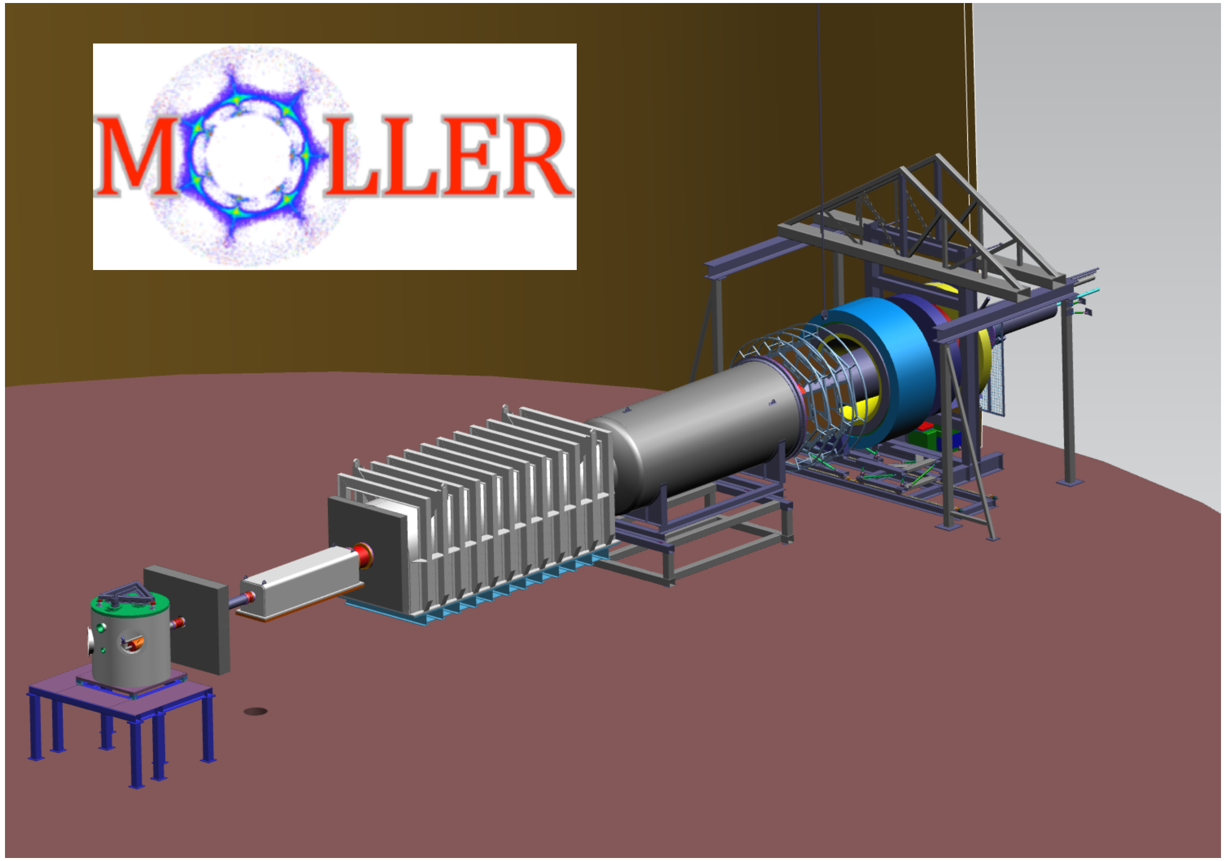
Deconvolution of the measured asymmetry at the MOLLER Experiment

CFNS Postdocs Meeting

July 14, 2023

Zuhal Seyma Demiroglu

Measurement Of a Lepton Lepton Electroweak Reaction



Jefferson Lab
Stony Brook University
Center for Frontiers in Nuclear Science
U.S. DEPARTMENT OF ENERGY Office of Science
JSA

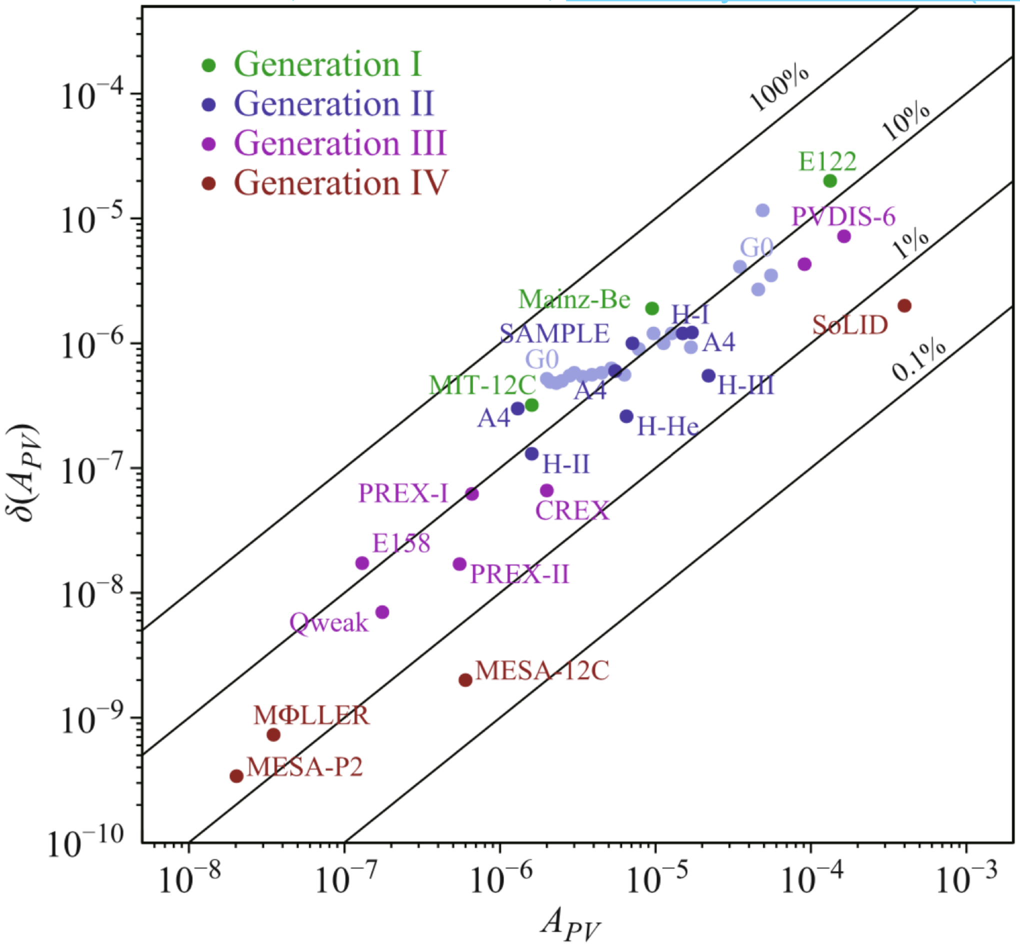
Parity Violating Asymmetry in Møller Scattering

- 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.

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

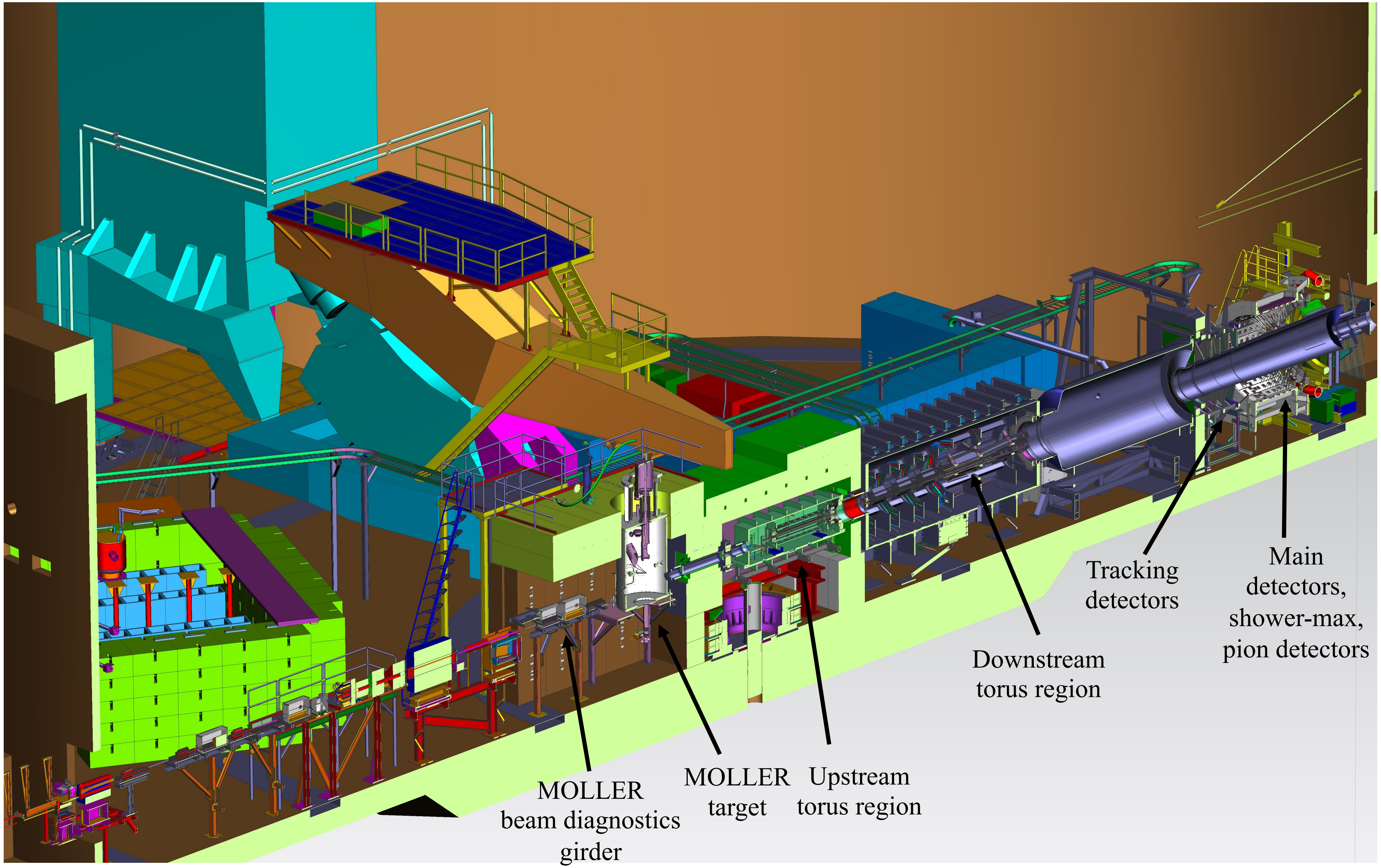
- A_{PV} is predicted to be ≈ 33 ppb at our kinematics.
  - Measure A_{PV} to an uncertainty of 0.8 ppb.
  - Achieve a 2.4% measurement of Q_W^e at an average Q^2 of 0.0056 GeV².

