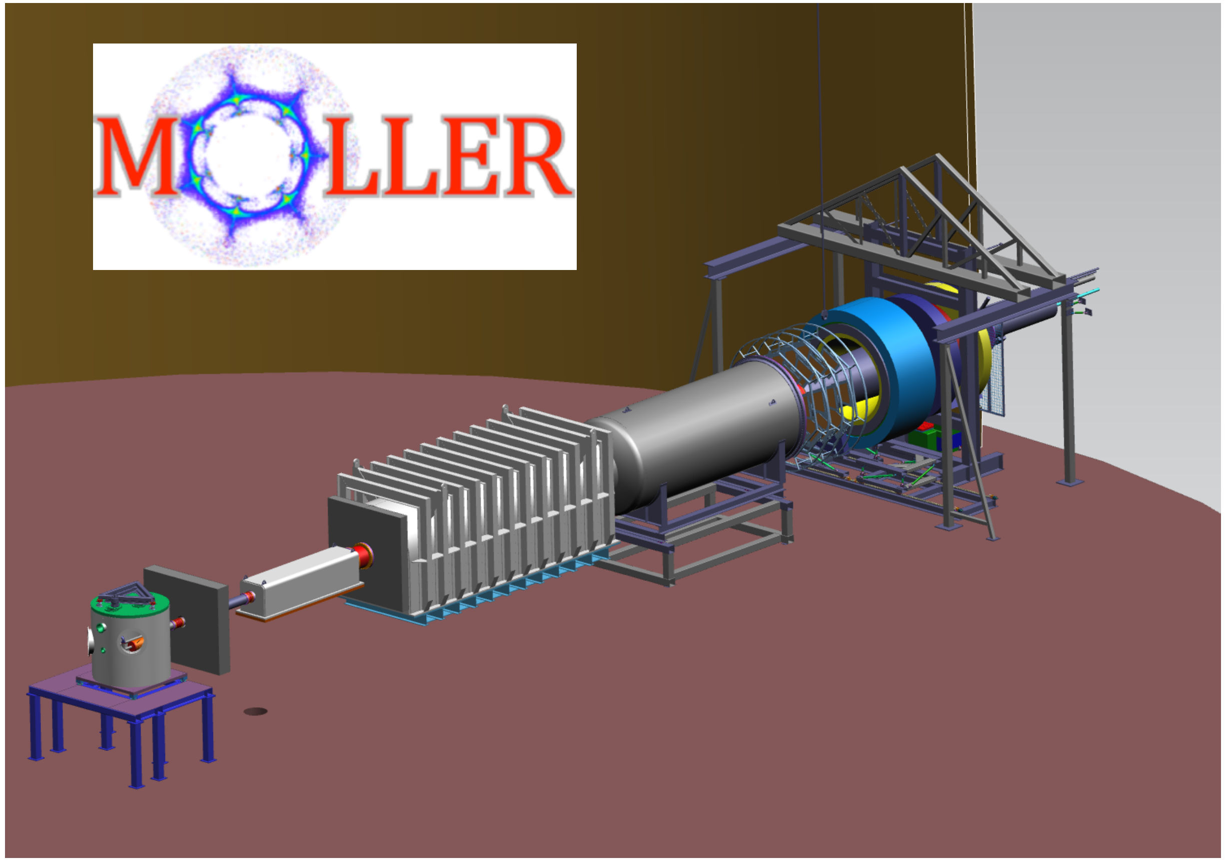
The MOLLER Experiment
Overview of the MOLLER Physics

JLab Hall A/C Collaboration Meeting

June 17, 2022

Measurement Of a Lepton Lepton Electroweak Reaction



Zuhal Seyma Demiroglu

on behalf of the MOLLER Collaboration

Jefferson Lab · Stony Brook University · Center for Frontiers in Nuclear Science · U.S. Department of Energy Office of Science · JSA

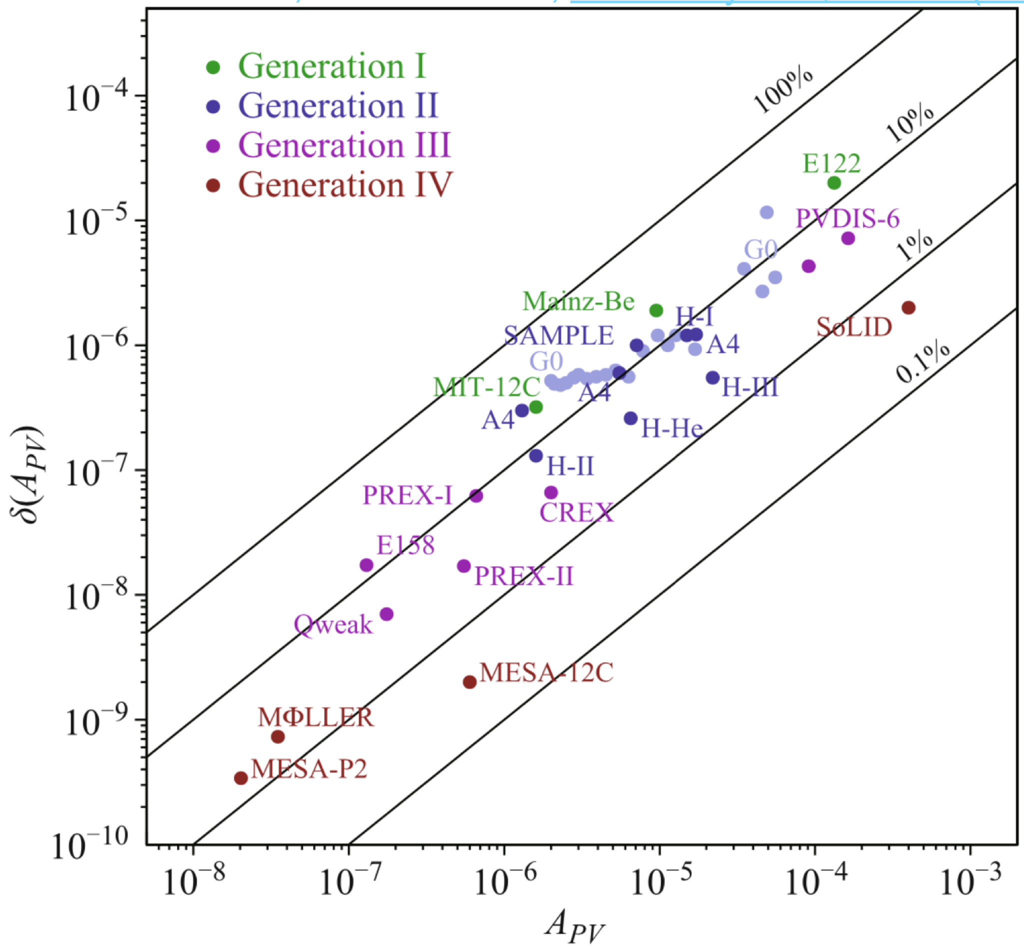
Parity Violating Asymmetry in Møller Scattering

- Ultra-precise measurement of parity-violating asymmetry A_{PV} in polarized electron-electron scattering.
  - A_{PV} results from interference between electromagnetic and weak neutral current amplitudes.
  - Proportional to the Q_W^e.

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

- A_{PV} is predicted to be ≈ 33 ppb at our kinematics.
  - Measure A_{PV} to an uncertainty of 0.8 ppb.
  - Achieve a 2.4% measurement of Q_W^e.

P. Souder, K. D. Paschke, Front. Phys. 11, 111301 (2016)

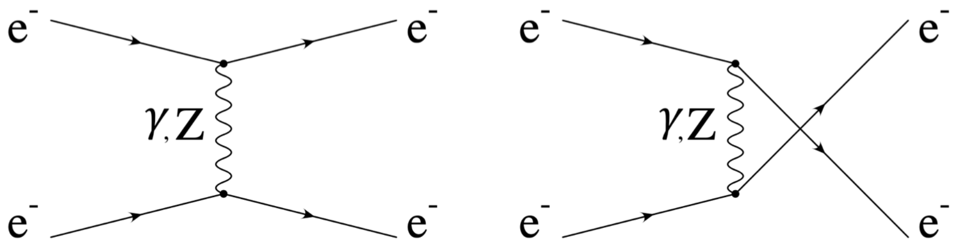


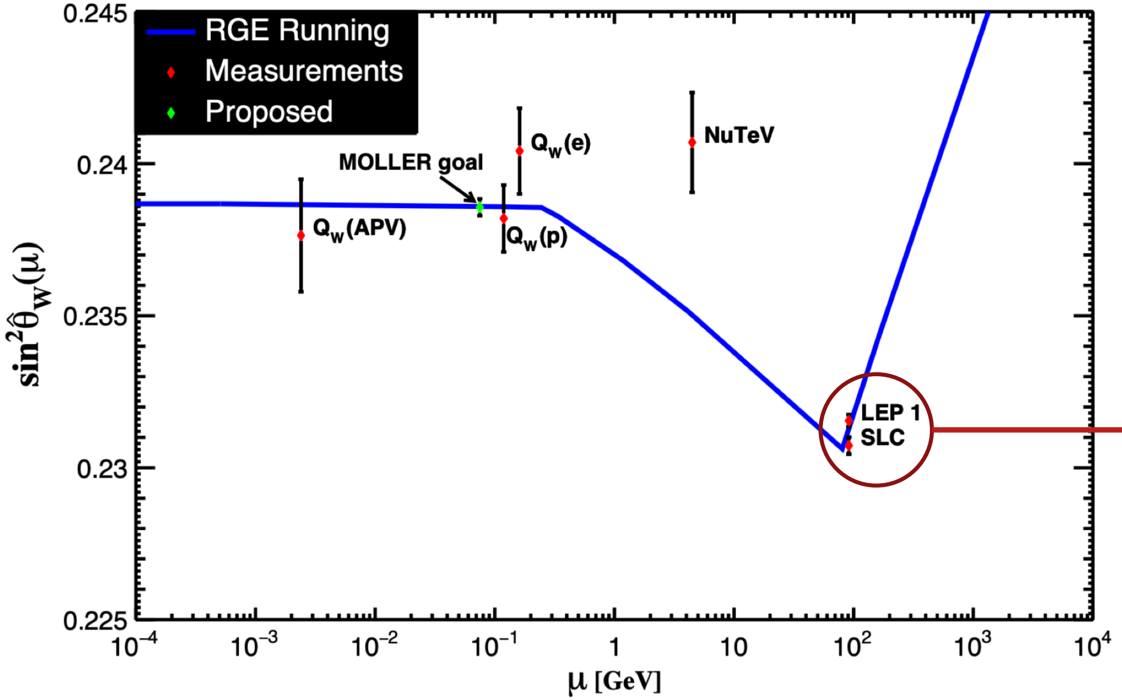
The precision of the measured value of the asymmetry in various PVES experiments

