Overview of the MOLLER experiment

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MOLLER

New Physics with Precision at Low Energies

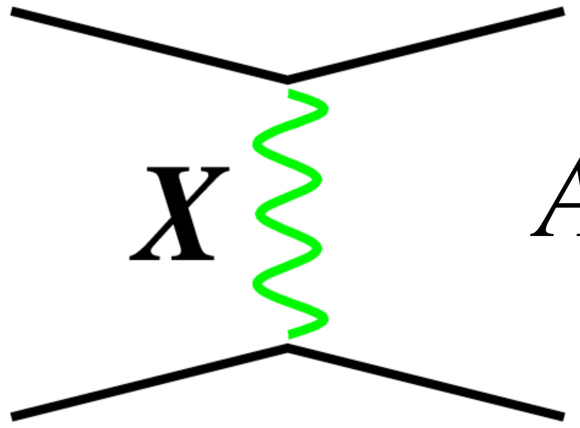
Low Q^2 offers complementary probes of new physics at multi-TeV scales

EDM, g_μ-2, weak decays, β decay, $0\nu\beta\beta$ decay, DM, LFV…

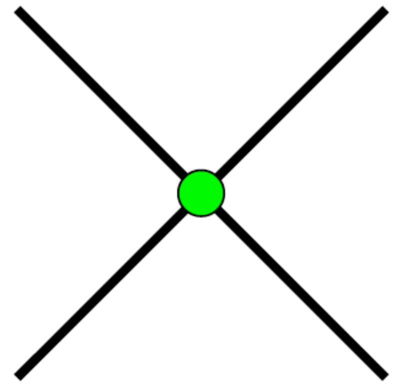
Parity-Violating Electron Scattering: *Low energy weak neutral current couplings (SLAC, Jefferson Lab, Mainz)*

Low energy NC interactions ($Q^2 << M_Z^2$)

Heavy mediators = contact interactions



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

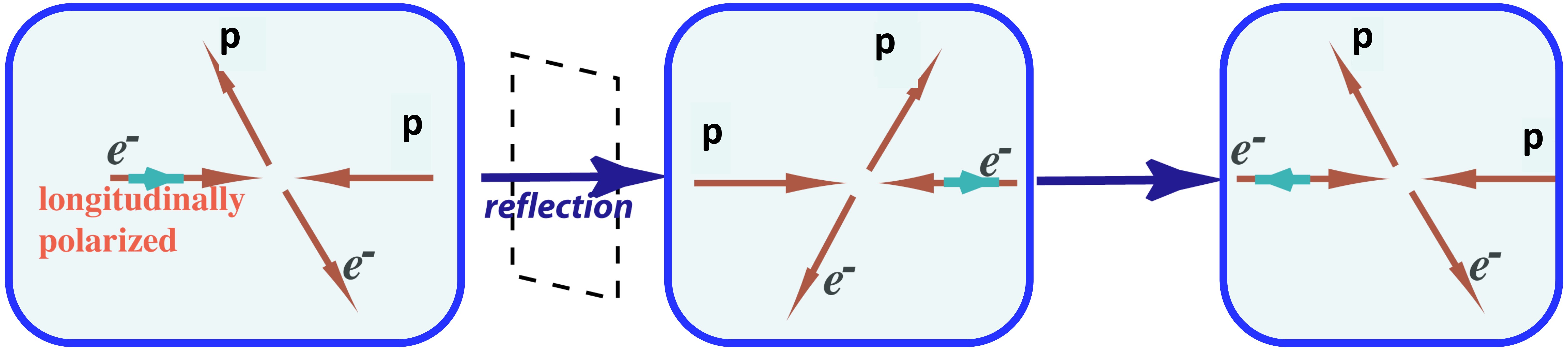


Contact interaction

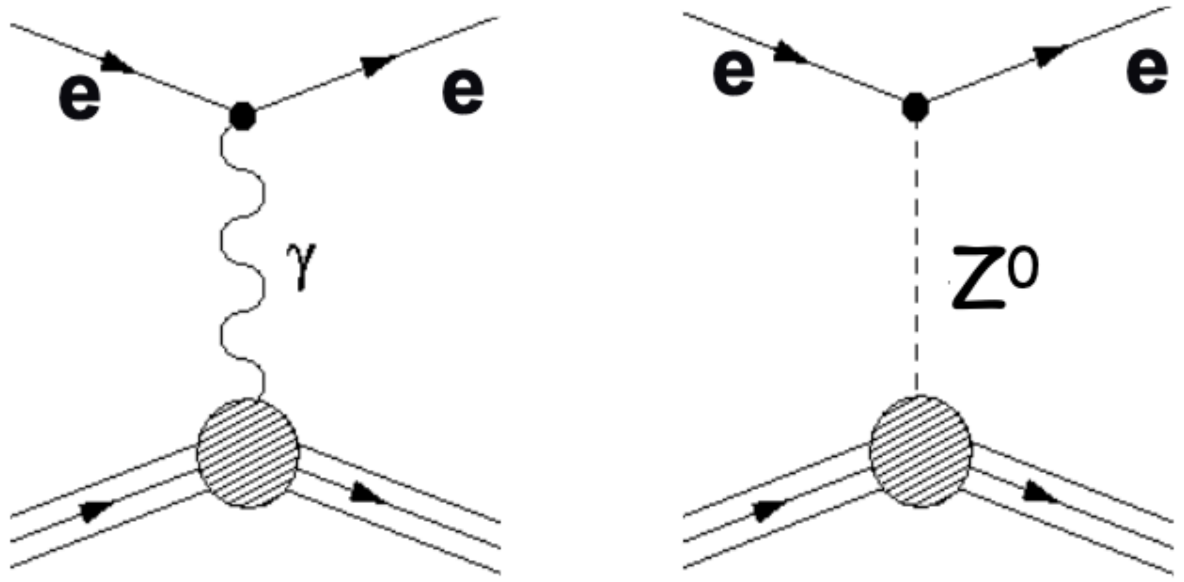
for **each fermion** and **handedness** combination reach, characterized by mass scale Λ, coupling g

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

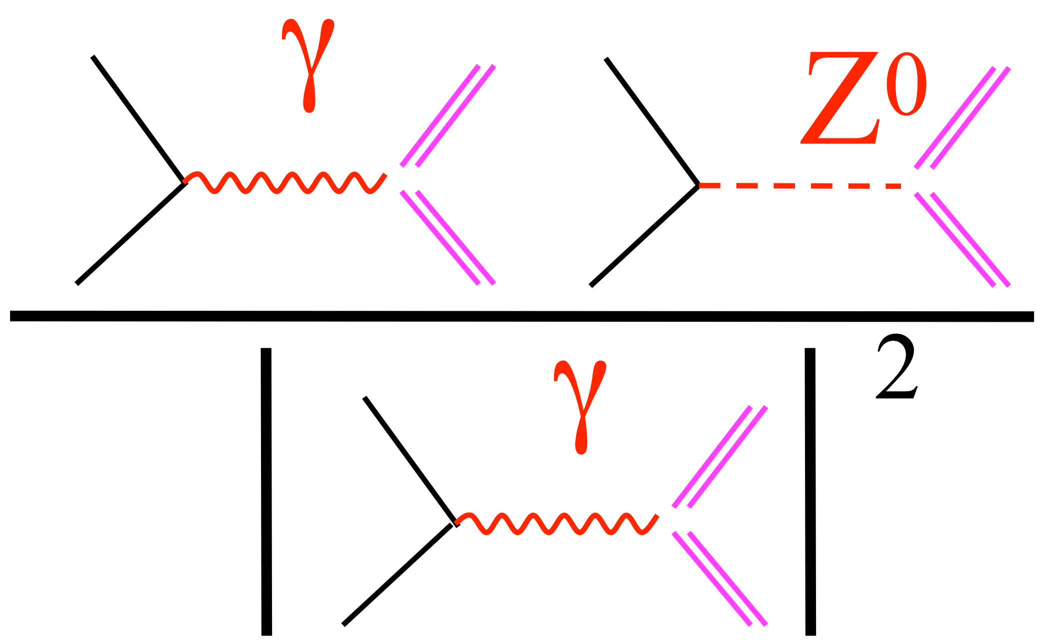
Electron Scattering and Parity-violation



- 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

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

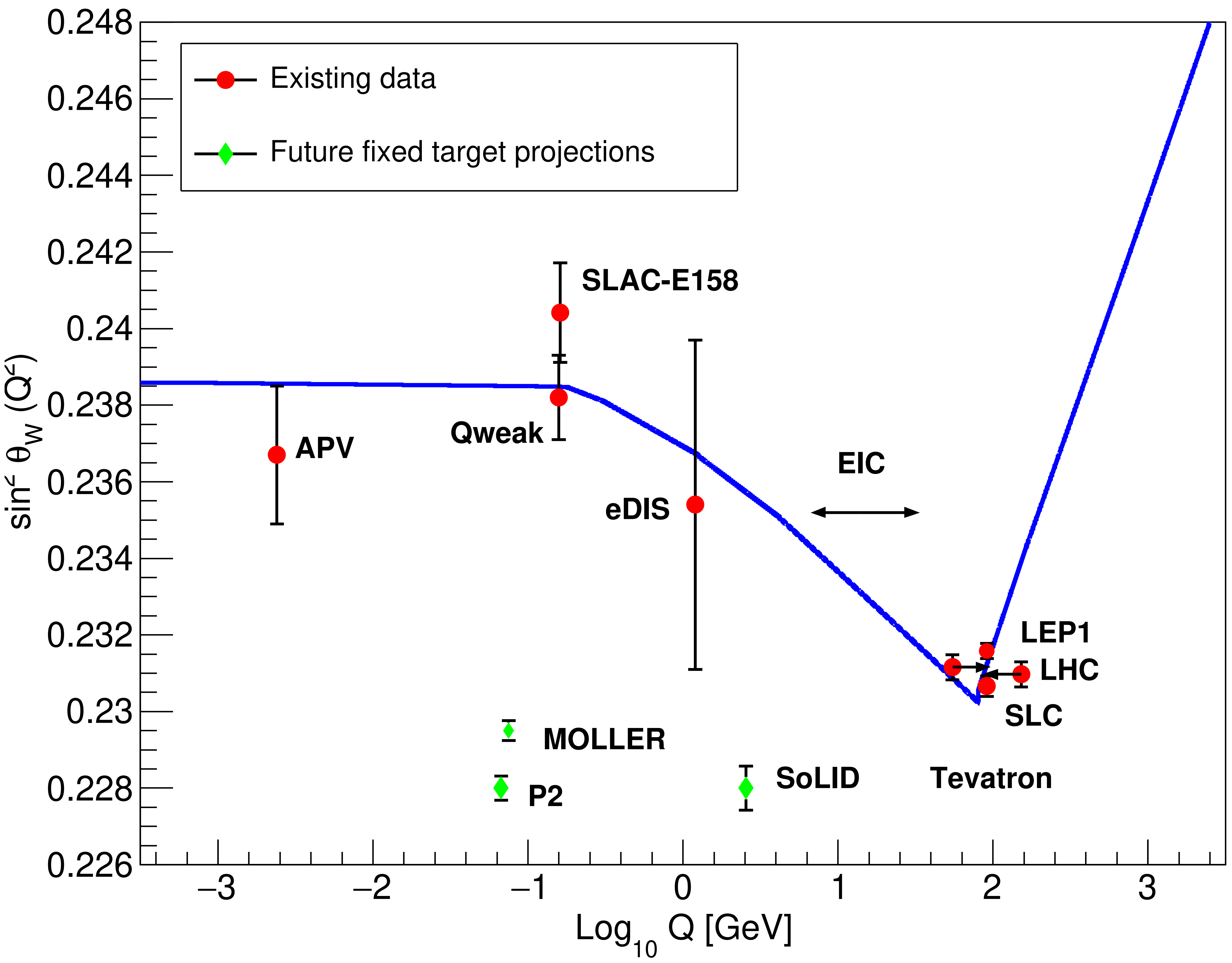
$$A_{PV} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

$\sim$ 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 unique 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} ~ 32 ppb $\delta(A_{PV})$ ~ 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:

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

→ ~ 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)

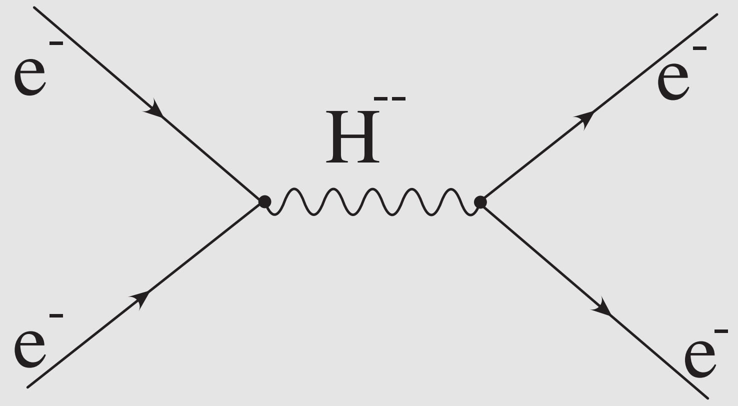
Examples of model sensitivity:

MOLLER: e^-e^- scattering

Lepton Number Violation

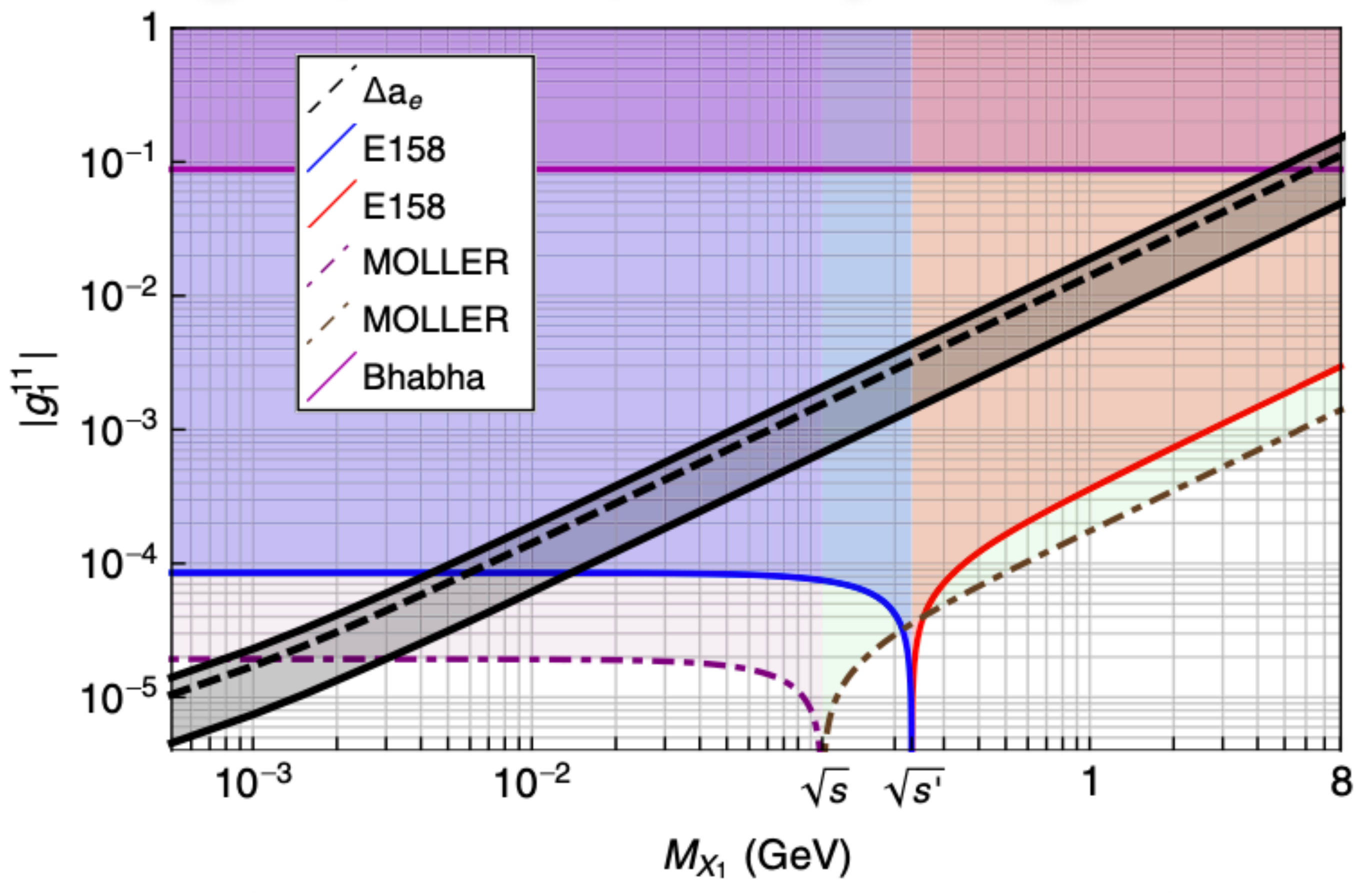
Λ > 5 TeV

Doubly-Charged Scalars



Significant reach beyond LEP-200

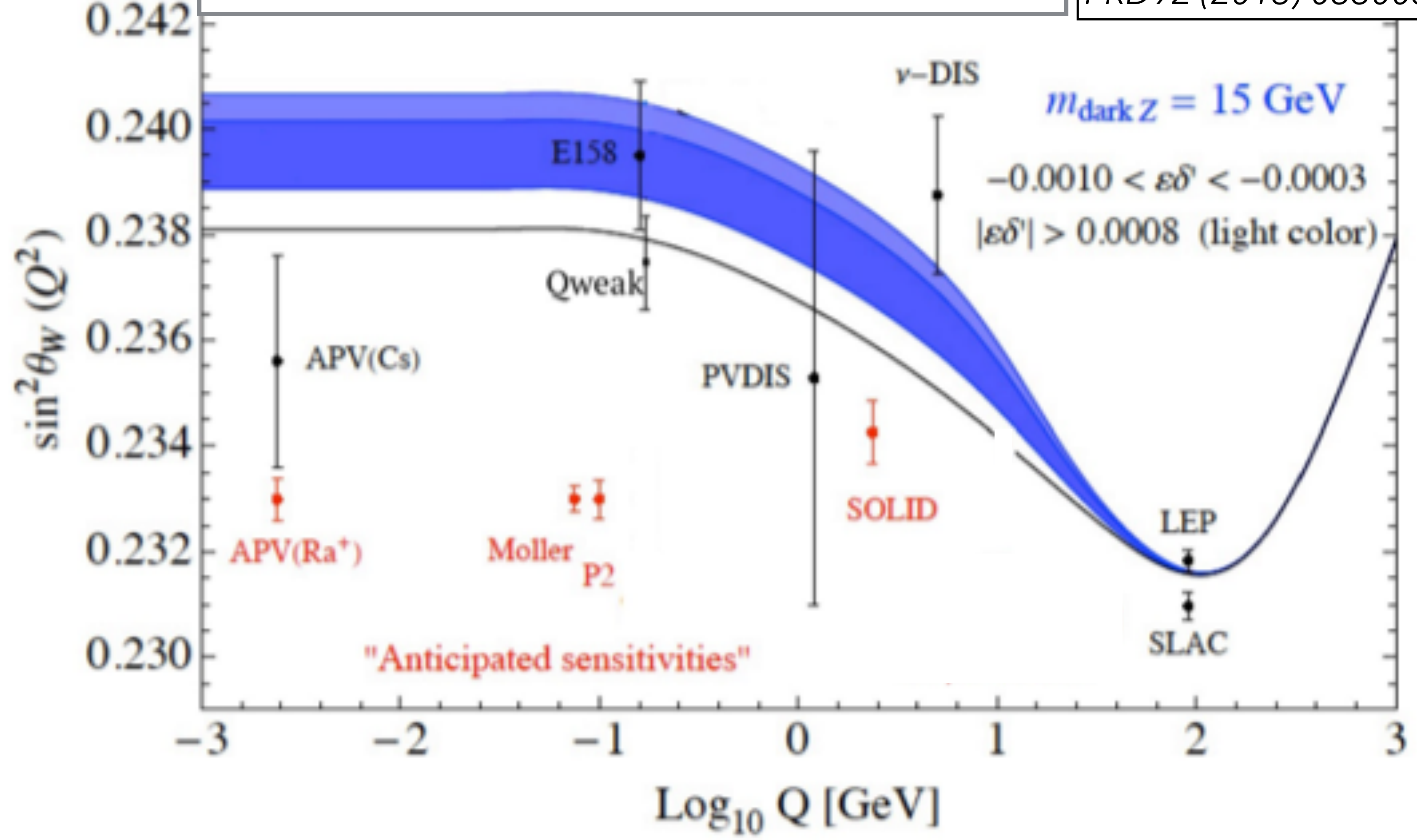
Light (<1 GeV) doubly-charged scalars



Gardner and Yan, PRD 102, 075016 (2020)

