MOLLER

Eric King – Temple University

2024 Hall A/C Summer Meeting

Intro: The MOLLER Experiment

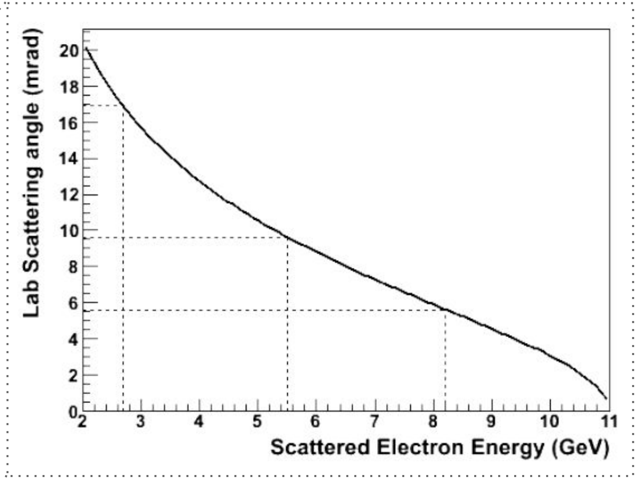
- **M**easurement **O**f a **L**epton-**L**epton **E**lectroweak **R**eaction
- Measure the weak mixing angle θ_W / weak charge of the electron Q_W^e
- Predicted A_{PV} ~32ppb
  - ΔA_{PV} ~0.8ppb
  - Gives a measurement of $Q_W^e[Q^2 = 0.0056 GeV^2] \pm 2.4\%$
- 344 PAC days

  $\Rightarrow$ 3 years of running

Run Period	1 kHz Width	PAC Days (prod)	Stat Error $\sigma(A_{meas})$	$\sigma(A_{PV})$	Efficiency	Calendar Weeks (prod)	(calib)
I	101	14	2.96 ppm	11.4%	40%	5	6
II	96	95	1.08 ppm	4.2%	50%	27	3
III	91	235	0.65 ppm	2.5%	60%	56	4
Total		344	0.55	2.1		88	13

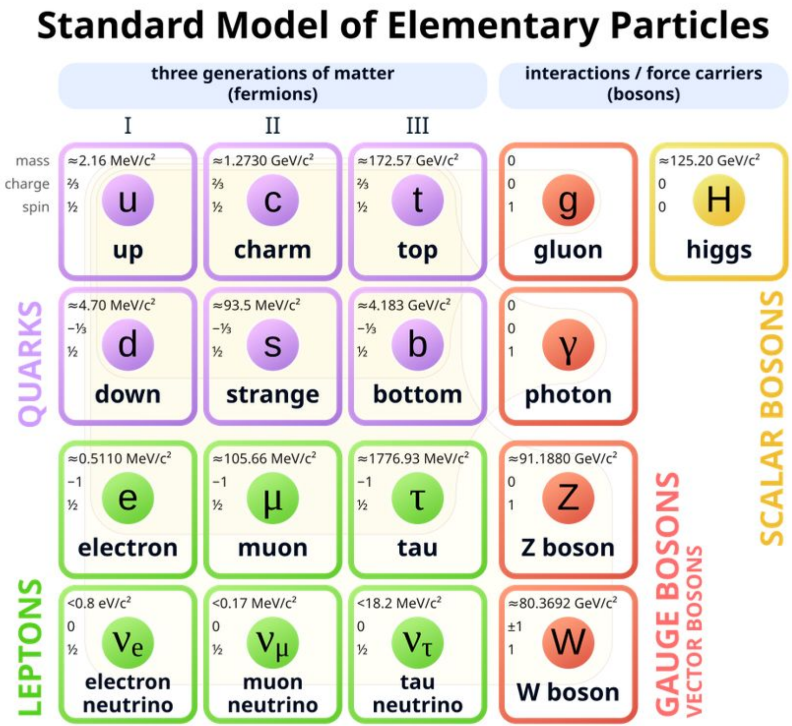
Intro: MOLLER Experiment Parameters

- Beam: Energy ~11GeV, ~70uA, 90% pol
- Target: 125cm liquid hydrogen
- Moller scattering angles 60° - 120° COM
  - 2 - 8 GeV scattering energy
  - 6 - 21 mrad lab angle
- Moller e- rates @ 65uA ⇒ 134GHz
- Errors: 2.1% (stat) + 1% (sys) = 2.4% (total)
- Will achieve a sensitivity of $\delta(\sin^2(\theta_W)) = \pm 0.00028$



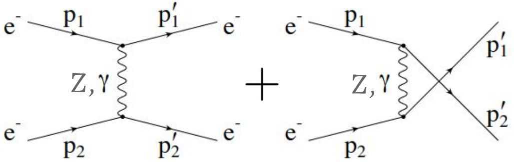
Physics: Standard Model [of Particle Physics]

- Physics most-successful theory
  - Describes 3 of 4 known forces
    - Strong (QCD)
    - Electroweak (QED + Weak)
  - Accurately describes observed particle interactions
  - Has made many successful predictions
    - $W^{\pm}$, Z^{o} , t , b , H.



