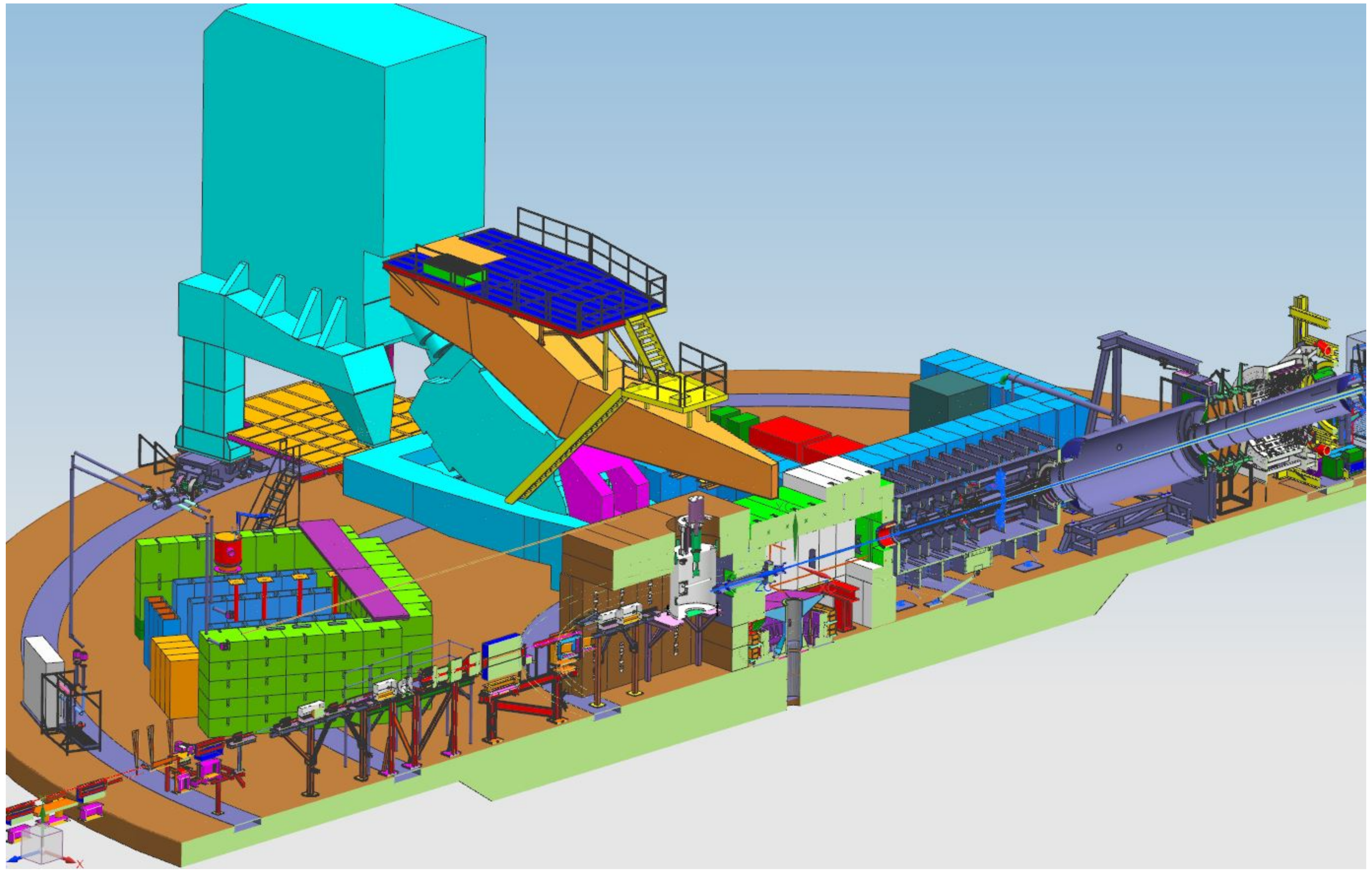
MOLLER Experimental Readiness Review 2



MOLLER Overview

This talk and next talk together describe how experimental design satisfies requirements

Charge questions:

- 5 (subsystem definitions)
- 12 (Collaboration Commitment)

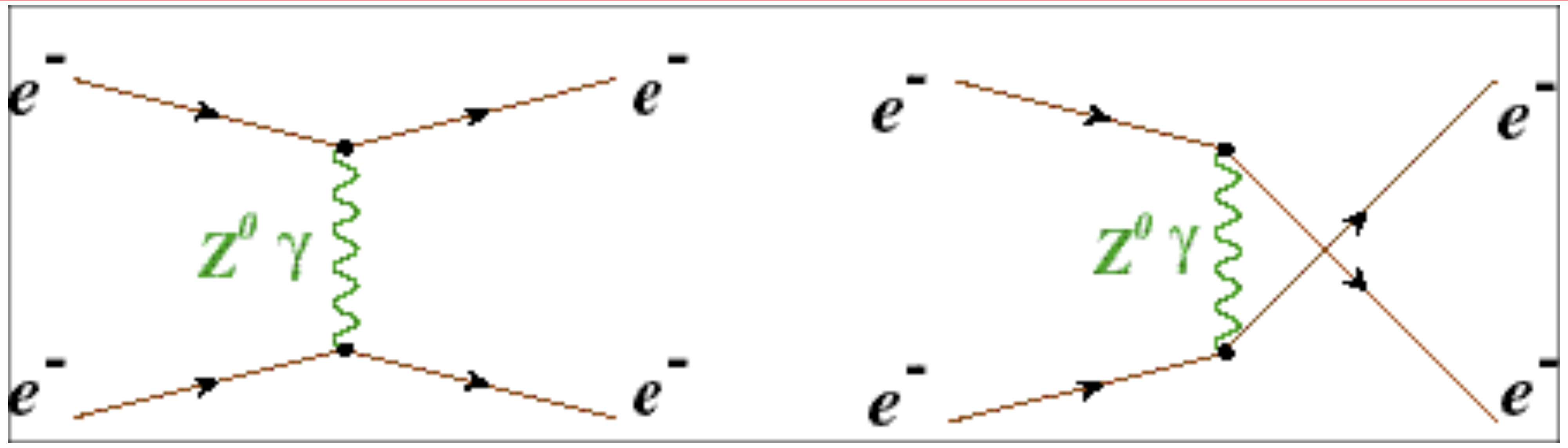
Krishna Kumar
MOLLER Collaboration Spokesperson
UMass, Amherst

July 29, 2025

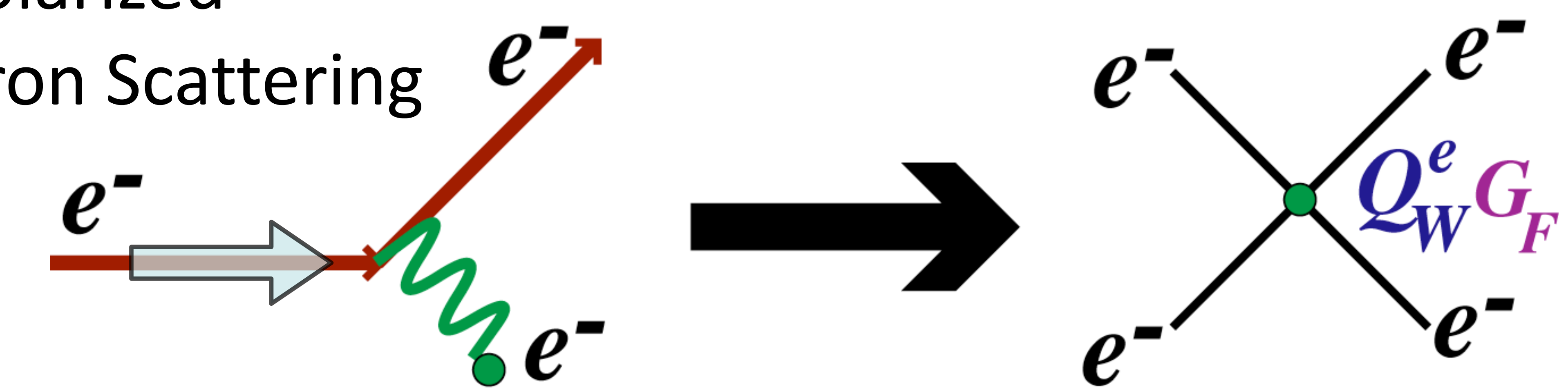
Outline

- **The MOLLER Observable**
- **The MOLLER Experimental Technique**
  - Overview of a parity violation experiment
  - Operational Parameters
- **The MOLLER Subsystems**
  - Scattered Flux Characteristics and Detector Requirements
  - Integrating and Counting Detectors
  - What’s Important and Not So Important
- **The MOLLER Collaboration**
  - Manpower and Commitment

The Observable: PV Asymmetry in Møller Scattering



Fixed Target Polarized Electron-Electron Scattering



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

COM Scattering Angle

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

$$Q^e_W = 1 - 4 \sin^2 \theta_W \sim 0.075$$

The Weak Charge of the Electron

$\delta(Q^e_W) = \pm 2.1\ \%$ (stat.) $\pm 1.1\ \%$ (syst.)

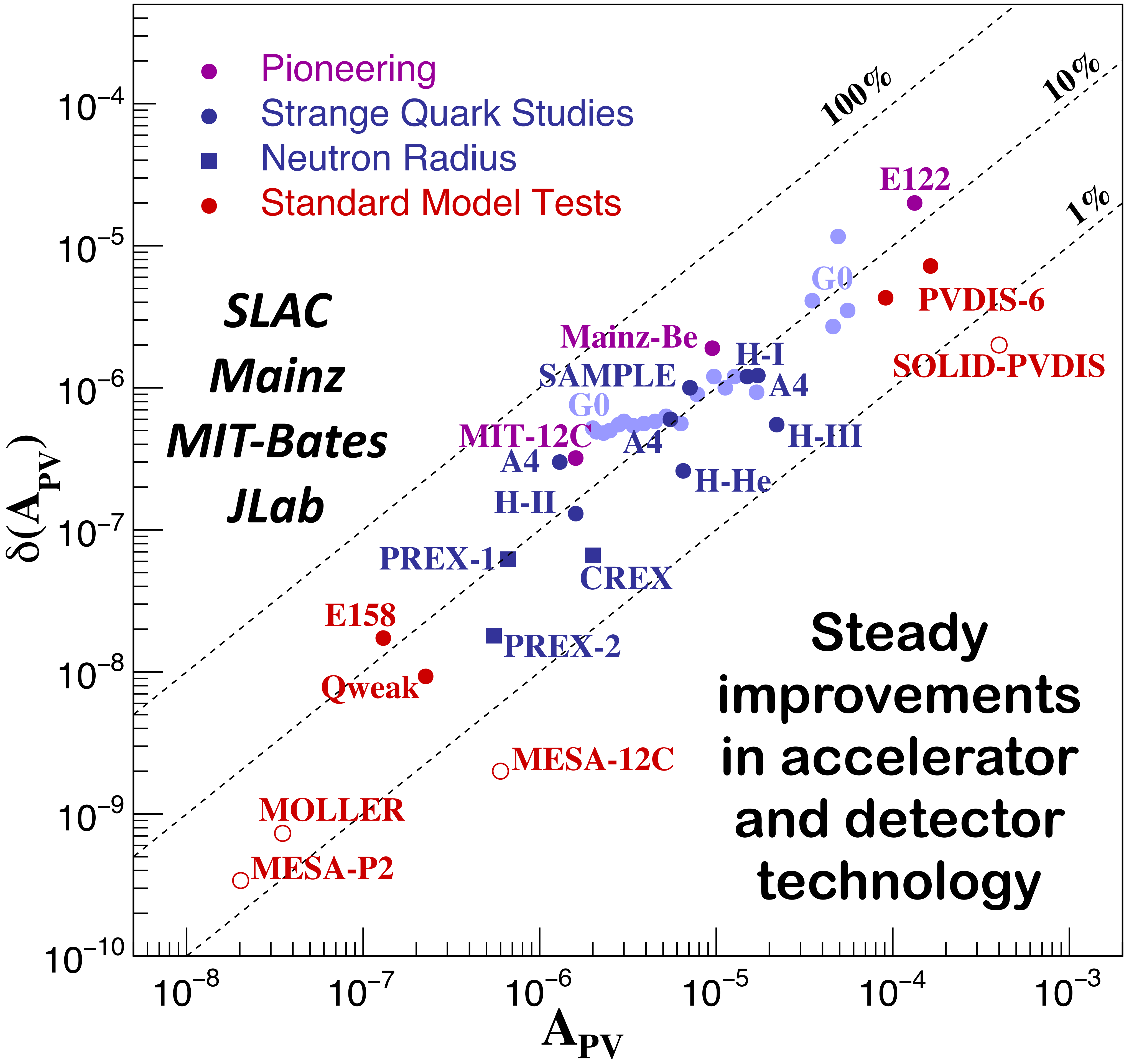
Jefferson Lab polarized electron beam

11 GeV, 65 μA   90% beam polarization

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

- **Unique sensitivity to TeV scale physics coupling more to leptons than to quarks**
- **Purely leptonic low Q^2 reaction: theory prediction accurately calculable with negligible hadronic physics uncertainty**

4^{th} Generation Parity-Violating Electron Scattering Experiment at JLab



Variety of Physics Topics:

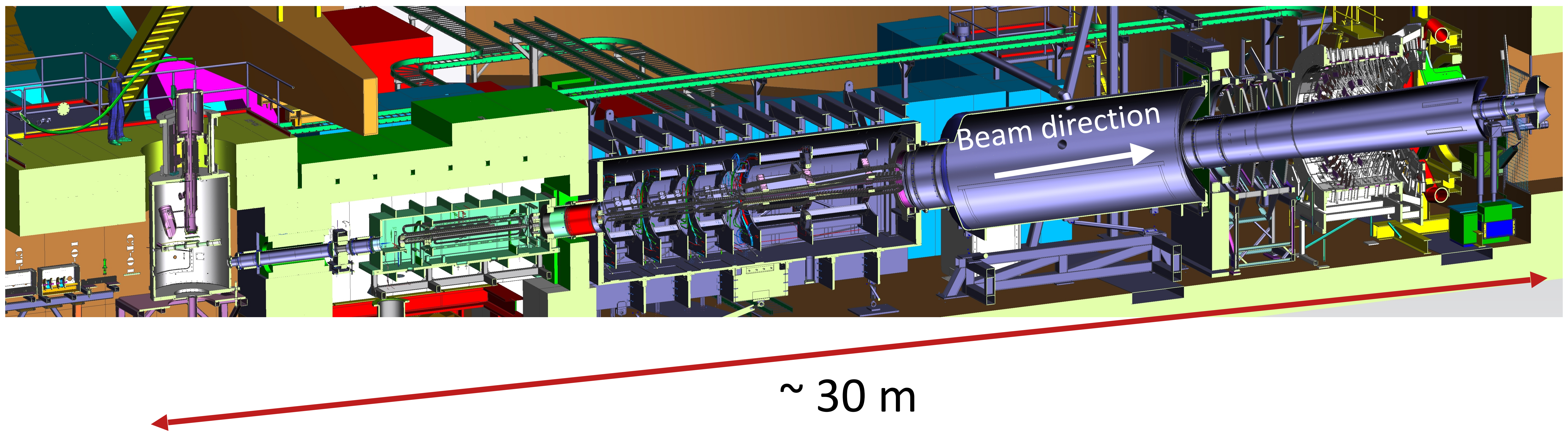
continuous interplay between hadron physics and electroweak physics

State of the Art

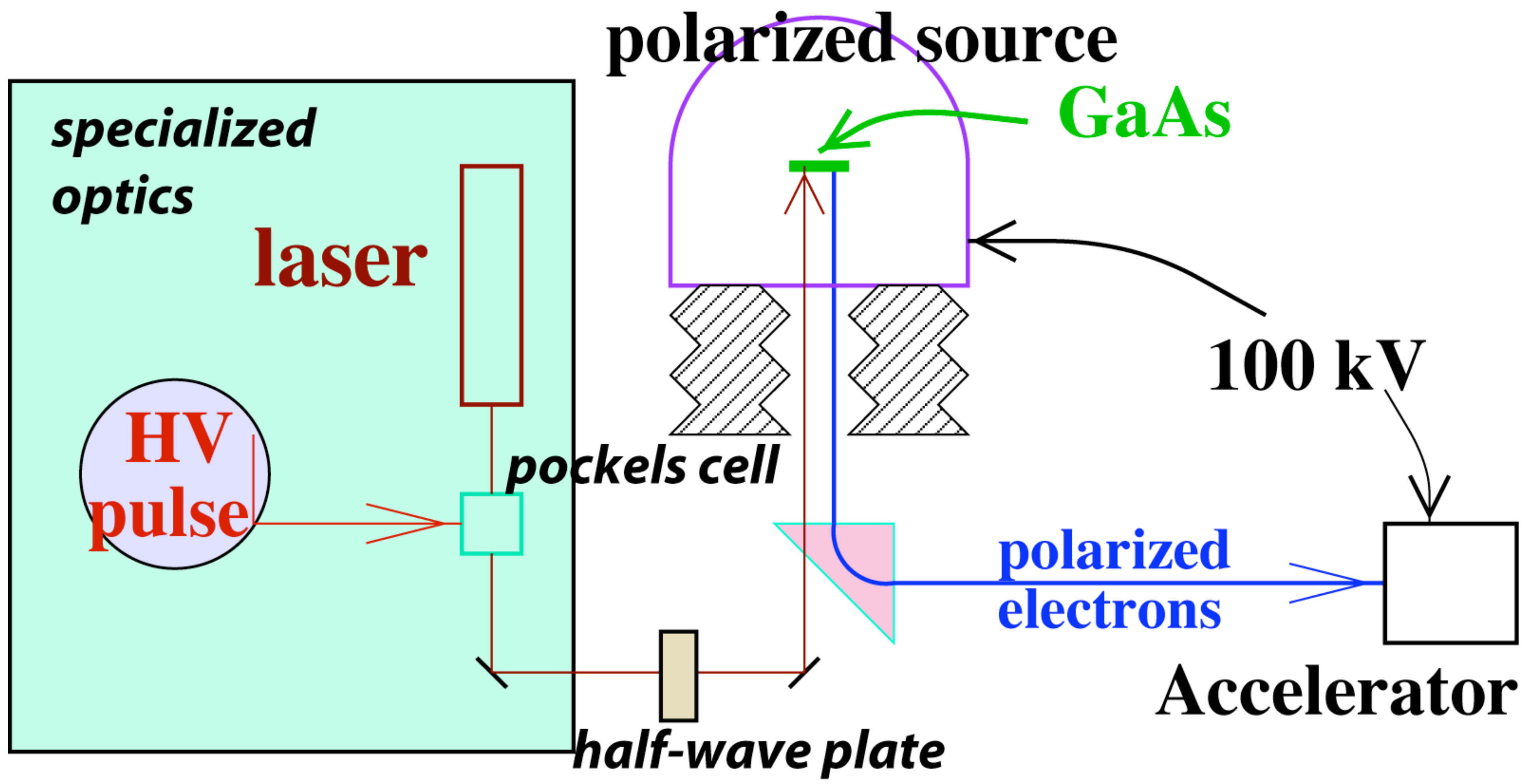
- sub-part per billion statistical reach and systematic control
- sub-1% normalization control

Unique opportunity leveraging 12 GeV Upgrade investment

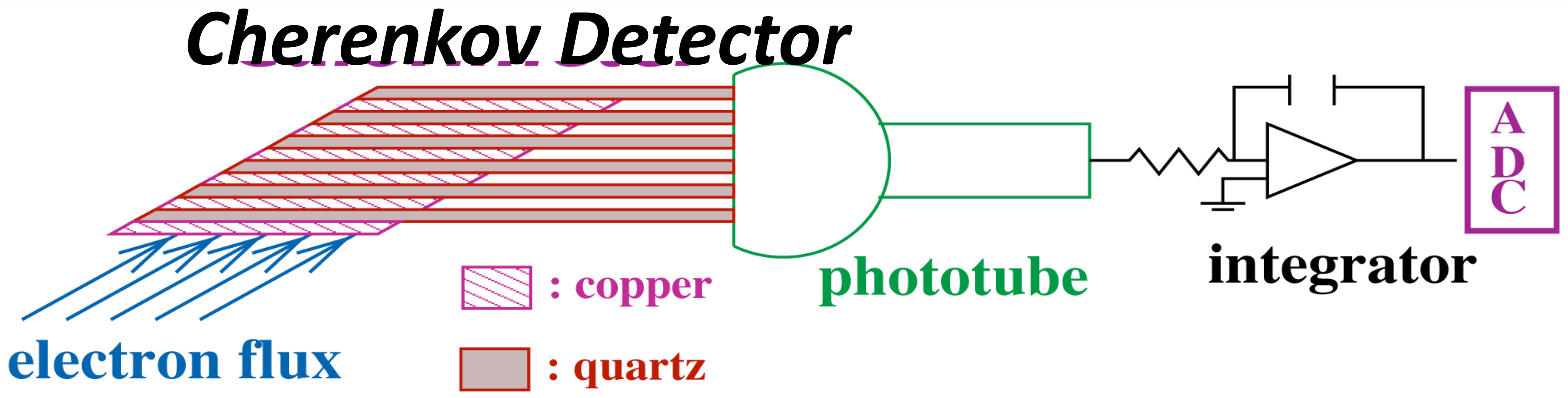
MOLLER: *Special purpose installation in Hall A*



Conceptual Overview of the Experimental Technique



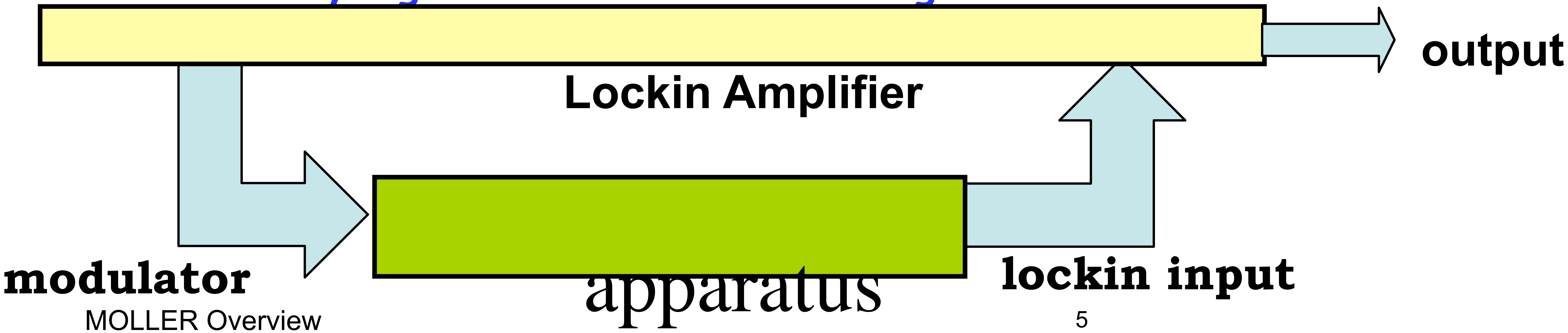
- Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency
- Rapid helicity reversal: polarization sign flips > 100 Hz to minimize the impact of drifts
- Helicity-correlated beam motion: under sign flip, beam stability at the sub-micron level



"Flux Integration": very high rates

direct scattered flux to background-free region

Tiny signal buried in known background



Apparatus:

beam, target, spectrometer, detectors and accelerator all interconnected!

