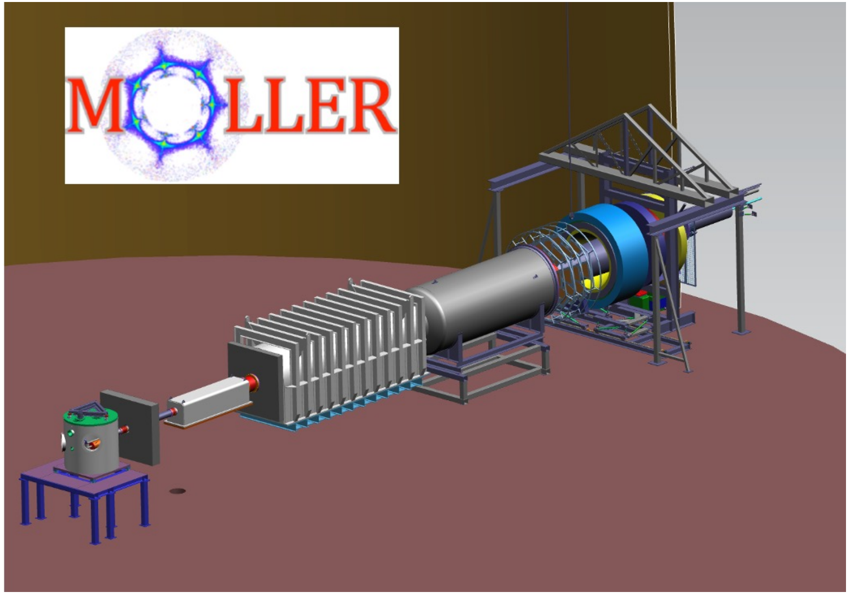
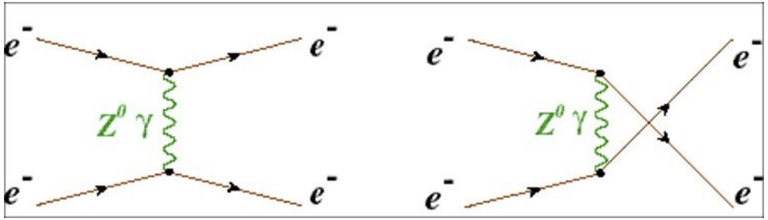
The MOLLER Experiment



David S. Armstrong

William & Mary

for the MOLLER Collaboration



CAP Annual Congress
Hamilton ON, June 7 2022

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

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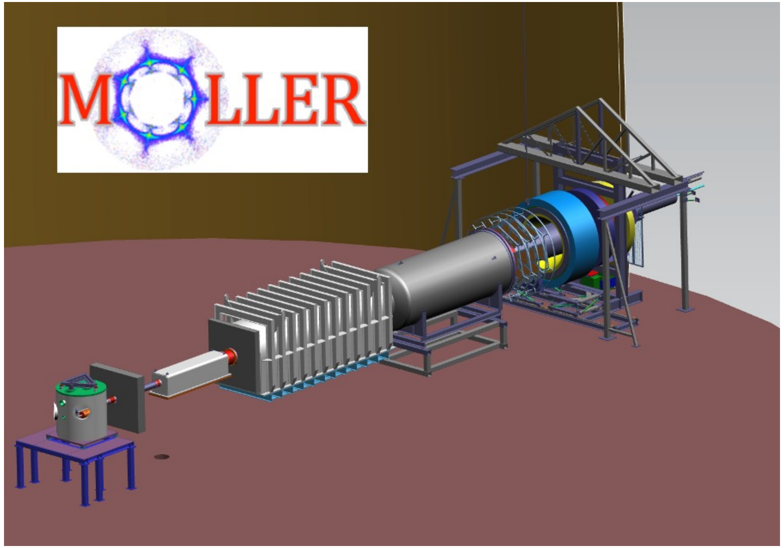
Overview

MOLLER: Measurement of a Lepton Lepton Elastic Reaction



1. The MOLLER Measurement
    - The observable and the experimental goal

2. The Science Case

3. The Experimental Technique:
    - Parity-violating electron scattering (PVES) asymmetry measurements
    - Unique Capabilities of 11 GeV Beam Delivery at Jefferson Laboratory
    - Experimental Design

4. The MOLLER Collaboration, schedule

Physics Context – Precision Low-energy physics

- Received Wisdom: Standard Model is incomplete: low-energy effective theory of more fundamental physics
- Low energy ($Q^2 \ll M^2$): Precision Frontier

  complementary to Energy Frontier measurements (LHC)

- ***Neutrino masses and role in the early universe*** $0\nu\beta\beta$ *decay*, θ_{13}, β *decay,…*
- ***Matter-antimatter asymmetry in the present universe*** *EDM, DM, LFV,* $0\nu\beta\beta$, θ_{13}
- ***Unseen Forces of the early Universe*** *Weak decays,* ***PVES****,* g_μ*-2,…*

Any LHC new physics signals likely will need additional indirect measurements to pin down their nature

- ***Neutrons:*** *Lifetime, P- & T-Violating Asymmetries* *[LANSCE, Grenoble, NIST, SNS…]*
- ***Muons:*** *Lifetime, Michel parameters, g-2, Mu2e* *[PSI, TRIUMF, FNAL, J-PARC…]*
- ***Atoms:*** *atomic parity violation*

- ***PVES:*** *Low-energy weak neutral current couplings, precision weak mixing angle*

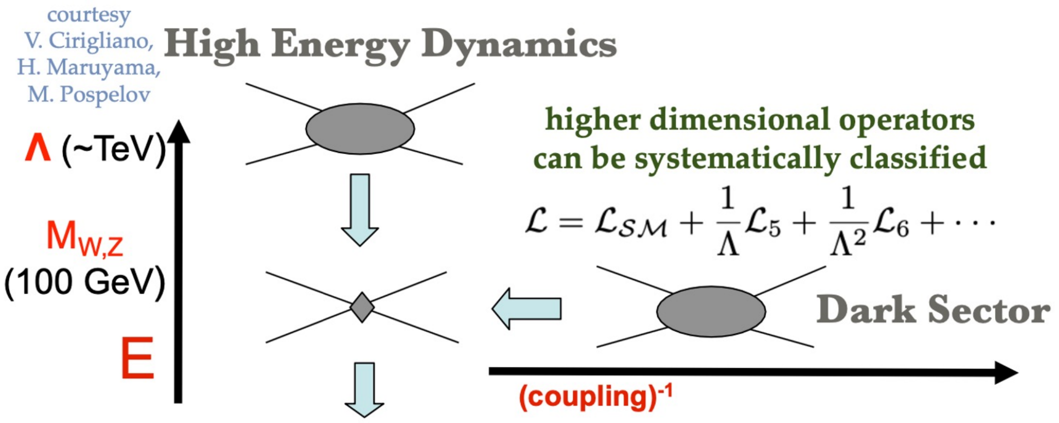
  [SLAC, Jefferson Lab, Mainz]

