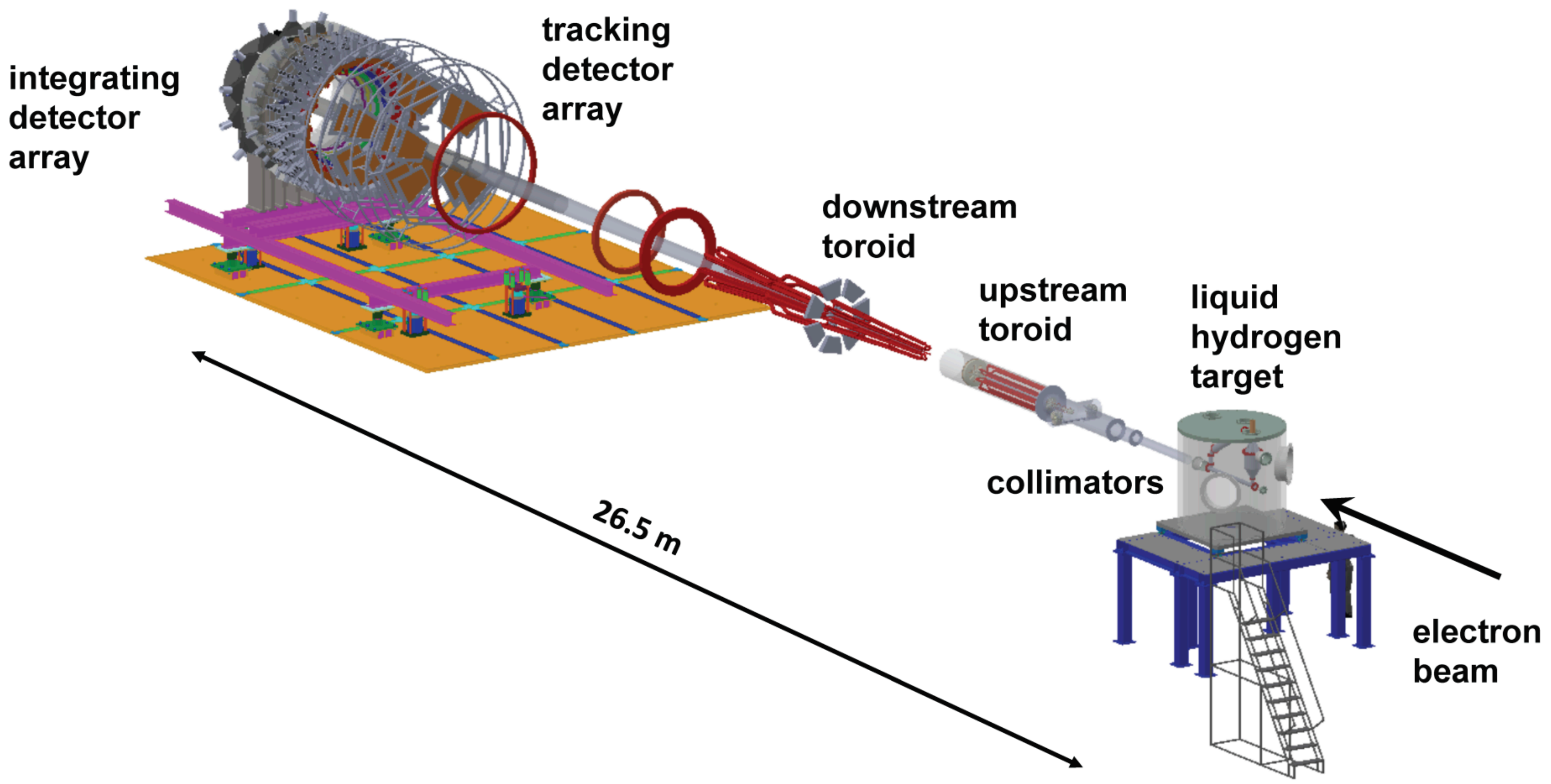
The MOLLER Experiment

Measurement of a Lepton-Lepton Electroweak Reaction

An Ultra-precise measurement of the weak mixing angle using Møller Scattering



Vassu Doomra (on behalf of the MOLLER Collaboration)

2025 Summer Hall A/C Collaboration Meeting
June 18, 2025

Jefferson Lab

Stony Brook University

Center for Frontiers in Nuclear Science

Outline

- Introduction
- Previous Weak Mixing Angle Measurements
- MOLLER Impact
- Detector Equipment

  - Target
  - Primary Acceptance Collimator
  - Spectrometer
  - Tracking Detectors
  - Main Integrating Detector
  - Auxiliary Detectors

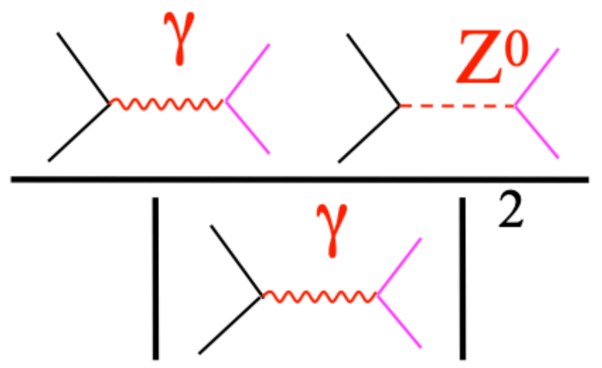
Parity Violating Asymmetry (A_{PV}) in Møller Scattering

- Measure A_{PV} in the scattering of longitudinal polarized electrons off unpolarized electrons:

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

Interference between electromagnetic and weak neutral current amplitudes

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

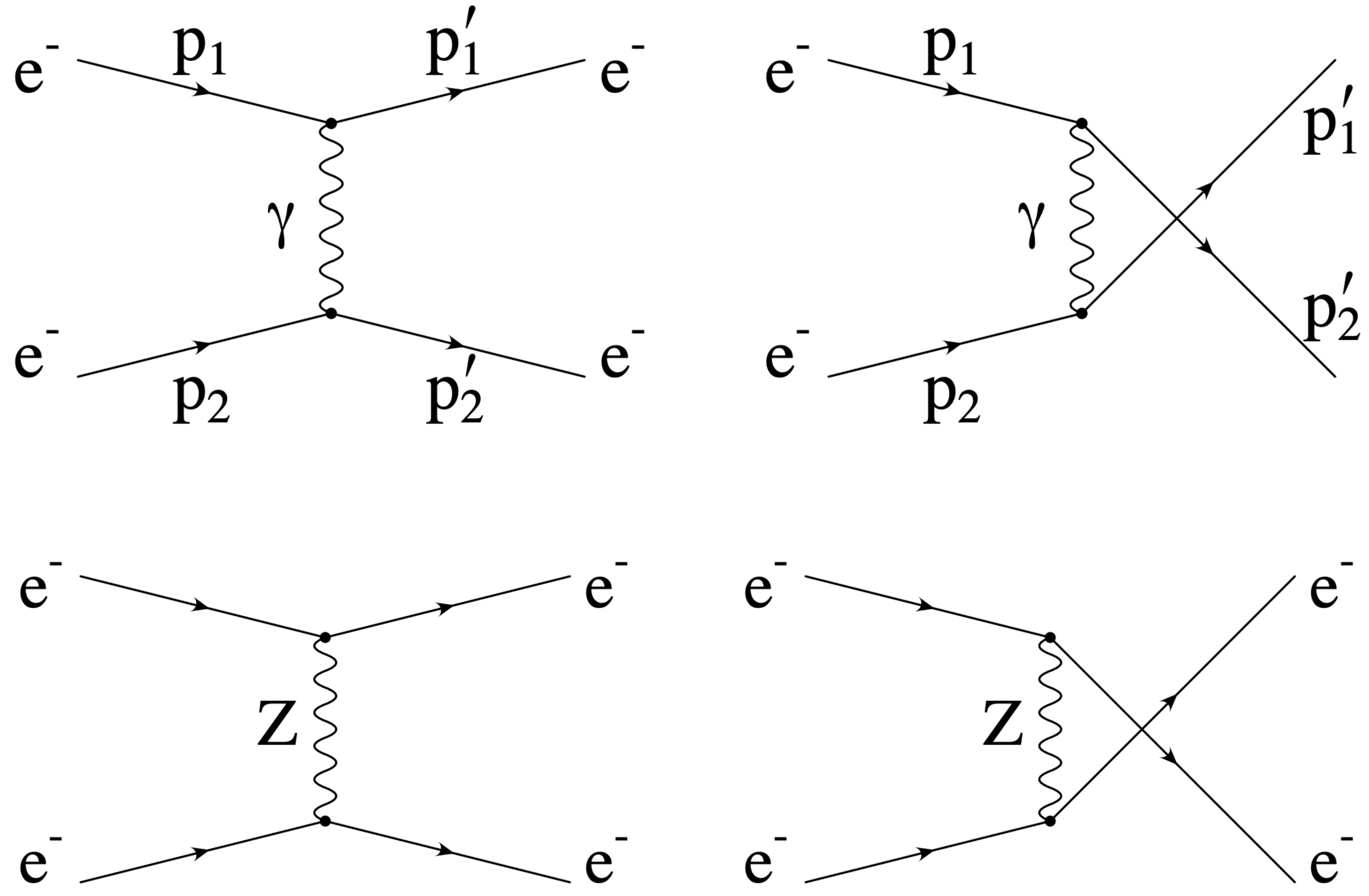


$$= mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4sin^2\theta_{COM}}{(3 + cos^2\theta_{COM})^2} Q_W^e$$

Derman and Marciano (1978)

Weak charge of electron $\boxed{Q_W^e} = 1 - 4sin^2 \boxed{\theta_W}$ Weak Mixing Angle

Predicted $A_{PV} \sim 33$ ppb



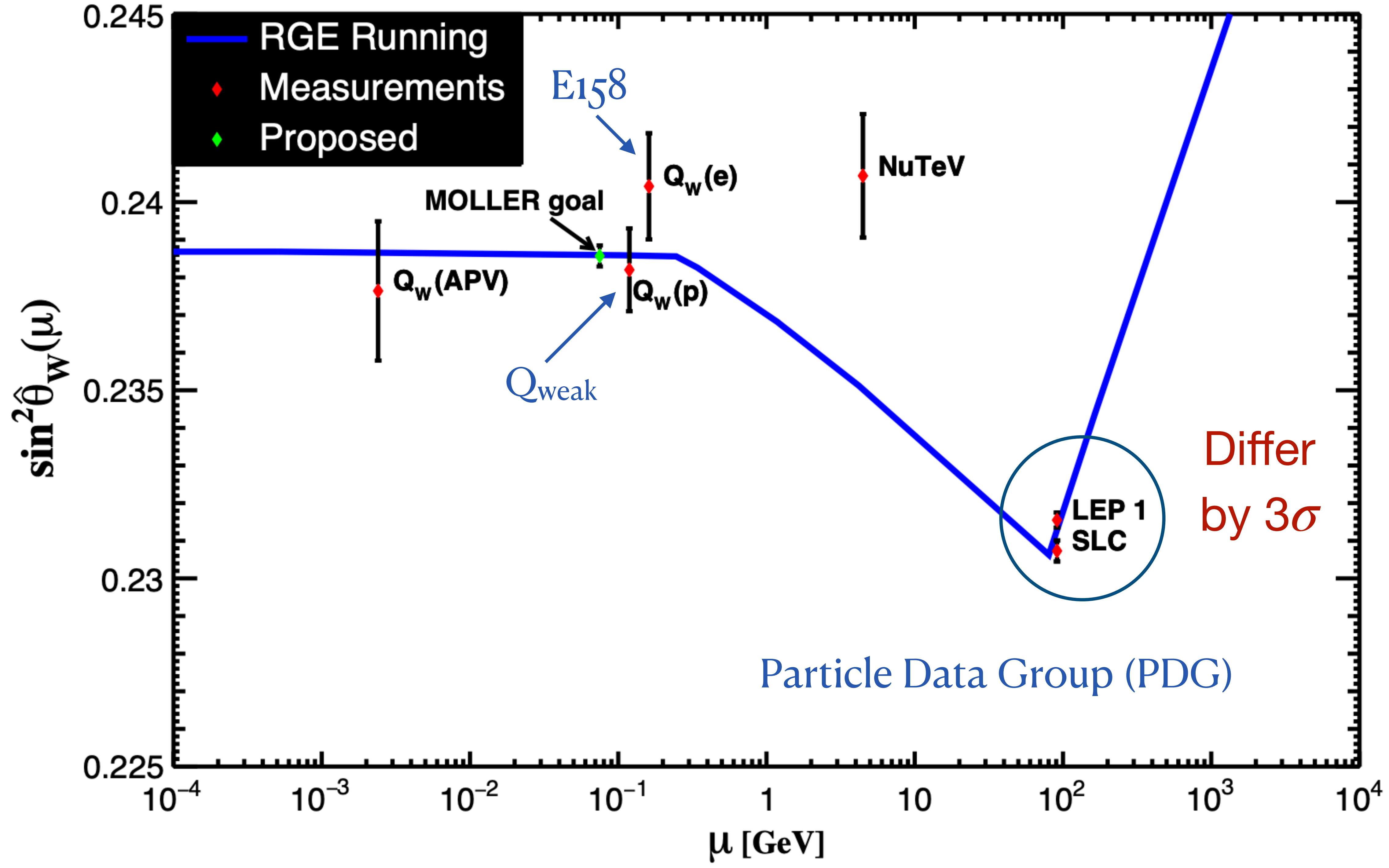
Tree Level Feynman diagrams for Møller scattering

The aim is to measure Q_W^e to an overall fractional accuracy of 2.3%.

Previous Weak Mixing Angle Measurements

Low Energy Measurements

- ✦ **APV: Atomic Parity Violation ^{133}Cs (1997)**
- ✦ **PV Moller Scattering**
  - SLAC E158 (2002 - 2003) limited statistics
  - Next generation: MOLLER (factor of 5 better)
- ✦ **PV Elastic e-p scattering: Q_{weak} (JLab 2018)**
- ✦ **Neutrino Deep Inelastic Scattering: NuTeV (FermiLab 1999)**



Measurements near Z^0 Pole

- ✦ **SLC at SLAC (1994-95) and LEP at CERN (1992): e^+e^- colliders**
  - High precision measurements

MOLLER A_{PV} would be the first low Q^2 measurement comparable to the high-precision measurements near Z-pole.

High Experimental Impact

- Search for new physics by looking for deviations from Standard Model predictions.

- Very precise experimental goal and the low energy scale of the reaction results in a remarkable sensitivity to probe TeV-scale dynamics.