Asymmetry Measurement Overview

Suppose instantaneous signal rate ~ 100 GHz and the beam helicity is reversed at 2 kHz

1 kHz Pulse Pair Width: ~100 ppm → 10 Billion Pairs: 1 ppb (average 10^7 s)

Detector D, Current I: F = D/I

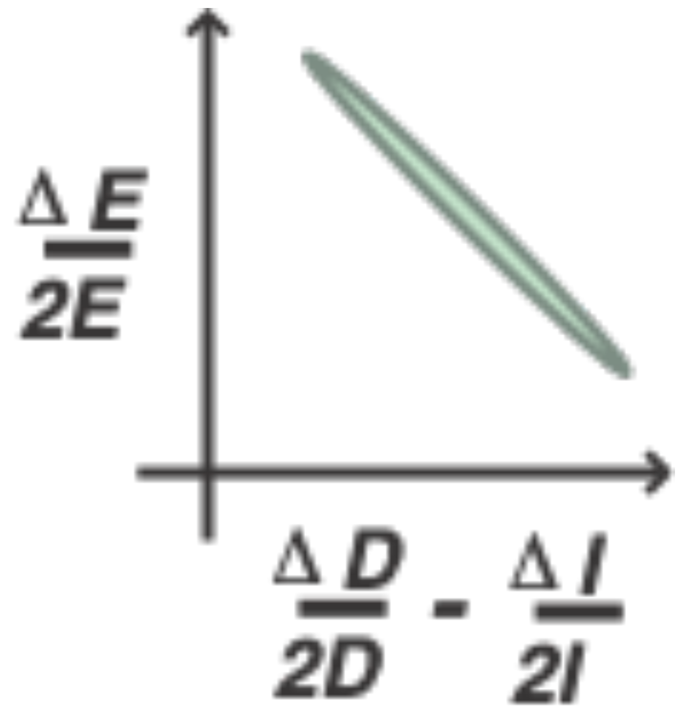
$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

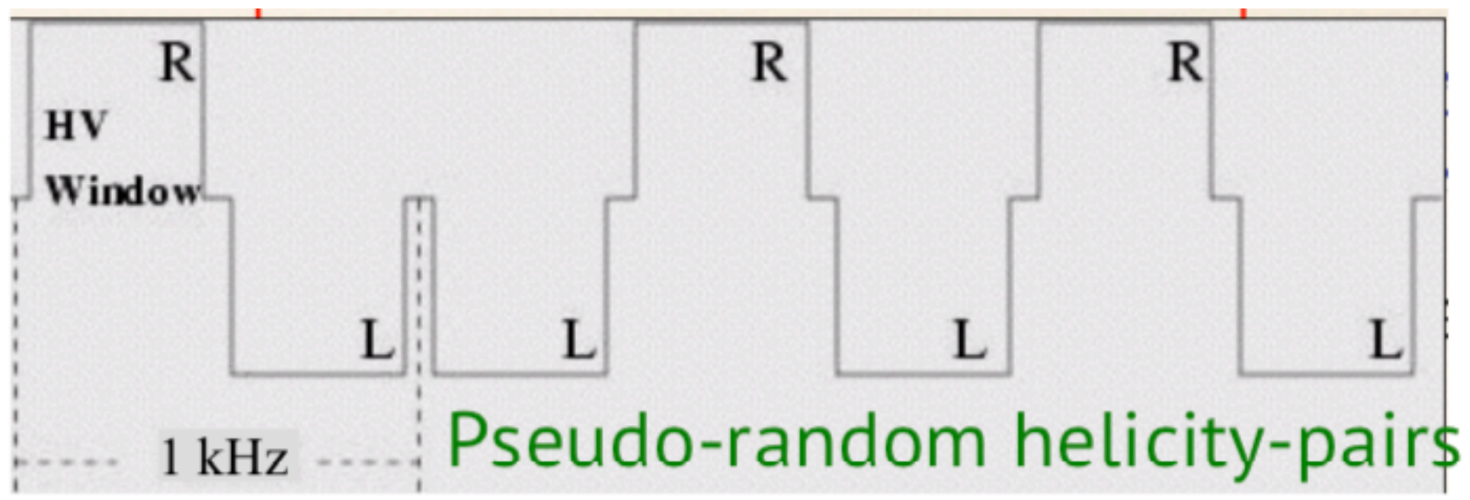
$$\left(A_{expt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

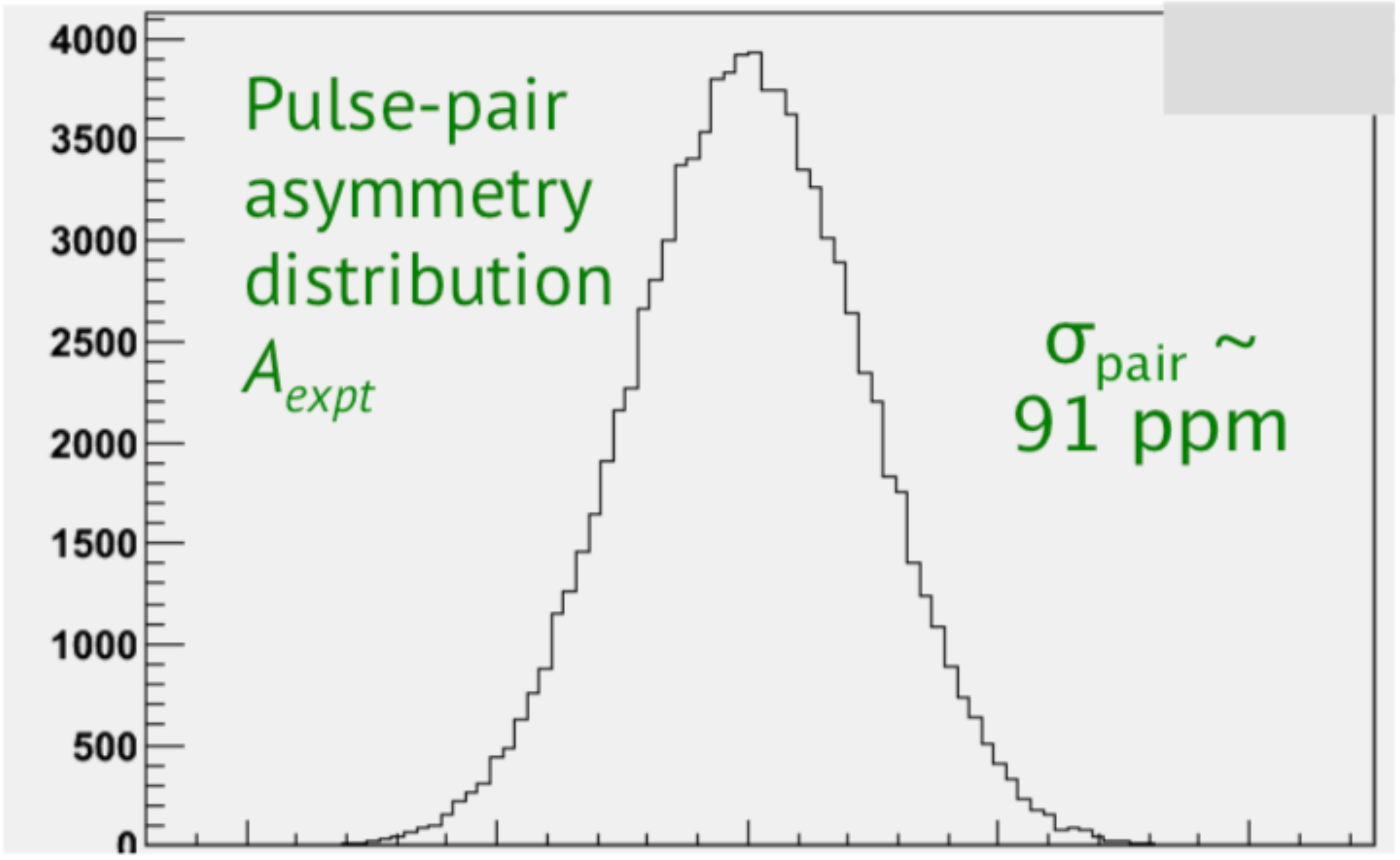
I order: $x, y, \theta_x, \theta_y, E$
II order: e.g. spot-size

Must minimize both random and helicity correlated fluctuations due to electron beam trajectory, energy and spot-size



After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects A_{phys}





$$\sigma_{A_{expt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}} = \frac{91\,\text{ppm}}{\sqrt{30\times10^9}} = 0.5\,\text{ppb}$$

Pulse-pair "width" σ_{pair} is the parameter that determines the statistical error

Essential Characteristics of the CEBAF Polarized Electron Beam

Highly intense, stable, 11 GeV electron beam with longitudinal beam polarization

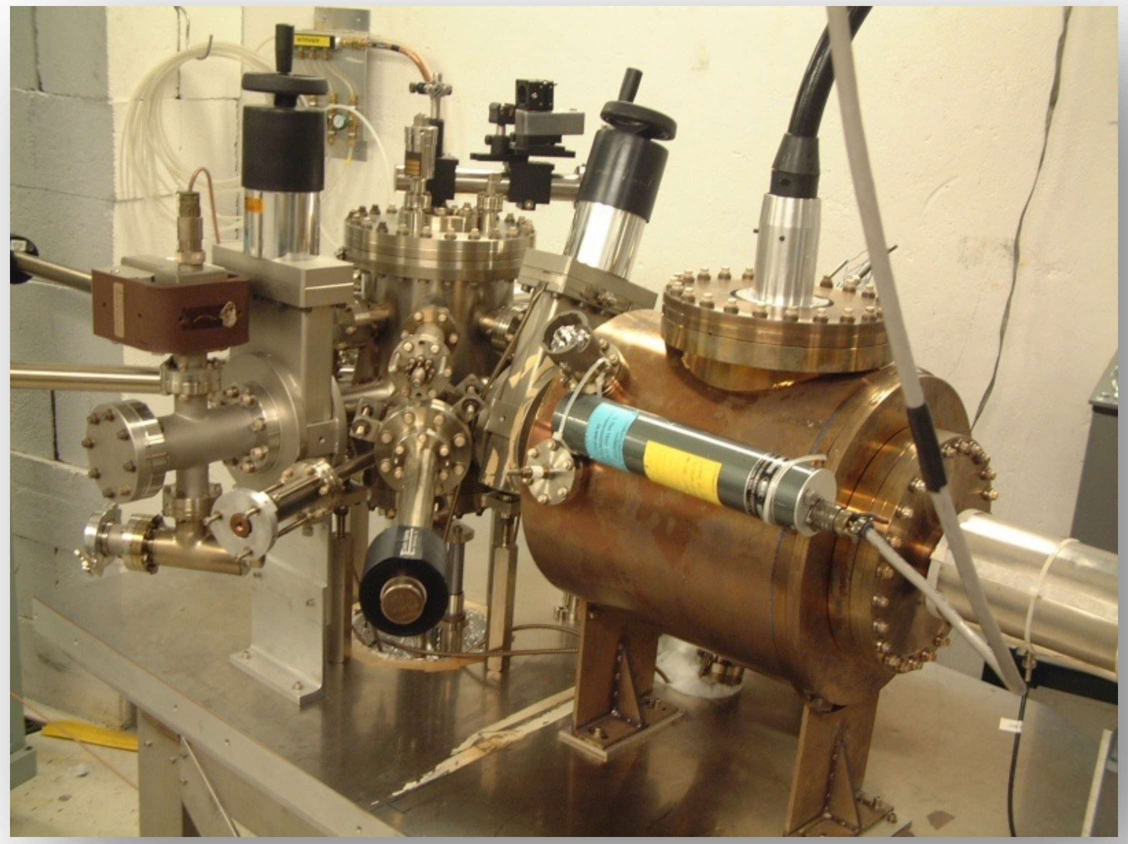


Figure of merit rises linearly with beam energy: experiment not viable below a few GeV with current state-of-the-art

Systematic control likely impossible without a "cold" "CW" machine

University of Virginia
Indiana University
Jefferson Lab

MOLLER will plan to use 1.96 kHz reversal to reverse the electron beam helicity

CEBAF beam properties: 2 kHz time scale (~ppm, microns) AND days (~ppb, nm) must be carefully tuned, actively monitored and maintained with proper diagnostics

Extensive operation experience manipulating injector characteristics: control systematics

10's of ppb beam charge asymmetry and ~ 1 nm control of position asymmetry

MOLLER's dedicated source team works closely with the Injector Group (as with PREX/CREX)

MOLLER Operational Parameters

Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
θ_{CM}	50°-130°
θ_{lab}	0.26°-1.2°
$\langle Q^2 \rangle$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$2.4 \cdot 10^{39}$
σ [μbarn]	≈ 60
Møller Rate @ 65 μA [GHz]	≈ 134
Statistical Width(1.92 kHz flip) [ppm/pair]	≈ 91
Target Raster Size [mm $\times$ mm]	5×5
Production running time	344 PAC-days = 8256 hours
ΔA_{raw} [ppb]	≈ 0.54
Background Fraction	≈ 0.10
P_B	$\approx 90\%$
$\langle A_{PV} \rangle$ [ppb]	≈ 32
$\Delta A_{stat}/\langle A_{expt} \rangle$	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.00023

$$\sigma_{A_{cxpt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}}$$

Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	$\sim$ **82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

$$A_{cxpt} \sim 26\,\text{ppb} \qquad \frac{\sigma_{A_{cxpt}}}{A_{cxpt}} = 2.1\%$$

$$\text{Combined} \quad \frac{\delta A_{PV}}{A_{PV}} = 2.4\%$$

Projected Uncertainties: Progression on Statistics Reach and Systematic Control

Uncertainty budget for A_{PV}

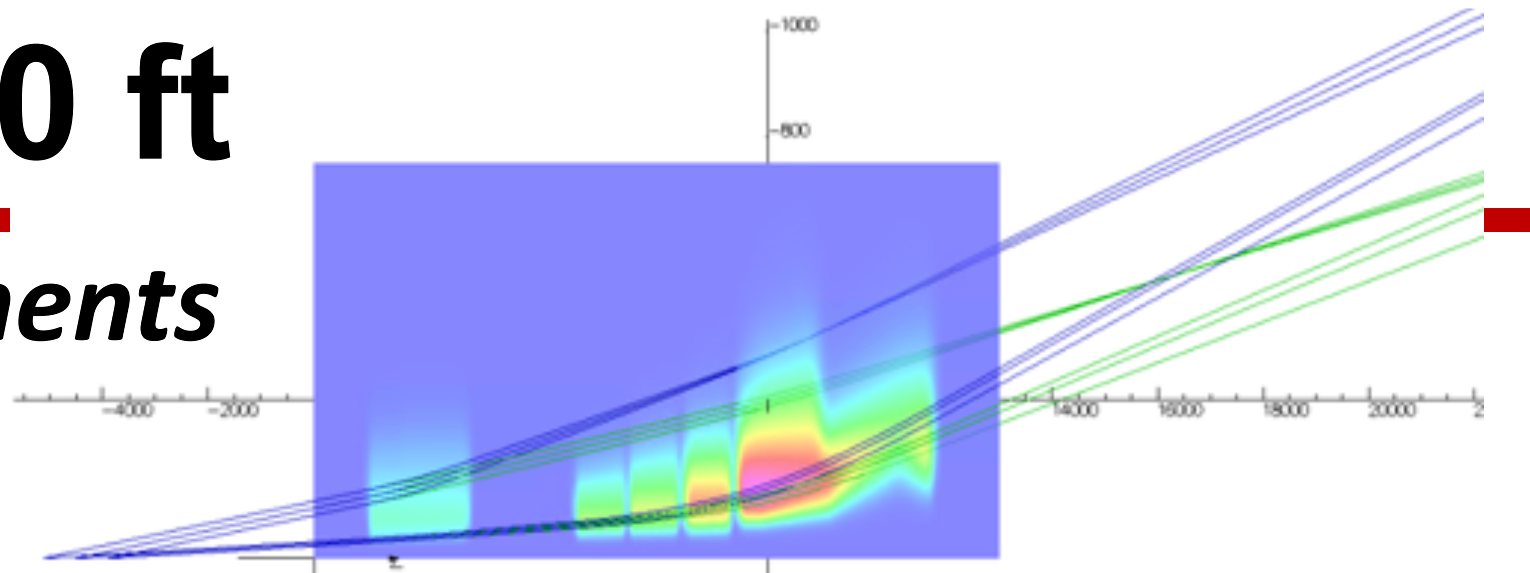
Error Source	Fractional Error (%) Run 1	Fractional Error (%) Ultimate
Statistical	**11.4**	**2.1**
Absolute Norm. of the Kinematic Factor	3	0.5
Beam (second moment)	2	0.4
Beam polarization	1	0.4
$e + p(+\gamma) \to e + X(+\gamma)$	2	0.4
Beam (position, angle, energy)	2	0.4
Beam (intensity)	1	0.3
$e + p(+\gamma) \to e + p(+\gamma)$	0.6	0.3
$\gamma^{(*)} + p \to (\pi, \mu, K) + X$	1.5	0.3
$e + Al(+\gamma) \to e + Al(+\gamma)$	0.3	0.15
Transverse polarization	2	0.2
Neutral background (soft photons, neutrons)	0.5	0.1
Linearity	0.1	0.1
Total systematic	**5.5**	**1.1**

Run Period	1 kHz Width	PAC Days (prod)	Stat Error $\sigma(A_{meas})$	Stat Error $\sigma(A_{PV})$
I	101	14	2.96 ppb	11.4%
II	96	95	1.08 ppb	4.2%
III	91	235	0.65 ppb	2.5%
Total		344	0.55	2.1

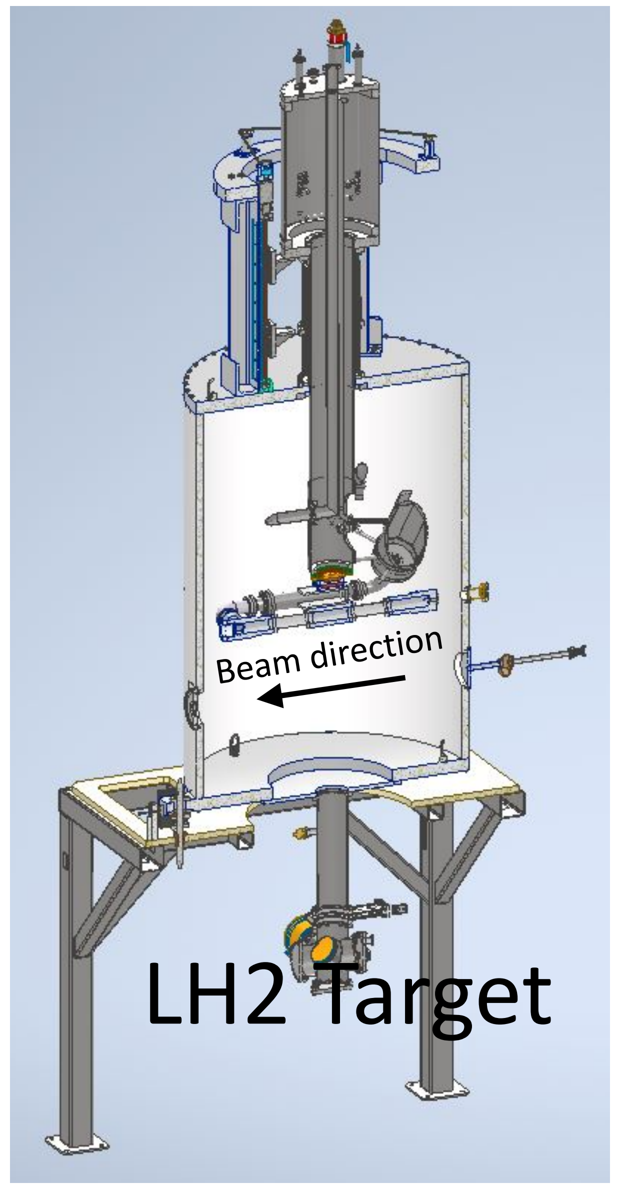
- **The ultimate uncertainties to be achieved progressively with operational experience**
  - 1 kHz width has ~ 40 ppm for unknown unknowns in Run 1
  - Polarimetry uncertainties for run 1 already achieved
  - Transverse polarization limits are modest for run 1
  - Inelastic background subtraction is statistics limited
- **Run 1 will have two goals**
  - Apart from achieving the statistics and systematic goals, we need to do studies to reach ultimate goals

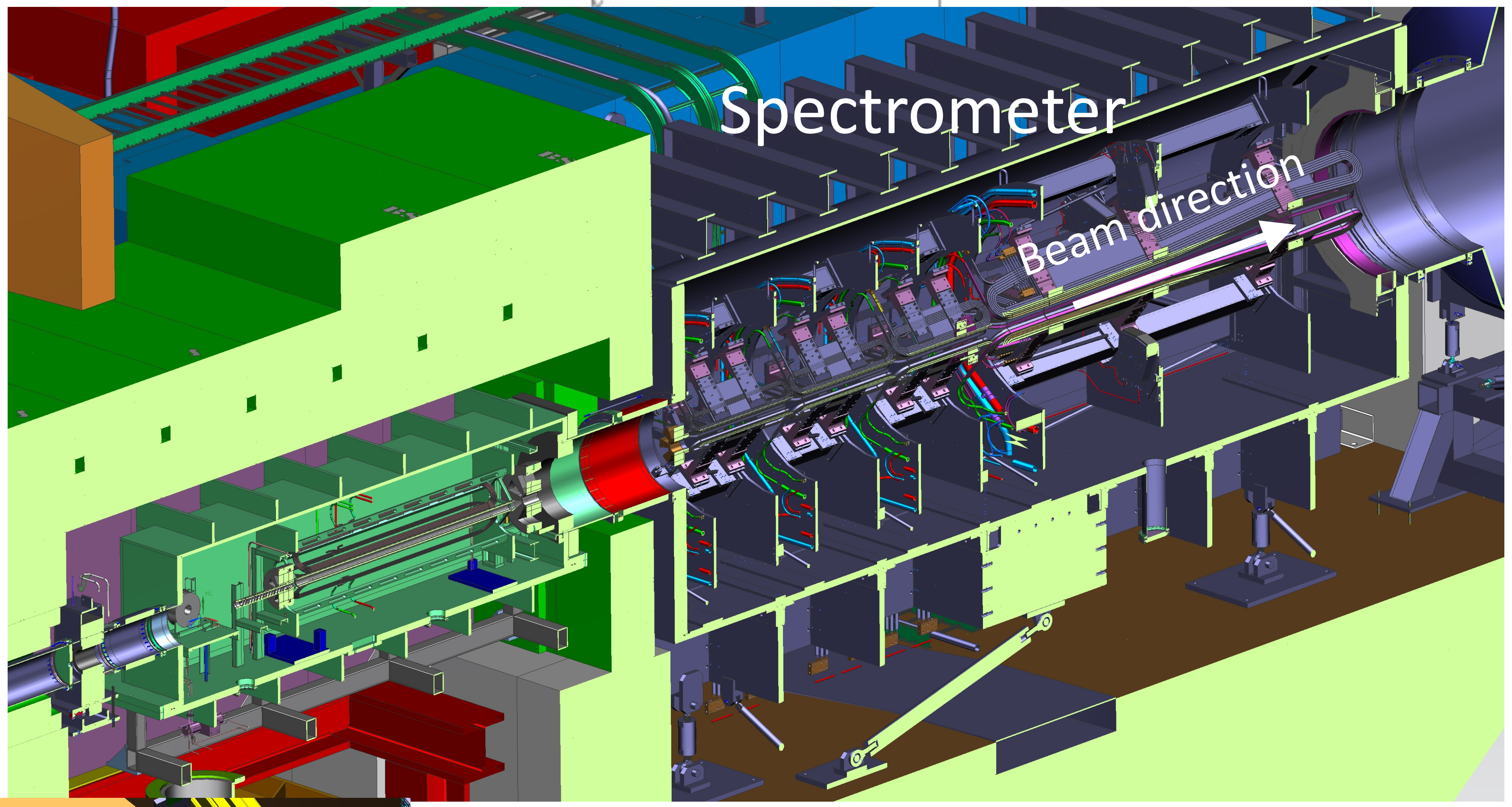
MOLLER Apparatus Characteristics From 30000 ft