Idea - *select observables that are:*

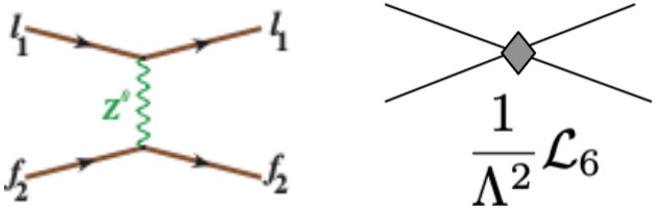
1) zero, or significantly suppressed, in Standard Model

2) Robust predictions within Standard Model

Context: SMEFT



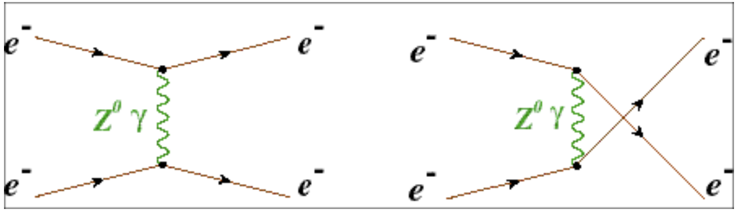
Standard Model
Effective Field Theory



Parity-violating electron scattering (PVES):

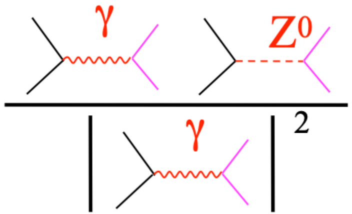
- Search for new flavour-diagonal neutral current couplings
- Tiny yet measurable deviations from precise standard model predictions
- Must reach sensitivity: $\Lambda \sim 10$ TeV
- Probe via electroweak interference in elastic electron scattering

Observable: Parity-violating asymmetry in Møller scattering



- Scatter longitudinally-polarized electrons from unpolarized target
- Probe neutral current via *Electroweak interference*
- Originally proposed by Ya. B. Zeldovich   JETP 36 (1959)

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



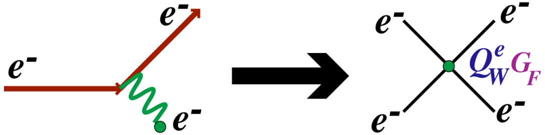
$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

Rapid reversal of electron helicity to measure Asymmetry

$$= -\mathrm{mE}\frac{\mathrm{G_F}}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}\mathrm{Q_W^e}$$

Θ : center of mass scattering angle

Weak charge of electron: $\mathrm{Q_W^e} = 1 - 4\sin^2\theta_\mathrm{W} \sim 0.075$



(weak charge suppressed in Standard Model)

MOLLER goal

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

- Measure: $A_{PV} \approx$ 35 ppb to 0.73 ppb precision
- Yields weak charge: $Q_W^e = 1 - 4\sin^2\theta_W$ with 2.1% (stat) and 1% (syst) precision
- Yields $\sin^2\theta_W$ to 0.1% precision
- Matches precision of best measurements at the Z pole

Requires:

11 GeV longitudinally-polarized electron beam

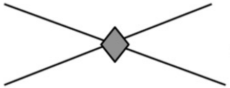
Detected flux of 135 GHz
8200 hrs data taking
3×10^{18} detected electrons

Custom Apparatus in Hall A at Jefferson Lab (Newport News, VA)

Comparison with high-energy Colliders

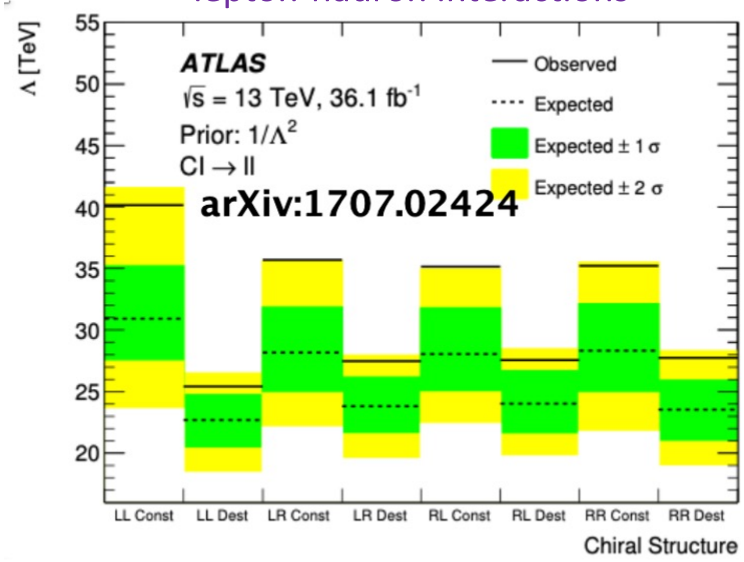
Lacking direct evidence for new particles beyond the Higgs, both colliders and fixed-target experiments search for new physics by looking for deviations from Standard Model predictions

Carefully chosen precision low-energy measurements complement direct searches



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

LHC (and future EIC) searches in lepton-hadron interactions



LEP200 searched in lepton-lepton interactions

e^+e^- Collisions	**LEP200 Reach**	$\Lambda_{LL}^{ee} \sim 8.3$ TeV
Fixed Target	**E158 Reach**	$\Lambda_{LL}^{ee} \sim 12$ TeV
MOLLER Reach		$\Lambda_{LL}^{ee} \sim 27$ TeV

MOLLER will access discovery space for new lepton-lepton couplings not otherwise accessible without a next generation linear collider, muon collider, or a neutrino factory

(new: SuperKEKB with polarized beams: Snowmass 2021 arXiv:2205:12847)