Physics: Parity-violating Møller Scattering

- CEBAF produces a polarized e-beam of alternating helicity
- Measuring the parity-violating asymmetry gives us access to the weak charge of the electron – Q_W^e
    - This allows us to extract a value for $\sin^2(\theta_W)$

$\sigma =$ 

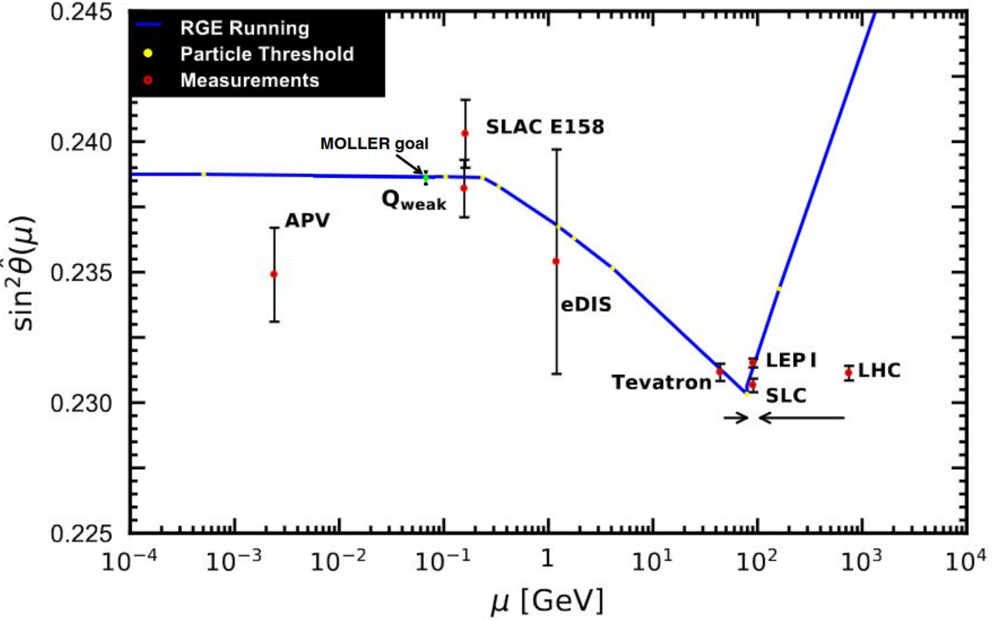
There are higher-order corrections

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

Particle	Q_{EM}	Q_W
u, c, t	$-\frac{2}{3}$	$+1 - \frac{8}{3}\sin^2\theta_W$
d, s, b	$+\frac{1}{3}$	$-1 + \frac{4}{3}\sin^2\theta_W$
e, μ, τ	-1	$-1 + 4\sin^2\theta_W$
p	+1	$1 - 4\sin^2\theta_W$
n	0	-1

MOLLER: Experimental Impact

- MOLLER will measure $\sin^2(\theta_W)$ at $Q^2 << M_Z^2$
- A high-precision at low Q^2 will allow comparisons of $\sin^2(\theta_W)$ across the running Q^2 range
- The MOLLER $\sin^2(\theta_W)$ measurement will match the precision of data taken at the Z-pole



