_{beam} = 65 \mu\text{A}$$



Hall A



# MOLLER Apparatus



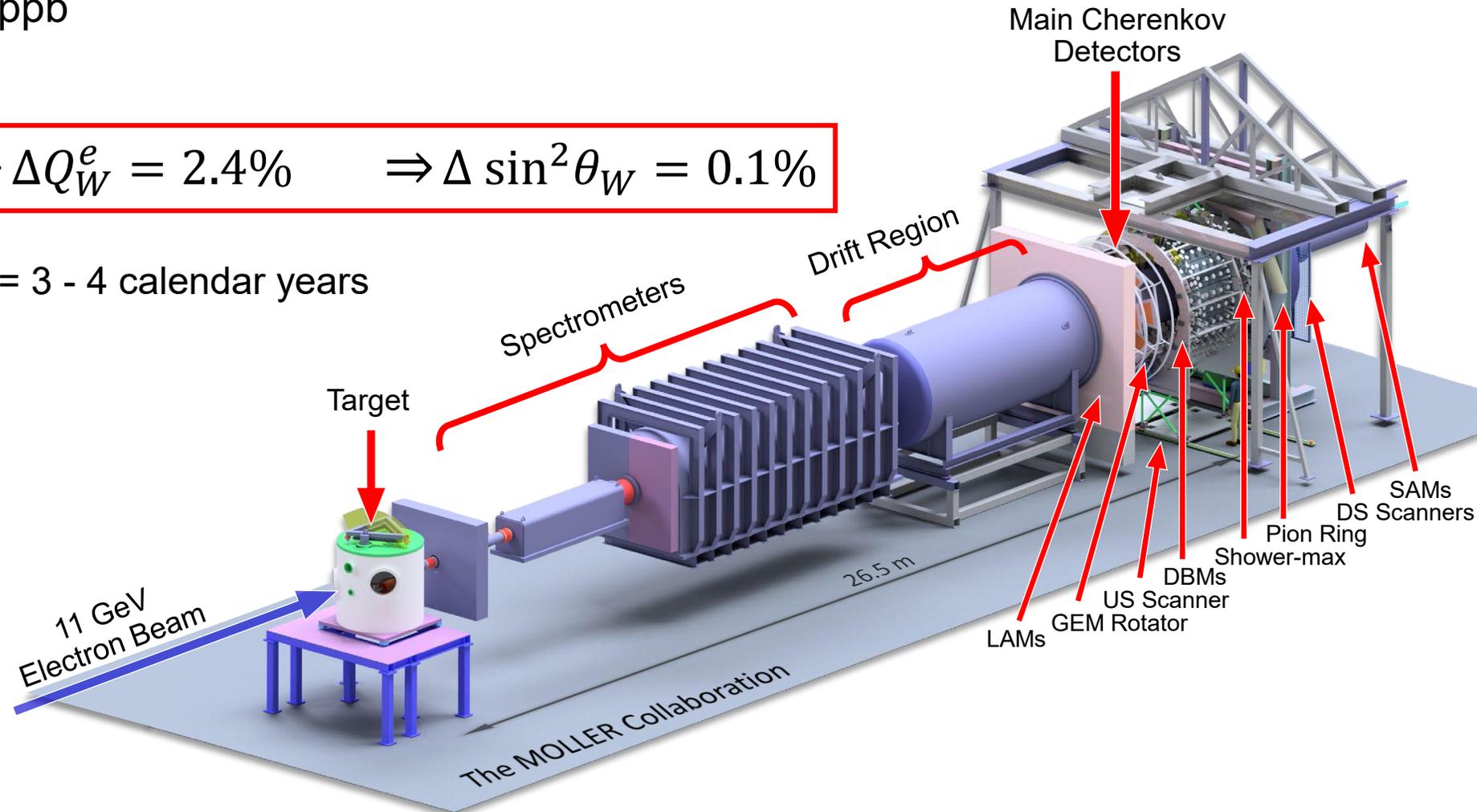
Measurement of a Lepton Lepton Electroweak Reaction

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

**MOLLER Goal:**

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

344 PAC days = 8256 hours = 3 - 4 calendar years



# Target System – LH2

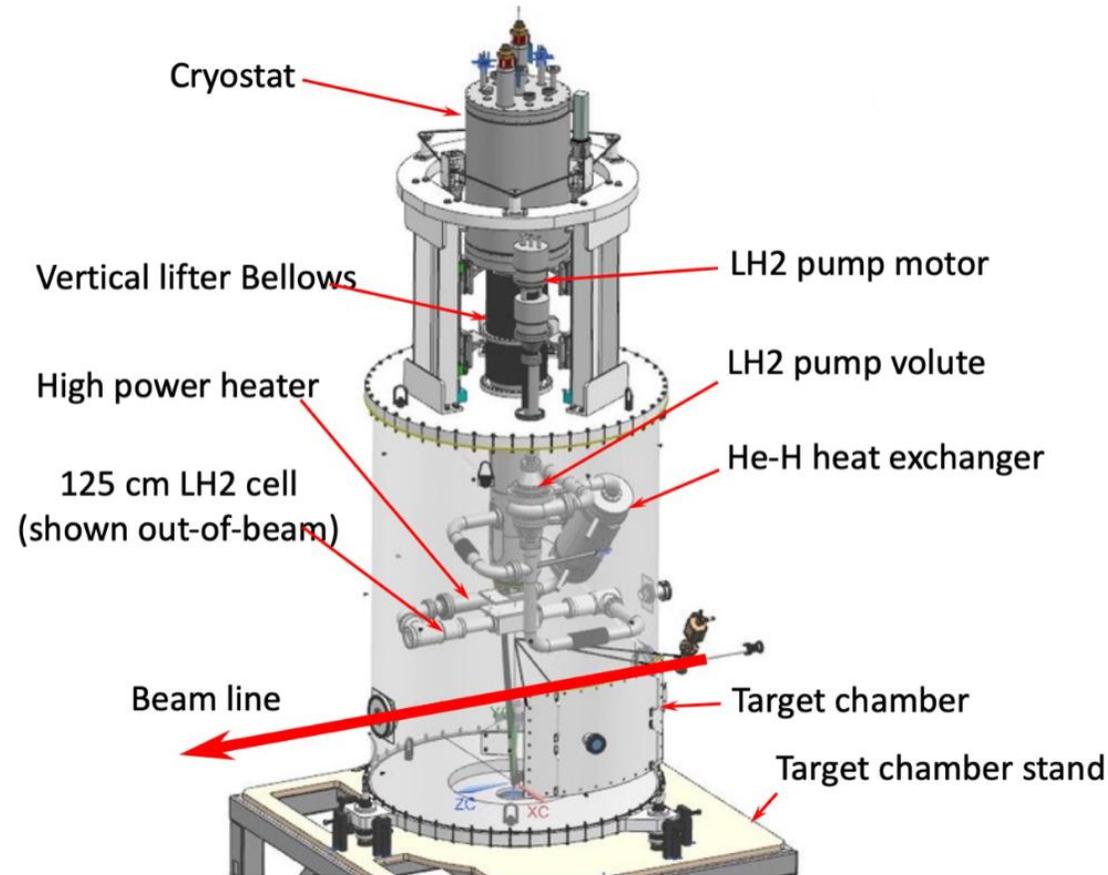
## Requirements:

- Minimize target density fluctuations
- Maximize luminosity

## Specs:

- 125 cm long LH<sub>2</sub> target
- 4 kW total power

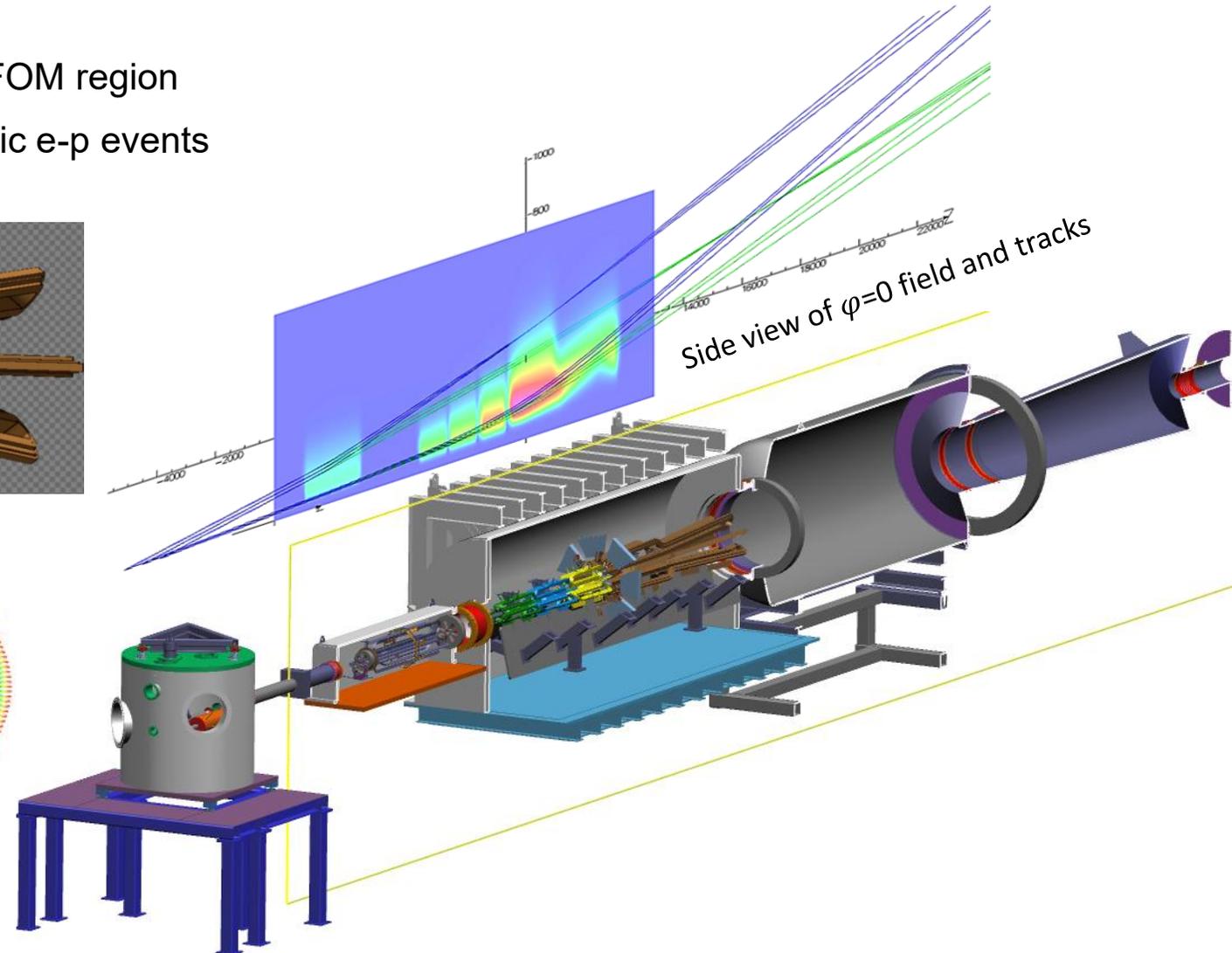
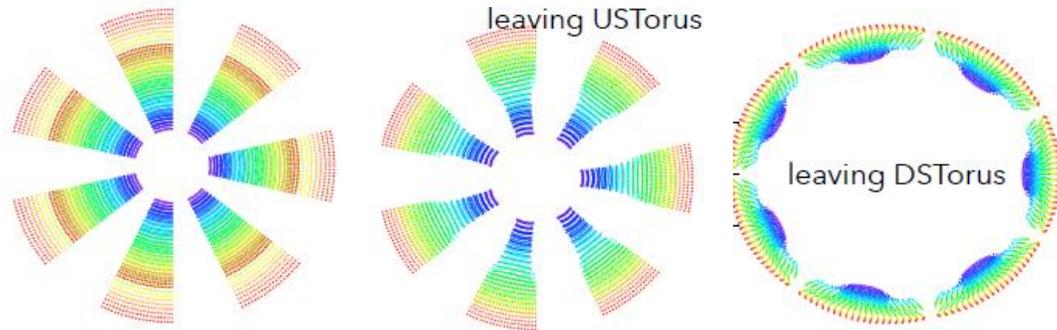
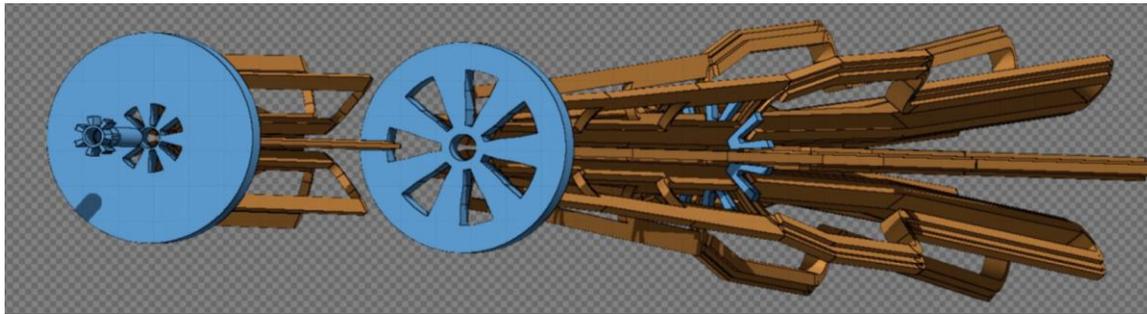
highest power  
LH2 target !!



