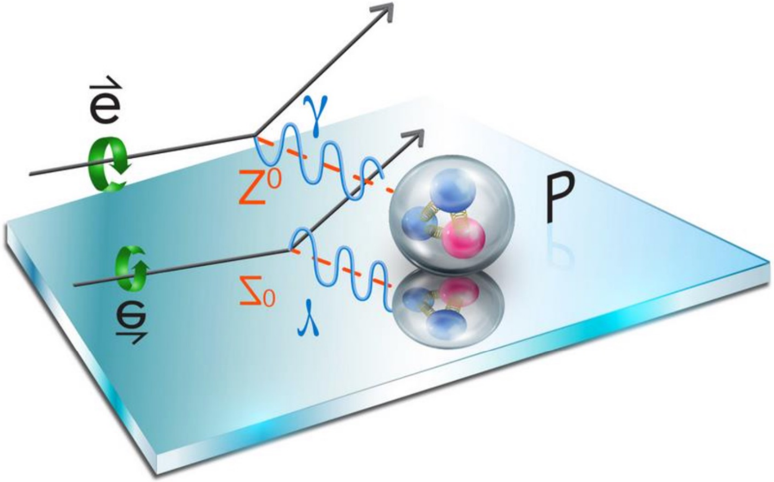
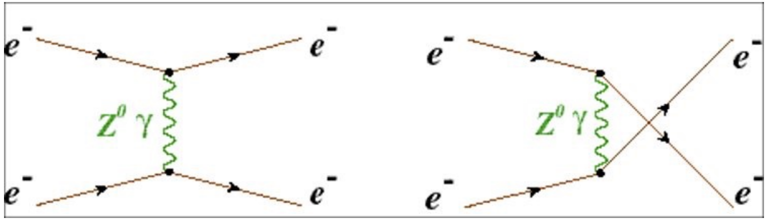
Parity-violating electron scattering measurements at Jefferson Lab

David S. Armstrong

William & Mary





QNP 2022
19th Int. Conf. on Quarks and Nuclear Physics
Sept. 5 - 9
"New Physics" parallel session

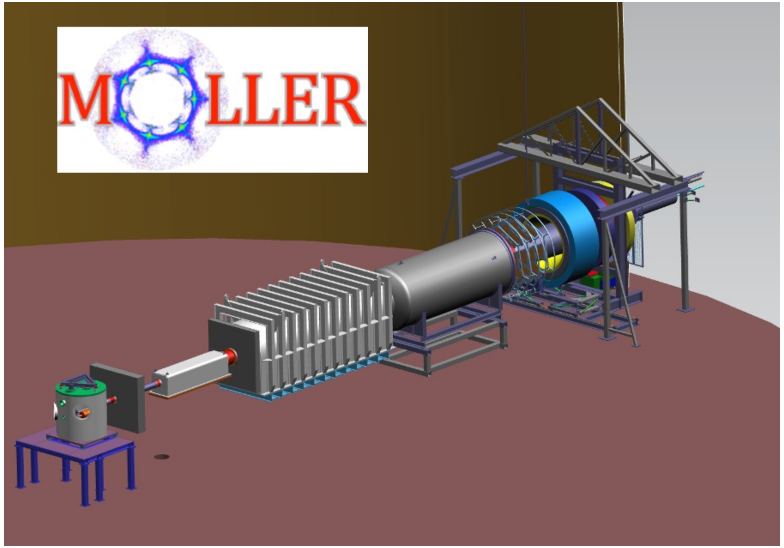
Overview

1. Parity-Violating electron scattering
   Physics context: Standard Model tests

2. Qweak at JLab (completed)

3. MOLLER at JLab (under development)

   MOLLER: Measurement of a Lepton Lepton Elastic Reaction



Physics Context – Precision Low-energy physics

- Received Wisdom: Standard Model is incomplete: low-energy effective theory of more fundamental physics
- Low energy ($Q^2 << M^2$): Precision Frontier
  complementary to Energy Frontier measurements (LHC)

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]*

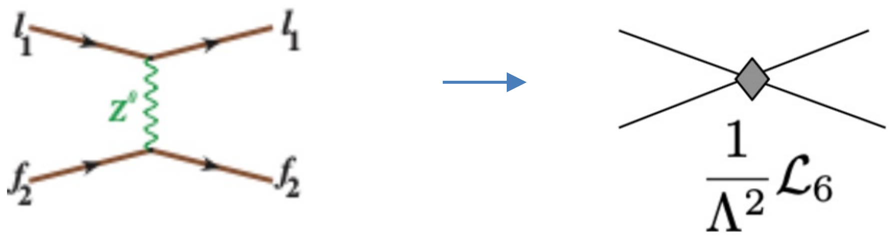
Ideal - *select observables that:*

1) *are zero, or significantly suppressed, in Standard Model*
2) *Have robust predictions within Standard Model*

Parity-violating electron scattering (PVES)

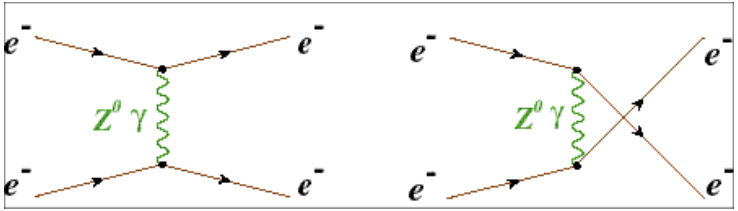
- Search for new flavor-diagonal neutral current couplings
- Tiny yet measurable deviations from precise standard model predictions
- Probe via electroweak interference in elastic electron scattering

- Analyze in context of Standard Model Effective Field Theory (SMEFT):