MOLLER: Experimental Impact

MOLLER will continue to push the envelope in A_{PV} and $\delta(A_{PV})$

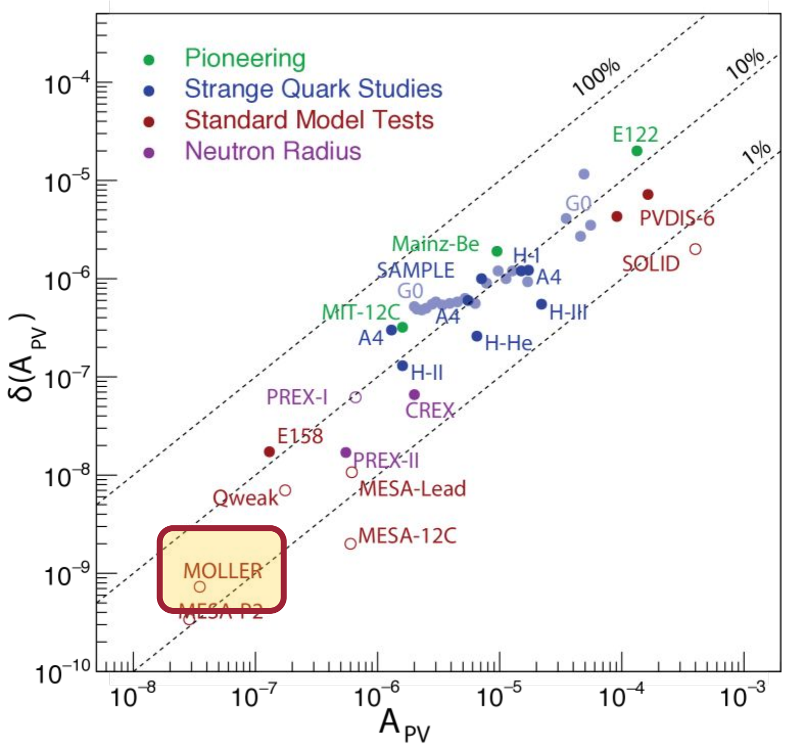


Image taken from P2 Experiment Paper arXiv:1802.04759v2

MOLLER: Experimental Impact

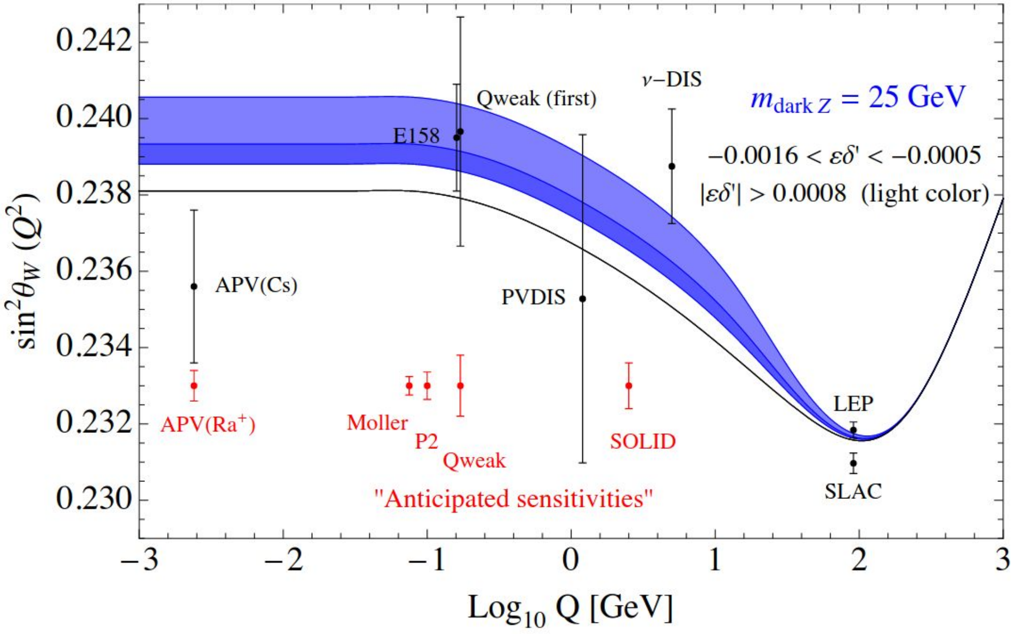
Can we learn anything new?

MOLLER's high-precision measurement of $\sin^2(\theta_W)$ in this region of interest has the potential to reveal new physics.

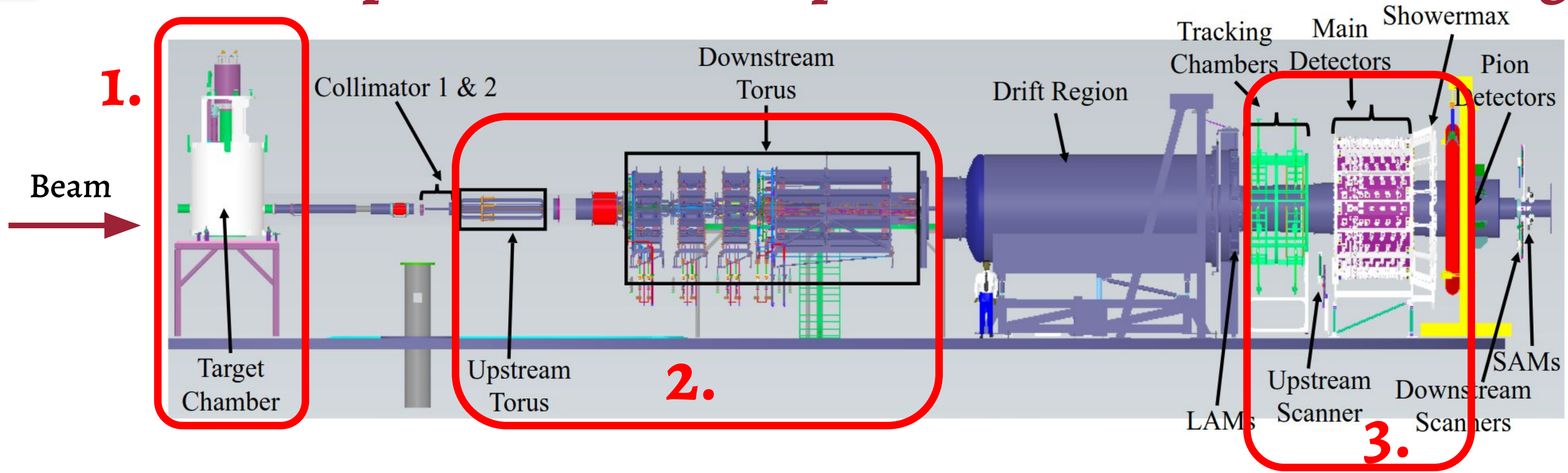
We're sensitive enough to examine our results for deviations from the Standard Model prediction.

