MOLLER Experiment

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Hall A Winter Meeting,
Jefferson Lab
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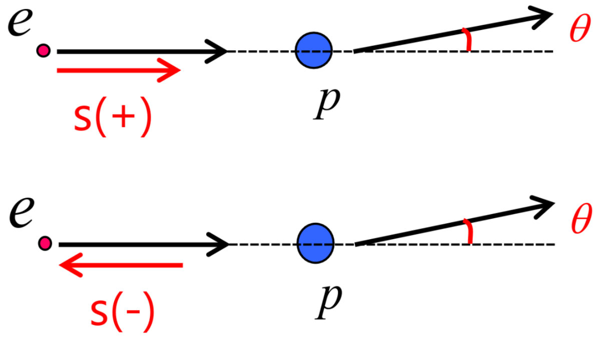
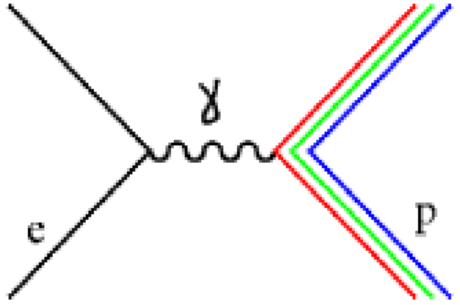
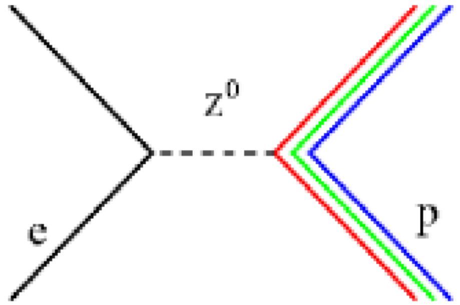
MOLLER Experiment

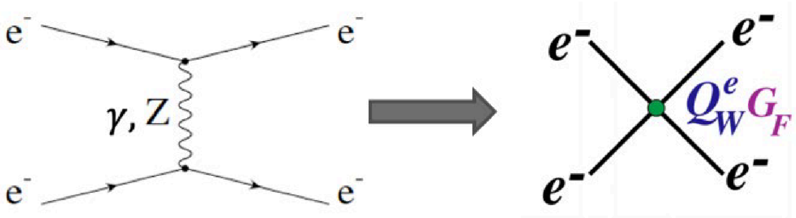
- Measurement Of a Lepton Lepton Electroweak Reaction(MOLLER).
- An experiment to make precise measurement of the Weak Mixing Angle with Møller Scattering.

Parity-Violating Møller Scattering









$$A_{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{Q^2}{M_Z^2} \quad \text{when } Q^2 \ll M_Z^2$$

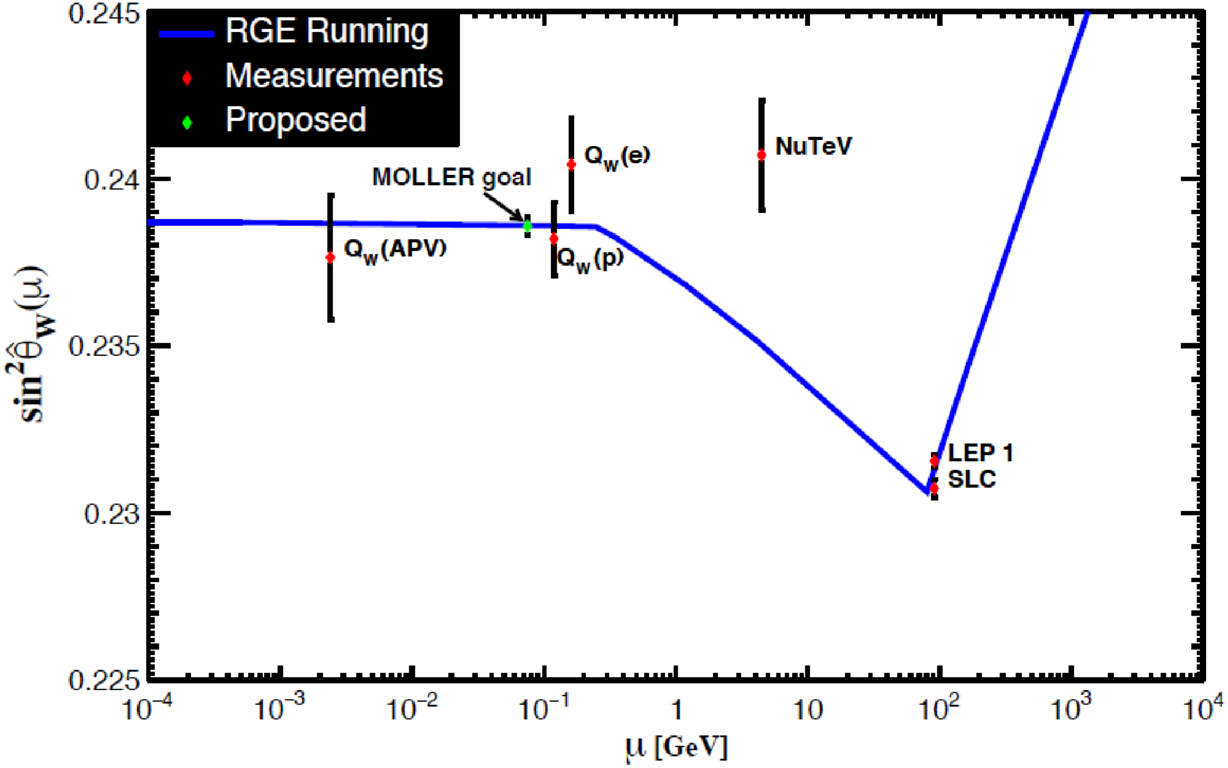
$$A_{\rm PV} = \frac{G_F}{\sqrt{2}\pi\alpha} \frac{mE^4 \sin^2\theta_{\rm CM}}{(3+\cos^2\theta_{\rm CM})^2} Q_W^e$$

$$Q_W^e = 1 - 4\sin^2\theta_W \equiv 0.0435.$$

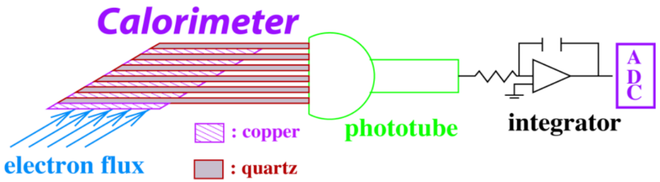
- To get to interaction amplitudes $\sim 1.5 \times 10^{-3} G_F$, we need ~2.4% measurement of Q_W^e.

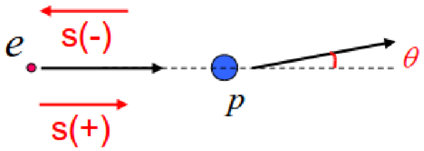
The weak mixing angle

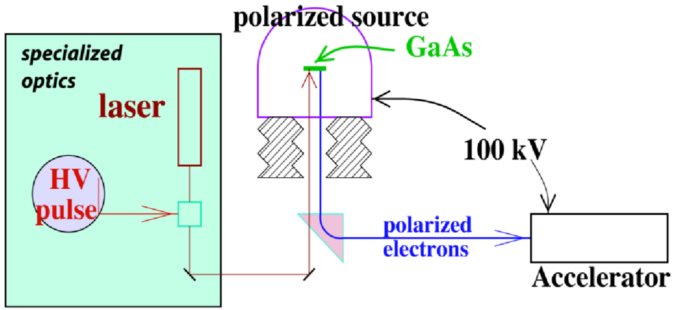
- We have precise value of $\sin^2\theta_W$ from the Standard Model.
- LEP1 and SLC differ at 3σ.
- MOLLER's proposed sensitivity of $\sin^2\theta_W$ is 0.00028.

