The MOLLER Experiment:
Measurement of a Lepton-Lepton Electroweak Reaction

Mark Pitt, Virginia Tech, for the MOLLER Collaboration

2019 Jefferson Lab User's Organization Annual Meeting

Newport News, VA

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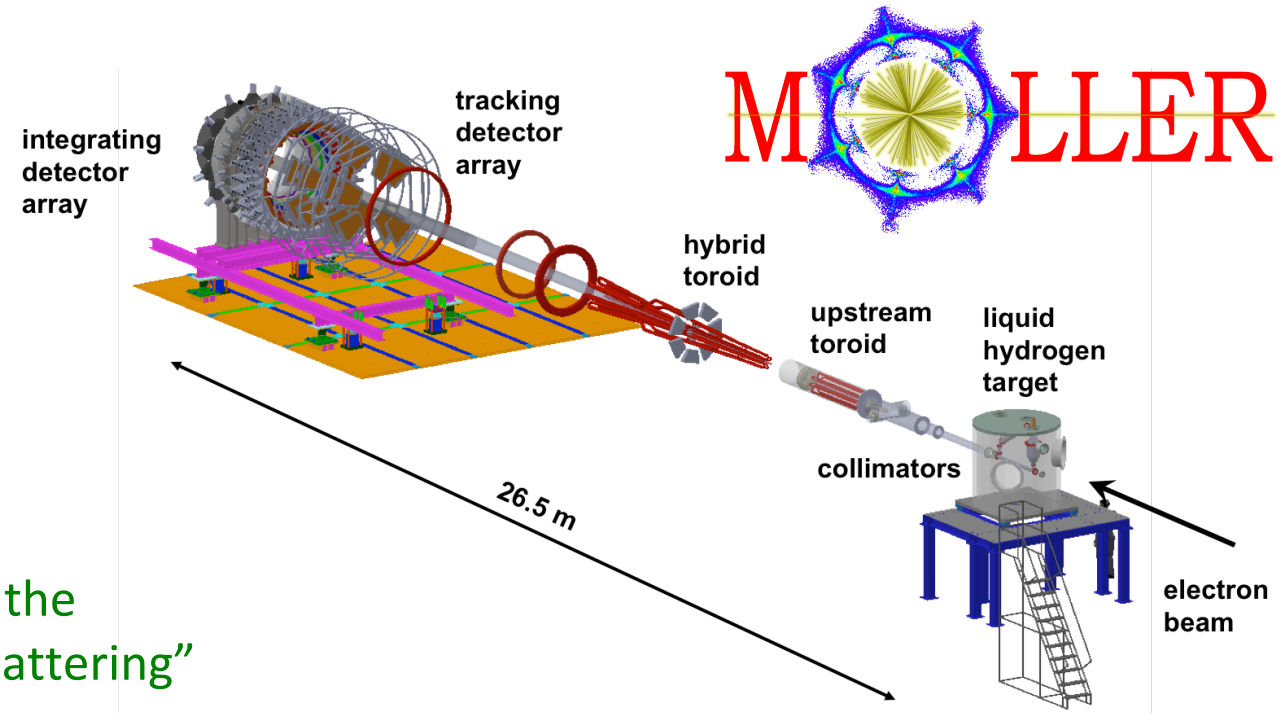

MOLLER experiment objective:

"An Ultra-Precise Measurement of the Weak Mixing Angle using Møller Scattering"

(arXiv:1411.4088)

- sensitive to new physics from multi-TeV dynamics and MeV-scale mediators

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Outline

- Parity-Violating Møller Scattering: Formalism and Physics Motivation
- MOLLER Experiment: Concept, design status, and R&D progress
- Project status, timeline, and outlook

The MOLLER Experiment: The Essentials

Elastic scattering of longitudinally polarized electrons on unpolarized electrons

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad \vec{e} + e \rightarrow e' + e'$$

Parity violating asymmetry:

A_{PV} ~ 33 × 10^{-9} or 33 ppb (parts per billion)

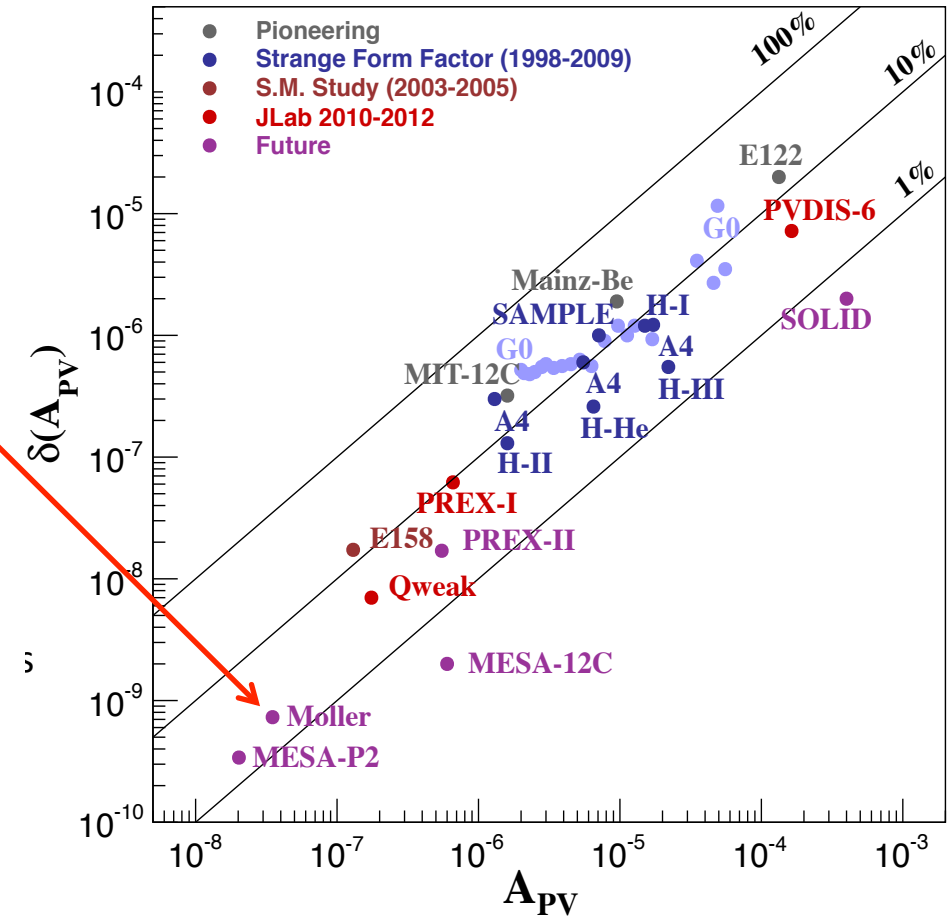
δA_{PV} ~ ± 0.8 ppb (2.4% precision)

⟶ next generation in size and precision of asymmetry for parity-violating electron scattering experiments

proportional to the electron's weak charge Q^e_W
- precisely predicted in Standard Model

At tree level $$Q^e_W = -\left(1 - 4\sin^2\theta_W\right)$$

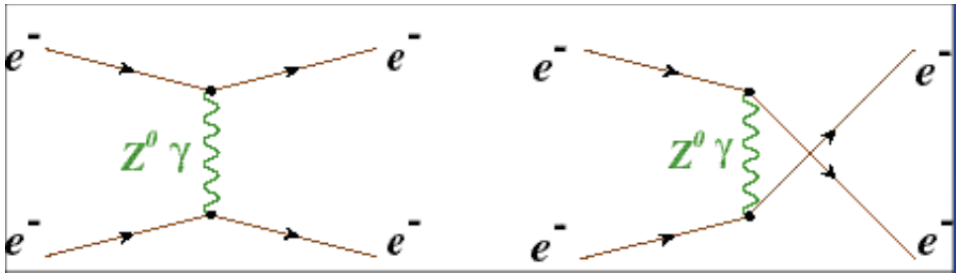
2.4% precision on Q^e_W 0.1% on $\sin^2\theta_W$



- MOLLER is an approved JLab experiment with DOE CD-0, currently seeking CD-1 approval
- **Will be factor of 5 improvement over previous measurement of SLAC E158**

Parity Violating Asymmetry in Møller Scattering

The parity-violating asymmetry in Møller scattering is predicted at the ~1% level of theoretical accuracy (expect <0.5% after full 2 loop calculations done) :



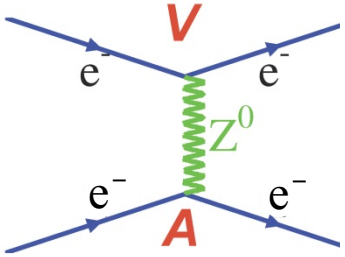
At tree level in Standard Model:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{A_\gamma A_Z}{A_\gamma^2} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4sin^2\theta}{(3+cos^2\theta)^2} Q_W^e,$$

