The MOLLER Experiment

Measurement **o**f a **L**epton **L**epton **E**lectroweak **R**eaction (**MOLLER**)

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Collaboration:
~ 120 authors, 30 institutions, 5 countries
Spokesperson: K. Kumar; UMass, Amherst

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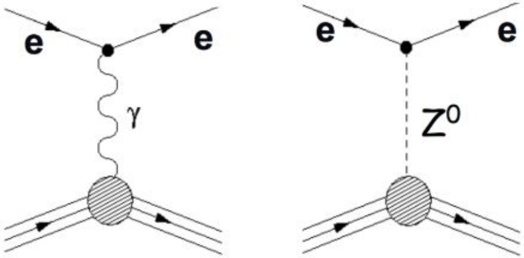
Outline

- Introduction to parity-violating electron scattering
- MOLLER experiment
- Science Context
- Overview of the Experimental Technique
- Summary

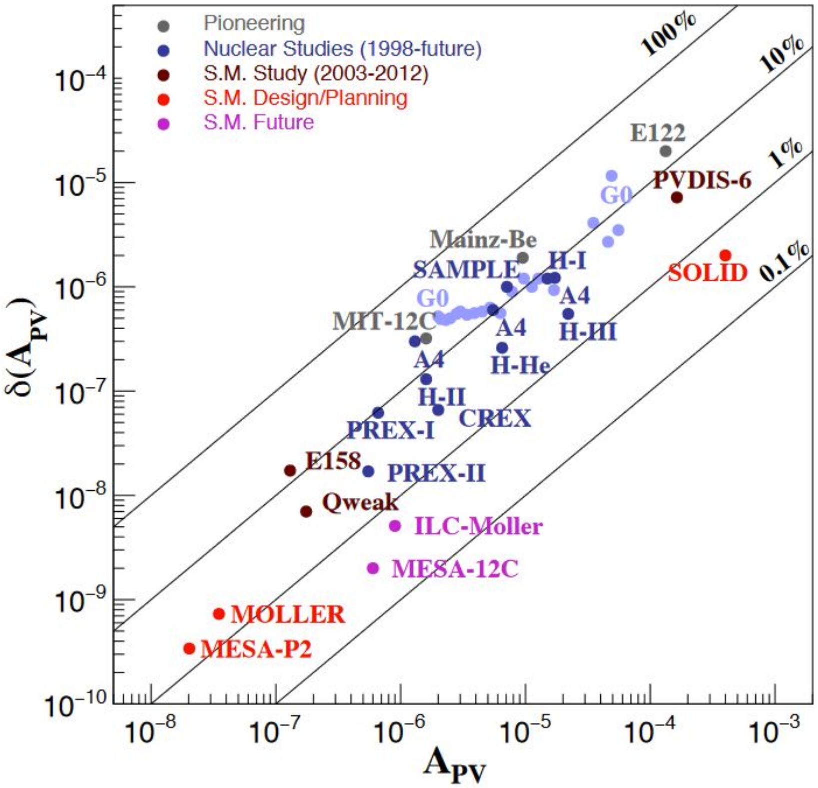
Introduction of Parity-violating electron scattering (PVES)

- Asymmetry of cross-sections of longitudinally polarized electrons off a nuclear target

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



Interference of electromagnetic and weak neutral current amplitude

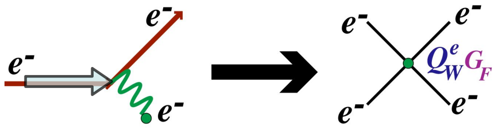


- PVES is used extensively to study nucleon, nuclear structures and for searches of new physics beyond the Standard model.

The Parity-Violating Asymmetry in Electron-Electron Scattering

$$\mathbf{A_{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$

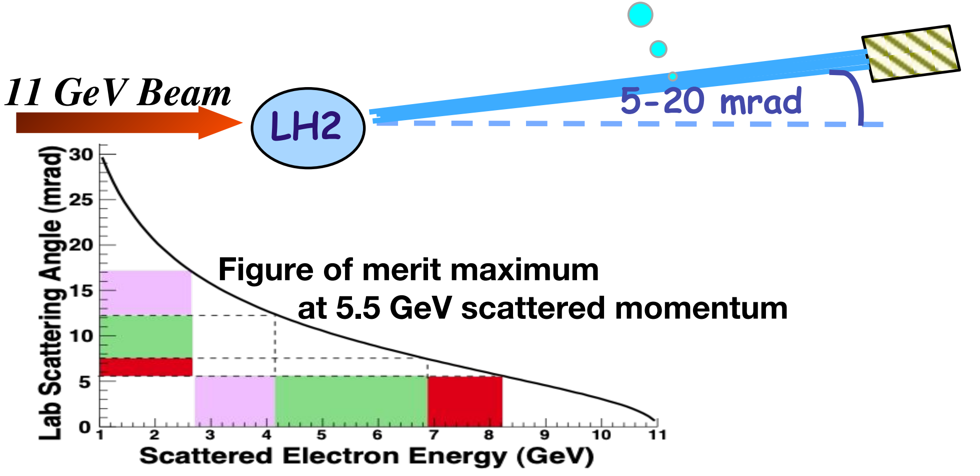
$$Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075$$



Proposed A_{PV} = 33 ±0.8 ppb (2.4%)

Reaction Kinematics

E (GeV)	11
E'(GeV)	2.0 - 9.0
Beam Current	65 (μA)
Polarization	~90%
Luminosity	2.4E39 $cm^{-2}S^{-1}$
MOLLER rate	134 GHz
Run time	344 PAC days



A Fundamental Parameter of the Electroweak Theory
The Weak Mixing Angle

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

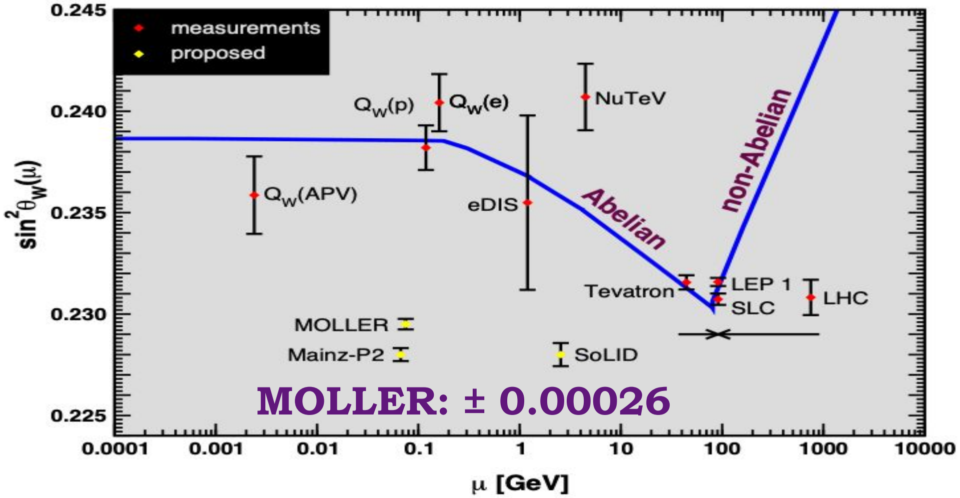
$$= -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

MOLLER Projection:

$\delta(\sin^2\theta_W)$ = ± 0.00023 (stat.) ± 0.00012 (syst.)

~0.1% measurement



MOLLER A_{pv} would be the first low Q^2 measurement comparable to the single best measurement at Z-pole

MOLLER measurement is the best among projected sensitivities for new measurements at low Q^2 or colliders over the next decade

Reaction at $Q^2 \ll M_Z^2$ is calculable to high accuracy

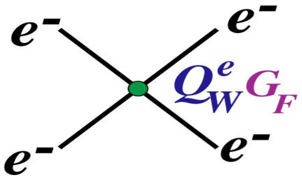
± 5σ discovery potential at $Q^2 \ll M_Z^2$

(ultra)-weak-electromagnetic interference

Weak Charge Measurements

leptonic and semi-leptonic weak neutral current amplitudes

$$\left|\mathrm{A}_\gamma + \mathrm{A}_\mathrm{Z} + \mathrm{A}_\mathrm{new}\right|^2 \rightarrow \mathrm{A}_\gamma^2\left[1+2\left(\frac{\mathrm{A}_\mathrm{Z}}{\mathrm{A}_\gamma}\right)+2\left(\frac{\mathrm{A}_\mathrm{new}}{\mathrm{A}_\gamma}\right)\right]$$



$$\mathrm{Q}^\mathrm{e}_\mathrm{W} \sim 0.045$$

$$\frac{\delta \mathrm{Q}^\mathrm{e}_\mathrm{W}}{\mathrm{Q}^\mathrm{e}_\mathrm{W}} = 2.4\%$$

$$\boxed{\mathrm{A}_\mathrm{new} \sim 0.001 \cdot \mathrm{G}_\mathrm{F}}$$

UNPRECEDENTED SENSITIVITY

$$\mathcal{L}_{\mathrm{e_1 e_2}} = \sum_{\mathrm{i,j=L,R}} \frac{\mathrm{g}^2_\mathrm{ij}}{2\Lambda^2} \bar{\mathrm{e}}_\mathrm{i}\gamma_\mu \mathrm{e}_\mathrm{i} \bar{\mathrm{e}}_\mathrm{j}\gamma^\mu \mathrm{e}_\mathrm{j}$$