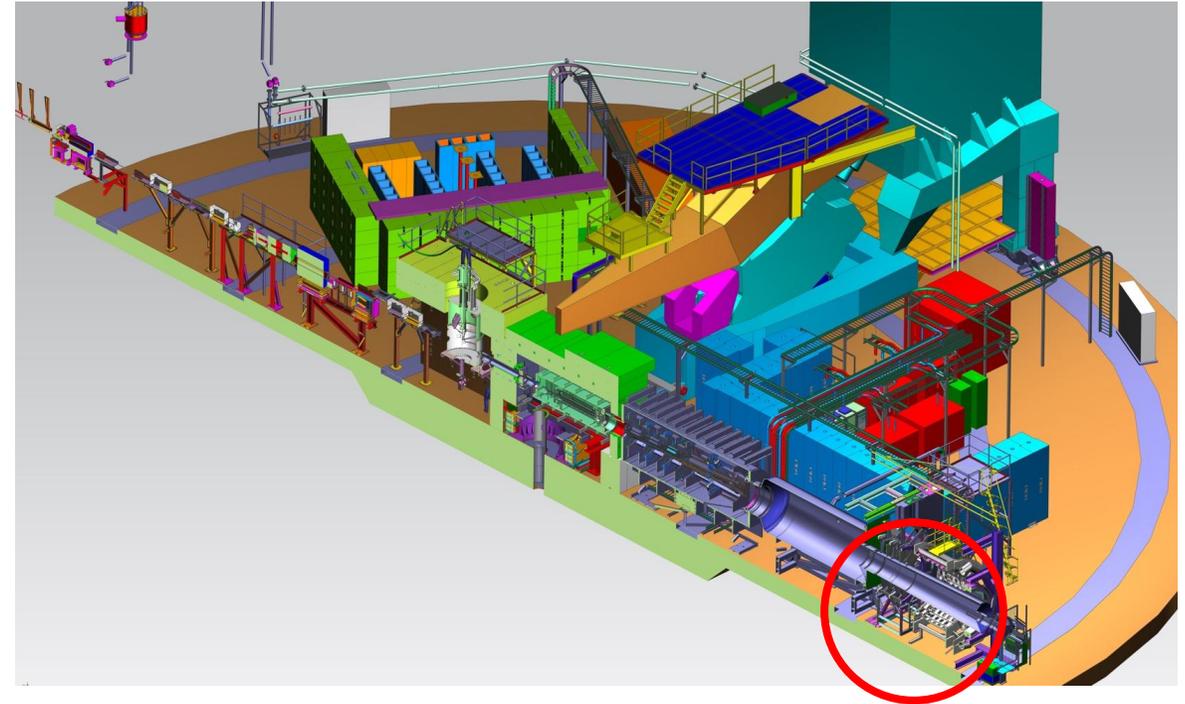
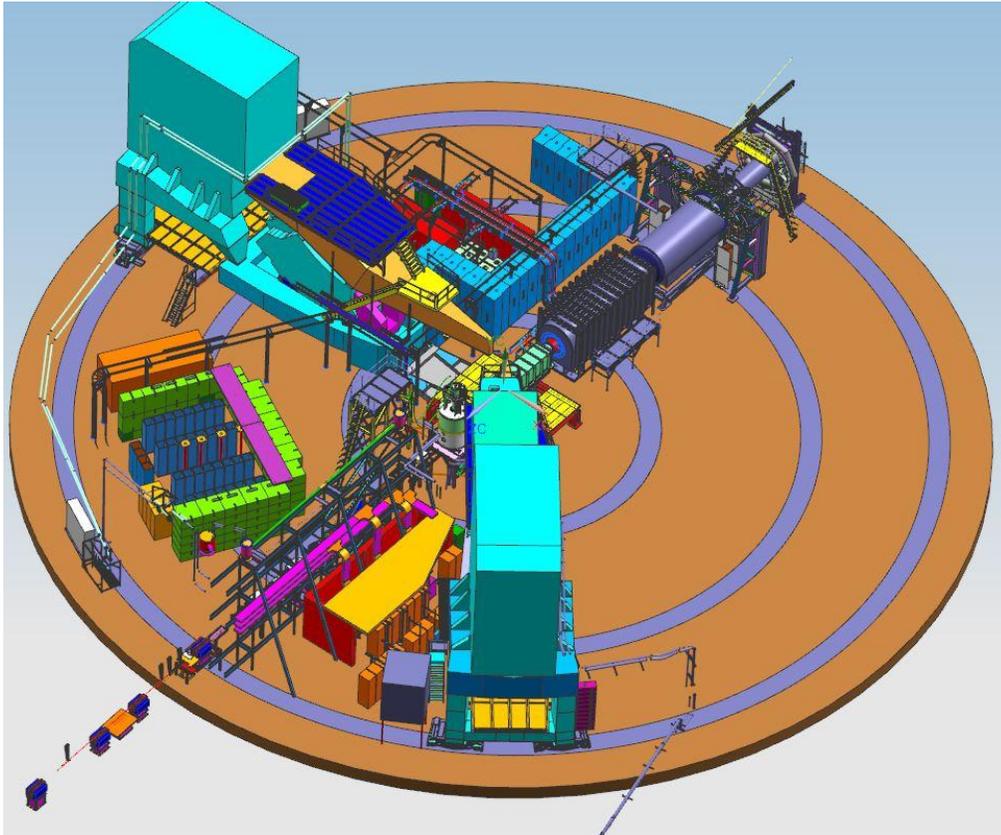
# Spectrometer

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



# Detector Region !



# Tracking System & Auxiliary Detectors

## Scattered Beam Monitors:

monitoring for false asymmetries

## Diffuse Beam Monitors (DBMs)

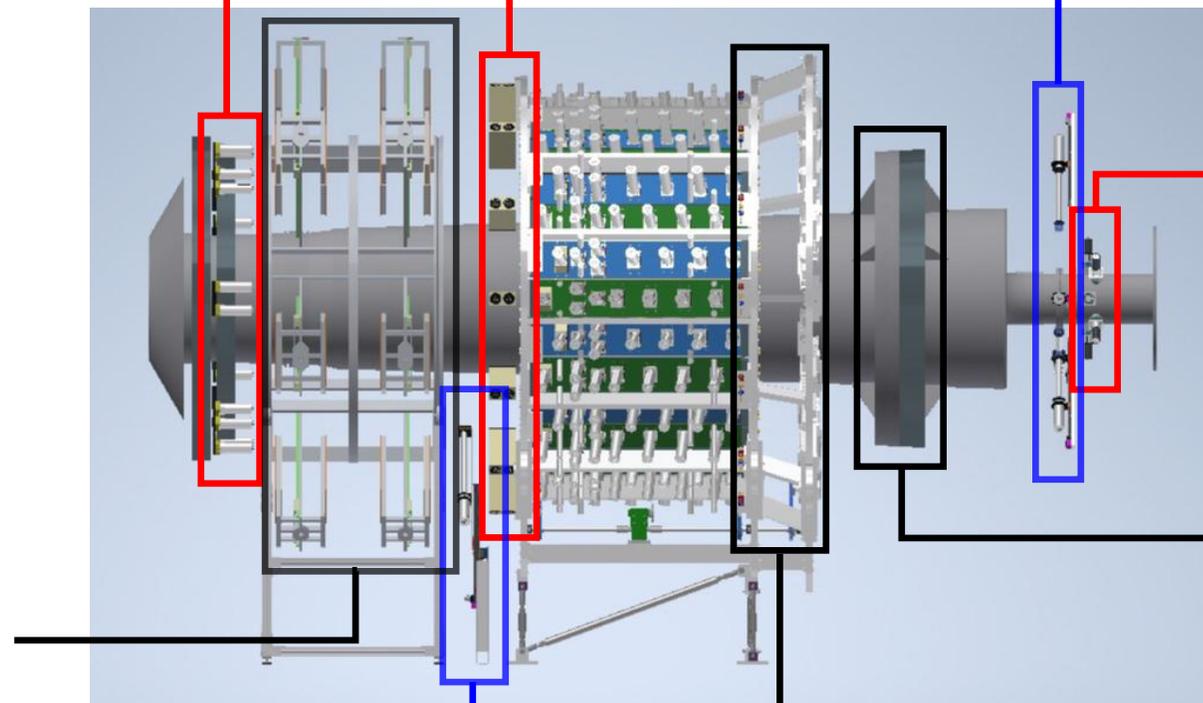
## Large Angle Monitors (LAMs)

## Scanners: scattered flux maps

## Downstream Scanners

4x1D scans

## Small Angle Monitors (SAMs)



## GEM Rotator: tracking system

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

## Upstream Scanner

2D scan

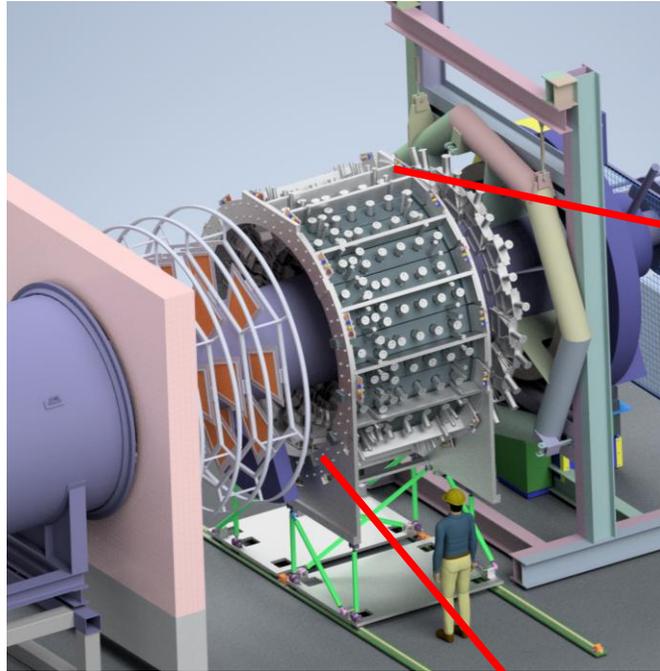
## Shower-max: second, independent measurement of Møller peak