Derman and Marciano (1978)

At tree level electron's weak charge is given by:

$$Q_W^e = -4 g_V^e g_A^e = -\left(1 - 4\sin^2\theta_W\right)$$



$$C_{ee} \equiv 2 g_V^e g_A^e$$

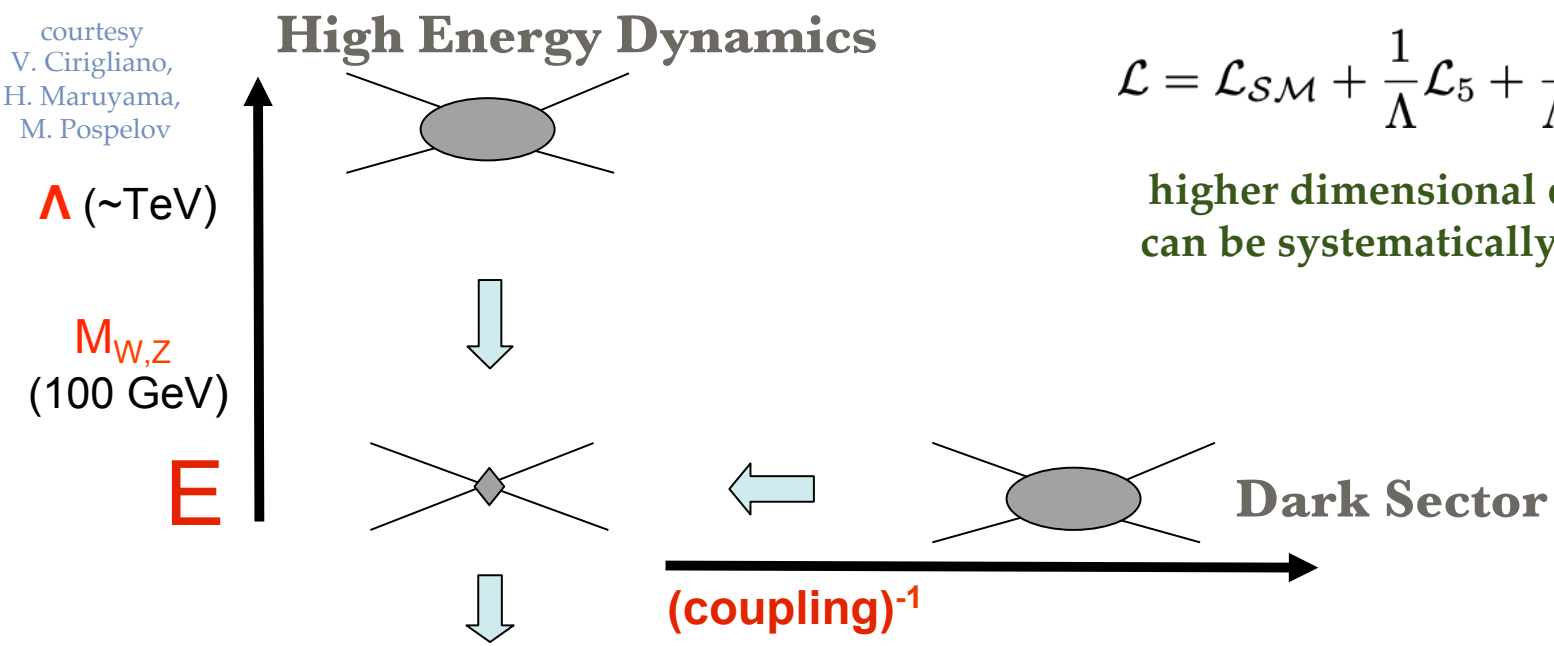
Møller A_{PV} and New Physics

Standard EW Model = Renormalizable Gauge Theory + Spontaneous Symmetry Breaking

➔ believed to be incomplete

Electroweak Interactions at scales much lower than the W/Z mass

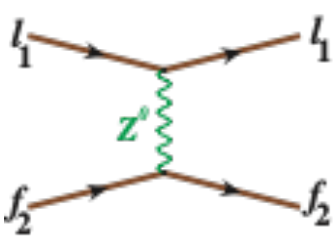
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov



$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

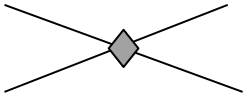
higher dimensional operators
can be systematically classified

Heavy Z's, light (dark) Z's, L-R models, compositeness, extra dimensions, SUSY…



Search for new flavor diagonal neutral currents

Tiny yet measurable deviations from
SM processes with precise predictions



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ 10 TeV

Physics Potential of Precision Q^e_W Measurement

The MOLLER experiment provides:

- **Excellent sensitivity to Beyond Standard Model (BSM) physics**

  High precision measurement $\delta(Q_W^e)/Q_W^e \sim \pm 2.4\%$

  of suppressed SM observable $Q_W^e = -\left(1 - 4\sin^2\theta_W\right) \sim -.046$

  sensitive to new neutral current amplitudes at ~ $10^{-3}\, G_F$

  Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade

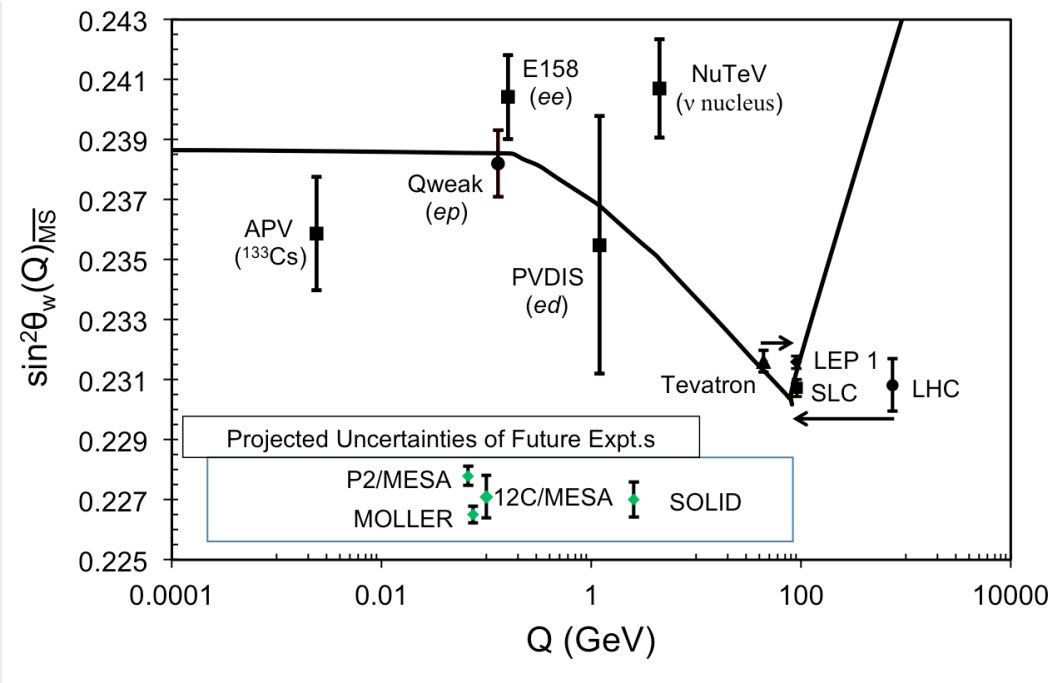
  - new TeV scale dynamics (Z', supersymmetry, doubly charged scalars,…)
  - weakly coupled MeV scale mediators (dark photons, …)

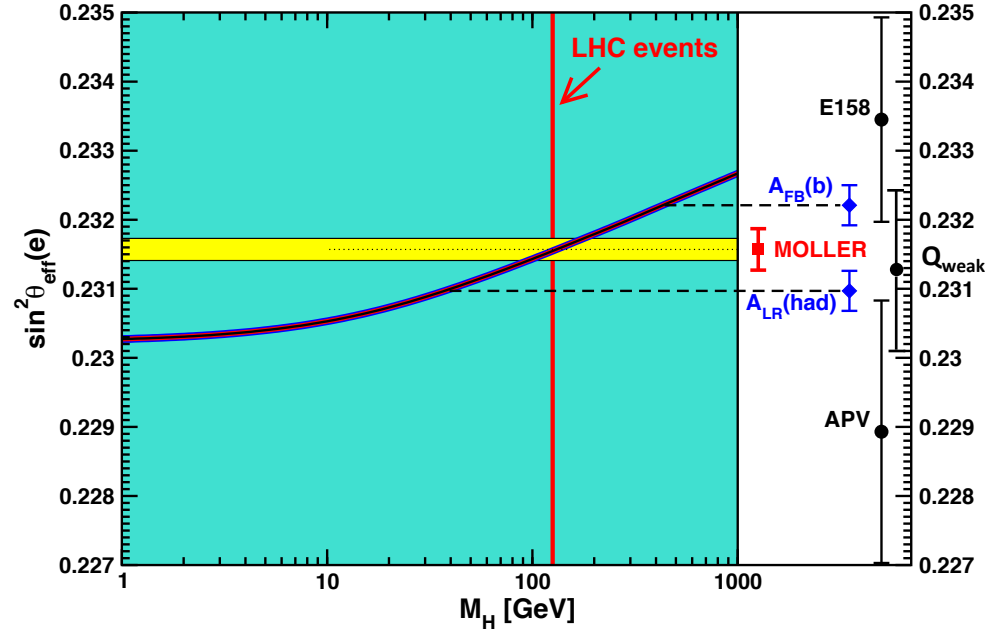
- **High precision benchmark point within the Standard Model**

$$\delta(\sin^2\theta_W) \sim \pm 0.00024\,(\text{stat.}) \pm 0.00013\ (\text{syst.})$$