Λ - is the scale of new dynamics

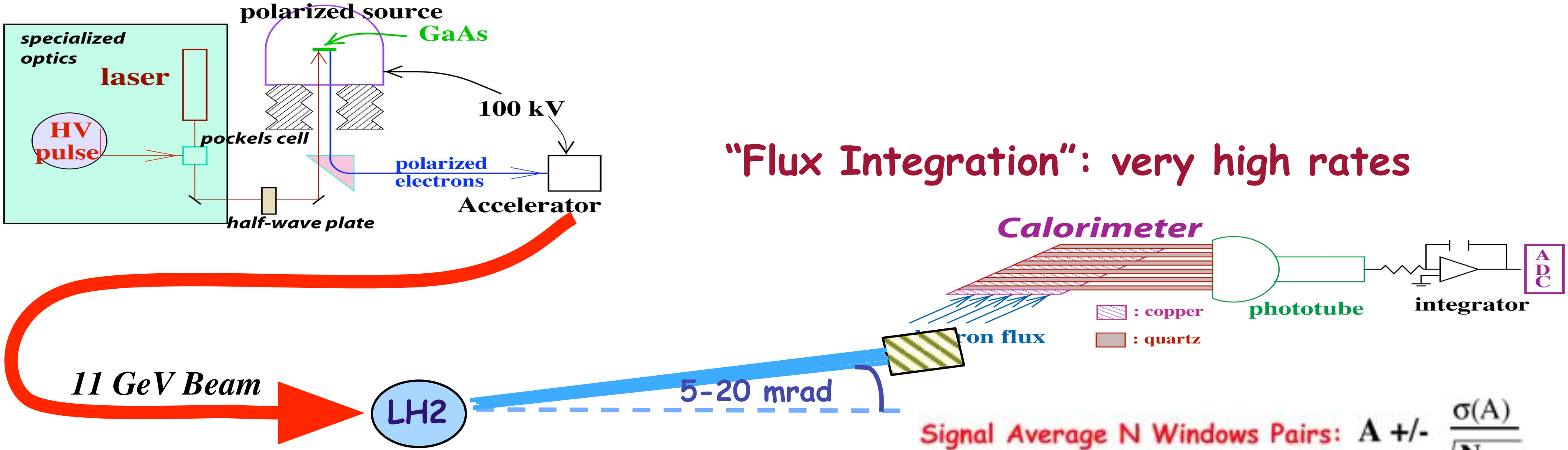
g_{ij} - is the strength of the interaction

$$\frac{\Lambda}{\sqrt{|\mathrm{g}^2_\mathrm{RR} - \mathrm{g}^2_\mathrm{LL}|}} = 7.5\ \mathrm{TeV}$$

If g_{ij}~1, then MOLLER measurement has the potential to probe new dynamics ~10 TeV Scale!!

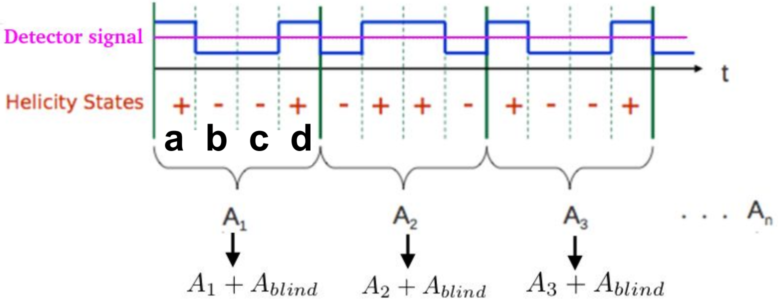
Technique Overview

"Flux Integration": very high rates

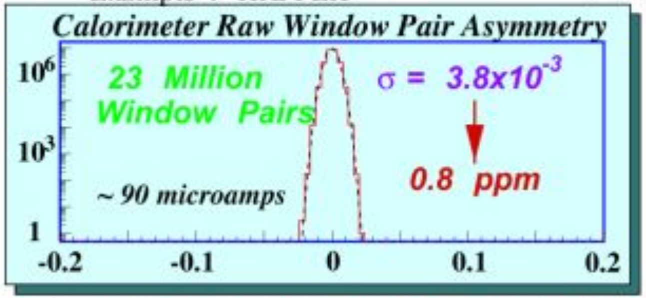


Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{windows}}}$

Example : HAPPEX



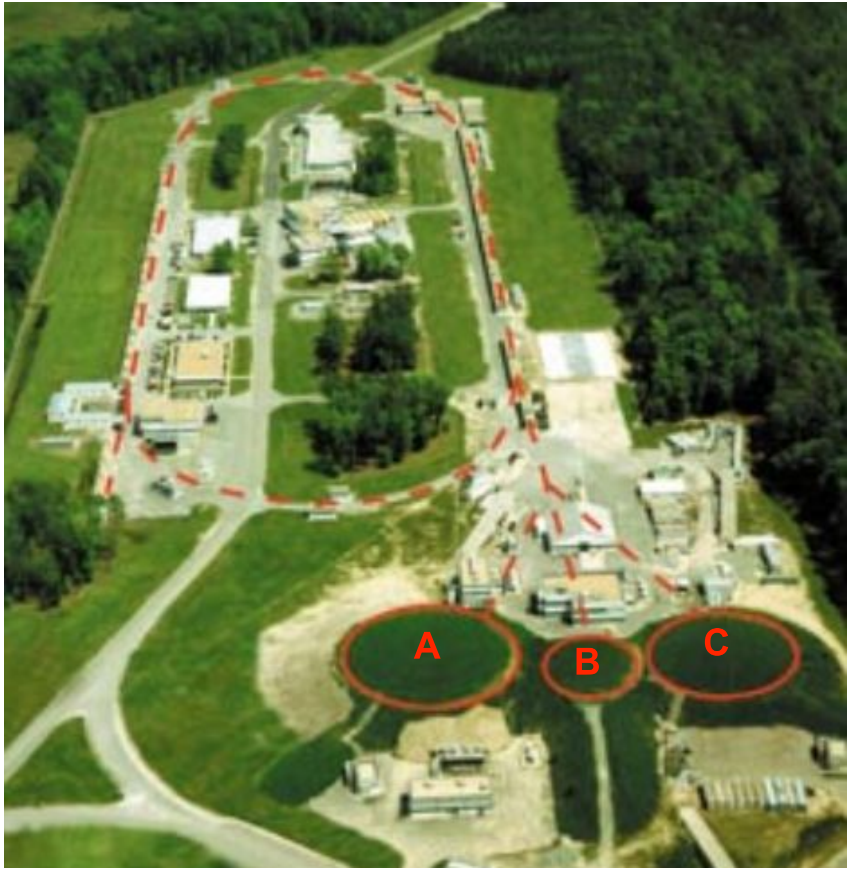
Rapid and Random helicity flip

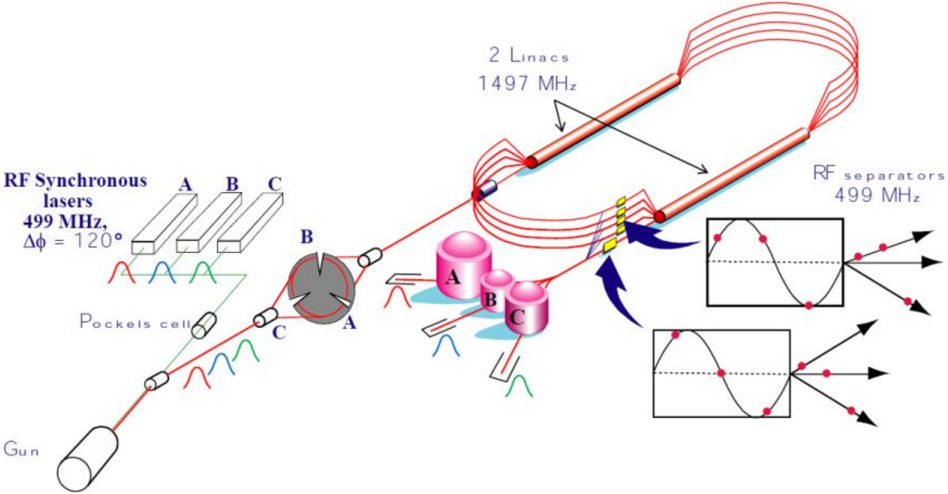


A1 = (a-b-c+d)/(a+b+c+d)

No non-gaussian tails to +/- 5σ

Jefferson Lab - is the best place for its excellent beam!!

