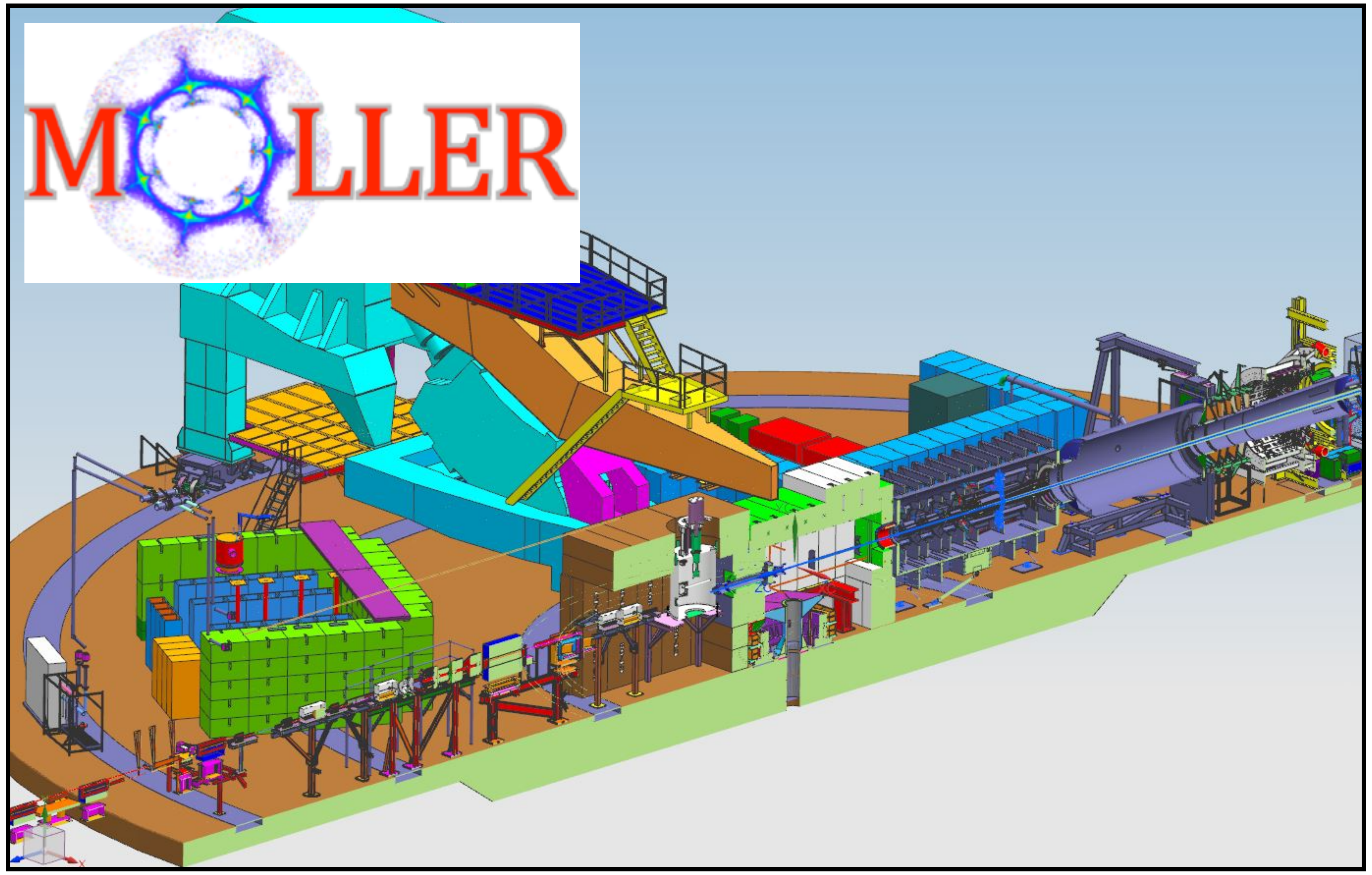
MOLLER Spectrometer Physics Overview



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July 28, 2025

High Precision Measurement

Precise measurement of parity-violation in electron-electron scattering to search for new physics

Difference in cross-section in scattering of left-handed vs right-handed electrons

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

A_{PV} ~ 32 ppb ***δ(A_{PV}) ~ 0.8 ppb***

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

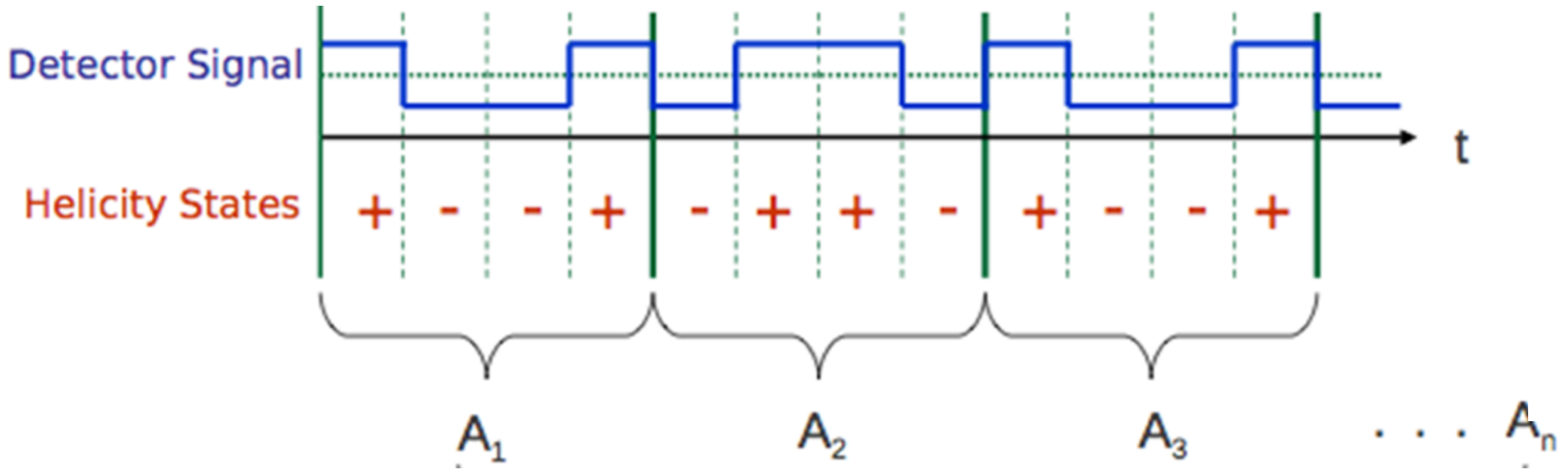
$$\sigma_{pair} = \sqrt{\frac{1}{N}}$$

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

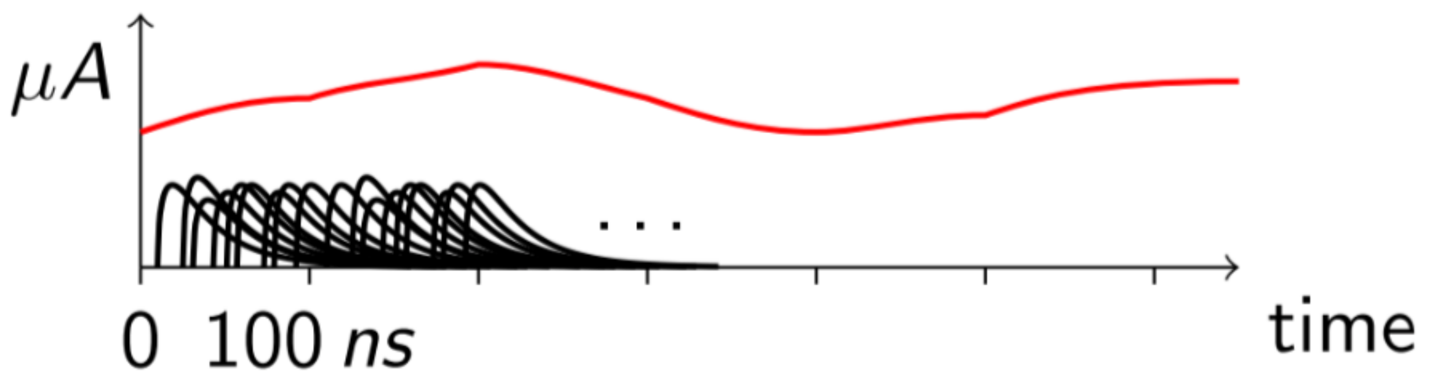
Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	**~ 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**

Rapid (1kHz) measurement over helicity reversals to cancel noise



Integration of analog detector current

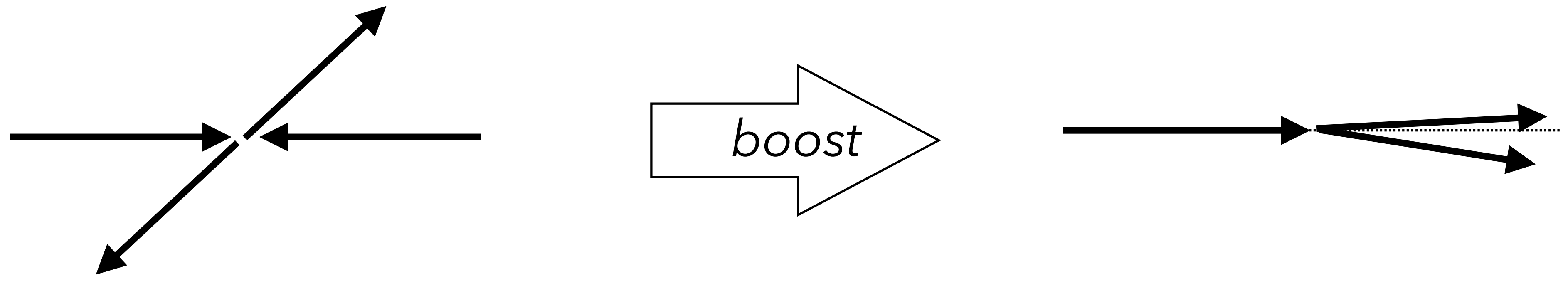


Systematic uncertainty budget

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**

- Asymmetry measurements at 960Hz, each with precision 91 ppm
- Requires ~130 GHz signal rate
- **Integration requires magnetic separation of backgrounds**

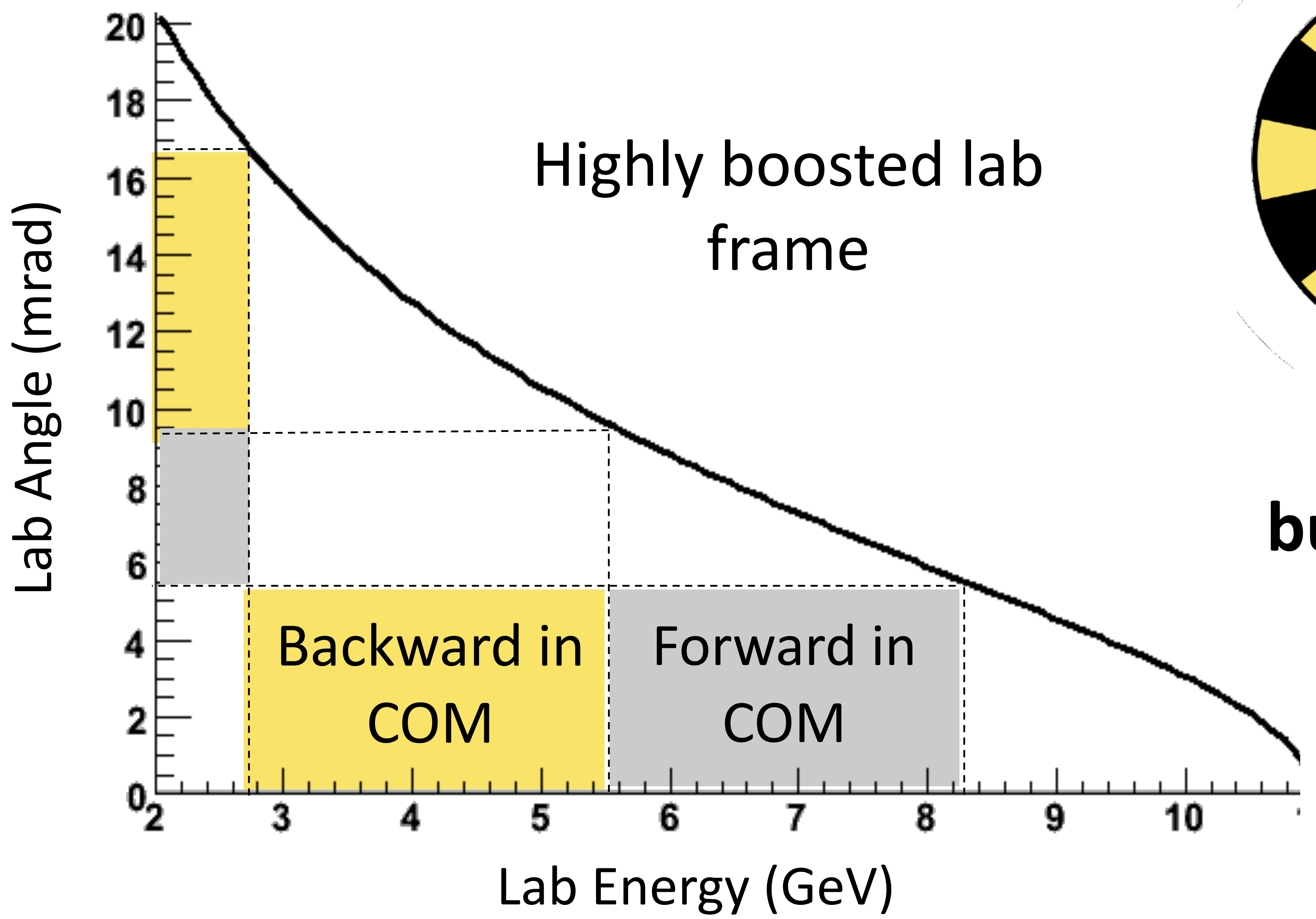
Seven Sectors and Optimizing the Figure of Merit



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

Figure of merit highest at $\theta_{CM} = 90°$

Optimum Acceptance [90°,120°]



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

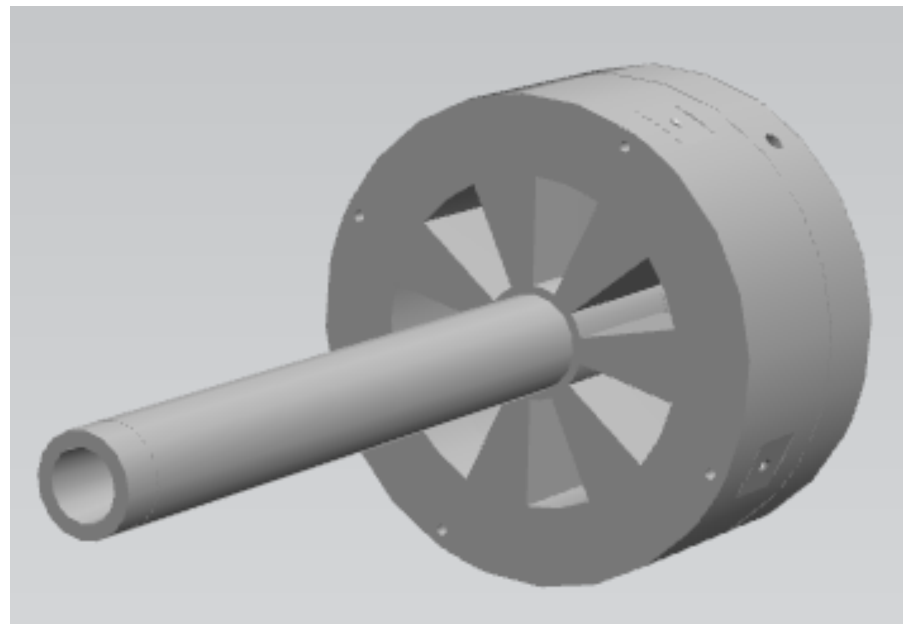
Requires polar-angle acceptance with broad range and very forward angles