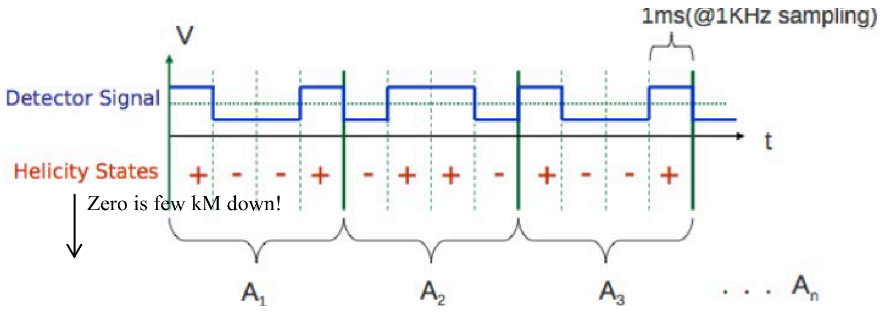


Parity Violating Scattering Experiment overview

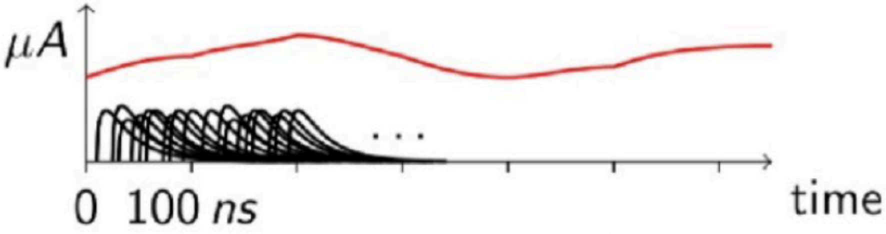








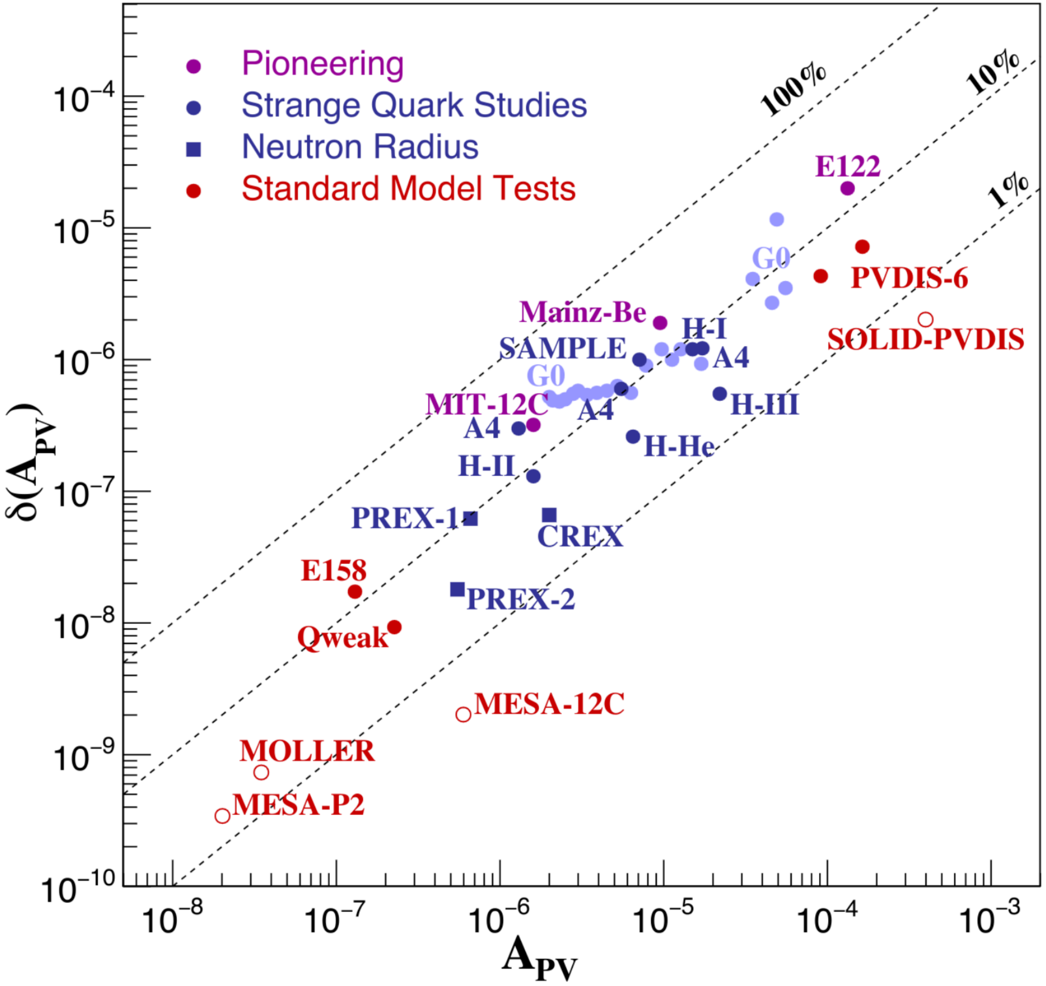
- Rapid helicity flipping.



- Integration of signal from each helicity window.

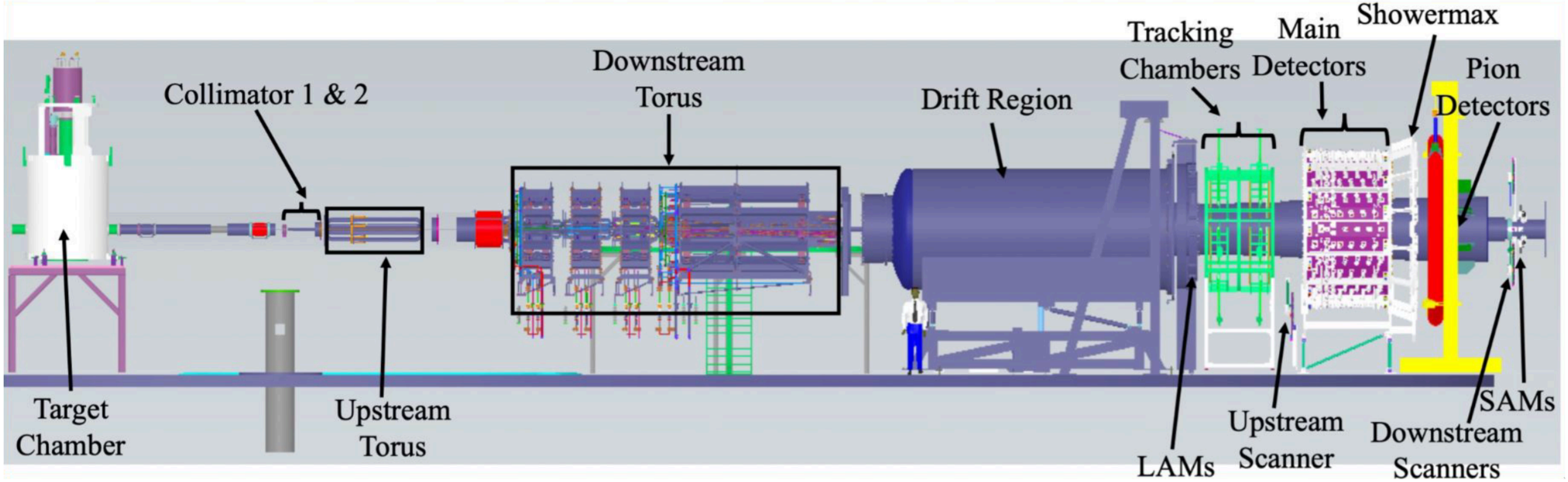
Parity Violating Experiments

- MOLLER has very stringent target for measured uncertainity.



MOLLER Experiment

- $A_{\rm PV} = 35.6$ ppb
- $\delta(A_{\rm PV}) = 0.73$ ppb
- $\delta(Q_W^e) = \pm 2.1\%(\text{stat}) \pm 1.0\%(\text{sys})$
- 65 μA electron beam 85% polarized
- Signal rate: 134 GHz
- Run Time: 8200 Hours
- 3×10^8 electrons detected.
- Target 1.25m long LH2



Polarized Electron Beam for MOLLER

Beam Property	Required 1kHz Random Fluctuation	Required cumulative helicity-correlation
Intensity	< 1000 ppm	< 10 ppb
Energy	< 108 ppm	< 1.4 ppb
Position	$< 47\ \mu$m	< 0.6 nm
Angle	$< 4.7\ \mu$rad	< 0.12 mrad

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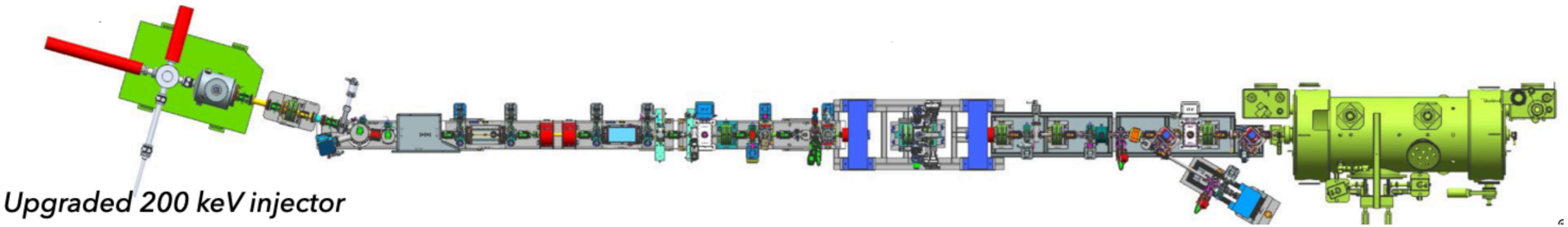
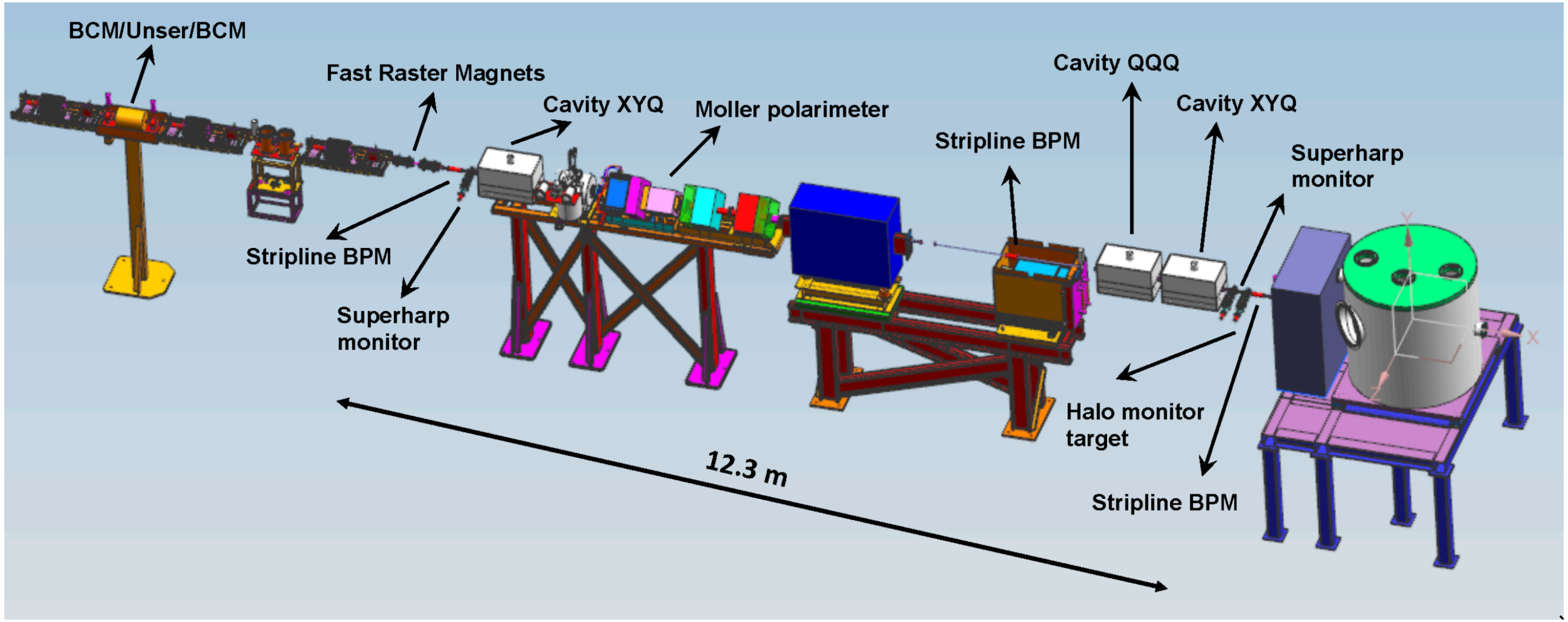
- Achievable based on previous experience, using careful setup at the source and injector, with upgraded components, precision monitors, feedback on intensity and position, and slow-reversals to cancel asymmetries



