An Overview of MOLLER Experiment at Jefferson Lab and VT Responsibilities

Devi L. Adhikari – Dec 08, 2023

Virginia Tech

VT workforce:

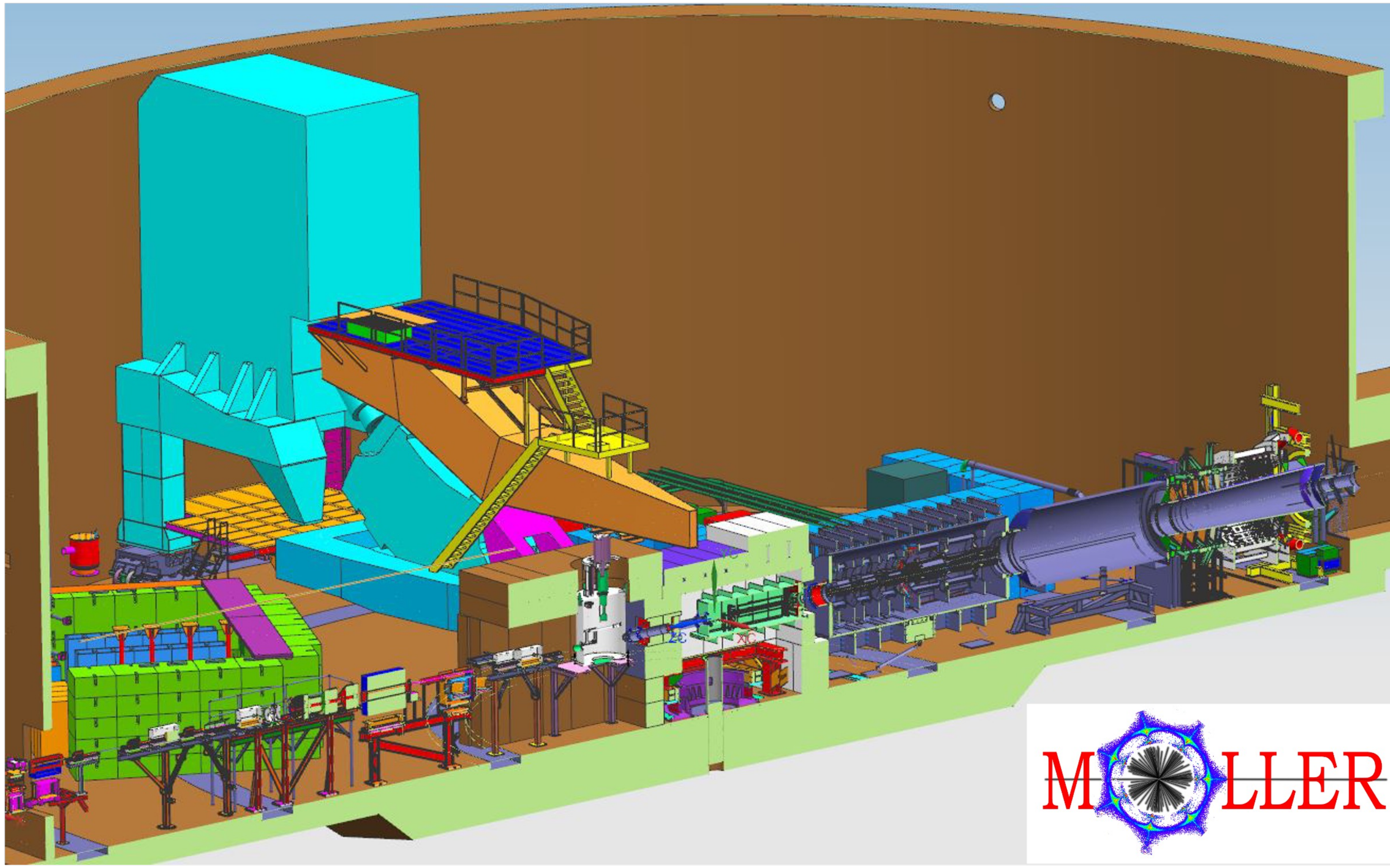
Mark Pitt
Devi Adhikari
Andrew Gunsch
Daniel Valmassei

CNP Research Day

Outline

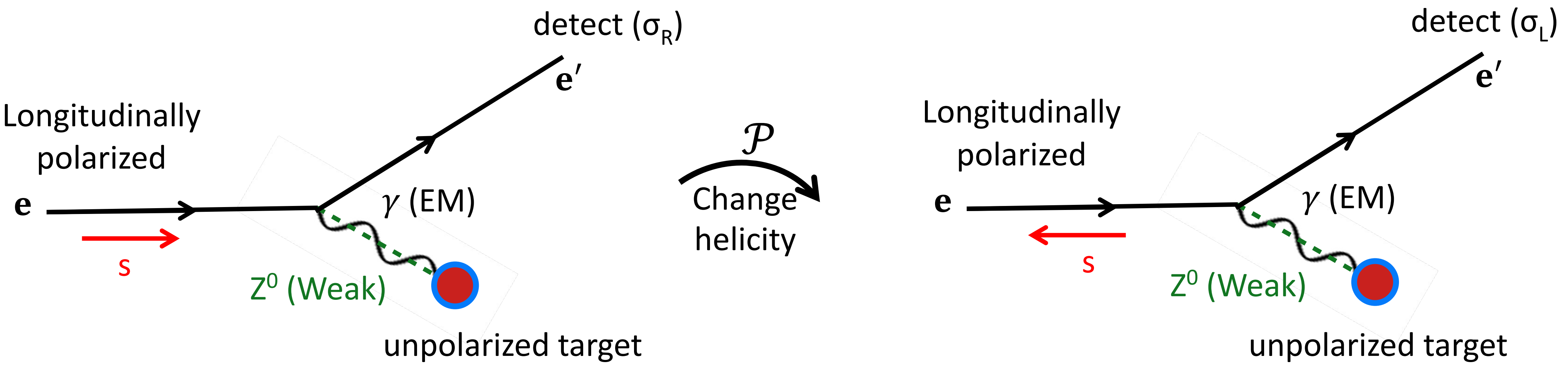
- Parity-violating electron scattering (PVeS) introduction and history
- MOLLER experiment overview
- Involvement and responsibilities of VT
- Summary and current status of the project

Measurement **O**f a **L**epton **L**epton **E**lectroweak **R**eaction



Parity Violation in Electron Scattering

- Parity operation is a mirror symmetry
  - ❖ flips the sign of spatial coordinates: $\mathcal{P}(x, y, z) \Longrightarrow (-x, -y, -z)$
- Not conserved in weak interactions (Wu Experiment, 1956)
- Scattering of longitudinally polarized electrons from unpolarized targets
- Change electron's helicity to mimic parity operation



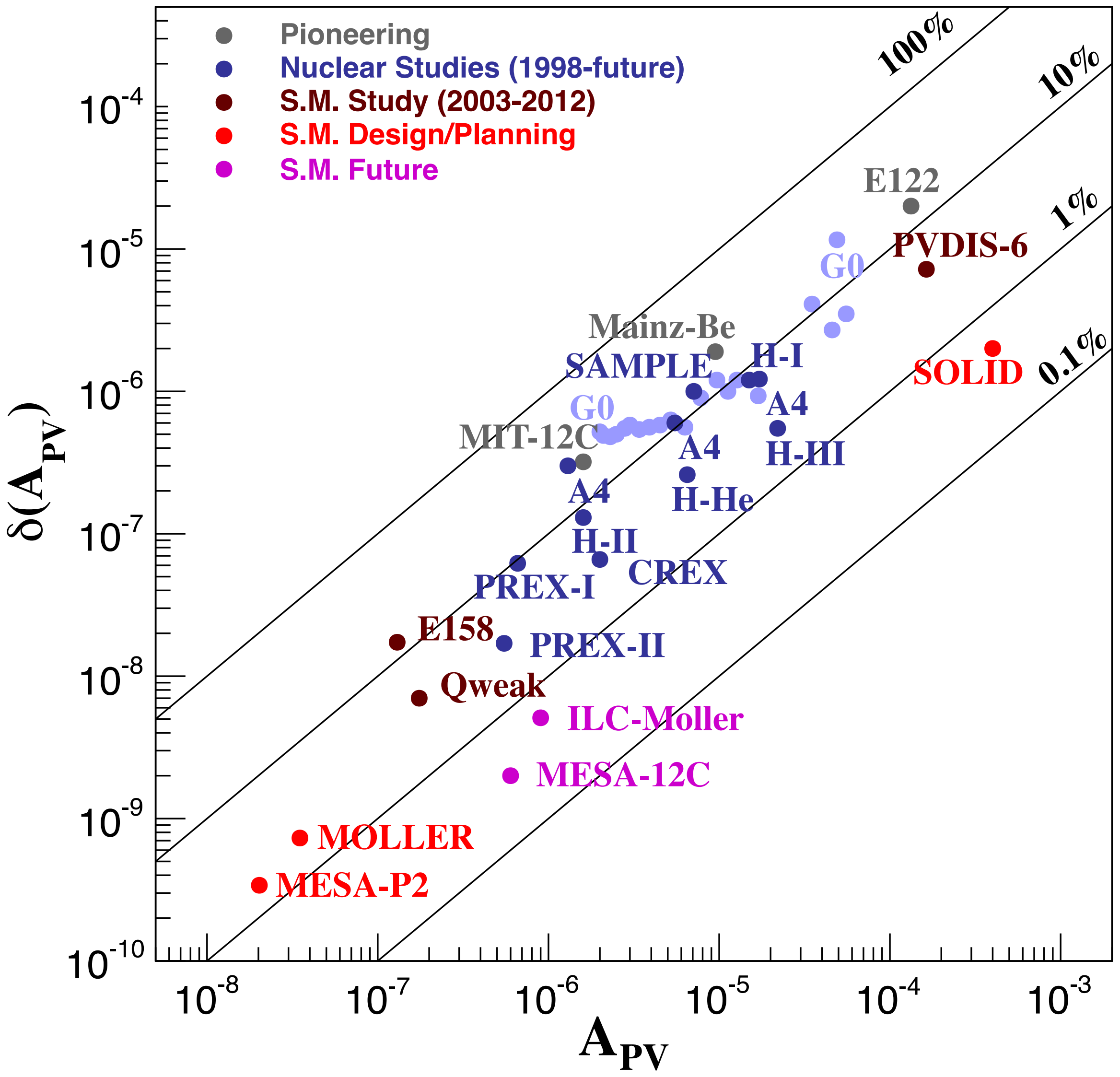
- Parity-violation creates tiny asymmetry (A_{PV}) in the detected flux between the beam's opposite helicity states:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

where $\sigma \sim |\mathcal{M}_\gamma + \mathcal{M}_{Weak}|^2 \rightarrow A_{PV} \approx \frac{2\mathcal{M}_\gamma (\mathcal{M}_{Weak})^*}{|\mathcal{M}_\gamma|^2}$, at $Q^2 \ll (M_{Z^0})^2$, A_{PV} is dominated by the interference between the weak and electromagnetic amplitudes

PVeS Experiments Summary

MØLLER



- E122 – 1st PVeS exp. (late 70's) at SLAC; PVDIS off D_2 target
- E158 – PV in Møller scattering at SLAC (2005)
- Significant improvement over time:
  - ❖ Photocathodes
  - ❖ Polarimetry
  - ❖ Beam stability to nanometer level
  - ❖ Cryotargets
  - ❖ Low noise electronics
  - ❖ Radiation-hard detectors

PVeS has become a precision tool!