Low-energy Weak Mixing Angle measurements

APV: atomic parity violation ^{133}Cs

- future measurement/theory: challenging

PV Moller scattering

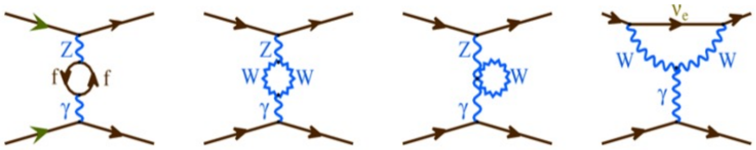
- SLAC E158 statistics limited, theory robust
- next generation: MOLLER (factor 5 better)

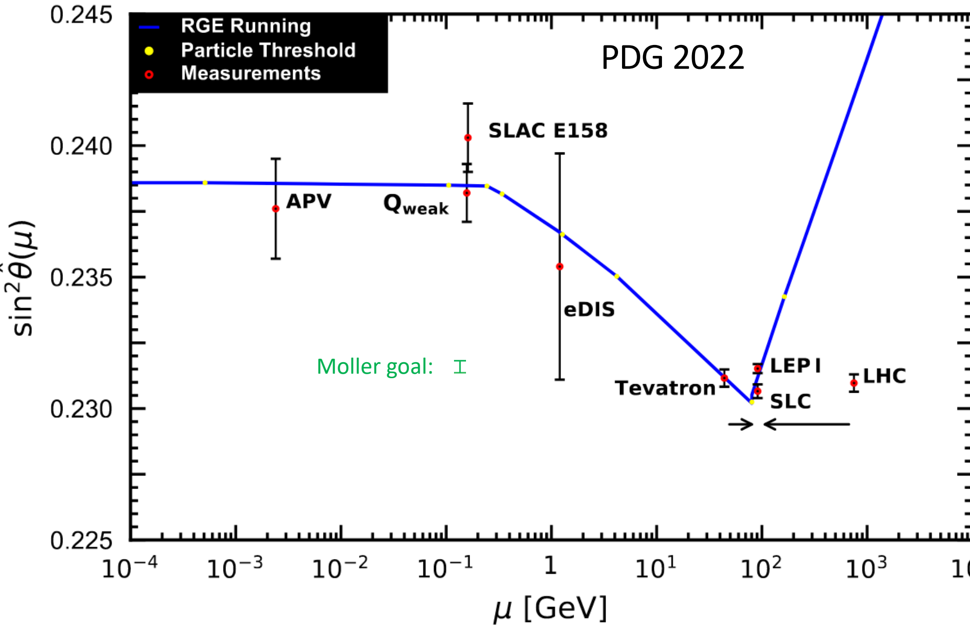
PV elastic e-p scattering

- Q_{weak} (JLab 2018) theory robust at low energy
- next generation: P2 at Mainz (factor of 3 better)

eDIS: PV deep inelastic scattering

- JLab 2014
- theory robust for ^2H in valence quark region
- next generation: SOLID (factor of 5 better)





PVES: Brief History

Pioneering (1978) early SM tests
SLAC E122 PVDIS – Prescott *et al.*   A = -152 ppm
Bates ^{12}C, Mainz Be

Strange Form Factors (1998 –2009)
SAMPLE, HAPPEX, G0, A4
A ~ 1 – 50 ppm

Standard Model Tests (2003 - 2018)
SLAC E158 Moller: A = - 131 ppb
(13% precision on electron's weak charge)
JLAB Qweak: A = -230 ppb

Neutron radii: (2012-2022)
JLab: PREX-I, PREX-II, CREX

Future: Standard Model, hadron structure studies:
MOLLER: A = - 35 ppb
Goal: 2.5% precision on electron's weak charge

P2@MESA, SOLID, 12C@MESA

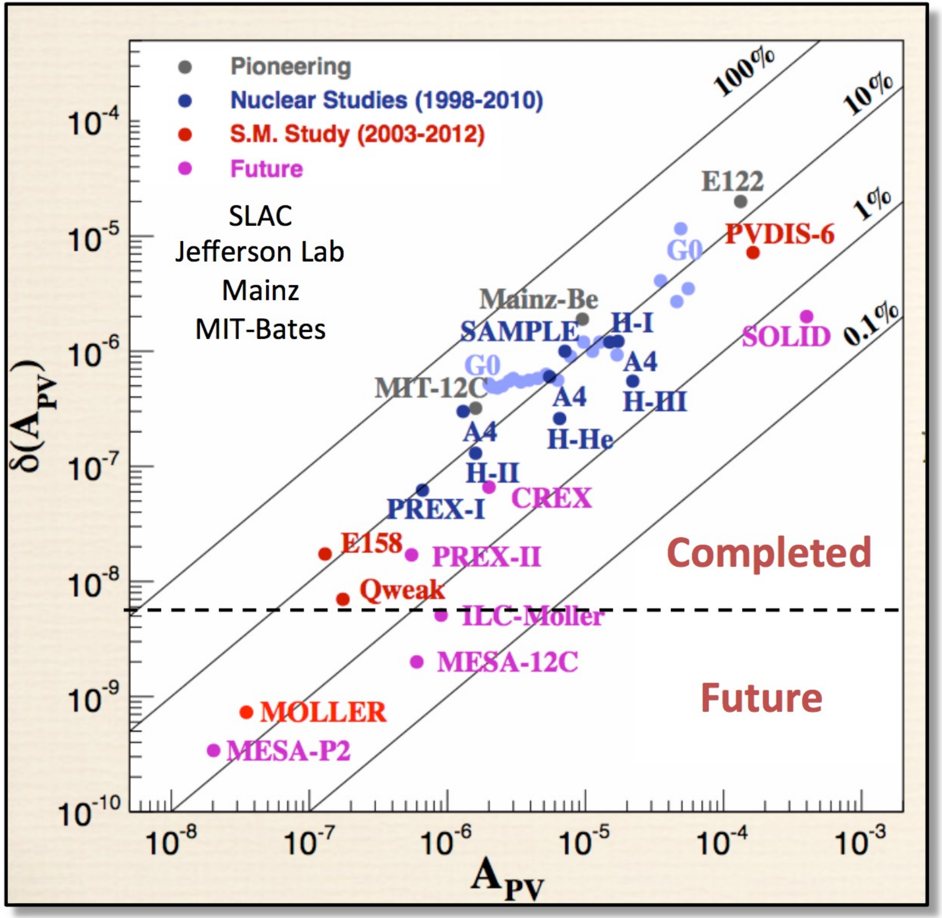
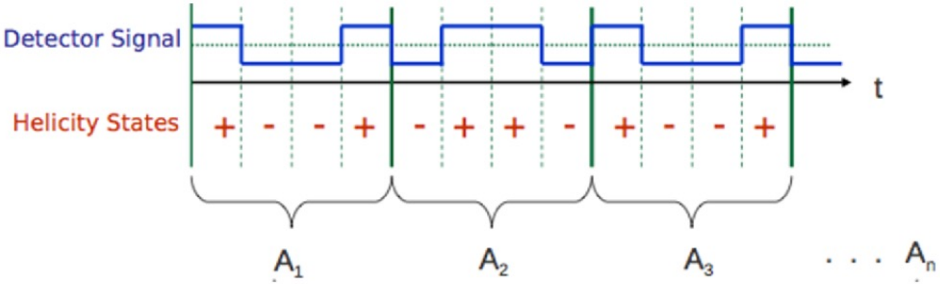