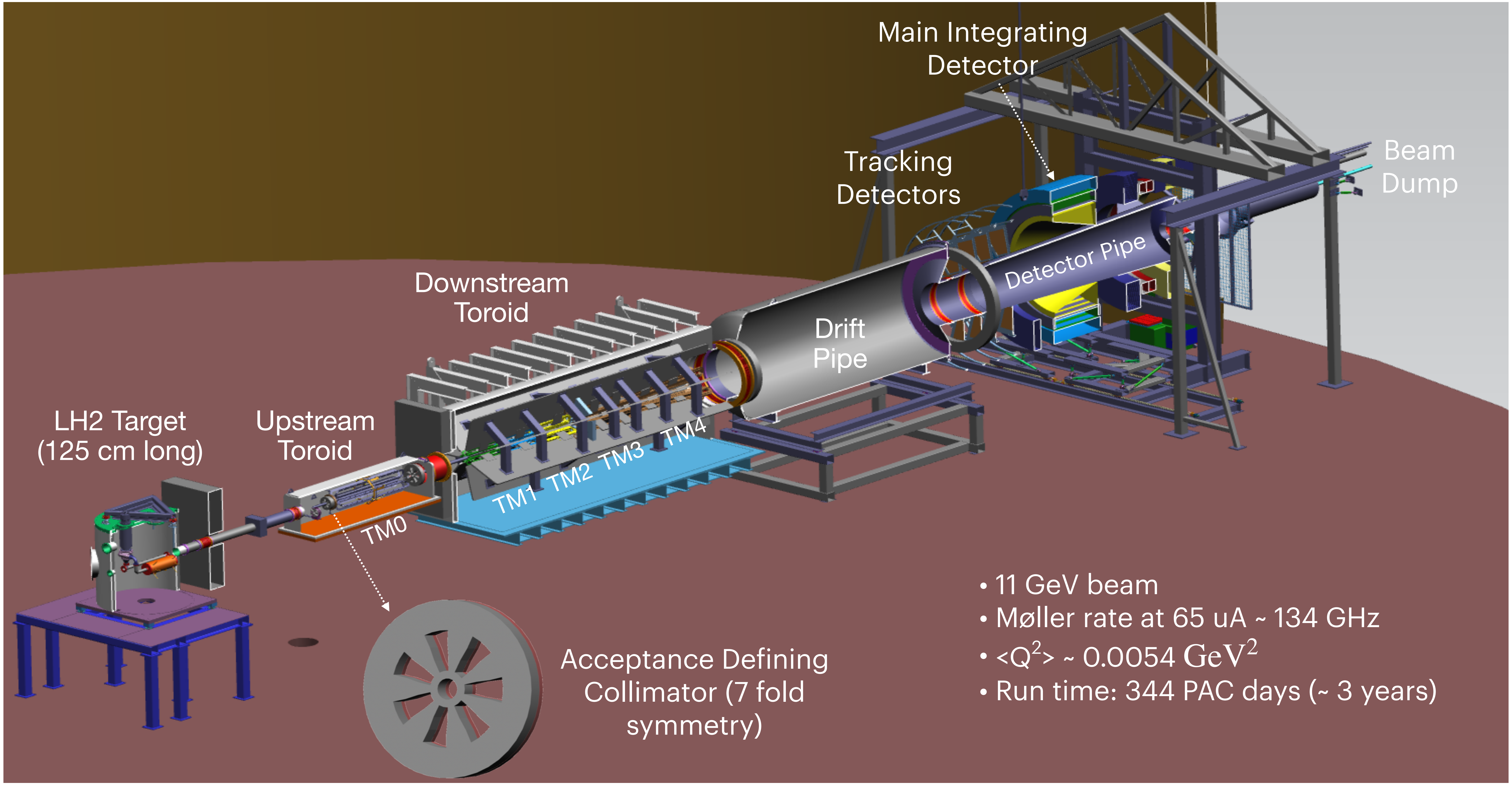
$$\delta(A_{PV}) \sim 0.8\, ppb \rightarrow \delta(Q_W^e) = \pm 2.1\,\text{(stat.)} \pm 1.0\,\text{(syst.)}\,\%$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}} \approx \frac{246.22\ \text{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \text{TeV}$$

Best Contact Interaction reach for leptons at low OR high energy

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

The MOLLER Apparatus



- 11 GeV beam
- Møller rate at 65 uA ~ 134 GHz
- <Q^2> ~ 0.0054 GeV^2
- Run time: 344 PAC days (~ 3 years)

Modes of Data Taking

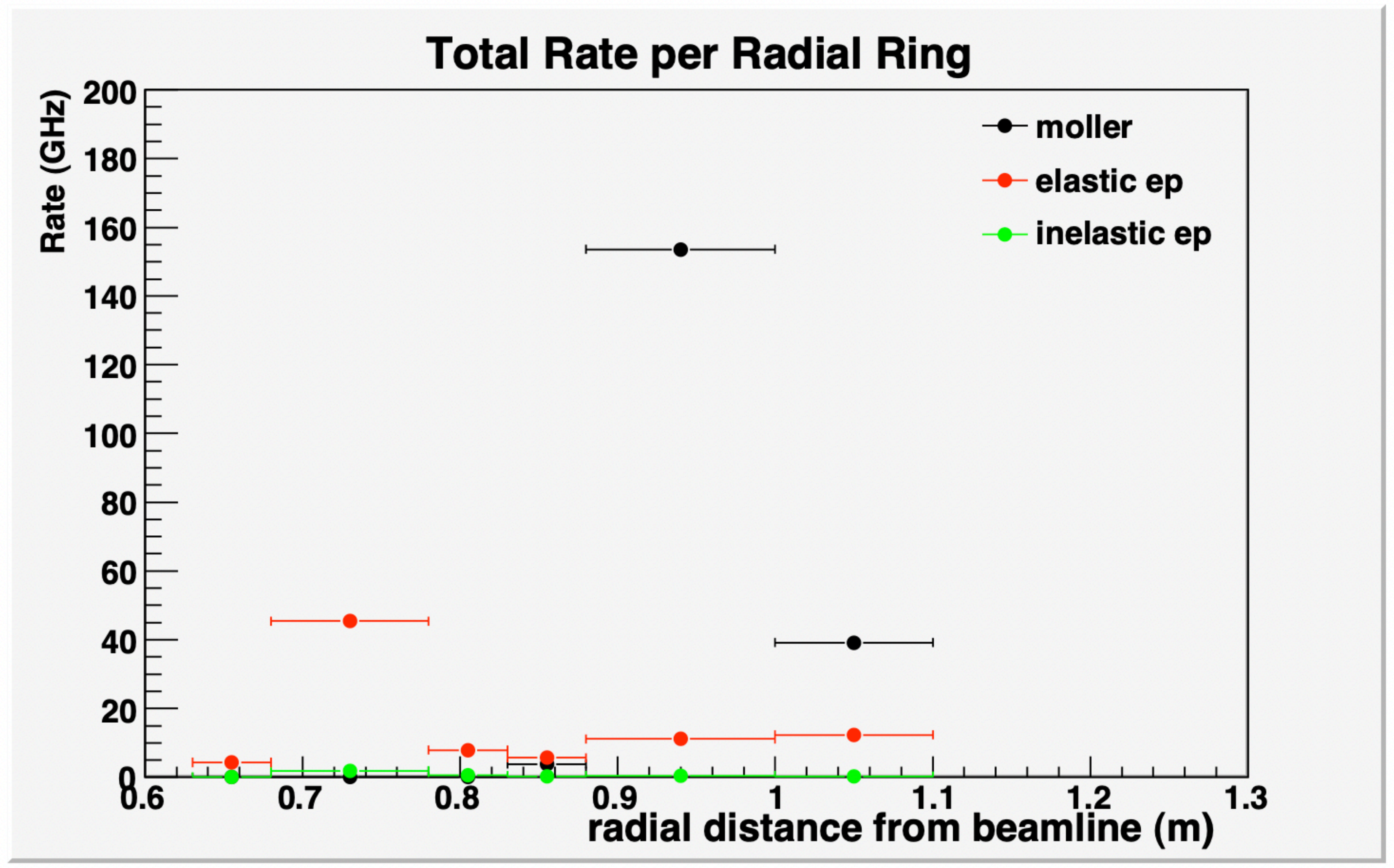
Counting Mode

- Low Beam current Calibration runs
  - Essential for Kinematic verification
  - Studying the response of Main Detector to scattered electron kinematics.
- Scattered electron rates sufficiently low to allow for individual electron counting.

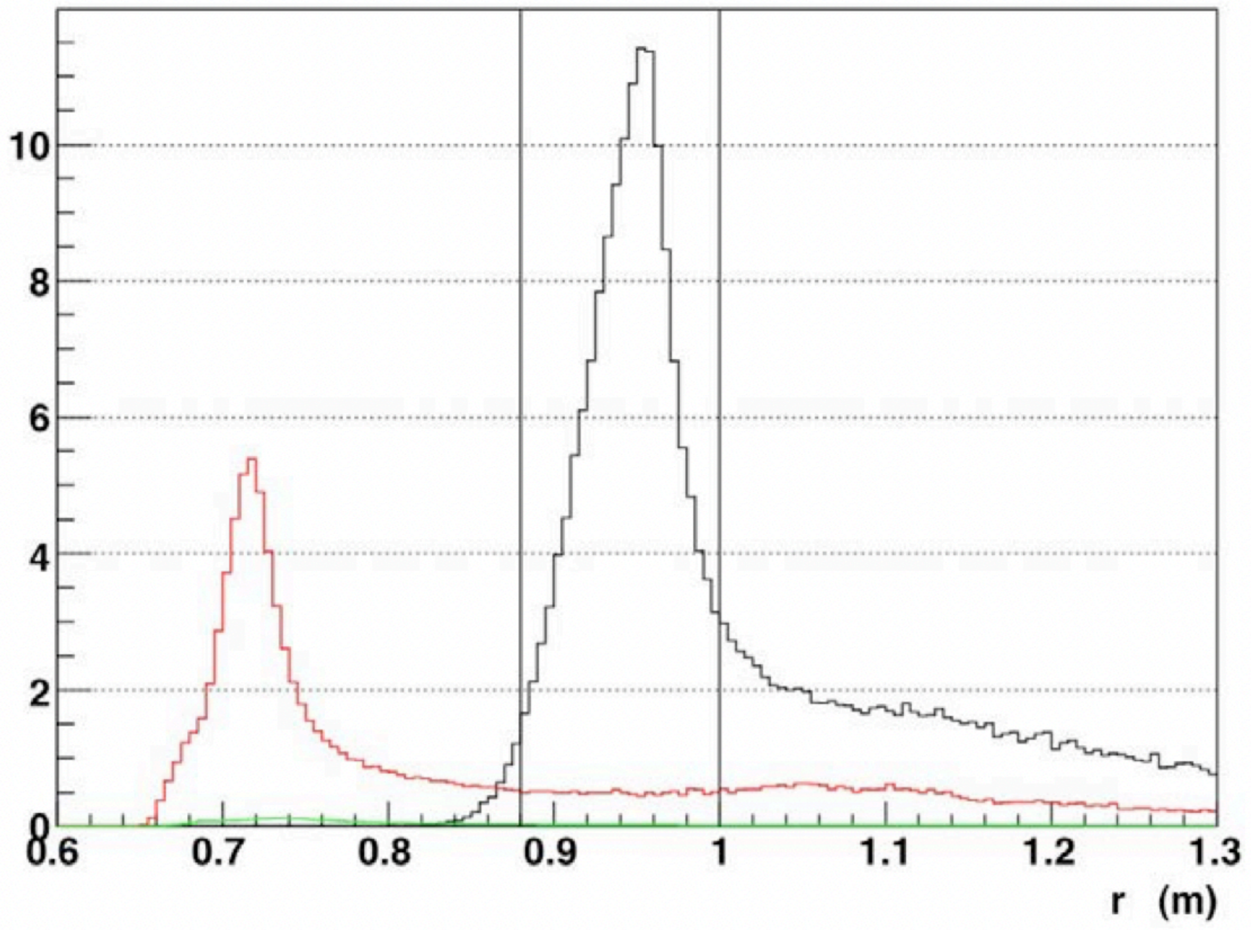
Integration Mode

- Operating at full beam current
  - Essential for Møller asymmetry measurement.
  - High electron rates in the Møller ring reaching up to 1 MHz/mm^2
  - Counting individual electrons not possible.

Tracking system will give a much finer grained view of radial event distributions at focal plane compared to main detectors – good for detailed check of background/optics expectations



What the main detectors "see"
(assuming perfect gain matching)



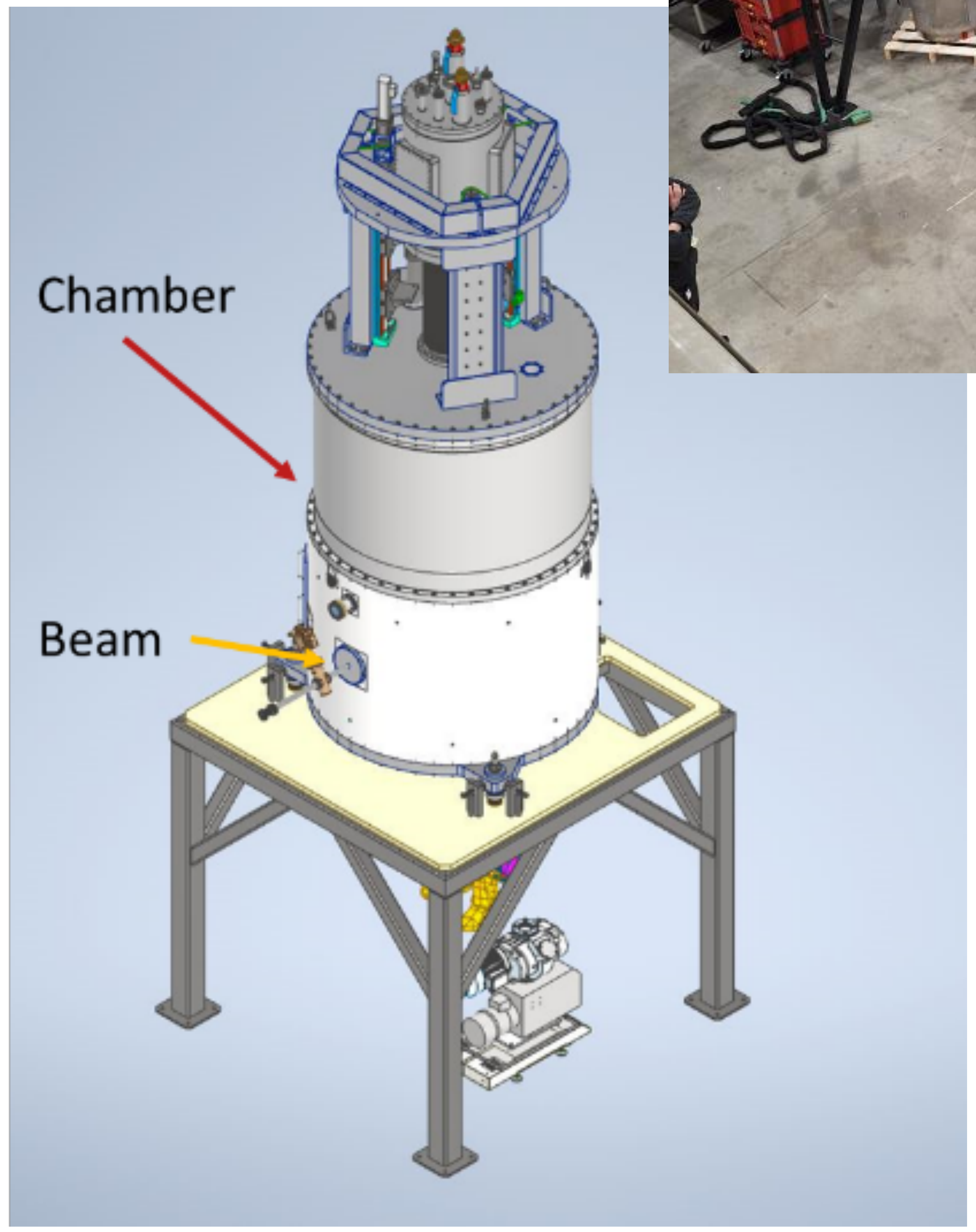
What a tracking system would see

LH_2 Target

- Largest LH2 target ever built!
- Irreducible backgrounds: Radiative e-p elastic and inelastic scatterings, relatively well understood
- Target designed using Computational Fluid Dynamic Simulations to meet the requirements.

