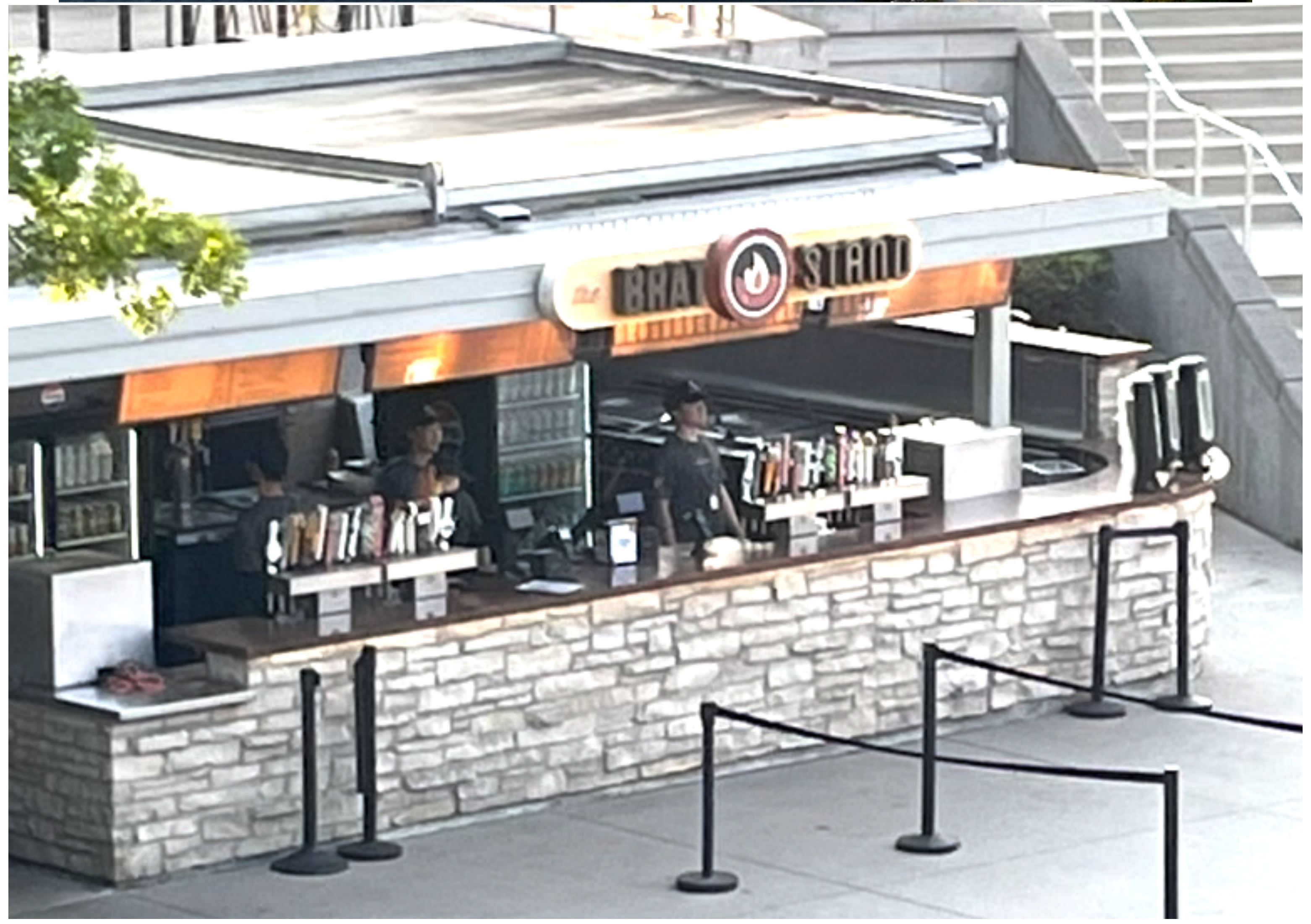
Measuring the Weak Charge of the Electron: The MOLLER Experiment

June 12, 2025

Kent Paschke
University of Virginia



MOLLER

New Physics with Precision at Low Energies

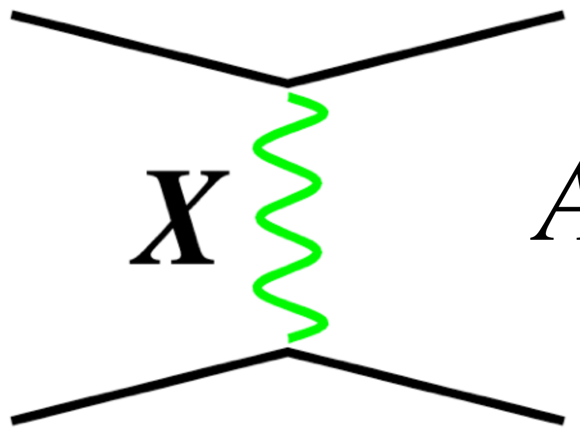
Low Q^2 offers complementary probes of new physics at multi-TeV scales

EDM, g_μ-2, weak decays, β decay, 0νββ decay, DM, CLFV…

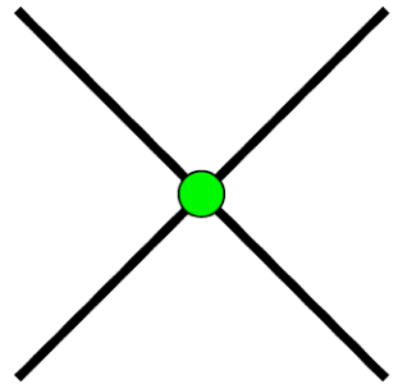
Parity-Violating Electron Scattering: *Low energy weak neutral current couplings (SLAC, Jefferson Lab, Mainz)*

Low energy NC interactions ($Q^2 \ll M_Z^2$)

Heavy mediators = contact interactions



$$A_X \propto \frac{1}{Q^2 - M^2} \sim \frac{g^2}{\Lambda^2} \rightarrow$$

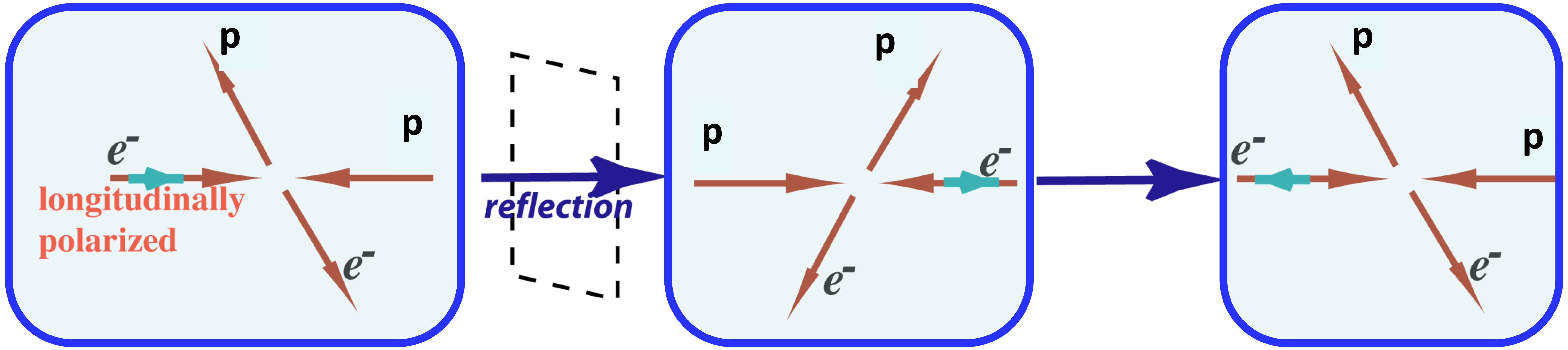


Contact interaction

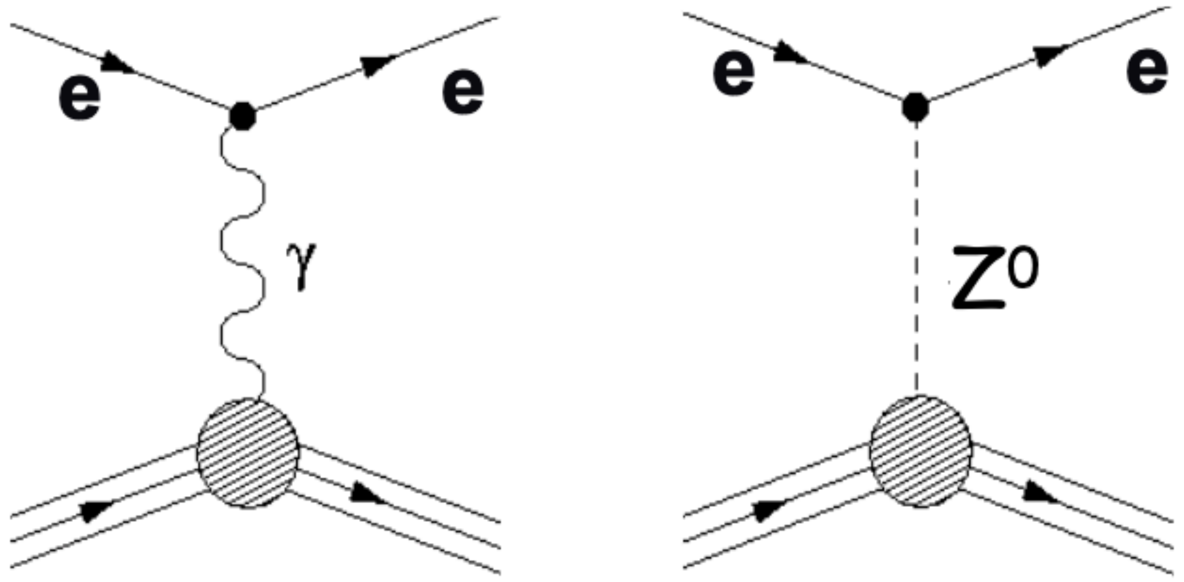
For any **fermion** and **handedness** combination, reach characterized by mass scale Λ, coupling g

New physics search "mass scale": quoted with $g^2 = 4\pi$

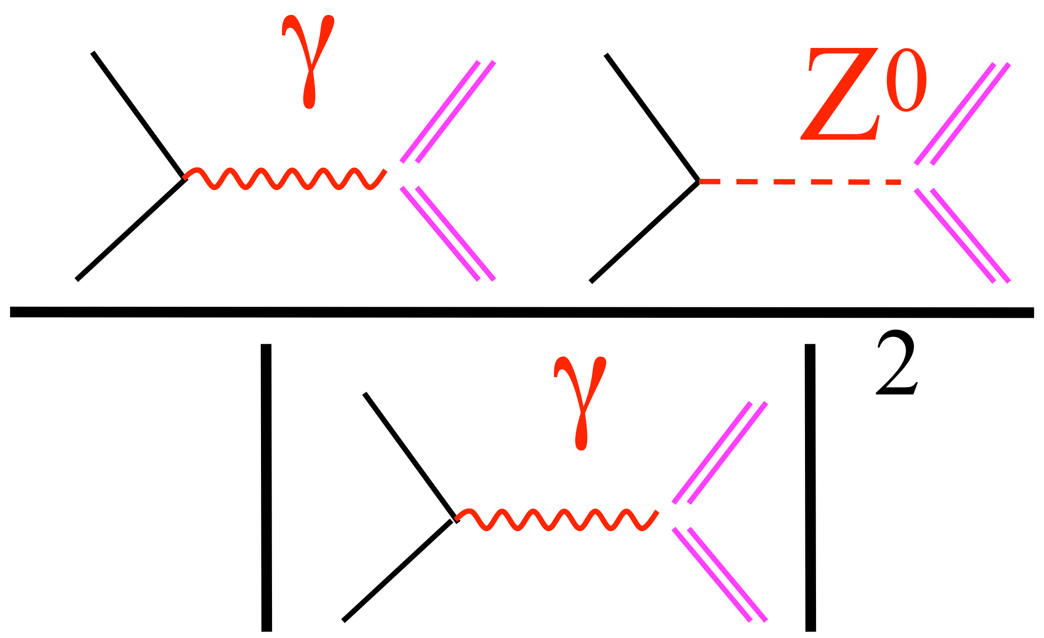
Electron Scattering and Parity-violation



- Incident beam is longitudinally polarized
- Change sign of longitudinal polarization
- Measure fractional rate difference



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



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

Scattering cross-section

$$\sigma = \left|\mathcal{M}_\gamma + \mathcal{M}_Z\right|^2$$

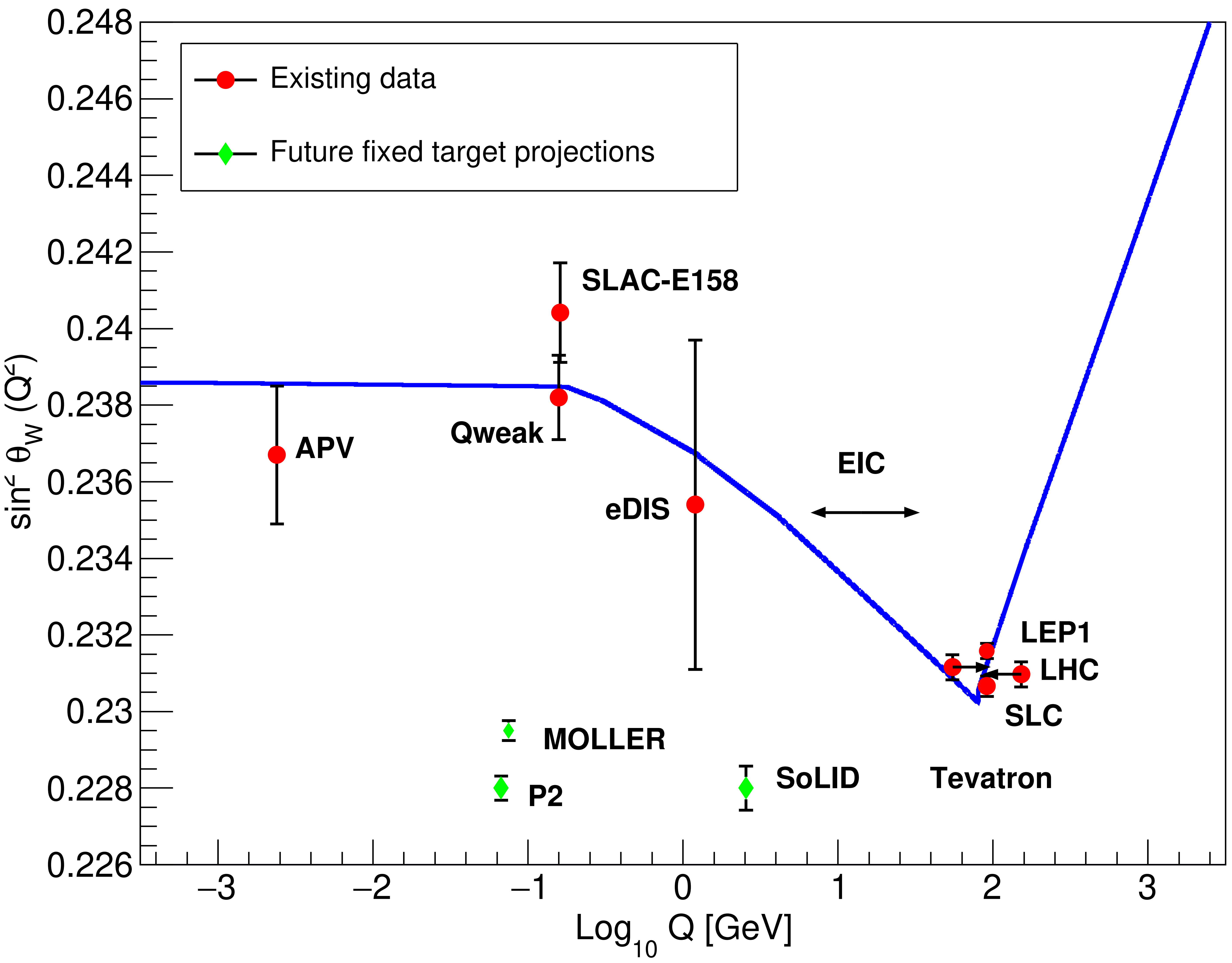
$$A_{PV} = -\boxed{mE\frac{G_F}{\sqrt{2}\pi\alpha}}\frac{4\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

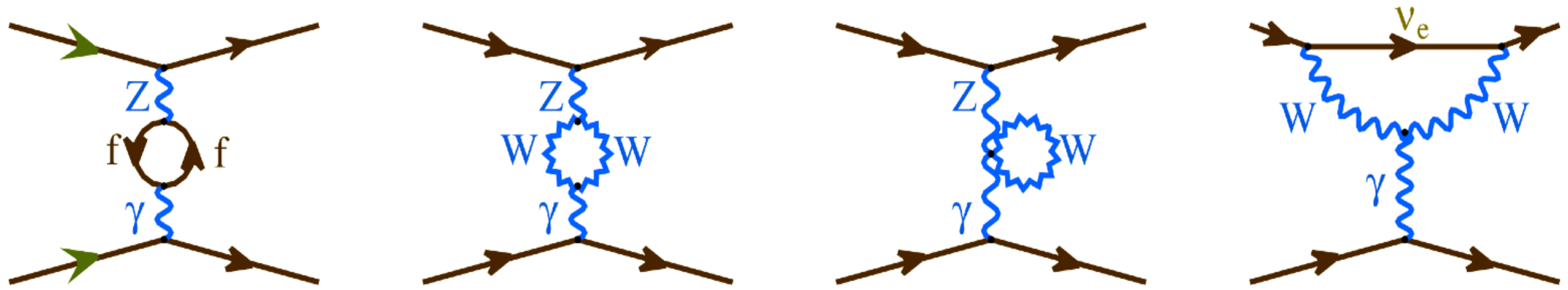
~ 2e-6

$$Q_W^e = 1 - 4\sin\theta_W$$

~ 0.0435

Comparing at the weak mixing angle





Renormalization scheme defines $\sin^2\theta_W$ at the Z-pole. γ-Z mixing and other diagrams are absorbed into the coupling constant

These channels (*ee* and *ep* elastic, *e*-D DIS) are all distinct probes in new physics phase space - the precision on $\sin^2\theta_W$ is not the story

MOLLER	ee	electron vector weak charge
P2	ep	proton vector weak charge
SoLID	eDIS	quark axial weak charge

MOLLER: Ultra-high precision measure of Q_W^e

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

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

Search for new flavor diagonal neutral currents

Unique (purely leptonic) new physics reach

Best Collider $\delta(\sin^2\theta_W)$:

A_l(SLD): 0.00026
A_{fb}(LEP): 0.00029
CMS(prelim): 0.00031

MOLLER projected:

$\delta(\sin^2\theta_W) = \pm\, 0.00024\ (stat.) \pm 0.00013\ (syst.)$

→ $\sim 0.1\%$ Matches best collider (Z-pole) measurement

Best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require the Giga-Z factory, linear collider, neutrino factory or muon collider

MOLLER Reach $\Lambda^{ee}_{RR-LL} \sim 38$ TeV

Erler et al., Ann.Rev.Nucl.Part.Sci. (2014)

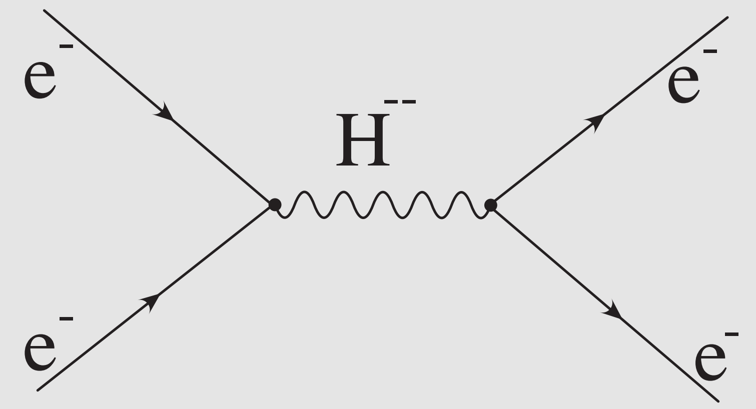
Examples of model sensitivity:

MOLLER: $e^- e^-$ scattering

Lepton Number Violation

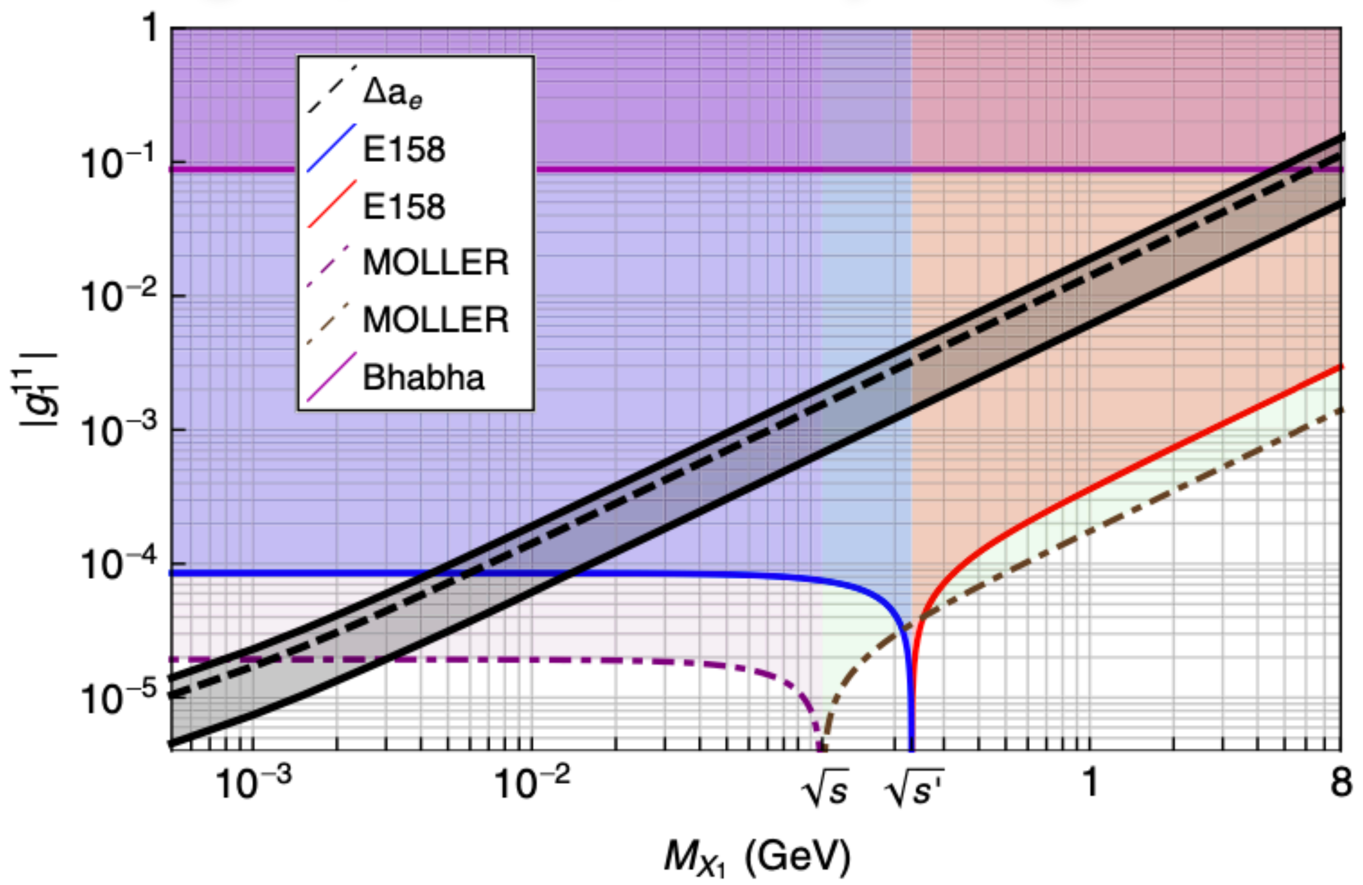
$\Lambda > 5$ TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