- Desired sensitivity: $\Lambda \sim 10$ TeV

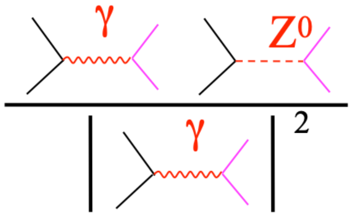
MOLLER: Parity-violating asymmetry in Møller scattering



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

Rapid reversal of electron helicity to measure Asymmetry

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

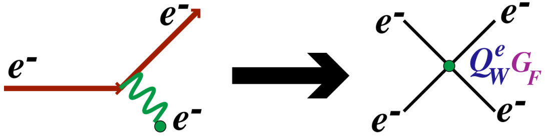


$$\propto \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

$$= -\mathbf{mE}\frac{\mathbf{G_F}}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}\mathbf{Q^e_W}$$

Θ : center of mass scattering angle

Weak charge of electron: $\mathbf{Q^e_W} = 1 - 4\sin^2\theta_W \sim 0.075$



(weak charge suppressed in Standard Model)

Qweak: Parity-violating asymmetry in ep scattering

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right)\right]$$

For forward angle scattering at low Q^2 :
A_{PV} accesses Q^p_W

"Form factor" term due to finite proton size – hadron structure – determined well by existing PVES high-Q^2 data

Weak charge of proton: $Q^p_W = 1 - 4\sin^2\theta_W \sim 0.075$

(weak charge suppressed in Standard Model)

Note: sensitivity to various New Physic models differs for Q^e_W and Q^p_W
$\rightarrow$ *Complementary probes*

Can parameterize New Physics sensitivity via deviations from Standard Model value of $\sin^2\theta_W$

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, QWeak

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

P2@MESA, SOLID, 12C@MESA

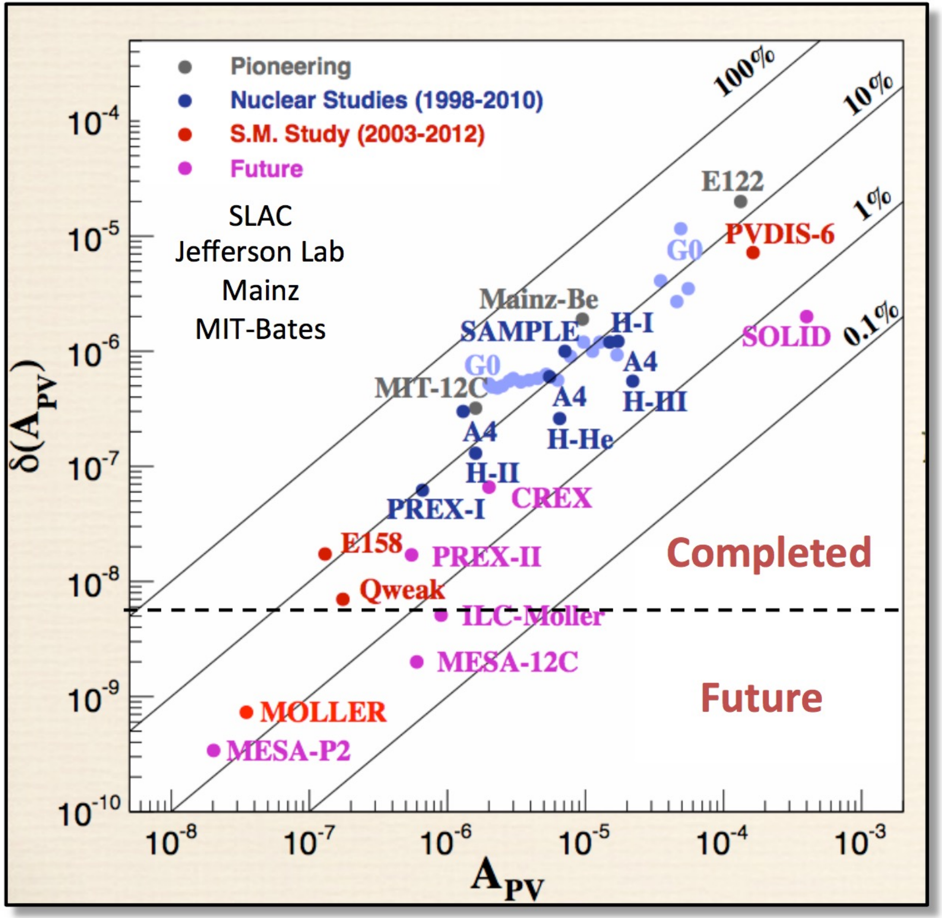
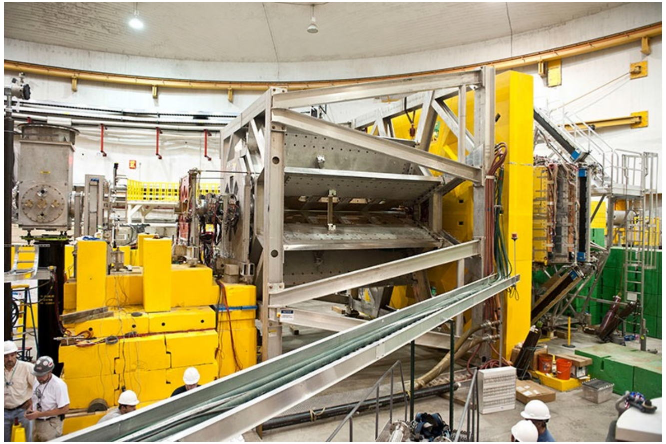


Figure courtesy of Kent Paschke

Qweak experiment

- **Hall C at Jefferson Lab** (Newport News, Virginia)