- 28 electromagnetic sampling calorimeters

## Pion Donut: quantifies pion background

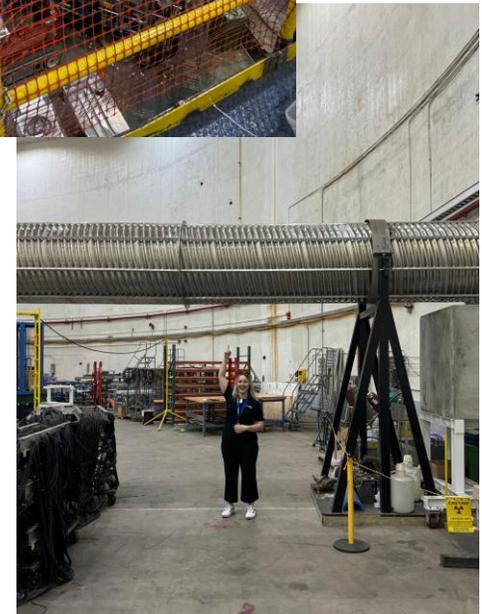
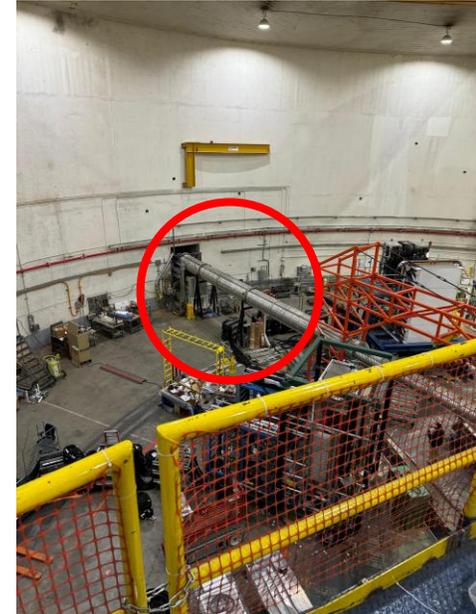
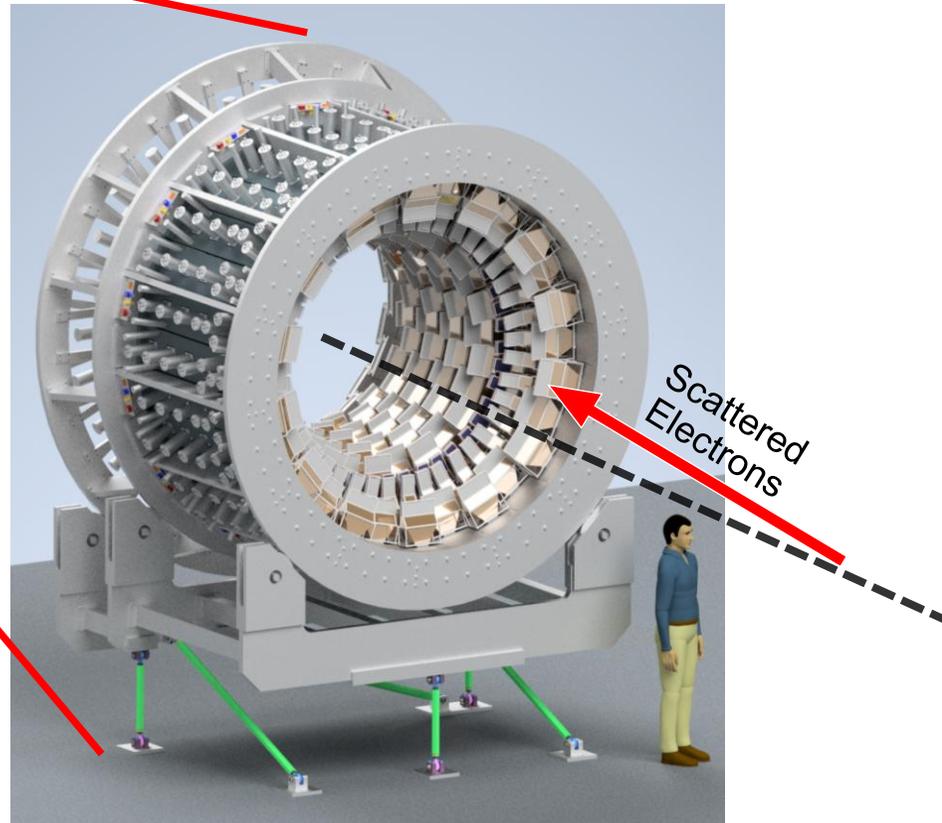
- 28 acrylic Cerenkov detectors

# Main Detector Array

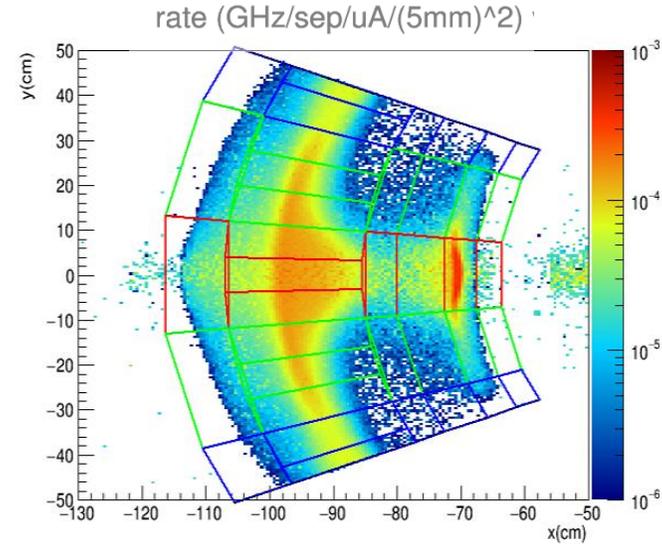


224 fused silica Cherenkov detectors

- Radially split into 6 Rings
- Azimuthally split into 28 Segments

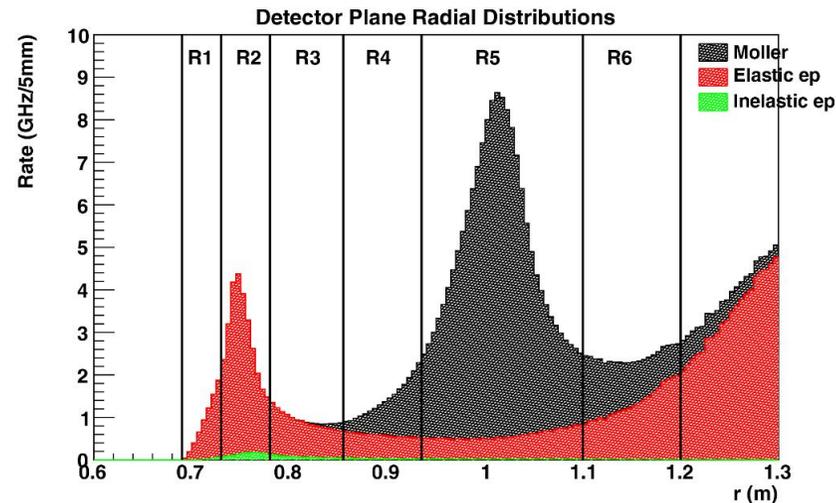
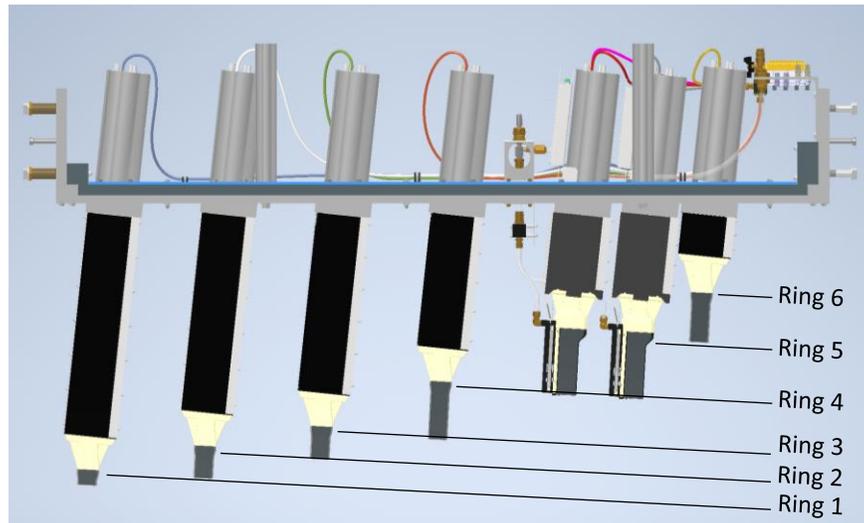


# Main Detector Array



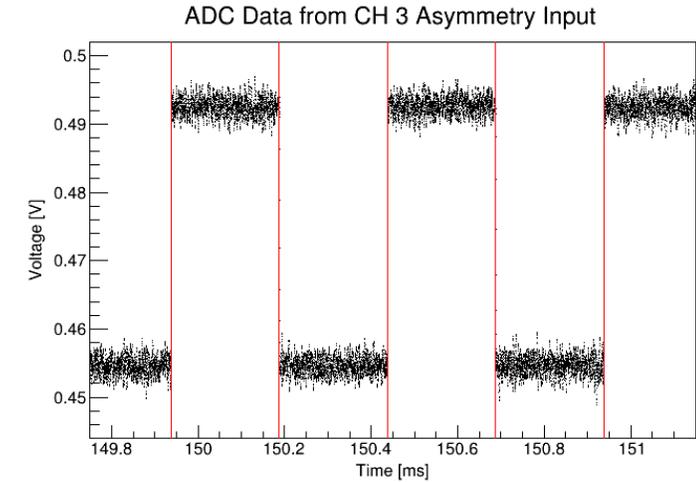
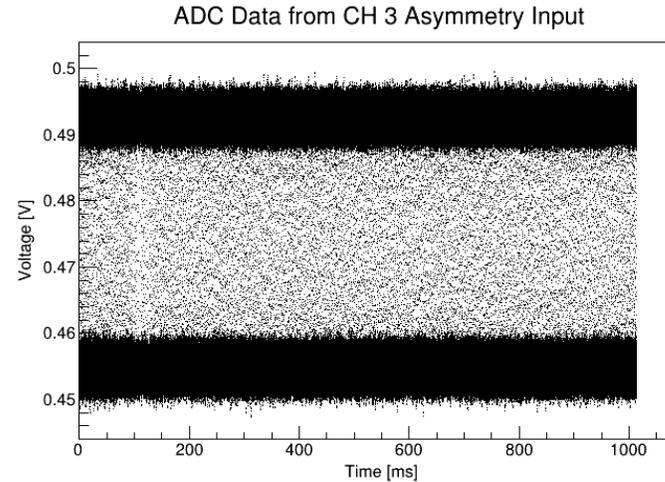
## 224 fused silica Cherenkov detectors

- Radially split into 6 Rings
- Azimuthally split into 28 Segments
- Located 26.5 m downstream from target
- Sufficient space for spectrometers to separate e-e and e-p peaks
- Full coverage of Møller events

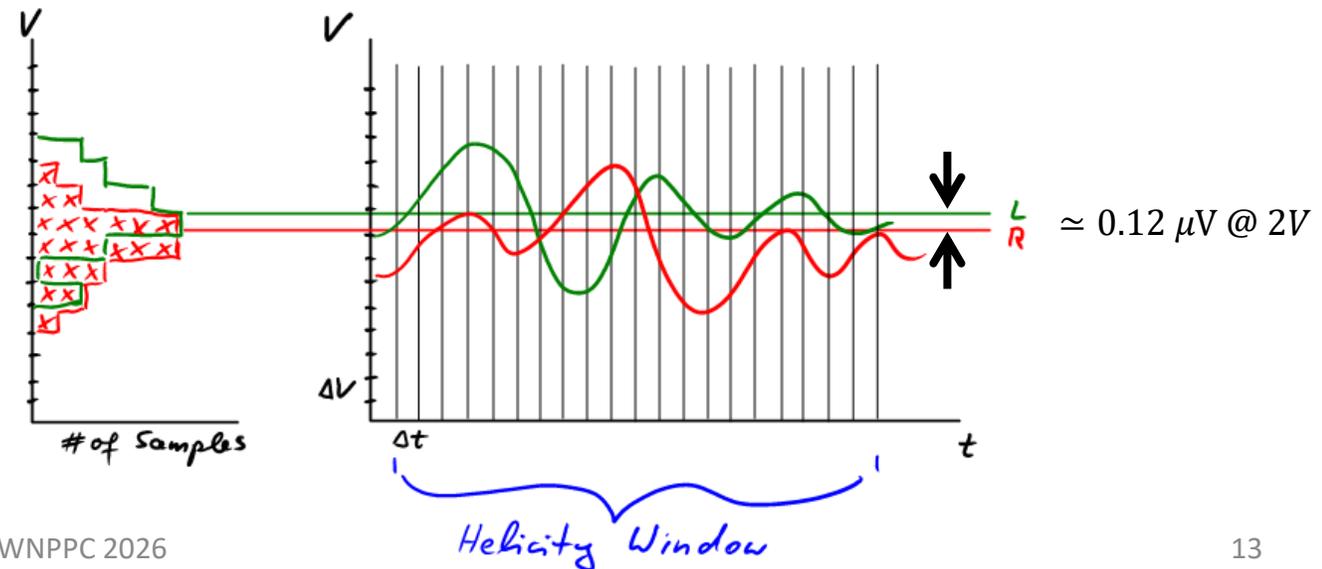


# Integrating MOLLER Analog-to-Digital Converter (ADC)

MOLLER ADC: reads **voltage** output from detectors and **integrates** over helicity windows

