Acknowlegements:
The E158, HAPPEX, PREX, CREX and MOLLER Collaborations

Many thanks to numerous collaborators for ideas, photos, slides, text….

Overview of the MOLLER Experiment at Jefferson Lab

Status and Auxiliary Measurements

Krishna Kumar
University of Massachusetts, Amherst

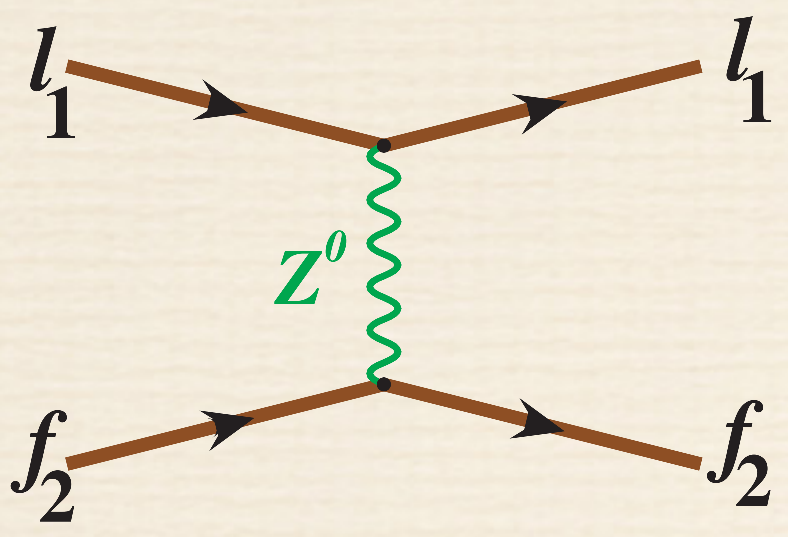
Marciana 2025, Elba
June 23, 2025

Outline

- **Introduction to Parity-Violating Electron Scattering (PVES)**
  - ***Historical Perspective on Neutral Weak Interactions***
- **The MOLLER Experiment**
  - ***Unprecedented Sensitivity to Beyond the Standard Model Physics***
  - ***The Experimental Design***
  - ***Status of the Construction Project***
- **Some “Lepton-Nucleus” MOLLER topics**
  - ***PV electron-proton inelastic scattering at very forward angles and high W***
  - ***Potential Transverse Asymmetry (AT) Measurements***
  - ***New JLab Experiment Approved to address the PREX AT puzzle: PR-12-24-007***
- **Summary and Outlook**

Introduction to Parity-Violating Electron Scattering (PVES)

Semi-Leptonic and Leptonic Weak Neutral Currents at $Q^2 \ll M_Z^2$



✦Neutrino Scattering
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- *opposite parity transitions in heavy atoms*
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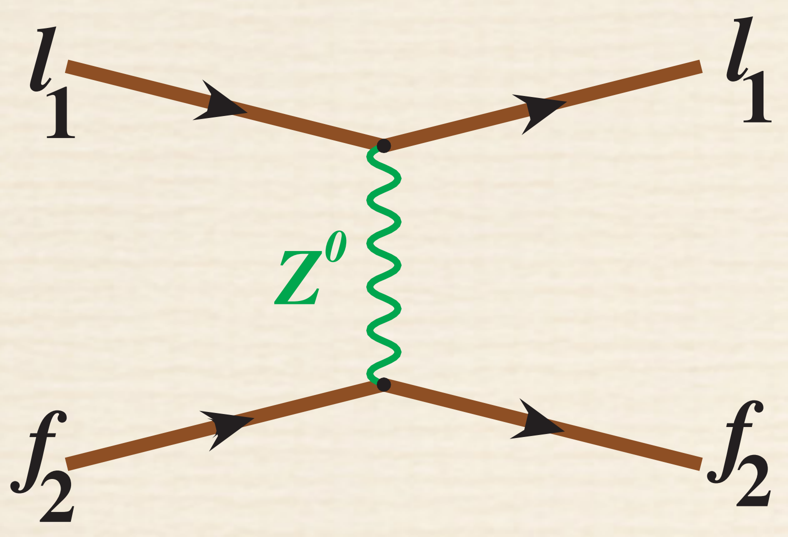

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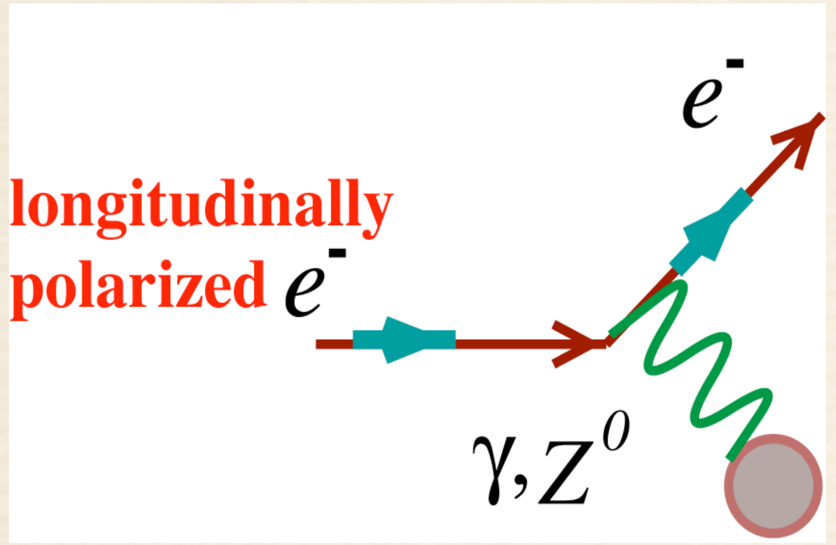

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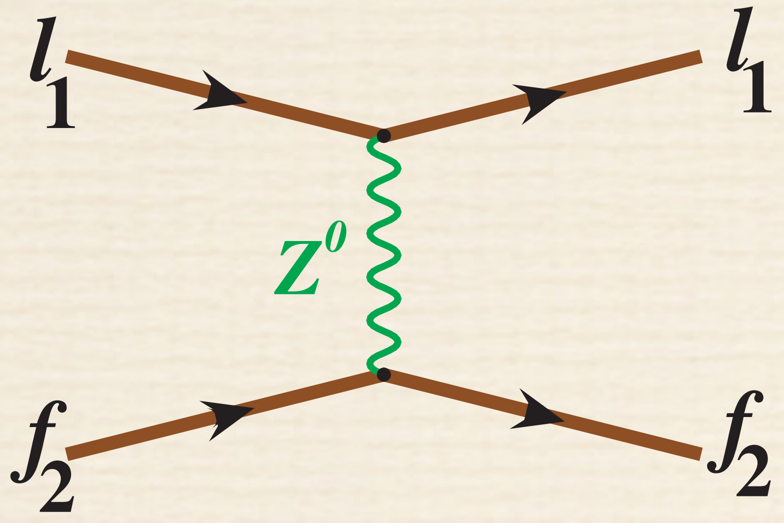

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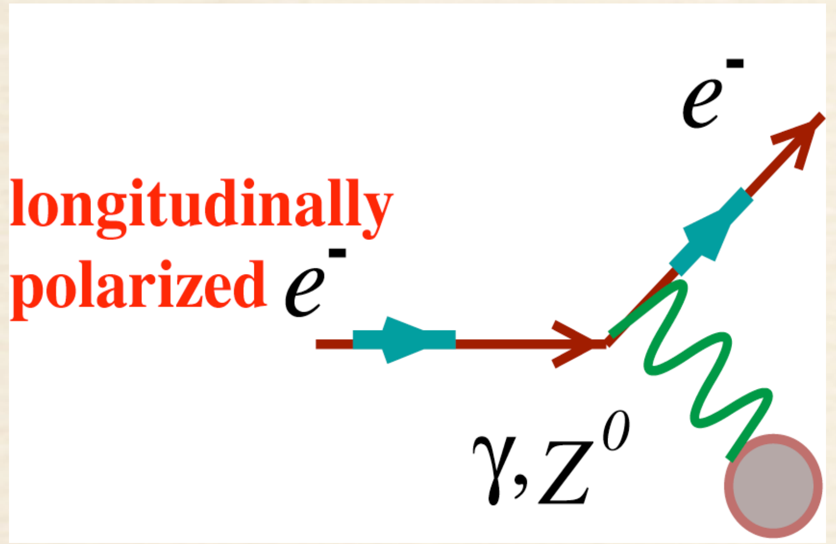

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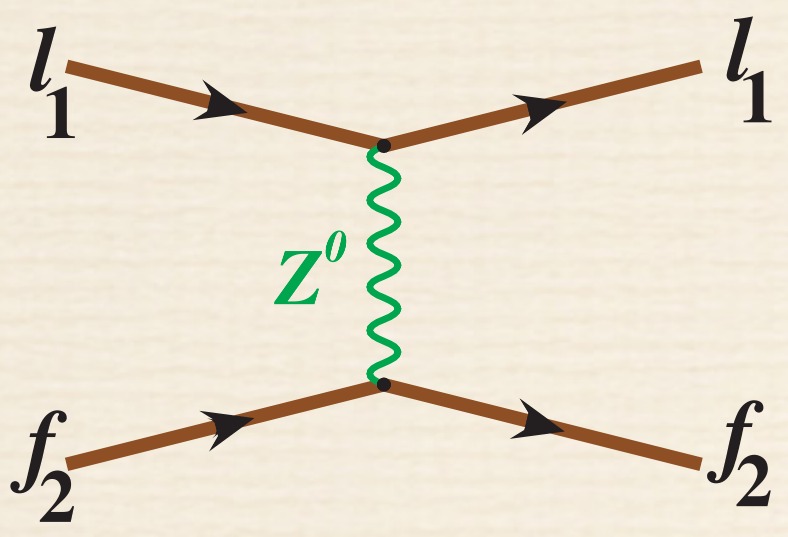

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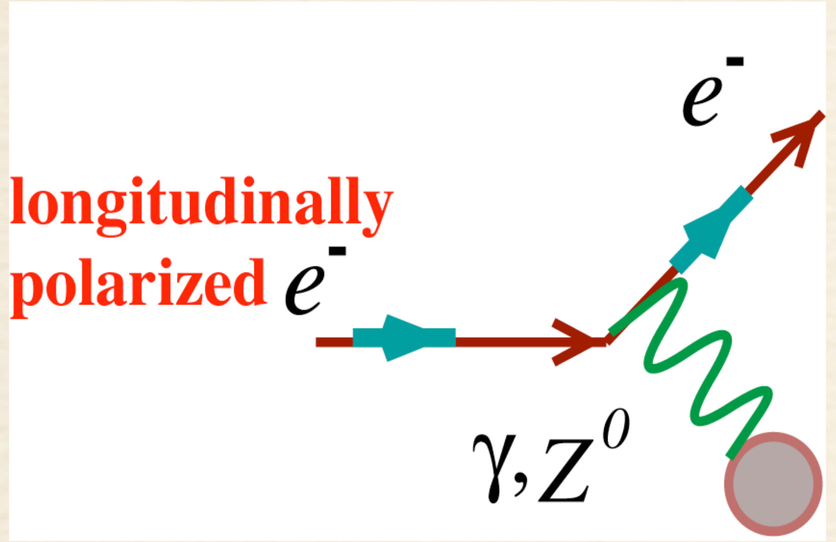

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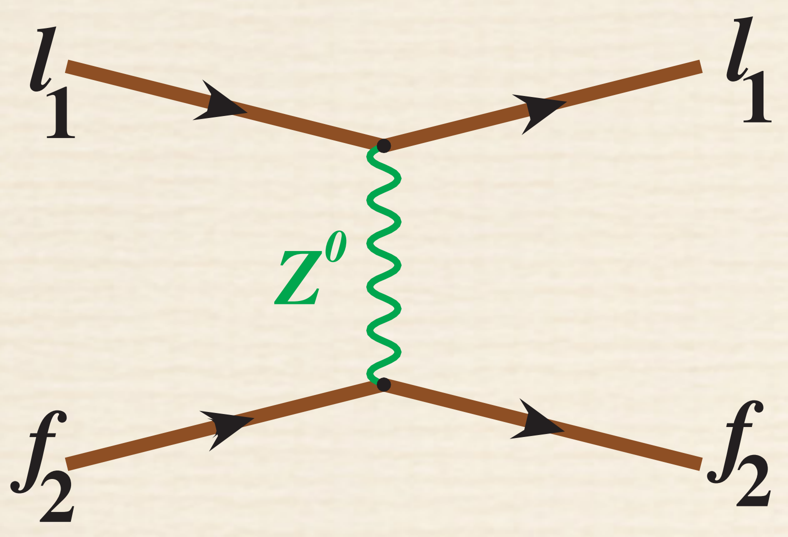