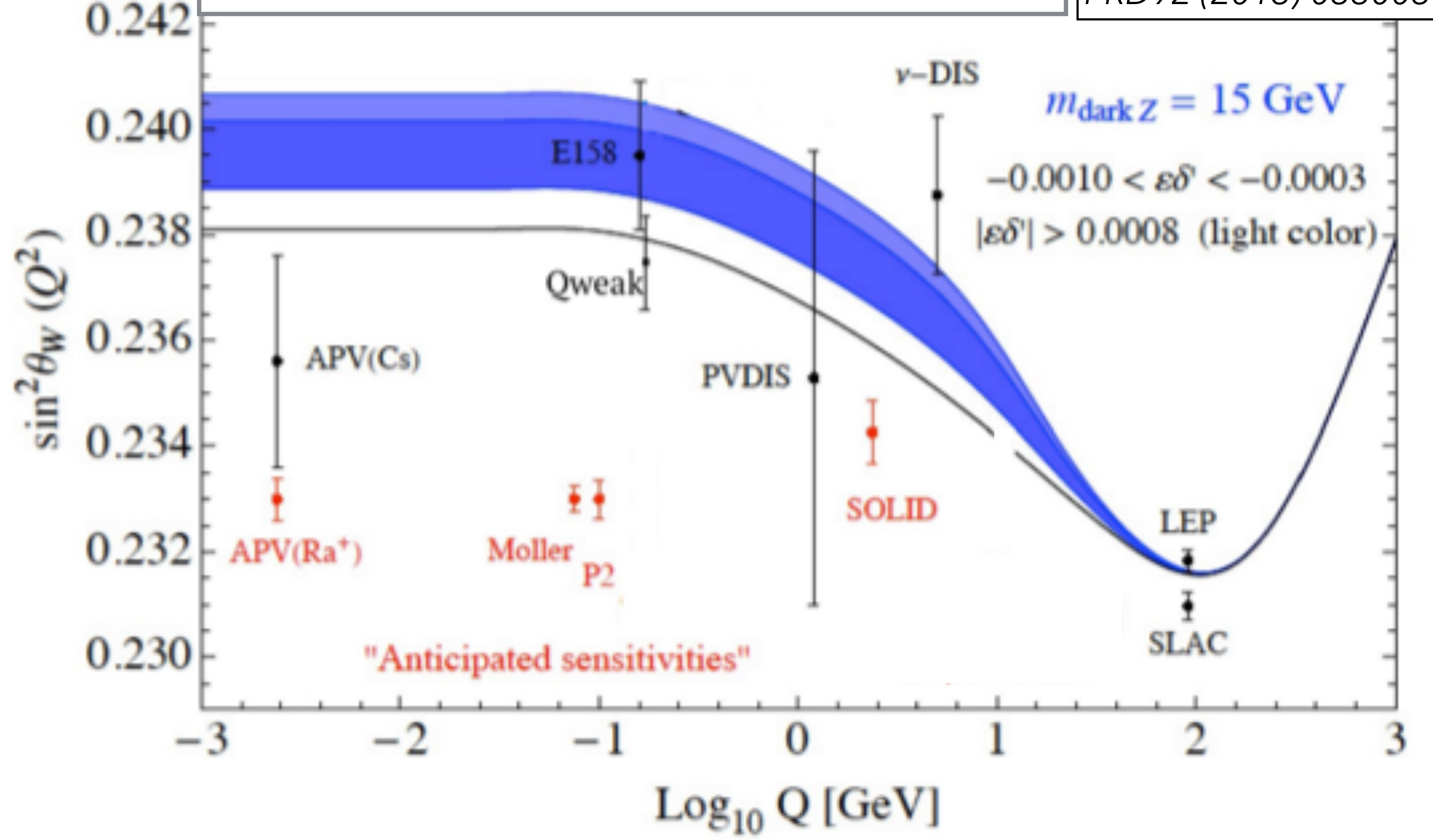
Light (<1 GeV) doubly-charged scalars



Gardner and Yan, PRD 102, 075016 (2020)

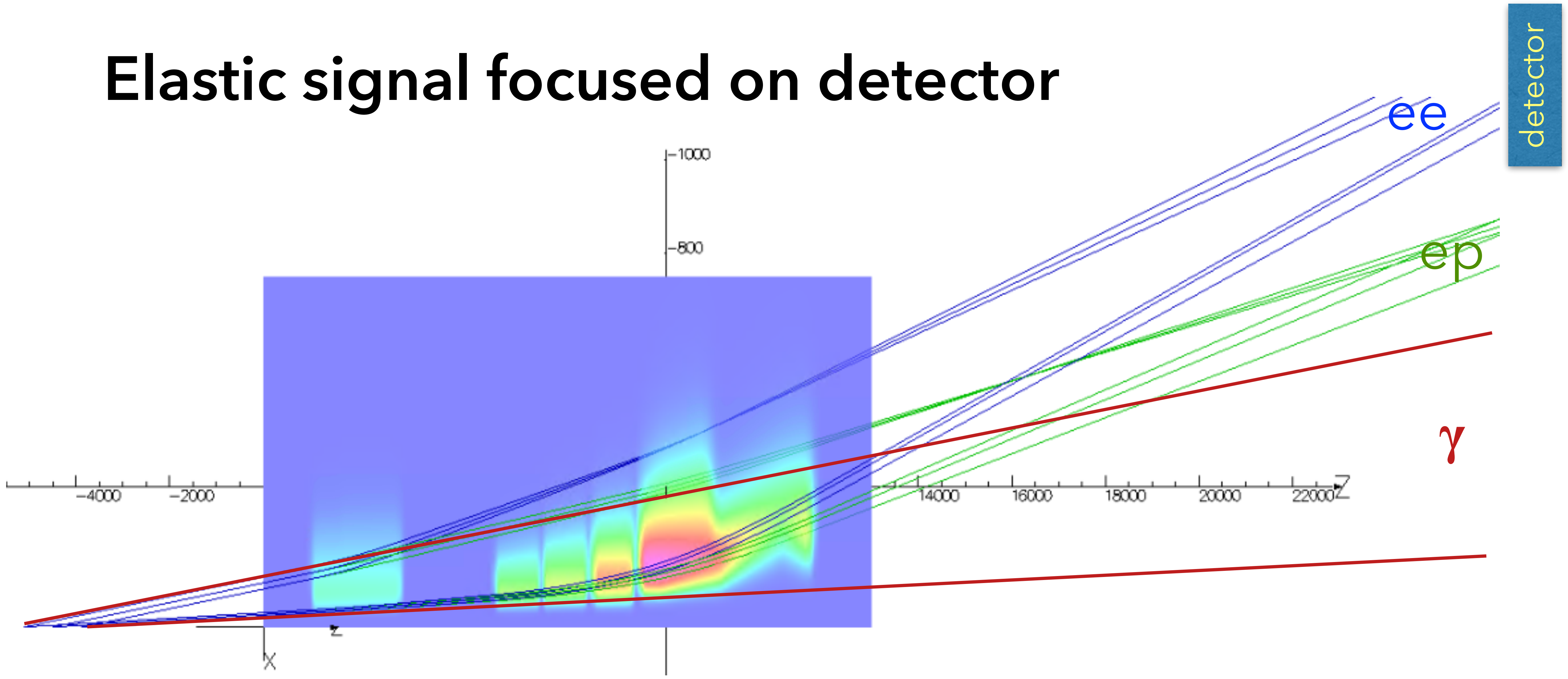
dark Z: mass mixing with Z^0

Davoudiasl, Lee, Marciano
PRD89 (2014), 095006
PRD92 (2015) 055005

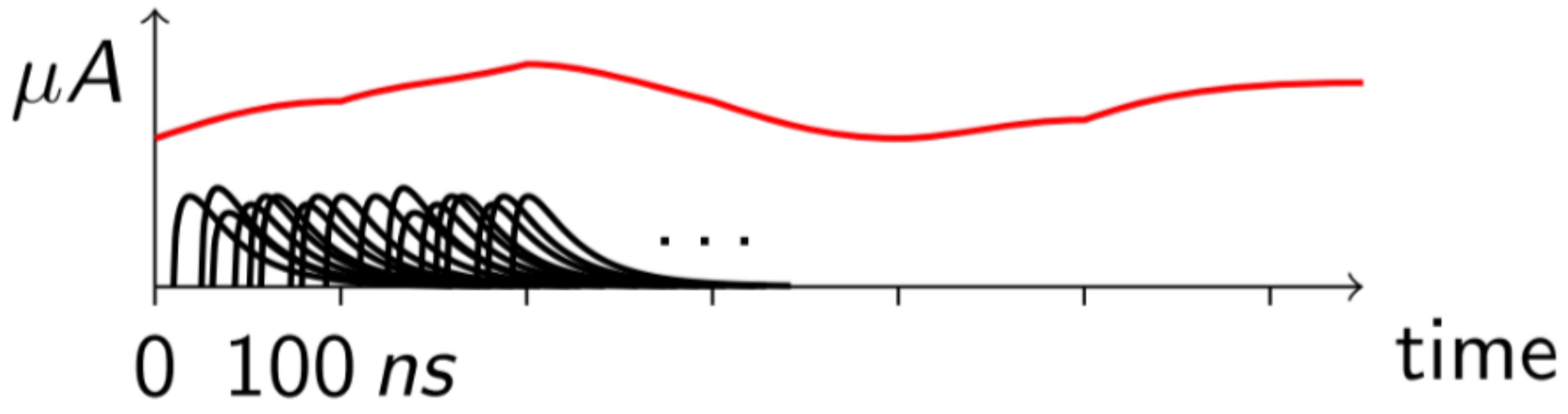


Measuring A$_{PV}$

Elastic signal focused on detector

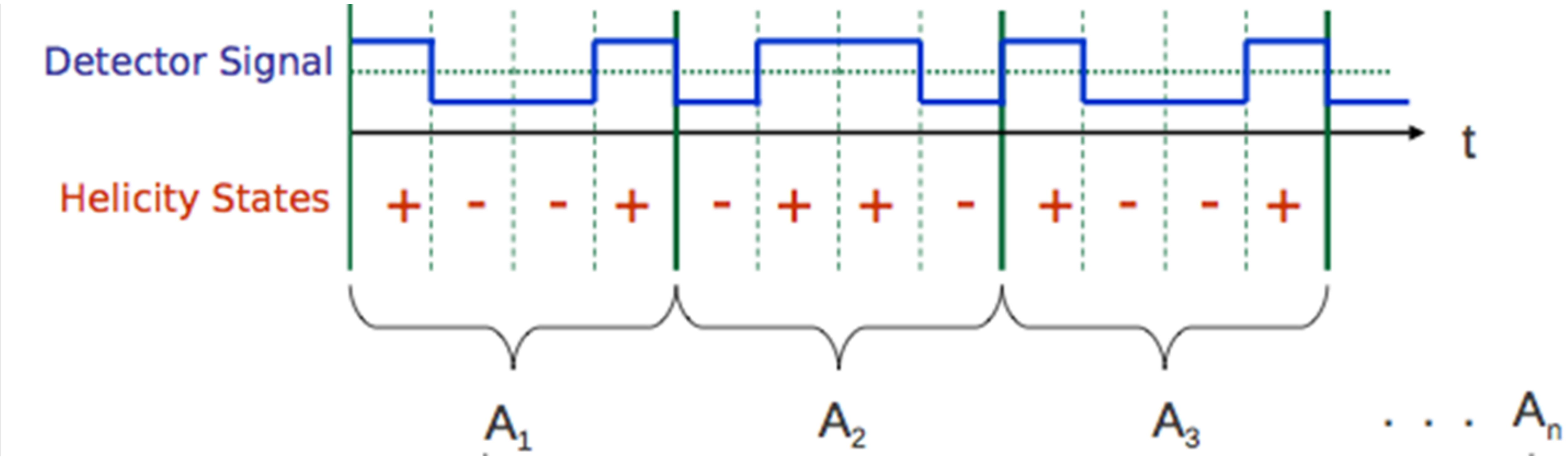


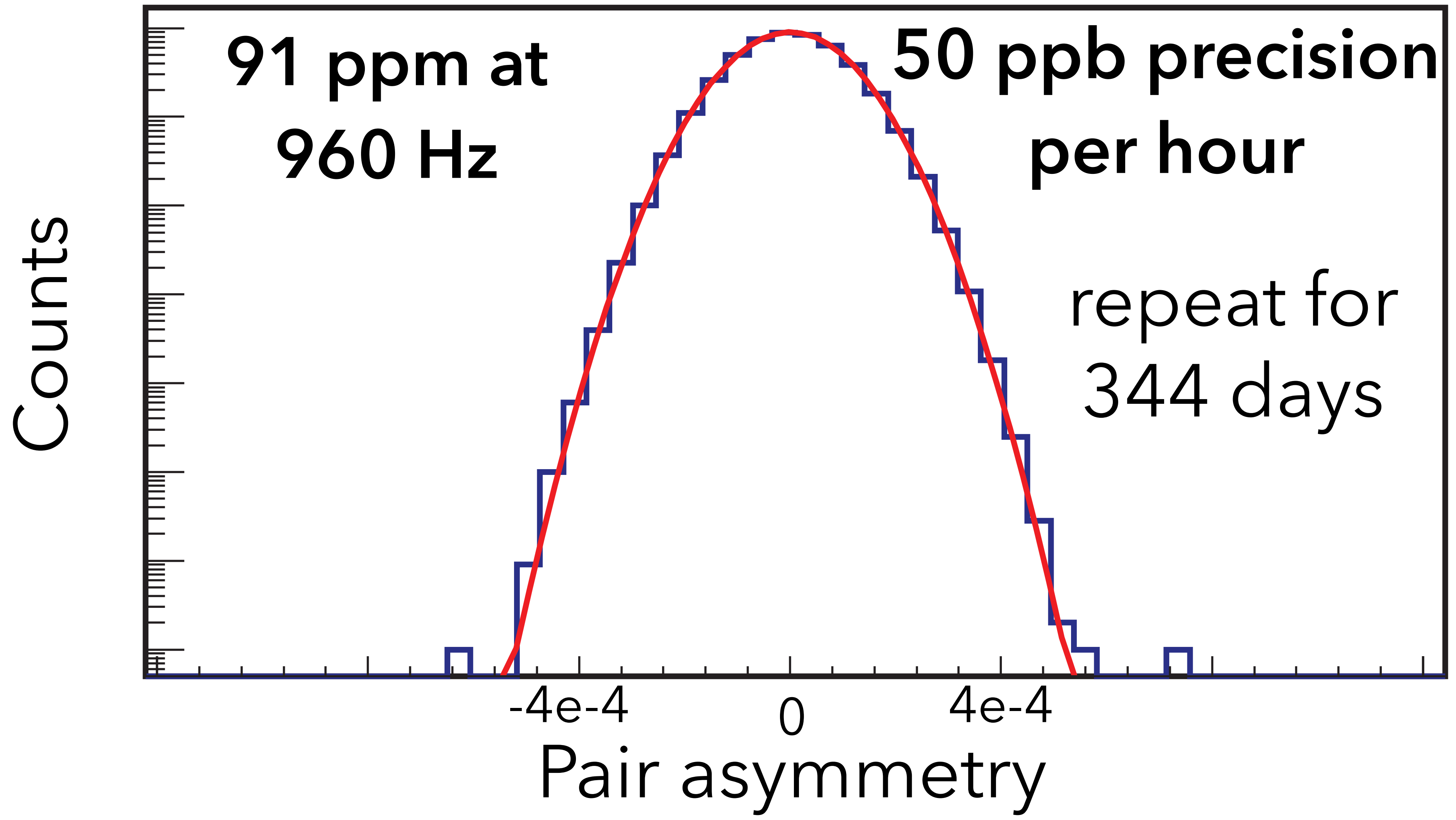
Integration of detector current



~130 GHz signal rate

Rapid (1kHz) measurement over helicity reversals





MOLLER

A_{PV} ~ 32 ppb with goal of 2% statistical, 1% systematic uncertainty

High luminosity and acceptance   *Møller Rate ~ 130 GHz*

- 125cm, 4.5kW LH_2 target
- 65 μA beam current at 11 GeV
- 85% polarization
- "large" acceptance (~100% of high FOM kinematics)

Control Noise *91 ppm at 960 Hz*

- Low noise detectors and readout electronics
- Rapid beam helicity flip
- Beam and target stability
- Precision monitoring and calibration

Integrate time

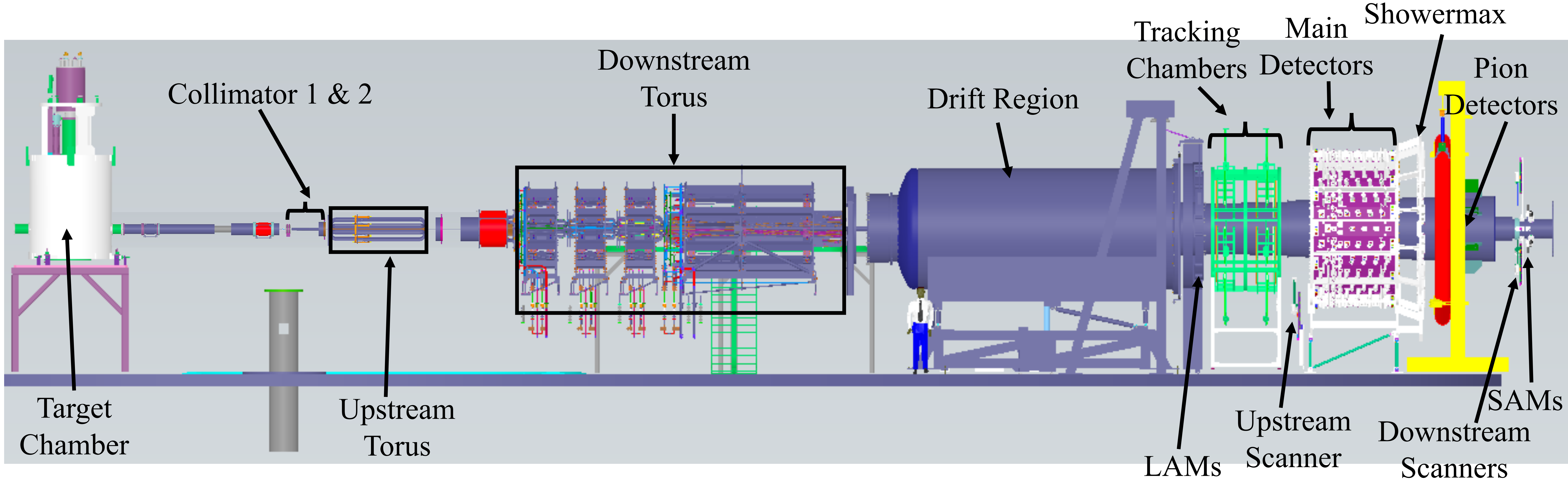
- 344 beam days (~3-4 calendar years)
- Radiation resistance for materials and electronics

Controlling Systematic Uncertainty

- background monitoring
- optics / acceptance calibration
- polarimetry
- Beam control, monitoring and calibration
- "spin reversal" tools

JLab: precision instrument with 25years of high precision PVES experiments

MOLLER collaboration: 40+years of experience including E158, Qweak, PREX/CREX



High Precision Measurement

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**

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

Uncertainty budget for A_{PV}

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

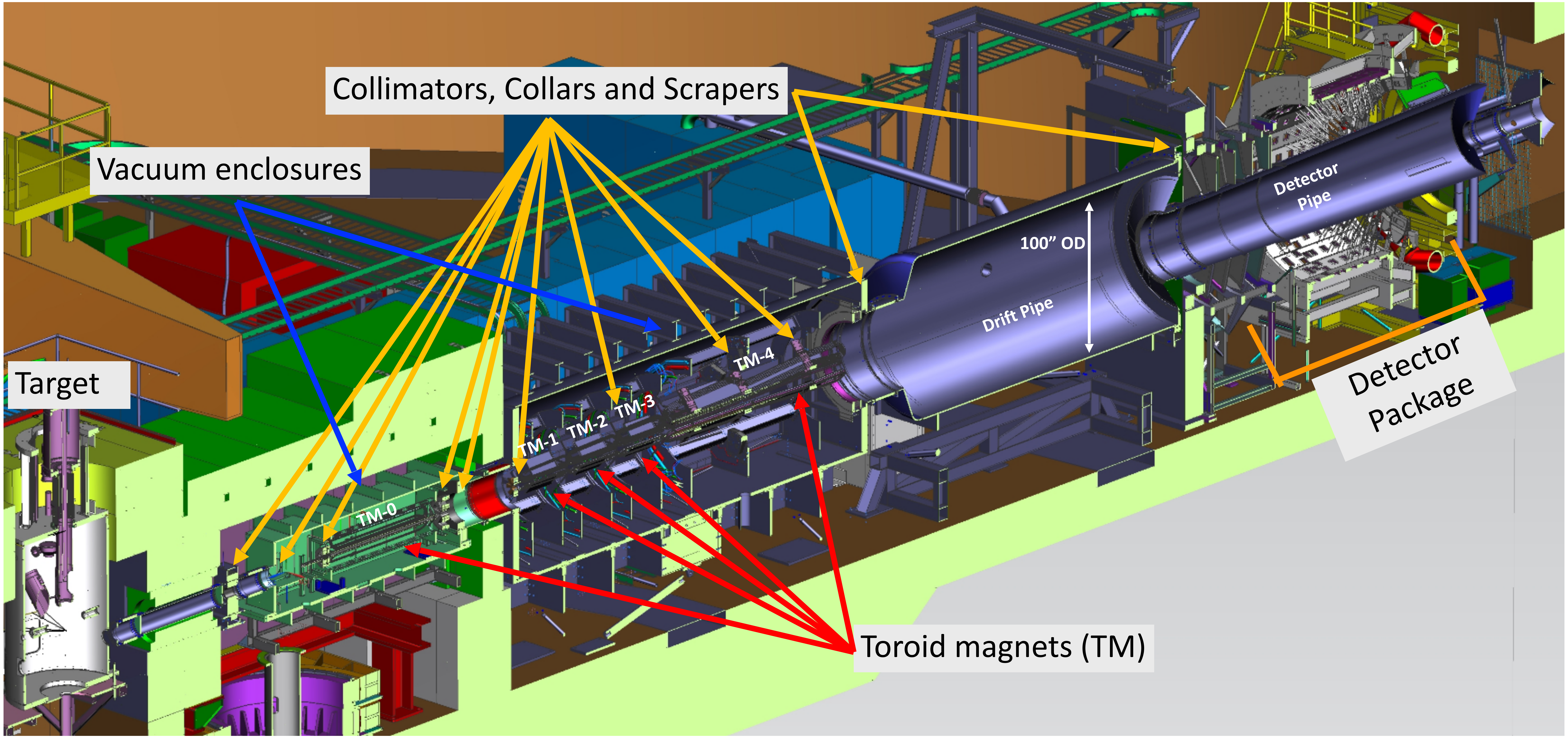
Combined $\frac{\delta A_{PV}}{A_{PV}} = 2.4\,\%$