- Beyond standard model searches
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

State-of-the-art:

- Sub-part per billion statistical reach and systematic control
- Sub-1% normalization control

Weak Mixing Angle Measurement – *Standard Model Test*

- MOLLER will have a factor of 5 improvement over E158 measurement

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

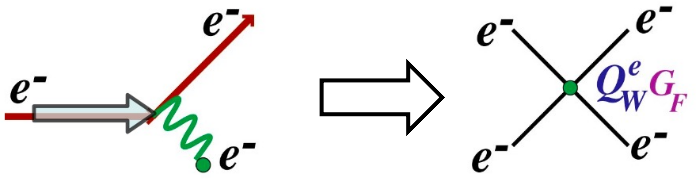
- Measure A_{PV} to an uncertainty of 0.8 ppb to achieve a 2.4% measurement of Q_W^e
- Electron's weak charge at tree level in term of the weak mixing angle:

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

- MOLLER precision:

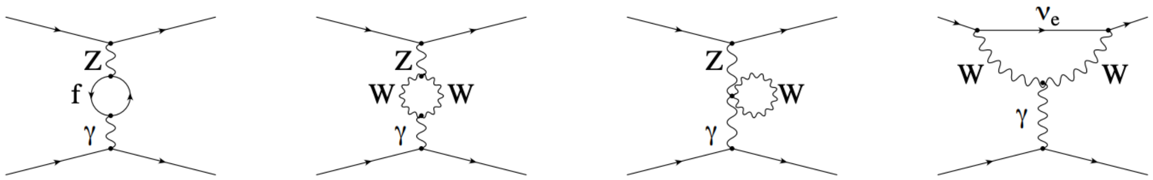
$$\delta(\sin^2\theta_W) = \pm 0.00023\ (\text{stat.}) \pm 0.00012\ (\text{syst.}) \Longrightarrow 0.1\ \%$$

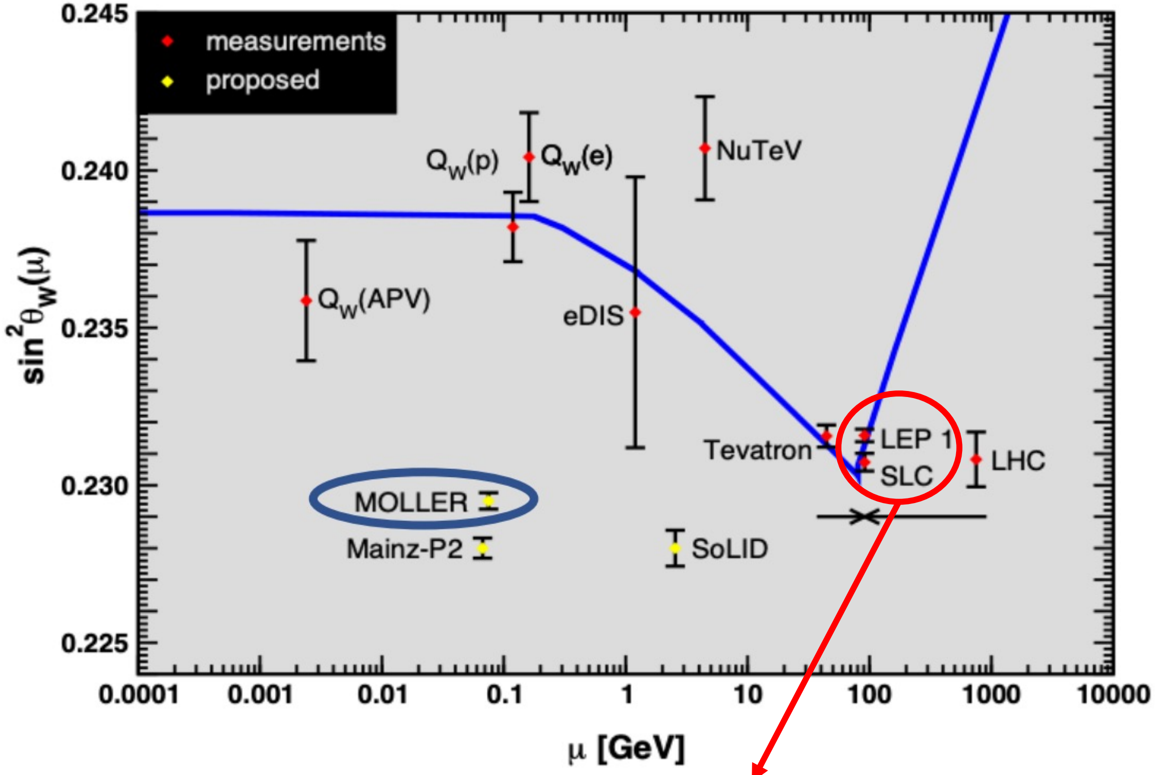
- Interaction Lagrangian:



$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$ Sensitive up to: $\frac{\Lambda}{g} = 7.5$ TeV

Electroweak radiative corrections cause the running of $\sin^2\theta_W$



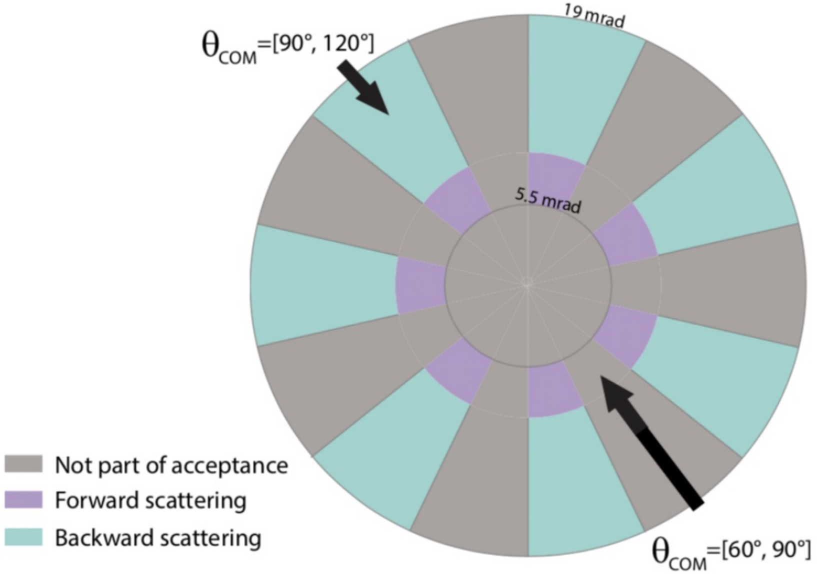


The most precise Z-pole measurements of $\sin^2\theta_W$ differ from each other by ~3σ

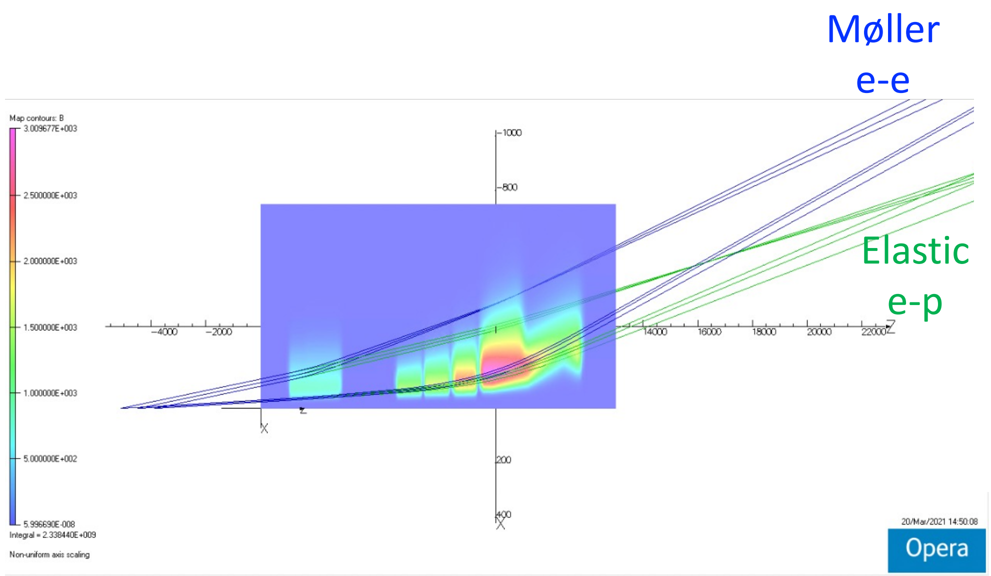
MOLLER Experiment Overview

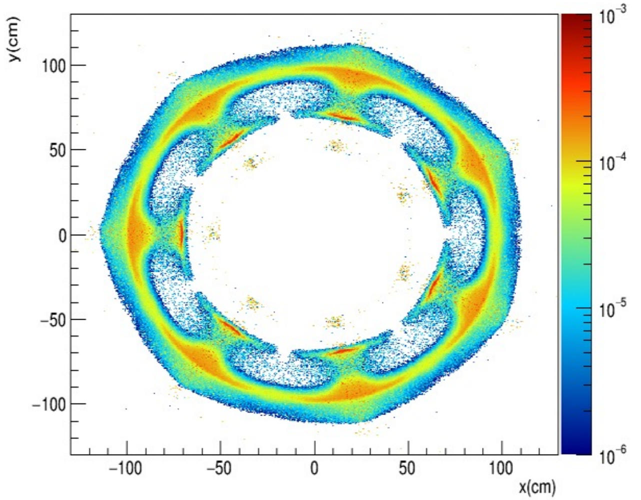
MOLLER

- The experiment's acceptance is determined by a specially designed collimator
  - ❖ Measure only forward or backward scattering in COM frame
- Spectrometer consists of a pair of 7-fold symmetry toroidal magnets
  - ❖ The odd-fold symmetry provides ~100% acceptance due to identical particle scattering
  - ❖ The toroidal magnets use a conventional resistive copper coil design
- The collimation system will protect the magnet coils from high rate, defines signal shape and remove backgrounds



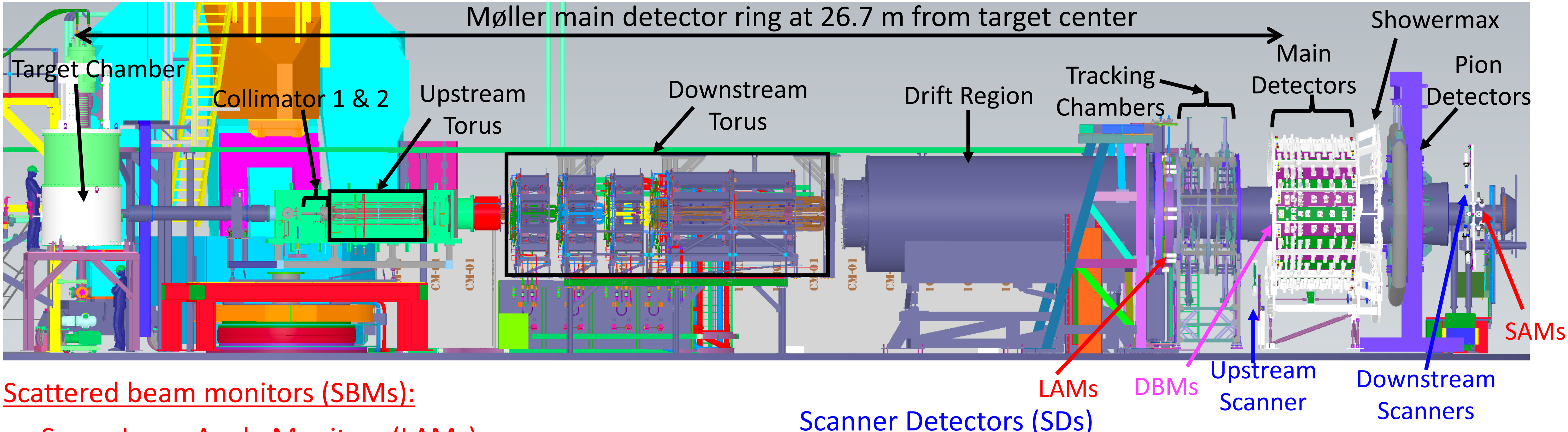
Parameter	Value
E	11 GeV
E'	2 – 9 GeV
θ_{CM}	60° – 90°
Target	125 cm long LH_2
Max. Luminosity	2.4×10^{39} cm^{-2} sec^{-1}
Moller Rate @ 65 μA beam current	134 GHz
Run Time	344 PAC-days
Polarization	≈ 90 %
$< A_{PV} >$	33 ppb





Simulated Møller and ep electron rates

MOLLER Equipment and VT Responsibilities



Scattered beam monitors (SBMs):

- Seven Large Angle Monitors (LAMs)
- Eight Small Angle Monitors (SAMs)
- Integrating Cherenkov detectors
- Sensitive to potential false asymmetry from rescattered background

Diffuse Beam Monitors (DBMs):

- Fourteen DBMs (7 open in sectors and 7 in closed sectors)

Scanner Detectors (SDs)

- One Upstream Scanner
  - Scans in two dimensions
  - Counting and integrating mode Cherenkov detectors
- Four Downstream Scanners
  - Each scanner scans radially in one dimension
  - Integrating Cherenkov detectors