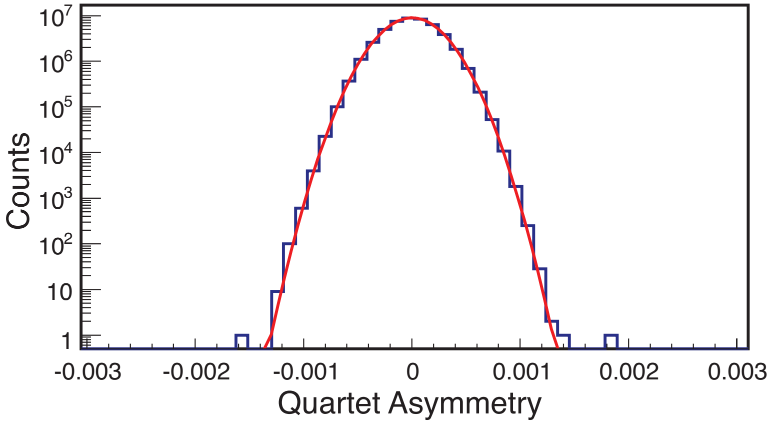


- Custom designed apparatus

- Data-taking: 2010 – 2012 (~ 1 year total beam time)
- Jefferson Lab record beam current: 180 μA
- Last experiment in Hall C in "6 GeV era" CEBAF
- First results on proton's weak charge (based on first 4% of the dataset)
  Phys. Rev. Lett. 111, 141803 (2013)

- Final result: **Nature 557, 207 (2018)**

$$\boxed{A_{PV} = -226.5 \pm 9.3 \text{ ppb}}$$

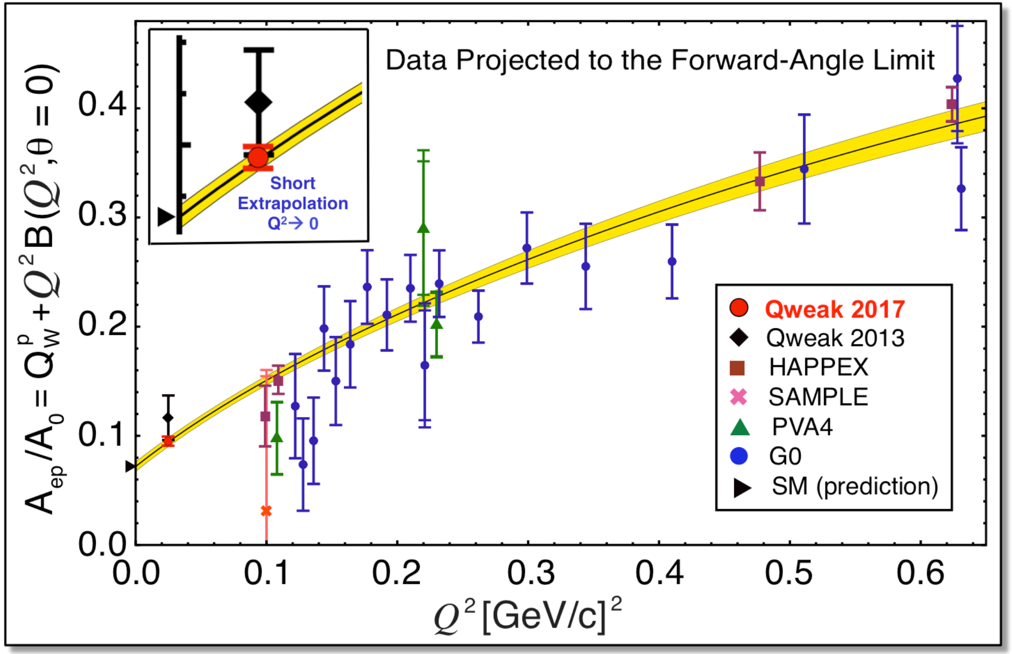


Qweak: Extracting Weak Charge from Asymmetry Result

$$\boxed{A_{ep} = -226.5 \pm 7.3(\mathrm{stat}) \pm 5.8(\mathrm{syst})\ \mathrm{ppb\ at}\ \langle Q^2 \rangle = 0.0249\ (\mathrm{GeV}/c)^2}$$

Global fit of world PVES data to extract proton's weak charge:

$$A_{ep}/A_0 = Q_W^p + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$



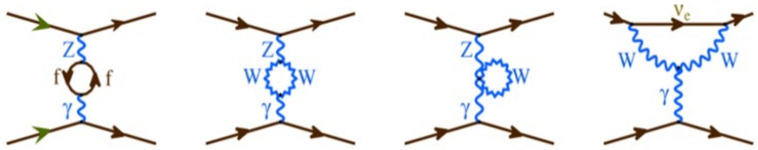
Standard Model:

$$Q_W^p = 0.0708 \pm 0.0003$$

Experiment:

$$Q_W^p = 0.0719 \pm 0.0045$$

Low-energy Weak Mixing Angle measurements



APV: atomic parity violation ^{133}Cs

- future measurement/theory: challenging

PV Moller scattering

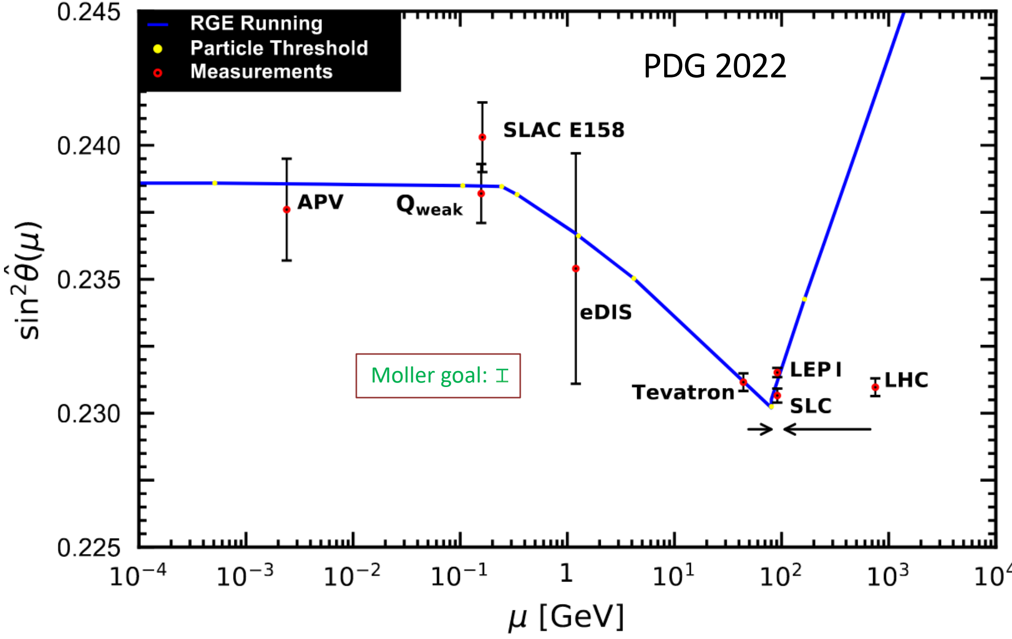
- SLAC E158: statistics-limited, theory robust
- next generation: MOLLER (factor 5 better)

PV elastic e-p scattering

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

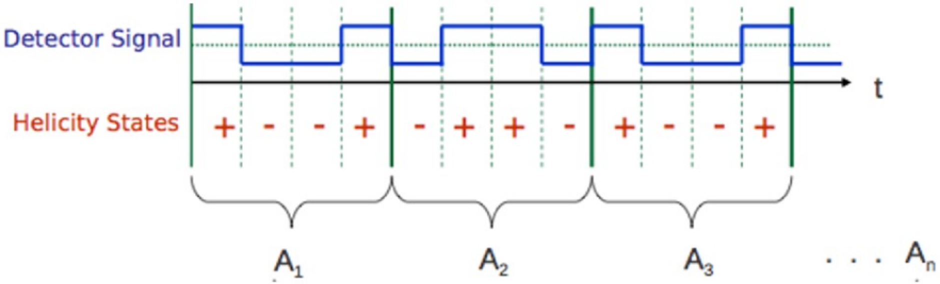
eDIS: PV deep inelastic scattering

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



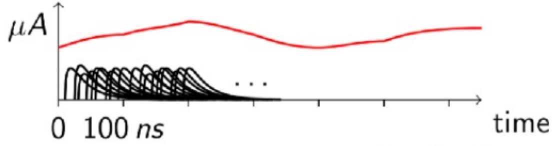
Measuring tiny asymmetries

Rapid (2kHz) helicity reversals



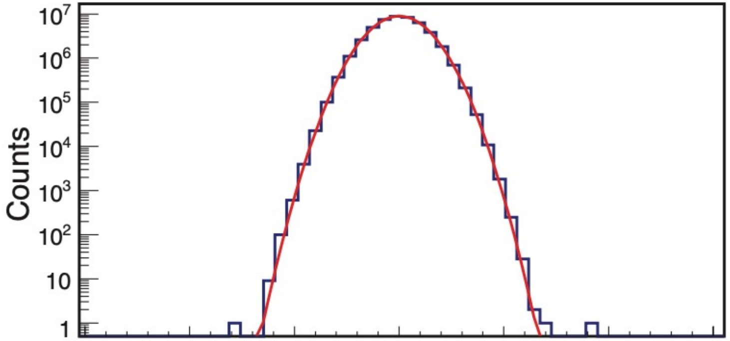
Place a detector where it sees the Møller scattered electron

Analog integrate detector current



Form an asymmetry over the helicity reversal

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



Specialized experimental techniques

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

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

MOLLER new physics reach: $\Lambda_{LL}^{ee} \sim 27$ TeV

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

Requires:

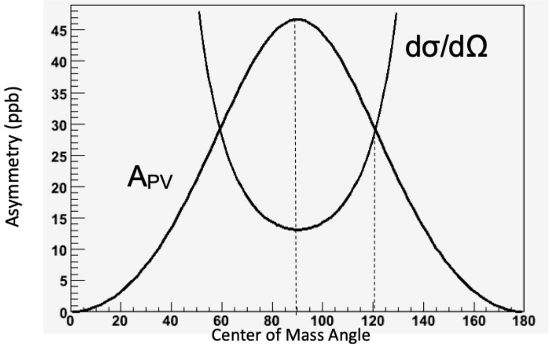
11 GeV longitudinally-polarized electron beam