Experimental design driven by these goals

Statistical Uncertainty: Measure A_{expt} with precision ~2%

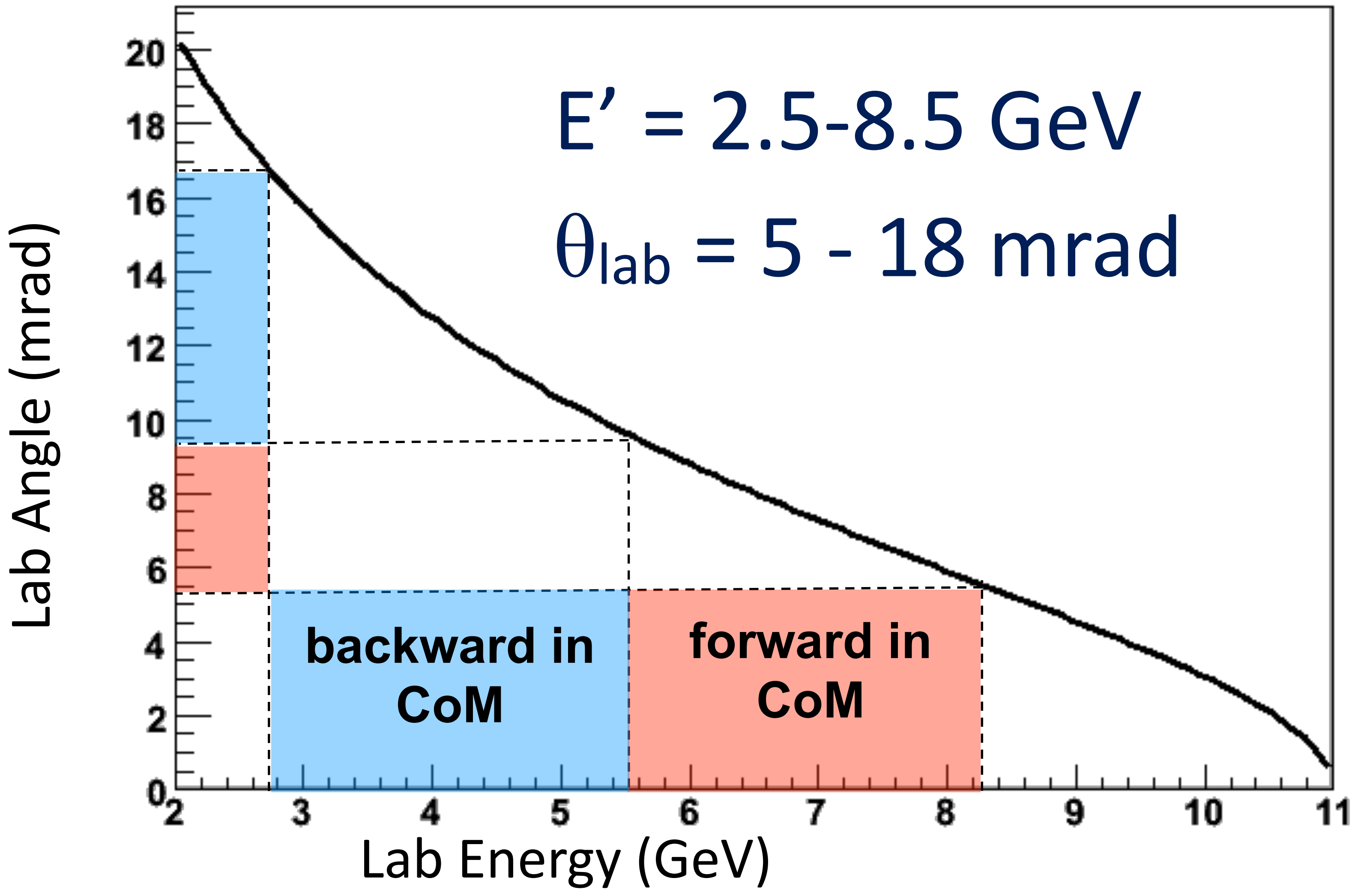
Systematic Uncertainty: Measure and/or minimize all systematic error sources so their individual contributions are <1%, resulting in statistics limited experiment

MOLLER Spectrometer Cutaway

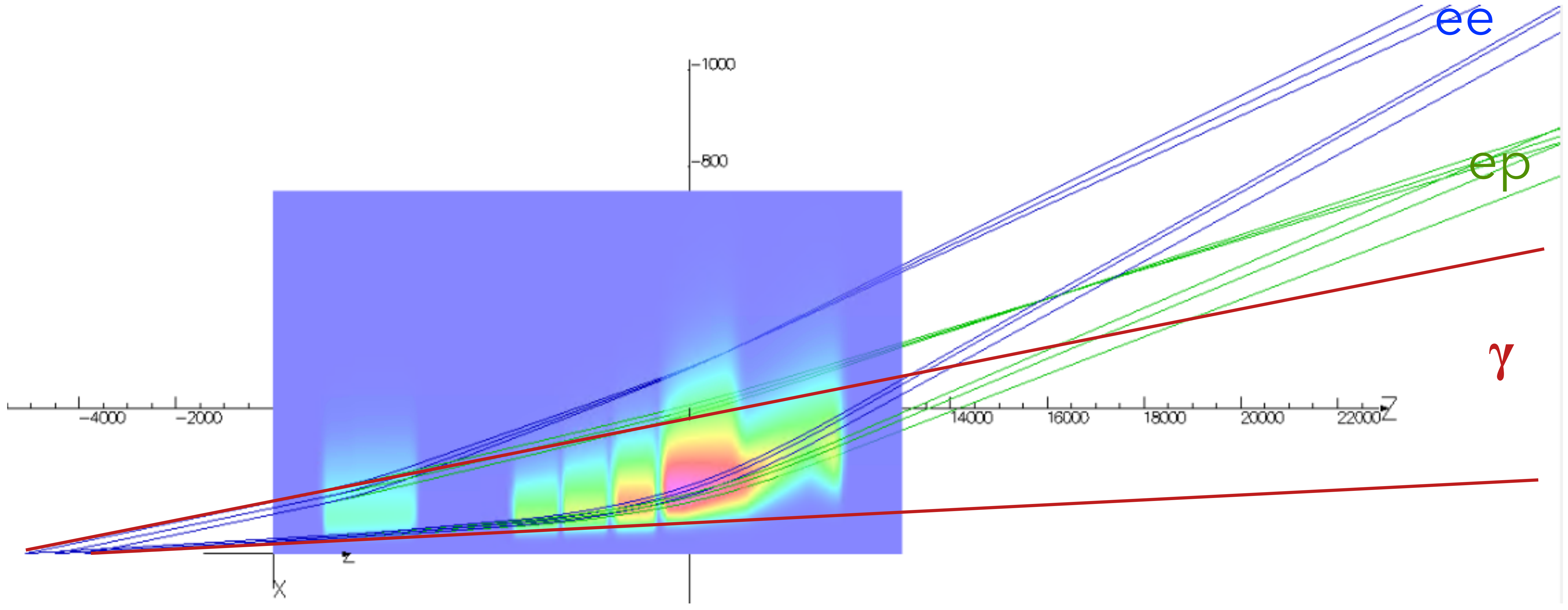


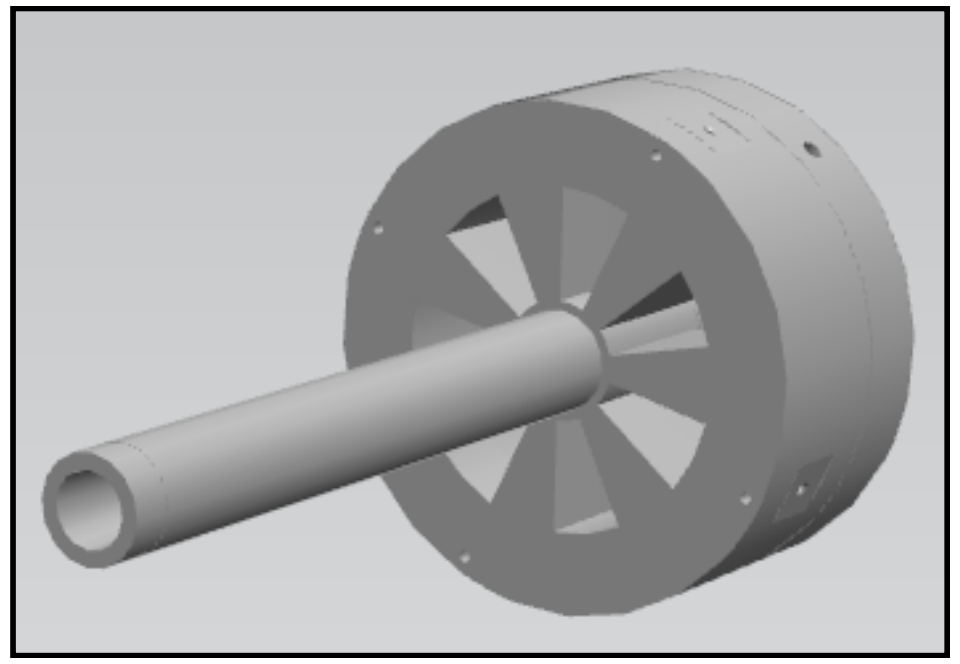
MOLLER Spectrometer Concept

FOM optimized for COM 90° ± 30°



Isolate E-θ correlation for ee scattering onto detector

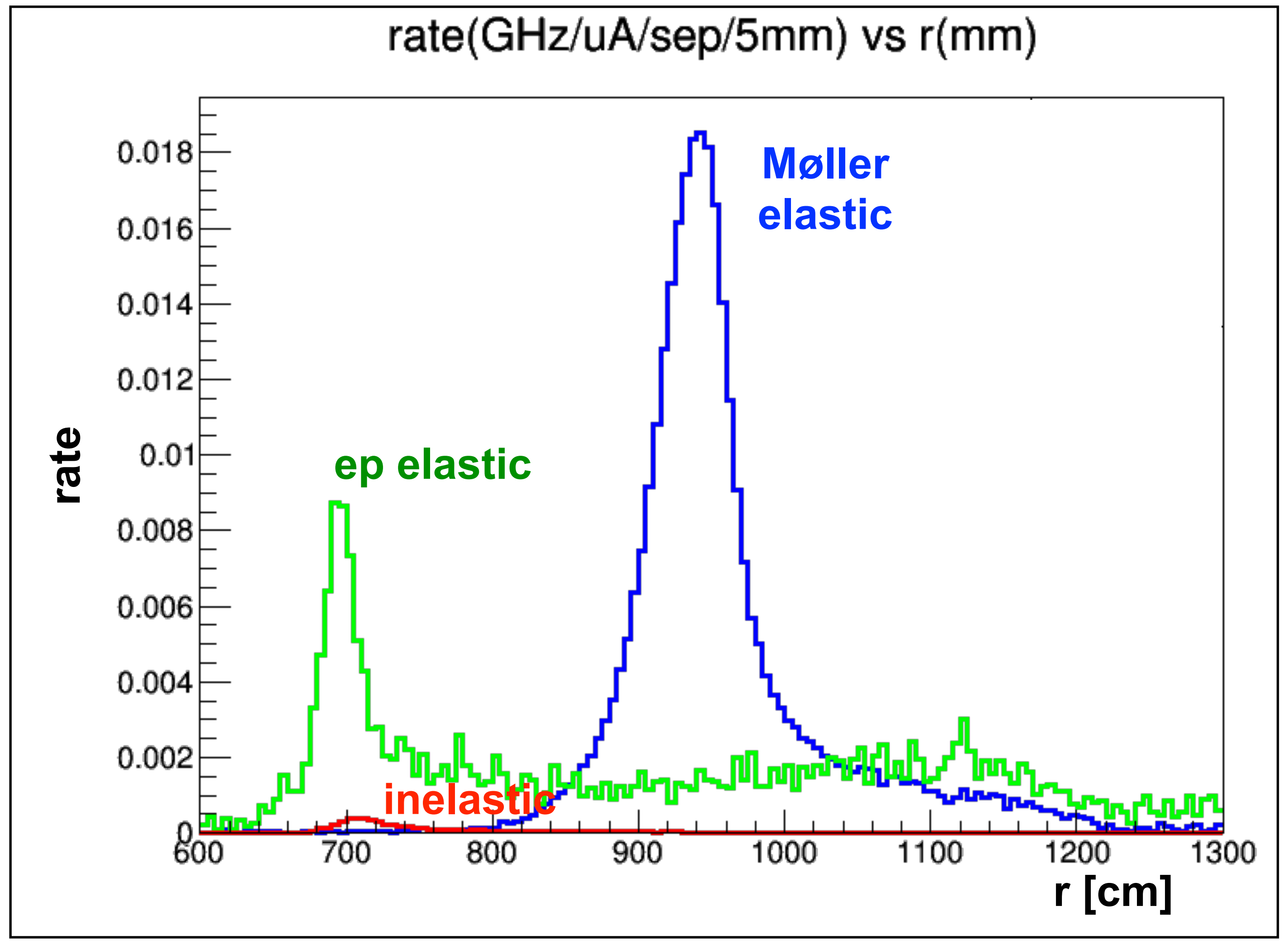




Acceptance defining collimator

- selects scattering angle
- blocks 50% of azimuth
- collimates exhaust beam

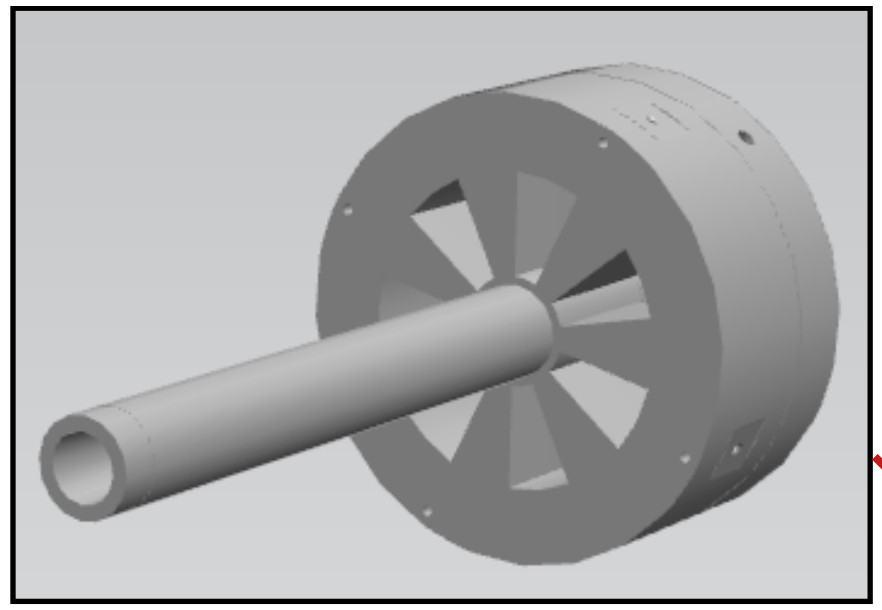
Azimuthal field from toroidal magnet separates *ee*, *ep*, and line of sight (γ) at detector plane

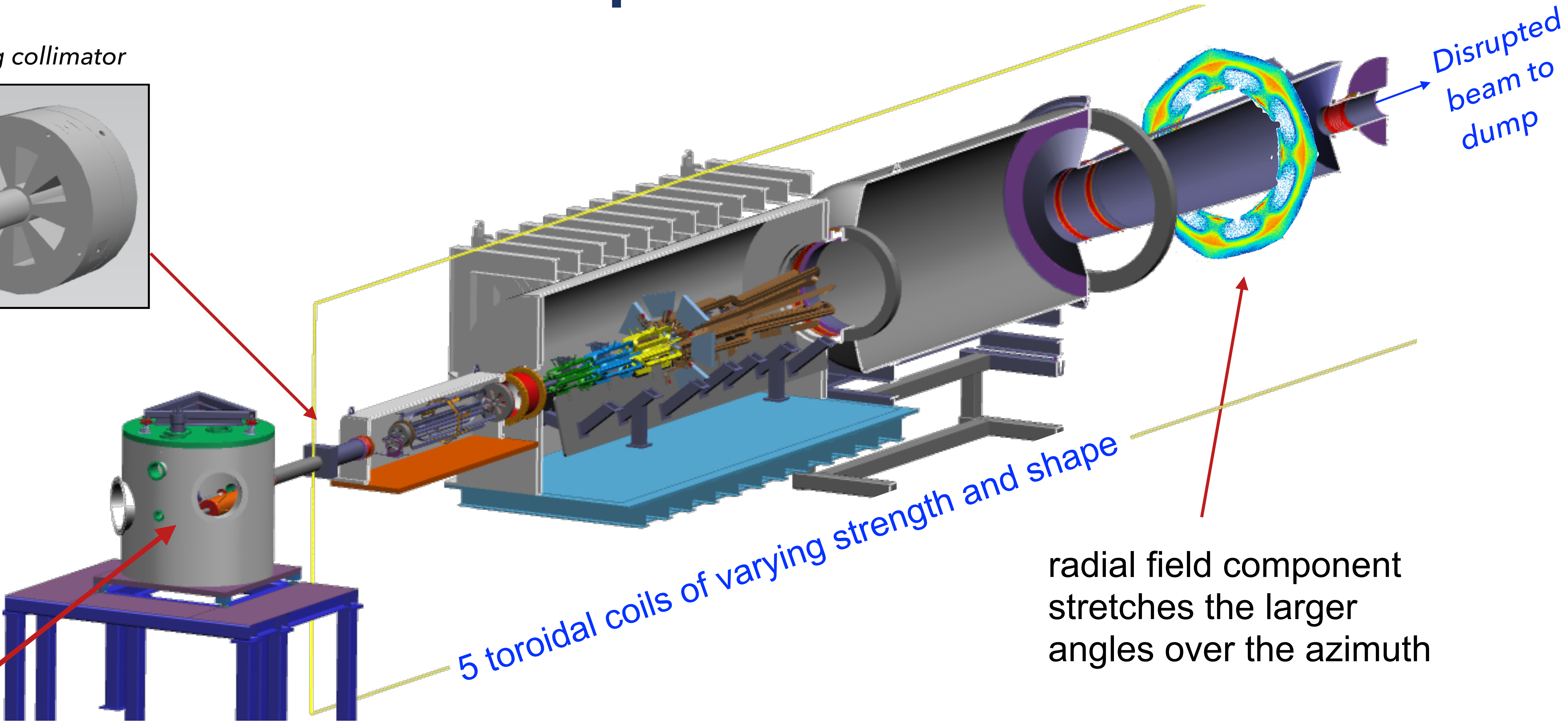


radial flux distribution

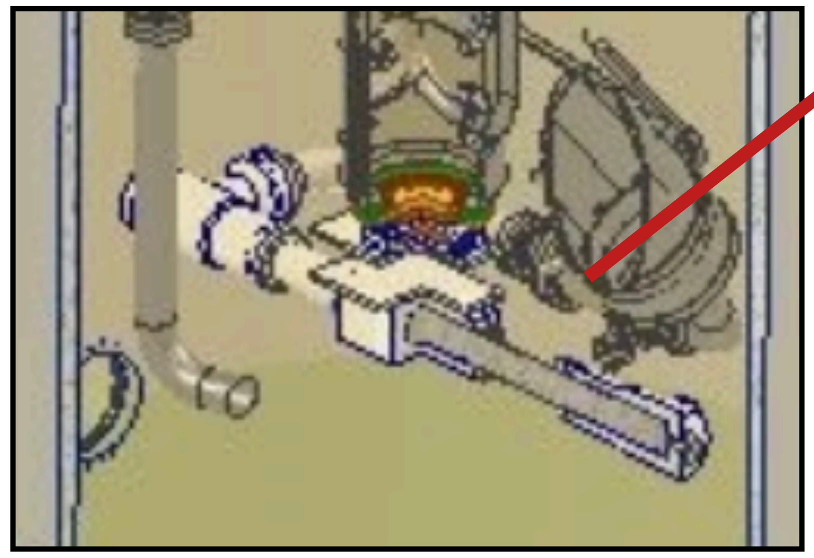
MOLLER Spectrometer

Acceptance defining collimator



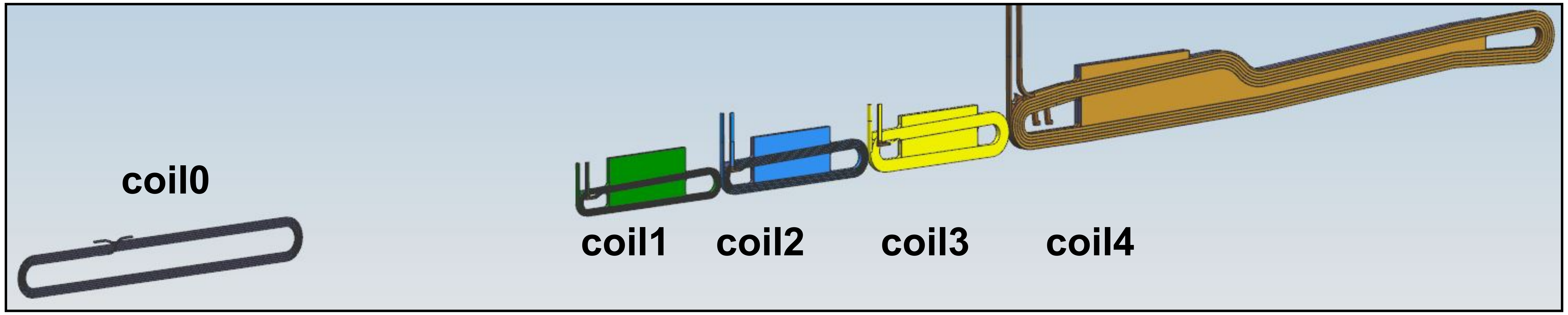


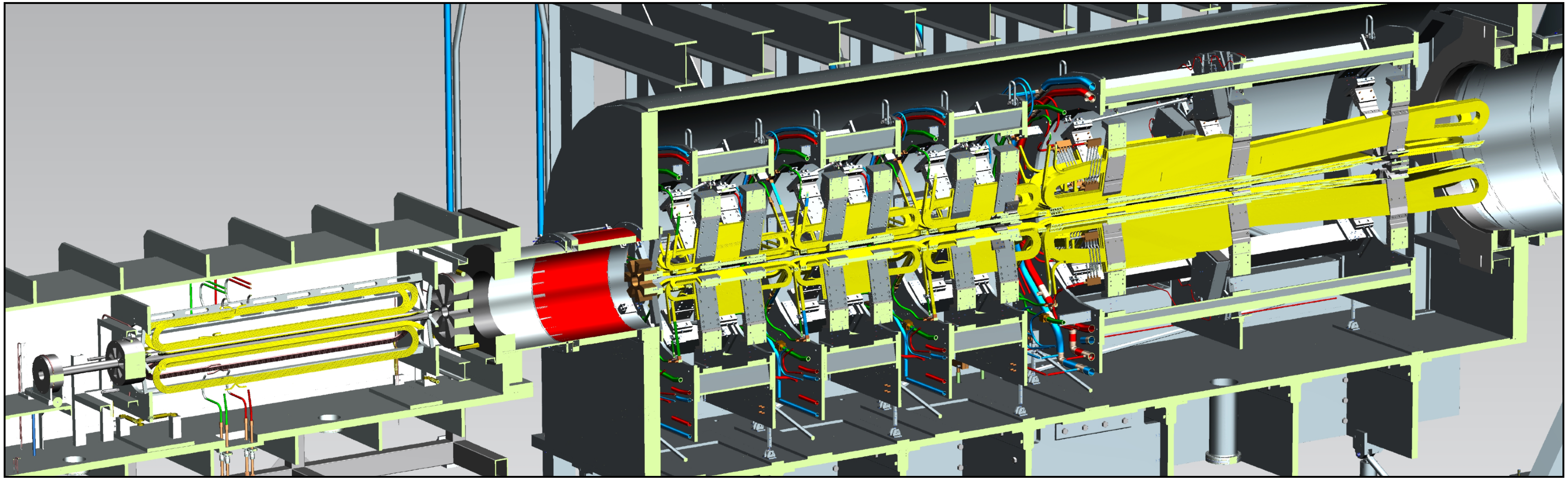
radial field component stretches the larger angles over the azimuth