Supported by MOLLER-NSF Midscale Funding Award, VT lead institutions

Large Angle Monitors (LAMs) Requirements

- Large angle, high rate, and small asymmetry
- “Null” asymmetry monitors as a check of helicity-correlated beam correction
- Monitor for potential false asymmetries from rescattered backgrounds
- Accepted flux is dominated by e-p elastic radiative tail
- Total rate gives stat. width ~3.3 x Ring 5 (main physics); smaller (7 vs. 33 ppb) asymmetry

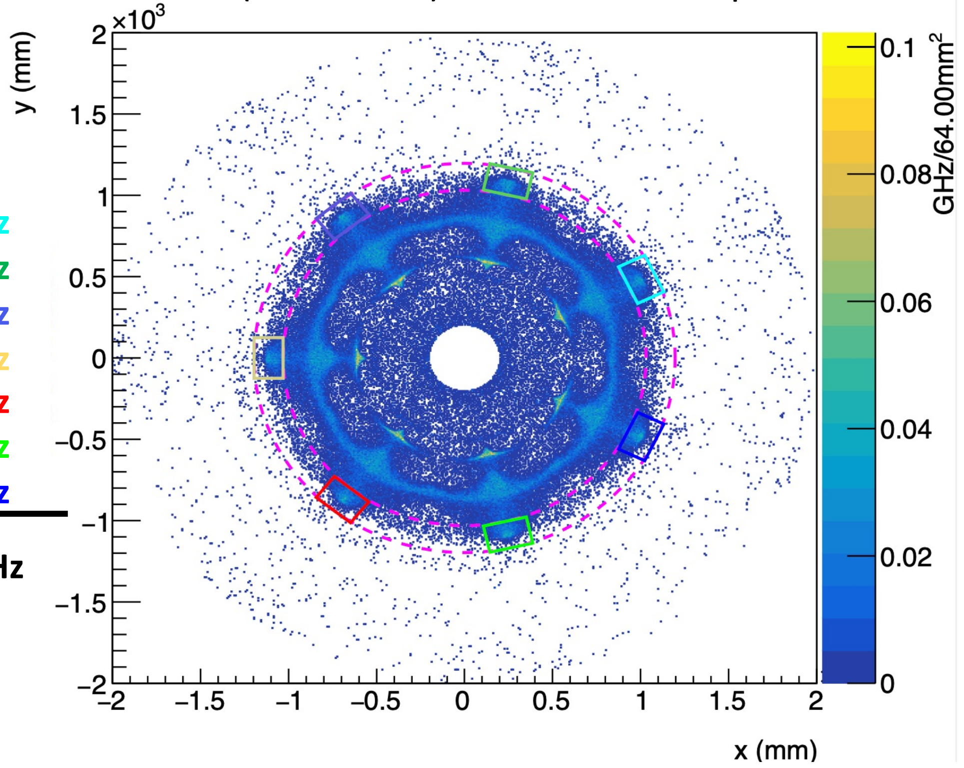
Process	Rate (GHz)	<A> (ppb)	<E> (GeV)
Møller	10.5	10	1.3
Elastic ep	21.2	4	1.1
Inelastic ep	0.1	332	
Total	**31.8**	**7**	

L = 250 mm
W = 165 mm
IR = 1031.5 mm

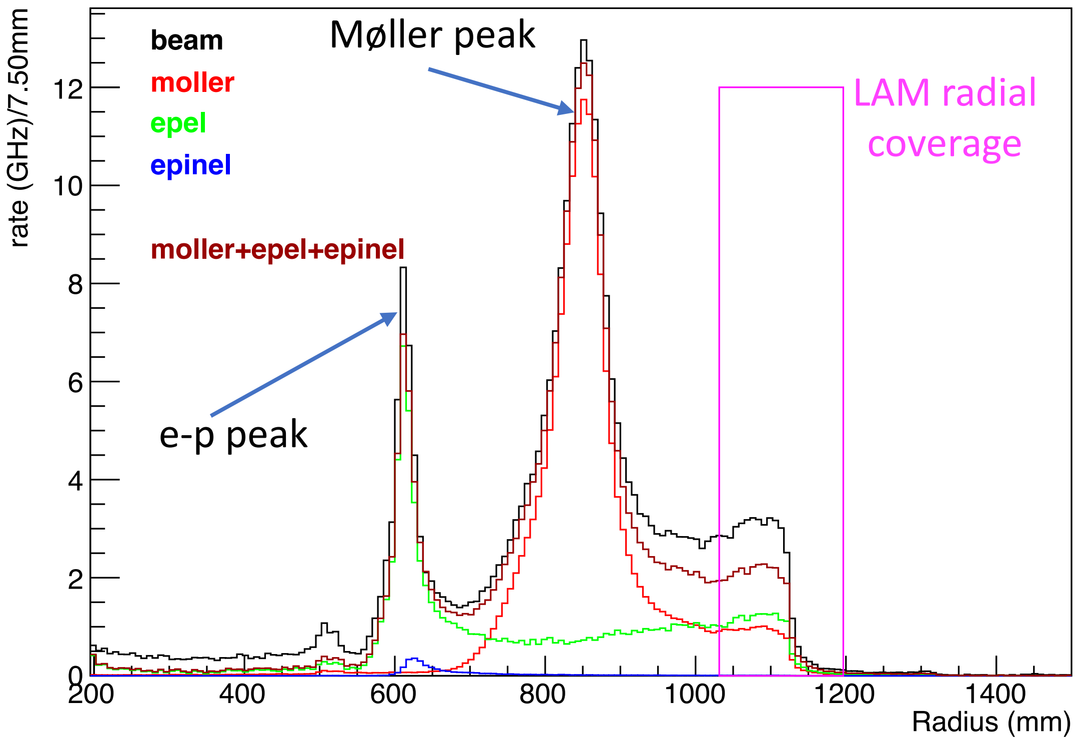
LAM1=4.72 GHz
LAM2=4.50 GHz
LAM3=4.44 GHz
LAM4=4.39 GHz
LAM5=4.40 GHz
LAM6=4.66 GHz
LAM7=4.64 GHz

Total=31.75 GHz

e-/π- (KE>1 MeV) XY dist. on LAM plane

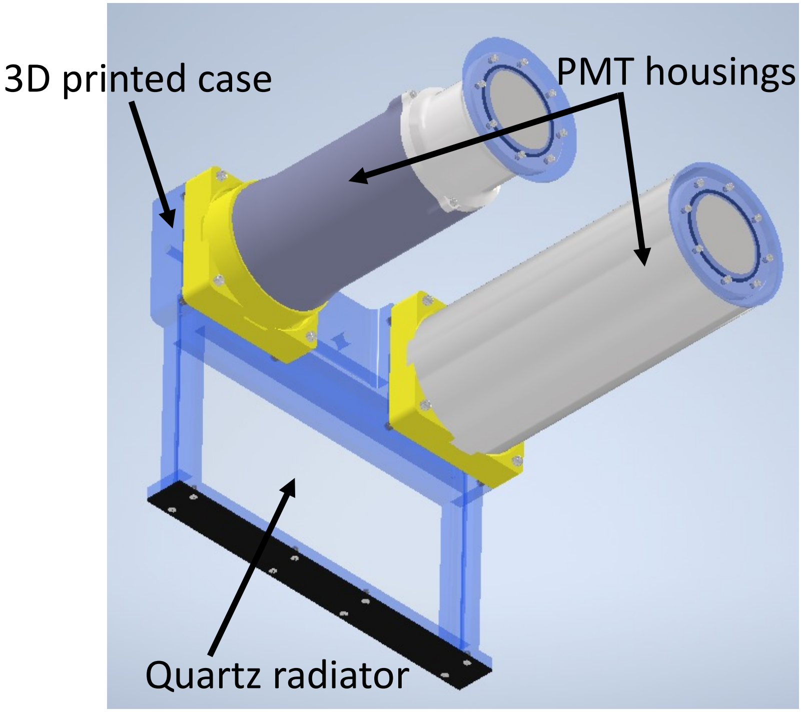


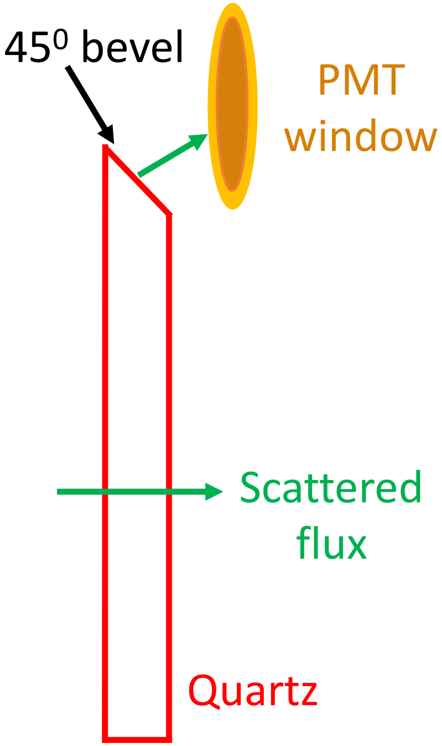
e-/π- (KE>1 MeV) radial dist. at LAM plane

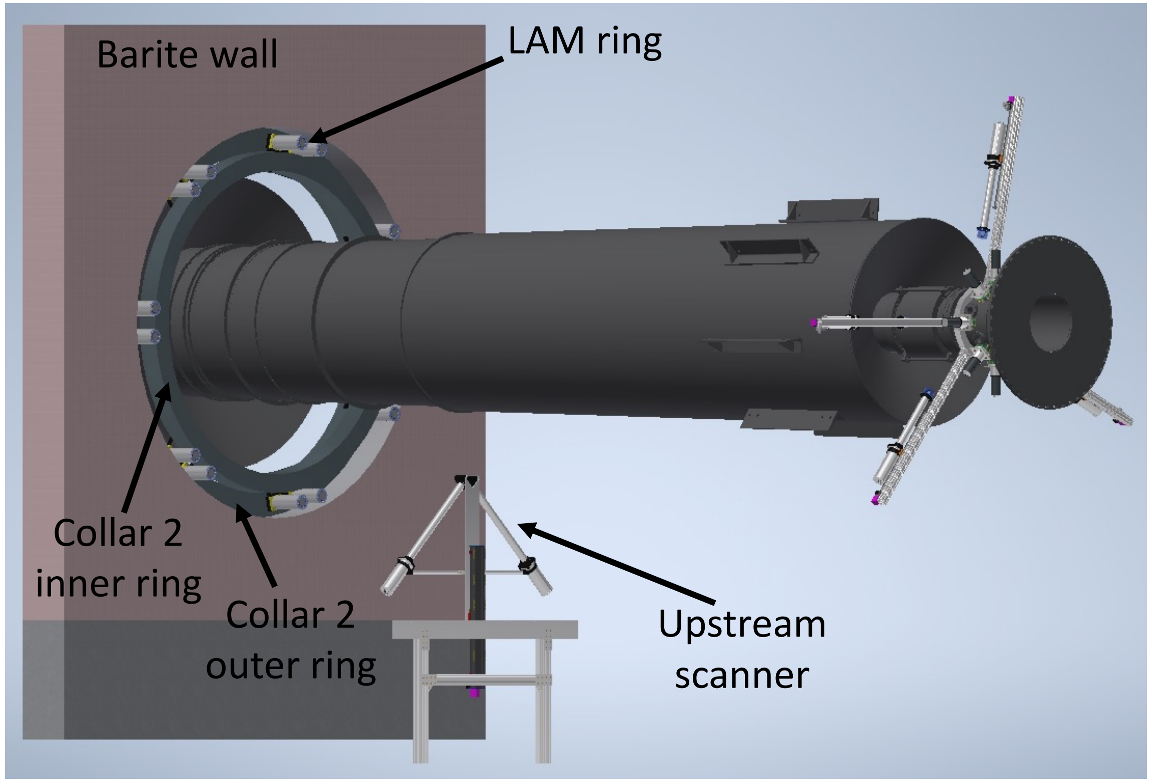


Large Angle Monitors (LAMs) Design

- Seven modules; one in each open sector
- Collar 2 (two Pb rings) blocks particles scattered (mostly secondaries) at large angles
- LAM quartz sits between collar 2 outer and inner rings
- Quartz radiator → 25×16.5×1 cm^3, zero bounce design (no need of lightguide)
- PMTs and bevel part of quartz will be behind the shadow of collar 2 outer ring
- Similar operating conditions as main detector ring 5