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



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

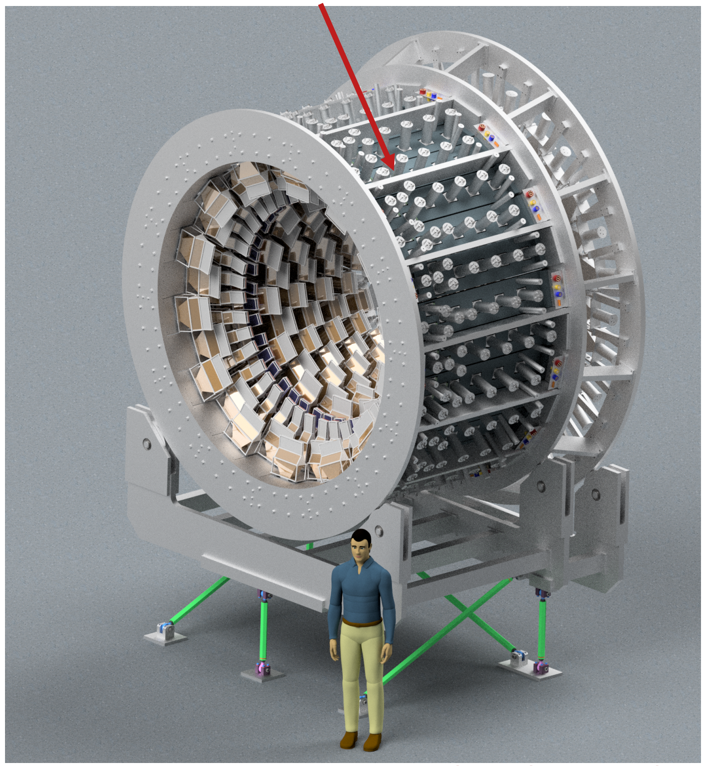
The MOLLER Experiment

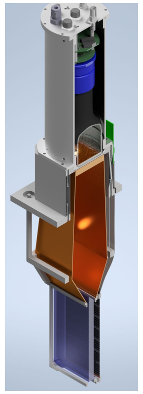


- 11 GeV beam (90% beam polarization)
- 1.25m LH_2 target
- Run time: 344 PAC days → 8256 h
- Full azimuth acceptance: 5-21mrad
- Møller rate at 65 μA ~ 134 GHz
- $A_{PV} \approx$ 33ppb
- Max Luminosity: $2.4{\times}10^{39}$cm^{-2}s^{-1}
- $\langle Q^2 \rangle$: 0.0056 GeV^2

Main Integrating Detector Segmentation

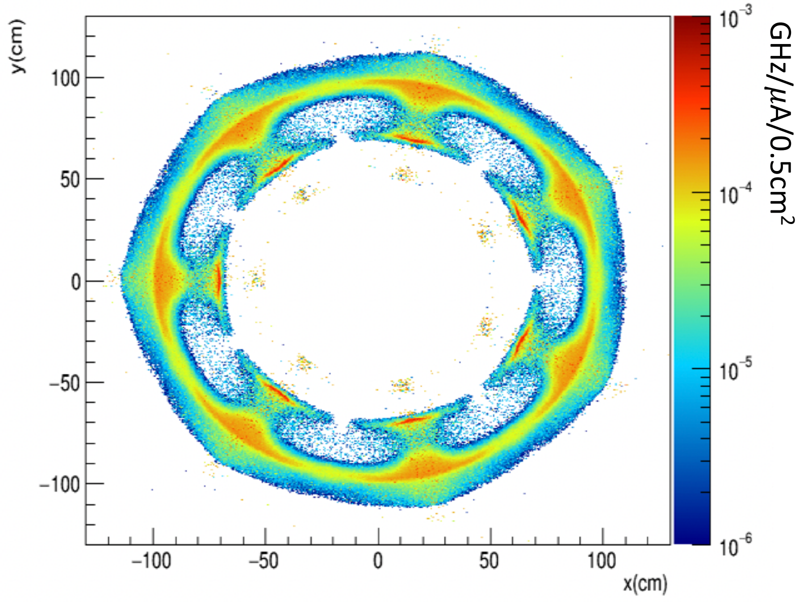
Thin Quartz (224)
6-ring Cherenkov detector



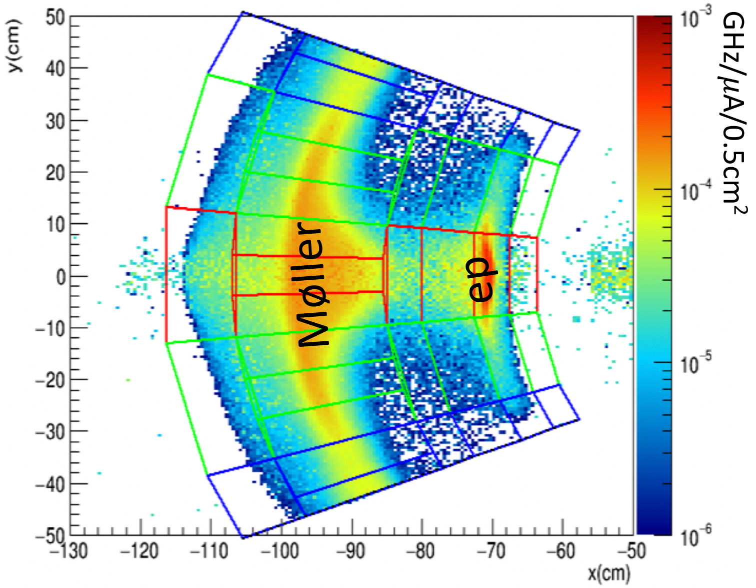


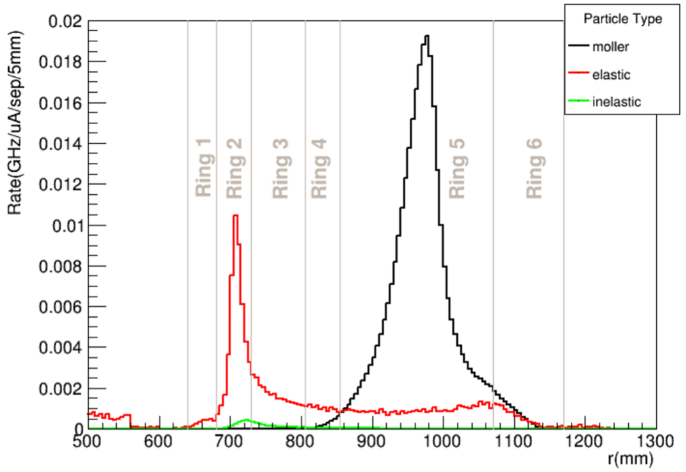
Michael Gericke

Simulated Møller and ep electron rates



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

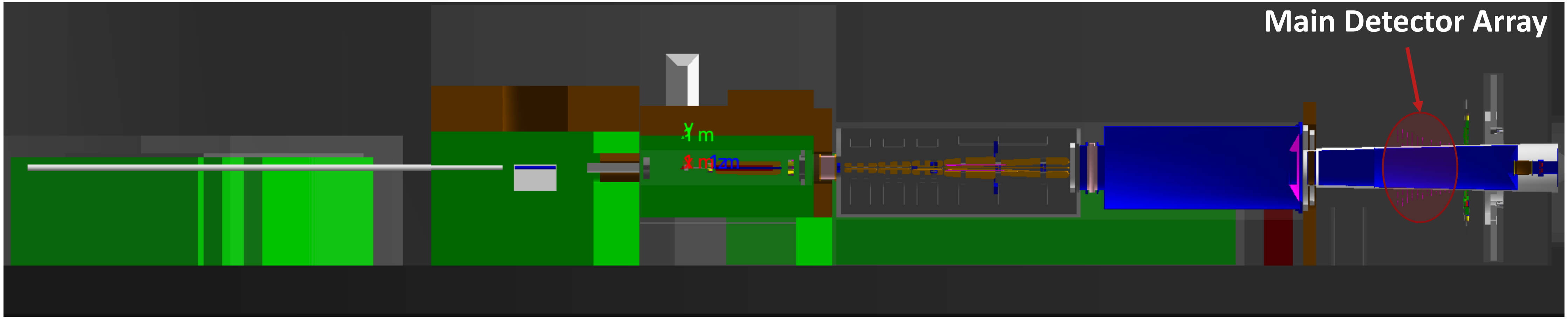




- **Integrating detectors** are an array of detectors based on quartz as the active element.
  - The thin detector array consist of 6 rings and 224 detectors.
    - 84 detectors in Ring 5 and 28 in each of the other rings

Detector Tiling and Tiles in the GEANT4 Simulation

- The main aim is to improve the ability to separate the Møller signal from the e-p elastic and e-p inelastic background.
- The radial dimensions of each quartz tile are set to maximize the Møller signal and get the best precision extraction of the Møller asymmetry in Ring5.