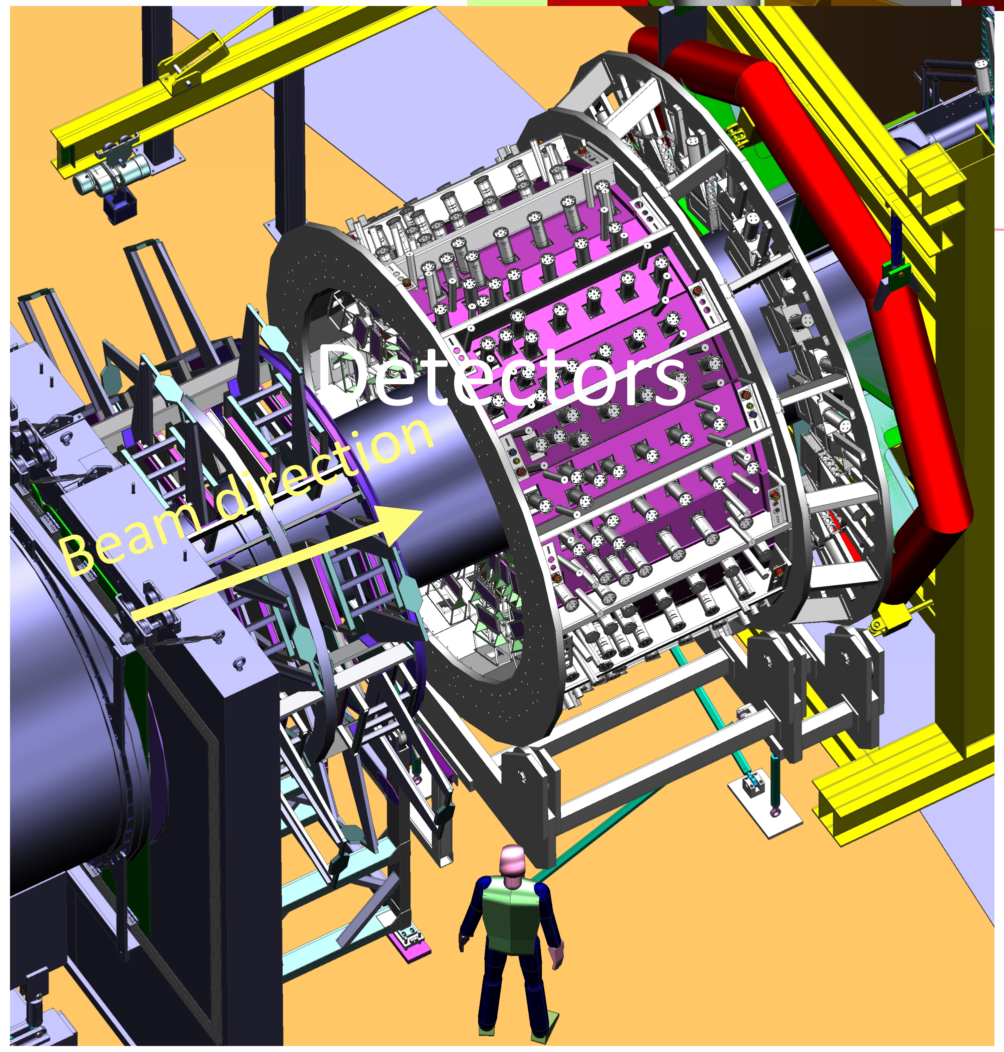
Evolutionary Improvements from Technology of Third Generation Experiments

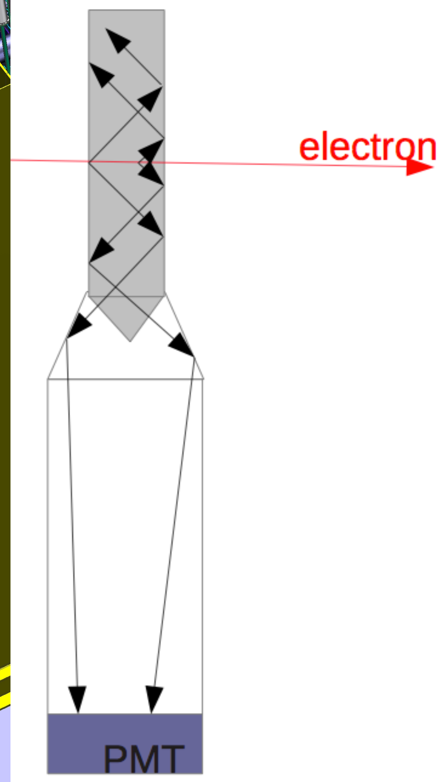


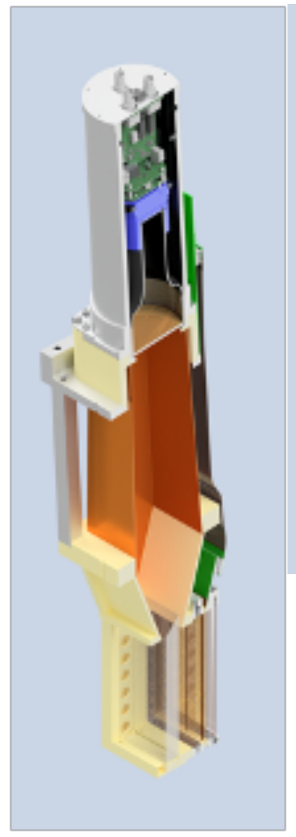
- High intensity polarized electron source
- ~ 134 GHz scattered electron rate
- 1 nm control of beam centroid on target
- ~ 9 gm/cm^2 liquid hydrogen target
  - 1.25 m: ~ 3.7 kW @ 70 µA
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - novel toroidal spectrometer assemblies
  - radiation hard, segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry



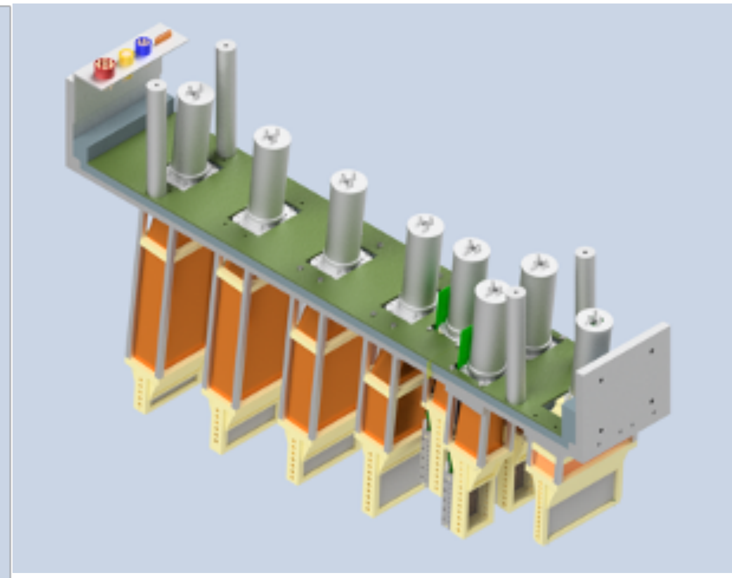








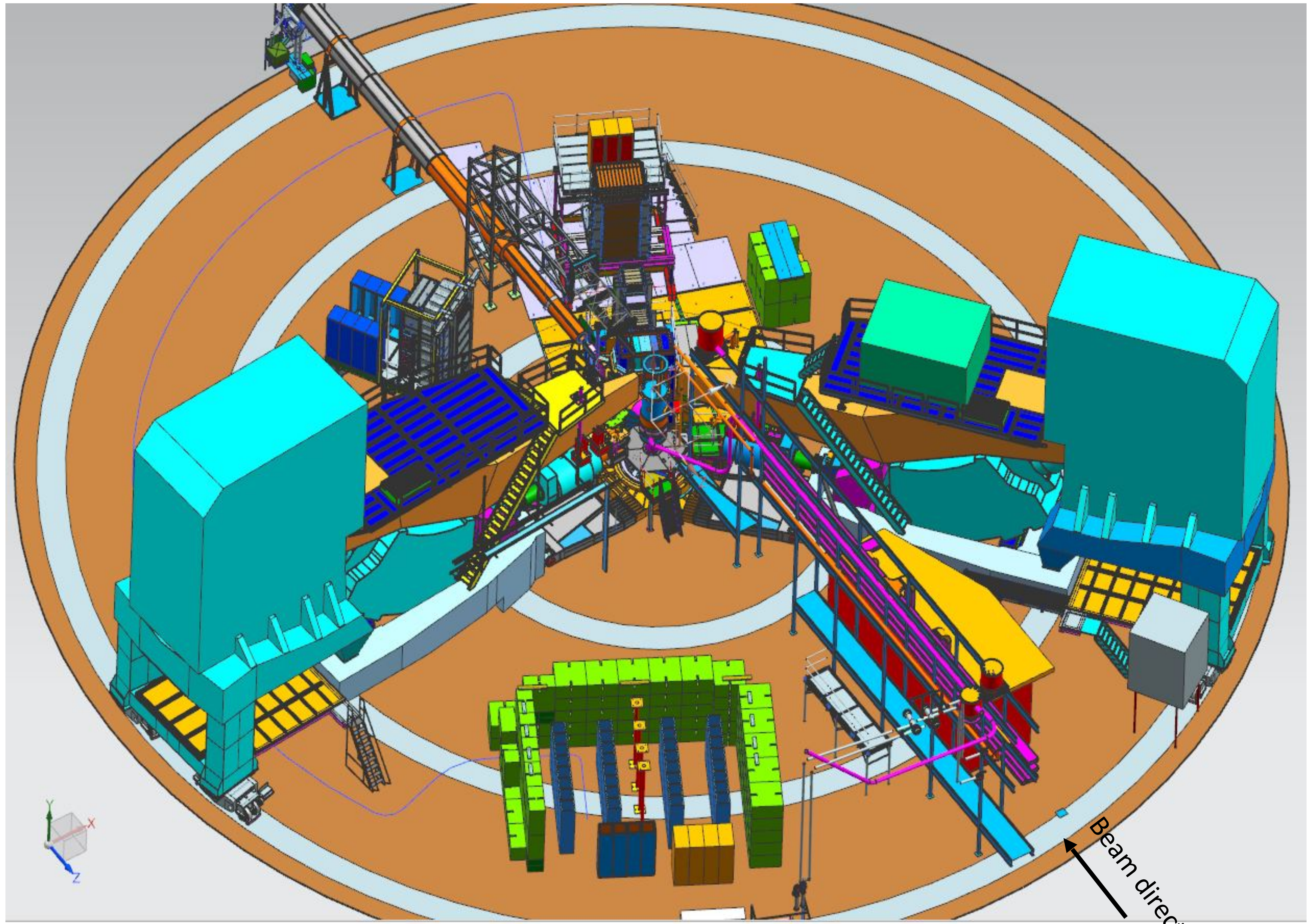
Single channel



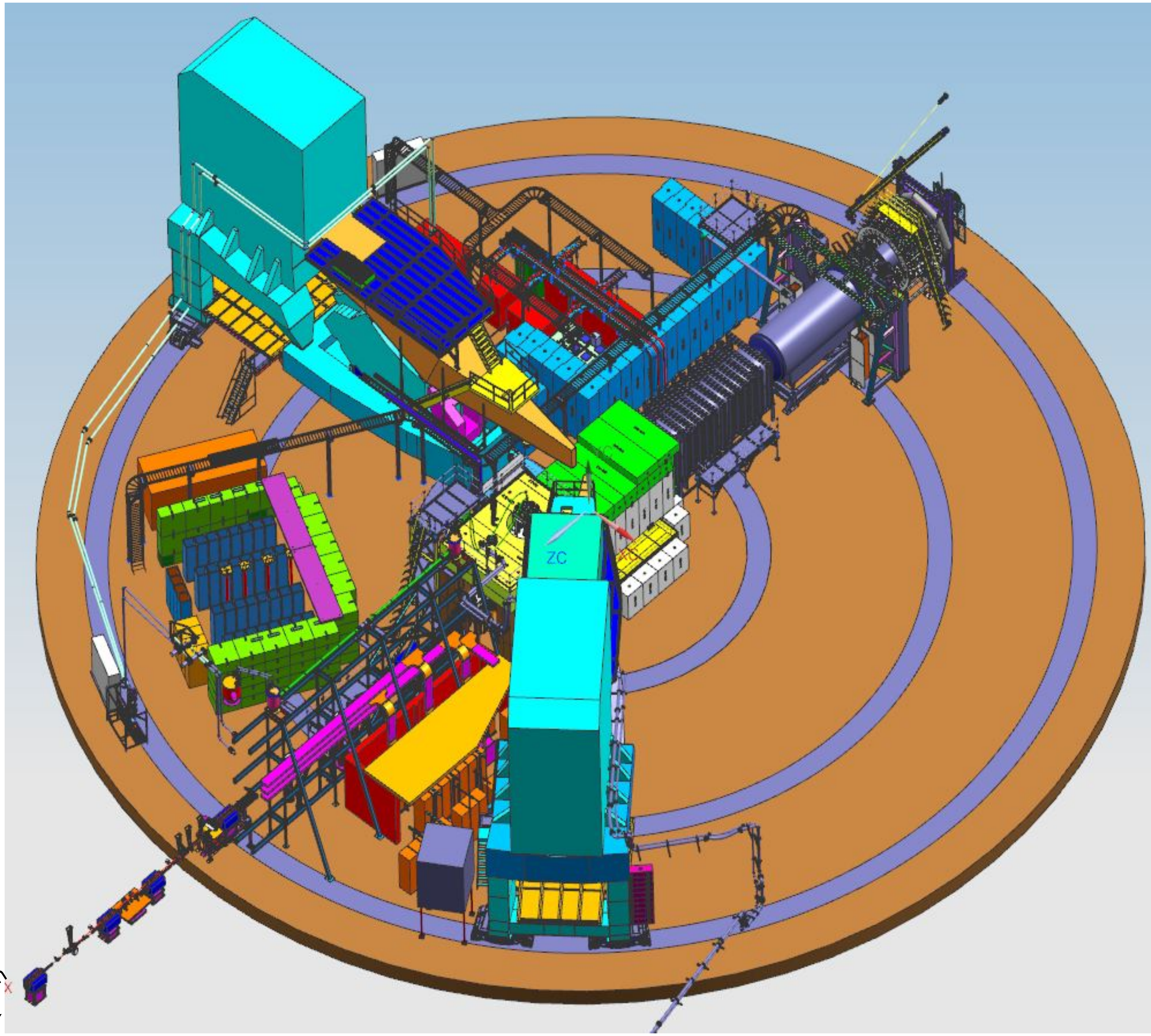
1/28th Segment

- **MOLLER Collaboration Team**
  - Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - Final Technical Design Report is public

Bird’s Eye View of Evolution from SBS to MOLLER

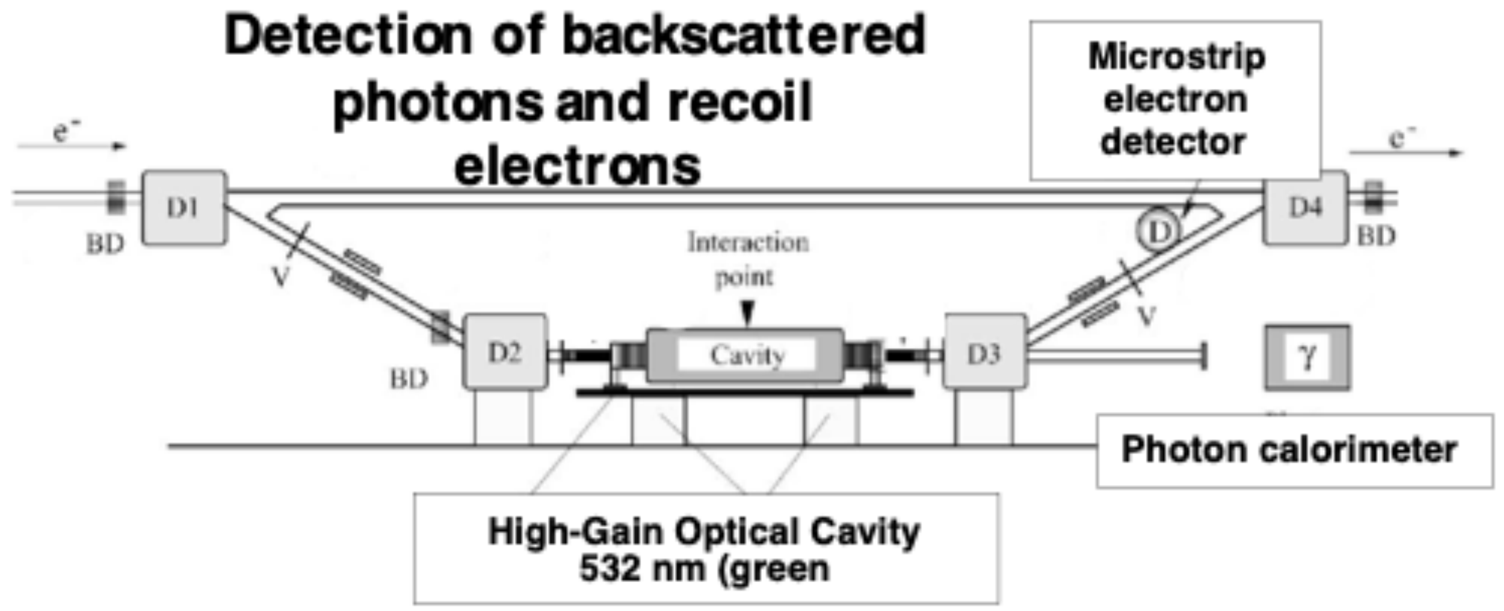


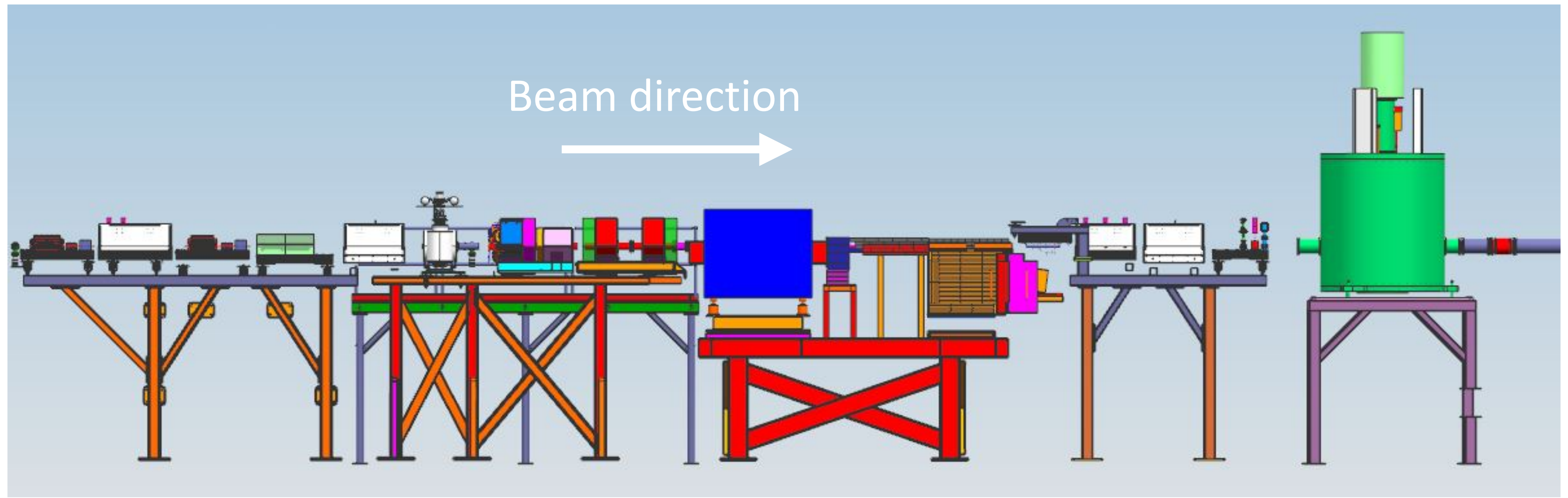
Beam direction



Beam direction

Beamline, Target and Polarimetry





Beamline and Beam Monitoring

- Redundant position, angle, intensity monitoring
- Intensity, position monitor resolution requirements

Indiana University
Virginia Tech
University of Virginia
Jefferson Lab

Electron Beam Polarimetry

- Two independent measurements
- Compton: continuous monitor
- Møller: invasive at low beam current

Temple University
University of Virginia
Jefferson Lab
Syracuse University
University of Manitoba