Beamline

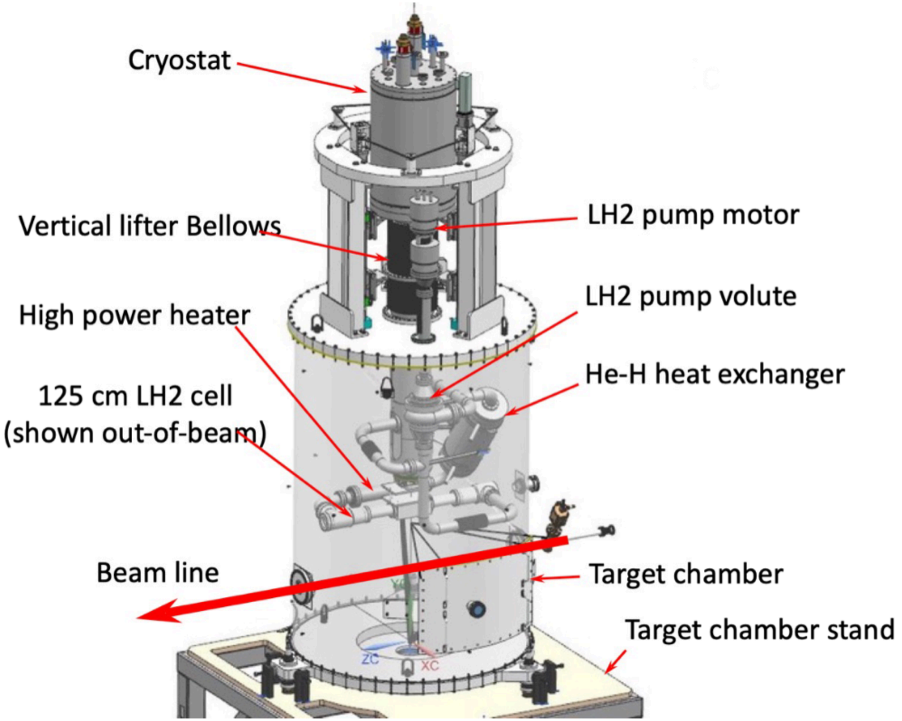
- Beamline implementation uses existing instrumentations and has provision of redundant measurement of beam position and angle.
- The final design includes instrumentation and optics design ensuring the physics requirements of beam properties will be met for the MOLLER experiment with the target moved 4.5m upstream of the pivot.



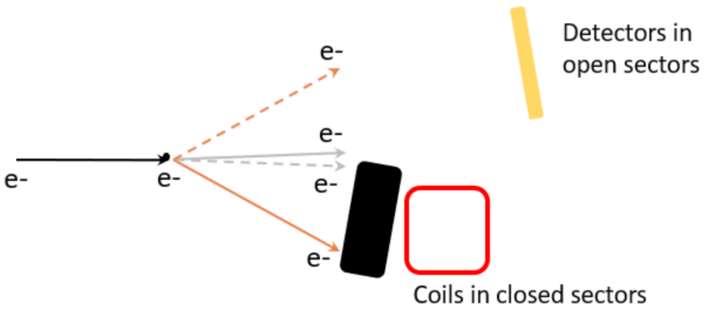
Target

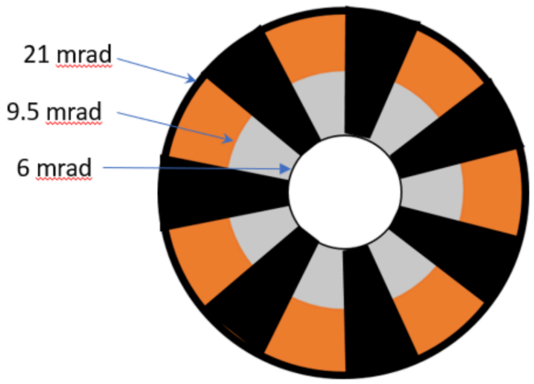
- 1.25m long liquid Hydrogen target.
- ∼4 kW power.
- Detailed study done with CFD calculations.

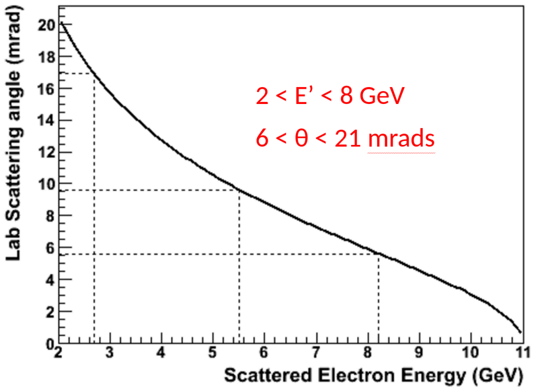
Cell Length	125m
Cell Thickness	8.93 g/cm^2
Radiation Length	14.6%
p,T	35psia, 20k



Spectrometer Concept



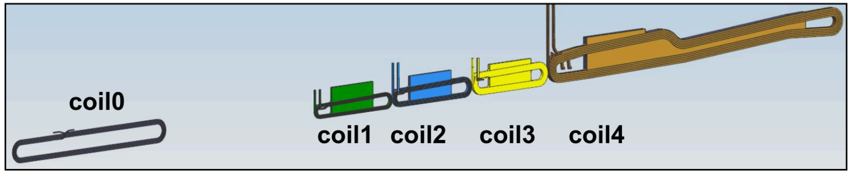


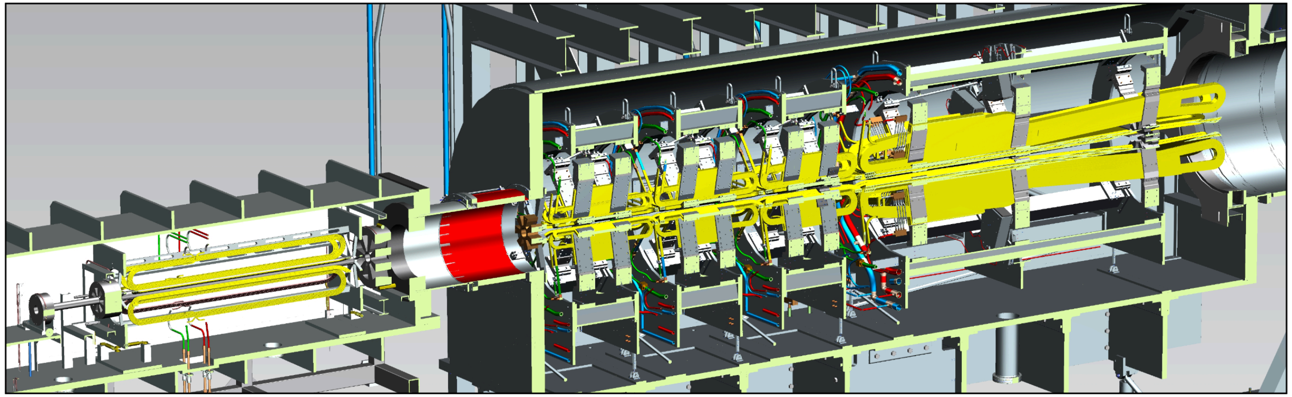


- The MOLLER spectrometer is an “open”, rather than high resolution, spectrometer.
- It moves the electrons away from the beamline and provides separation of the electrons which scatter via different processes in the target
- The Møller electrons have a strong energy angle correlation.