Tile Asymmetry Deconvolution Analysis

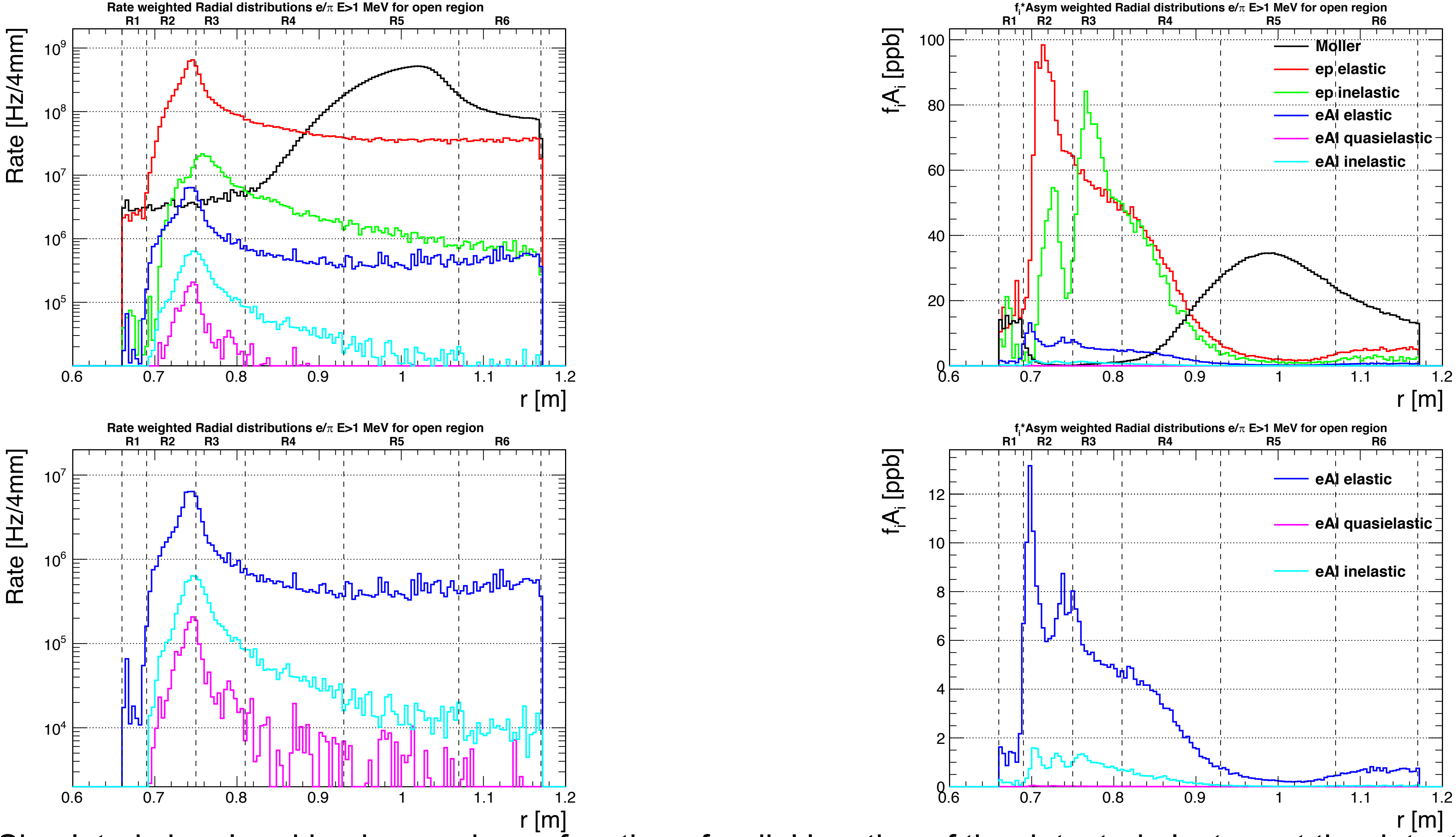
- The deconvolution analysis is used to extract the asymmetries in the signal and background processes from the data.

- In i_{th} (r,ϕ)bin, measured asymmetry;

$$A_m^i = f_{ee}^i\, A_{ee}^i + f_{ep-elastic}^i\, A_{ep-elastic}^i + f_{ep-inelastic}^i\, A_{ep-inelastic}^i + f_{eAl-elastic}^i\, A_{eAl-elastic}^i + f_{eAl-inelastic}^i\, A_{eAl-inelastic}^i$$

- The dilution for a given process:
  - $f_k = N_k / \sum_j N_j$, N_k: The rate of detected events from process k.
- Run the physics generators (Moller, epelastic, epinelastic, pion, elasticAl, inelasticAl, quasielasticAl) with 1M events.
- The deconvolution analysis is based on the 5 process fit.
  - Moller, ep-elastic, ep-inelastic (separated into three bins in W: $1 < W < 1.4$ GeV, $1.4 < W < 2.5$ GeV, $2.5 < W < 6$ GeV).

Tile Asymmetry Deconvolution Analysis



- **Left:** Simulated signal and background as a function of radial location of the detected electron at the detector plane.
- **Right:** The dilution weighted asymmetries, $f_i\ A_i$.

Toy Dataset Simultaneous Fit Results

det132 @21.3m

Processes	Expected A (ppb)	σ_A (ppb)	$\frac{\sigma_A}{\lvert A\rvert}$ (%)
Møller	-34.65	0.73	2.10%
ep-elastic	-26.94	1.81	6.72%
ep-inelastic (W1)	-514.05	84.93	16.52%
ep-inelastic (W2)	-521.64	39.00	7.48%
ep-inelastic (W3)	-437.49	93.41	21.35%

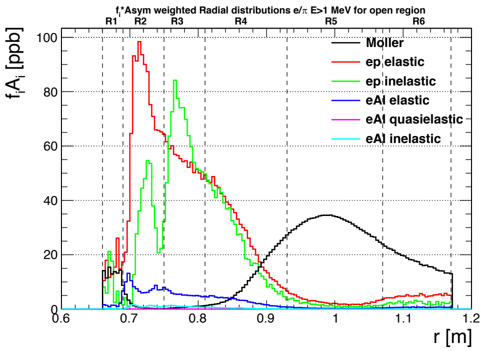
Quartz Tiles

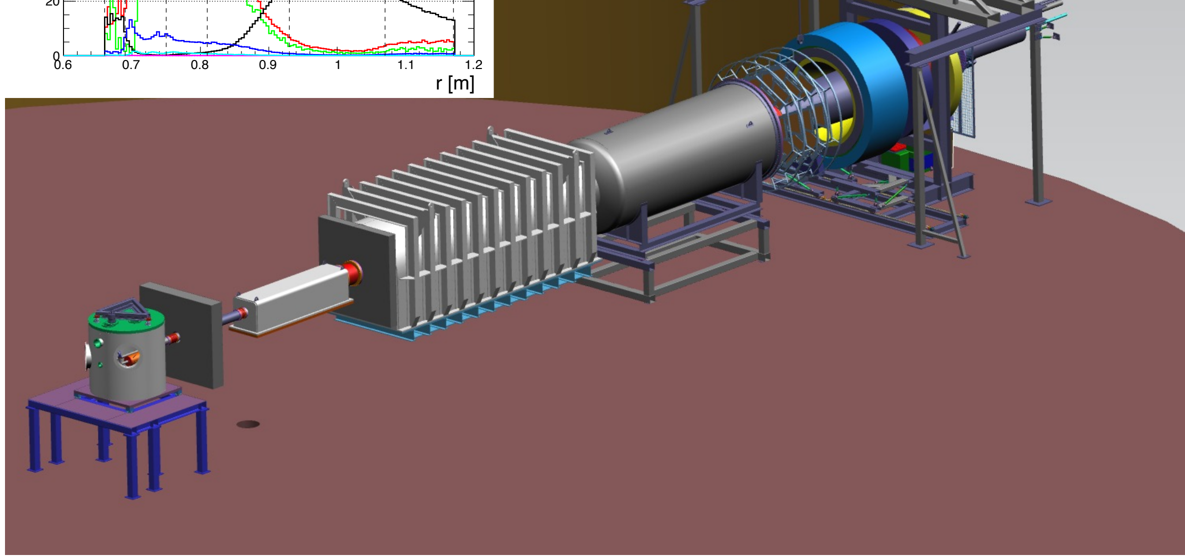
Processes	Expected A (ppb)	σ_A (ppb)	$\frac{\sigma_A}{\lvert A\rvert}$ (%)
Møller	-34.44	0.70	2.04%
ep-elastic	-26.95	2.25	8.37%
ep-inelastic (W1)	-531.11	106.12	19.98%
ep-inelastic (W2)	-522.37	48.49	9.28%
ep-inelastic (W3)	-433.58	118.63	27.36%

Results of the simultaneous fit to the 18 quartz tile asymmetries.
The asymmetries in Ring5 and their fitting errors in ppb and in % are shown.

Summary

- The radial and azimuthal segmentation of the detector, combined with the toroidal spectrometer optics and the kinematics of the various background processes enables us to untangle the Moller asymmetry from those of the dominant background processes.