Weak Mixing Angle Measurements

- Electron's weak charge at tree level in term of the weak mixing angle is given by

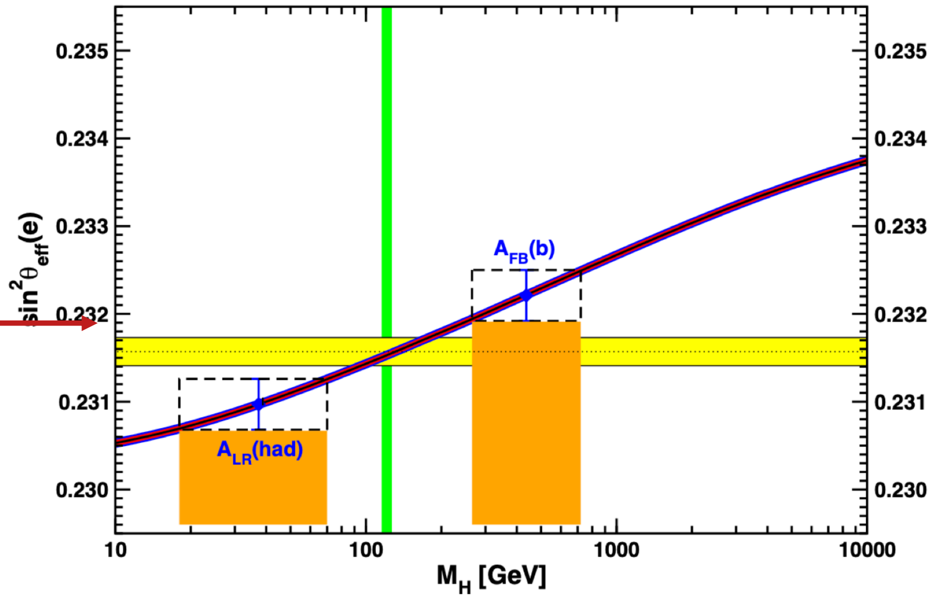
$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$





The measurement of the weak mixing angle as a function of the energy scale μ

J. Erler, arXiv:1710.06503



The most precise Z-pole measurements of $\sin^2\theta_W$ differ from each other by $\sim 3\sigma$

Weak Mixing Angle Measurements at Low Energy

- Effective weak mixing angle:

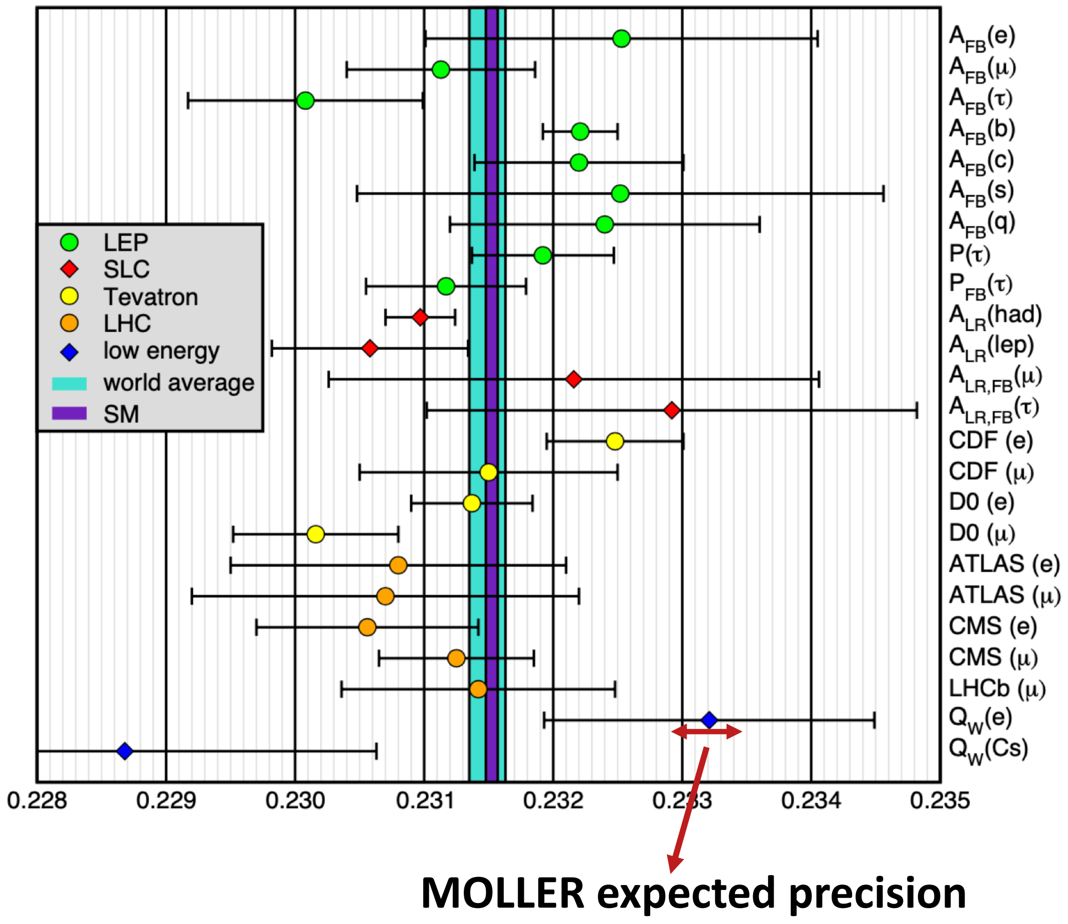
$$\sin^2\theta^l_{eff} \equiv \frac{1}{4}\left(1 - \frac{v_l}{a_l}\right)$$

- MOLLER A_{PV} would be the first low Q^2 measurement to match the precision of the single best high energy measurement at the Z^0 resonance.

- MOLLER projection:

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

J. Erler, arXiv:1710.06503

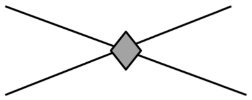


All measurements of the effective leptonic weak mixing angle.

Comparison with High Energy Colliders

Krishna Kumar

- MOLLER experiment is very complementary to other precision low energy experiments and direct searches at high energy colliders.



$$\frac{1}{\Lambda^2}\mathcal{L}_6 \qquad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} \simeq 7.5\ \text{TeV}$$

- Search for new physics by looking for deviations from Standard Model predictions.

e+e- Collisions

$\Lambda_{LL}^{ee} \sim 8.3\ TeV$ (LEP200 reach)

Fixed Target

$\Lambda_{LL}^{ee} \sim 12\ TeV$ (E158 reach)

$\Lambda_{LL}^{ee} \sim 27\ TeV$ (MOLLER reach)

LEP200: Lepton-Lepton interactions

E158: PV Møller Scattering

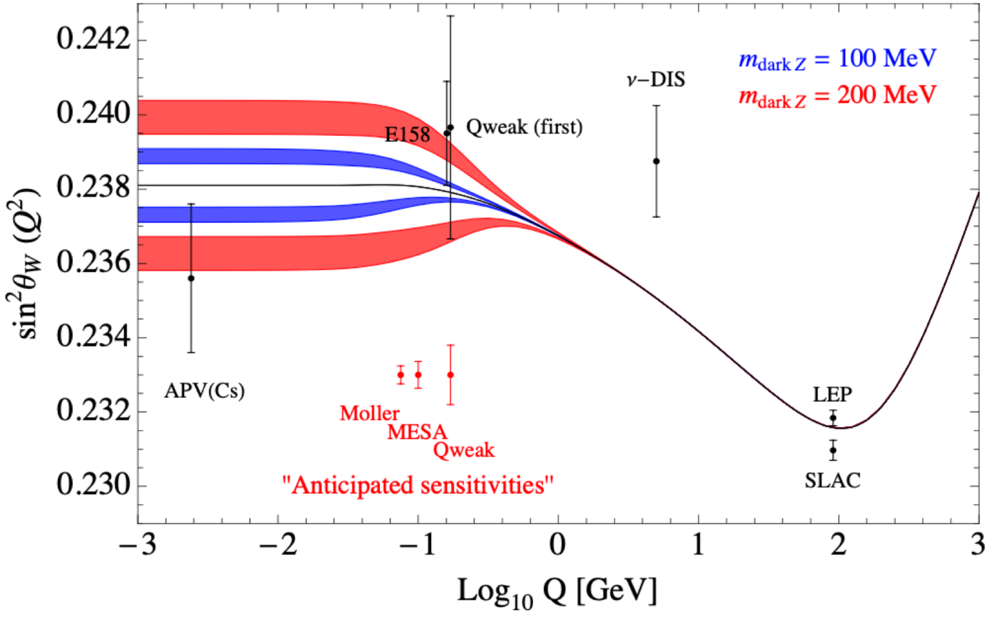
- **MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory.**

New Physics Beyond the Standard Model

✓ MOLLER provides a unique window to new physics at MeV and multi-TeV scales, complementary to direct searches at high energy colliders.

- Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade.
  - weakly coupled MeV scaled mediators (**dark *Z*** → parity violating effect visible in low energy experiments (if $Q^2 \lesssim m_{Z_d}^2$))

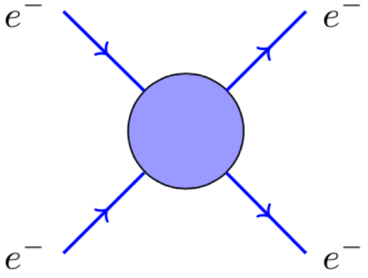
H. Davoudiasl, H.-S. Lee, W. J. Marciano, arXiv:1402.3620

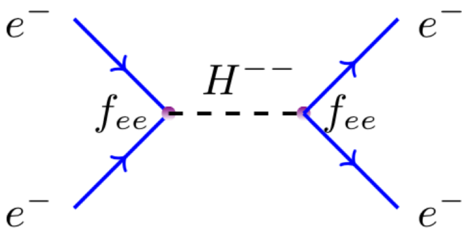


Running of the effective weak mixing angle, $\sin^2\theta_W(Q^2)$ with energy scale Q.