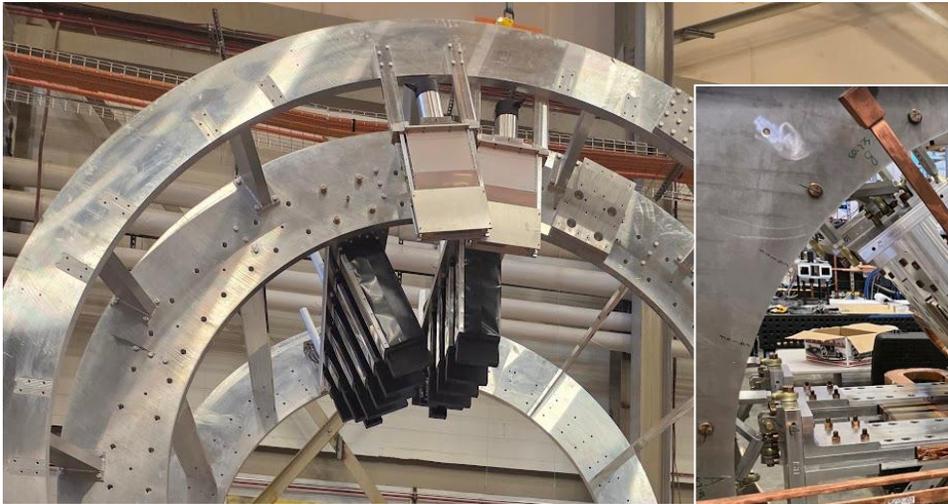


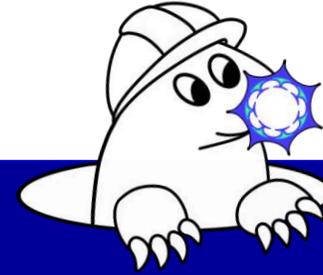
- Trying to measure a 33 ppb asymmetry:  
 $\approx 0.12 \mu\text{V} @ 2\text{V}$
- Amplitude resolution:  $\approx 4\text{V}/2^{17} \approx 32 \mu\text{V}$
- Massively over-sample within each helicity window



# Current Status

- Fabrication, assembly, and installation ongoing
- Expecting beam at the start of 2027





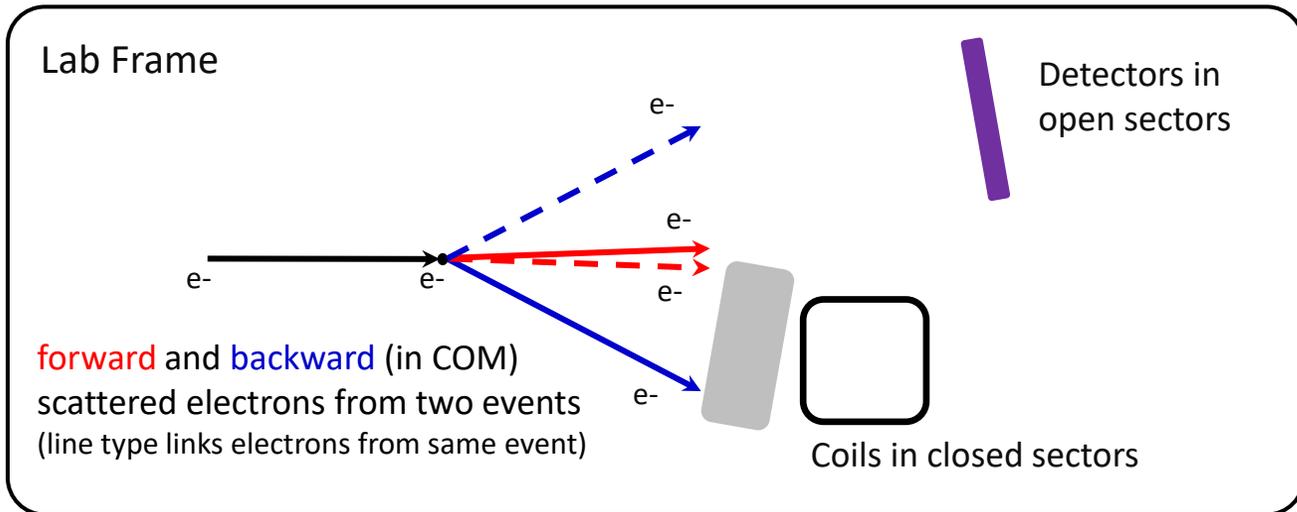
# Thank You

# Appendix

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

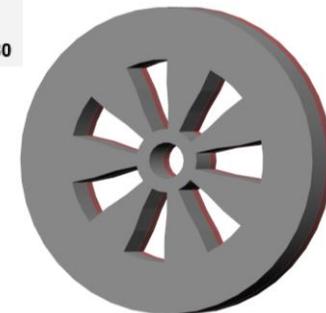
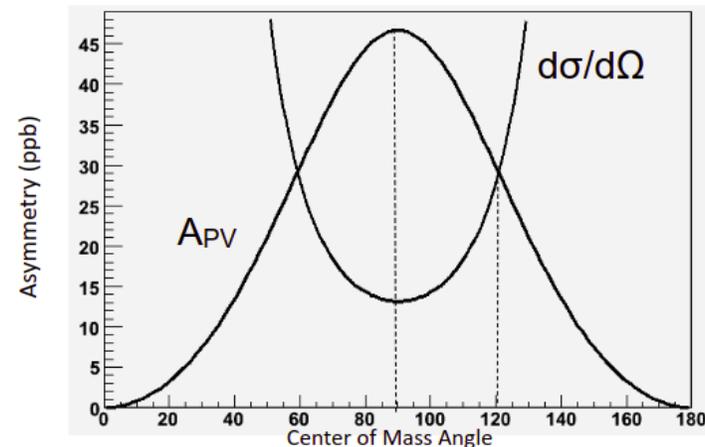
Error Source	Fractional Error (%)
<b>Statistical</b>	<b>2.1</b>
Absolute Norm. of the Kinematic Factor	0.5
Beam (second moment)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	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
<b>Total systematic</b>	<b>1.1</b>

# 100% Azimuthal Acceptance



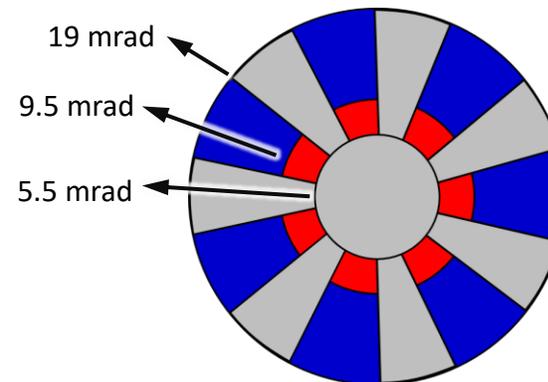
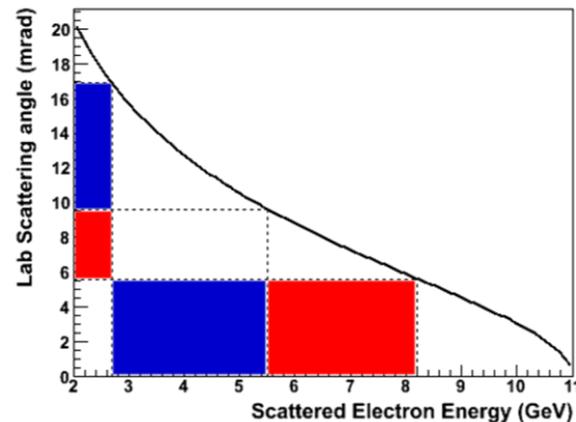
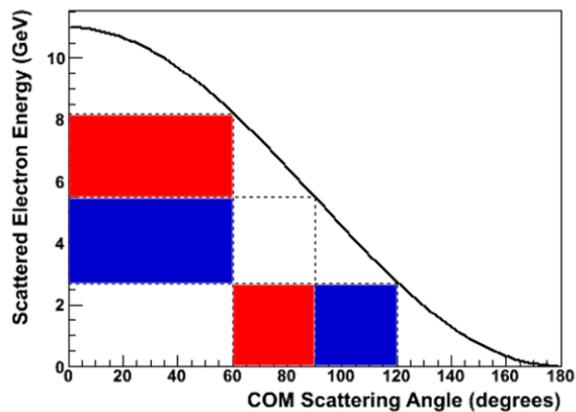
Any odd number of coils will allow for 100%  $\phi$  acceptance

Highest figure of merit at  $\theta_{CM} = 90^\circ$



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

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



acceptance defining Coll.2  
5 m downstream of target

- Forward Scattering
- Backward Scattering
- Not in Acceptance

# Measuring $A_{pV}$

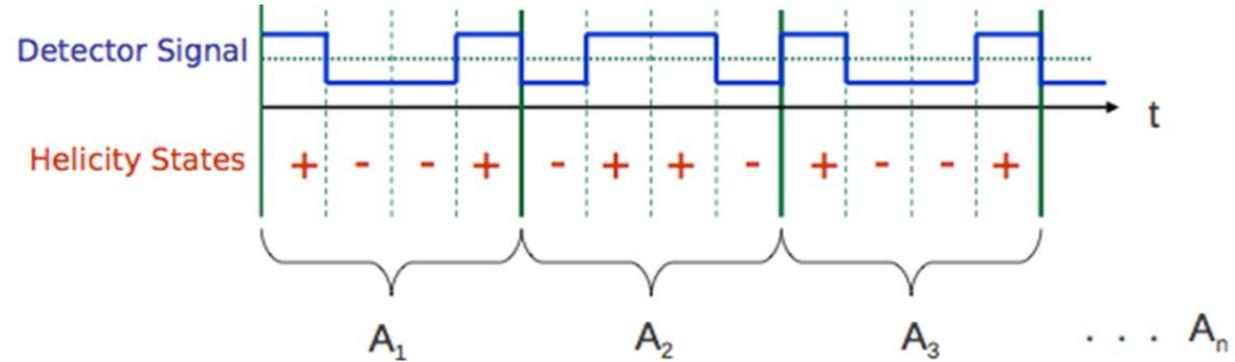
**Flux Integration** from light collected in Cherenkov detectors

**Calculate Asymmetry** from adjacent data window pairs

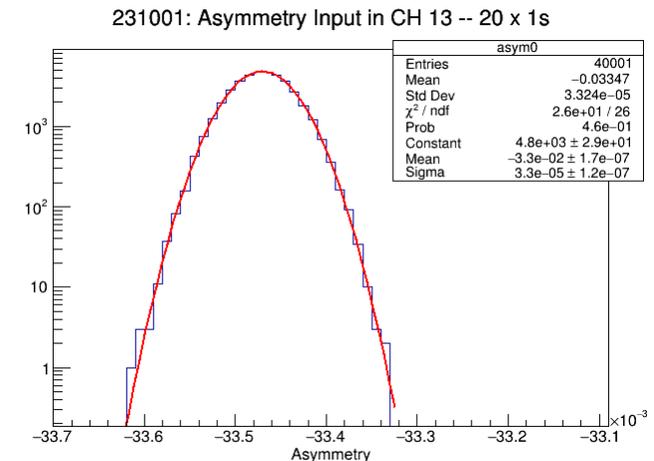
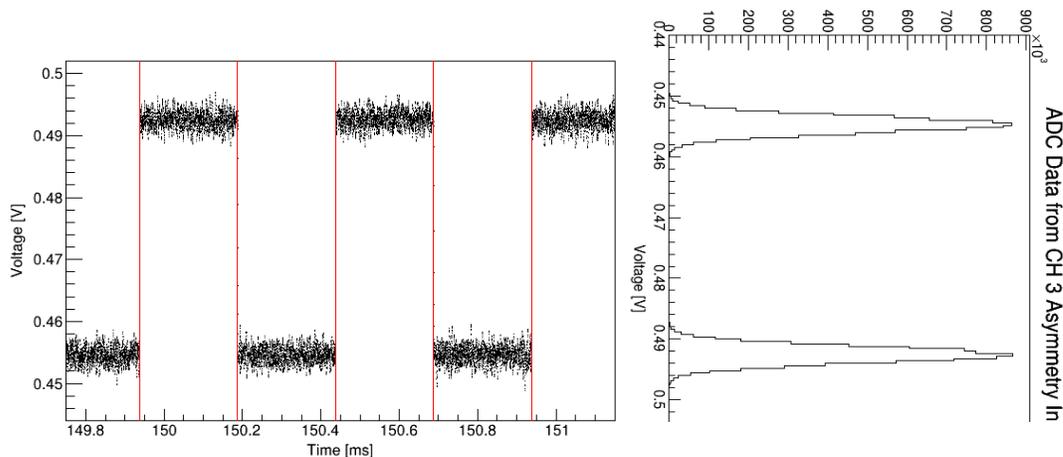
$$A_i = \left( \frac{F_R - F_L}{F_R + F_L} \right)_i \cong \left( \frac{\Delta F}{2F} \right)_i$$