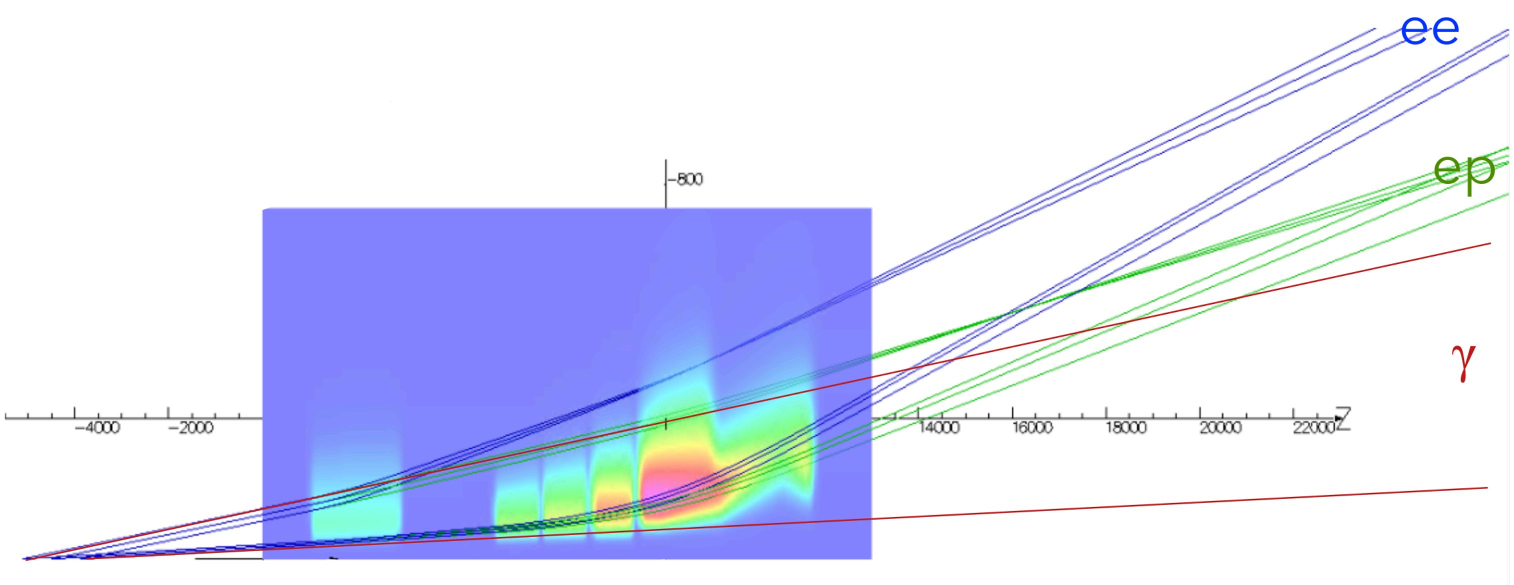
Spectrometer

- Includes the set of warm magnets, the collimators which define the acceptances, the lintels and collars which shield components, including the main detectors.
- Also the detector window, beampipe itself and the bellows.
- It also includes the necessary water and power supplies, connections and the required instrumentation.

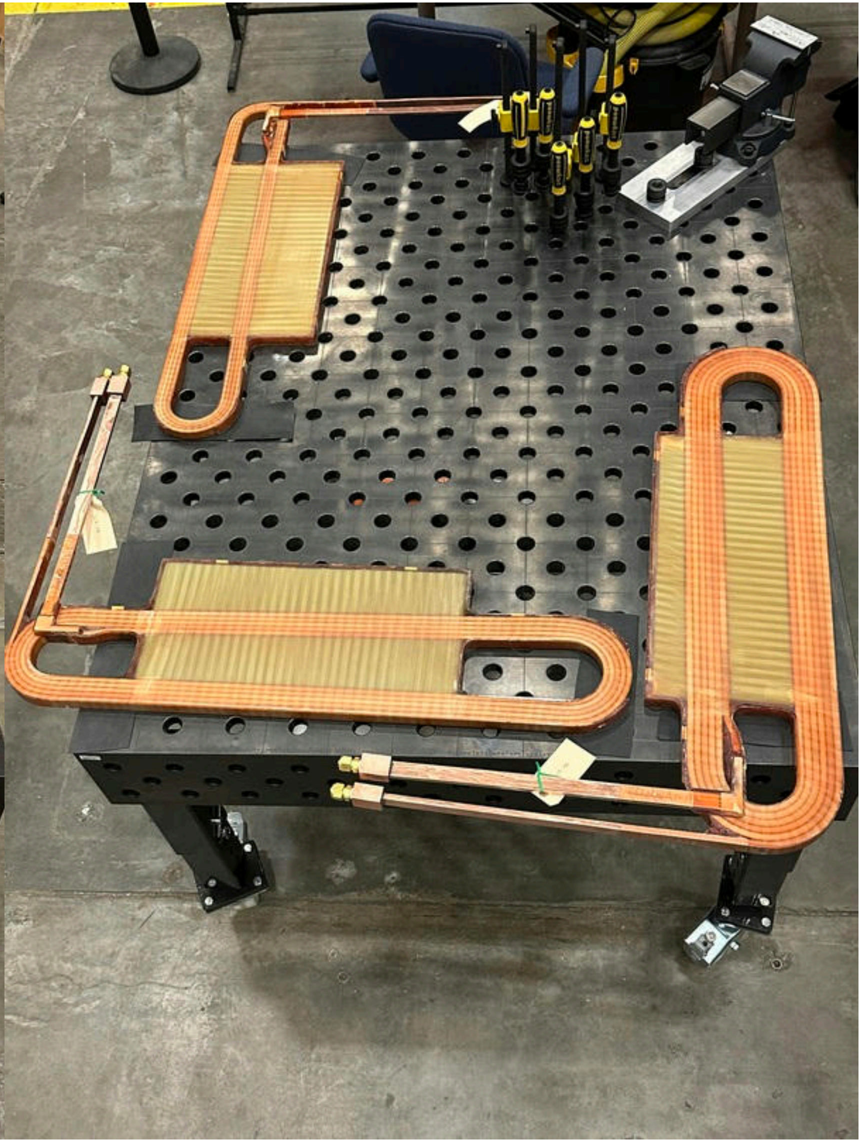




Magnetic field



- Separates elastically scattered electrons from the line-of-sight photons, and separates ee elastic from ep elastic via the recoil E vs theta correlation.
- Fringe magnetic field does azimuthal defocusing for full azimuthal coverage at main detector.

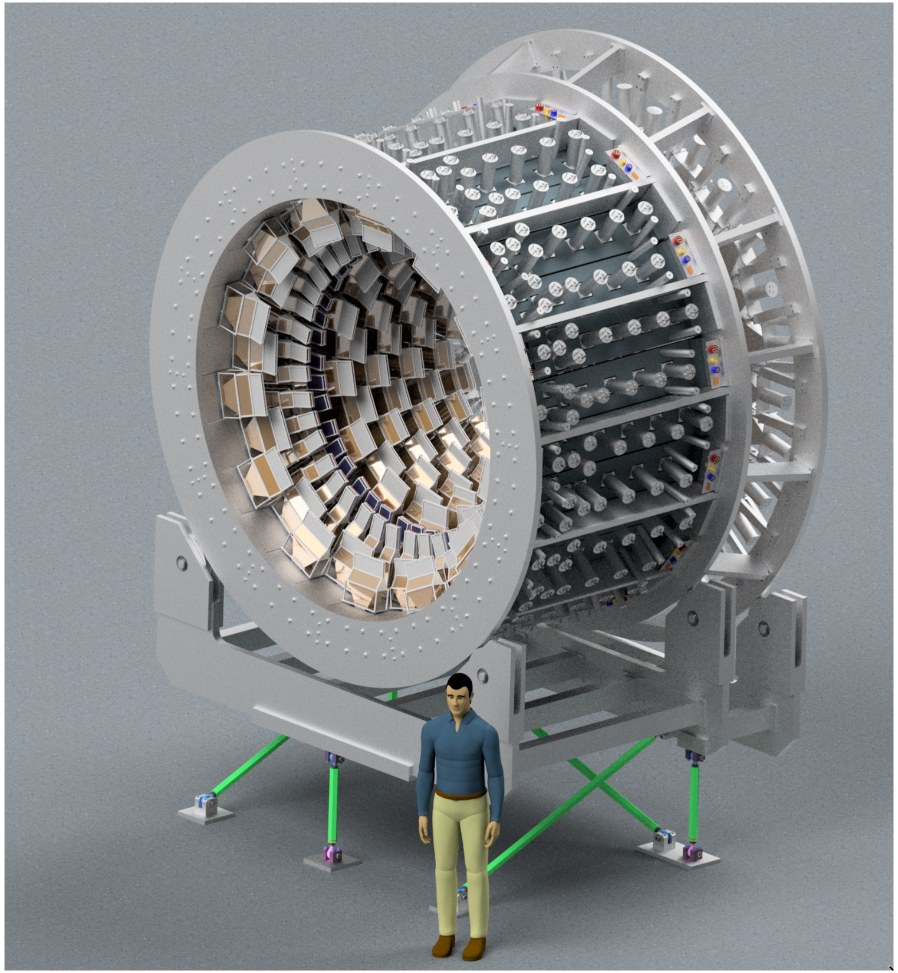



- Procurement of components and their assembly and test is well underway.

