The MOLLER Experiment

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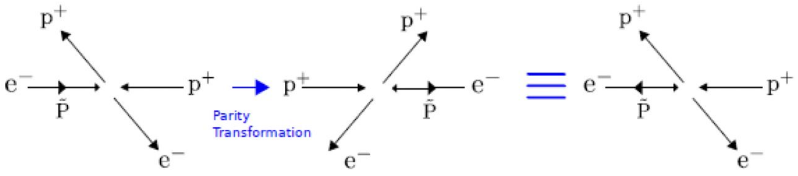
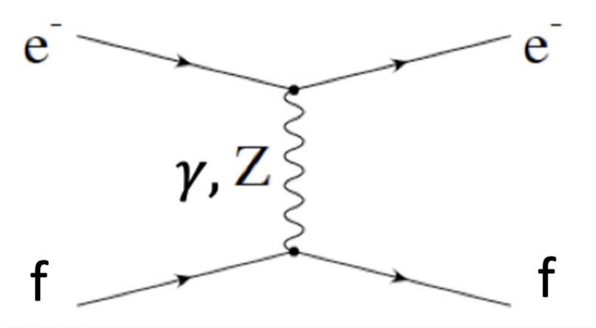
Parity-Violating Electron Scattering





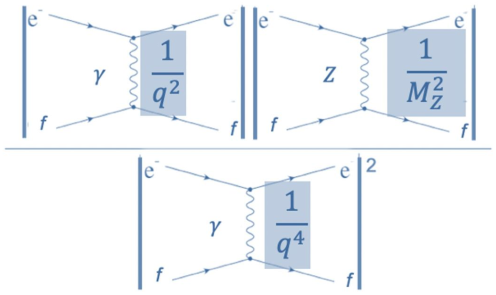
$$A_{PV} = \frac{\frac{d\sigma^R}{d\Omega} - \frac{d\sigma^L}{d\Omega}}{\frac{d\sigma^R}{d\Omega} + \frac{d\sigma^L}{d\Omega}} \propto \frac{M^{EM} \cdot M^{NC}}{|M^{EM}|^2}$$

- For neutral currents, the differential cross section depends on the helicity of the electron.

- The PV asymmetry, A_{PV} is defined as the fractional difference in cross sections between left/right handed helicities

To estimate the size of the asymmetries

APV ~

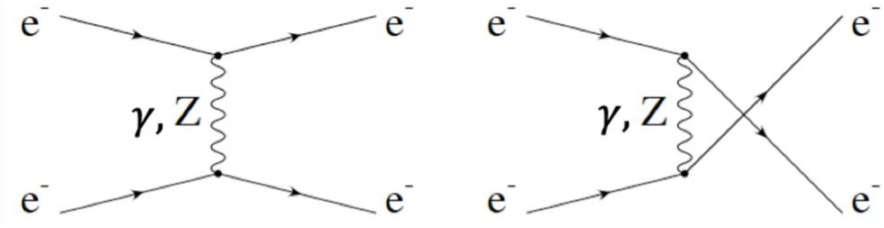


$$= q^2\ (GeV^2)\times 10^{-4}$$

Parity-Violating Møller Scattering

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad \text{(tree level)}$$

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



A_{PV} directly probes the weak charge of the electron which determines the weak mixing angle

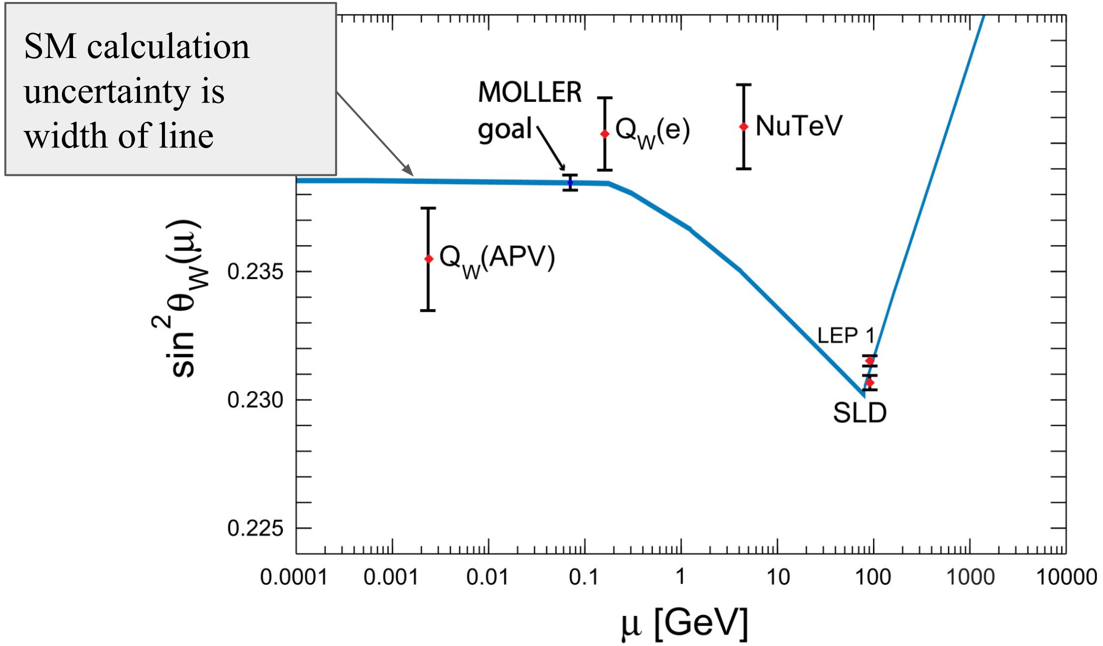
- Weak charge of electron suppressed in Standard Model since $\sin^2\theta_W \sim 0.23$
- MOLLER plans to measure A_{PV} to 2.4% precision → 0.12% precision in $\sin^2\theta_W$ (± 0.0028)

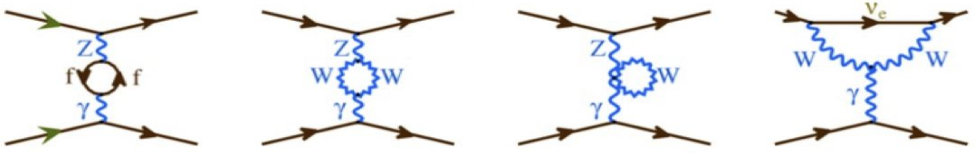
Particle	q_{EM}	$g_V = Q_w/2$
e^-	-1	$-\frac{1}{2} + 2\sin^2\theta_W$
u	$\frac{2}{3}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{3}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_W$
p	1	$\frac{1}{2} - 2\sin^2\theta_W$
n	0	$-\frac{1}{2}$

Running of $\sin^2\theta_W$

- Weak neutral current amplitudes are functions of the weak mixing angle, which runs with energy (established at 6σ).
- Measurements at Z-pole measure SM properties of Z boson → low sensitivity to new physics
- Off Z-pole sensitivity to new (PV) physics is in the quantum loops
- MOLLER precision matches the best Z-pole measurements!