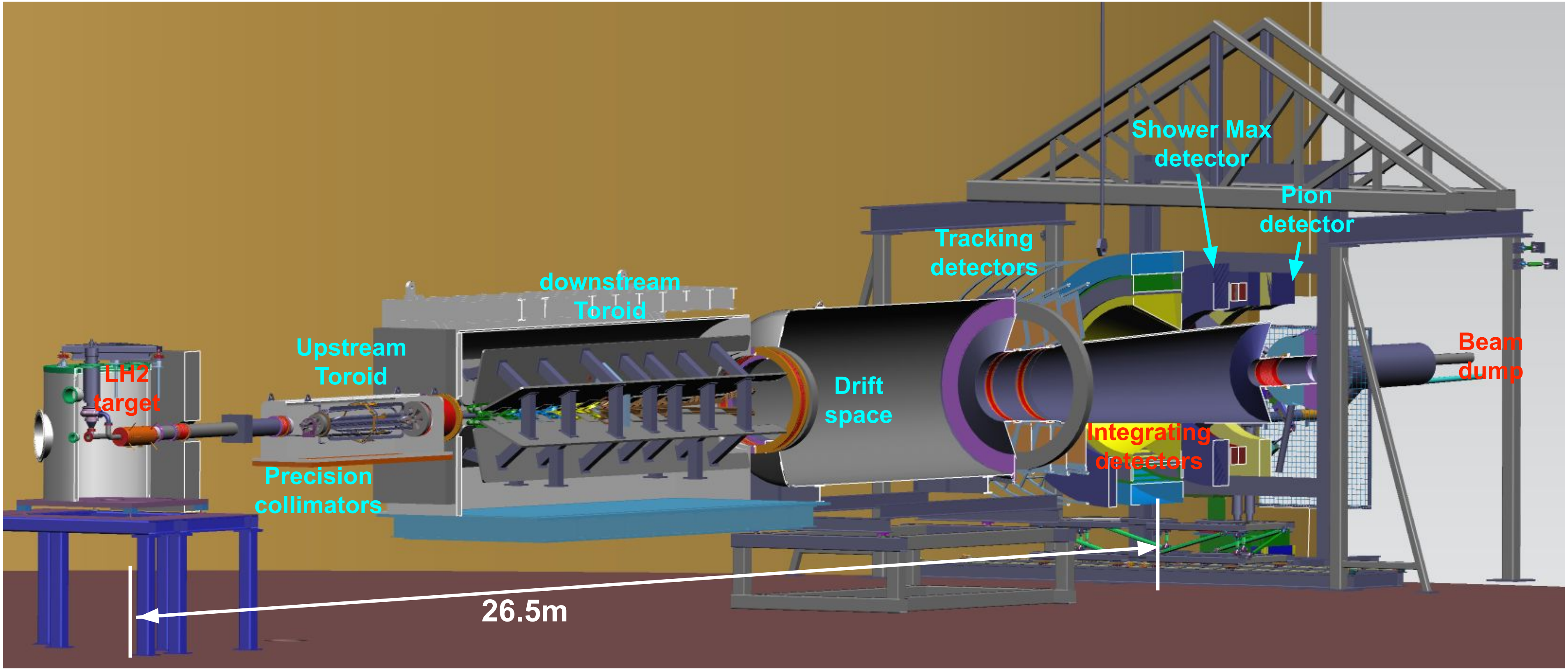




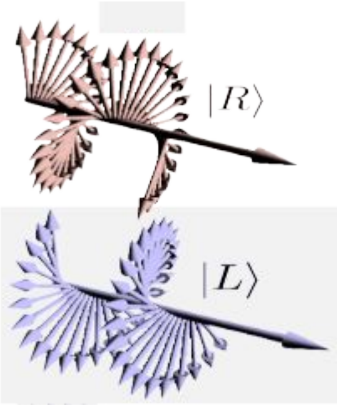
Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

MOLLER in Hall A at Jlab

Unique opportunity leveraging the 12 GeV Upgrade investment

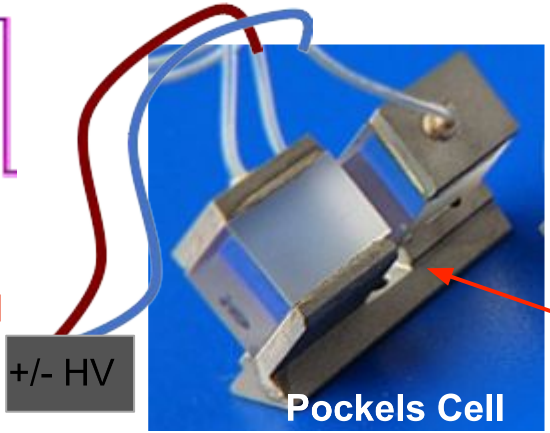


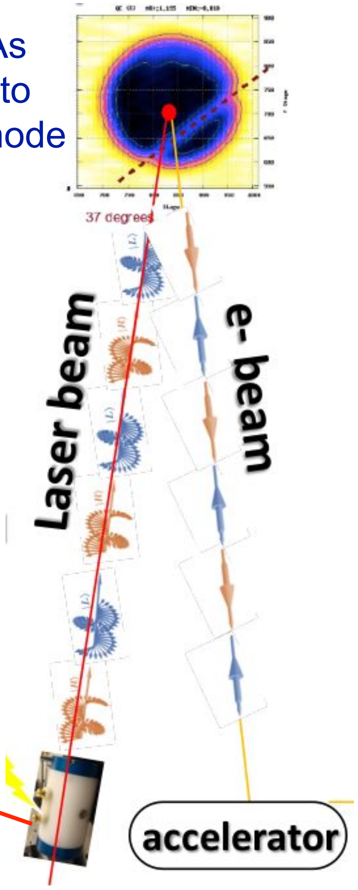
Polarized Electron Source

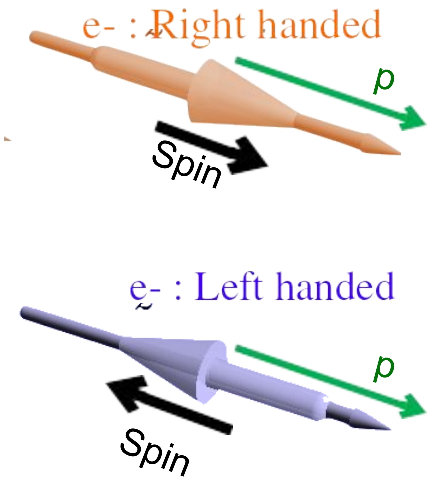


Circularly polarized light

Randomized Helicity Signal





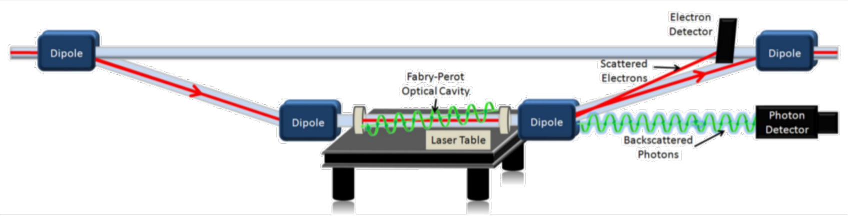


Identical (as much as possible) beams for two-helicity states

Helicity flip is rapid and random:
1.92 kHz flip rate to keep systematics under control

Polarimetry in the experimental Hall

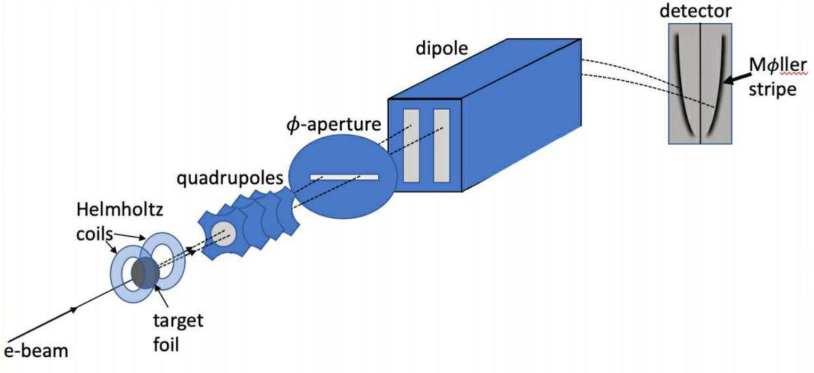
Compton Polarimetry



- Continuous, non-invasive measurement
- Utilized integrating technique with photon detector
- Evaluated systematic uncertainty
- Polarimeter runs will be taken continuously alongside the main detector data

