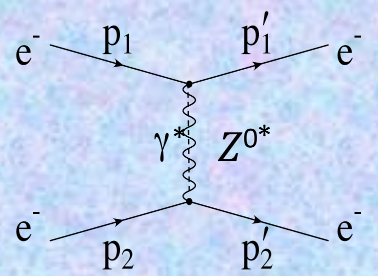
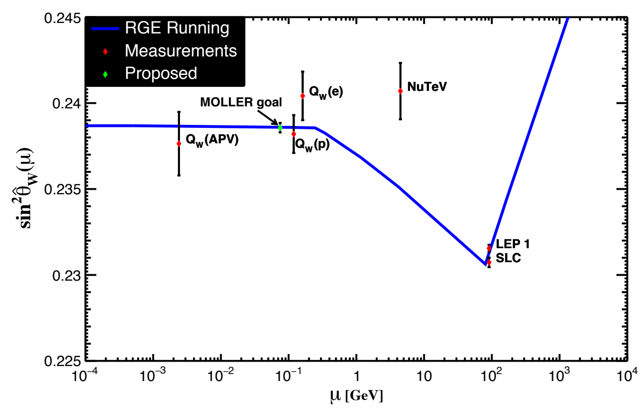
The MOLLER Experiment: A Precision Electroweak Probe

Measurement
Of
Lepton-
Lepton
Electroweak
Reaction





Dustin McNulty – Idaho State University
for the MOLLER Collaboration

June 20, 2023

Jefferson Lab

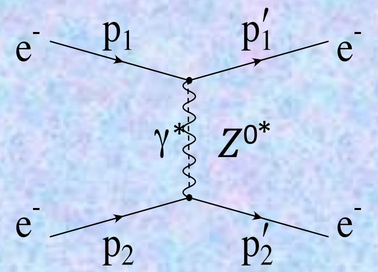
Idaho State University

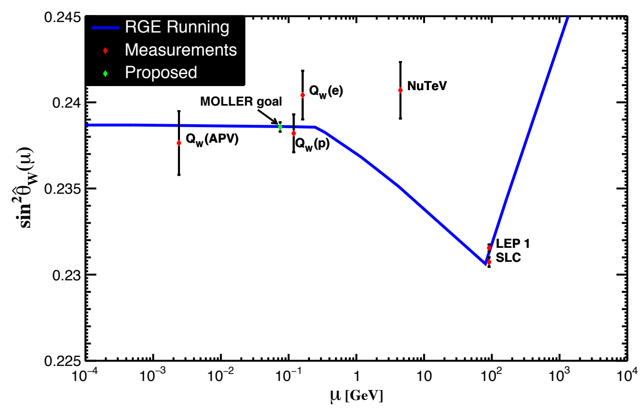
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- MOLLER introduction
  - Physics motivation and reach
  - Parity Violation and Møller scattering
  - MOLLER measurement
- MOLLER apparatus
  - Pol. source, spectrometer and optics
  - Main and auxiliary detectors
  - Systematic errors
- Summary

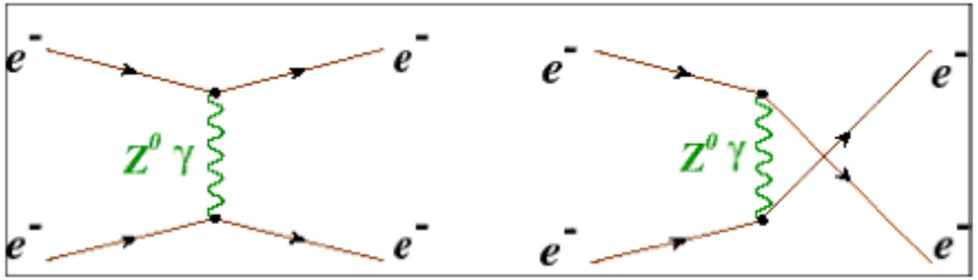
***M**easurement*
***O**f*
***L**epton-*
***L**epton*
***E**lectroweak*
***R**eaction*





Møller Scattering A_{PV}

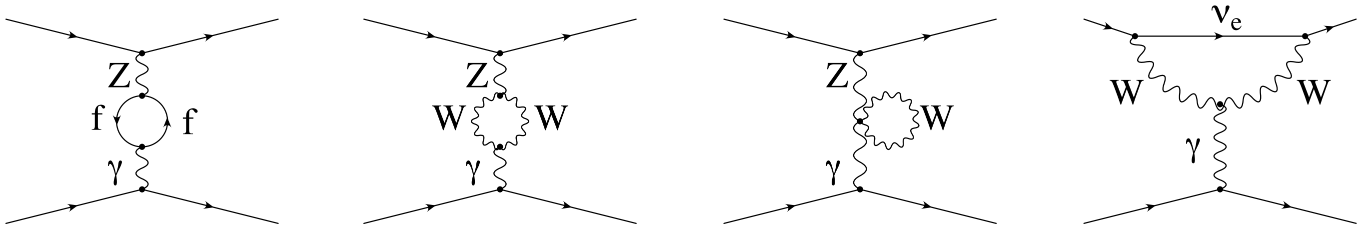
- MOLLER is aimed at precision measurement of the parity-violating asymmetry A_{PV} in fixed target, polarized electron-electron (Møller) scattering.
- Standard Model gives remarkably precise prediction for Møller A_{PV} which can be measured as a test

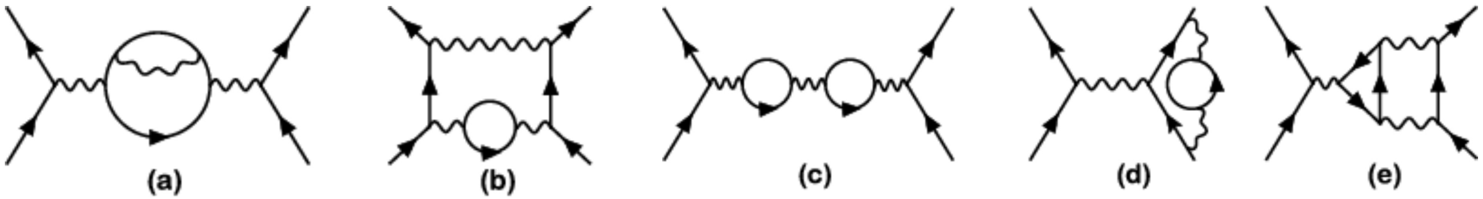


$$A_{PV} = \frac{A_\gamma A_Z}{A_\gamma^2} = m_e E \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+\cos^2\theta)} Q_w^e$$

Weak charge of electron : $Q_w^e \equiv 4 \cdot g_V^e \cdot g_A^e = -(1 - 4\sin^2\theta_w)$ Weinberg (Weak) mixing angle

- γ - Z mixing diagrams and W loops, "Hard" radiative corrections involving the massive vector bosons—modify the tree level prediction significantly.





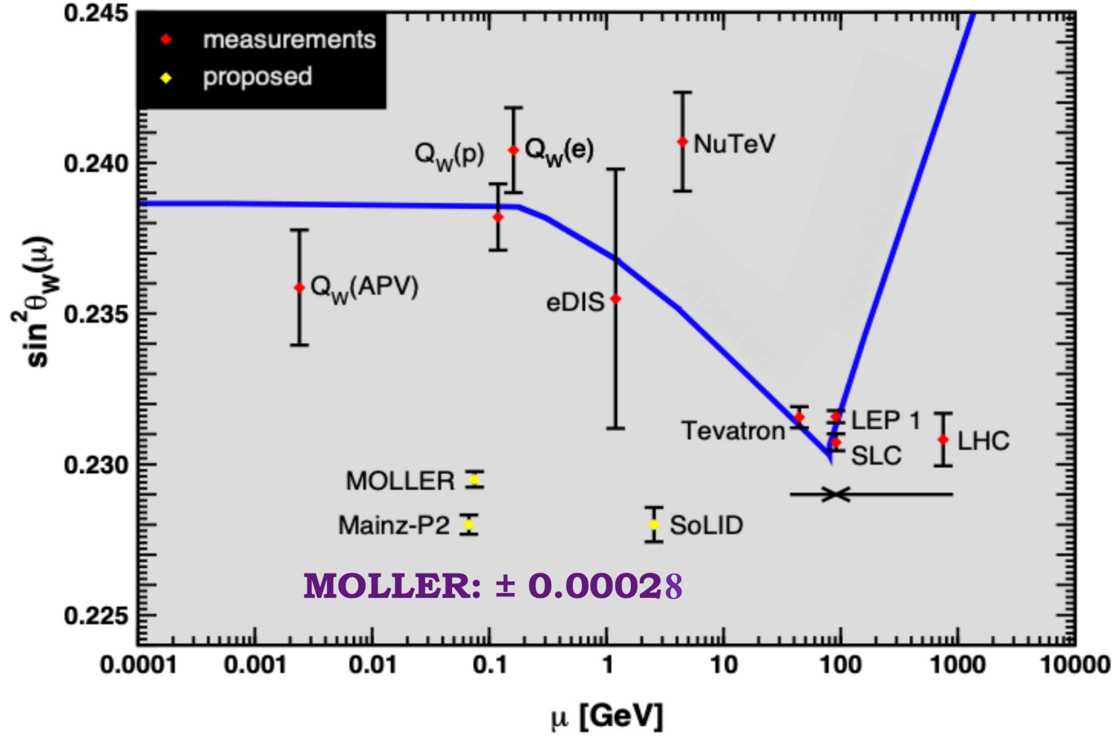
- **Two groups working on full 1-loop and leading 2-loop radiative corrections**

--Aleksejevs and Barkanova
Series of publications

--Du, Freitas, Patel and Ramsey-Musolf
Recent closed-fermion loops: arXiv:1912.08220

The Weak Mixing Angle

- Played a central role in developing and validating electroweak theory, especially testing at the quantum loop level



- γ - Z mixing and other diagrams are absorbed into the coupling constant causing it to 'run' as a function of energy scale.
- Renormalization scheme defines $\sin^2\theta_w$ at the Z-pole.