Weak Mixing Angle Running in MS scheme





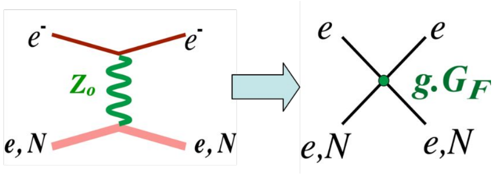
Sensitivity to New Physics at TeV Scales

Many new physics models give rise to new neutral current interactions

Heavy Z’s and neutrinos, technicolor, compositeness, extra dimensions, SUSY etc..

Low energy WNC interactions ($Q^2 << M_Z^2$)

Heavy mediators = contact interactions



Low energy (Q^2 << M_Z) interactions modelled as contact interactions with new physics entering in loops of order g/Λ (coupling g, mass scale Λ)

$\Lambda \sim 7.5$ TeV → $g \sim 1$, $\Lambda \sim 47$ TeV → $g \sim 2\pi$

$$\left|\mathbf{A}_\gamma + \mathbf{A}_\mathbf{Z} + \mathbf{A}_\mathbf{new}\right|^2 \rightarrow \mathbf{A}_\gamma^2\left[1 + 2\left(\frac{\mathbf{A}_\mathbf{Z}}{\mathbf{A}_\gamma}\right) + 2\left(\frac{\mathbf{A}_\mathbf{new}}{\mathbf{A}_\gamma}\right)\right]$$

$\mathbf{Q_W^e \sim 0.045}^*$

$$\frac{\delta \mathbf{Q_W^e}}{\mathbf{Q_W^e}} = \mathbf{2.4\%}$$

$$\mathbf{A}_\mathbf{new} \sim \mathbf{0.001 \cdot G_F}$$

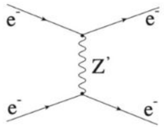
UNPRECEDENTED SENSITIVITY

So test SM predictions by looking for deviations i.e., shifts in the central value

New (Low Energy) Physics Examples

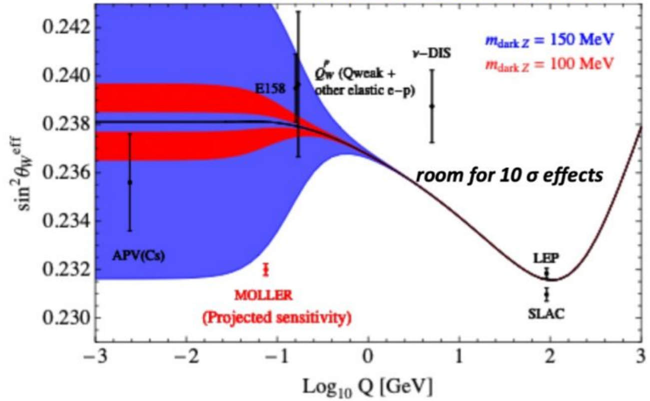
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



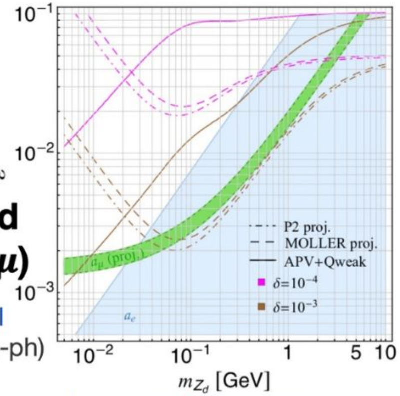
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano

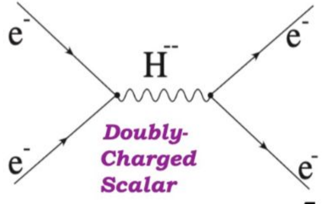


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



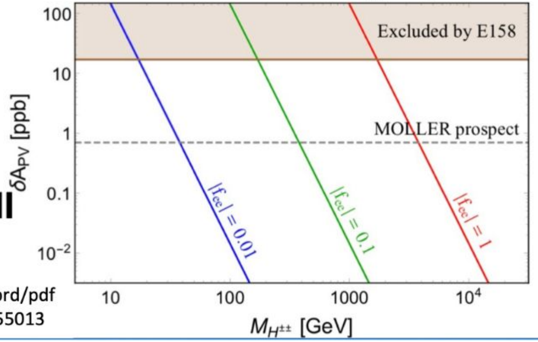
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \text{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

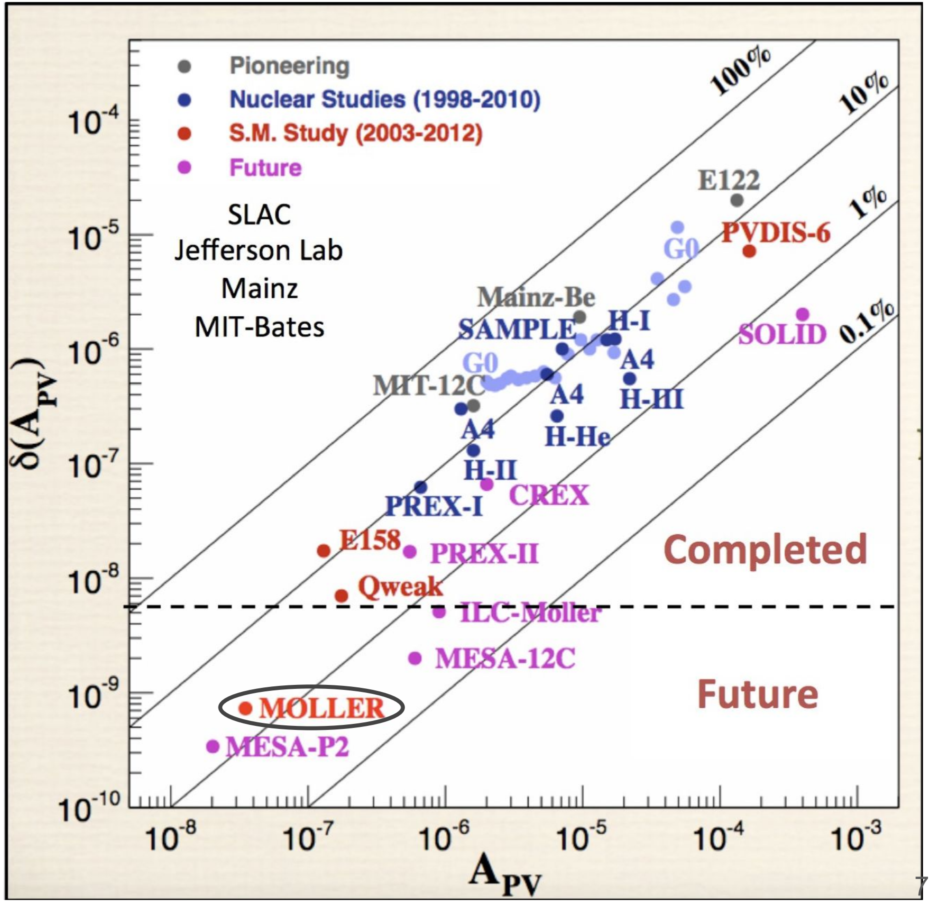
Specific Scenario for Type-II SeeSaw

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.98.055013



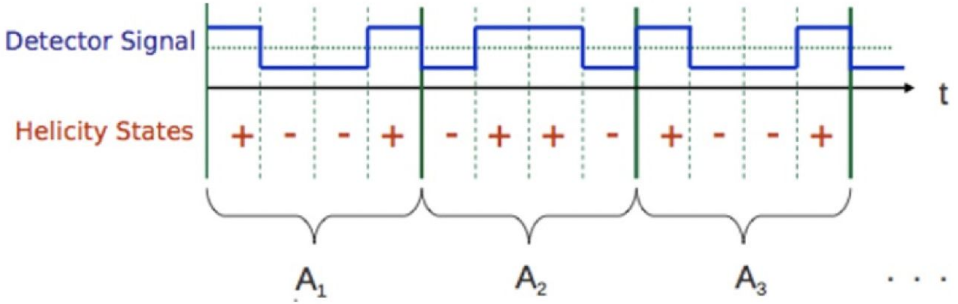
PVES Past and Future

Existing and past measurements range over at least 4 orders of magnitude in size and uncertainty