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

Custom Apparatus in Hall A at Jefferson Lab

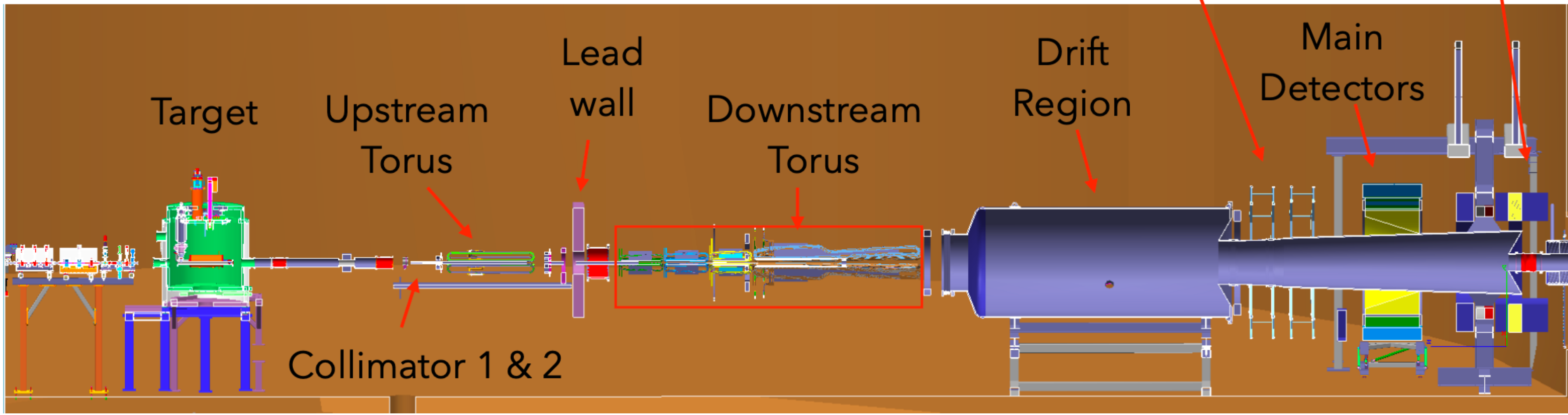
Experimental Overview

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



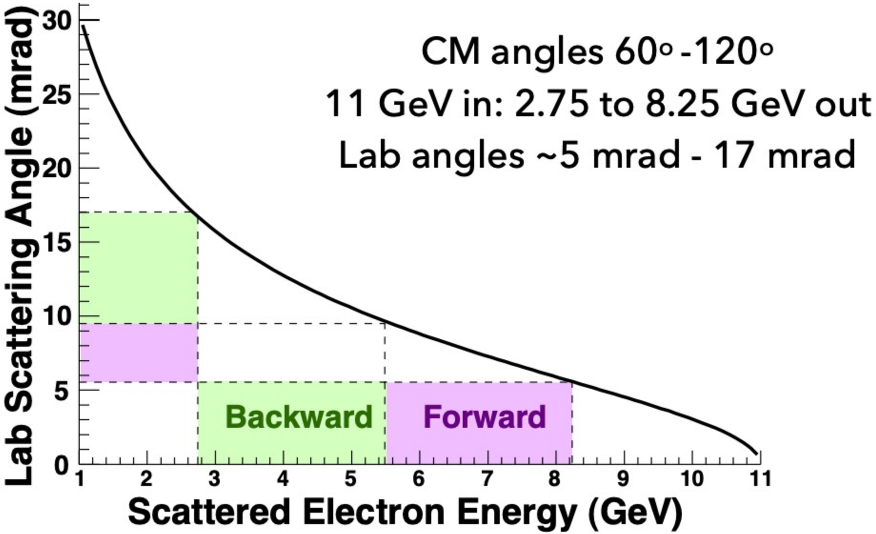
SAMs,
Pion
Detectors,
Scanners