Atomic Parity Violation: Cs-133
✦ future measurements and theory challenging

Neutrino DIS: NuTeV
✦ future measurements and theory challenging

PV Møller Scattering: E158 at SLAC
✦ statistics limited, theory robust

✦ next generation: MOLLER (factor of 5 better)

PV elastic e-p scattering: Qweak
✦ theory robust at low beam energy

✦ next generation: P2 (factor of 3 better)

PV Deep Inelastic Scattering: PVDIS
✦ theory robust for ^2H in valence quark region

✦ factor of 5 improvement: SOLID

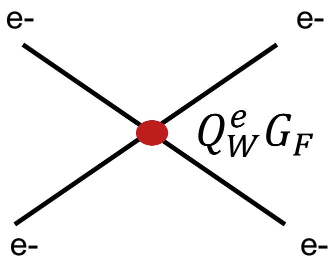
MOLLER Sensitivity to New (BSM) NC Weak Interactions

MOLLER

Weak charge measurement from purely leptonic neutral current amplitudes

$$|A_\gamma + A_Z + A_{new}|^2 \longrightarrow A_\gamma^2\left[1 + 2\left(\frac{A_Z}{A_\gamma}\right) + 2\left(\frac{A_{new}}{A_\gamma}\right)\right]$$

Constraint on new 4-fermion contact interactions



$$Q_W^e \sim 0.045$$

$$\frac{\delta Q_W^e}{Q_W^e} \sim 2.4\%$$

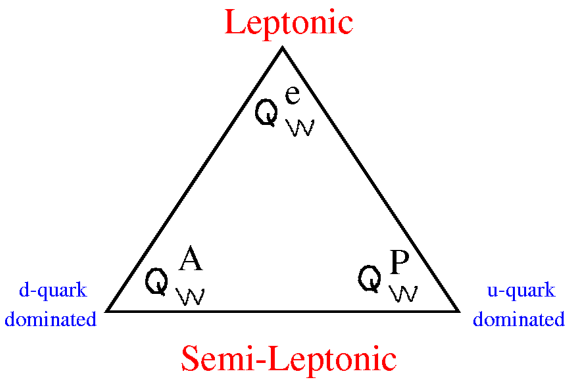
$$A_{new} \sim 0.001 \cdot G_F$$

Unprecedented sensitivity!

✦ In this way, new physics can reveal itself through interference with SM physics

(as long as $Q^2 << M_Z$ so that A_Z not imaginary – underscores importance of low energy measurements in looking for these new interactions

PVES Initiative: Complementarity



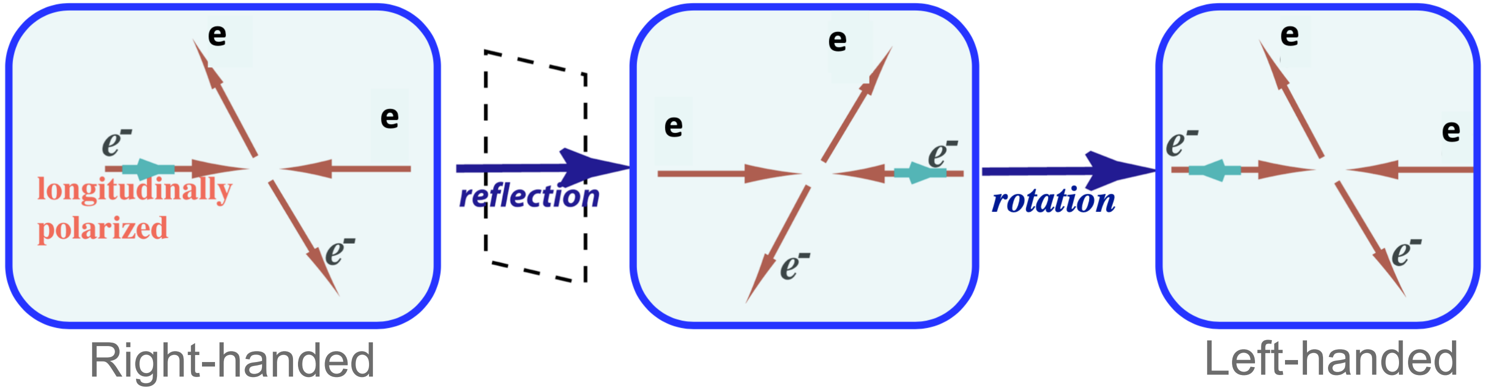
Other complementary semi-leptonic measurements off quarks:

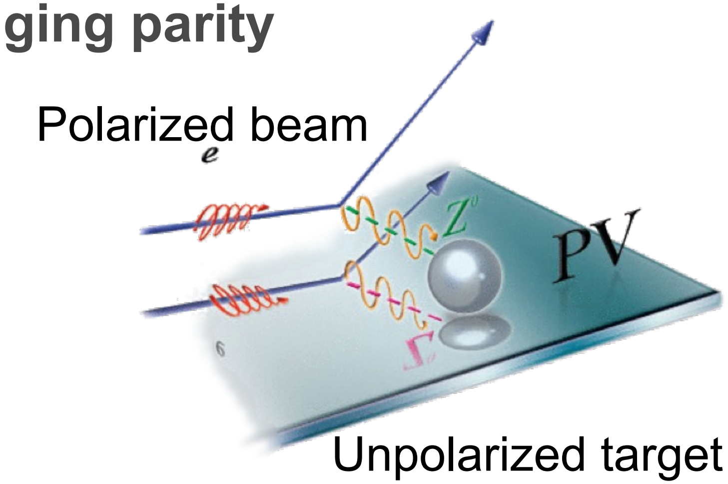
- $\delta(Q_W(^{133}\mathrm{Cs})/A) \sim 0.6\ \% \Longrightarrow A_{new} \sim 0.0033 \cdot G_F$ Atomic PV Future Cs meas. ?
- JLab Qweak: $\delta\left(Q_w^p\right) \sim 6\ \% \Longrightarrow A_{new} \sim 0.0045 \cdot G_F$ Future Mainz P2: Improve by factor of 3
- $\delta(2C_{2u} - C_{2d}) \sim 5\ \% \Longrightarrow A_{new} \sim 0.004 \cdot G_F$ SOLID (at JLab): unique sensitivity to axial quark couplings

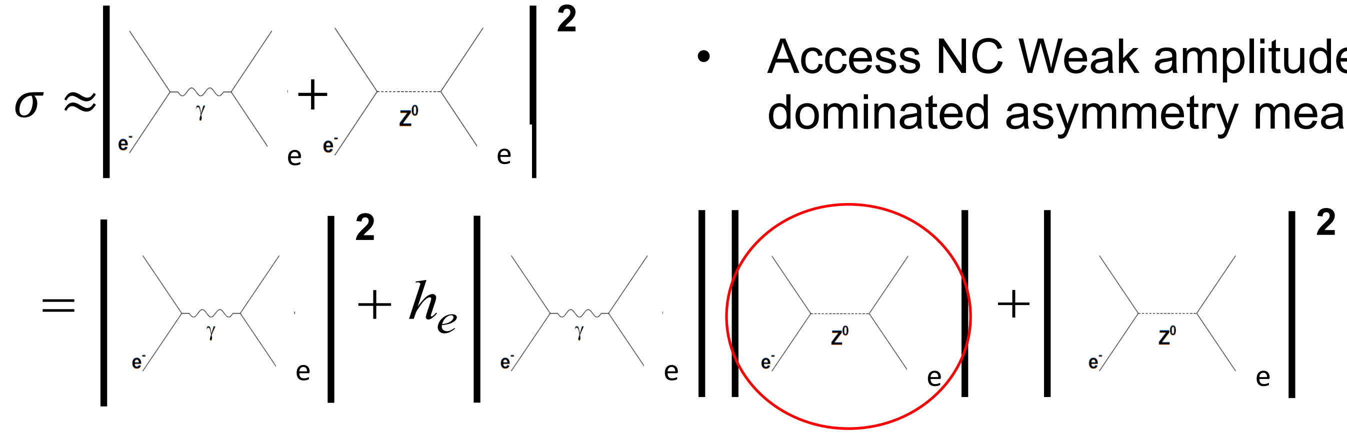
Electron Scattering and Parity Violation

✦ Use unique parity violation signature of weak force to access Neutral Current scattering amplitude

Parity Transformation: Changing beam helicity is equivalent to changing parity







- Access NC Weak amplitude (A_Z) via EW interference dominated asymmetry measurement
- Flip sign of longitudinal beam polarization while measuring flux
- Measured observable is parity violating fractional rate difference or asymmetry (A_{PV})

Born Approx: $$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{A_Z}{A_\gamma} \propto Q_w^e \equiv 4 \cdot g_V^e \cdot g_A^e = -(1 - 4\sin^2\theta_w)$$

4 Decades of Technical Progress

✦ photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, rad hard detectors

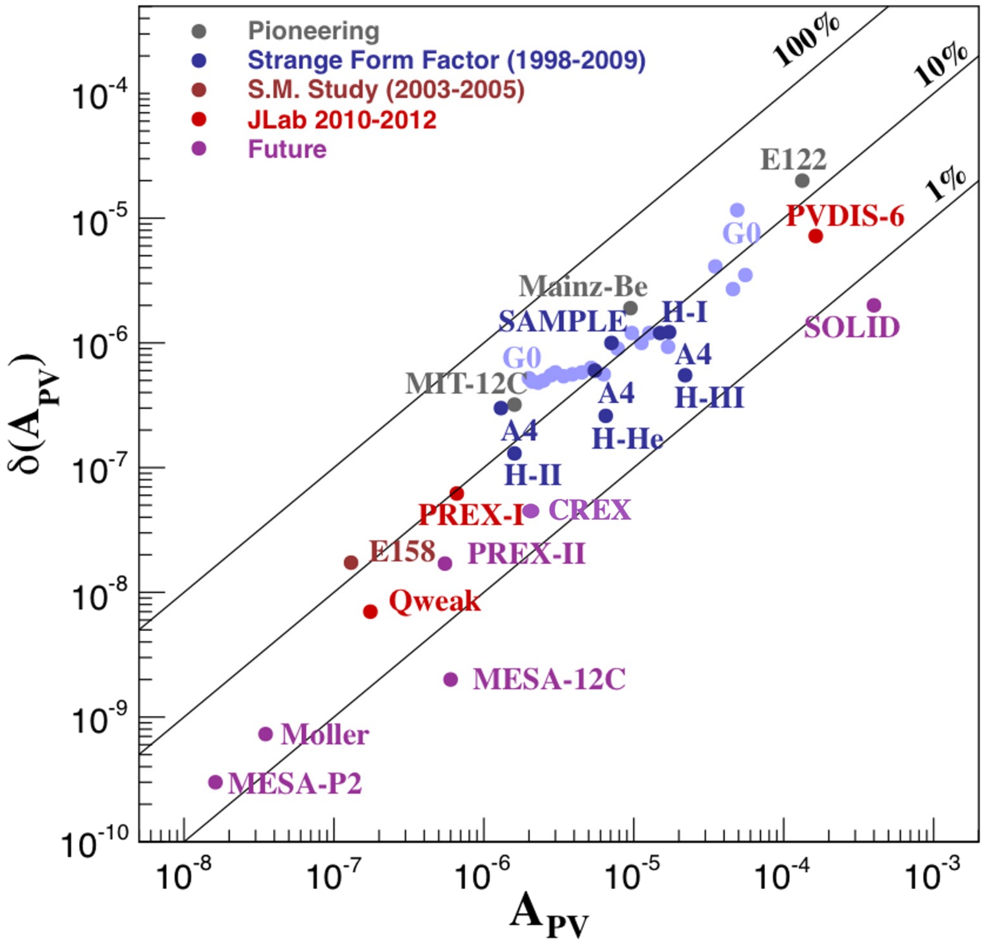
- E122 – 1st PVES Expt (late 70's at SLAC)
- Mainz & MIT-Bates in mid 80's
- JLab program launched in mid 90's
- E158 at SLAC measured PV Møller scattering in mid 2000's