~ 0.1% precision, comparable to sensitivity of best collider determinations

Weak Mixing Angle – $\sin^2\theta_W$





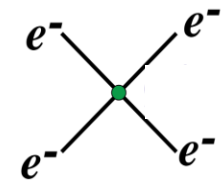
- Two most precise values of $\sin^2\theta_W$ at Z pole (SLC A_{LR} and LEP A^b_{fb}) disagree by 3σ; MOLLER has comparable sensitivity to these two values
- Many classes of Beyond Standard Model physics have little sensitivity at Z-pole but significant effects in measurements away from Z-pole such as low energy measurements
  - On Z resonance; A_Z is imaginary, no interference term $\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1+\left(\frac{A_{new}}{A_Z}\right)^2\right]$
  - Off Z resonance; electroweak interference $\left|A_\gamma + A_Z + A_{new}\right|^2 \rightarrow A_\gamma^2\left[1+2\left(\frac{A_Z}{A_\gamma}\right)+2\left(\frac{A_{new}}{A_\gamma}\right)\right]$
- **Significant discovery potential at $Q^2 << M^2_Z$**

Mass Reach of Proposed MOLLER Measurement

Model-independent way to quantify effects of potential new high energy dynamics (ie. heavy Z's, compositeness, extra dimensions, supersymmetry, …) is from expressing them in terms of neutral "contact" 4-fermion interactions:

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

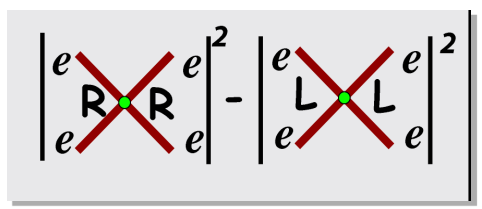
Eichten, Lane, and Peskin, PRL50, 811 (1983)



Λ = mass scale $\quad g_{ij}$ = chirality coupling

MOLLER 2.4% Q^e_W measurement

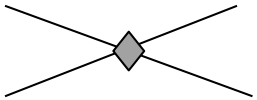
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$



- Best contact interaction reach for leptons at low OR high energy
- To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider,neutrino factory or muon collider

Mass Reach Comparison with Colliders

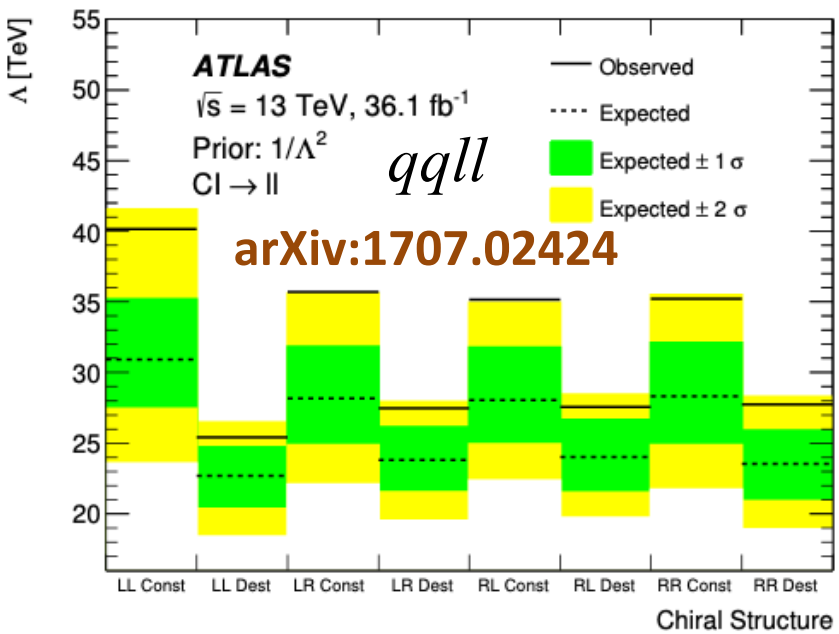
Carefully chosen low energy experiments complement direct searches



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Lacking any direct evidence for new particles besides the Higgs, both colliders and fixed target experiments search for new physics by looking for deviations from Standard Model predictions

LHC searching for lepton-hadron interactions



LEP200: lepton-lepton interactions

llll

e^+e^- Collisions
LEP200 Reach $\Lambda^{ee}_{LL} \sim 8.3$ TeV

Fixed Target
E158 Reach $\Lambda^{ee}_{LL} \sim 12$ TeV

MOLLER Reach $\Lambda^{ee}_{LL} \sim 27$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

Global Context Summary

best contact interaction reach for leptons at low OR high energy: similar to LHC reach with semi-leptonic amplitudes

To do better for a 4-lepton contact interaction would require: Giga-Z factory, linear collider, neutrino factory or muon collider

$$\delta(\sin^2\theta_W) = \pm\, 0.00023\ (stat.) \pm 0.00012\ (syst.) \Rightarrow \sim 0.1\%$$

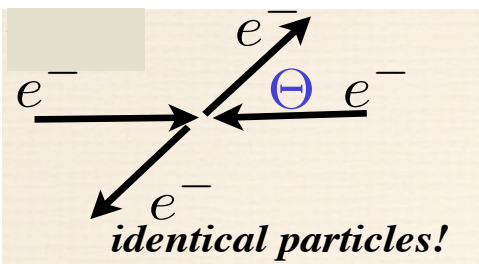
Best projected uncertainties among projects being considered over next 10 years: worldwide and at any energy scale

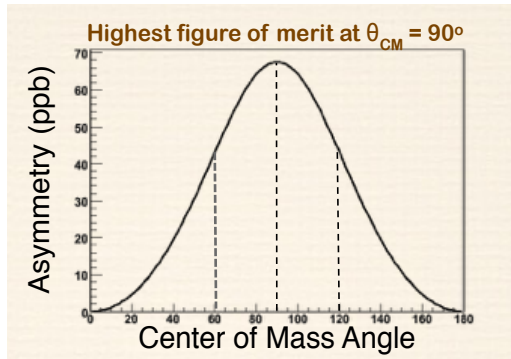
- **If LHC sees ANY anomaly in Runs 2 or 3**
  - The unique discovery space probed by MOLLER will become a pressing need, like other sensitive probes (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - …

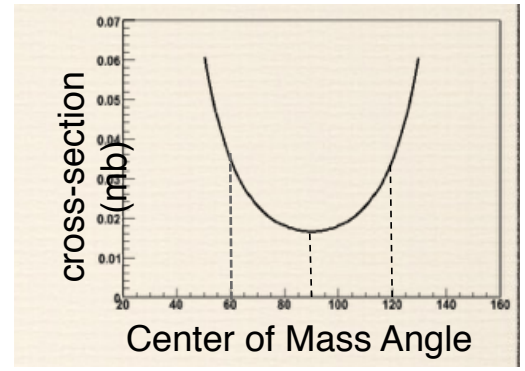
Most sensitive discovery reach over the next decade for CP-/flavor-conserving or LNV scattering amplitudes

MOLLER Experiment: Design Parameters

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{A_\gamma A_Z}{A_\gamma^2} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4sin^2\theta}{(3+cos^2\theta)^2} Q_W^e,$$