No promises.

Low Q2 Weak Mixing Angle Measurements and Rare Higgs Decays – Maciano and Lee 2016



MOLLER Spectrometer: Experimental Beamline Design

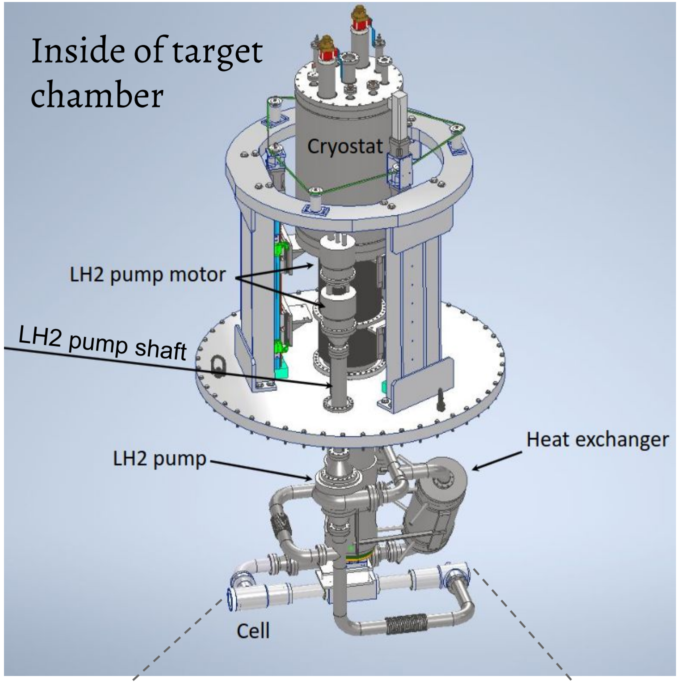


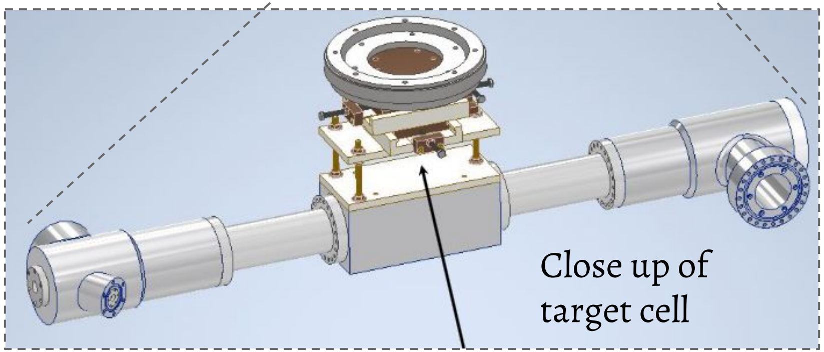
1. Electron beam scatters on liquid hydrogen target: Møller scattering & Mott scattering are the main processes.
2. Two regions of toroid magnets focus the Møller electrons towards the main detectors while separating out the ep-elastic scatters.
3. Detectors integrate the total track signal – I'll touch on the main detector here
    - Supplementary detectors systems: SAMS (Small angle monitors), Pion detectors (calorimeters) behind lead donut, GEM trackers, Showermax Detectors

MOLLER Spectrometer: Target

Target Specs:

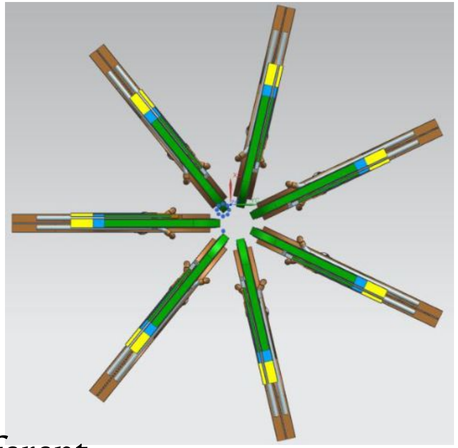
- Liquid hydrogen LH2
- Length: 125 cm ⇒ thickness: 9g/cm^2
- Rad Length: 14.6%
- Pressure: 35 PSIA
- Cryo-temp: 20K
- Angular acceptance (θ): 5-20 mrad
- Target power: 4000 W





*Images taken from Silviu's MOLLER Meeting May 2024 Slides

MOLLER Spectrometer: Magnet Design



- Spectrometer designed for 7-fold symmetry around beam axis
  - Odd-fold symmetry covers azimuthal acceptance
  - Five-fold disfavored due to optics; 9-fold constrained by space

- Shape of the toroid field magnets designed to separate out scatters from different interactions
  - Elastic moller scatters
  - Elastic e-p scatters

- The upstream torus provides early bending with a couple meters of drift space before downstream torus magnets separate by momentum creating the Moller e- focus on the detector.