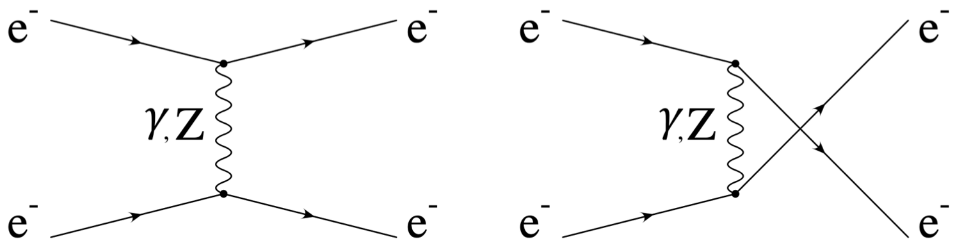


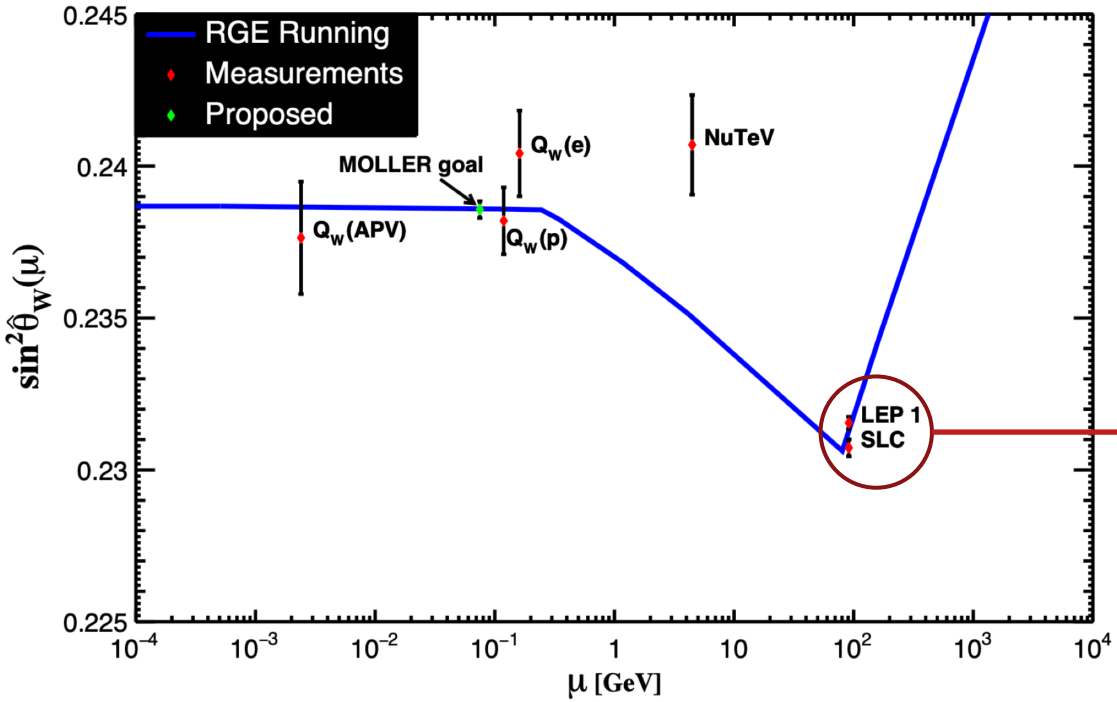
Backup

Weak Mixing Angle Measurements

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

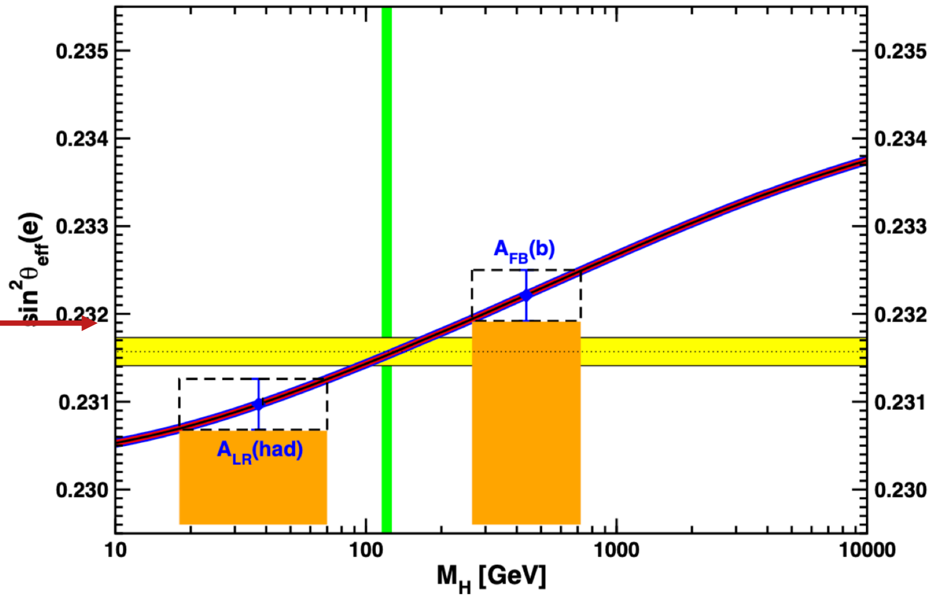
$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$





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 $\sim 3\sigma$

Jefferson Lab

Weak Mixing Angle Measurements at Low Energy

- Effective weak mixing angle:

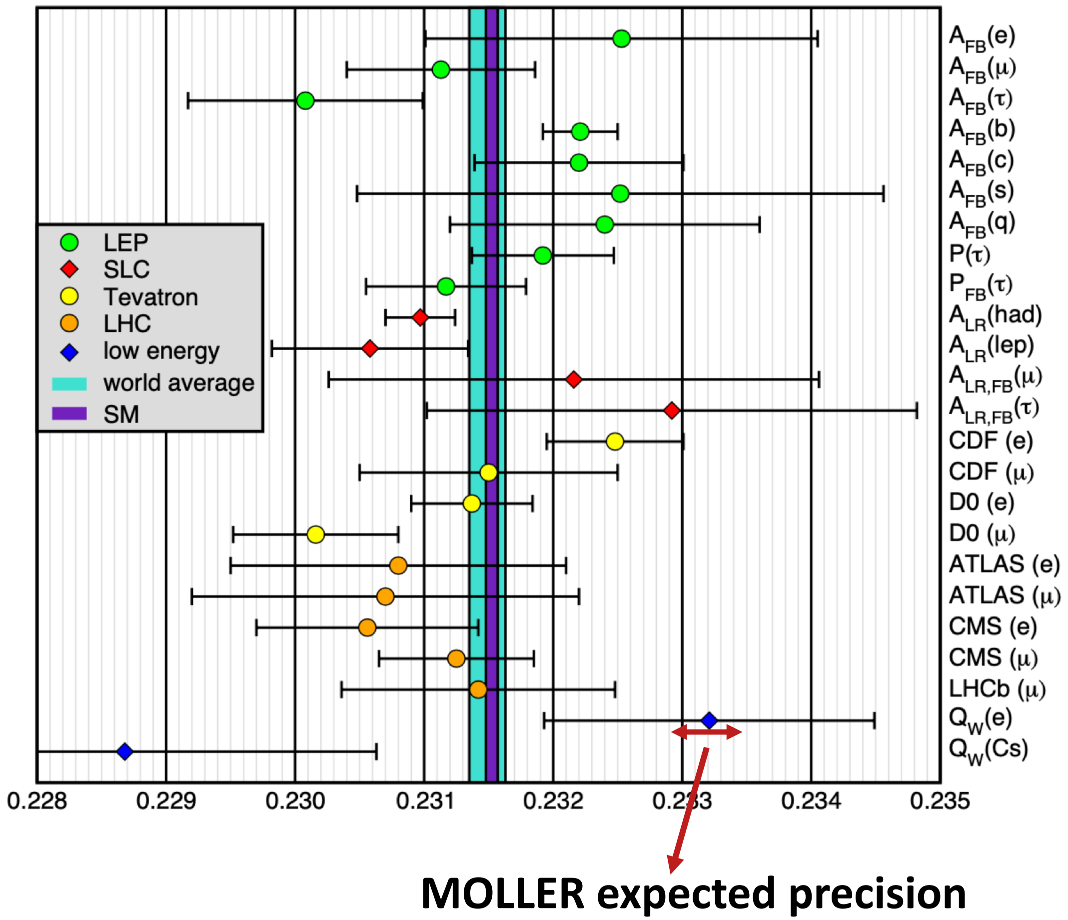
$$\sin^2\theta^l_{eff} \equiv \frac{1}{4}\left(1 - \frac{v_l}{a_l}\right)$$

- 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

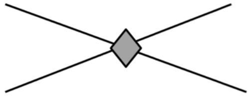


All measurements of the effective leptonic weak mixing angle.