Several dependencies and some MIE scope

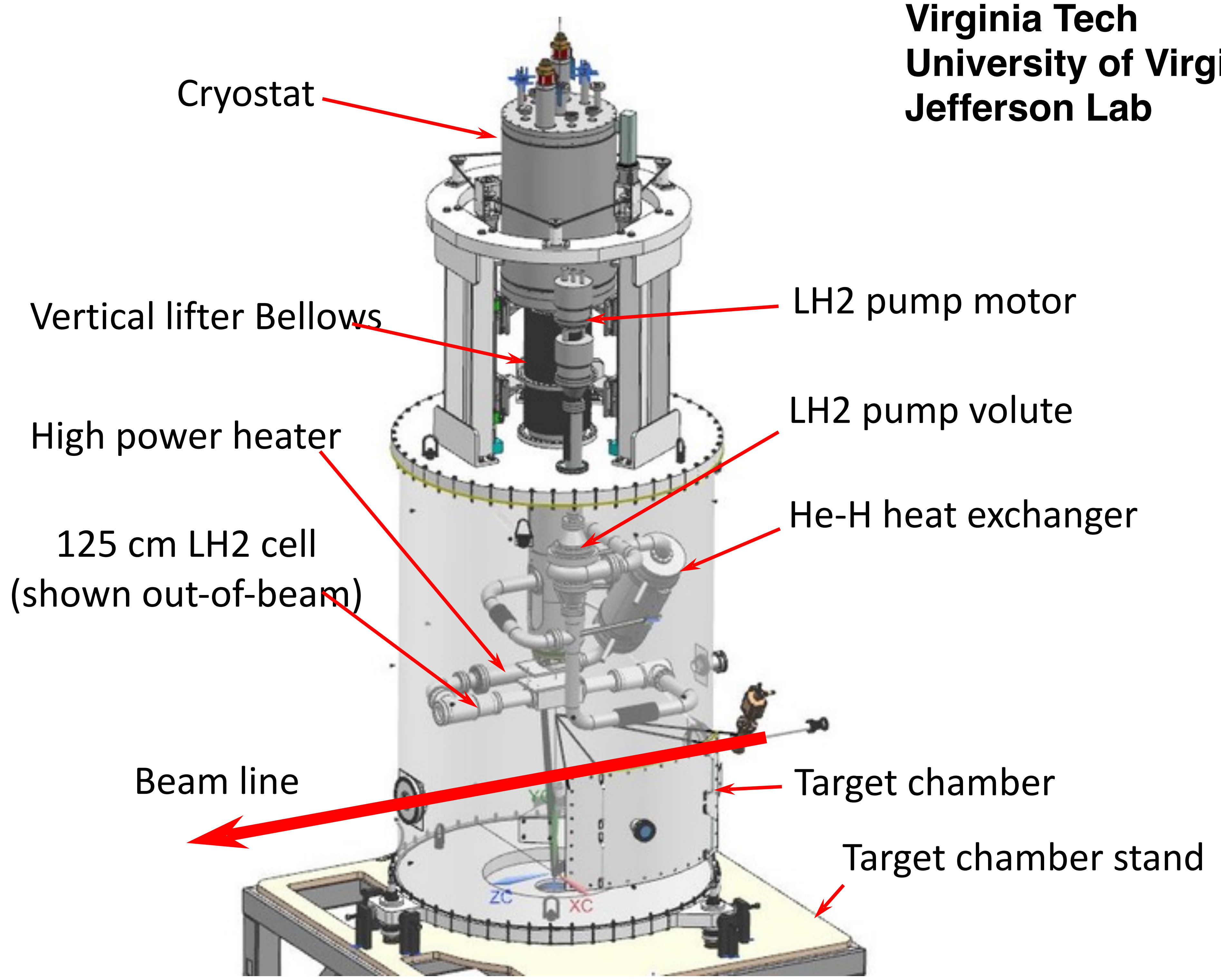
Liquid Hydrogen Target

Jefferson Lab

- up to 70 µA on 125 cm LH_2 target - 3.7 kW
- Q_{weak} experience: use of CFD (computational fluid dynamics)

Main requirement: minimize target density fluctuations (Δρ/ρ):

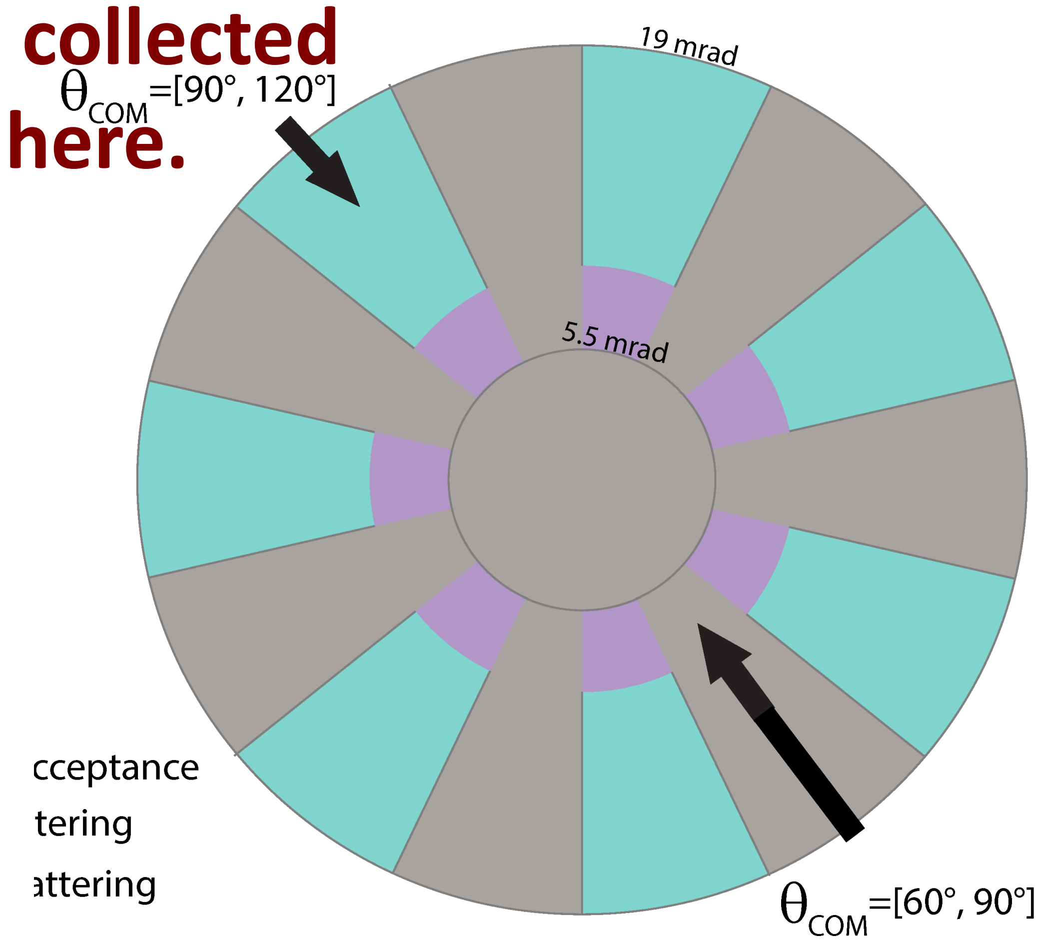
Γ_{target} < 30 ppm for 70 µA, 5x5 mm² raster, 1.92 kHz flip



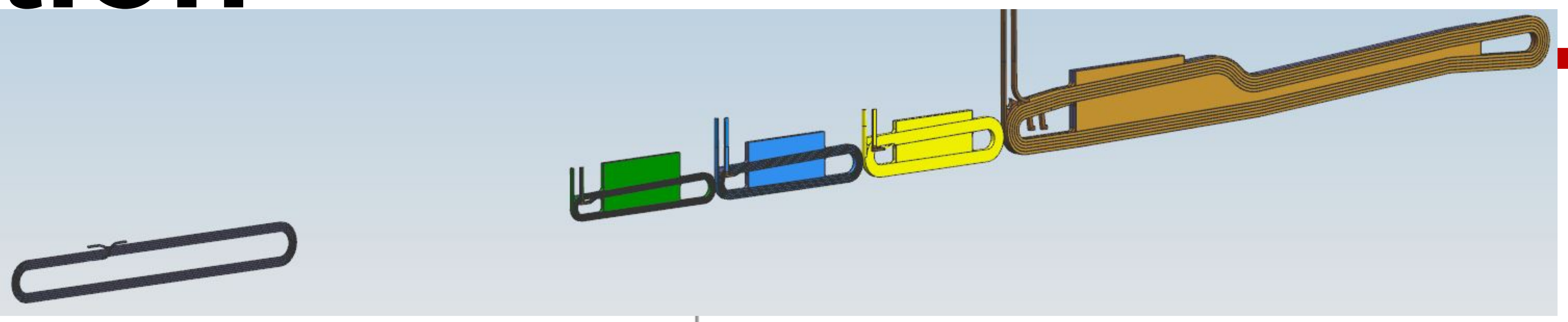
Spectrometer Acceptance and Collimation

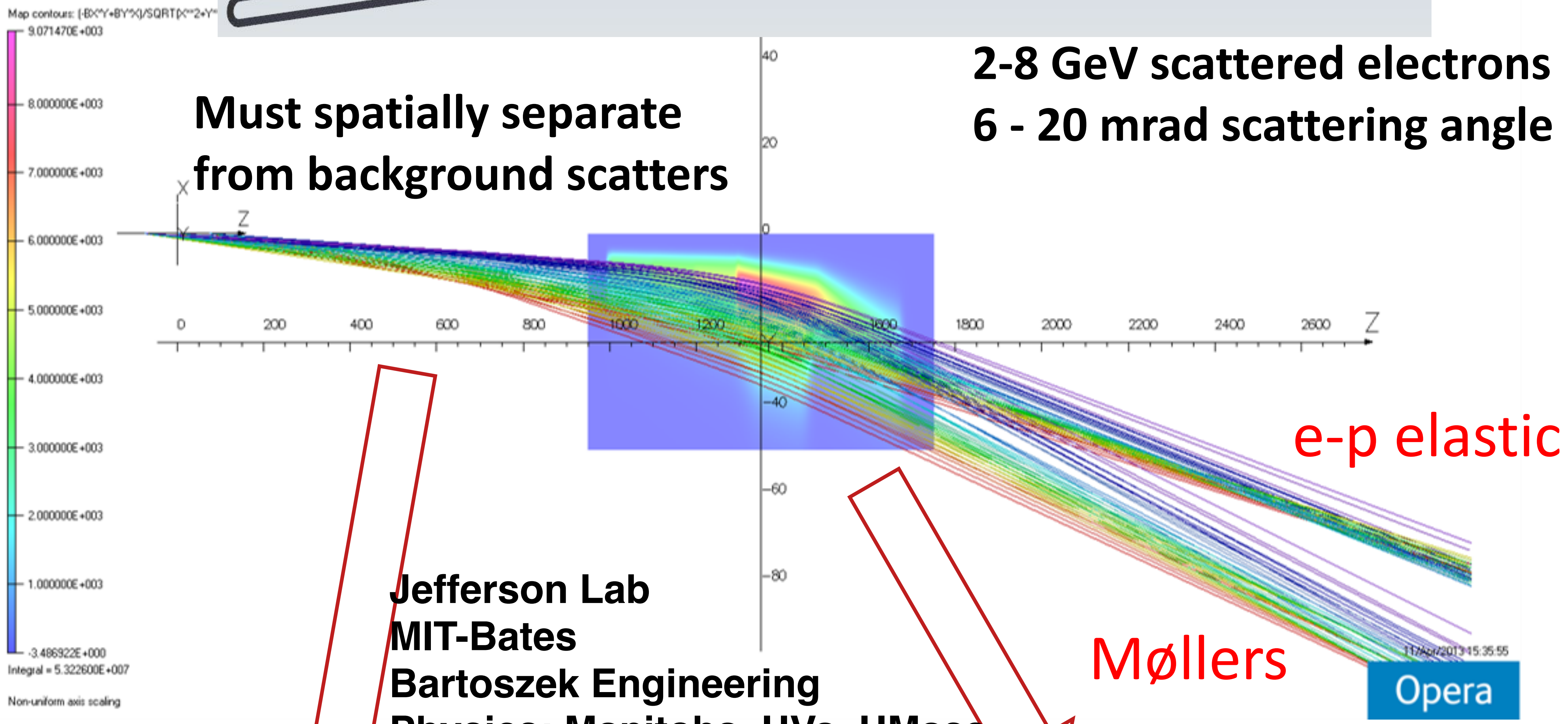
- Accept all Møller scattered electrons in range Θ_{CM} = 50° – 130°
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

…are collected over here.



The rays that are blocked here…





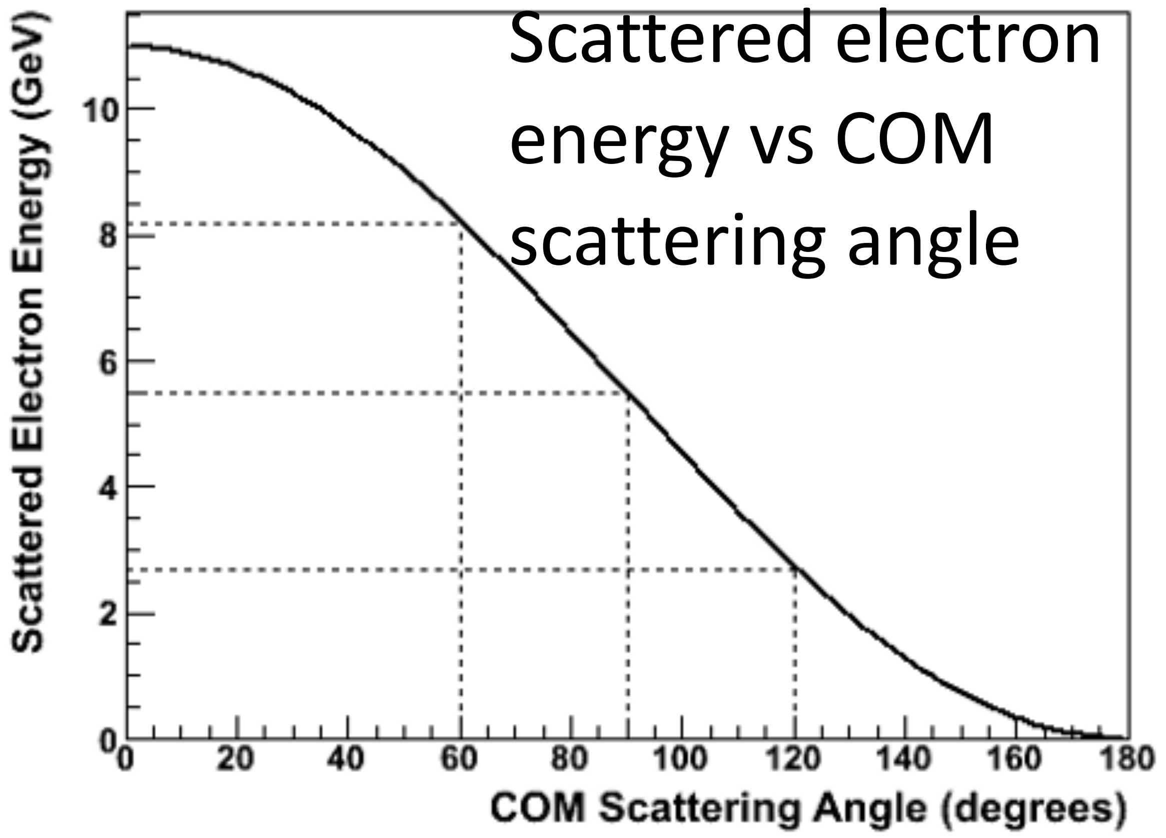
Must spatially separate from background scatters

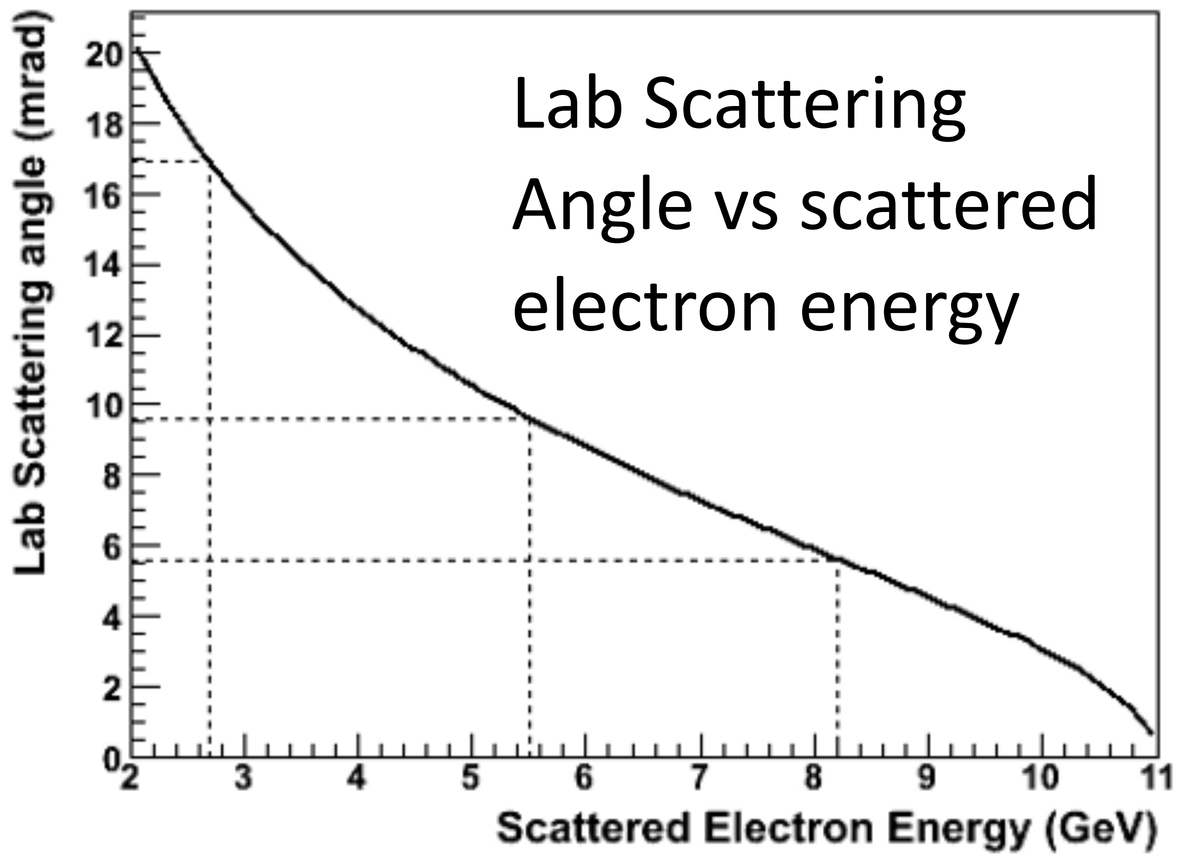
2-8 GeV scattered electrons
6 - 20 mrad scattering angle

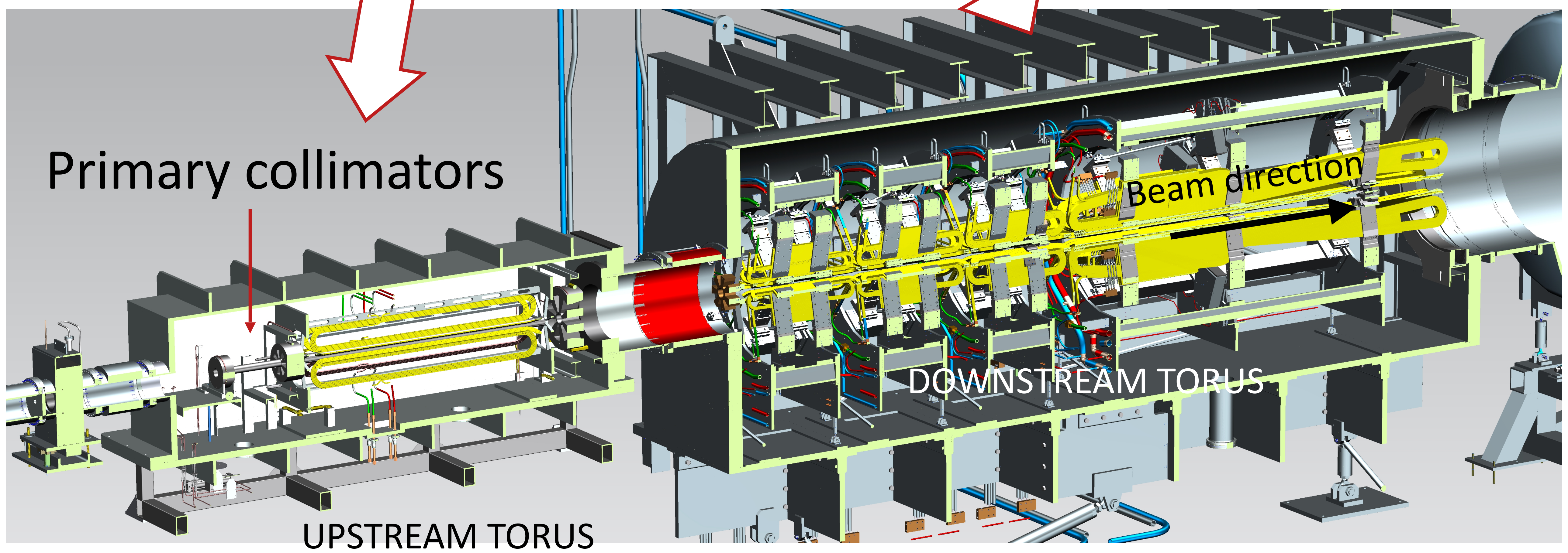
e-p elastic

Møllers

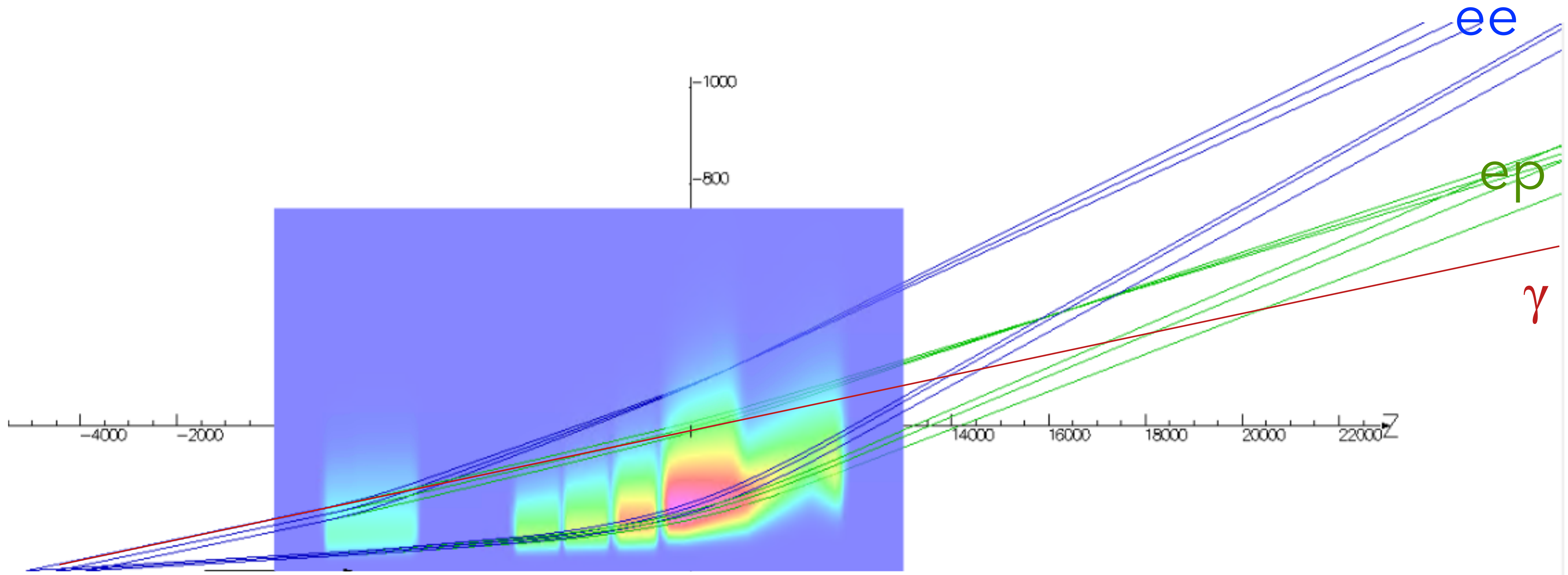
Jefferson Lab
MIT-Bates
Bartoszek Engineering
Physics: Manitoba, UVa, UMass