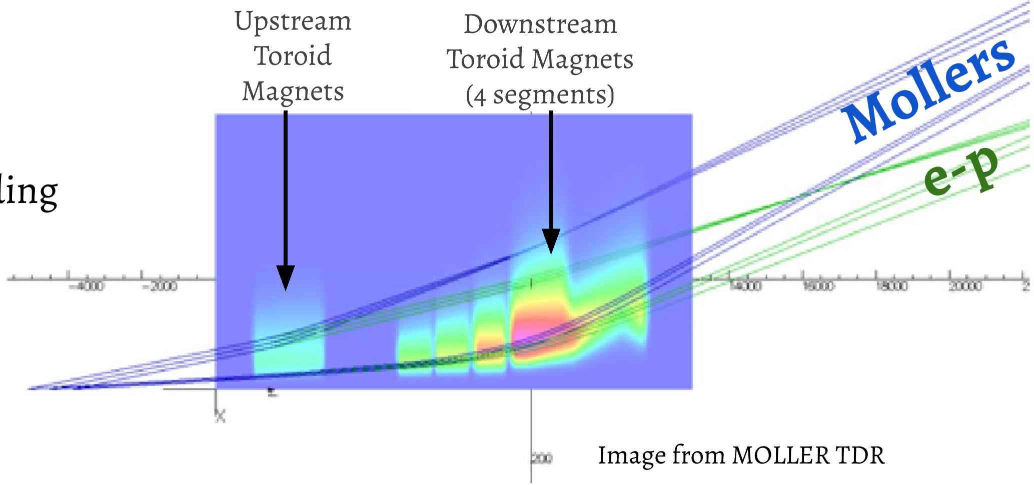


Image from MOLLER TDR

MOLLER Spectrometer: Main Detector

- Average electron rate over the detector is about 50kHz/mm^2, peak rates can exceed 1MHz/mm^2.
  - Pixel detectors and pulse detection, perhaps possible, would be cost prohibitive.
- Main detector consists of six segmented rings with a total of 224 quartz tiles.
  - Each connected to a PMT
- Moller scattering events are focused onto ring 5 of the detector.

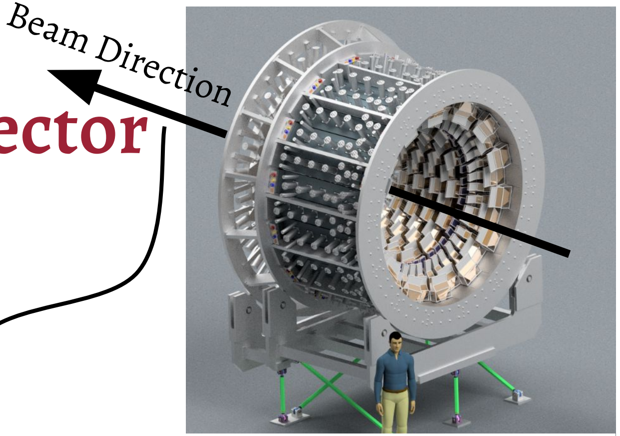
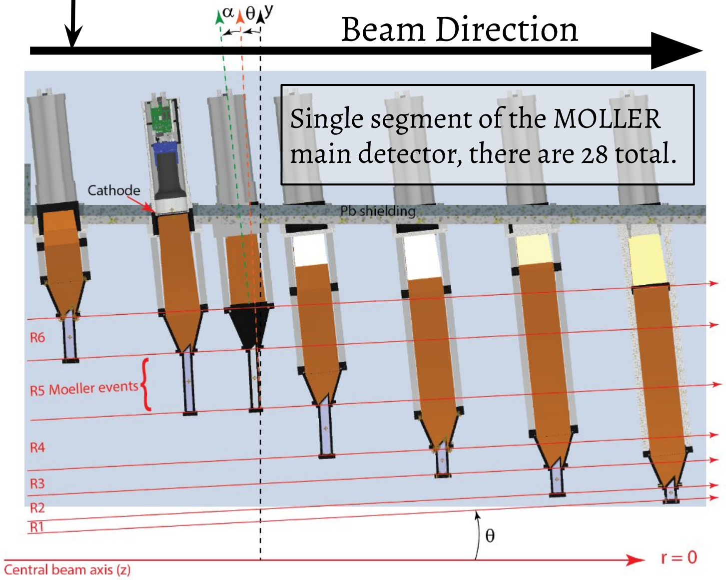