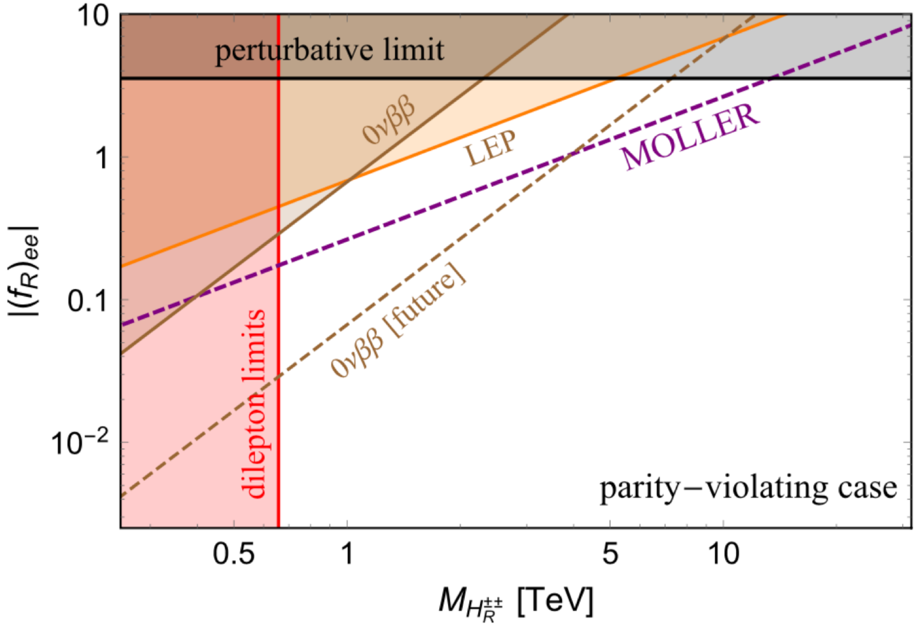
New Physics Beyond the Standard Model

- Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade.
  - high energy (multi-TeV) scale dynamics (Z’, electron compositeness, supersymmetry, **doubly charged scalars**,…)





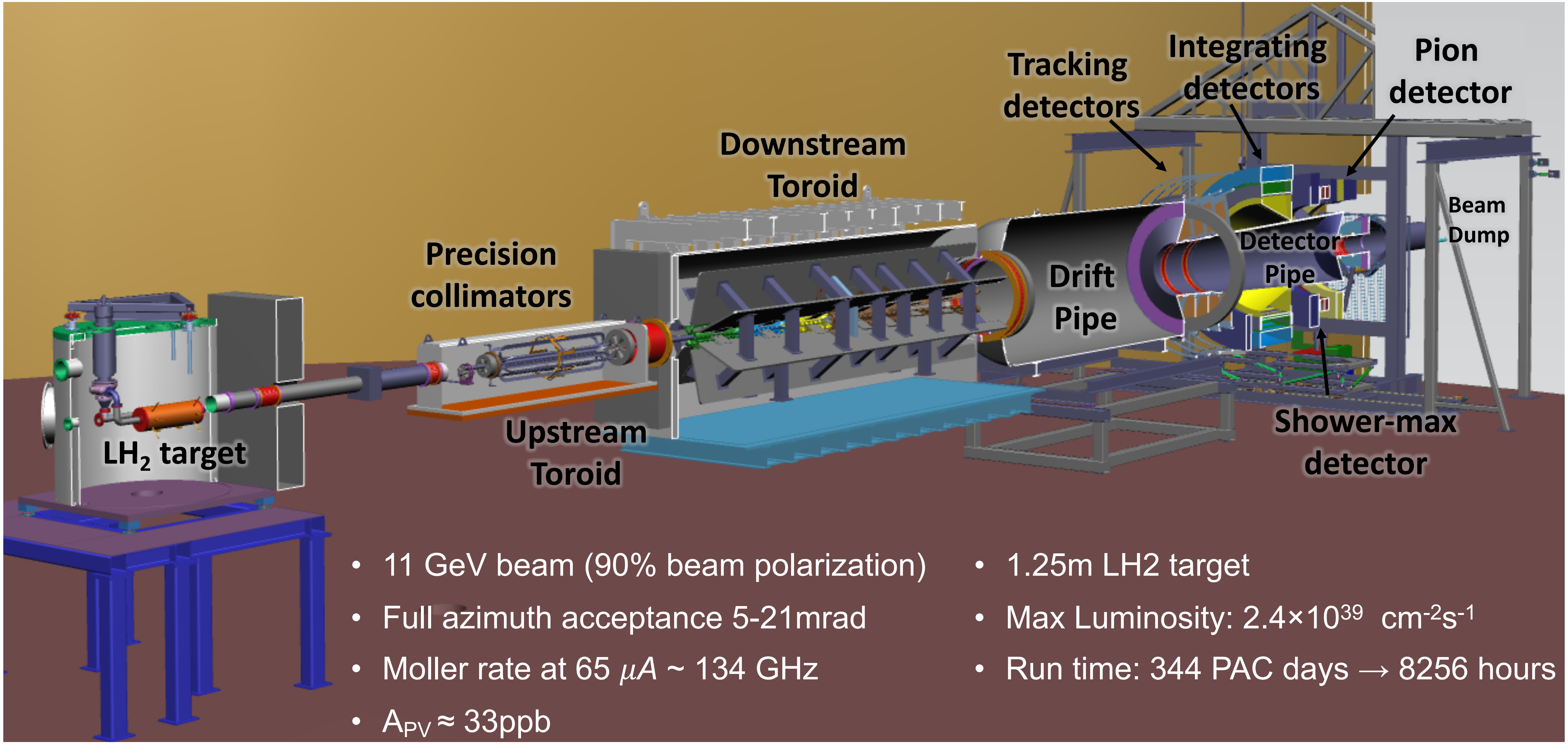
P. S. B. Dev, M. J. Ramsey-Musolf, Y. Zhang
PHYSICAL REVIEW D 98, 055013 (2018)



MOLLER prospect for the RH doubly-charged scalar mass $M_{H_R^{\pm\pm}}$ in the parity-violating LRSM and the coupling $|(f_R)_{ee}|$

- $M_{H_R^{\pm\pm}}$ could be probed up to ≃10 TeV for a $\mathcal{O}(1)$ Yukawa coupling by MOLLER → This is far beyond the direct search capability of LHC or even future 100 TeV colliders.

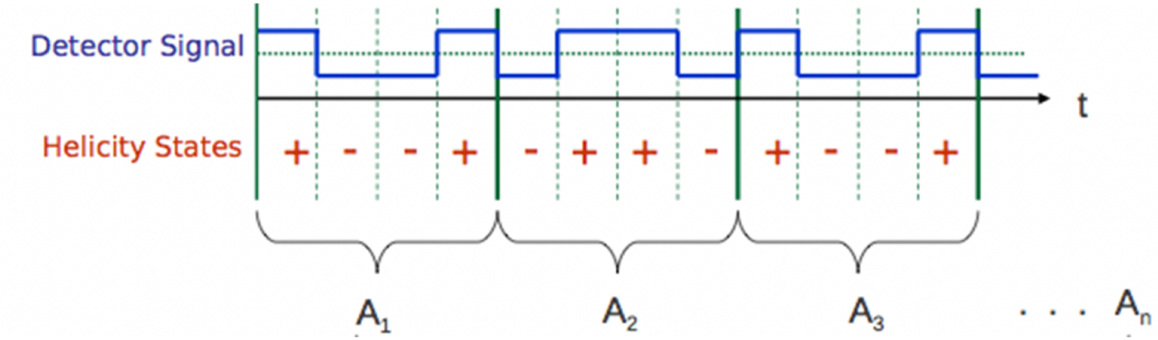
The MOLLER Experiment



- 11 GeV beam (90% beam polarization)
- Full azimuth acceptance 5-21mrad
- Moller rate at 65 μA ~ 134 GHz
- $A_{PV} \approx$ 33ppb
- 1.25m LH2 target
- Max Luminosity: 2.4×10^{39} $cm^{-2}s^{-1}$
- Run time: 344 PAC days → 8256 hours

How Do We Take the Bulk of Our Data?

Both slow and rapid helicity reversals



Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	**~ 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**

MOLLER specification is 10 ppm resolution for relative beam intensity measurement for 1 kHz window pairs.

- The raw signal from the detectors integrated for each helicity window (0.52 ms) and asymmetry formed from in a single helicity patterns.
  - MOLLER is designing around a helicity flip rate of 1.92 kHz.

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

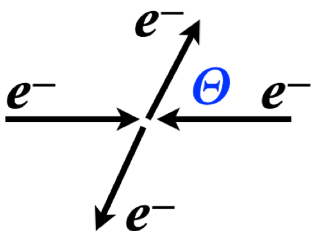
- Remove the correlations of flux to beam intensity, position, angle, and energy fluctuations:

$$A_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum \left(\alpha_j (\Delta X_j)_i\right)$$

- Repeat 30 billion times to get desired statistical error.