**Remove Correlations** due to beam intensity, position, angle, energy fluctuations, etc.

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

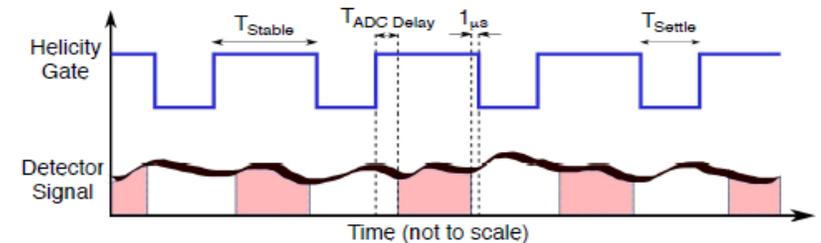
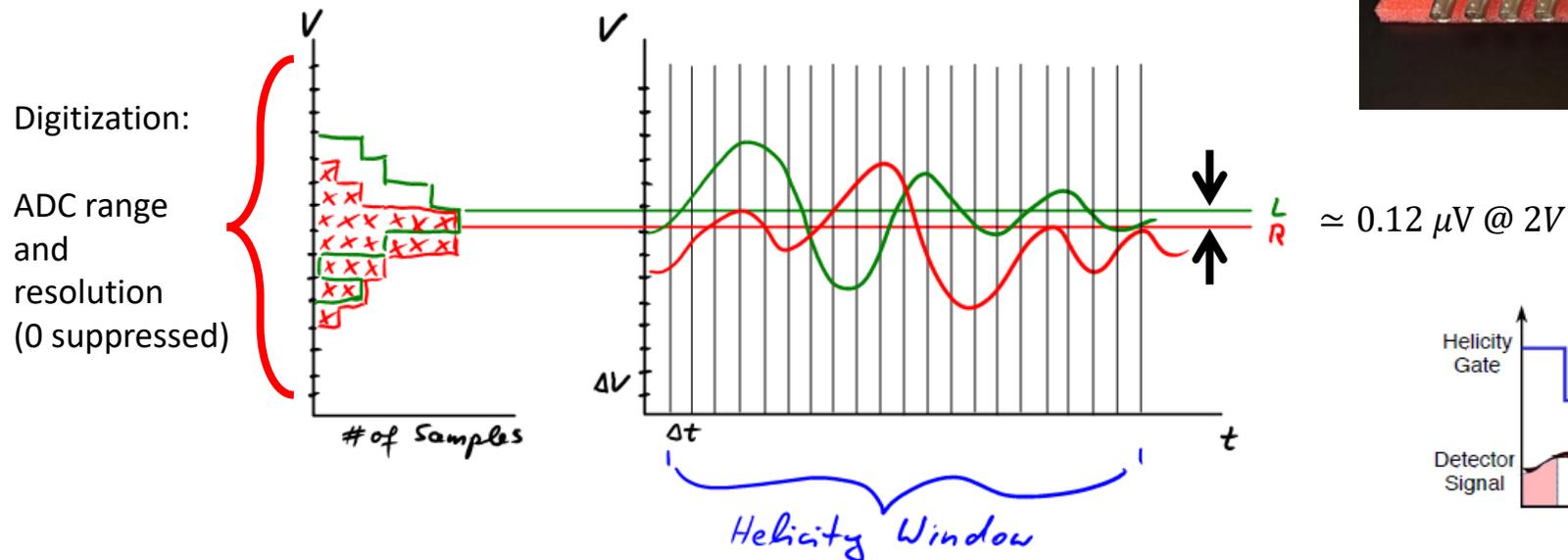
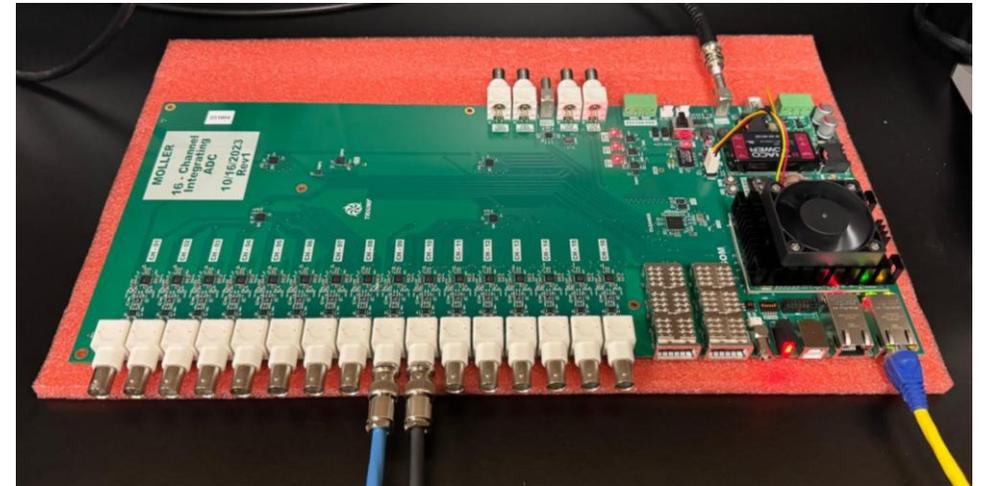


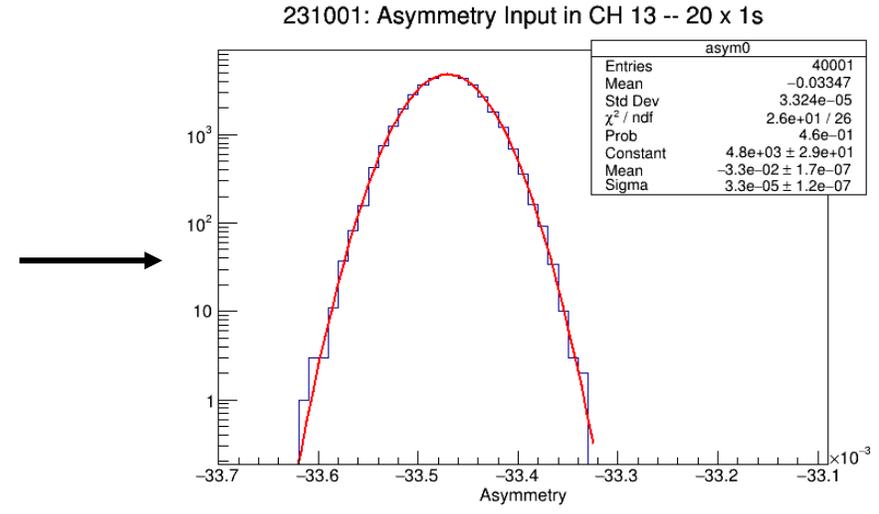
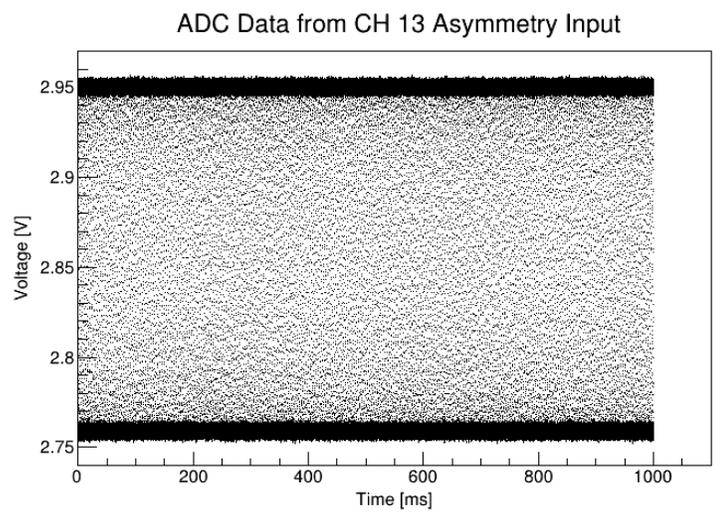
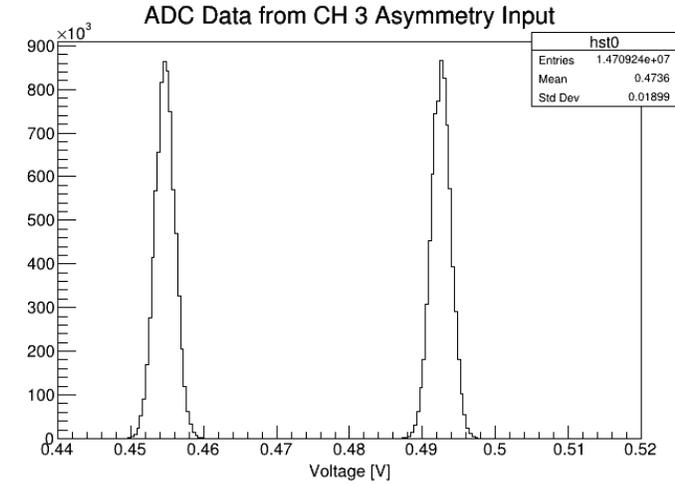
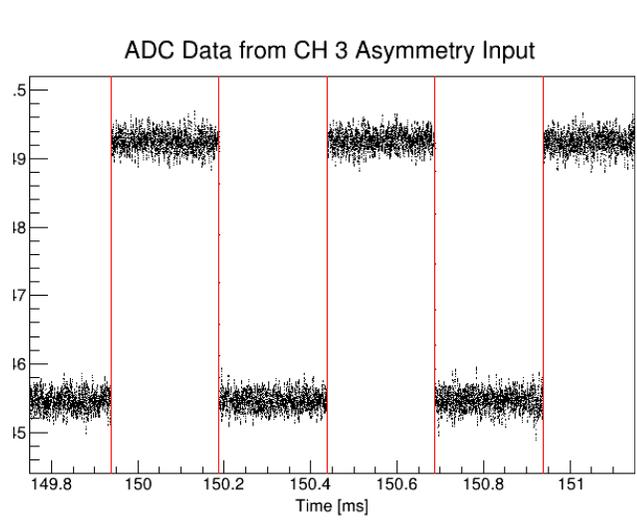
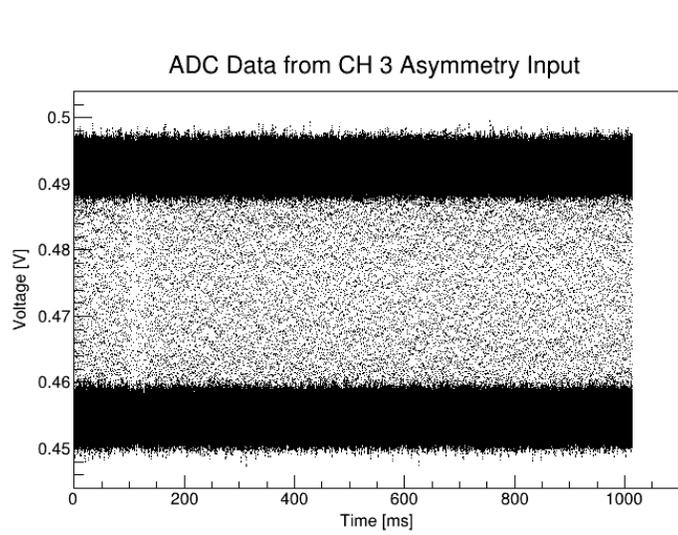
$A_{pV}$  predicted to be  $\approx 33$  ppb



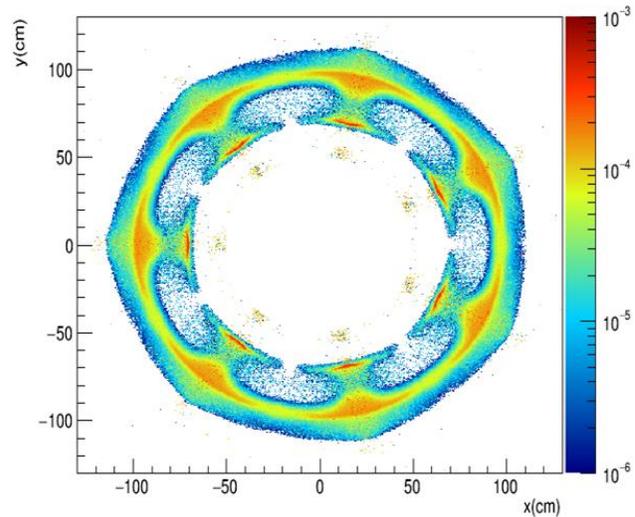
# Integrating MOLLER ADC

- Trying to measure a 33 ppb asymmetry  $\approx 0.12 \mu\text{V} @ 2\text{V}$
- Optimize parameters: PMT signal, ADC range, resolution (timing and amplitude)
- Selected ADC: 18 bit, 15 Msps ( $\sim 14\,705\,882$  Hz actual)
- Dynamic range:  $\pm 4.096 \text{ V}$
- Amplitude resolution:  $\approx 4\text{V}/2^{17} \approx 32 \mu\text{V}$
- Massively over-sample within each helicity window