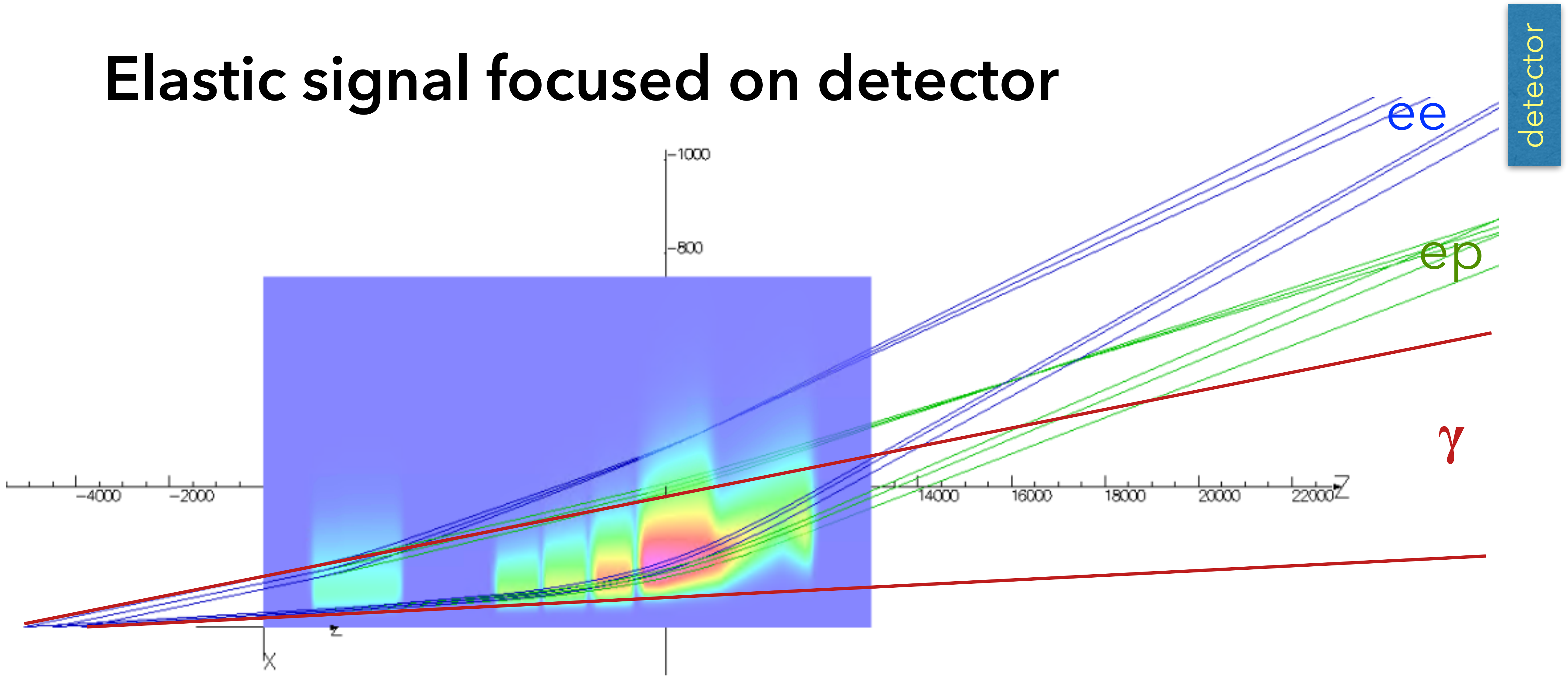
dark Z: mass mixing with Z^0

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

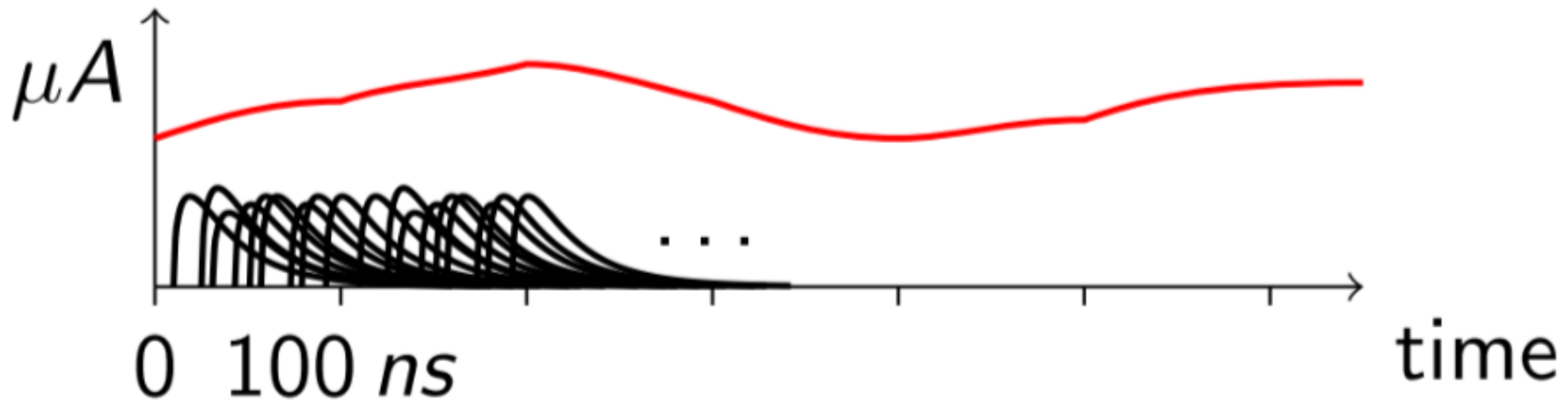


Measuring A_{PV}

Elastic signal focused on detector

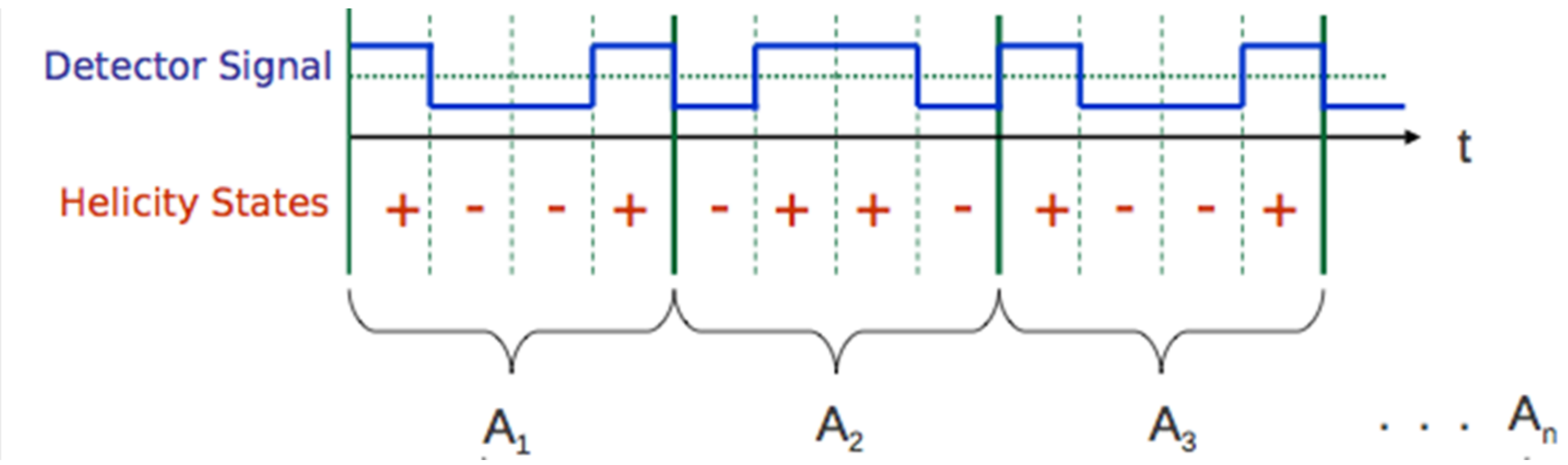


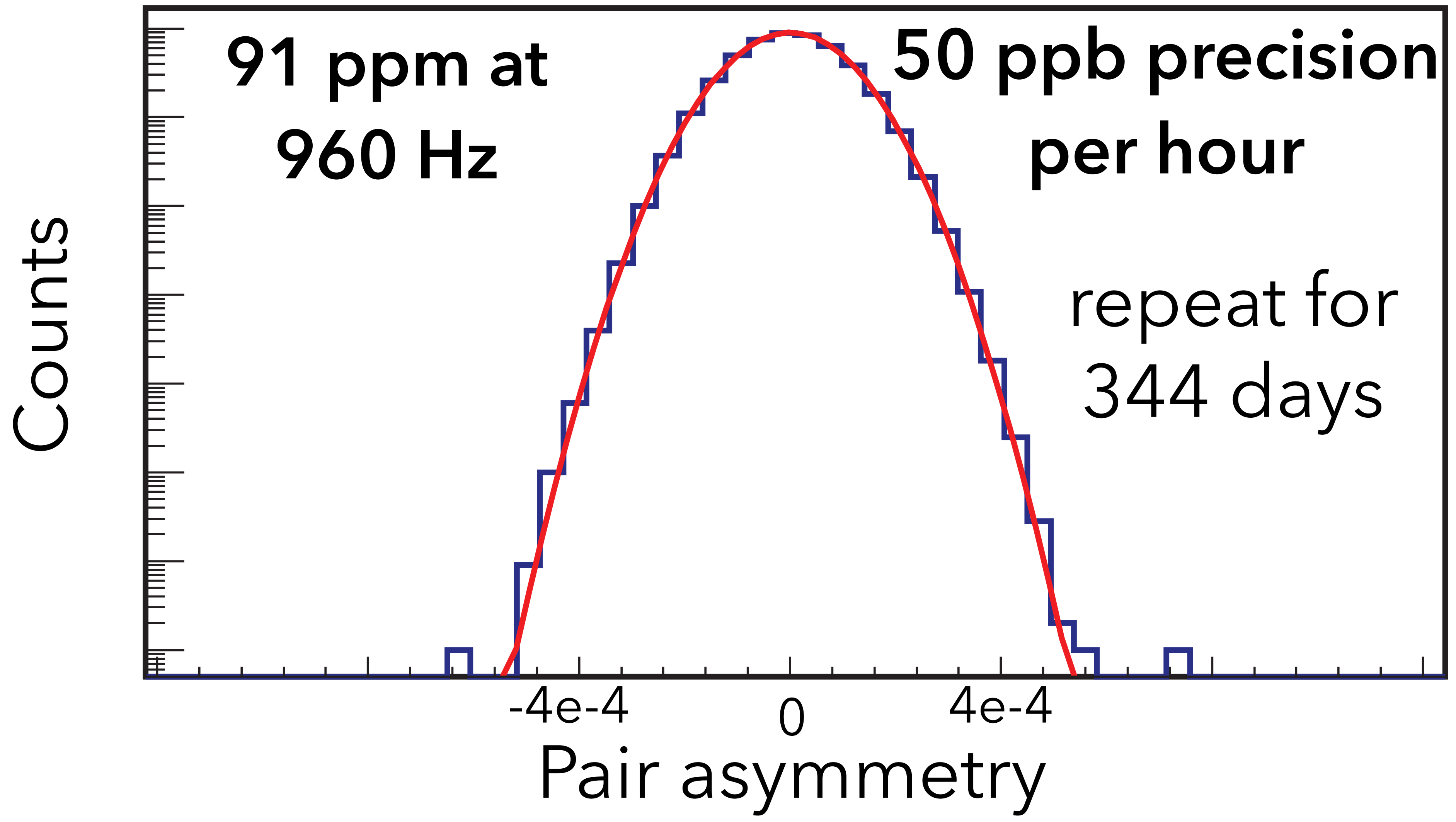
Integration of detector current



~130 GHz signal rate

Rapid (1kHz) measurement over helicity reversals





MOLLER

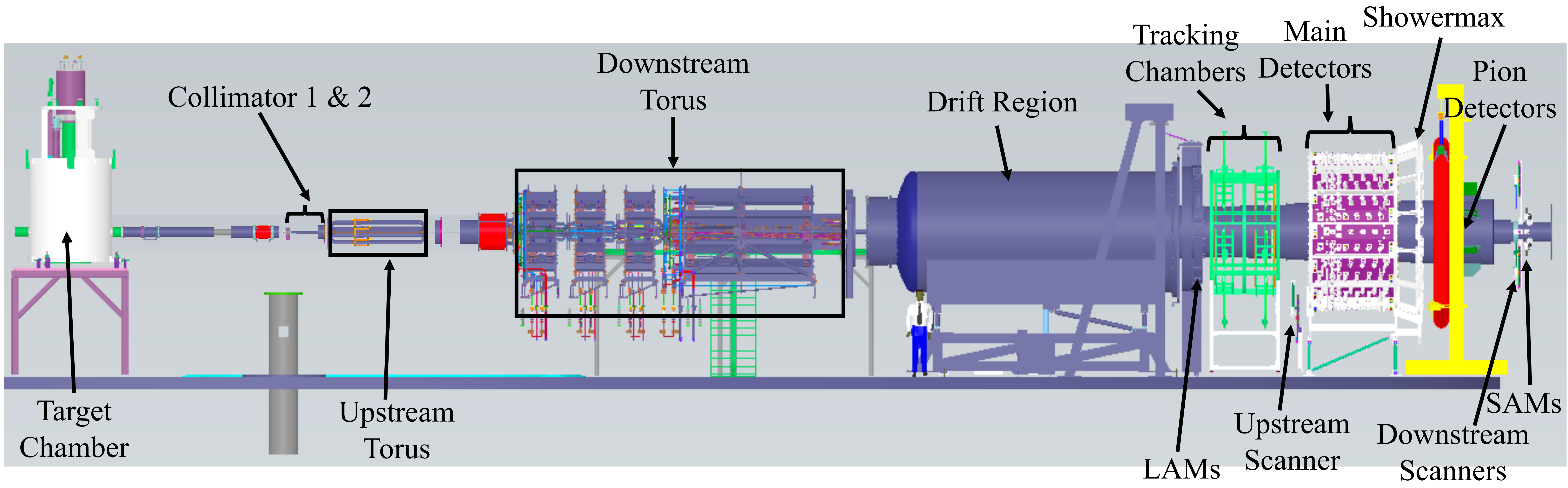
A_{PV} ~ 32 ppb with goal of 2% statistical, 1% systematic uncertainty

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)

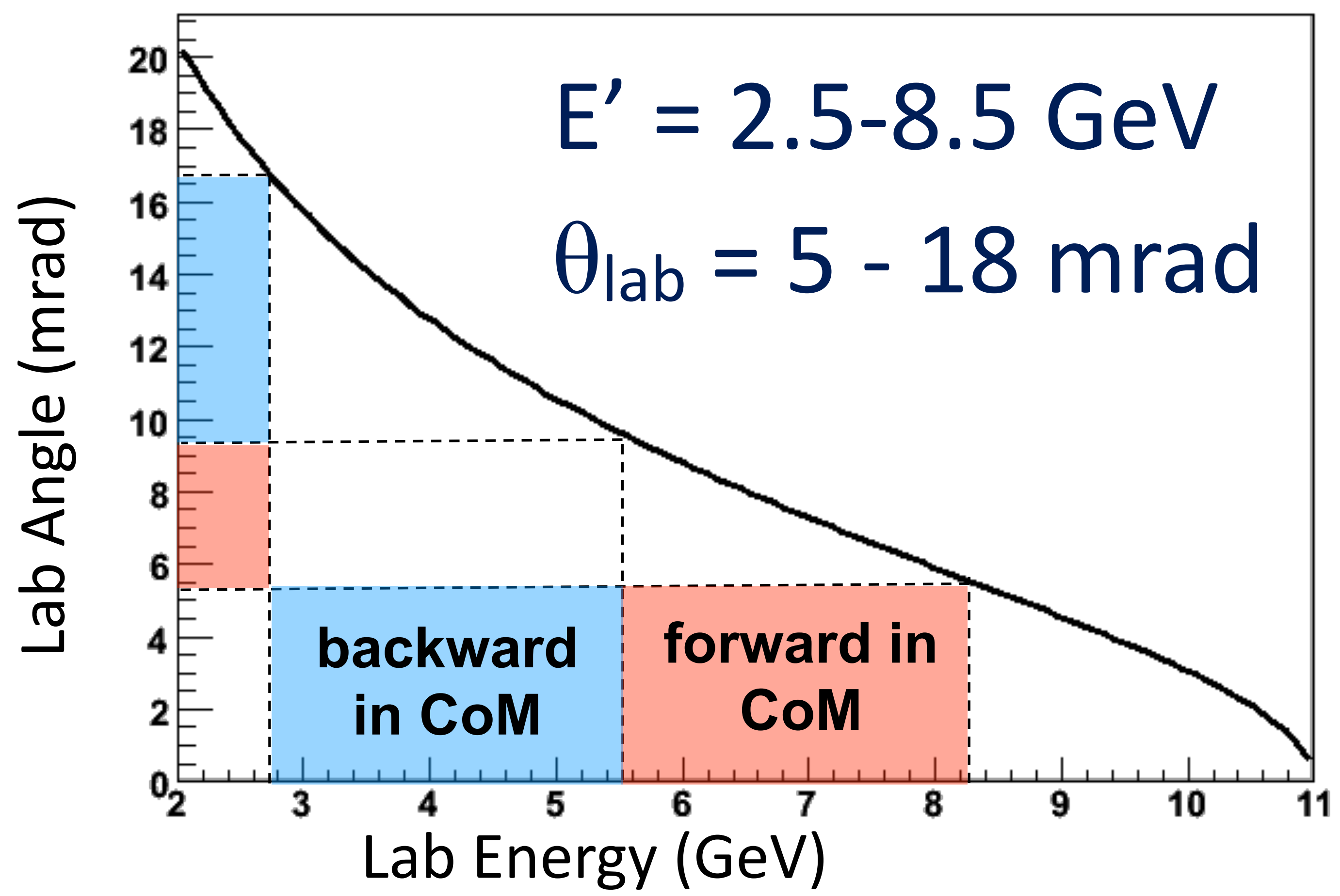
Control Noise *91 ppm at 960 Hz*
- Rapid beam helicity flip
- Beam and target stability
- Precision monitoring and calibration
- Low noise detectors and readout electronics

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

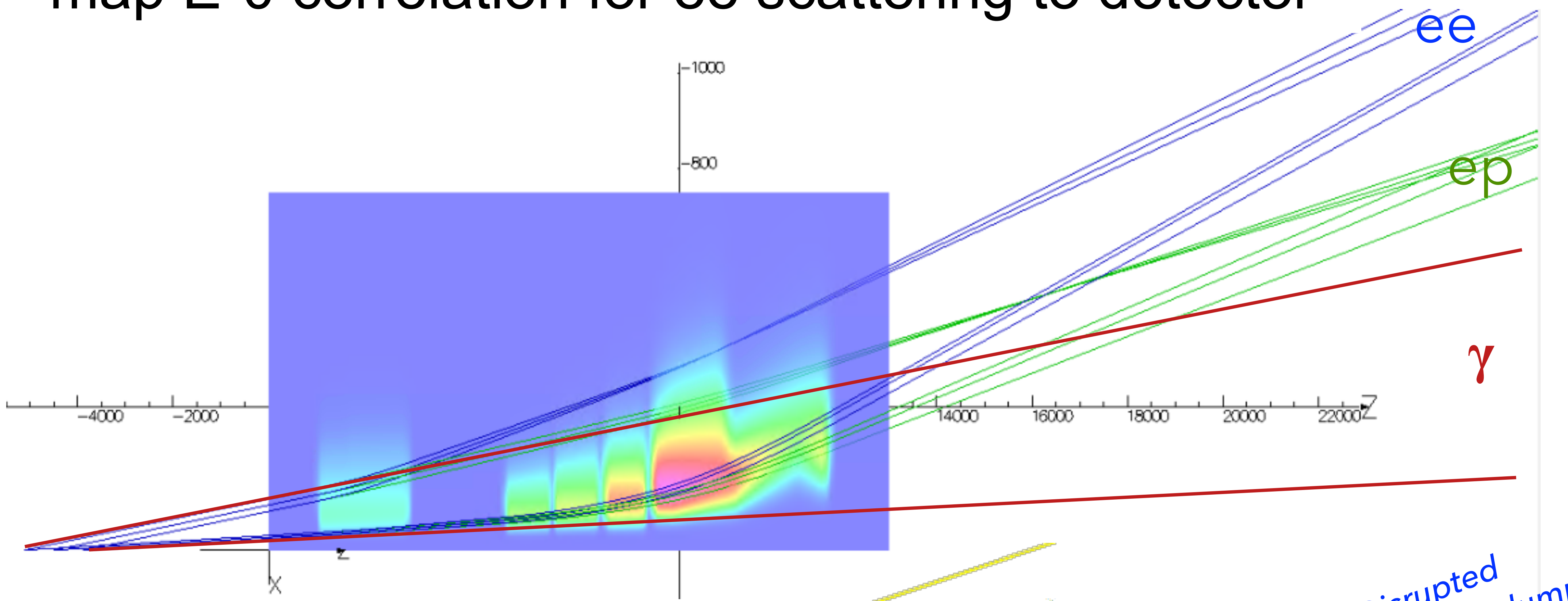
Controlling Systematic Uncertainty
- background monitoring
- optics / acceptance calibration
- polarimetry
- Beam control, monitoring and calibration
- “spin reversal” tools



MOLLER Spectrometer

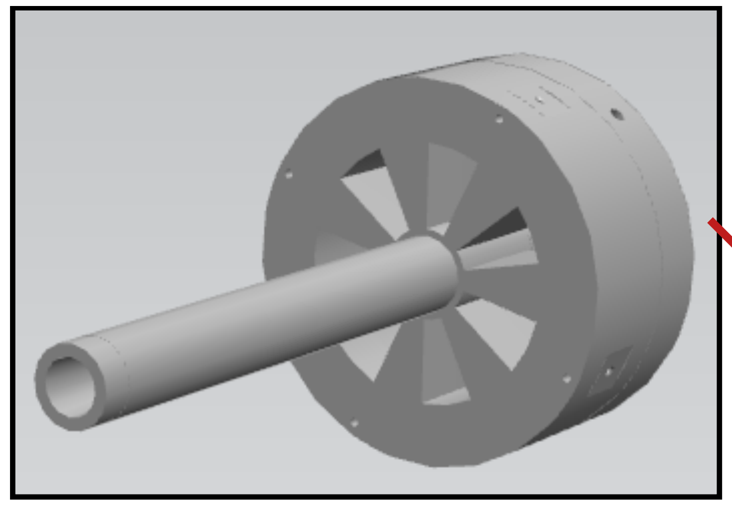


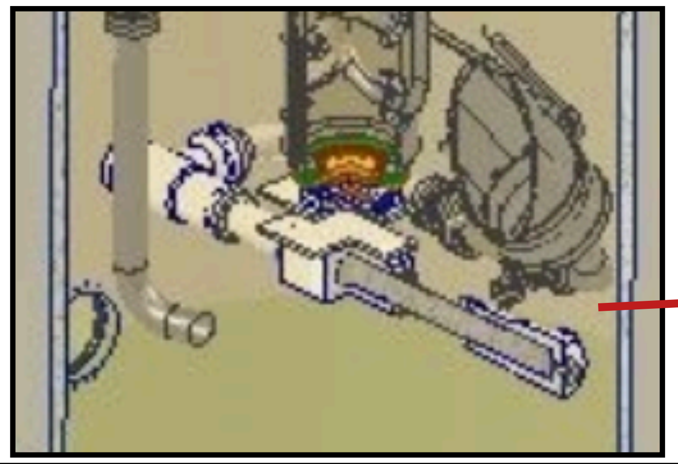
map E-θ correlation for ee scattering to detector



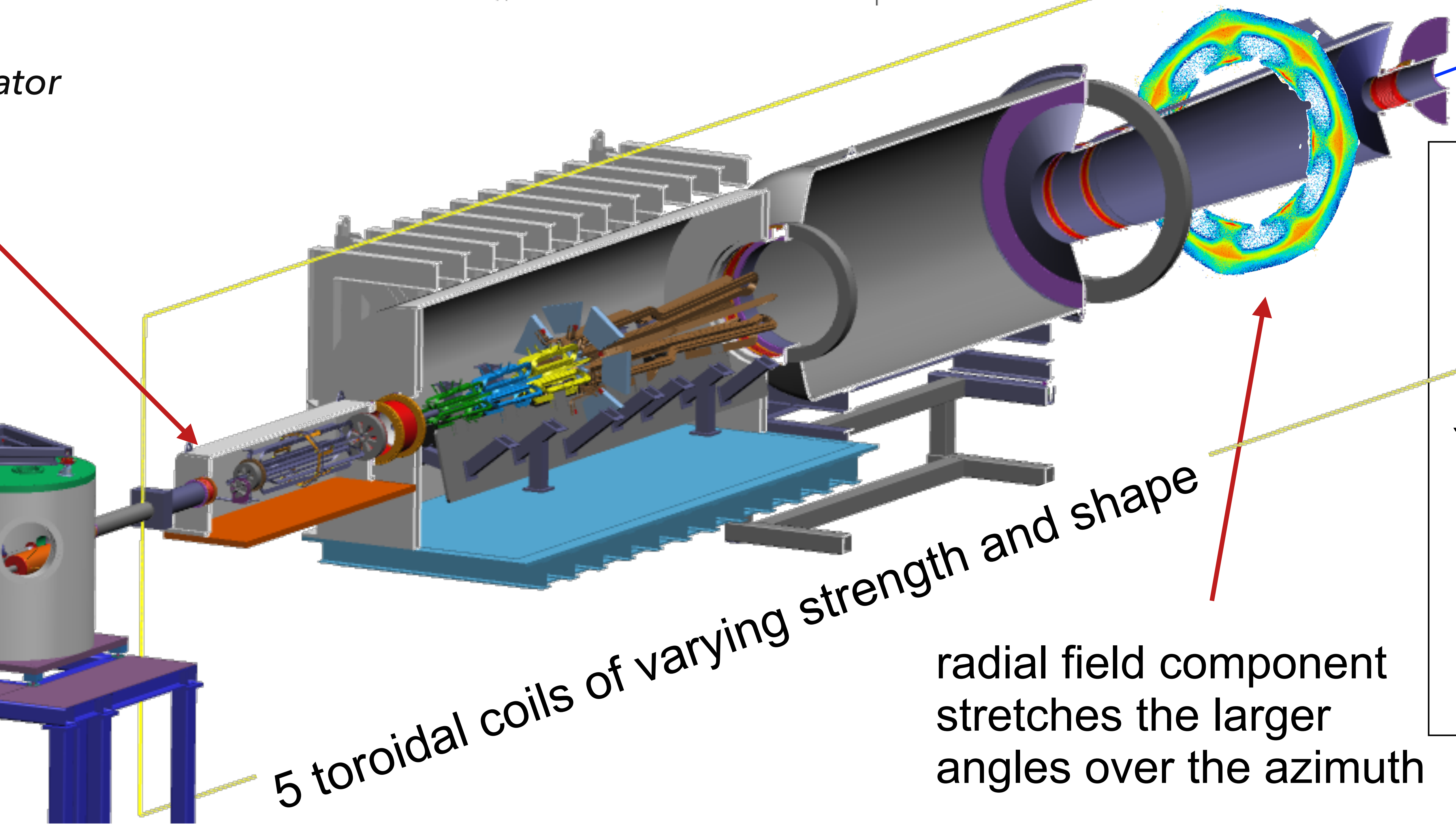
azimuthal field separates ee, ep, and line of sight (γ) at detector plane