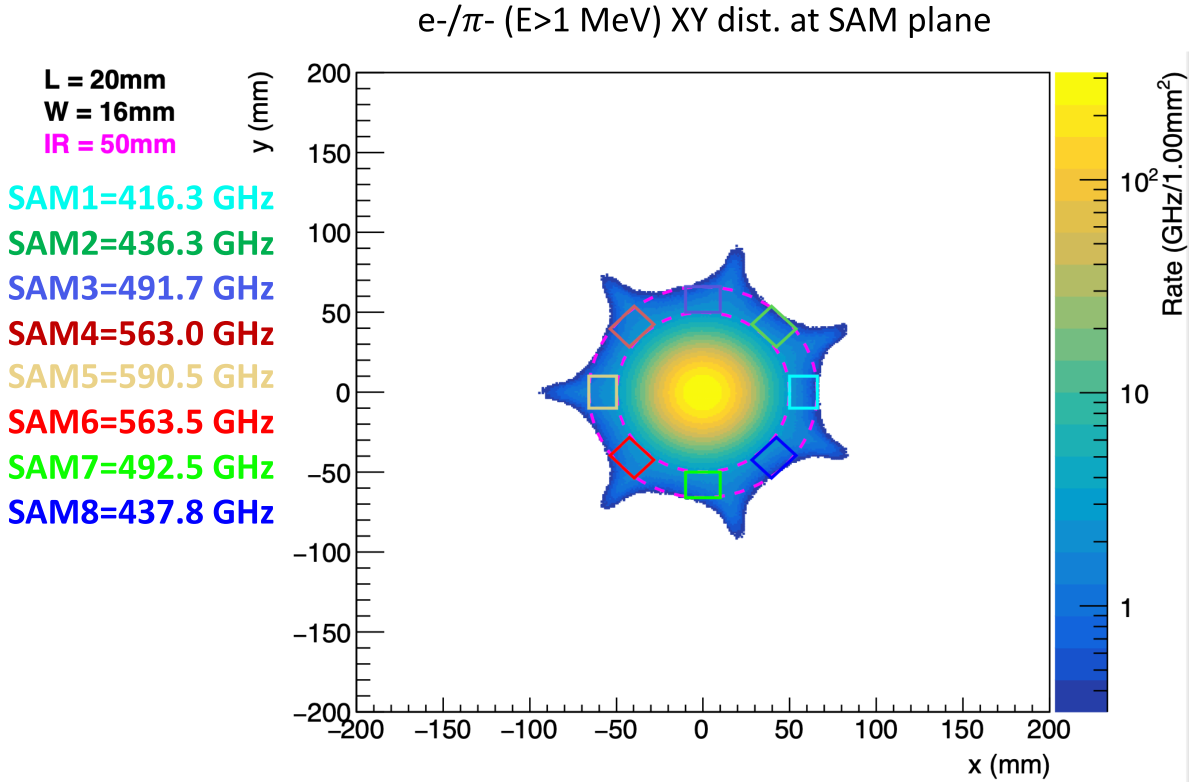


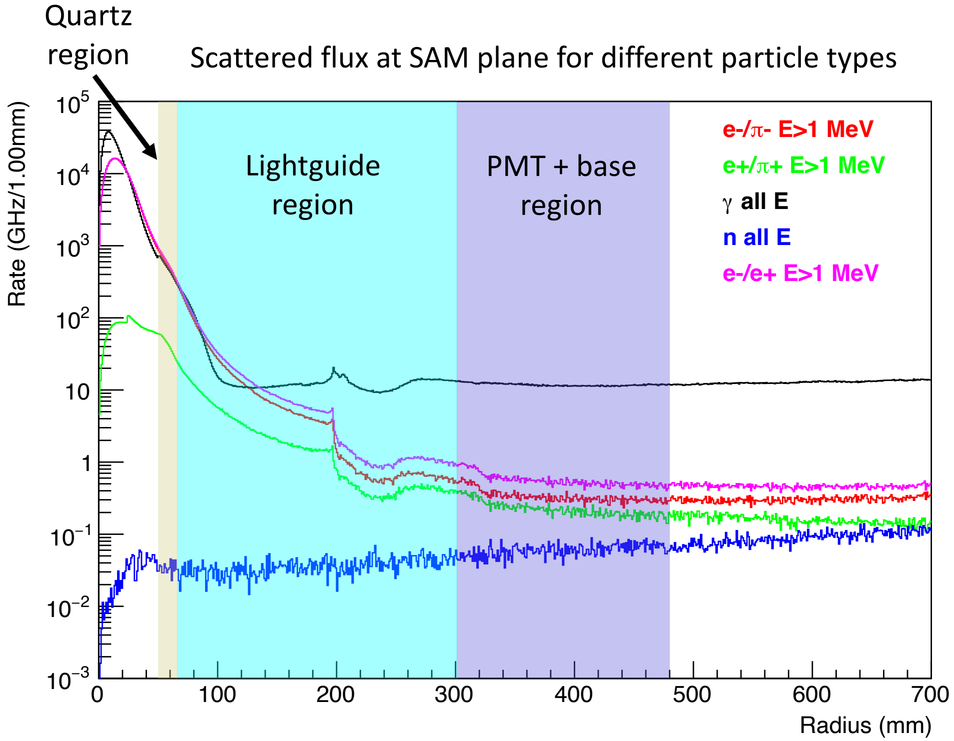




Small Angle Monitors (SAMs) Requirements

- Eight SAMs symmetric around azimuth
- Small lab scattering angle ~0.1^0 (50 mm – 66 mm radial distance)
- High rate ~450 GHz per SAM, rate depends on at with azimuth the SAM is located
- Small asymmetry ~3 ppb, order of magnitude smaller than main Møller asymmetry
- "Null" asymmetry monitors as a check of helicity-correlated beam correction procedure
- Monitor for potential false asymmetries from rescattered backgrounds

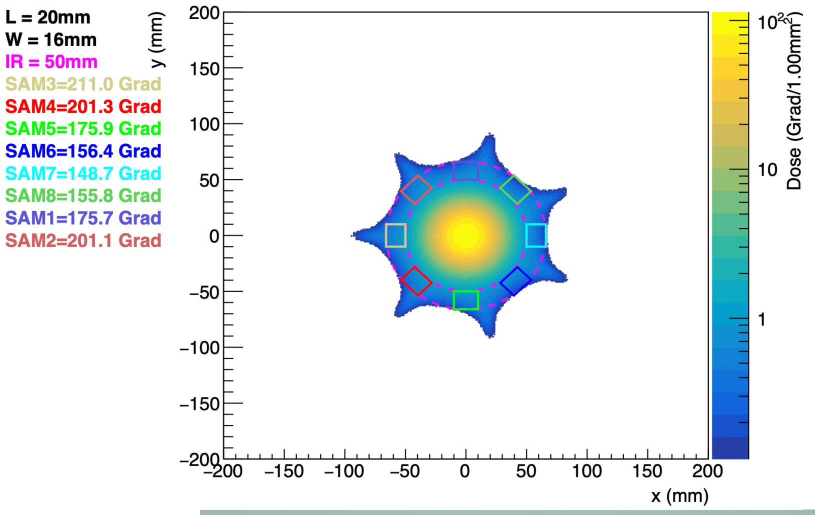


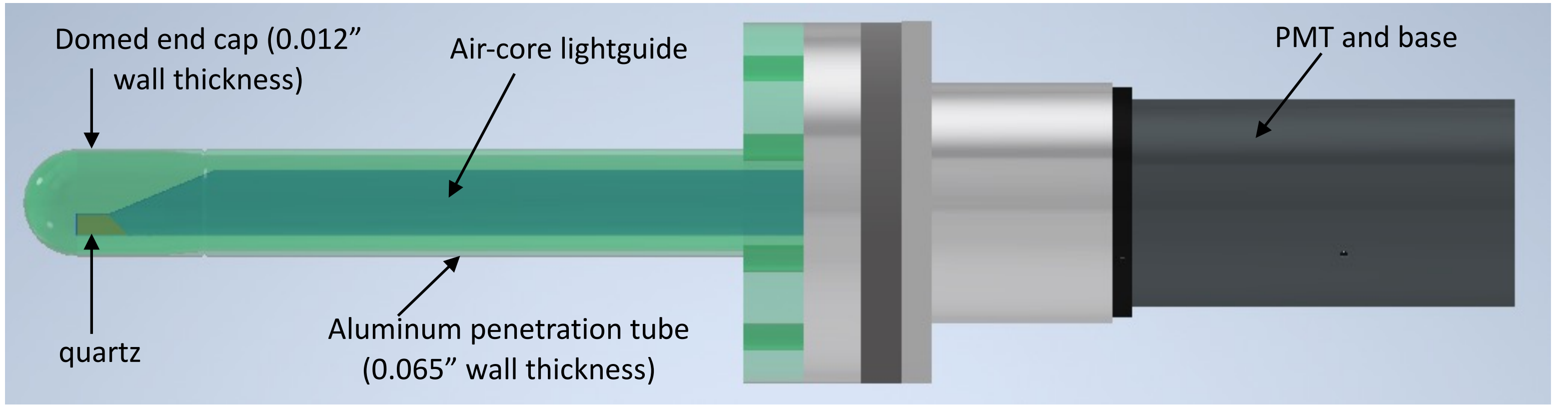


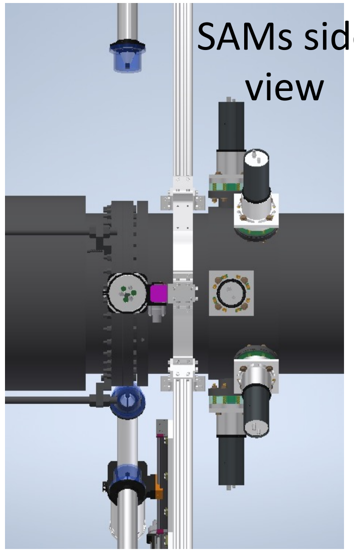
Small Angle Monitors (SAMs) Design and Radiation Damage Concern

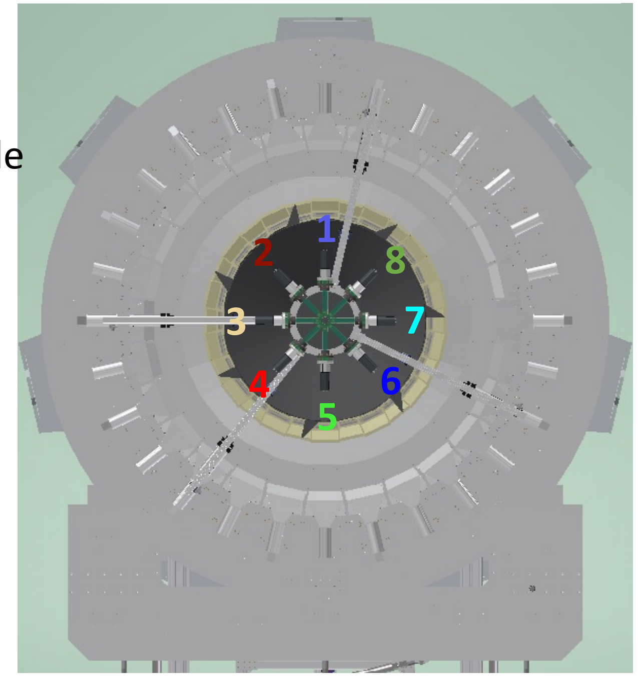
- Small quartz block (1.6 x 2.0 x 0.6 cm^3), air-core light guide, and PMT (Hamamatsu R375)
- Estimated total dose for 8256 hours of production running from simulation
  - ❖ 170 Grad (MIP Energy Deposition method)
- Q_{weak} "SAM" quartz had dose of ~35 Grad with no evidence of damage
- ~57 Grad dose per year for MOLLER production running
  - ❖ New quartz replacement at the beginning of each calendar year can mitigate the risk of damage
  - ❖ PE yield could drop from ~8 PE to ~1 PE and the detectors would still satisfy their requirements