Target		Beam	
Cell Length	125 cm	I_{max} , E	70 µA, 11 GeV
Cell Thickness	> 8.4 g/cm^2	Raster area	< 25
Al windows in beam	< 0.25 mm	Beam Spot	>100 µm
p, T (cold)	35 psia, 20 K	Helicity Flip Rate	1920 Hz
θ,φ Acceptance	5-20 mrad, 2π	Cell alignment tolerance	0.5 mm
LH2 pump flow	< 25 l/s		
Target Power	**4500 W**	Max Beam Power	**3200 W**

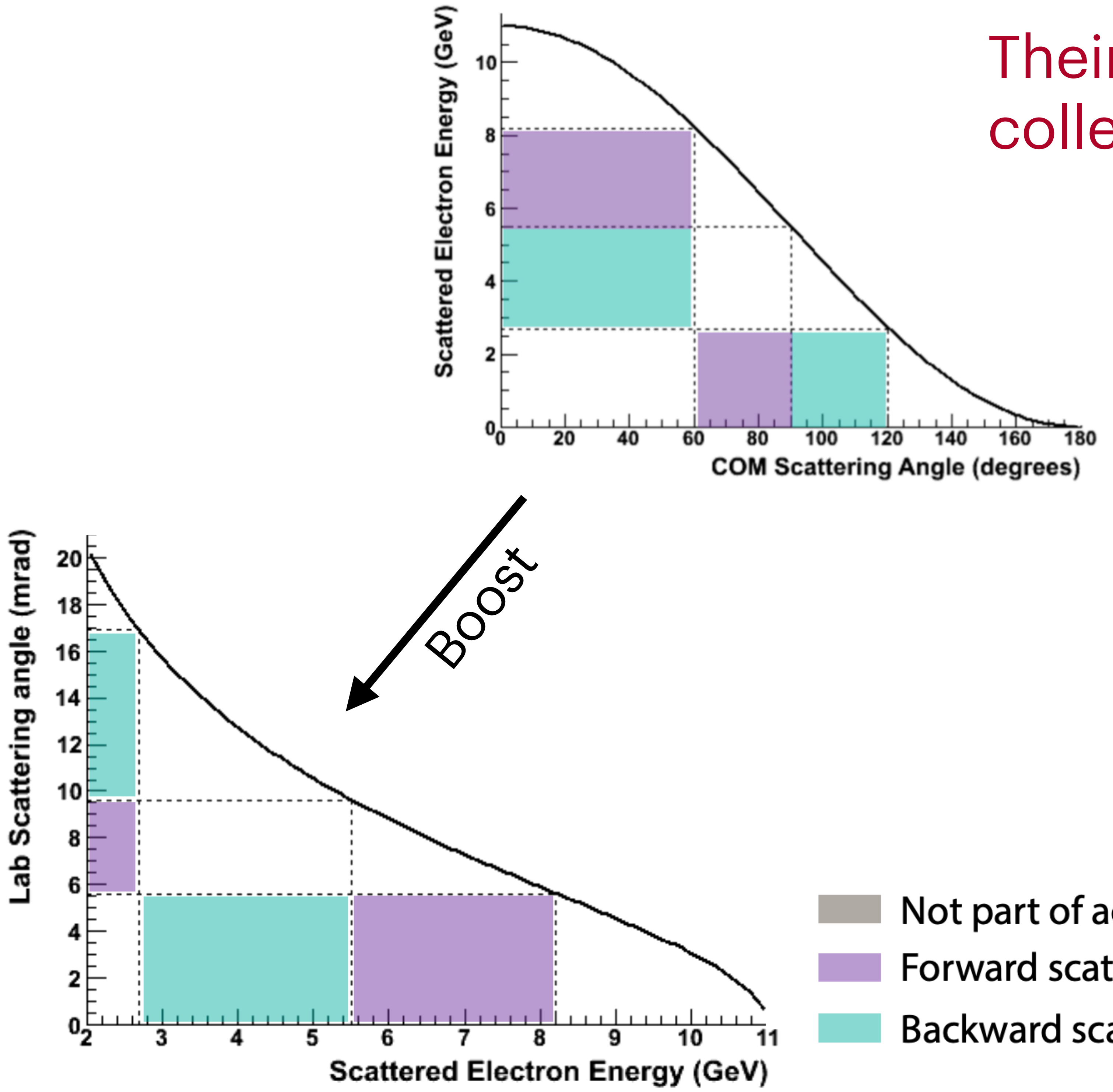
LH2 density reduction ***< 1% @ 70 µA***
LH2 density fluctuations ***δp/p < 30 ppm @ 960 Hz***
0.6x Qweak δp/p @ 1.5x beam power



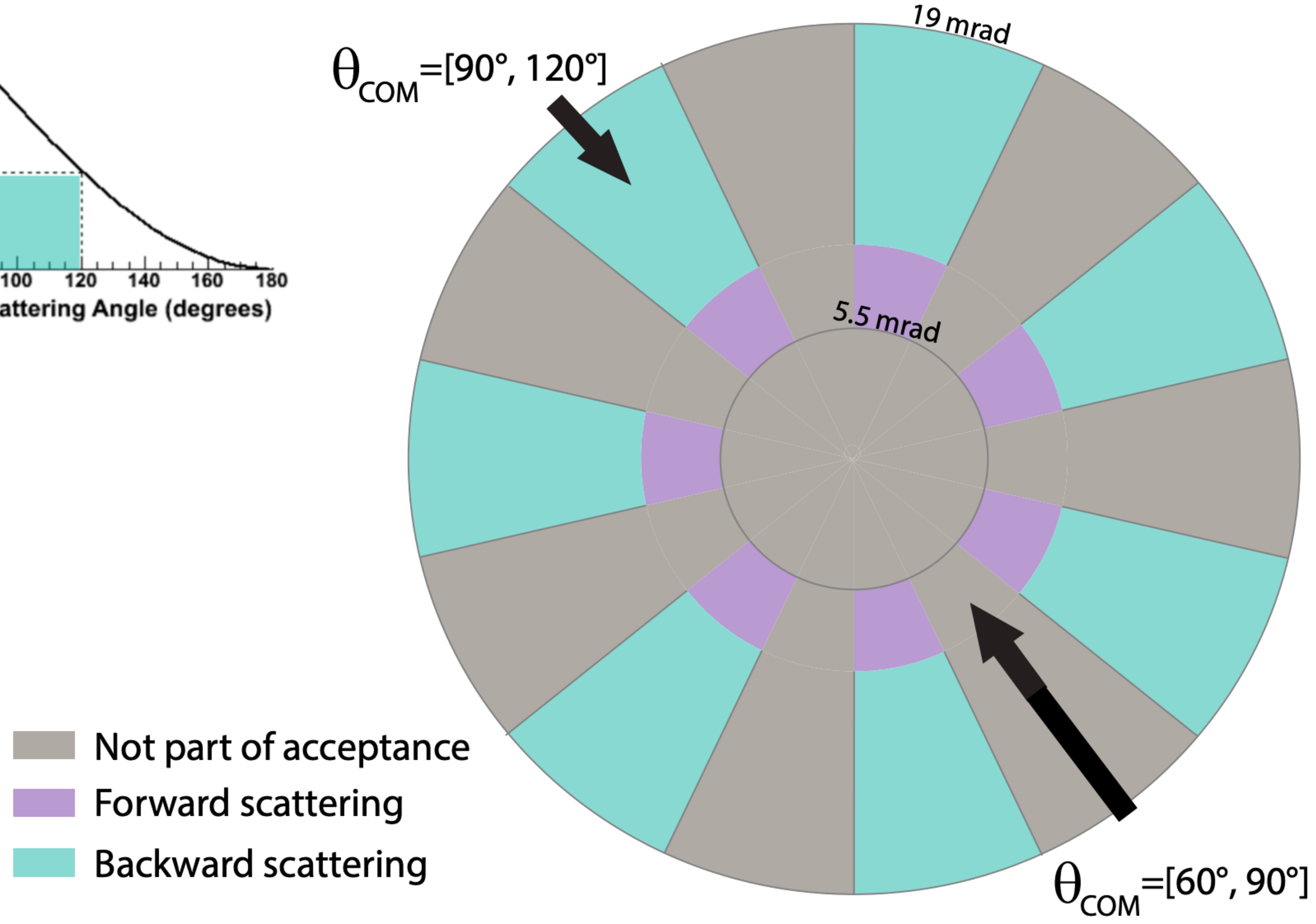
Precision Collimator System

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

- Utilizing the fact that Møller scattering is identical particle scattering.
- Accepting Møller scattered electrons around θ_{COM} = 90^0 where the asymmetry is at a maximum.
- The odd number of coils allow for 100% acceptance by always detecting one of the electrons involved in the scattering.



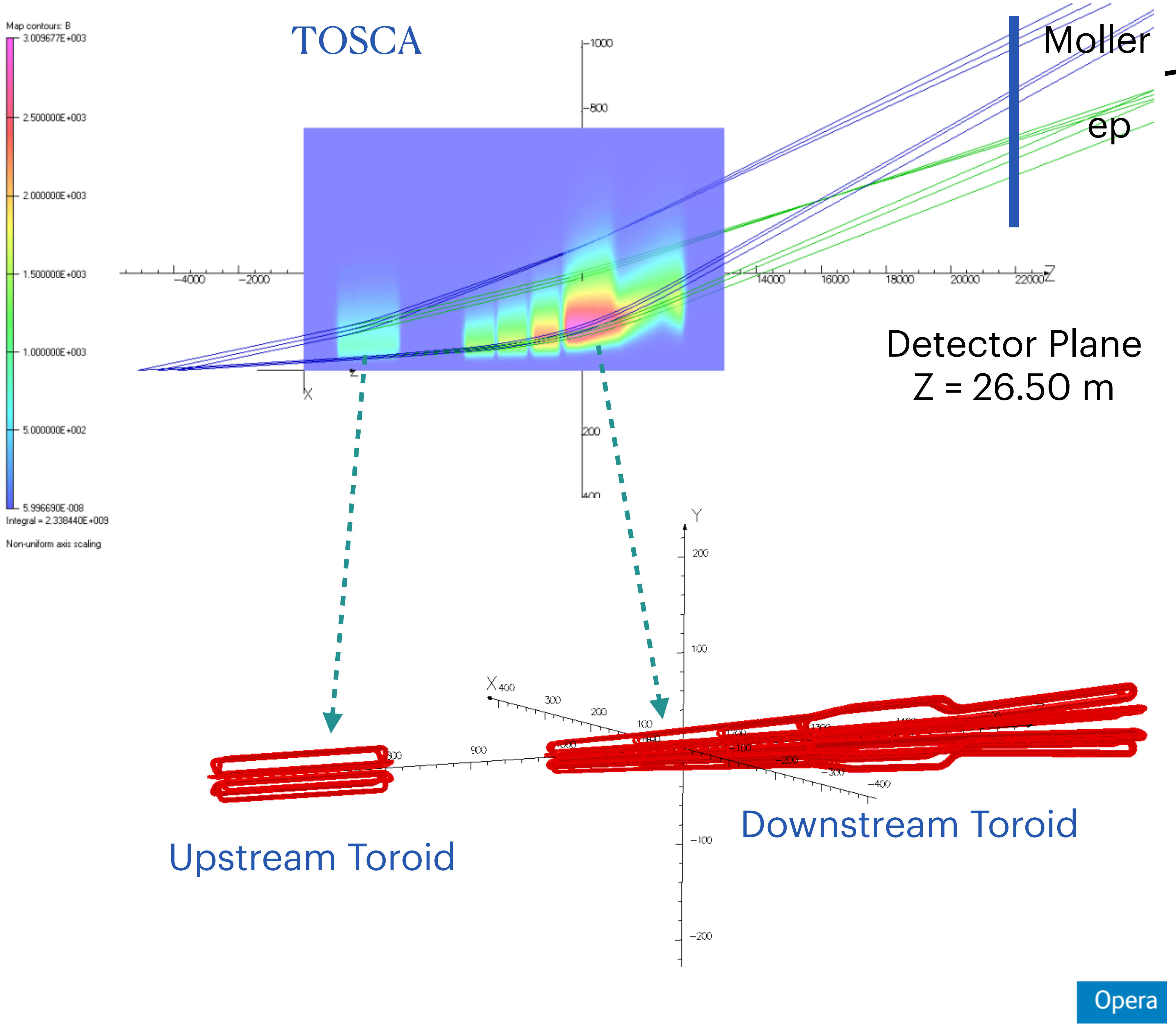
Their partners are collected over here...



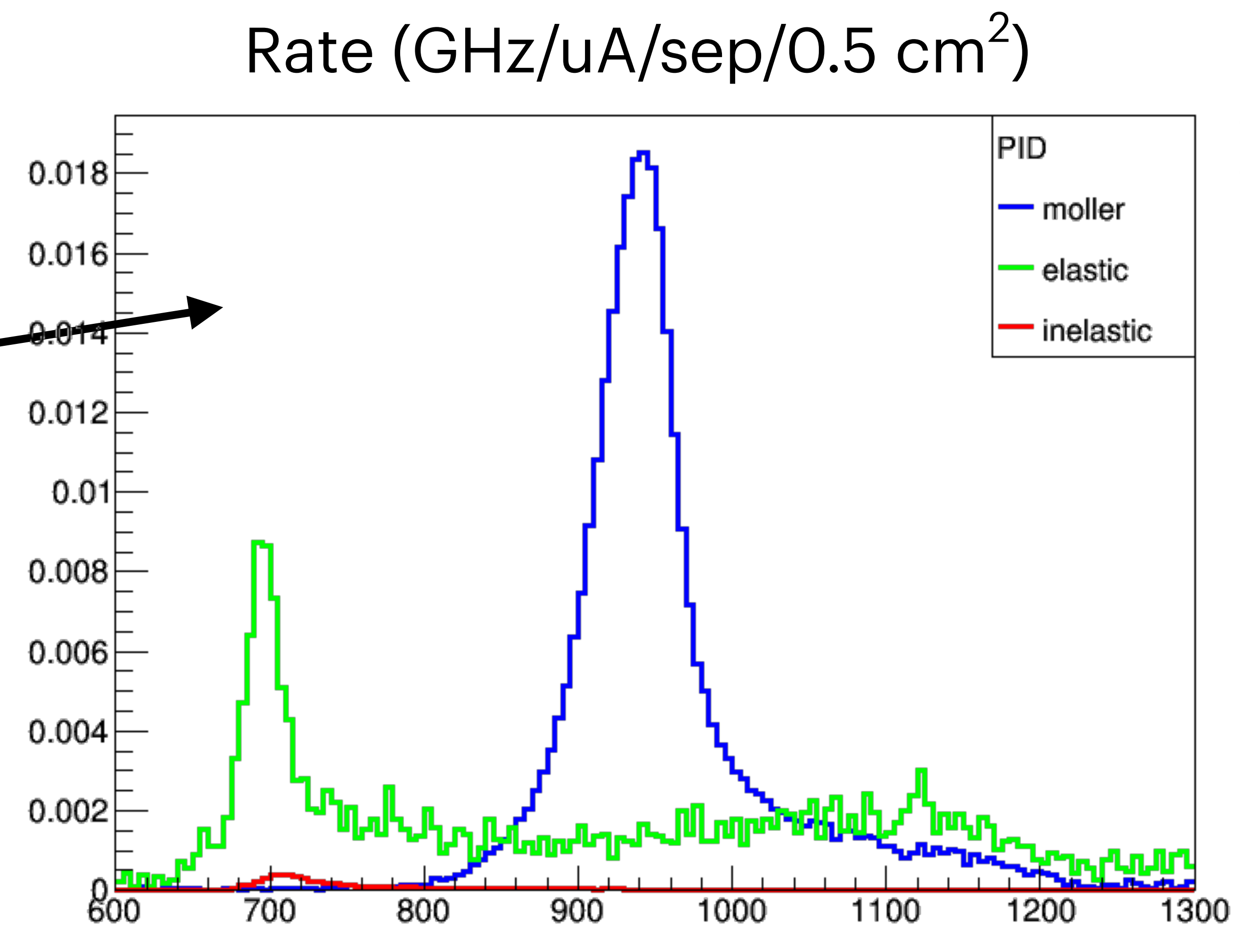
The rays that are blocked here...

- COM Angles : 60^0 - 120^0
- 11 GeV in; ~ 2 - 8 GeV out
- 50% azimuth, 100% acceptance!