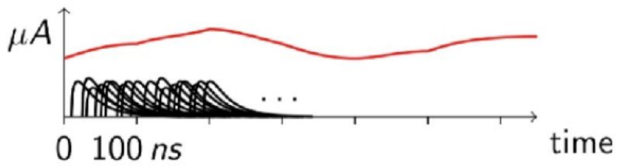
Measuring Tiny Asymmetries

Rapid (2kHz) Helicity Reversal



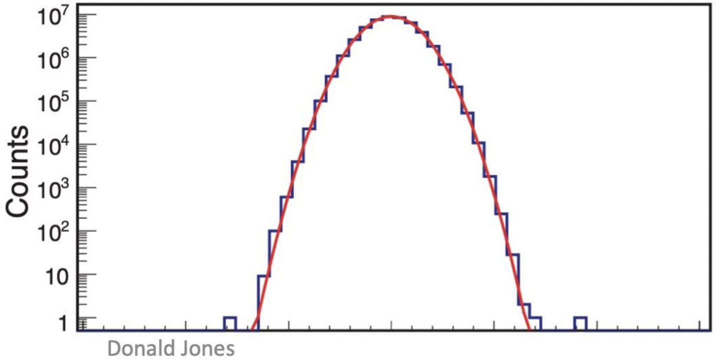
~ GHz rate, so no counting electrons

Analog integrate detector current



Form an asymmetry over the helicity reversal

Measure to 0.01% at 1 kHz,
repeat for a year straight (8200 hrs)



- Must be able to measure backgrounds to remove them
- Measure and remove pedestal
- Monitor and isolate spurious asymmetries (e.g, from electronics noise)
- Precision beam parameter and current measurements
- Other things…

MOLLER (Measurement Of a Lepton-Lepton Electroweak Reaction)

$A_{PV} = 35.6$ *ppb*

$\delta(A_{PV}) = 0.73$ *parts per billion*

$\delta(Q^e{}_W) = \pm\, 2.1\ \%\ (stat) \pm 1.0\ \%\ (syst)$

$\langle \mathbf{Q^2} \rangle = \mathbf{0.0056\ GeV^2}$

signal rate: 134 GHz
run time: 8200 hours
~$3\text{x}10^{18}$ electrons detected
Target 1.25m long LH2
65 μA electron beam 85% polarized

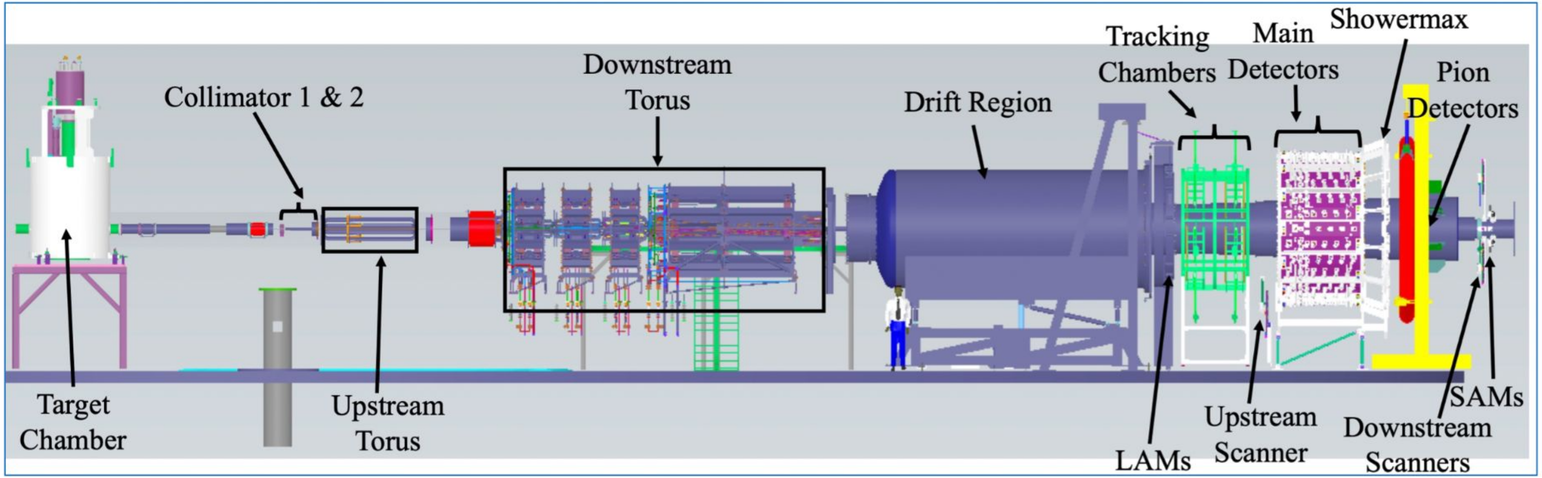
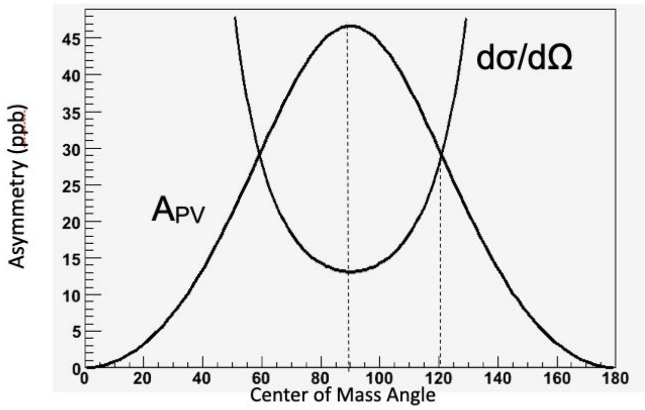
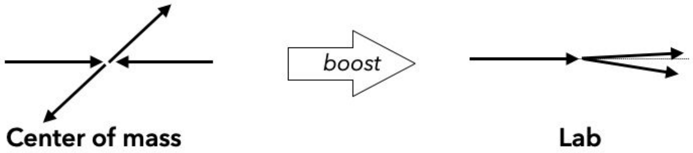