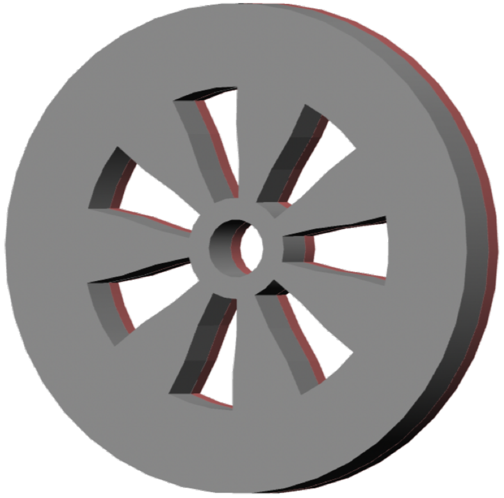
MOLLER Kinematics and Acceptance

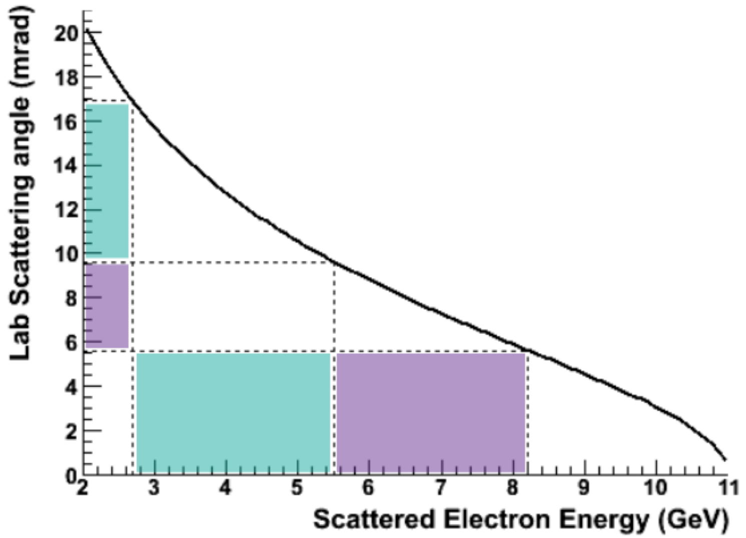
- Identical particles.

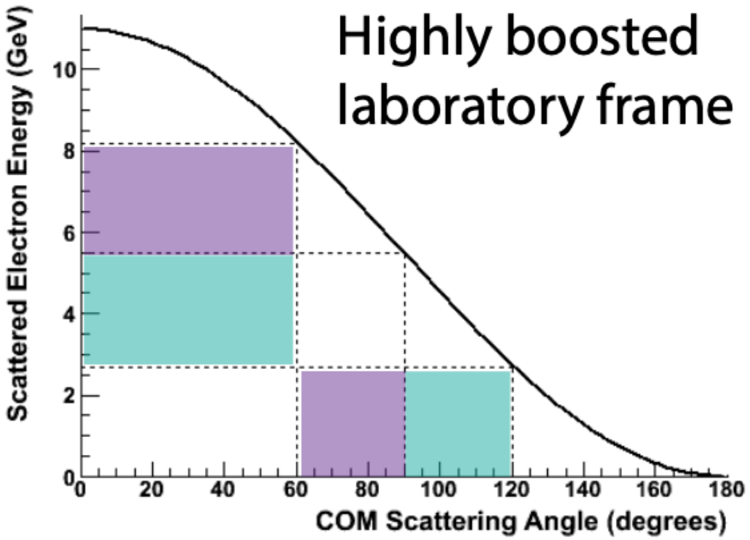


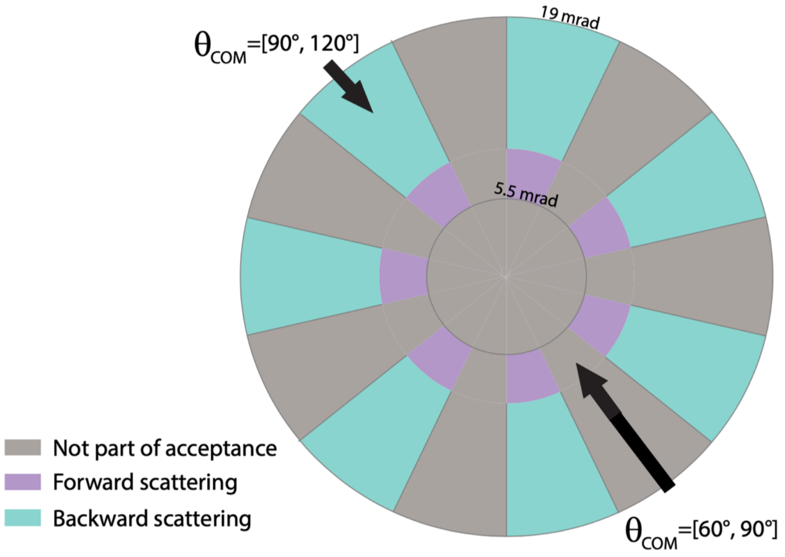
- Measure either forward or backward scattering in CM frame.
- Full azimuthal acceptance for Møller scatters from 6 <θ_{lab}< 20 mrad