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

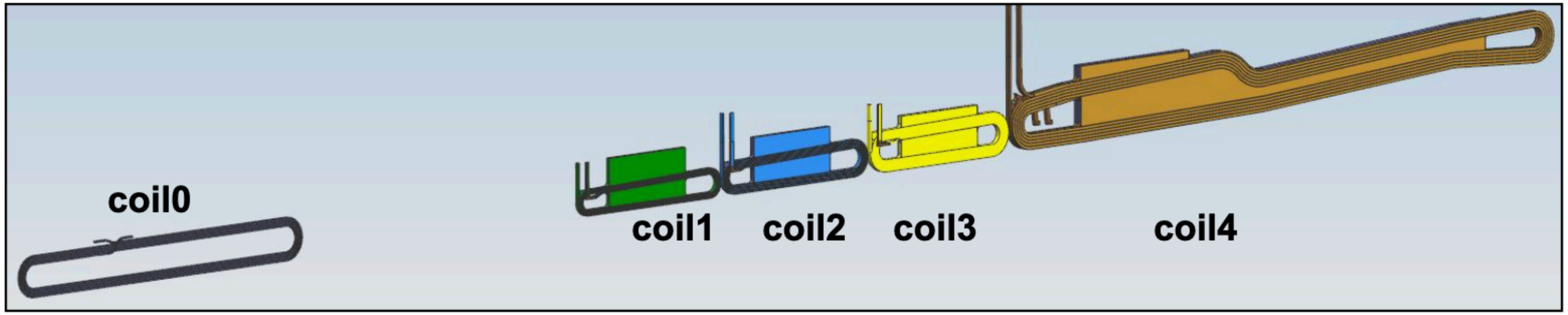
but provides detection of each event in 100% of the azimuth while leaving ample space for the magnetic elements and supports

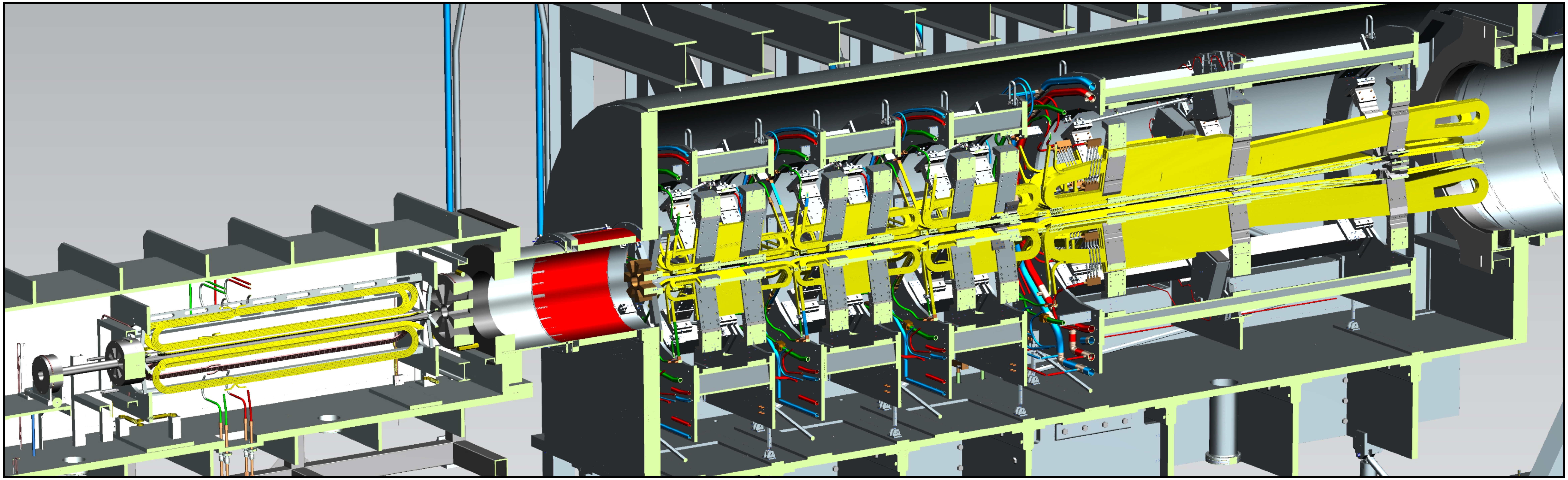
Spectrometer Outline

Acceptance defining collimator 1 & 2

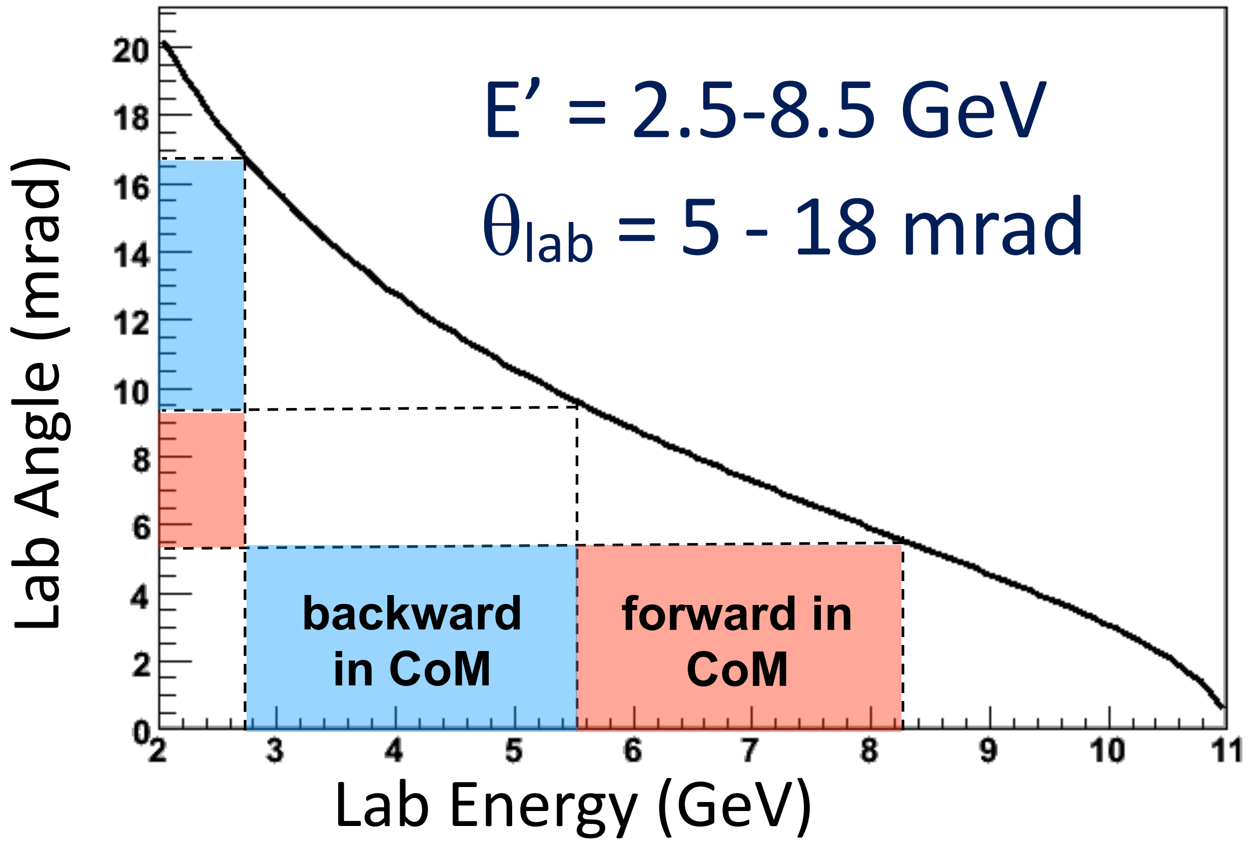


5 toroidal coils of varying strength and shape

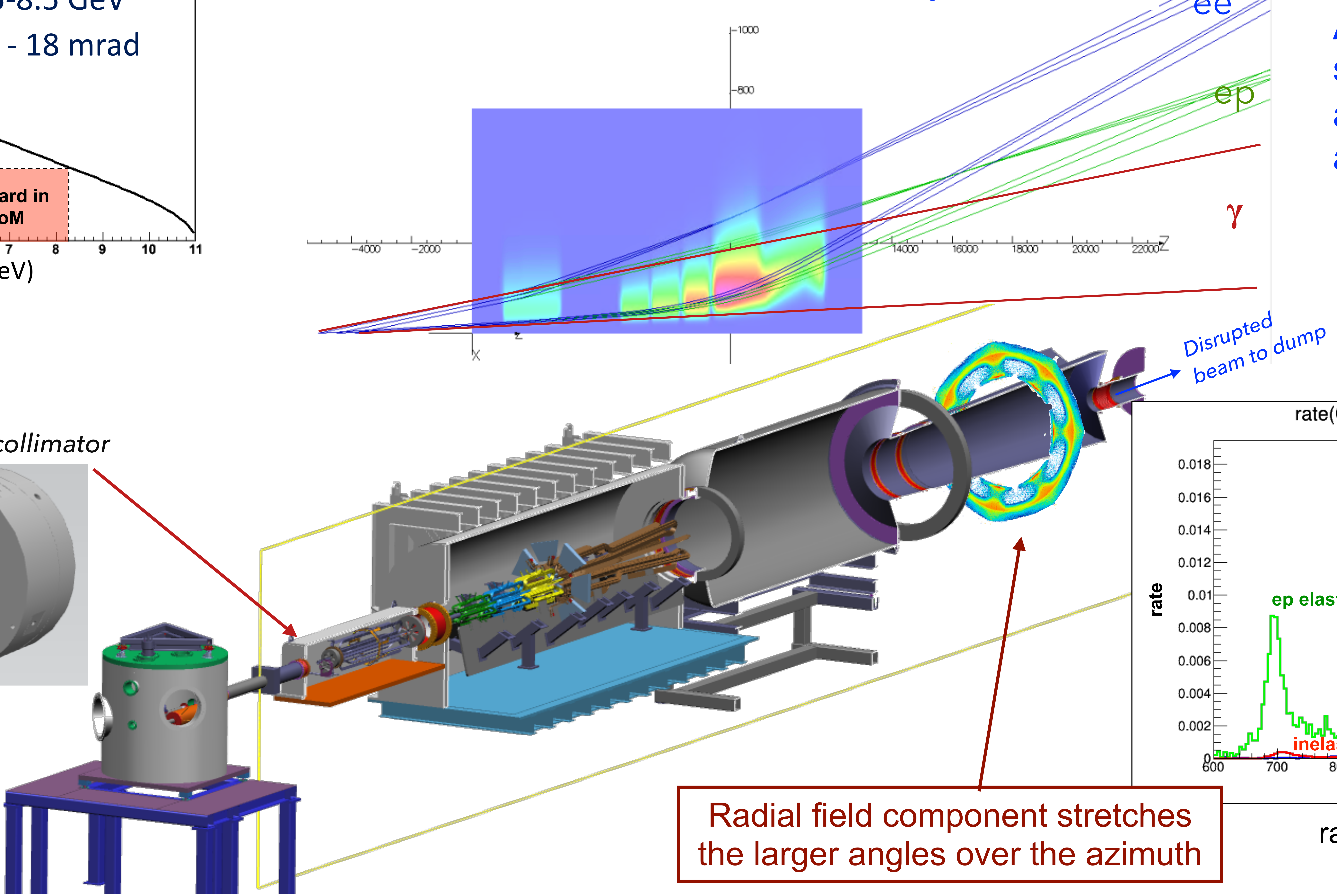




MOLLER Spectrometer

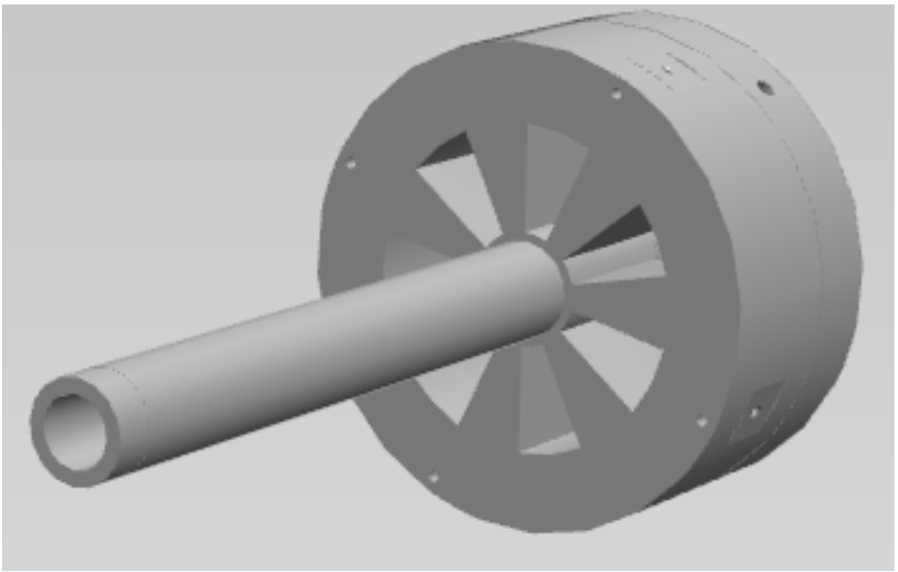


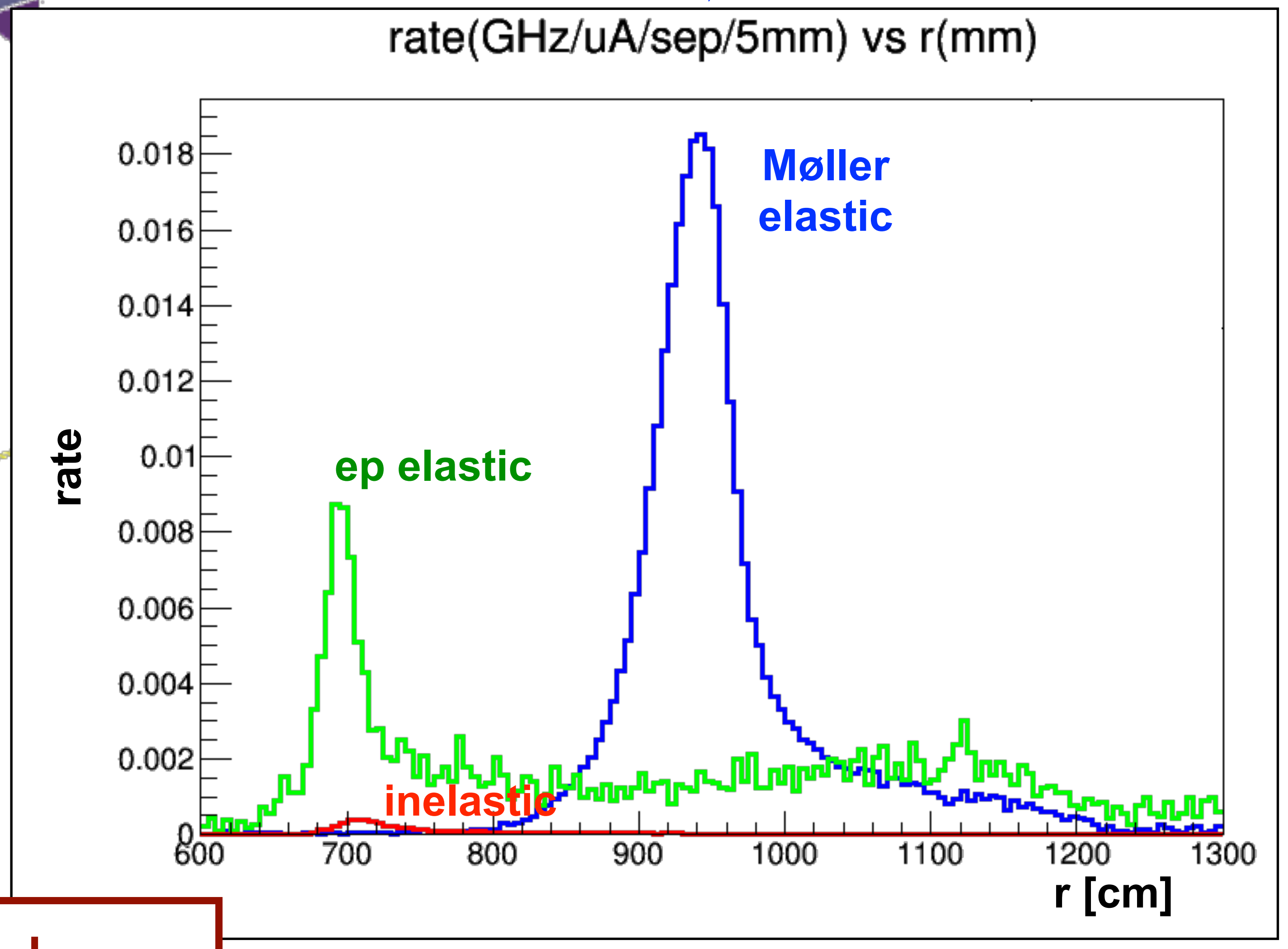
map E-θ correlation for *ee* scattering to detector