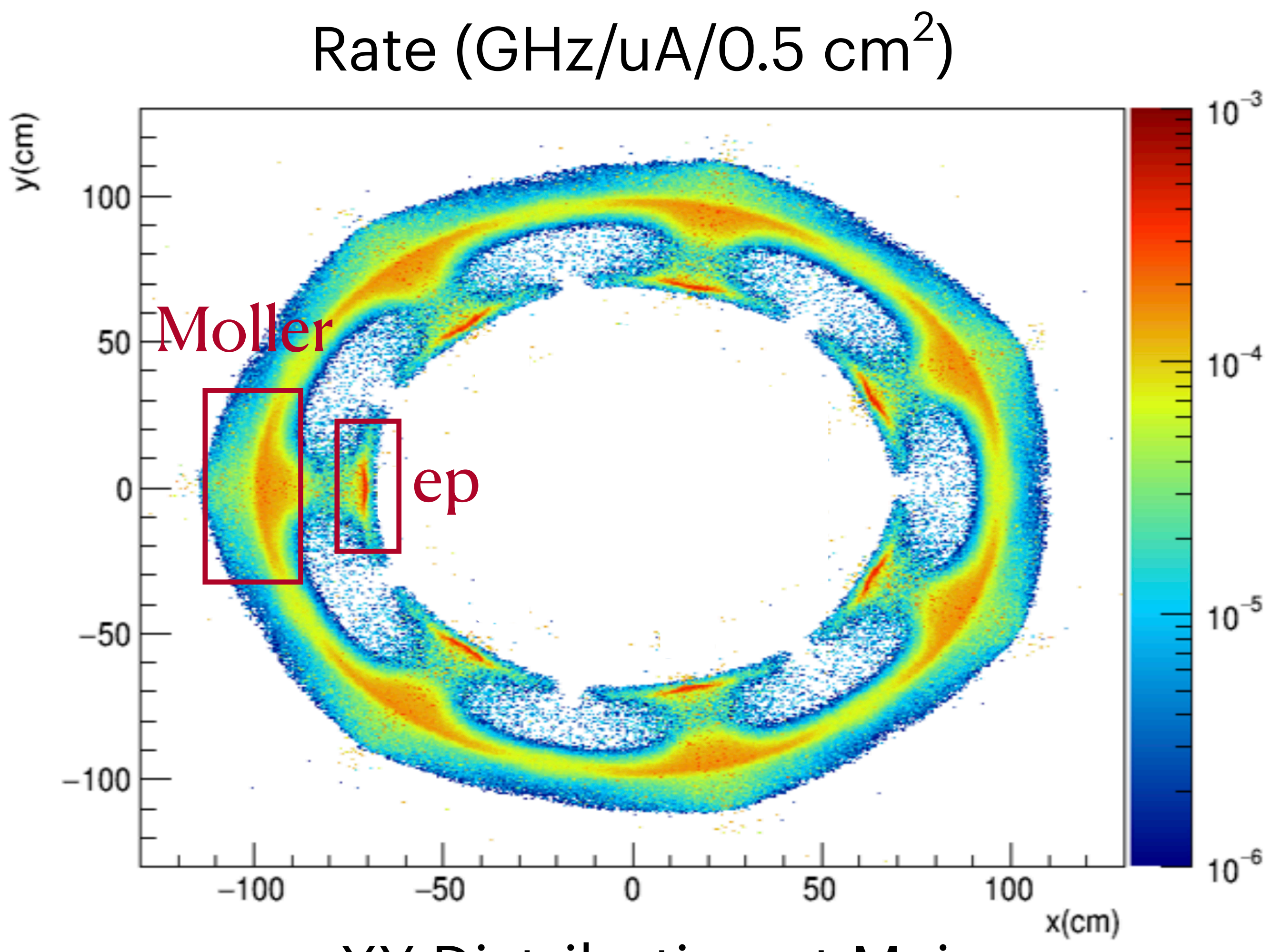
Spectrometer Concept



Simulations performed by the spectrometer group (Juliete et. al.)



Radial Distribution at Main Detector Plane

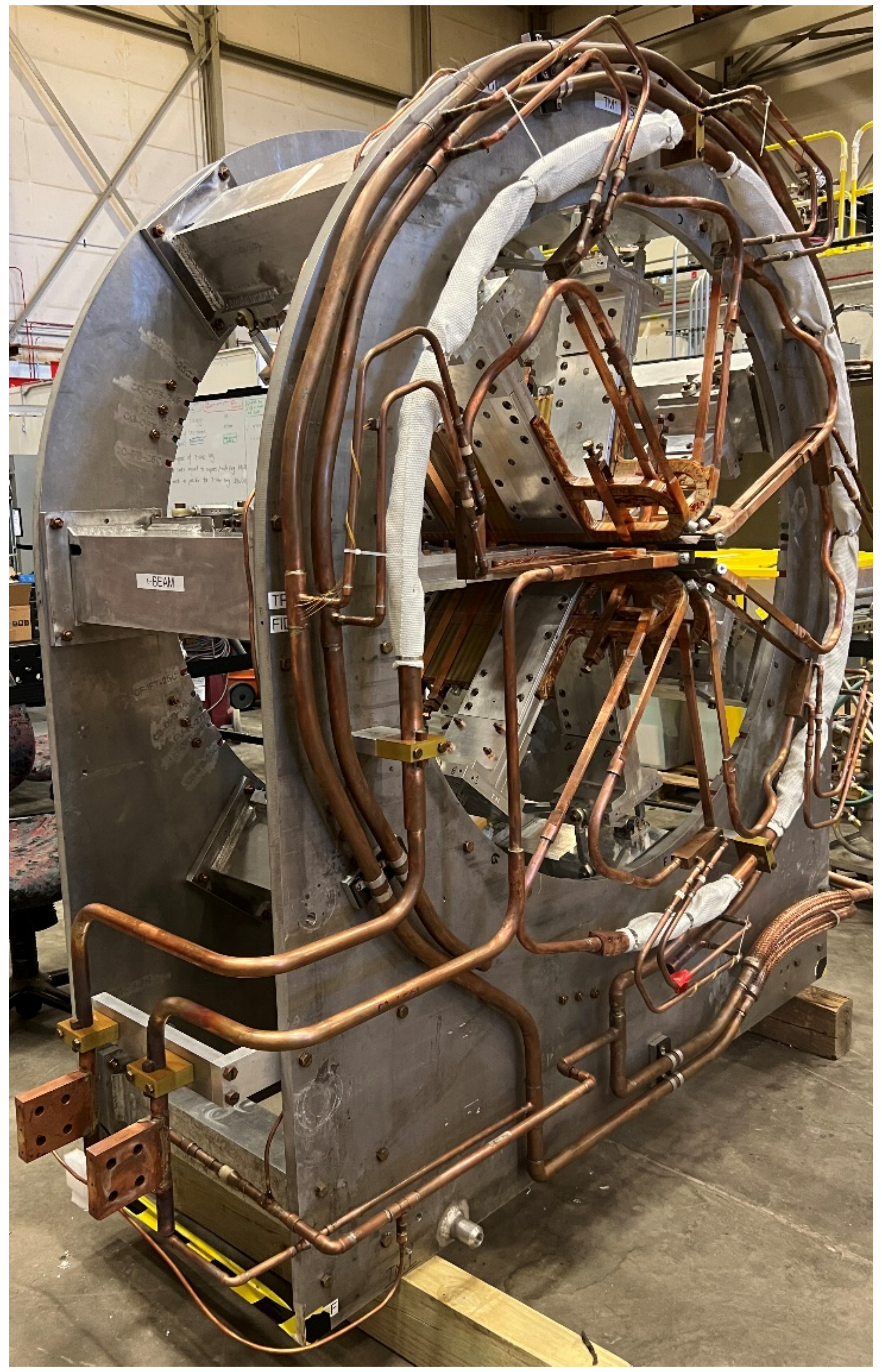


XY Distribution at Main Detector Plane

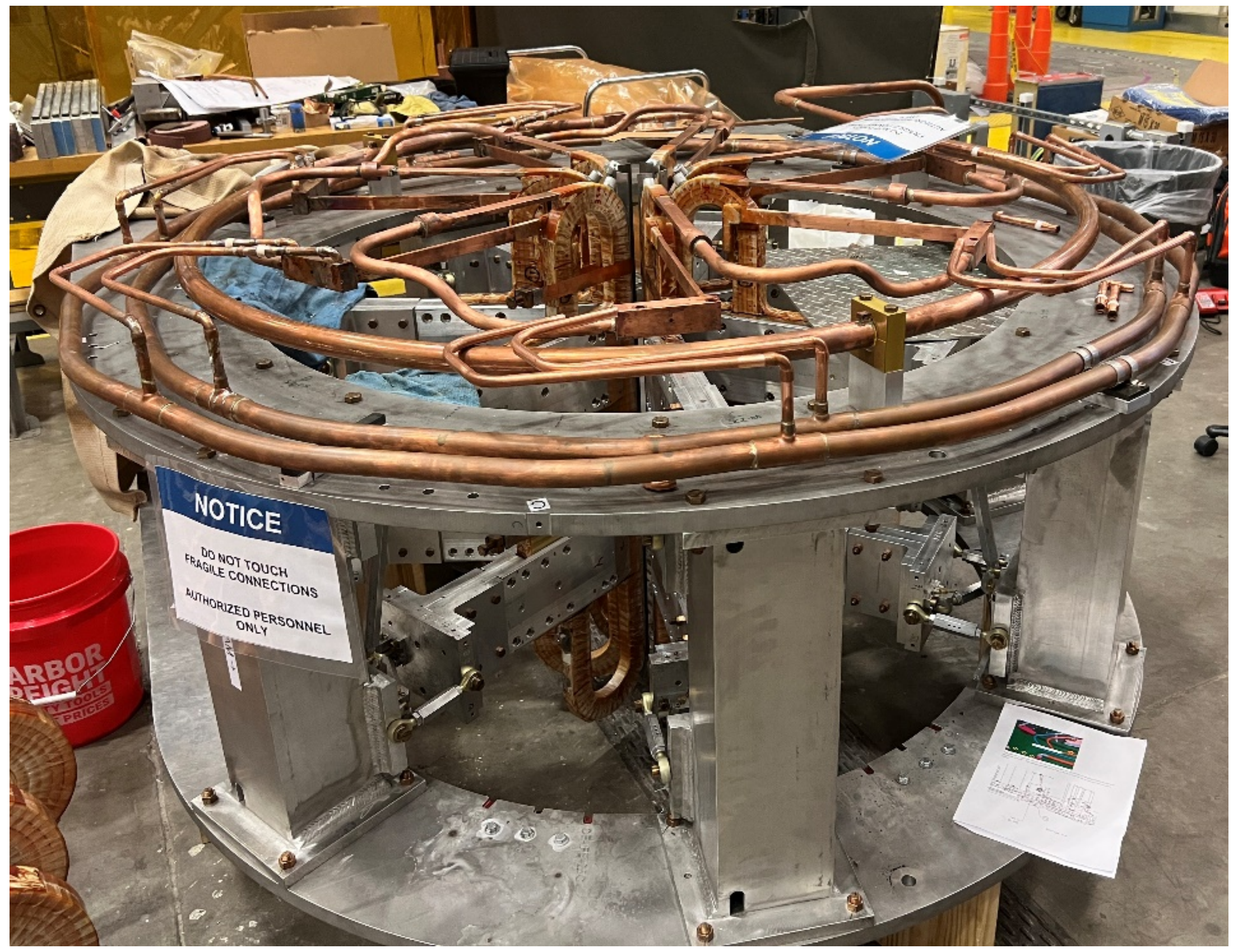
- Major Backgrounds: ep elastic and inelastic scatterings in the target.
- Two back to back toroidal magnets (upstream & downstream).
- Focus Moller electrons from full acceptance (~ 2-8 GeV) to tight radial locations on the main detector.
- Provide kinematic separation between Møller and Mott-scattered electrons at the main detector.