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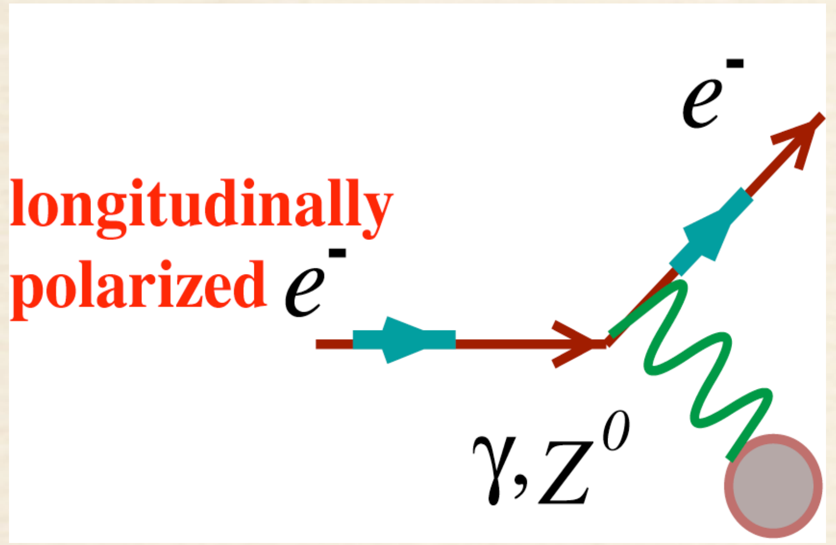

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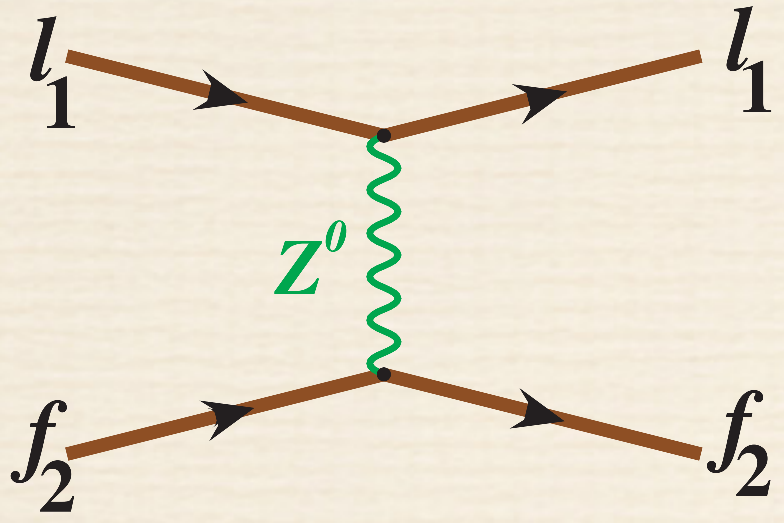

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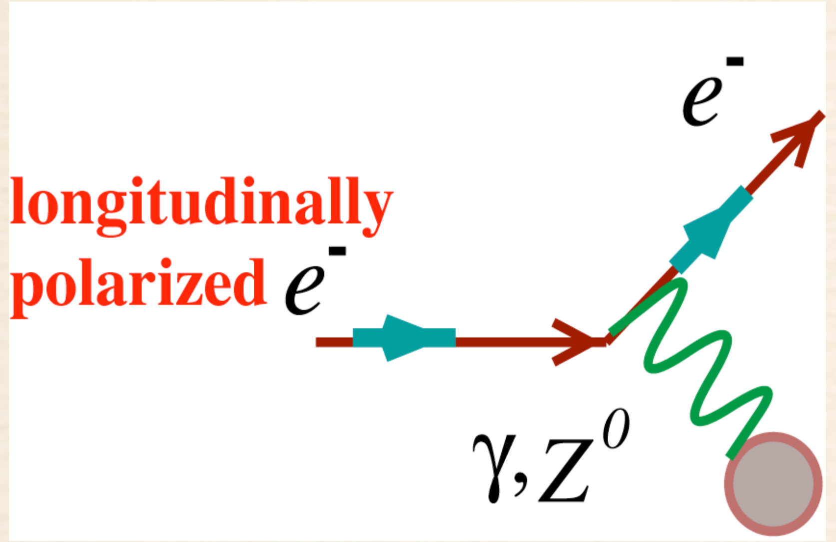

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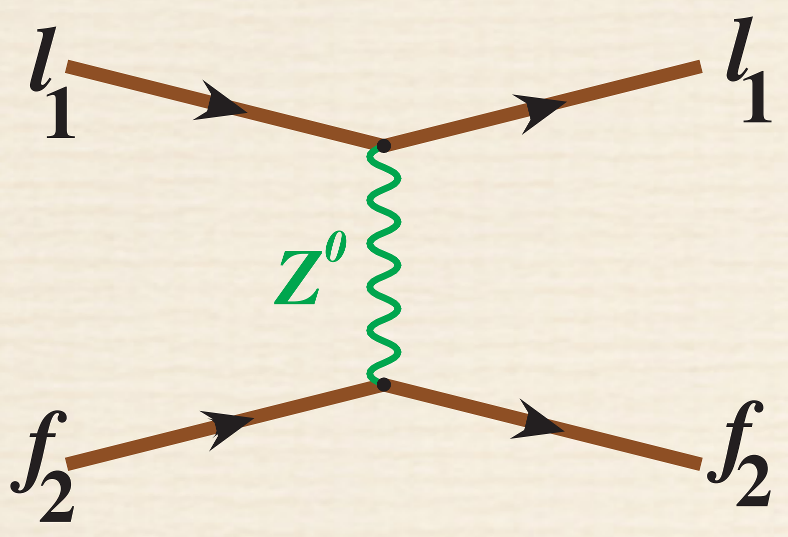

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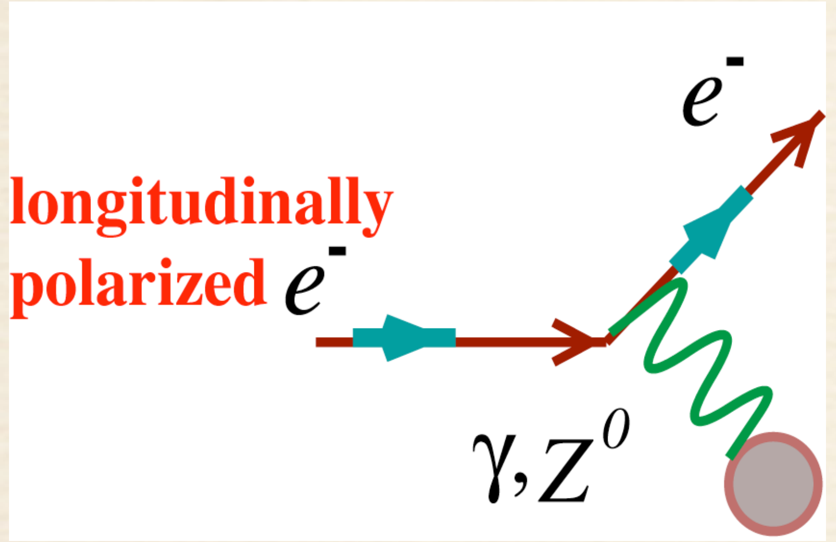

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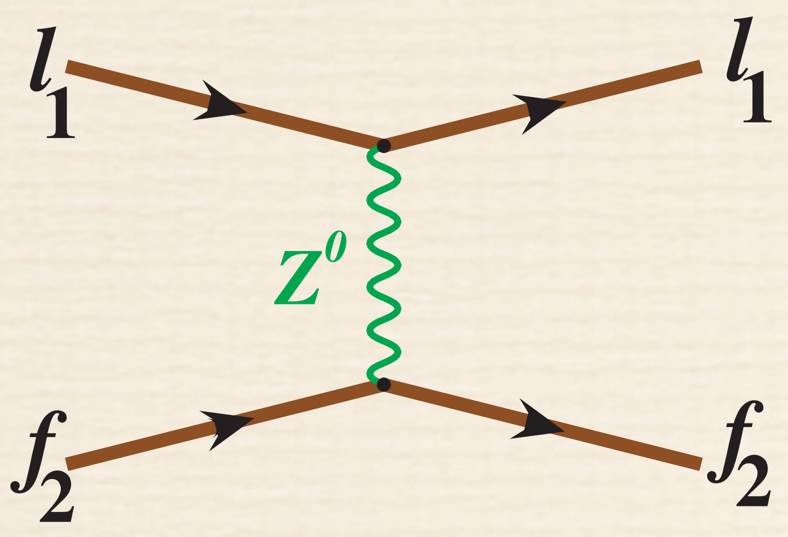

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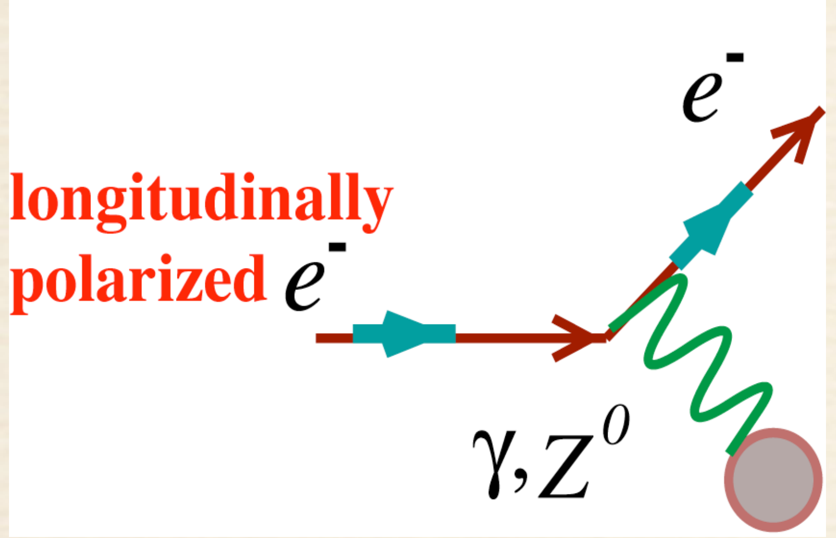