Hall A JLab PVES Experiments:

(Flux Integration Technique)

1999	***HAPPEX-I:***	***2 MHz***	***(A_{PV} ~ 15 ppm)***
2004	***HAPPEX-II:***	***100 MHz***	***(A_{PV} ~ 1.5 ppm)***
2009	***HAPPEX-III:***	***2 MHz***	***(A_{PV} ~ 25 ppm)***
2010	***PREX-I:***	***2 GHz***	***(A_{PV} ~ 0.5 ppm)***
2019	***PREX-II:***	***4 GHz***	***(A_{PV} ~ 0.5 ppm)***
2020	***CREX:***	***50 MHz***	***(A_{PV} ~ 2 ppm)***
2026	***MOLLER:***	***135 GHz***	***(A_{PV} ~ 0.035 ppm)***

PVeS Experiment Summary



1st generation
2nd generation
3rd generation
4th generation

- Parity-violating electron scattering has become a powerful precision measurement tool

The MOLLER Measurement and Observable Sensitivity

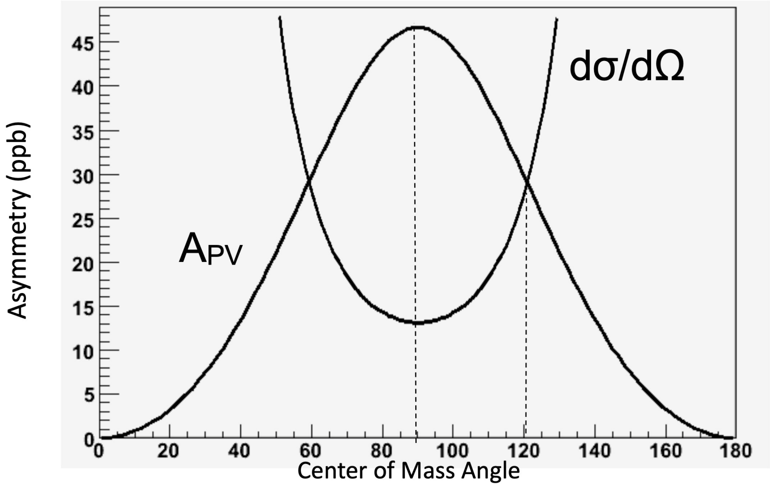
- At proposed kinematics: 11 GeV CEBAF e− beam (65 μA, 90% pol.), and 100% acceptance of scattered Møller electrons from 5 mrad $< \theta_{lab} <$ 20 mrad (~$60° < \theta_{cm} < 120°$) :

→ Predicted $\langle A_{PV} \rangle = 35.6$ ppb at $\langle Q^2 \rangle = 0.0056$ (GeV/c)^2

(with total integrated signal detection rate of 135 GHz)

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

Highest figure of merit at $\theta_{cm} = 90°$



- For 49 (PAC) week run: 3×10^{18} Møllers detected

→ $\delta(A_{PV})$ = 0.73 parts per billion

→ $\delta(Q_W^e)/Q_W^e = \pm 2.1\%$ (stat) $\pm 1.0\%$ (syst)

→ $\delta(\sin^2 \theta_W) = \pm 0.00026$ (stat) ± 0.00012 (syst)

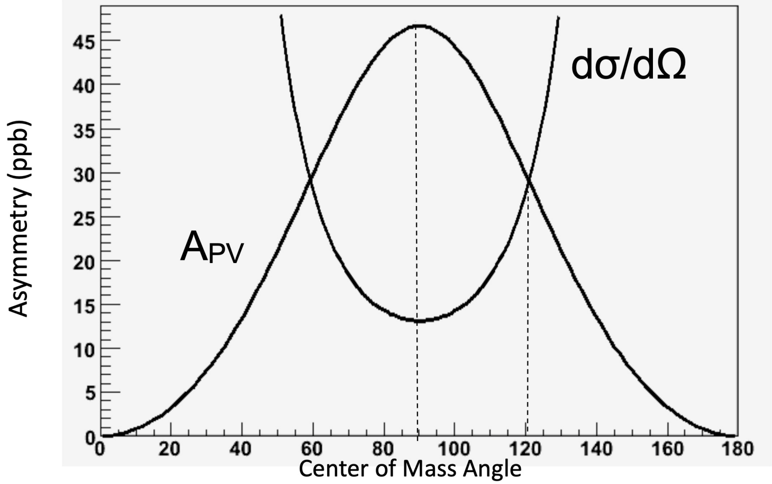
$$\Longrightarrow \frac{\delta(\sin^2 \theta_W)}{\sin^2 \theta_W} \approx 0.1\% \text{ precision!}$$

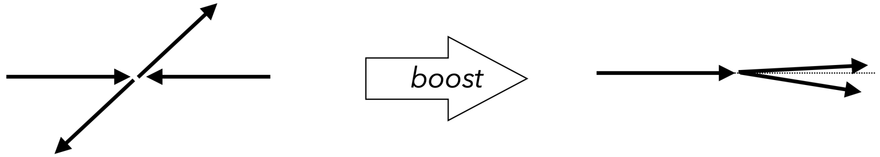
✦ Statistics-limited precision!

Identical Particle Scattering and Full Acceptance

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

Highest figure of merit at $\theta_{cm} = 90°$

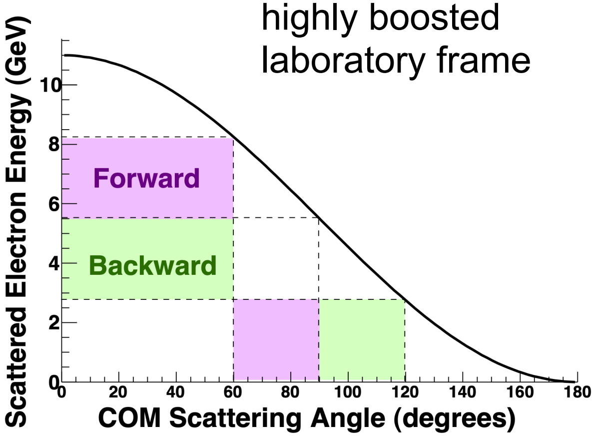




Center of mass

Lab

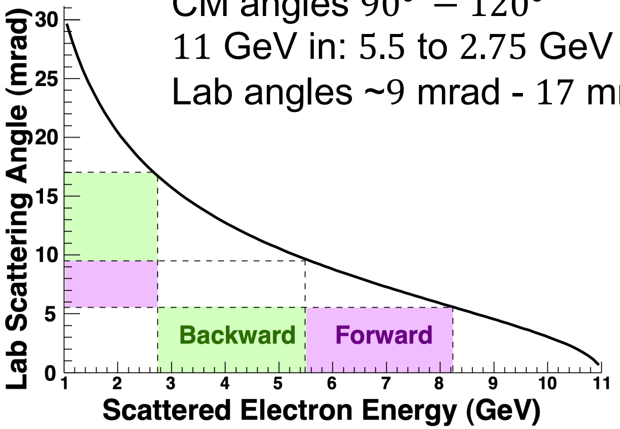
highly boosted laboratory frame

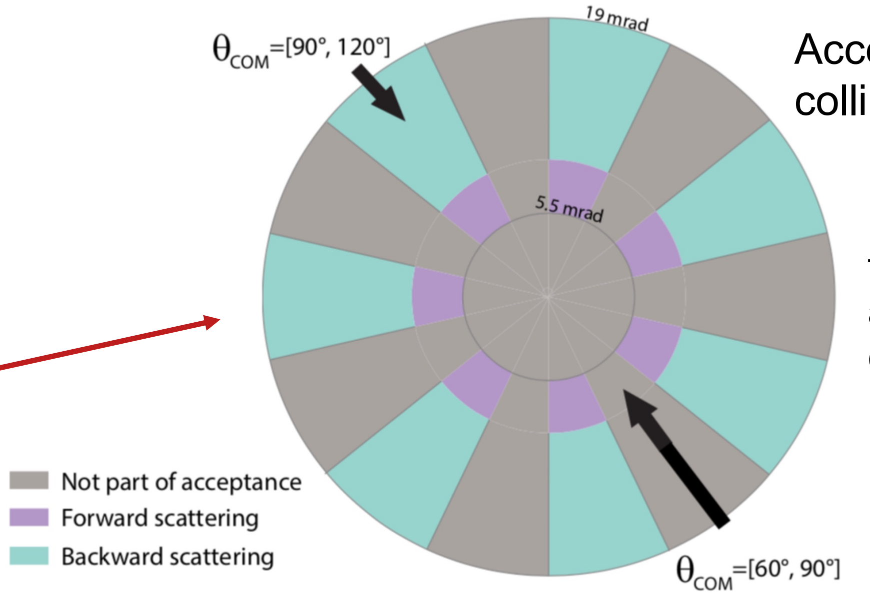


CM angles $90° - 120°$

11 GeV in: 5.5 to 2.75 GeV out

Lab angles ~9 mrad - 17 mrad





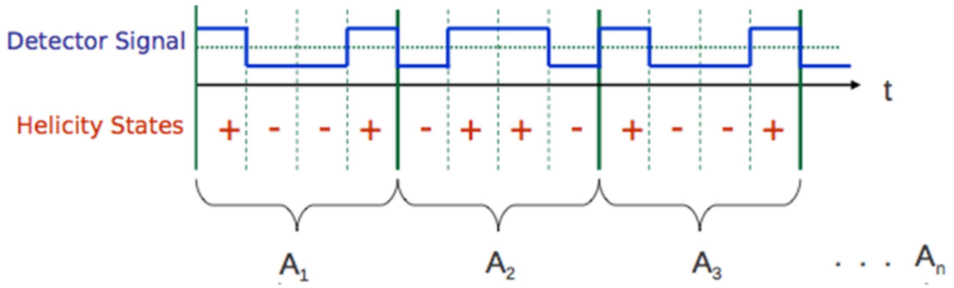
Acceptance defining collimator

Unique concept allows for ~full azimuthal acceptance, but challenging design

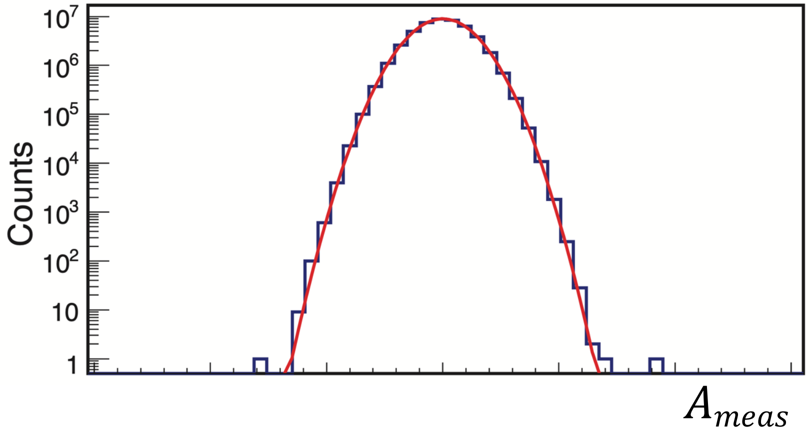
- Identical particles
- Measure either forward or backward scattering