Acceptance defining collimator
7-fold symmetry

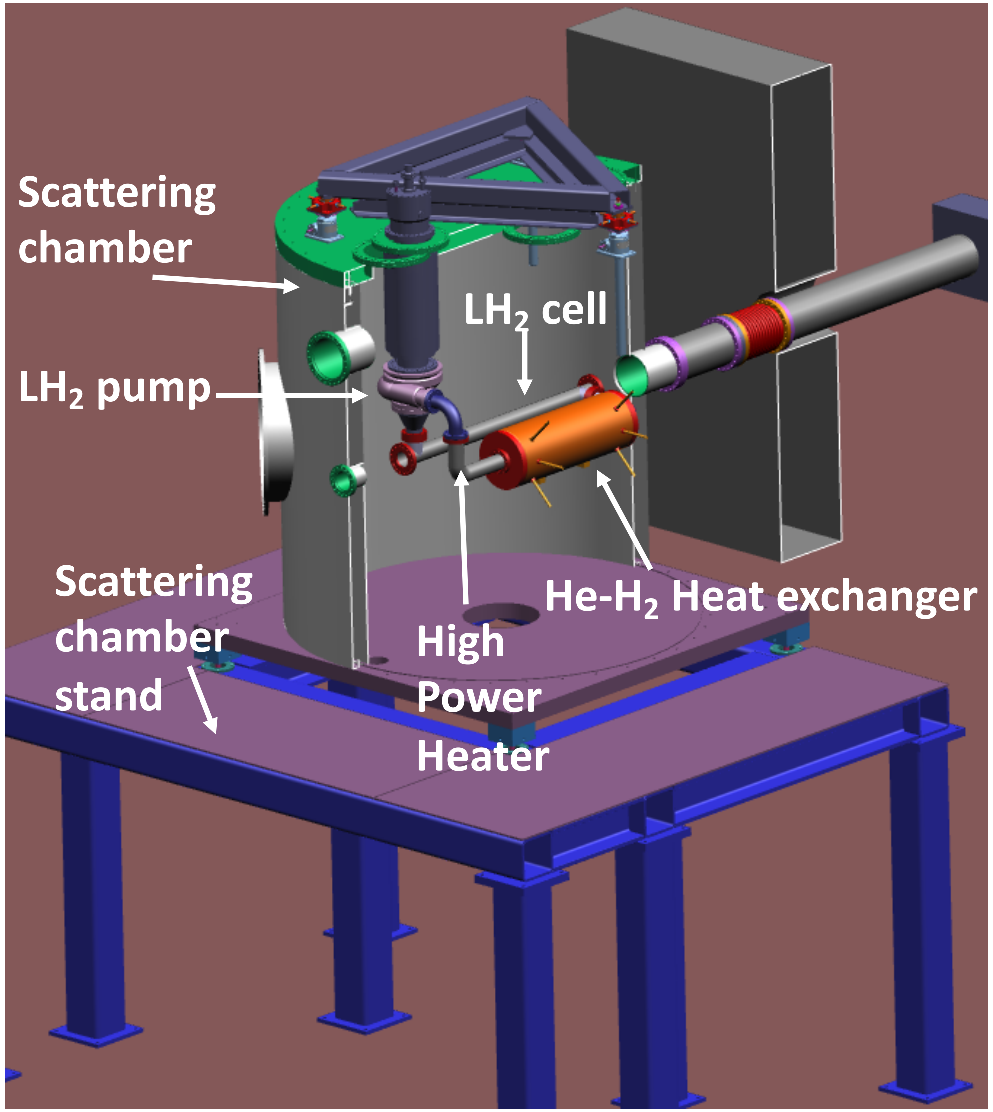








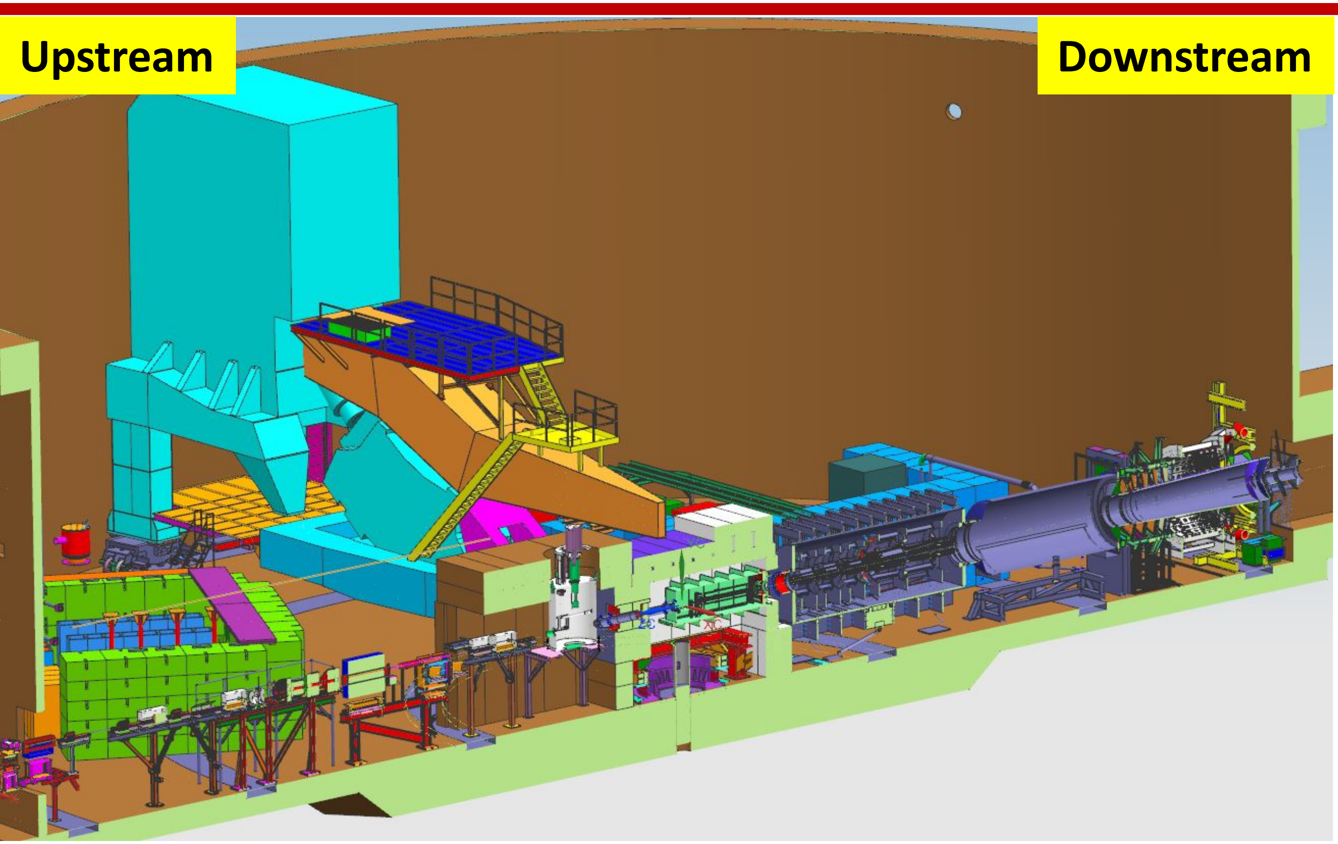
Liquid Hydrogen Target



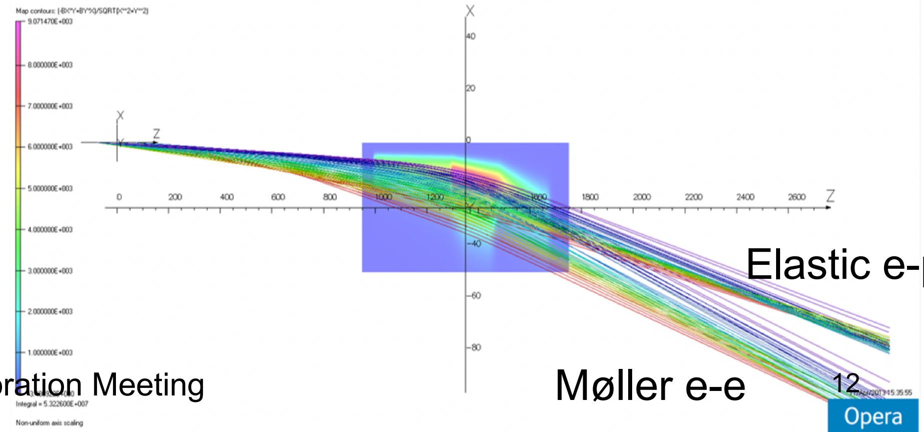
- Q_{weak} target is the precursor for the MOLLER target.
  - Target power needs to go from 3 kW to 4kW.
  - Target flow needs to go from 17l/s to 25l/s.
  - Target noise needs to decrease from 47ppm to 30ppm.

Target Parameters	
Cell length	125 cm
Cell thickness	8.93 g/cm^2
Radiation length	14.6%
p, T	35 psia, 20K
ϕ acceptance	5 mrad (0.3°)
Target power	4000 W

MOLLER Spectrometer



- Extent of spectrometer scope is 26.5 m.
- Defines the acceptance of the experiment.
- Consists of a pair of 7-fold symmetry toroidal magnets.
  - The odd-fold symmetry provides ~100% acceptance for the identical-particle Møller scattering process.
  - The toroidal magnets use a conventional resistive copper coil design.
- The collimation system will protect the magnet coils from the high rate, sculpt the signal shape and remove the backgrounds.

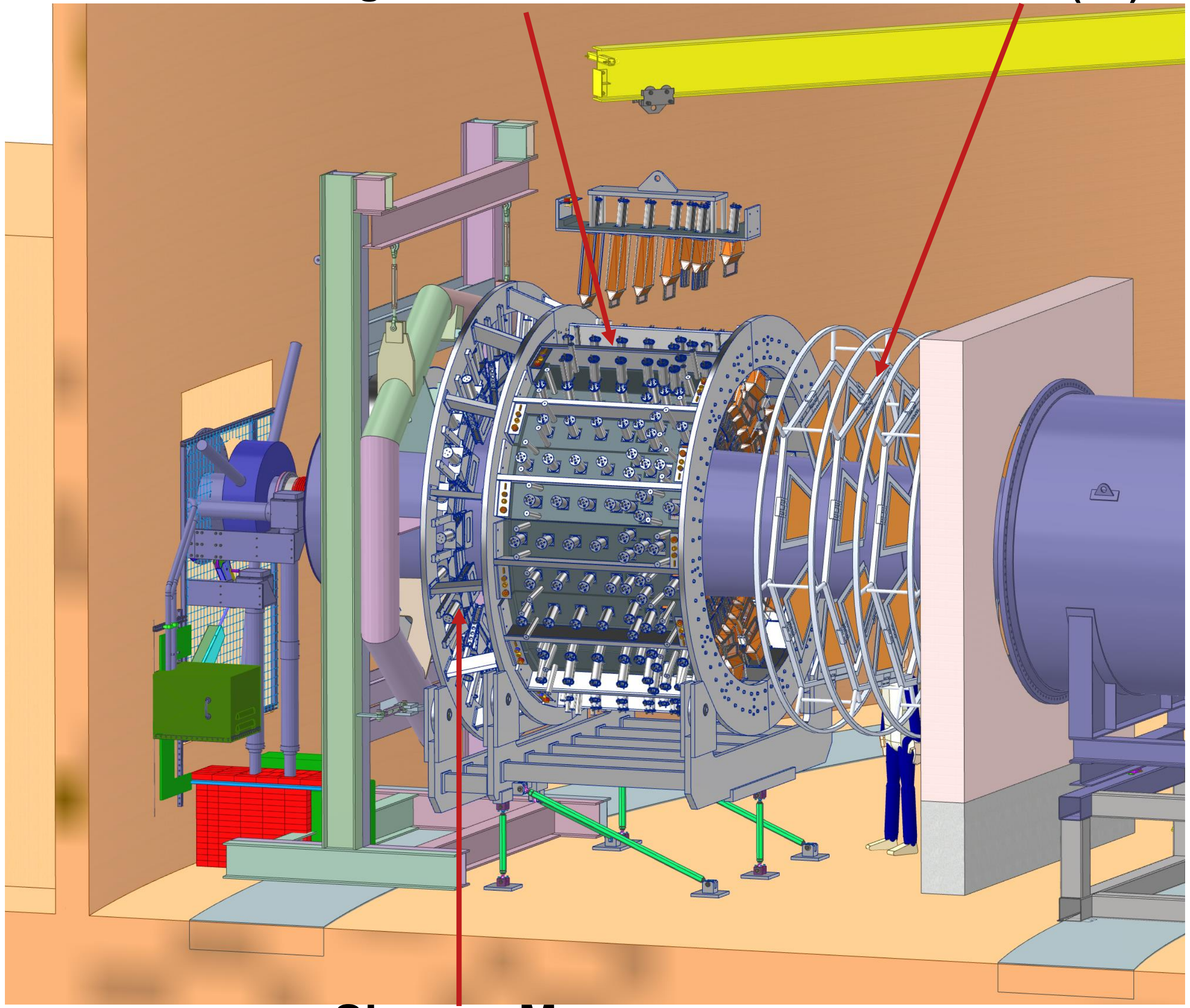


The spectrometer allows us to separate the Møller electrons from the different backgrounds.

Integrating and Tracking Detectors Overview

Thin Quartz (224)
6-ring Cherenkov detector

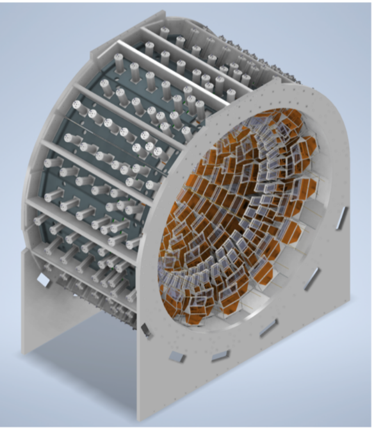
GEM
Modules (28)



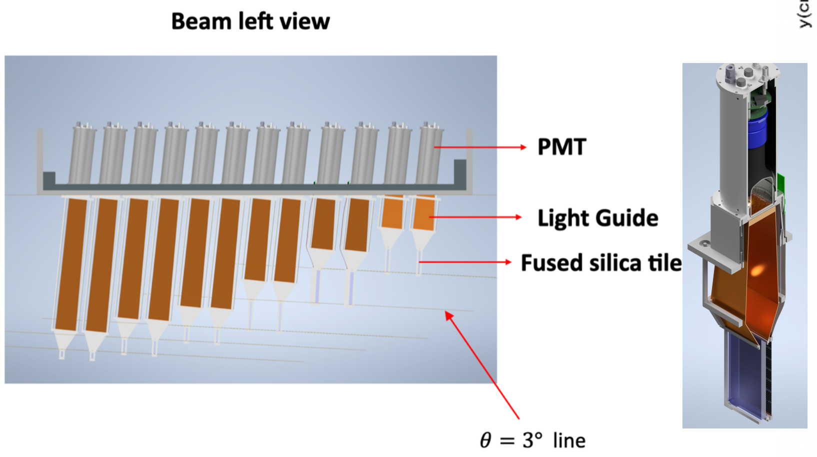
Shower-Max
Detector (28)

- **Integrating detectors** are an array of detectors based on quartz as the active element.
  - Asymmetry measurements of both signal and background, and beam and target monitoring.
  - 6 concentric rings. Ring 5 primarily capturing the Møller electron signal.
- **Shower-Max detector** concept uses a layered "stack" of tungsten and fused silica (quartz) to induce EM showering and produce Cherenkov light
  - Provides additional measurement of Ring 5 integrated flux $\Rightarrow$ less sensitive to low energy and hadronic backgrounds.
  - Will also operate in tracking mode to give additional handle on background pion identification.
  - Will have good resolution over full energy range ($\lesssim$ 25%), radiation hard with long term stability and good linearity.
- **Pion detector**
  - Hadronic dilution/asymmetries
- **Integrating monitors** are "canaries", looking for a variety of anomalous helicity correlations
  - Small Angle (SAMs); Large Angle (LAMs); Diffuse Background (DBMs); Scanners (remotely controllable)
- **GEMs**
  - Spectrometer calibration, electron scattering angle distribution and background measurements.