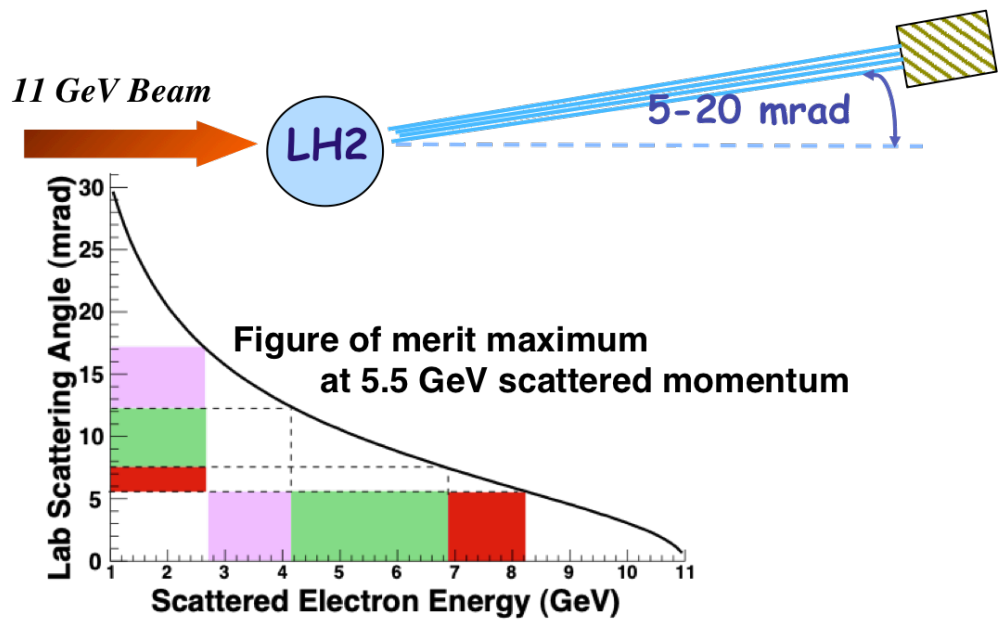




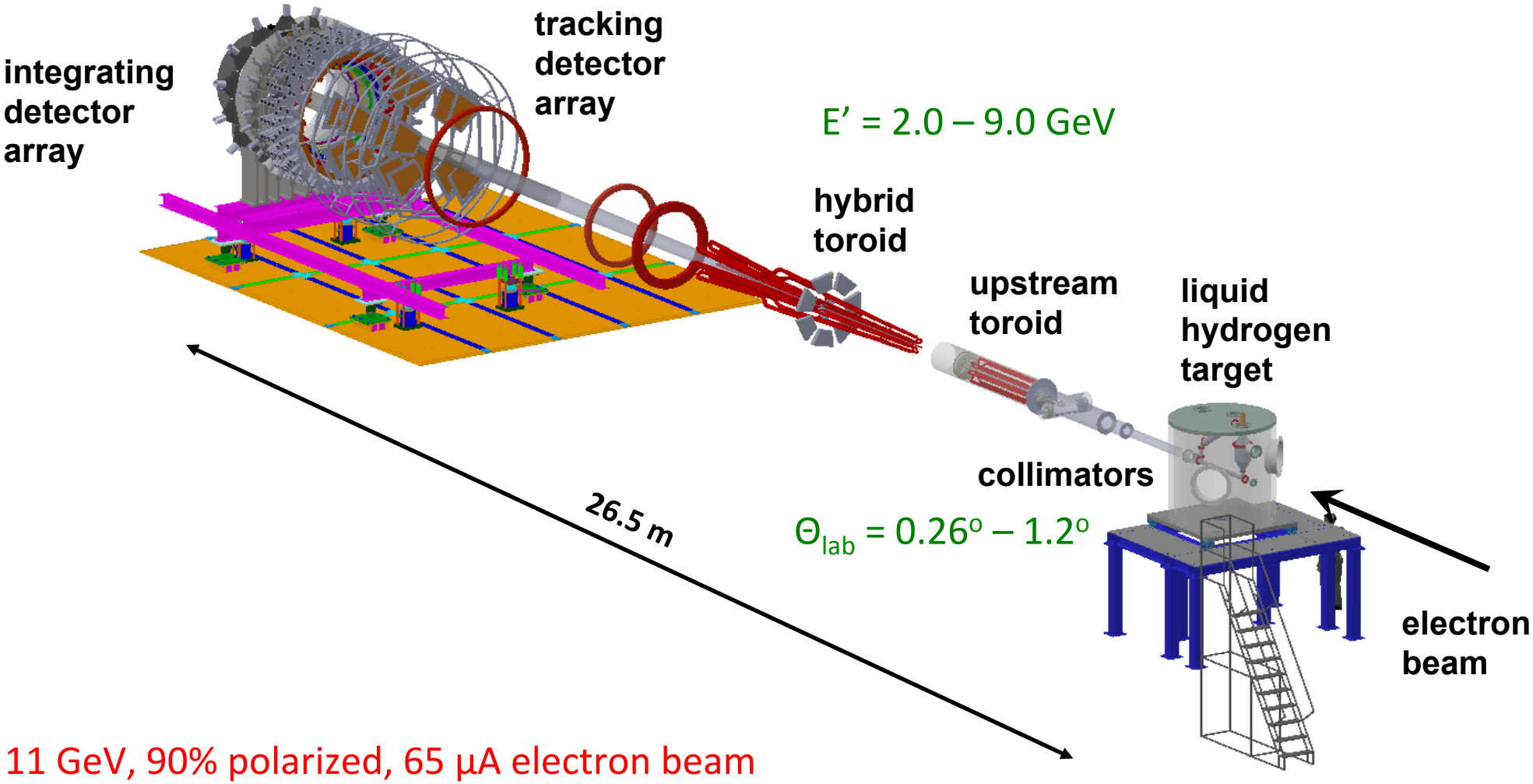


Experiment designed to be nearly symmetric about θ_{CM} = 90° where FOM ($A^2\sigma$) is highest.

- θ_{CM} = 50° – 130° θ_{lab} = 0.26° – 1.2°
- E_{beam} = 11 GeV E' = 2.0 – 9.0 GeV
- 125 cm long LH_2 target, designed for beam currents up to 70 μA
- @65 μA, Moller rate ~ 122 GHz,
  total rate ~ 139 GHz
- Irreducible background fraction~ 12%
- Nominal beam polarization ~ 90%



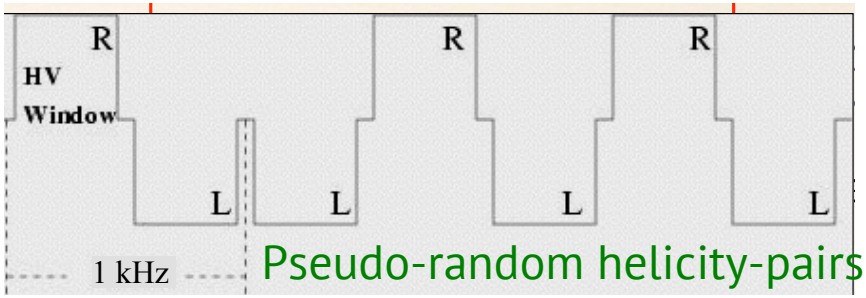
MOLLER Experiment: Conceptual Overview



- 11 GeV, 90% polarized, 65 μA electron beam
- 125 cm long, 4 kW LH_2 target
- Precision collimation ("2-bounce" design minimizes backgrounds)
- Novel two (warm) toroid spectrometer with 7 azimuthal segments; just fits into Hall A.
- Variety of integrating and counting detectors for main measurement and backgrounds

Parity-Violating Electron Scattering Method

How do we take the bulk of our data? Pretty simple actually…



• **Flux integration:** Integrate the light signal in the Cerenkov detectors and record response *F* every 0.5 msec (planned data-taking rate is 1.92 kHz)

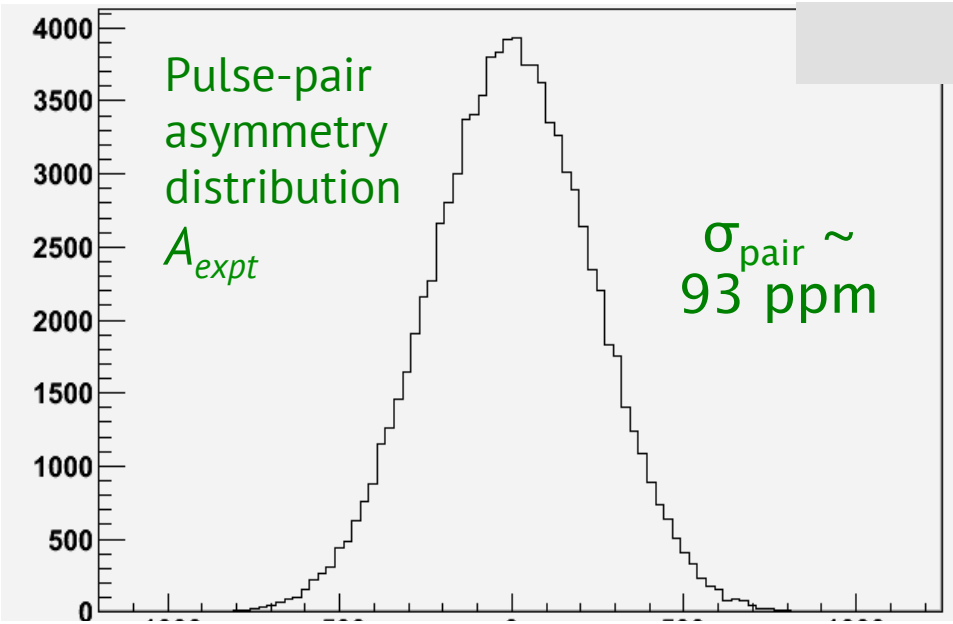
• **Flip the electron beam helicity** and form the asymmetry from adjacent data samples for i^{th} pair:

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

• **Remove correlations** to beam intensity, position, angle, and energy fluctuations:

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

• Repeat 30 billion times! (8256 hours of data-taking) to get desired statistical error



$$\sigma_{A_{cxpt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}} = \frac{93\,\text{ppm}}{\sqrt{30\times10^9}} = 0.5\,\text{ppb}$$

Pulse-pair "width" σ_{pair} is the parameter that determines the statistical error

Projected Uncertainty Budget and Experimental Challenges

$$A_{cxpt} \sim A_{PV}\left(1 - f_{bkgd}\right)P_b \sim$$
$$(33\,\text{ppb})\left(1 - .12\right)(.90) \sim 26\,\text{ppb}$$

$$\delta\left(A_{\text{statistical}}\right) = 0.56\,\text{ppb}$$

$$A_{PV} = \frac{\frac{A_{cxpt}}{P_b} - f_{bkgd}A_{bkgd}}{1 - f_{bkgd}}$$

Error Source	Fractional Error (%)
Statistical	**2.1**
Absolute Normalization 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
Total systematic	**1.1**

All systematics required at sub-1% level

Statistics: High power beam, target; large acceptance; minimize random noise sources

Beam quality: Minimize helicity-correlated beam properties; small random fluctuations

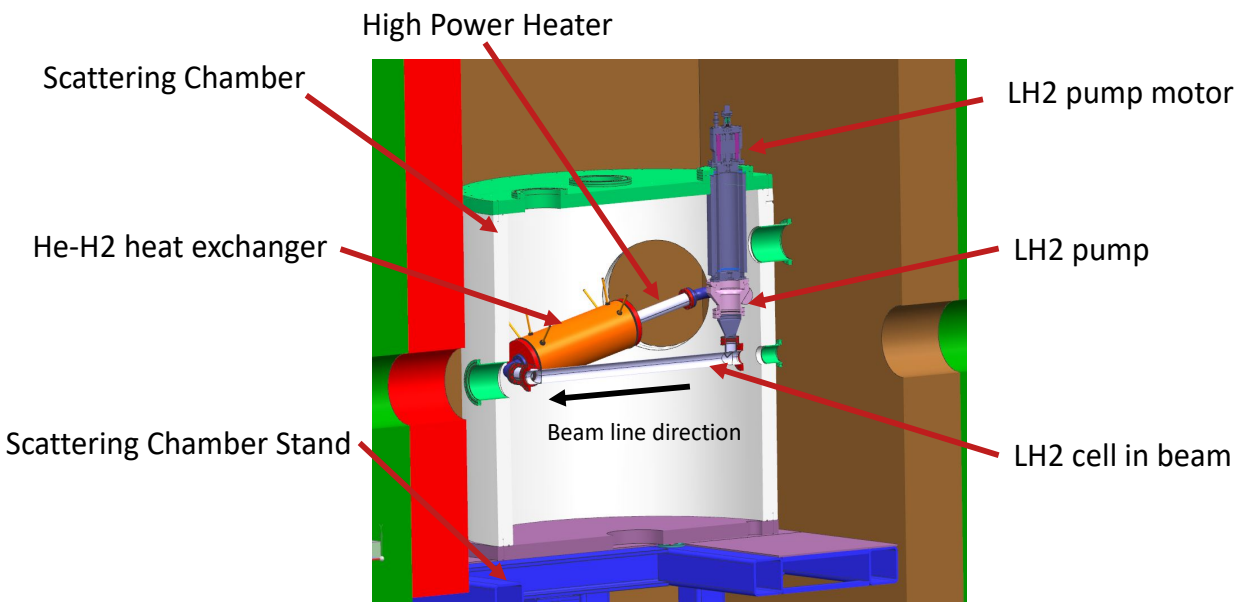
Polarimetry: Redundant, high-precision polarimetry

Backgrounds: Novel spectrometer, “2 bounce” collimation, auxiliary detectors

Tracking: kinematic factor, backgrounds

High Power Liquid Hydrogen Cryotarget

- MOLLER goal: up to 70 μA on 125 cm LH_2 target - 4.0 kW power
- Build on Qweak success of using CFD (computational fluid dynamics) for target design
- Qweak target successfully operated up to 2.9 kW (compared to previous high of ~ 1.0 kW)



Main goal: minimize target density fluctuations (Δρ/ρ) ("target boiling noise")

$$\Gamma_{stat} = \sqrt{\Gamma_{count}^2 + \Gamma_{target}^2} \quad \text{want } \Gamma_{target} << \Gamma_{count}, \Gamma_{count} \sim 84\,\text{ppm}$$

Projection for MOLLER based on G0 and Qweak experience

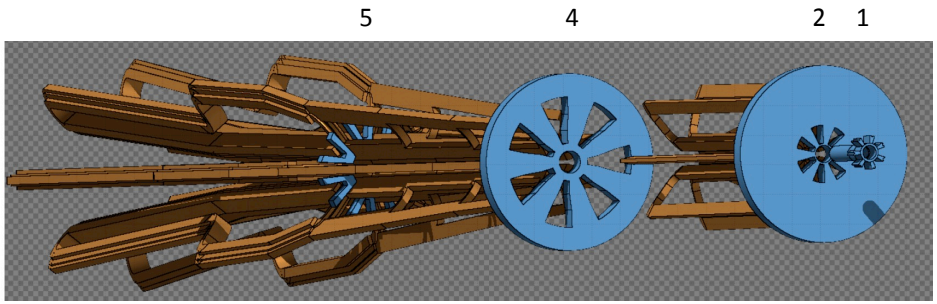
Γ_{target} < 30 ppm for 70 μA, 5x5 mm^2 raster, 2 kHz flip

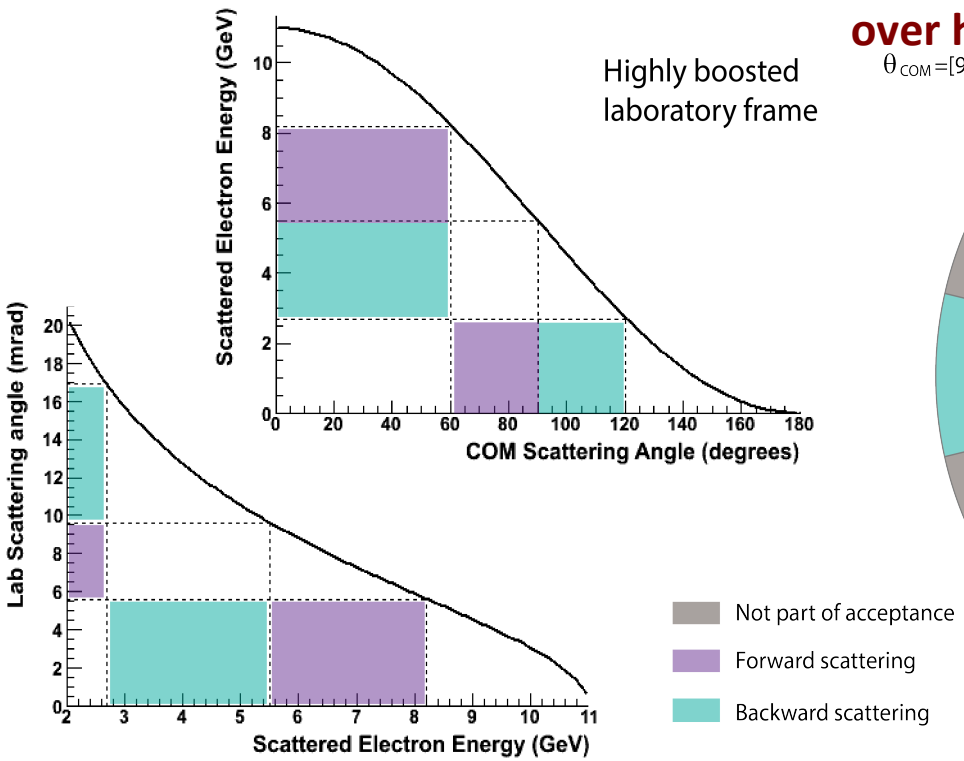
Spectrometer – Kinematics and Azimuthal Acceptance