Acceptance defining collimator



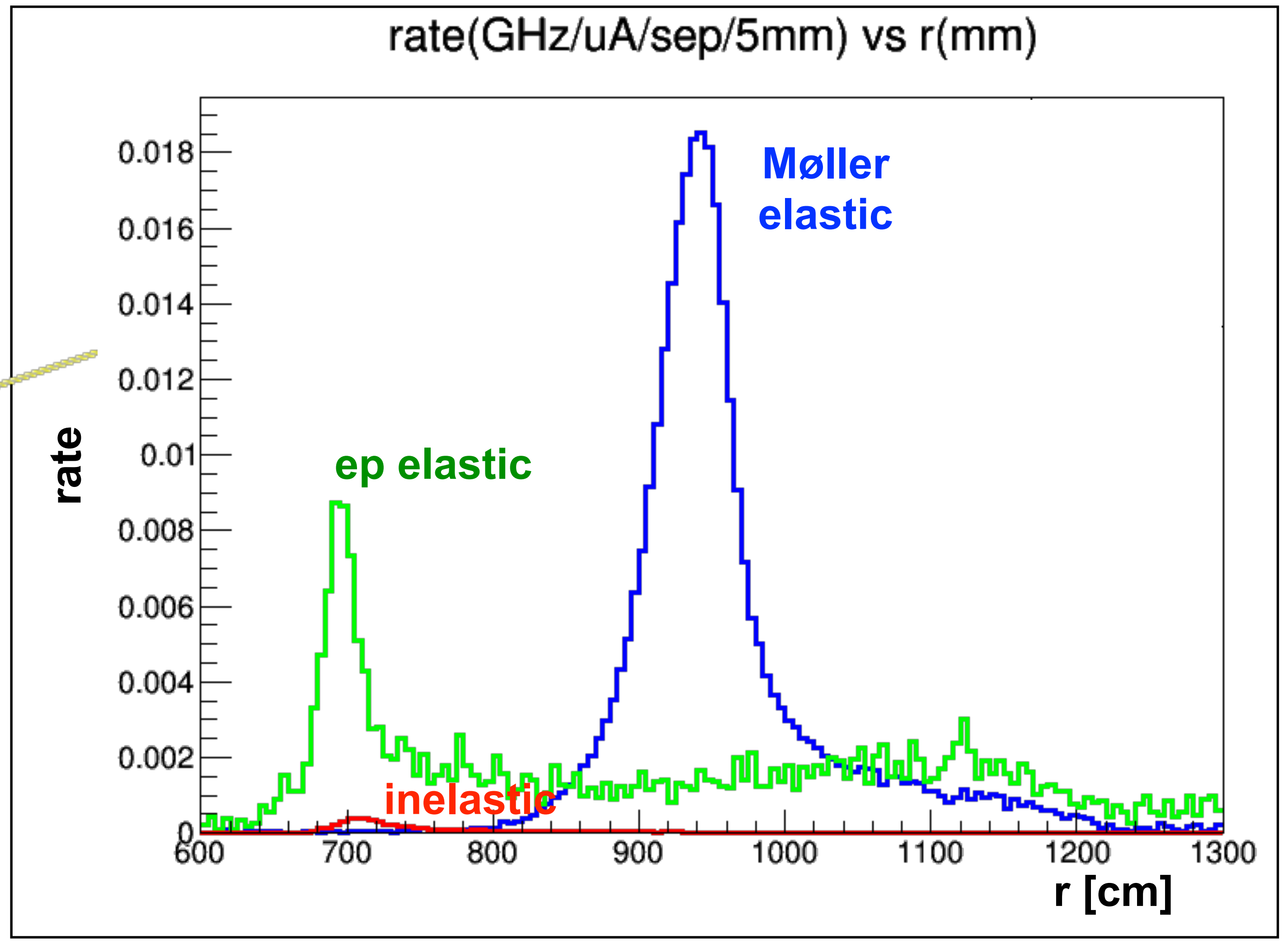


4.5kW LH_2 cryotarget
high power, high stability



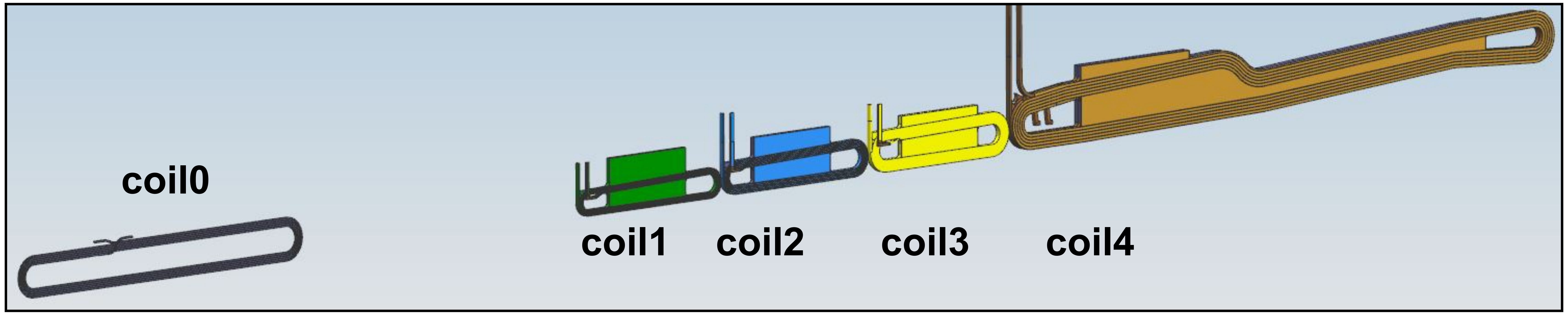
5 toroidal coils of varying strength and shape

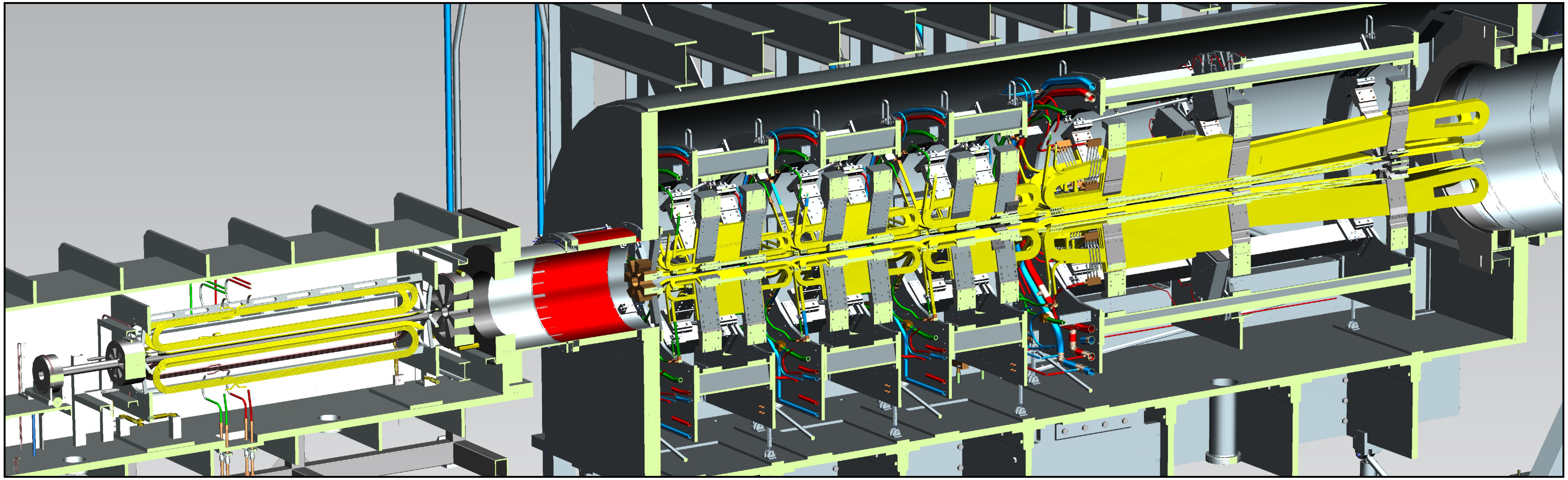
radial field component stretches the larger angles over the azimuth



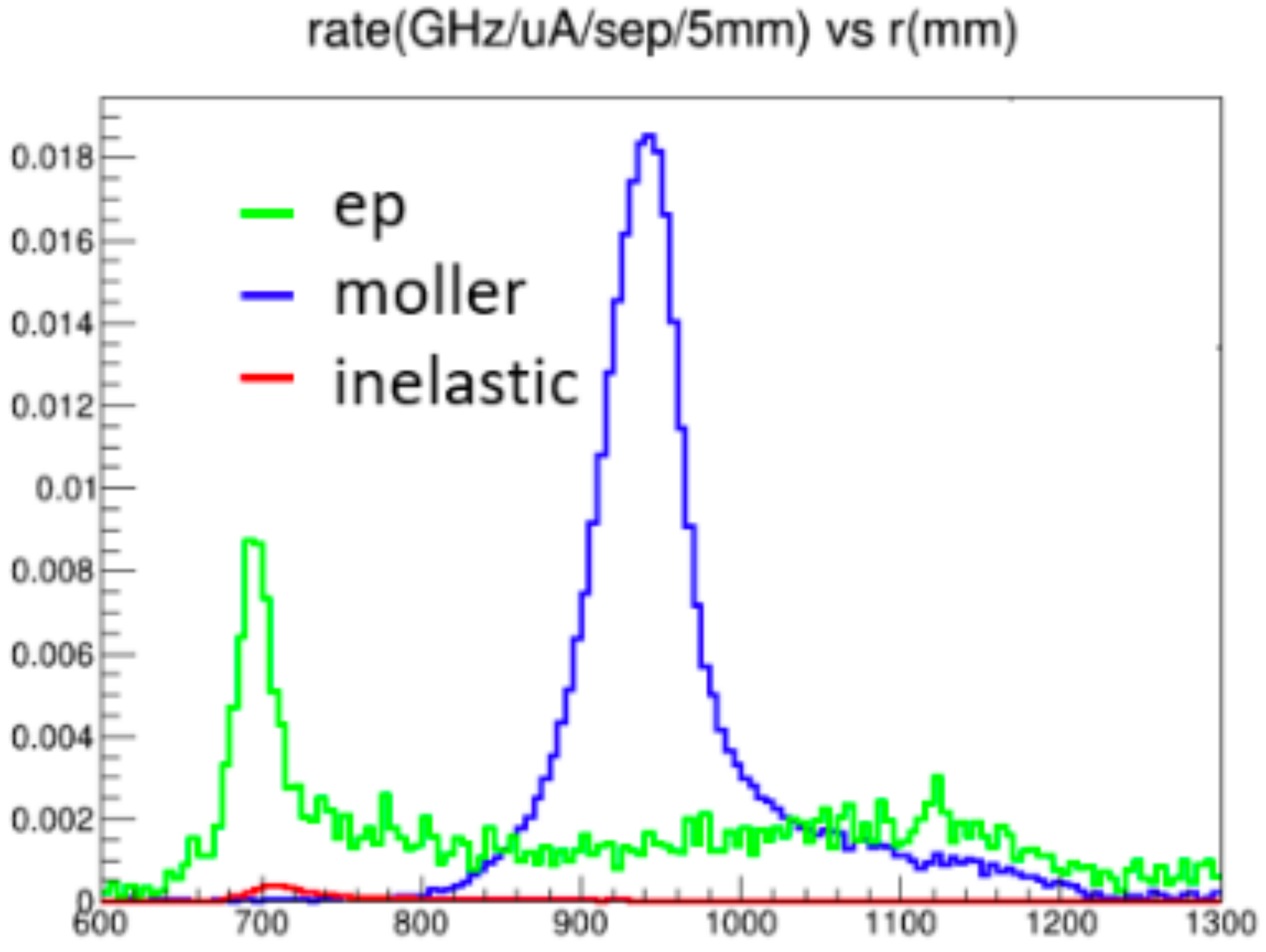
radial flux distribution

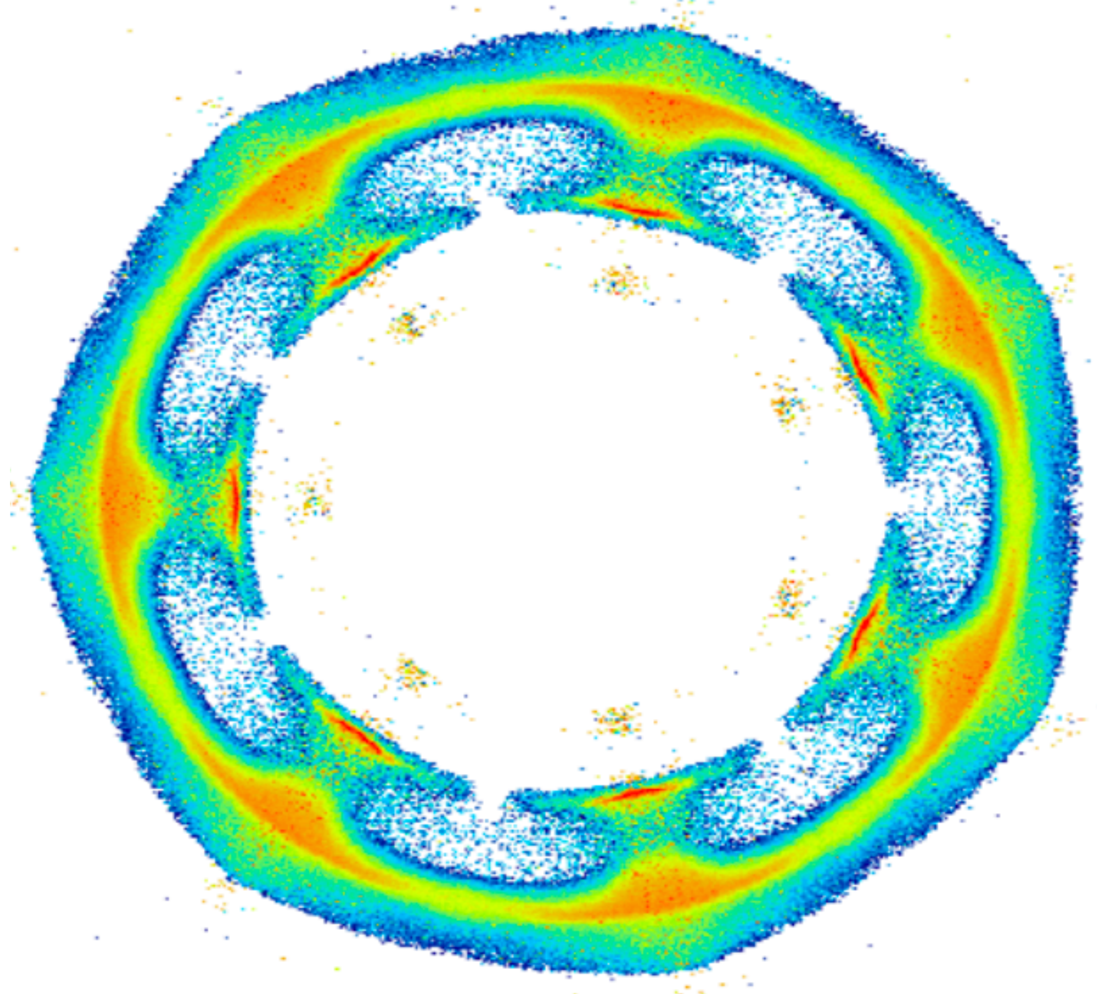
Spectrometer Detail

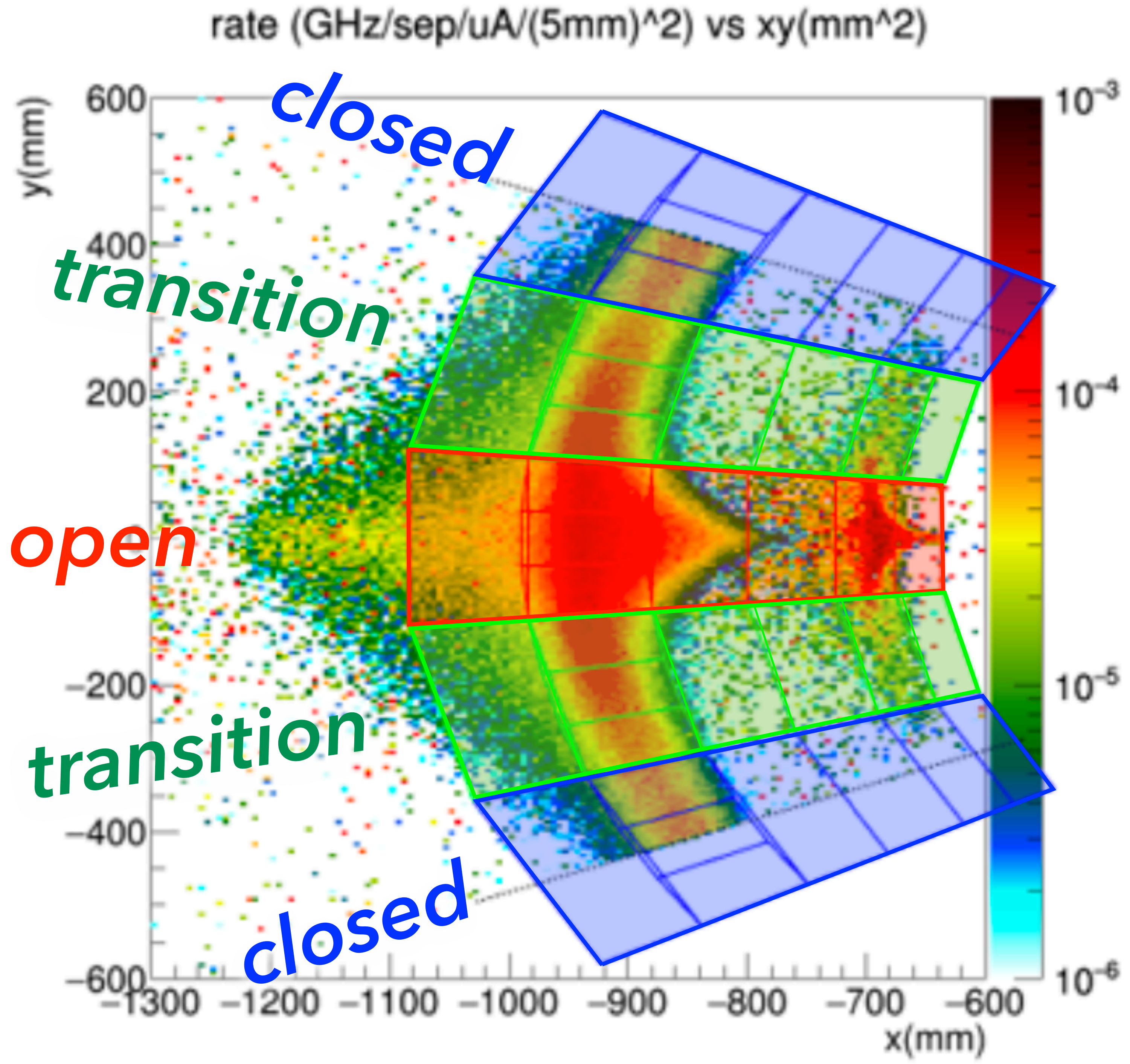




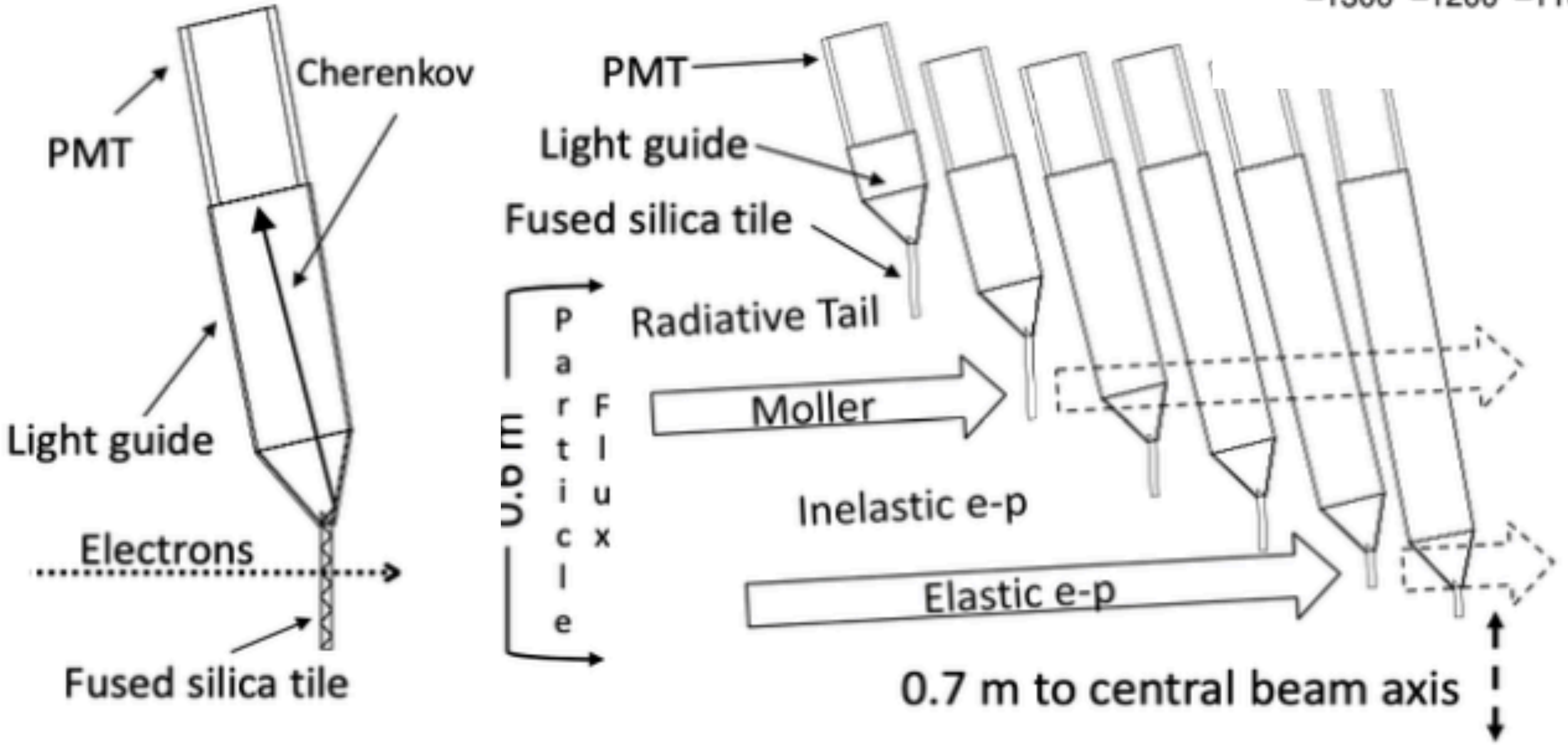
Detectors





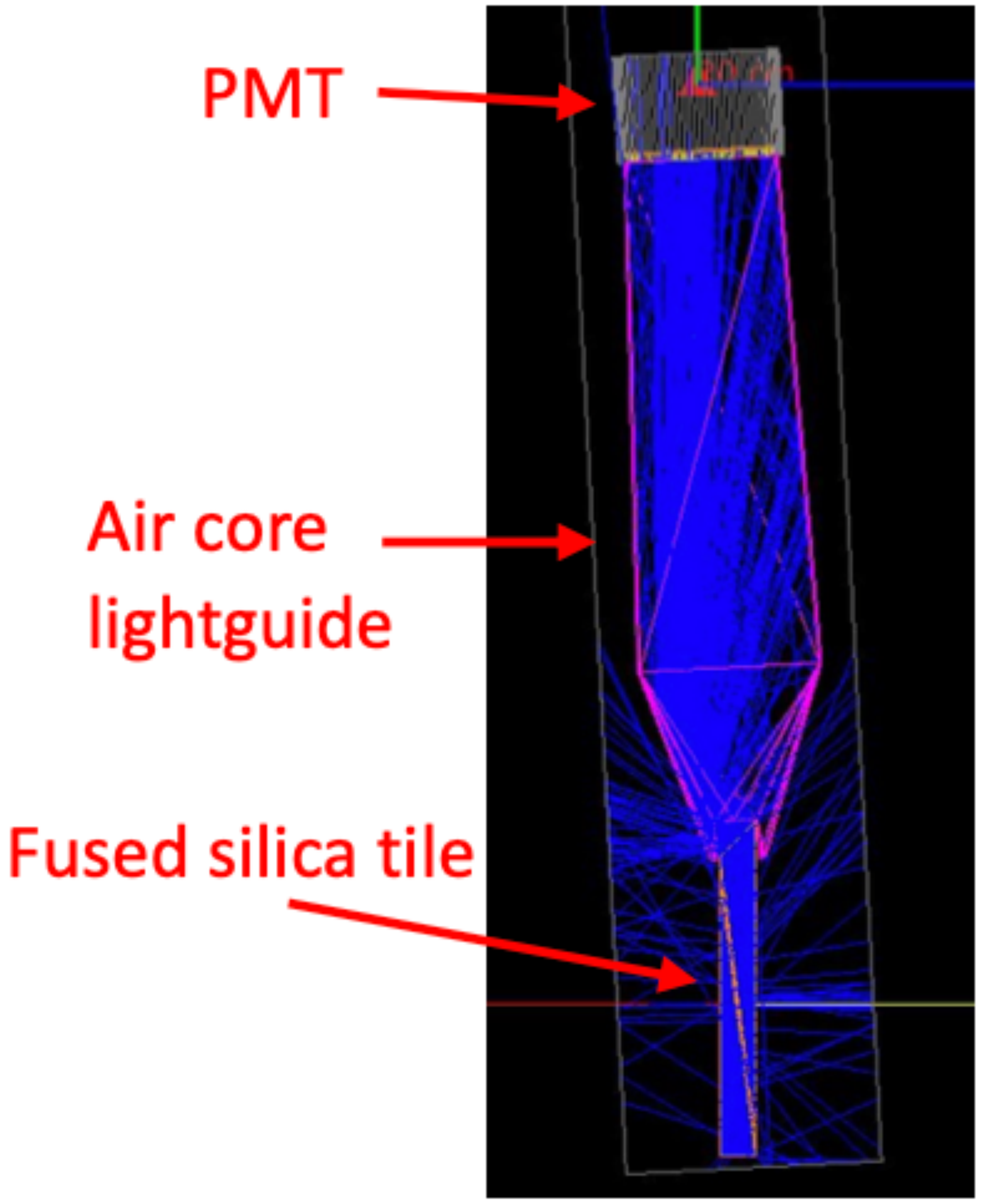


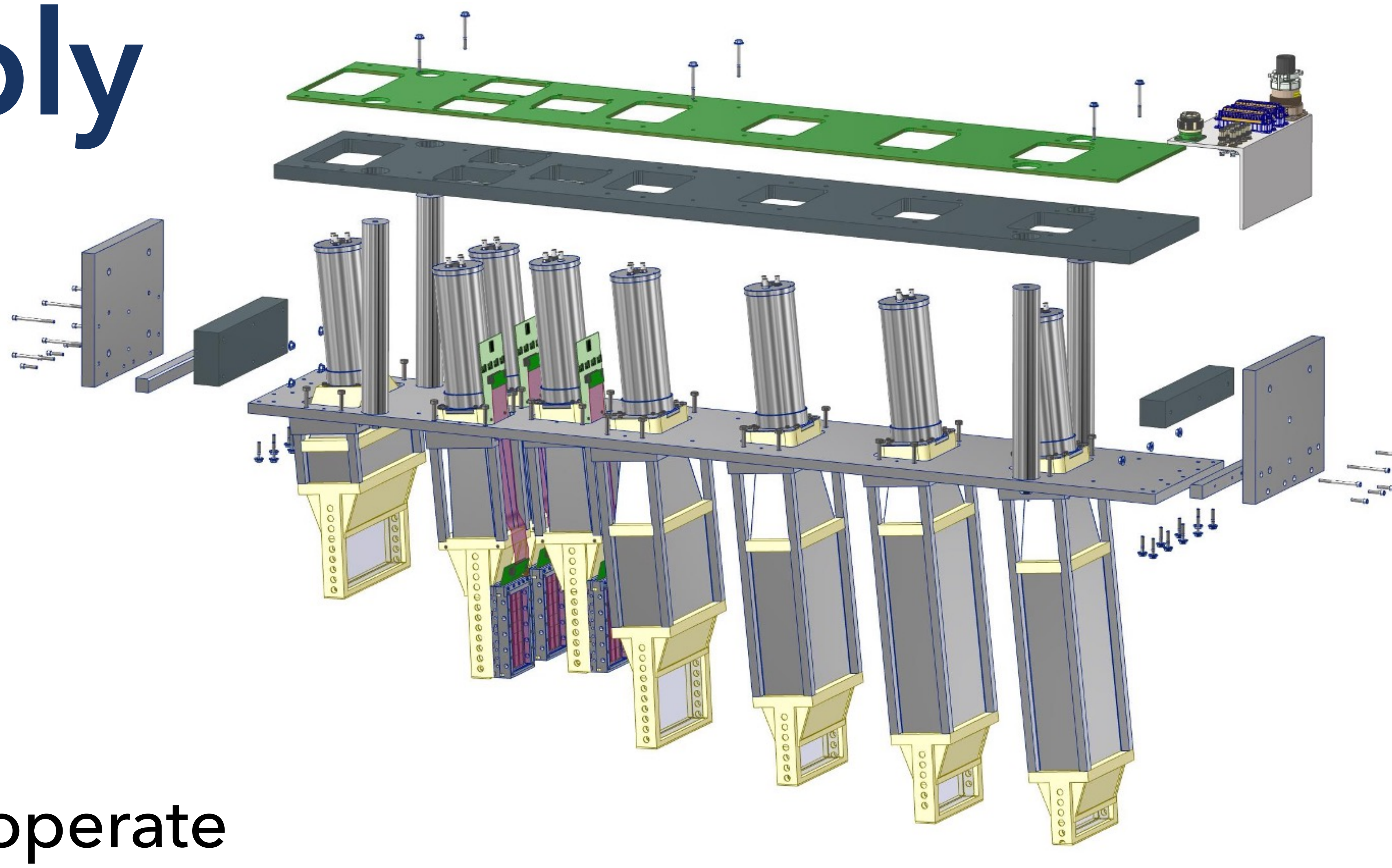
- Primary A_{PV} measurement uses an array of thin quartz detectors
- High level of segmentation to separately measure Møller signal and background signals