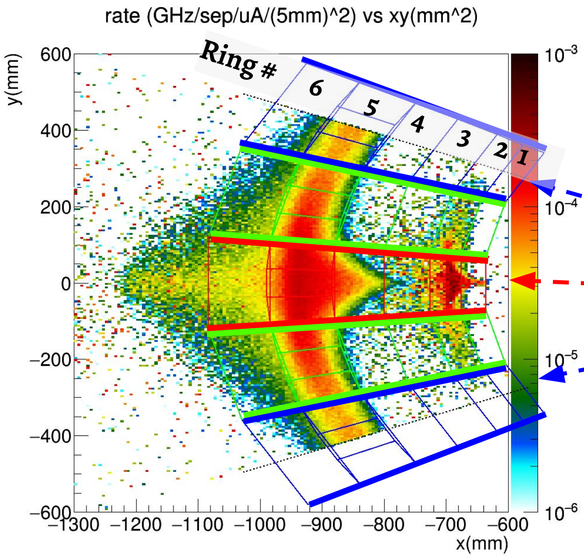
Image from MOLLER TDR

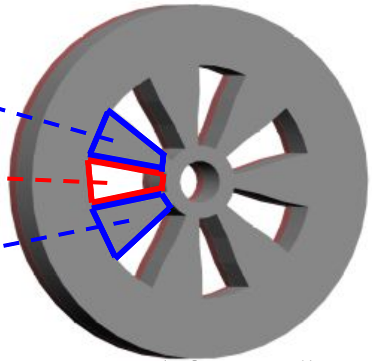
Example quartz tile



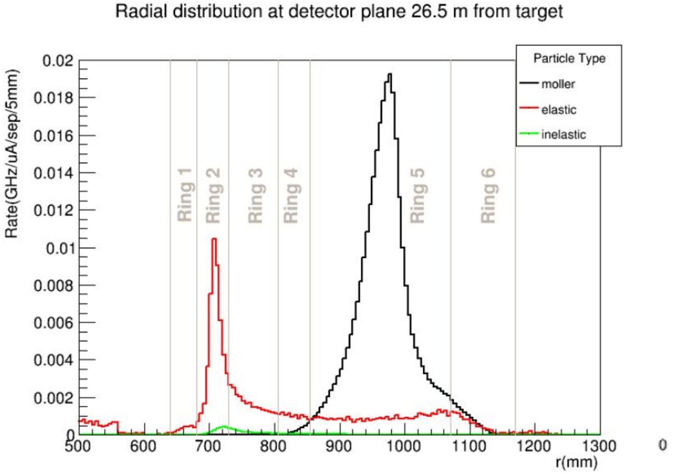
MOLLER Spectrometer: Main Detector

- Signals in the closed sectors originate from bending by toroid magnet fringe fields.
- Highest intensity signals focused onto ring 5.





Acceptance defining collimator upstream of toroid magnets



MOLLER Spectrometer: Supplementary Detectors

Supplementary Detector Systems:

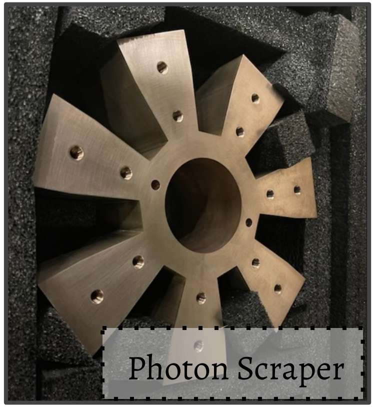
- GEM (Gaseous Electron Multiplier) Detectors:
    - To be used to track reconstruction.
- Showermax Detectors:
    - Provide a secondary asymmetry measurement.
- Pion Detectors:
    - Calorimeters embedded in Pb donut to measure pions.

MOLLER: Component Production / Procurement

Multiple components have been fabricated or procured.

- 15 month time window which has already begun; everything has been ordered.
- Components are undergoing quality checks.

Portion of the DS Toroid vacuum box structure.



Photon Scraper

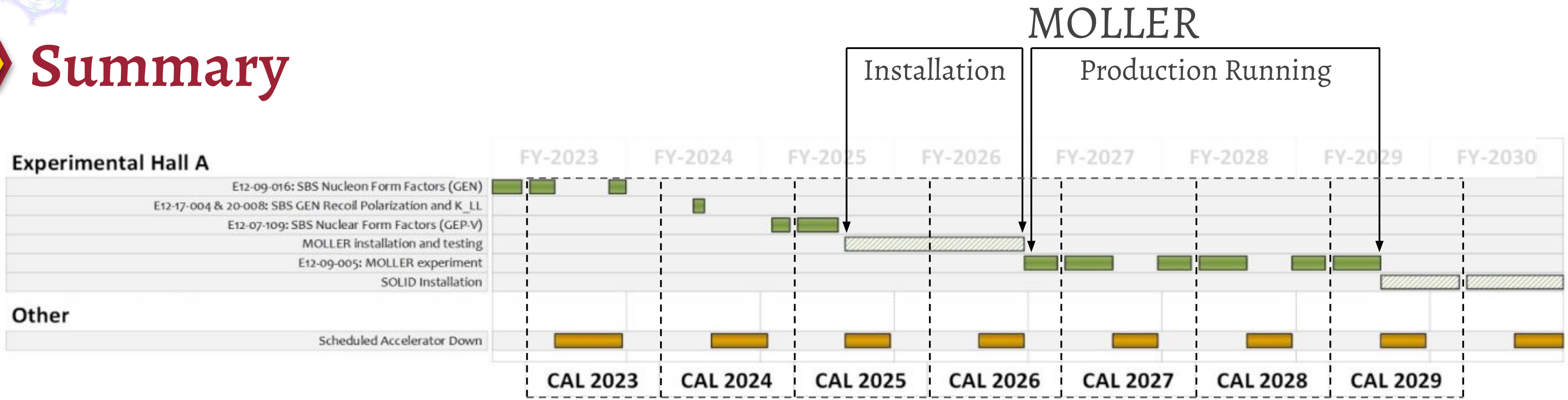
Collimator 6A

Collimator 5

MOLLER: Component Production / Procurement

Toroid magnet coils are now on hand.