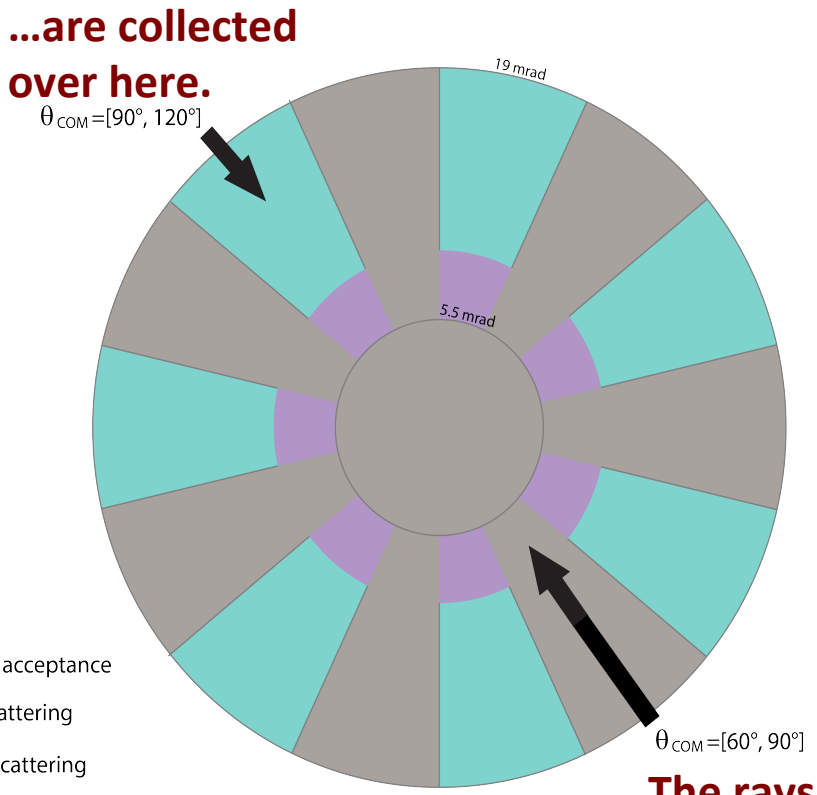
Optimized spectrometer:

50% azimuth, 100% acceptance

FOM optimized at 90° in COM

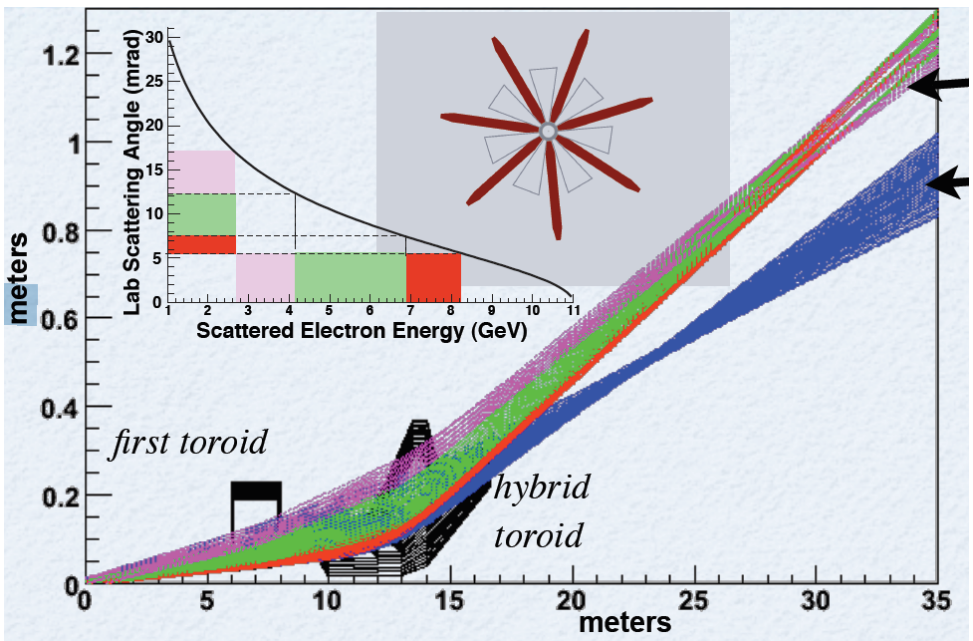






- Accept all Møller scattered electrons in range Θ_{CM} = 50° – 130°
- Exploit identical particle nature for 100% acceptance; needs odd number of coils

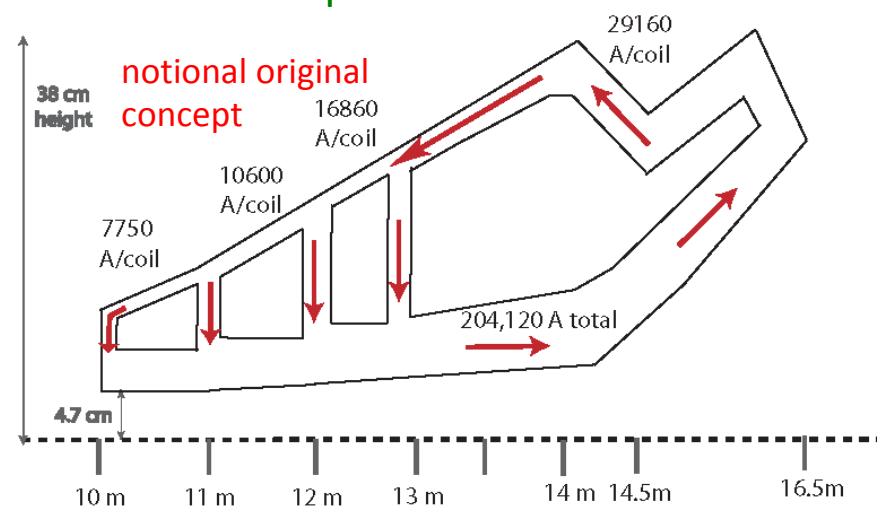
Spectrometer – Signal/Background Separation

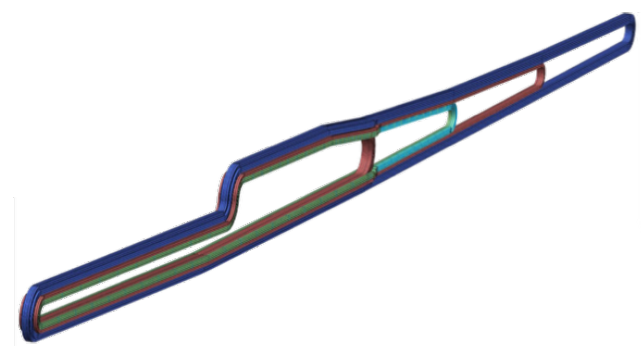


Møller

e-p

Downstream "hybrid" toroid – multiple current return paths



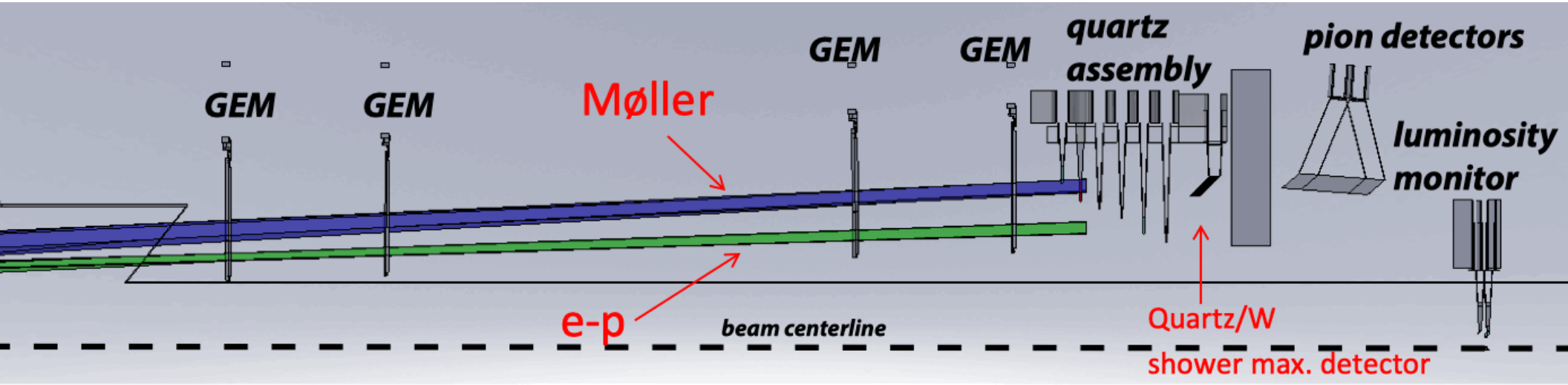


Spectrometer employs a novel two toroid design

- Upstream toroid has conventional geometry
- **Downstream "hybrid" toroid novel design** inspired by the need to focus

Møller electrons with wide scattered energy range E' = 2.0 – 9.0 GeV while separating them from Mott (e-p) scattering background