Main Detector

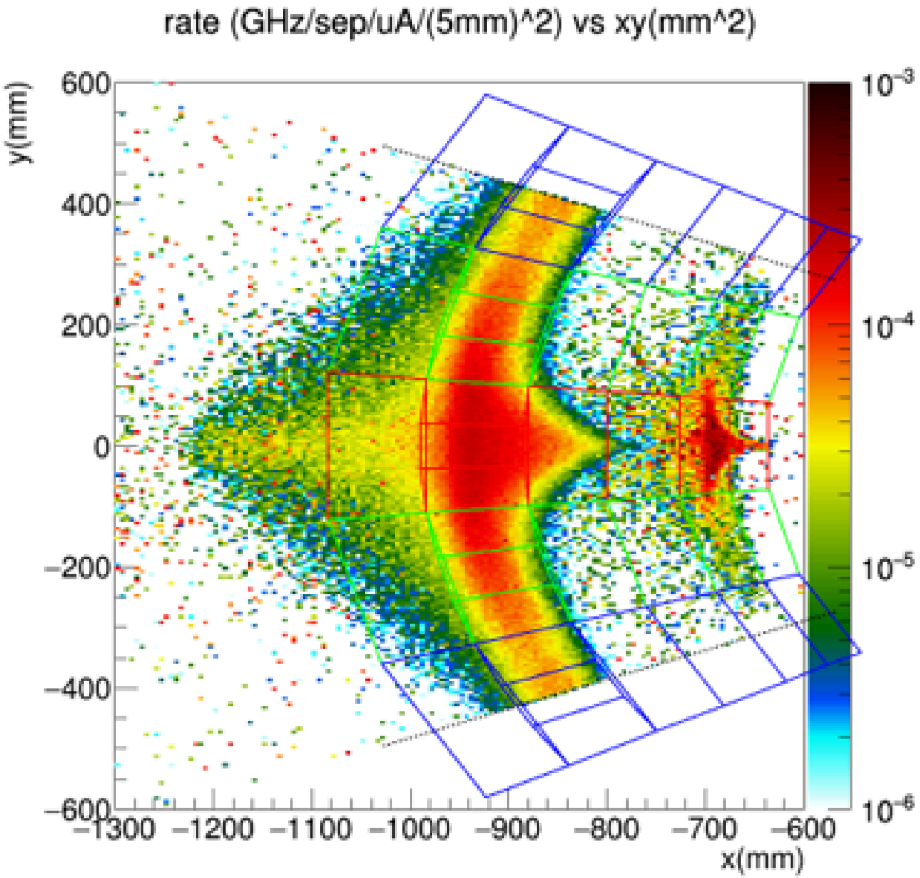
- The main detector is highly segmented system with 6 rings.
- The Møller signal is collected in “Ring 5”, which is divided into 84 detector elements.
- The rest of the 5 rings are divided into 28 elements each.

More on this in next talk by Sayak.



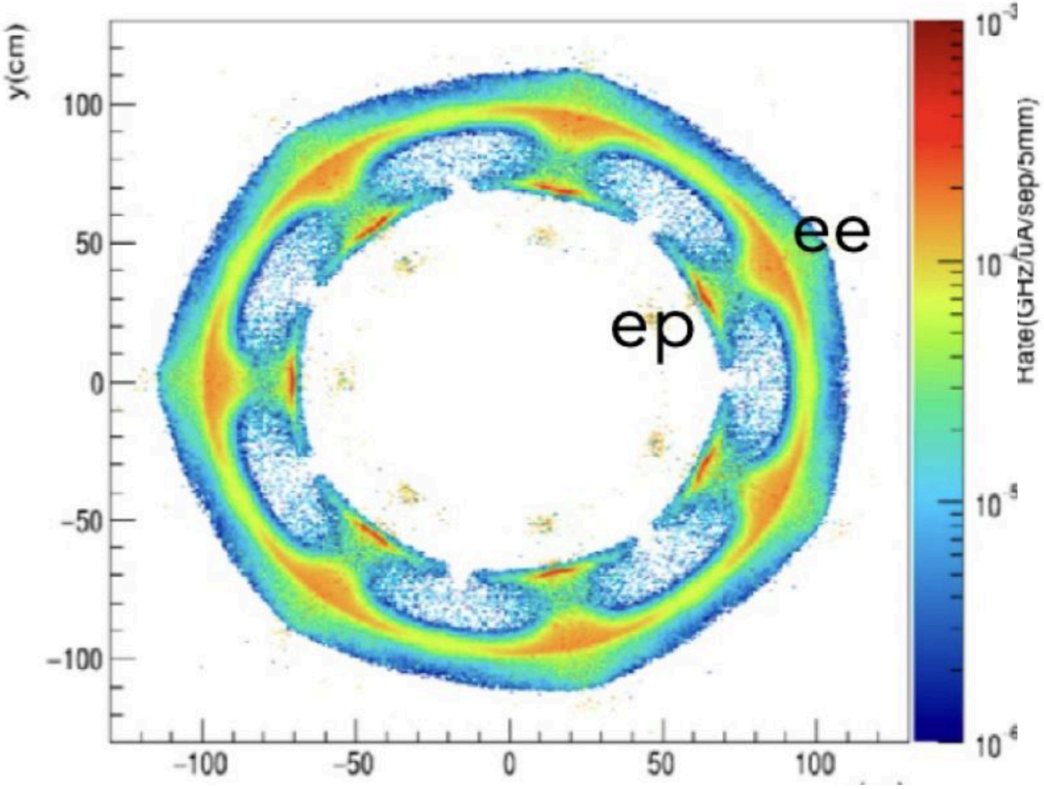
Signal in an Open Sector

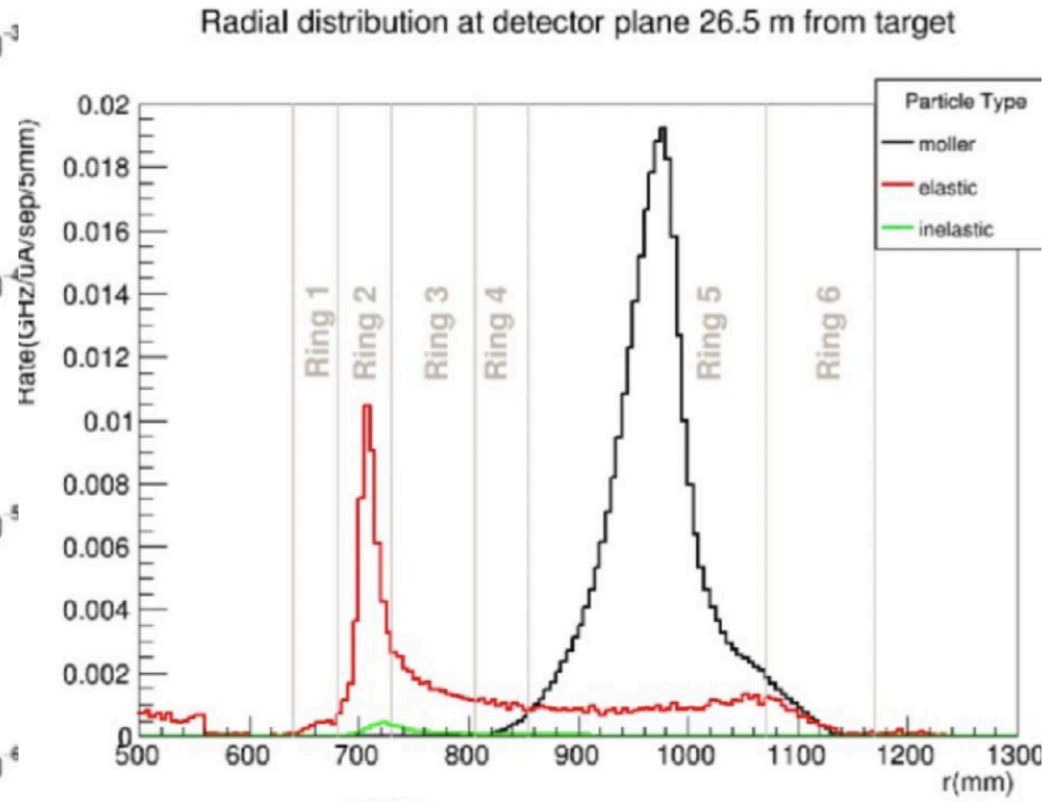
- The detector elements in the main detector are quartz tiles.
- There are six rings and 7 acceptance sectors.
- The Møller signal events end up in Ring 5.



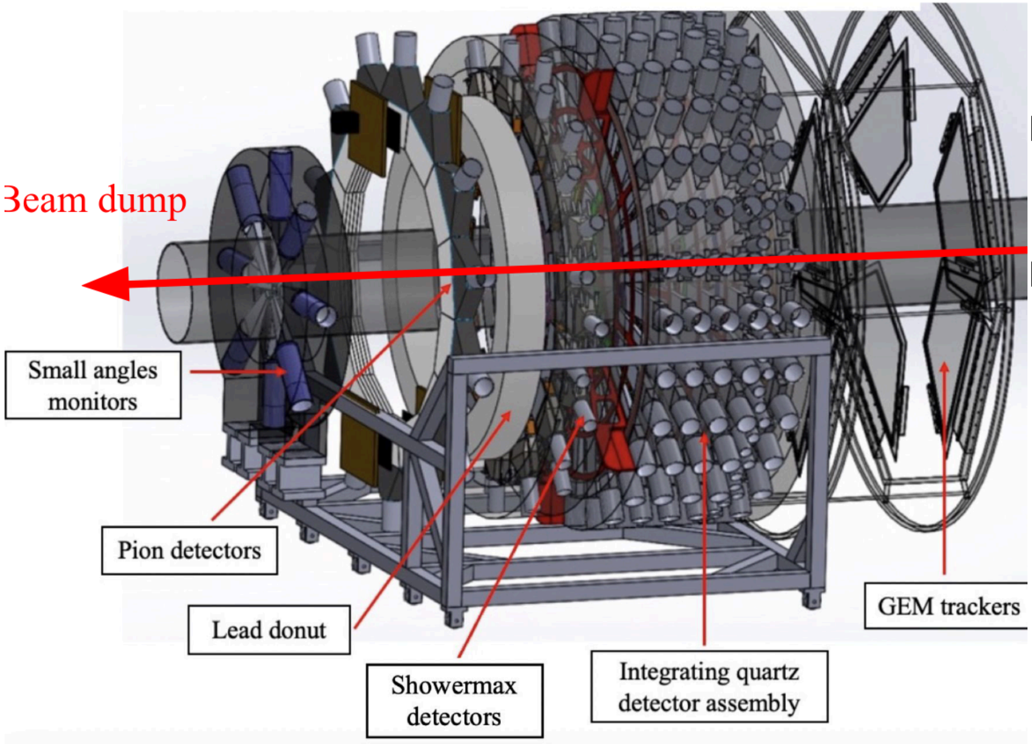
The Møller Signal

- The main detector is highly segmented system.
- The Møller signal is collected in "Ring 5" of the main detector.