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

Acceptance defining collimator

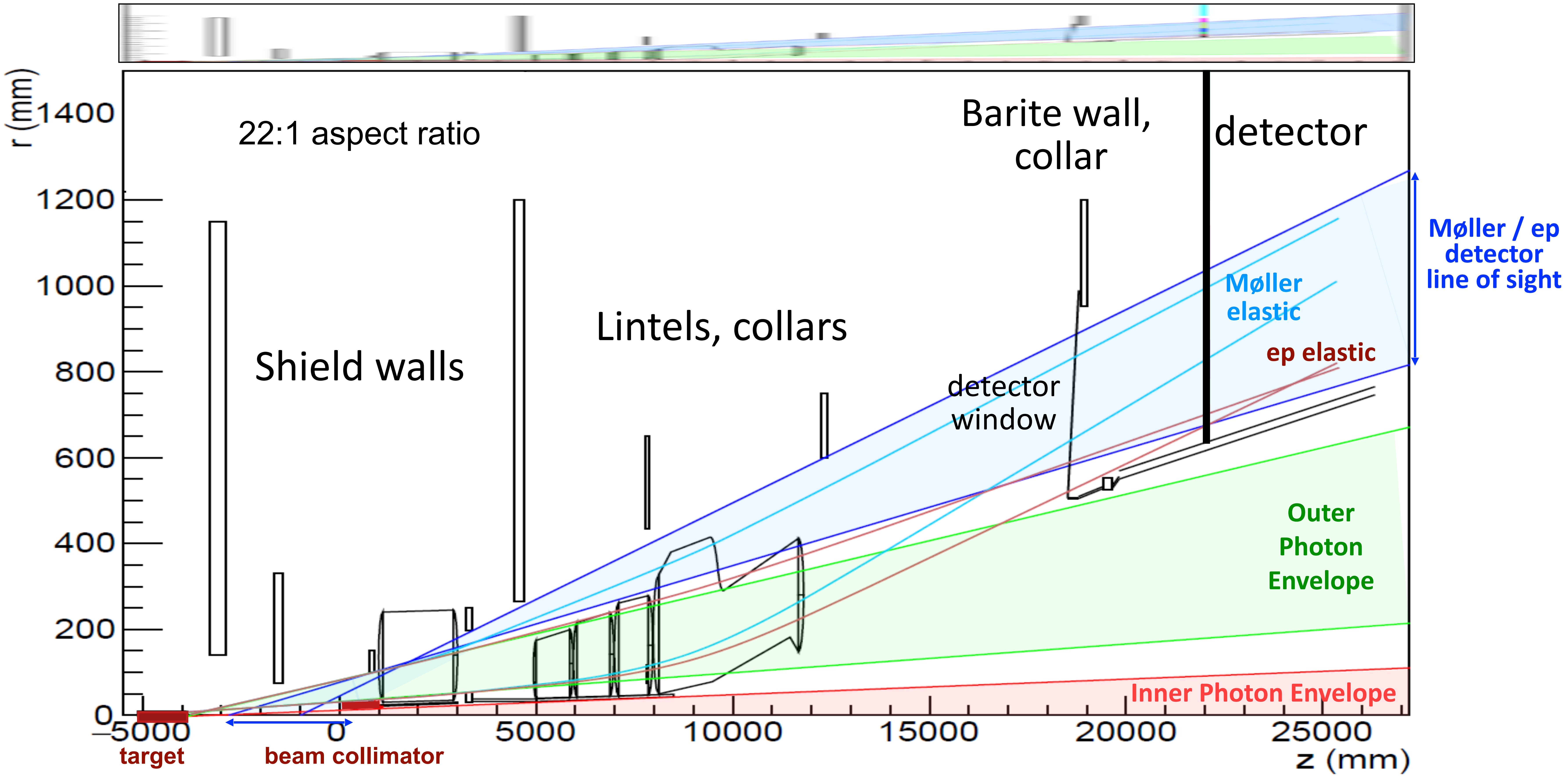




radial flux distribution

Radial field component stretches the larger angles over the azimuth

Spectrometer Conceptual Function



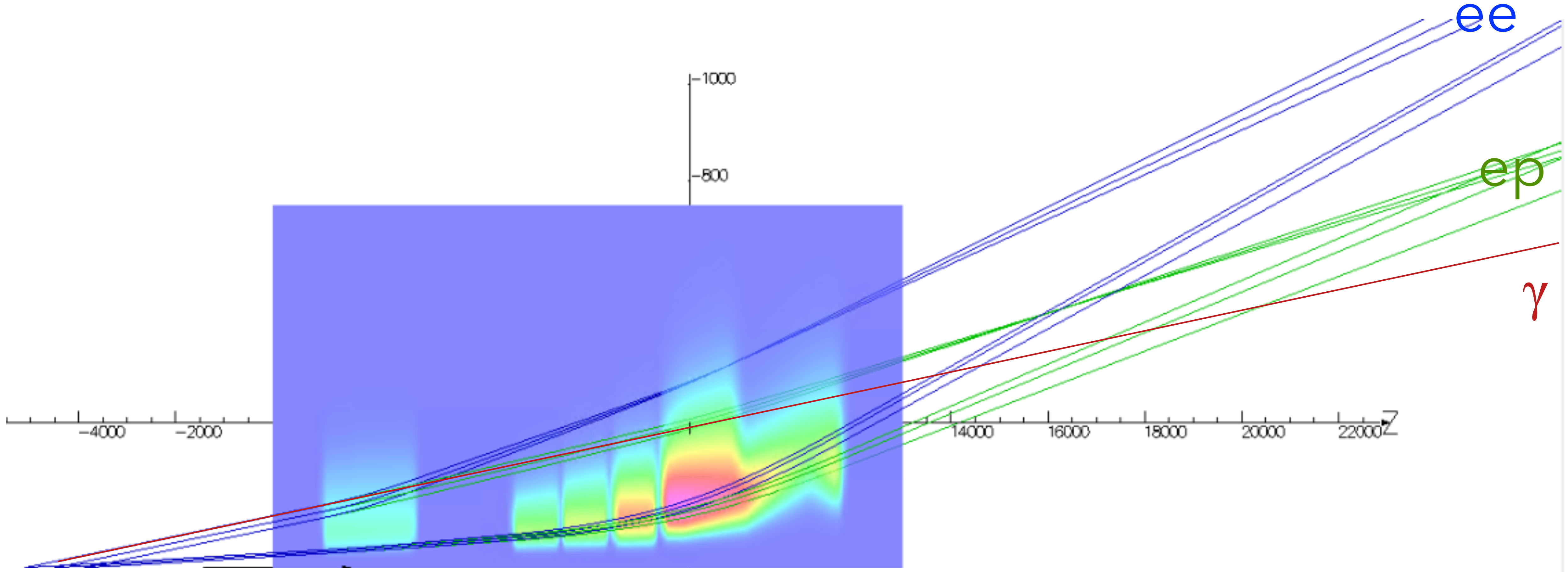
Irreducible background: radiated and/or inelastic ep or aluminum scattering, pions

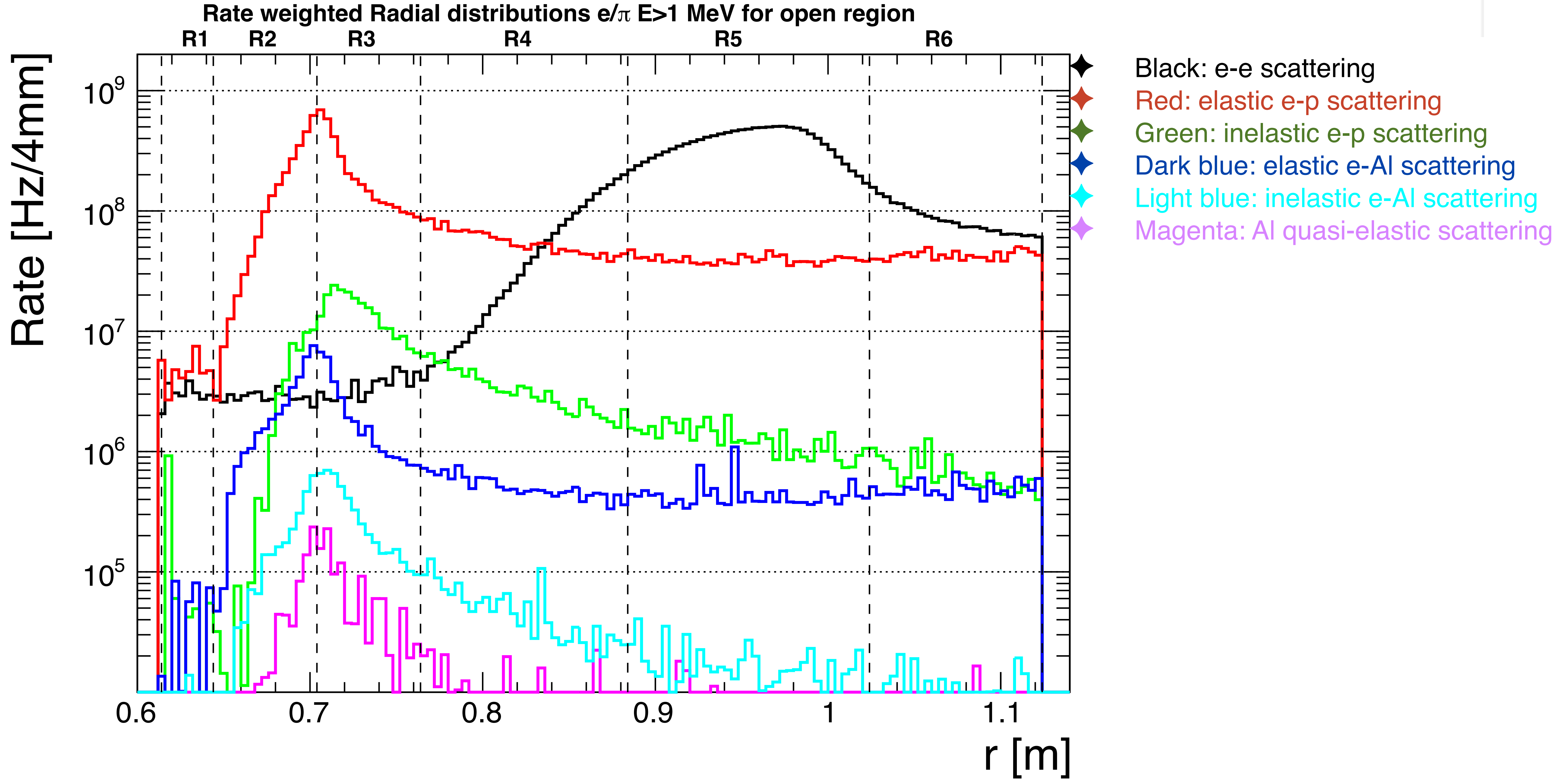
Reducible background: rescattering from photons (2-bounce design), beam line, or radiative tail *e*± from target

Hygiene on reducible background sources is a major focus

Relatively small "source" terms for re-scattering could create difficult-to-model backgrounds

Background deconvolution



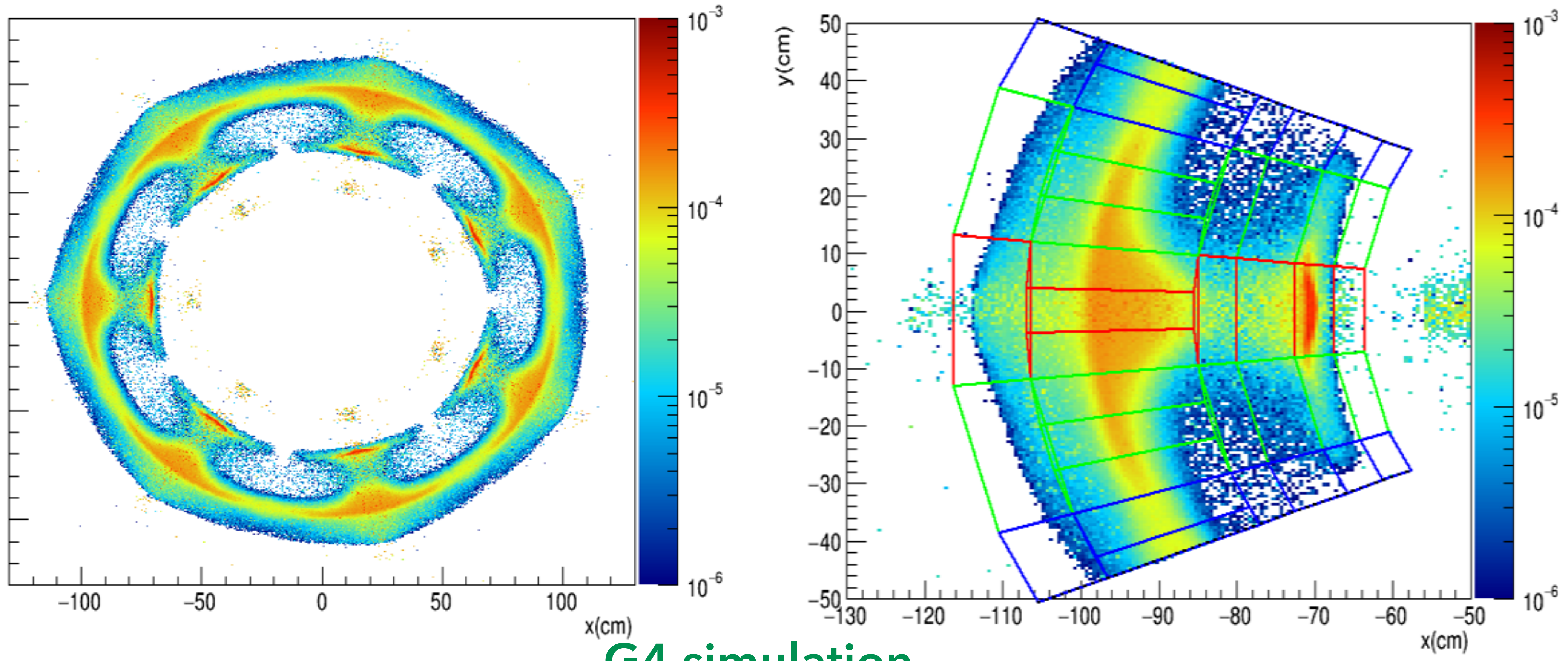


G4 simulation

Each detector septant segmented (radial,azimuthal)