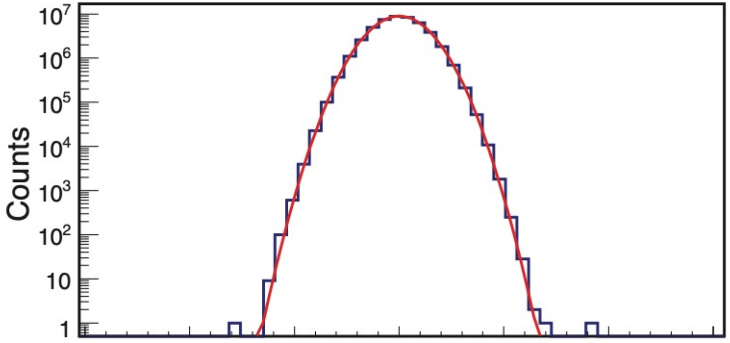
Figure courtesy of Kent Paschke

Measuring tiny asymmetries

Rapid (2kHz) helicity reversals

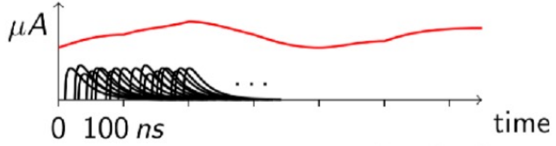


Measure to 0.01% at 1 kHz,
repeat for a year straight



Place a detector where it sees the Møller scattered electron

Analog integrate detector current



Form an asymmetry over the helicity reversal

Specialized experimental techniques

- Precise spectrometer to separate signal
- Low noise electronics
- Precise beam control and measurement
- …

Beam Performance

Intense, stable, high energy electron beam with longitudinal beam polarization.

Must control any changes in beam properties correlated with helicity-flip both on rapid 2 kHz time scale (~ppm, microns) AND days (~ppb, nm): carefully tuned, actively monitored and maintained with proper diagnostics.

(Helicity Correlated Beam Asymmetries)

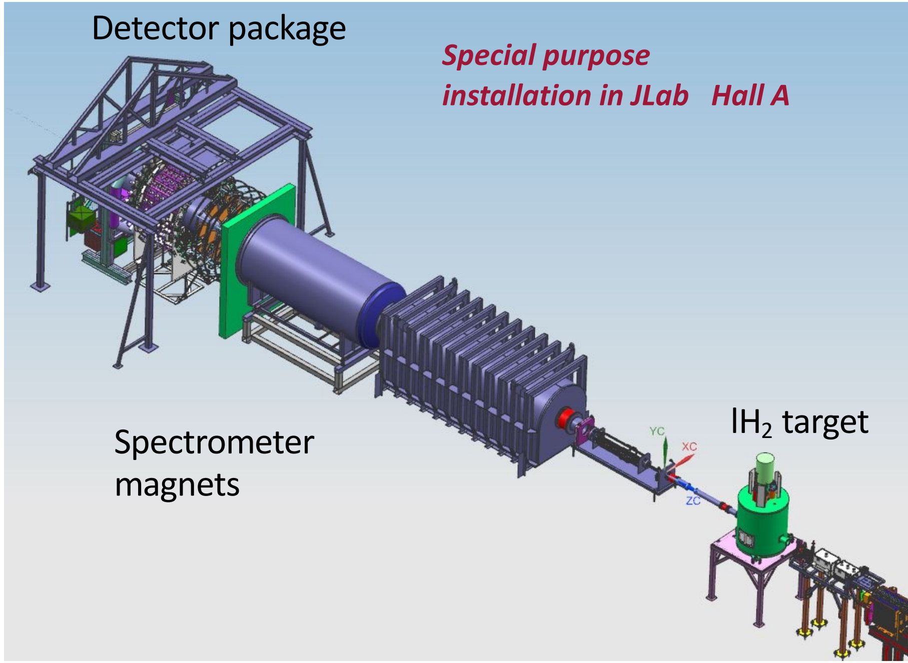
	MOLLER (344 PAC days)	MOLLER Run 1 (25 PAC days)	PREX II achieved (~19 PAC days)
Intensity	<10ppb	<30ppb	20ppb
Energy Asymmetry	<0.7ppb	<3.5ppb	1.6ppb
Position Difference	<0.6nm	<3nm	2.5nm
Angle Difference	<0.13nrad	<0.6nrad	0.6nrad
Size Differences	<10ppb	<50ppb	5-30ppb

- Evolutionary improvements in helicity-flip control over the 25 year history of PVES measurements at JLab
- Likely only possible with a superconducting CW machine such as the JLab CEBAF acceleratorr

Meeting PVES Challenges for MOLLER

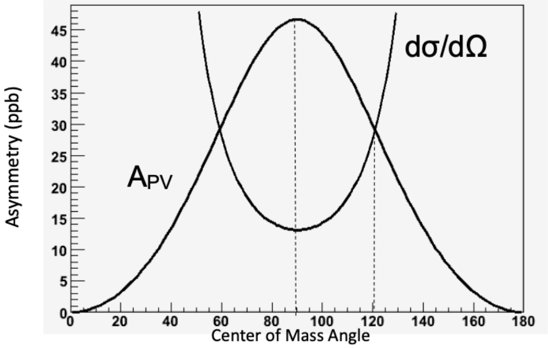
$A_{PV} \approx 35$ ppb with $\approx 2.5\,\%$ precision