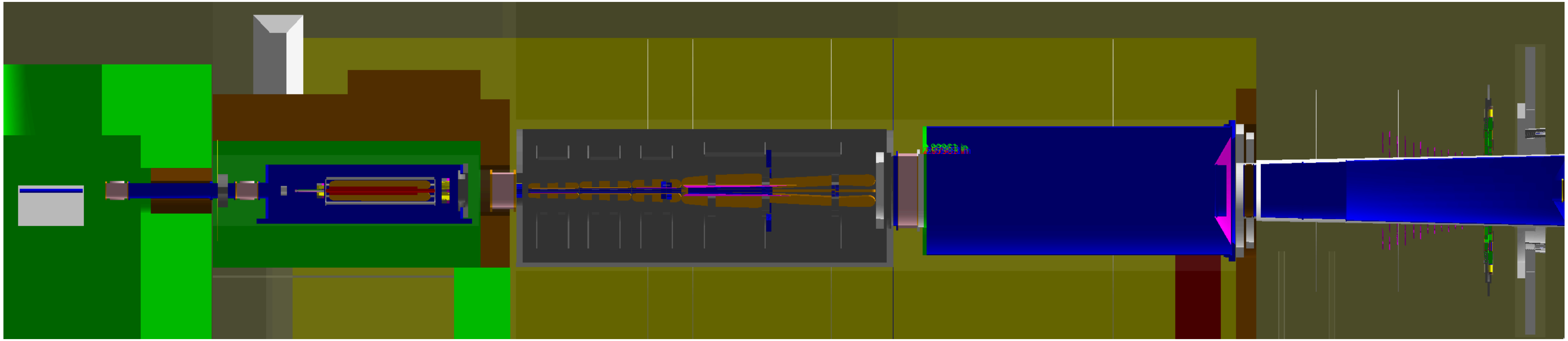
Counting Mode Detectors



- For calibration, the detector will operate in counting mode.
- With low electron rate, the retractable GEM detectors used for counting mode.

Simulation

- Møller has a comprehensive framework for the detector simulation called "remoll".
- The simulation framework is written using Geant4.
- Uses GDML files to create geometries; makes it easy to simulate additional geometries and make precise changes without the need of recompilation.

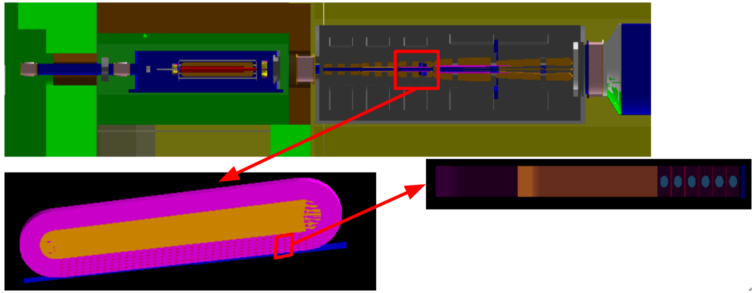


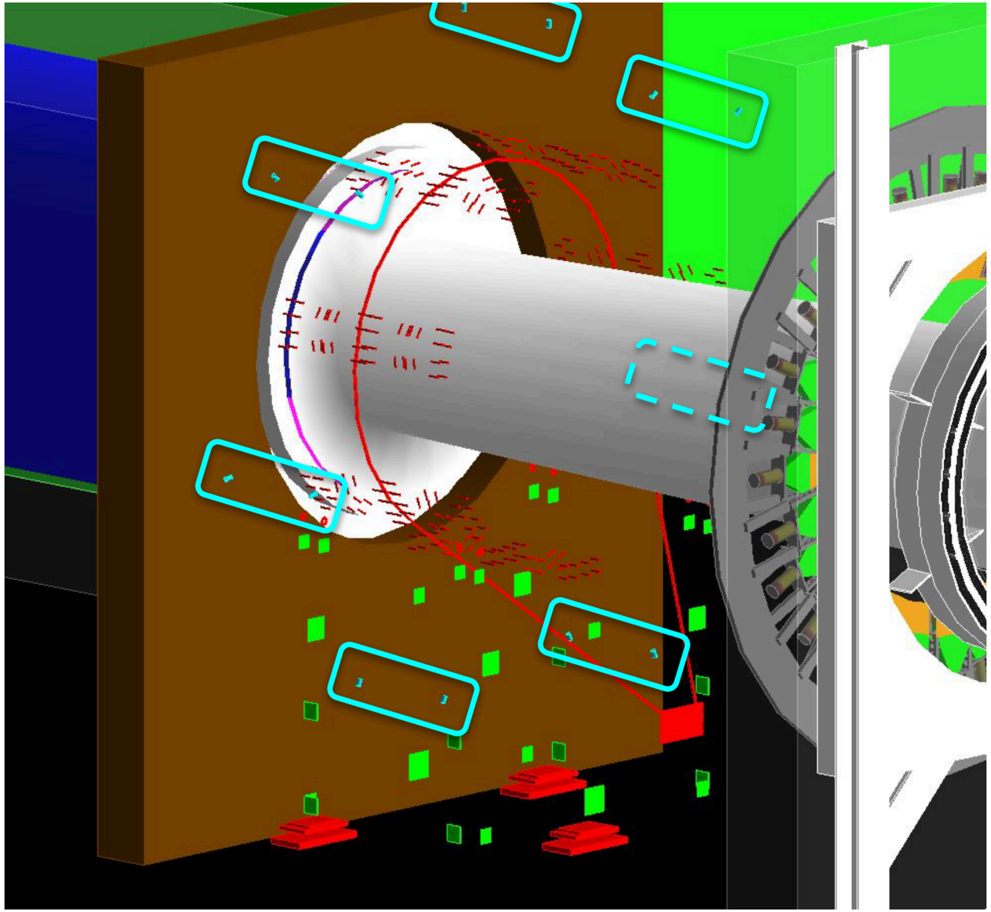
Custom Generators and Physics Processes

- Remoll has different Particle generators tailored for different purposes.
  - Møller
  - Elastic ep
  - Inelastic ep etc.
- Has custom physics processes.

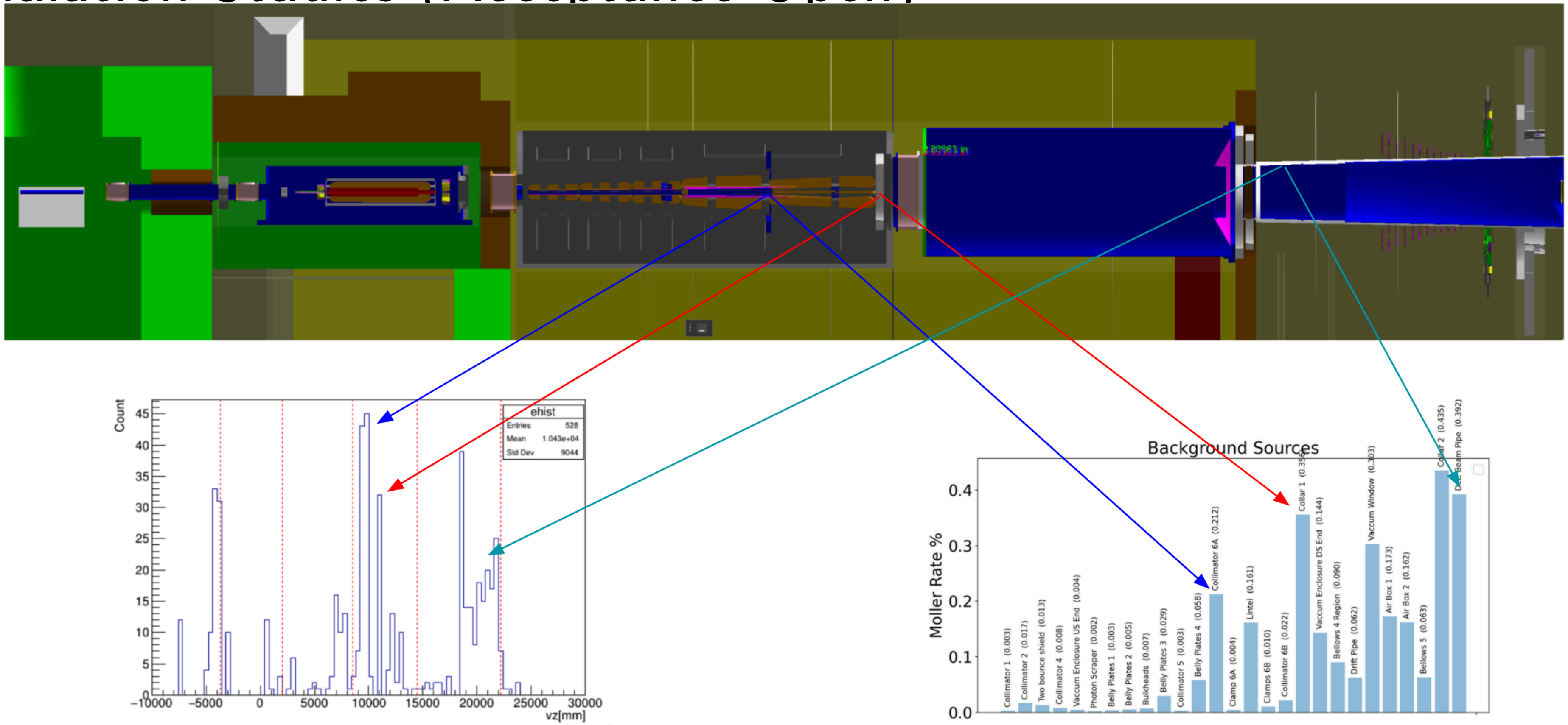
Simulation Studies

- Simulations used to study:
  - Collimation components,
  - Radiation load,
  - Shielding,
  - Ferrous Materials....