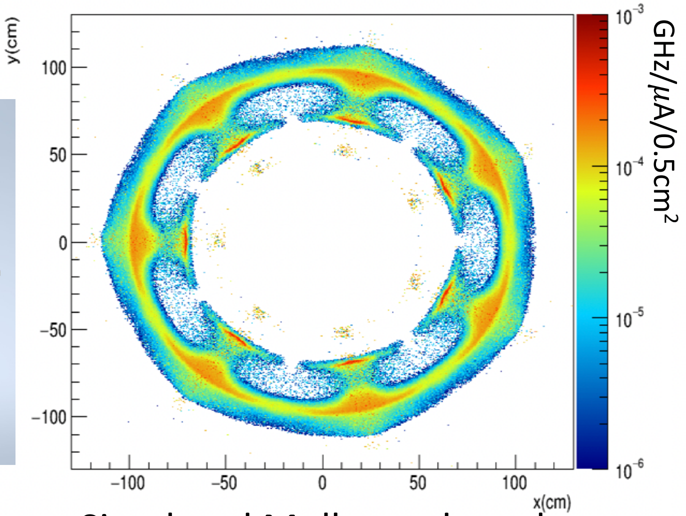
Detector Plane Segmentation



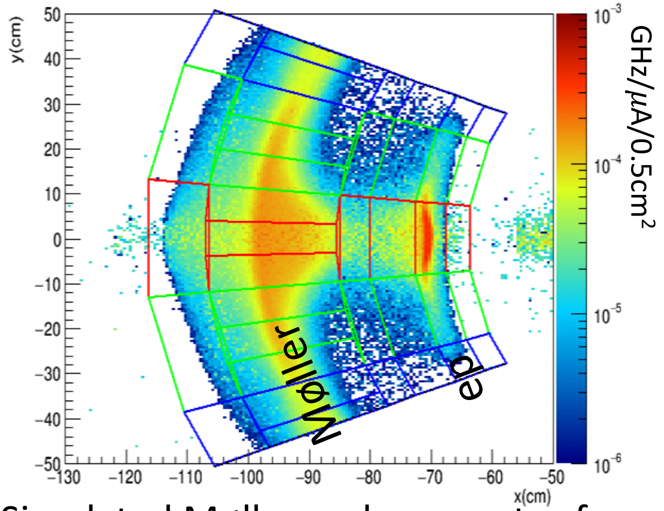
Detector assembly



Michael Gericke

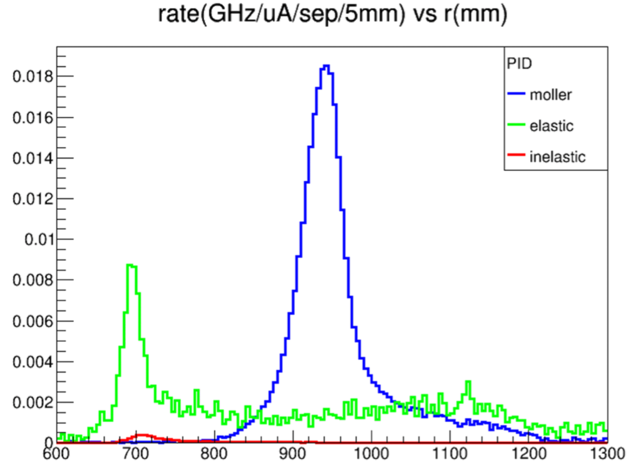


Simulated Møller and ep electron rates



Simulated Møller and ep e- rates for superimposed azimuthal and radial bins in one toroidal sector.

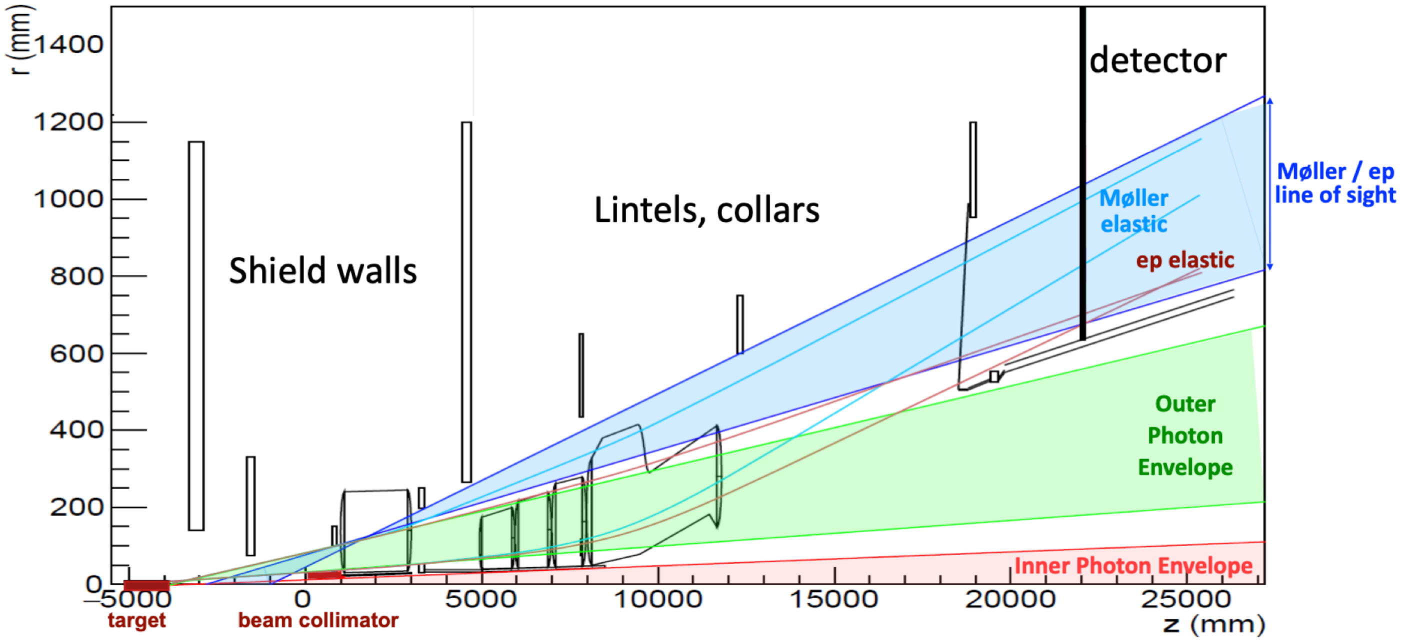
- The thin detector array consist of 6 rings and 224 detectors.
  - 28 segments around the annulus
  - Each segment has a total of 8 detector modules (3 ring 5 detectors + others)
  - 84 detectors in Ring 5 and 28 in each of the other rings
  - Each detector module consists of a quartz, tile, an air-core light guide, and a PMT.
- High level of segmentation separates irreducible backgrounds from Møller signal.
  - The modules must overlap slightly, to cover the azimuth so that the rings need to staggered along the beam direction. They also need to be spaced such that assembly and access to quartz tiles is possible.

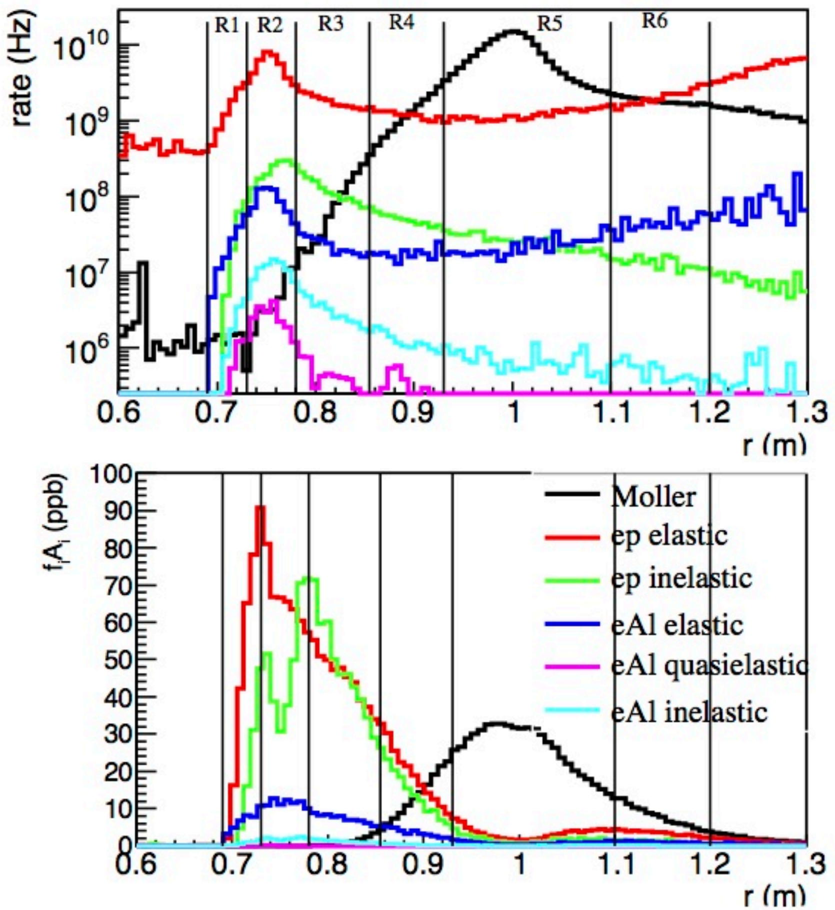


Radial dist. at detector plane 26.5m from target, all φ includes rad. eff.