- 65 μA beam current, 11 GeV beam energy
  90% polarized beam
- High-power cryogenic hydrogen target:
  1.25 m long, ~9 g/cm^2 , 4 kW
- Rapid electron helicity reversal (1920 Hz)
- Ultra small scattering angle:
  toroidal magnets, large acceptance
- 135 GHz detected rates: data-taking in integrating mode
- Radiation-hard, highly-segmented detectors
- Low noise 18-bit ADCs
- Exquisite control of helicity-correlated beam parameters
- Four different kinds of helicity reversal:
  Rapid (Laser beam at source: Pockels cell)
  Slow (insertable λ/2 plate in laser beam)
  Ultra slow (Wien-reversal, g-2 spin flip)
- Two independent high-precision (0.4%) beam polarimeters
- High resolution Beam Current monitors
- Dedicated Tracking system for kinematics/background determinations



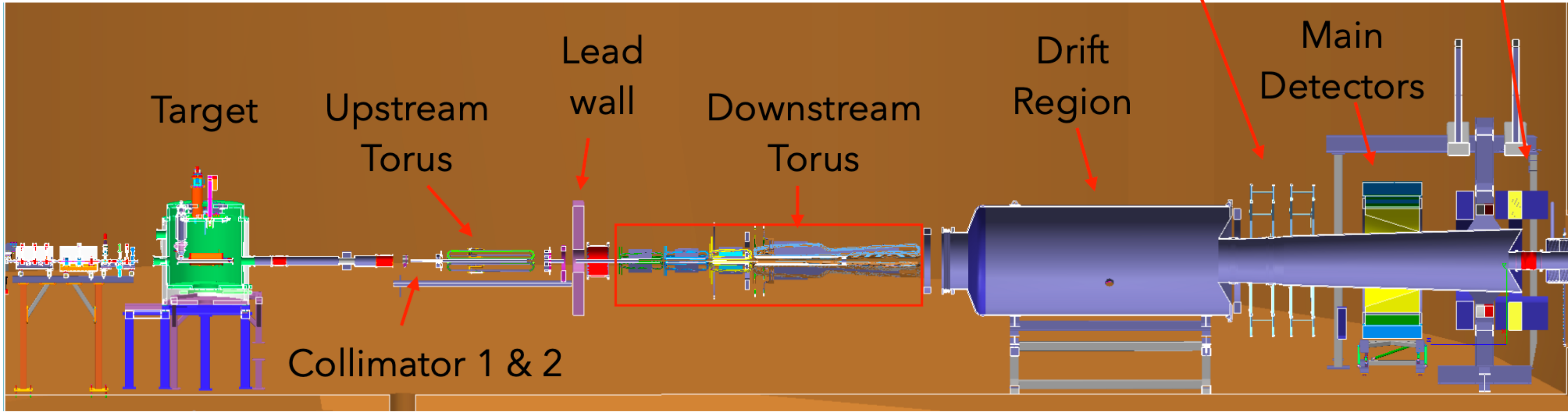
Experimental Overview

Highest figure of merit at $\theta_{CM} = 90°$



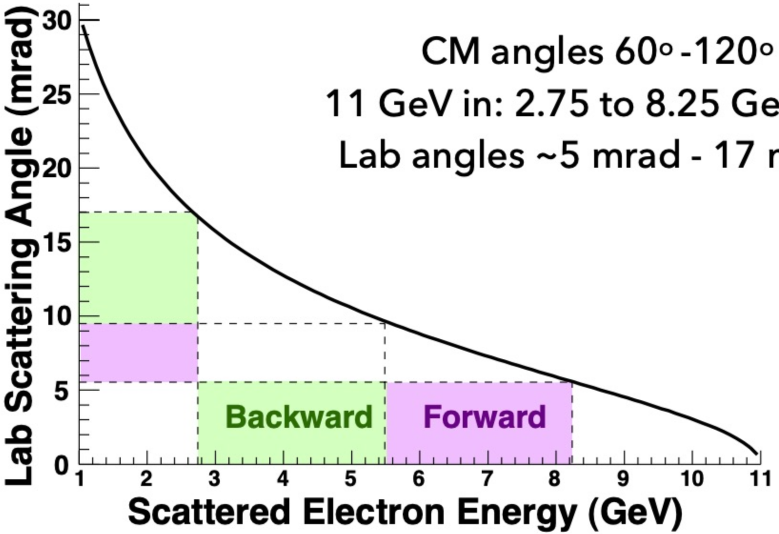
Tracking Chambers

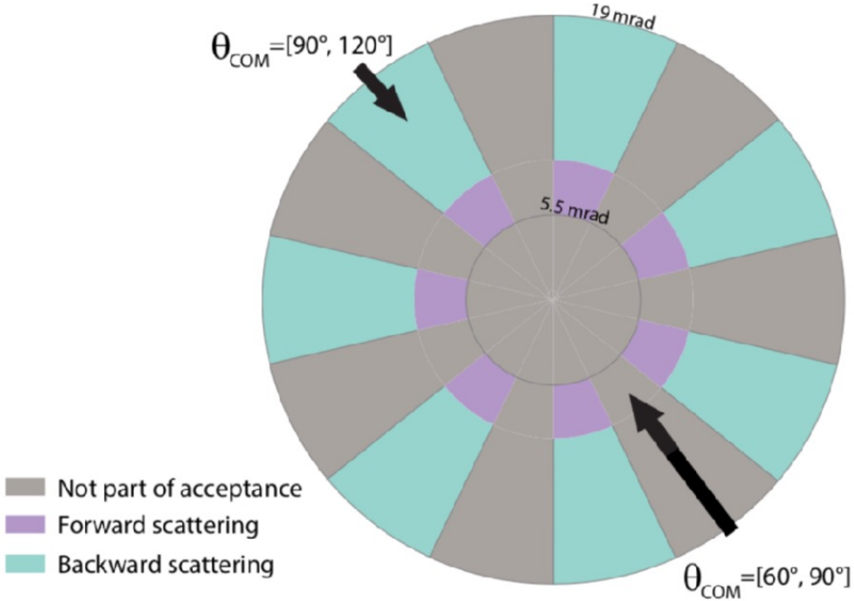
SAMs, Pion Detectors, Scanners



Exploiting Identical Particles

Since you only need either the forward or the backward scatter, accept forward+backward for half the azimuth