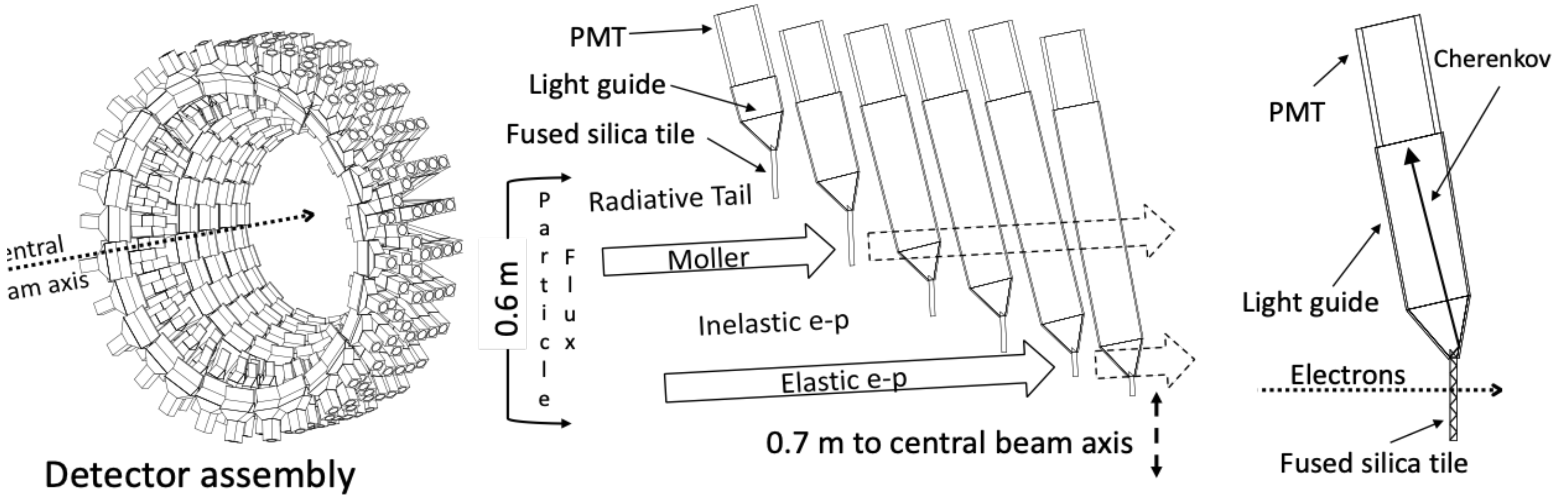
Wide variation in relative rates of various scattering processes

1) e-e 2) elastic e-p 3) inelastic e-p 4) e-Al



G4 simulation

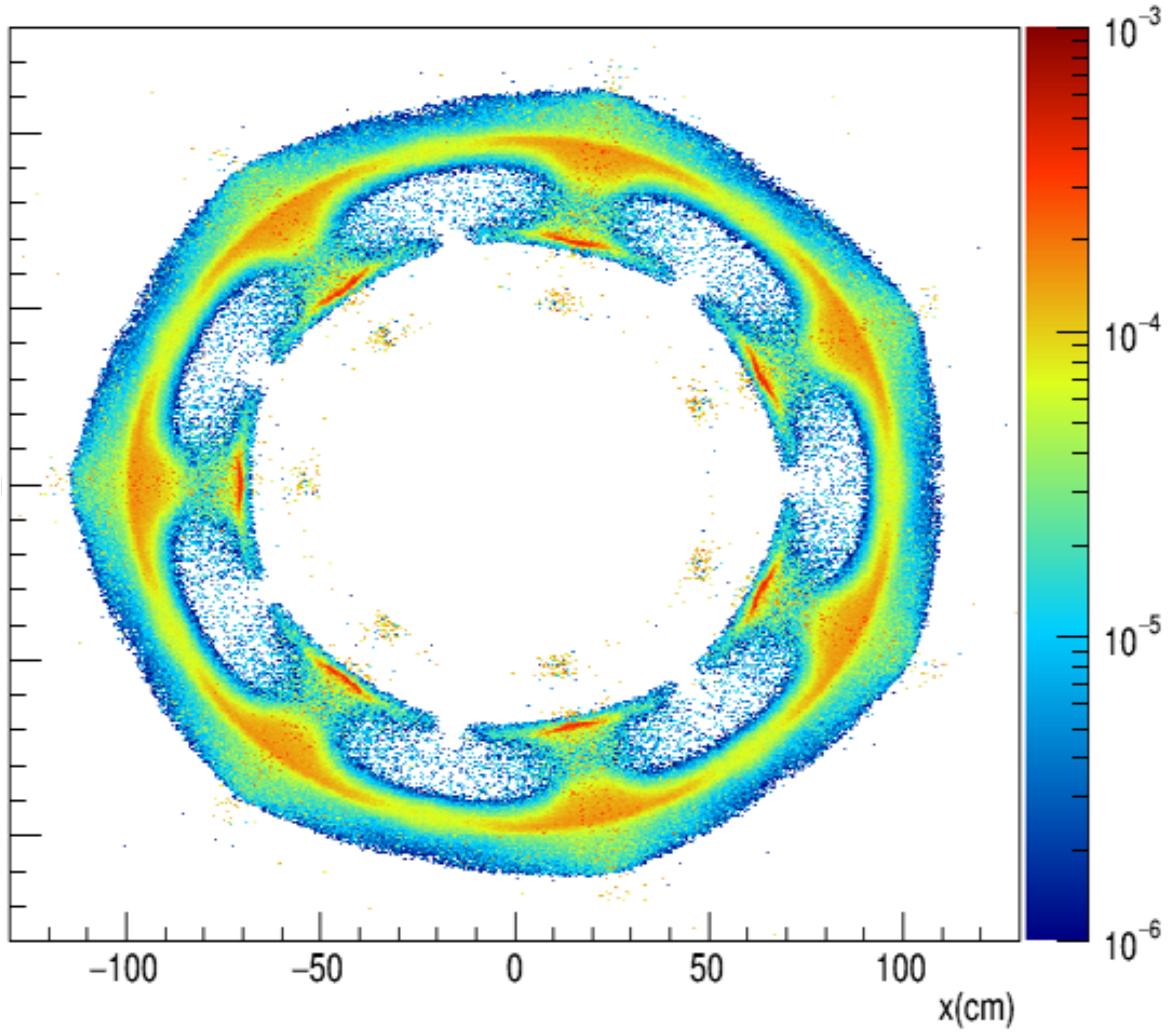
Both radial and azimuthal segmentation in scattered flux measurements required

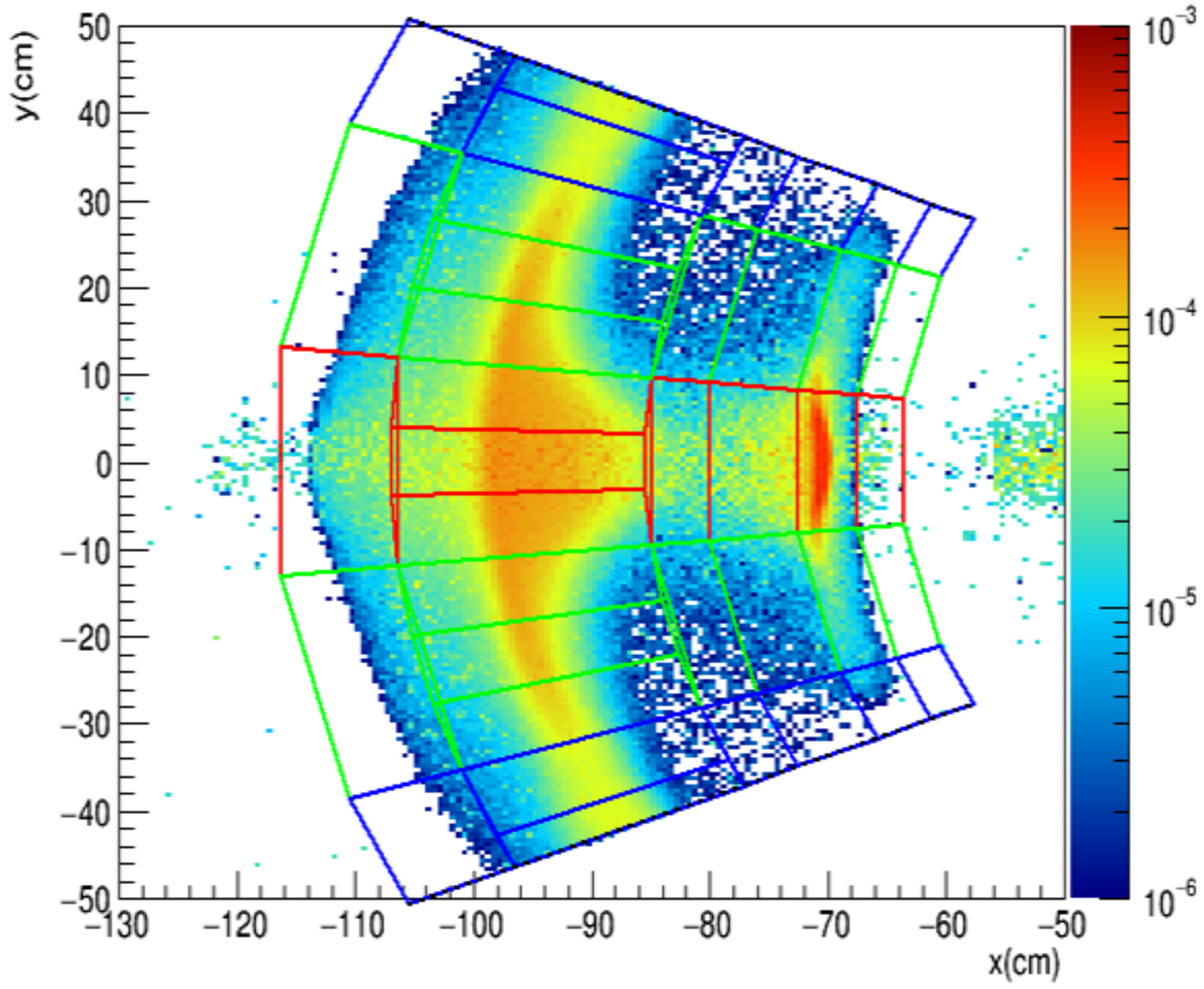


thin quartz Cerenkov detectors are insensitive to soft backgrounds

Flux Distribution

- The MOLLER acceptance derives from the acceptance-defining collimator
- The accepted flux is well contained within detectors
- The field is generated by coil currents, with no ferrous materials
- Field gradients are modest in the region of accepted particles, so position sensitivity is low
- Acceptance, normalization, and irreducible backgrounds are not highly sensitive to precise location of coils
- Edges of acceptance (clipping in the spectrometer) and rescattering in the beamline (uncancelled fringe fields along the beam axis) dominate alignment tolerance for spectrometer components