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

Detector Assembly

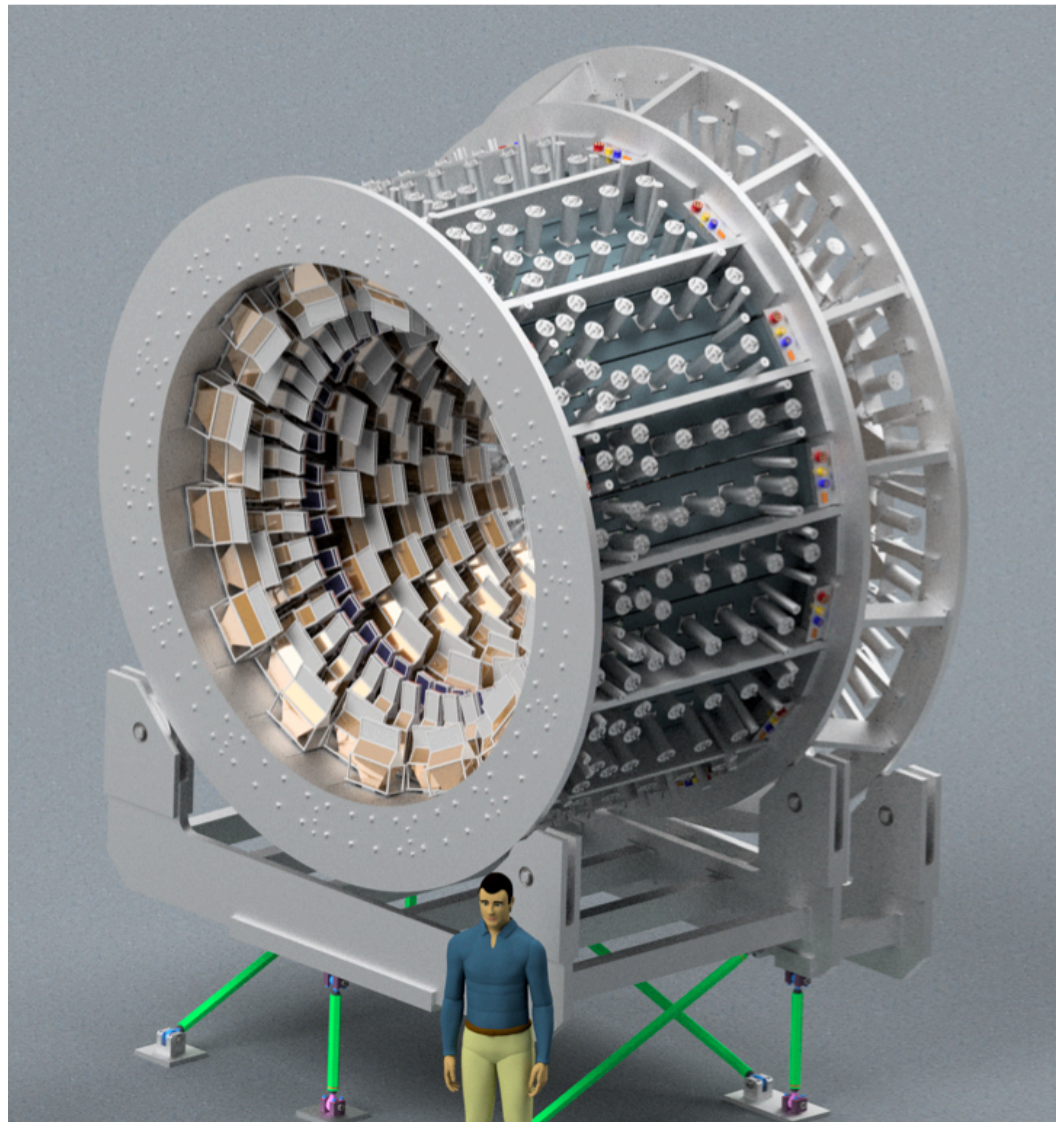




PMT + base, electrons operate in integrating mode and counting mode (for calibration)

Radiation hard, to survive experiment lifetime

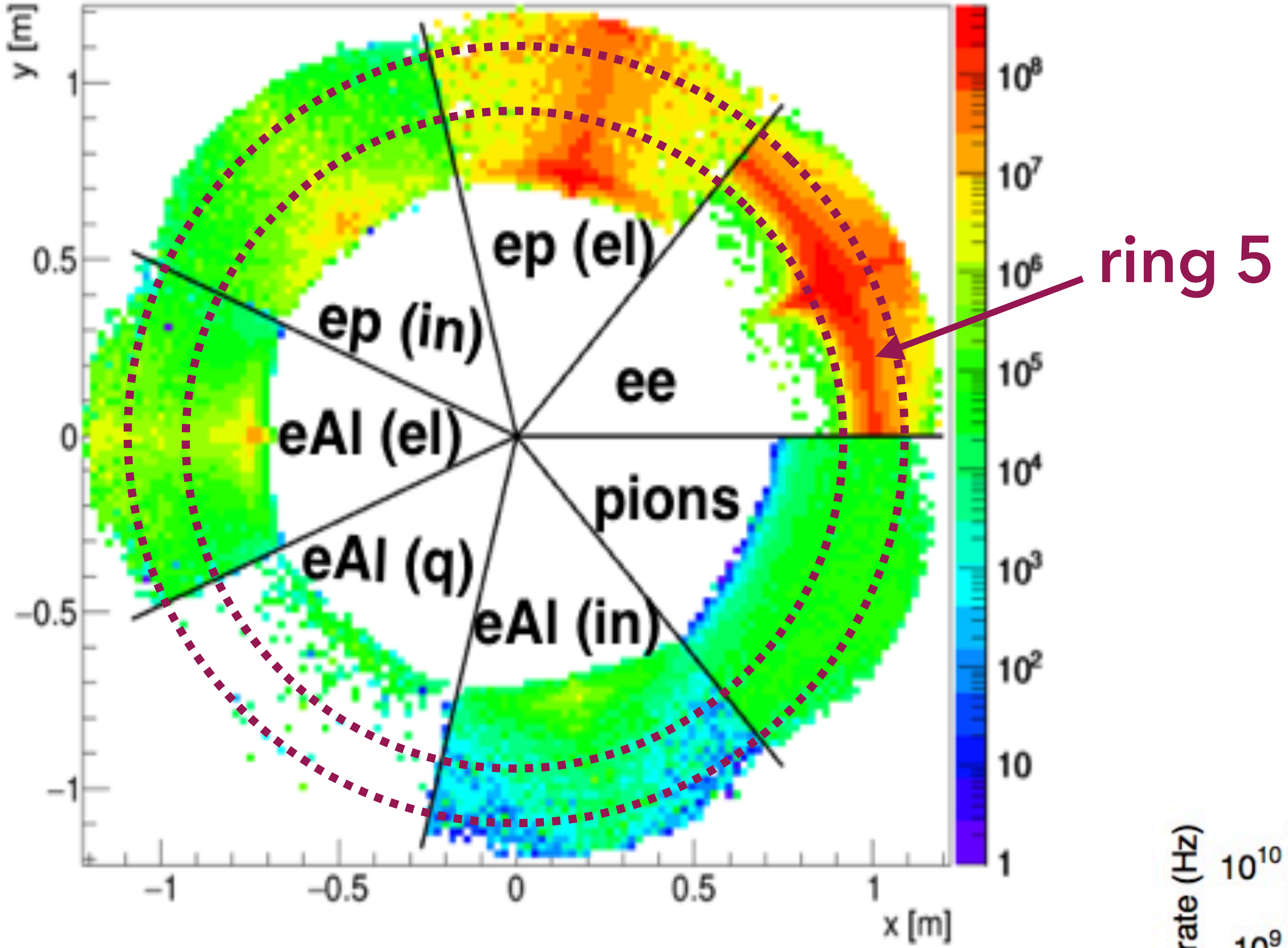
Rates / PMT: 4 MHz - 4 GHz
Total rate: ~220 GHz



Thin quartz, optimized for >25 pe and <4% noise (above counting statistics)
(simulations + in-beam tests)

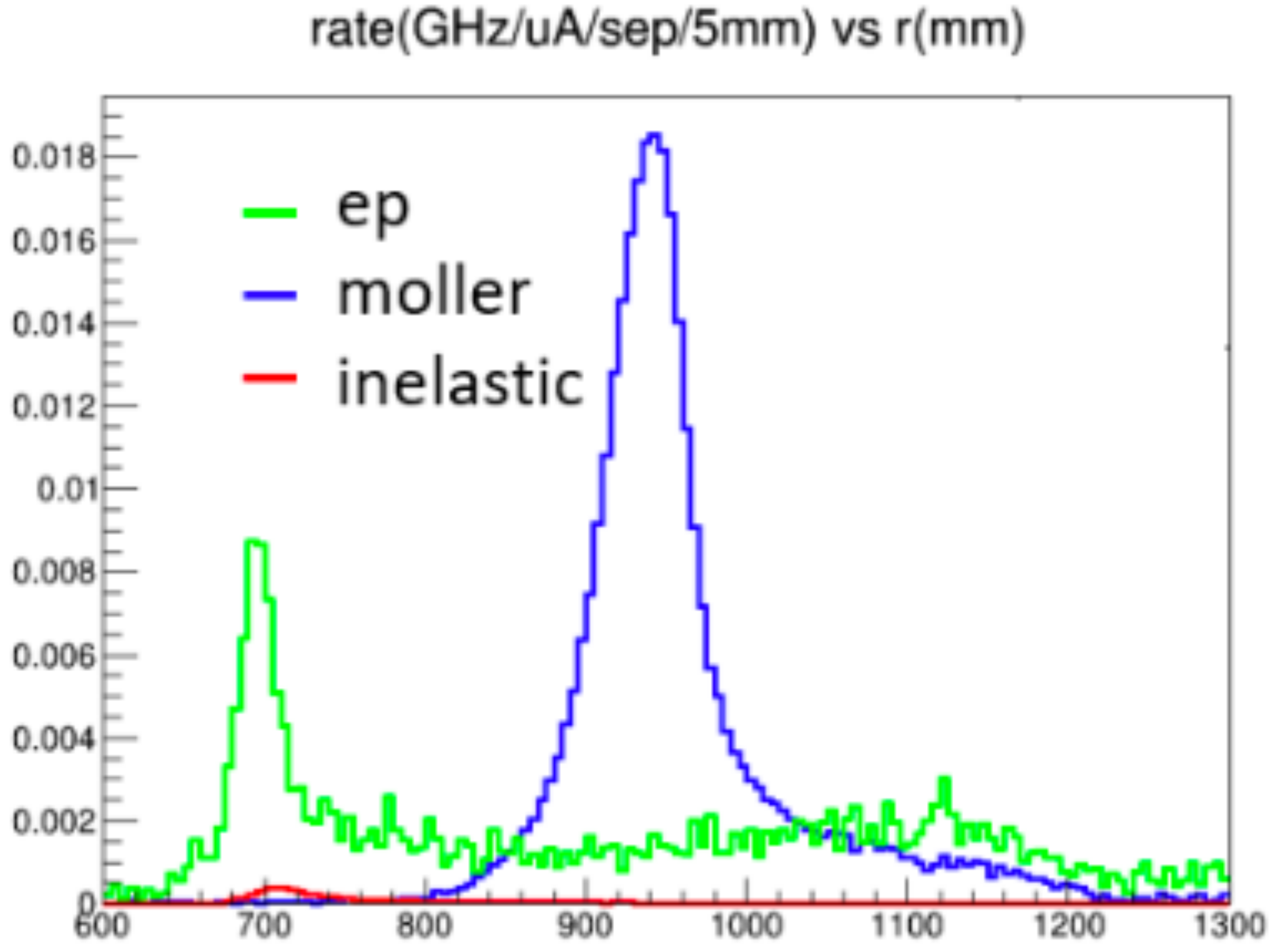
Irreducible Backgrounds

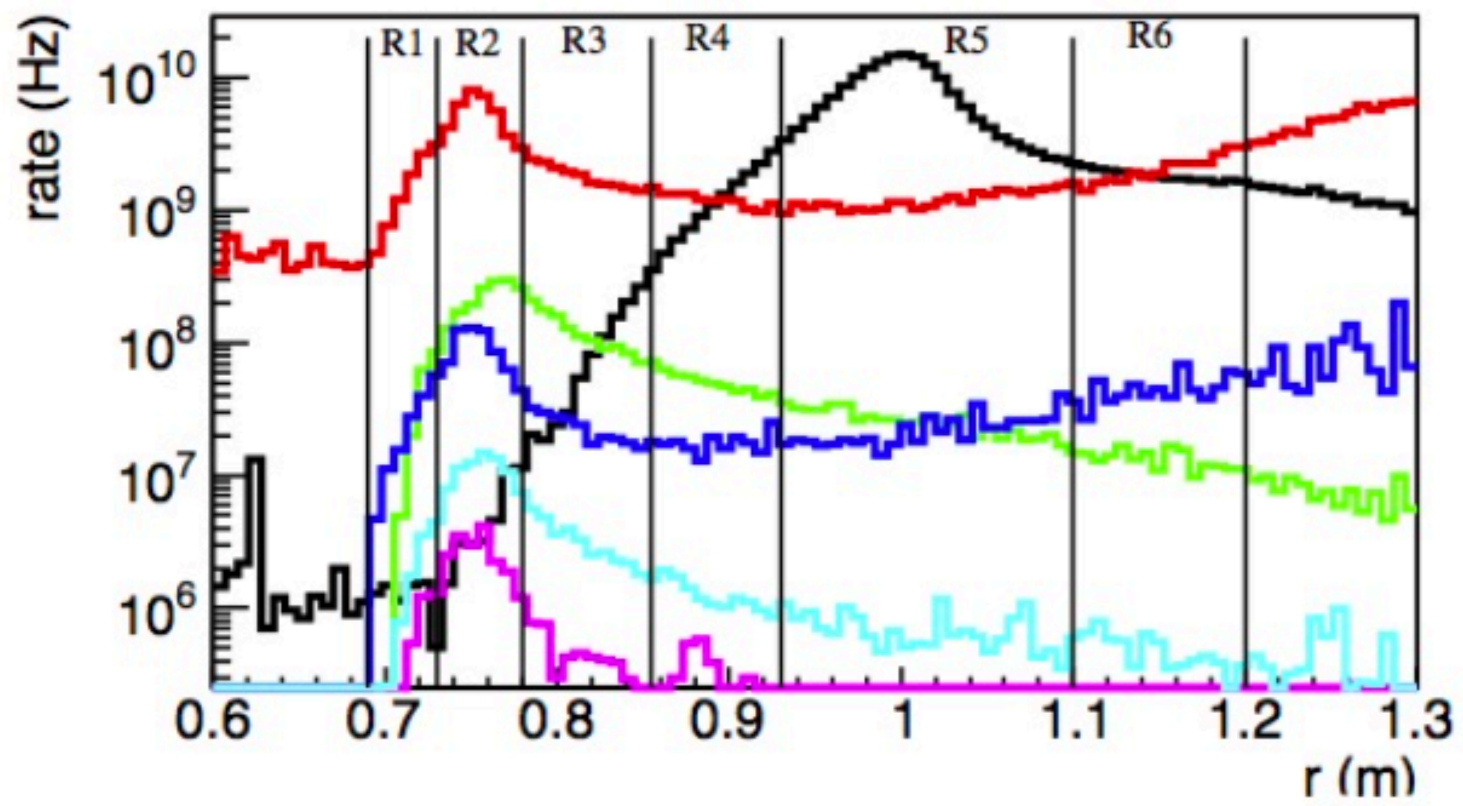
Illustration of signal and background distributions

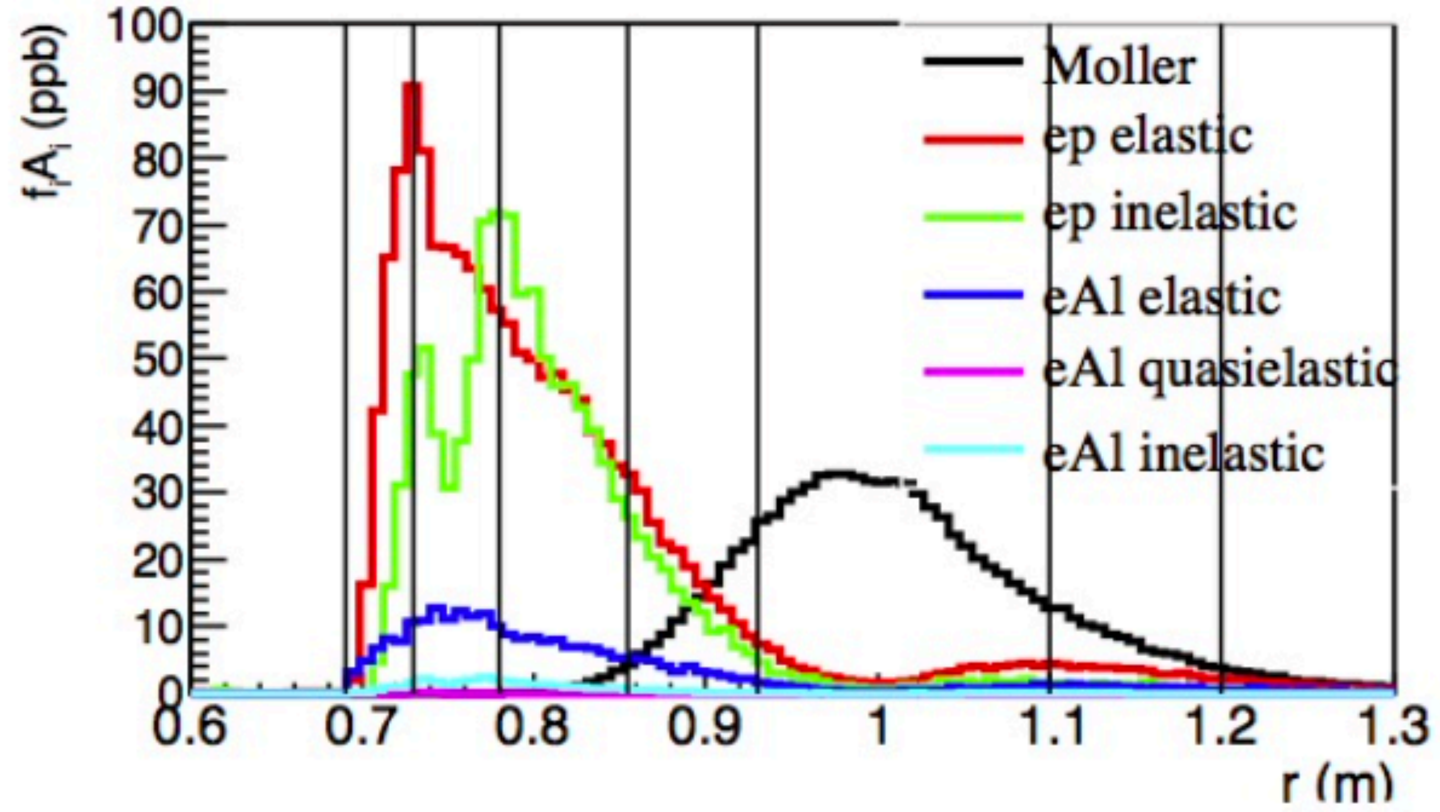


Radial / Azimuthal binning - measures backgrounds under the Møller peak

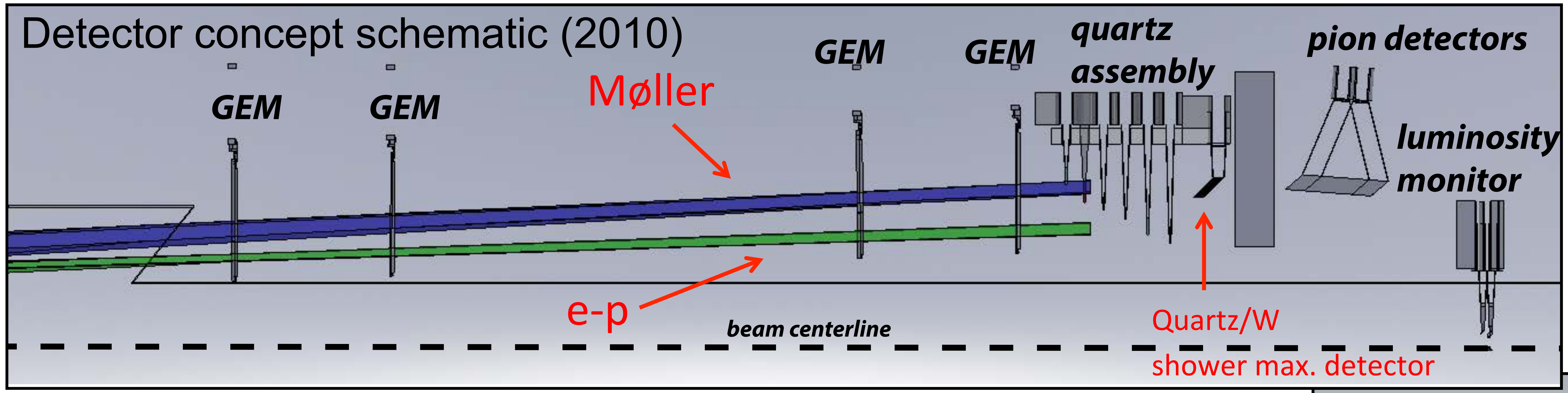
Incident electrons radiate to lower energy, scatter in background processes but matching energy-angle correlation of Møller scattering