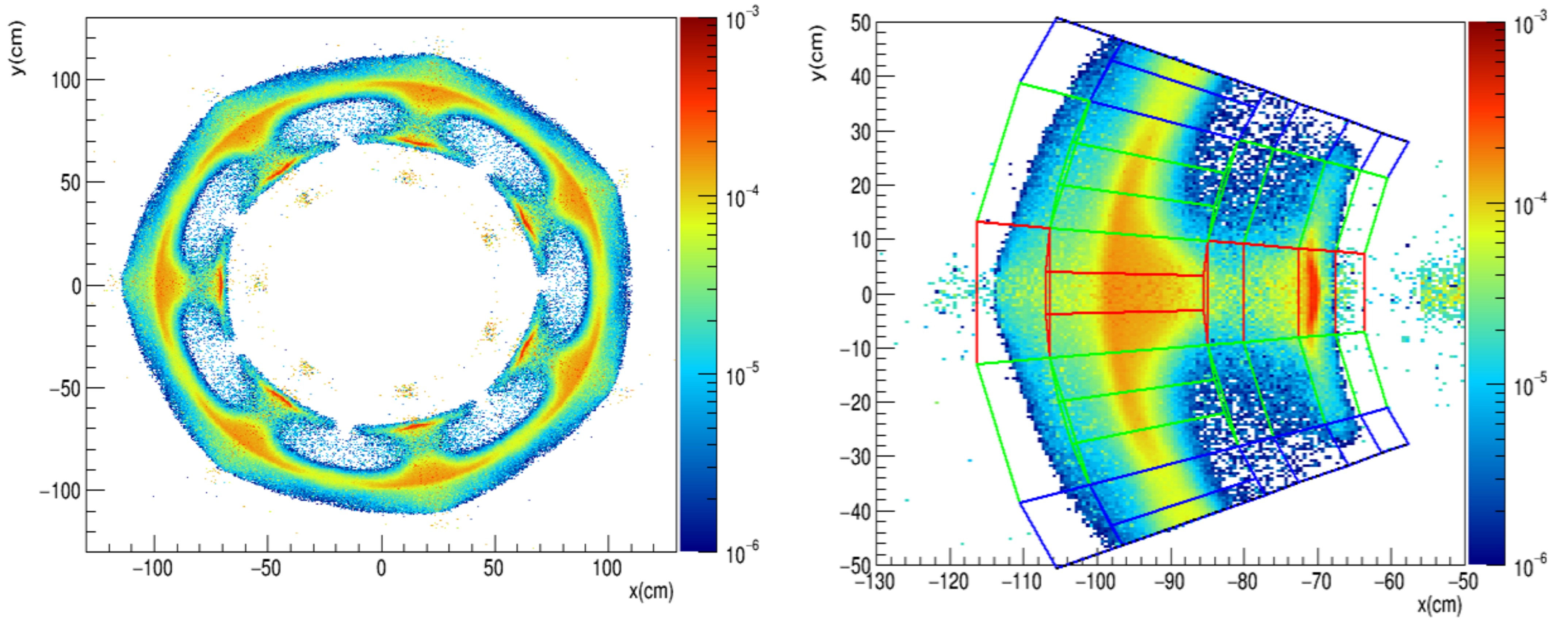




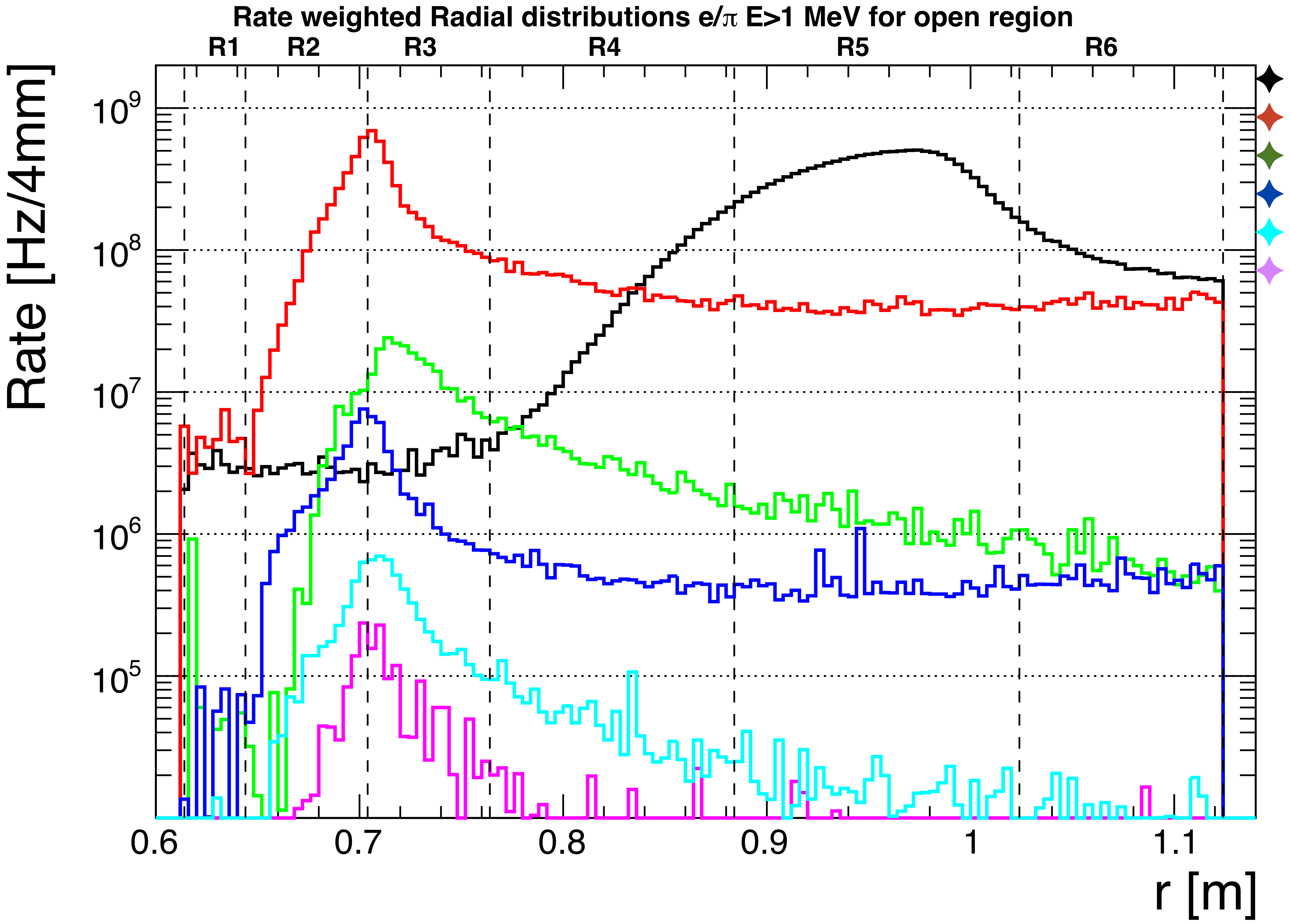


Capturing the Scattered Flux



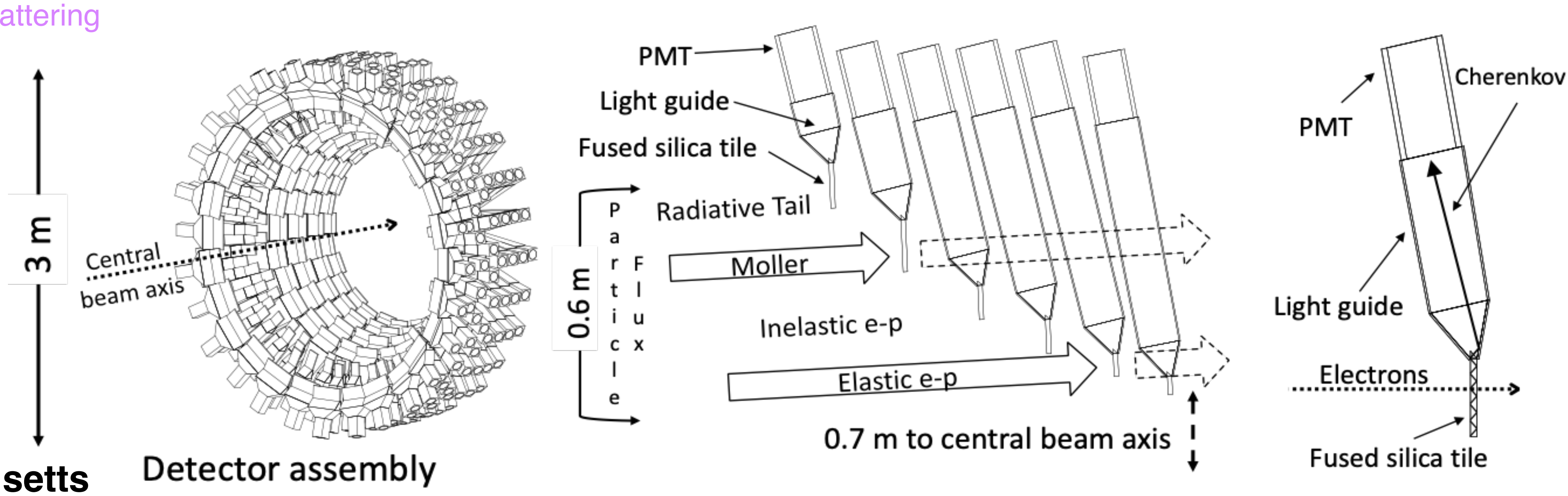


Wide variation in flux intensity and weights of different scattering processes: 1) e-e, 2) elastic e-p, 3) inelastic e-p



Black: e-e scattering
Red: elastic e-p scattering
Green: inelastic e-p scattering
Dark blue: elastic e-Al scattering
Light blue: inelastic e-Al scattering
Magenta: Al quasi-elastic scattering

Both radial and azimuthal segmentation in scattered flux measurements required



Idaho State University
University of Manitoba
University of Massachusetts
Bartoszek Engineering

Overview of Detector Systems Requirements

- Intercept the primary electron flux with a radiation hard pure Cherenkov radiator (fused silica or "quartz") with high radial and azimuthal segmentation

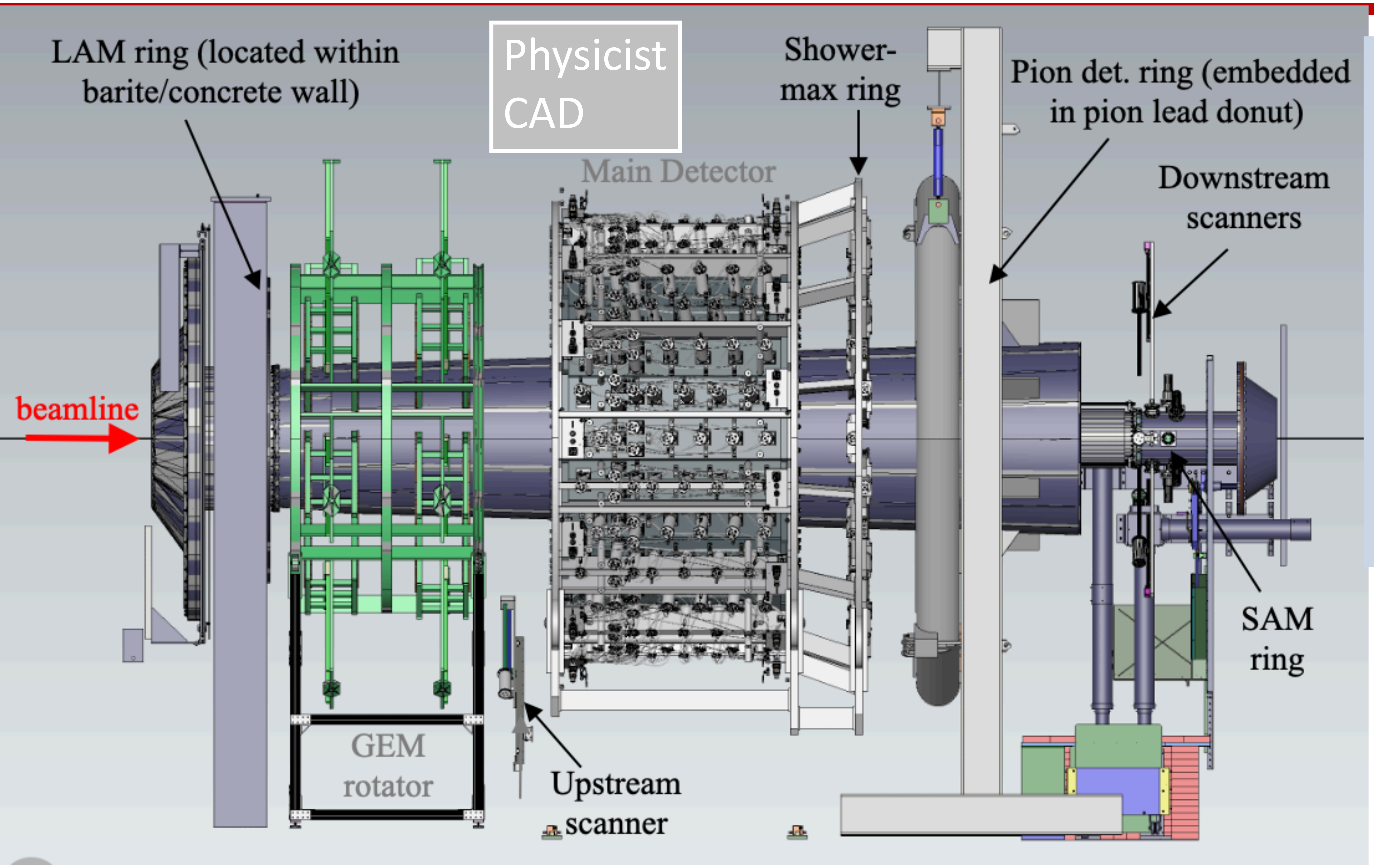
- Ensure the required sensitivity to the electron flux asymmetry in the quartz tiles, approaching the shot-noise-limit with little additional background or crosstalk

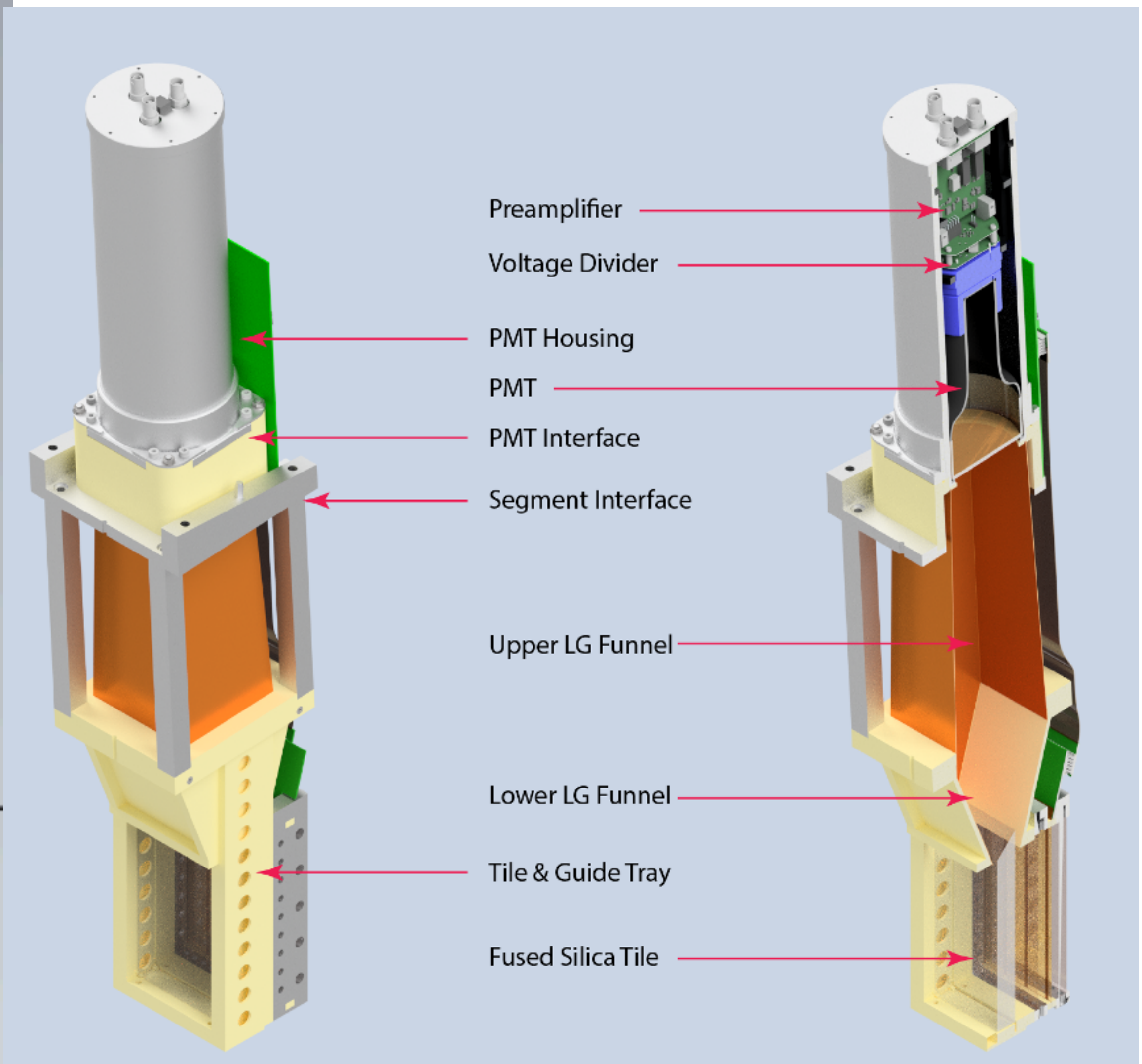
- Calibrate the primary electron flux, the irreducible electron background and their relationship to the spectrometer optics and acceptance collimators

- Measure the anticipated few per mille pion/muon background flux rate and infer their PV asymmetry contribution in the Møller ring

- Monitor the small-angle and large angle scattered flux at the fringes of the acceptance as an additional monitor of beam helicity correlations in the primary beam parameters and beam halo

Primary and Auxiliary Integrating and Tracking Detectors

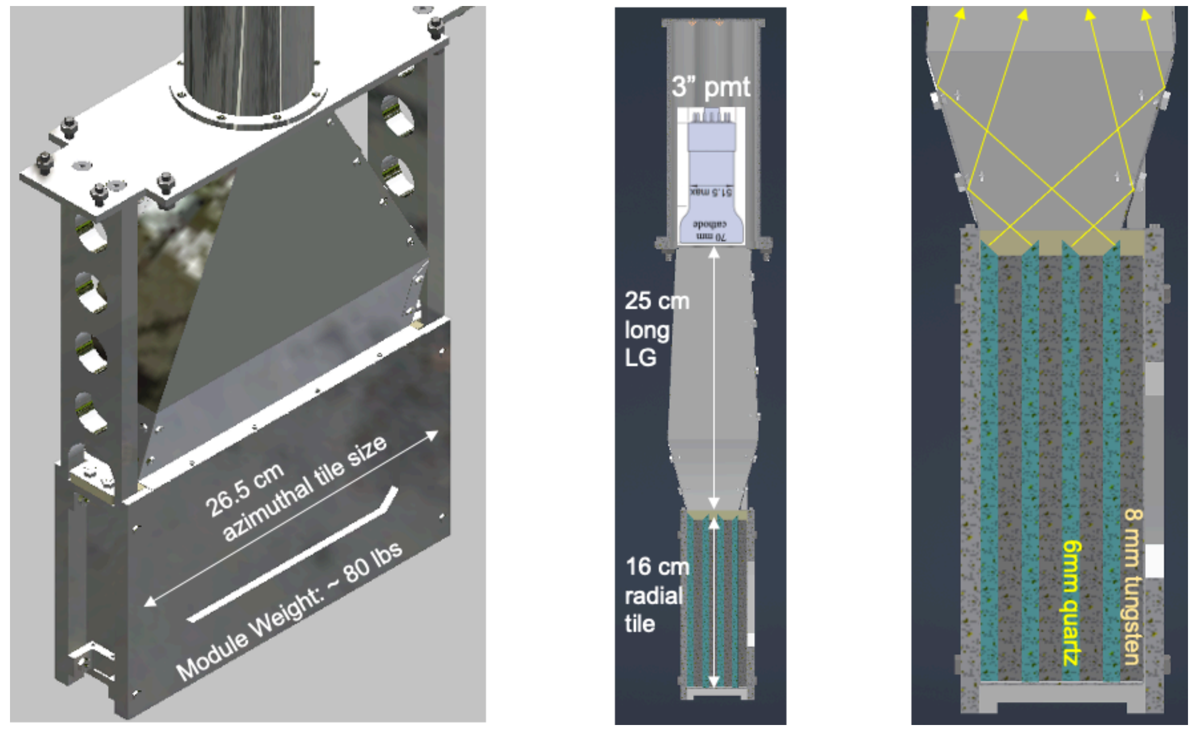




Requirement for Ring 5:

Detector resolution < 25%

excess noise < 4%



Integrating (current mode) detectors:

asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

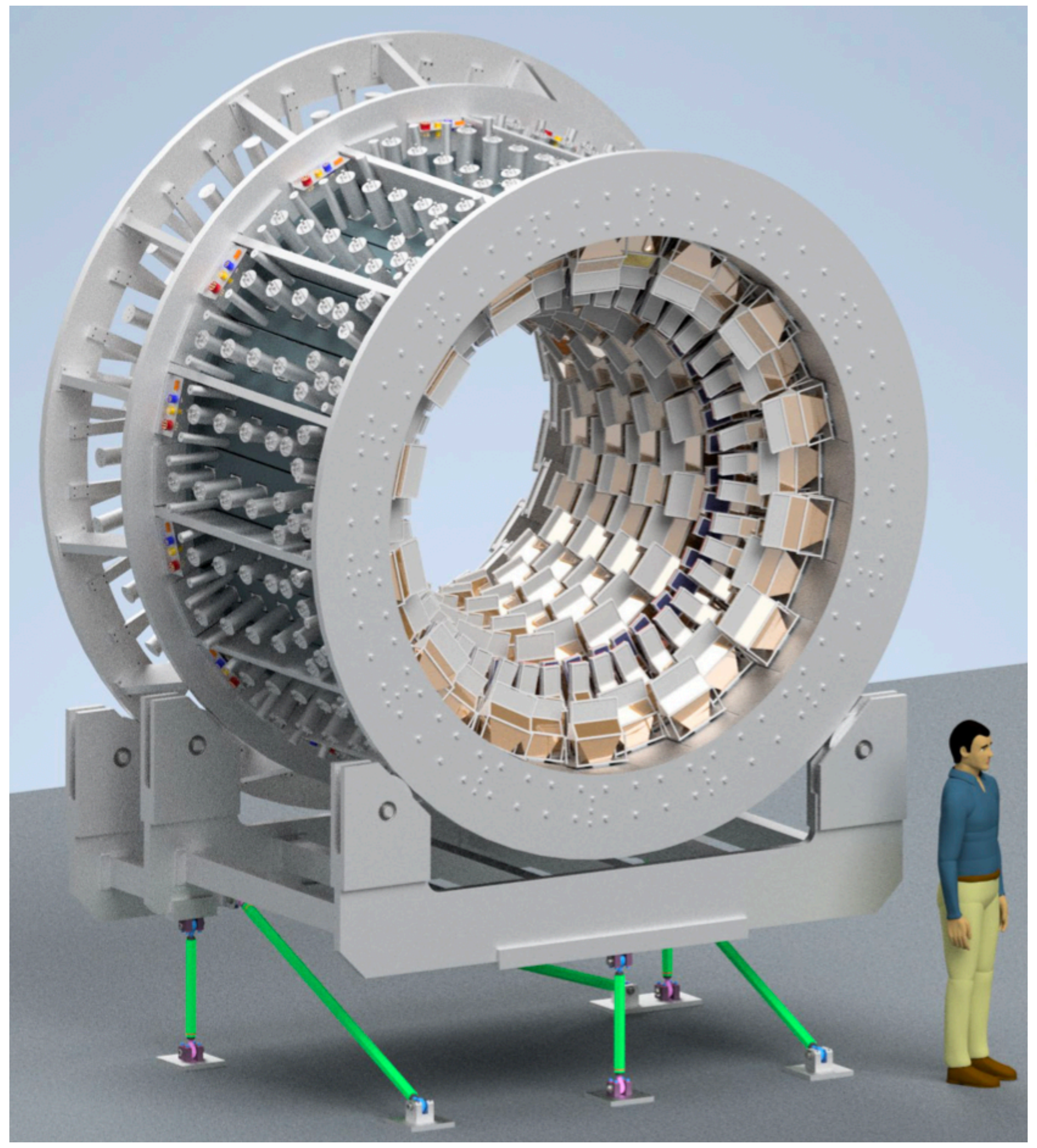
- Gas electron multipliers (GEM) detectors
- “Pion” acrylic Cherenkov detectors

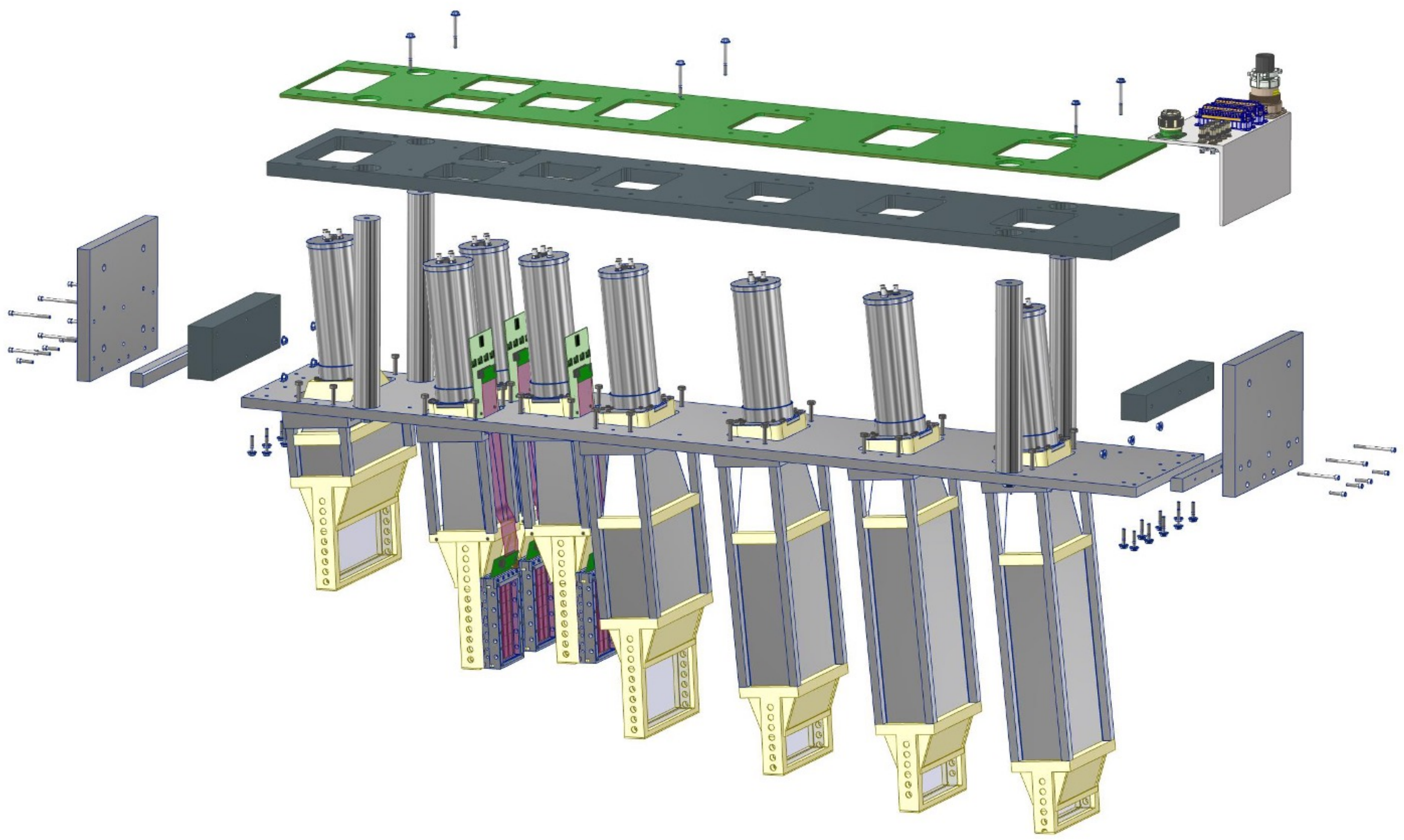
Readout Electronics:

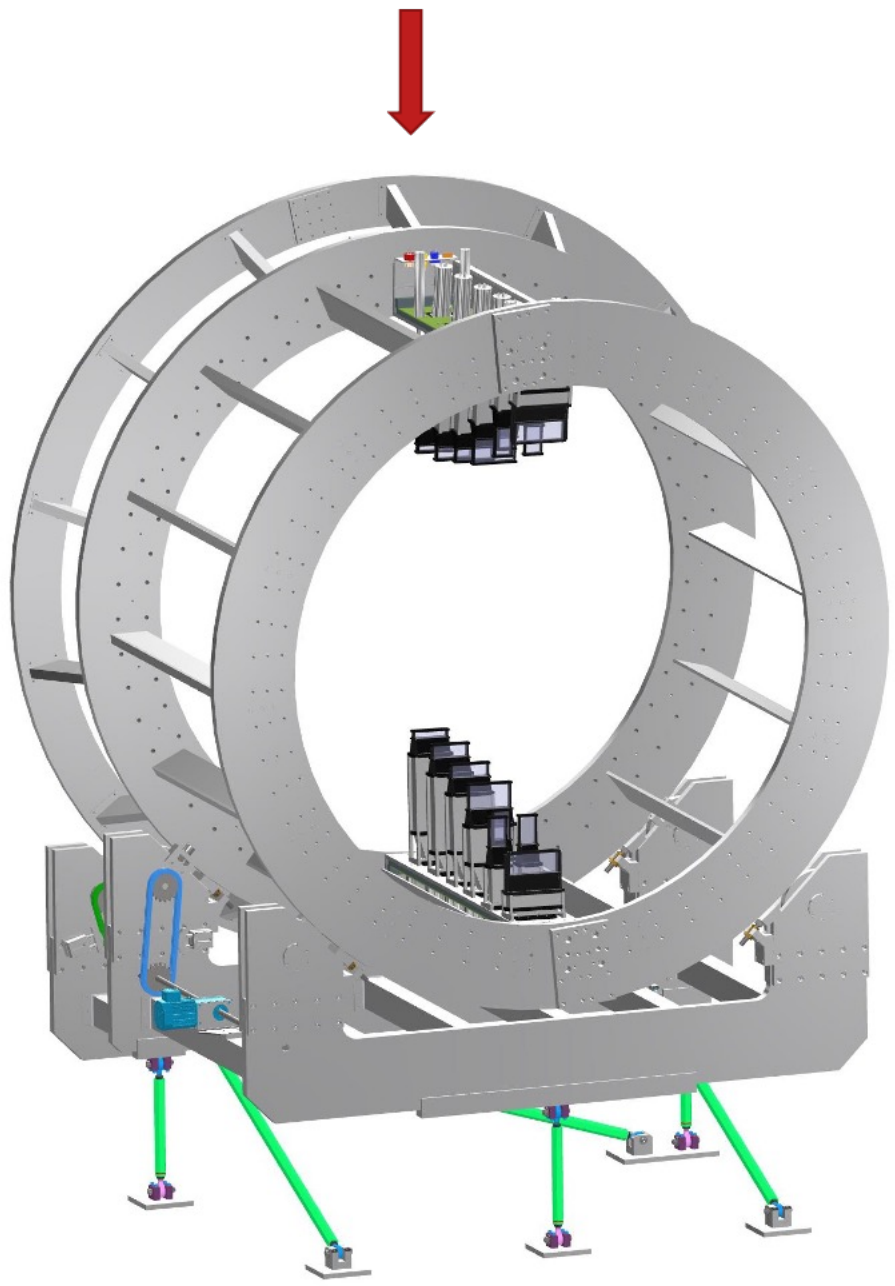
Ohio University

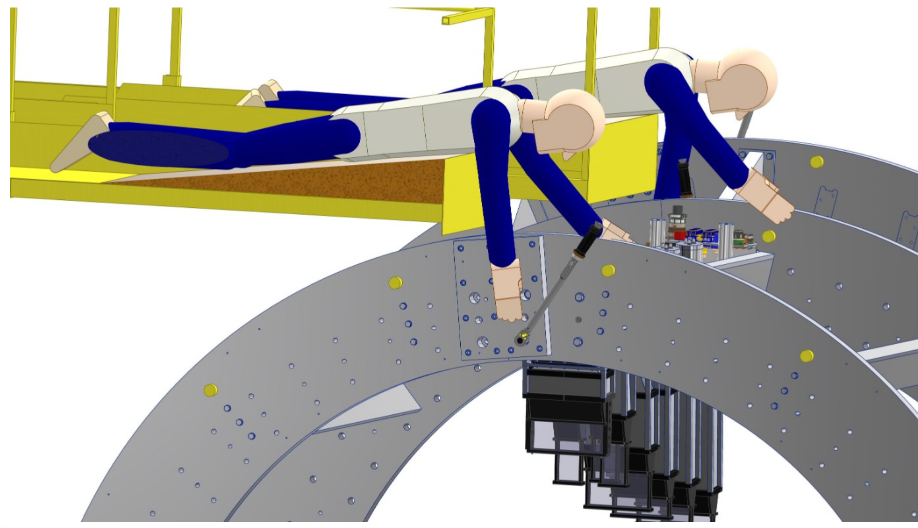
- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

Main Detector Assembly

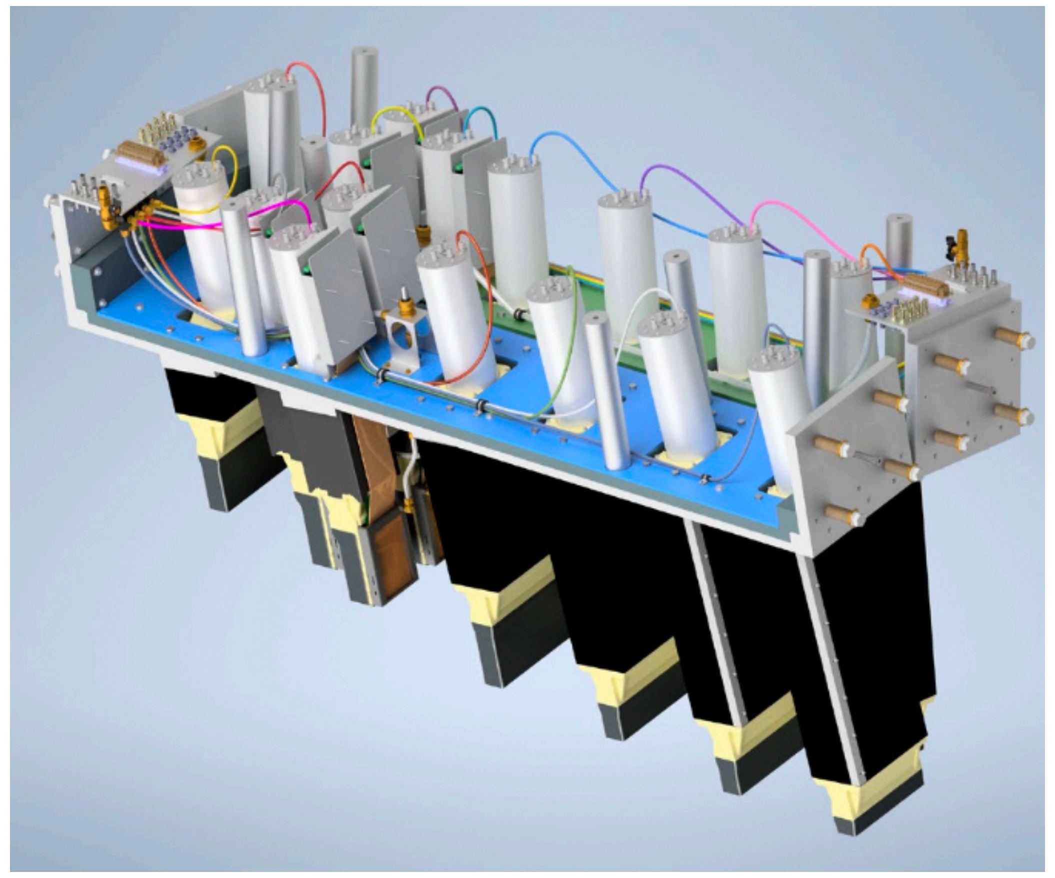


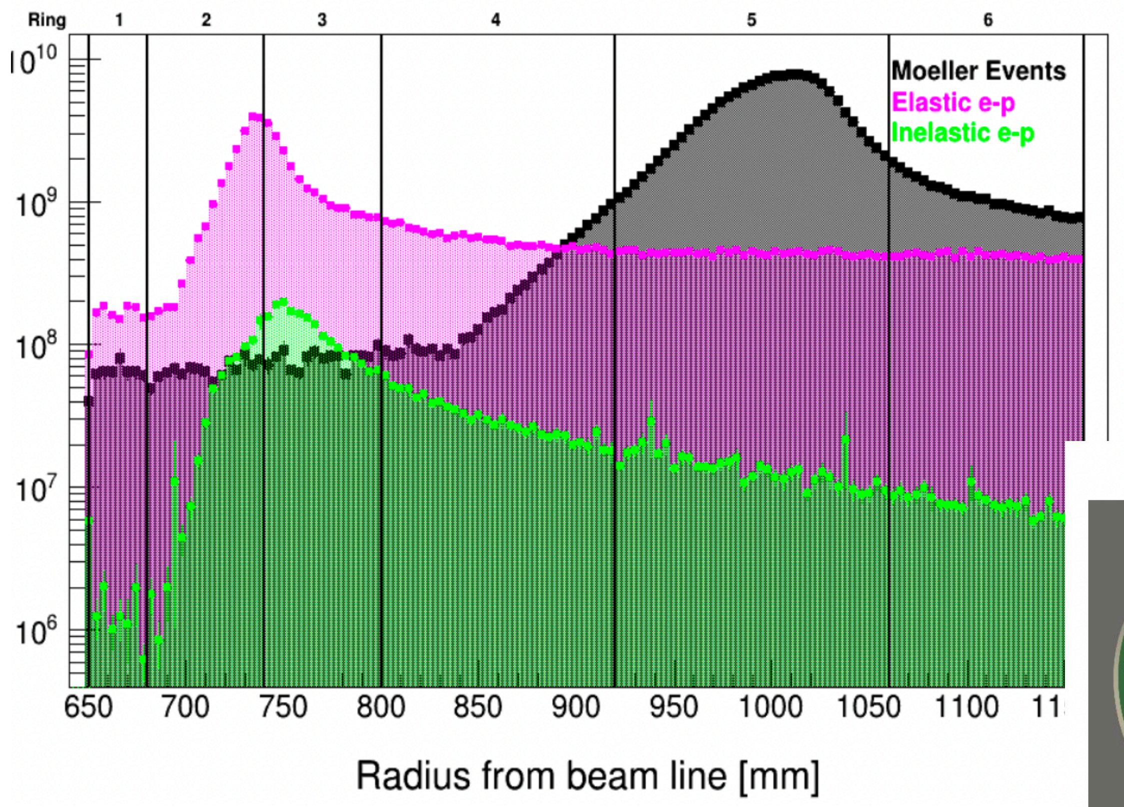


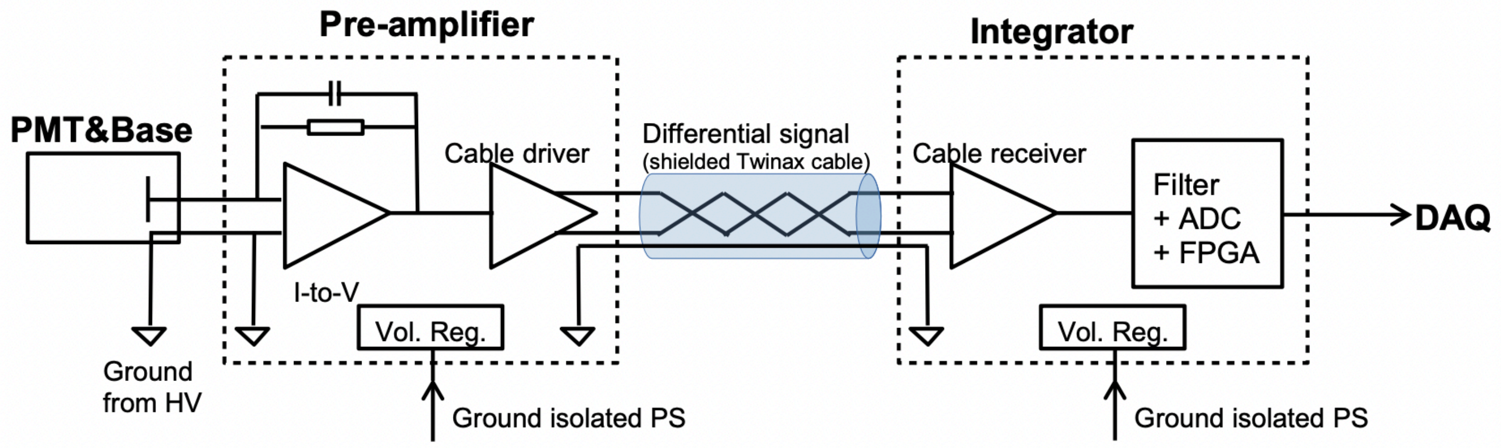


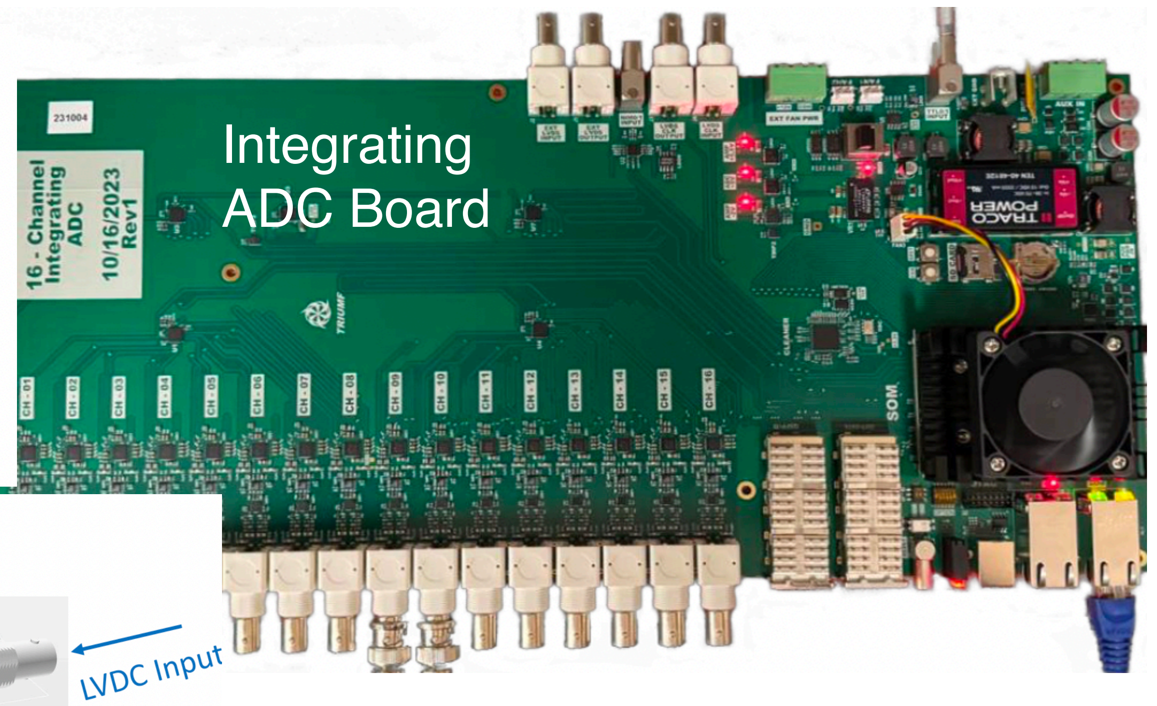


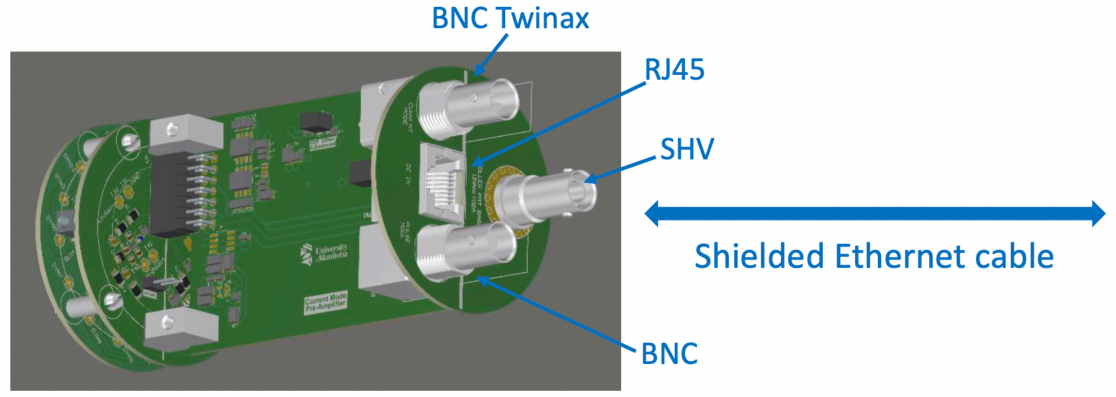
Idaho State University
University of Manitoba
University of Massachusetts
Bartoszek Engineering