Polarization systematic goal = 0.4%

Moller Polarimetry



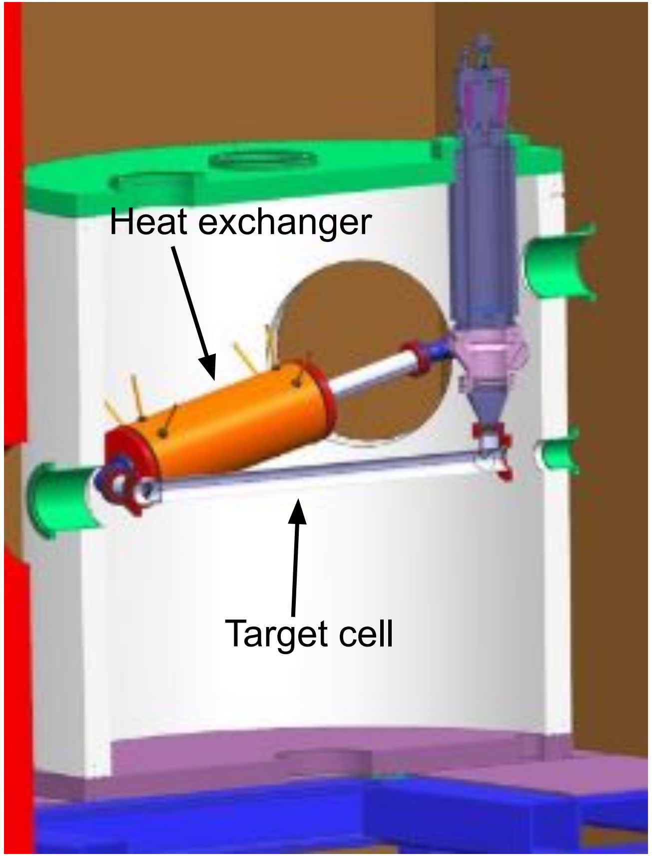
- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Spectrometer redesigned for 11 GeV
- Polarimeter runs will be taken approximately every week

CREX Collaboration (part of MOLLER collaboration too) reported $P_e = 87.09 \pm (0.44\%\ dP_e/P_e)$

Target - The high power LH2 target built ever!!

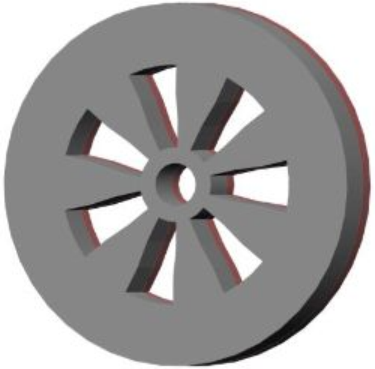
Cell length	125cm
Cell Thickness	9 g/cm^2
Radiation length	14.6%
pressure, Temperature	35 psia, 20K
θ, ϕ Acceptance	5-20 mrad, 2π
LH2 pump flow	25 l/s
Target Power	**4 kW**

LH2 relative density reduction - $\Delta\varrho/\varrho$ < 1% at 65 μA
LH2 density fluctuations - $\delta\varrho/\varrho$ < **30 ppm at 1920 Hz**

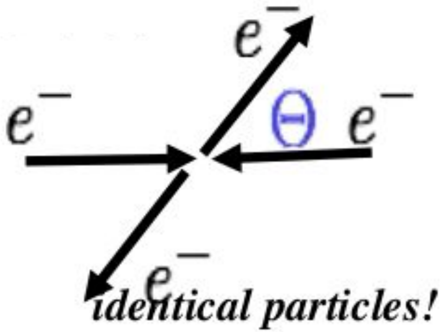


Collaboration has extensive expertise to build such target system

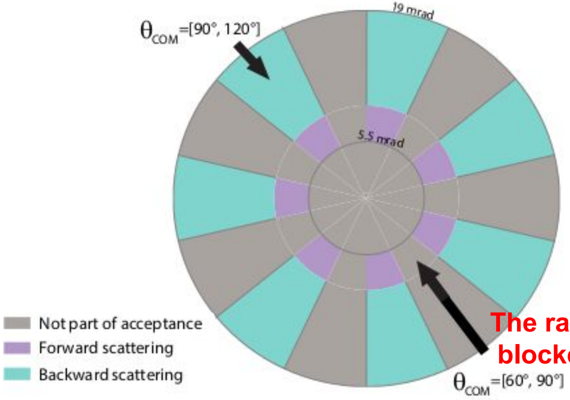
Precision Collimator systems



Acceptance defining collimator
- 7-fold symmetry

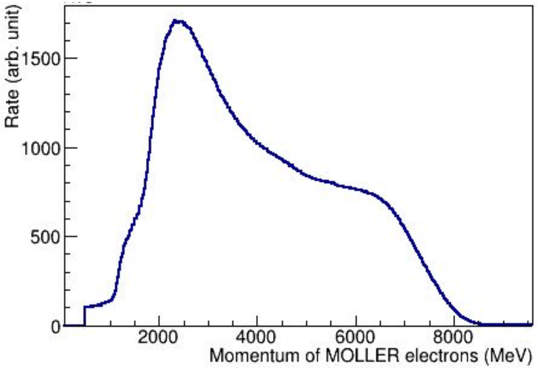


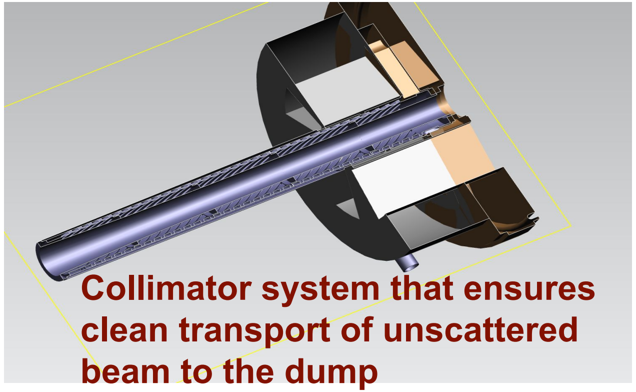
Their partners are collected over here..



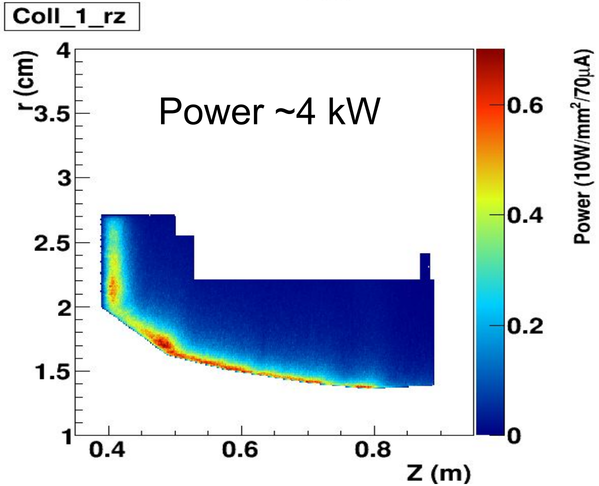
The rays that are blocked here..