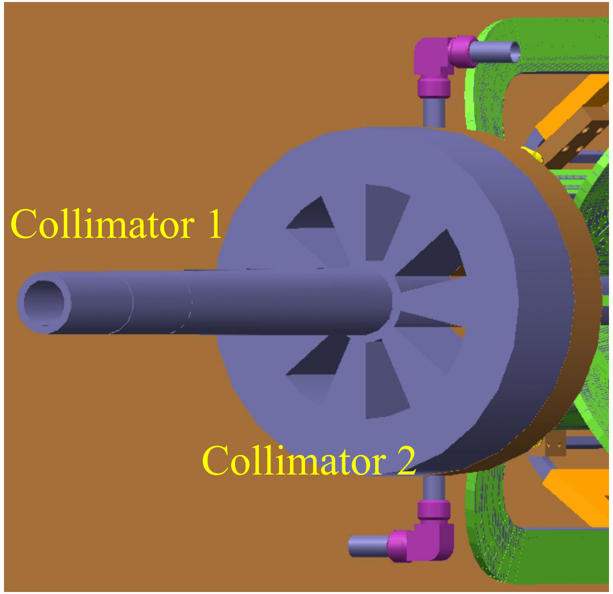
Figure of Merit and Collimation

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

Highest figure of merit at θ_{CM} = 90°







Acceptance

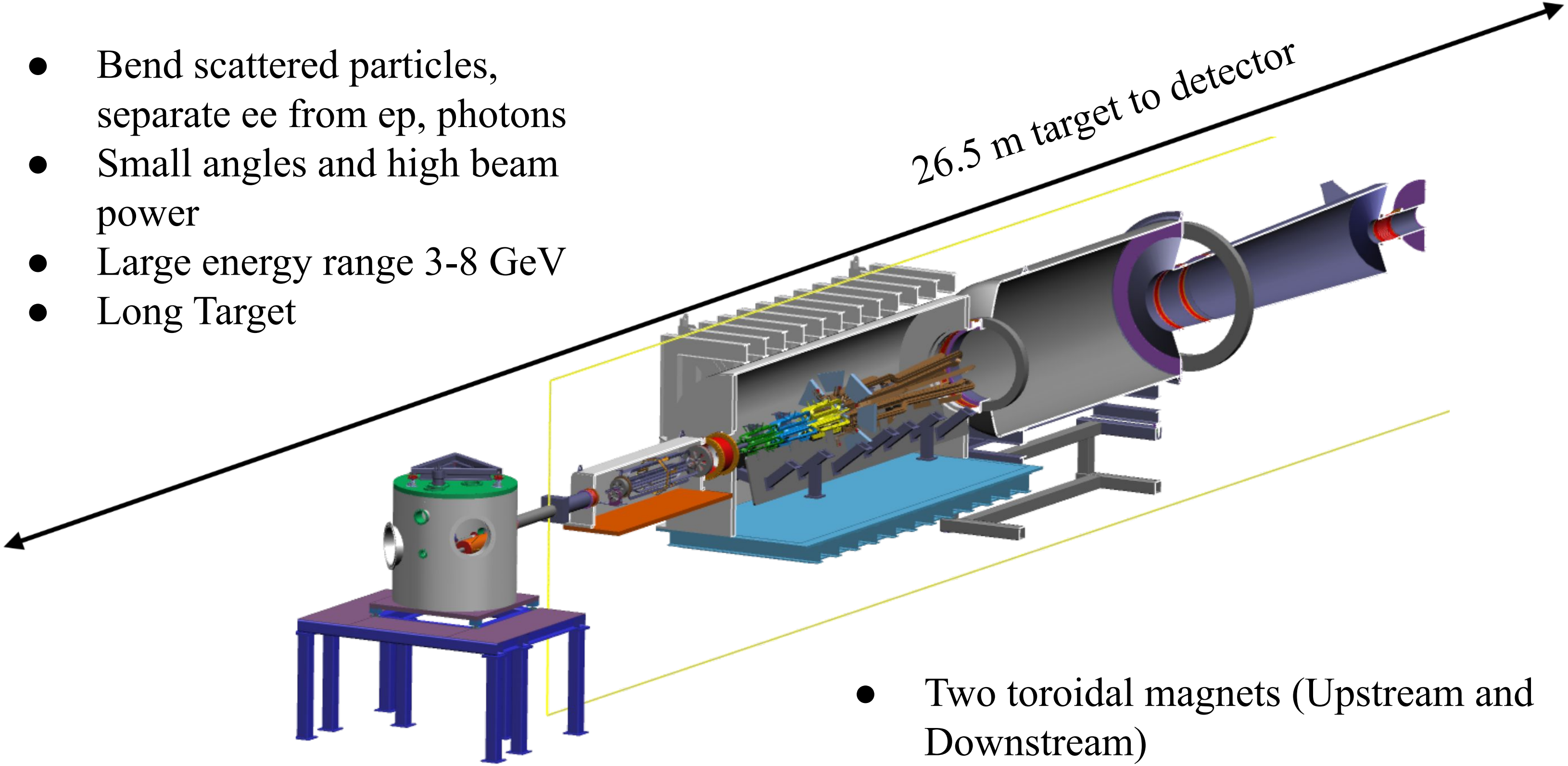
11 GeV in: 2 < E' < 8 GeV out

$60^o < \theta_{CM} < 120^o$

$6 < \theta_{lab} < 21$ mrad

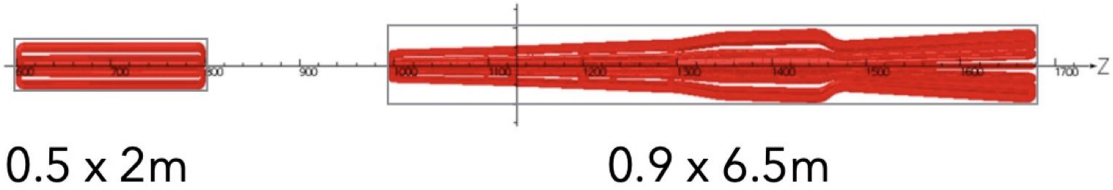
Spectrometer Concept

- Bend scattered particles, separate ee from ep, photons
- Small angles and high beam power
- Large energy range 3-8 GeV
- Long Target

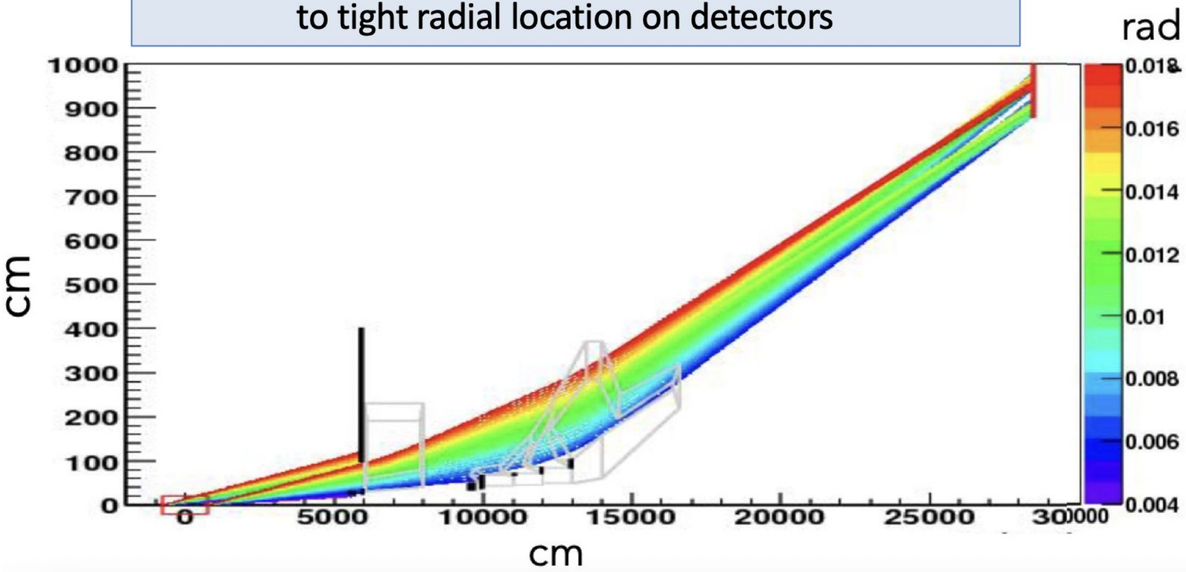


- Two toroidal magnets (Upstream and Downstream)
- Collimation + “shields” or “blockers”
- Vacuum pipe to take beam to dump