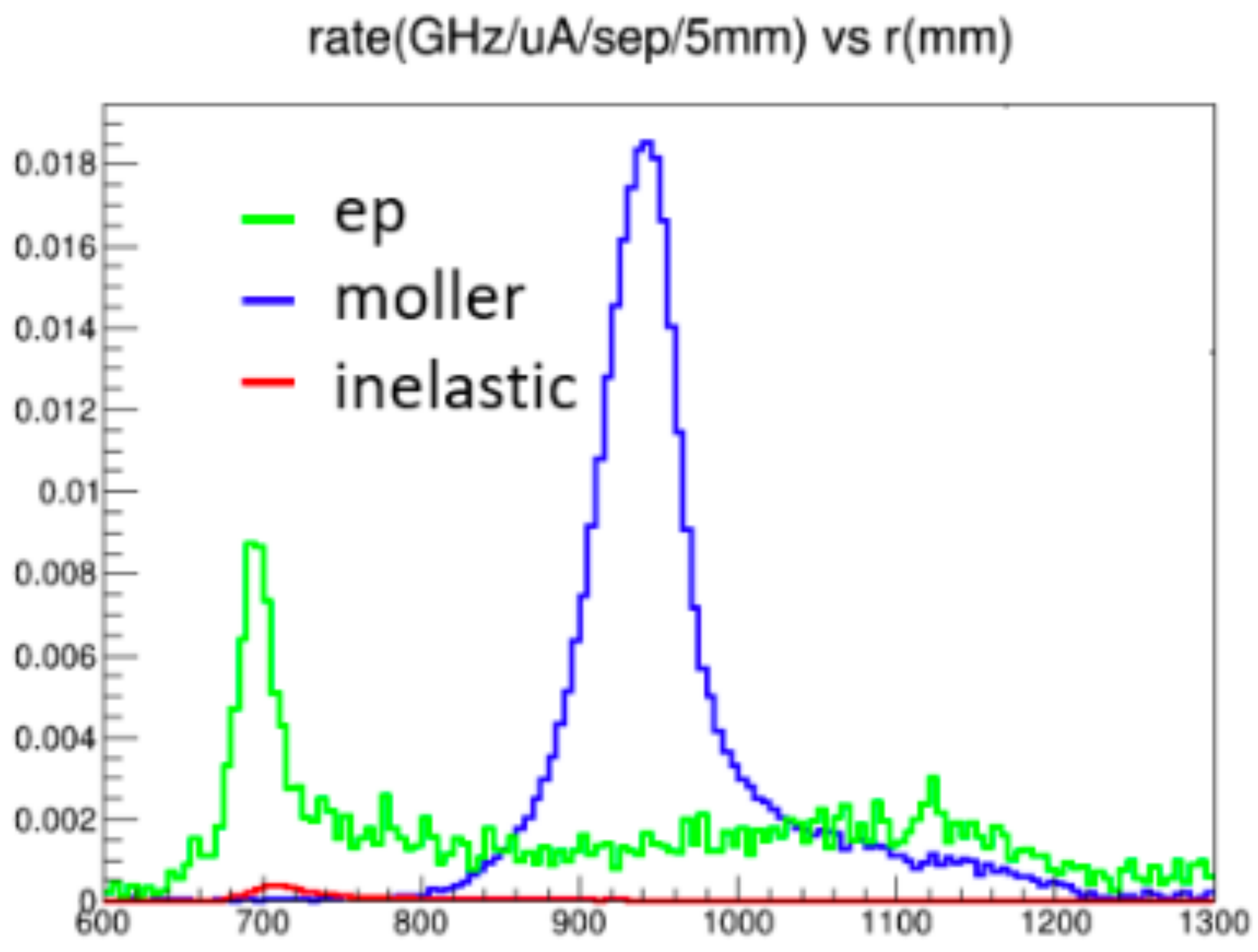
4.5kW LH_2 cryotarget
high power, high stability

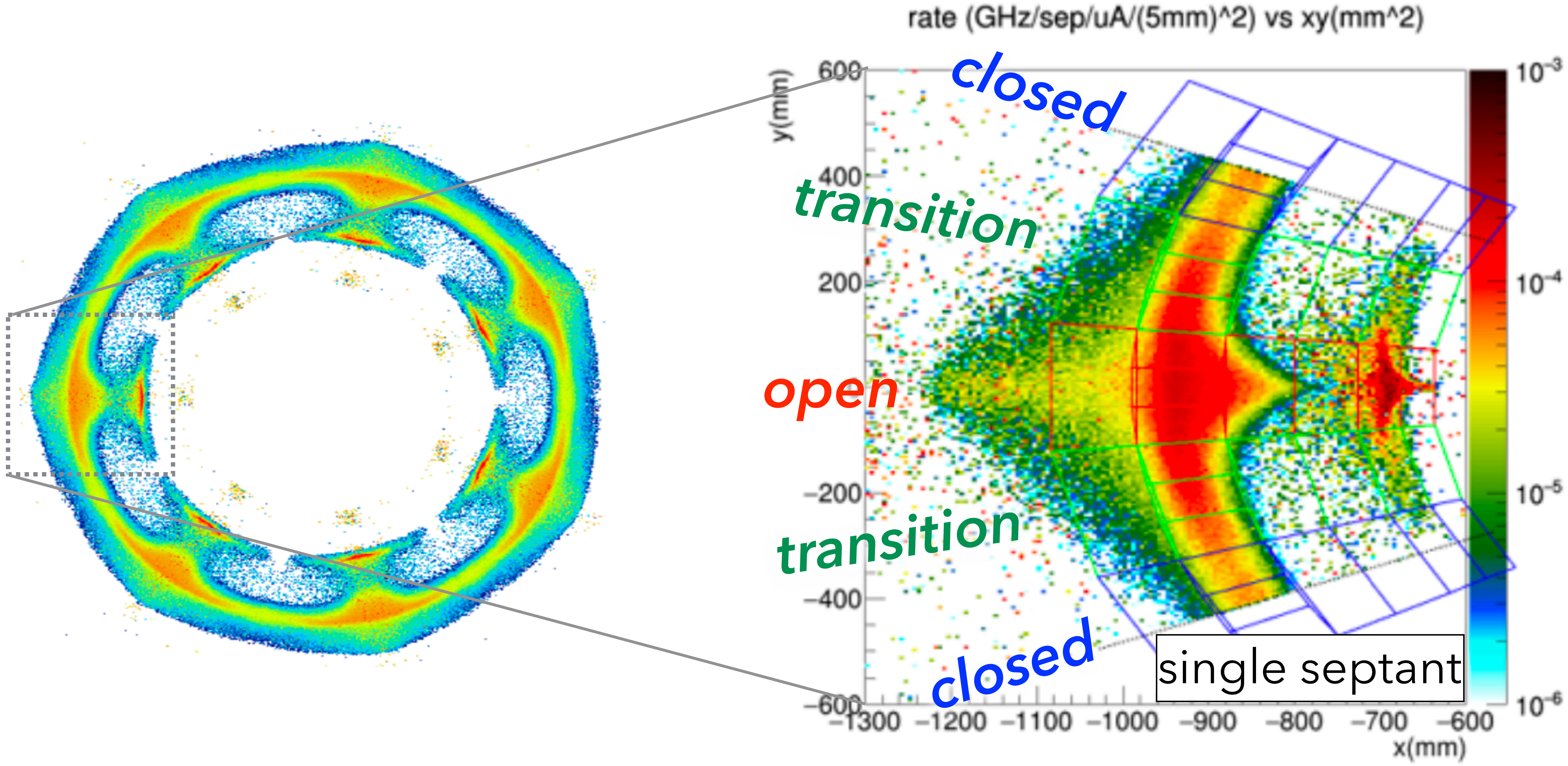
Spectrometer Detail





Flux Distribution at Main Detectors

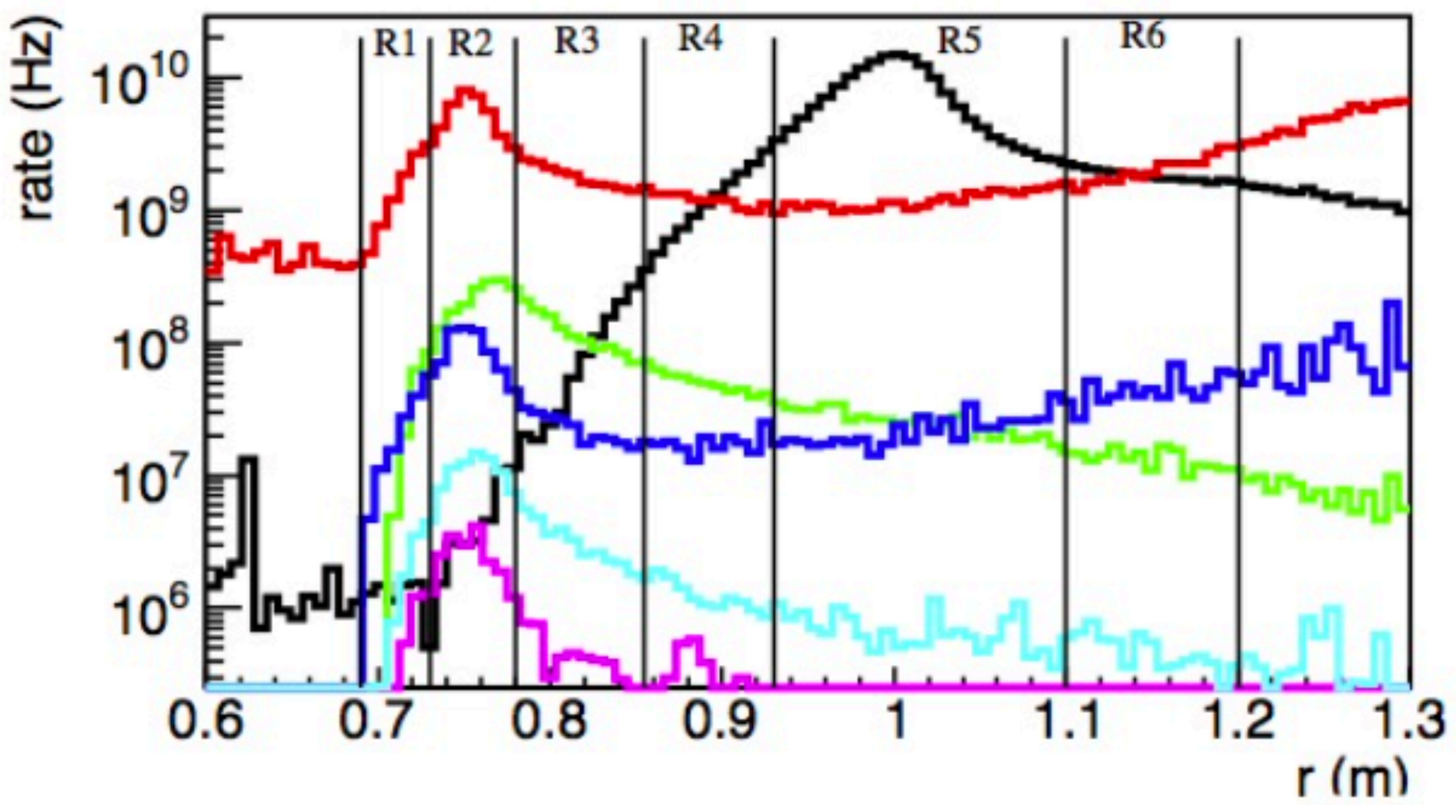


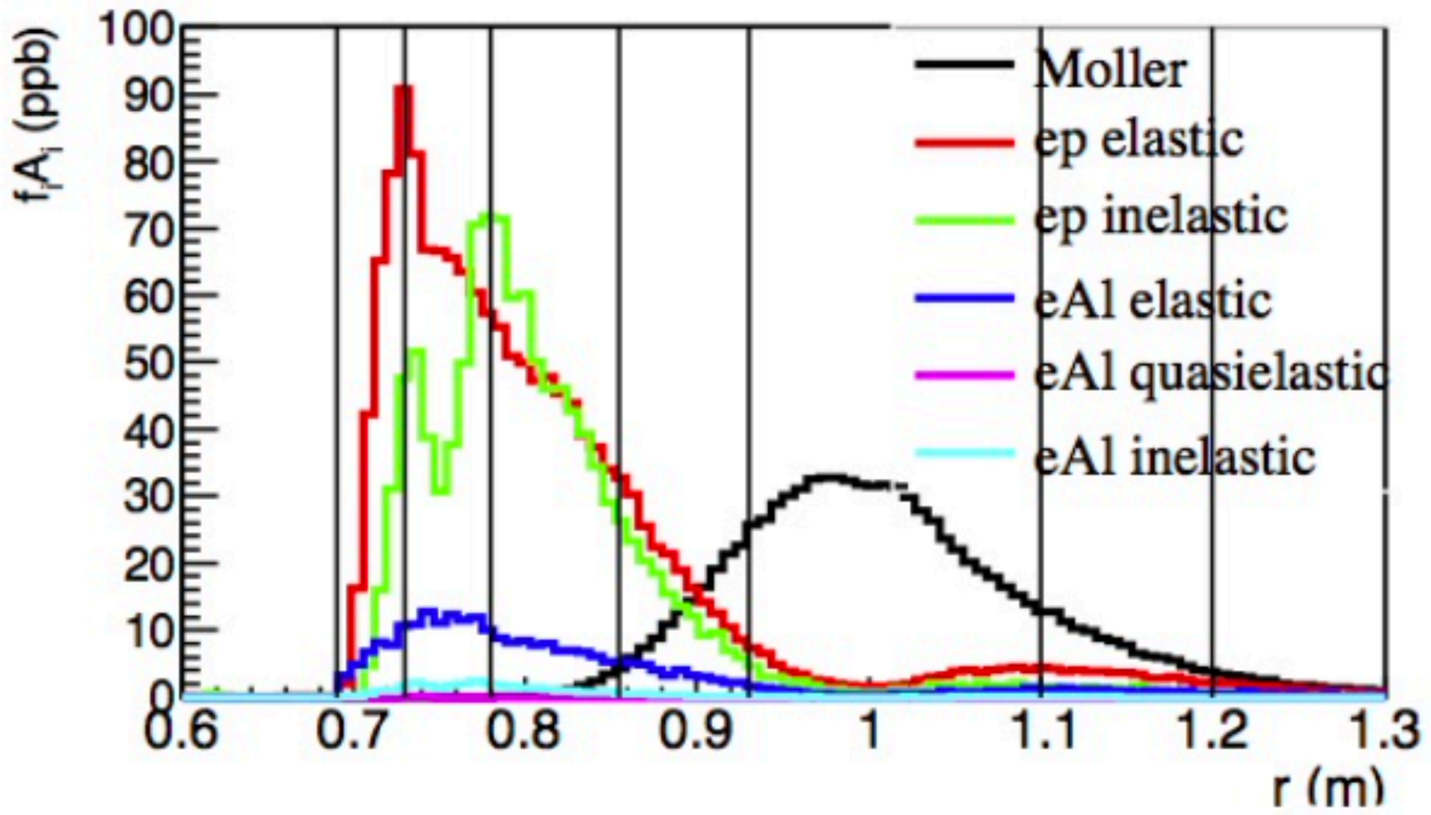


Radial / Azimuthal binning - measures backgrounds under the Møller peak

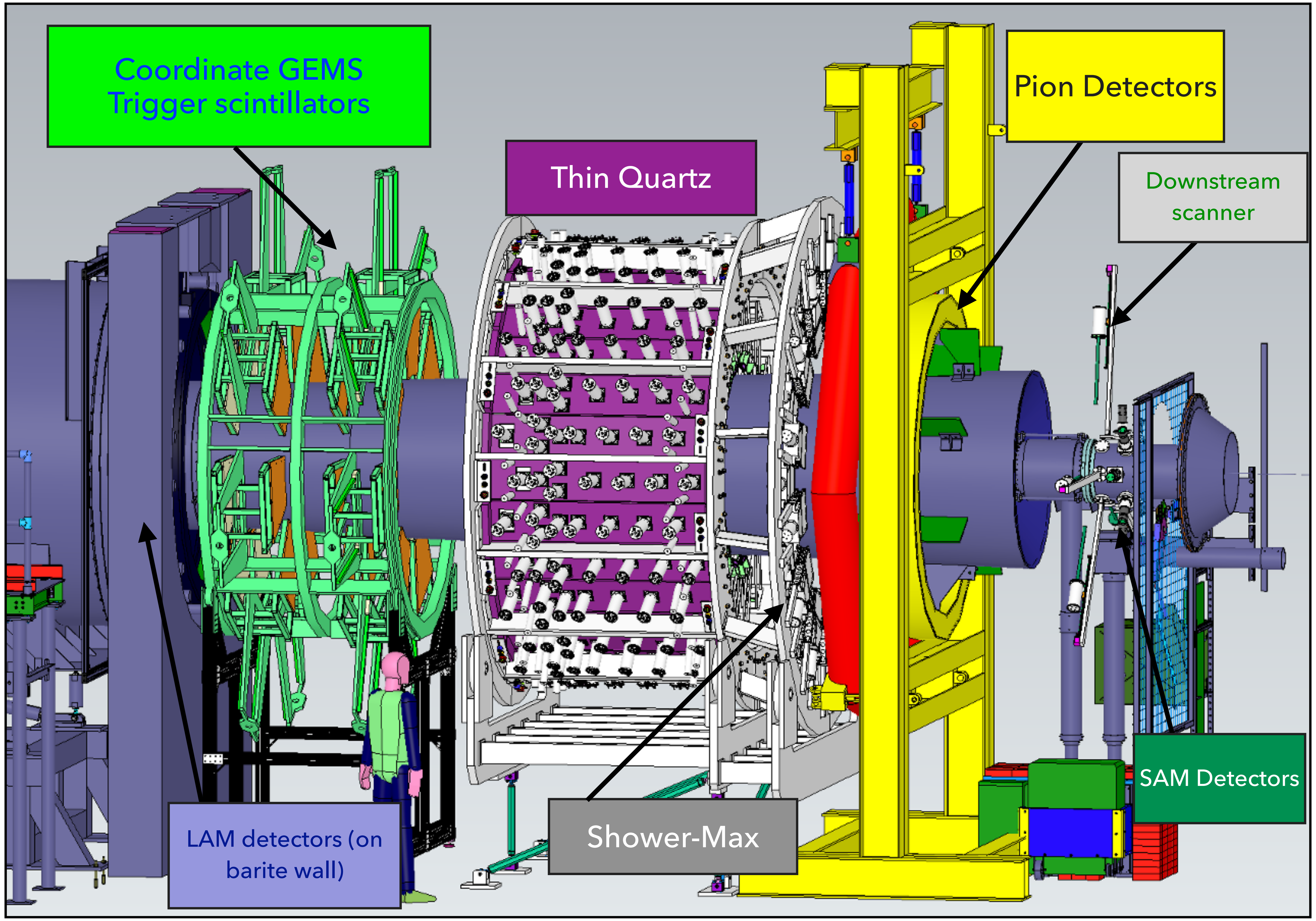
"Irreducible" Backgrounds

radiative background processes from target





Detector Package



Integrating Detectors:

For asymmetry measurement

- **Thin Quartz "Main Detectors"**
  optimized for resolution, segmented for extracting background contributions
- **Shower Max detectors**
  less resolution, different weighting and sensitivity than main detectors
- **Pion Detectors**
  After heavy absorber, sample pion background to provide pion asymmetry subtraction

GEM Tracking Detectors:

low rate calibration runs

Auxiliary detectors- LAM, SAM, Scanner

for calibrations and cross-checks

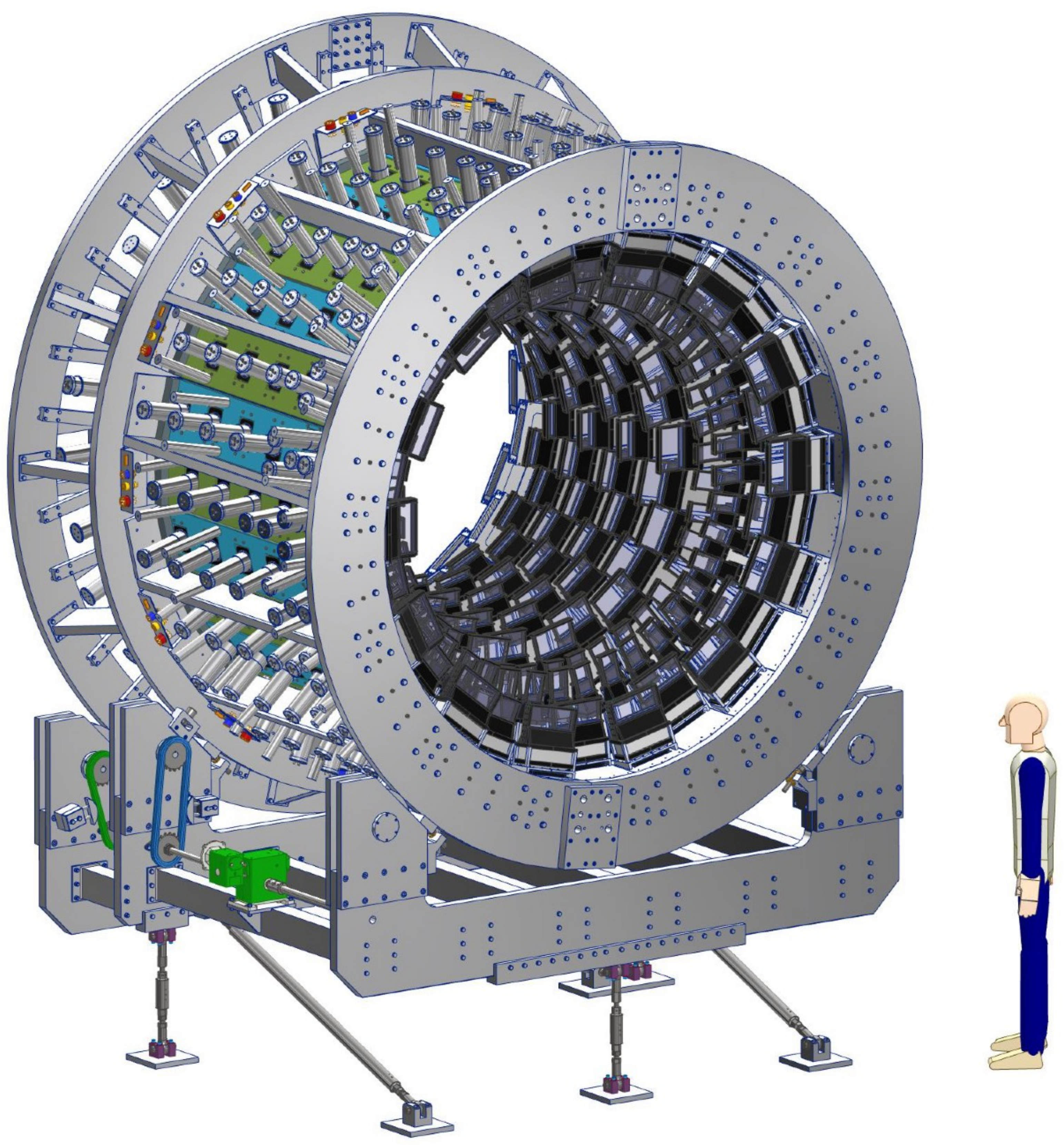
Integrating mode: for asymmetry measurement