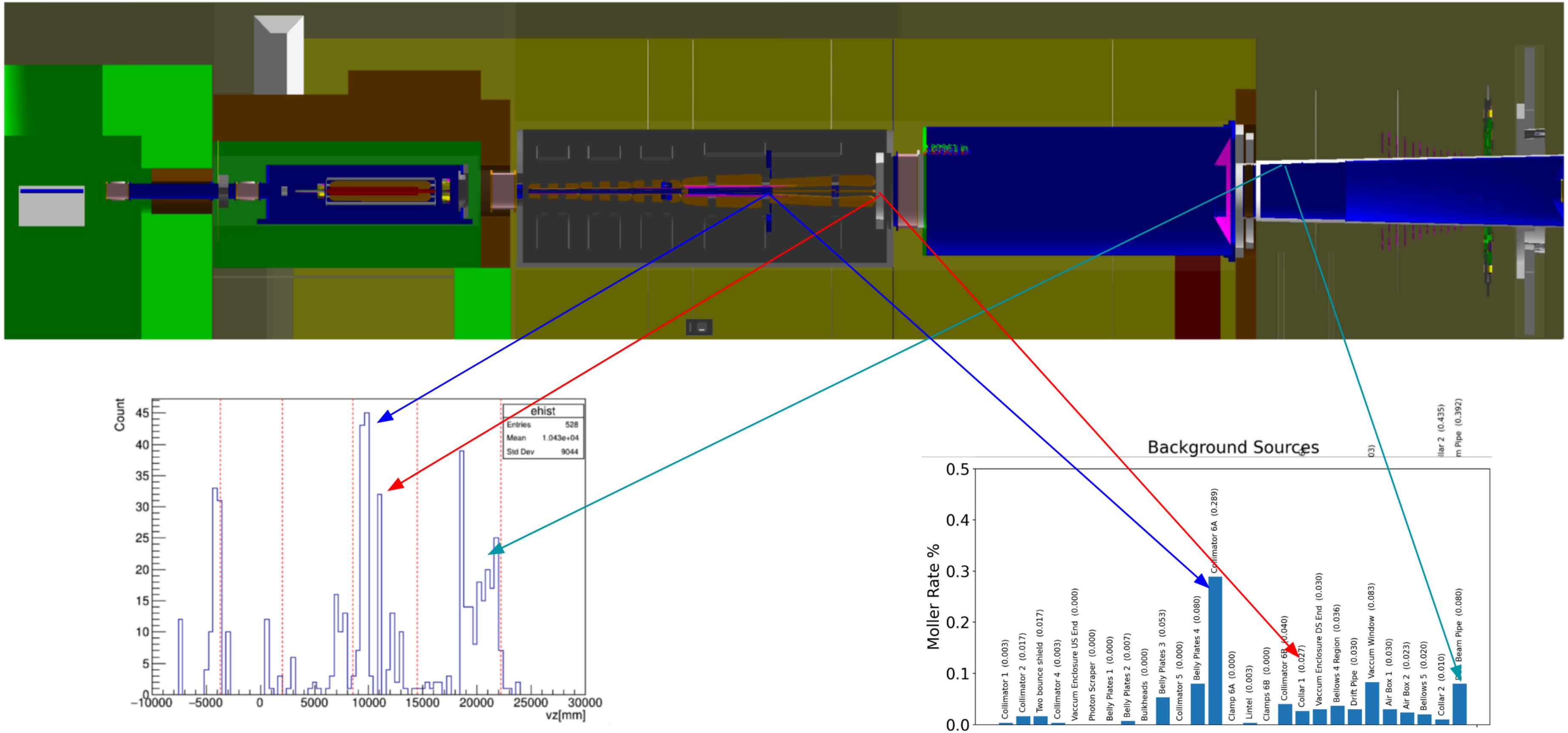


Simulation Studies (Acceptance Open)



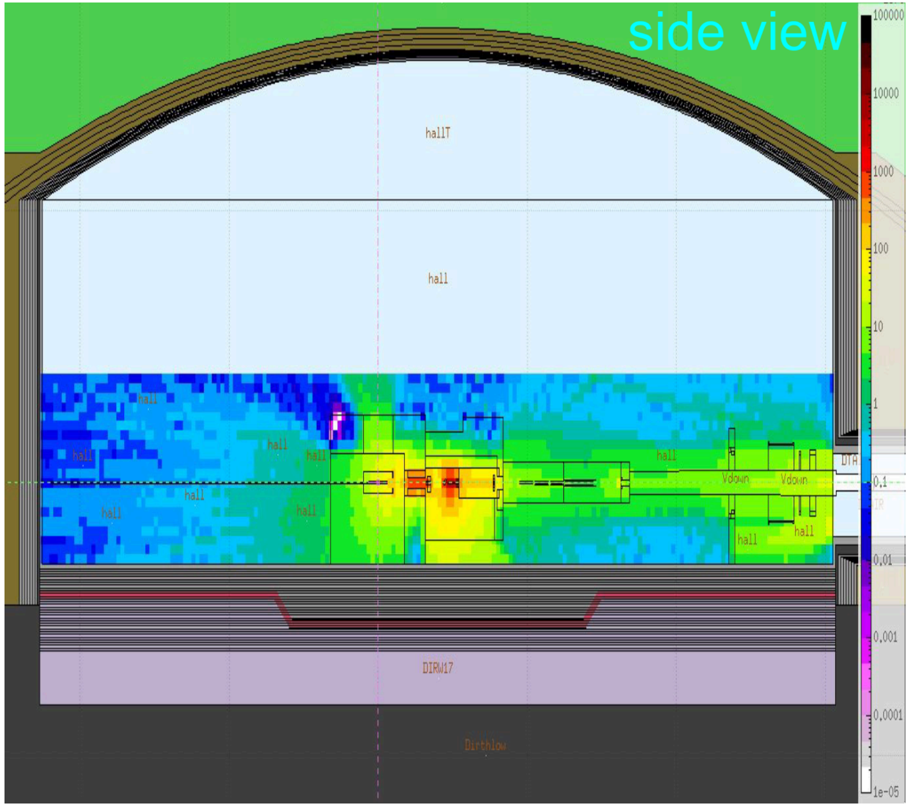
- Using simulation we can do very detailed analysis of source of background from each of the collimation components and the edges in the spectrometer.
- well-defined edge-scattering from radiative tail of signal processes.

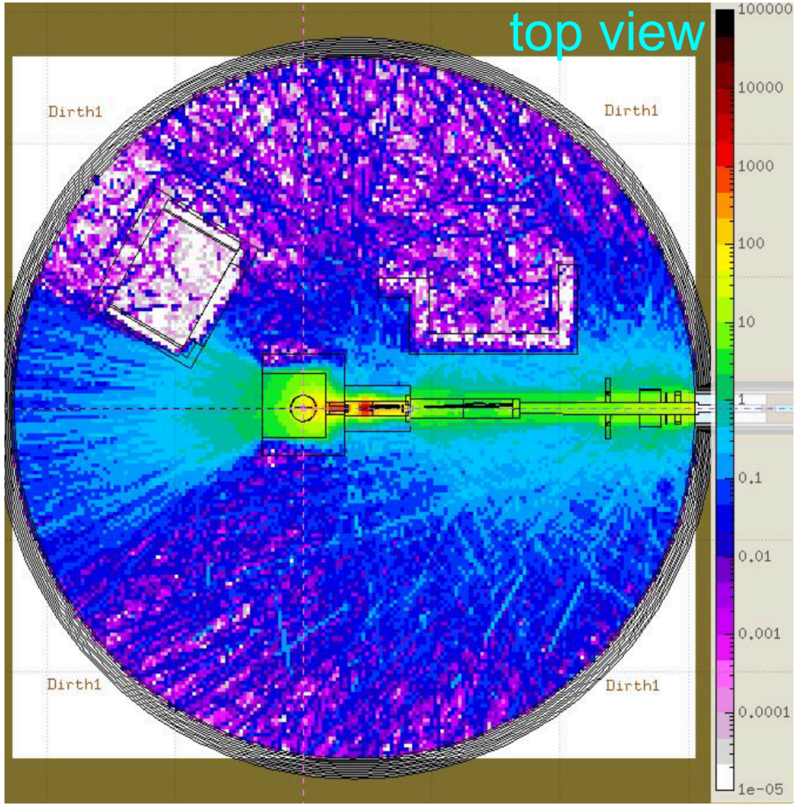
Simulation Studies (Acceptance Closed)



- Blocking acceptance to focus on rescattering in the beamline, looking for sensitivity to beam tails