Spectrometer Concept

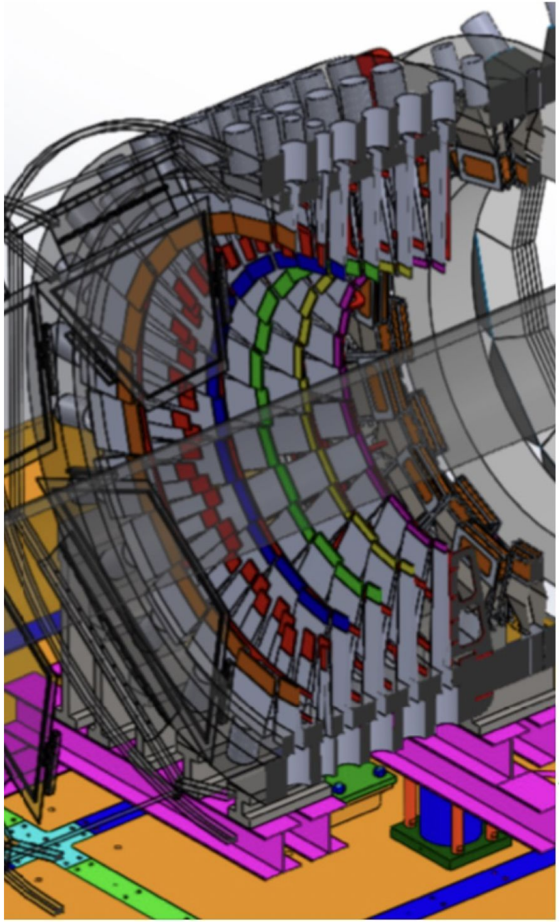


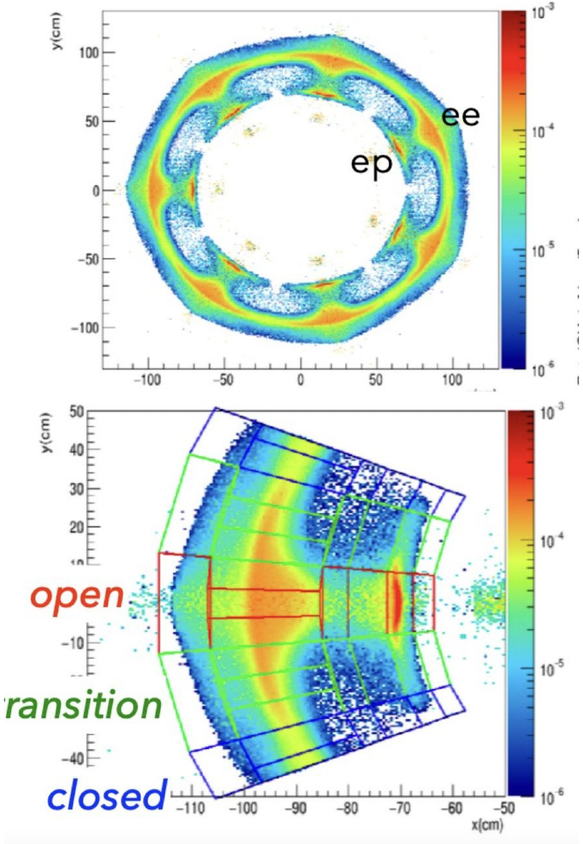
Focus Moller electrons from full acceptance (3 – 8 GeV) to tight radial location on detectors



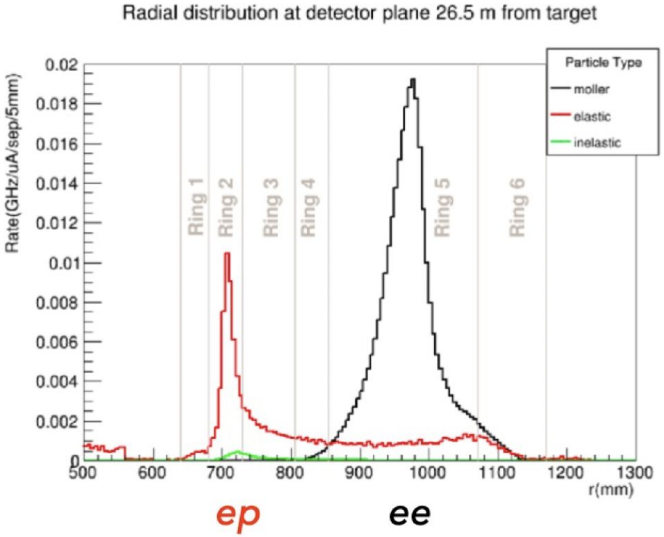
- Two toroidal spectrometers with 7 identical coils uniformly spaced in the azimuth.
- US torus provides pre-bending. Roughly 2 m separation between US and DS magnets to allow ee and eps to drift radially.
- Radial fringe fields provide azimuthal defocusing so that Mollers populate full azimuth at detector plane