Spectrometer Components

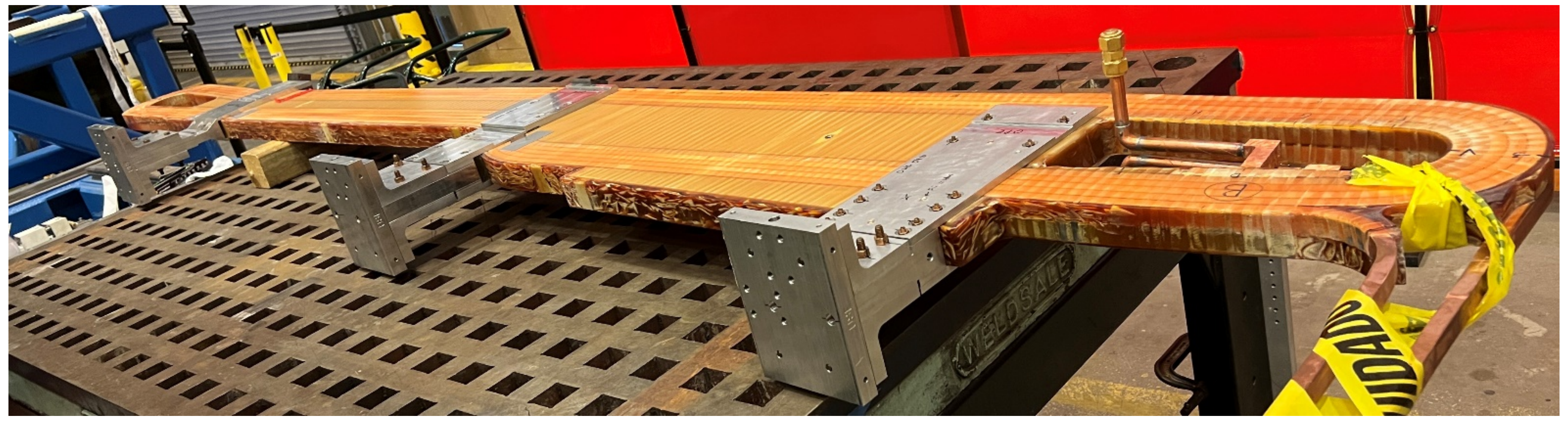
DS Enclosure



TM-1 Complete



TM-2

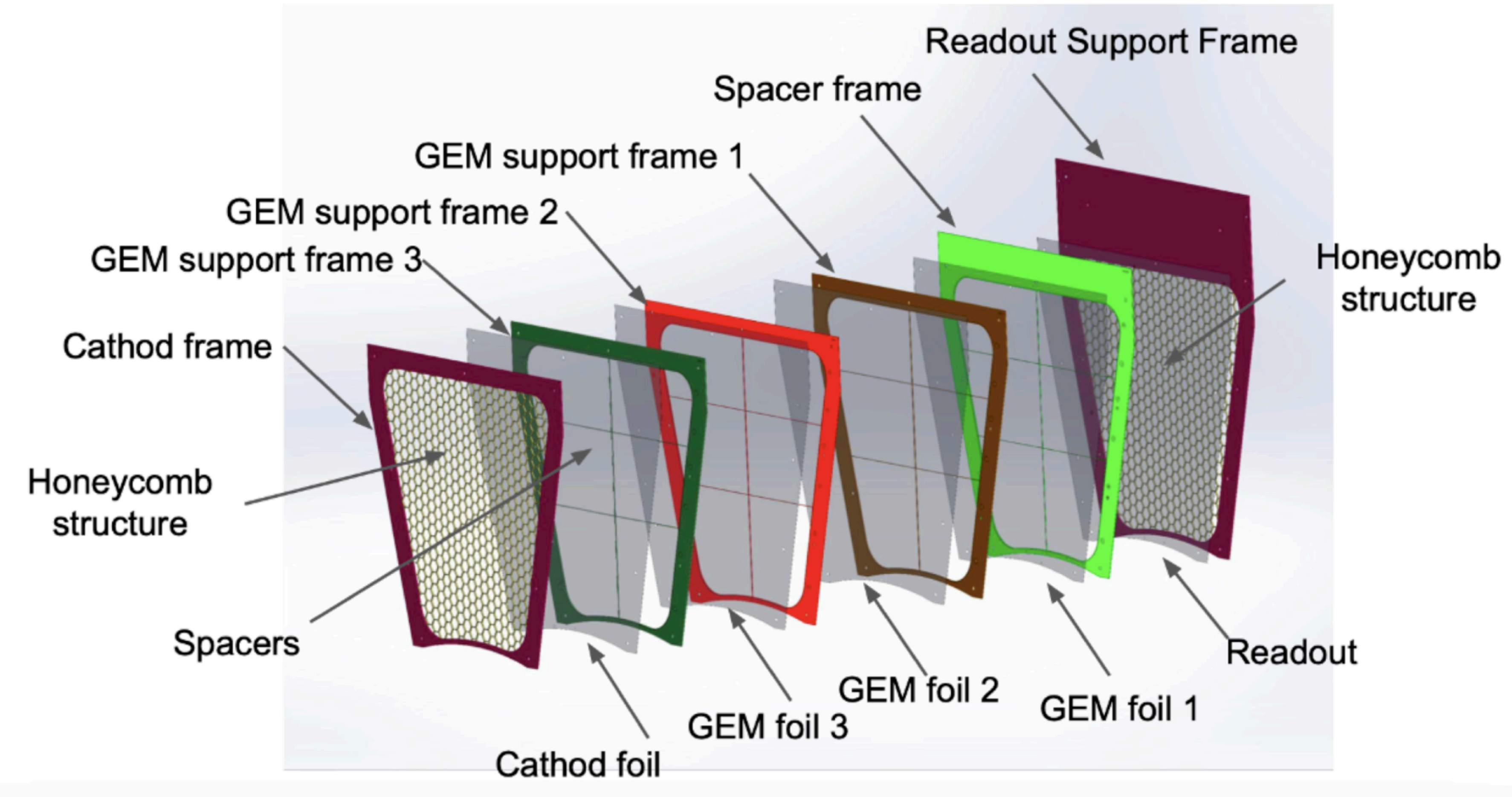


SC-4 Coil

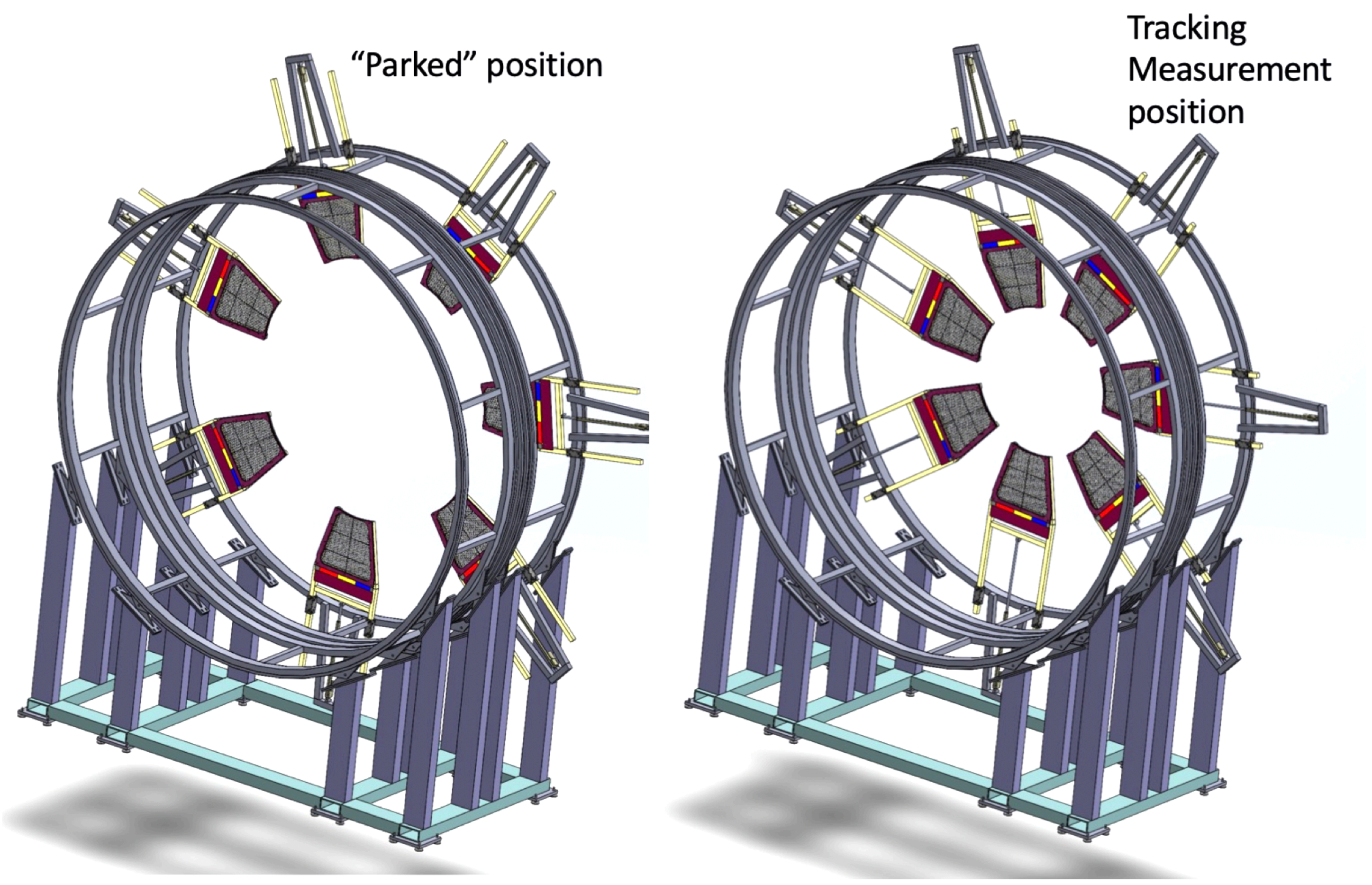
*Pictures from Michael Dion's talk at 2025 MOLLER Collaboration Meeting

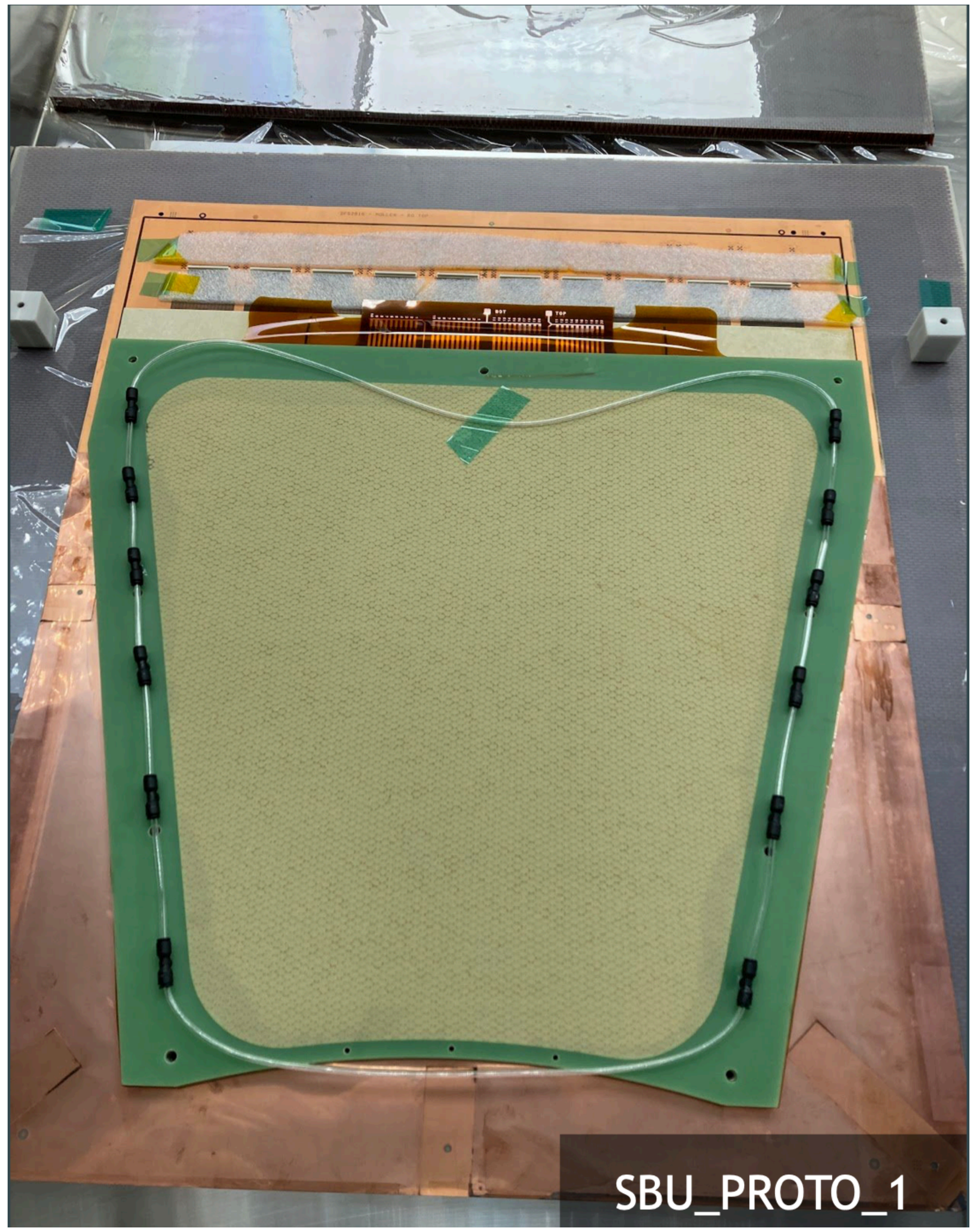
Tracking Detectors

- Four layers of Gas Electron Multipliers (GEMs) in each of the seven sectors.
- Mounted on a pair of rotating support wheels to allow measurements of the full azimuthal acceptance.
- Used in low beam current measurements (counting mode).
- Measure the track positions r and ϕ and also the directions r′ = $\frac{dr}{dz}$ and $\phi' = \frac{d\phi}{dz}$.



7 modules per layer and total of 4 layers.





James Shirk, Brynna Moran

Goals of Tracking Detectors

- Determine the average kinematic factor and it's associated uncertainty

Requires a sieve collimator and thin C foil targets

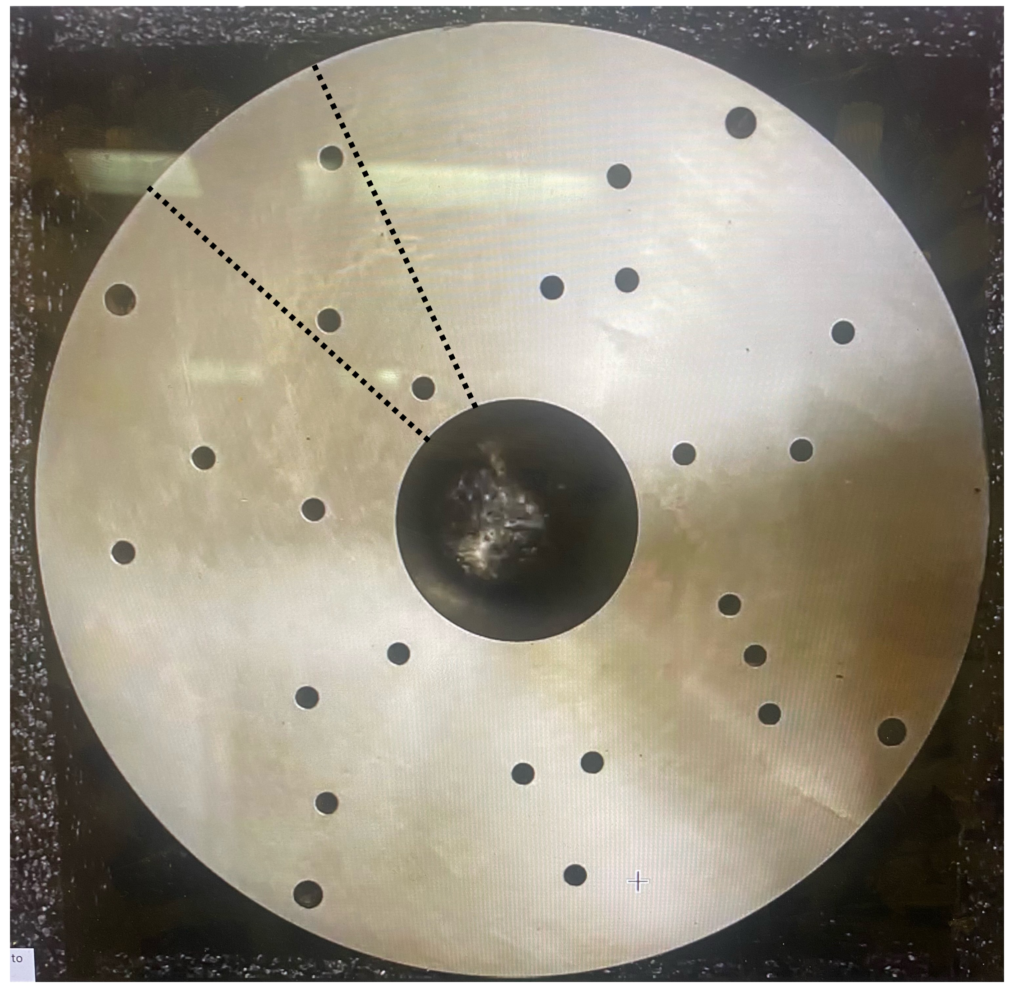
$$KF = \frac{A_{PV}}{Q_w^e} = m_e E_{beam} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{2y(1-y)}{1+y^4+(1-y)^4} \qquad y = \frac{E'}{E_{beam}}$$

- Verify the acceptance of the toroidal spectrometer.

- Measure the position dependent light-output response of the quartz detector.

Goal: Measure KF to a fractional accuracy of less that 0.5%

Sieve Collimator



IR: 26.5 mm
OR: 98 mm
Thickness 100 mm

Holes Diameter: 5 mm

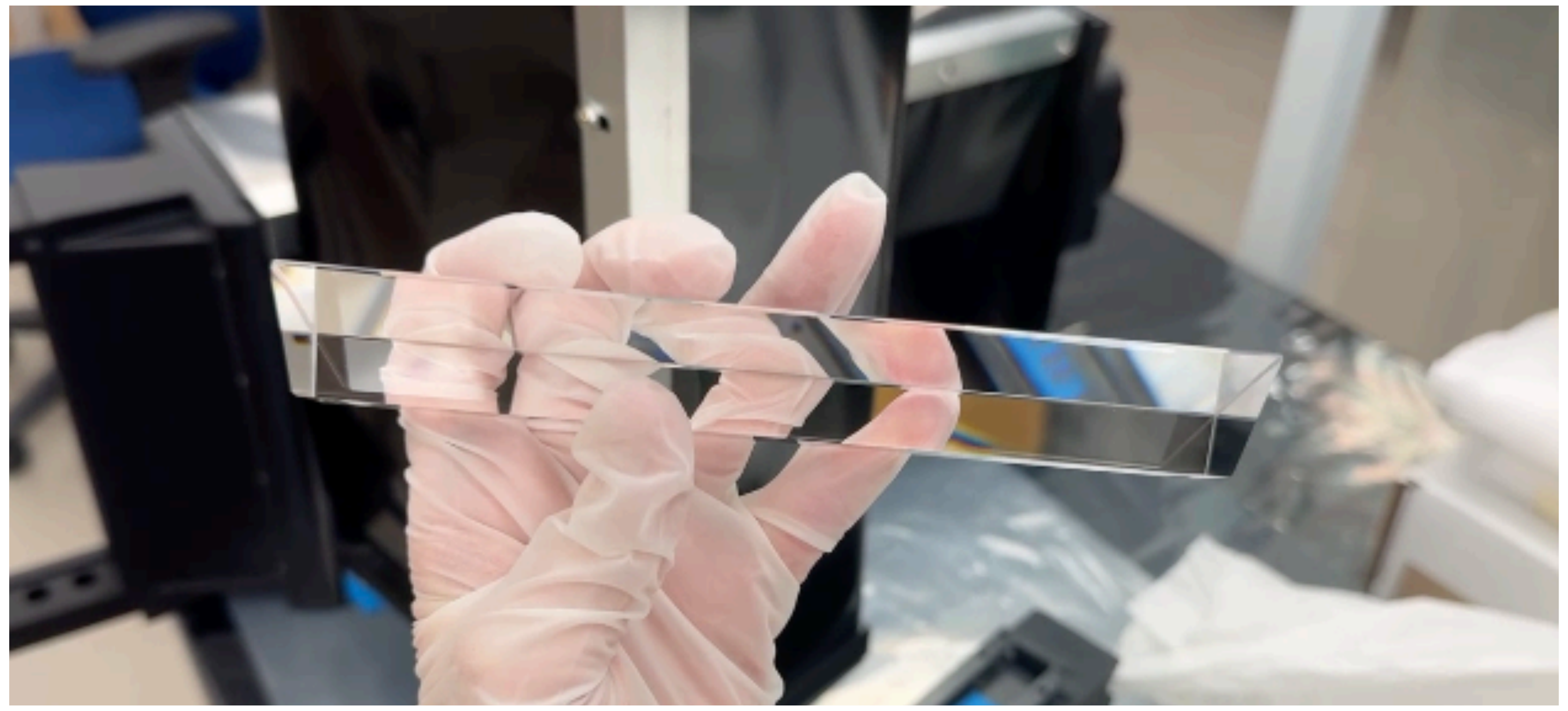
Main Integrating Detector

- The Main integrating detectors measure the physics asymmetry for Møller scattering as well as for the background processes.