Momentum distributions

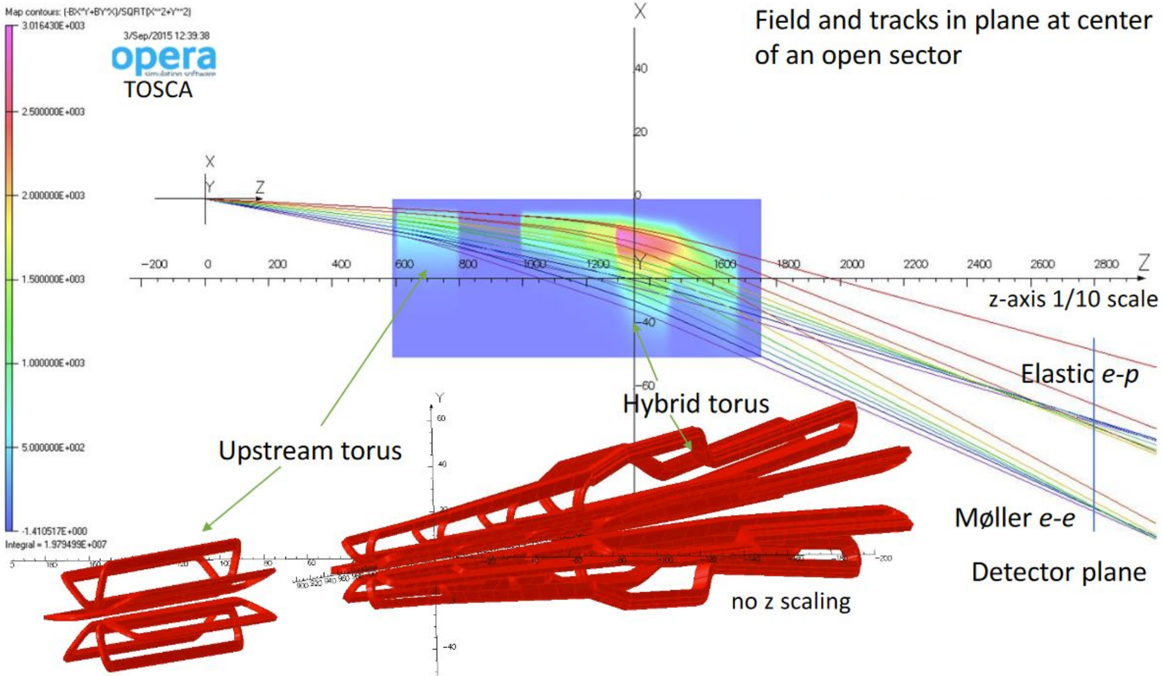


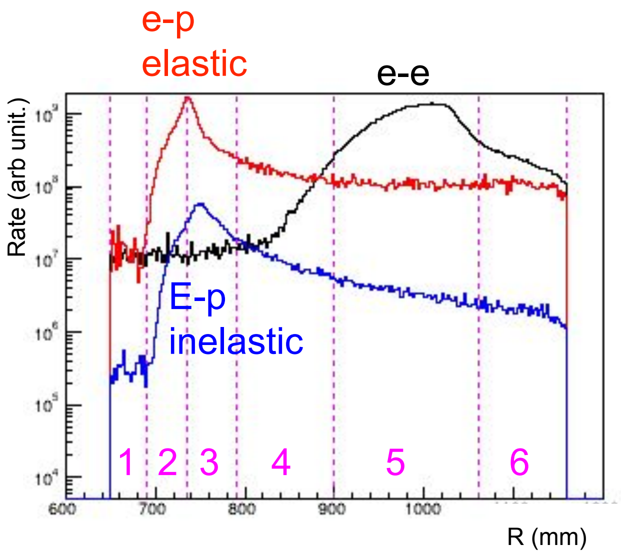


Collimator system that ensures clean transport of unscattered beam to the dump



Spectrometers



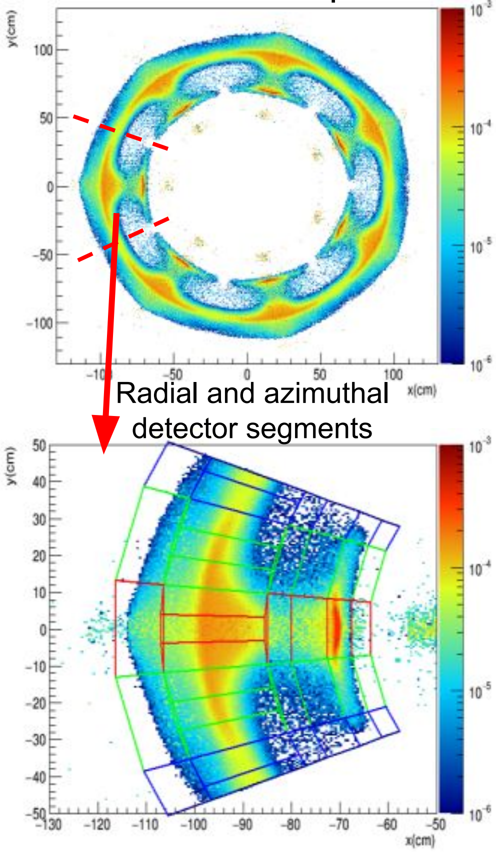


Rate distributions

- The odd number of coils allow for 100% acceptance by always detecting one of the two electrons involved in the scattering
- The spectrometer allows us to separate the Møller electrons from the different backgrounds (largest being e-p elastic)

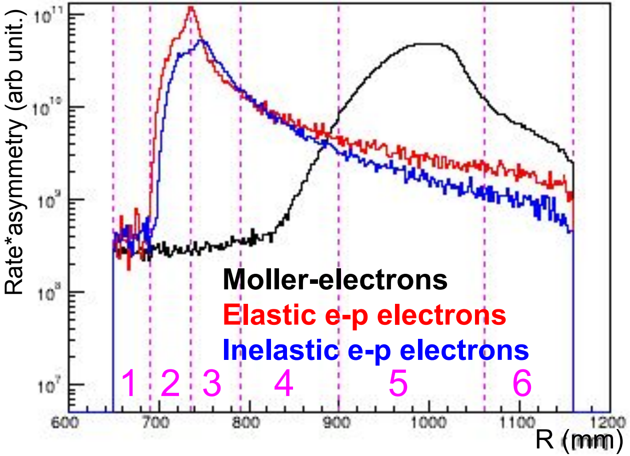
Integrating detector -Array of thin Cherenkov detectors