Main Detectors

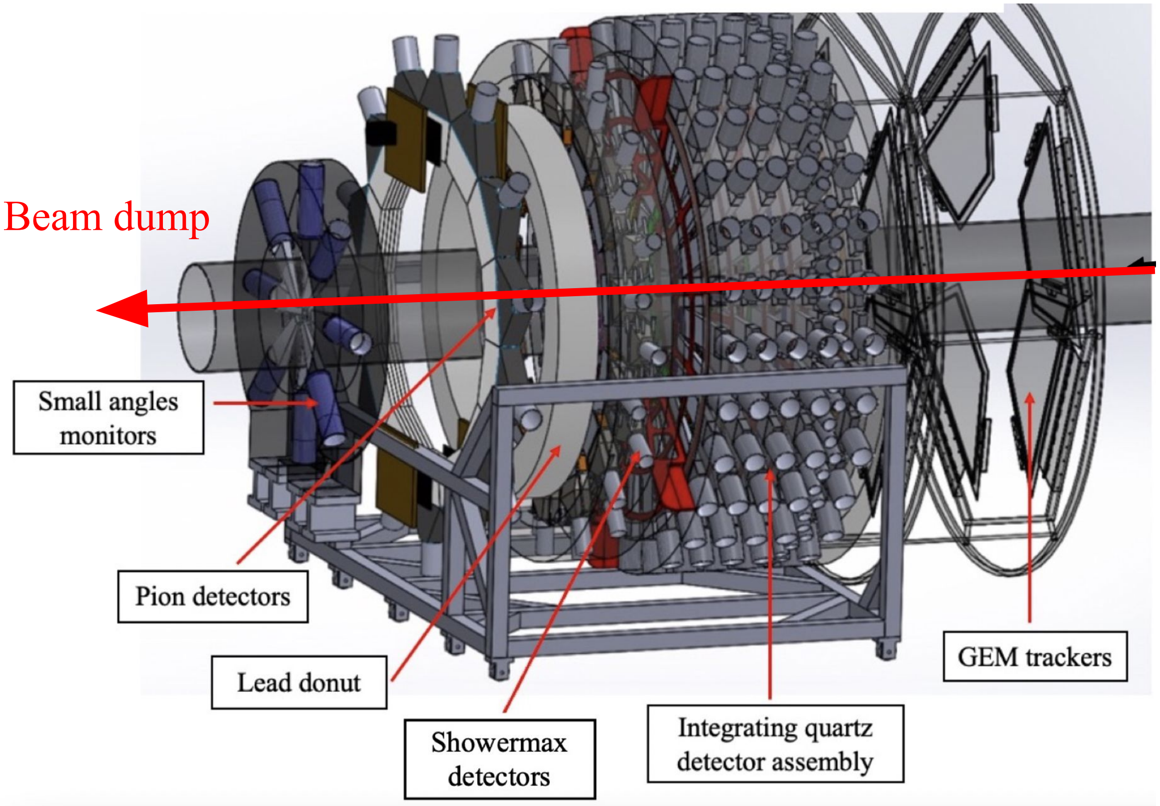




- Main Detectors made from fused silica (quartz)- radiation hard, good resolution
- Highly segmented geometry to be able to detect Moller events and deconvolute backgrounds



Auxiliary Detectors



GEM detectors: Tracking, reconstruction of kinematics

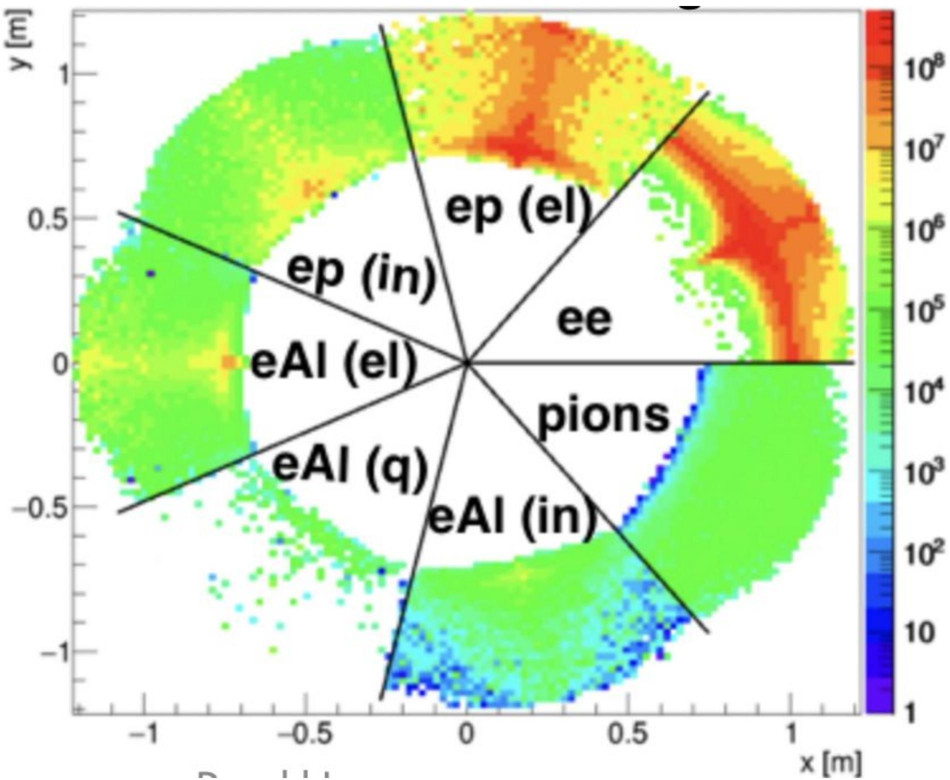
Showermax detectors: Additional asymmetry measurement with energy weighting, reduced sensitivity to soft and hadronic backgrounds

Pion Detectors: Measures pions

Small Angle Monitors: Scattered beam monitors to detect possible scattered beam off of downstream elements e.g., collimators, shielding components