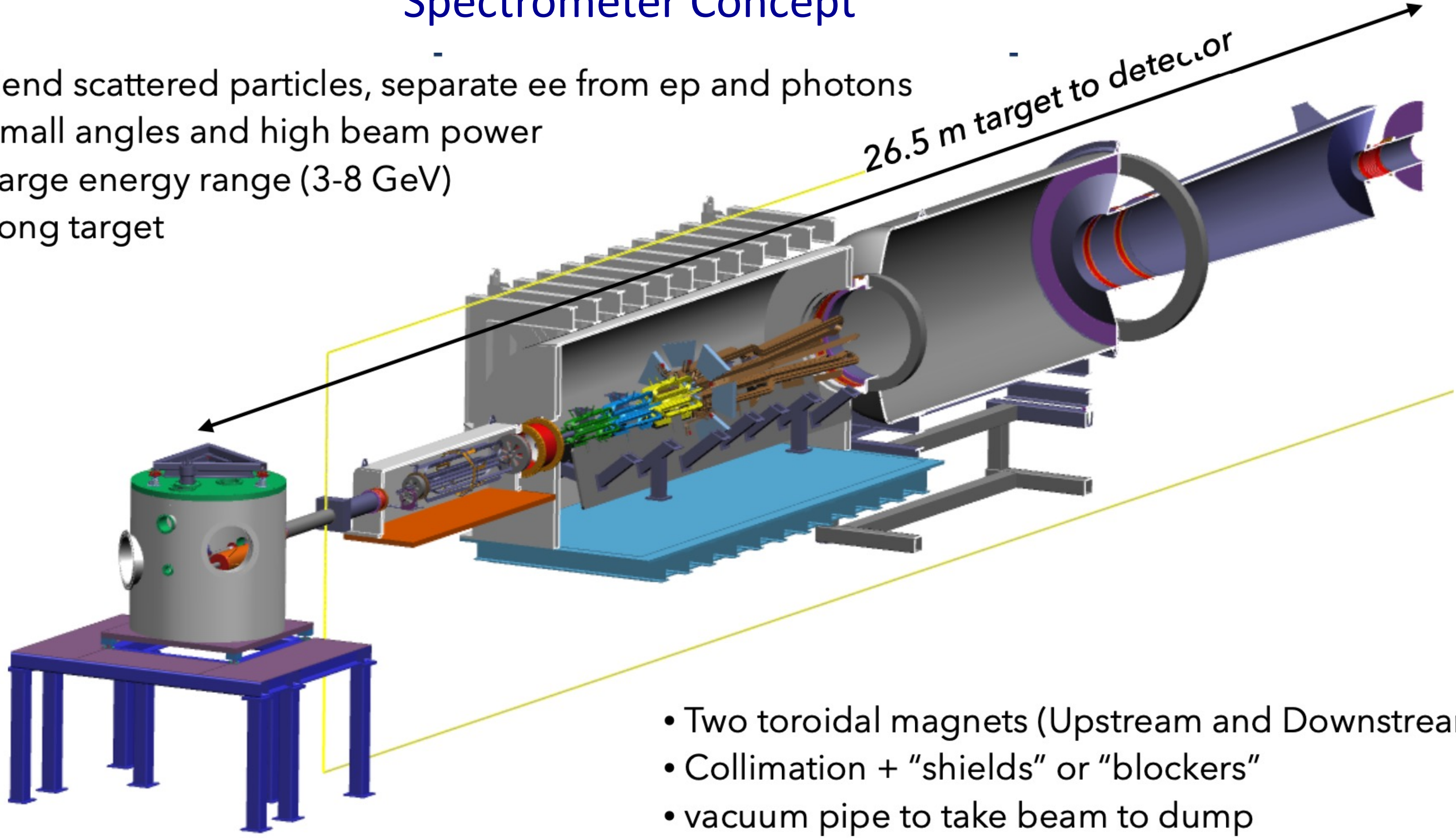




Unique concept allows for full azimuthal acceptance (effectively) even leaving space for coils but makes for a challenging design

Spectrometer Concept

- Bend scattered particles, separate ee from ep and 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