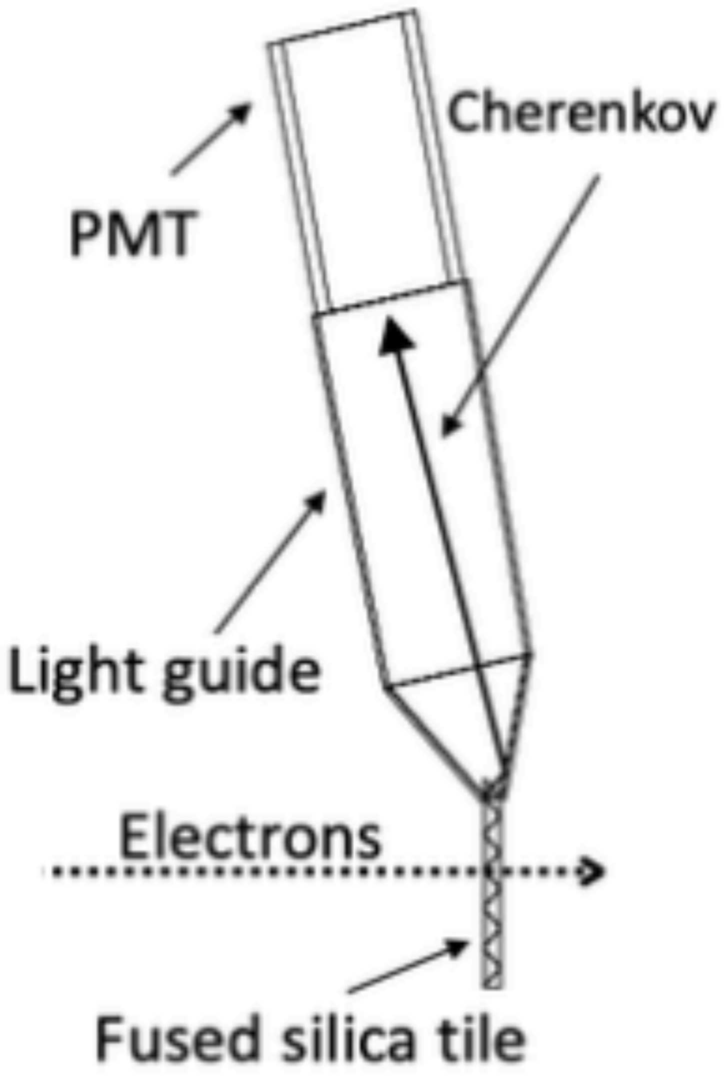
Counting mode: very low beam current, counting and/or tracking for calibration

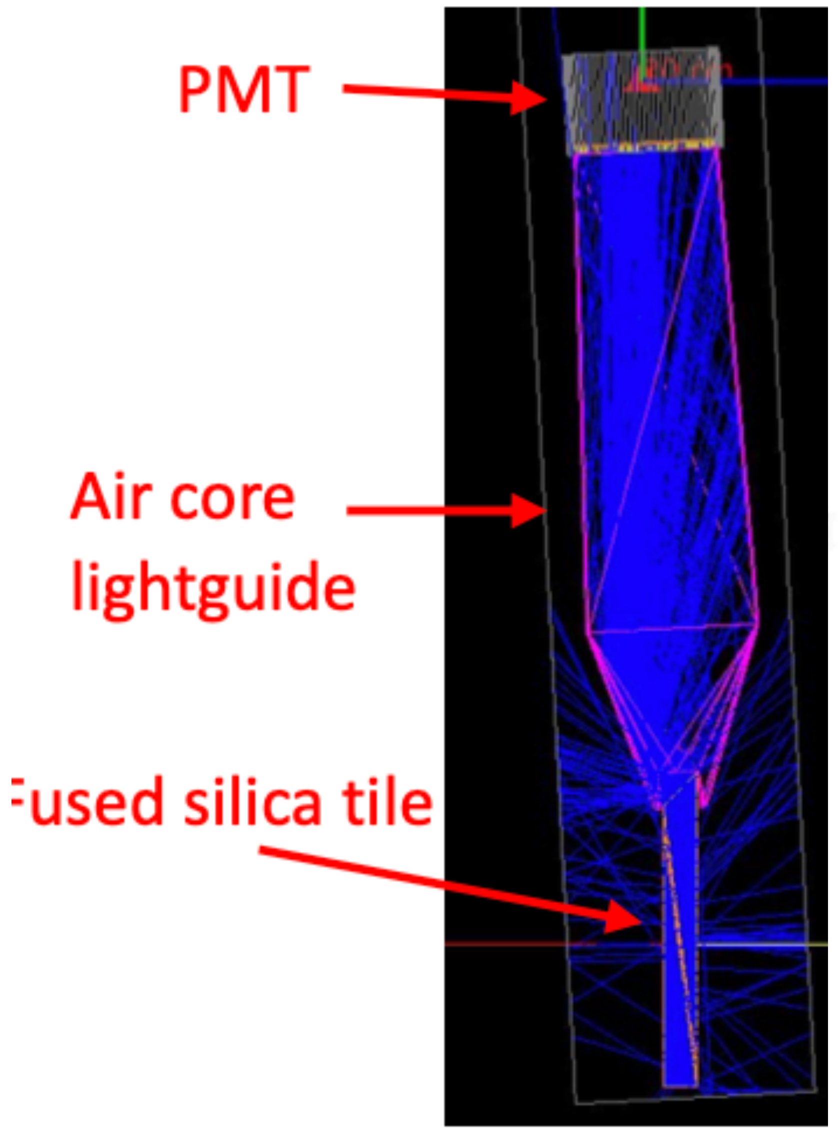
Main Detector

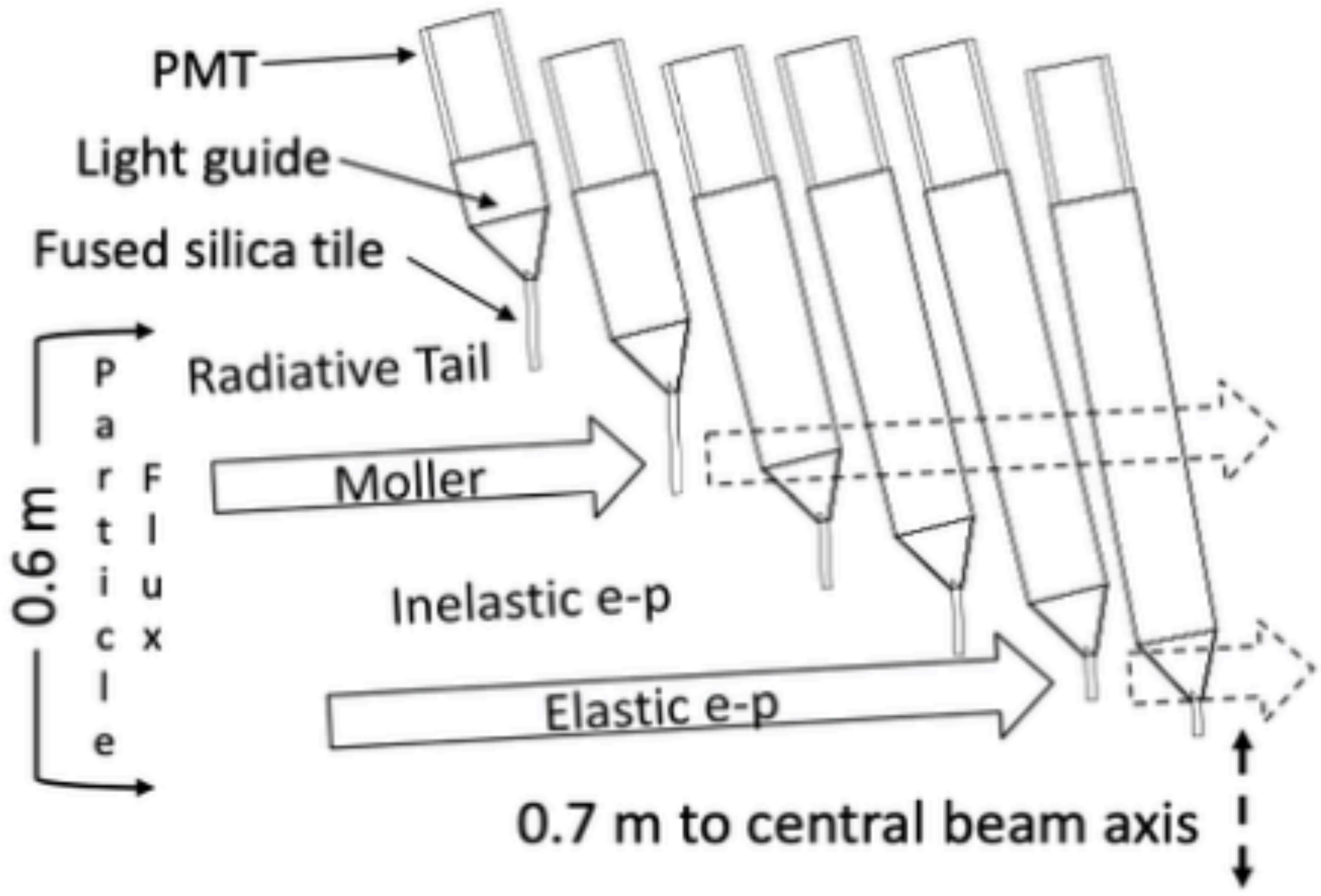
Primary A_{PV} measurement uses an array of thin quartz detectors

- 6 radial "rings"
- 224 tiles total, over 7 septants

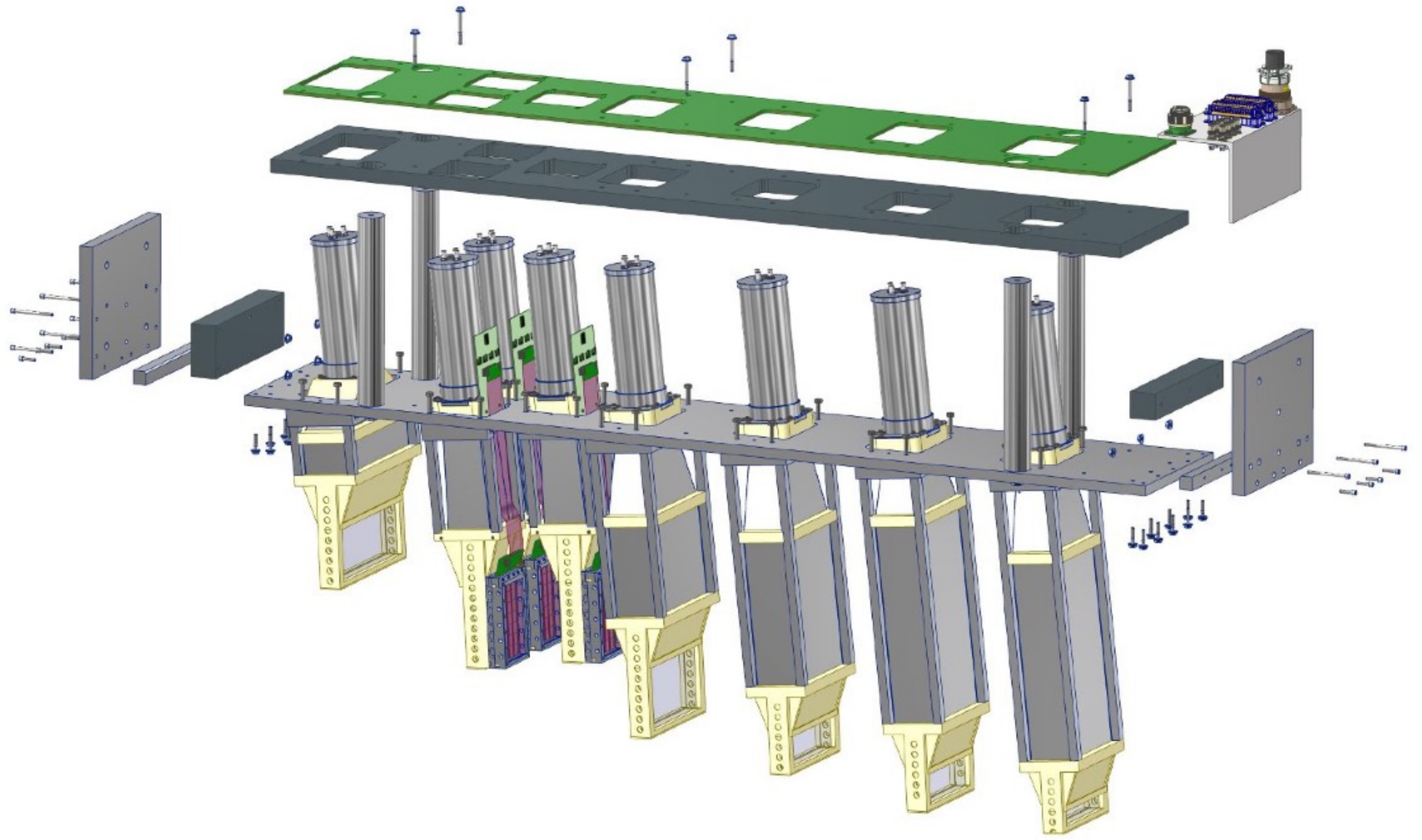








PMT + base, electrons operate in integrating mode and counting mode (for calibration)



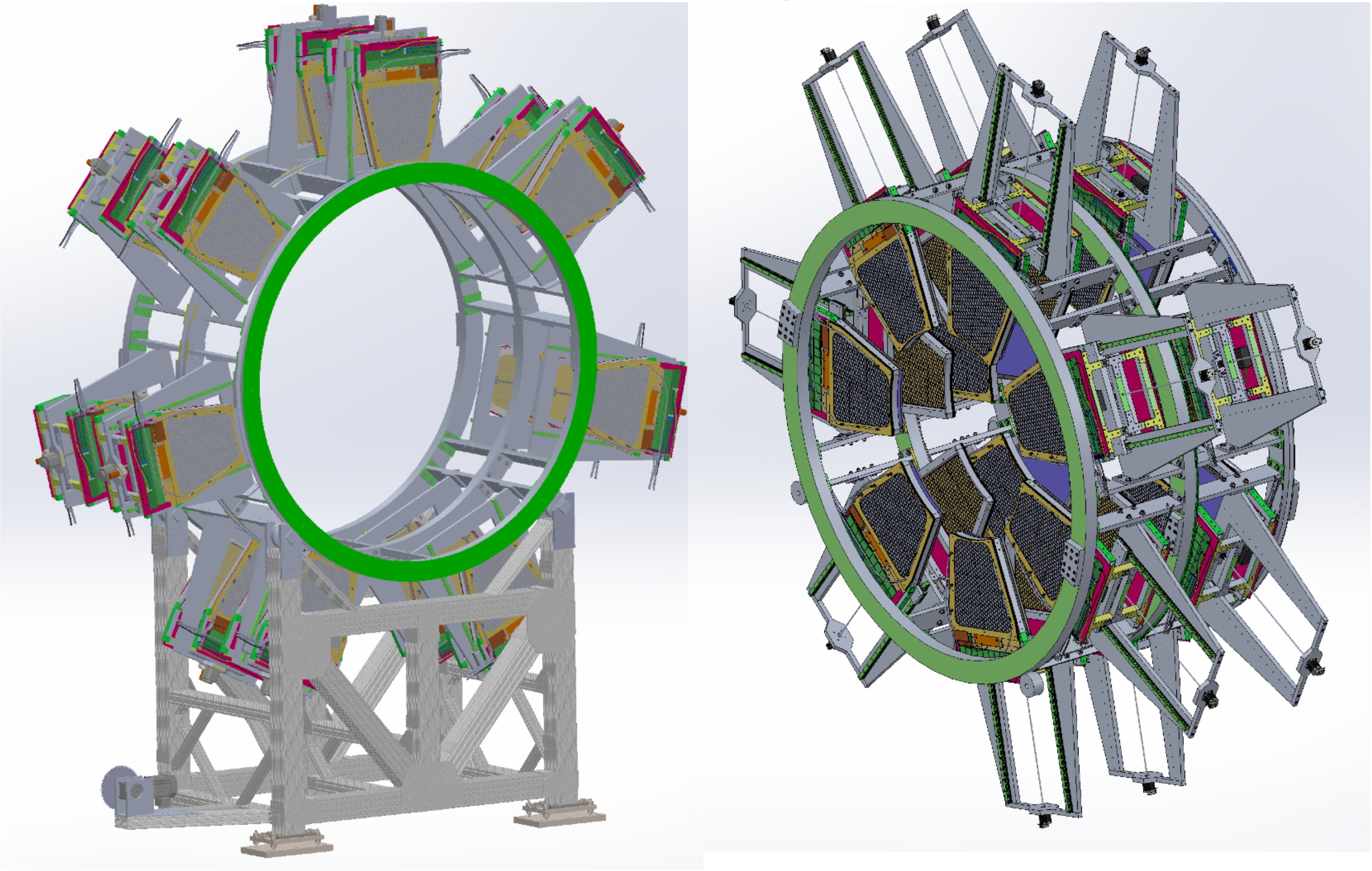
Radiation hard, to survive experiment lifetime

Rates / PMT: 4 MHz - 4 GHz

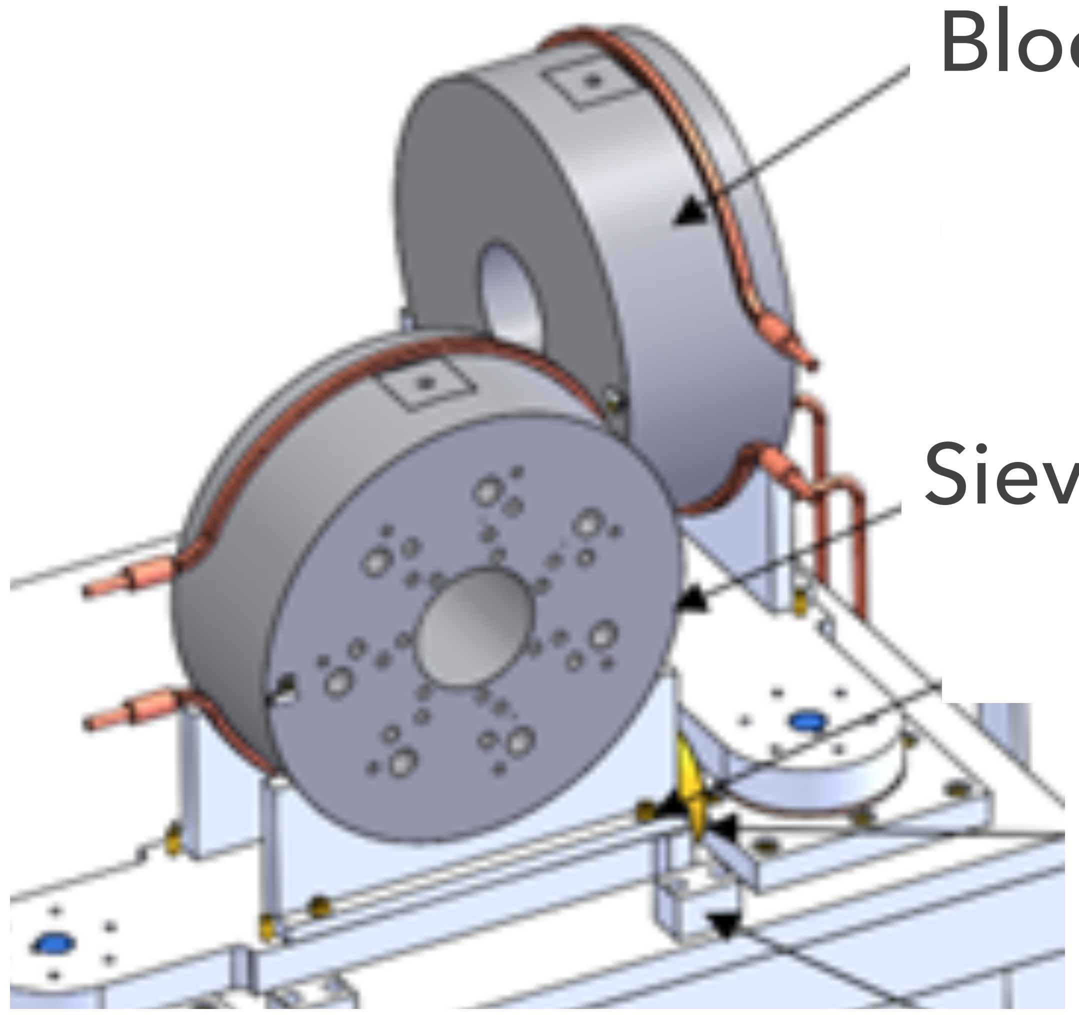
Total rate (Møller + ep): ~220 GHz

Tracking Detectors

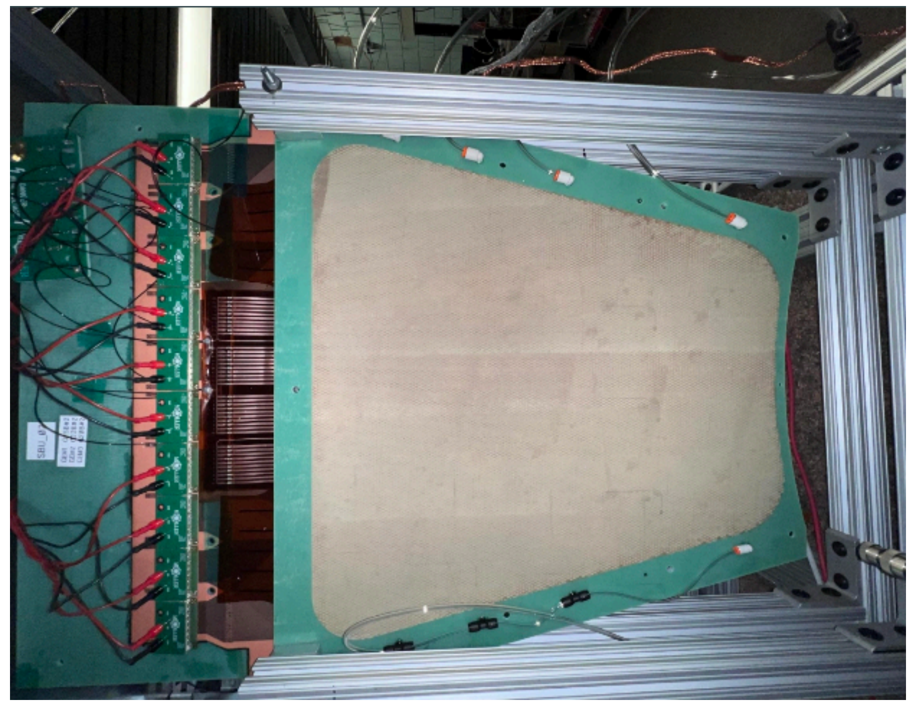
GEM rotating mount

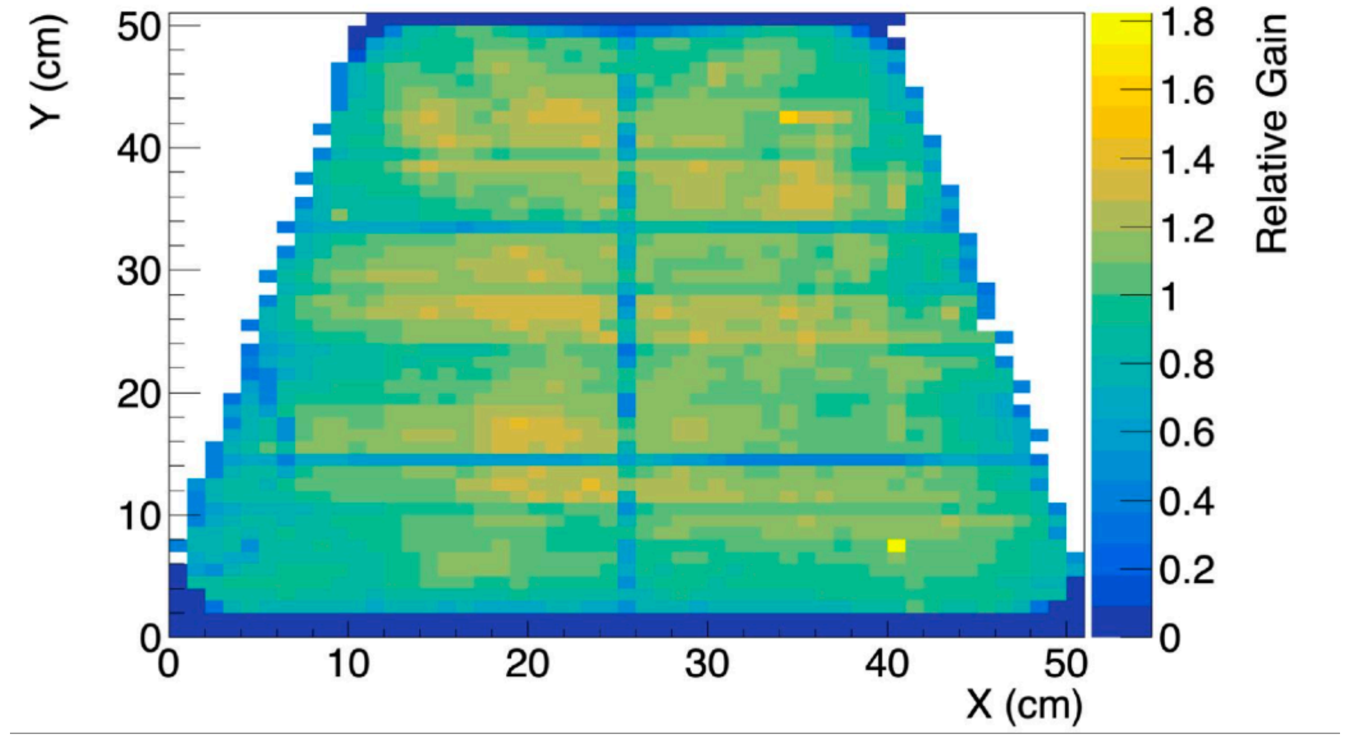


At very low currents (few nA) tracking calibration runs will be used to
- study response function of integrating detectors
- benchmark spectrometer optics and acceptance
- test for background sources