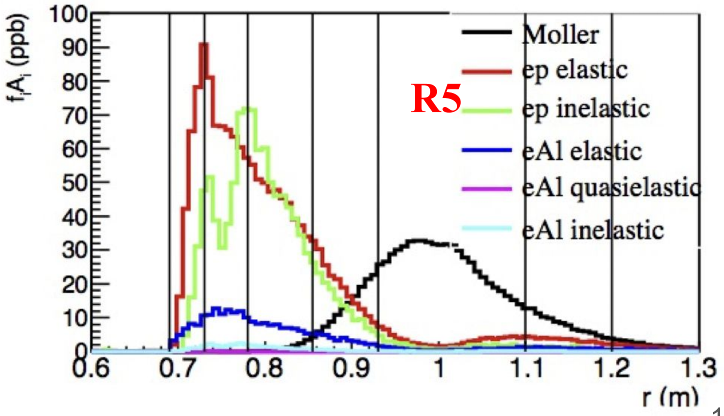
Irreducible Backgrounds

Illustration with each septant showing a different fundamental background

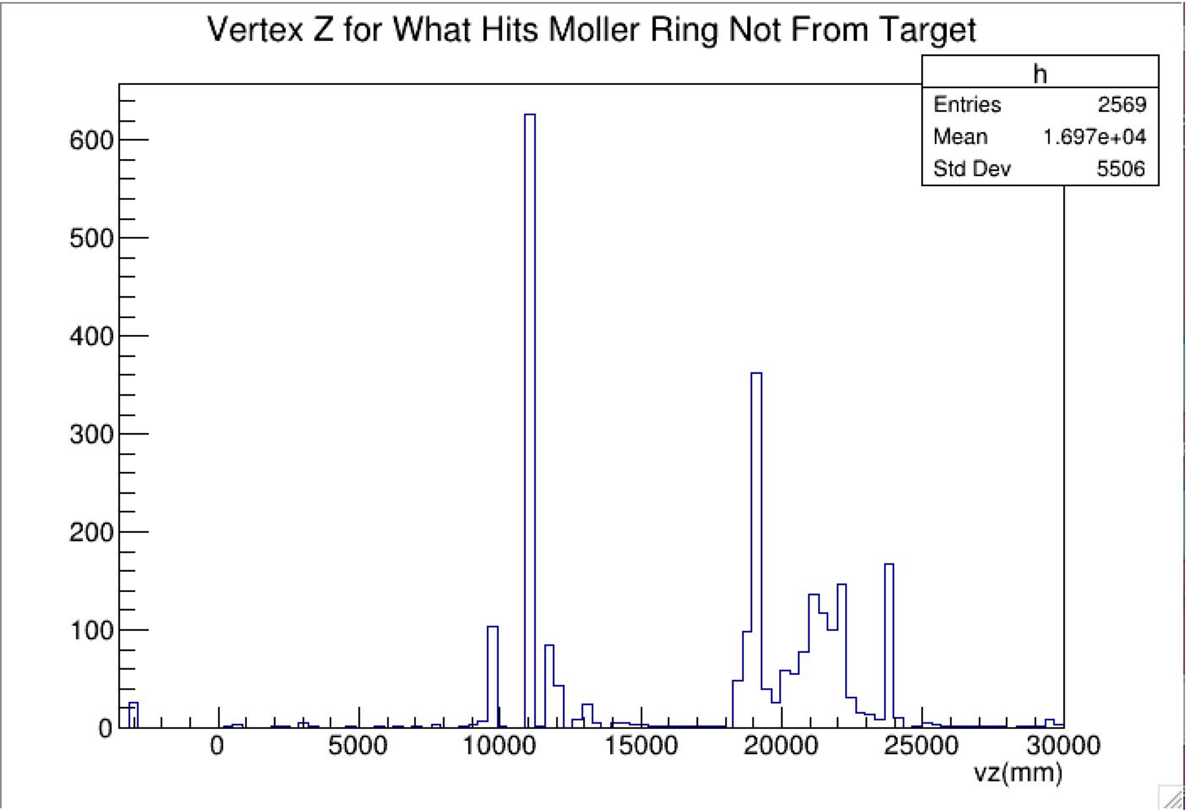


Various background sources from the target that make it through the spectrometer also make it to the main detector

Must deconvolute backgrounds from main signal



Reducible Backgrounds



Secondary electron/positron sources

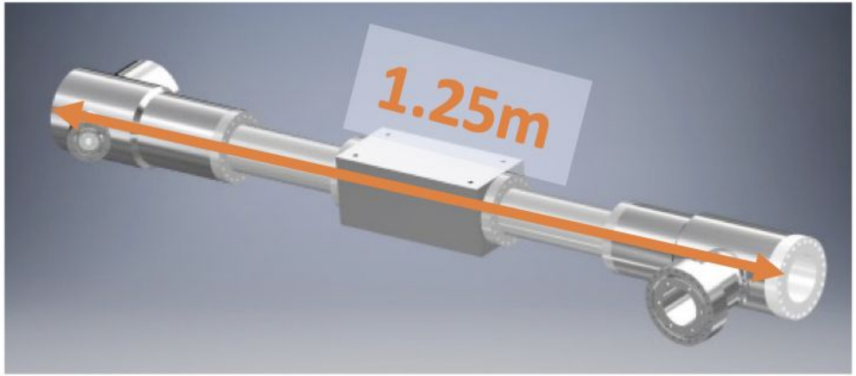
Other backgrounds aren't directly through acceptance channel, but are

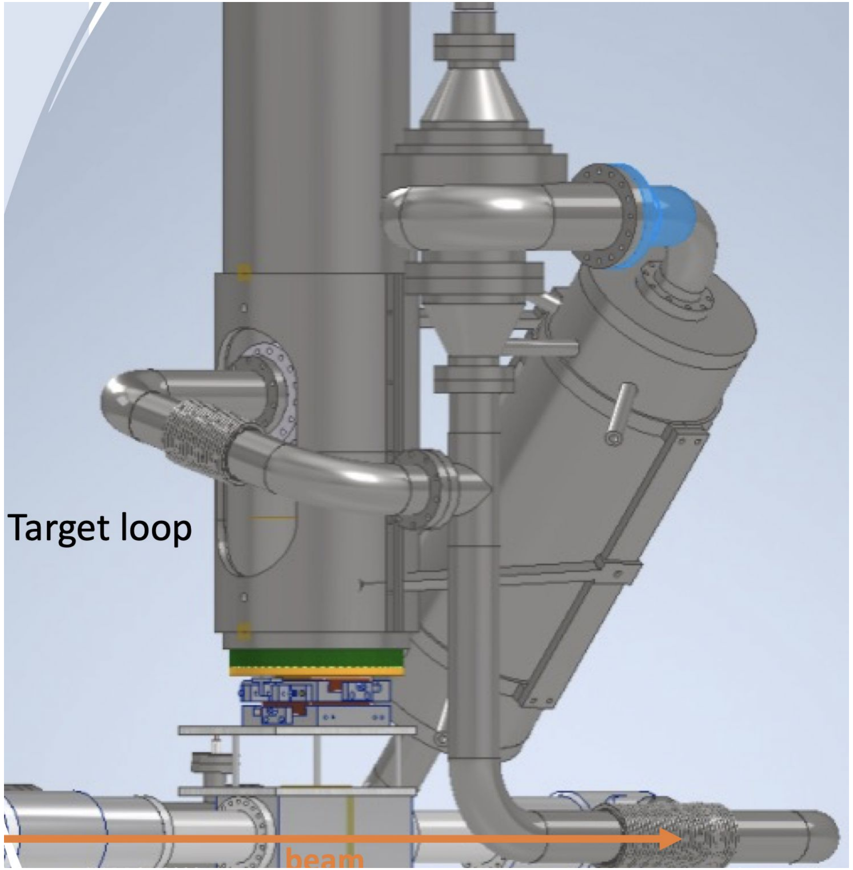
- Rescattering of the beam that makes its way through the spectrometer to the dump
- Off energy particles through the acceptance that rescatter off edges and surfaces that make it to the detector

Characterize through simulation and optimize shielding and collimating components to minimize such backgrounds.

Production Target

- 1.25 m long LH2 target (greatest electron yield per radiation length)
- 4 kW high power target
- Studied extensively using CFD (small density fluctuations)