Measuring this tiny asymmetry

✦ Rapid (2 kHz) helicity reversals



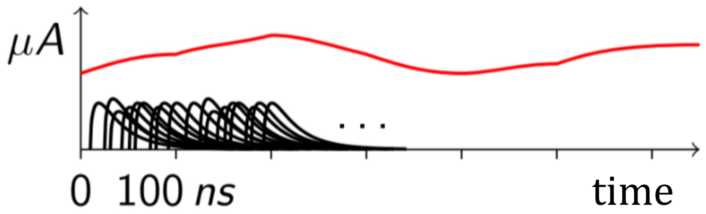
✦ Measure to 0.01% at 1 kHz, repeat for a year straight



No non-Gaussian tails to $\pm 5\sigma$

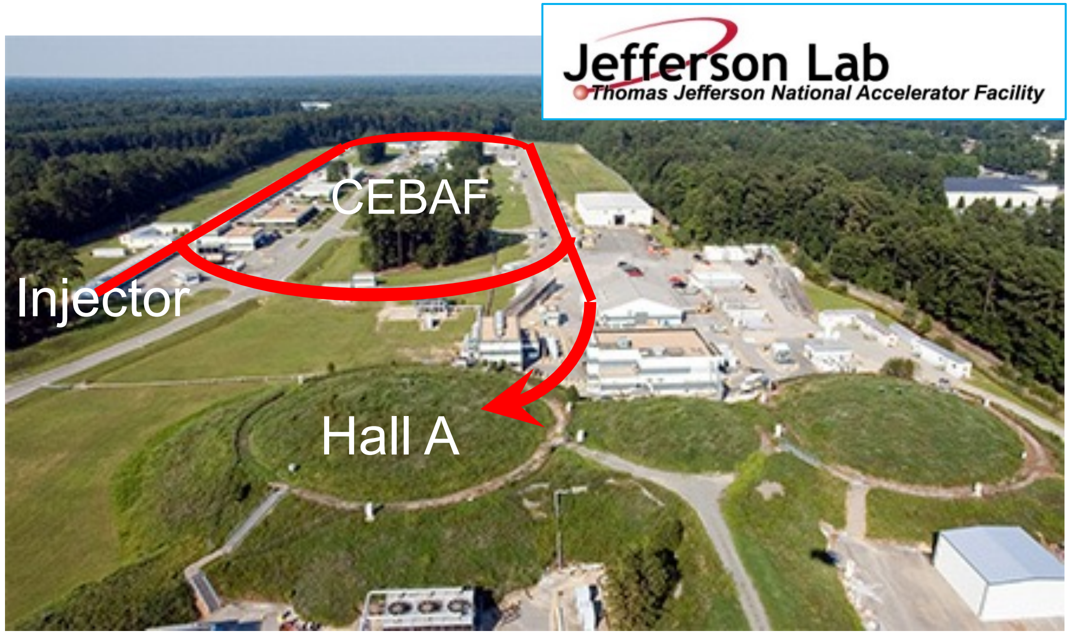
✦ Place a detector where it sees the Møller scattered electron flux

✦ Analog integrate detector current over individual helicity windows

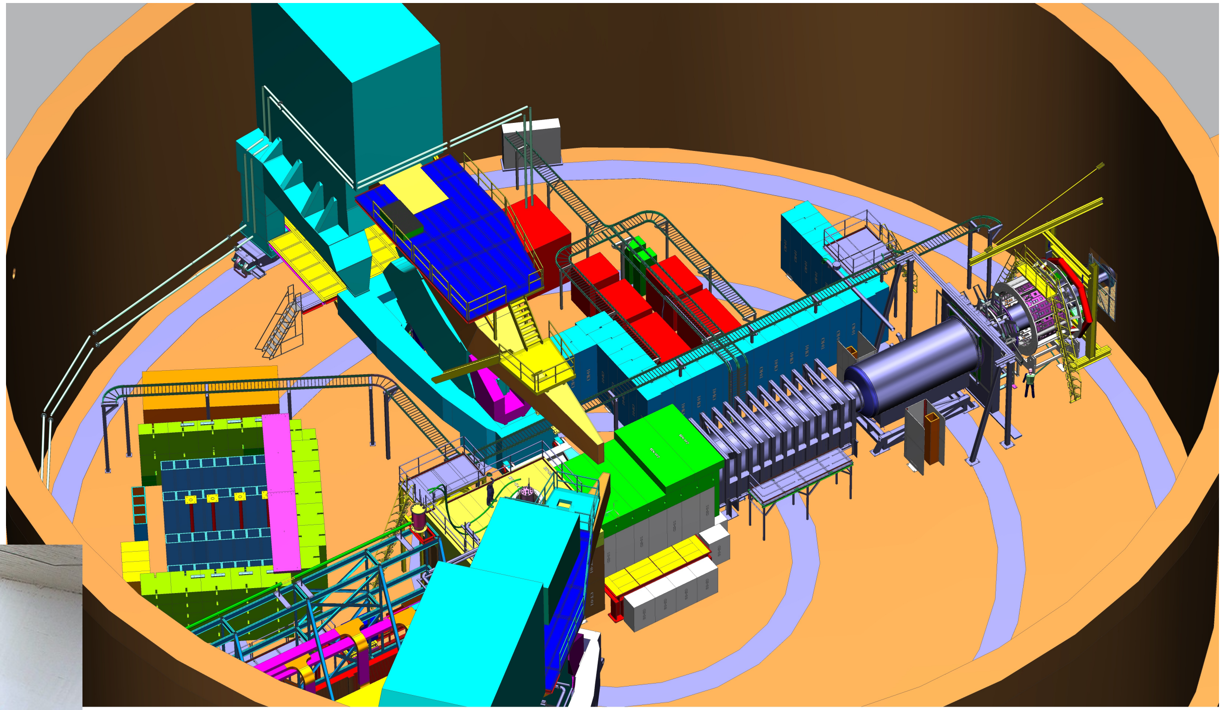


✦ And form the asymmetry: $A_{meas} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$

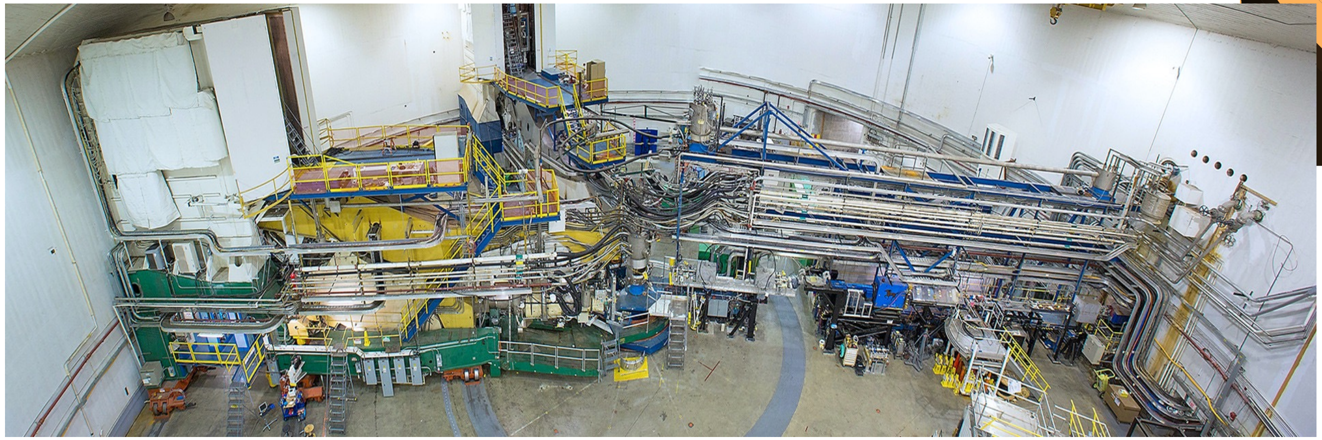
MOLLER at Jefferson Lab's Hall A



Hall A: MOLLER apparatus (start installation in 2025)



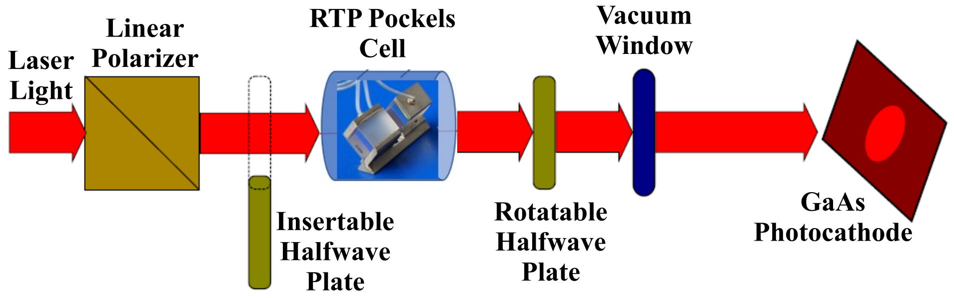
Hall A photo (6 GeV era)