Dose from MIP energy deposition



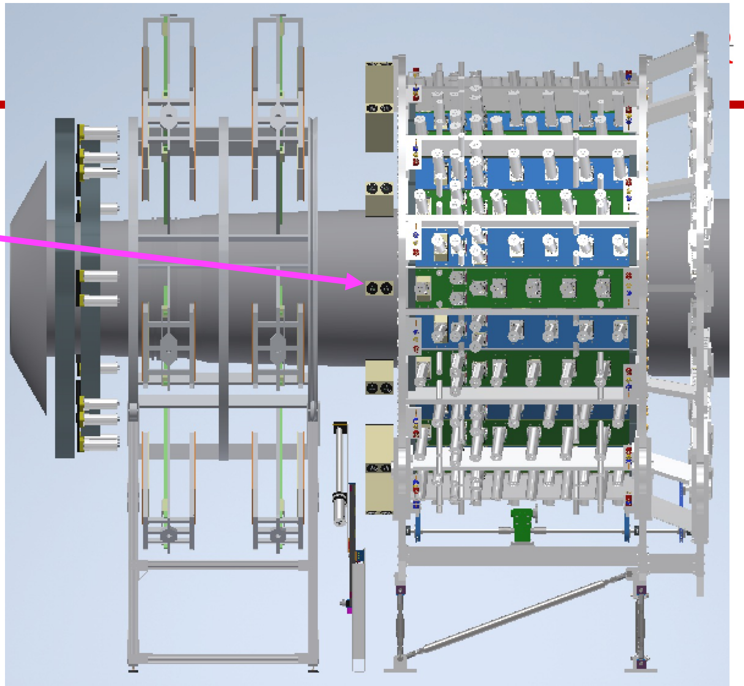


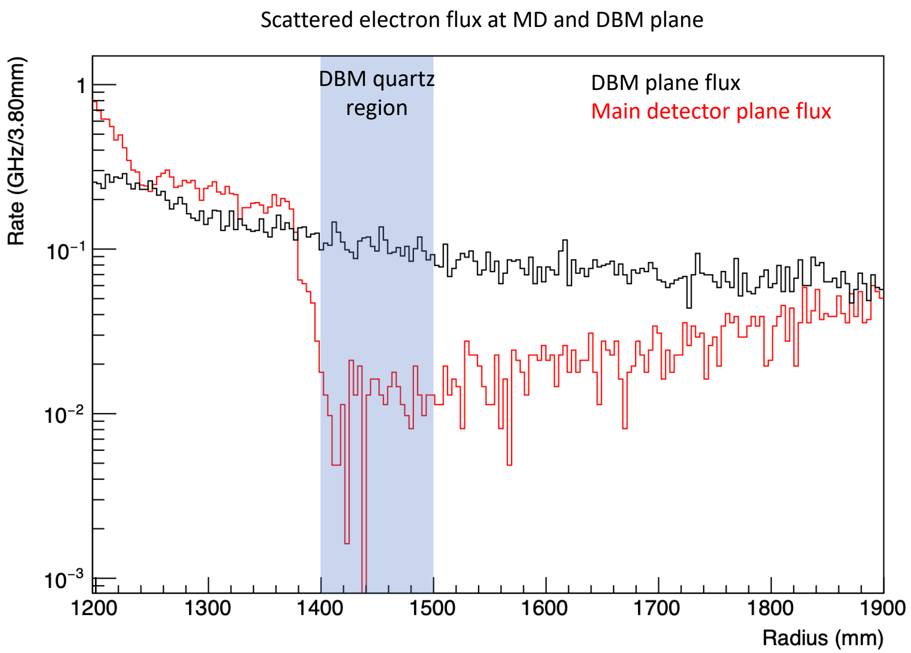


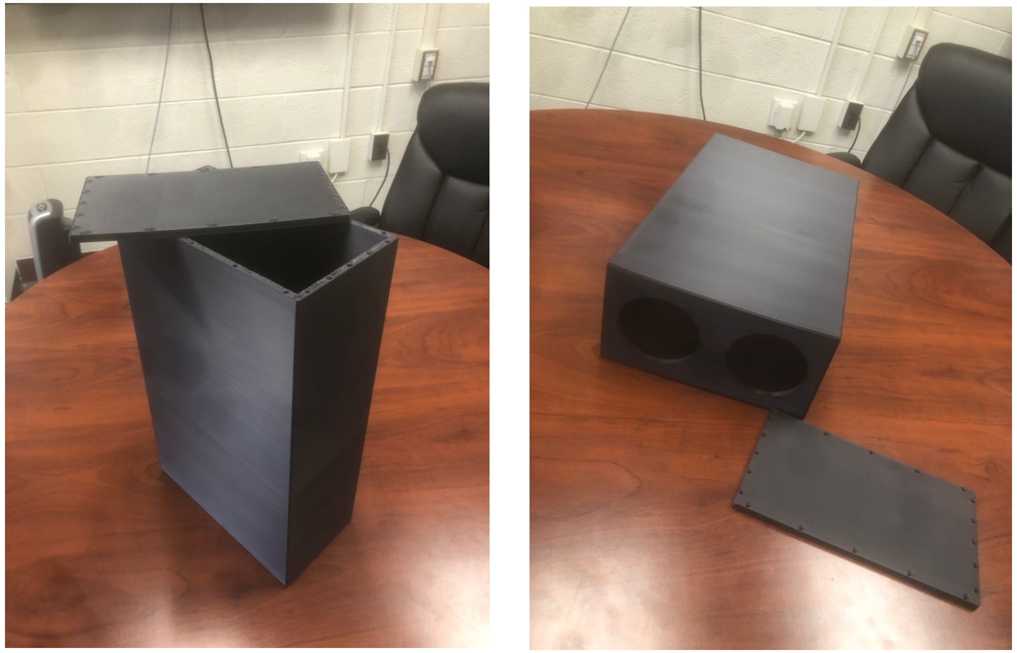


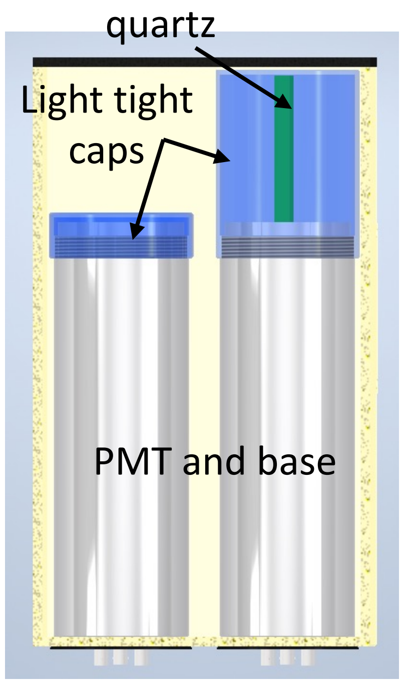
Diffuse Beam Monitors (DBMs)

- The location just upstream of main detector array satisfies the requirements for diffuse beam monitor detectors
- Locate 14 DBM boxes: one bare ET 9305 QKB PMT and one PMT attached to quartz block 10 x 7.1 x 1.0 cm^3 with optical glue in open and closed sectors
- “Shadow” of lead collar 2 will have no flux from primary interactions in target – only secondary diffuse background is observed here
- Rate in each quartz DBM detector ~36 MHz during production running, dominated by secondary interactions





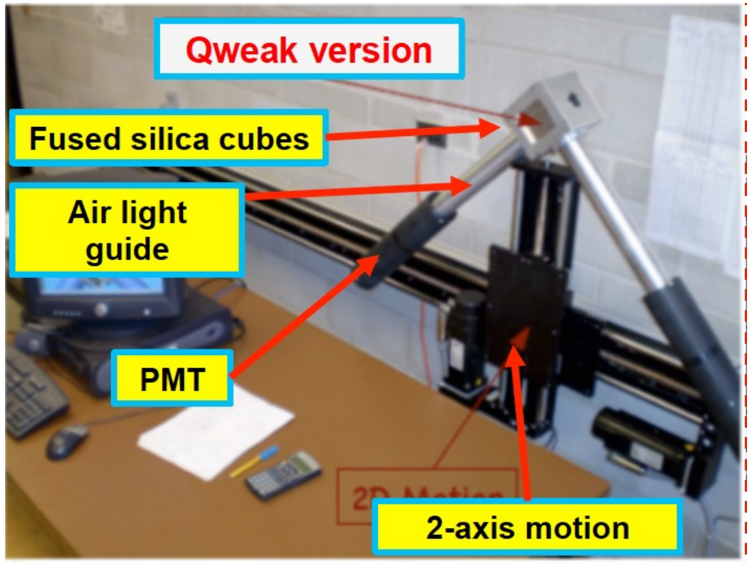


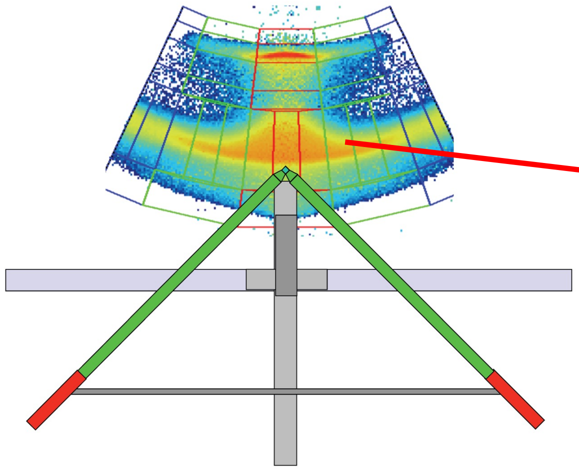


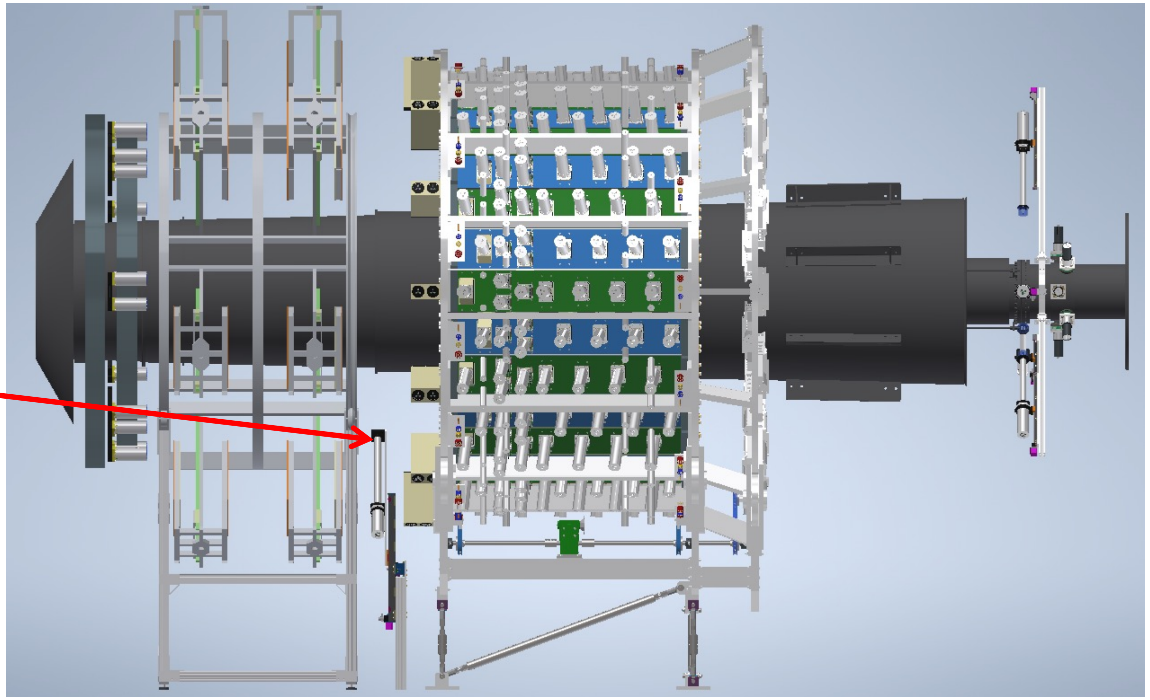
Upstream 2D Scanner Requirements and Goals

MOLLER

- Monitor scattered rate distribution for combination of two sectors at low and high beam currents; verify they are the same; monitor stability of kinematics and backgrounds
- Operates in counting and integrating modes
- Can monitor for shifts ~0.5 mm in the profile, which could happen from a drift of 10^{-3} in the B*dl of the spectrometer field
- Full scan in < 1 hour
- Can provide a more regular (if needed) monitor of the stability of the profile than the full tracking system which will only be deployed every few weeks