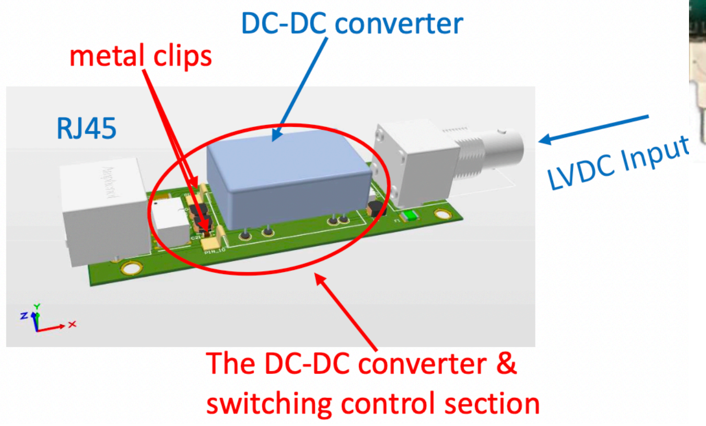






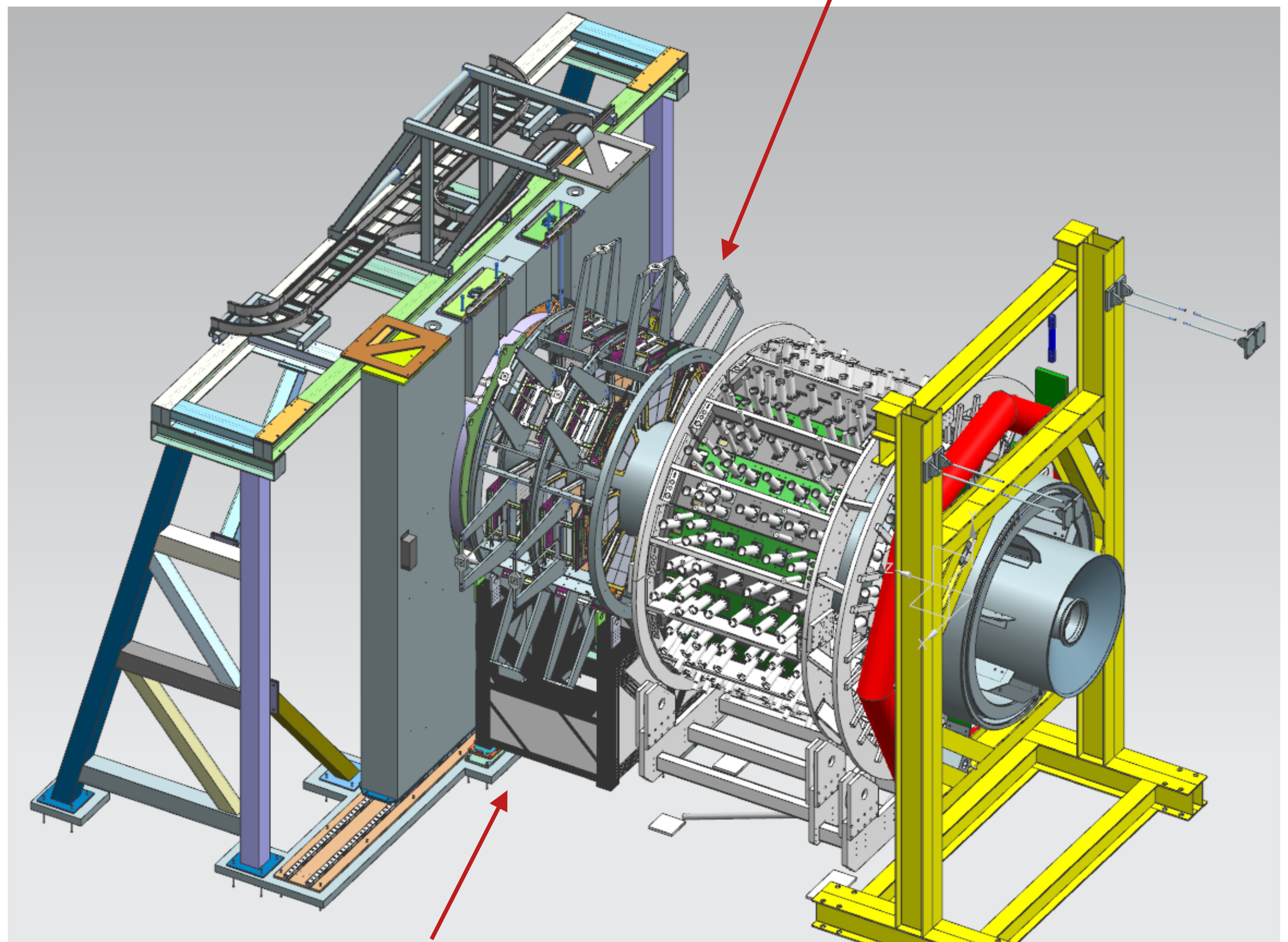




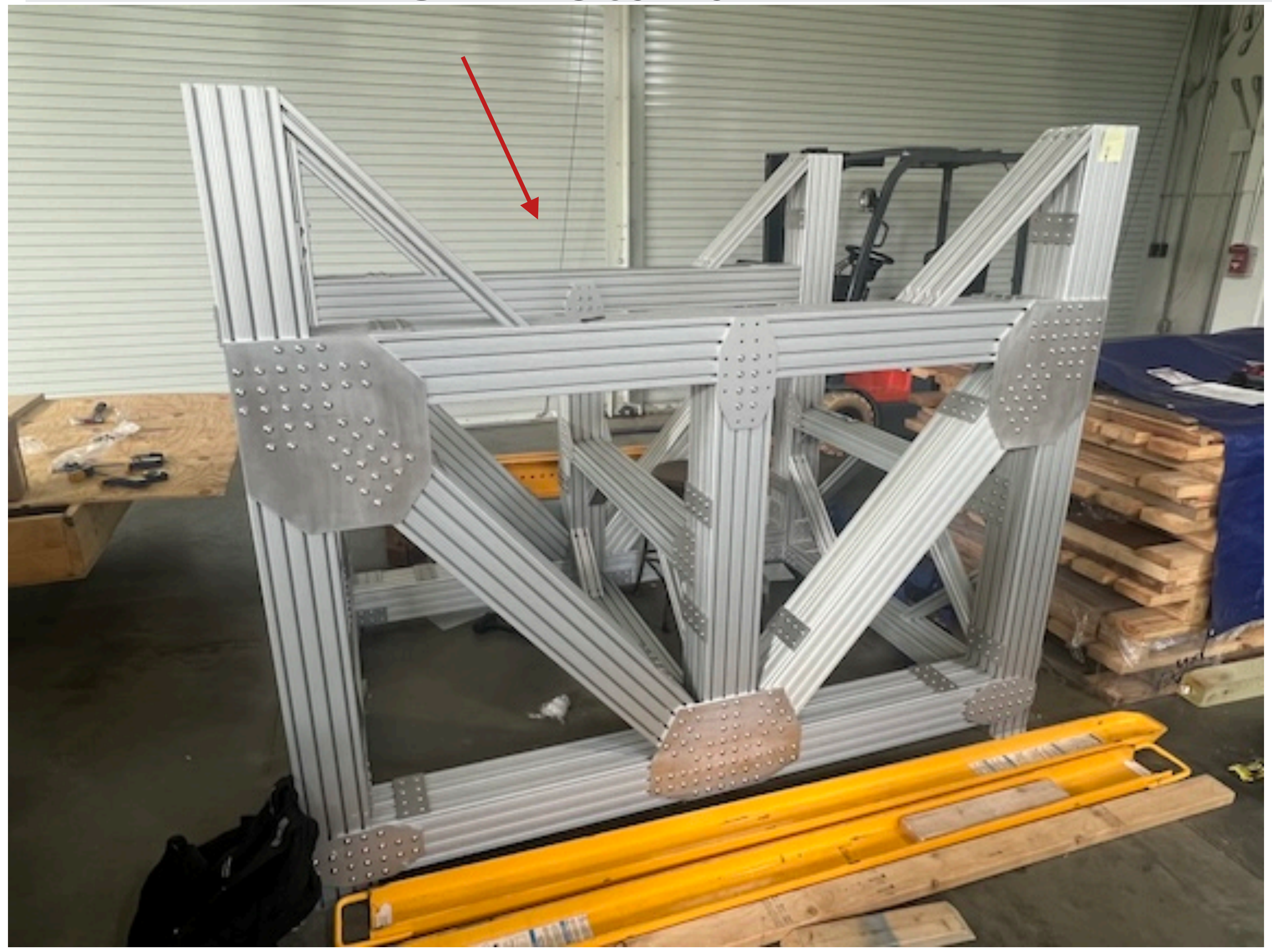


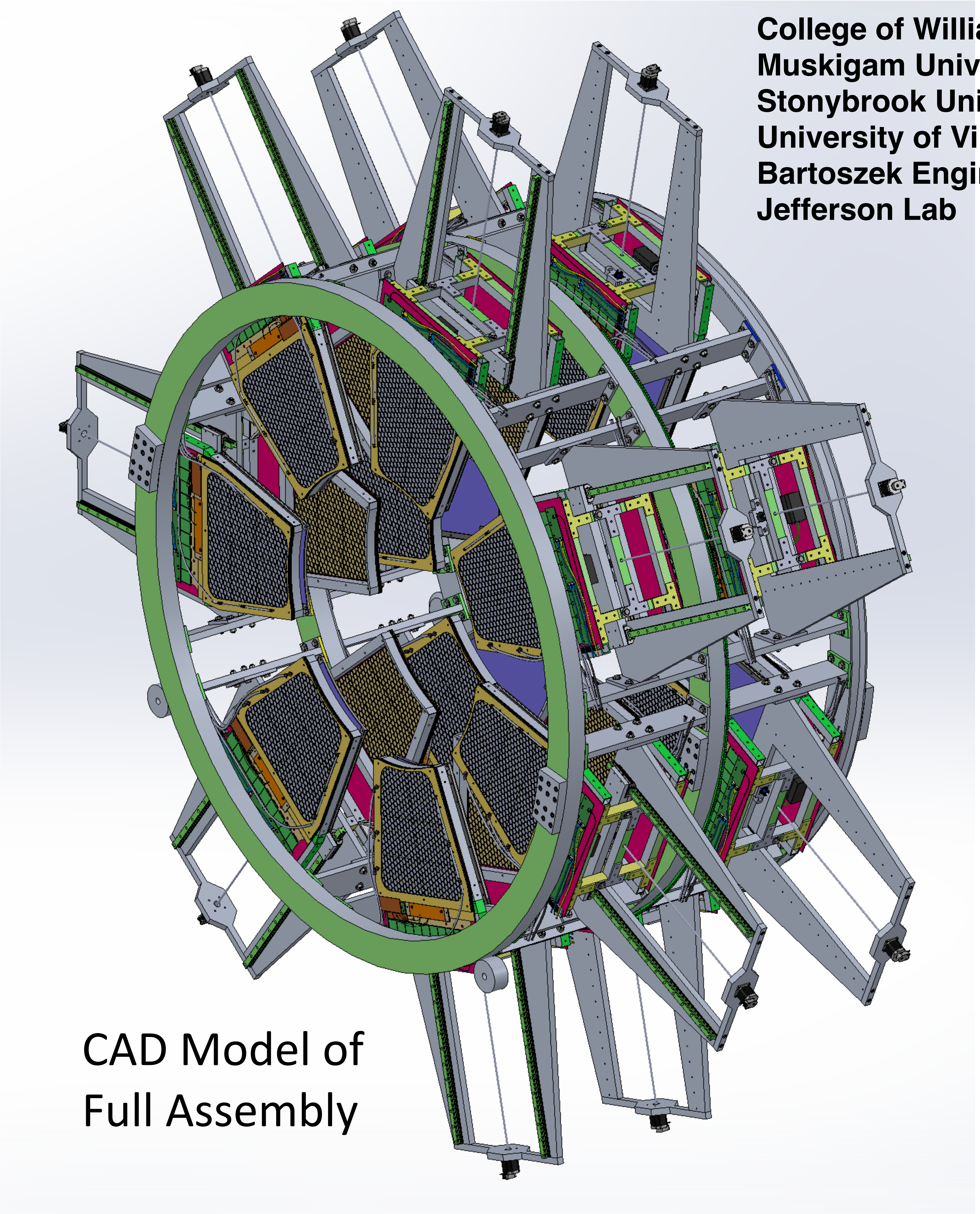
Jefferson Lab

Tracking Detector System



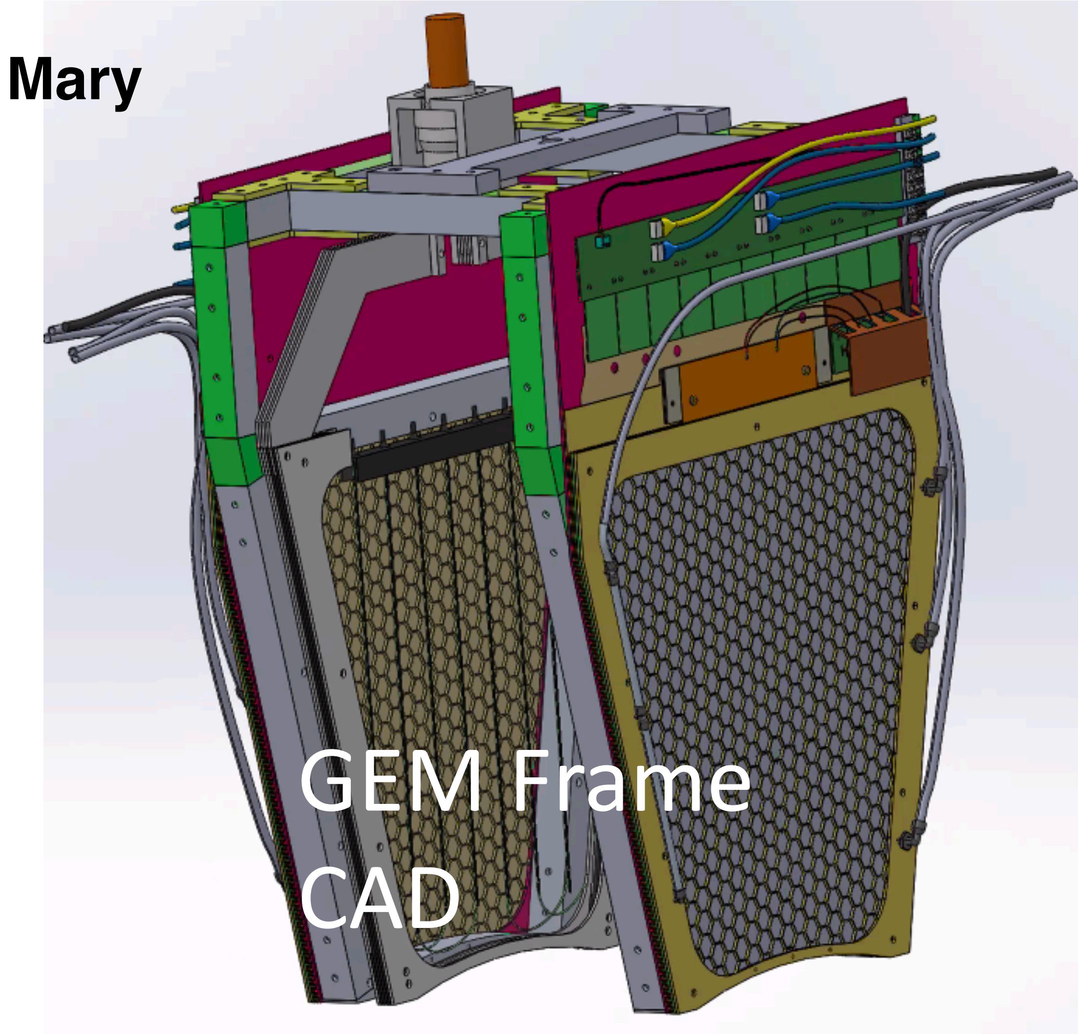
GEM Stand





CAD Model of Full Assembly

College of William and Mary
Muskigam University
Stonybrook University
University of Virginia
Bartoszek Engineering
Jefferson Lab

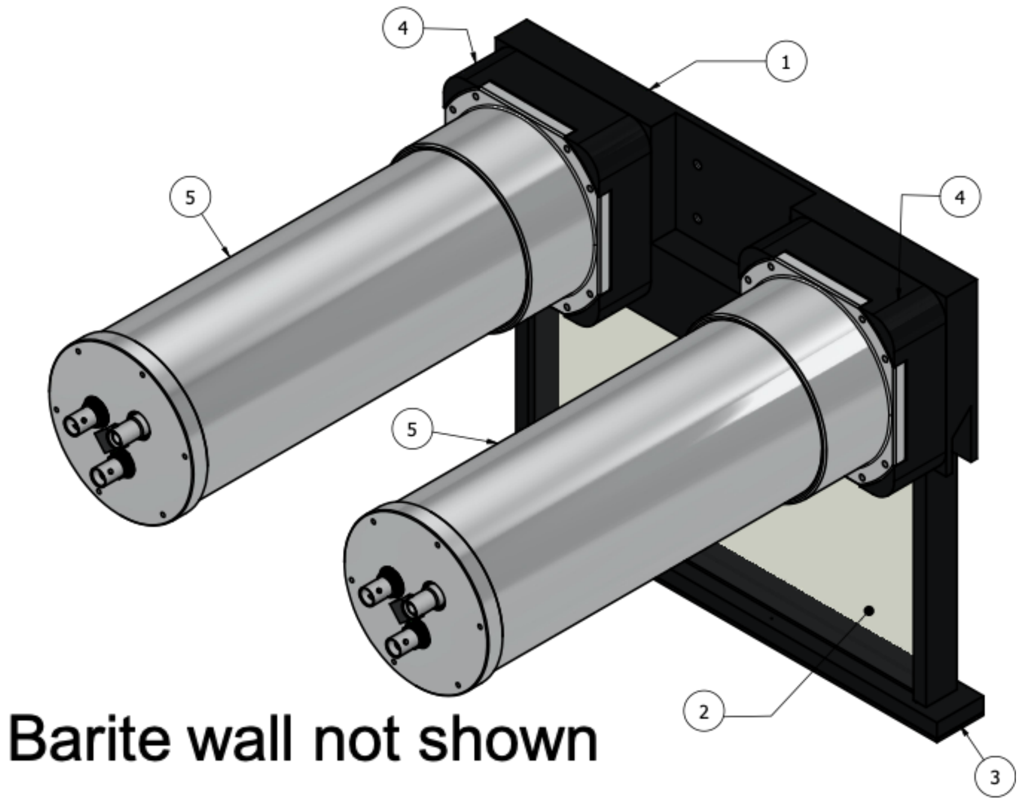


GEM Frame CAD

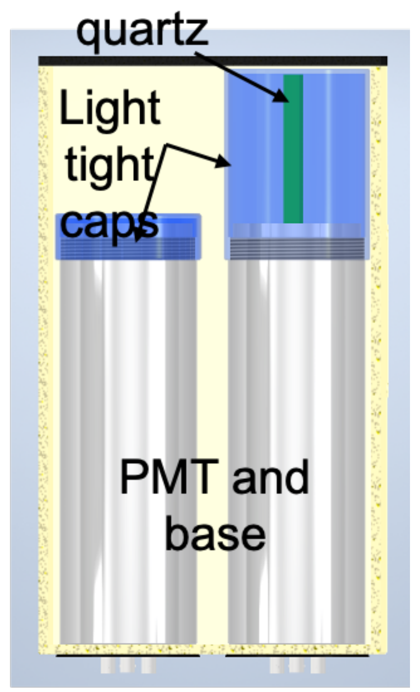
Production GEM at UVa

Auxiliary Detectors

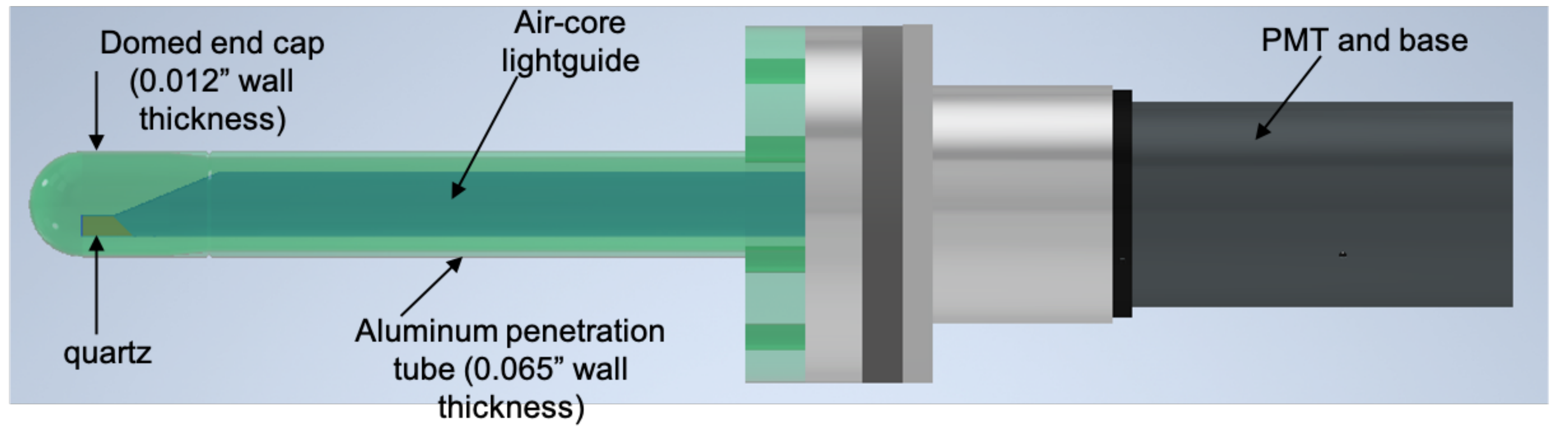
LAM (large angle monitor) detectors: 25 x 16.5 x 1 cm^3 quartz radiator read out by two 3 inch PMTs