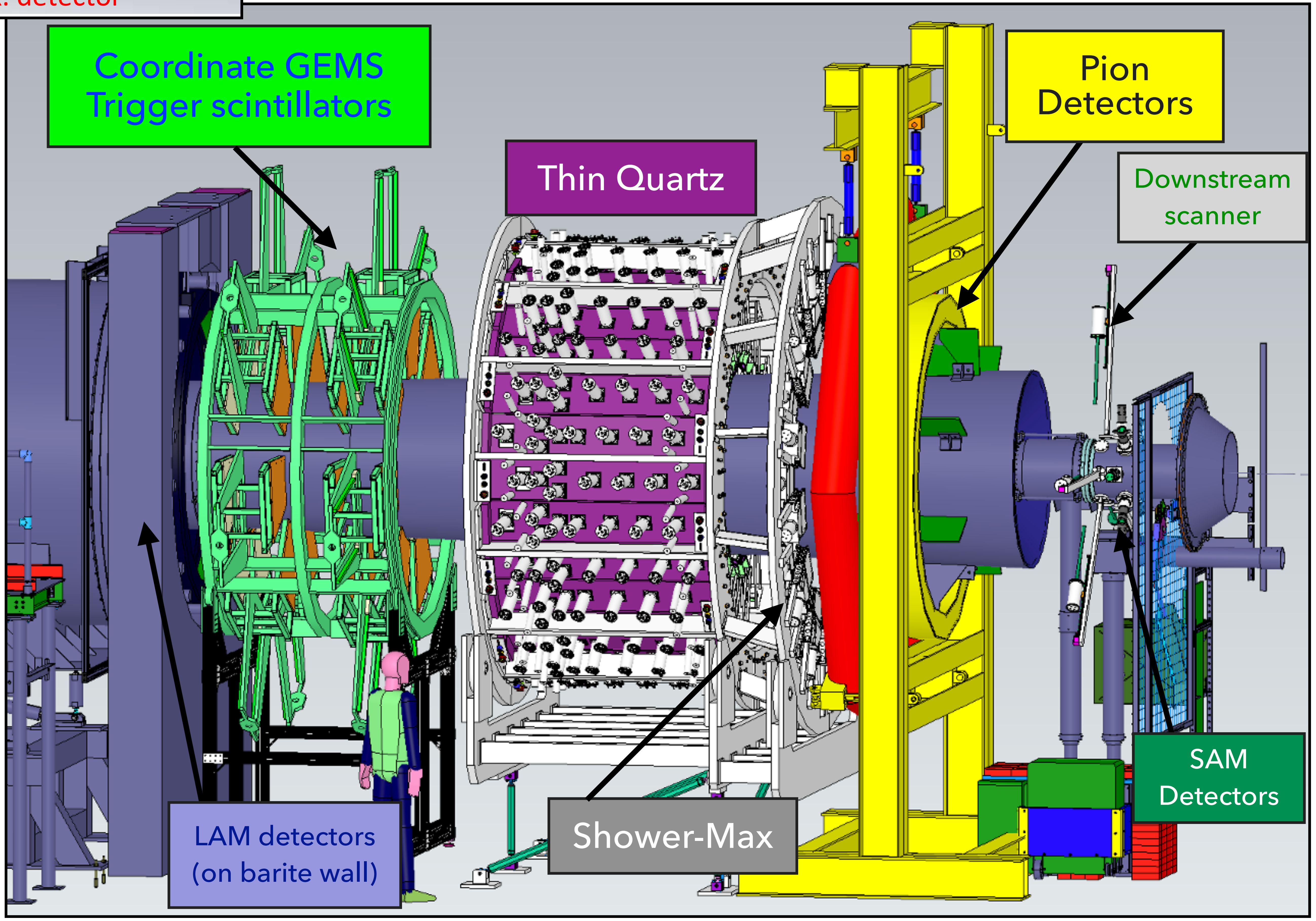


Detector Package

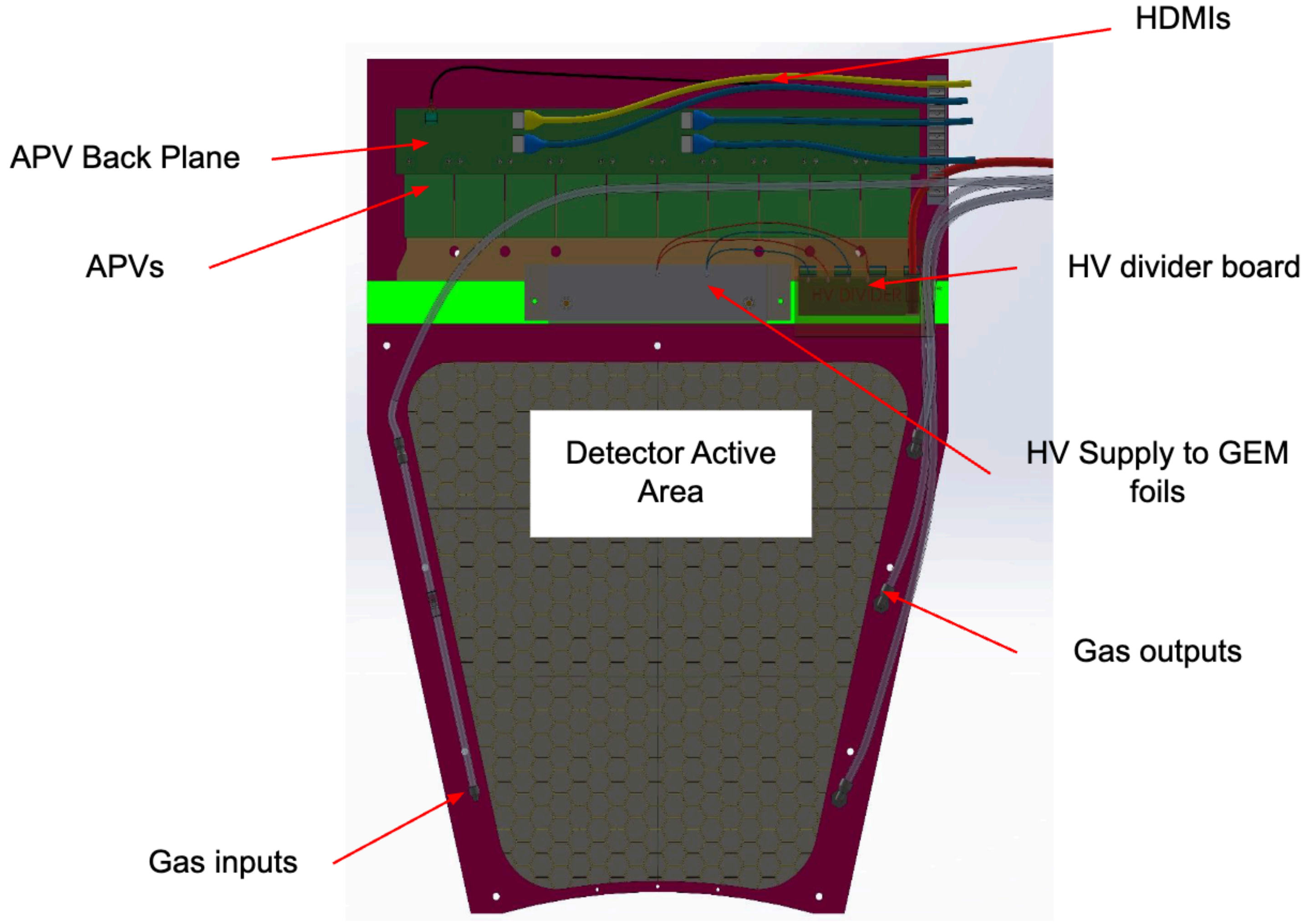


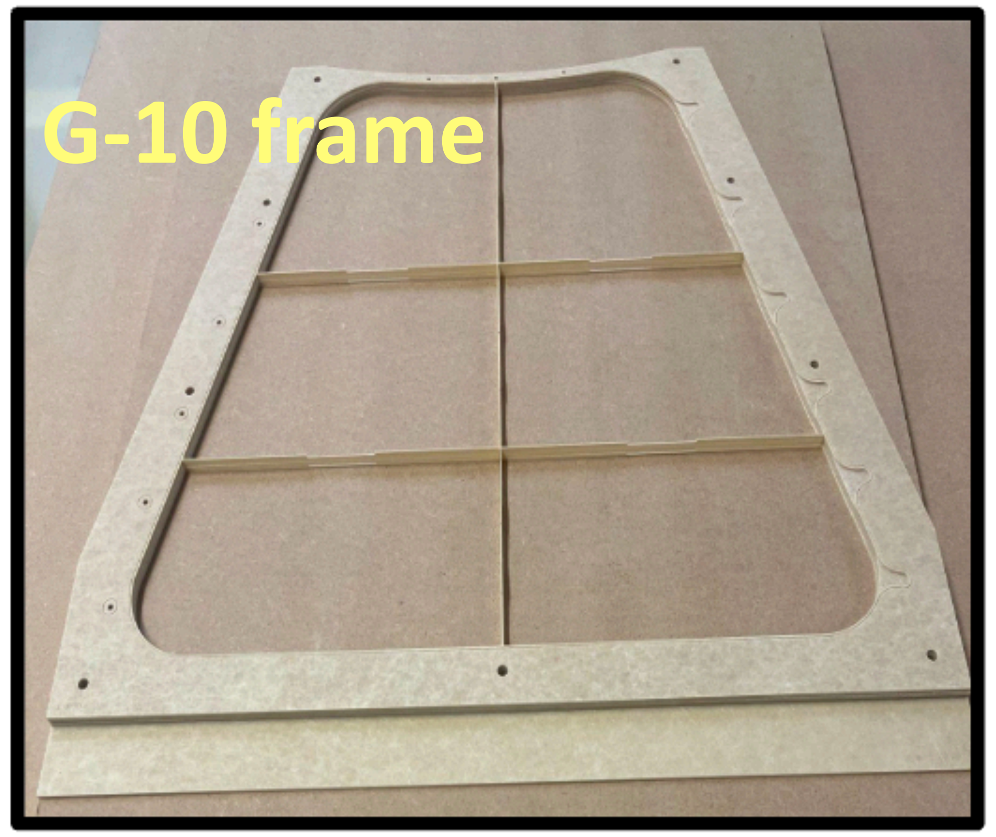
Tracking detectors and auxiliary detectors for calibration and background studies

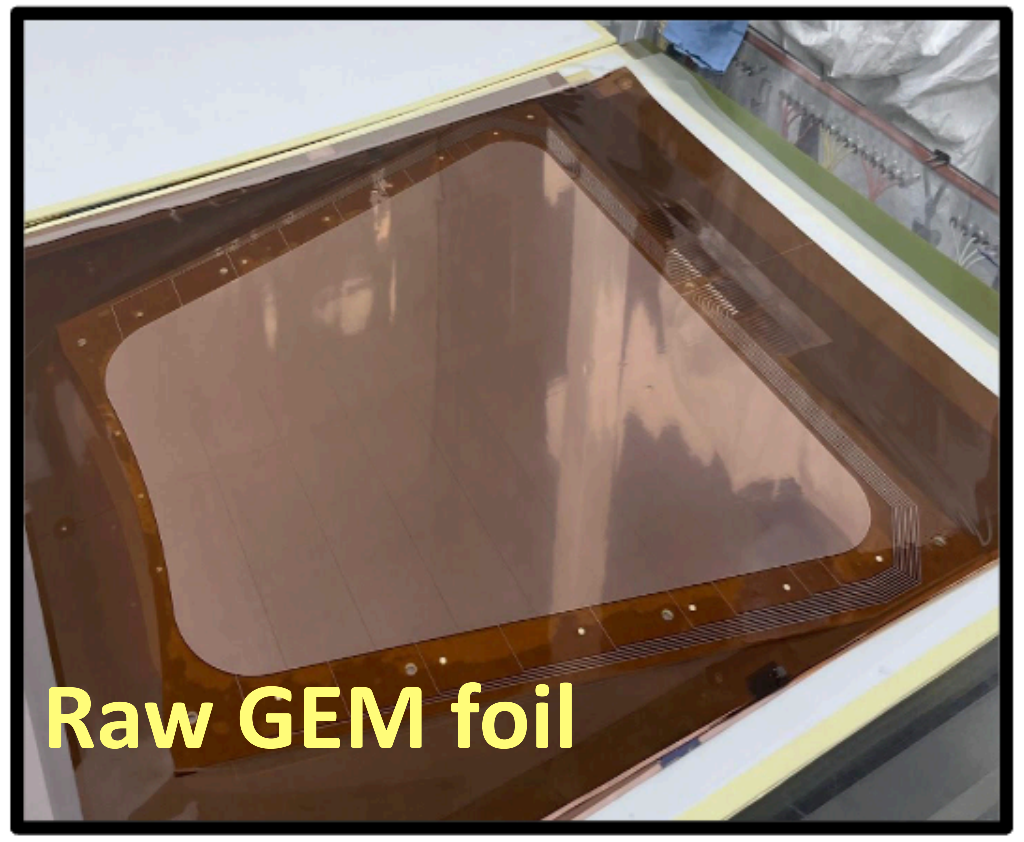
Integrating mode: asymmetry measurement
Counting mode: counting/tracking for calibration