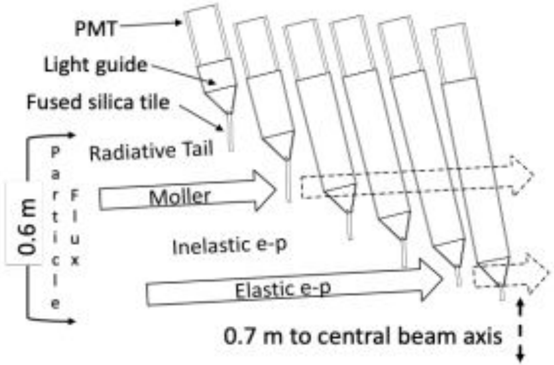
At the detector plane

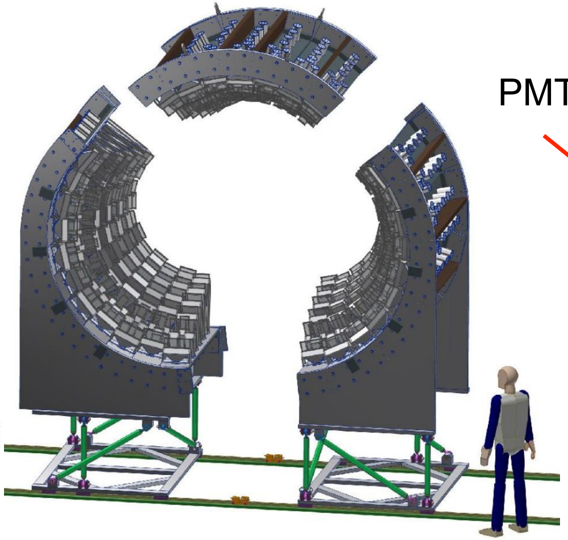


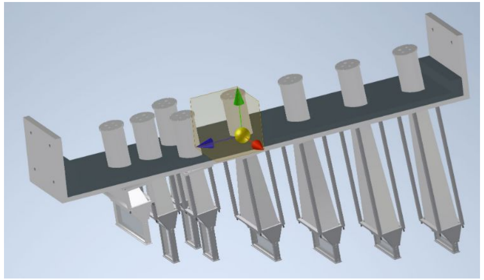
Radial and azimuthal detector segments

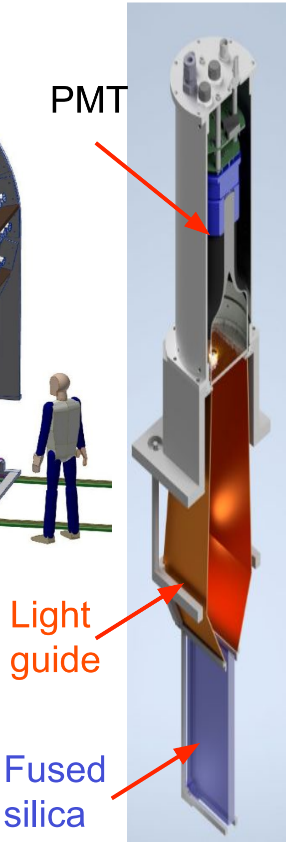
Rate*Asymmetry distributions



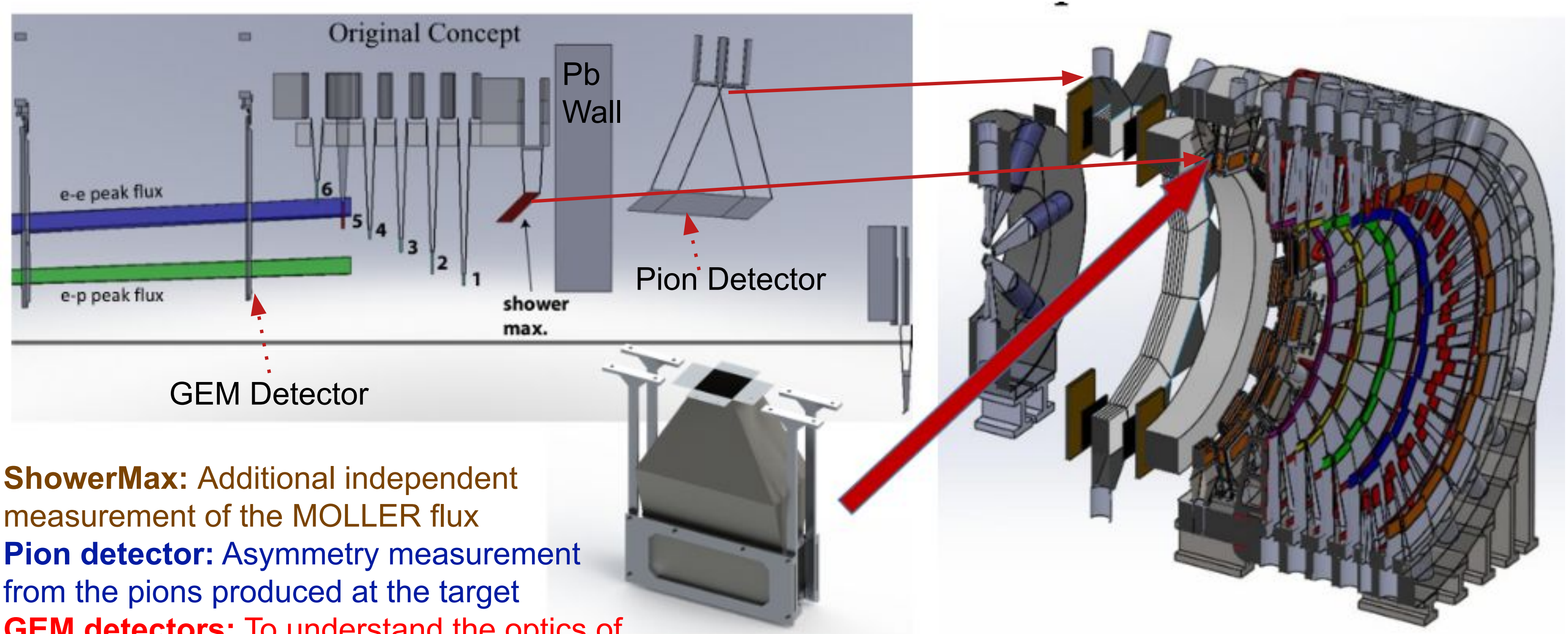








Auxiliary detector systems



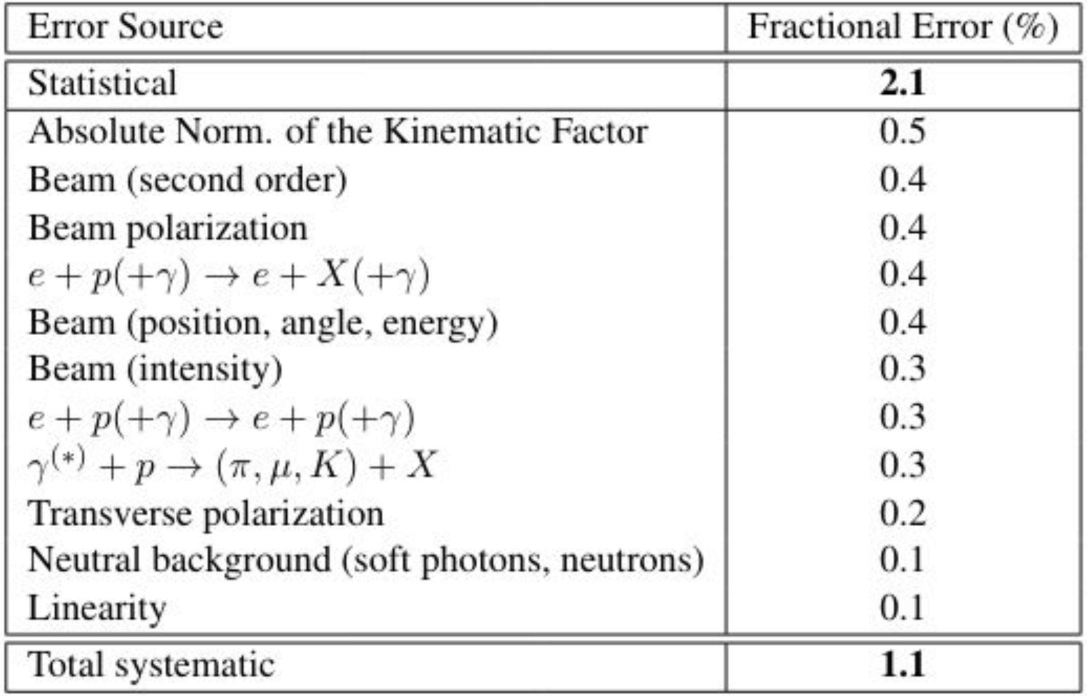
ShowerMax: Additional independent measurement of the MOLLER flux

Pion detector: Asymmetry measurement from the pions produced at the target

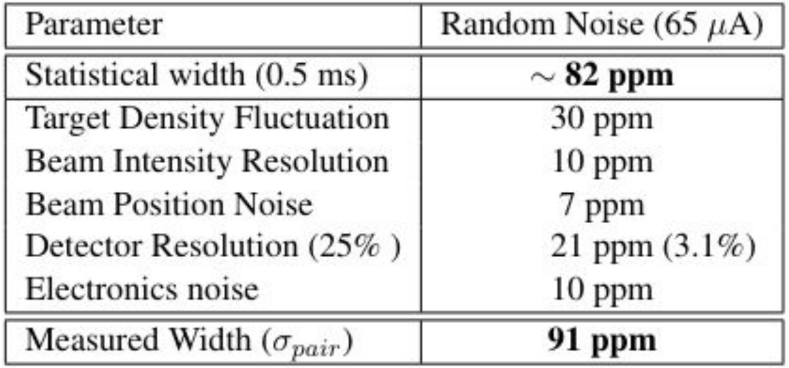
GEM detectors: To understand the optics of the spectrometer and rate distributions of particles at the detector plane

Array of Integrating detectors

Statistical and Systematic Error Budgets



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



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**

$$\sigma_{A_{expt}} = \frac{\sigma_{pair}}{\sqrt{(8.3\times 10^{7}.N_{days})}} = 0.54\ \text{ppb}$$