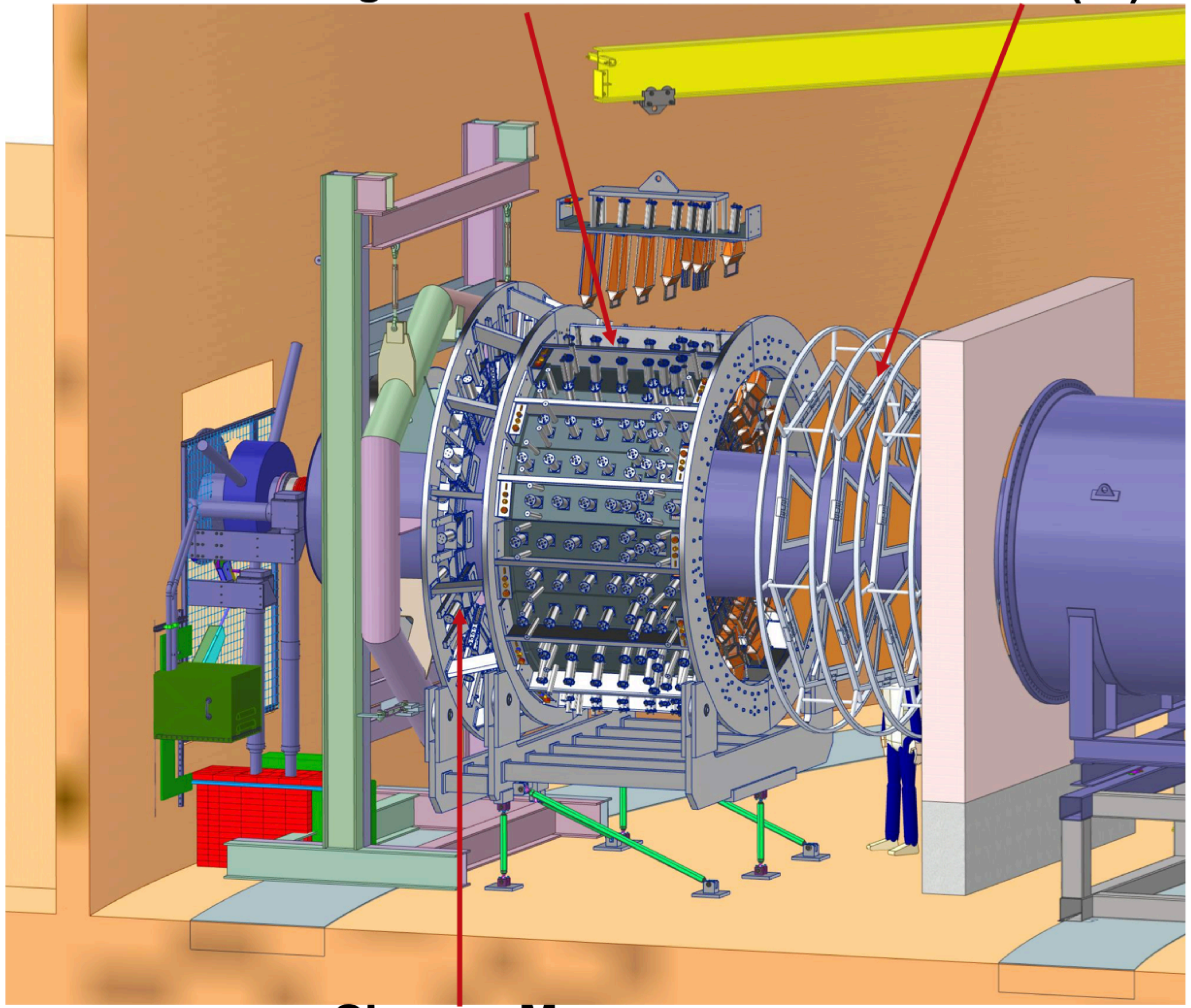
- Radiation hard fused-silica Cherenkov detectors with radial and azimuthal segmentation.

- Total of 6 rings and 224 detectors.

  - 84 detectors in Ring 5 and 28 in each of the other rings.
  - Covers a radial region between 60 - 110 cm.
  - The Møller asymmetry measurement will occur in Ring 5.



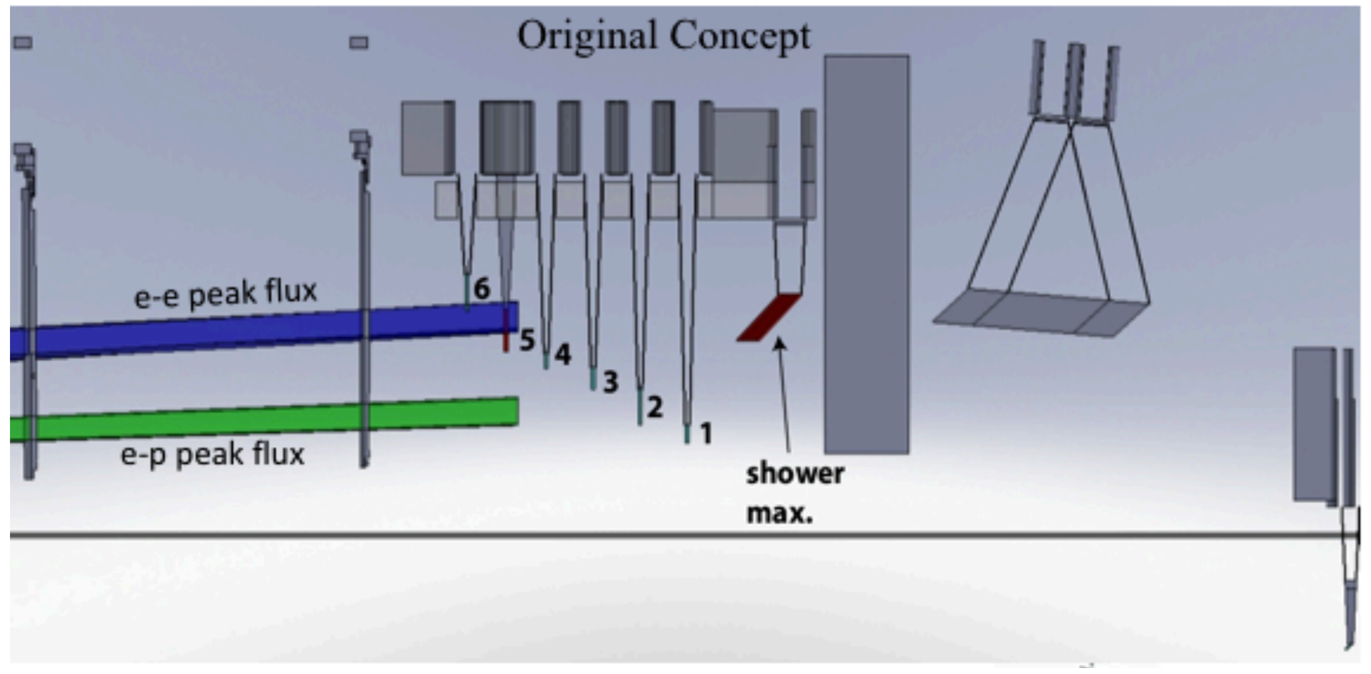
Quartz Crystal: Brynne Blaikie's Talk at MOLLER Collaboration meeting 2025

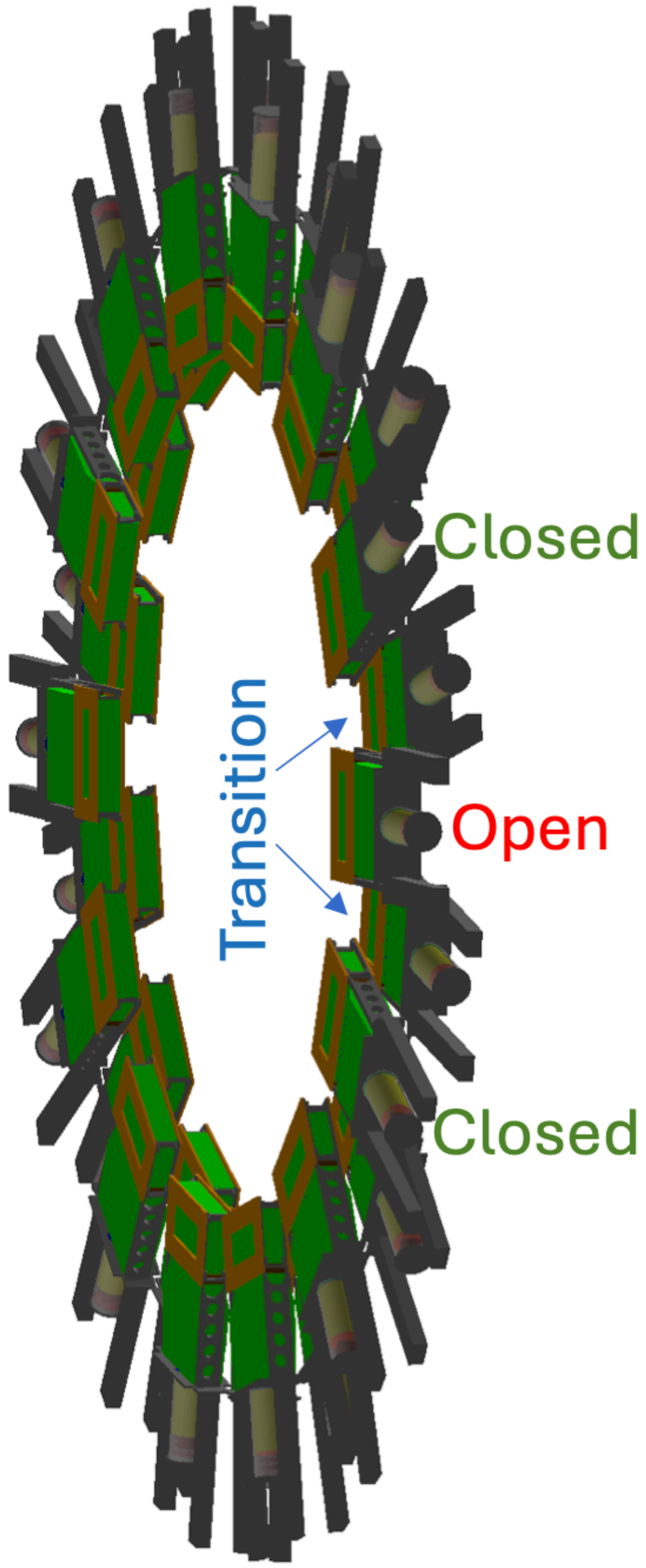


Shower-Max Detector

Shower-Max Detector is a quartz-tungsten Electromagnetic Calorimeter.

- Intercepts the same scattered electron flux as the main Møller Ring 5
- Provides a supplemental energy-weighted measurement of the Møller signal with less sensitivity to hadronic background.
- Total 28 modules in 7 septants





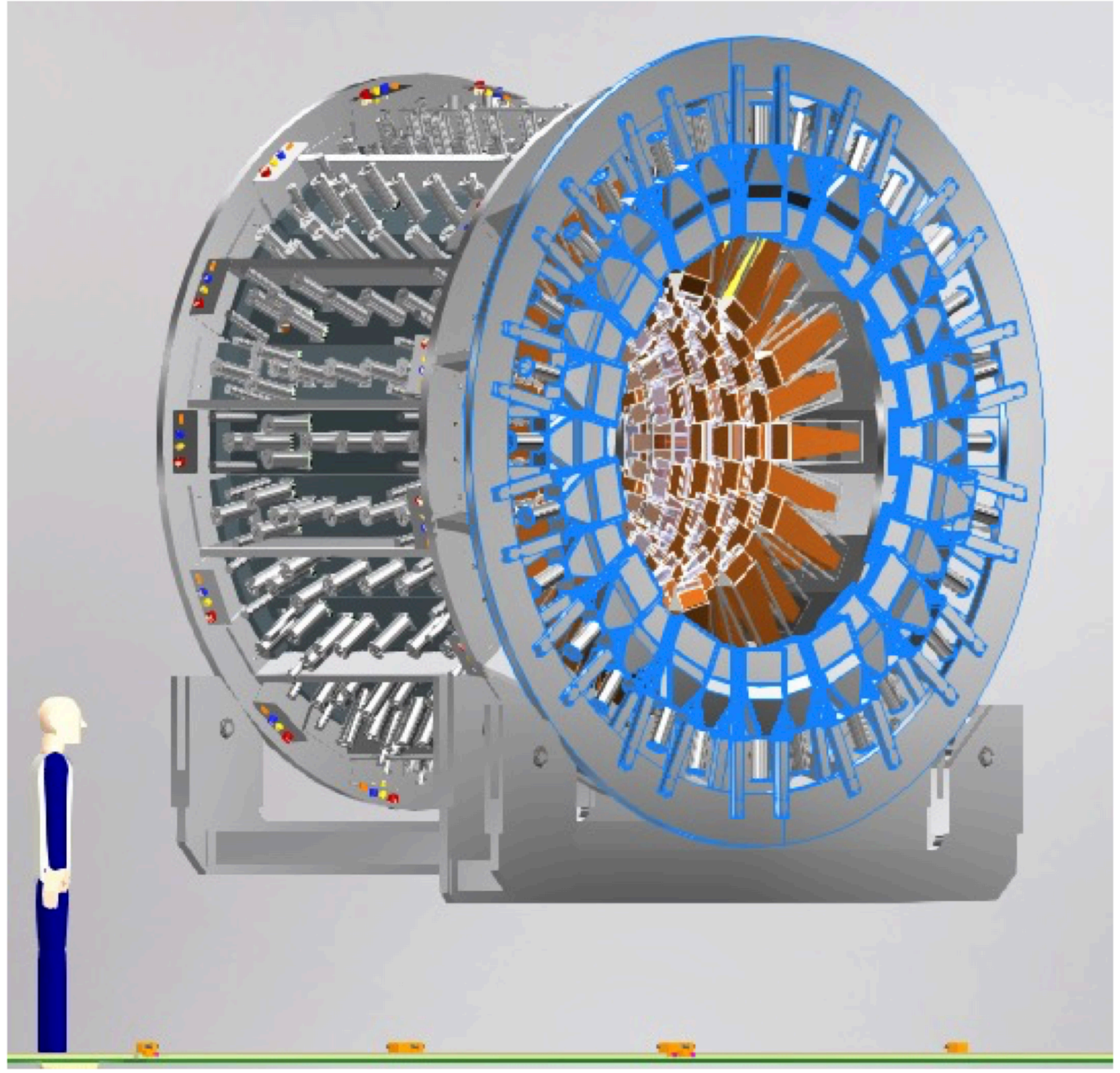


Fig: Int det system with Showermax ring in the beam downstream (front in the picture)