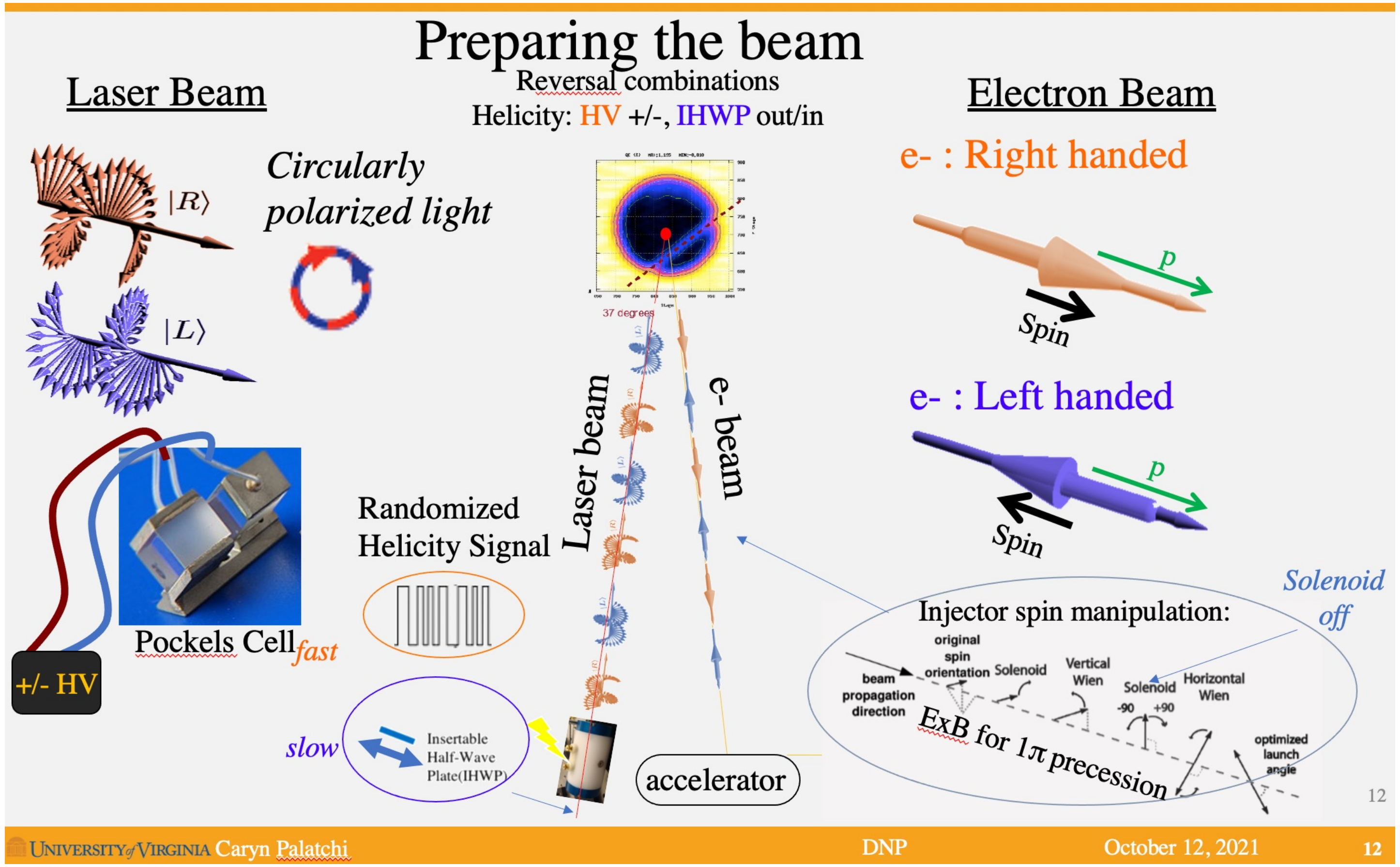


Experimental Apparatus: Injector Beam Preparation

- Precision polarized source laser alignment
- A new and improved RTP Pockels cell for fast flipping
- Independent methods for "slow" helicity reversals: (important for cancelling helicity-correlated false asymmetries)

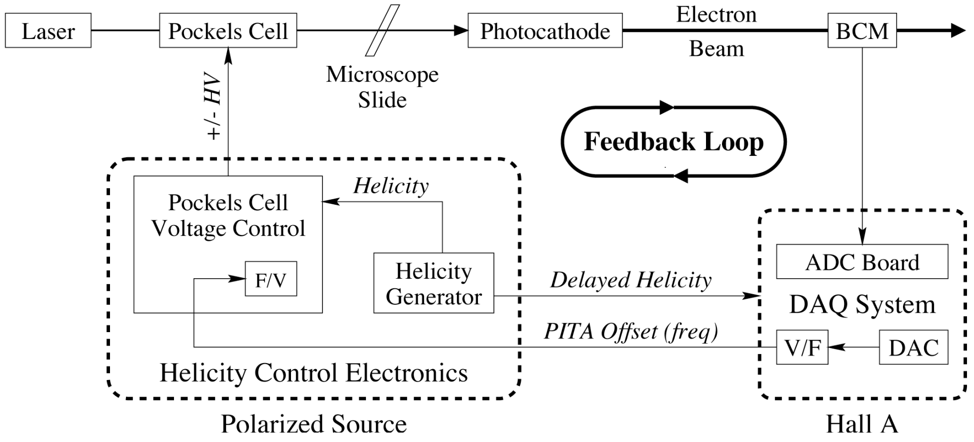
1. Insertable half-wave plate for source laser: --state (In or Out) changed every ≈8 hrs of production
2. Injector e-beam spin manipulator (Wien filter): --configuration (Right or Left) changed on once a month time scale
3. 'g-2' spin flip by changing incoming beam energy and spin precession. Will do at least once during MOLLER

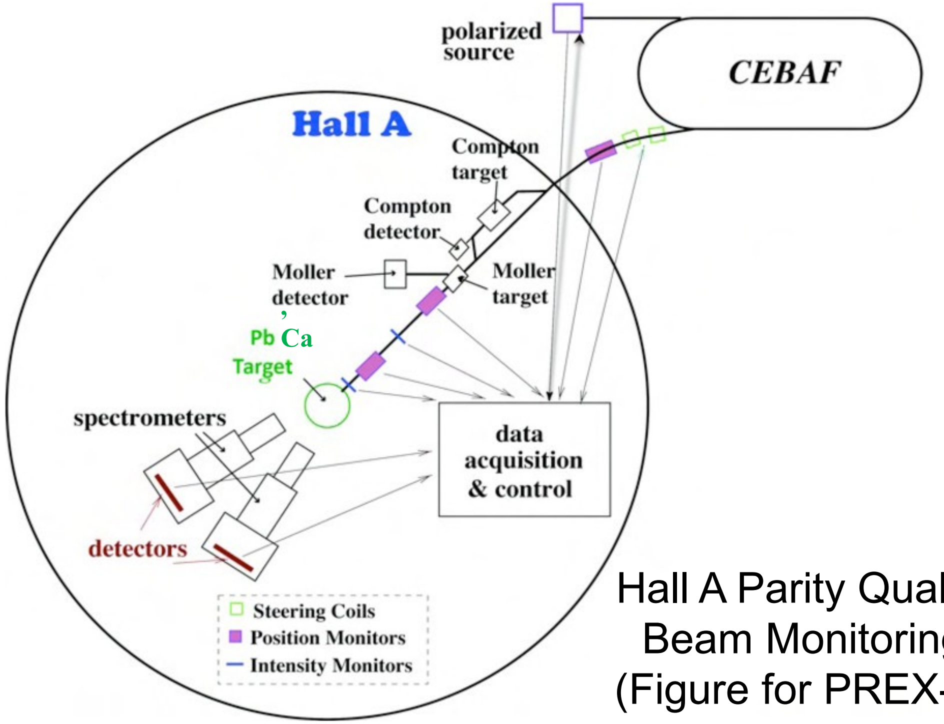




Experimental Apparatus: Beam Monitoring

- Active feedback on beam intensity asymmetry (A_Q)



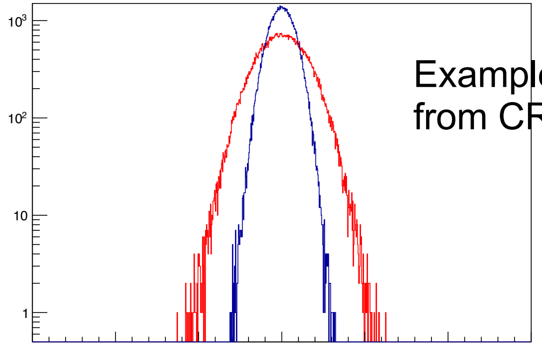


Hall A Parity Quality Beam Monitoring (Figure for PREX-II)

- Precision beam position monitoring with *active* calibration of detector slopes (α_E and α_i's)—detector's response to tiny changes in beam positions, angles and energy (ΔM's) (*beam modulation system*)

$$A_{corr} = \underbrace{A_{meas} - A_Q}_{A_{raw}} - \underbrace{(\Sigma \alpha_i \Delta M_i + \alpha_E \Delta M_E)}_{A_{beam}}$$

Beam motion corrections

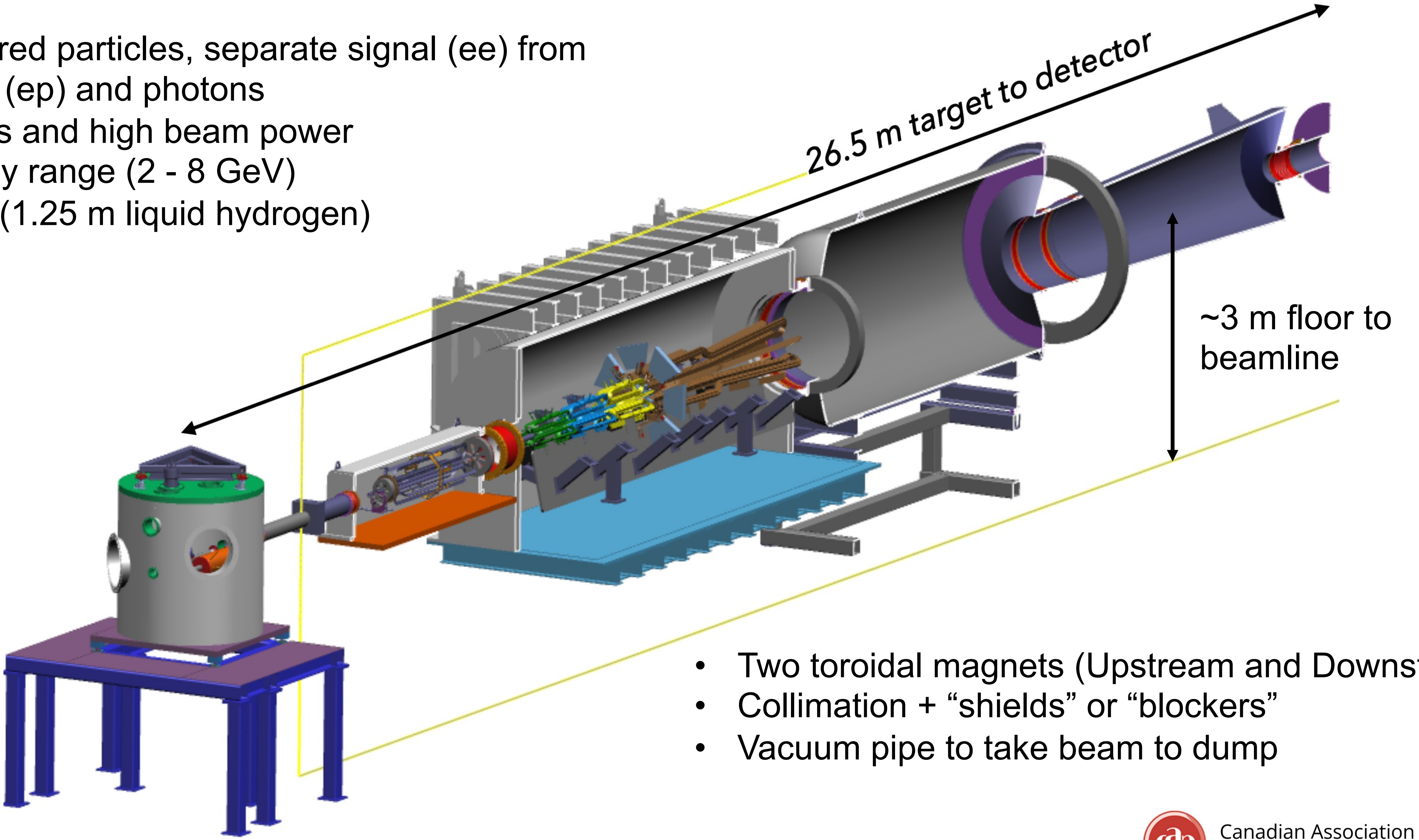


A_{PV}: A_{raw} (red), A_{corr} (blue)