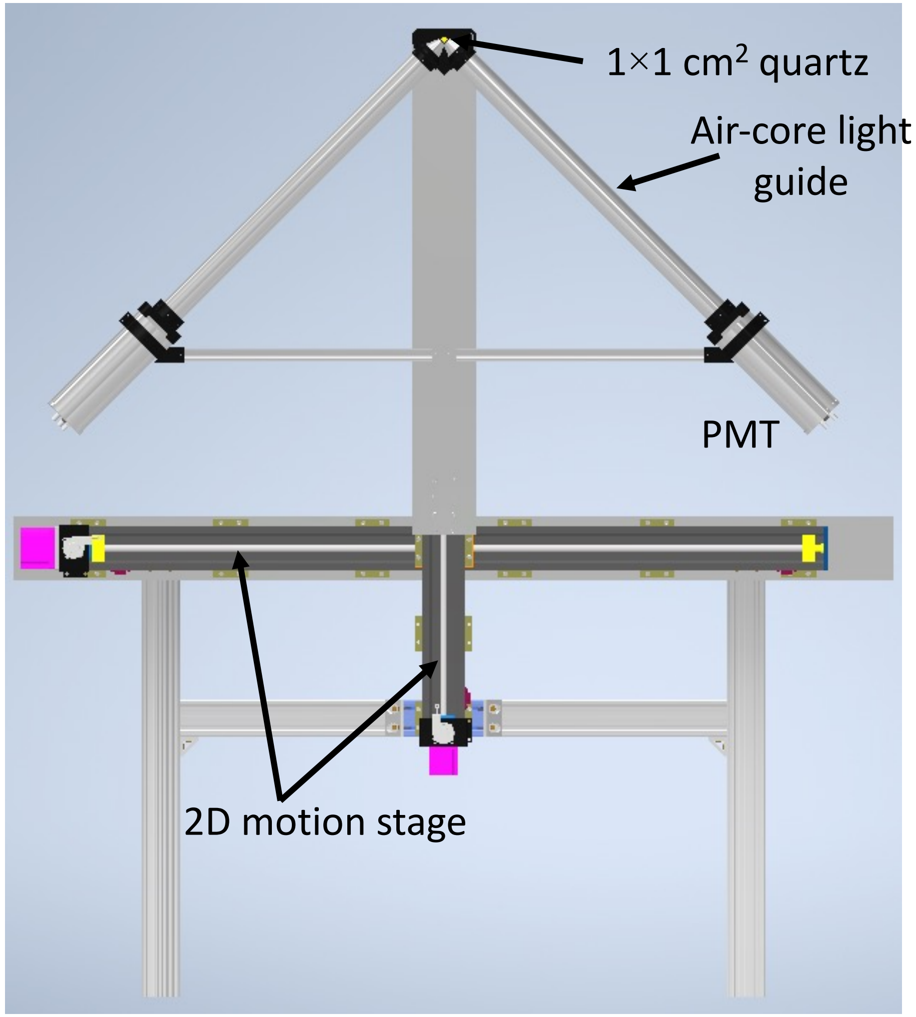


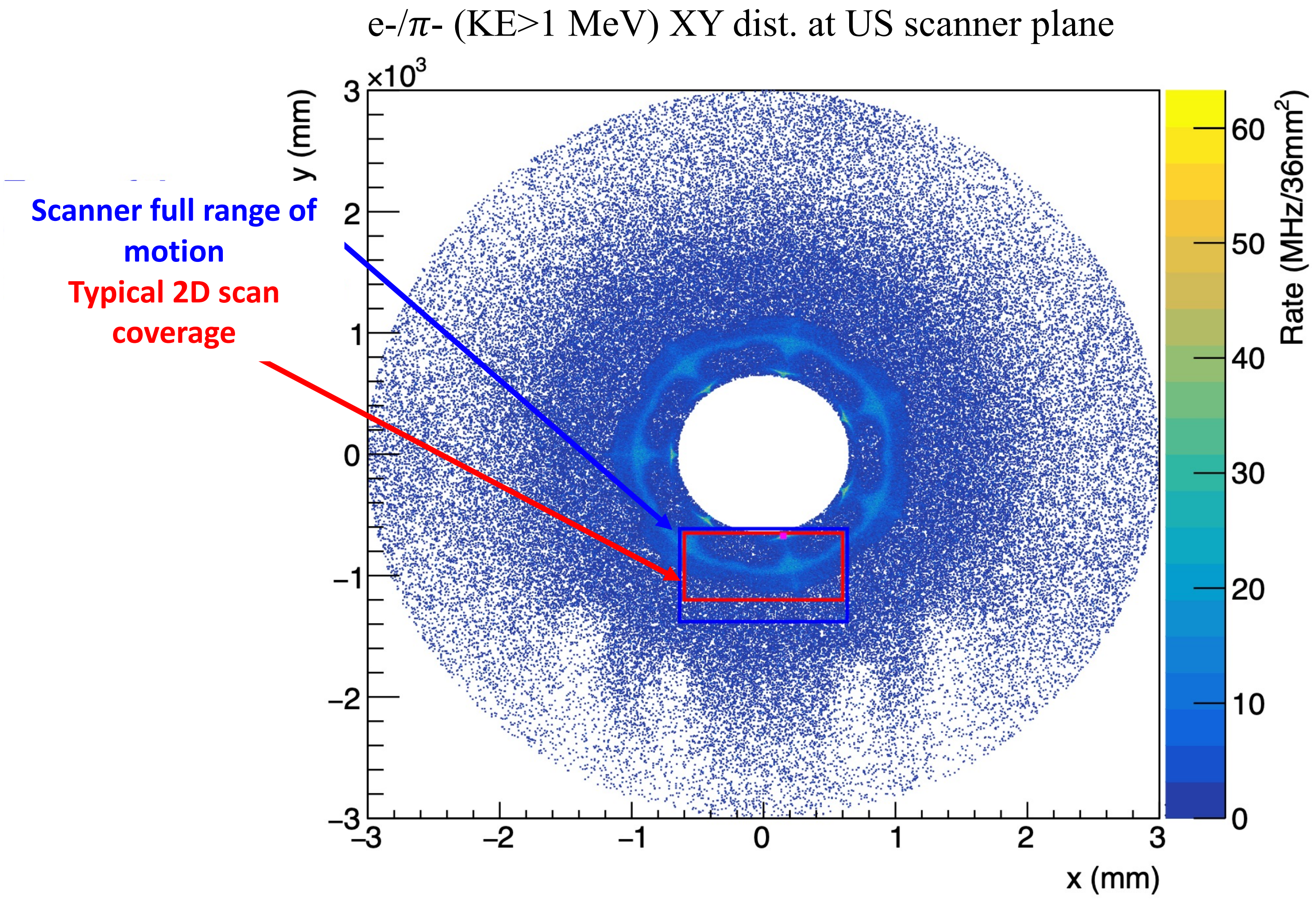




MOLLER

- It uses the concept from Qweak (1×1 cm^2 quartz tile), air-core light guide, and ET 9305 QKB PMT
- Will see a rate up to ~2.62 MHz/μA

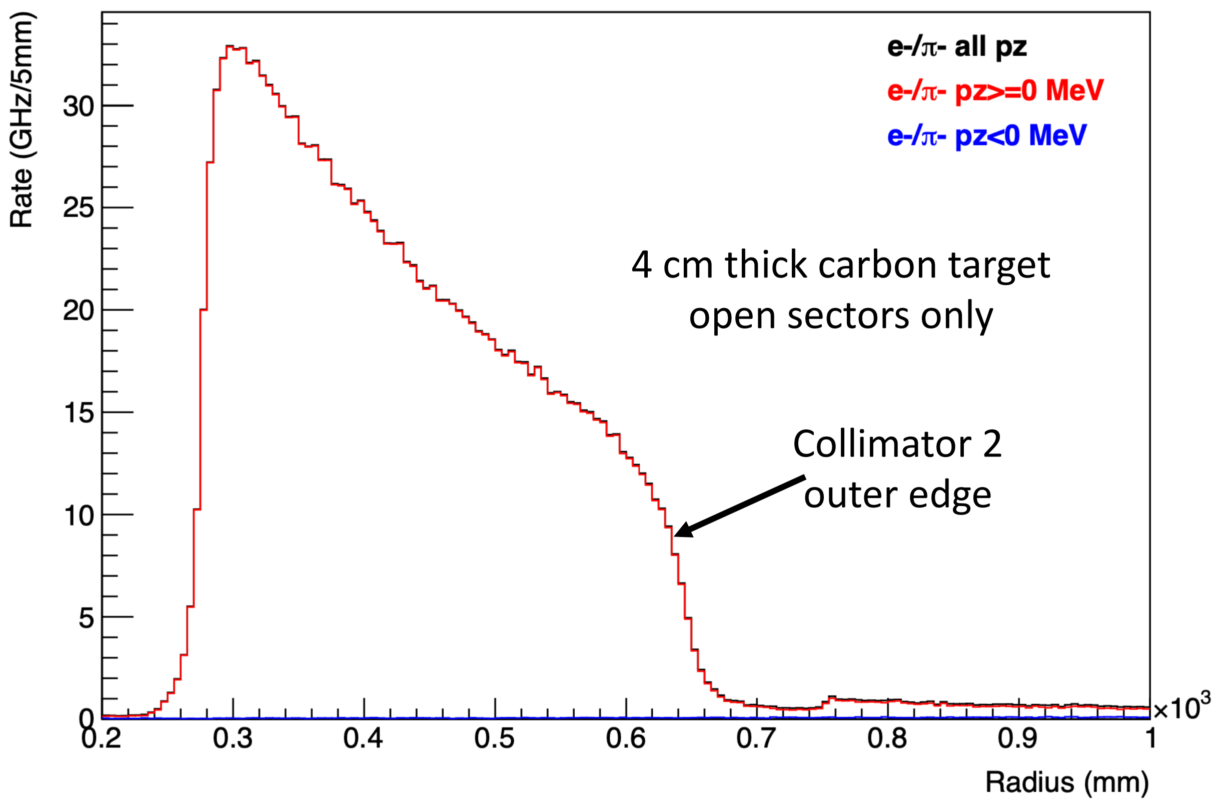




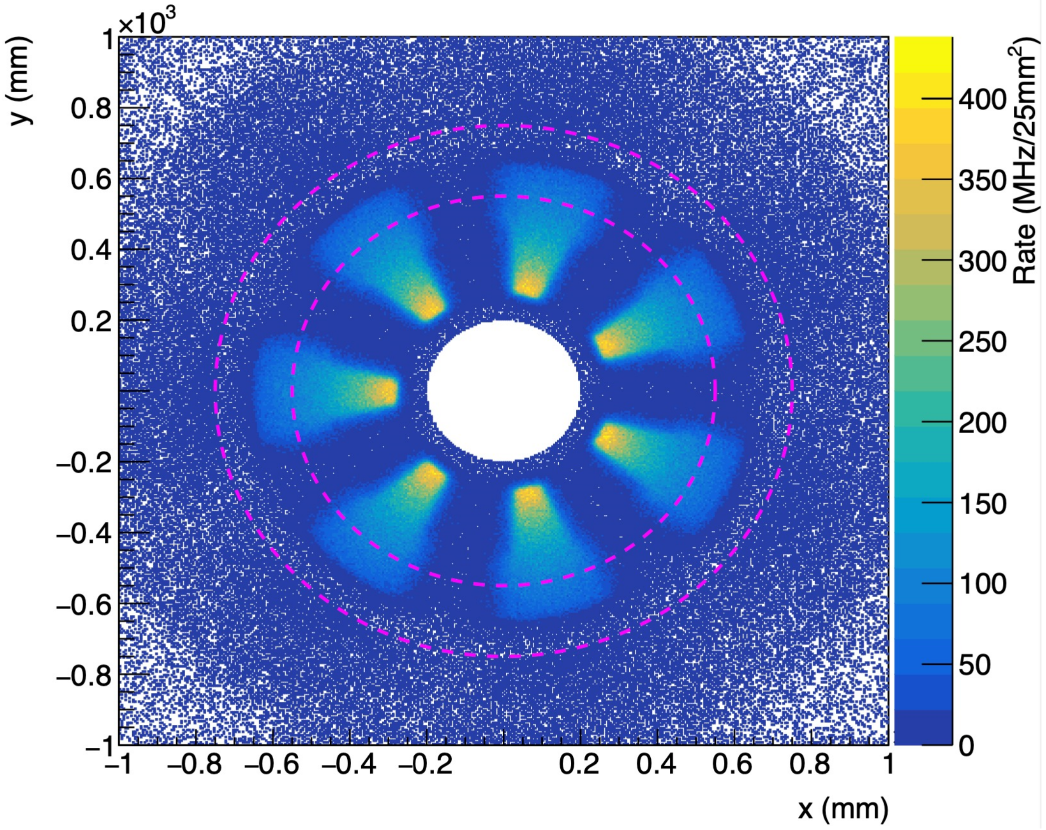
Rate Profile in Downstream Linear Scanners