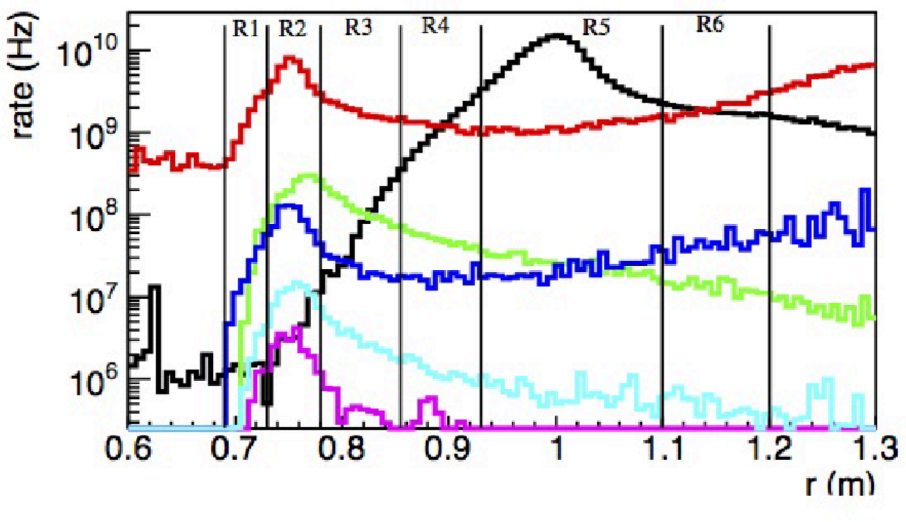
FLUKA Simulations

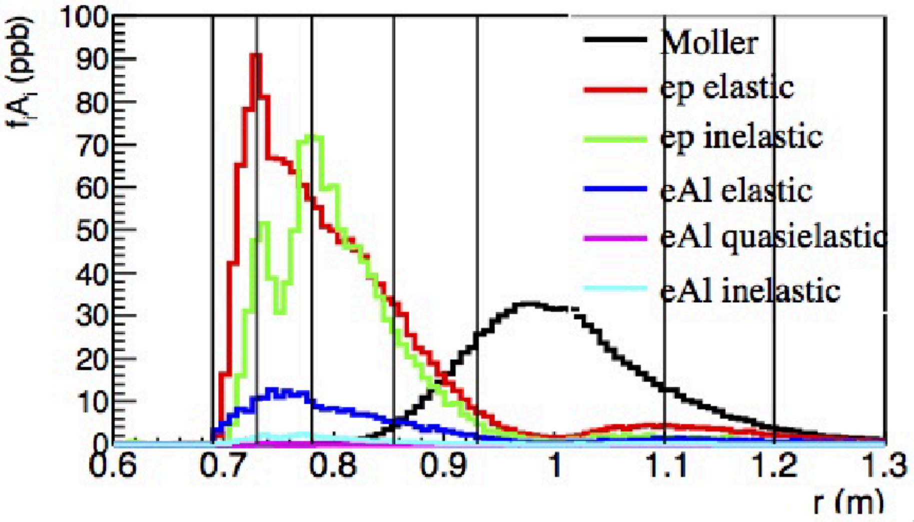




- Detailed radiation dose study is done with FLUKA and Geant4 simulation.

Backgrounds





- The ep elastic and ep inelastic scattering form irreducible backgrounds.
- By measuring the asymmetry across the detector plane we can “deconvolute” the Møller asymmetry from these backgrounds

Project Status

MOLLER Collaboration

~160 authors, 37 instutions, 6 countries

K. Kumar: Contact

R. Fair: Project Manager

Includes experience from E158, PREX, Qweak, PVDIS, HAPPEX, G-Zero

- Fabrication and qualification activity ramping up in test lab for spectrometer, soon to start at William & Mary for detectors.

- CD3A - All items in procurement
- CD 2/3 reviews complete.
- ESSAB review in April for final CD2/3 approval.

- MOLLER will be ready for installation mid-2025
- Ready for Physics in fall 2026.
- First Physics result for publication in mid 2027.
- Schedule ~15 months for procurement/ fabrication and ~15 months assembly.

Summary

- The MOLLER measurement of the very small parity-violating asymmetry requires an extremely high signal rate, very low noise, and the ability to control or correct for other asymmetric signals
- A novel spectrometer concept lies at the heart of a carefully designed experimental apparatus which, combined with the capabilities of CEBAF and Jefferson Lab, will be able to meet these challenges
- MOLLER builds on success of previous experiments PREX-2 and CREX.
- We have comprehensive simulation framework that guides most of the design parameters.
- Design of the components is complete.
- Will be ready for Physics in fall 2026!
- First Physics result for publication expected in mid 2027!

Backup

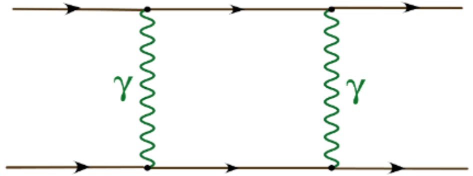
Transverse Analyzing power

electron beam polarized
transverse to beam direction

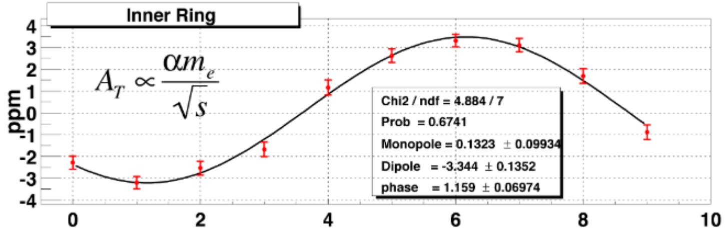
$$A_T \propto \vec{S_e} \cdot \left(\vec{k_e} \times \vec{k'_e}\right)$$

(a left-right analyzing power)

Interference between one- and
two-photon exchange



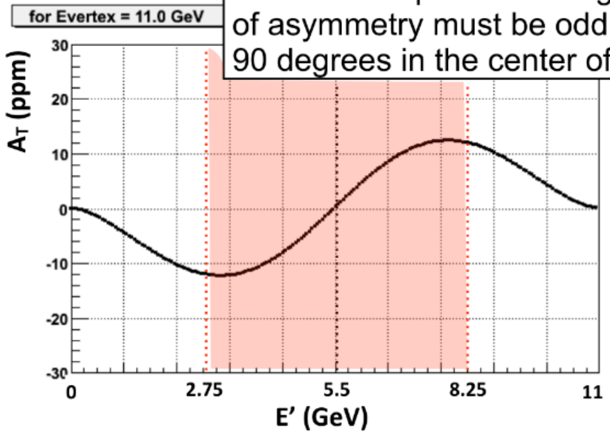
Measured at E158



Theory References:

1. A. O. Barut and C. Fronsdal, (1960)
2. L. L. DeRaad, Jr. and Y. J. Ng (1975)
3. Lance Dixon and Marc Schreiber:hep/ph-0402221

For identical particles: magnitude of asymmetry must be odd around 90 degrees in the center of mass

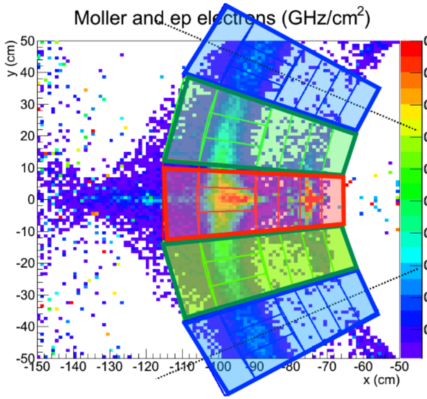


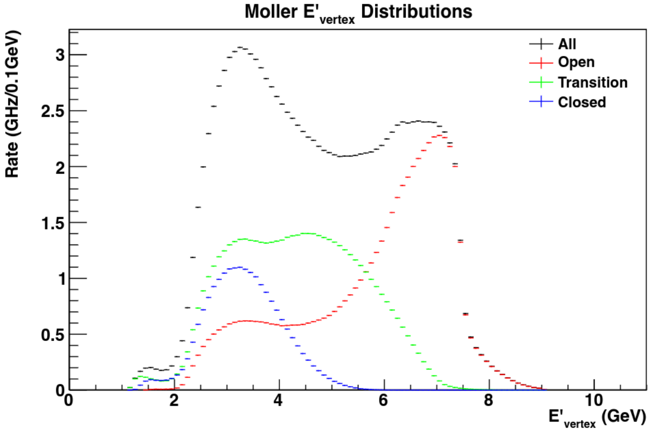
Potential systematic error in A_{PV}.
Suppressed by
- small transverse polarization
- azimuthal acceptance symmetry
- acceptance symmetry in c.m.s. polar angle

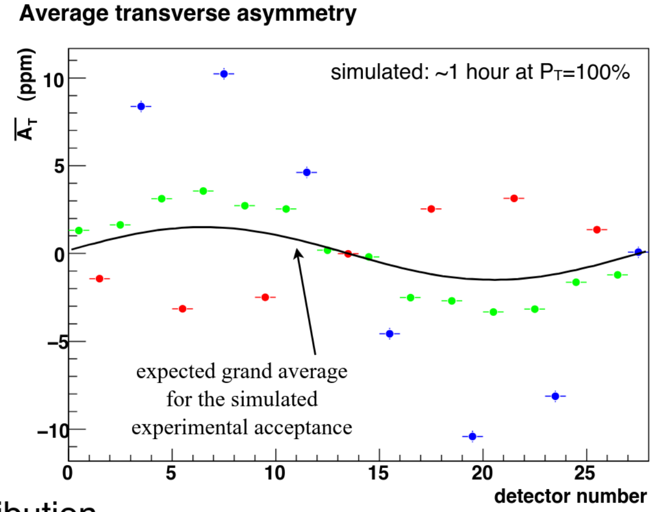
Parity experiments have always fretted about this, but the polarimeters optimized for longitudinal polarization were really bad at precisely measuring it

Transverse Polarization

Transverse polarization analyzing power has been measured and calculated for *ee* scattering
It is relatively quite large relative to A_{PV} but varies widely over the acceptance







- Unique signature of transverse beam polarization over azimuthal detected distribution
- 50 ppb error on A_T*P_b in 4 hours: 1° precision
- Over entire run: feedback will hold transverse polarization small (<<1 degree)
  - Initial beam setup ~ 1-2 degrees vertical, similar in horizontal with spin dance?
  - 10^{-4} change in beam energy ~ 2° horizontal, so quality of beam energy lock will be important
  - 10^{-3} linac imbalance is also ~2° horizontal P_T
  - “Feedback” of integrated value of PT to correct offset.
  - Wien in injector, at 1° - 2° level or beam energy at 10^{-4} level for horizontal component
  - Over entire run, feedback will hold transverse polarization small (<<1 degree)
  - Note: this is also how the g-2 energy flip will be fine-tuned