Summary



<u>Timeline</u>:

- ➢ MOLLER on track to be ready for installation in Spring 2025
- ➢ Installation beginning in Summer 2025.
- ➢ Begin taking data in Fall 2026
- ➢ Conclude MOLLER runs in Spring 2029.

<u>MOLLER Collaboration</u>

Spokesperson: Krishna Kumar
Project Manager: Ruben Fair

~160 Authors
37 Institutions
6 Countries

Backup Slides

Experimental Challenges

- Very high-precision Experiment
  - A_{PV} is very small
    - Need lots of statistics
    - Quality beam
  - Need very precise understanding of systematic uncertainties.
    - Exercise considerable control of reducible backgrounds
    - Have an appreciable understanding of irreducible backgrounds
  - Precision polarimetry: 0.4% systematic uncertainty required.
  - Collaboration is getting a head start on analysis.

Experimental Challenges: Beam Performance

Parity quality beam will require a lot of attention:

- Energy and angle fluctuations on par with other recent parity experiments.
- Intensity and position set more aggressive goals compared to past experiments.

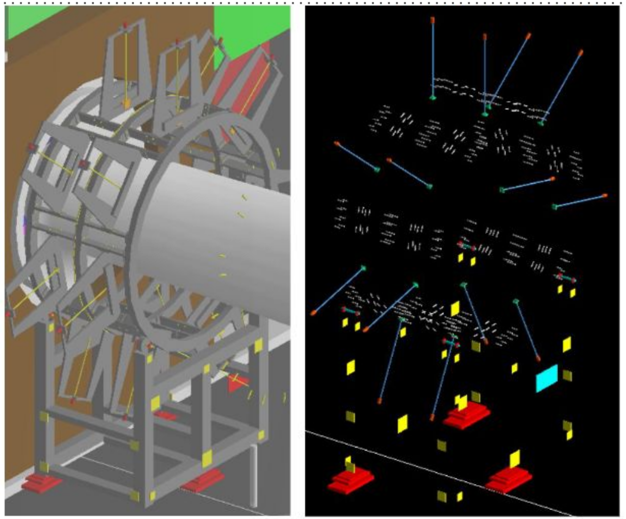
Beam Property	Defining Equation	Required 960Hz pair random fluctuations	Cumulative Helicity Correlation (full data set)
Intensity	$A_q \equiv \frac{I_0 - I_1}{I_0 + I_1}$	< 1000 ppm	< 10 ppb
Energy	$A_E \equiv \frac{E_0 - E_1}{(E_0 + E_1)} = \frac{\Delta E}{2E}$	< 110 ppm	< 1.4 ppb
Position	$D_x = \Delta x \equiv x_0 - x_1$	$< 50 \times 10^{-6}$ m	$< 0.6 \times 10^{-9}$ m
Angle	$\Delta\theta \equiv \theta_0 - \theta_1$	$< 10 \times 10^{-6}$ radian	$< 0.12 \times 10^{-9}$ radian
Spot-size	$\Delta\sigma/\sigma \equiv \frac{\sigma_0 - \sigma_1}{\frac{1}{2}(\sigma_0 + \sigma_1)}$	-	$< 10^{-5}$

	Q_{weak} [12] (achieved)	PREX-2 (achieved)	CREX (achieved)	MOLLER (required)
Intensity asymmetry	30 ppb	25 ppb	-88 ppb	10 ppb
Energy asymmetry	0.4 ppb	0.8 ± 1 ppb	0.1 ± 1.0ppb	< 1.4 ppb
position differences	4.4 nm	2.2 ± 4 nm	-5.2 ± 3.6nm	0.6 nm
angle differences	0.1 nrad	$< 0.6 \pm 0.6$ nrad	-0.26 ± 0.16nrad	0.12 nrad
size asymmetry (quoted)	$< 10^{-4}$	$< 3 \times 10^{-5}$	$< 3 \times 10^{-5}$	$< 10^{-5}$