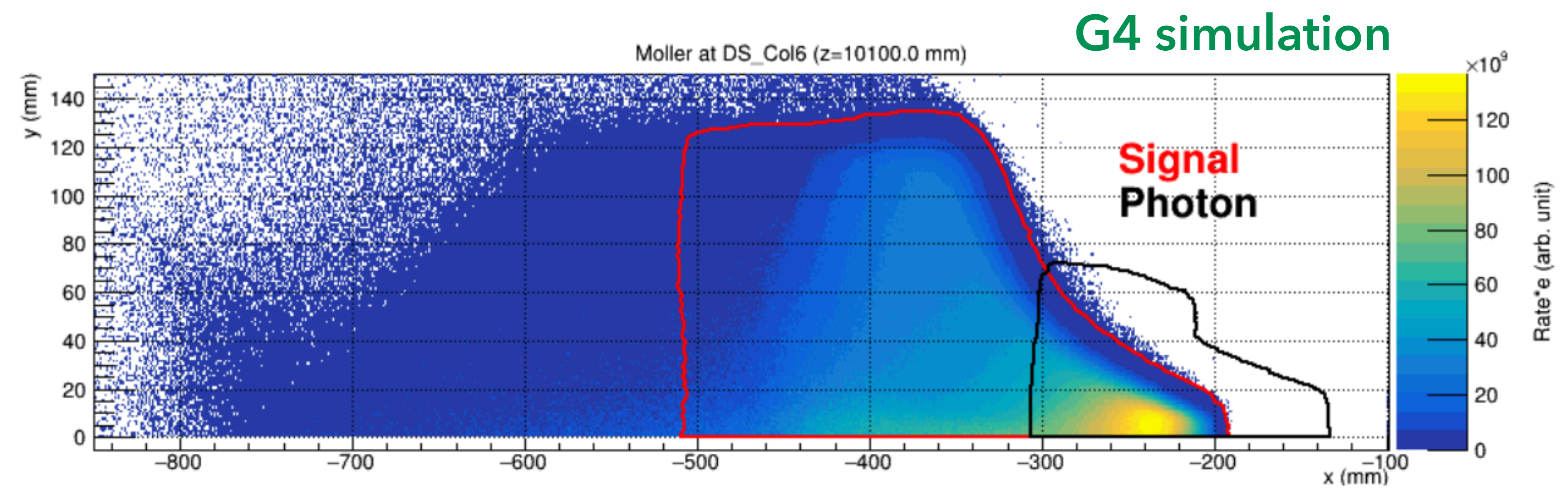


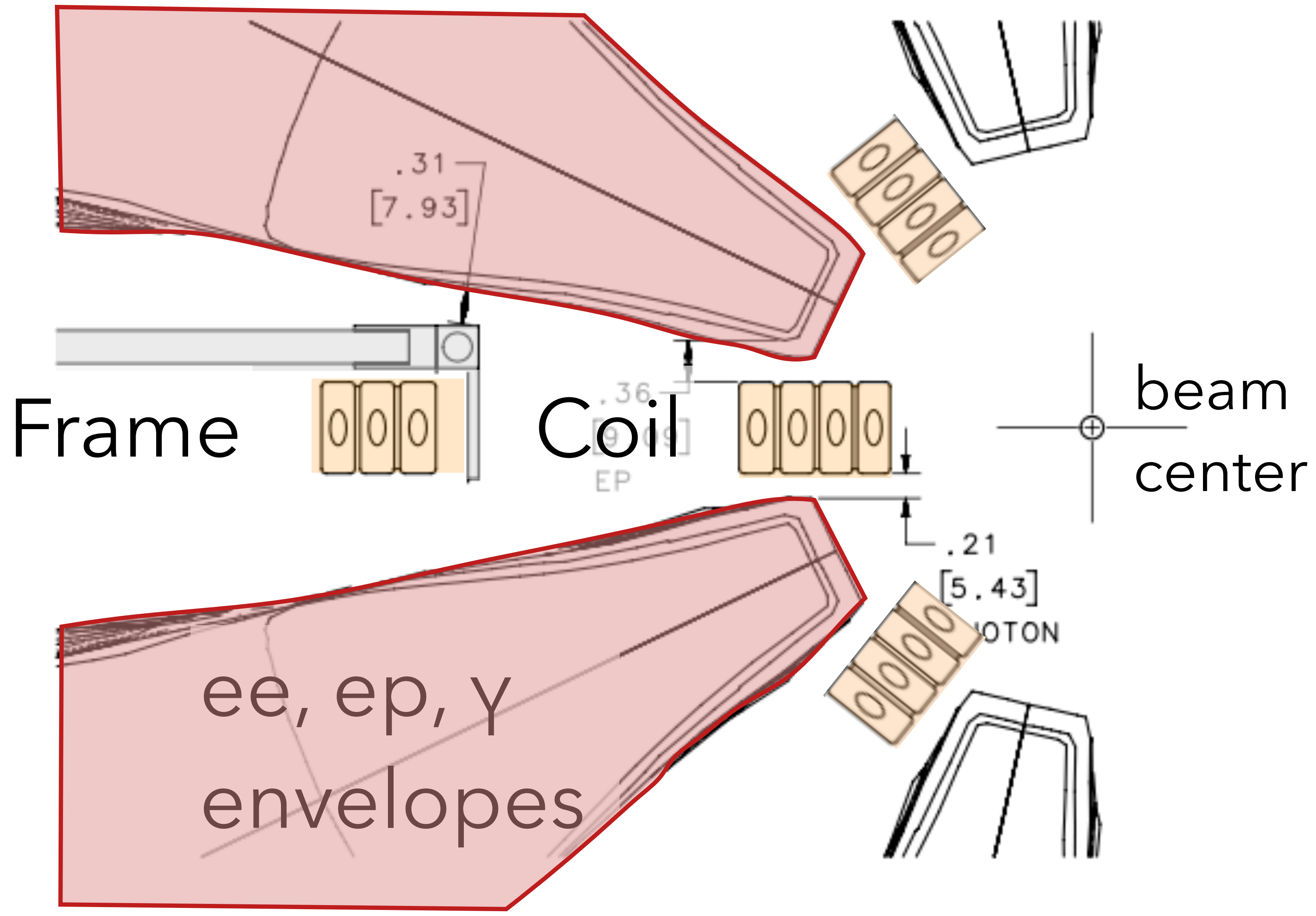


Envelopes

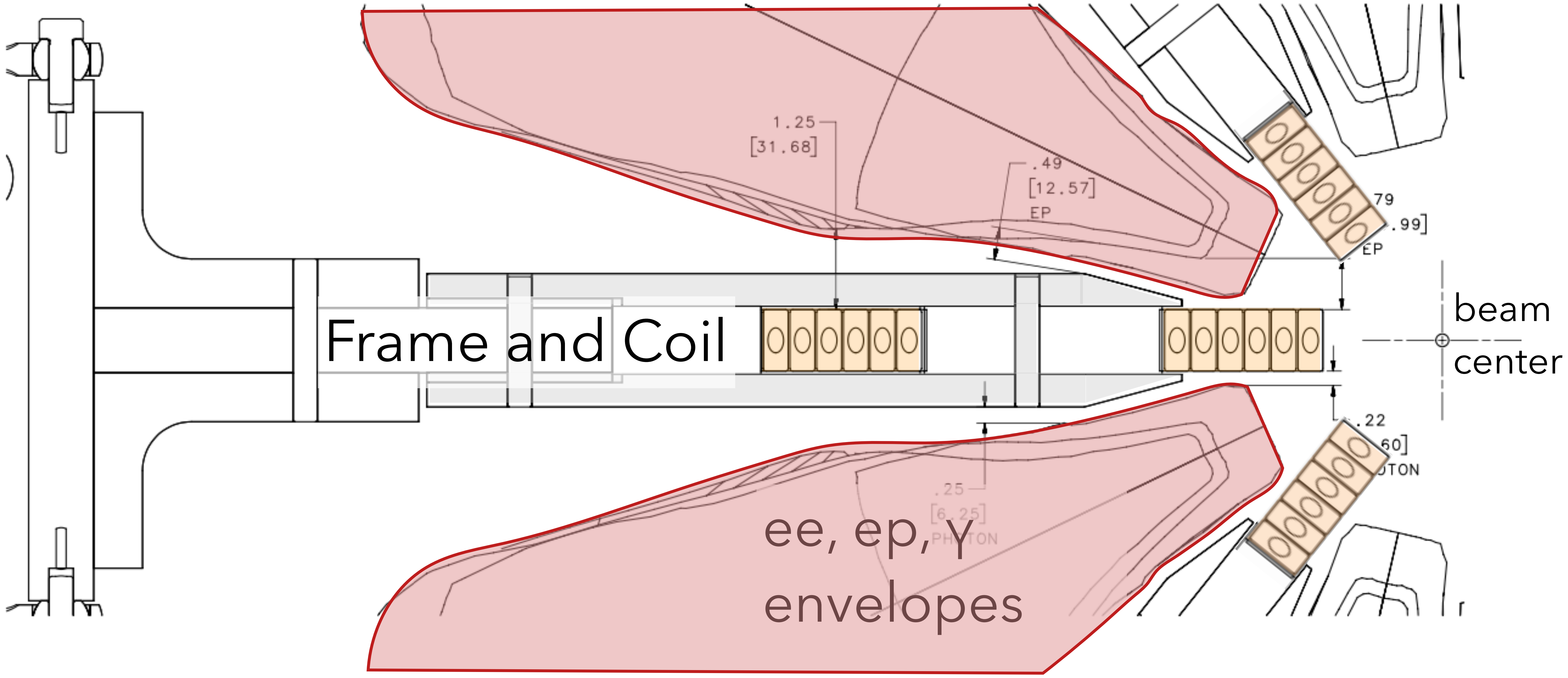
Engineering has been guided by “envelopes” of simulation *ee*, *ep*, and photon distributions as they traverse the spectrometer (demarcated at 0.1% of maximum flux).

This identified open regions for support structures, visualized tolerance for acceptance path and identified regions of close approach for further study.



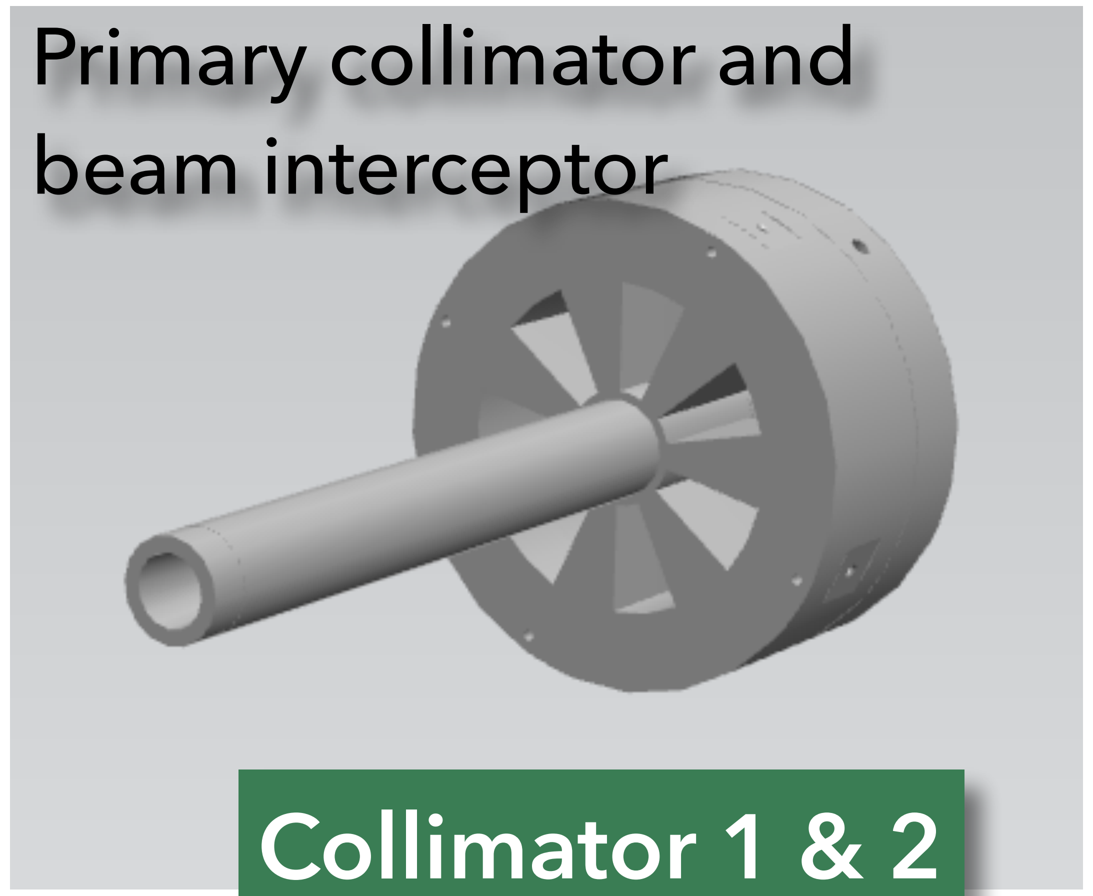


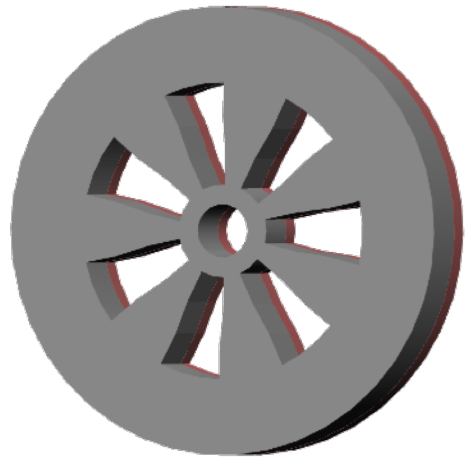
TM1



TM3

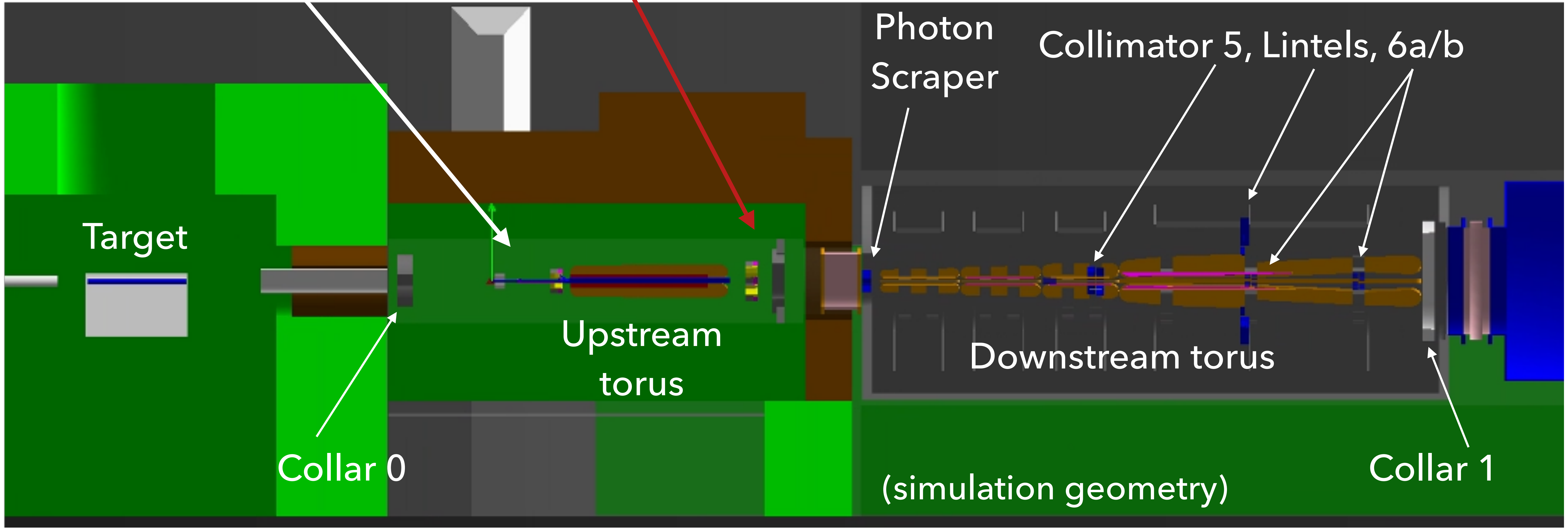
Collimation





Design optimized with

- “2-bounce” principle: rays from the target cannot illuminate a surface with line of sight to the detector
- G4 simulation of rescattered backgrounds



collimator	Power@65μA
1: beam interceptor	3500 W
2: primary	950 W
4: cleanup	60 W
Lintels; photon blockers; 6a/b	<55 W each

Ferrous Materials

Double-spin ee or γe scattering from ferrous material can have large asymmetry.

Goal: $A_f < 10^{-11}$

Estimate false asymmetry A_f as

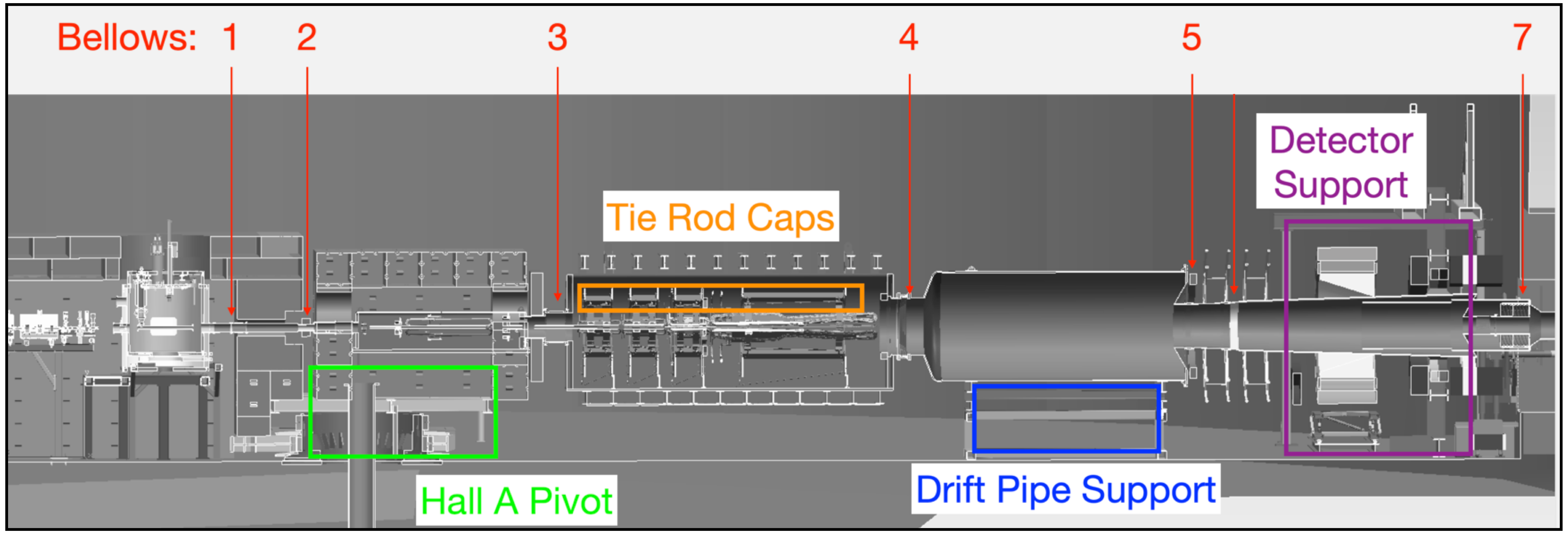
$$A_f = f_r P_e P_s A_n$$

f_r rate fraction of process
P_e incident electron polarization
P_s material electron polarization
A_n analyzing power

Conservative estimates: $A_n \sim 10^{-3}$, $P_e \sim 0.3$ - 1

P_s in ~1G ambient field:

- mild steel: $\sim 10^{-2}$
- Stainless steel: $\sim 10^{-5}$-10^{-7}
- Inconel 625: $\sim 10^{-8}$
- Aluminum (paramagnetic): $< 10^{-9}$



$\longrightarrow$ **f_r bound of 10^{-2} -10^{-9} corresponds to 10^{-6}-10^{-13} absolute rate**

Simulations in G4, using *ad hoc* “biasing” for rare event estimation

Examples: Bellows, pivot and HRS structure, coil support hardware in high fields, rebar, support frames, motors and power supplies, vacuum and water connections

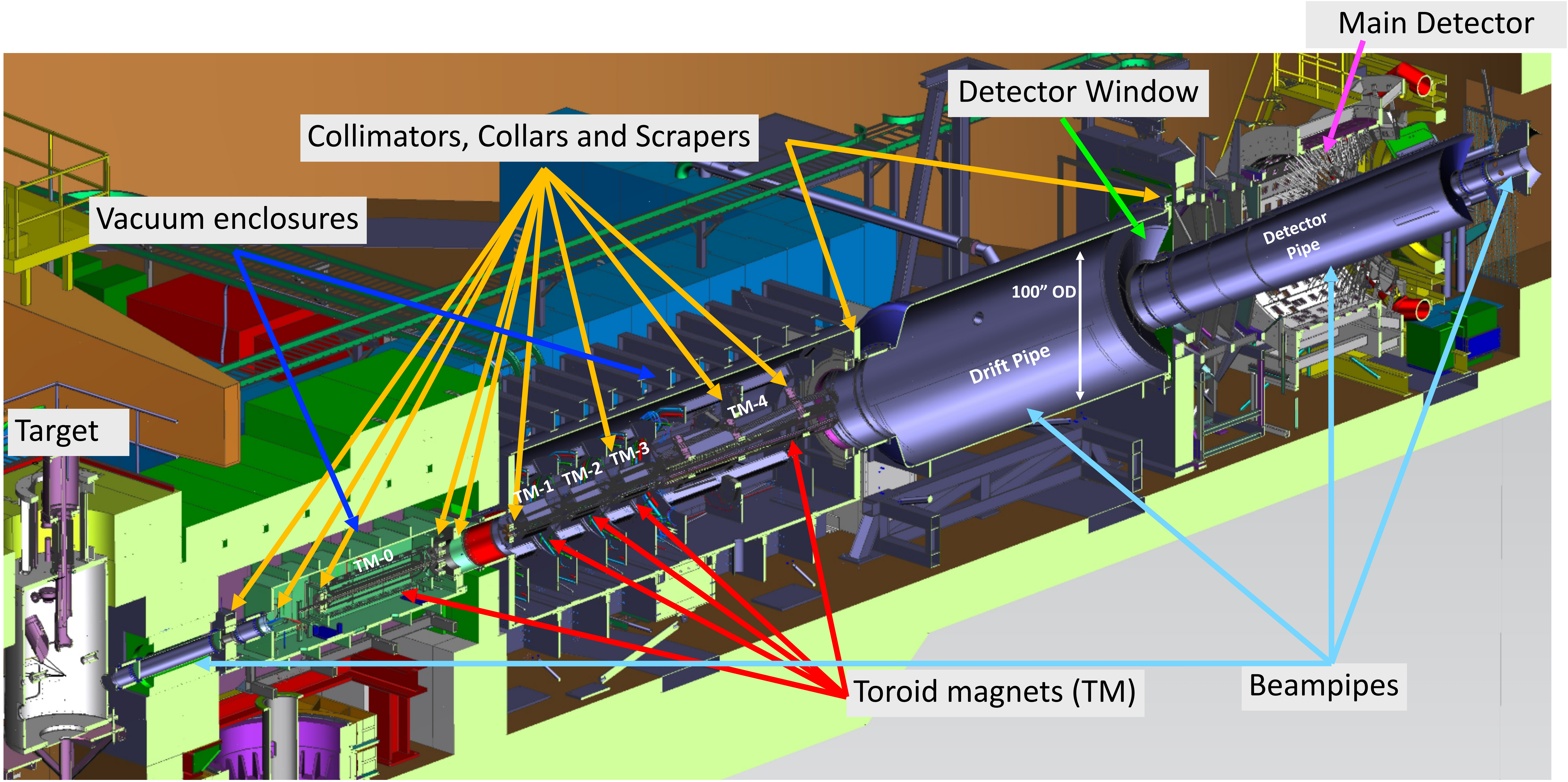
Resulting in: new shielding, materials specifications, and other design modifications to control technical risk

Summary

- The MOLLER apparatus is optimized with an acceptance covering $\theta \in 0.3°$ -1° in angle and $p \in 2.5$-8.5 GeV
- The unusual requirements have led to an unusual configuration, with unusual challenges
- Design has been guided by detailed G4 simulation, both for acceptance and background reduction
- Alignment tolerances mostly driven by edges of acceptance channels and symmetry around the beam axis
- Ferrous components are excluded from high field regions, with careful qualification of any materials with non-negligible magnetic susceptibility

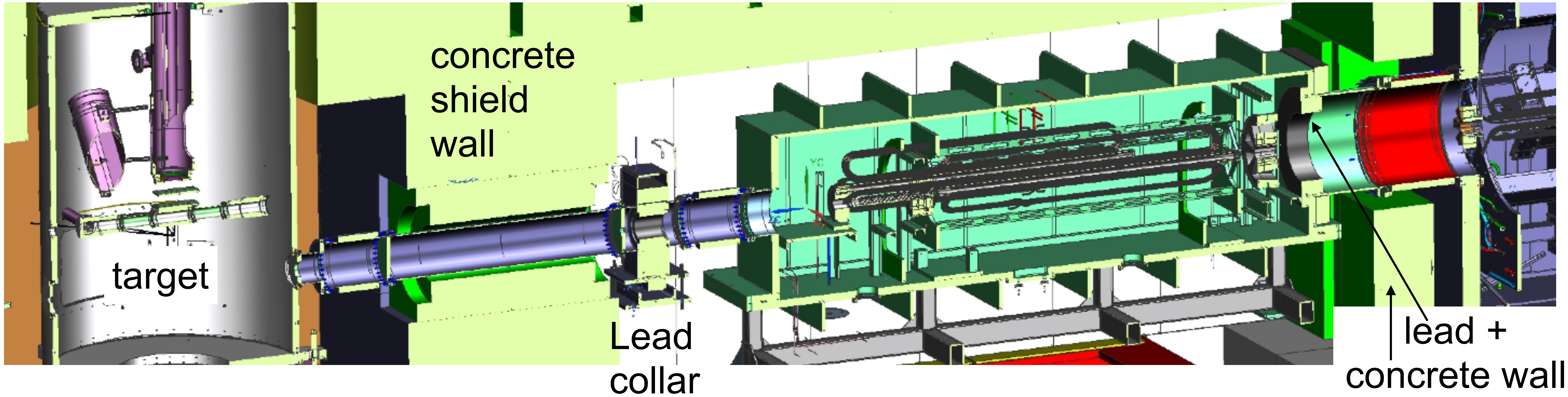
Appendix

MOLLER Apparatus Overview



Collars, walls, Shielding collimators

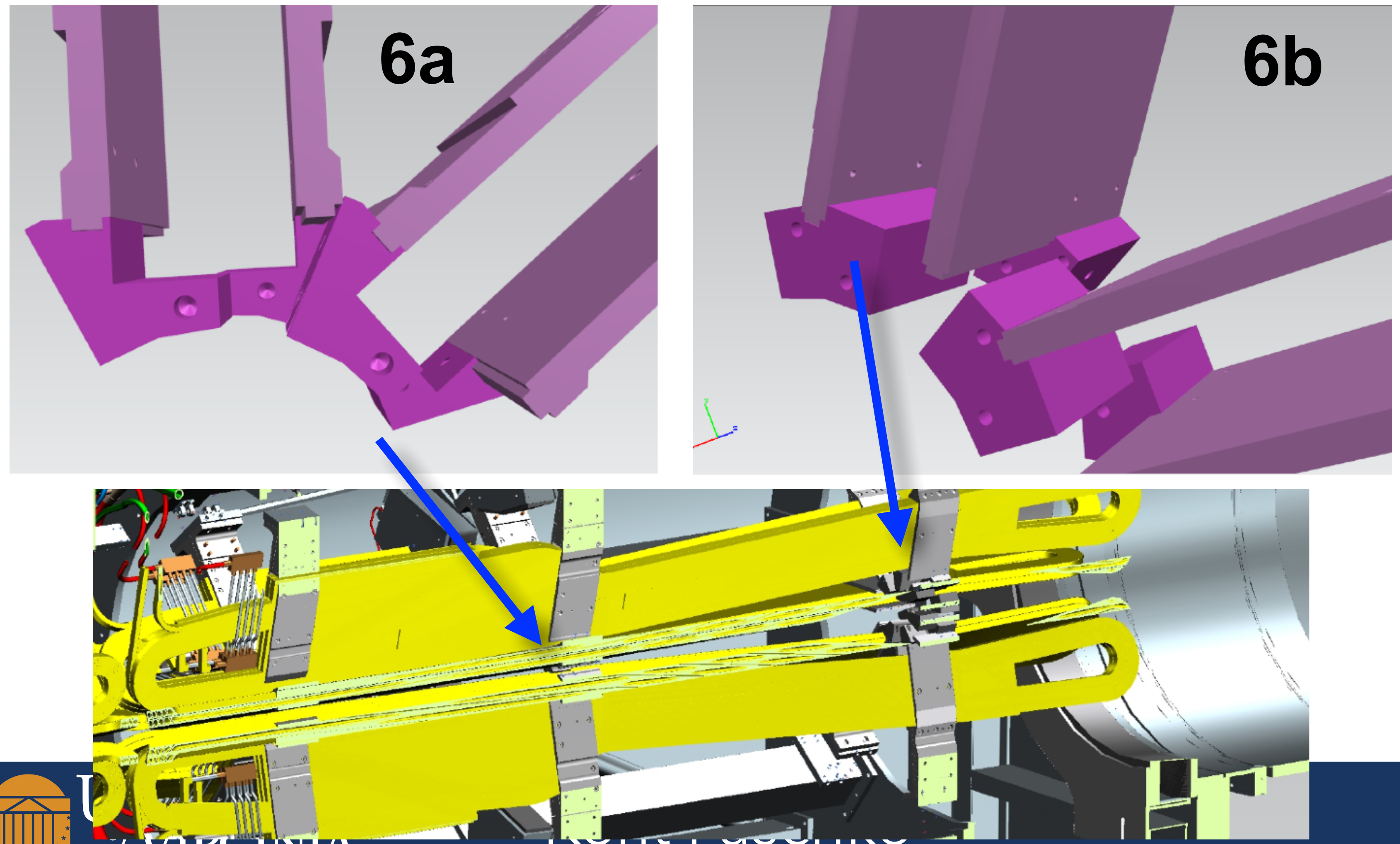
Collars and walls



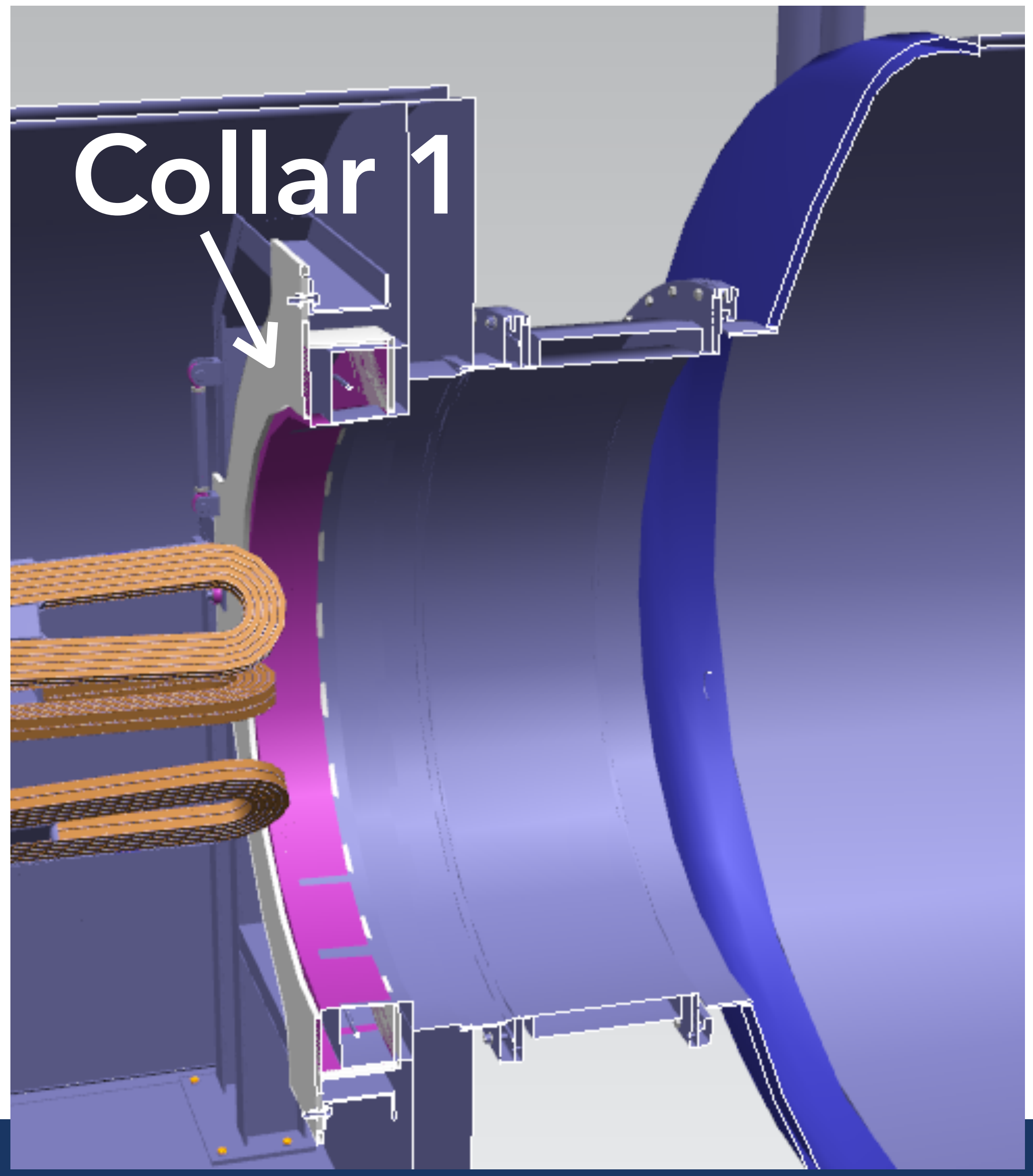
Radiated flux swept out by spectrometer, re-scatters in vacuum enclosures, support structures, etc.