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)

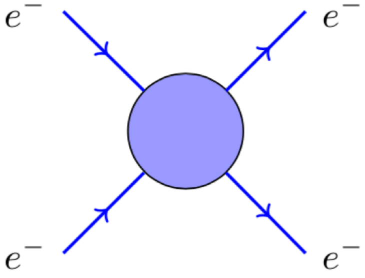
LEP200: Lepton-Lepton interactions

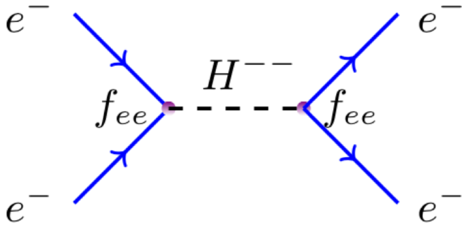
E158: PV Møller Scattering

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

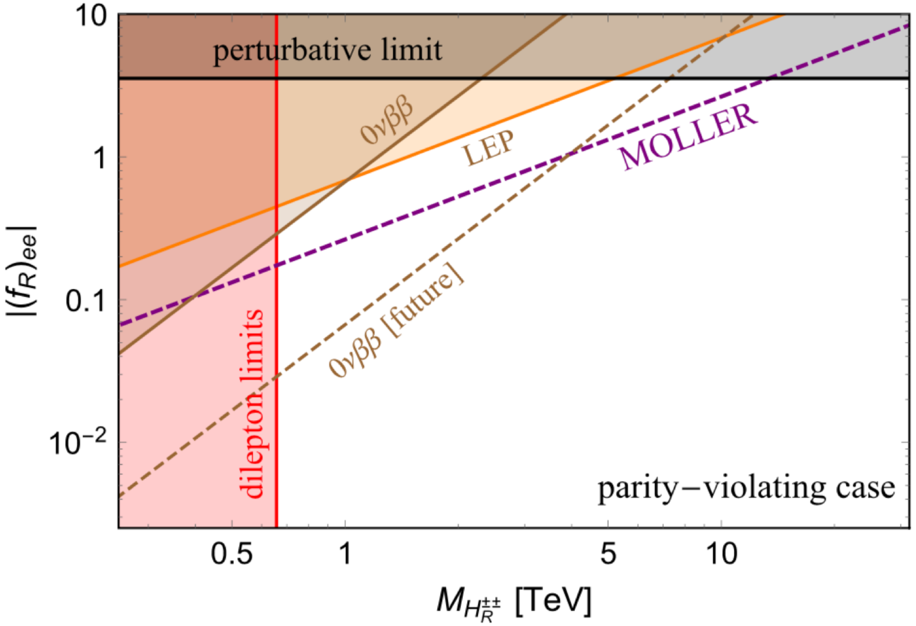
New Physics Beyond the Standard Model

- 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 $|(f_R)_{ee}|$

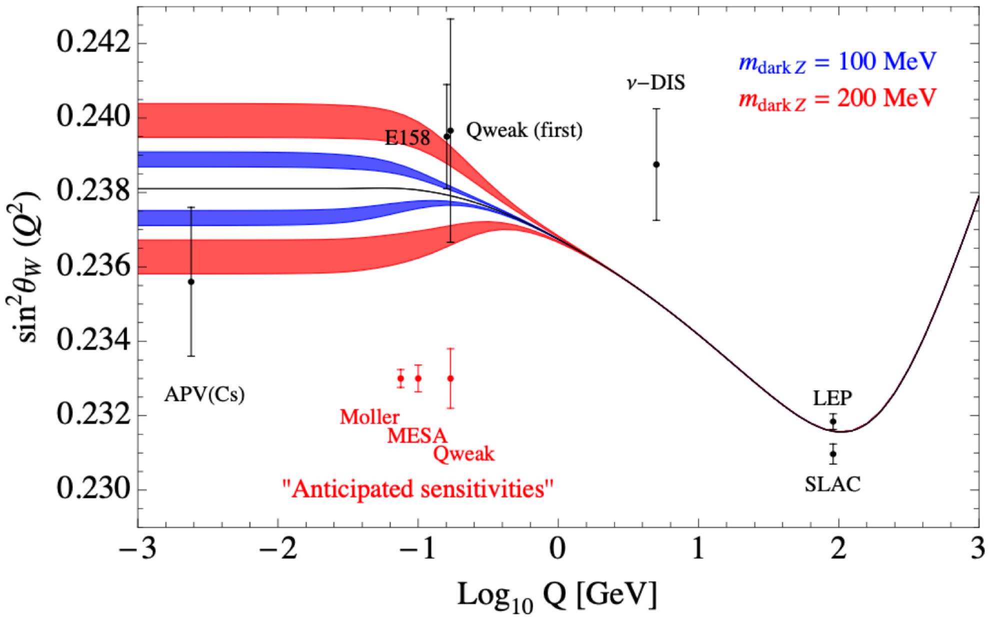
- $M_{H_R^{\pm\pm}}$ could be probed up to ≃10 TeV for a $\mathcal{O}(1)$ Yukawa coupling by MOLLER → This is far beyond the direct search capability of LHC or even future 100 TeV colliders.

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.

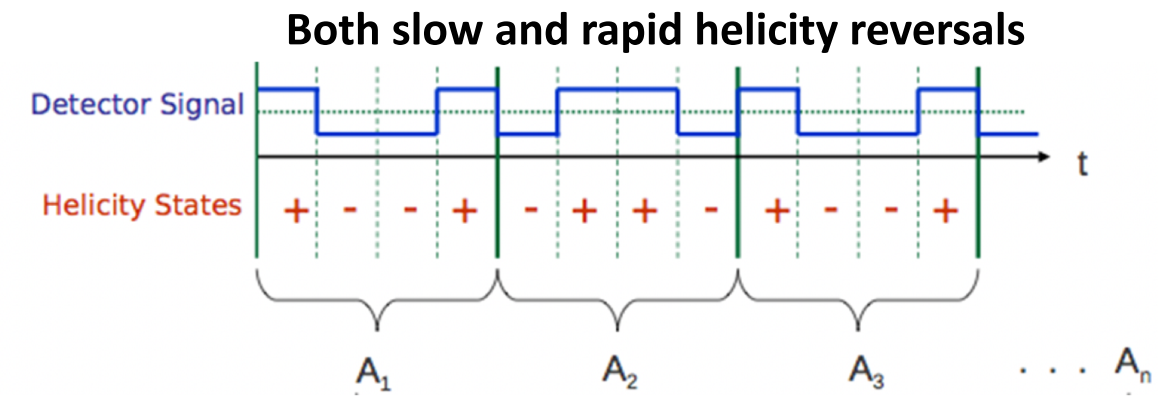
- Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade.
  - weakly coupled MeV scaled mediators (**dark *Z*** → parity violating effect visible in low energy experiments (if $Q^2 \lesssim m^2_{Z_d}$))

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.

How Do We Take the Bulk of Our Data?



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**

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.

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

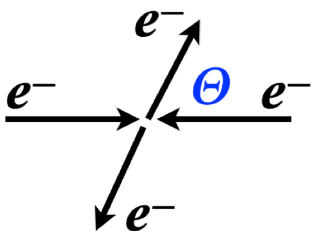
- Remove the correlations of flux to beam intensity, position, angle, and energy fluctuations:

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

- Repeat 30 billion times to get desired statistical error.

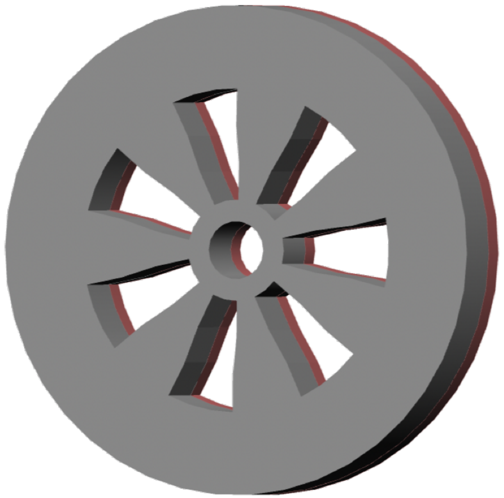
MOLLER Kinematics and Acceptance

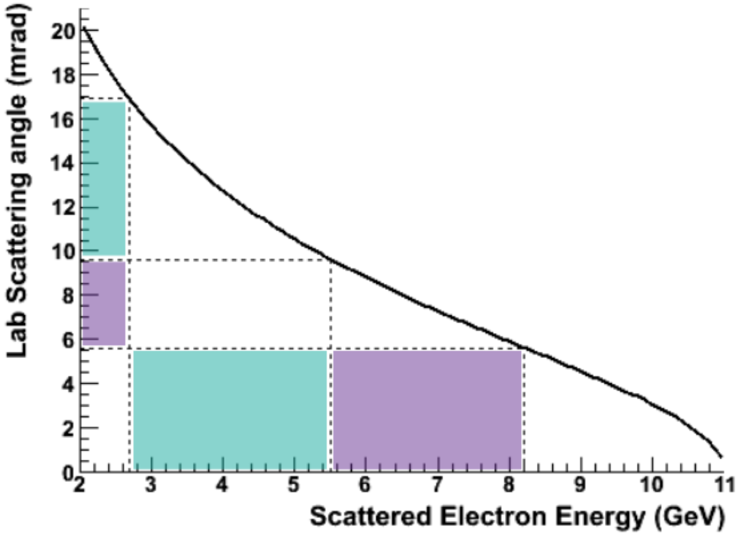
- Identical particles.