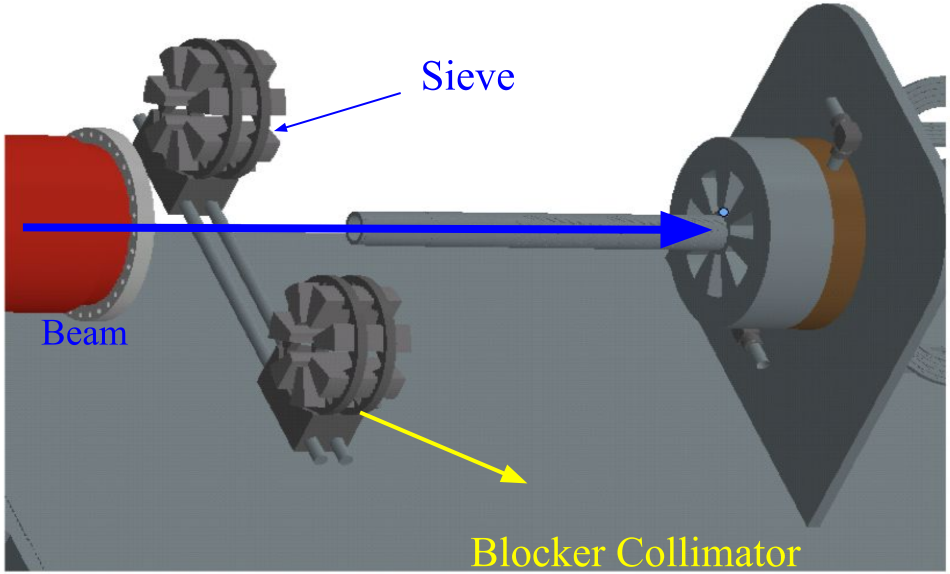


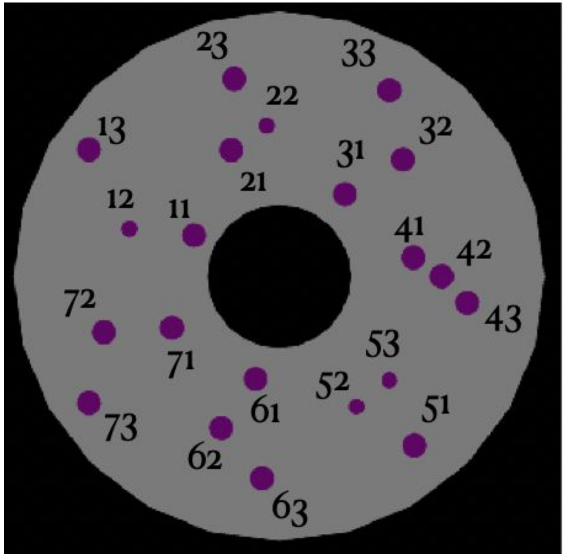


Sieve and Blocker

- Sieve needed for optics calibration, verification of optics model, study magnetic fields.

- Design nearly complete. Optics group concurrently thinking of run plan





- Blocker collimator to block main acceptance

- Necessary to study backgrounds

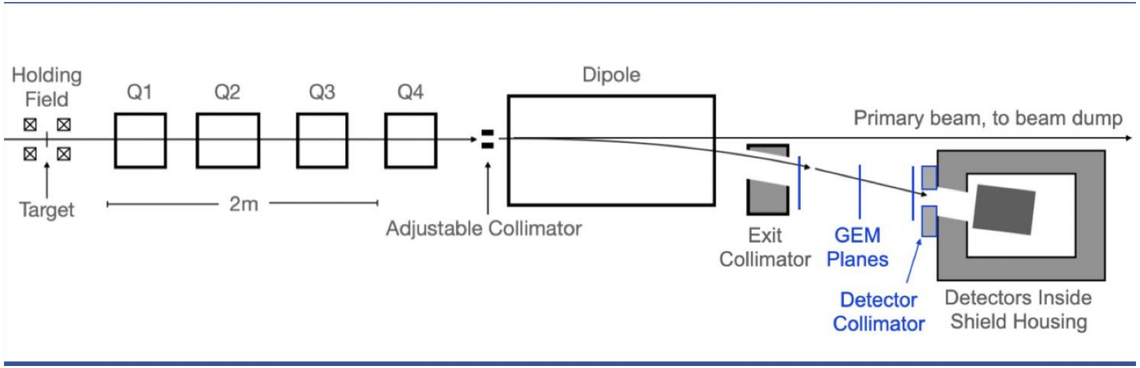
Beam Studies for Parity-Quality Beam

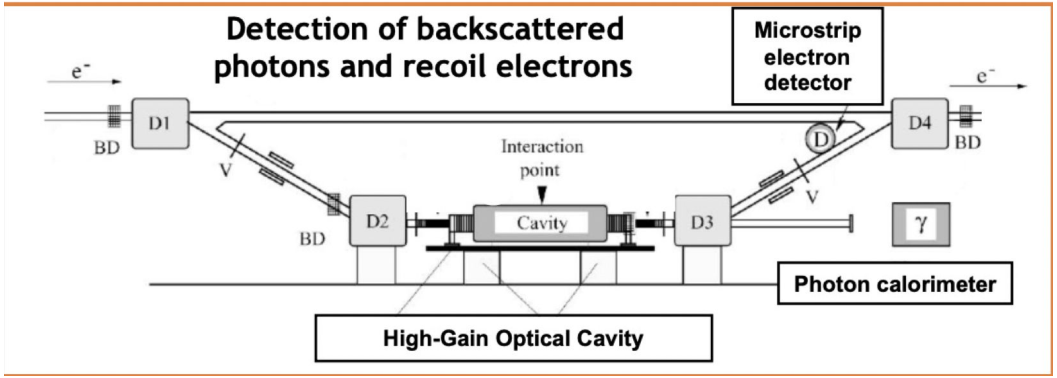
- New 200 kV gun and booster installed in the injector
- Injector OPS has scheduled beam studies in the next couple of months for MOLLER involving measuring beam characteristics
- Parity-quality beam group for MOLLER has plans to do their own beam studies planned for next month using the parity DAQ. Look at things like Wien flip, beam tails, position differences etc.

Polarimetry

Moller Polarimeter

- Additional DS components, including GEMs and detection collimation (systematics)
- Recently performed saturation scans after GEn to better understand systematics





Compton Polarimeter

- CREX achieved 0.44% precision with only photon detector.
- Electron detector under development. Two technologies: diamond microstrip and HVMAPs

Analysis Framework

- Analysis tools for both integrating and counting data stream expected to be ready for commissioning, characterizing and operating the MOLLER apparatus

- Counting mode needed things like optics calibration, background studies, detector alignment, acceptance model etc. **Proposed plan is to build from PREX and SBS Podd analyzers. SBS has had a lot of GEM analysis development.** Use G4 simulation to help aid in development.

- Integrating mode → JAPAN(Just Another Parity ANalyzer). Built out of QWeak and used for PREX-II/CREX analysis.

- Analysis meetings to be resumed to think about what is needed and start implementation.

Project Status

- Received CD3A → Items for purchase
- CD 2/3 reviews schedule - things are on track
- Technically driven schedule ~ 15 months construction and ~ 18 months installation
- MOLLER will be ready for installation by 2025

MOLLER Collaboration

~ 160 authors, 37 institutions, 6 countries

K. Kumar: Contact
J. Fast: Project Manager

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

MOLLER MIE CD-3a Schedule			2023				2024				2025				2026				2027				2028			
	Start	End	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4	FQ1	FQ2	FQ3	FQ4
CD-3a Authorization	3/16/23	3/16/23																								
Magnet Coil, Collimator Procurements	1/13/23	7/10/24																								
Magnet Power Supply Procurement	1/13/23	6/21/24																								
Beam Pipes and Bellows Procurements	1/13/23	4/3/24																								
Hydrogen Target Procurements	1/13/23	8/17/23																								
Moller Polarimeter Procurement	1/13/23	6/13/23																								
CD-2/3	1/1/24	1/5/24																								
CD-3a Scope Complete (L3 Milestone)	7/19/24	7/19/24																								
Procurement/Fabrication/Assembly	1/5/24	11/6/24																								
Assembly in Hall A	2/10/25	1/13/26																								
Commissioning/KPP validation	1/13/26	3/5/26																								
Ready for CD-4 (L3 milestone)	3/5/26	3/5/26																								
CD-2/3 (L1 Milestone)	6/10/24	6/10/24																								
CD-3a Scope Complete (L2 Milestone)	7/2/25	7/3/25																								
All Equip Ready for Hall (L2 Milestone)	12/18/25	12/18/25																								
CD-4 (L1 Milestone)	3/3/28	3/3/28																								

Summary

- MOLLER plans to measure the weak charge of electron with 2.4% precision.
- 2.4% measurement translates to 0.12% precision measurement of $\sin^2\theta_W$. Precision matches measurements at Z-pole!
- Design nearly complete. Order and test components as needed.
- MOLLER will be ready to roll in 2025. Data taking 2026-2028.