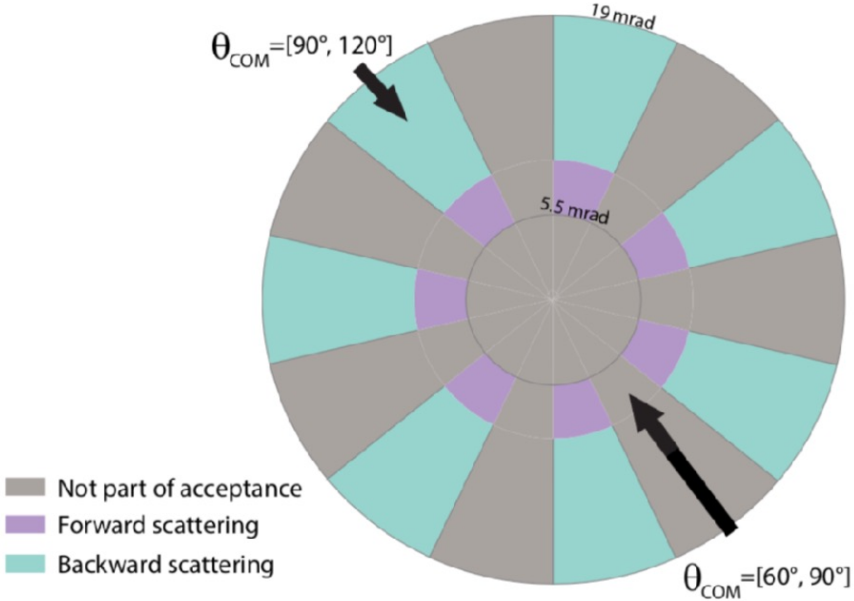
Tracking
Chambers



Exploiting Identical Particles

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

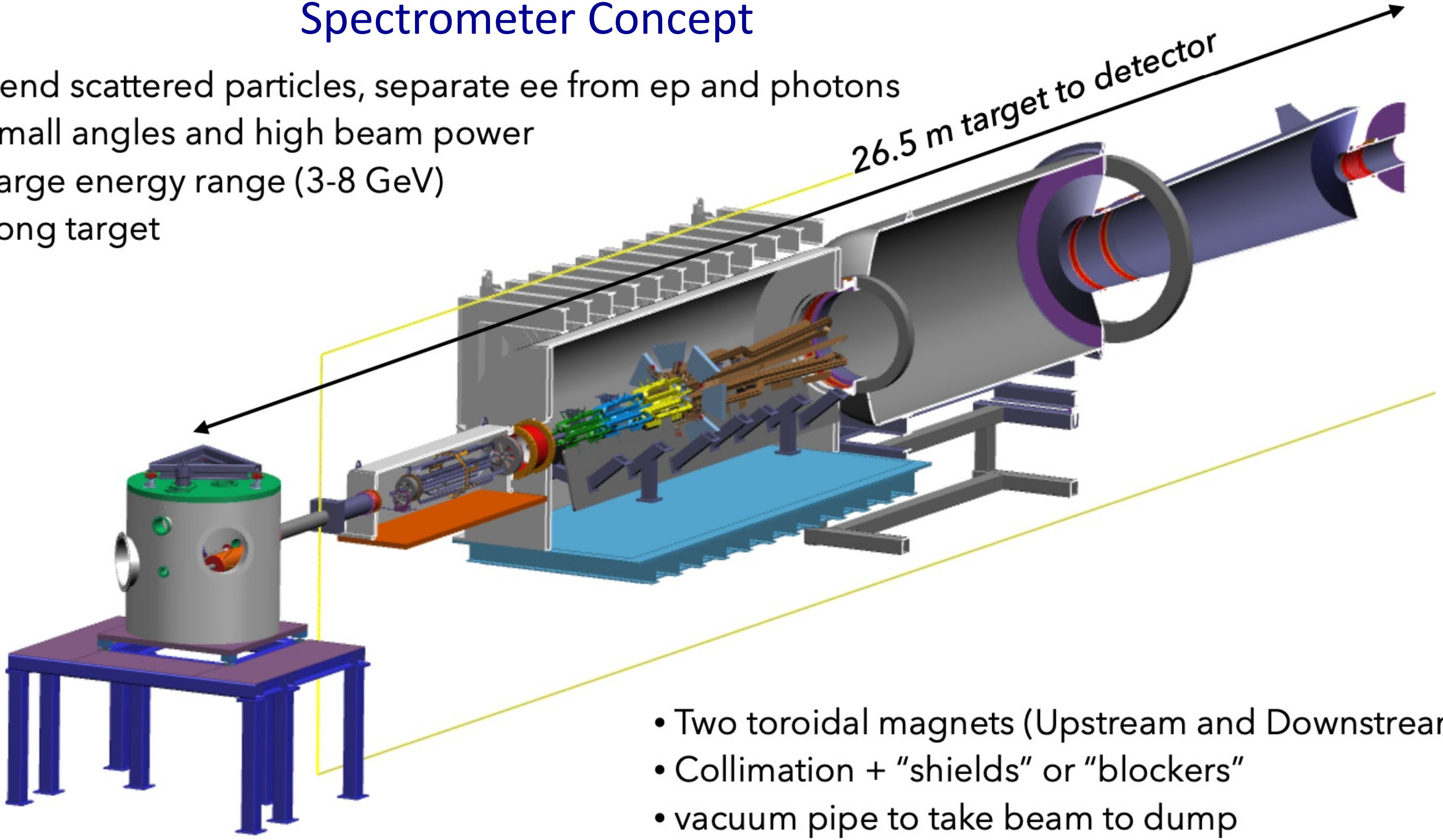




Unique concept allows for full azimuthal acceptance (effectively) even leaving space for coils but makes for a challenging design