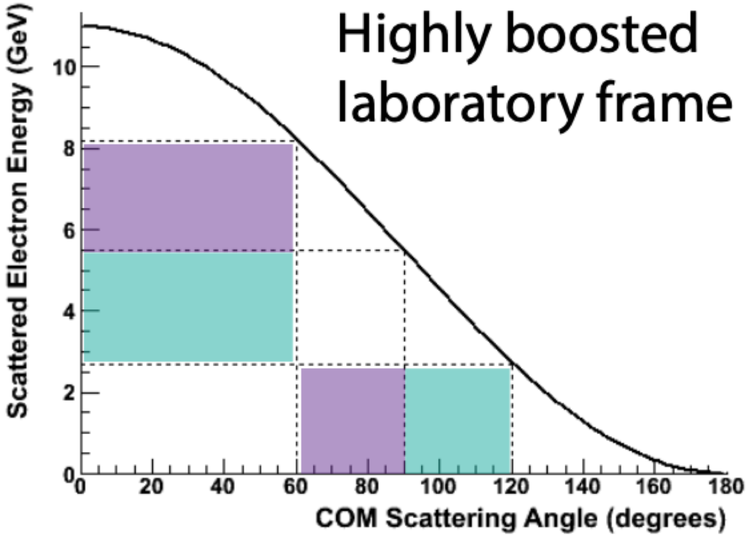


- Measure either forward or backward scattering in CM frame.
- Full azimuthal acceptance for Møller scatters from 6 < θ_{lab} < 20 mrad

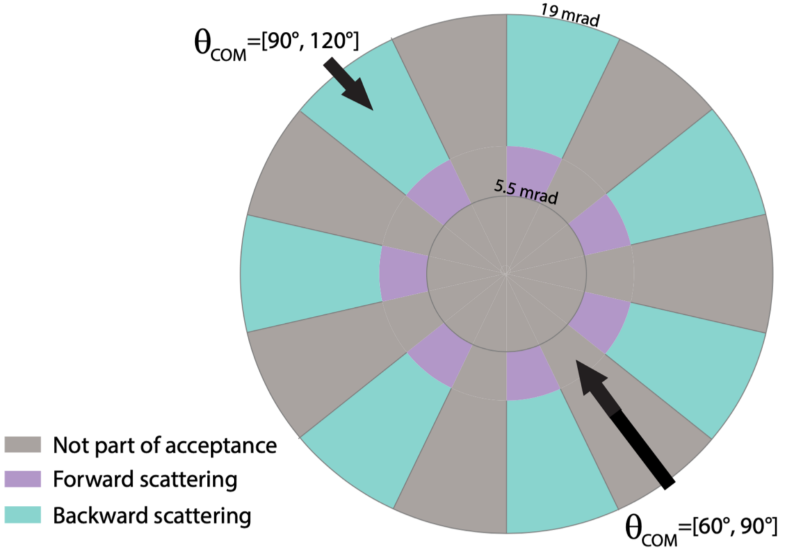
Acceptance defining collimator
7-fold symmetry



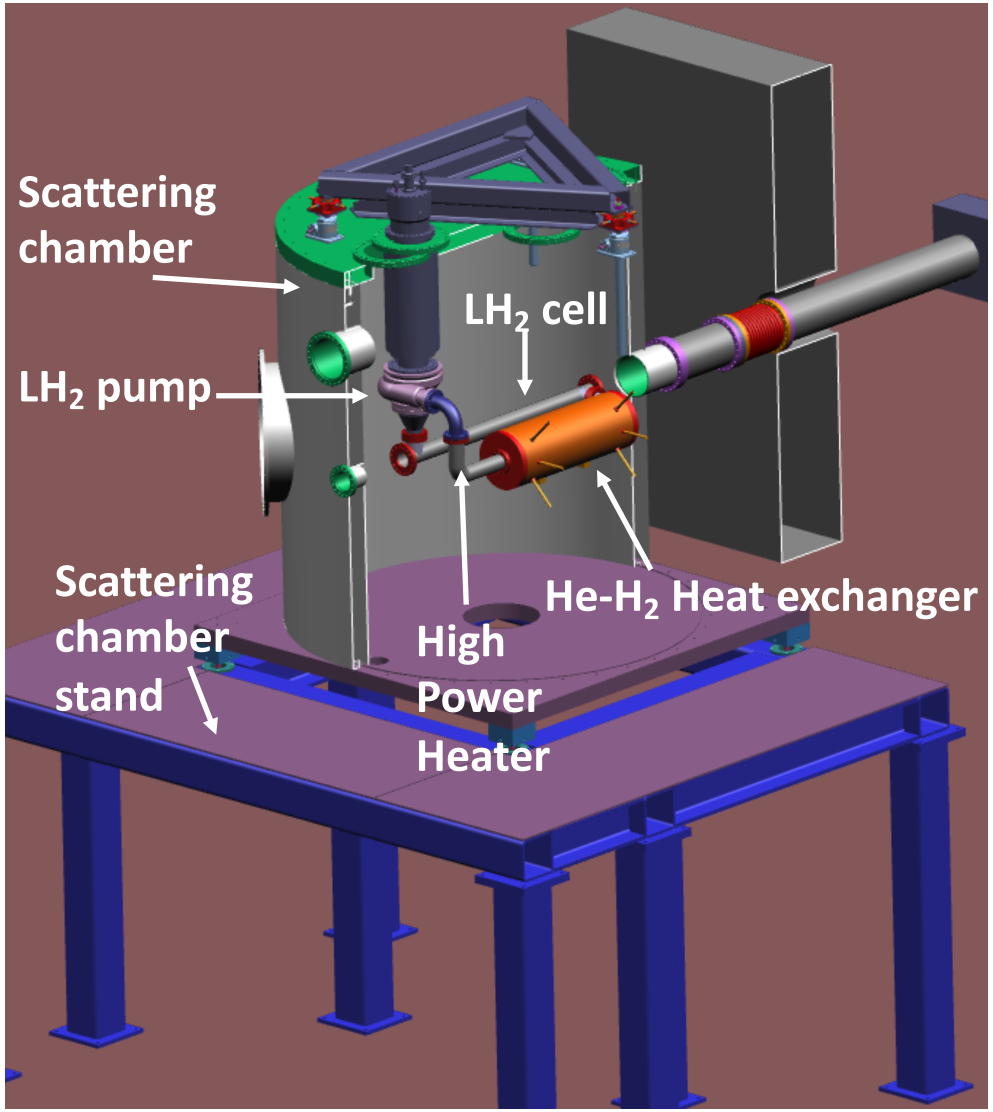




Highly boosted laboratory frame



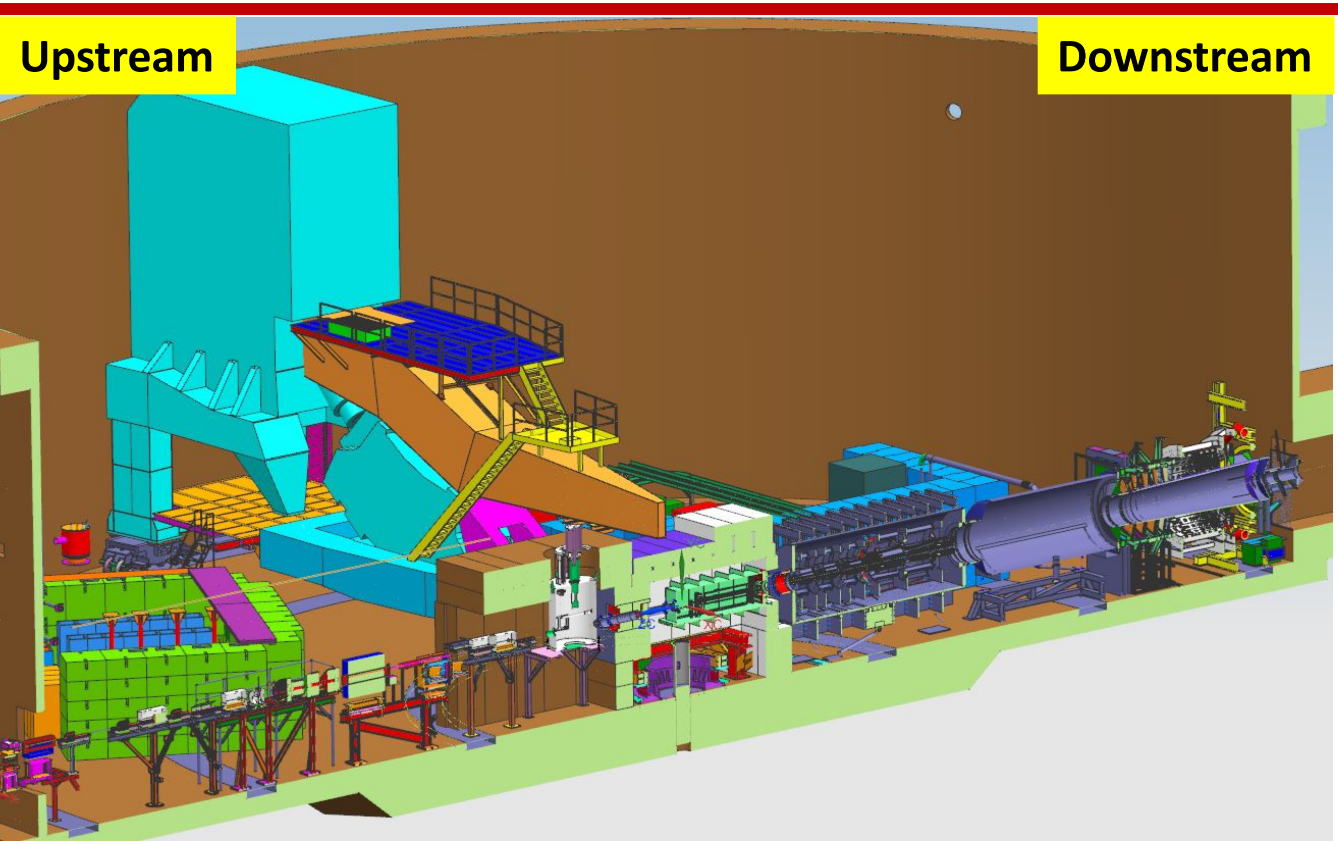
Liquid Hydrogen Target



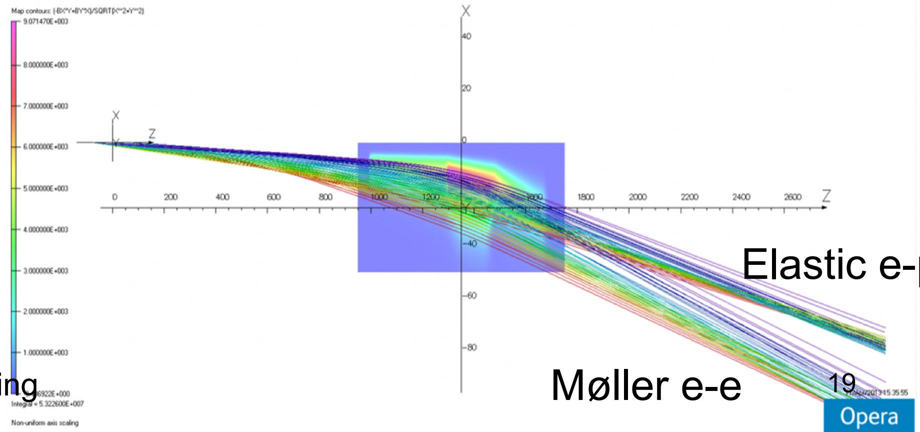
- Q_{weak} target is the precursor for the MOLLER target.
  - Target power needs to go from 3 kW to 4kW.
  - Target flow needs to go from 17l/s to 25l/s.
  - Target noise needs to decrease from 47ppm to 30ppm.