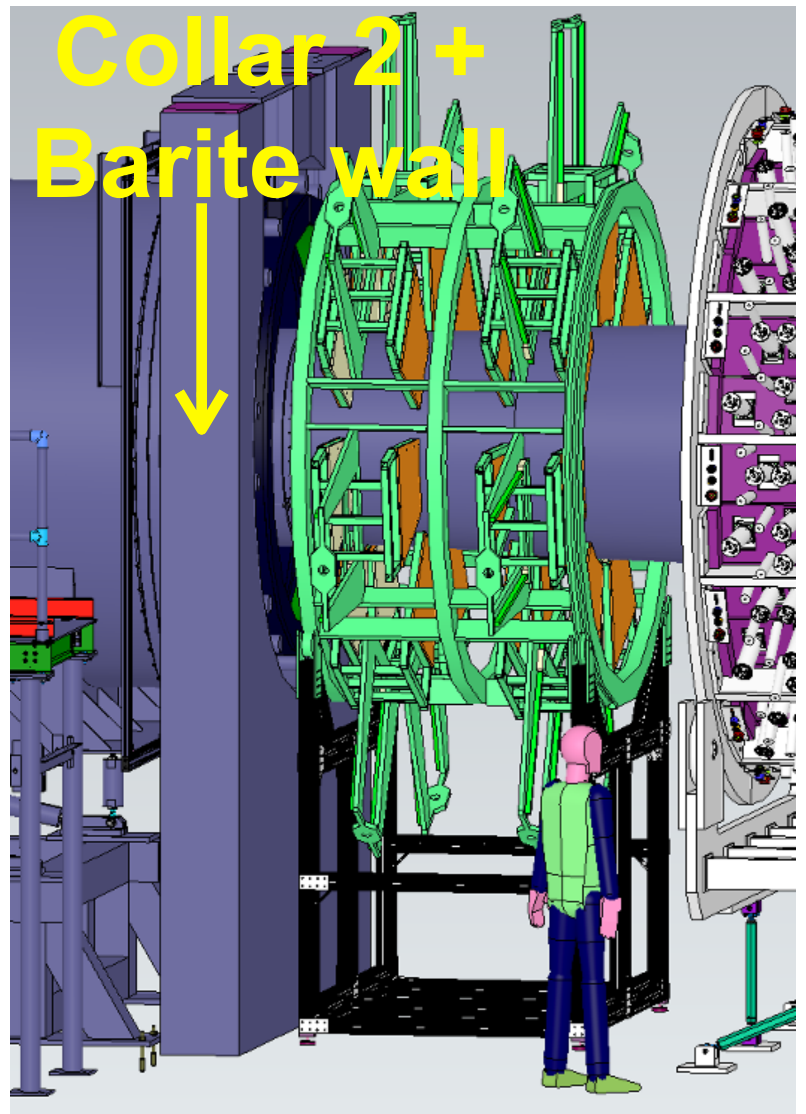
Lead collars and concrete shield walls cut off this background

Collimator 6a/b (coil 4): Intercept off-axis scatters in beampipe that are swept out between coils by magnet fringe fields



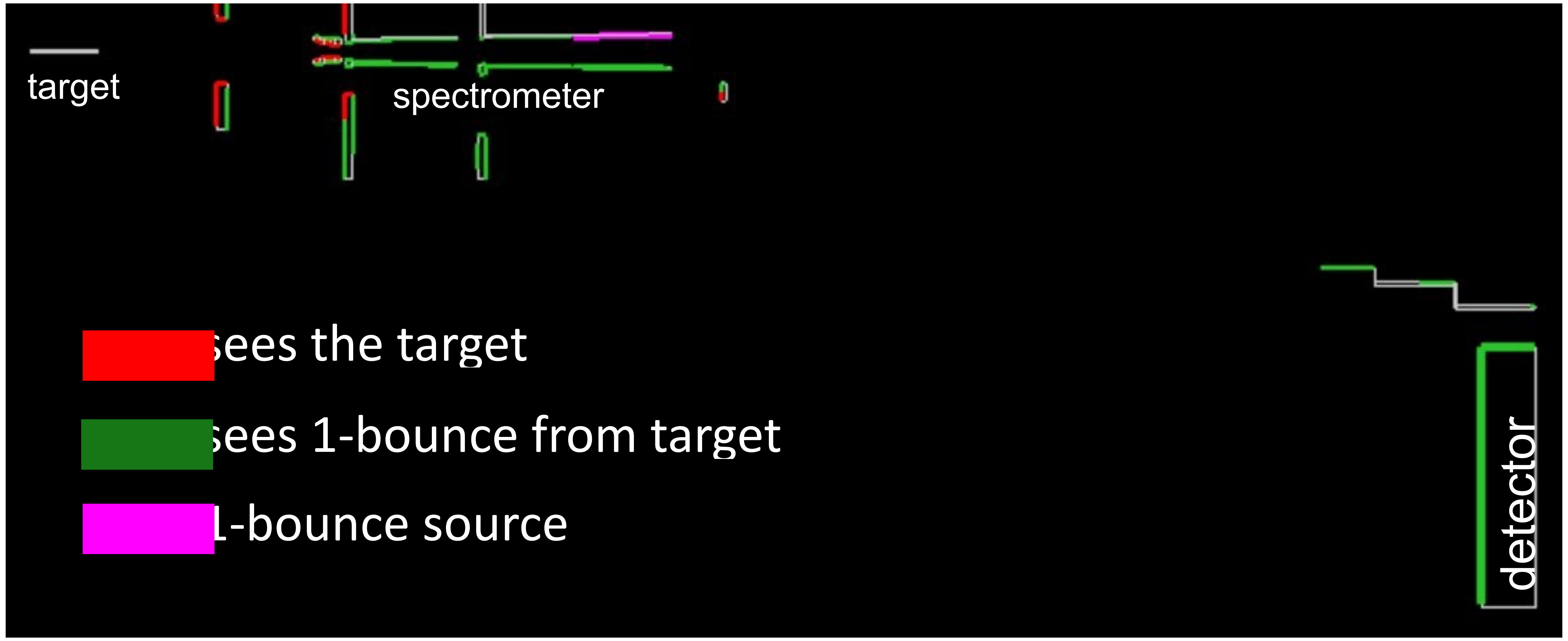
Designed to meet background requirements with magnet alignment tolerance





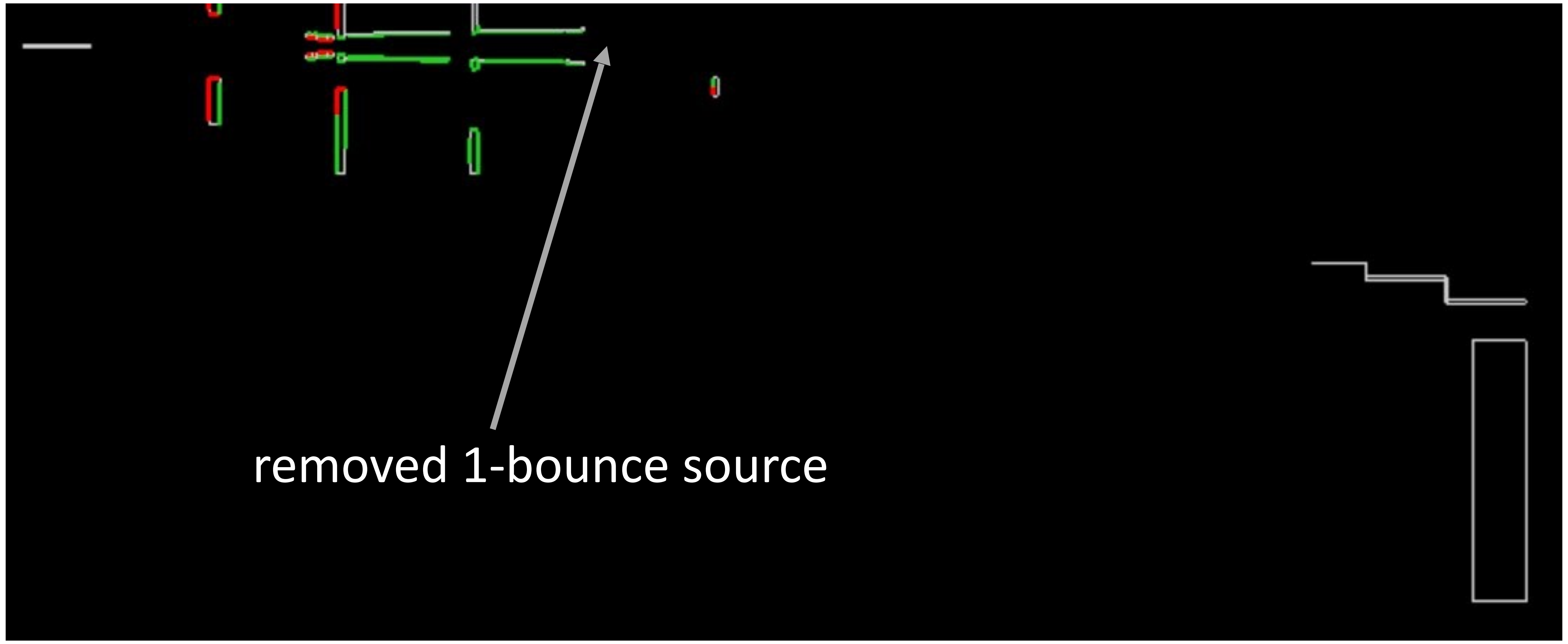
Background Hygiene: design for "2-bounce"

Avoid "1-bounce" line-of-sight to target



- Python code
  - Target, collar, collimators, beam shields, detector (600, 690-1300 mm)
  - Uses straight lines to simulate an isotropic source (with random position, angle)
  - Surfaces that "see" the target (red) become new sources
  - Make it so detectors see no red surfaces

- Tolerance study
  - move the collimators and/or coils by +/-1 mm w/o seeing green on the detectors



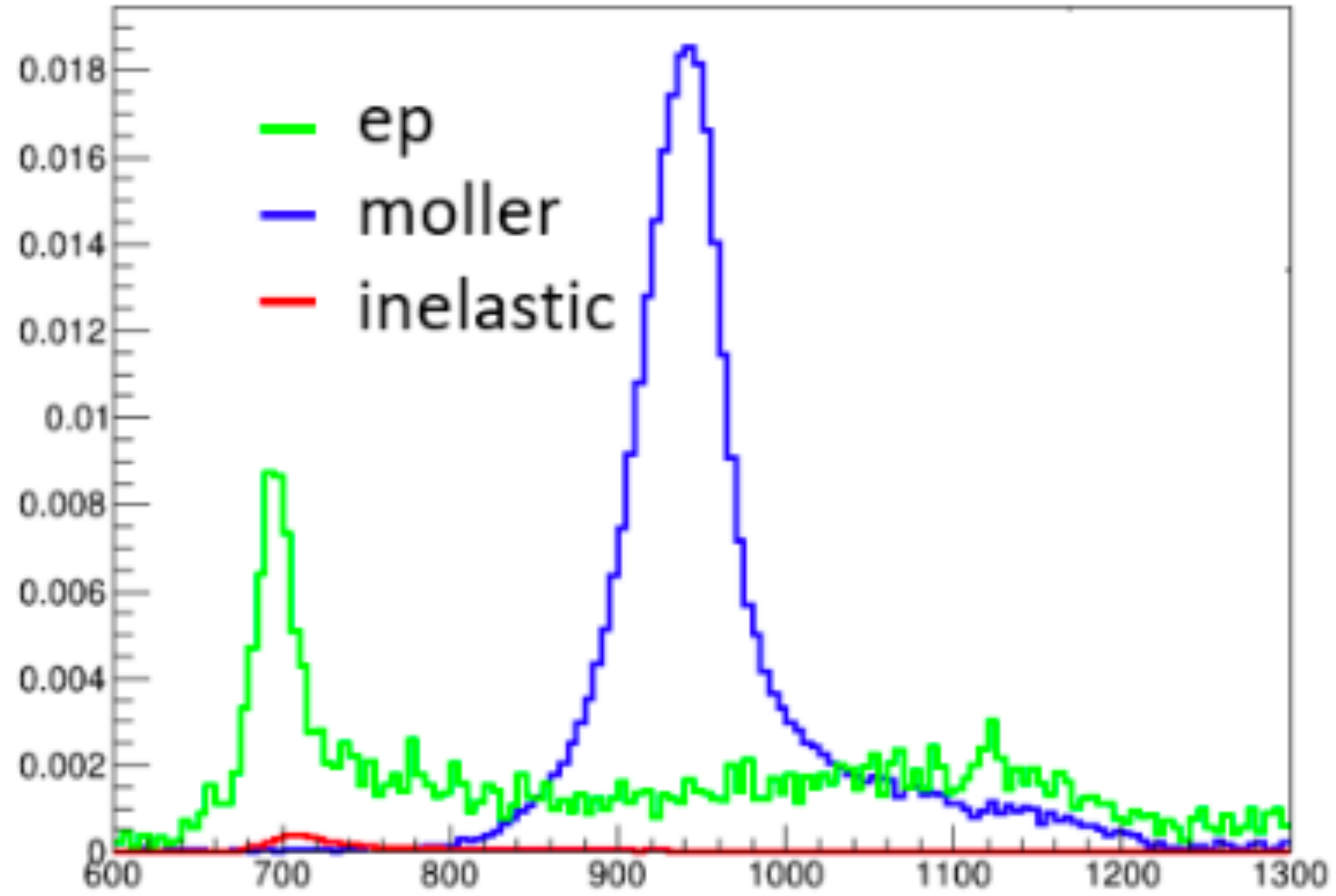
Tracking and Counting detectors

"Event mode" tracking with few nA beam current for:

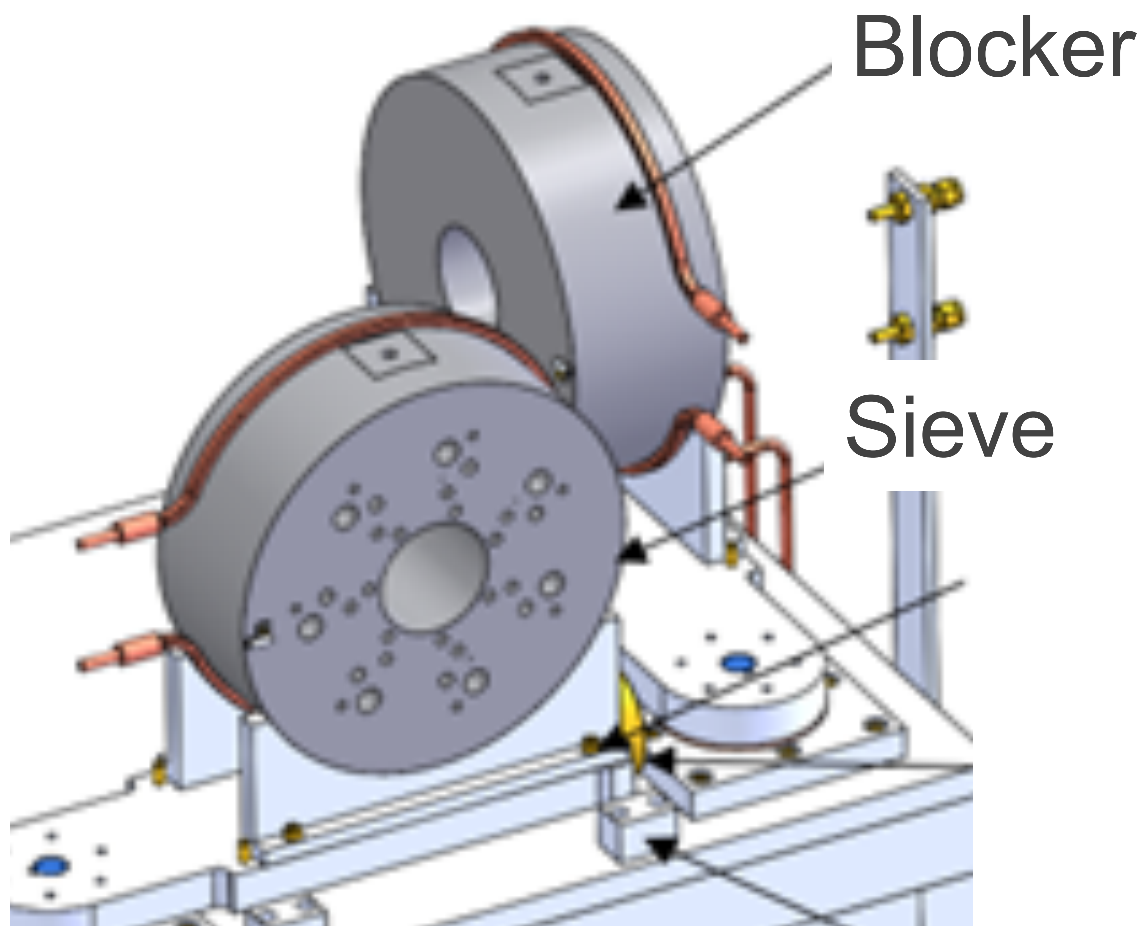
- kinematic weighting in asymmetry interpretation
- Verification of spectrometer optics
- background estimation

$$\mathcal{A} \equiv \frac{mG_F}{\sqrt{2}\pi\alpha} \frac{4E\sin^2\theta}{(3+\cos^2\theta)^2}.$$