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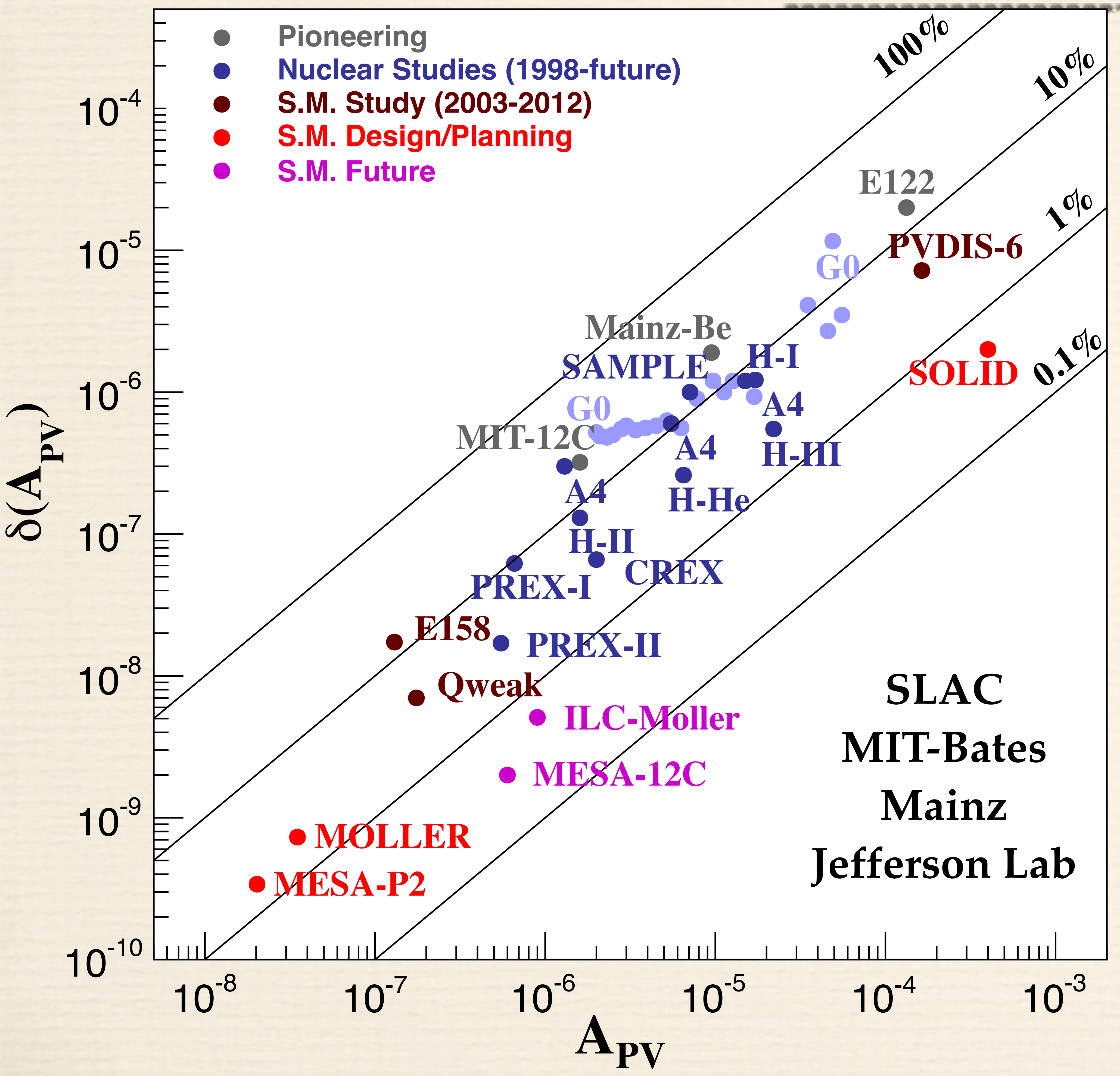
- *Since late 90's: precision measurements with carefully chosen kinematics can probe physics at the multi-TeV scale via ultra-precise $\sin^2\theta_W$ measurements*

Four Decades of PVES



Parity-violating electron scattering has become a precision tool

- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

Continuous interplay between probing hadron structure and electroweak physics

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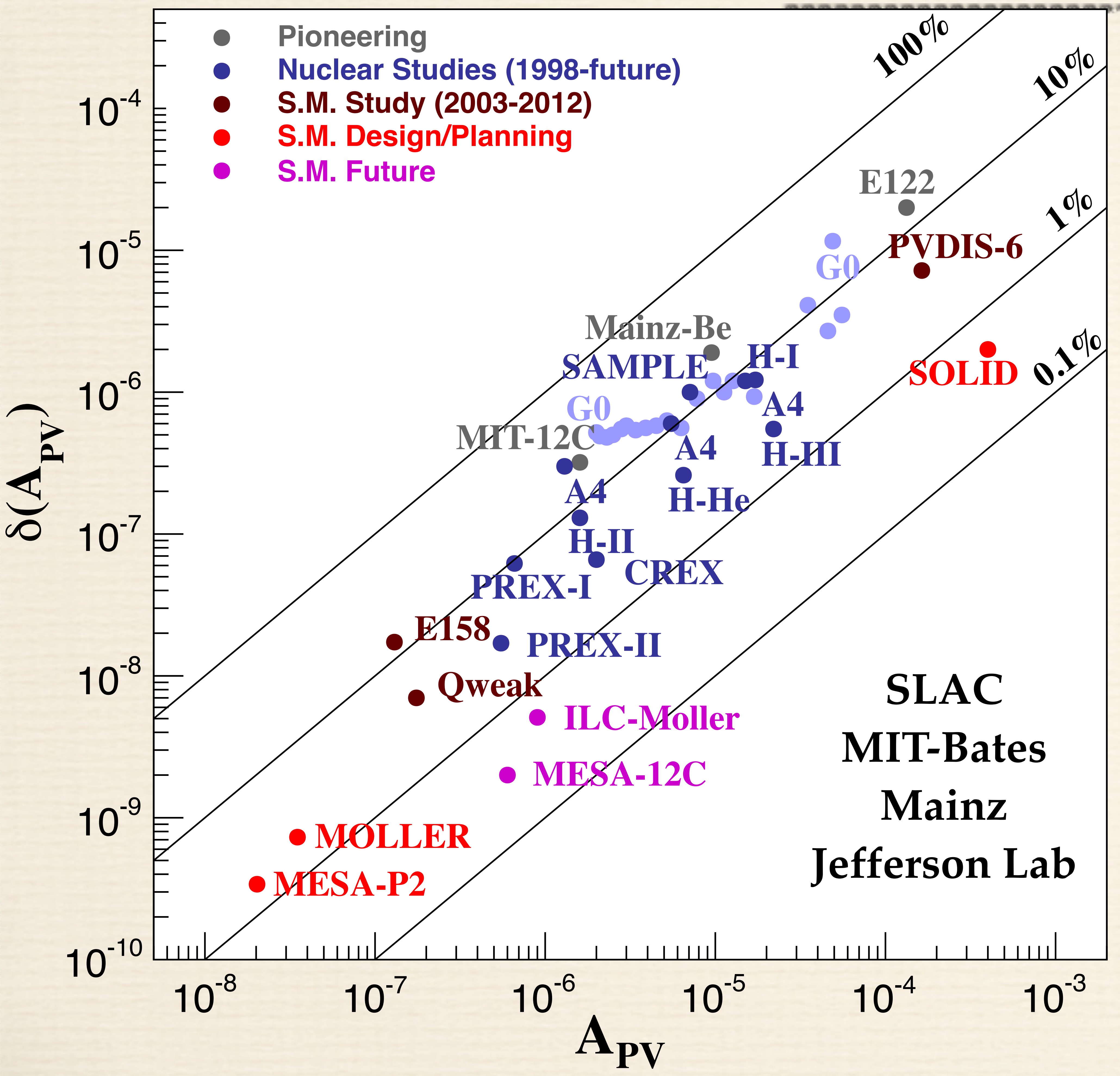

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State-of-the-art:

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

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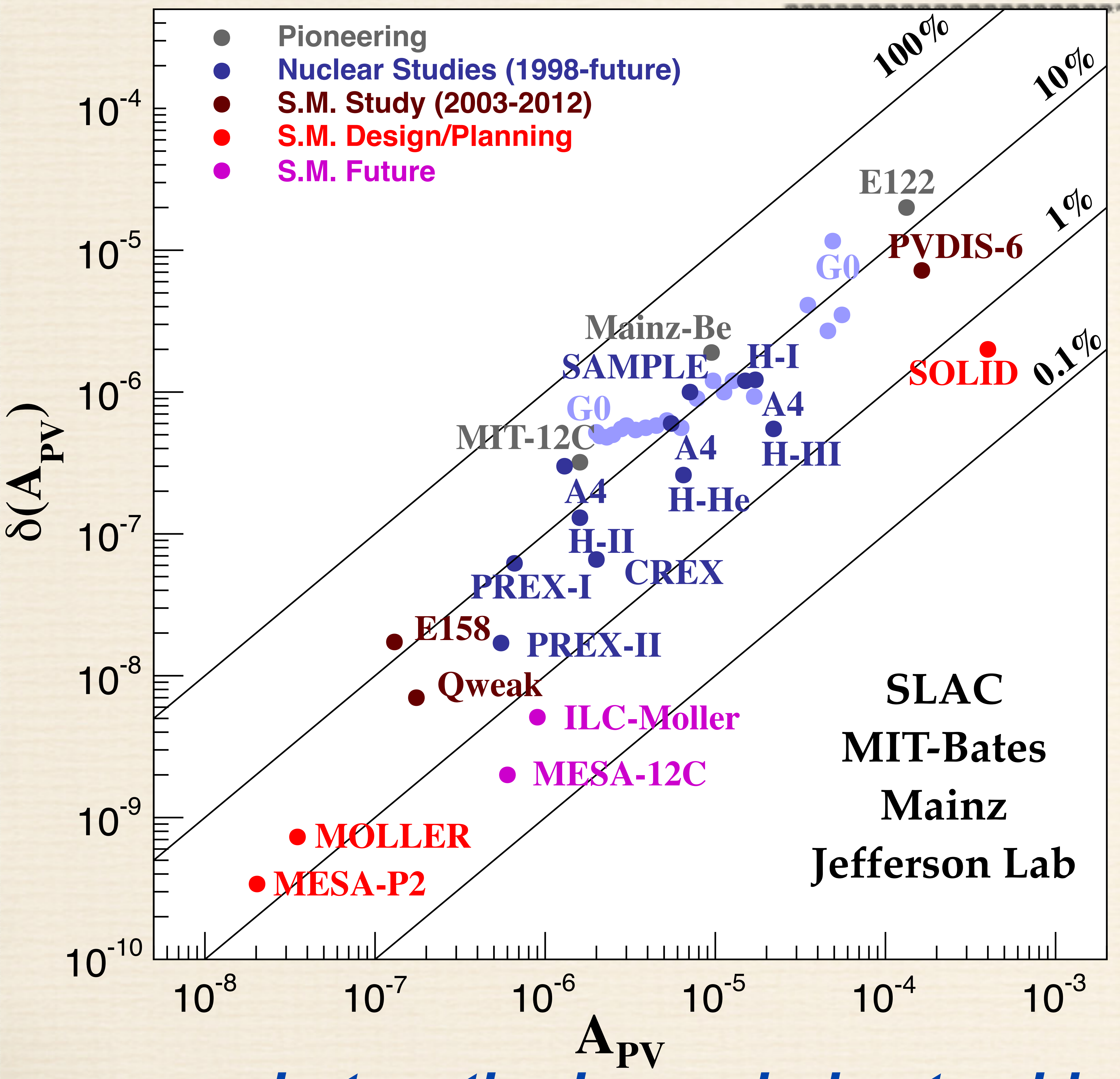

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photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors

Modern EW Physics

Unravelling "New Dynamics" in the Early Universe:
how did nuclear matter form and evolve?

Nuclear Physics Initiatives:
"Low" Energy: $Q^2 << M_Z^2$

courtesy
V. Cirigliano,
H. Maruyama,
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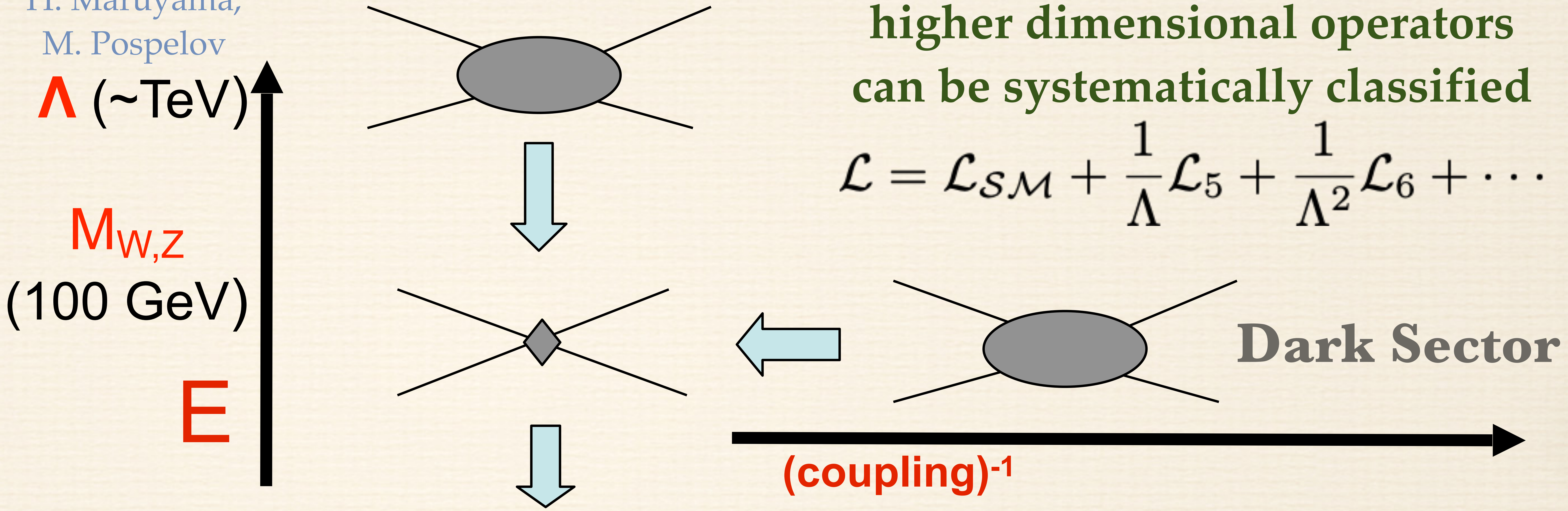
High Energy Dynamics