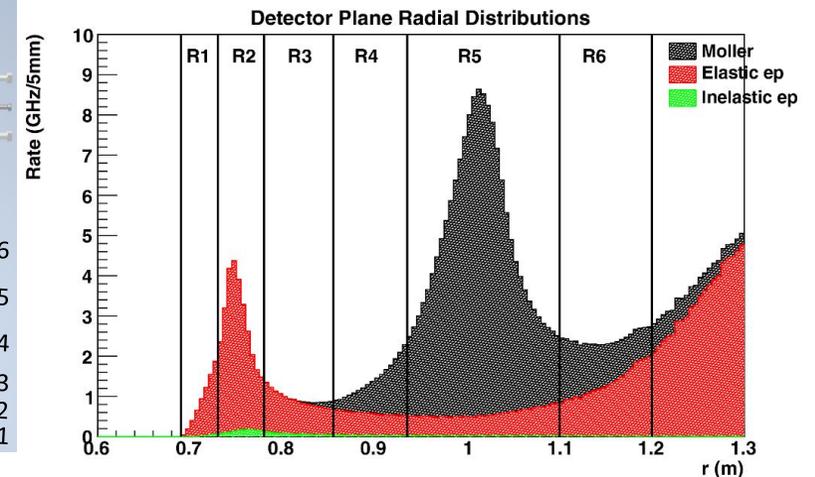
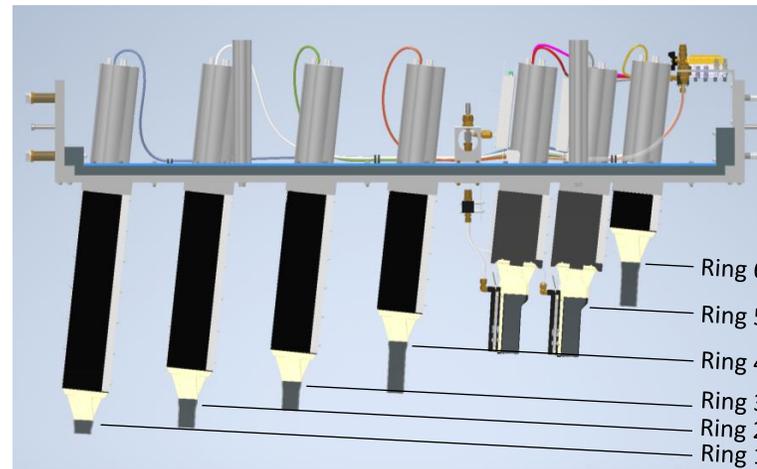
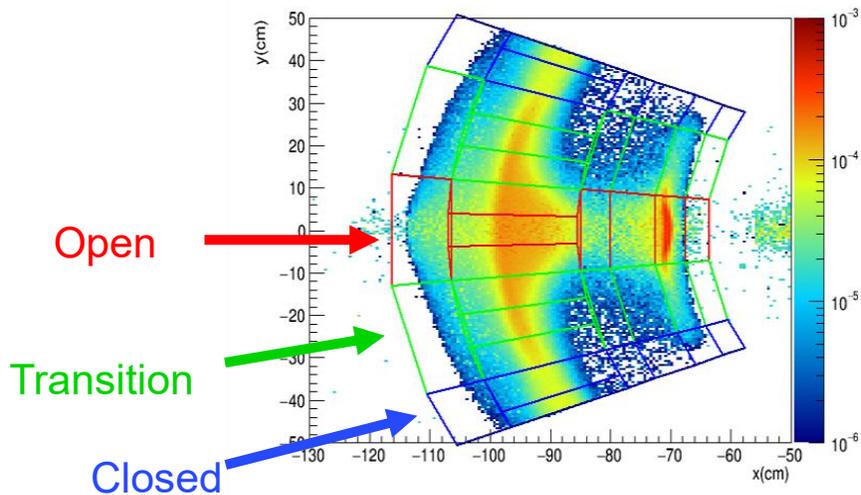




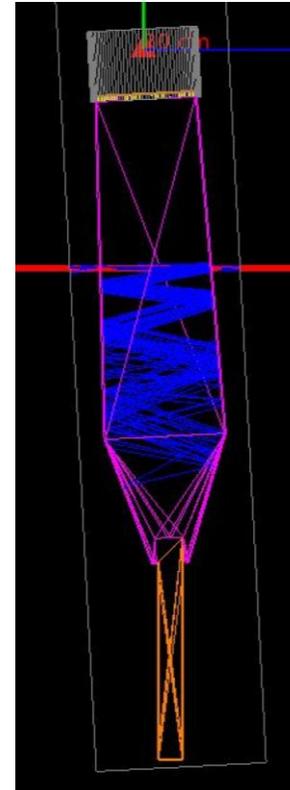
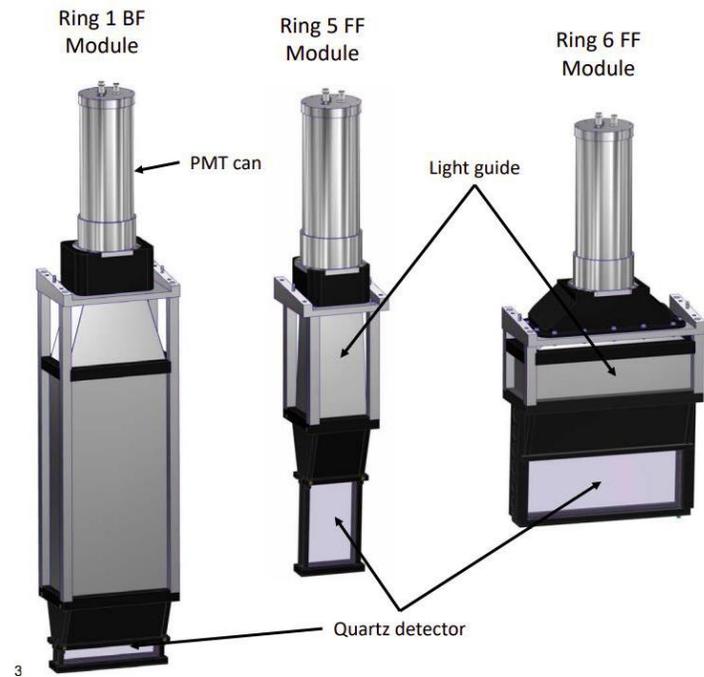
Square Wave Asymmetry Input:  
 $-33 \times 10^3 \text{ ppm} \pm 17 \text{ ppm}$



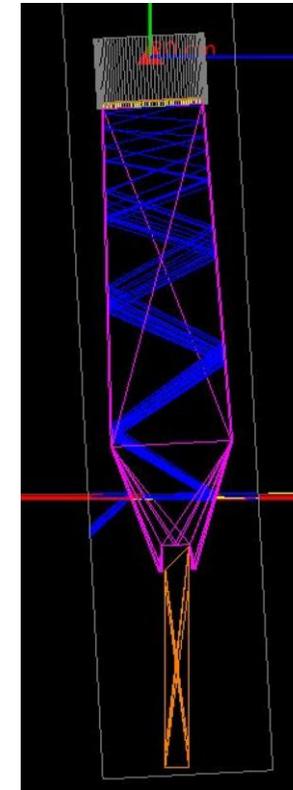
- 224 Detectors
  - Radially split into 6 Rings
  - Azimuthally split into 28 Segments
- Located 26.5 m downstream from target
  - Sufficient space for spectrometers to separate e-e and e-p peaks
- Full coverage of Møller events
- Integration and event mode data collection



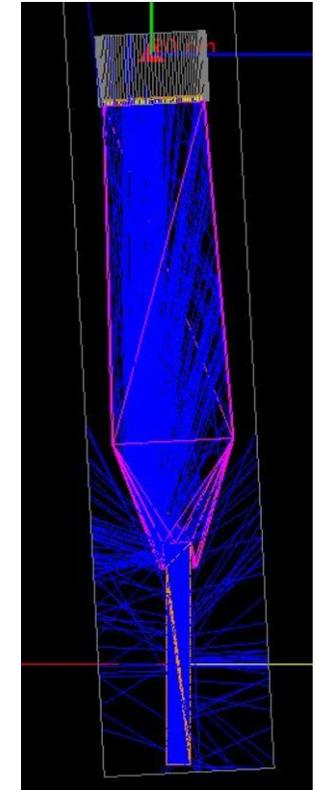
# Main Detector Elements



Upper guide events



Lower guide events

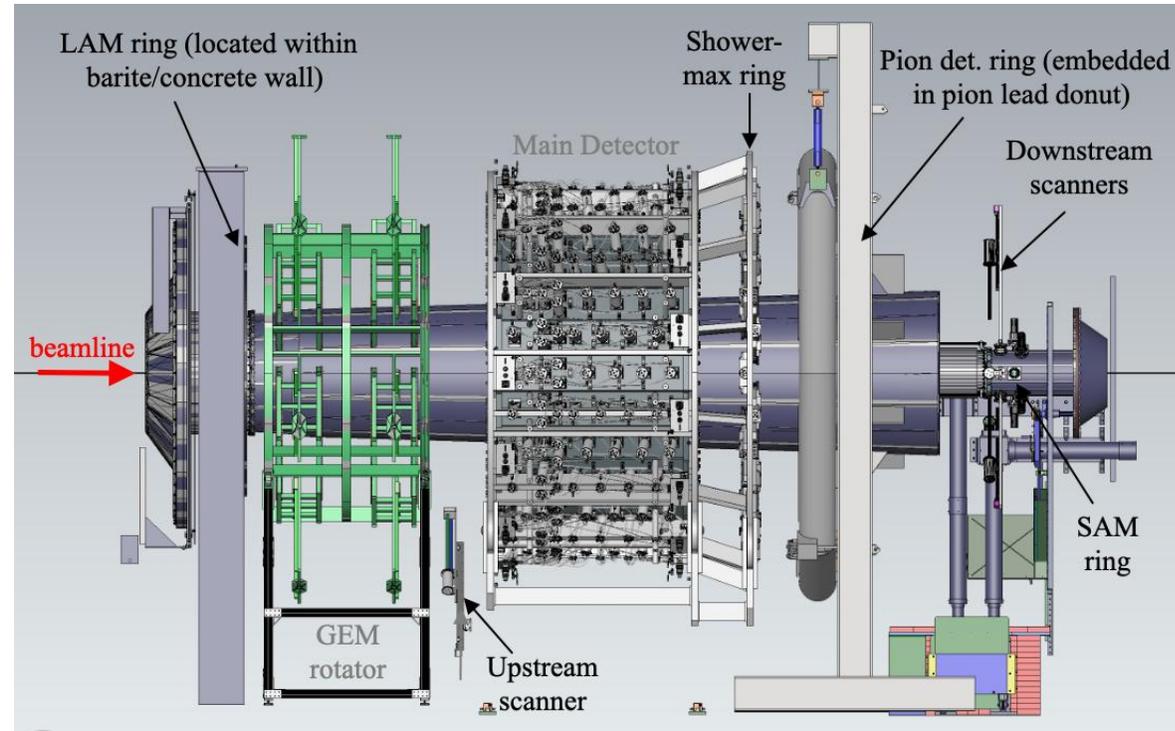


Quartz events

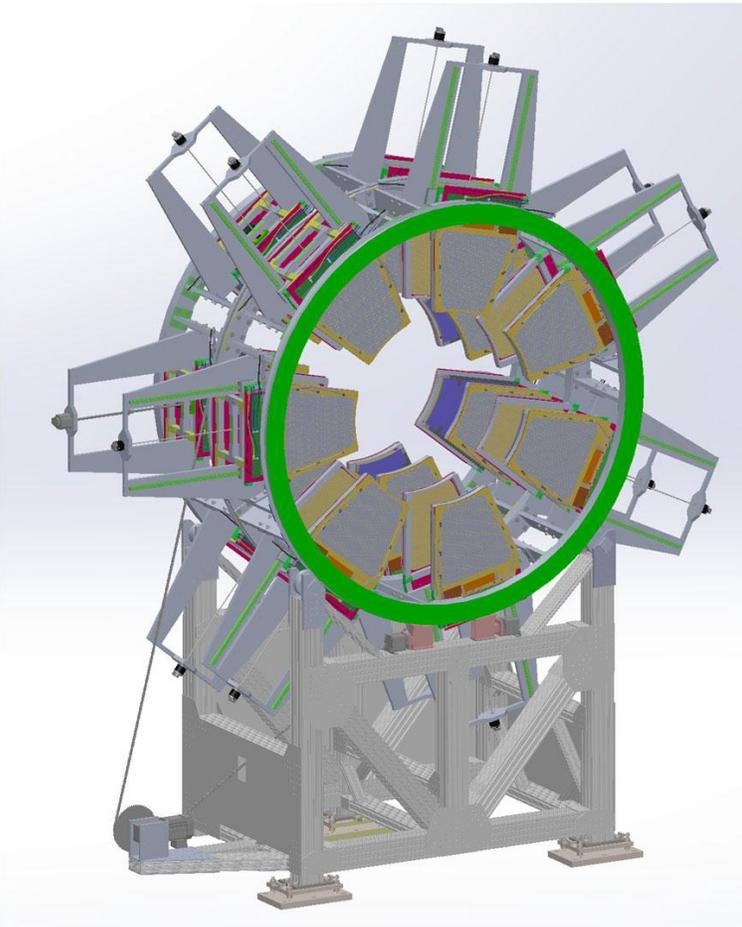
**Integrating (current mode) detectors:** asymmetry measurements in both signal and background, beam and target monitoring