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

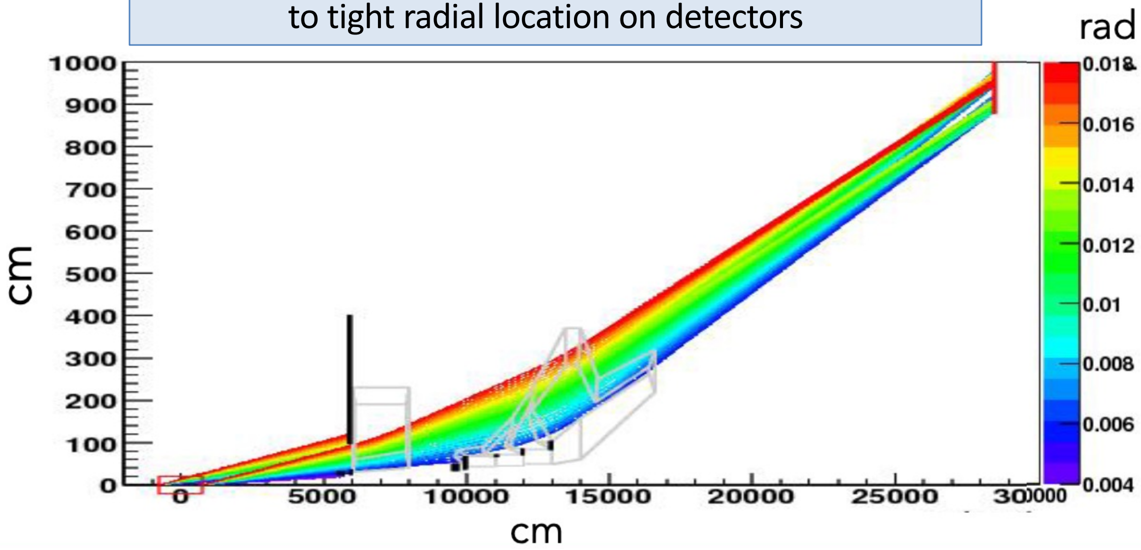
Magnet Concept

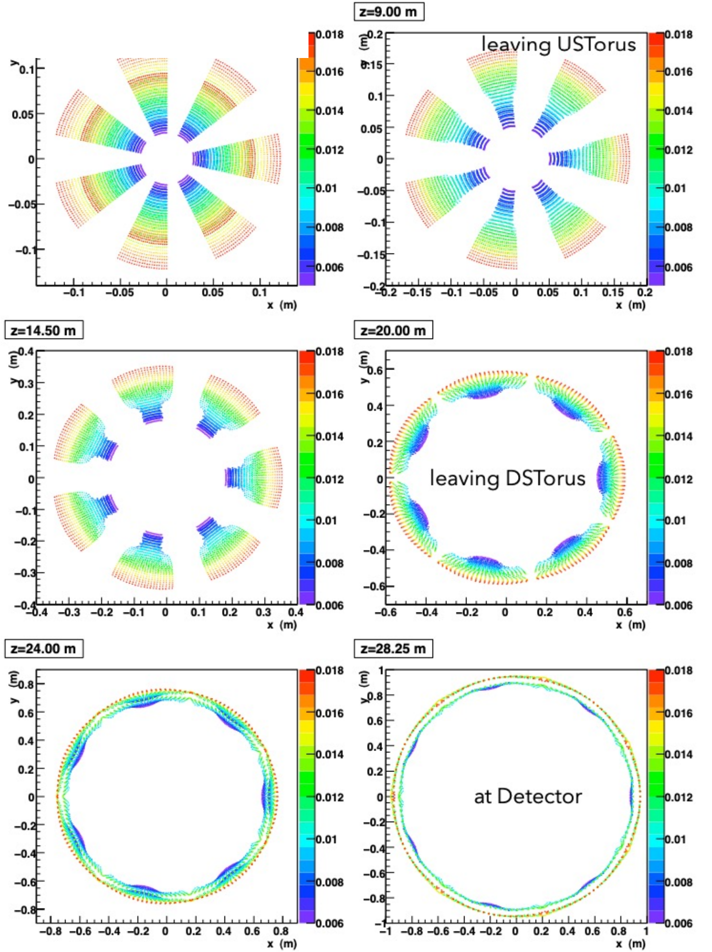
long and skinny

0.5 x 2m

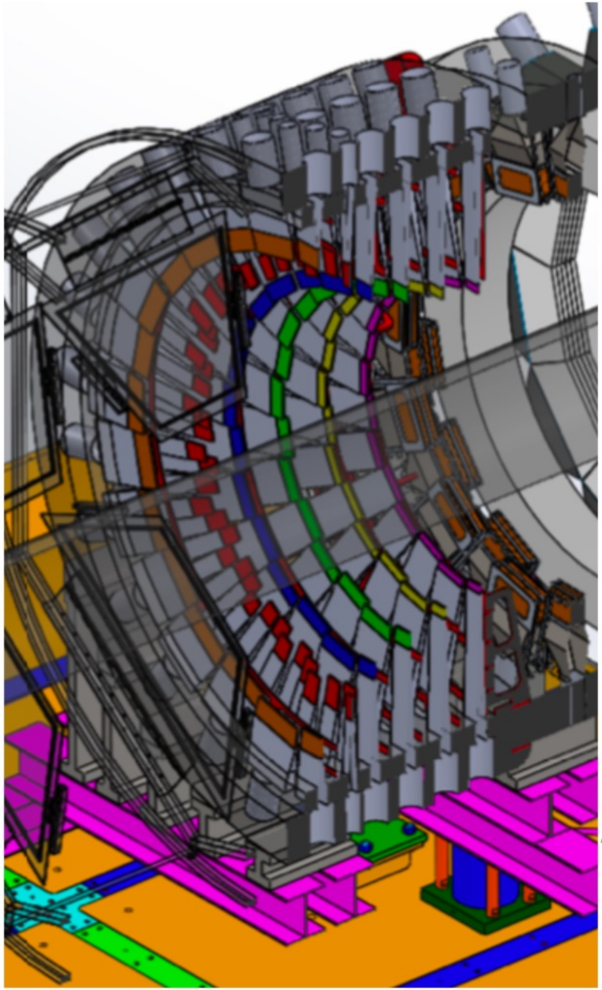
0.9 x 6.5m

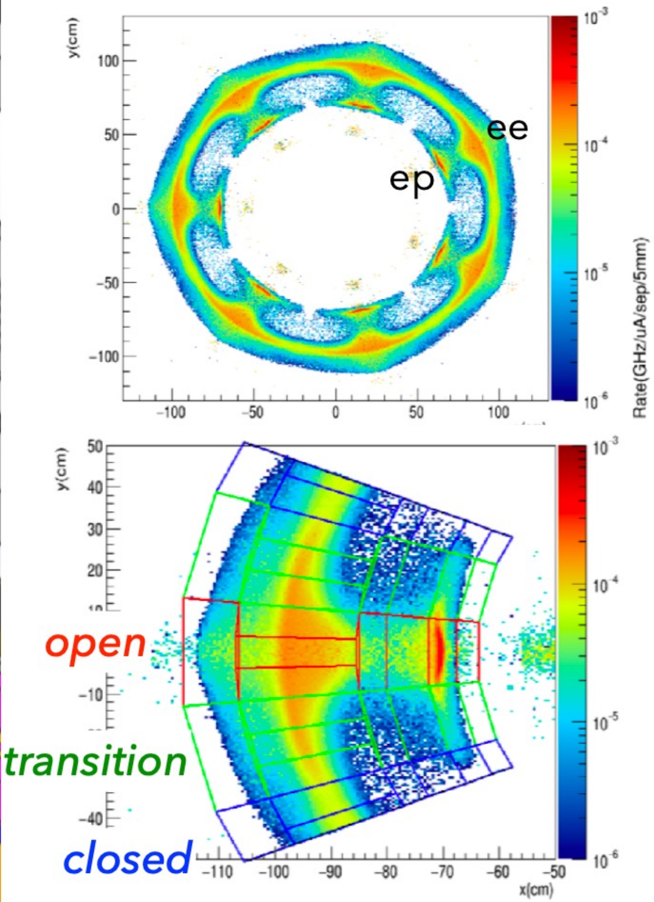
Focus Moller electrons from full acceptance (3 – 8 GeV) to tight radial location on detectors