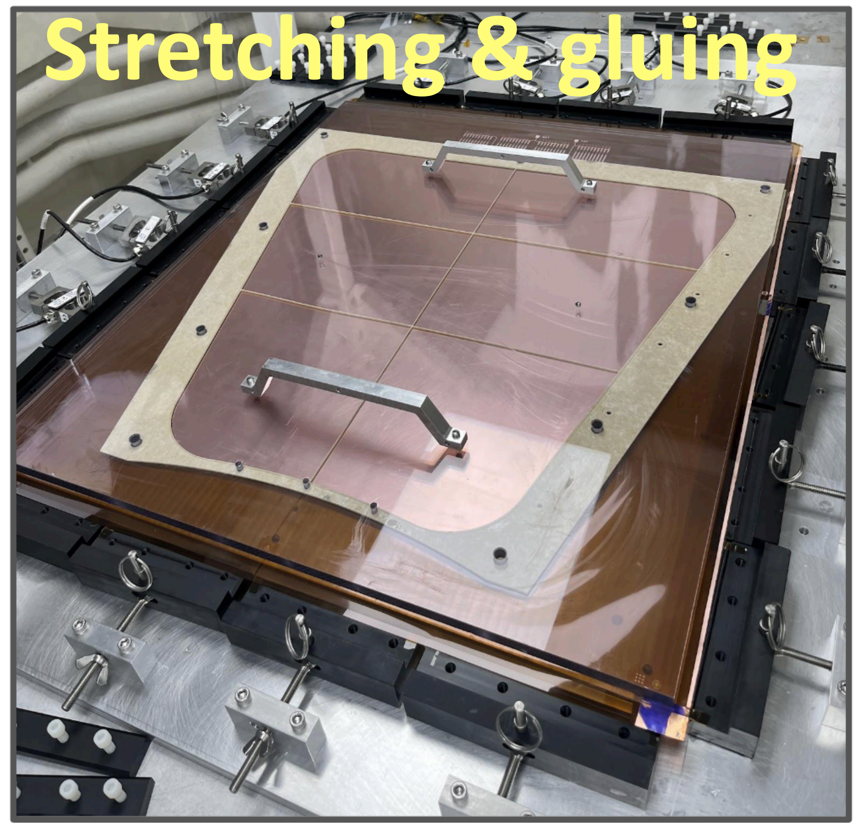


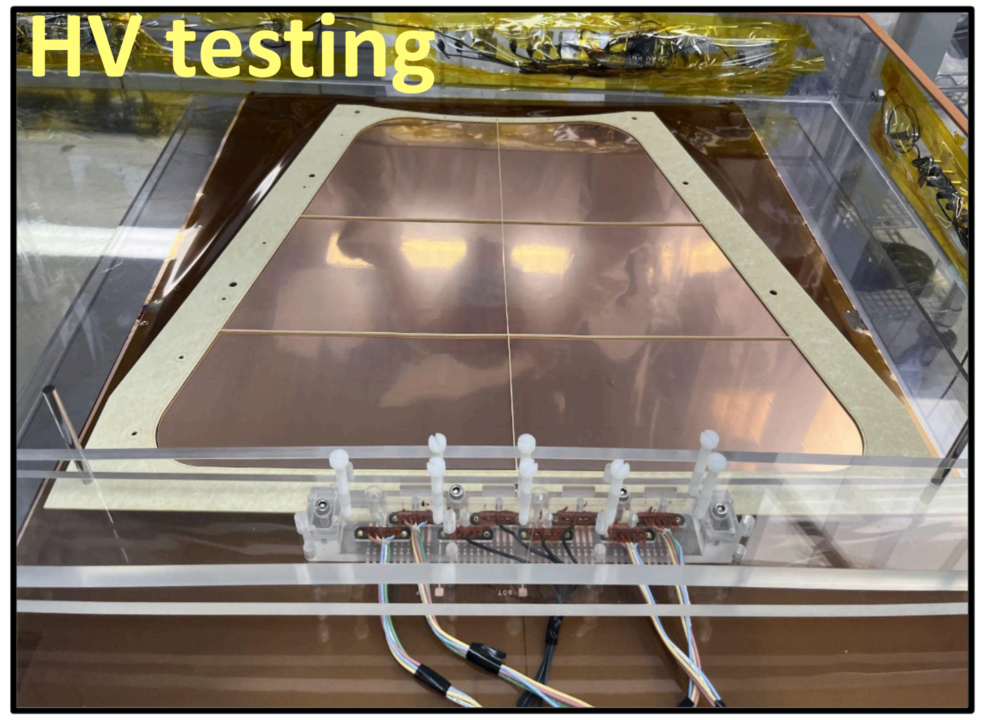
GEM tracking chambers

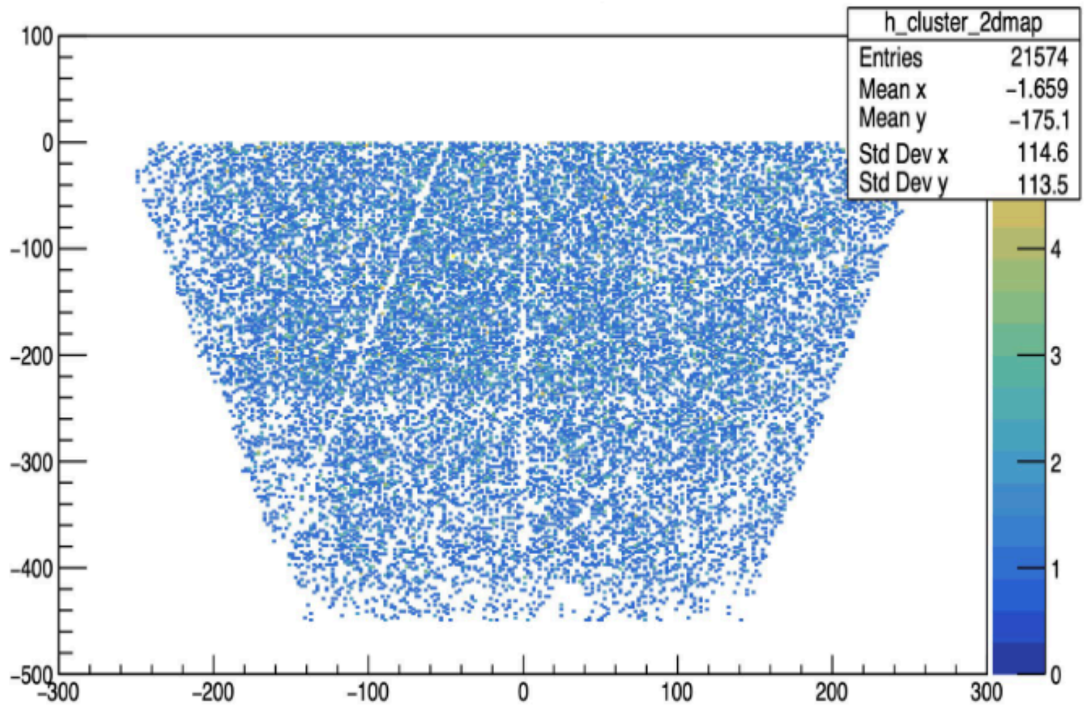




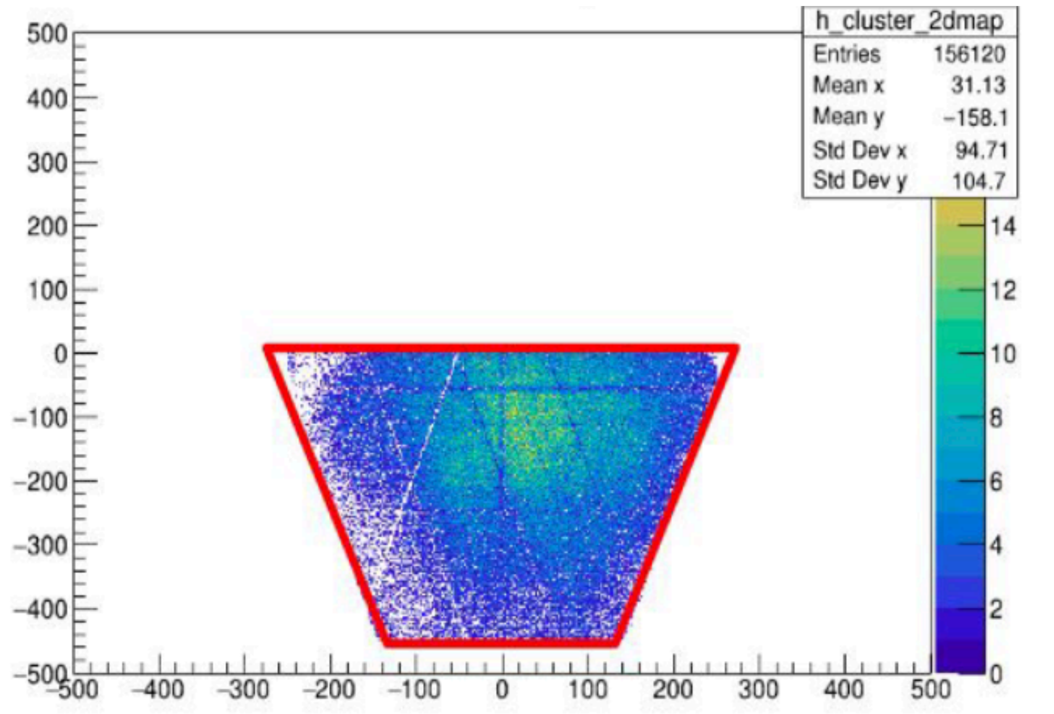








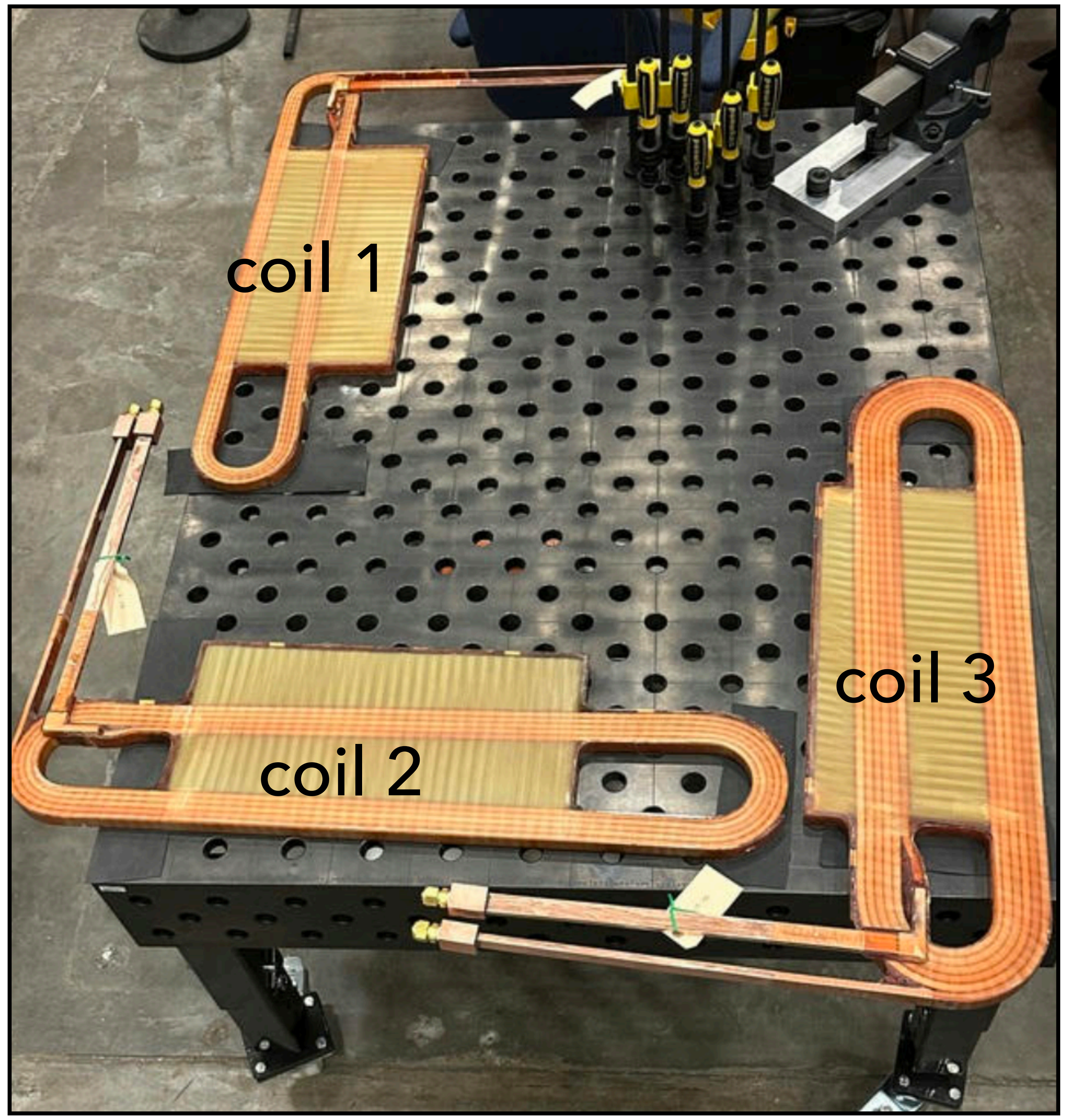
Cosmic data 2D cluster map

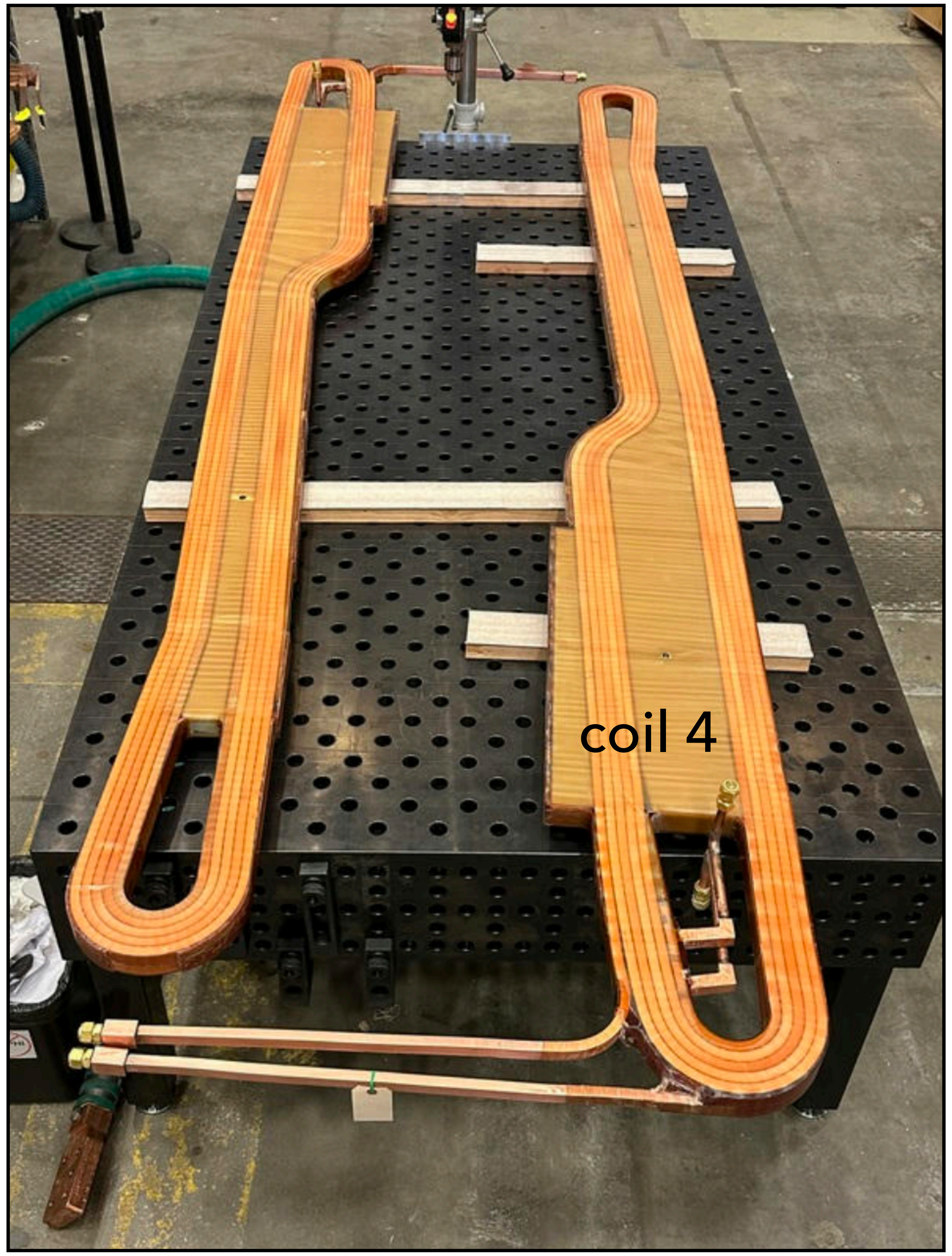


Overlapped X-Ray data 2D cluster map

N. Liyanage, UVa

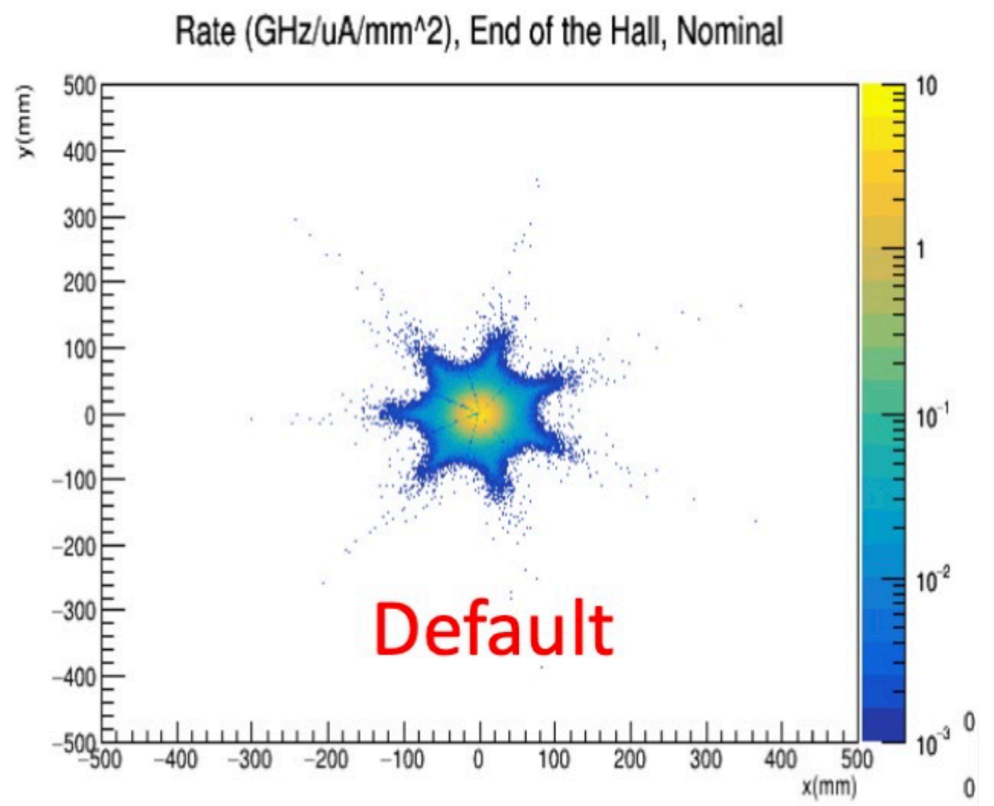
MOLLER spectrometer coils

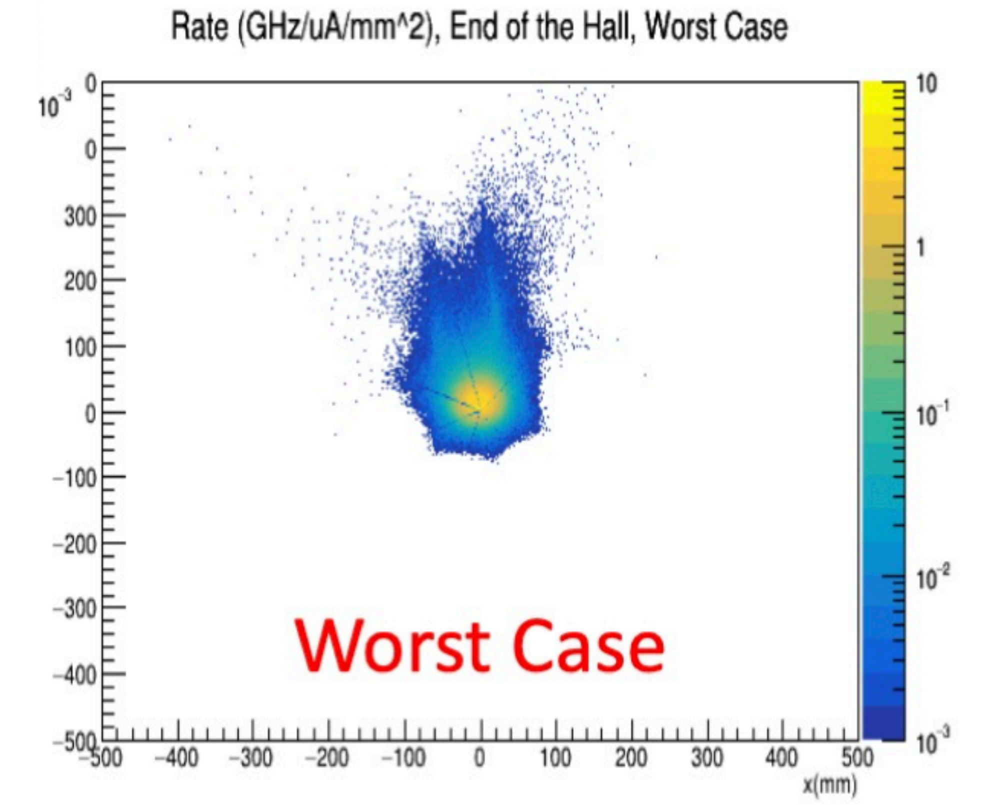




beam leaving hall
sensitive to coil alignment

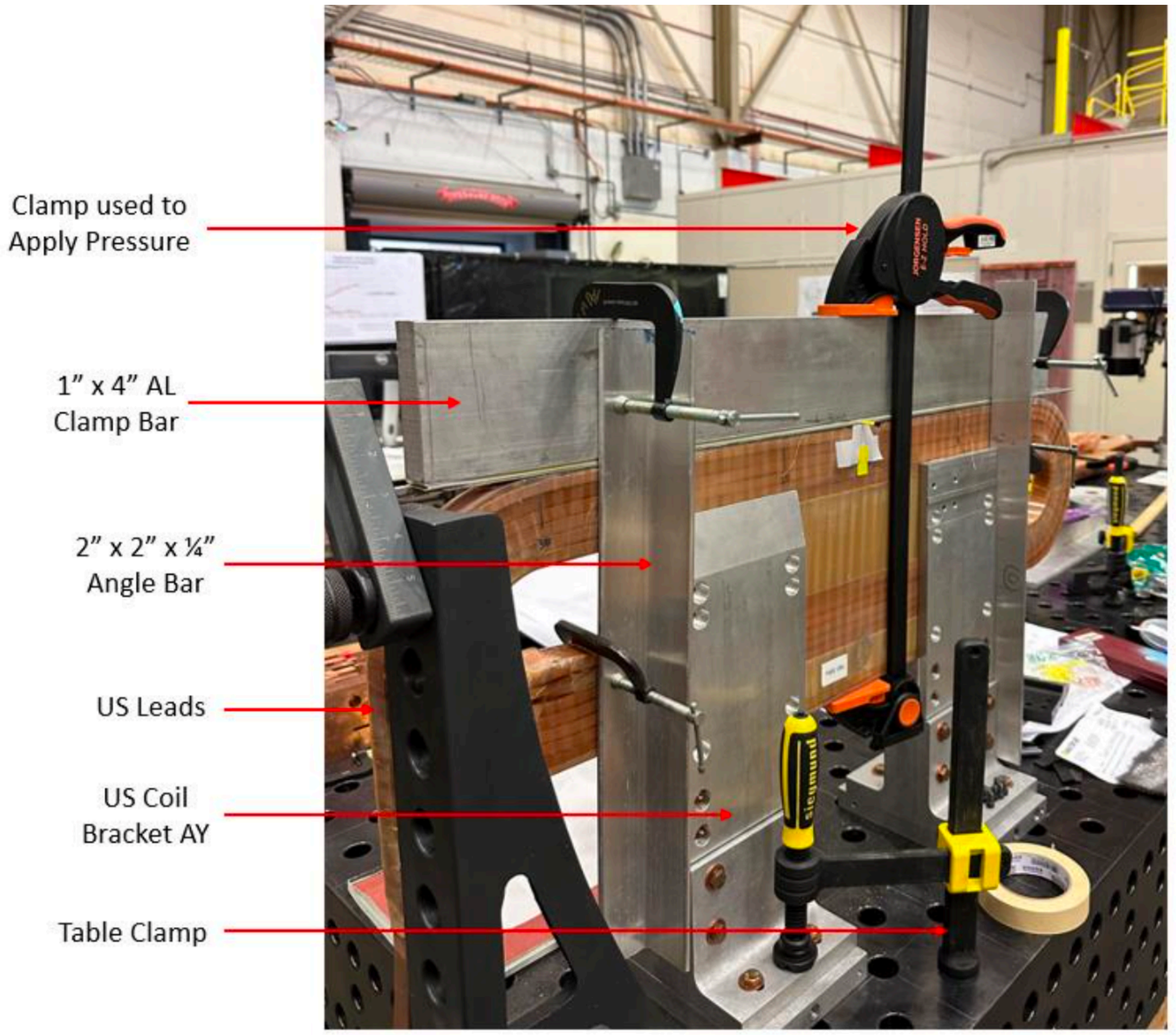
simulated illustration:



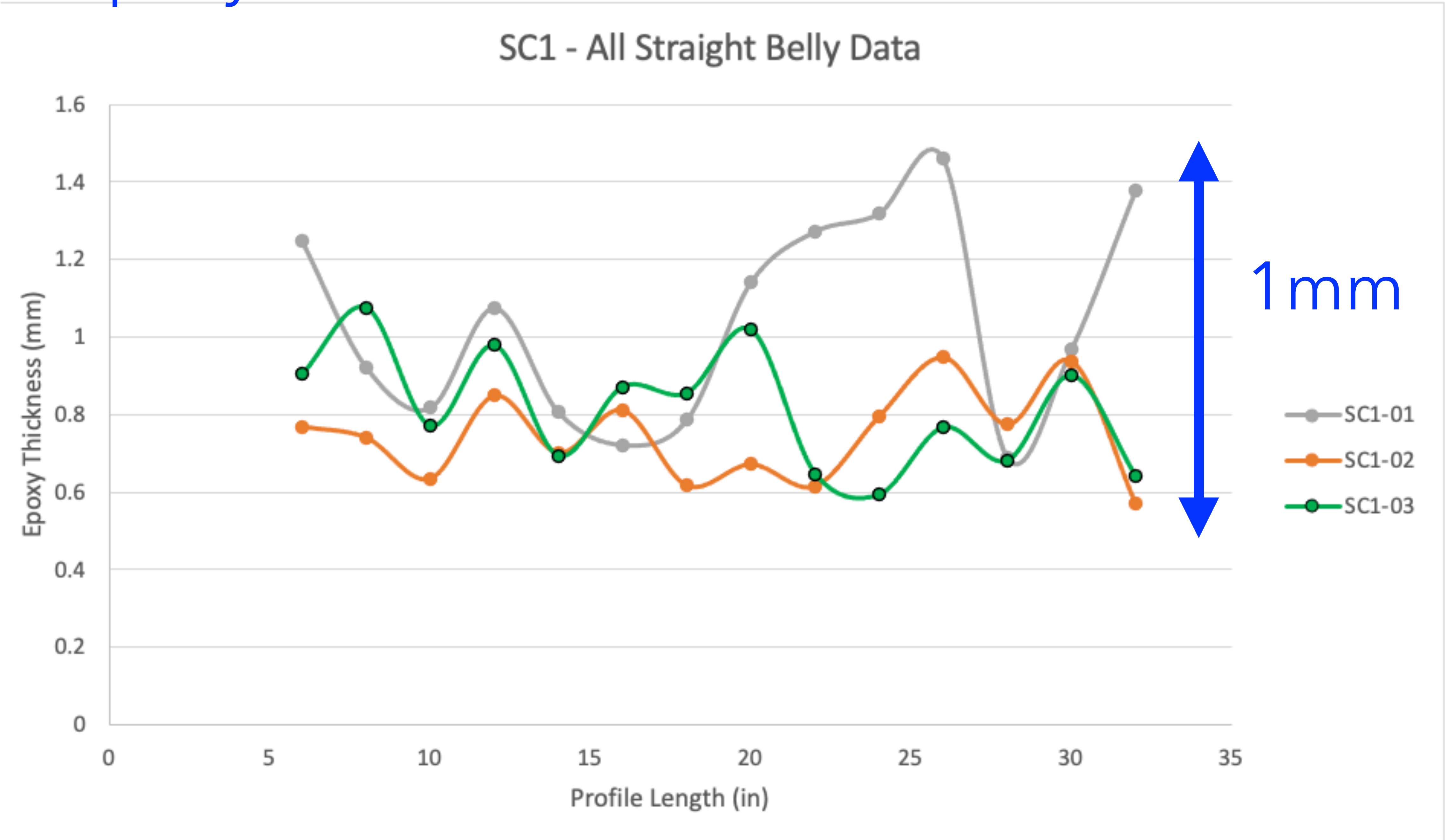


Quality Assurance and Fitting

Test fitting of magnet and collimator mounting



Epoxy thickness variation measurement

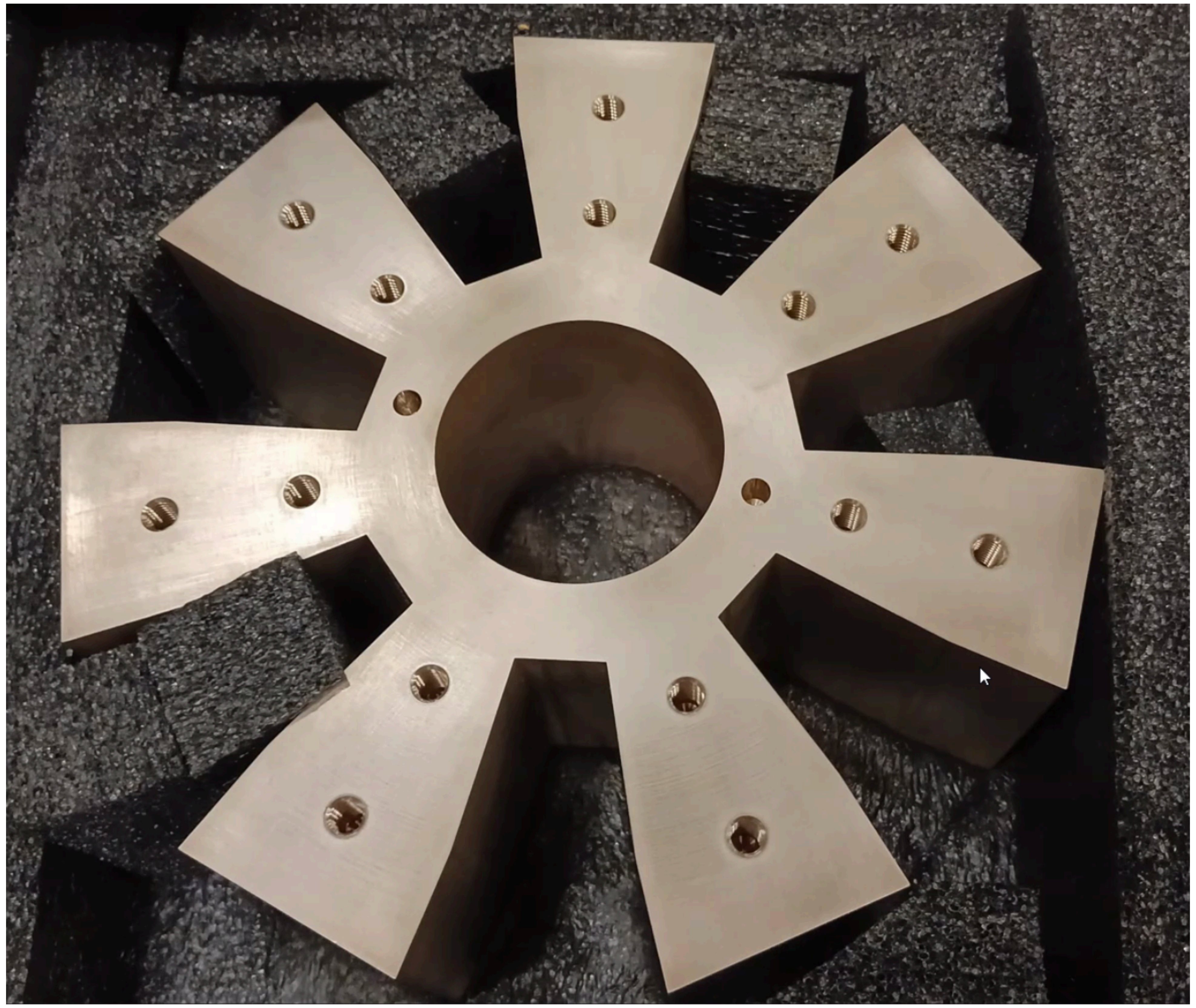


MOLLER components

Long lead items in fabrication, QA

Inconel bellows

Tungsten collimators



Stainless steel bellows, welds passed magnetic susceptibility measurements

MOLLER status

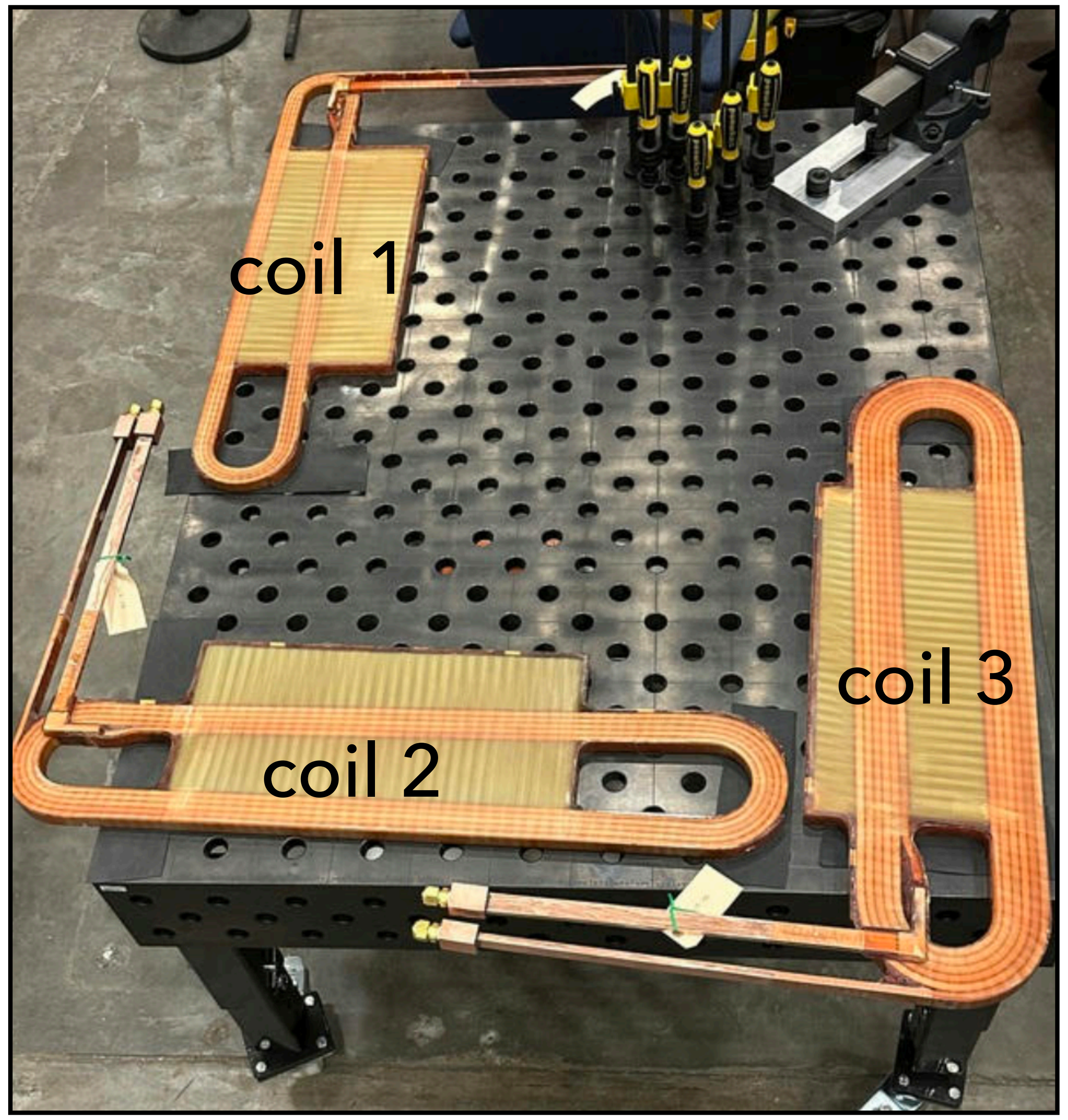
- Fabrication has started for long-lead items
- Fabrication and qualification activity underway at JLab
- Expect to launch rest of fabrication/procurement with ESAAB review in spring