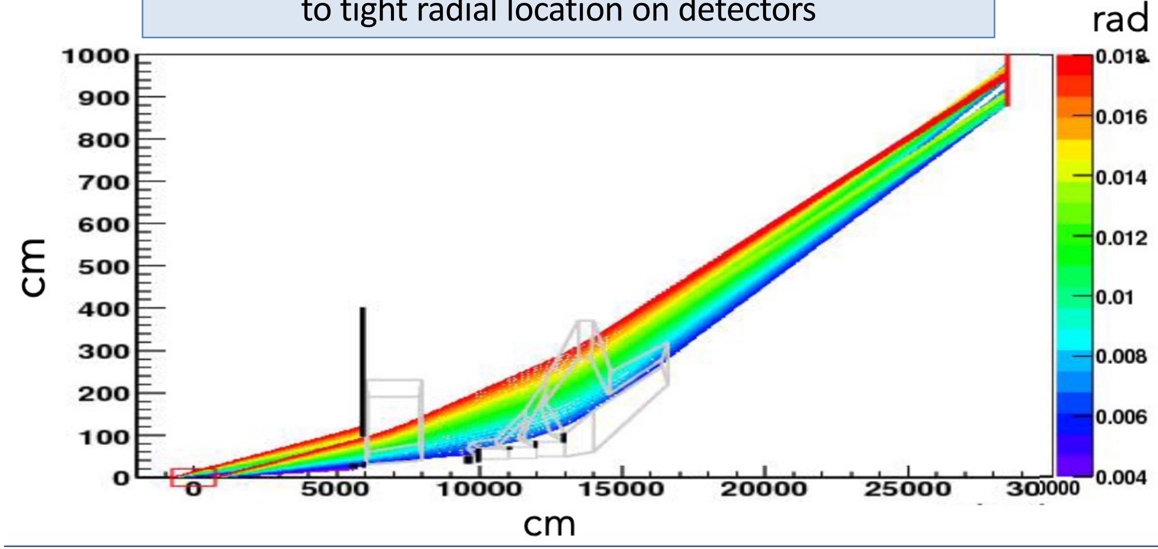
Magnet Concept

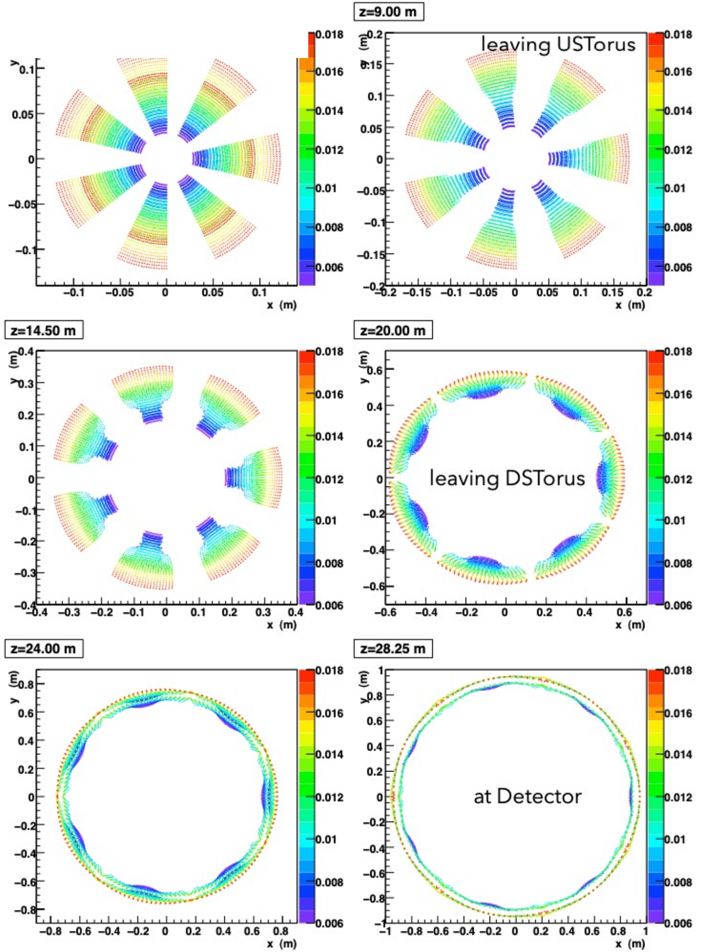
long and skinny

0.5 x 2m

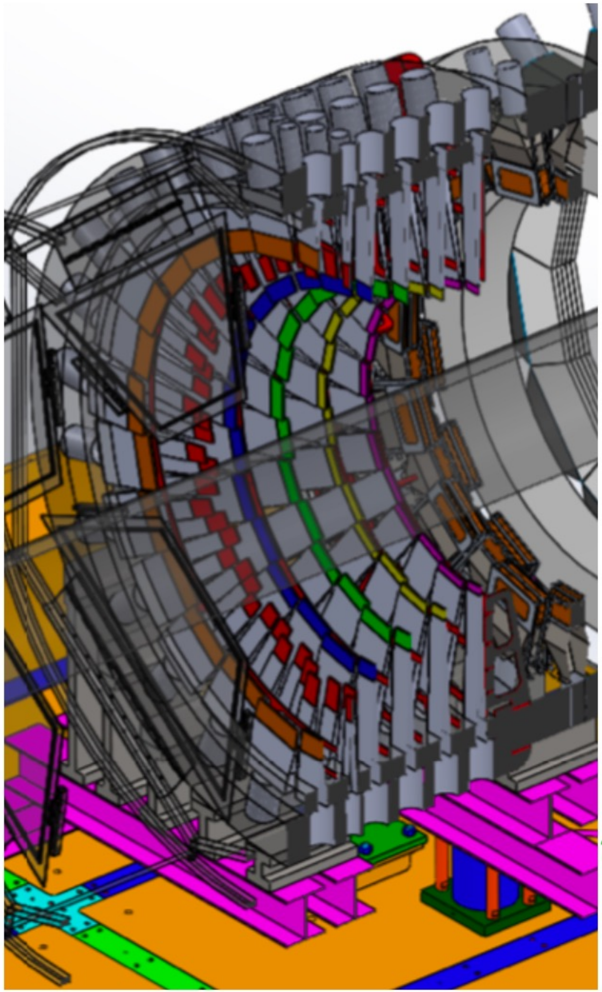
0.9 x 6.5m

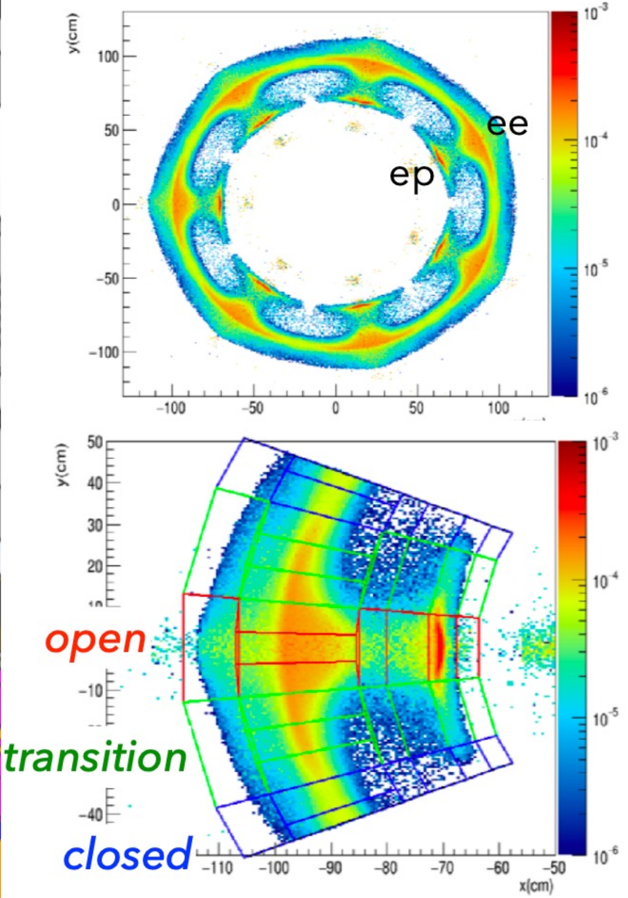
Focus Moller electrons from full acceptance (3 – 8 GeV) to tight radial location on detectors