higher dimensional operators
can be systematically classified

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



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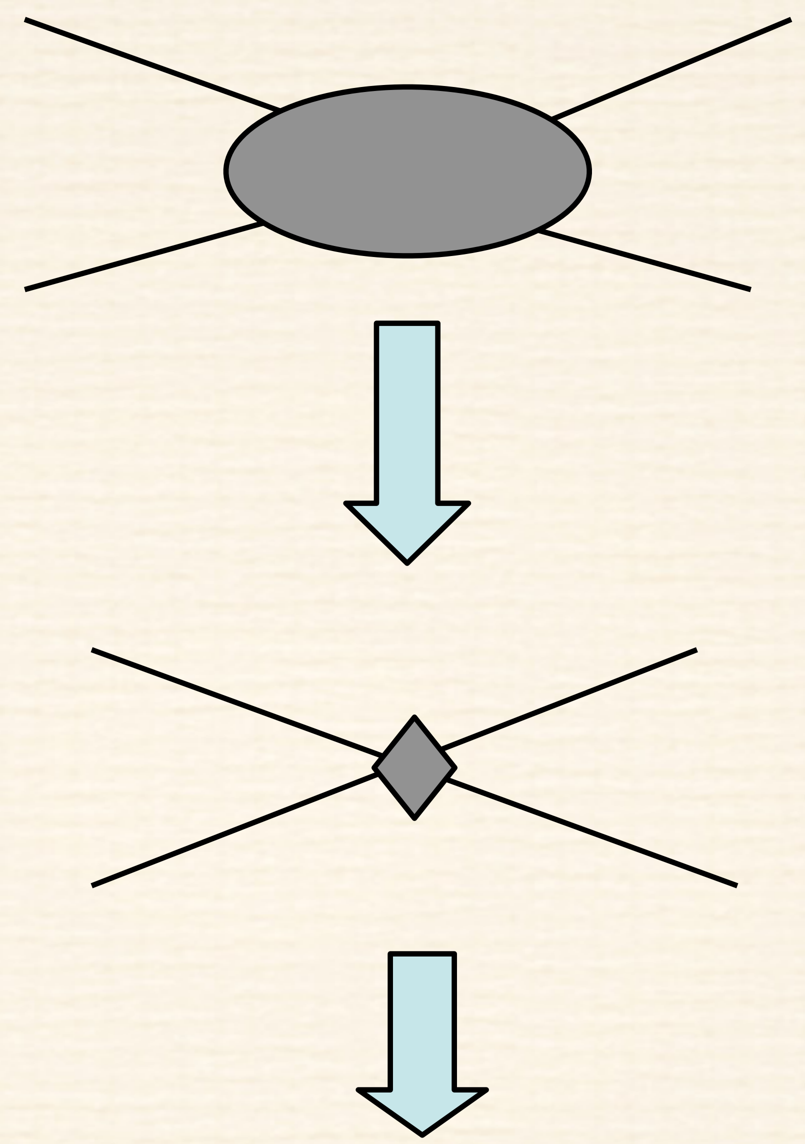
High Energy Dynamics

Λ (~TeV)

$M_{W,Z}$
(100 GeV)

E



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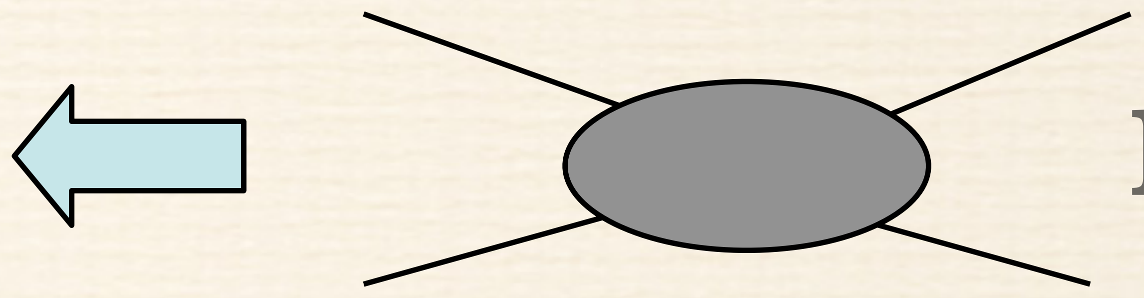
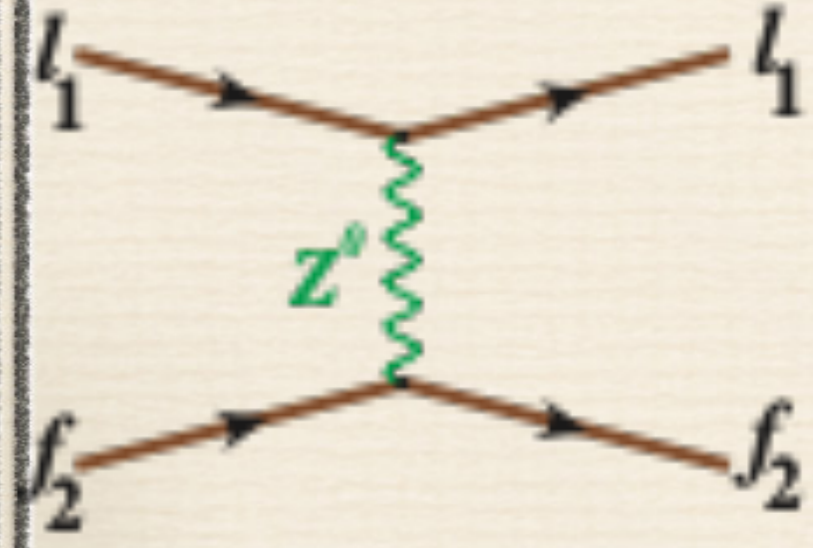


Dark Sector

(coupling)$^{-1}$

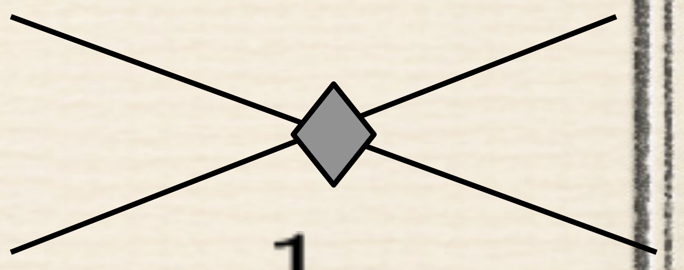
Leptonic and Semileptonic Weak Neutral Current Interactions



Search for new flavor diagonal neutral currents

Tiny yet measurable deviations from precisely calculable SM processes

must reach Λ ~ 10 TeV



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Thumb Rule: Weak mixing angle must be measured to sub-0.5% precision

Neutral Current "Bookkeeping"

Electron scattering weak charge measurement

—> weak vector coupling of the target contituents

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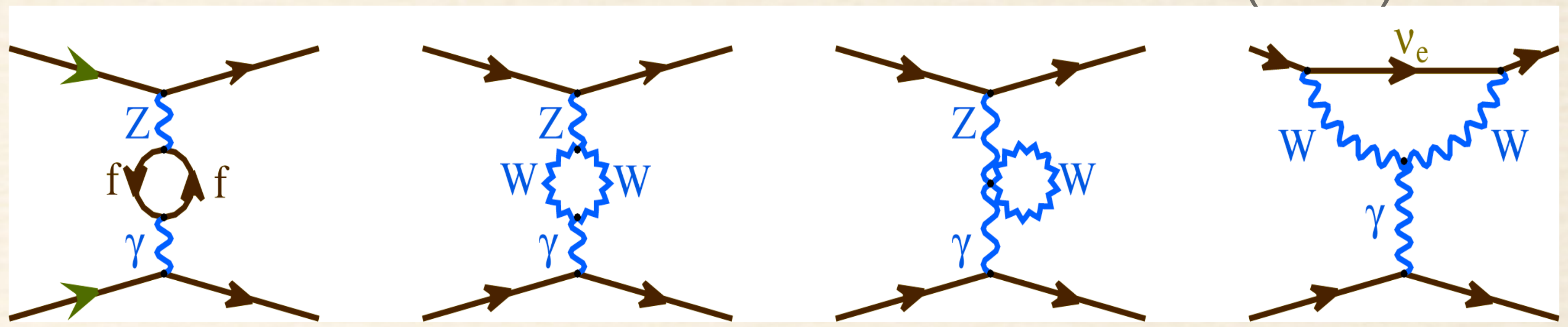

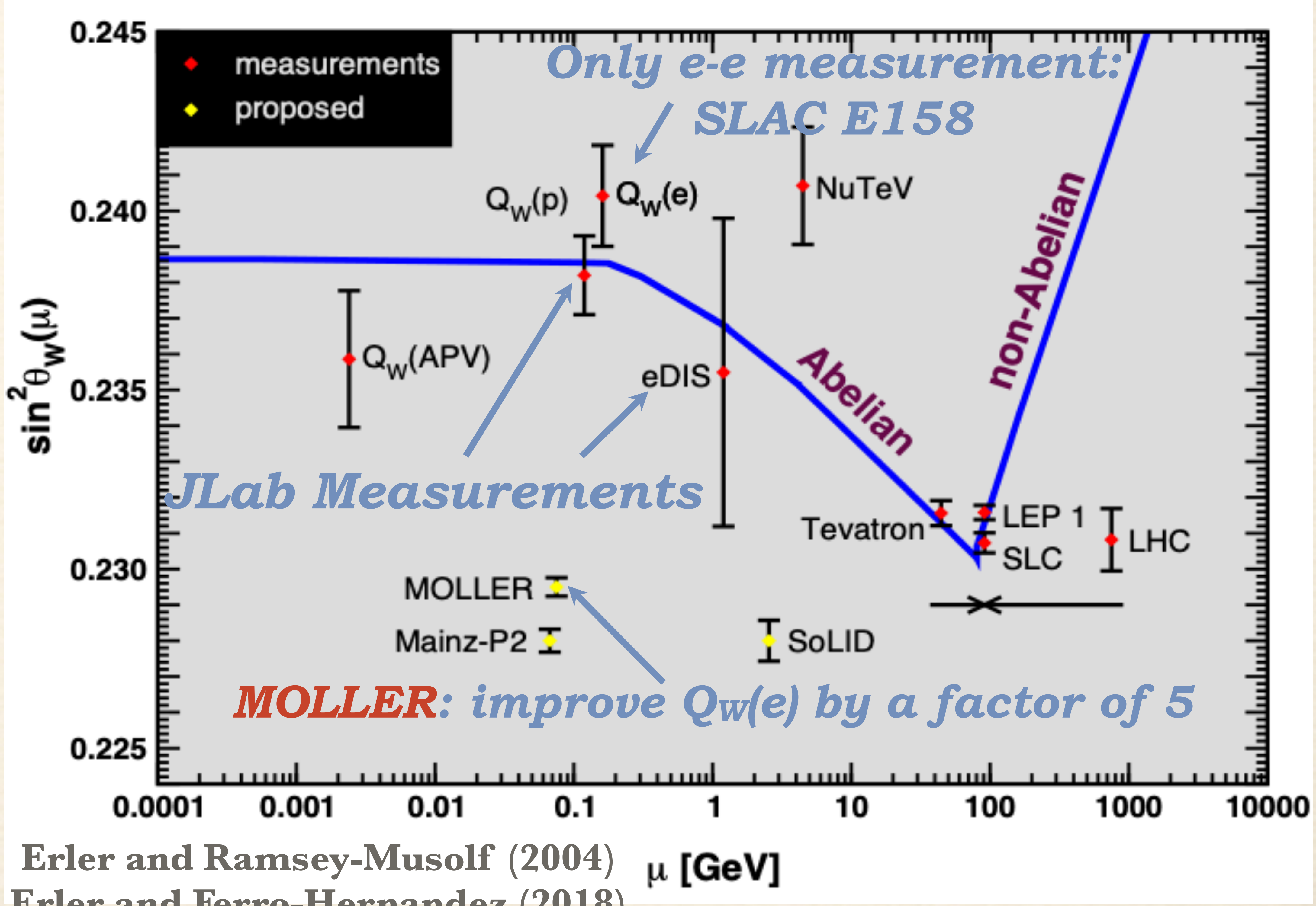

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✦ future measurements challenging, theory improving