- Precision beam polarimetry:
  1. Continuous monitoring with Compton polarimeter
  2. Invasive Møller polarimetry

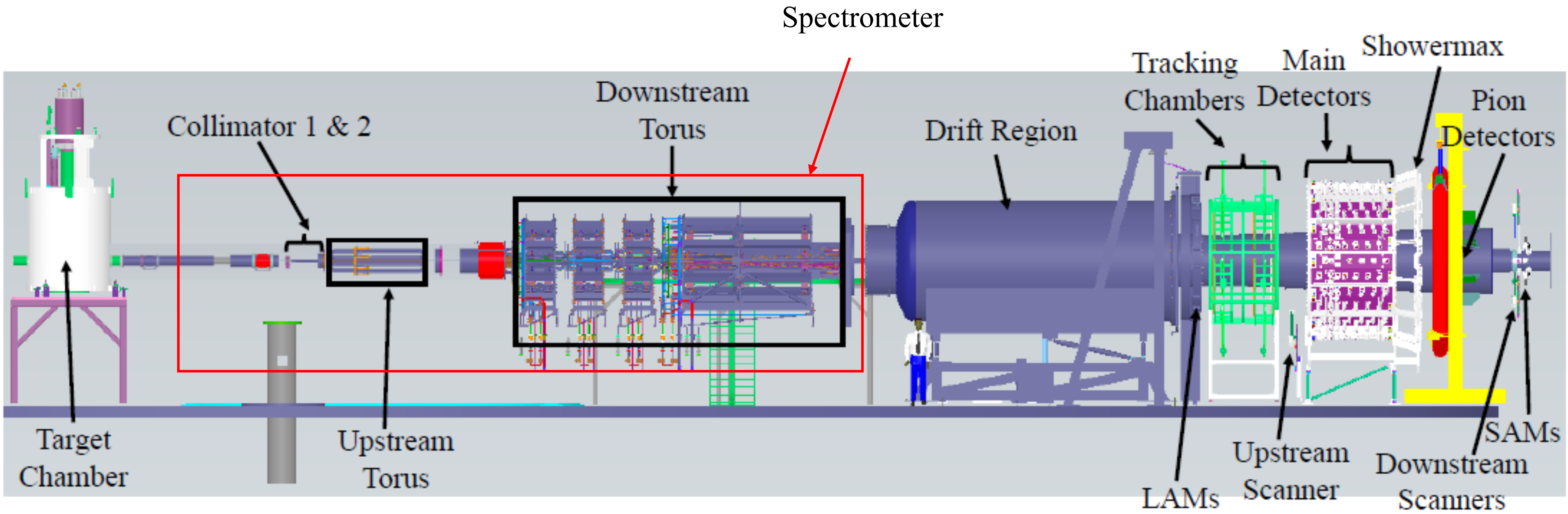
Spectrometer Concept

- Bend scattered particles, separate signal (ee) from background (ep) and photons
- Small angles and high beam power
- Large energy range (2 - 8 GeV)
- Long target (1.25 m liquid hydrogen)



- Two toroidal magnets (Upstream and Downstream)
- Collimation + “shields” or “blockers”
- Vacuum pipe to take beam to dump

Apparatus Overview (from target to dump)