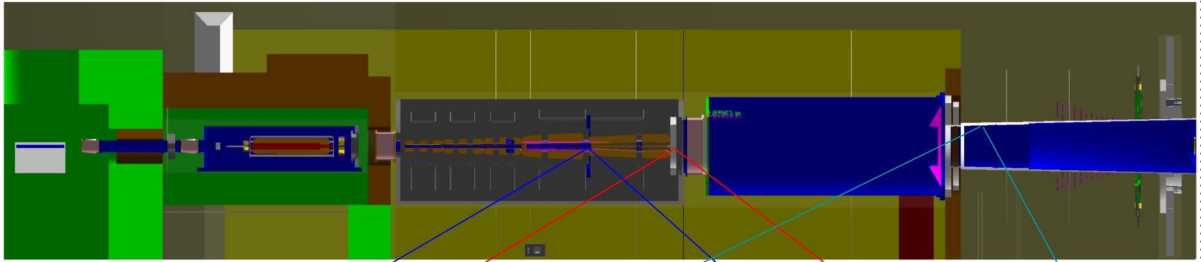
*Tables taken from MOLLER TDR

Experimental Challenges: Understanding Backgrounds

Considerable work has gone into having a high-level understanding beamline backgrounds and looking for particular sensitivities and efforts to quantify, and reduce if necessary, ferrous materials backgrounds.



Examination of ferrous materials components of the GEM rotator



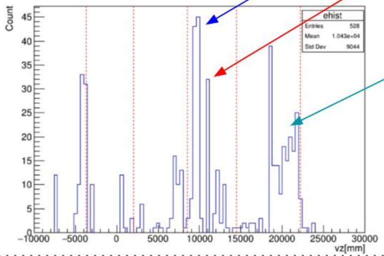
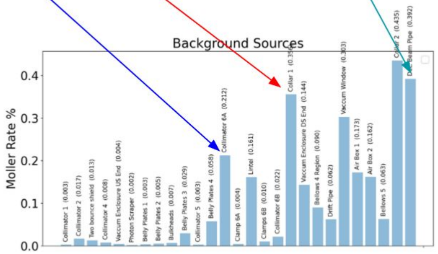


Image taken from Prakash's backgrounds talk – May 2024 MOLLER Collaboration Meeting.

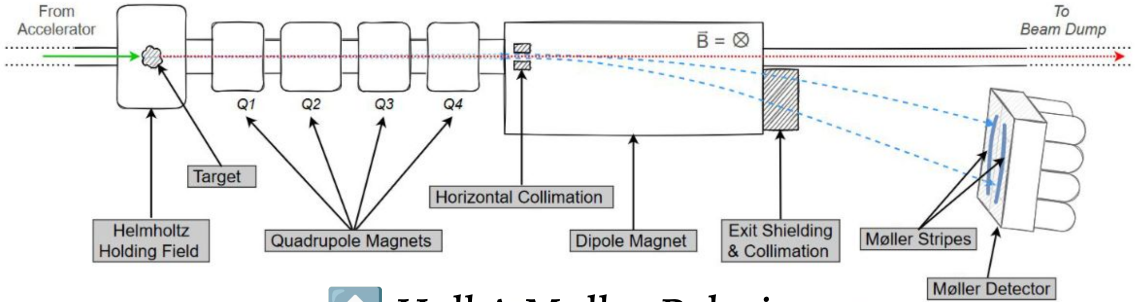


Experimental Challenges: Polarimetry

Polarimetry goal for MOLLER is 0.4%

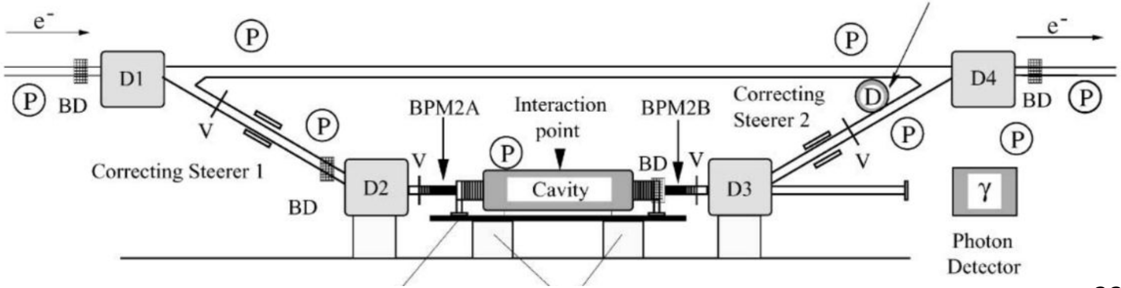
- Moller polarimeter has a working plan to reduce systematic uncertainty [achieved 0.85% during CREX] – GEM installation; addt'l collimation; beamline adj.

- Compton polarimeter achieved a 0.44% precision during CREX with only the photon detector.
    - Electron detector to be installed.



⬆️ Hall A Moller Polarimeter

⬇️ Hall A Compton Polarimeter



Analysis

- Collaboration is getting a head start on analysis.
  - We would like to have our feet on the ground running for MOLLER commissioning.

- Weekly analysis meetings are run by Paul King
  - Considerable work putting together mock data generator and documentation on data structure.

- Analysis of integrated data will continue to use JAPAN
  - Forked to https://github.com/JeffersonLab/japan-MOLLER