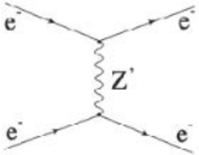
$$A_{expt} \sim 26\ \text{ppb}$$

$$A_{pv} = \frac{\frac{A_{expt}}{Pe} - f_b A_b}{1 - f_b} \sim 33\ \text{ppb}$$

Collaboration has performed many successful parity experiments at Jefferson Lab

-Developed expertise on different subsystems

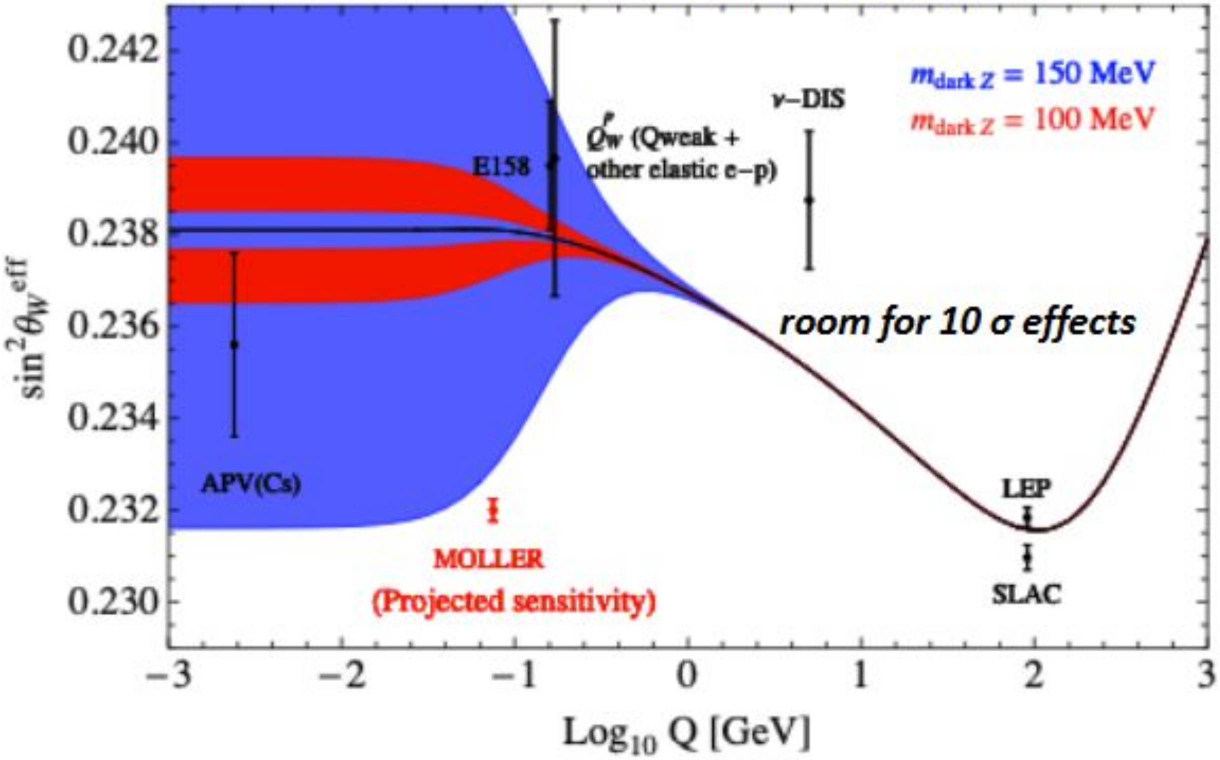
One (of many) new physics potentials



Heavy Photons
(A' mixed with Z_0):
The Dark Z

- Models can accommodate the existence of new bosons that would have a large impact at low Q^2

H. Davoudiasl, H-S. Lee and W. Marciano



Summary

- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (the 11 GeV CEBAF beam) created by the JLab 12 GeV upgrade
- The science case remains compelling and the intention is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- An enthusiastic and well-experienced international collaboration is working for the design, construction, operation and physics analysis of the experiment.
- Currently, at engineering design phase; First physics run - end of 2025.

- Thank You

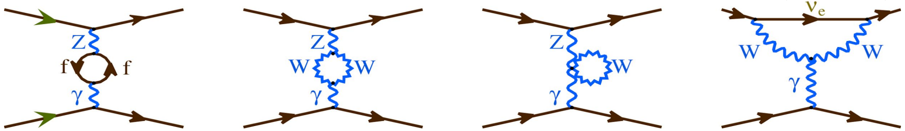
Appendix

Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

$$
\begin{aligned}
A_{PV} &= \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\Big\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}} \\
&+ \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2] \\
&+ F_1(y,Q^2)+F_2(y,Q^2)\Big\}
\end{aligned}
$$

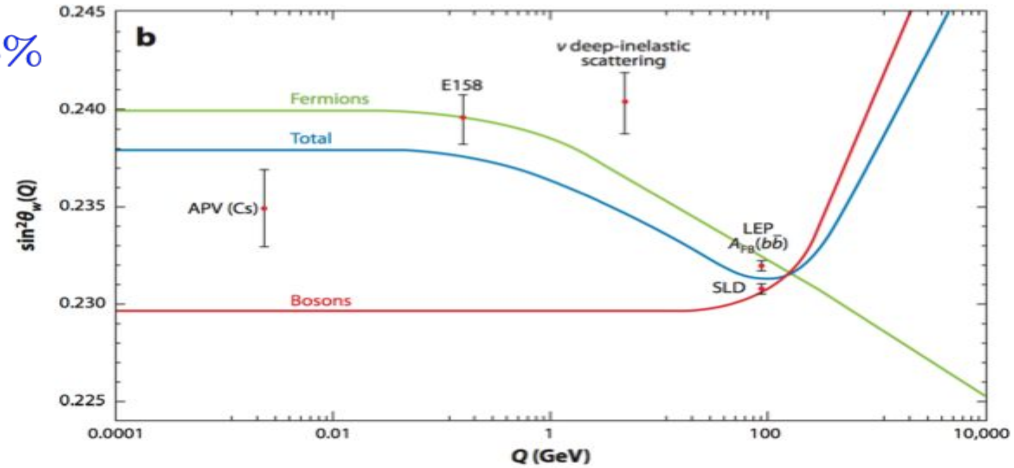
Czarnecki and Marciano (1995)



$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on “normalization” errors



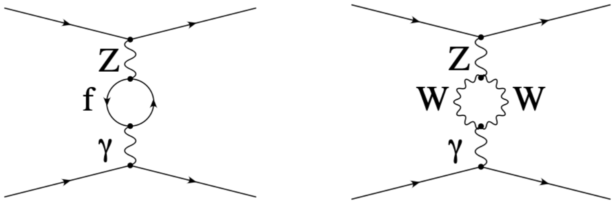
Theory Prediction

EW Theory Prediction Uncertainty Well Below Projected Experimental Uncertainty

Czarnecki and Marciano (1995)

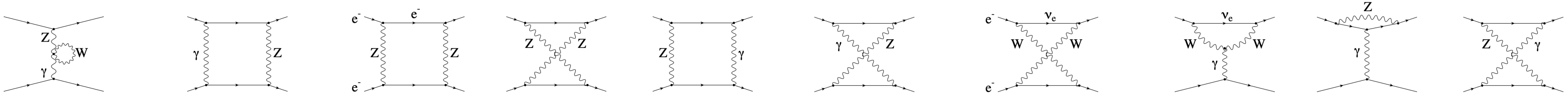
$$A_{PV}(ee) \propto \rho G_F \left[1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\mathrm{MS}}}\right] + \cdots$$

Dominant Contribution at 1-loop



κ(0) known to 1% of itself

Erler and Ramsey-Musolf (2003)



Report submitted to DOE in September 2016: response to Science Review recommendation

$\delta(Q^e_W)$ (theory) ~ 1.4%, expect to achieve < 0.5% with compete treatment of 2-loop

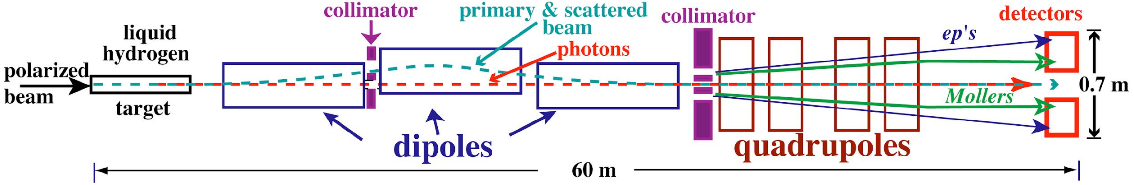
MOLLER $\delta(Q^e_W)$ goal = ± 2.1 % (stat.) ± 1.1 % (syst.)

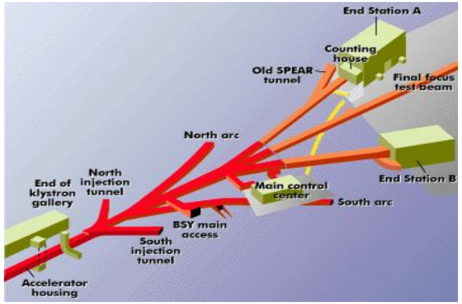
First PVES Measurement with TeV-scale sensitivity