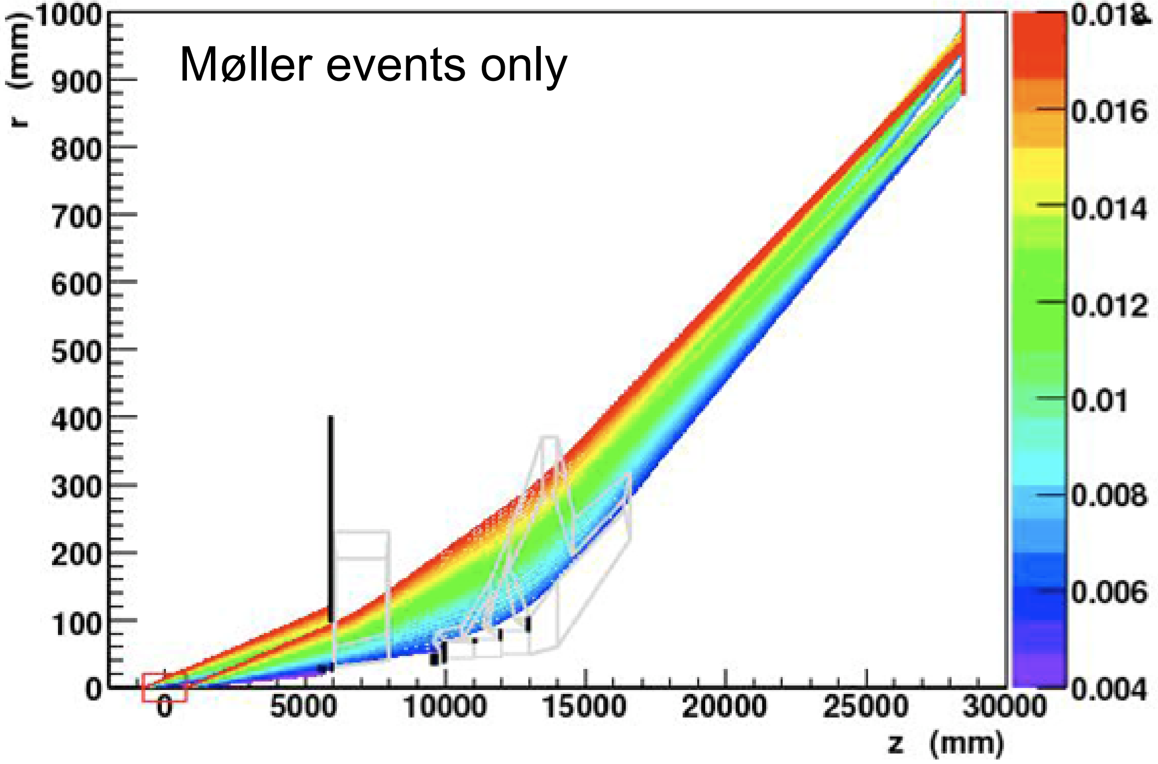


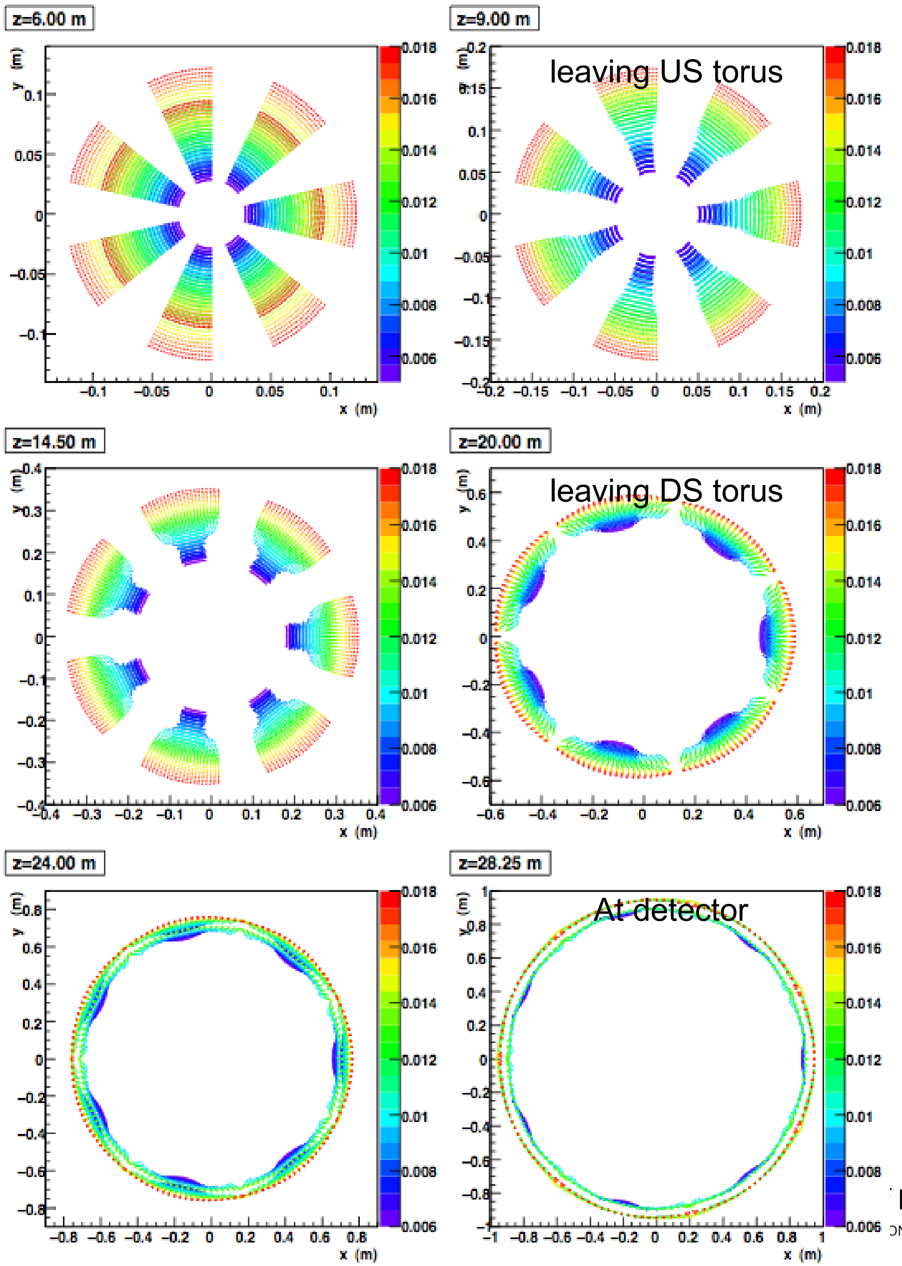
Magnet Concept and Spectrometer Optics

Long and Skinny Design

US Torus DS Torus

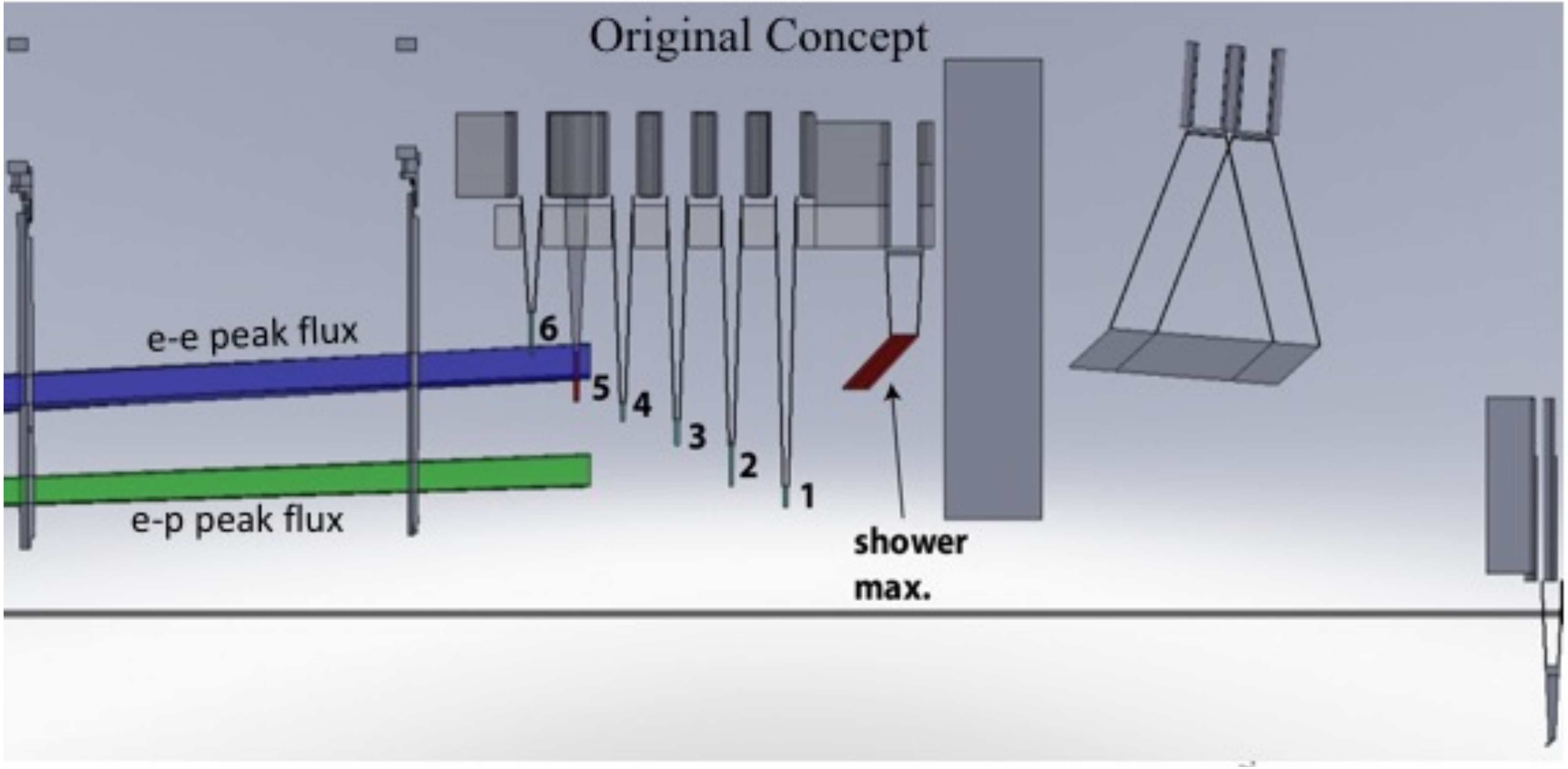
0.5 m x 2 m 0.9 m x 6.5 m





Physicists

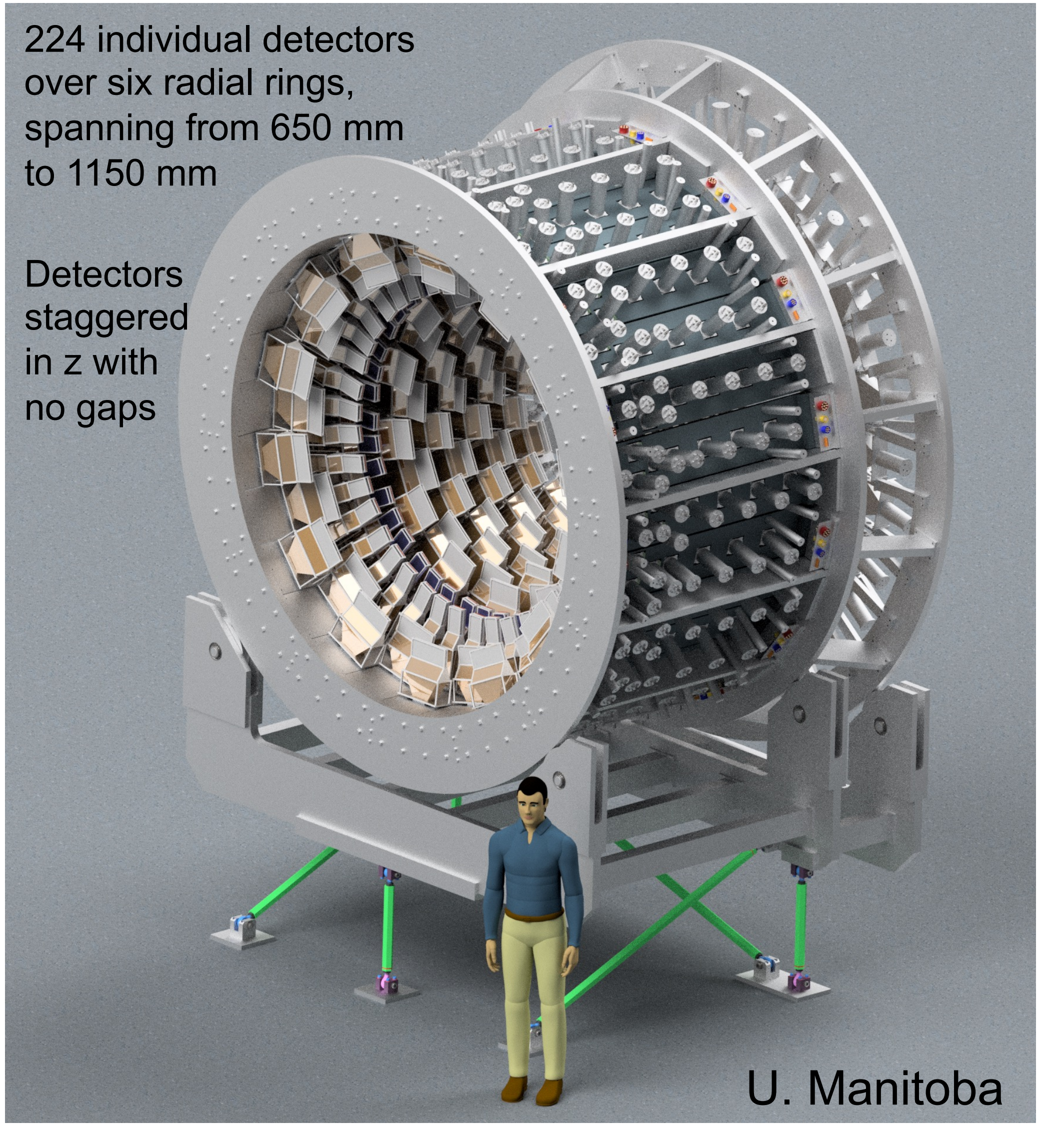
Main Detector (original concept)



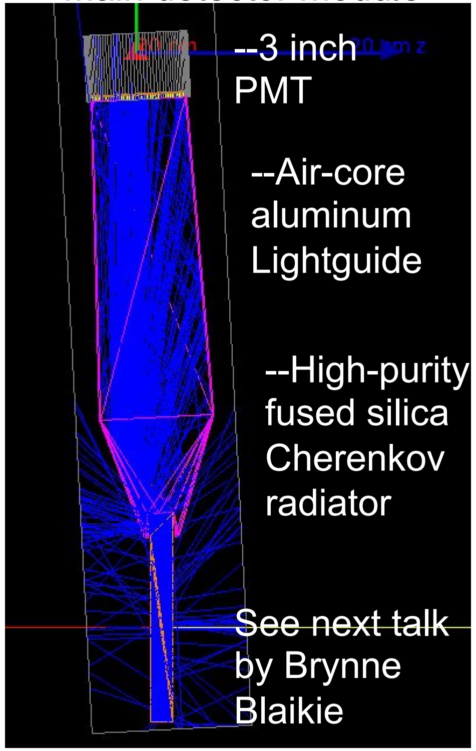
Main Detector

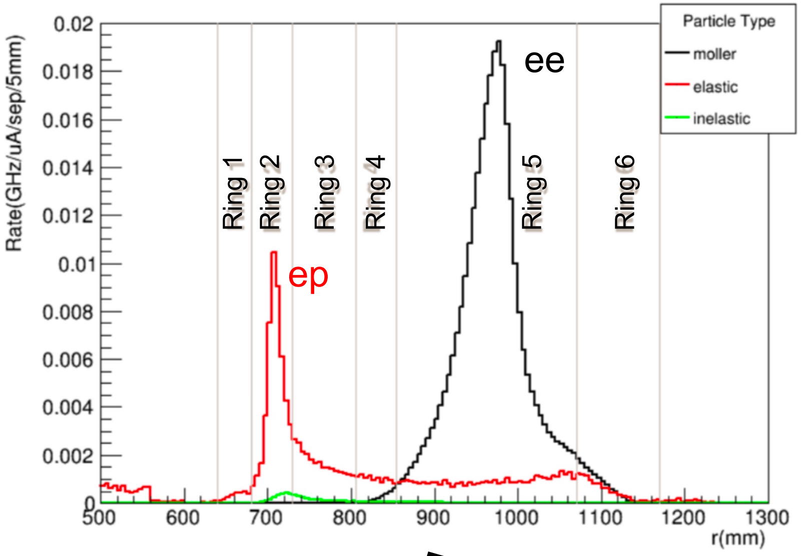
224 individual detectors over six radial rings, spanning from 650 mm to 1150 mm