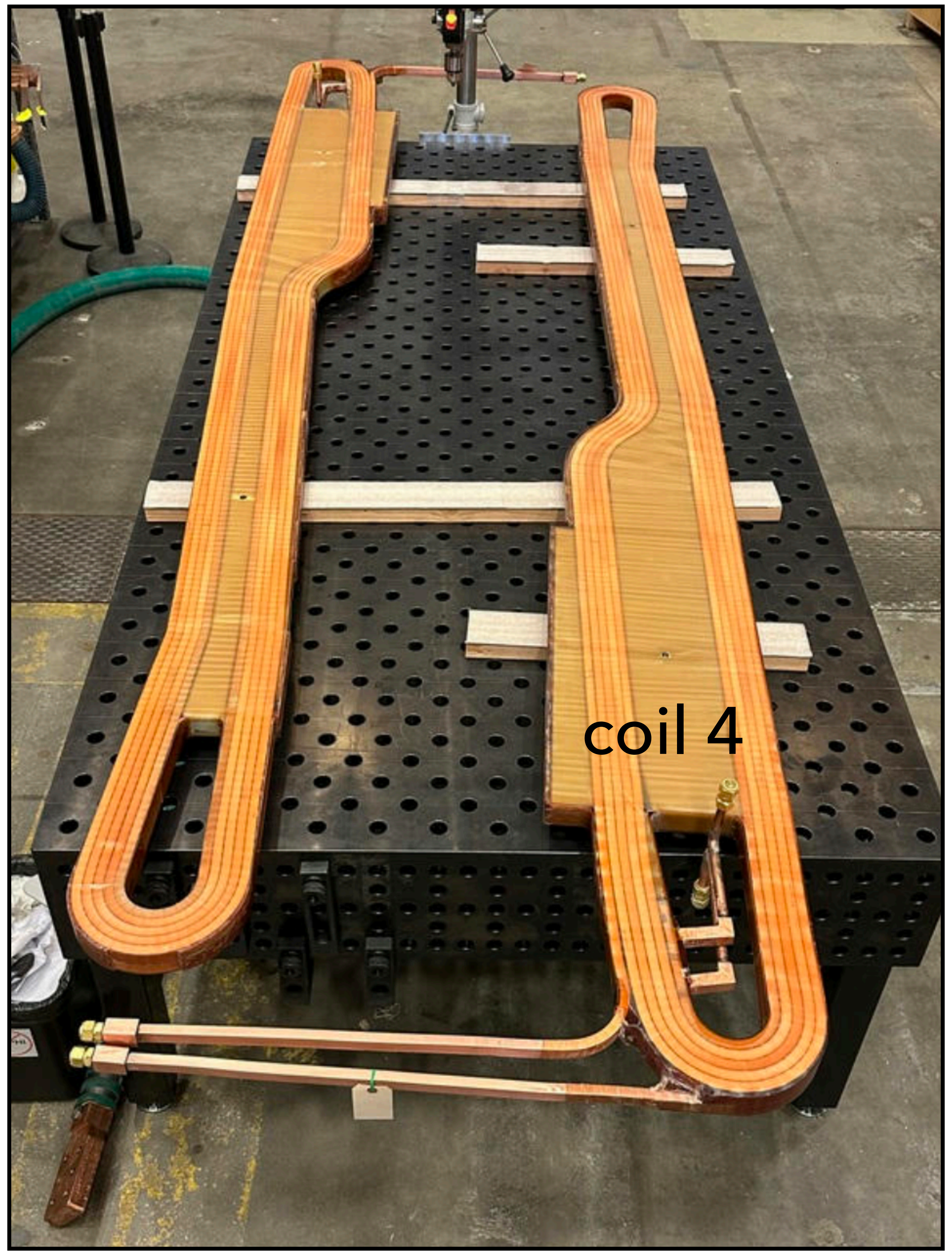
MOLLER Collaboration

~ 160 authors, 37 institutions, 6 countries

K. Kumar: Spokesperson
R. Fair: Project Manager

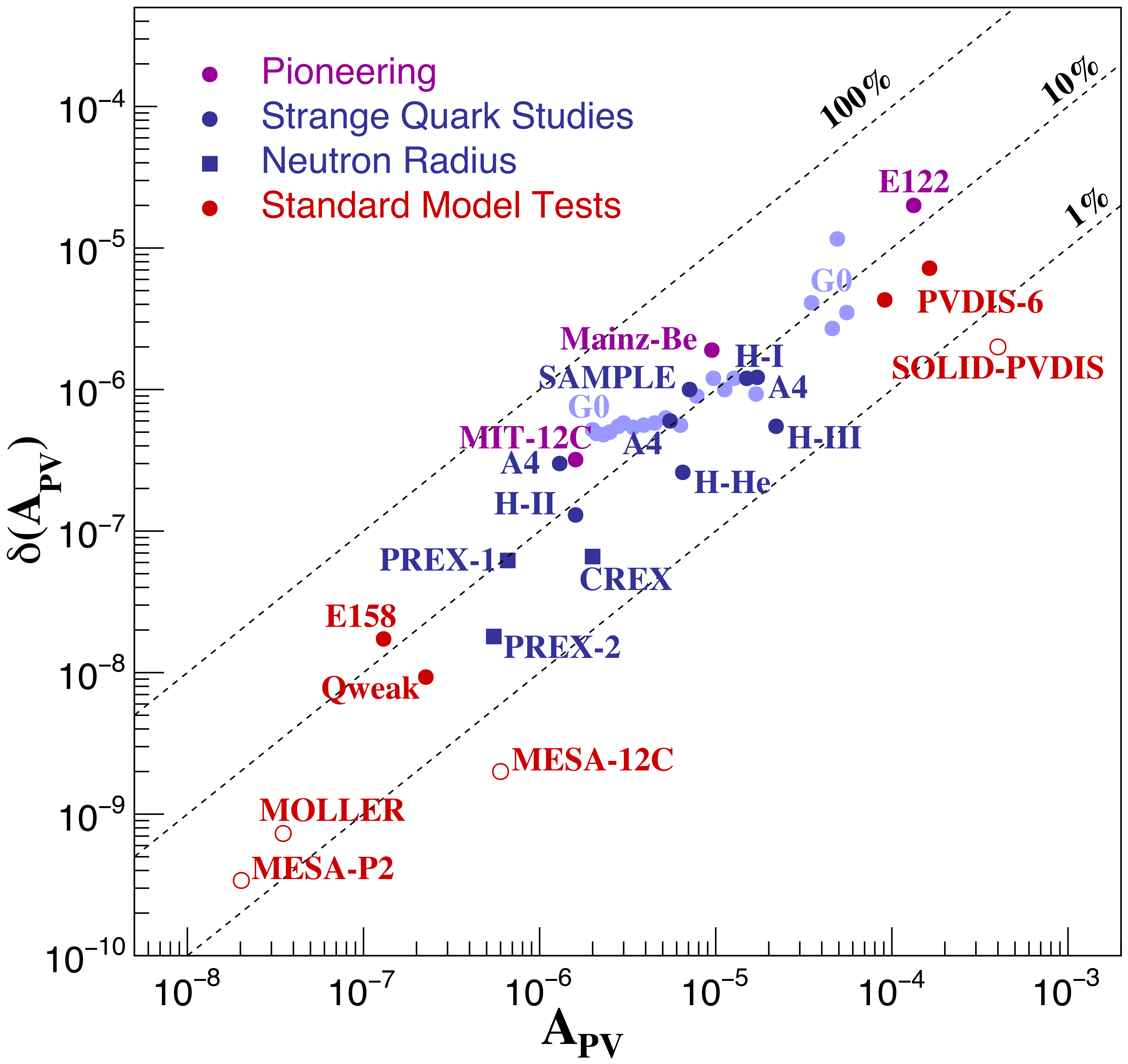
Includes experience from E158, PREX, Qweak, PVDIS, HAPPEX, G-Zero

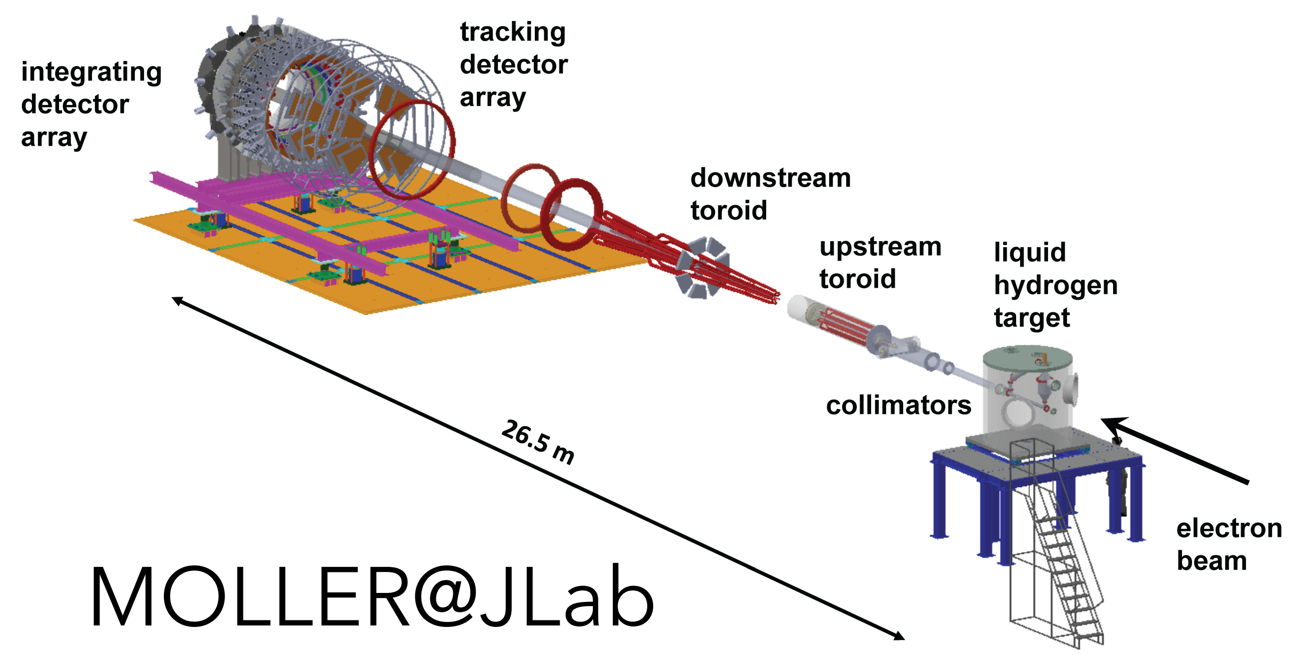


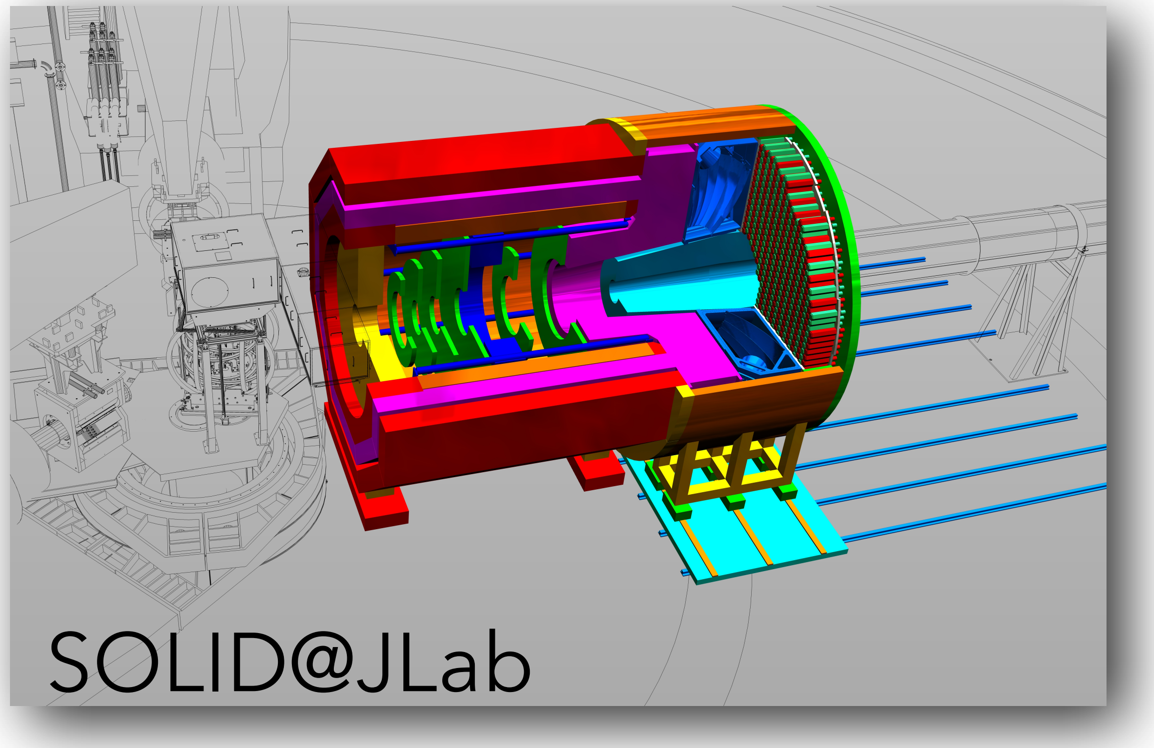


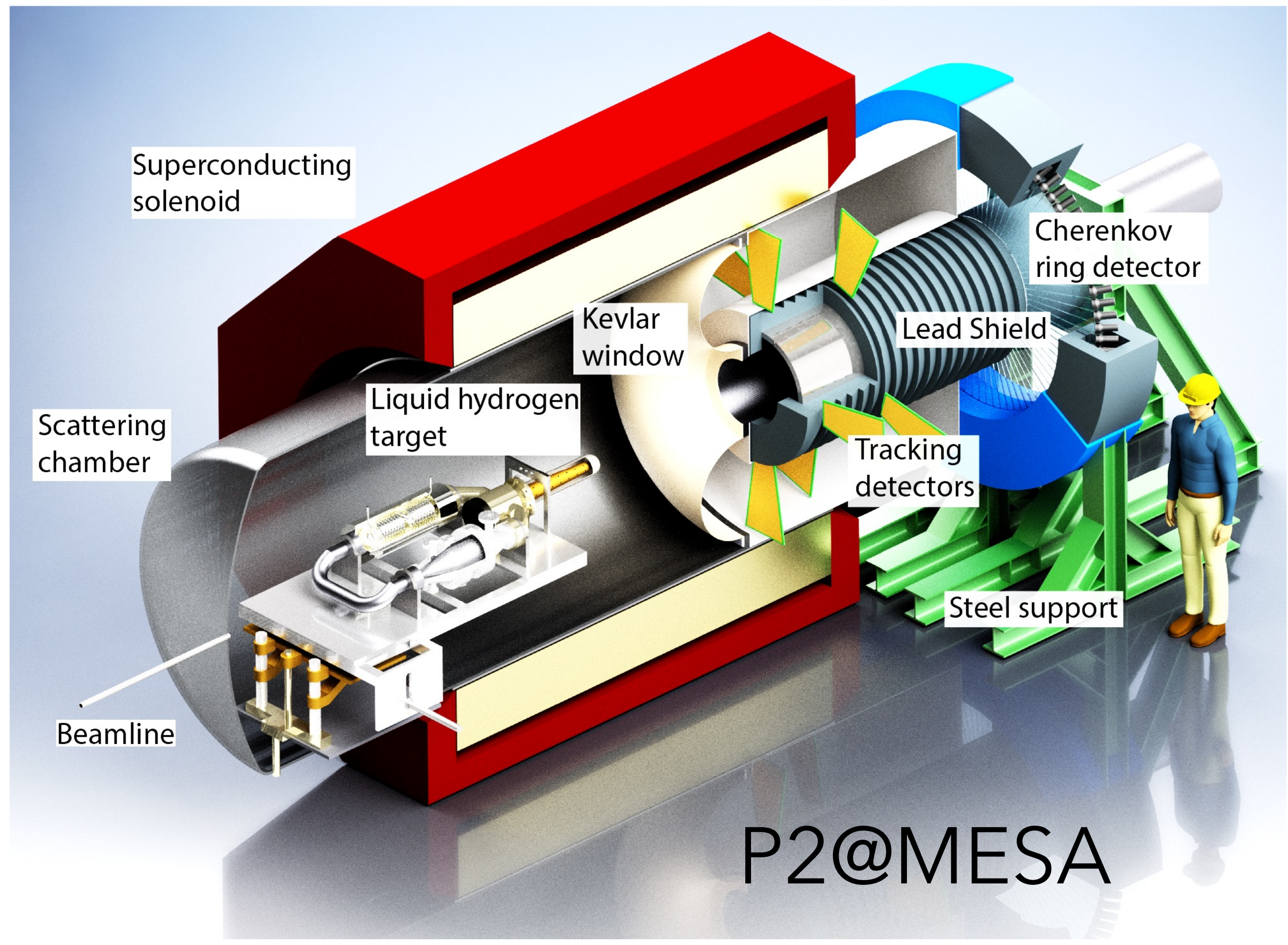
- Will be ready for assembly mid-2025
- Ready for physics in fall 2026
- With an on-time start, you should expect the first physics publication in mid-2027

Next-generation Experiments will provide precise BSM probes









	A_{PV}	$\delta(A_{PV})$	$\delta(A_{PV})/A_{PV}$
SoLID	500 ppm	3 ppm	0.6%
MOLLER	35 ppb	0.8 ppb	2.2%
P2	20 ppb	0.4 ppb	2.0%

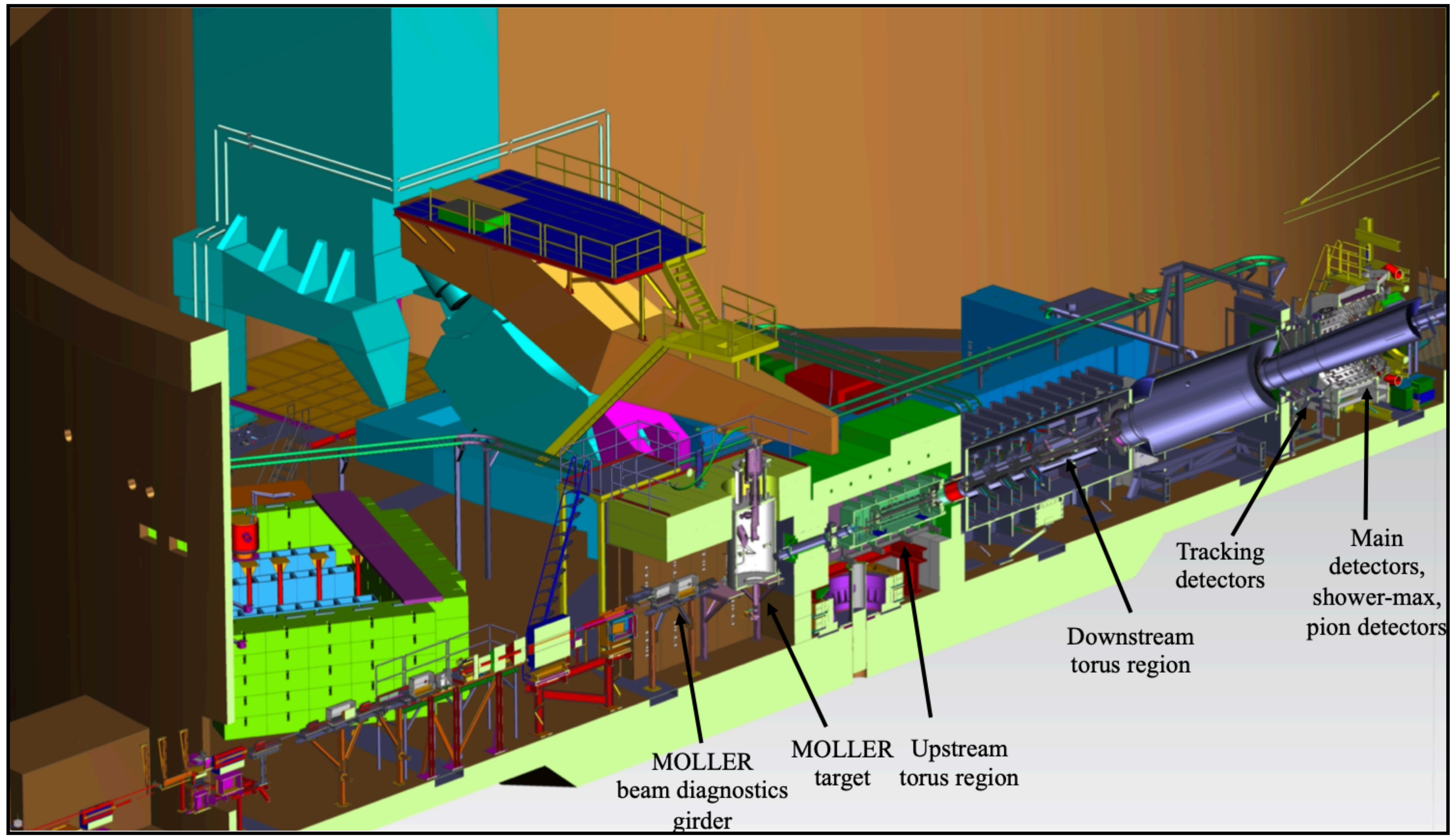
MOLLER	ee	electron vector weak charge
P2	ep	proton vector weak charge
SoLID	eDIS	quark axial weak charge

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 next year with a path to begin running in 2026



Appendix

MOLLER parameters

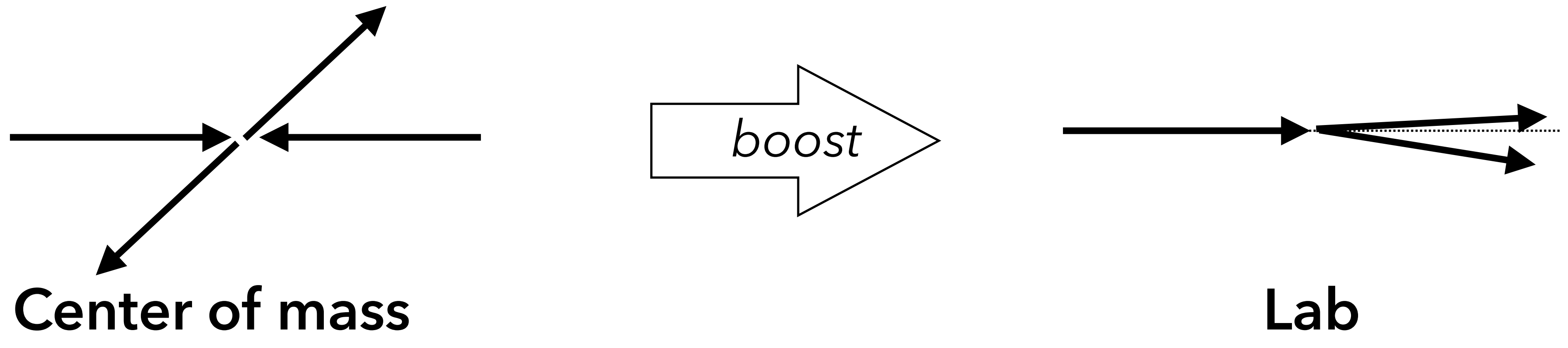
Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
$\theta_{\rm CM}$	$50°$-$130°$
$\theta_{\rm lab}$	$0.26°$-$1.2°$
$\langle Q^2 \rangle$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$2.4 \cdot 10^{39}$
σ [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
$P_{\rm B}$	$\approx 90\%$
$\langle A_{PV} \rangle$ [ppb]	≈ 32
$\Delta A_{stat}/\langle A_{expt} \rangle$	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.00023

from MOLLER TDR

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**

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

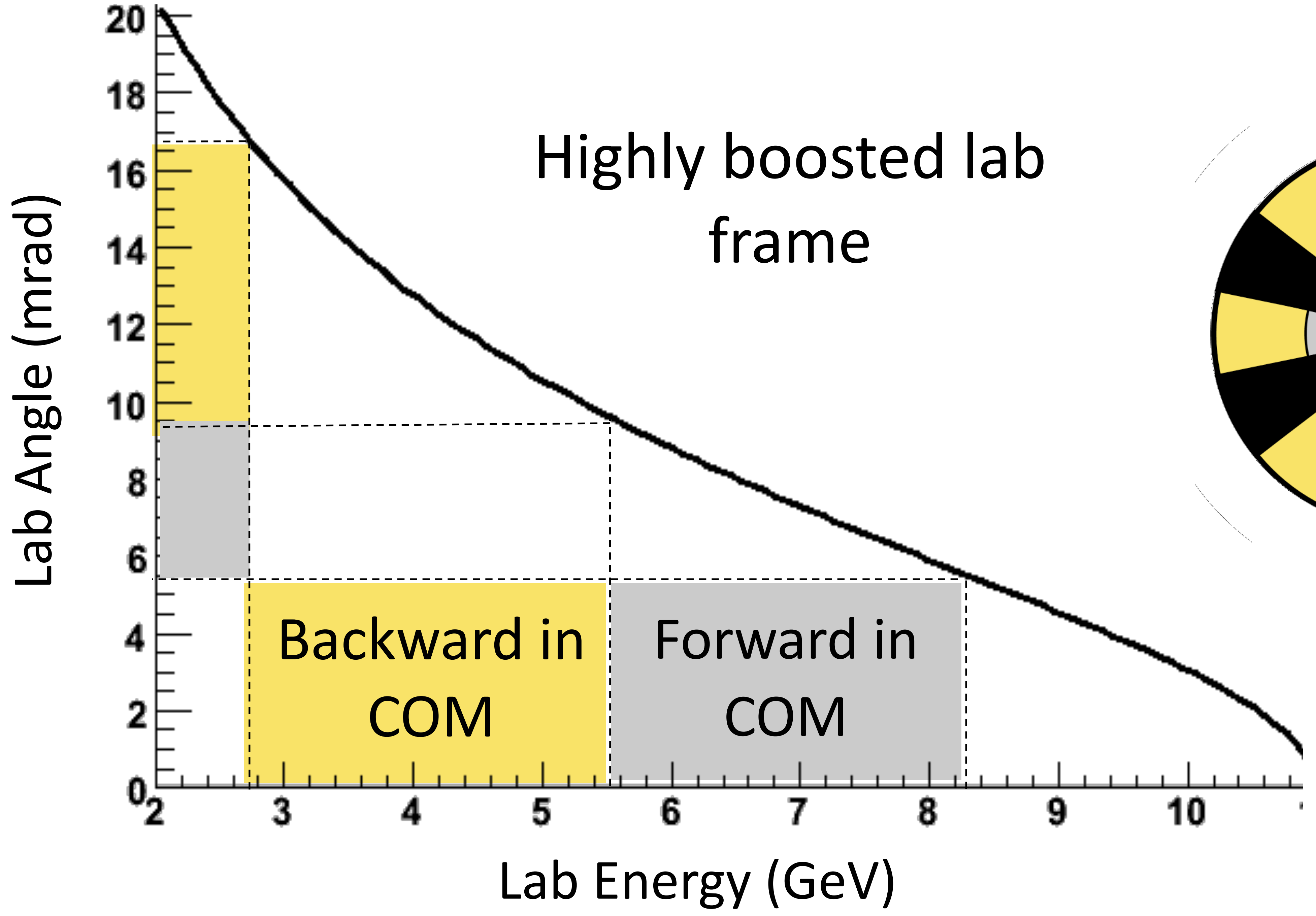
Figure of Merit and Design for Precision



Identical particles, so same to measure either forward or backward scattering.