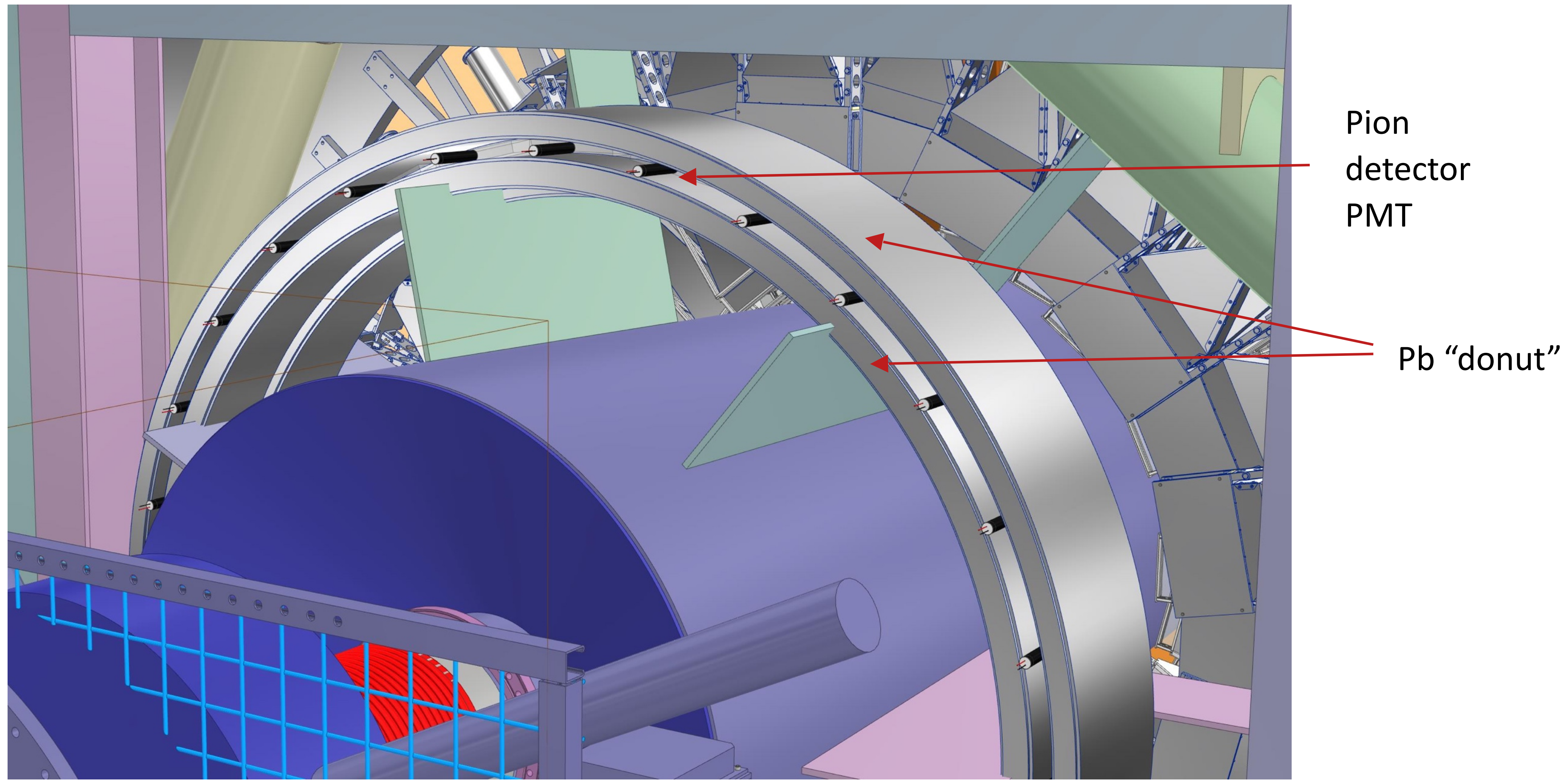
Image Courtesy: Sudip Bhattarai

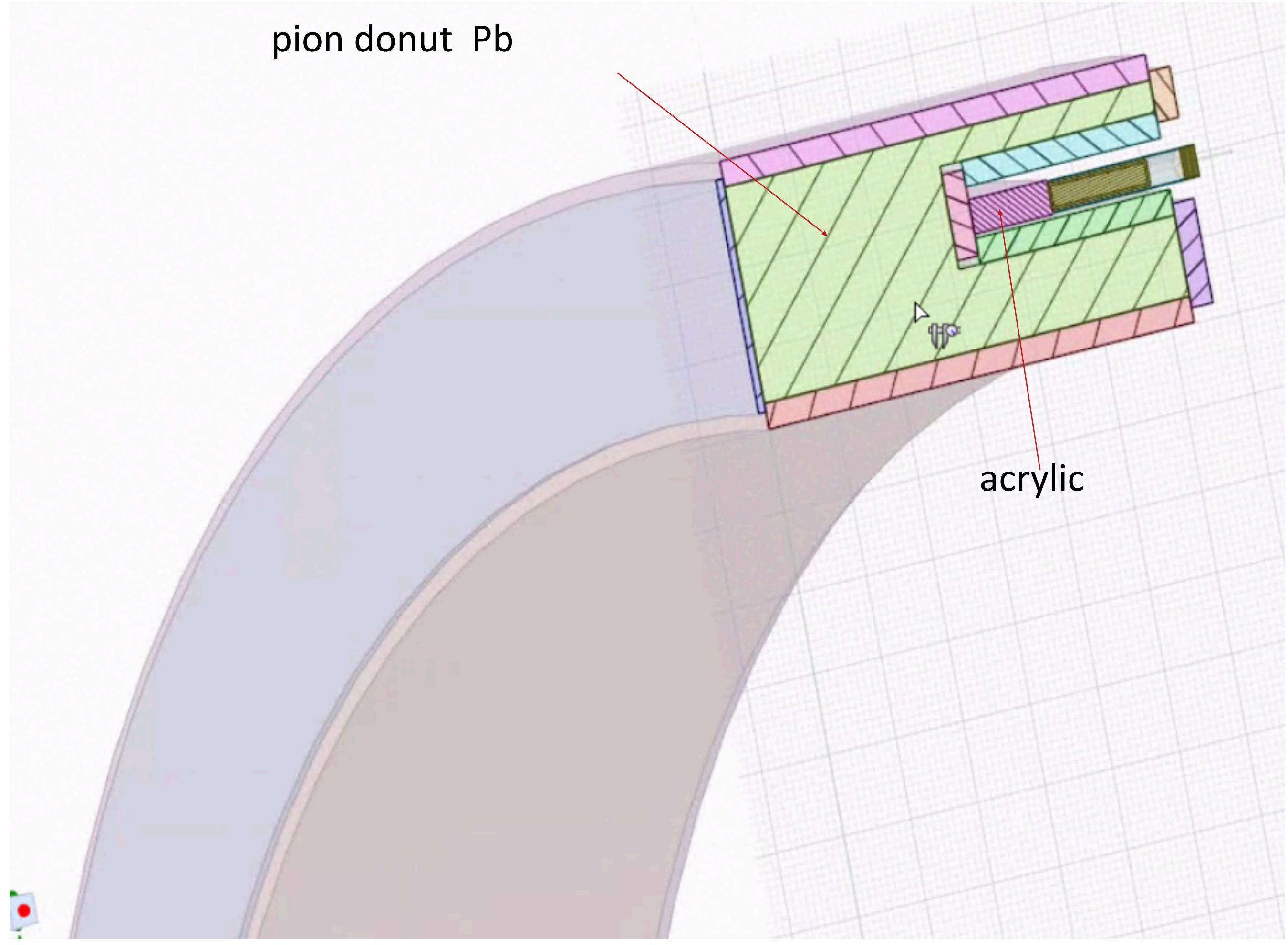
Pion Detector

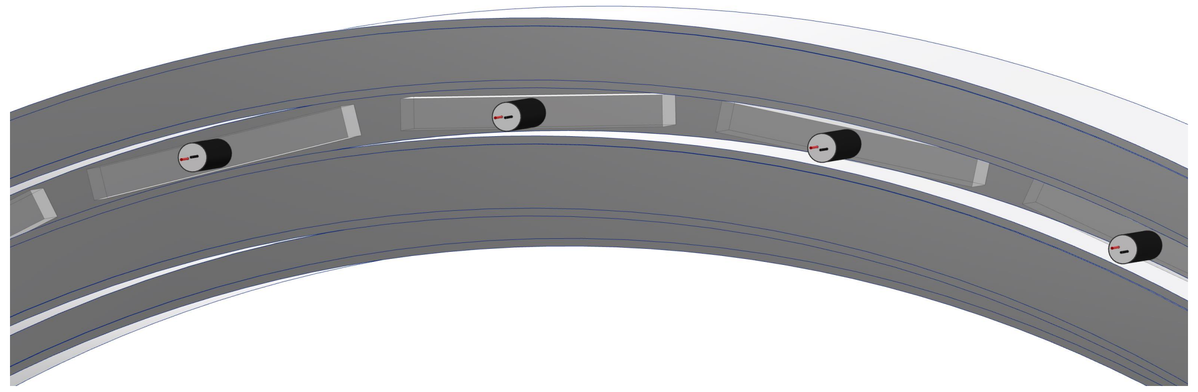
Pion Detector is a Lucite Cherenkov detector.

- Downstream of both the MD and the Shower-max detector behind a Pb absorber donut (to range out the Møller electrons).
- Will determine the hadronic asymmetry (in integration mode) and the dilution (in the counting mode).

$$f^{\pi} = \frac{R^{\pi}}{R^{e} + R^{\pi}}$$



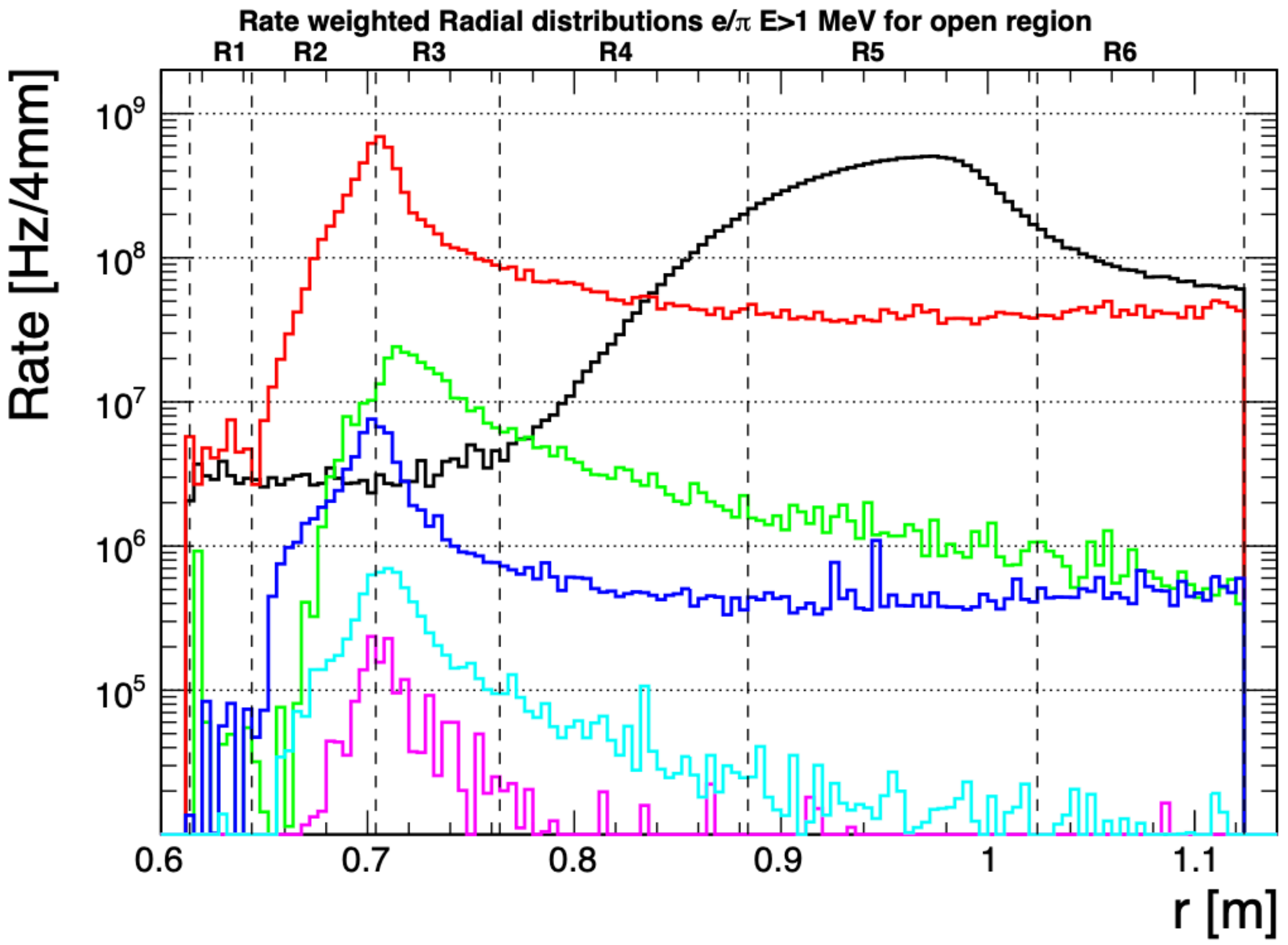


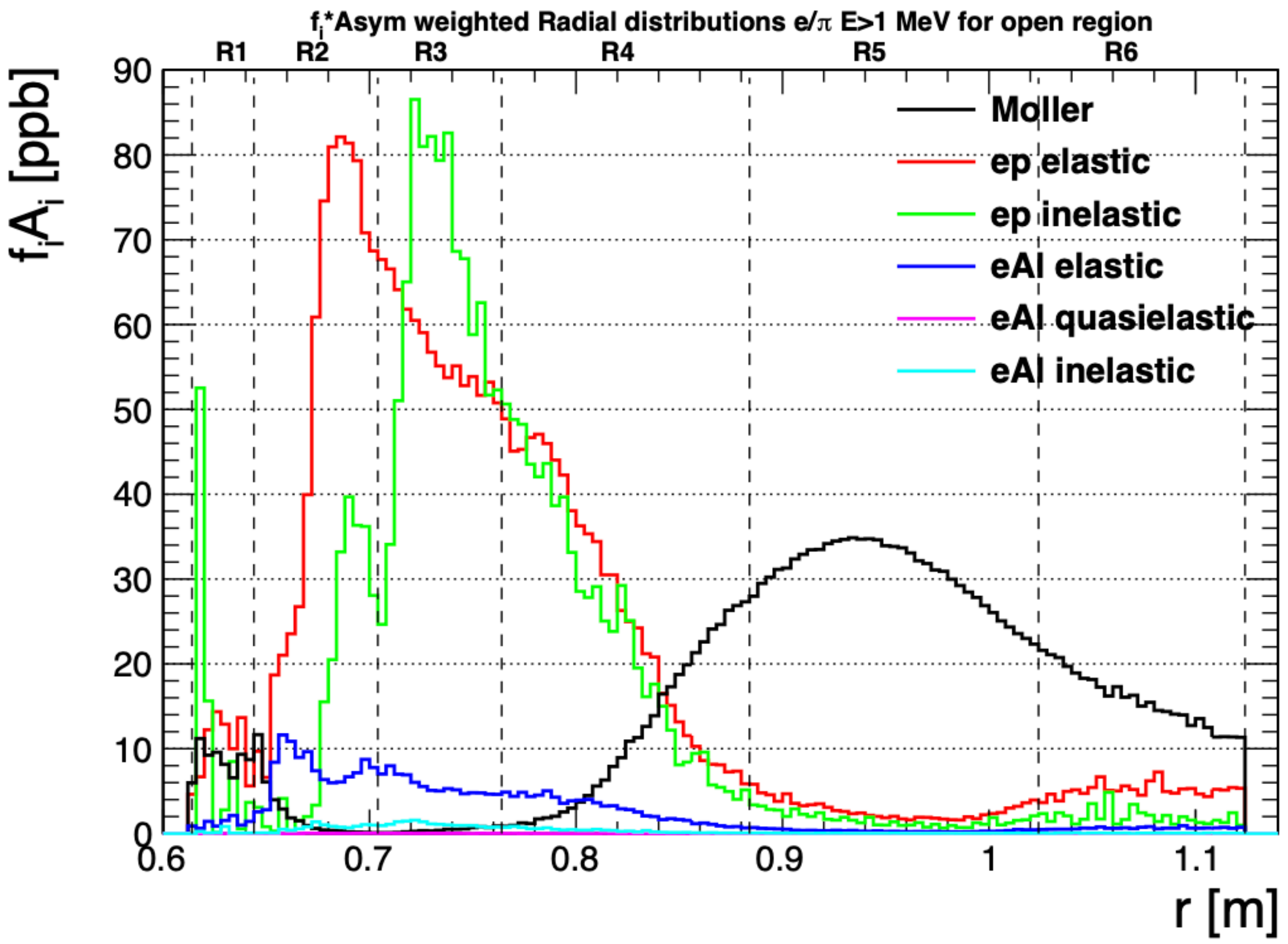


- Pion detectors encased in Pb donut to largely range-out Moller electron signal (45 X_0)
- 28 identical acrylic detectors (7 cm deep, 21 cm wide, 2.54 cm thick). Each read out by single PMT