- Four 1-D scanners scan radially 55 – 75 cm at four azimuthal locations (just upstream SAM Z-location)
- Use magnet off spectrometer with thick carbon target
- Expected to pick off the outer edge of collimator 2 (acceptance defining collimator)
- Sharp transition of e-/ π- rate around 650 mm radius is due to the acceptance defining collimator (collimator 2) cutoff

e-/π- (KE>1 MeV) radial dist. at DS scanner plane

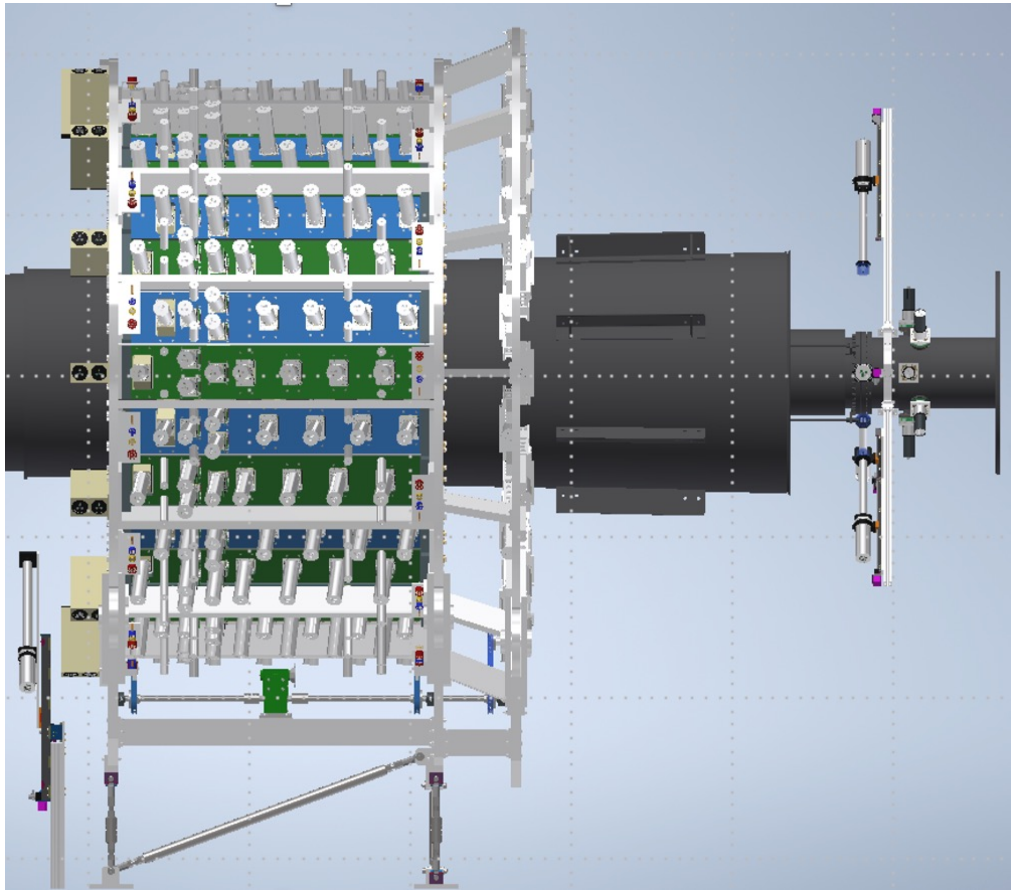


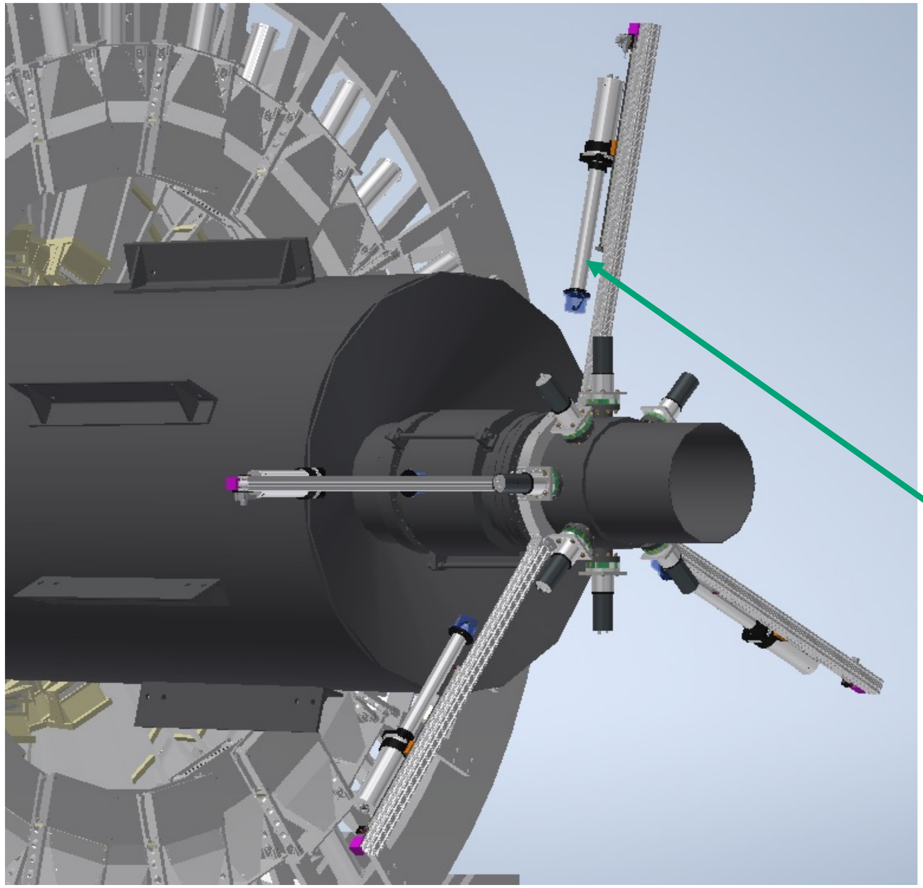
e-/π- (KE>1 MeV) XY dist. at DS scanner plane

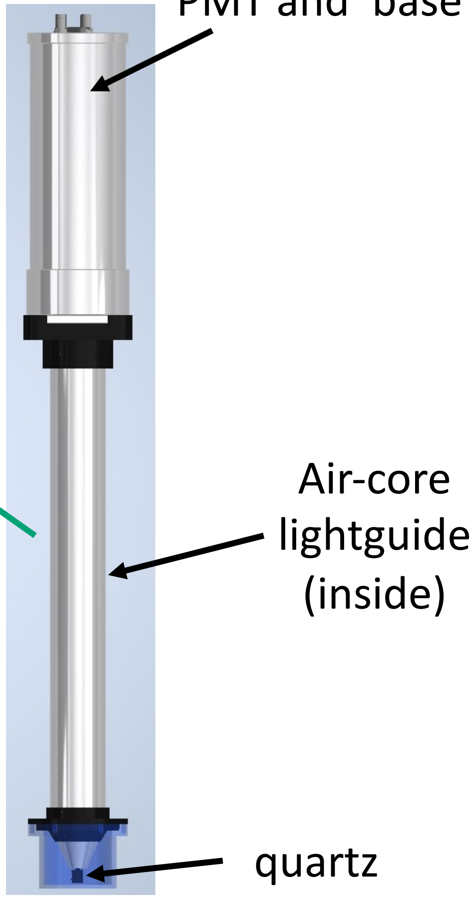


Downstream Linear Scanner Design

- It uses 1×1 cm^2 quartz tile
- Air-core lightguide and ET 9305 QKB PMT (3-inch diameter window)
- Velmex sliding motion stage for linear motion
- Will be parked at larger radii when not in use

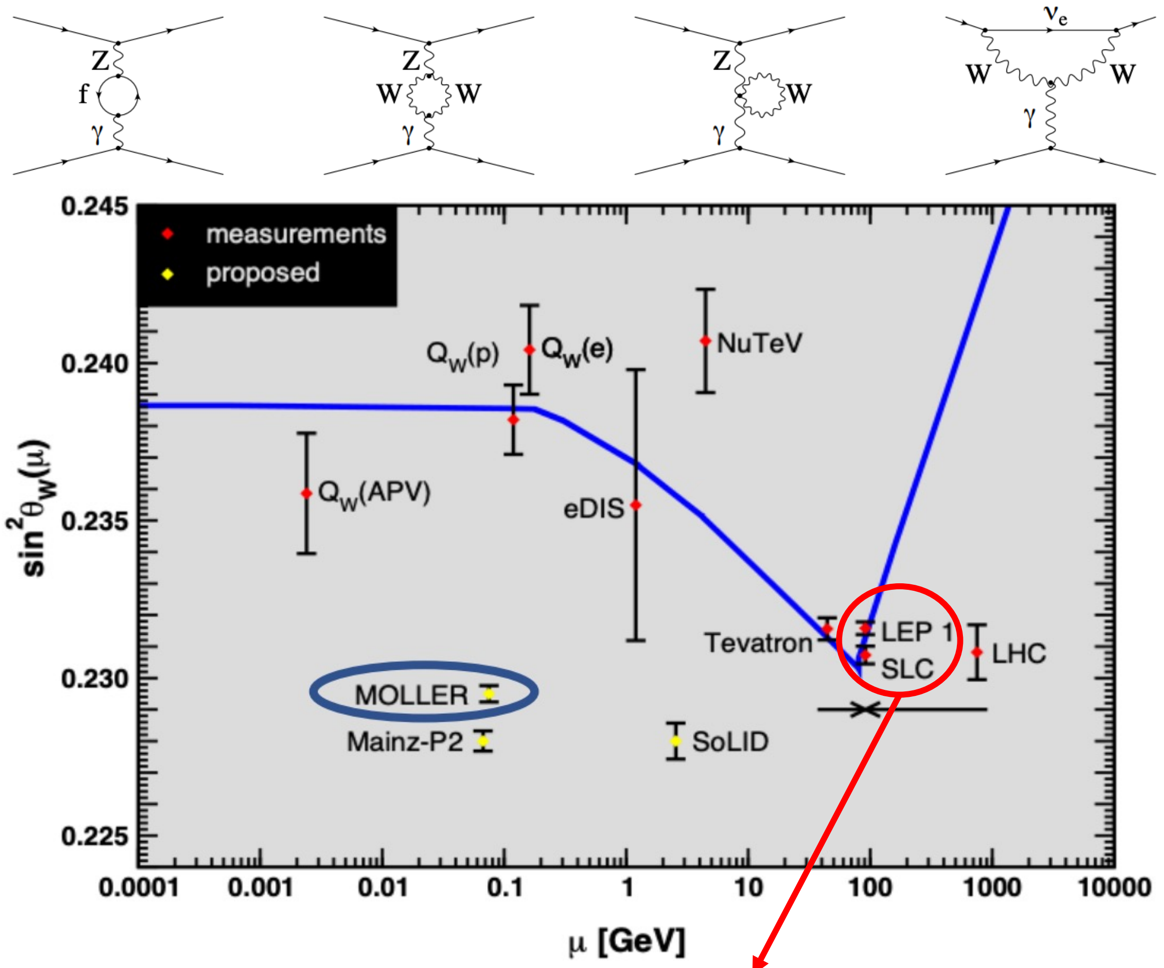






- The MOLLER experiment will use PVeS to search new dynamics
  - ❖ 0.1% precision on $\sin^2_{\theta_W}$
- Currently working prototype testing; construction will begin soon (2024)
- CD-3A Approval in March 2023
- CD-2/3 Director's Review in August 2023
- CD-2/3 Independent Project Review in October 2023
  - ❖ anticipate approval in March 2024
- VT is responsible for design, construction, and operation of various scattered beam monitors and scanners
  - ❖ Prototype detectors were tested at MAMI beam facility
  - ❖ Production of final detectors will take place over the next few months