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

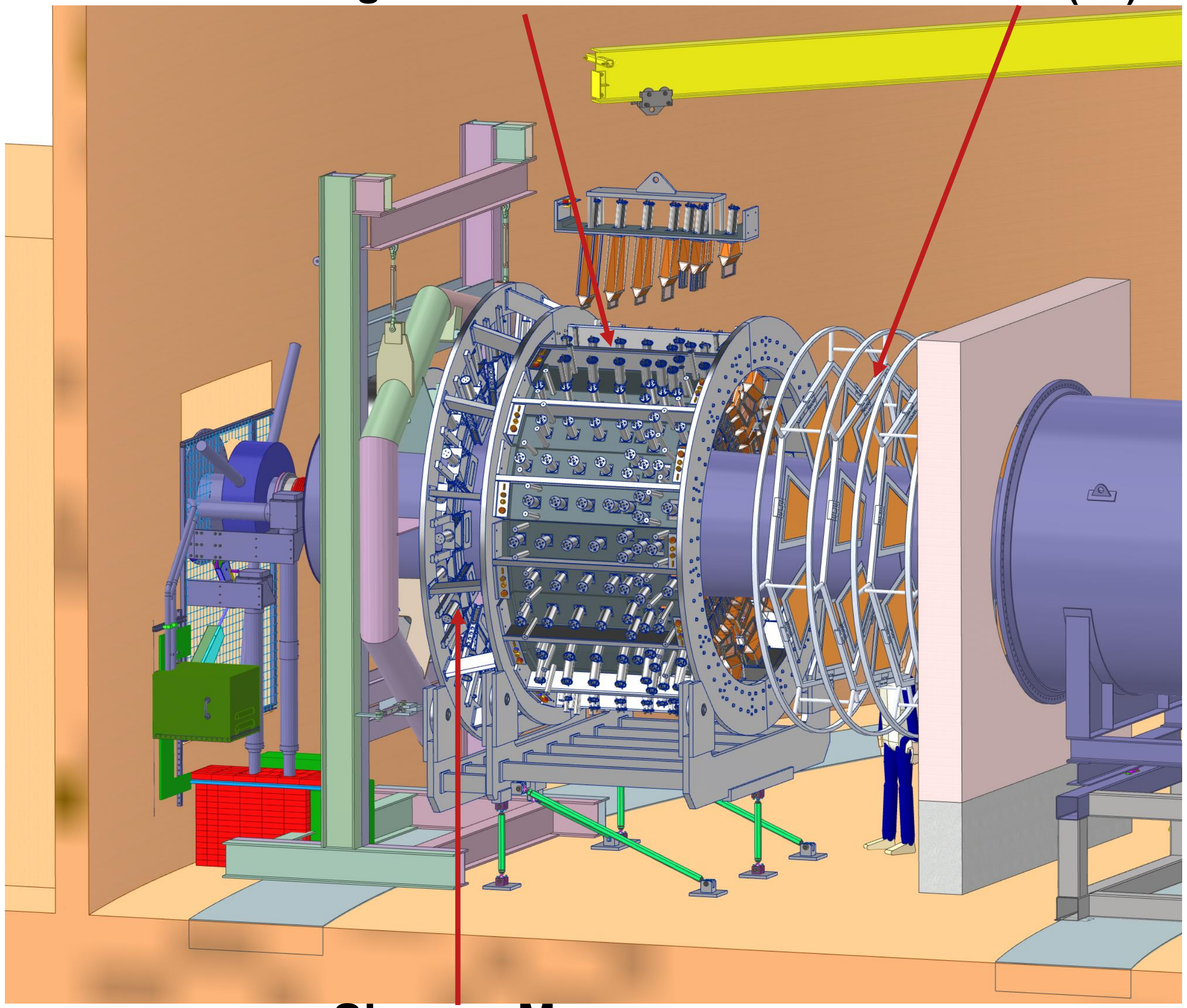


- Extent of spectrometer scope is 26.5 m.
- Defines the acceptance of the experiment.
- Consists of a pair of 7-fold symmetry toroidal magnets.
  - The odd-fold symmetry provides ~100% acceptance for the identical-particle Møller scattering process.
  - The toroidal magnets use a conventional resistive 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

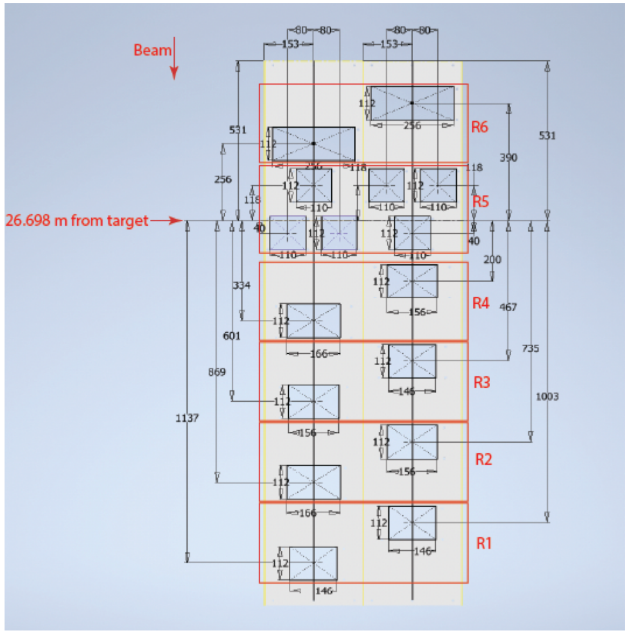


- **Integrating detectors** are an array of detectors based on quartz as the active element.
  - Asymmetry measurements of both signal and background, and beam and target monitoring.
  - 6 concentric rings. Ring 5 primarily capturing the Møller electron signal.
- **Shower-Max detector** concept uses 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.

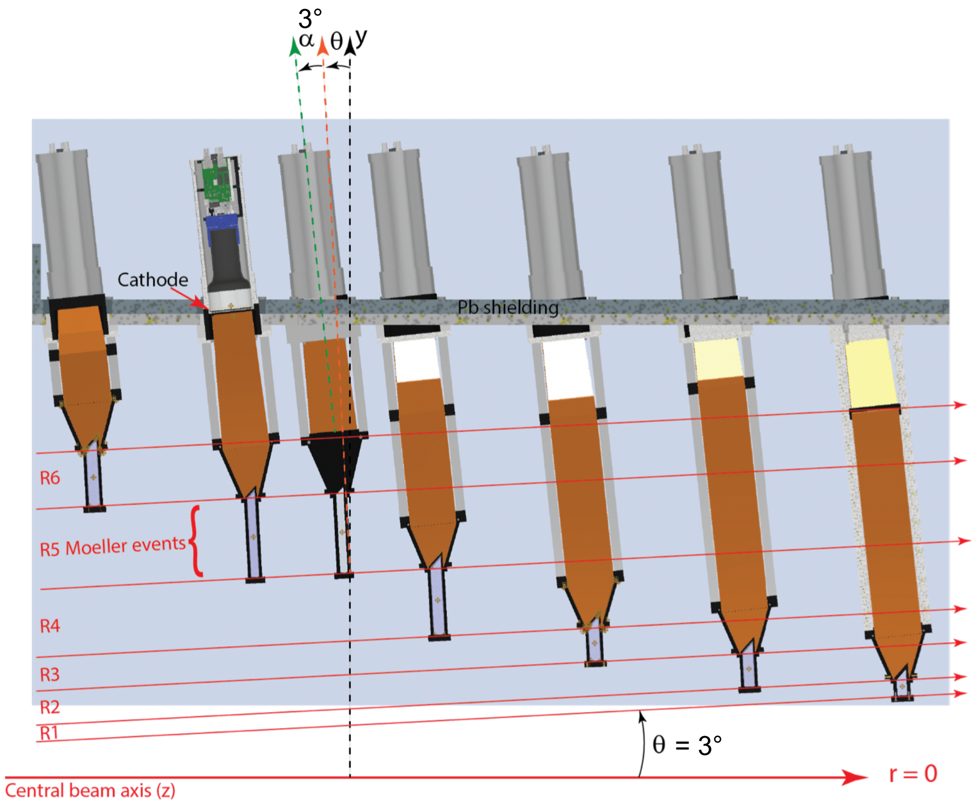
Main Detector Array

Michael Gericke

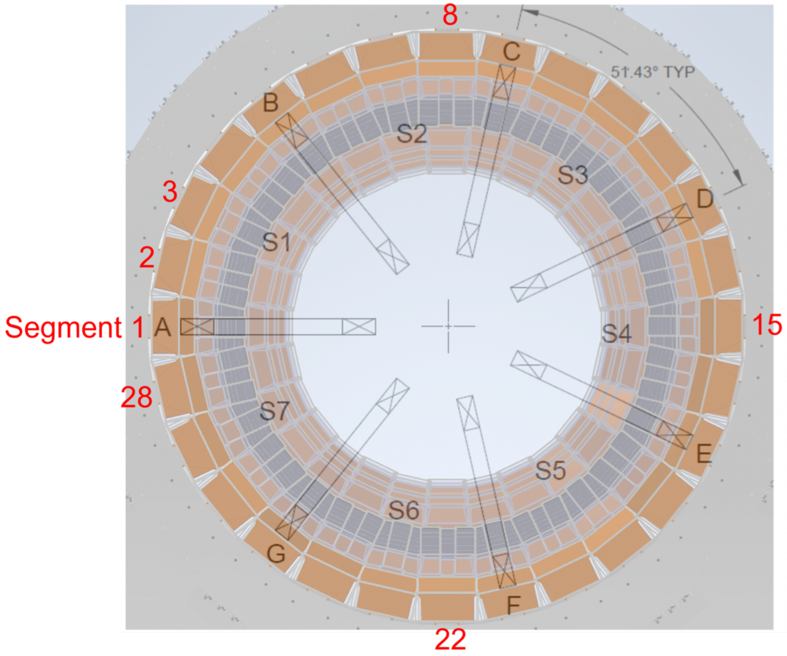
- The main detector is separated into 28 azimuthal segments and 6 radial regions.
  - There are 8 detector modules in each segment.
  - The tiles are covering the entire azimuth and radial region.