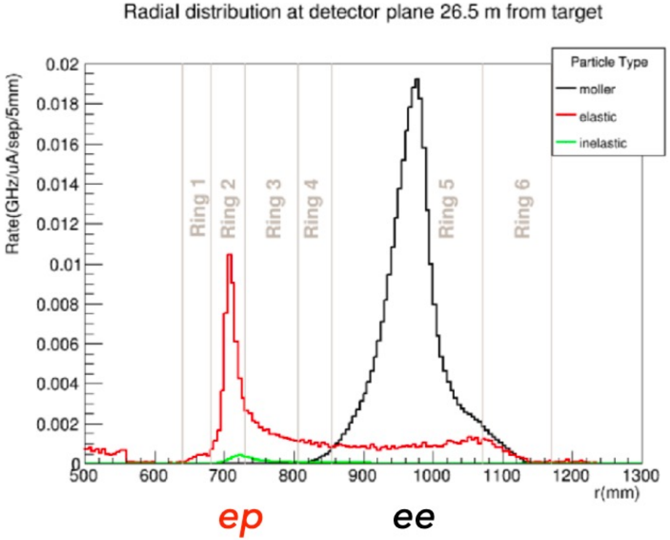


Main Detector

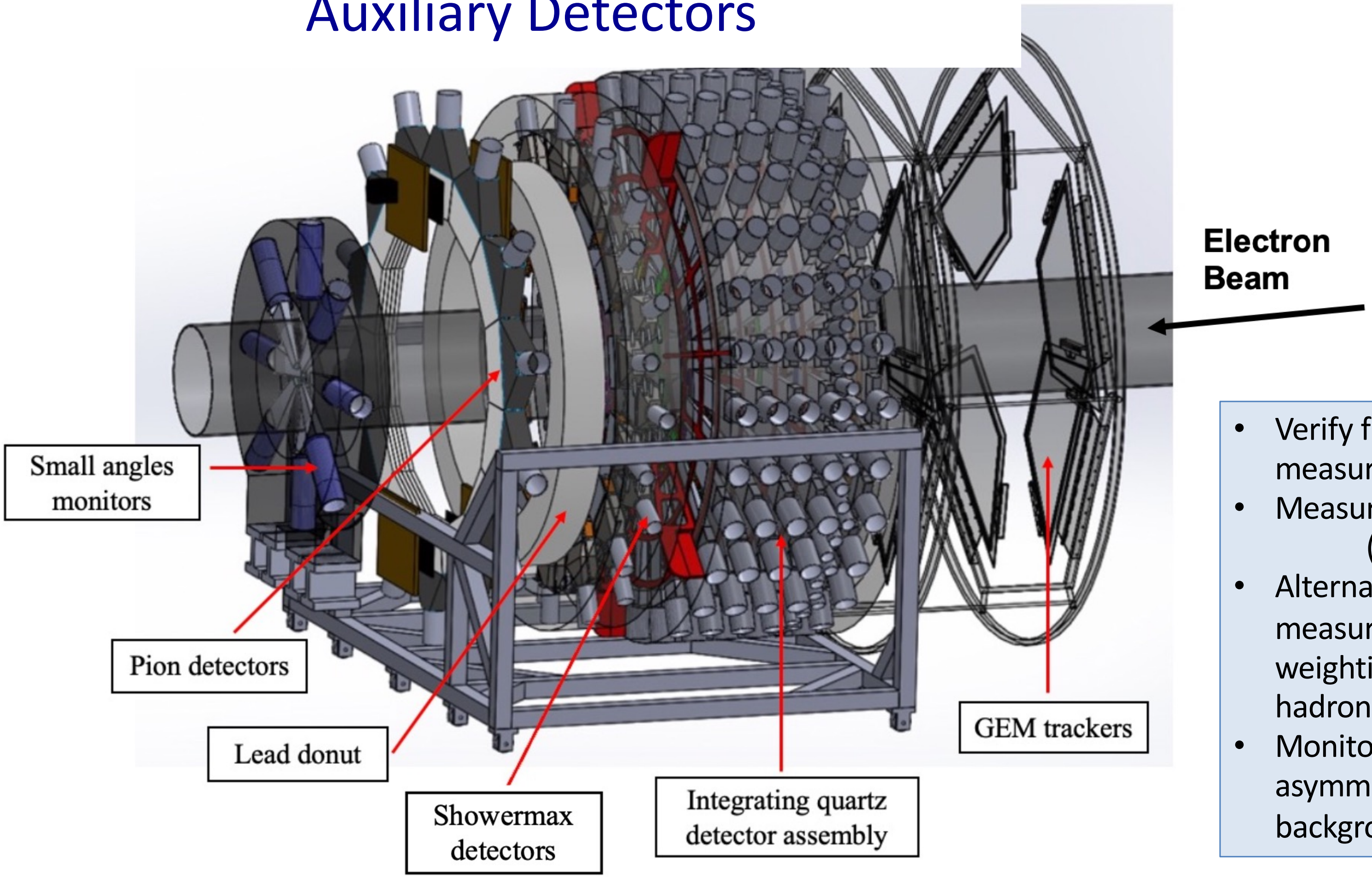




- Radiation hard fused-silica Cerenkov detectors
- Highly segmented for background deconvolution



Auxiliary Detectors



- Verify flux distributions and measure kinematics
- Measure backgrounds (pions/muons)
- Alternate asymmetry measurement with energy-weighting, reduced sensitivity to hadronic and soft backgrounds.
- Monitoring potential false asymmetries in irreducible backgrounds.

MOLLER Collaboration

~160 authors, 37 institutions, 6 countries

Spokesperson: K. Kumar, UMass, Amherst

Executive Board Chair and Deputy Spokesperson: **M. Pitt**, Virginia Tech

Other Executive Board Members: D. Armstrong (William & Mary), J. Fast (JLab), C. Keppel (JLab), F. Maas (Mainz), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

Major Equipment Funding:

U.S. Dept of Energy
U.S. National Science Foundation
Canada Foundation for Innovation/Research Manitoba
NSERC

Present Status: Engineering, Design, Prototyping phase

More information: arXiv/1411.4088

DOE CD-2: expected Fall 2022
Data-taking: 2025-2027

MOLLER: Canadian Content

University of Manitoba:
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University of Winnipeg:
B. Jamieson, R. Mammei, J.W. Martin

University of Northern British Columbia:
E. Korkmaz

Memorial University, Grenfell:
A. Aleksejevs, S. Barkanova

Key CanCon elements:

Toroidal Spectrometer Design: Juliette Mammei
Main Integrating Detectors and Integrating electronics: Michael Gericke
Pion Detector Design: Wouter Deconinck
18 bit ADCs: U. Manitoba & TRIUMF (engineering)
Radiative corrections: Aleksandrs Aleksejevs, Svetlana Barkanova

… and several transplanted Canucks in the US, like me

Summary

- MOLLER: precision measurement of A_{PV} in electron-electron scattering
- Requires unique characteristics of Jefferson Lab 12 GeV accelerator
- Canadian contributions essential
- $\sin^2\theta_W$ to 0.1% – will match best measurements at Z-pole
  $\rightarrow$ Precision Standard Model test
- New physics reach for flavour-diagonal lepton couplings to 27 TeV

Merci Beaucoup / Thank you