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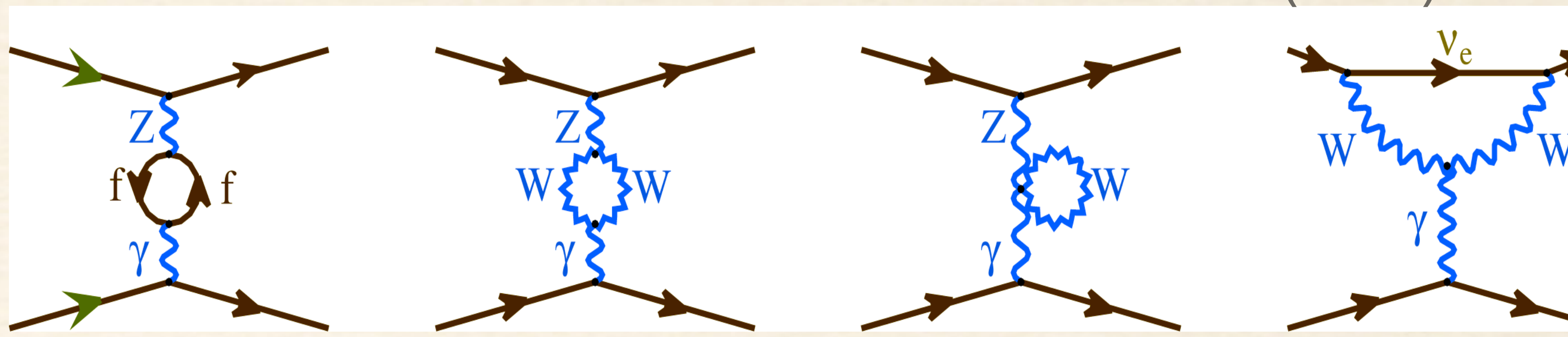

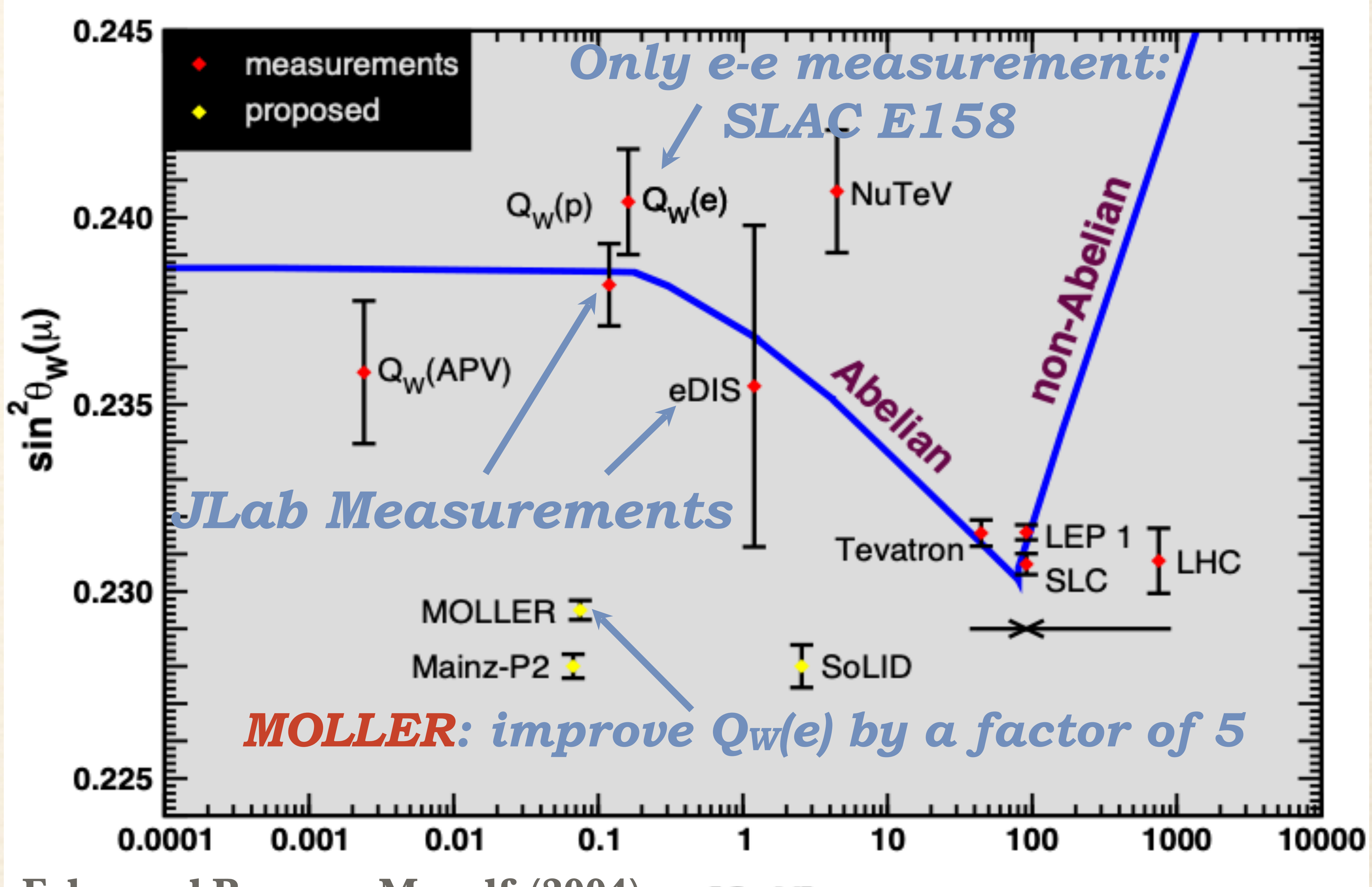

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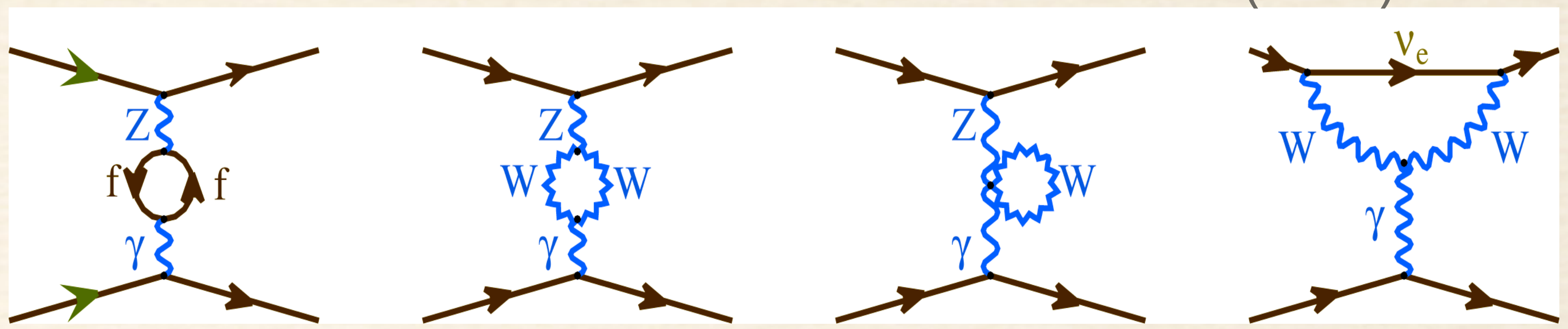

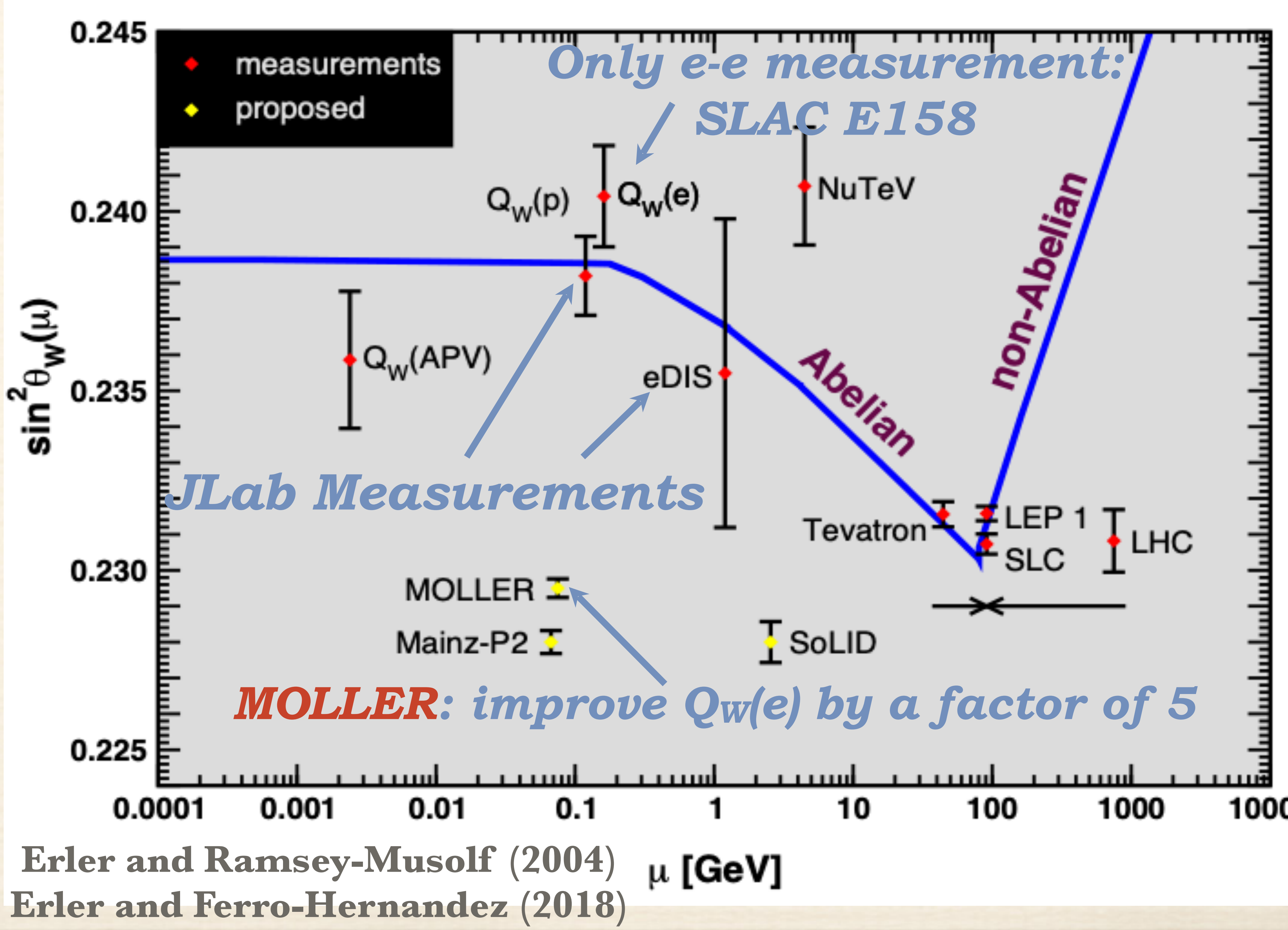

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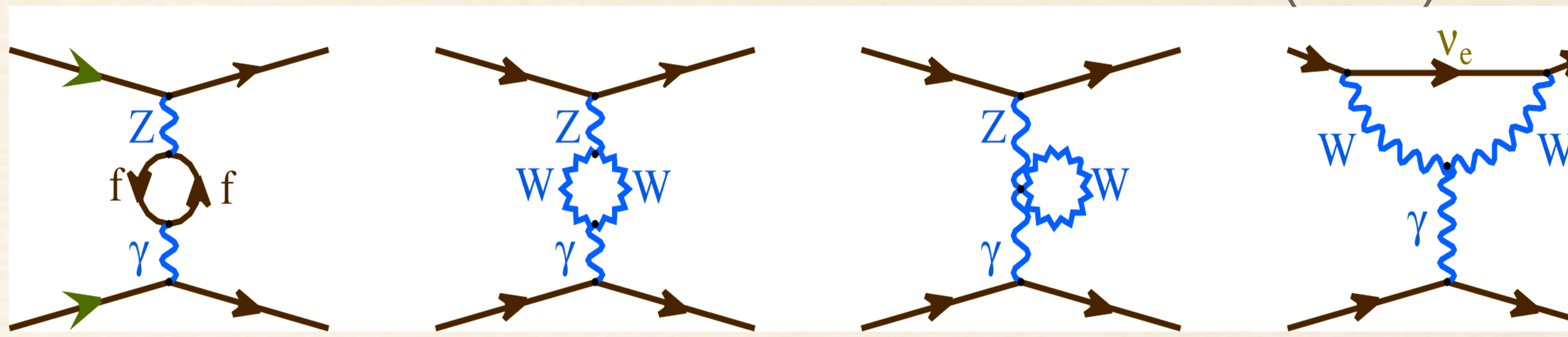