GEM chambers prototyped, in production
Testing via x-ray source and cosmic ray



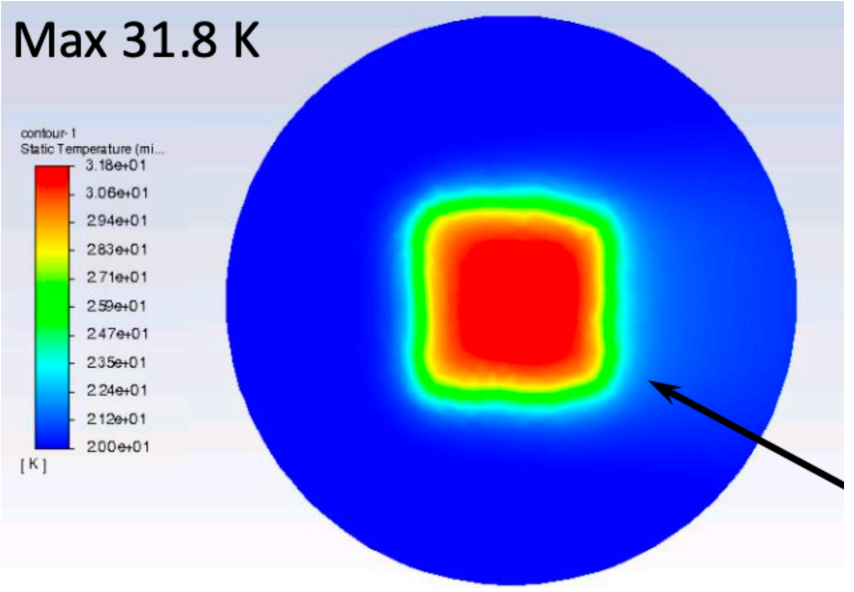


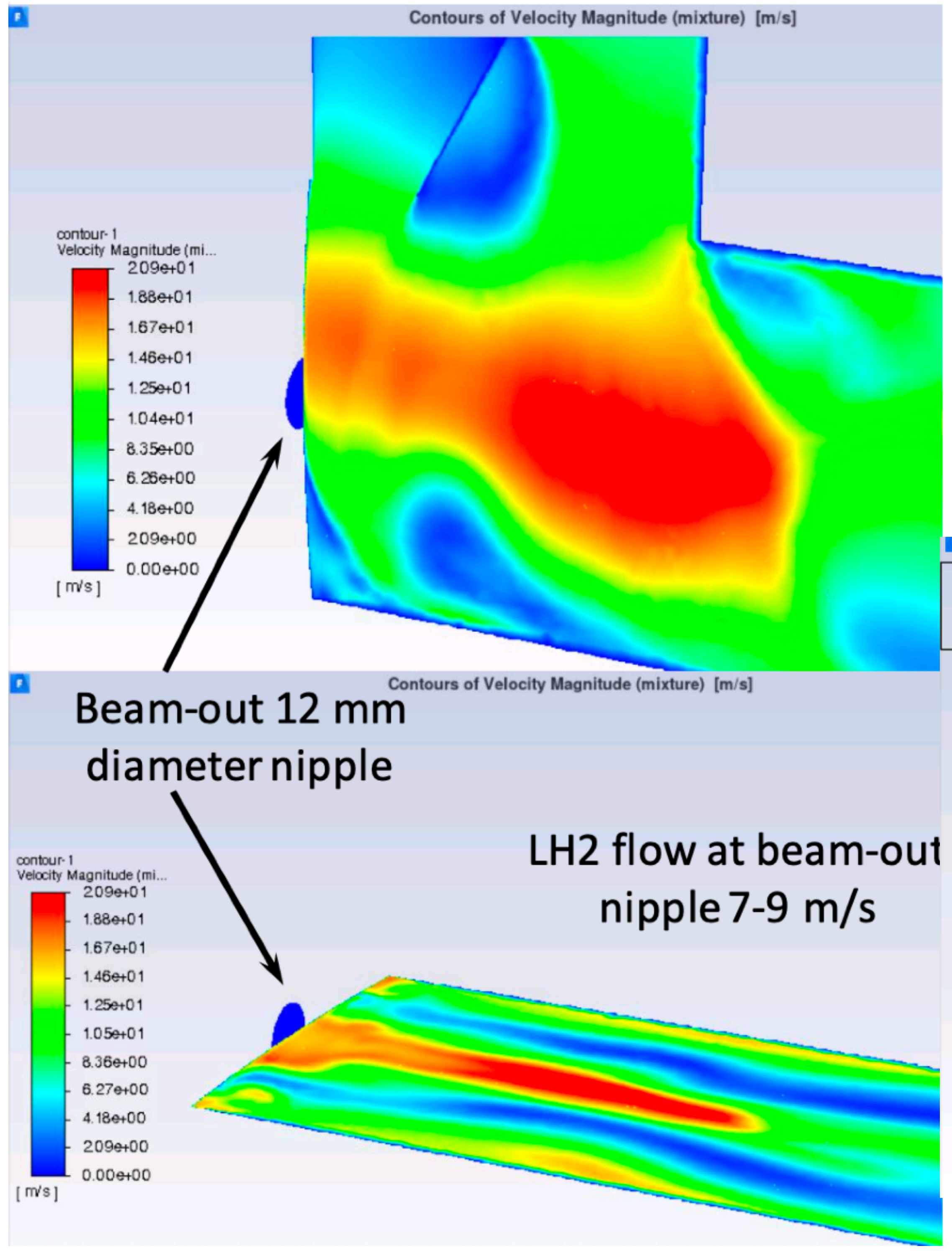
Blocker collimator to study backgrounds from scattering of exhaust beam

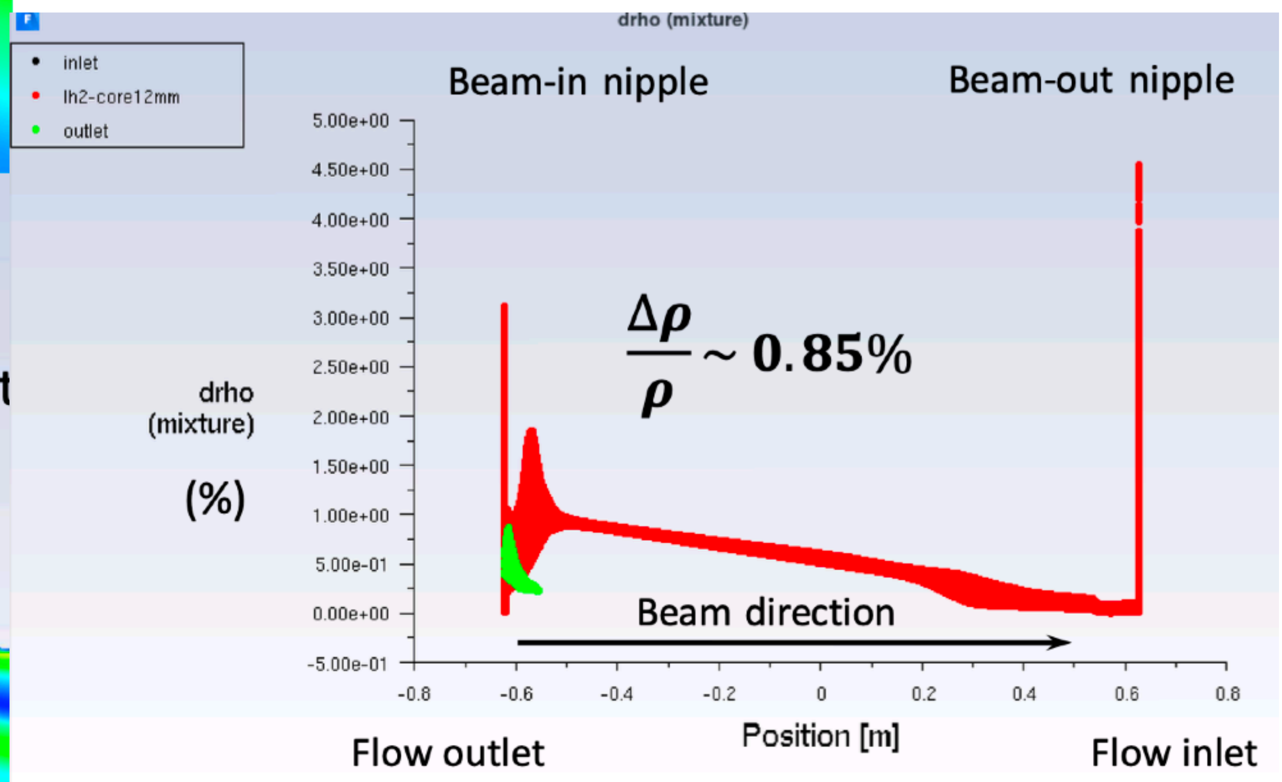
Sieve collimator for known "point source" to benchmark spectrometer optics

LH2 Target

- 4.5 kW target power, 3.3 kW beam power
- density loss $\Delta\rho/\rho < 1\%$
- density fluctuations $\delta\rho/\rho < 30$ ppm
- CFD model guided/qualified design
- matches experience with 2.5kW Qweak target







Helicity Correlated Beam Properties

MOLLER requirements

Beam Property	Required cumulative helicity-correlation	Systematic contribution
Intensity	< 10 ppb	~ 0.1 ppb
Energy	< 1.4 ppb	~ 0.05 ppb
Position	< 0.6 nm	~ 0.05 ppb
Angle	< 0.12 nrad	~ 0.05 ppb
Spot Size	< 10 ppm	~ 0.1 ppb

Keeping beam asymmetries small

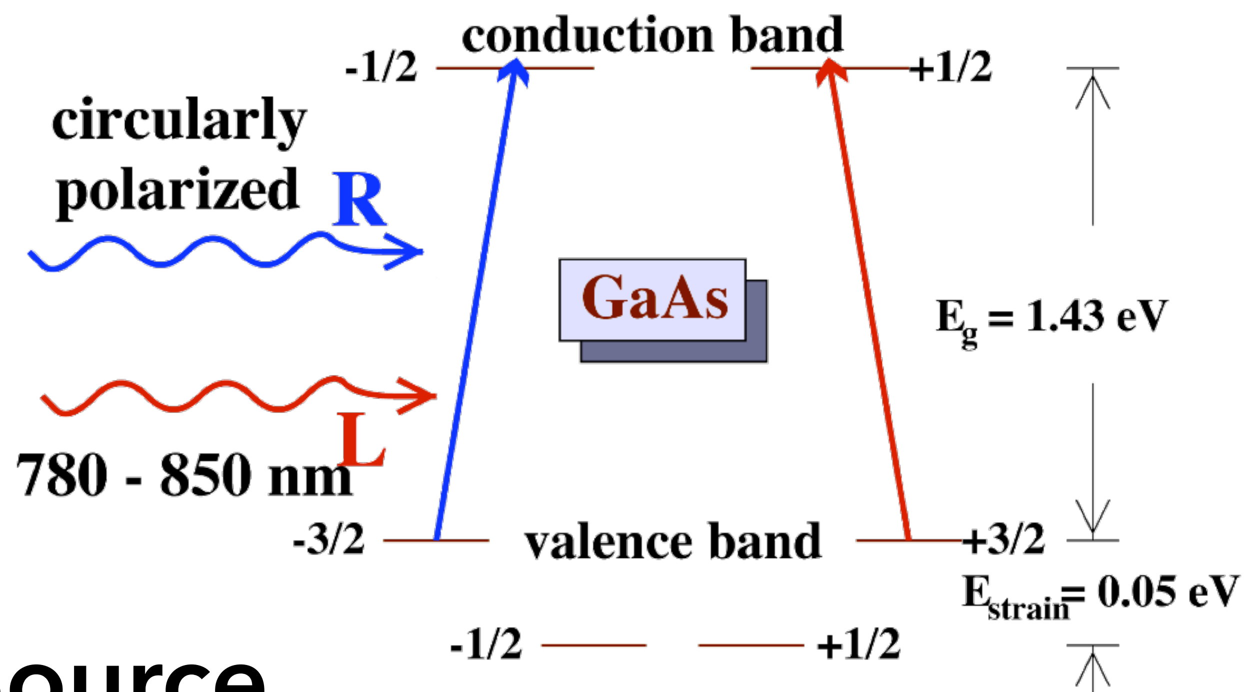
- *Special techniques with the polarized source laser optics*
- *Beam transport optimization*
- *"slow reversals" that flip the sign of beam asymmetries*
- *feedback*

Beam correction analysis

Two calibration techniques

- *beam modulation for calibration*
- *linear regression*

Demonstrated precision and accuracy in the PREX-2 analysis



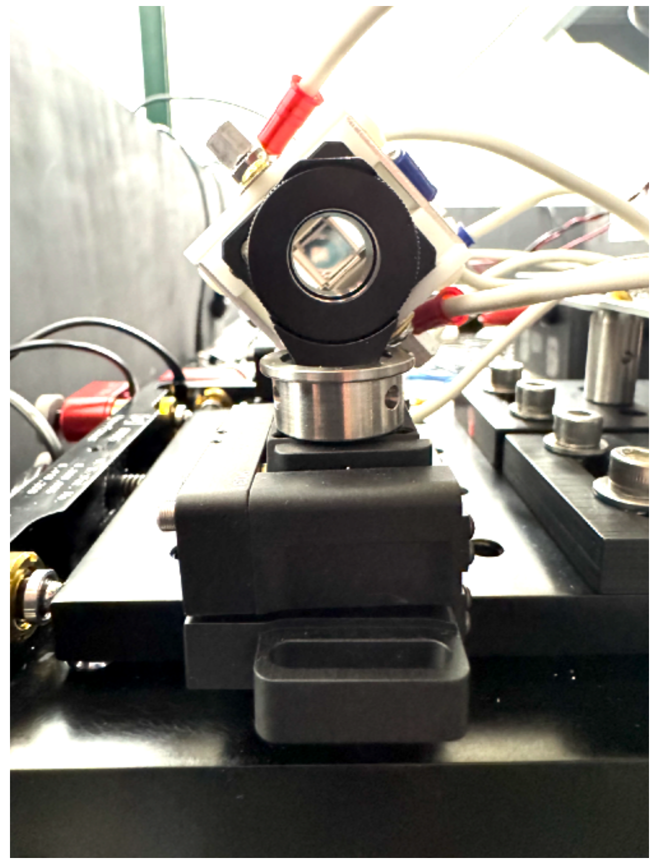
Polarized Source

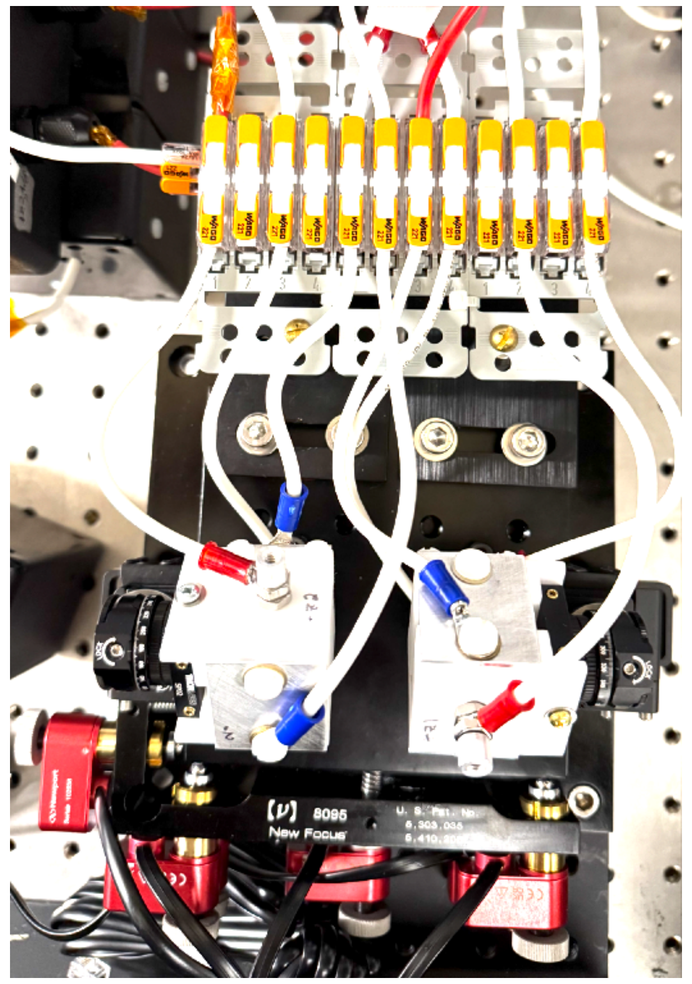
- High intensity, high polarization through photoemission from GaAs photocathode
- Rapid-flip of beam helicity by laser polarization flip
- Pockels cell to flip laser polarization
- Beam must look the same for the two polarization states
- Photocathode: analyzing power for linear light

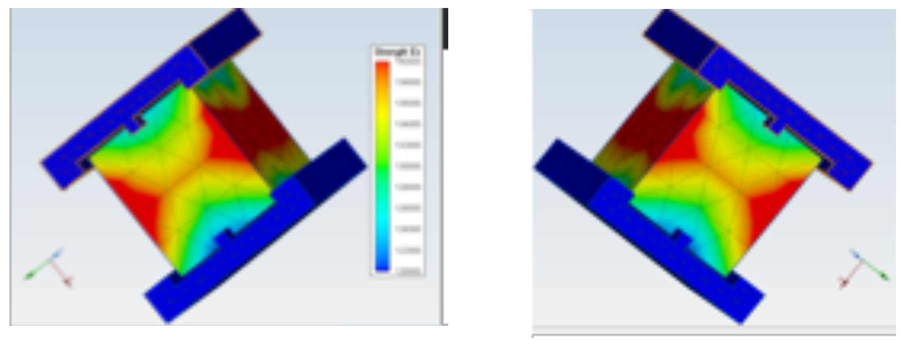
RTP Pockels cell

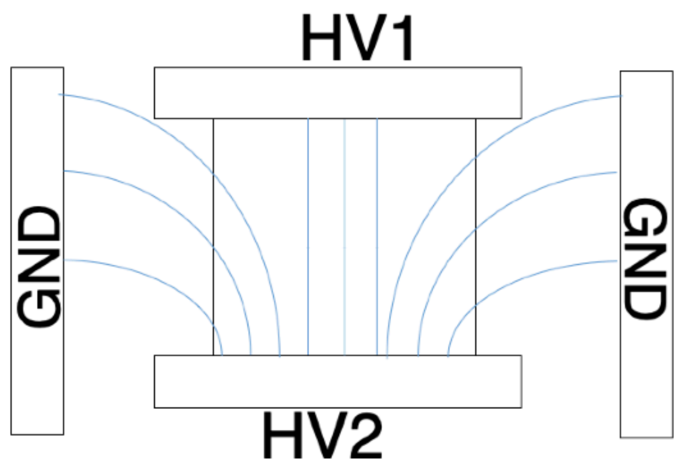
Goal: 2kHz flipping, ~10 μs transition

- Optimized RTP cell developed, in use since 2019
- Using E-field gradients to control non-uniformities
- New versions improve performance and reliability