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

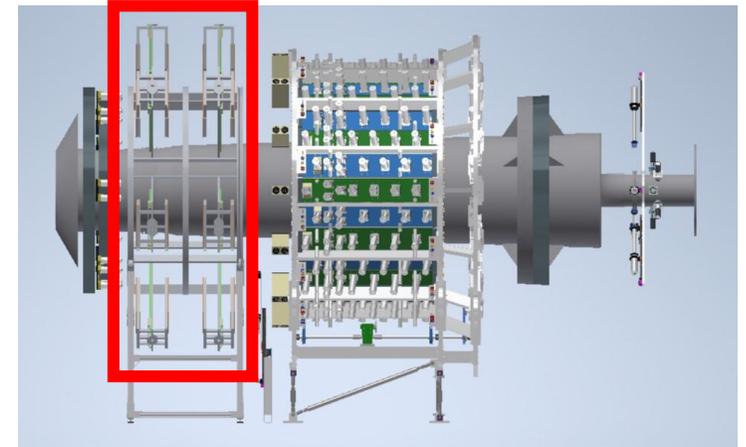
- GEMs and Scintillators
- Shower-max
- Pion Detectors
- Scattered Beam Monitors
  - Large Angle Monitors
  - Small Angle Monitors
  - Diffuse Beam Monitors
  - Upstream Scanners
  - Downstream Scanners
- HVMAPS
- Main Cerenkov Detectors



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



- 28 identical GEM modules
  - 4 layers of 7 GEM modules
- 14 identical trigger scintillators
  - 2 layers of 7 scintillators

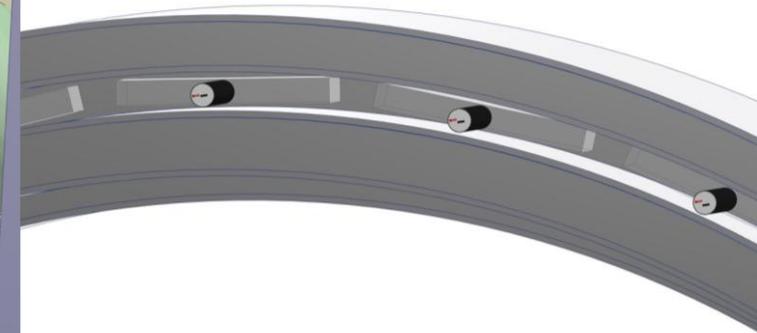
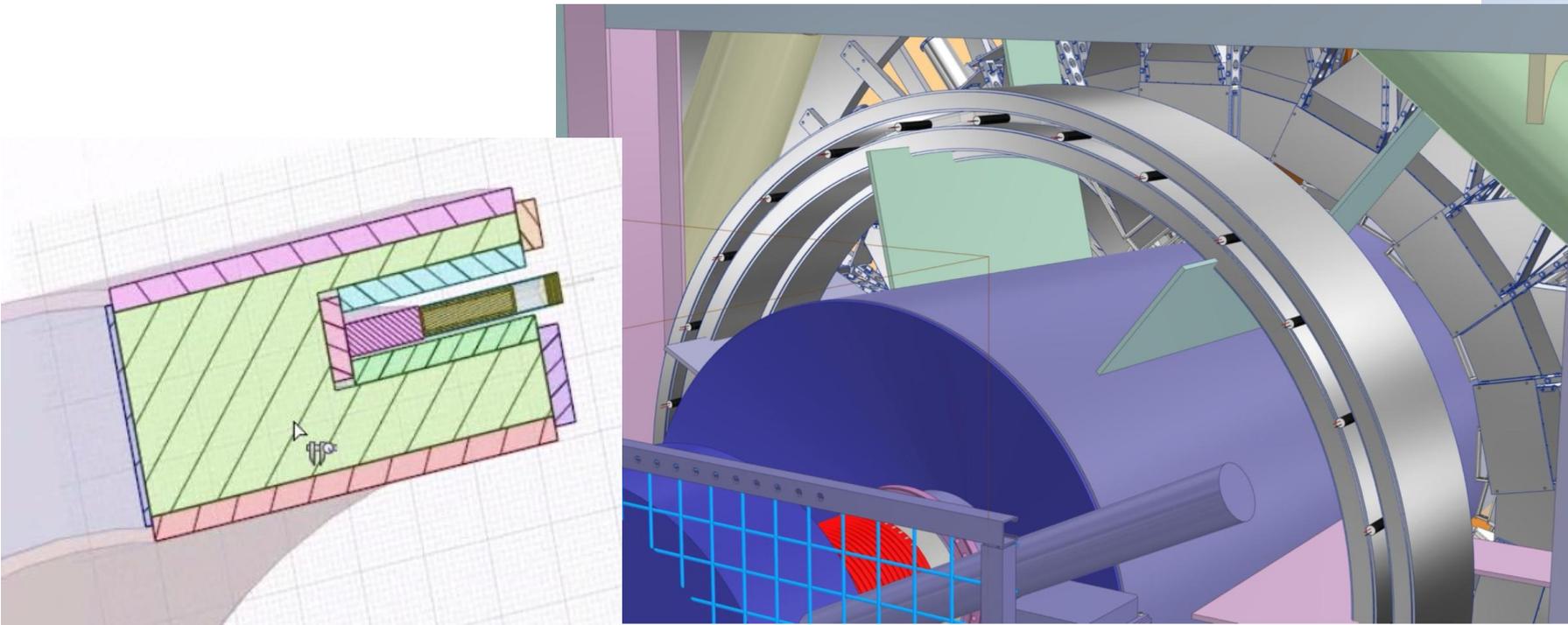
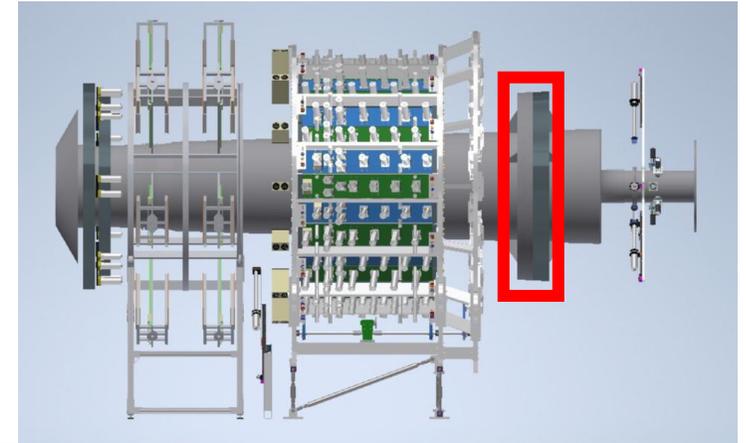


## Requirements:

- stand capable of rotating  $51.4^\circ$  (full  $360^\circ$  coverage) with minimum 3 stopping positions
- radial extraction of GEMs and scintillators during high current beam
- minimize mass in scattered electron path
- structure primarily manufactured with aluminium

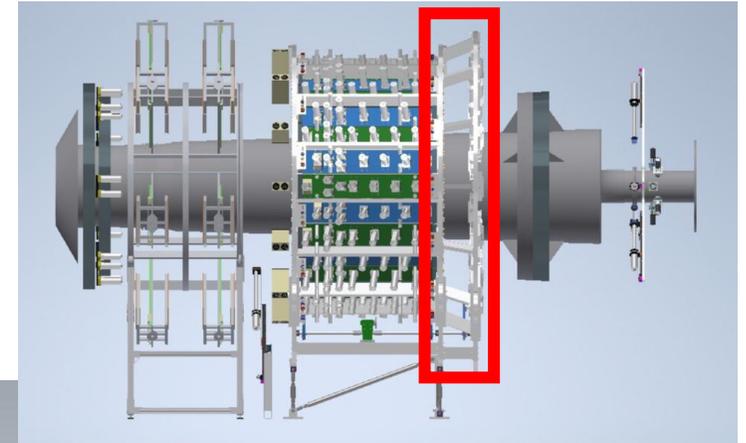
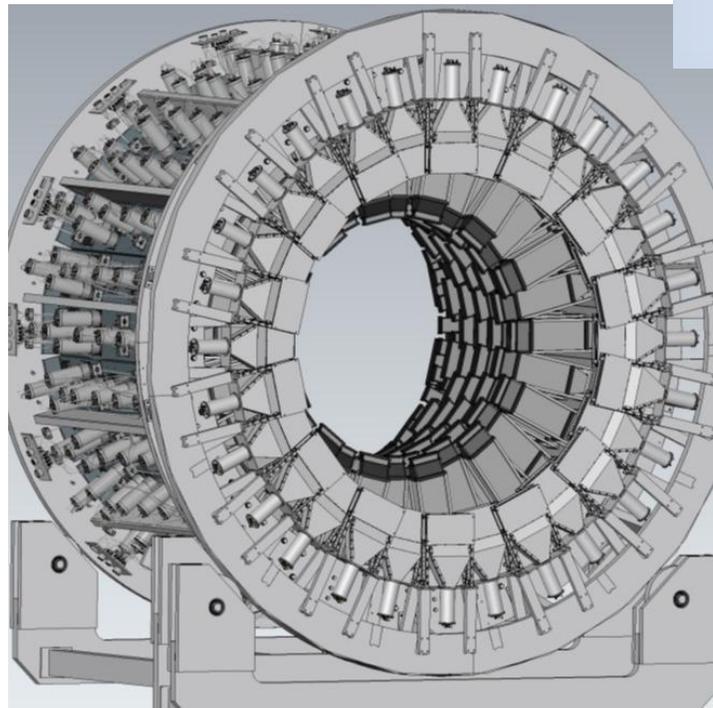
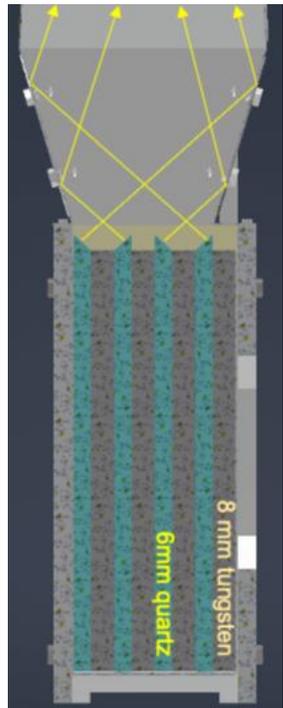
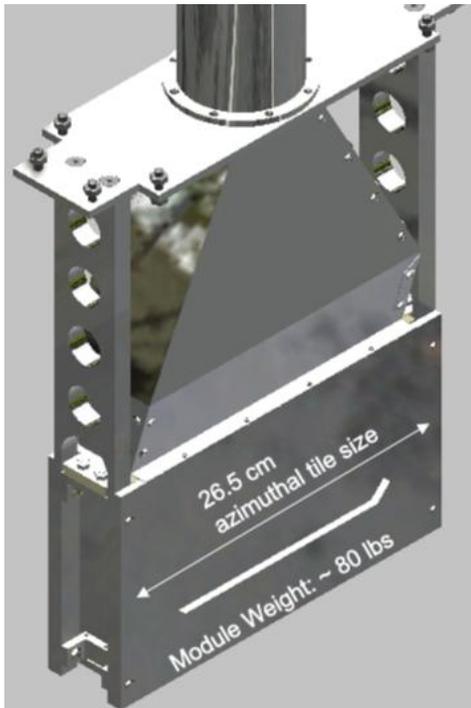
## Goal: Quantify pion background contamination in Møller signal asymmetries

- 28 identical acrylic Cerenkov detectors
  - 7 cm deep x 21 cm wide x 1" thick
- encased in Pb donut, downstream of shower-max detectors to suppress Møller electrons by  $> 10^3$