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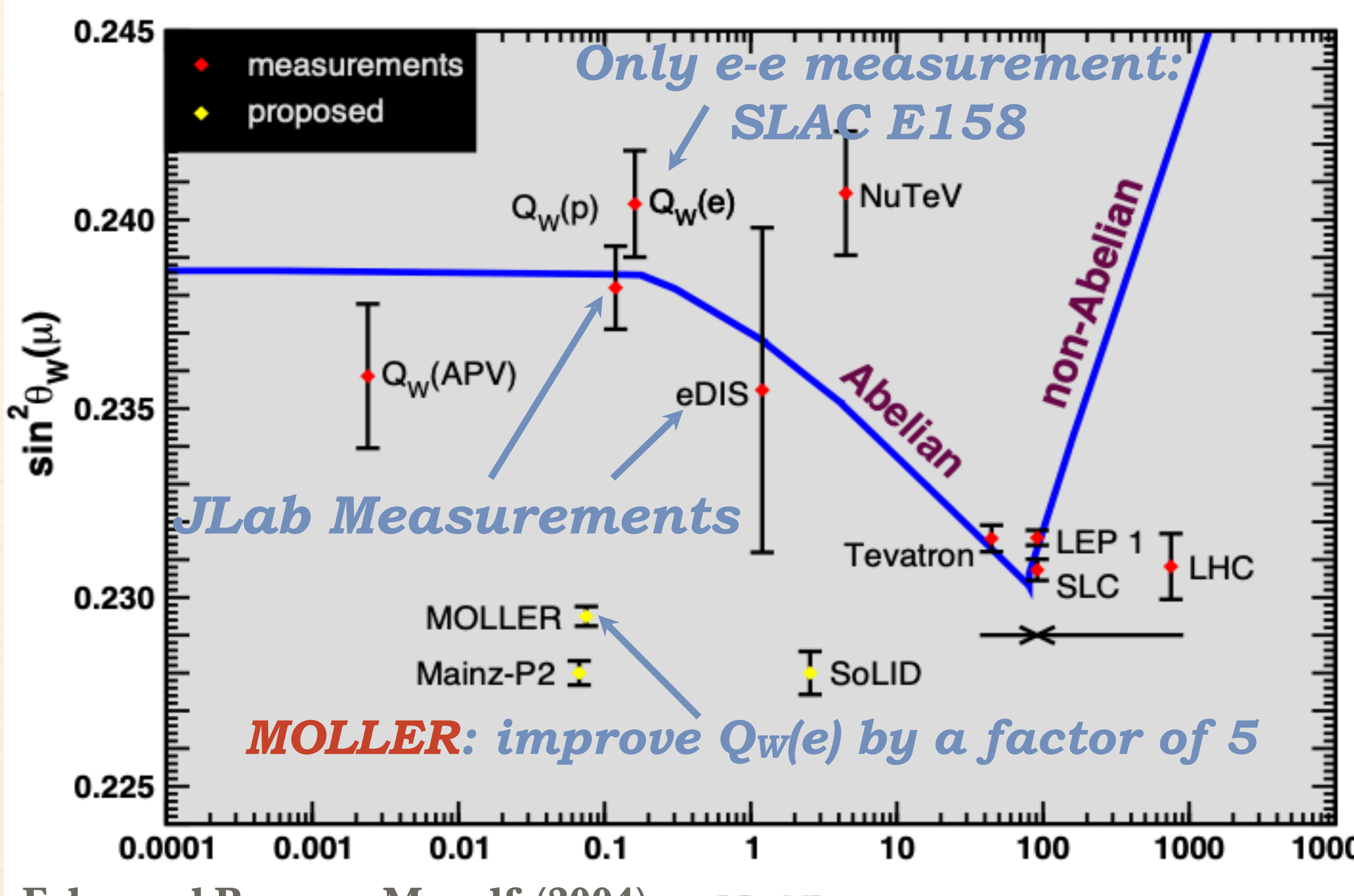

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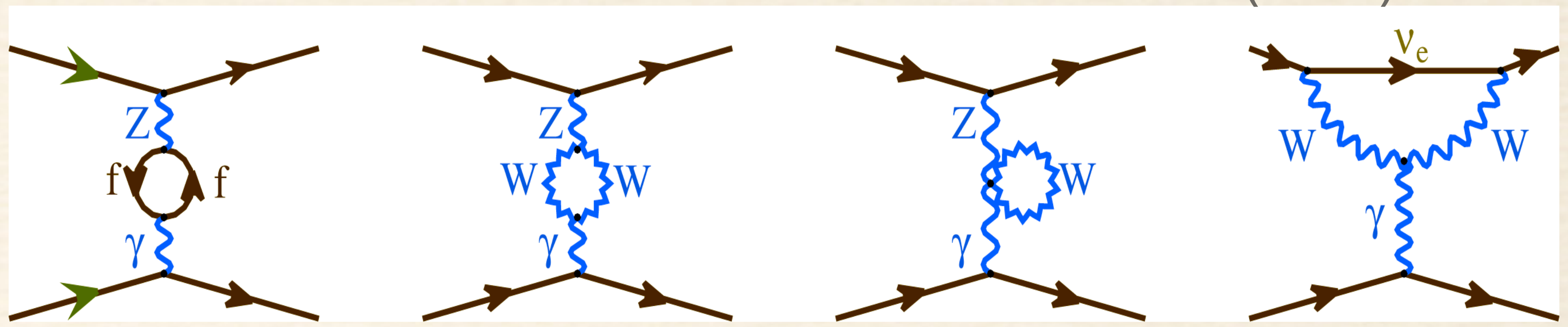

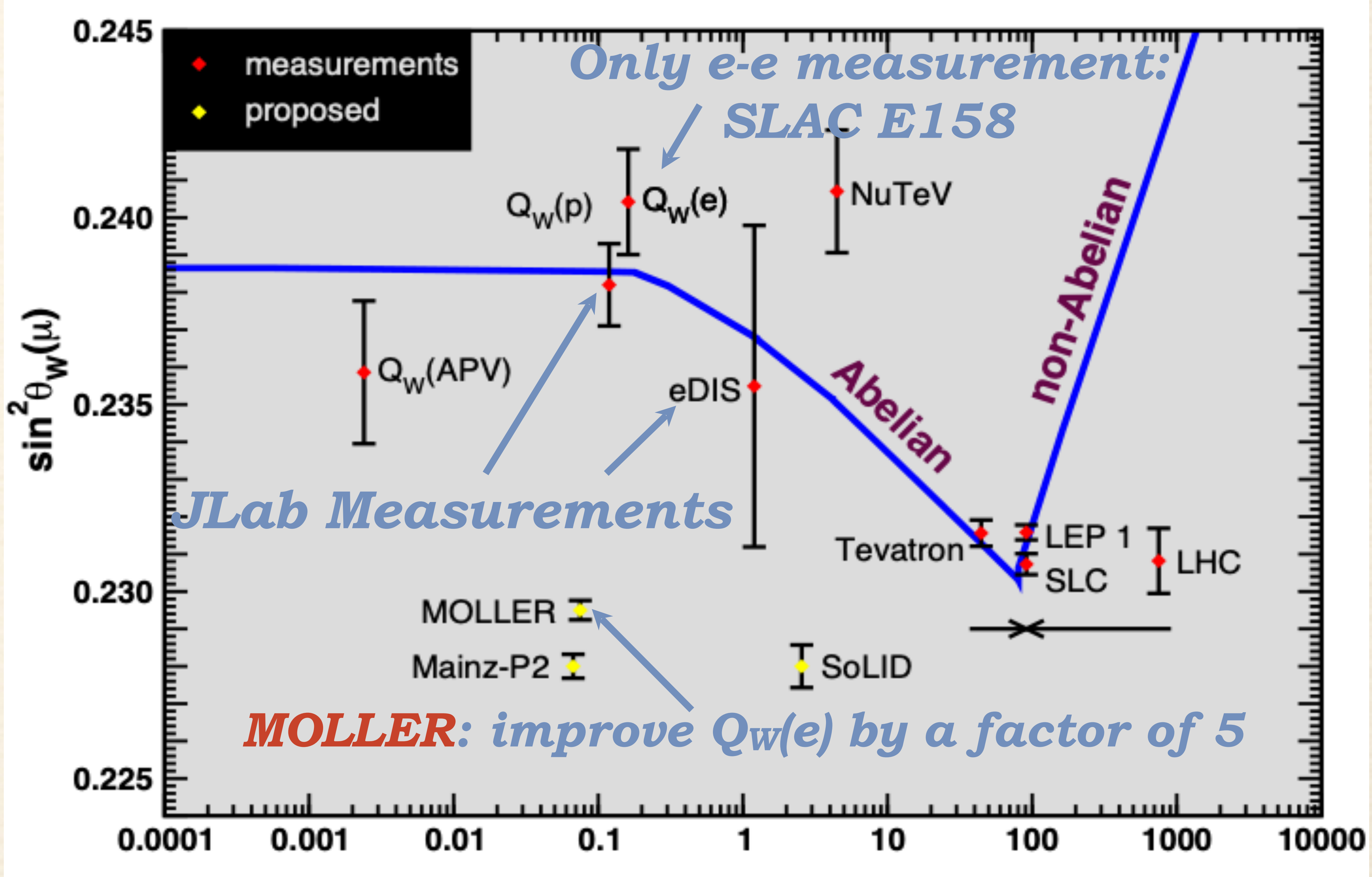

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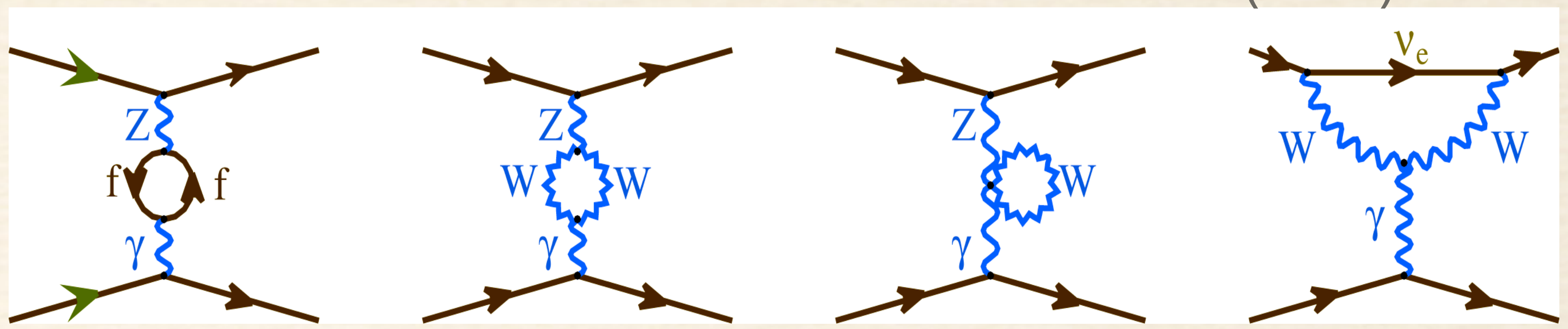