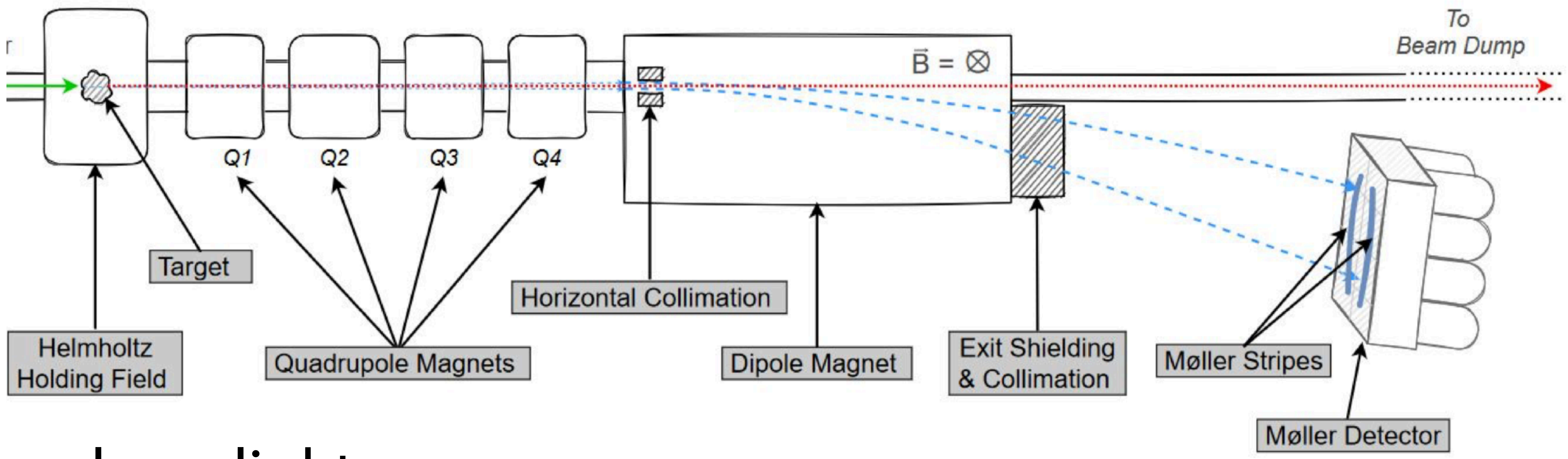


Polarimetry

Goal: 0.4% with two, independent measurements which can be cross-checked

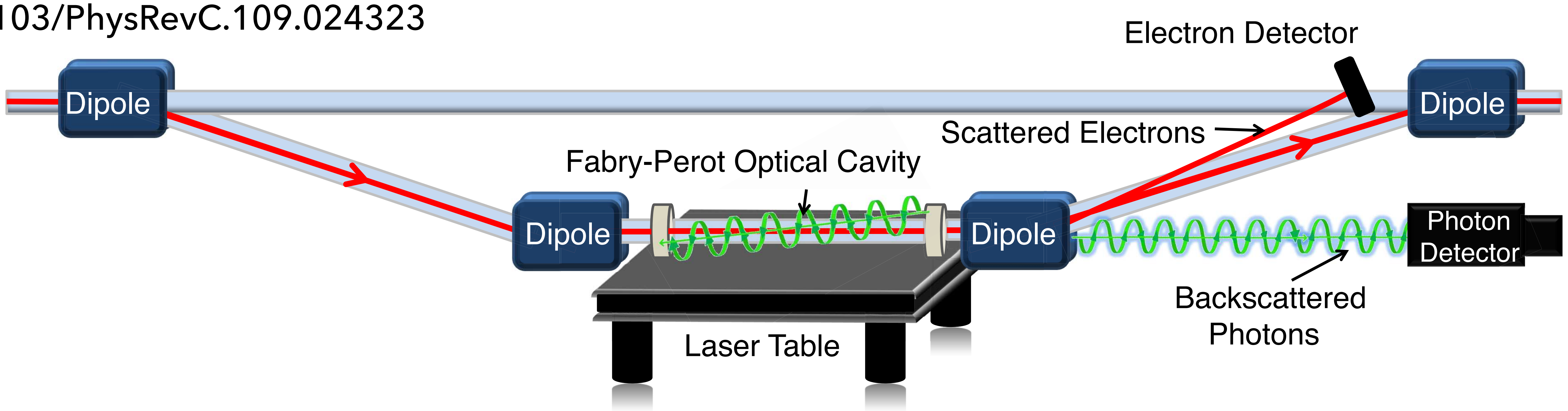
Møller Polarimeter

- "high field" iron target - well-known magnetization at saturation
- Coincidence of identical particles - low background
- QQQQD spectrometer - optimized to suppress Levchuk correction uncertainty



Compton Polarimeter

- Detection of backscattered photons and recoil electrons from laser light
- Independent photon and electron analyses are possible
- New publication: dP/P = 0.36% https://doi.org/10.1103/PhysRevC.109.024323



Both systems have important upgrades underway (detectors, target, DAQ, analysis, and simulation studies).
The Møller polarimeter is closer to ready for high precision at 11 GeV, with smaller and less crucial upgrades.

MOLLER Schedule and Outlook

First exploration of the current concept in 2007, first proposal in 2009. It's been a long road

Expected schedule:

- Fall 2025 - Dec 2026: Assembly in Hall A
- Jan 2027: commissioning
- Late 2027: First physics publication expected
  - A_T transverse single spin asymmetry
  - A_{PV} result, matching E158 precision

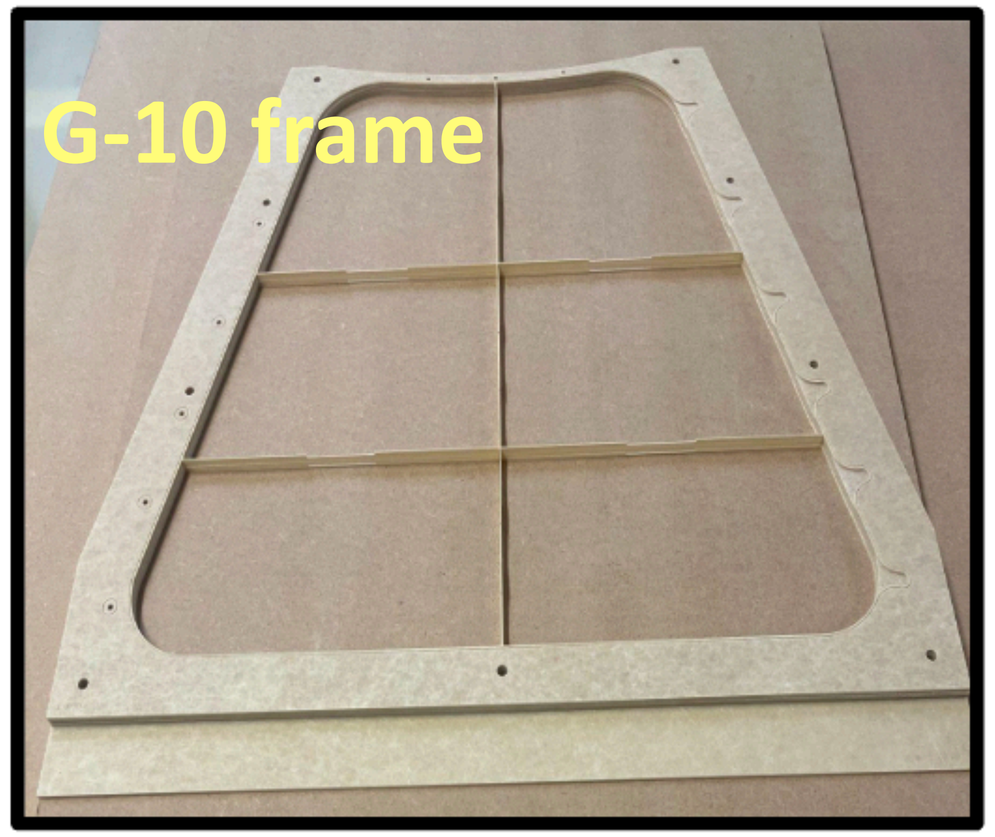
Project (fabrication/assembly) fully funded, mostly allocated

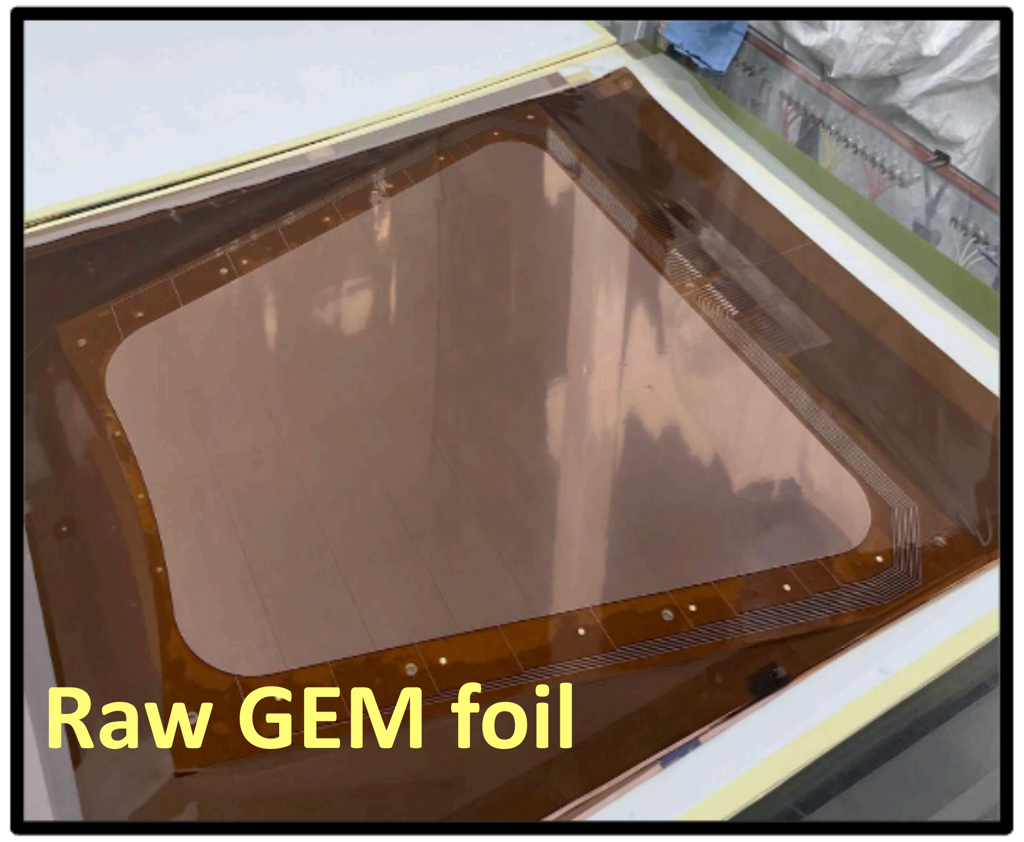
IRA funding for DOE managed project, + NSF + CFI / Research Manitoba / NSERC

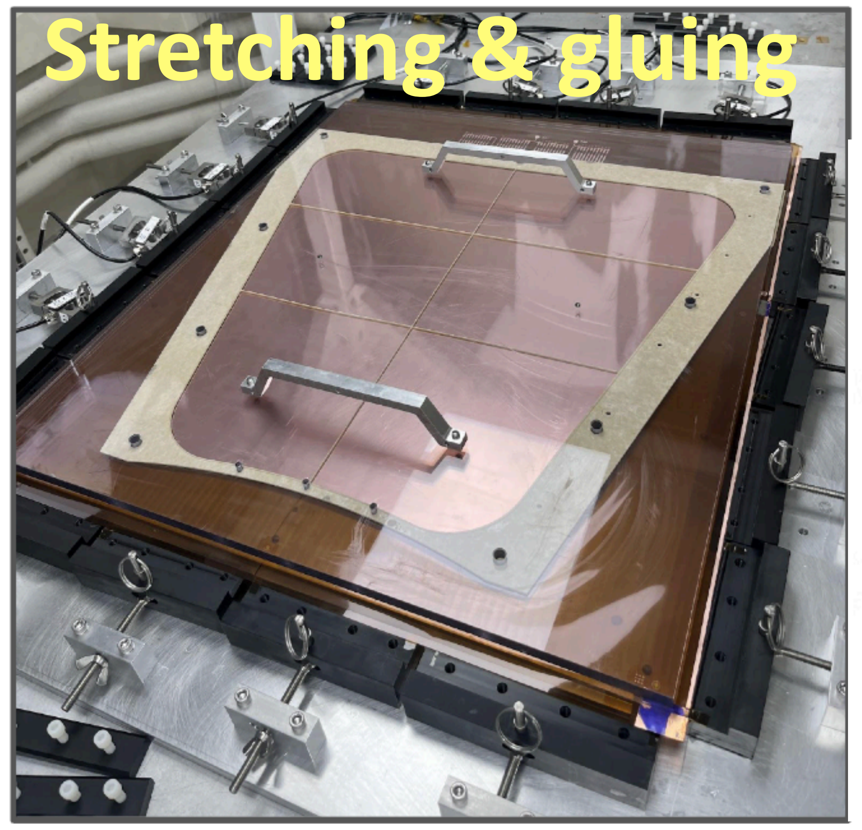
Remaining (political) risks:

- approximately 4 calendar years required to complete running, with usual operations at JLab
- Collaboration relies on DOE-NP and NSF research funds (also NSERC, but that isn't in question)