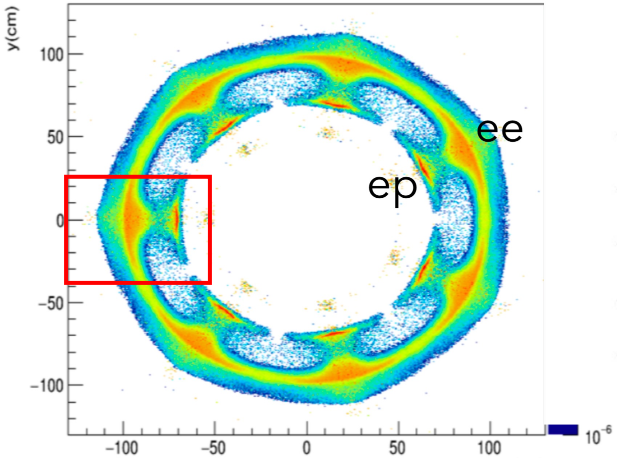
Detectors staggered in z with no gaps

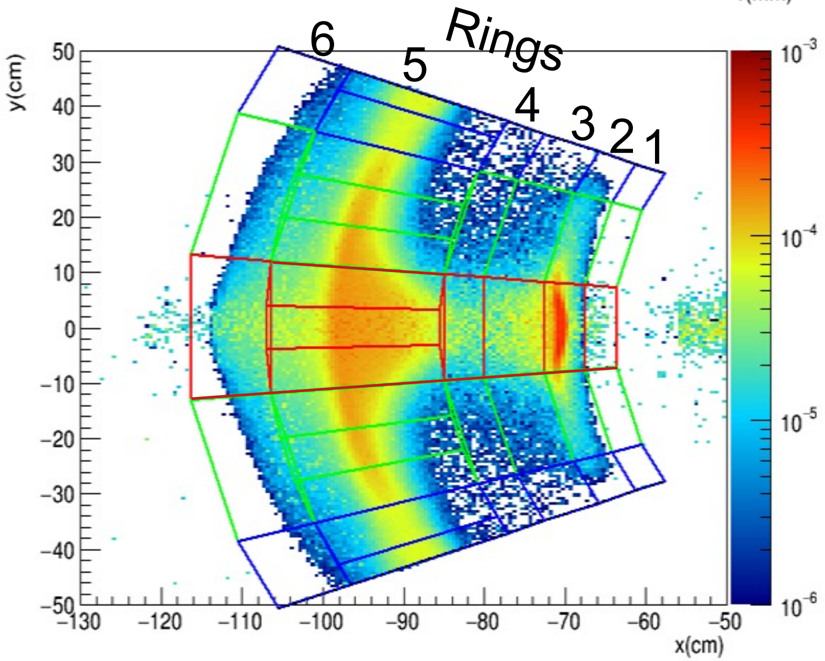


Main detector module



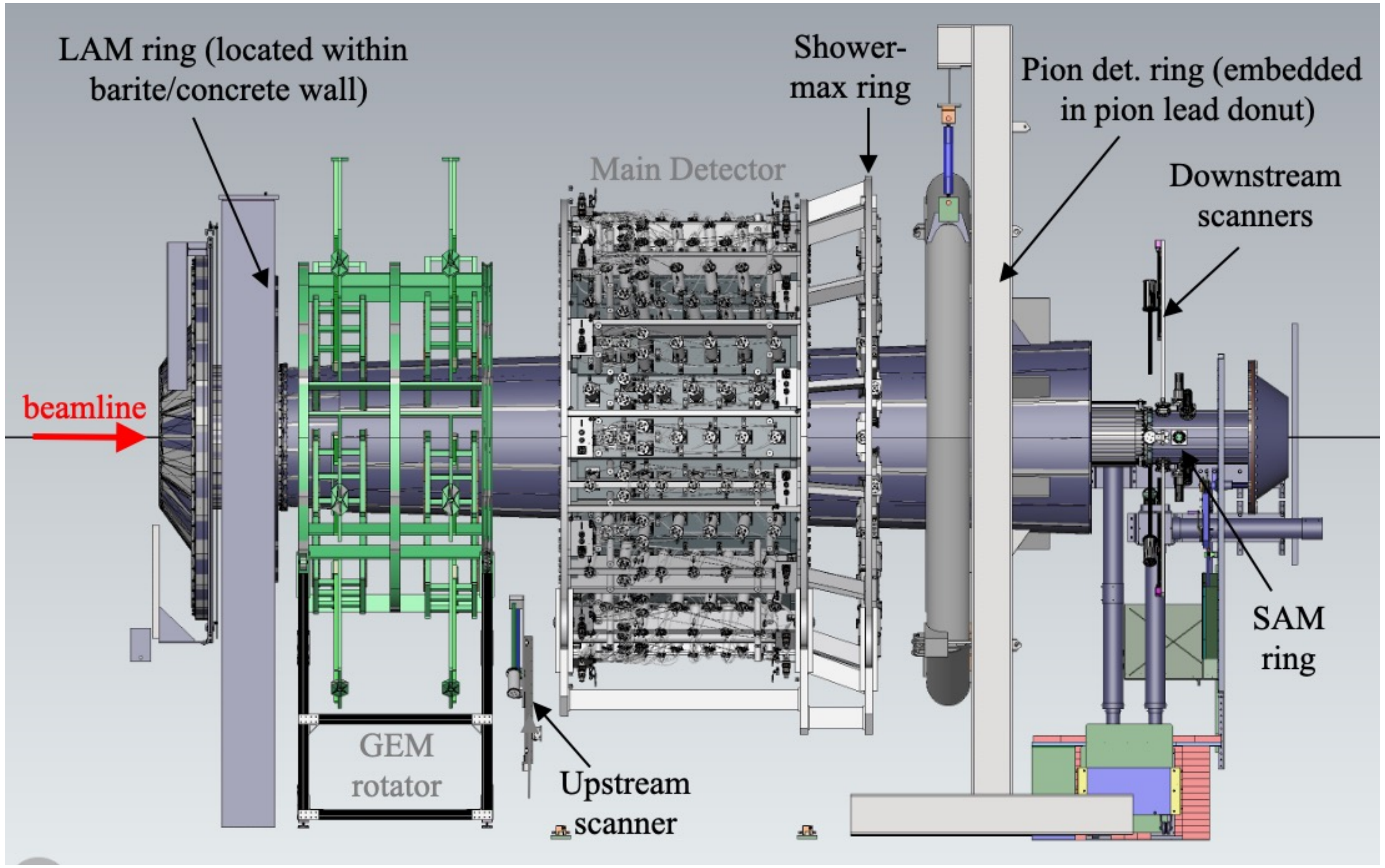






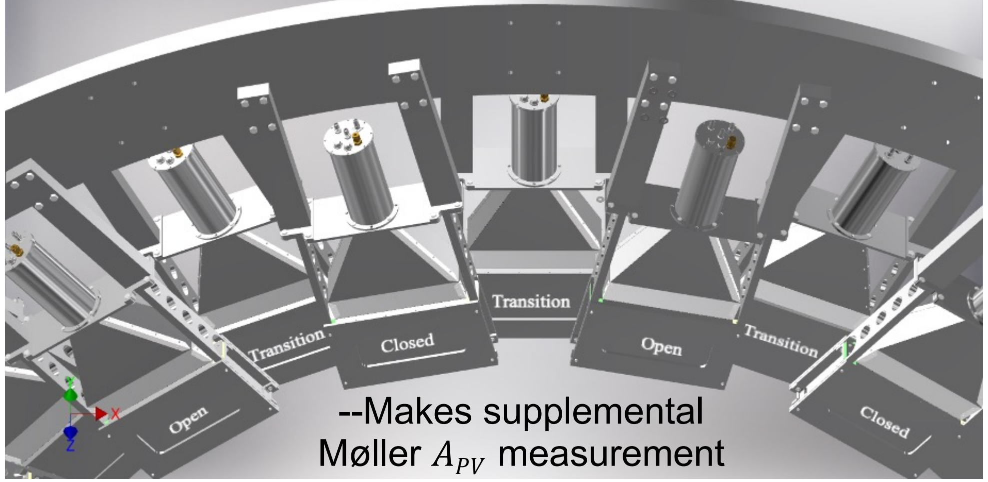
Auxiliary Detectors

✦ Used to monitor and help ensure the quality of experimental setup and production data; Enable increased understanding and control of systematic effects and background asymmetries



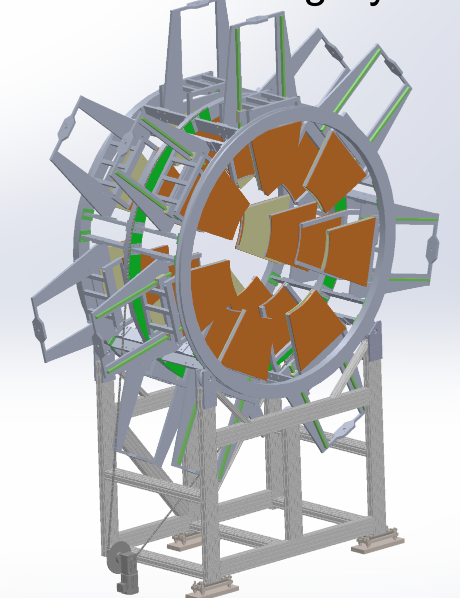
- Various Beam Scattering Monitors: LAM and SAM rings, and upstream and downstream scanners

- Shower-max EM sampling calorimeter



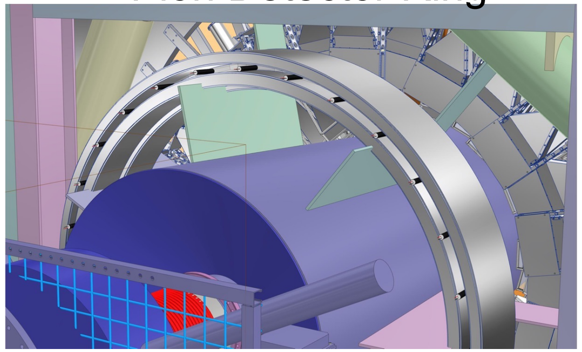
--Makes supplemental Møller A_{PV} measurement

- GEM Tracking System



--For kinematic calibrations

- Pion Detector Ring



--Measures pion bkgd in main and shower-max detectors

Projected Systematic Errors

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
$e + p(+\gamma) \to e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \to e + Al(+\gamma)$	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**

Summary

- MOLLER proposed precision on $\sin^2 \theta_w$ is ~0.1% (on par with most precise collider experiments).
  (This will be a significant test of electroweak theory and provide powerful search for new potential physics)

- MOLLER gives best contact interaction reach for leptons at low or high energy!
  (Need new lepton collider to do better!)

- MOLLER is a fully funded project with a strong collaboration and integrated Jefferson Lab management team; achieved CD-1 project status in Nov 2021, CD-3a in Jan 2023; CD-2/3 review will take place this fall; installation scheduled to start in early 2025 and commissioning in 2026

Thank you!