MOLLER Backgrounds

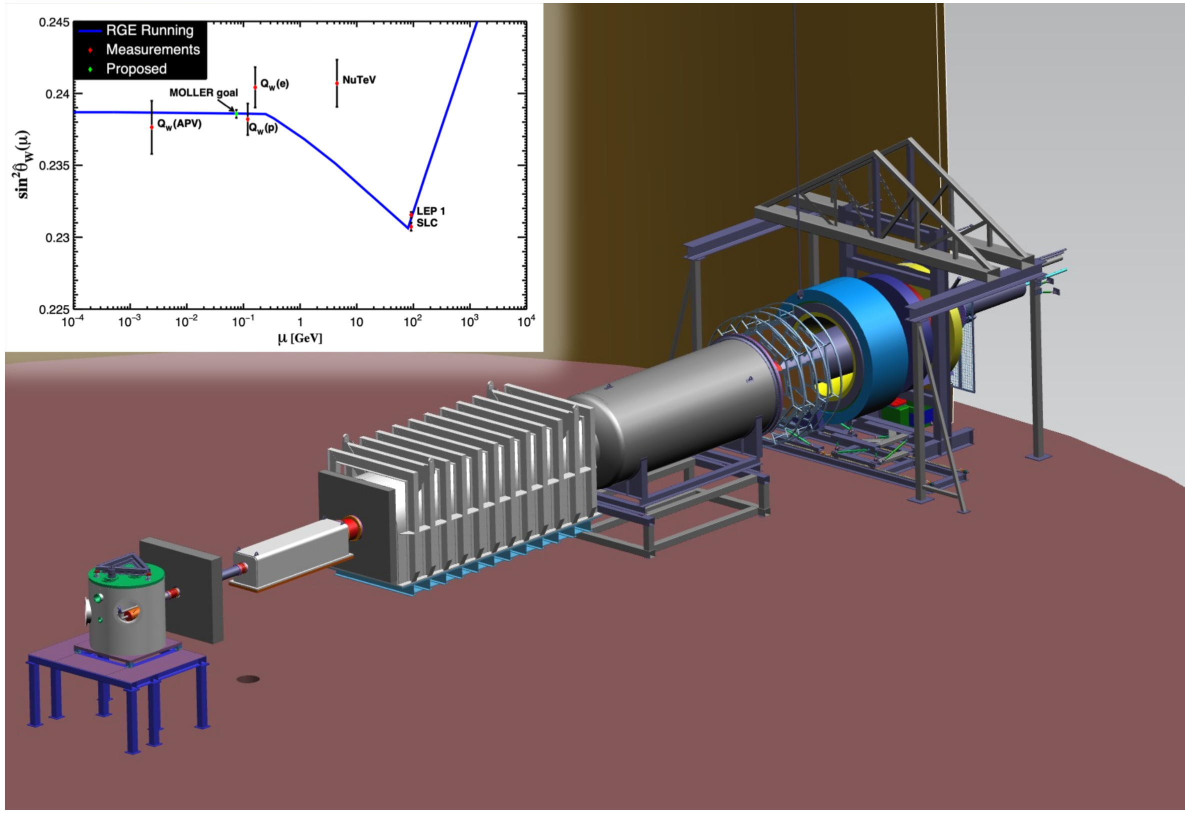
- Irreducible backgrounds arise from scattering off the target material that will pass through the spectrometer and arrive at the detector plane.
  - The principal irreducible background under the Møller "peak" is radiative elastic ep scattering.
- We will deconvolute the signal from the background using the segmented detector plane
- Other background sources
  - Photons and neutrons from 2 bounce collimation system.
  - Pions and muons : photo-production and DIS





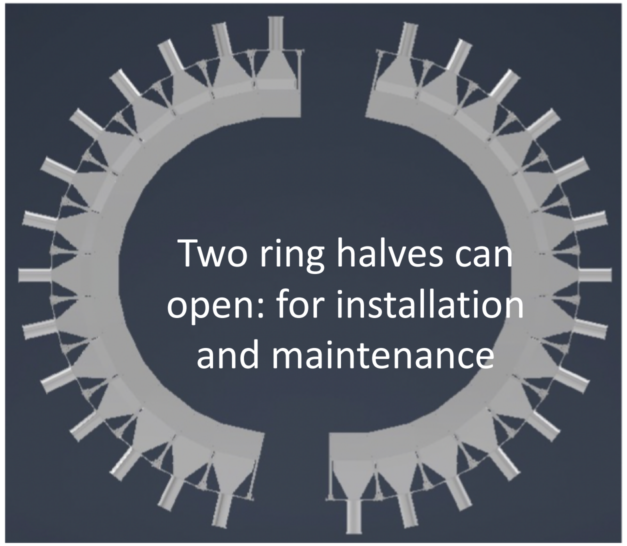
Summary

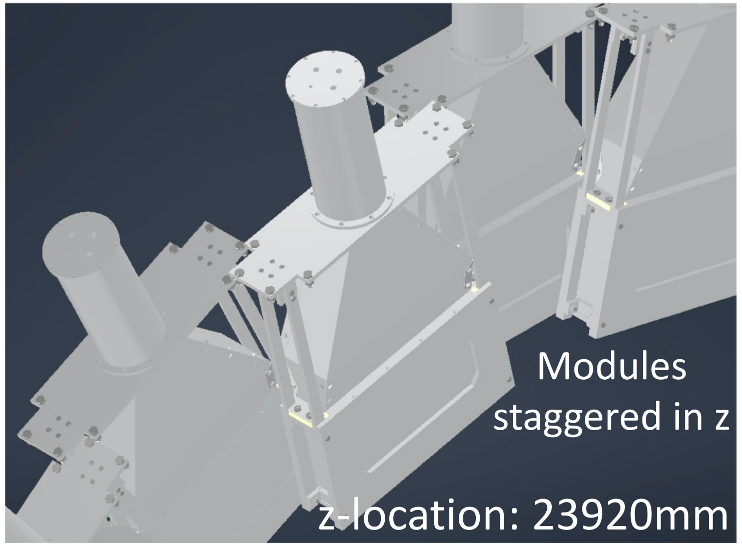
- MOLLER represents a compelling opportunity to take advantage of the 11 GeV JLab beam at the upgraded facility.
  - Most sensitive probe of new flavor and CP-conserving neutral current interactions.
- The unique discovery capability in MOLLER will be very important.
  - If LHC sees any anomaly in high luminosity phases of 14 TeV.
  - MOLLER provides excellent sensitivity to Beyond Standard Model physics.

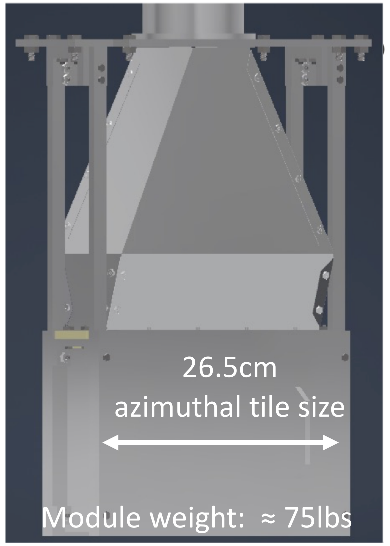


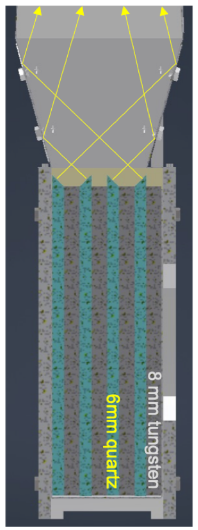
Backup

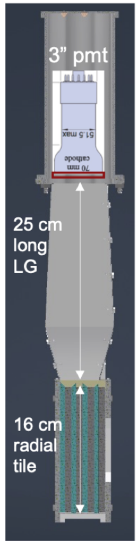
Shower-Max Detector





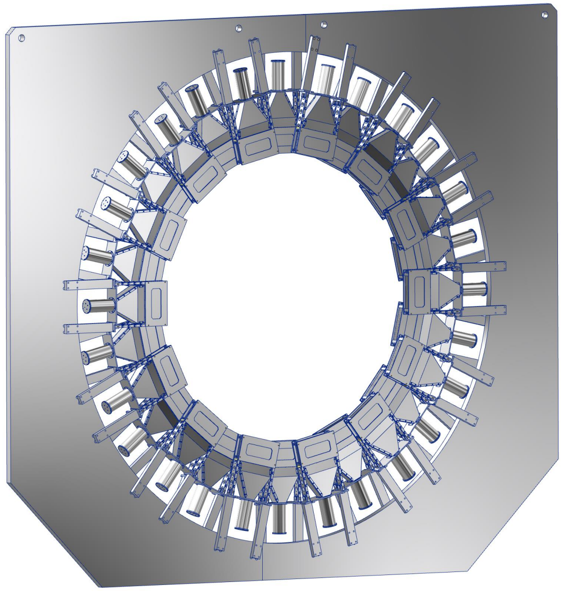






Dustin McNulty

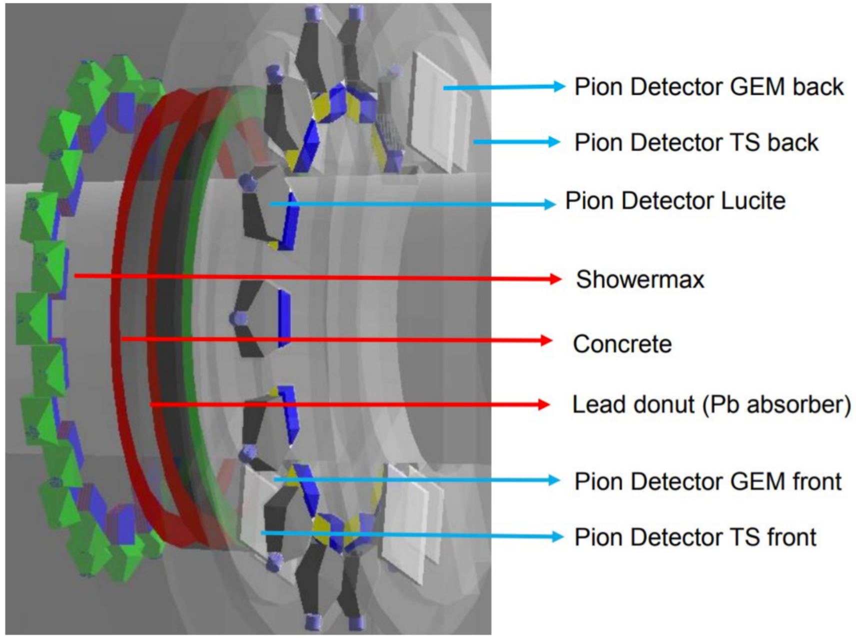
- ShowerMax detector: ring of 28 sampling calorimeters intercepting physics signal flux 1.7 m downstream of Ring 5
- Detector *z*-location and radial acceptance near finalized.
- New (final) quartz and tungsten tile sizes determined.
- CAD model updated and passed to engineer (Larry M Bartoszek) for FEA and external ring support structure design.
- Simulations of expected radiation loads in each quartz layer have been performed.