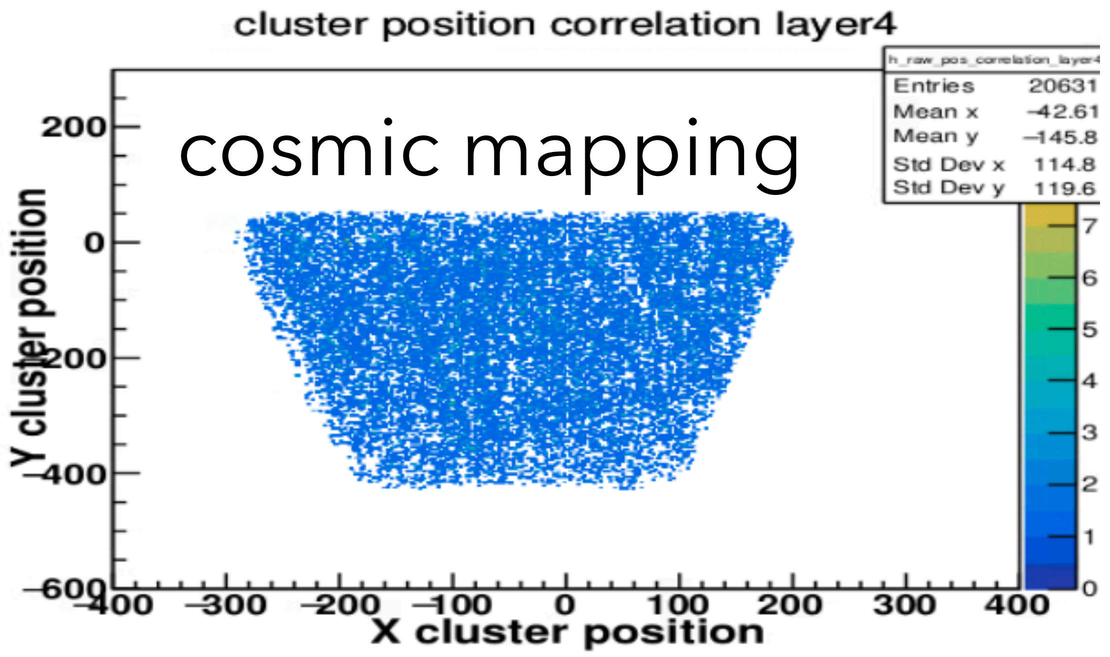
GEM tracking chambers

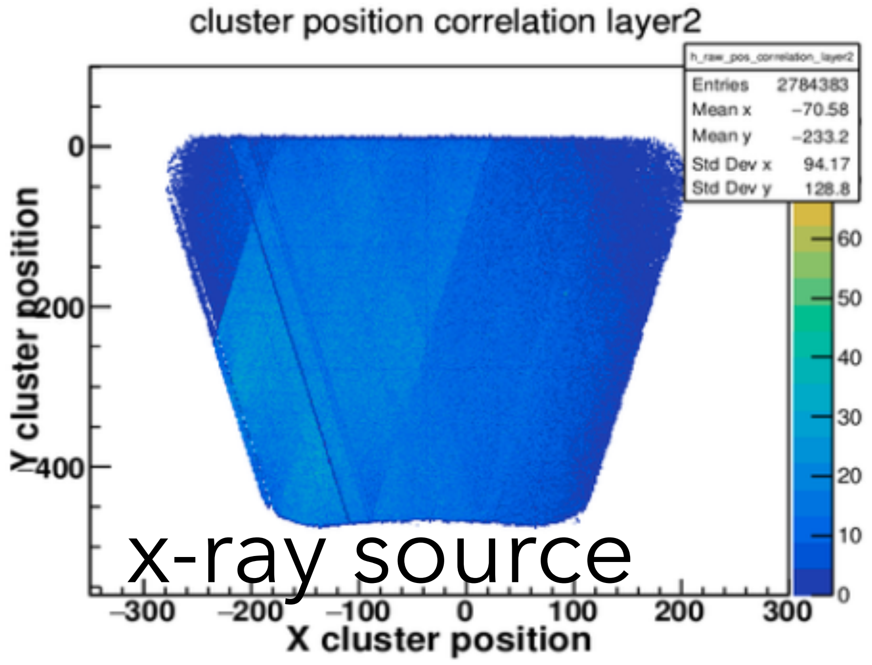


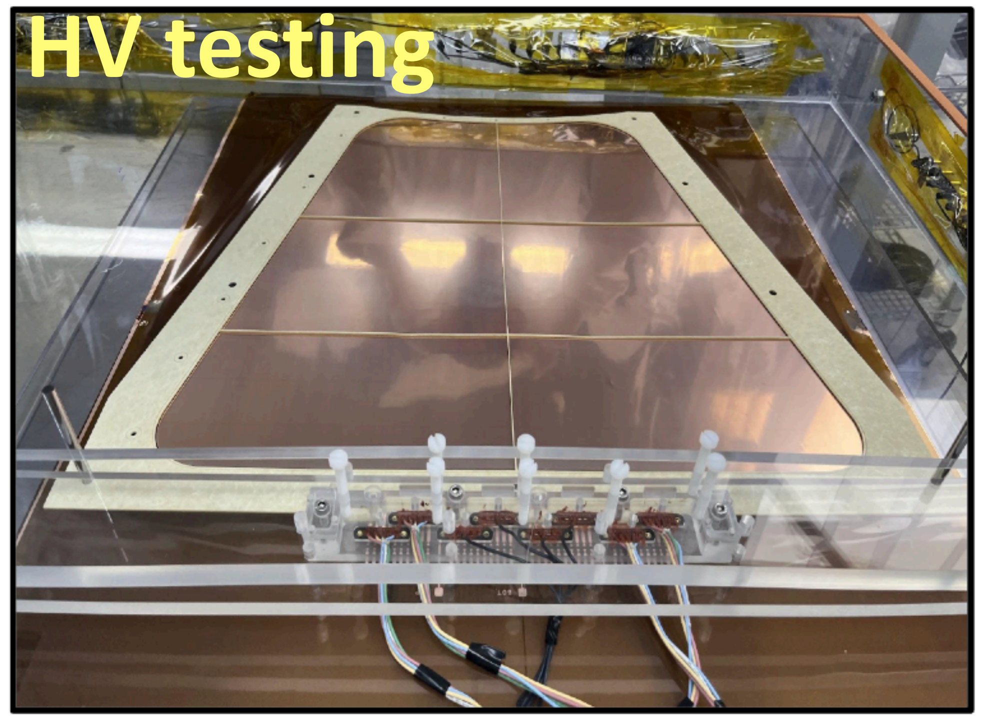




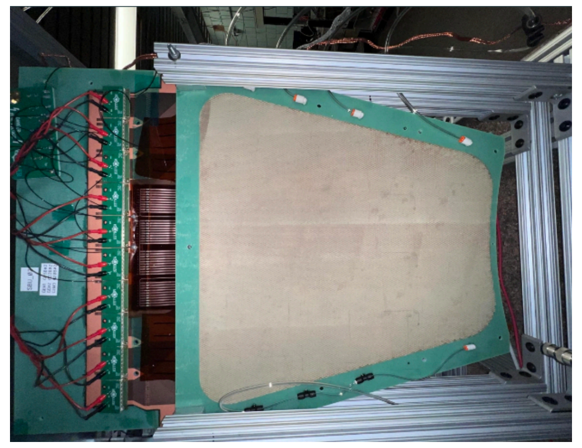
UVA

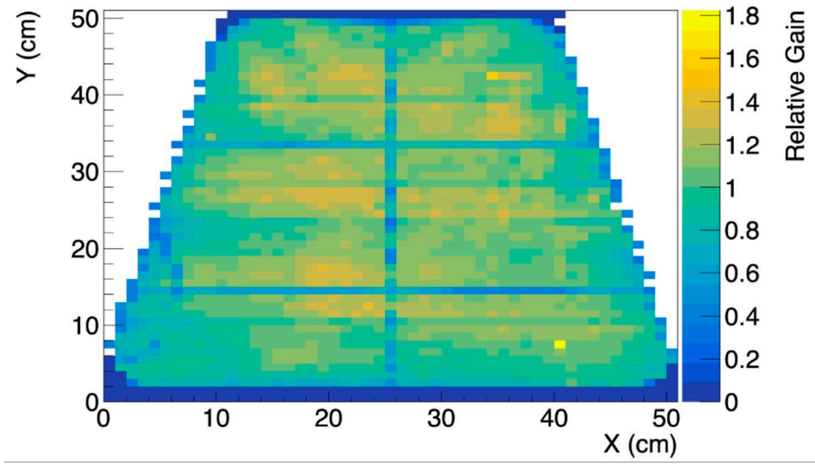




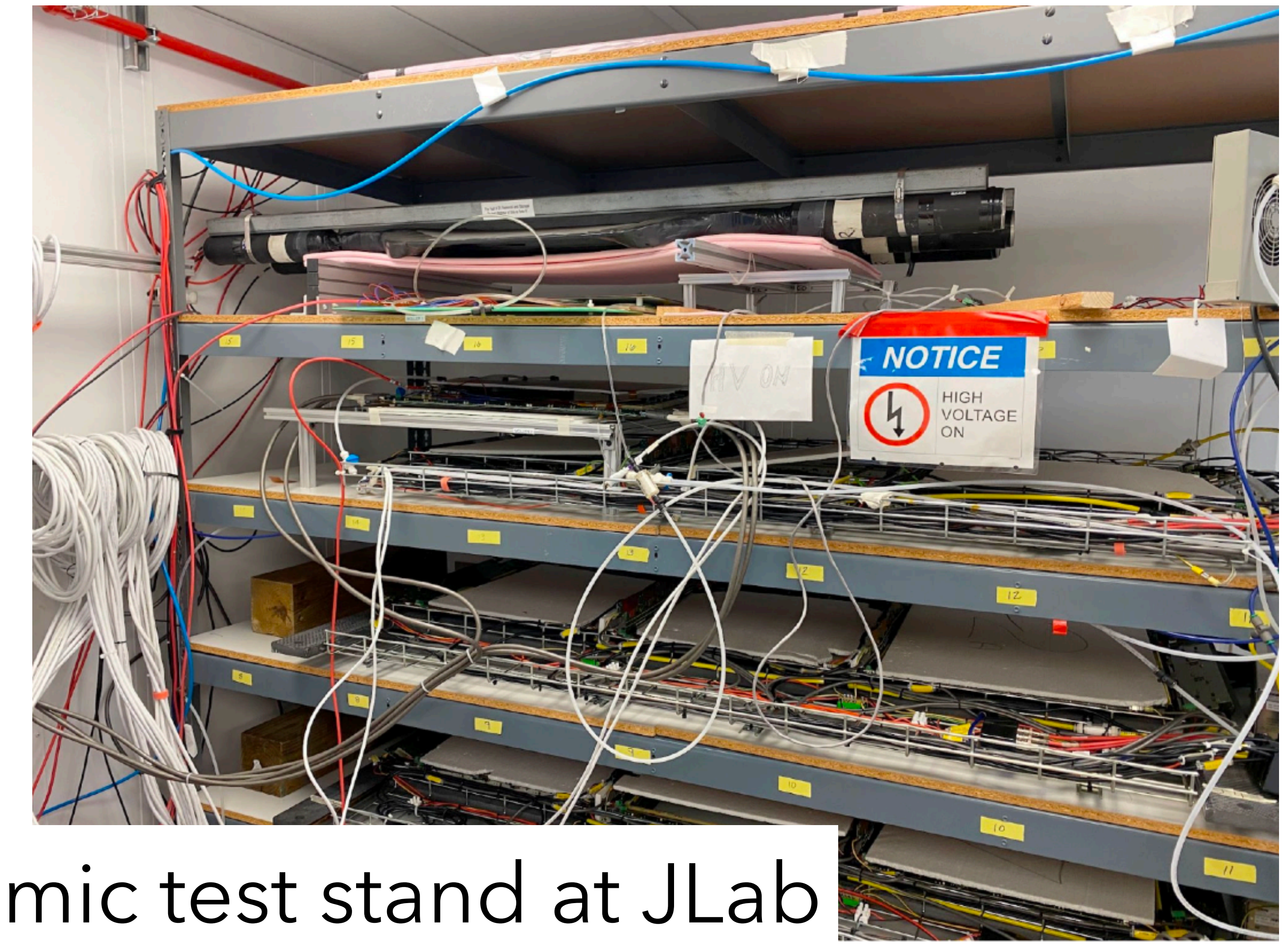


SBU



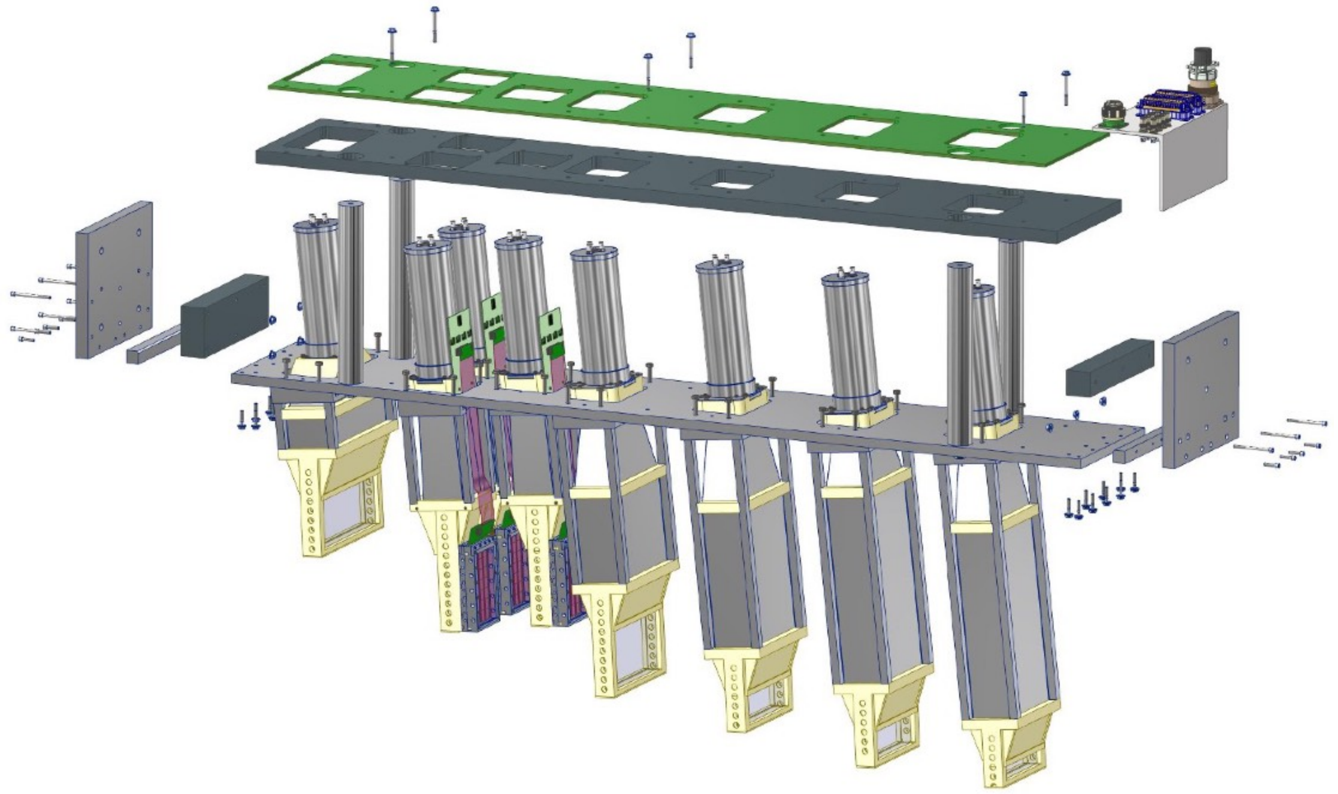


UVa and SBU GEMs in production, qualification



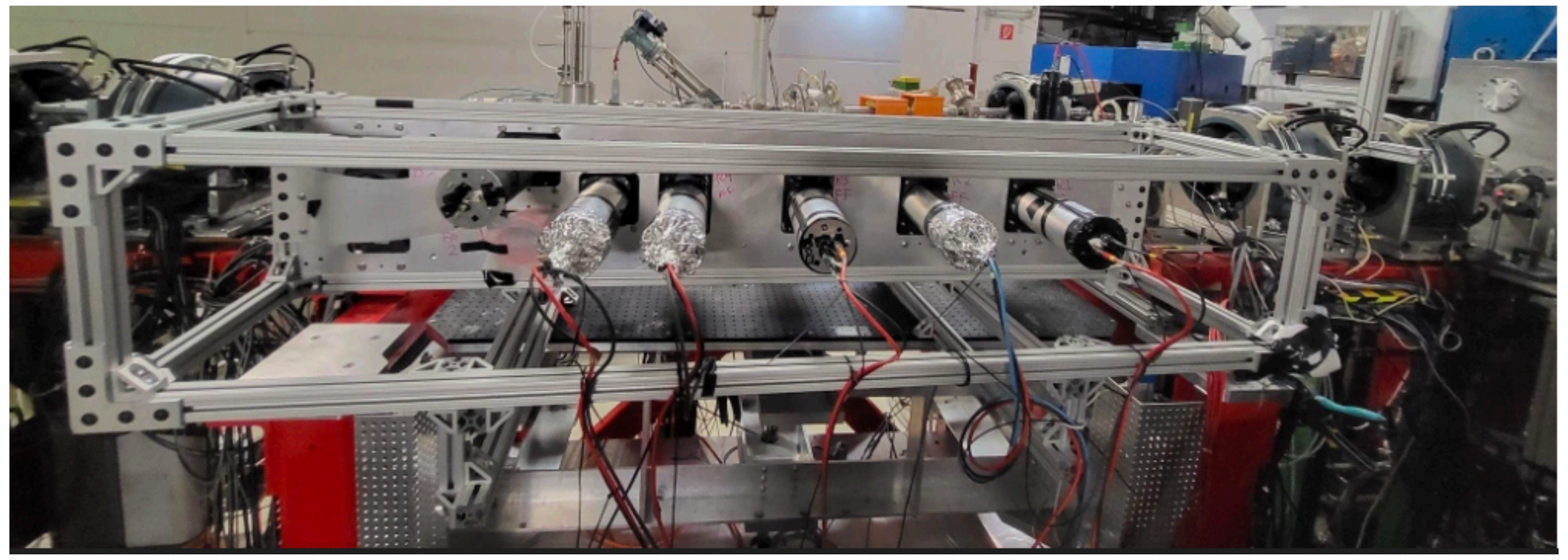
Cosmic test stand at JLab

Detectors / electronics



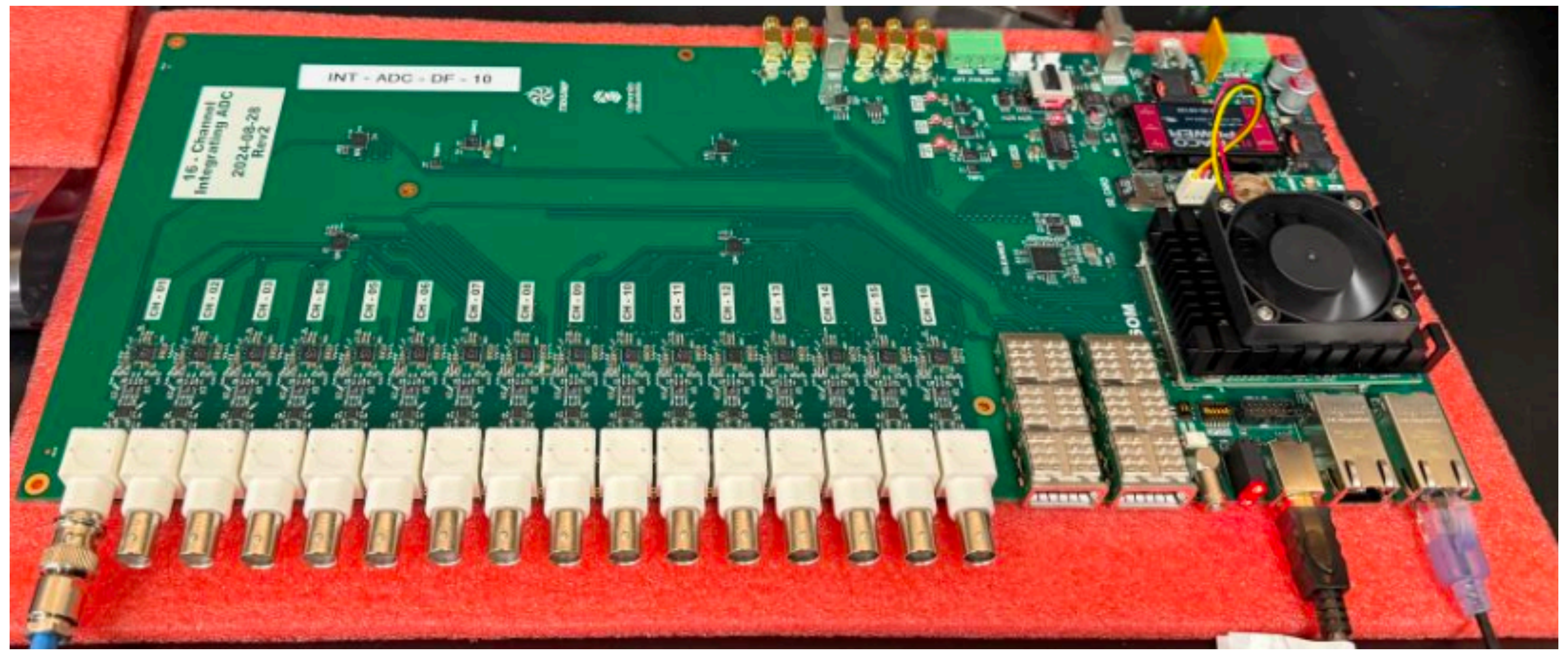
thin quartz assembly modules
in cosmic test stand

Main detector assembly
in Mainz test beam

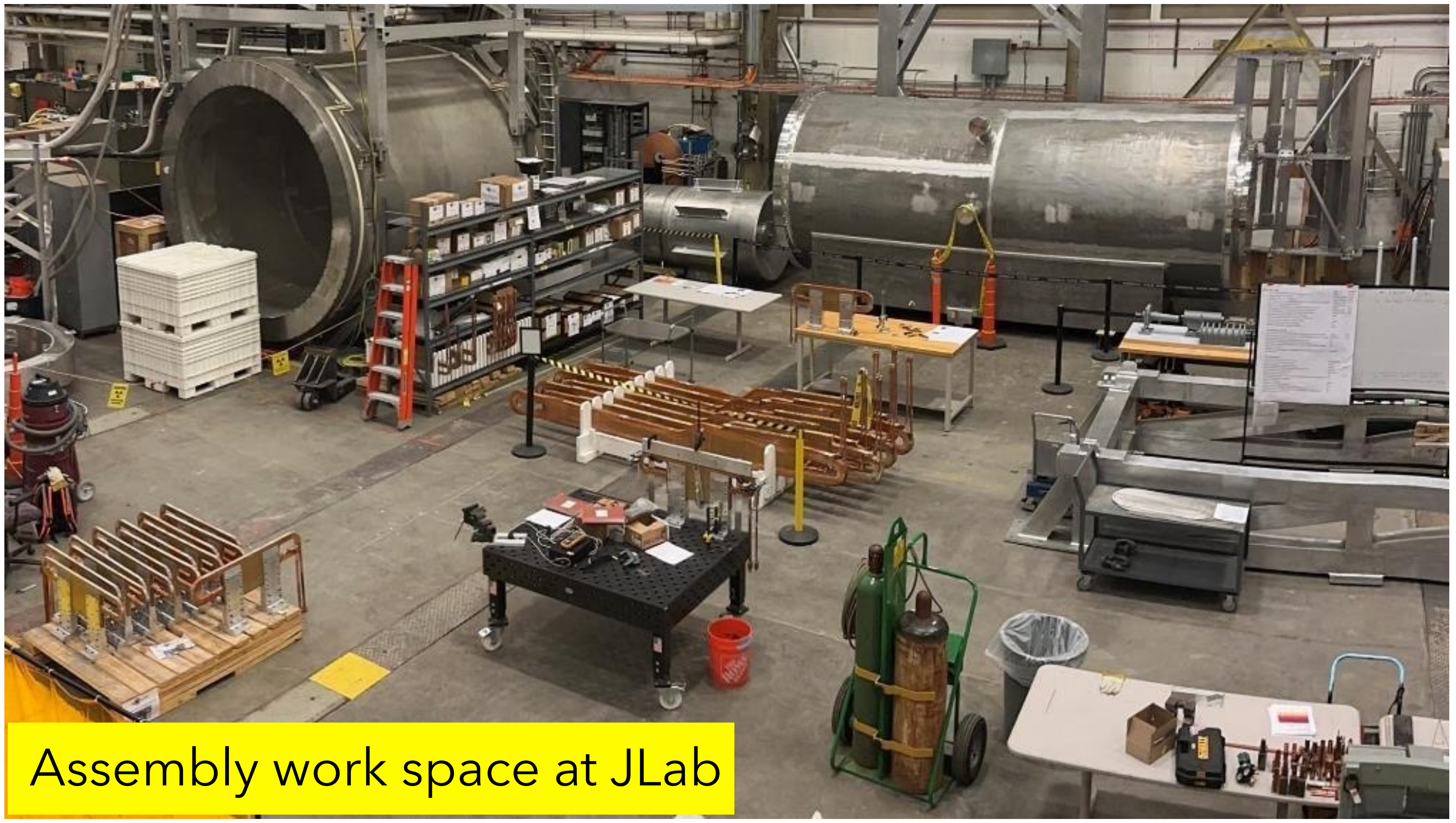


shower-max
detector

low-noise electronics (Manitoba)



Spectrometer Components

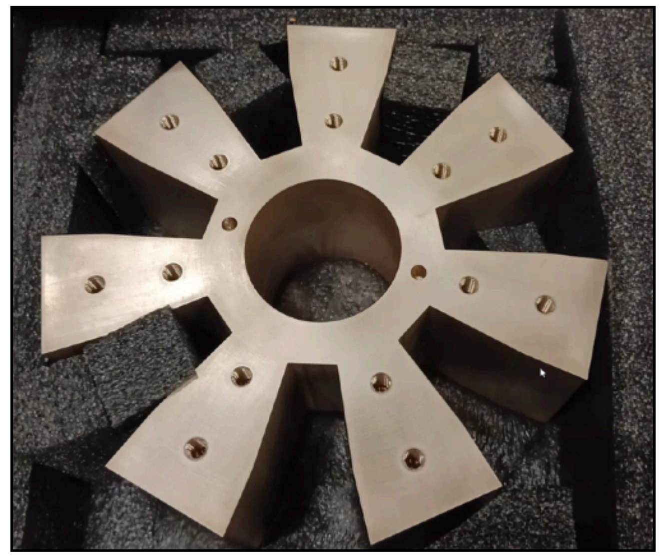


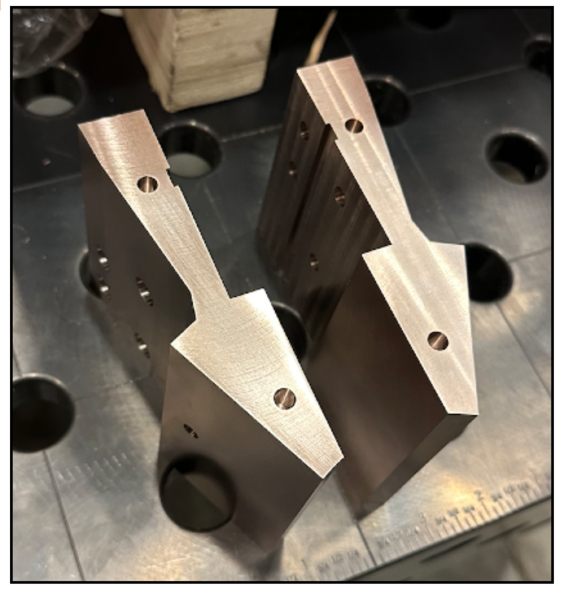
Assembly work space at JLab

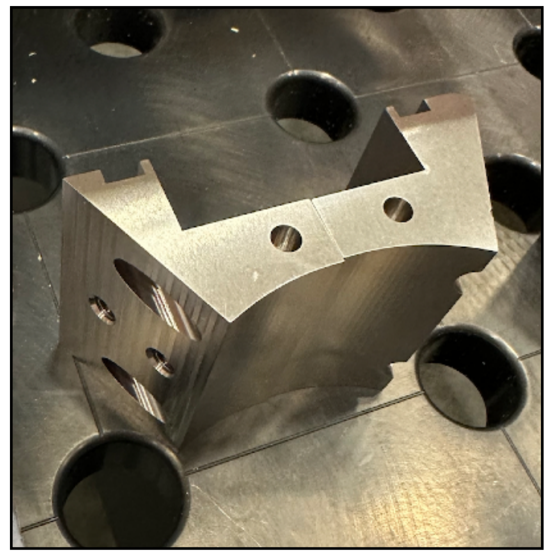
TM3 Power Supply on-site

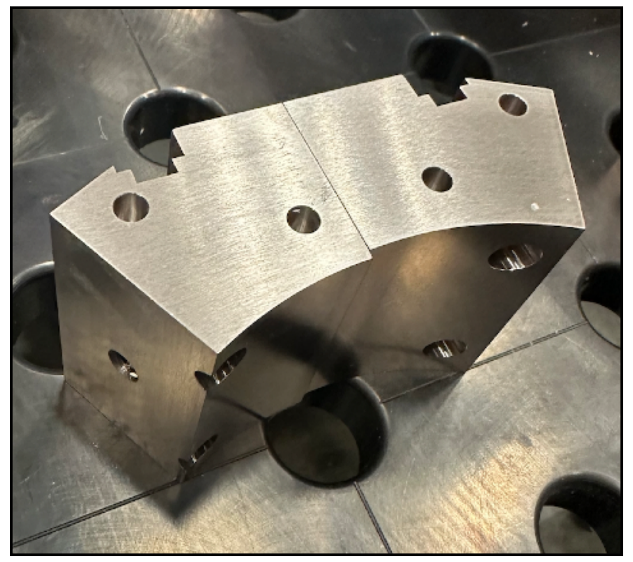
Torus enclosure at vendor

Lead Pion Donut

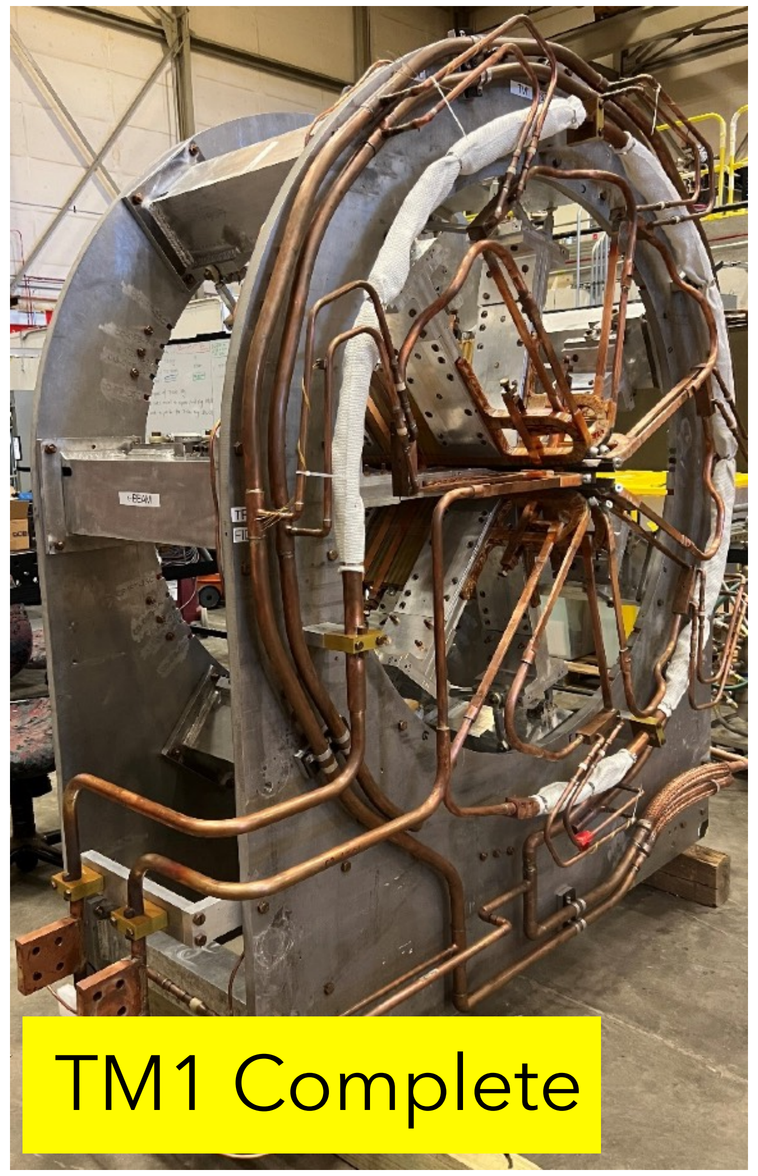








Collimators



TM1 Complete

SC4 coil fixtured

TM2 now complete

SC0 coils in production

Detector beampipe
Frame Weldment

Beam pipes elements


Bellows 1 and 2


Bellows 3


Bellows 4

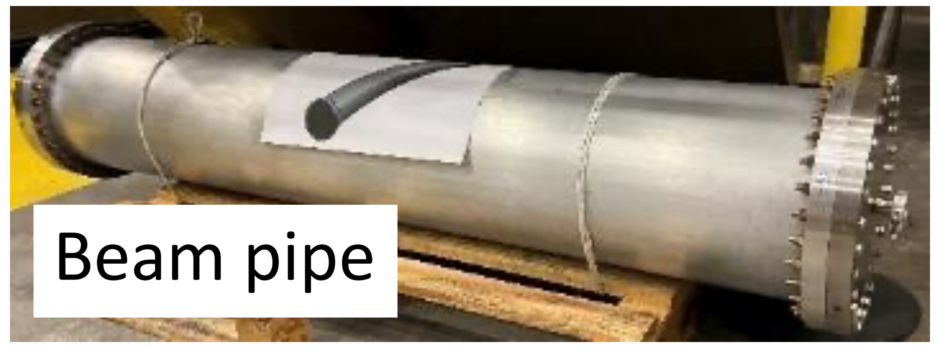

Bellows 5


Bellows 7


Detector Pipe with Neckdown window


Drift Pipe


SAM Pipe


Beam pipe

Summary

Electroweak physics studies with PVES are a powerful tool in the search for new physics

MOLLER, designed for ultra-high precision, will search for new interactions from 100 MeV to 10s of TeV, with reach into new physics phase space that cannot otherwise be accessed.

MOLLER is starting fabrication, to start assembly this fall and begin running early 2027