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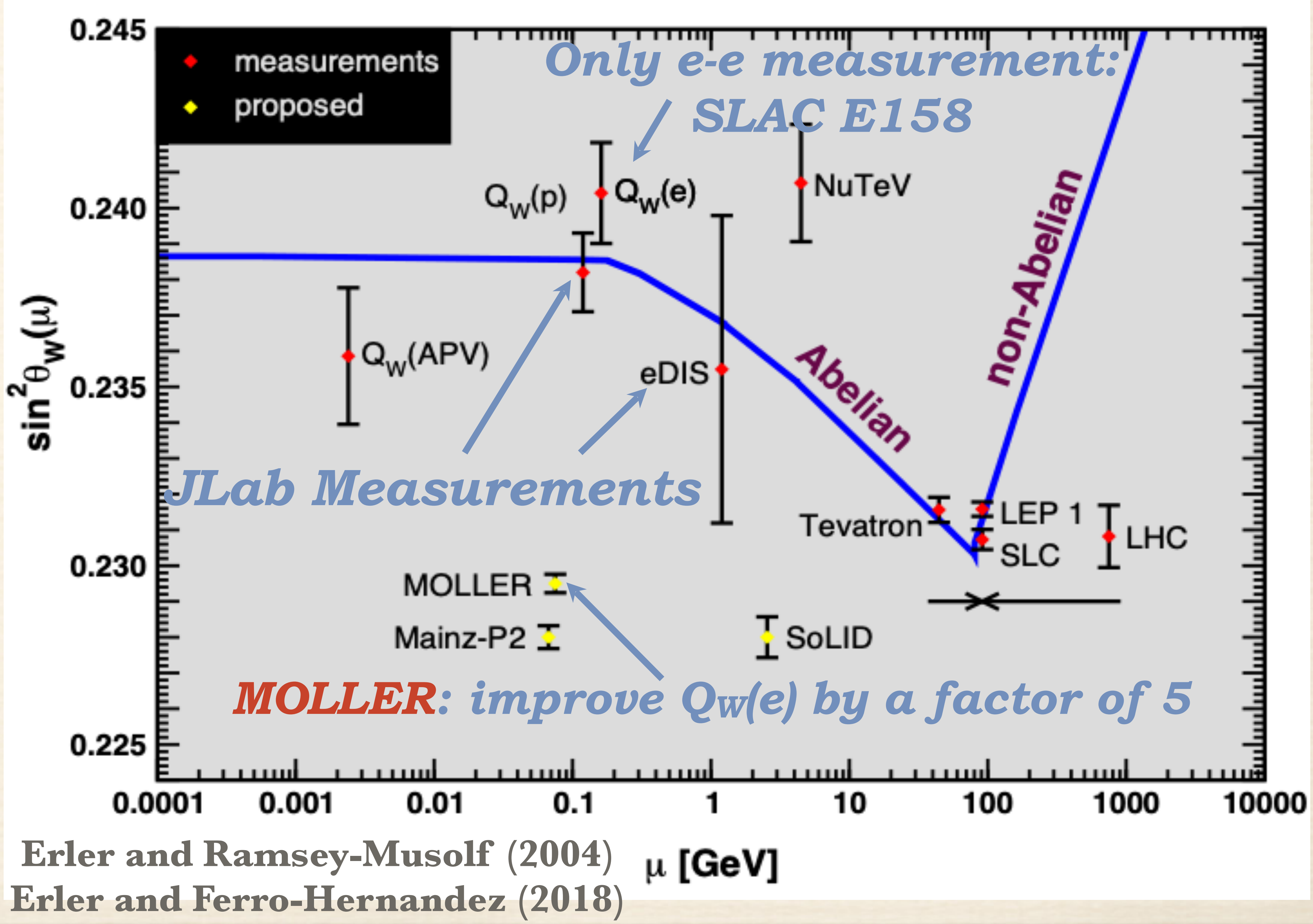
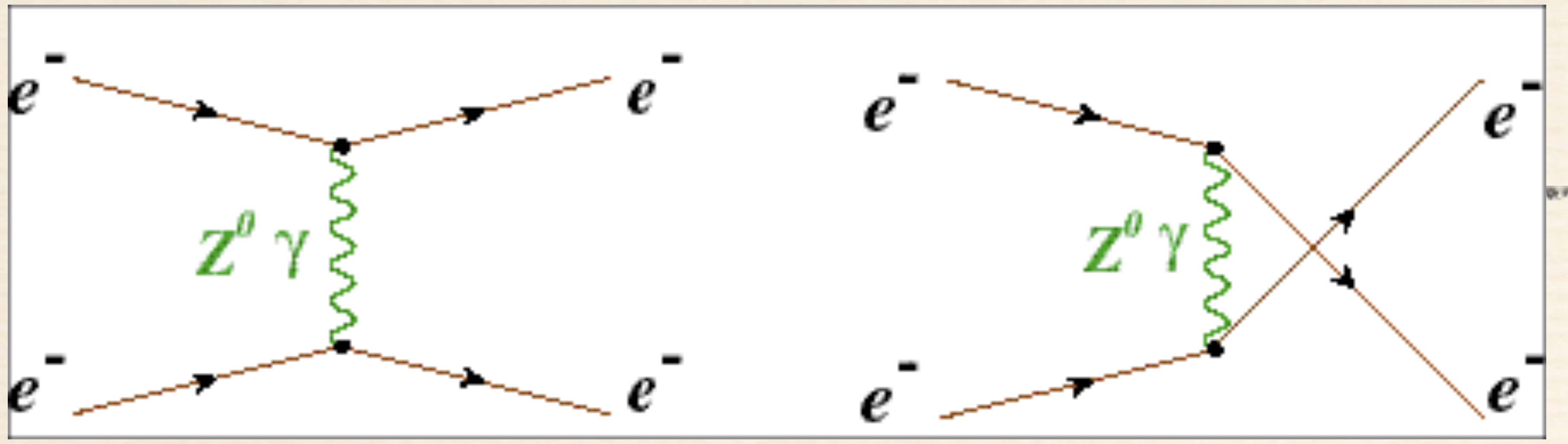
- ✦ theory robust for ^{2}H in valence quark region
- ✦ factor of 5 improvement: SOLID

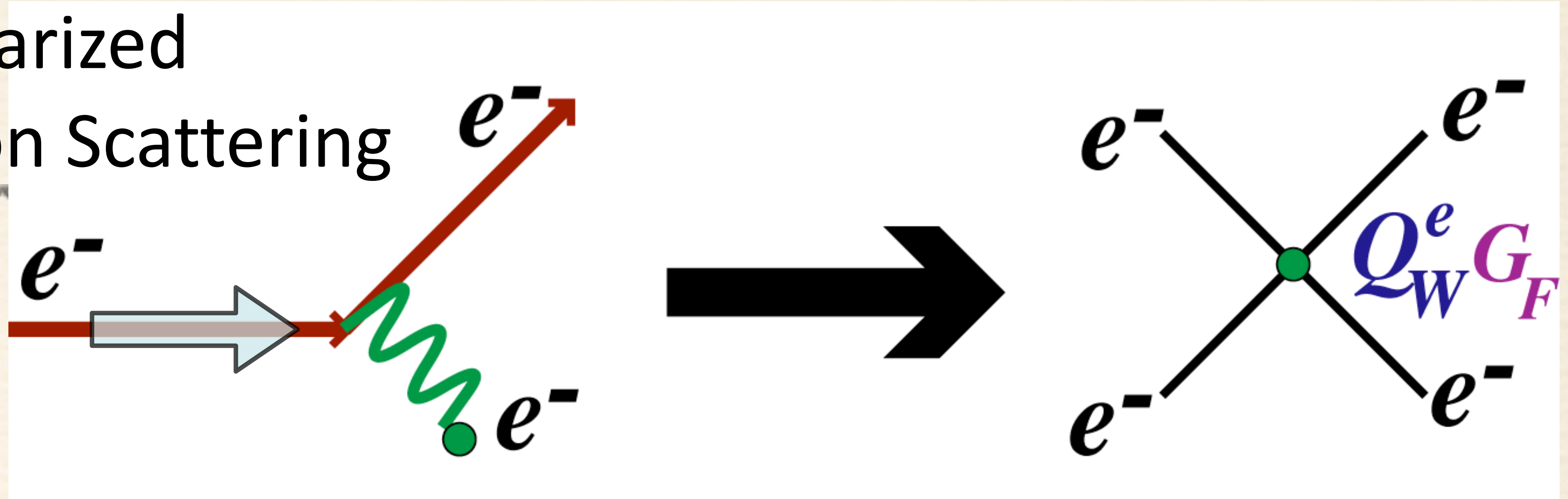


The MOLLER Experiment

The MOLLER Physics Reach



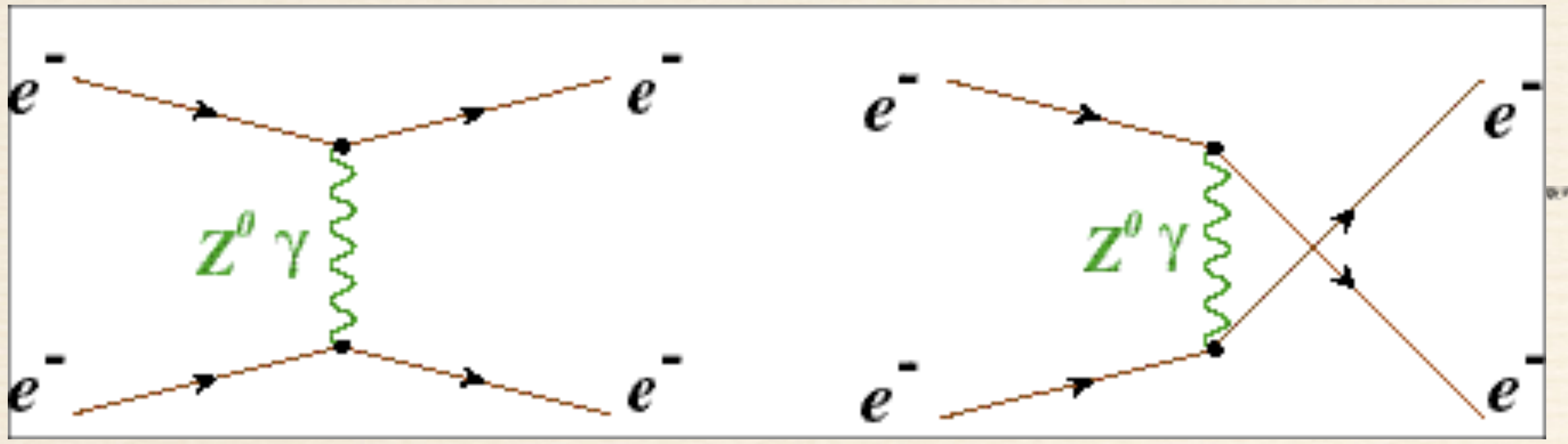
Fixed Target Polarized
Electron-Electron Scattering



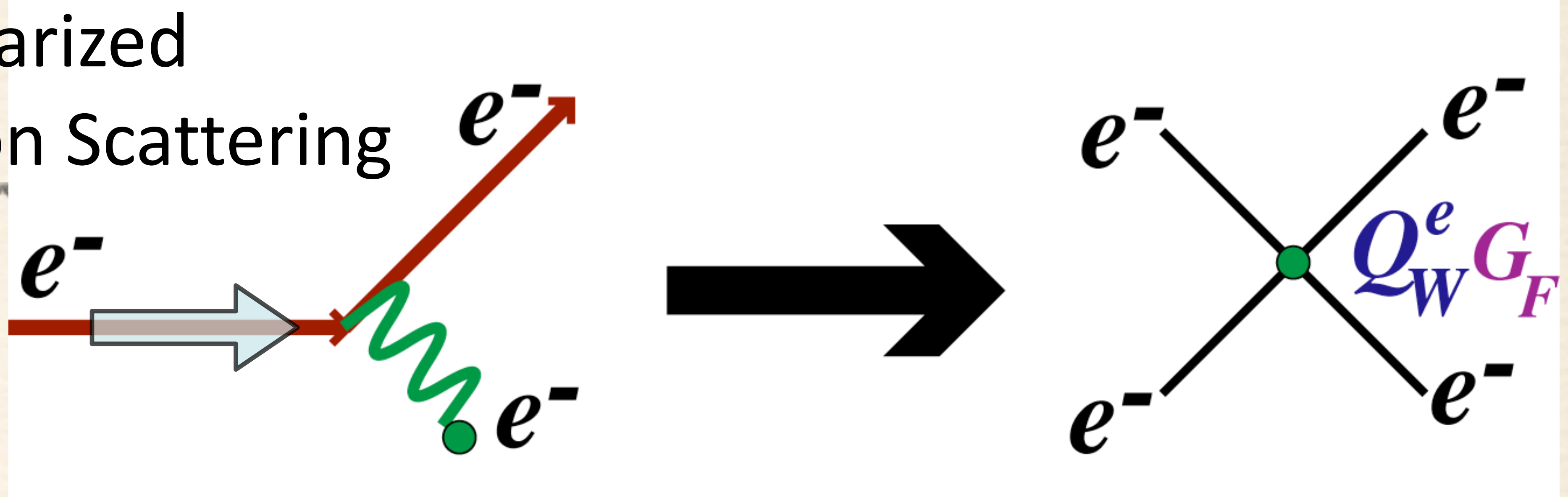
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$