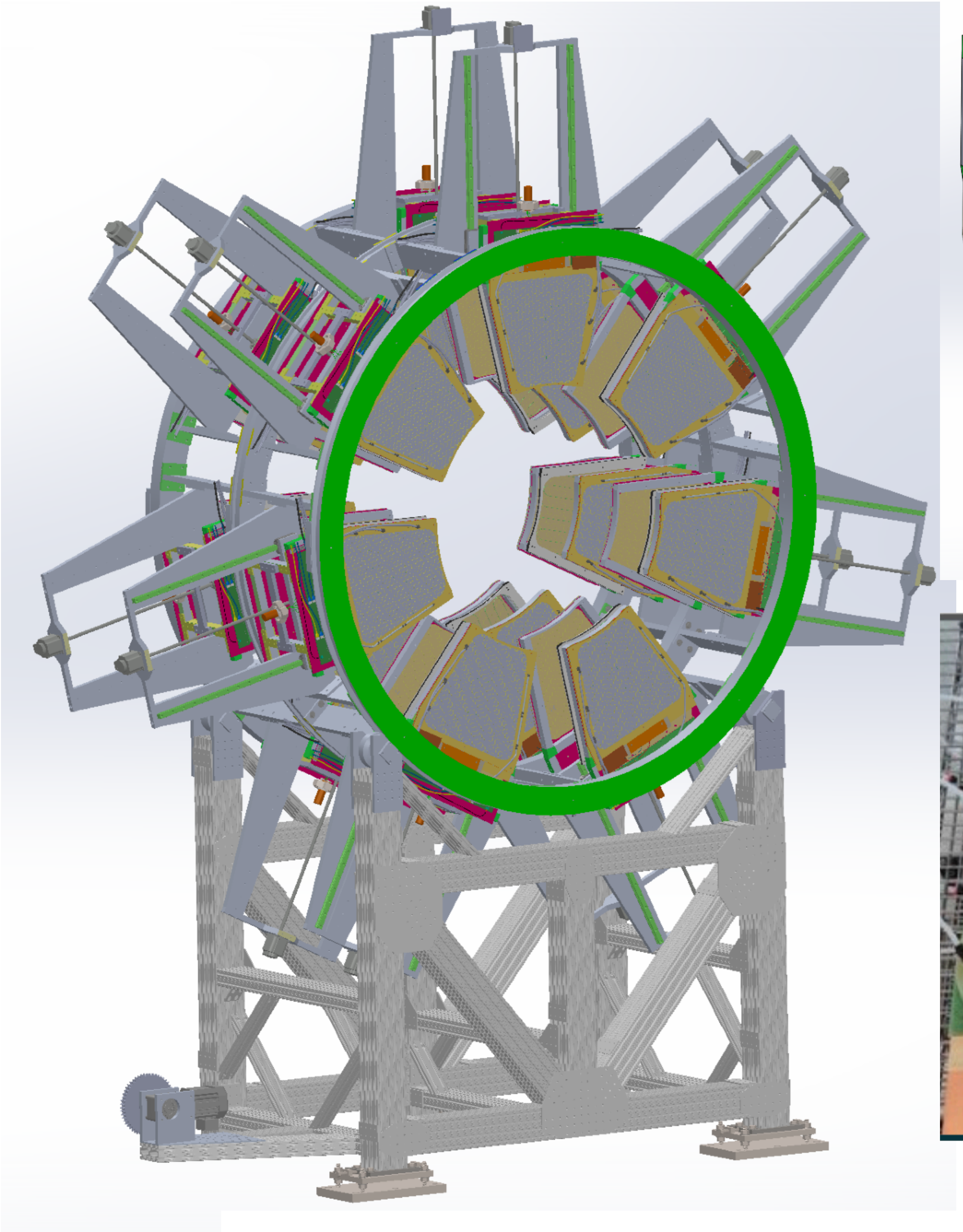
Verify design acceptance model

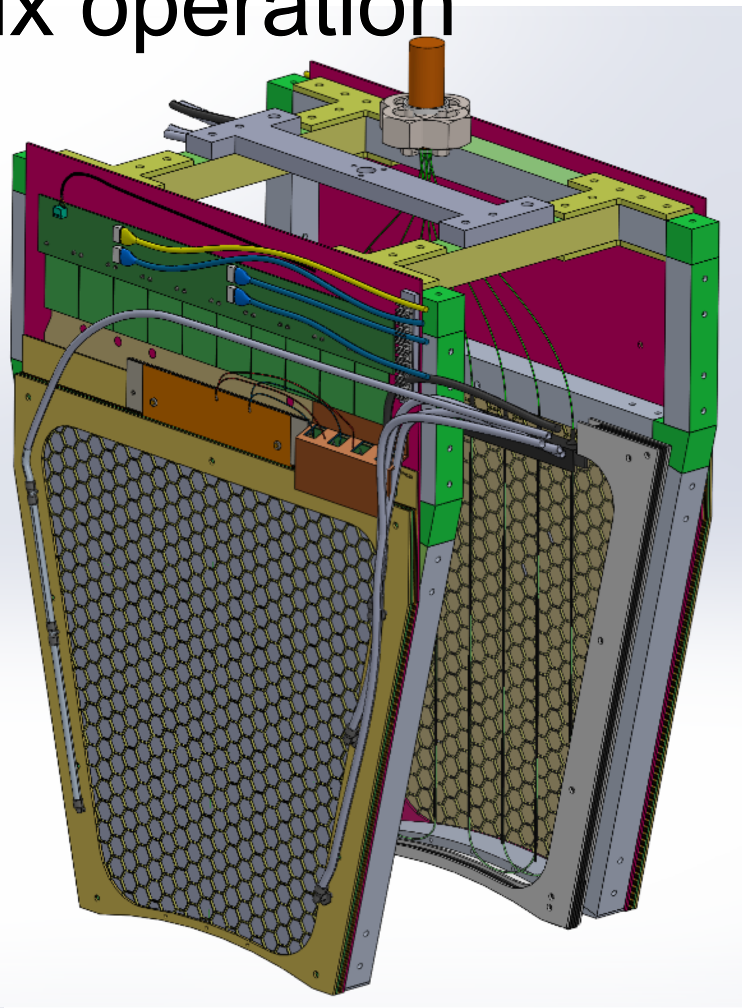


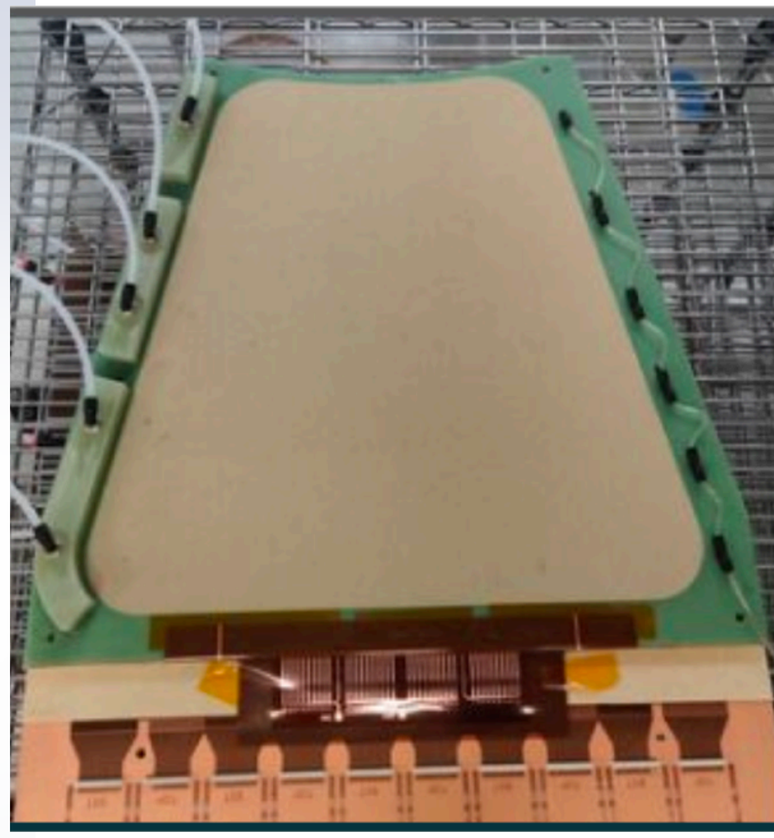
Calibration using insertable sieve blocker



GEM chambers and trigger scintillators inserted for calibration, removed for high flux operation

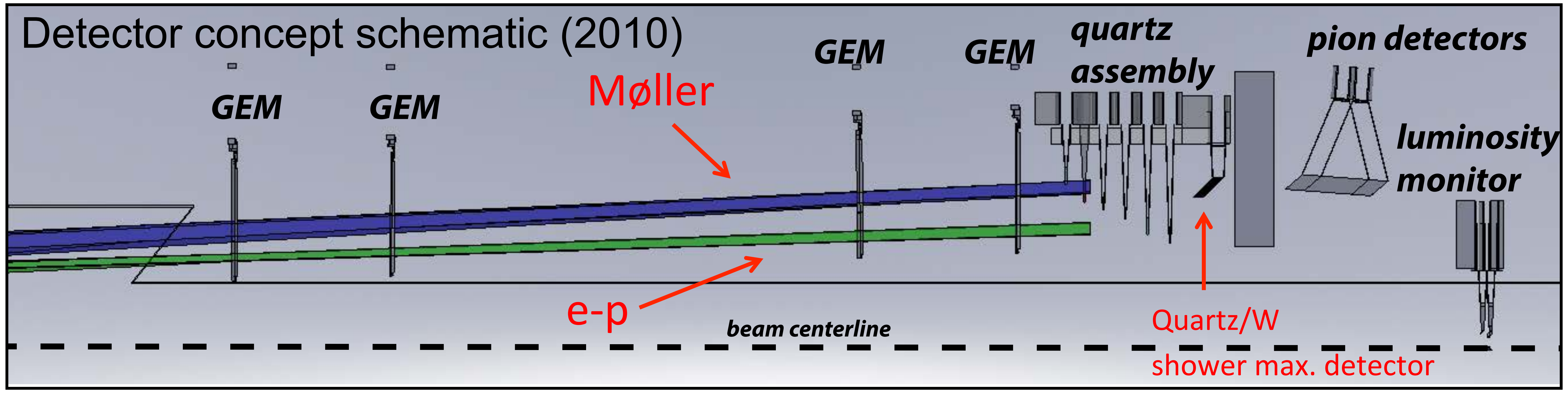






Integrating detectors also operate in a triggered "event mode" for calibration

Detector Package



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

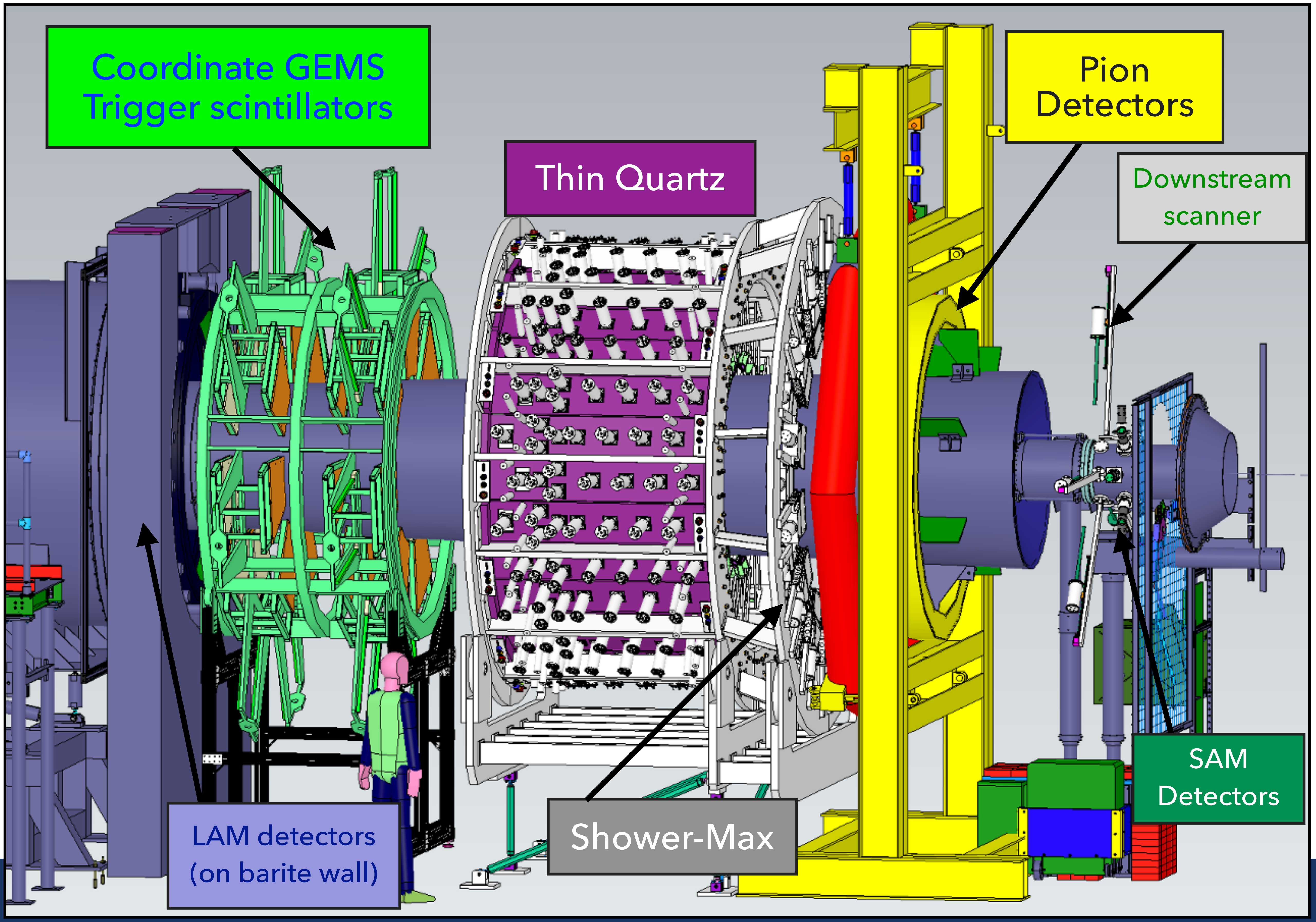
Auxiliary detectors for background and calibration studies

- 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; have a redundant way to measure this asymmetry

- 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 asymmetry in the Møller ring

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



Background deconvolution

$$A_{PV} = \frac{\frac{A_{expt}}{P_b} - f_b A_b}{1 - f_b}$$

Radial / Azimuthal binning - measures backgrounds under the Møller peak

- Elastic ep: ~10% of the signal, asymmetry is well known
- Inelastic ep: <0.3% of the signal but asymmetry ~20x larger, not well known
- The inelastic contribution is prominent in rings 2 and 3, will be measured there