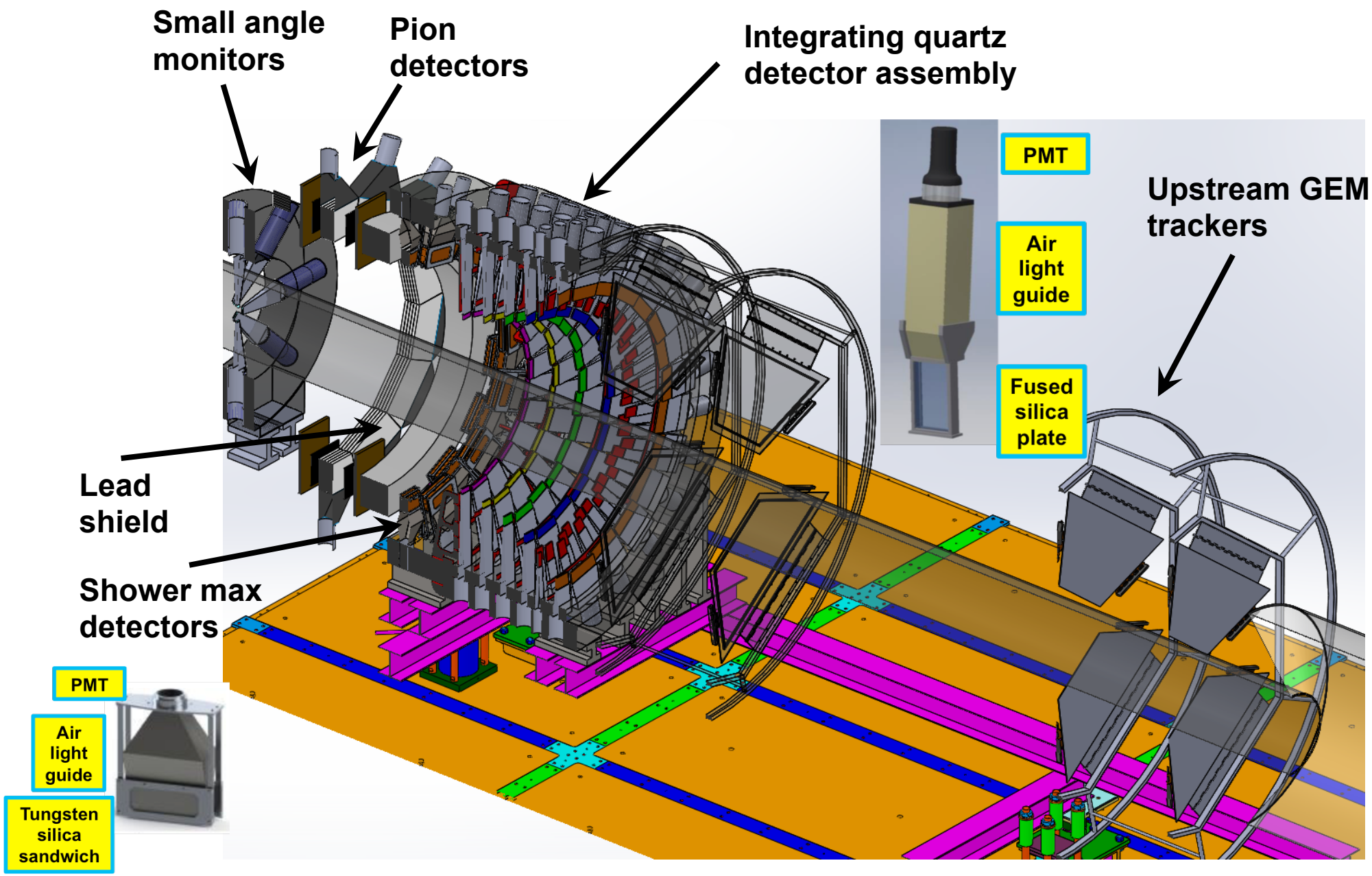
Detectors Overview



- Integrating (current mode) detectors: asymmetry measurements of both signal and background, and beam and target monitoring.
- Tracking (counting mode) detectors: spectrometer calibration, electron scattering angle distribution and background measurements.

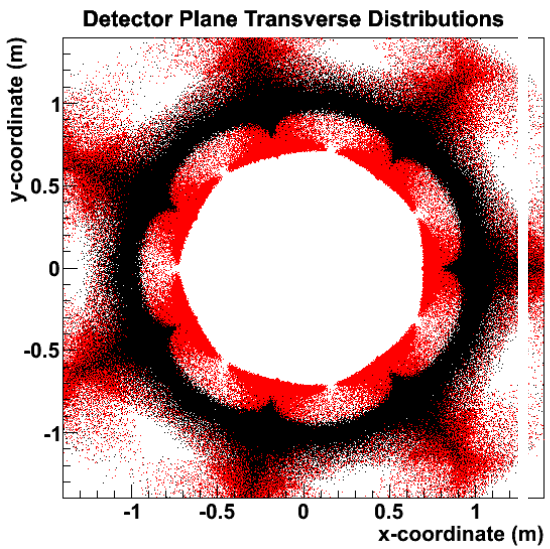
Quartz	A_{PV} measurements for Møller, elastic and inelastic e-p events
Quartz/W	Shower max. detector, provides a second, independent measurement of Møller peak
Pion detector	Acrylic Cerenkov dets + two GEM planes for hadronic dilution/asymmetries
Lumis (small angle monitors)	monitor for target density fluctuations, false asymmetries
GEMS	backgrounds, kinematics, spectrometer diagnostics