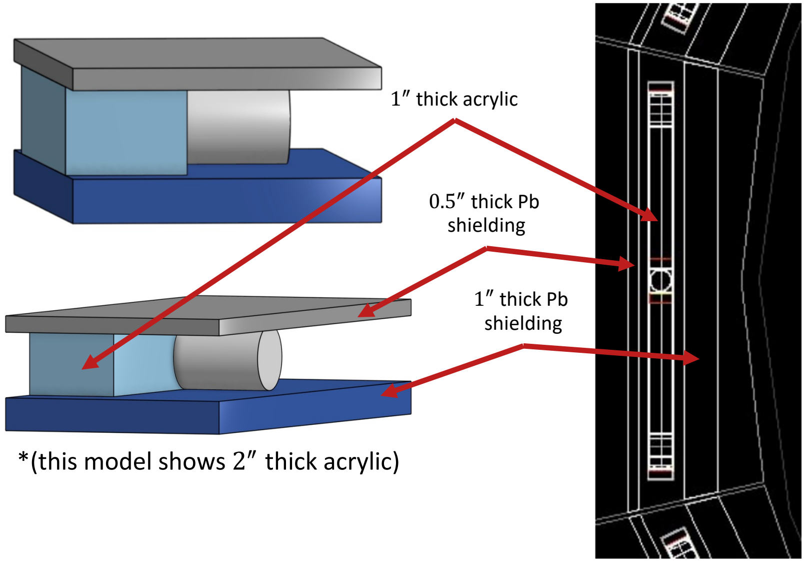


Larry M Bartoszek

Pion Detector

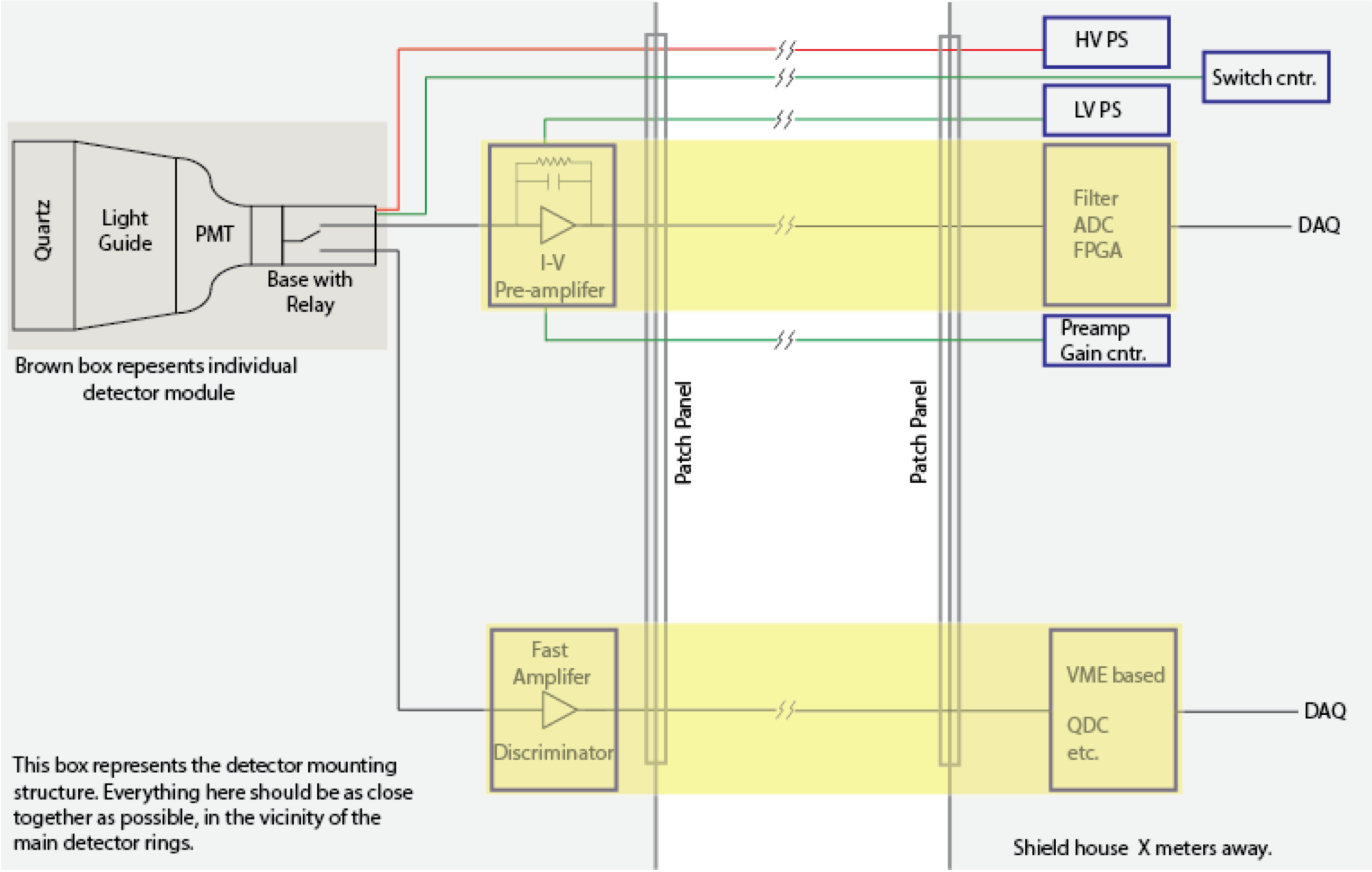
David Armstrong Wouter Deconinck





- Original design had to be modified because of ShowerMax spray.
  - π/e photoelectron ratio ~10^{-3} due to ShowerMax secondaries producing copious flux of soft electrons (< 5 MeV) at pion detector
    - optimize optical design of lucite to maximize π/e ratio by using pion directionality, and allow for shielding at outer radial side
- New design is essentially a stack of lead-lucite-lead slabs [90° rotated design]:
  - $1''$ lucite layers (one or multiple)
  - PMT downstream, direct coupling to lucite
  - No more wedge, no more lightguide
  - Shielding on all sides, including outer radial side
- Rotated design indicates performance of up to 60% π/e photoelectron ratio
- Planned studies of rotated design:
  - Improved modeling of coupling to PMT
  - Optimization of length/thickness of lucite/shielding
  - Radiation at PMT (shielded from all sides)

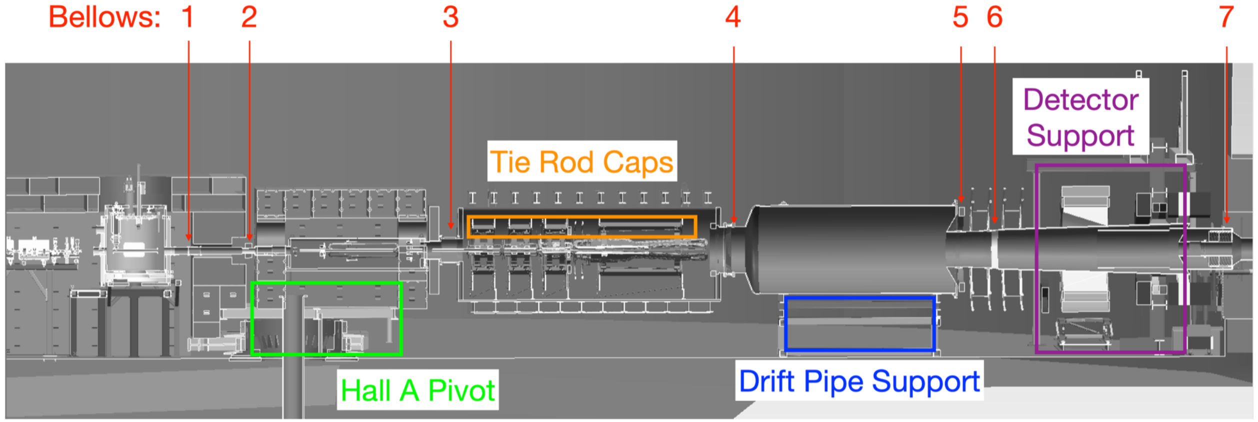
Integrating Detector Signal Chain



Michael Gericke

- Separate readout chain for integration and counting mode
- In integration mode, chain goes from base to I-V preamp to ADC board (fully differential)
- Counting mode chain starts from base via separate cable
- Base is switched between the two modes via reed relay with a simple 5 V switching voltage.
- The highest rate in a single quartz detector will be ~5 GHz, while the lowest rate will be a few hundred MHz.

Potential Background Asymmetries from Ferrous Materials



Elevation view of the MOLLER spectrometer, marked up from JLab CAD drawings.
The locations of potentially ferromagnetic materials are indicated.

Bellows: Inconel 625
Hall A Pivot, Tie Rod ends,
Detector support: mild steel
Drift pipe and downstream torus support: mild steel (possibly)

- Potential backgrounds to the Møller scattering asymmetry due to scattering from polarized materials along the beam line or elsewhere in the Hall. → polarized materials are most likely due to ferromagnetic materials/components.

- Estimate false asymmetry A_f as;

$$A_f = f_r P_e P_s A_n$$

f_r: rate fraction of process
P_e: incident electron polarization
P_s: material electron polarization
A_n: analyzing power

- Goal: $A_f < 10^{-11}$
- In ~1G ambient field:
  Mild steel: $P_s \sim 10^{-2}$
  Stainless stee: $P_s \sim 10^{-5} \sim 10^{-7}$
  Inconel 625: $P_s \sim 10^{-8}$
  Aluminum (paramagnetic): $P_s < 10^{-9}$