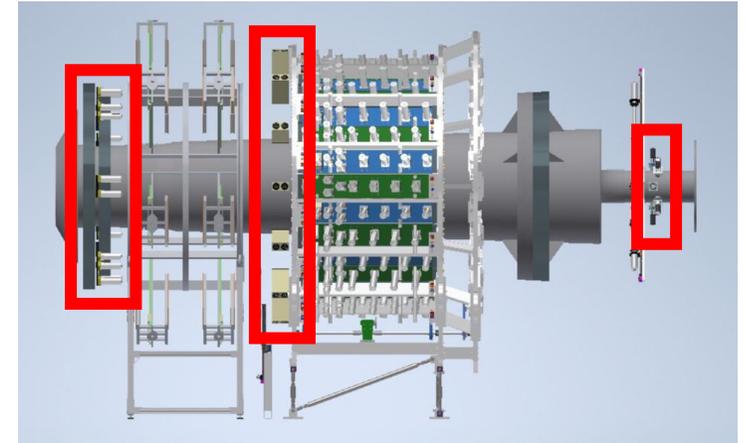
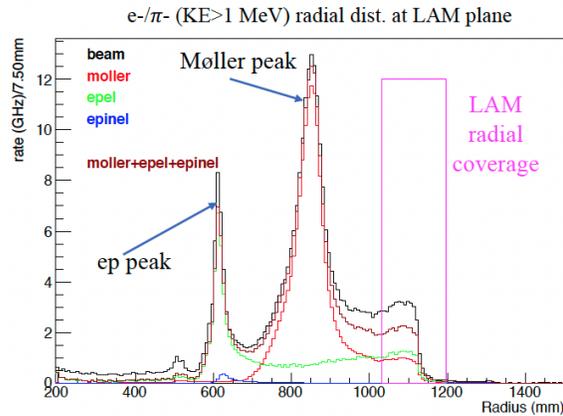
## Goal: second, independent measurement of Møller peak

- electromagnetic sampling calorimeter
  - higher E – samples more, lower E – samples less
- 28 modules downstream of Ring 5
- layered quartz and tungsten



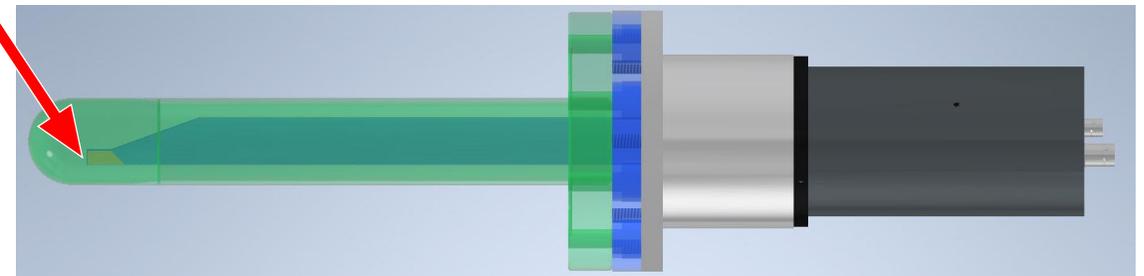
# Scattered Beam Monitors

- 7 Large Angle Monitors (LAMs)
  - rate dominated by e-p elastic tail



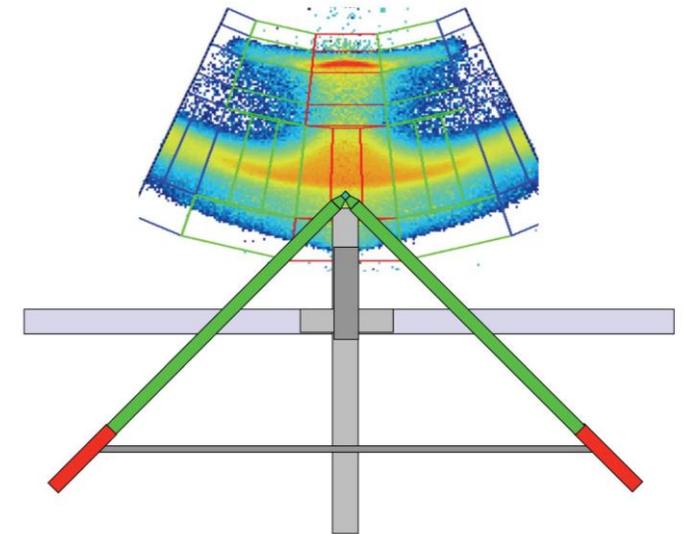
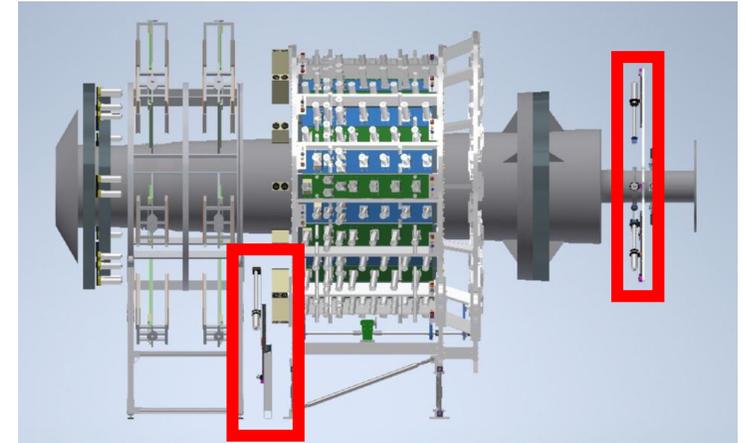
- 14 Diffuse Beam Monitors (DBMs)
  - monitor for large false asymmetries
- 8 Small Angle Monitors (SAMs)
  - monitor for target density fluctuations, false asymmetries

Quartz



## Scanner Detectors

- 1 Upstream Scanner
  - scattered rate distribution for one sector
  - 2D scanning for integration and counting mode
  - verify both currents same distribution
  - monitor stability of kinematics and backgrounds
  - full scan complete in < 1 hour
  - 1 x 1 cm<sup>2</sup> quartz tile
- 4 Downstream Scanners
  - 1D radial scanning for integration mode
  - 50 – 70 cm radial scanning at 4 azimuthal locations
  - located by SAMs for the outer edge of Coll. 2
  - magnet off, 4 cm carbon target



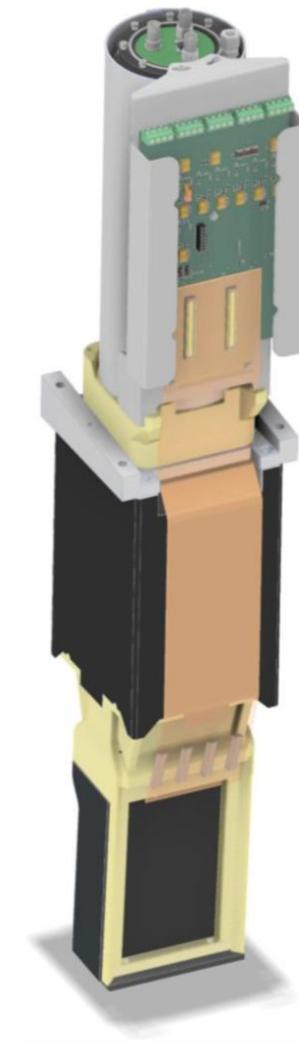
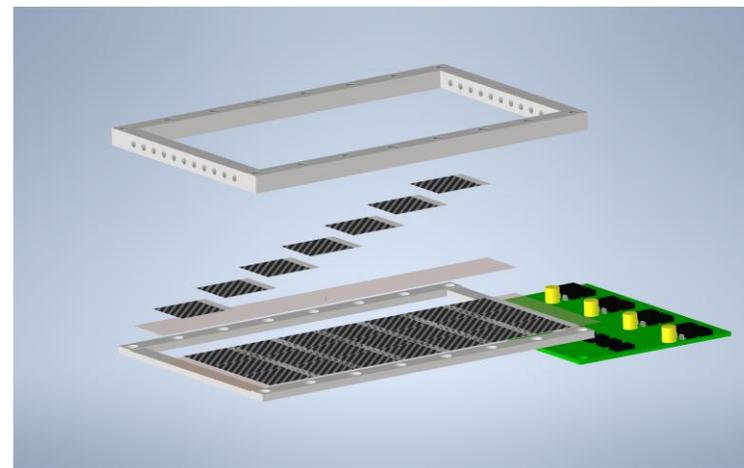
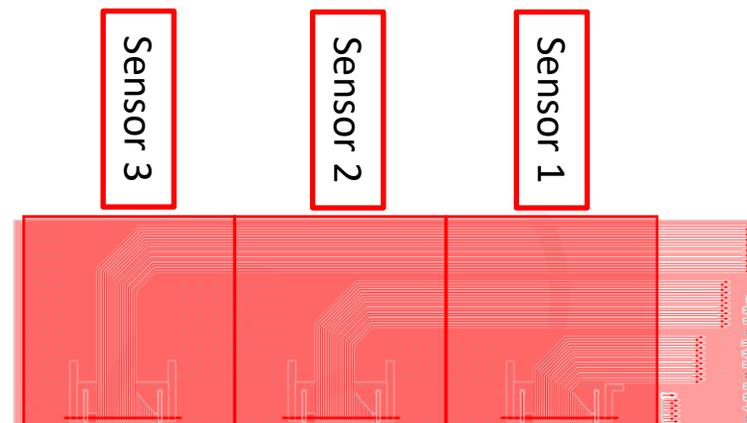
## High Voltage Monolithic Active Pixel Sensors

- active pixel size:  $80 \times 80 \mu\text{m}^2$ 
  - readout electronics, filters, amplifiers all integrated into chip
- overall detectable region size:  $2 \times 2 \text{ cm}^2$
- 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

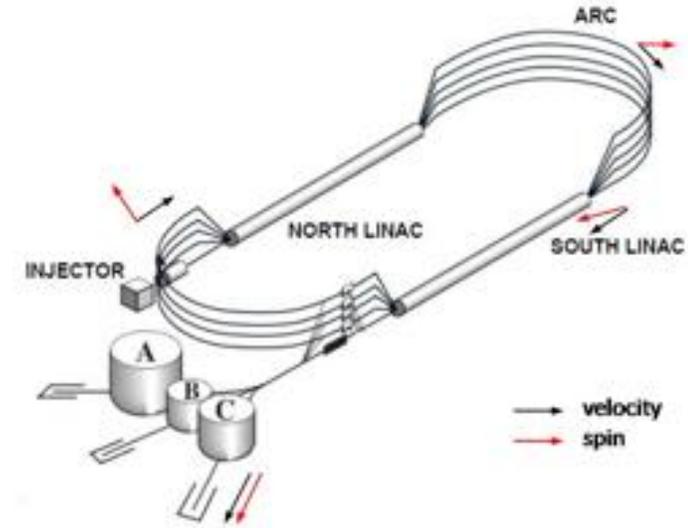
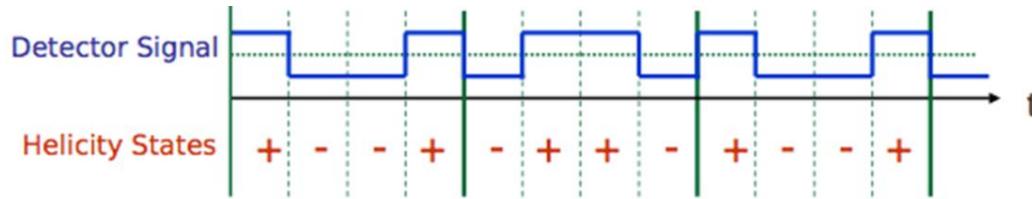
$$R = 2.2 \times 10^{-4} \times 70/25 \approx 600 \text{ kHz/mm}^2 \quad \Rightarrow \quad \approx 4 \text{ kHz/pixel}$$



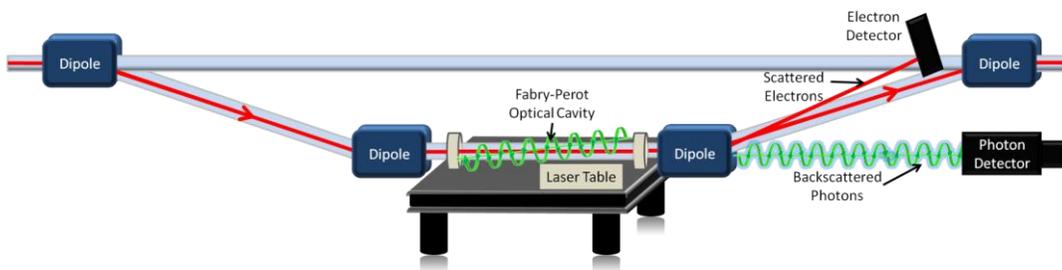
# Electron Beam and Polarimetry



- 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