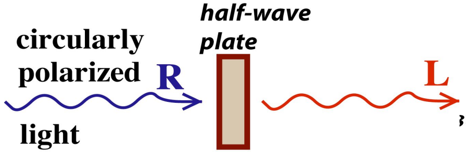
Previous Measurement: SLAC E158

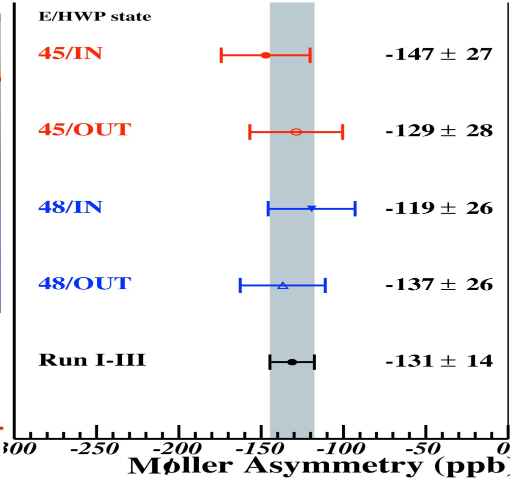
1997-2004

~ 10 ppb raw sensitivity at highest E_{beam} ~ 0.5% error on weak mixing angle







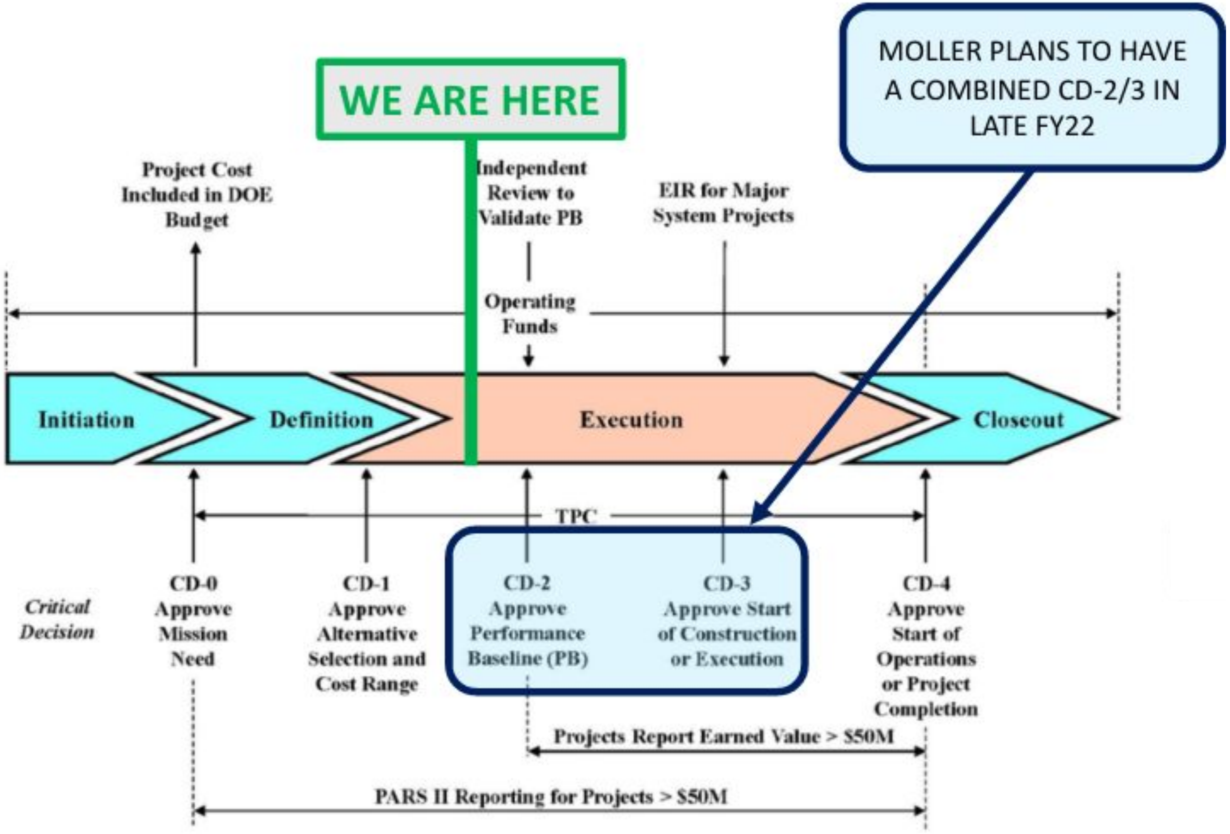


$$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$$

Phys. Rev. Lett. **95** 081601 (2005)

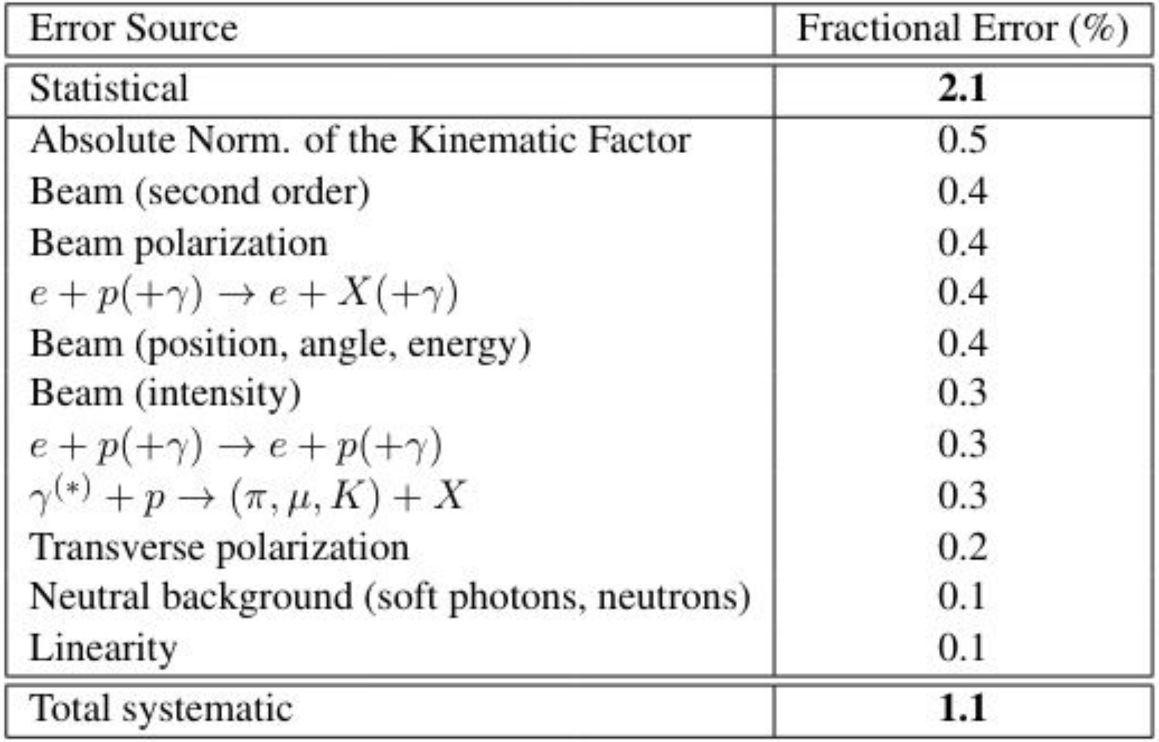
Project Status

Typical DOE Acquisition Management System



- **Approved the Critical Design (CD) 1 status by the Office of Nuclear Science, Department of Energy on December 2020.**
- Collaboration is planning for the CD2/3 review by late 2022 or early 2023.
- Projected end of physics running mid-2028.

Statistical and Systematic Error Budgets



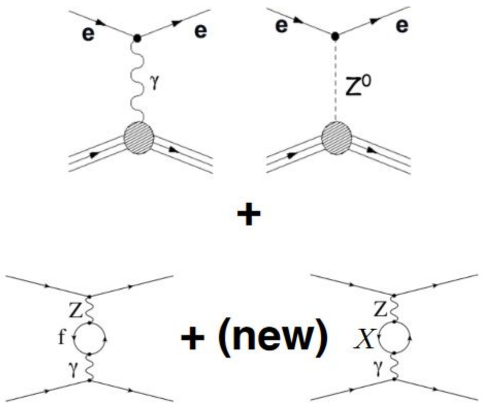
Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Norm. of the Kinematic Factor	0.5
Beam (second order)	0.4
Beam polarization	0.4
$e + p(+\gamma) \rightarrow e + X(+\gamma)$	0.4
Beam (position, angle, energy)	0.4
Beam (intensity)	0.3
$e + p(+\gamma) \rightarrow e + p(+\gamma)$	0.3
$\gamma^{(*)}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

Run	**% Stat. error**	**Eff. (%)**	**PAC days**
1	11.0	40	14
2	4.05	50	95
3	2.43	60	235
Total	**2.1**		**344**

Collaboration has performed many successful parity experiments at Jefferson Lab

-Developed expertise on different subsystems

Complementarity to LHC indirect searches



+ NNLO + .. + N∞LO

- In the absence of direct measurements the LHC has also focused on setting limits based on deviations from SM calculations
- While the HL-LHC will set new limits to hadronic interactions the unique lepton-lepton interaction used by MOLLER could only be matched by a new e^+e^- collider or neutrino factory

e^+e^- Collisions	LEP200 Reach	$\Lambda_{LL}^{ee} \sim 8.3$ TeV
Fixed Target	E158 Reach	$\Lambda_{LL}^{ee} \sim 12$ TeV
	MOLLER Reach	$\Lambda_{LL}^{ee} \sim 27$ TeV