Image Courtesy: David Armstrong

Irreducible Background Deconvolution



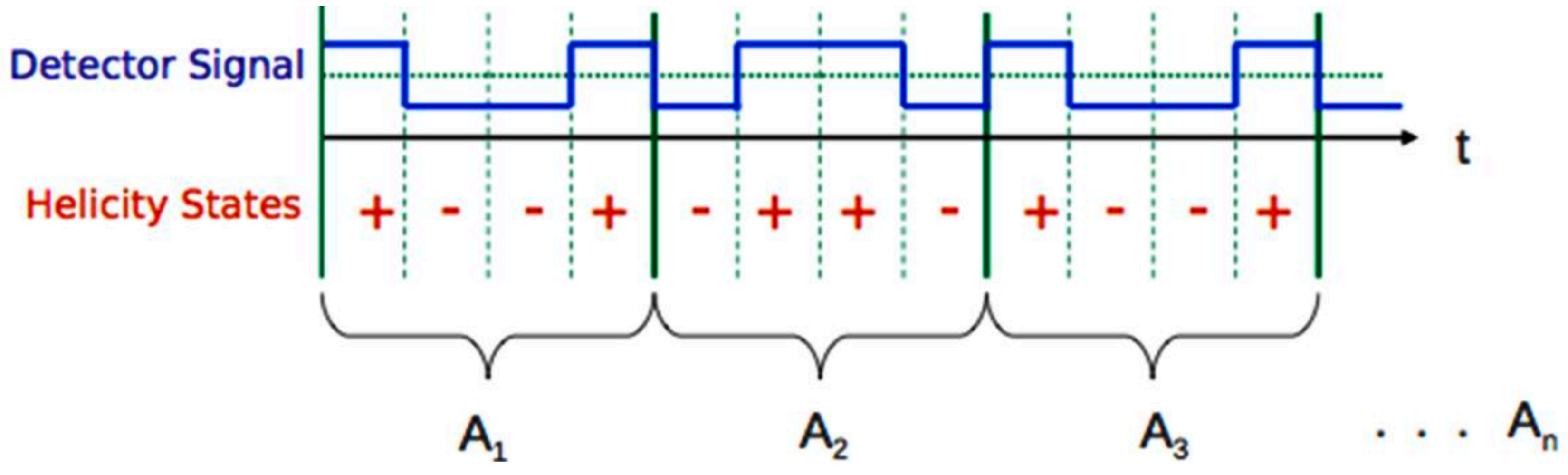


Plots From Zuhal Seyma Demiroglu

- Deconvolute the signal from the background using the segmented detector plane
- Elastic ep: ~10% of the signal, asymmetry is well known
- Inelastic ep: < 0.3% of the signal but asymmetry is ~20x larger, not well know,
- The inelastic contribution is prominent in Rings 3 and 4, will be measured there.

Experimental Measurement of A_{PV}

- Flux-integration technique for measuring A_{PV}
- The response of the quartz detectors is proportional to the scattered flux.
- The scattering asymmetry is measured for a pair of windows with right-(left-) handed polarization as



Corrected for helicity correlated beam fluctuations

$$A_i^{raw} = \left(\frac{F_R - F_L}{F_R + F_L}\right)_i \approx \left(\frac{\Delta F}{2F}\right)_i \qquad < A > = \frac{1}{N}\sum_i^N A_i^{raw}$$

Asymmetry contribution from other background sources and their dilutions

Corrected due to spectrometer acceptance

$$A_{\rm PV} = \frac{\boxed{R_{\rm kin}}}{\boxed{P_{\rm B}}} \frac{1}{\left(1 - \sum f_i^{\rm bkgd}\right)} \left(\langle A\rangle - \boxed{A_F} - \boxed{A_{\rm lin}} - \boxed{\sum_i f_i^{\rm bkgd} A_i^{\rm bkgd}}\right)$$

Beam Polarization

A False Asymmetry term

Non-linearity correction

Summary

- High precision test of electroweak theory in a low-energy setting.
  - Can help resolve discrepancies in $sin^2\theta_W$ measurements.

- We are about 70% complete with construction so it's about time to have ERR2 (scheduled for the end of July).
  - Target part of the review will happen at a later date in the Fall.

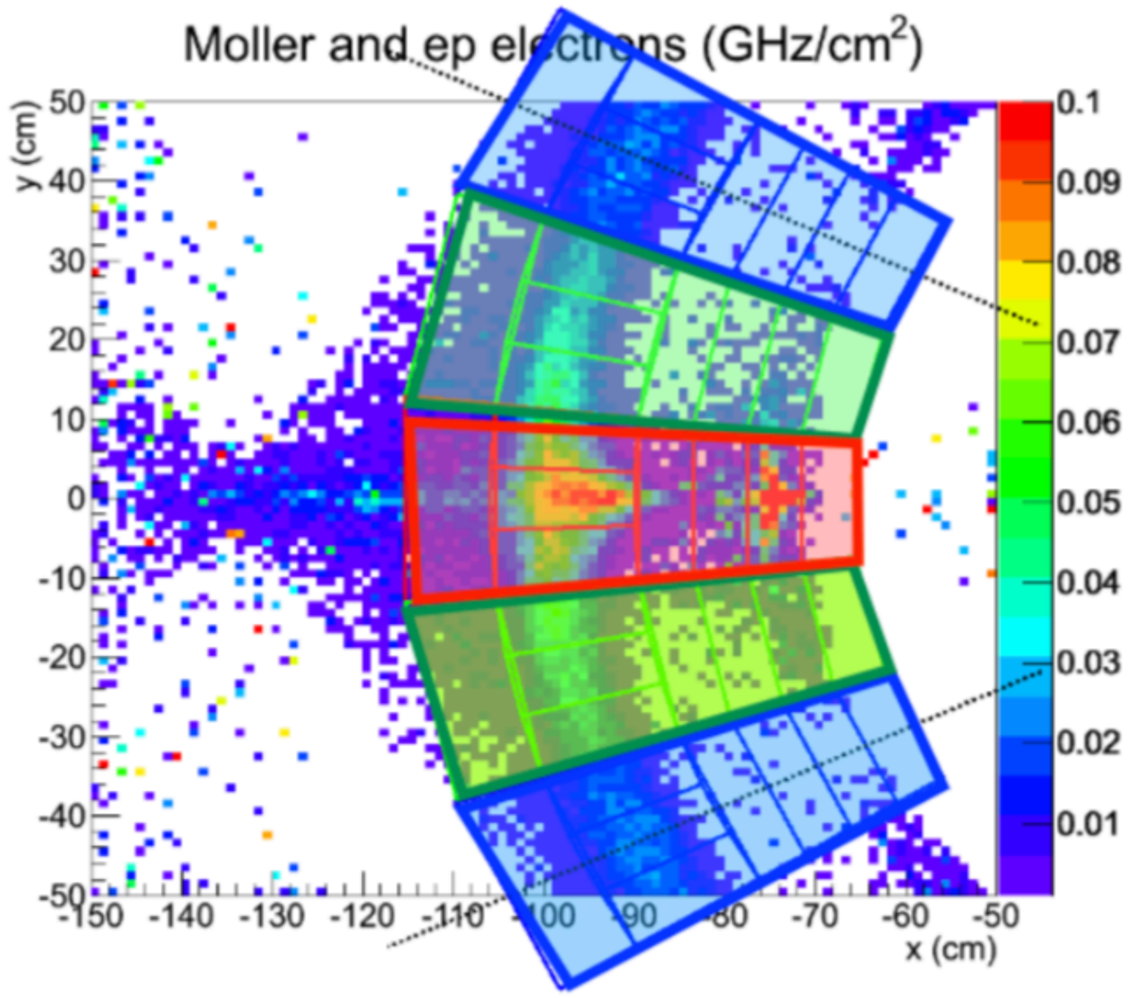
- EER3, will allow us to turn the equipment on and take data, tentatively scheduled for Aug, 2026.

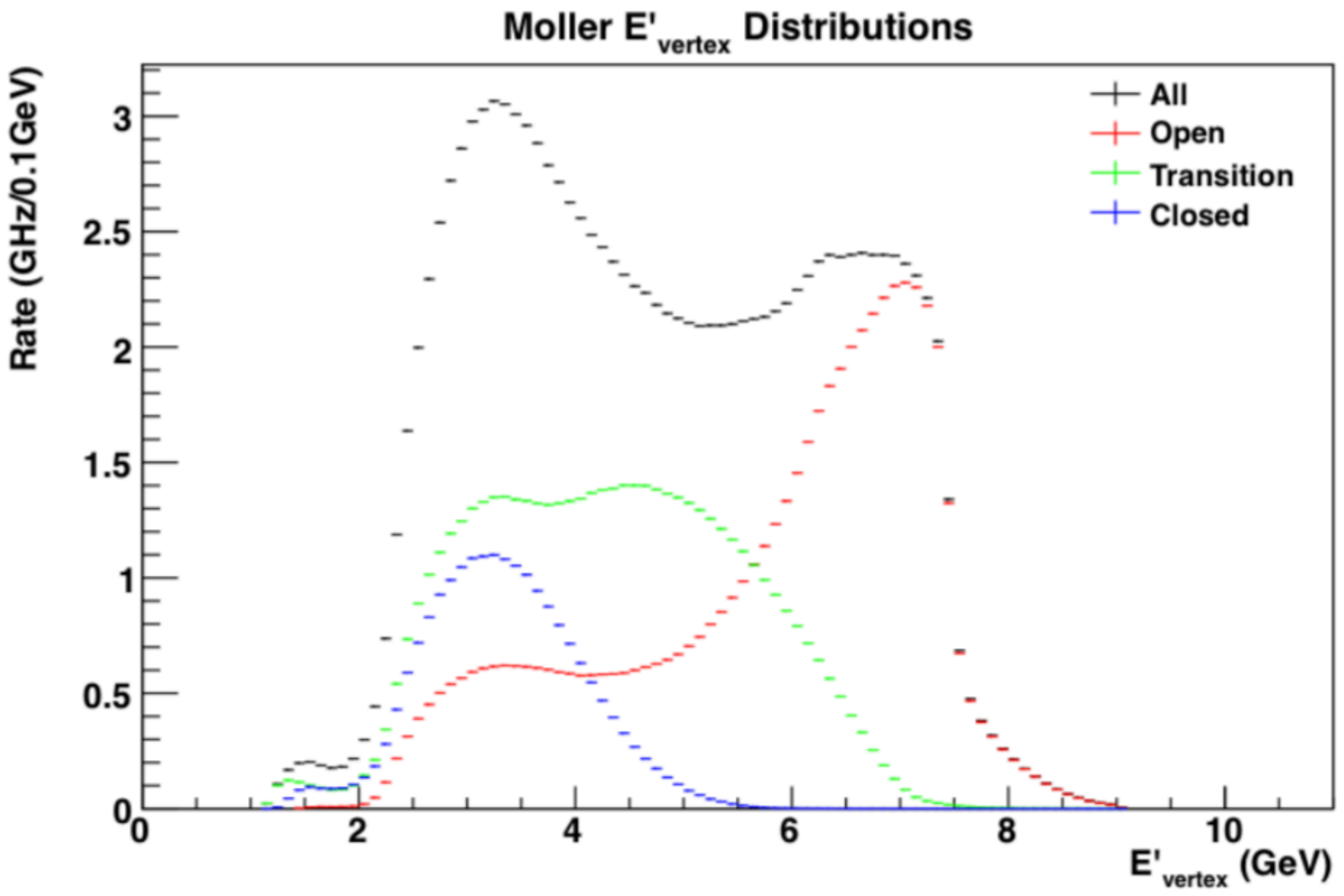
- We are less than 2 years away from having physics data!

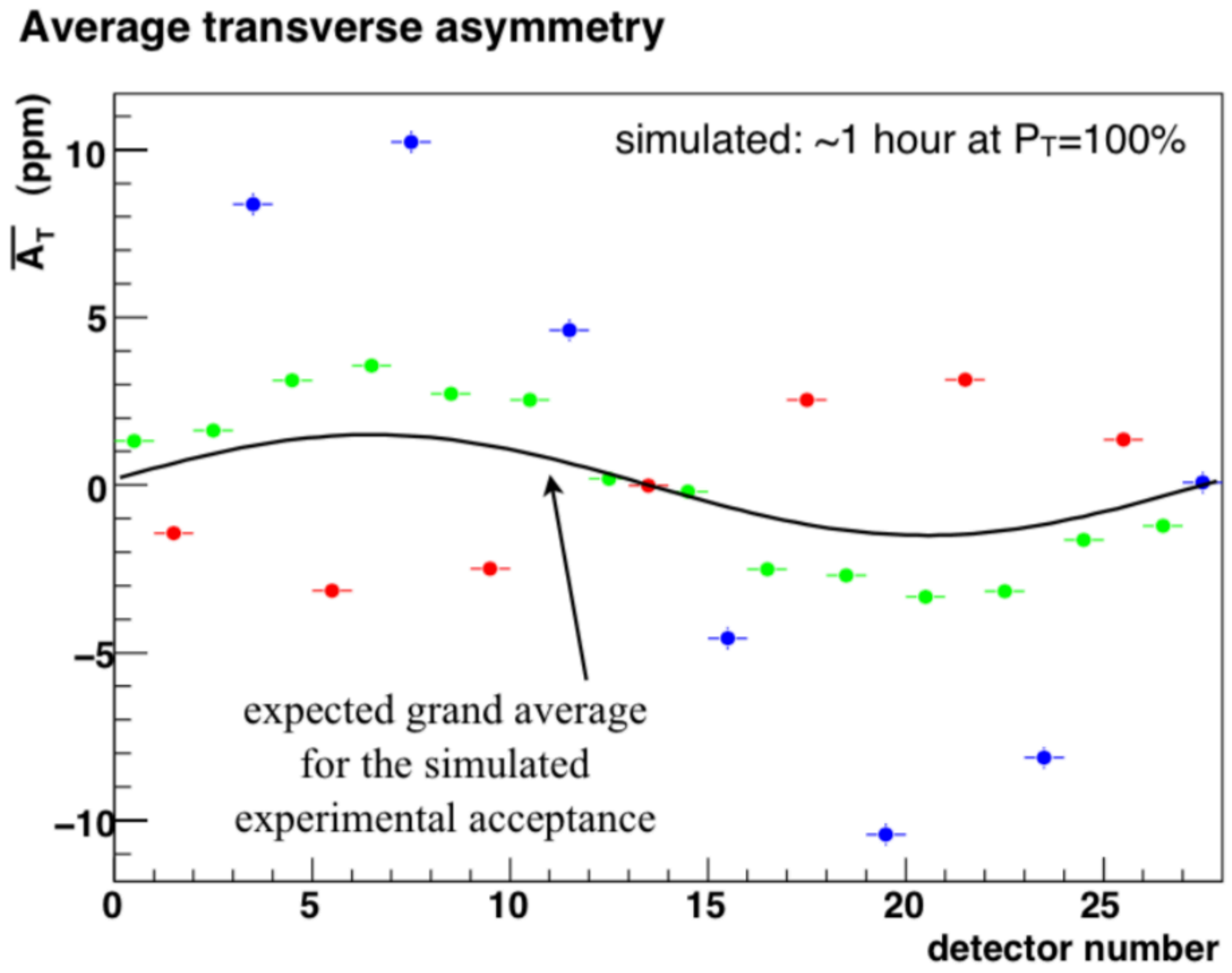
BackUp

Transverse Polarization

Transverse polarization analyzing power with azimuthal segmentation.







For Identical Particles, the magnitude of asymmetry
must be odd around 90 degrees in the center of mass.

Higher-Order Radiative Corrections

- The tree-level electroweak theory prediction for the weak charge of electron is modified even at the 1-loop level.
- θ_W becomes dependent on the energy scale at which the measurement is carried out.
- Hard radiative corrections involving the massive vector bosons at the loop level modify the tree-level prediction quite significantly.
  Czarnecki and Marciano (1996) [arXiv:hep-ph/9507420]
- The dominant effect comes from the γ-Z mixing diagrams.
  Czarnecki and Marciano (2000) [arXiv:hep-ph/003049]