Figure of merit highest at θ_{CM} = 90°

Optimum Acceptance [90°,120°]



How do you maximize the azimuthal acceptance of the spectrometer?

Idea: 50% Azimuth, 100% Acceptance

Identical particles - you only need one of the two for flux integration

Odd number of octants. Accept CM[60°,120°] so you always get one of the two electrons from each Møller scattering event

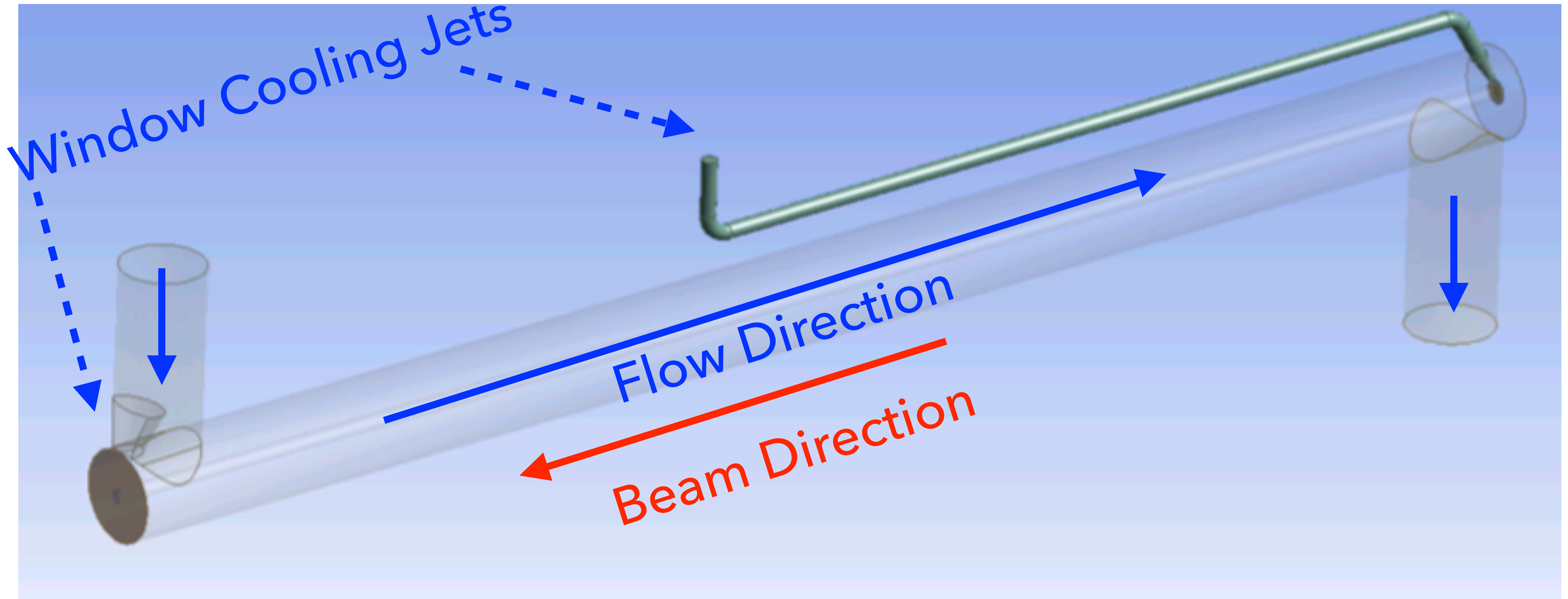
Requires polar-angle acceptance with broad range and very forward angles

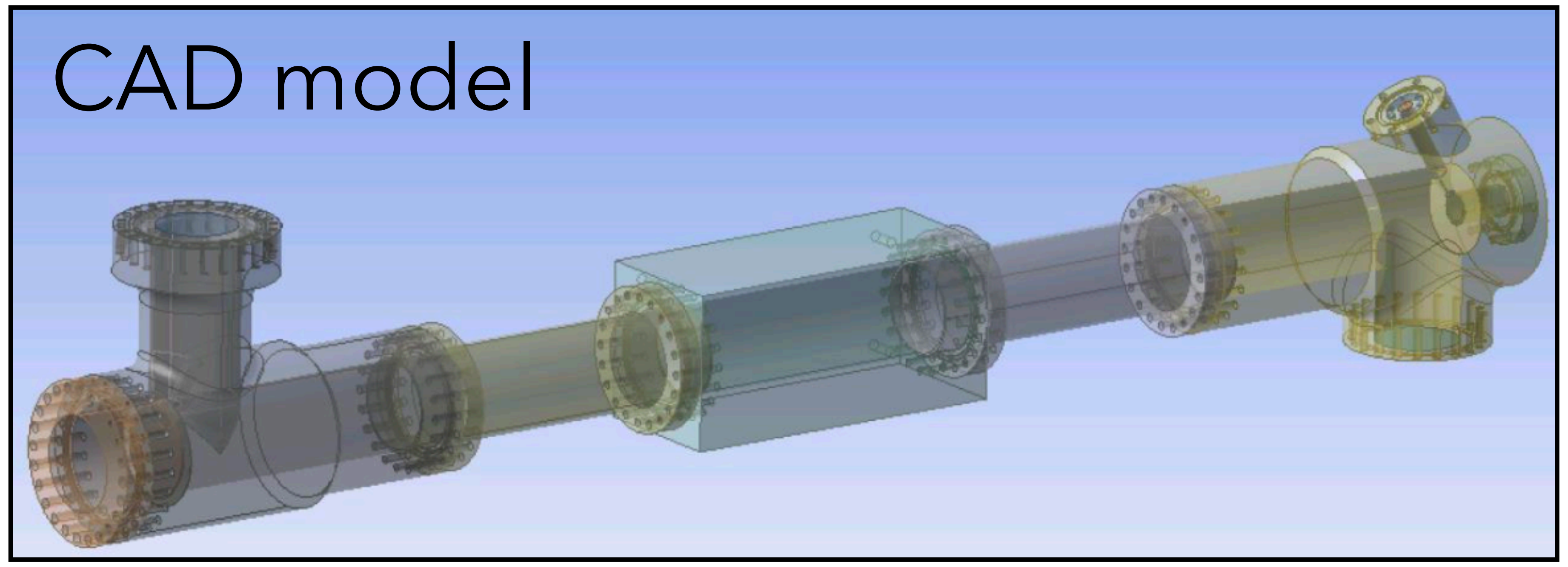
- E' = 2.5-8.5 GeV
- θ_{lab} = 0.3° - 1.1°

but provides 100% of the azimuth while leaving ample space for the magnetic elements and supports

Target

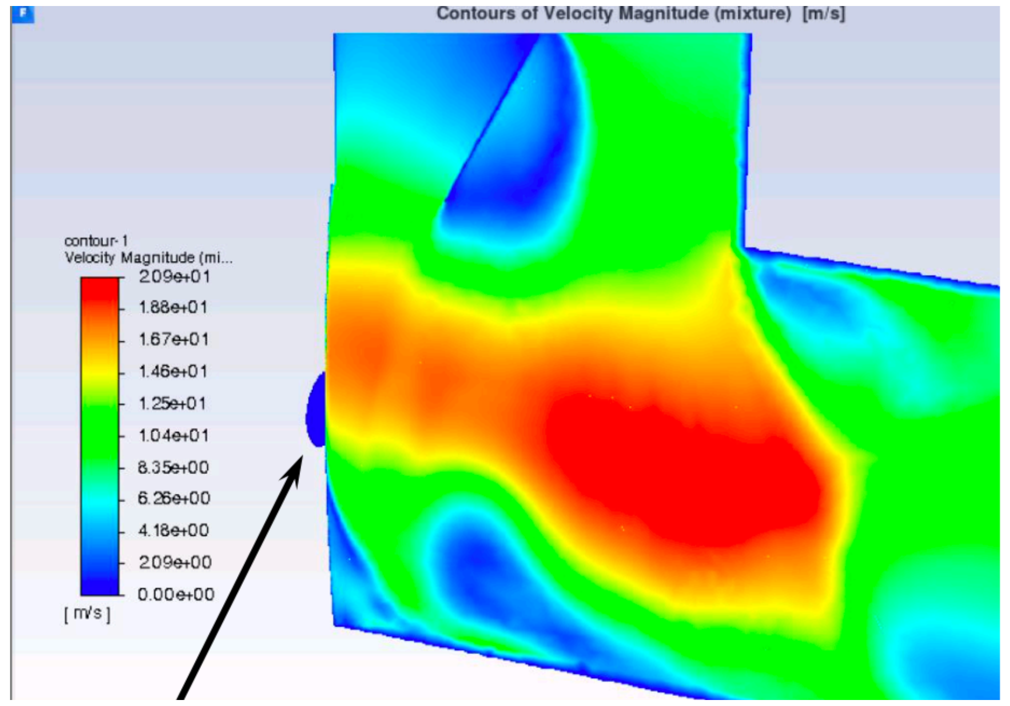
- 125 cm long LH2
- 3300W/4500W beam/total power
- 3.7K subcooled
- 25 l/s flow
- dρ/ρ<30 ppm at 960 Hz



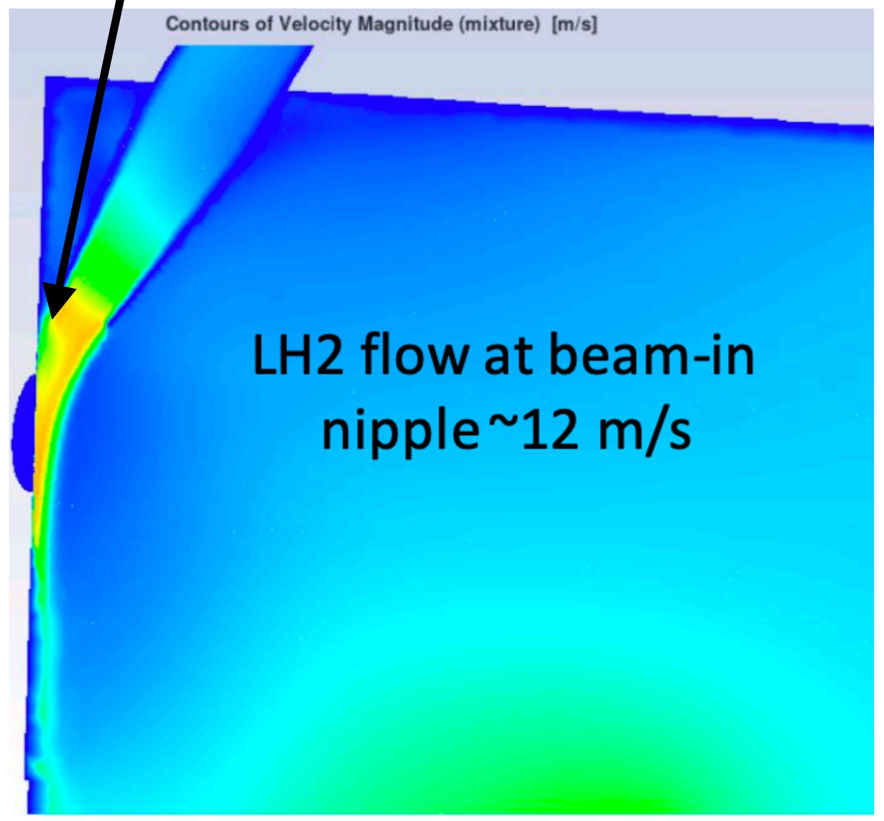


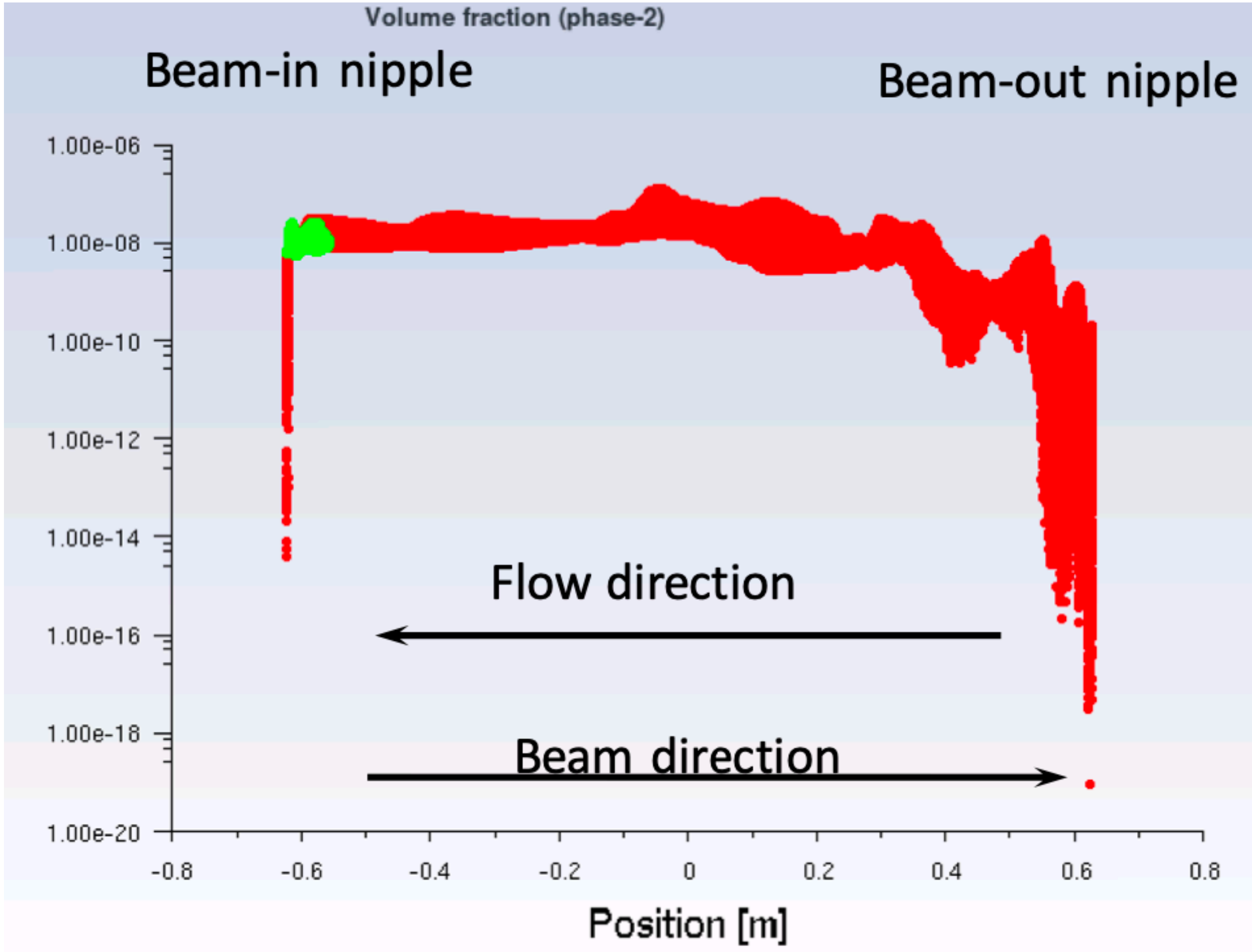
Designed using CFD modeling

Benchmarked on previous croytargets, including previous highest power target: Qweak at 2500 W total



Cooling jets create high flow velocity on windows





phase change $<10^{-7}$

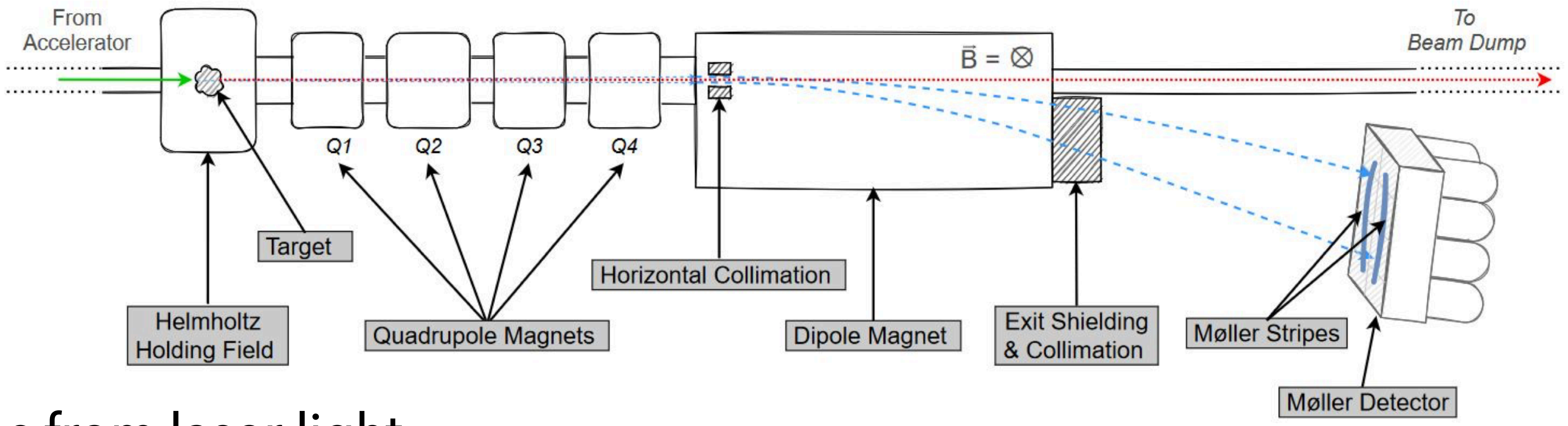
CFD calculates density noise pair width ~2ppm at 960Hz

Polarimetry

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

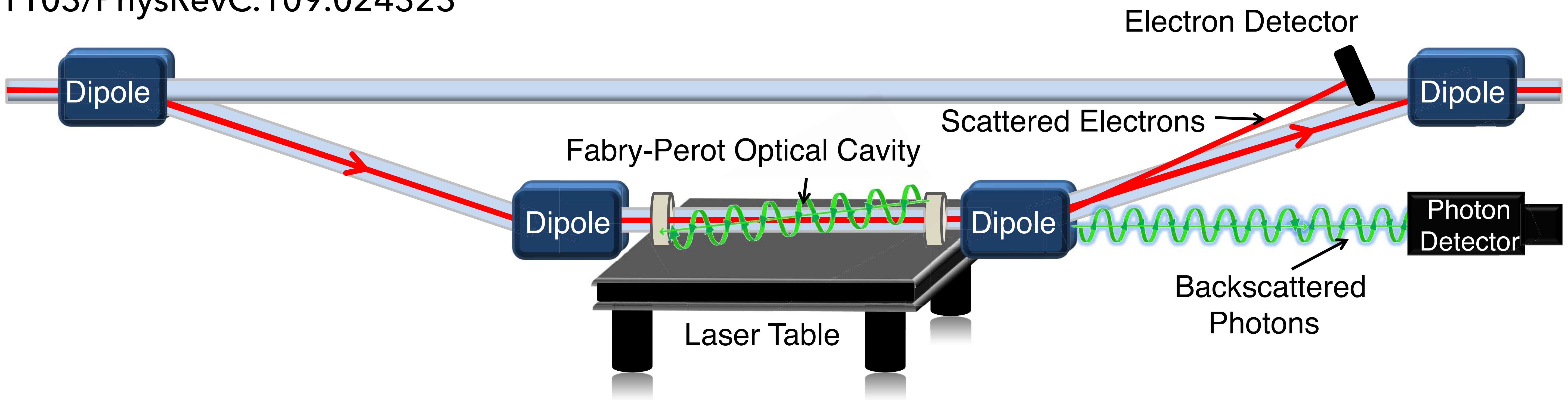
Møller Polarimeter

- "high field" iron target - well-known magnetization at saturation
- Coincidence of identical particles - low background
- QQQQD spectrometer



Compton

- 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

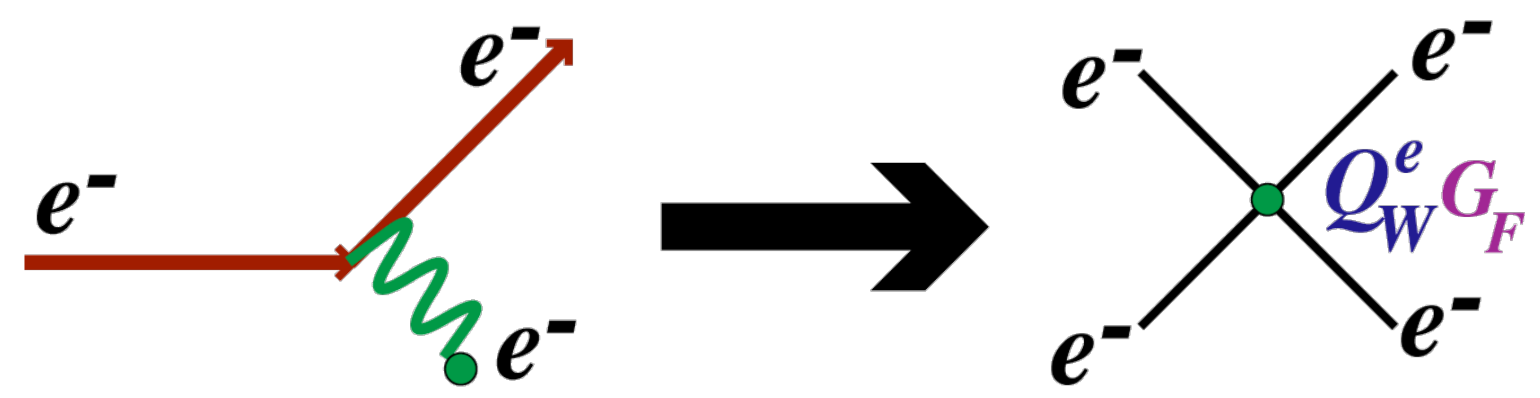


Both systems have important upgrades underway (detectors, target, DAQ, analysis, and simulation studies). The Møller polarimeter is closer to ready for high precision at 11 GeV, with smaller and less crucial upgrades.

SLAC-E158: Weak charge of the electron

1997-2004

Møller (ee) scattering



+ new

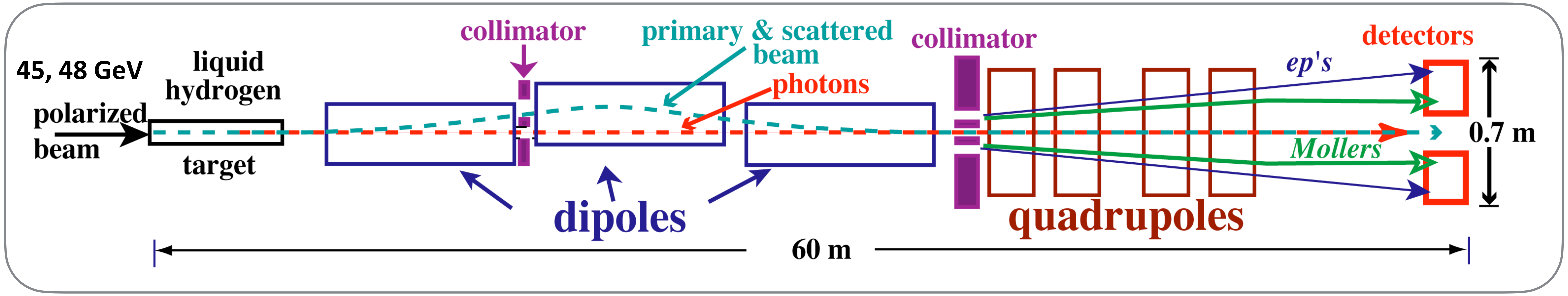
$$Q_W = 1 - 4\sin^2\theta_W$$

SM highly suppressed, so even a weakly-coupled or heavy new physics scenario can stand out

High-power (1kW) LH_2 target, 18% radiator

Dipole chicane + quadrupole spectrometer
45, 48 GeV, 4-7 mrad scattering angle

High beam polarization and current



First Measurement of the electron-electron weak interaction

A_{PV} = (-131 ± 14 ± 10) ppb

$$\frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

LEP200

$$\Lambda^{ee}_{VV} \sim 17.7\ \text{TeV}$$

E158 Reach

$$\Lambda^{ee}_{RR-LL} \sim 17\ \text{TeV}$$