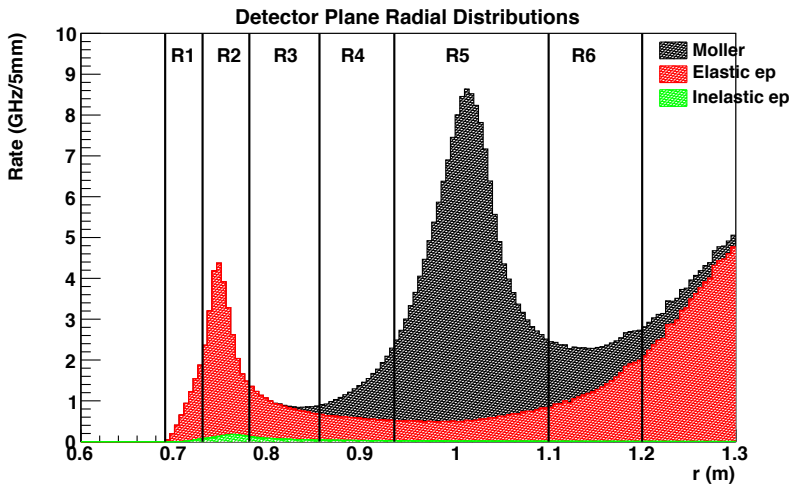
Perspective View of Detector Assembly



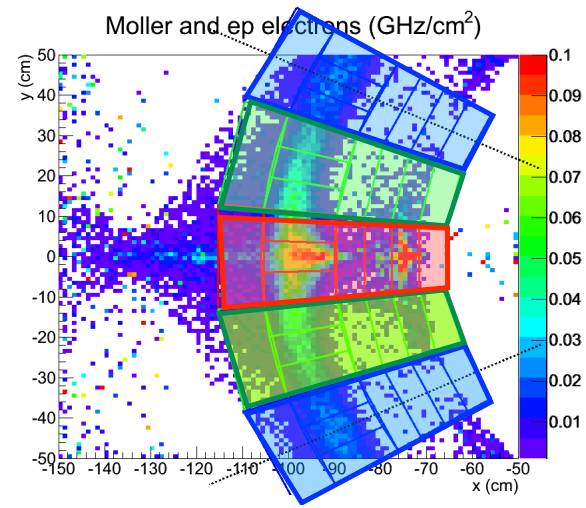
Detector Plane Segmentation

Quartz Cerenkov detectors will have radial and azimuthal segmentation





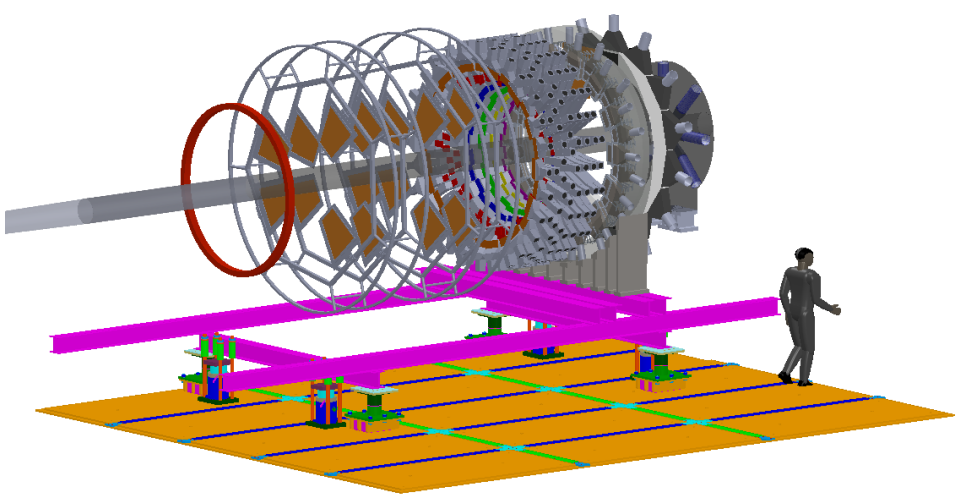
Main Moller peak in Region 5



Proposed Segmentation

Azimuthal defocusing –

Different φ, different θ_{CM} bins



28 azimuthal channels per radial bin

Moller peak (region 5): 84 azimuthal channels per radial bin

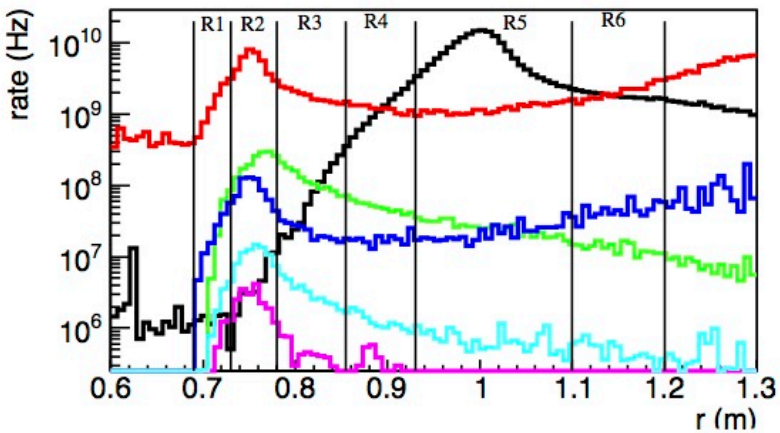
224 total channels

Rate per channel ~ few MHz – GHz

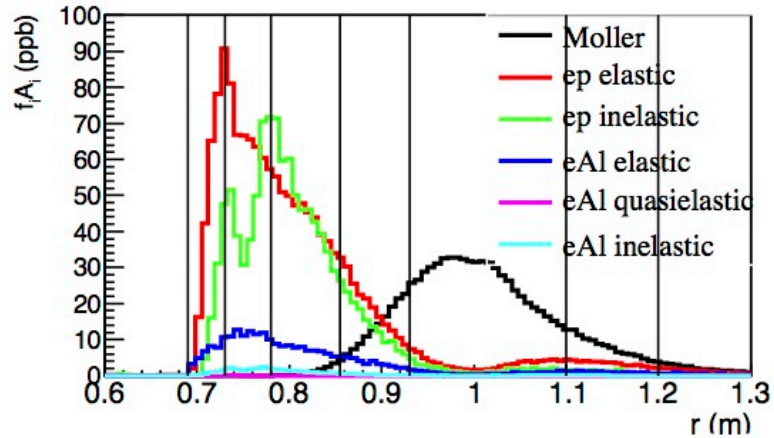
(overall rate ~ 139 GHz)

Measurement of Background Asymmetries/Dilutions

Radial rate distribution



Radial f_i A_i distribution: Contributions to A_{PV}



$$A_{PV} = \frac{\frac{A_{cxpt}}{P_b} - f_{bkgd}A_{bkgd}}{1 - f_{bkgd}}$$

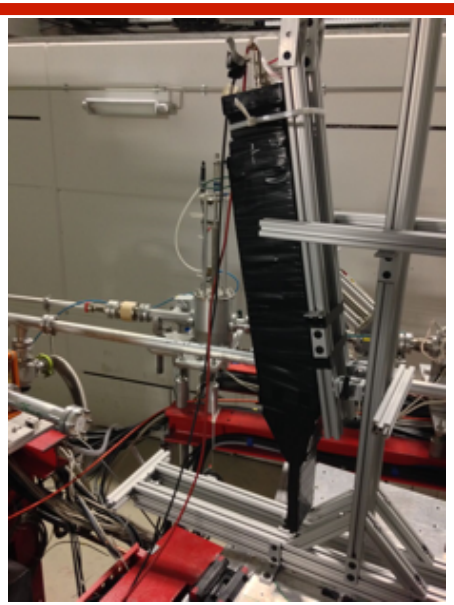
Radial binning of measurements – measurement of background asymmetries under "Møller peak"

- Elastic e-p: ~12% of signal; asymmetry well known
- Inelastic e-p: <0.5% of signal but asymmetry ~ x20 larger and not well known

  → The inelastic contribution dominates rings 2 and 3, measured there

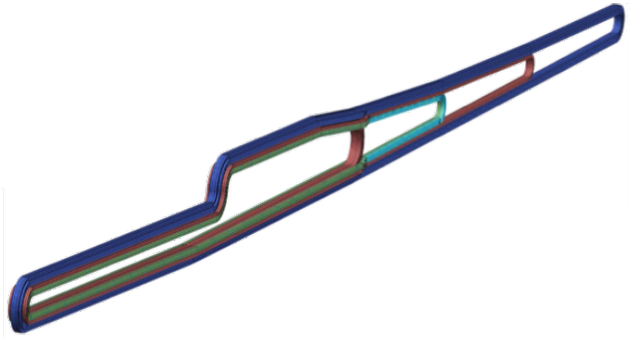
Simulated 18 asymmetry-type fit exploiting radial/azimuthal segmentation completed

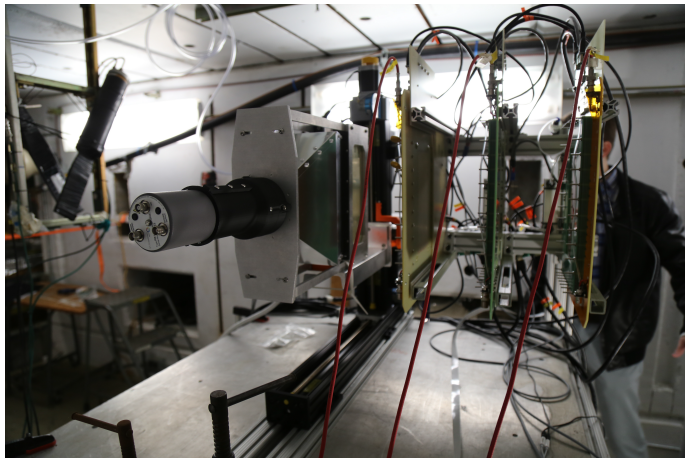
Some Recent R&D Activities



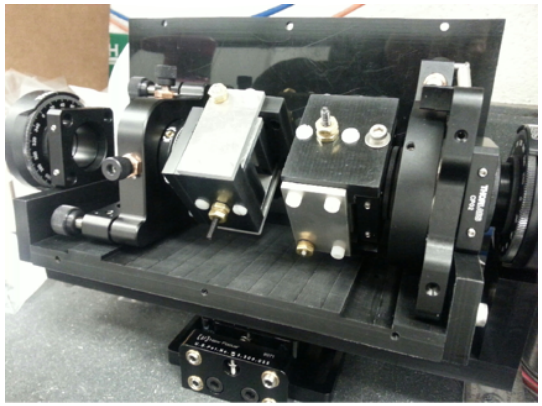
Quartz and air light guide tests at Mainz MAMI

Prototype low noise I-V preamplifier





Tests of shower max prototype at SLAC endstation A



RTP Pockels cell tests for rapid helicity reversal

Prototype “hybrid” torus coil tests

Timeline and Status

MOLLER collaboration: ~ 120 authors, 30 institutions, 5 countries;
Spokesperson: K. Kumar, U. Mass, Amherst

- JLab PAC approval Jan. 2009, JLab Director's review Jan. 2010
- JLab PAC37 Ranking/Beam Allocation Jan. 2011 (A rating, 344 PAC days)
- Strong endorsement from DOE Science Review in Sept. 2014
- Second Director's Review in Dec. 2016
- DOE CD-0 status achieved in Dec. 2016; paused in Jan. 2017
- Project team formed in Jan. 2019; Project Manager: Howard Fenker
- Director's Review in April 2019 – Technical Readiness, Risk, Cost

"…the Committee finds the maturity of the proposal to be appropriate for this stage of the project. …encourage the Project to work with the Laboratory and the funding agency to obtain the support needed to expeditiously finalize the conceptual design, develop a defensible cost range, and produce the deliverables required for a CD-1 review."

- MOLLER is a line item in President's and House budgets for FY 20
- Current efforts directed toward CD-1 review, preparing to get CD-1 in April 2020
- 4 years construction, 3 years of running

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 the high luminosity phases of 14 TeV LHC are becoming available ("LHC Run 3")
  - best discovery reach for flavor and CP conserving processes over the next decade

- An enthusiastic and well-experienced international collaboration is eager to launch into the design, construction, operation, and physics analysis of the experiment