Electroweak radiative corrections cause the running of $\sin^2\theta_W$



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

MOLLER Experiment History and Current Status

MOLLER collaboration: ~160 authors, 37 institutions, 6 countries; Spokesperson: K. Kumar, U. Mass, Amherst

- JLab PAC approval Jan. 2009, JLab Director's review January 2010
- JLab PAC37 Ranking/Beam Allocation January 2011 (A rating, 344 PAC days)
- Strong endorsement from DOE Science Review in Sept. 2014
- Second Director's Review in December 2016
- DOE CD-0 status achieved in December 2016; paused in January 2017
- Project team formed in January 2019
- Director's Review in April 2019 – Technical Readiness, Risk, Cost
- Director's Review in January 2020
- CD-1 Director's Review in August 2020
- DOE MOLLER CD-1 Independent Project Review, October 2020
- MOLLER-NSF Midscale Technical and Cost Review, October 2020
- MOLLER CD-1 Approved in December 2020
- MOLLER-NSF Midscale Funding Awarded, February 2021, VT lead institution
- DOE OPA IPR Annual Review, November 2021
- CD-3A Approval in March 2023
- CD-2/3 Director's Review in August 2023
- MOLLER CD-2/3 Independent Project Review in October 2023, anticipate CD-2/3 Approval in March 2024

MOLLER Equipment and VT Responsibilities

Scattered beam monitors (SBMs):

- Seven Large Angle Monitors (LAMs)
- Eight Small Angle Monitors (SAMs)
- Integrating Cherenkov detectors
- Sensitive to potential false asymmetry from rescattered background

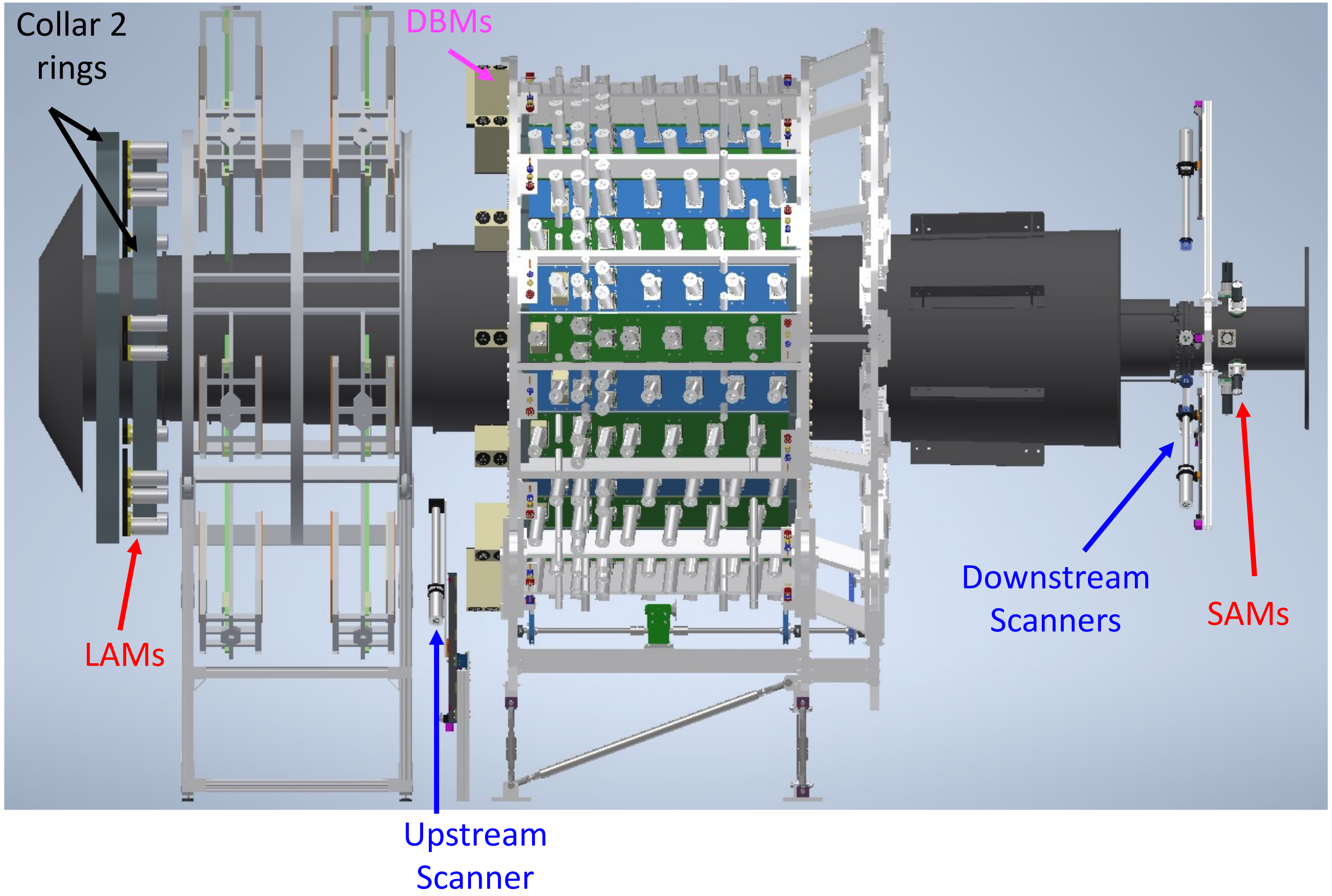
Diffuse Beam Monitors (DBMs):

- Fourteen DBMs (seven bare PMTs and 7 PMTs plus quartz)

Scanner Detectors (SDs)

- One Upstream Scanner
  - ❖ Scans in two dimensions
  - ❖ Counting and integrating mode
- Four Downstream Scanners
  - ❖ Each scanner scans radially in one dimension
  - ❖ Integrating mode

MOLLER detector CAD

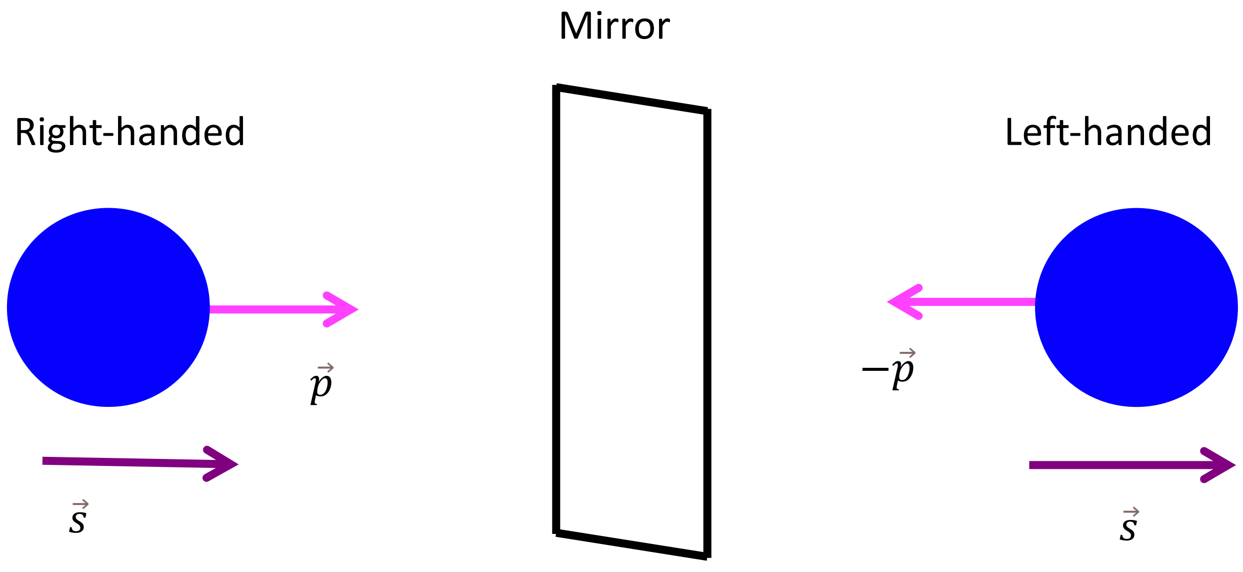


Parity Operation and it’s Violation in Electron Scattering

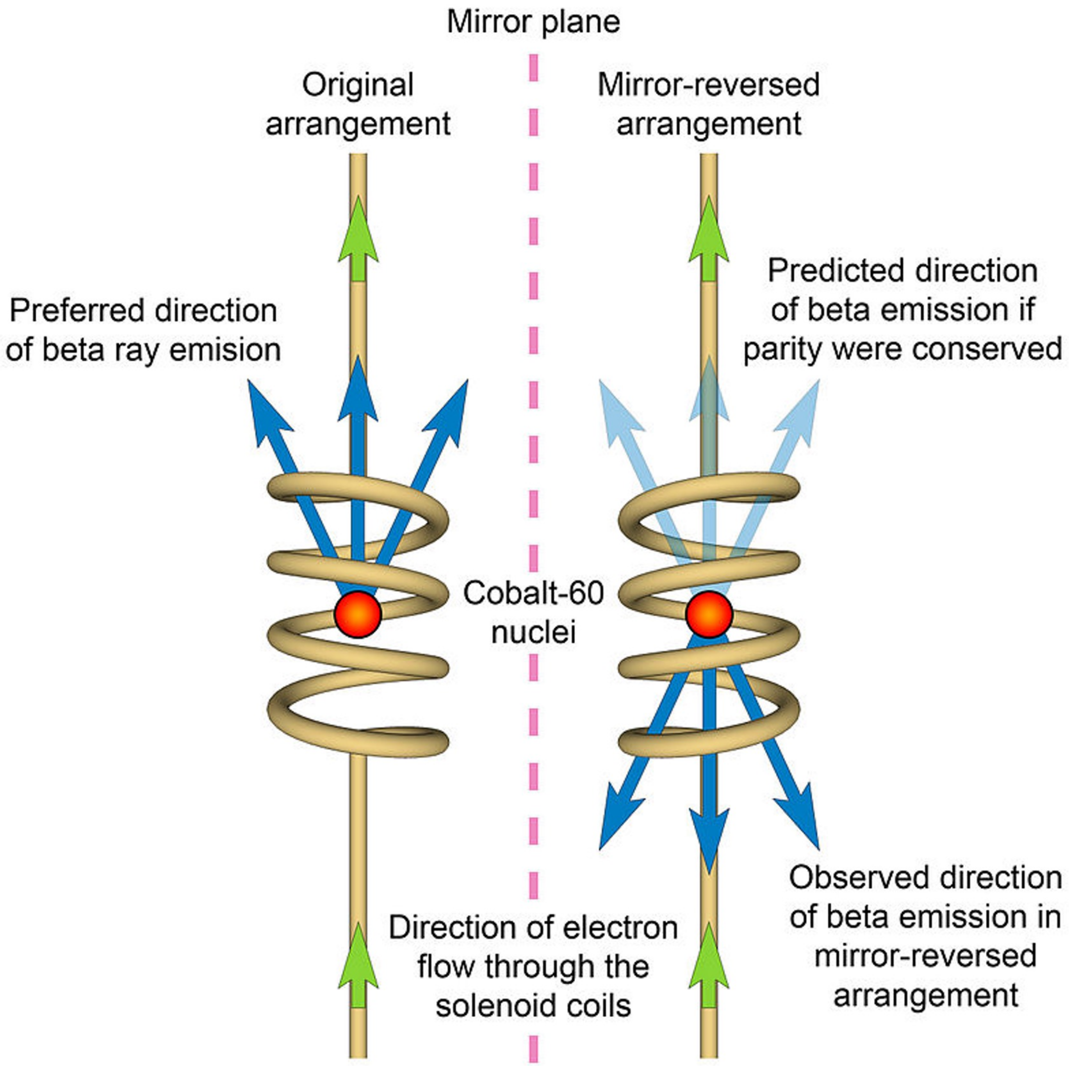
- Mirror symmetry → inversion of spatial coordinates:

$$\mathcal{P}(x,y,z) \Longrightarrow (-x,-y,-z)$$

- Not conserved in weak interactions
- Parity operation is same as changing helicity
  - ❖ change electron’s helicity to mimic parity operation
- Parity-violation creates tiny asymmetry (A_{PV}) in the detected flux



$h = \vec{s}\cdot\hat{p} \ = +s$ Parity operation $h = \vec{s}\cdot(-\hat{p}) \ = -s$



Wu Experiment (1956)
The first experimental observation of parity-violation in weak interaction