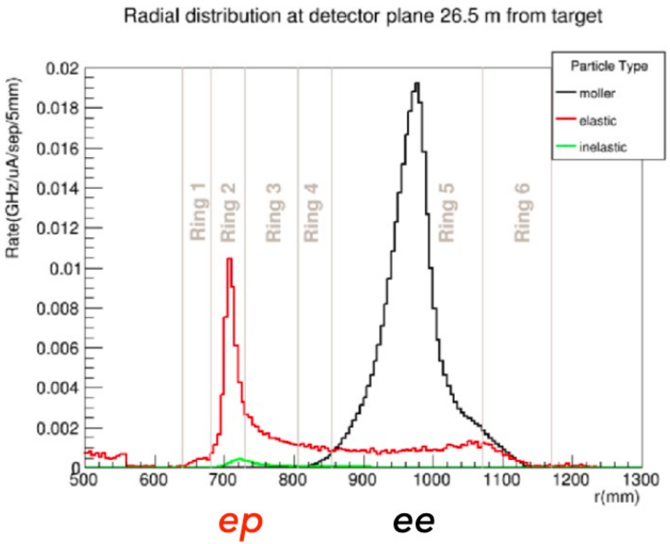


Main Detector

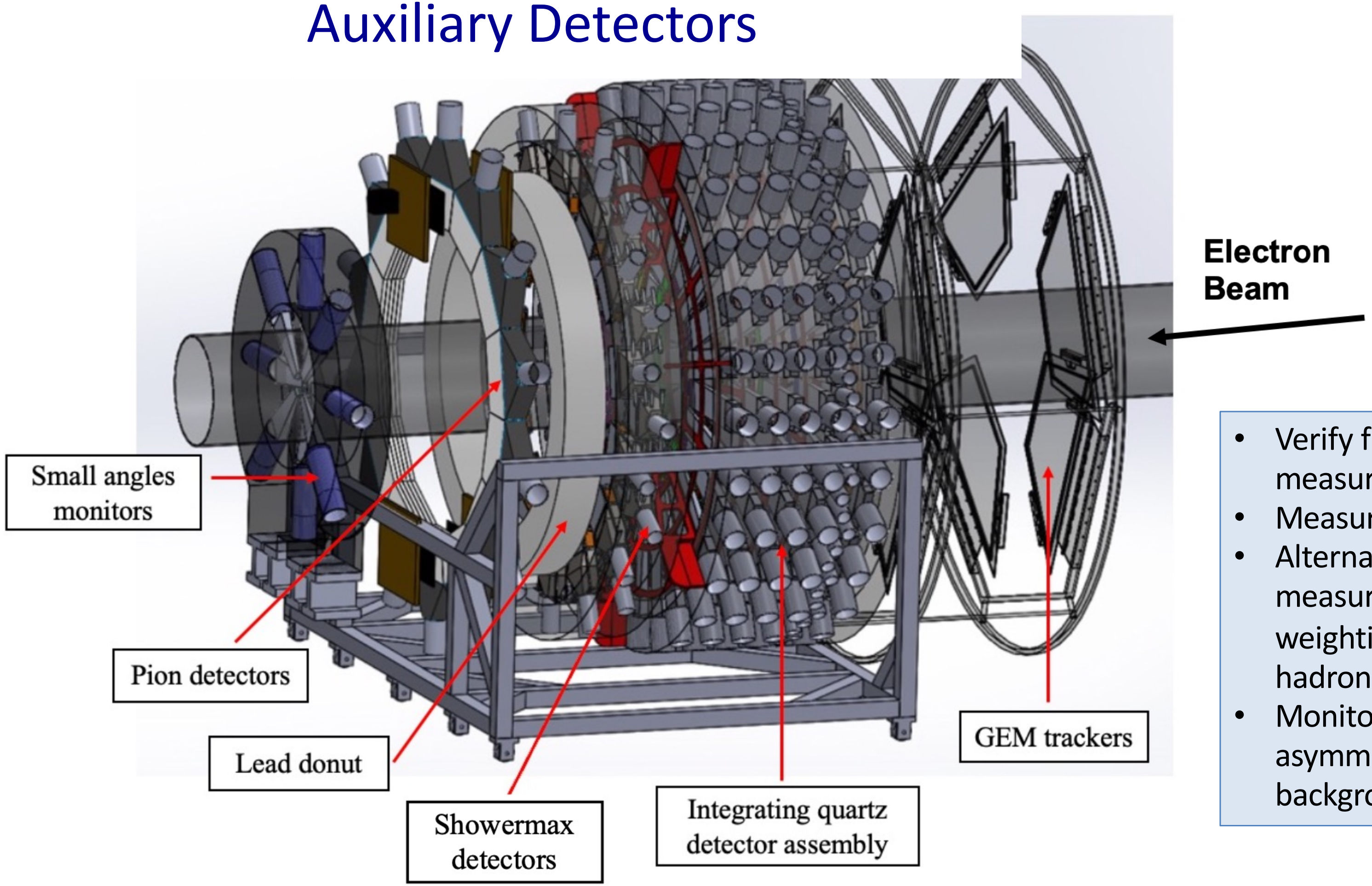




- Radiation hard fused-silica Cerenkov detectors
- Highly segmented for background deconvolution



Auxiliary Detectors



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

MOLLER Collaboration/Schedule

~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
DOE CD-2/3: expected 2023
Data-taking: 2025-2027

More information: arXiv/1411.4088

Summary

Qweak: precision measurement of A_{PV} in electron-proton scattering

- $\sin^2\theta_W$ to 0.46% – excellent agreement with Standard Model prediction

MOLLER: precision measurement of A_{PV} in electron-electron scattering

- $\sin^2\theta_W$ to 0.1% – will match best measurements at Z-pole
  $\rightarrow$ Precision Standard Model test

- New physics reach for flavor-diagonal lepton couplings to 27 TeV

Thanks to the Organizers, and thanks to you for listening!