Front-flush and back-flush segment plates



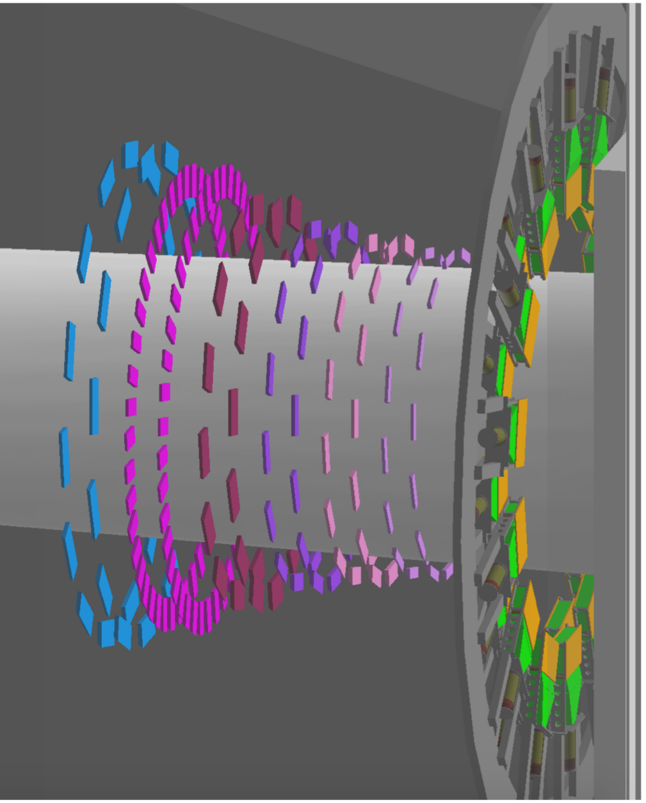
Arrangement of the detector modules in the front-flush segment plate.



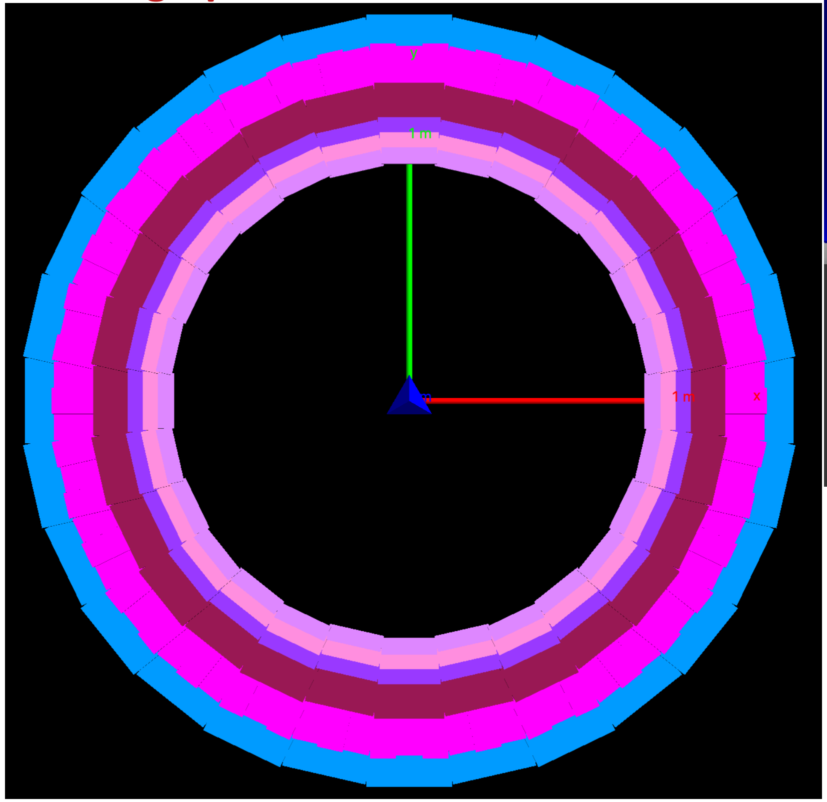
Front view (looking downstream) of the main detector array.

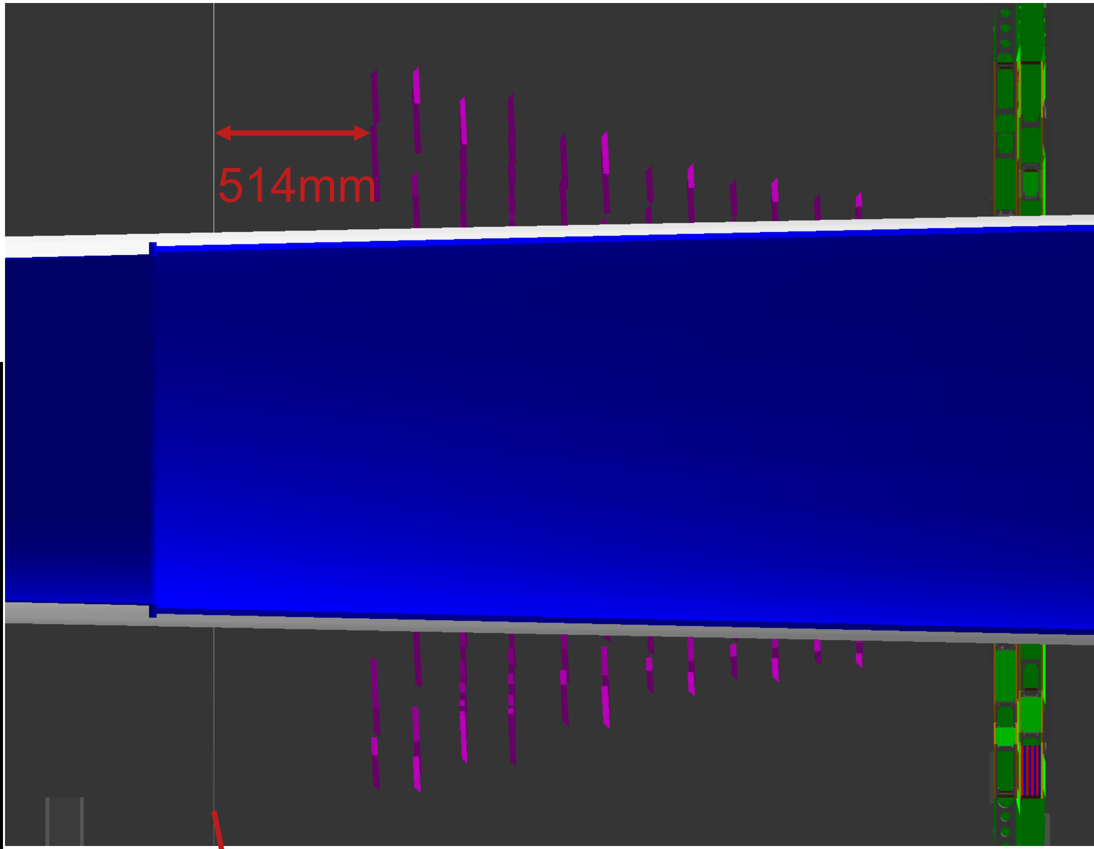
Tiles in the GEANT4 simulation

- Placing a virtual detector plane in the upstream end of the quartz tiles.
  - z-position of the virtual detector plane: 21309.65mm.



Looking upstream





Virtual detector plane, d132

The Size of the Quartz Tiles

Quartz Tiles (FF)				Quartz Tiles (BF)			
Ring	Rmin [mm]	Rmax [mm]	L [mm]	Ring	Rmin [mm]	Rmax [mm]	L [mm]
R1FF	716.72	746.72	30	R1BF	723.69	753.69	30
R2FF	732.49	792.49	60	R2BF	739.45	799.45	60
R3FF	778.24	838.24	60	R3BF	785.1	845.1	60
R4FF	823.6	943.6	120	R4BF	830.48	950.48	120
R5FF	929.43	1069.43	140	R5FF	926.22	1066.22	140
R5BF	934.17	1074.17	140	R5BF	937.35	1077.35	140
R6FF	1051.41	1151.41	100	R6BF	1058.37	1158.37	100

	x [mm]	y[mm]	z[mm]
Ring1	169	30	20
Ring2	179	60	20
Ring3	190	60	20
Ring4	213	120	20
Ring5	80	140	17
Ring6	260	100	20