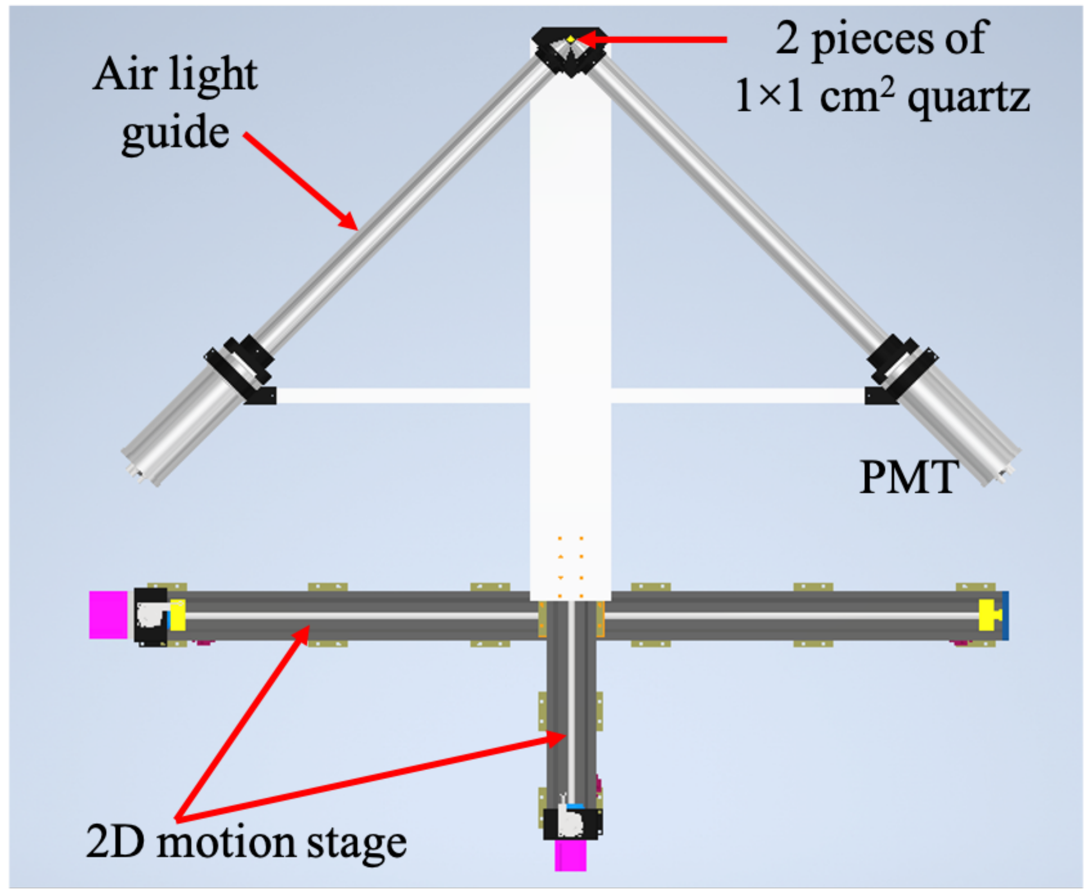
DBM (diffuse beam monitor) detectors: Bare PMT and PMT + quartz

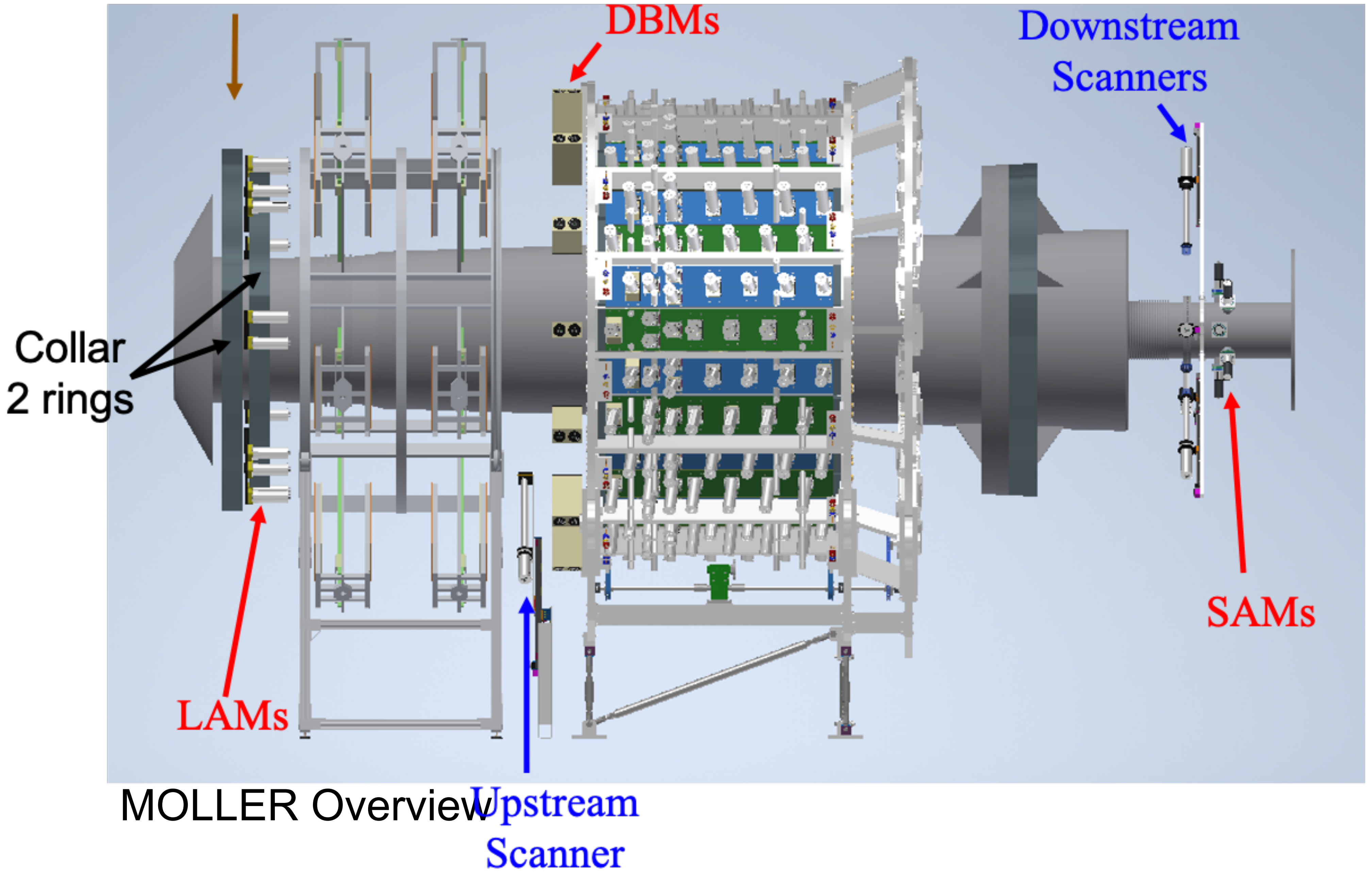


SAM (small angle monitor) detectors: Small quartz block, air-core light guide, 2 inch PMT detecting at small (0.1°) lab scattering angle



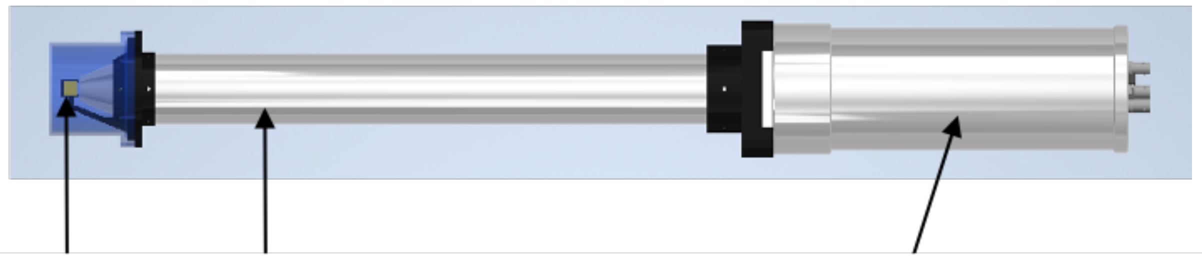
Upstream scanner: 2D profile scanner in one septant

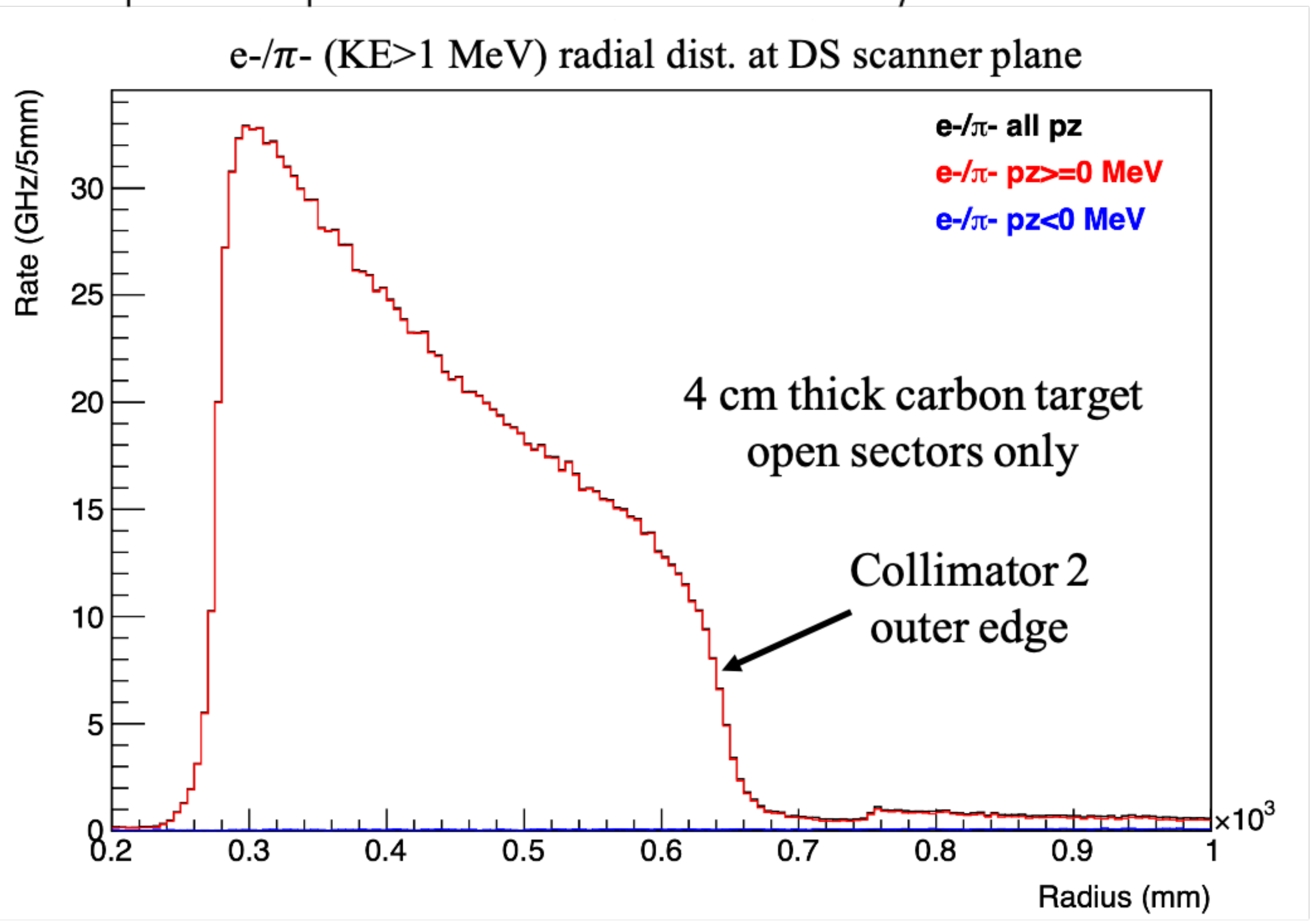


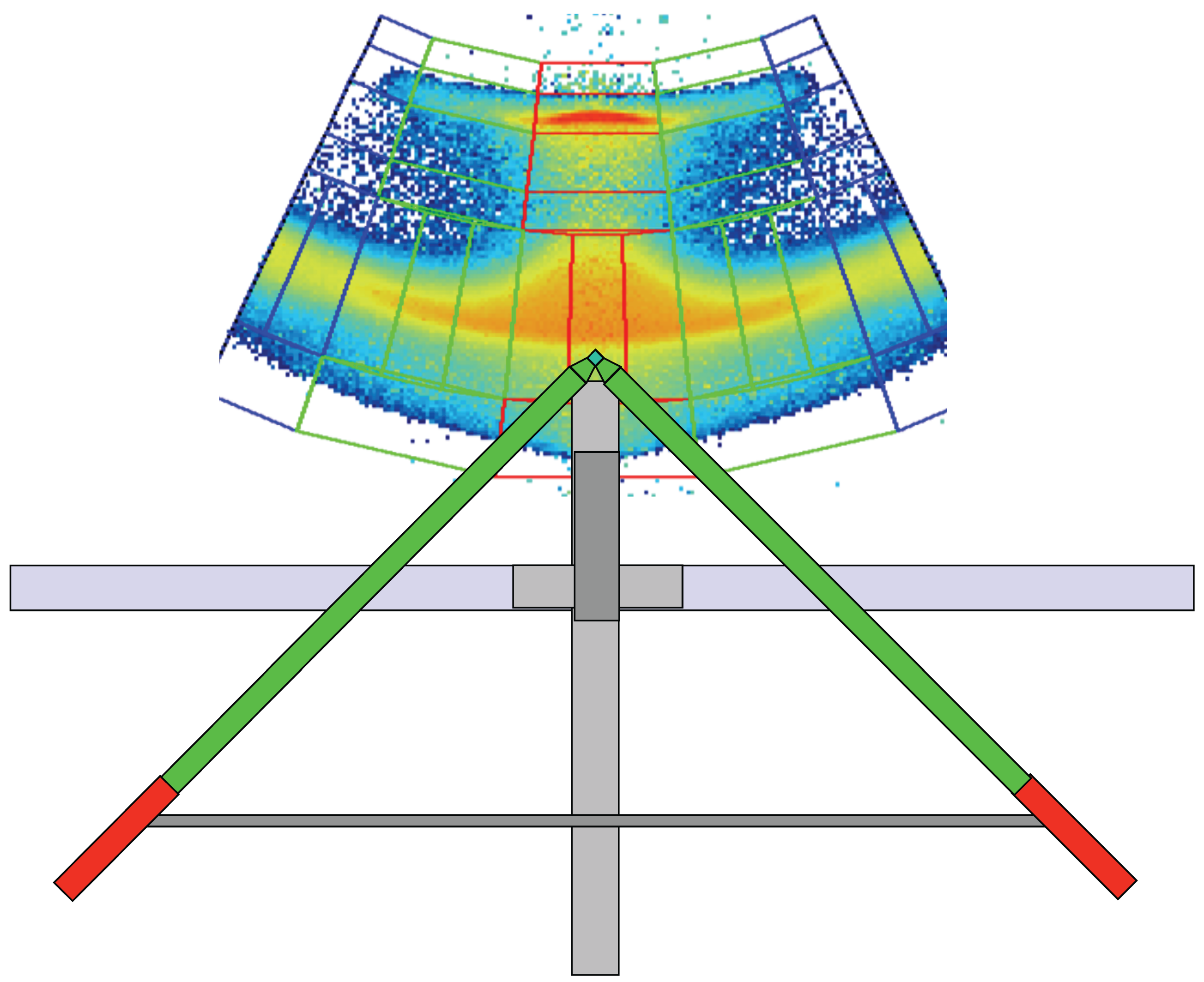


MOLLER Overview

Downstream scanner: four identical scanners that scan radially







What is important and what is not so important for a PVES experiment (Part 1)

- Polarized Source preparation and continuous communication is critical
- Beam parameter monitoring resolution at flip frequency is important and demanding, but absolute calibration is less important modulo understanding of pedestals
- Absolute energy scale is required only at the 0.1% level; however, we will be very sensitive to transverse polarization components (which we will monitor online) so we effectively have a very sensitive energy monitor and energy drifts will be obvious in our online diagnostics
- Target absolute density reduction is quite small and we don’t need to know it accurately; of course density fluctuations at the flip frequency is a critical requirement that drove the design of the target system
- There is no unusual requirement on LH2 target purity; we just require whatever has been accomplished in previous Hall A experiments.

What is important and what is not so important for a PVES experiment (Part 2)

- Sufficient to place primary acceptance collimator within 1 mm of beam axis; we in fact have a sensitive diagnostic tool during commissioning to ensure this requirement
- We are relatively insensitive to the details of the magnetic field map and “movement/drift” of spectrometer coils
- The main detector material, apart from radiation hardness, must have negligible scintillation response: critical to minimize soft backgrounds
- Our tracking system measurements are primarily focused on validating our Monte Carlos with full radiative corrections, validating the basic magnetic properties of the spectrometer and extracting the kinematic factor (properly momentum-acceptance-weighted analyzing power); we do not need absolute tracking efficiencies, just knowledge of any significant position variations

MOLLER Collaboration: ~ 180 authors, 34 institutions, 4 countries

Spokesperson: K. Kumar, UMass, Amherst

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

Other Executive Board Members

D. Armstrong (William & Mary), R. Fair (JLab), M. Gericke (Manitoba), M. Jones (JLab), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

MOLLER Working Groups

Polarized Source
Beam Instrumentation
Hydrogen Target
Spectrometer
Integrating Detectors
Tracking Detectors
Hall Integration
Polarimetry
Electronics/DAQ/Offline
Simulations
Physics Extraction

MOLLER Physics Liaison:
Ciprian Gal

Technical Board

Chair: Kent Paschke,
Scientific Coordinator

MOLLER Project Personnel

R. Fair, MOLLER Project Manager

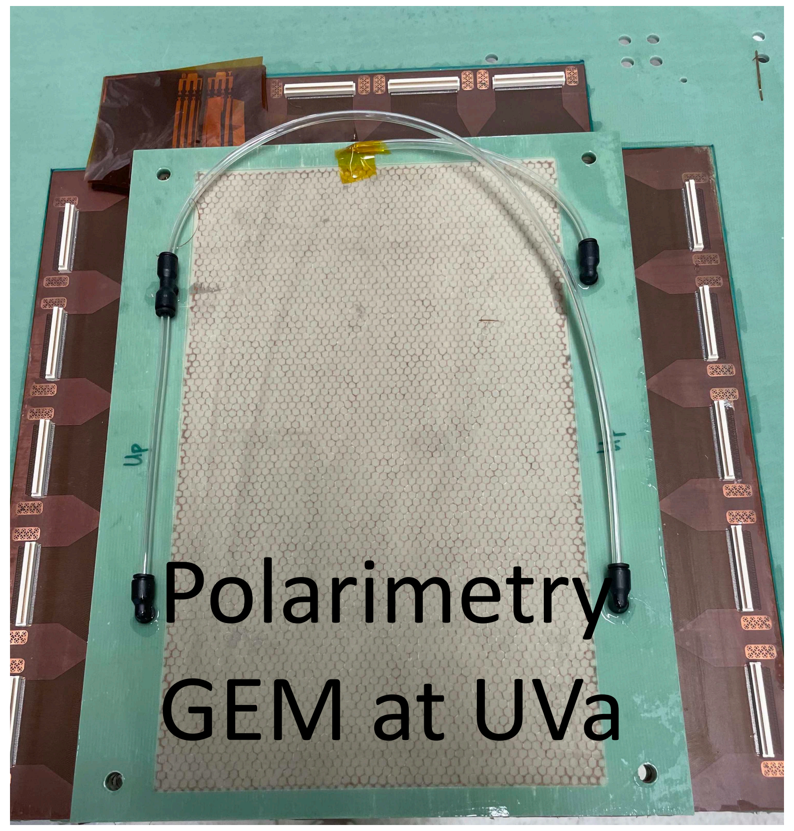
- **Project Leads**
- **Control Account Managers**
- **Technical Leads**

We have just added 3 new working groups to coordinate software development

- **Integrating Analysis Software**
- **Counting Analysis Software**
- **Online Monitoring Software**

The MOLLER Collaboration is Busy in Multiple Locations

- The MOLLER MIE Team centered at JLab has intense activity ongoing in multiple buildings
- The NSF and CFI funded university locations are also buzzing with activity producing detectors
- Everything is on track to begin installation in November after SBS deinstallation.
- In parallel, our active simulation efforts have evolved into the development of online and offline software and analysis tools



Jefferson Lab

Collaboration Commitment

- By an informal count, there are ~ 15+ undergraduates, 25+ graduate students (of which at least 15 are signed up as PhD students) and 10+ postdocs engaged in MOLLER-related activities as of this moment. This number is likely to increase somewhat over the next couple of years, though one has to watch federal funding of research in the near future
- The Collaboration's Institutional Board representing 34 institutions plans to develop and implement a shift policy, specifying the shift staffing process and requirements for the anticipated multiple years of data collection
- The Collaboration is committed to manning these shifts even if the running time is extended beyond the nominal 3 years provided our research awards continue to get funded at the current levels
- I note that the MIE project manages the local technical staff carrying out MOLLER technical activities and have a detailed plan for how key technical experts will help commission major subsystems and transfer training to the collaboration for physics running
- I also note that a significant number of Hall A/C staff have made major contributions to the development of MOLLER and will not only contribute during the physics phase but also help manage the junior User scientists on site for MOLLER physics.

Summary

- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (11 GeV CEBAF beam) enabled by the 12 GeV upgrade
- The science case remains compelling and the plan is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- You are going to hear our responses to the charge questions; we believe we have all the tools and plans in place to start installation as scheduled
- An enthusiastic and well-experienced international collaboration with an integrated project team is eager to complete construction and deployment of the apparatus, followed by commissioning and a long campaign of data collection and physics analysis; we are building on extensive experience from previous experiments at JLab
- The Hall A PVES experiments have a track record of publishing promptly