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

The MOLLER Physics Reach



Fixed Target Polarized
Electron-Electron Scattering



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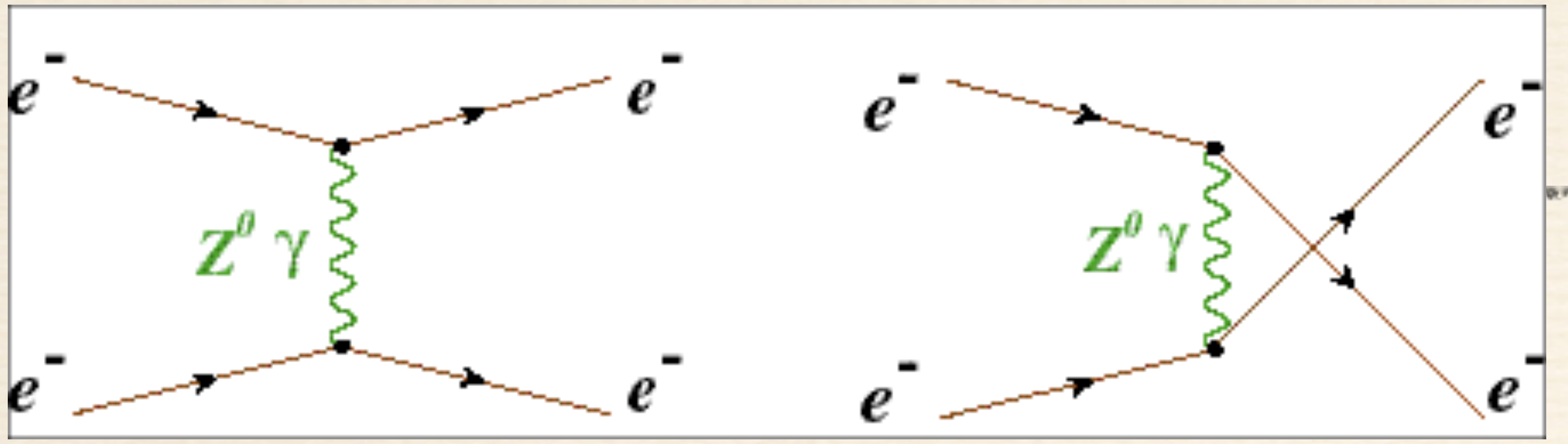
11 GeV, 65 μA   90% beam polarization

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

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

The MOLLER Physics Reach



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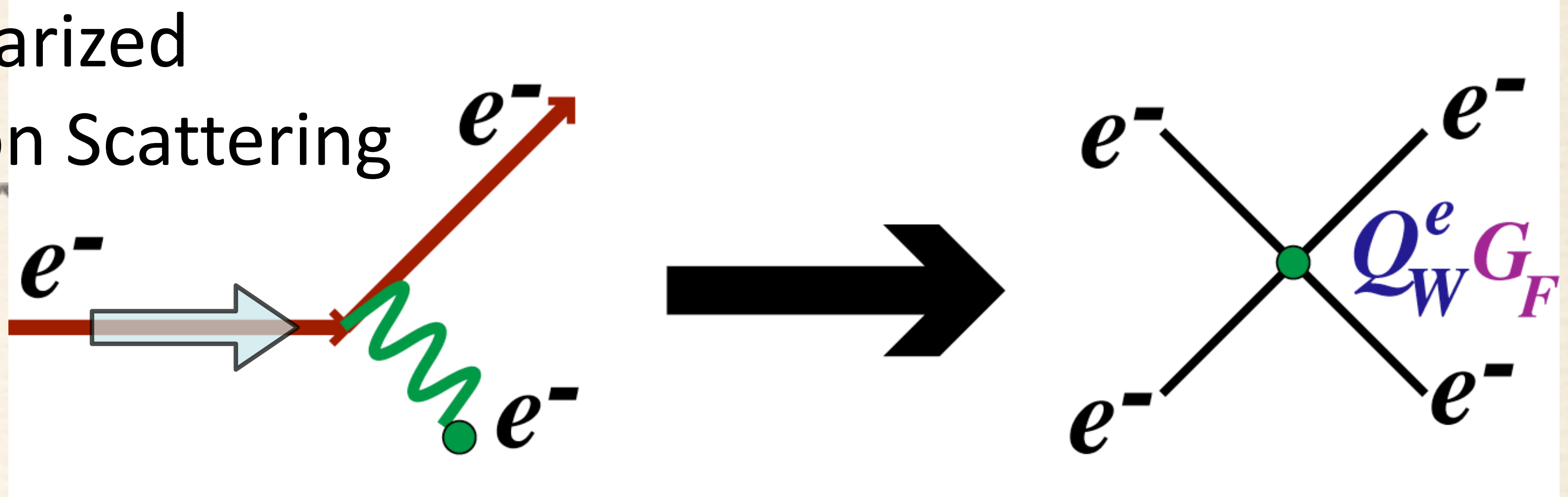
Electron-Electron Scattering



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11 GeV, 65 μA   90% beam polarization

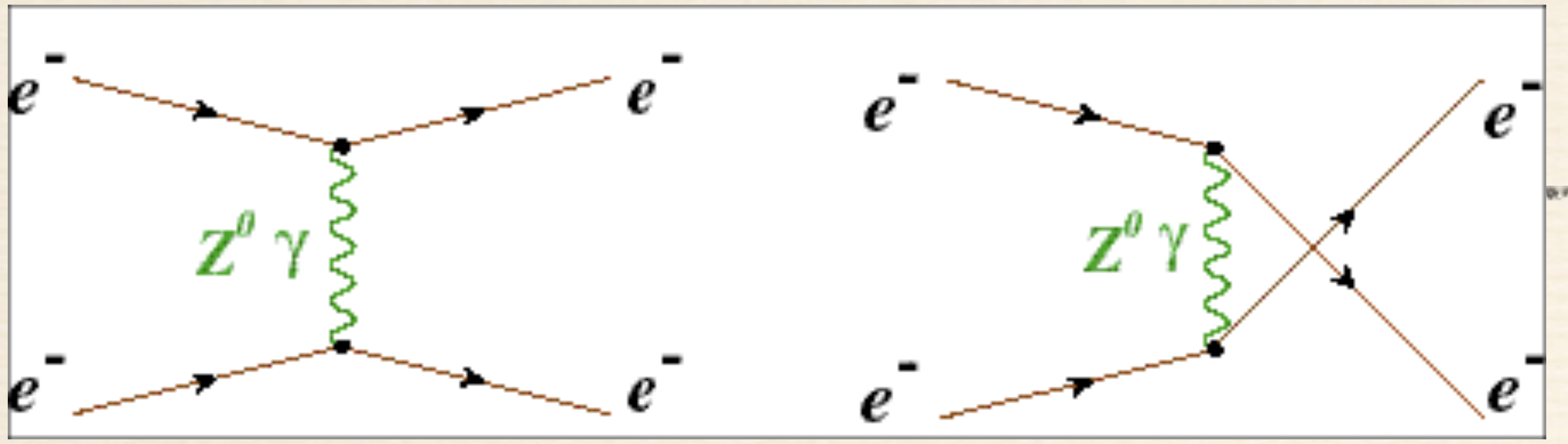
A_{PV} ~ 32 ppb   *$\delta(A_{PV})$ ~ 0.8 ppb*

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

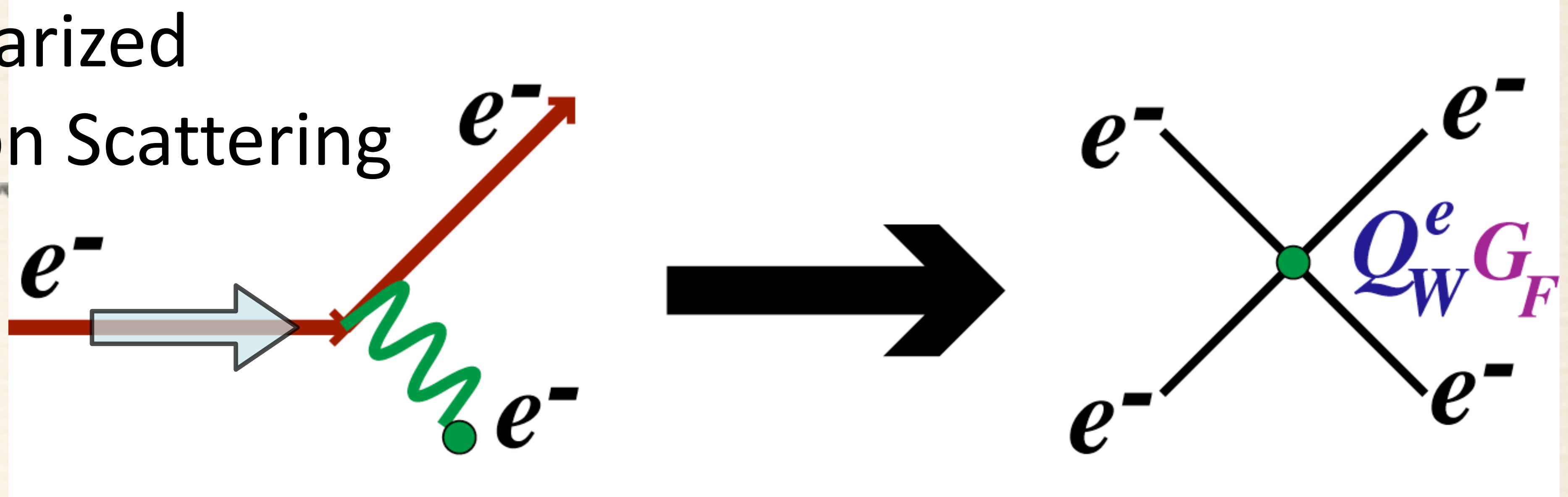
$\delta(\sin^2\theta_W) = \pm 0.00023$ (stat.) ± 0.00012 (syst.)

⇨ *~ 0.1%*

The MOLLER Physics Reach



Fixed Target Polarized Electron-Electron Scattering



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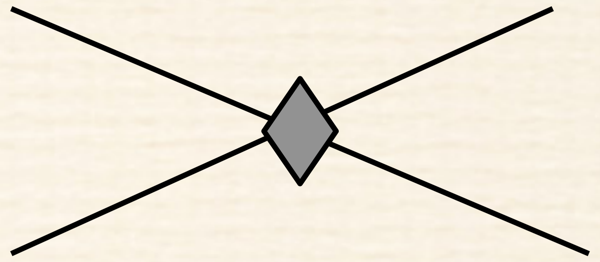
$+$  $\dfrac{1}{\Lambda^2}\mathcal{L}_6$ ***New Physics***

11 GeV, 65 μA 90% beam polarization

A_{PV} ~ 32 ppb δ(A_{PV}) ~ 0.8 ppb

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

$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R}\frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j$$

$\delta(\sin^2\theta_W) = \pm\, 0.00023$ (stat.) $\pm\, 0.00012$ (syst.)

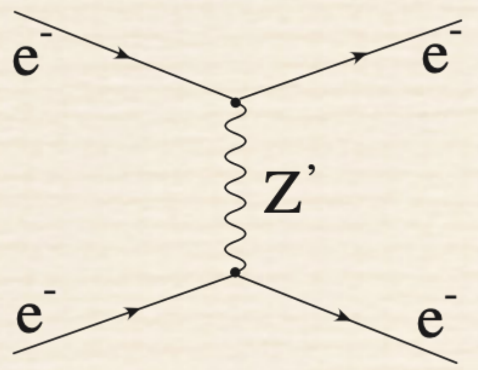
~ 0.1%

$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5\ \text{TeV}$$

Sensitivity akin to a 500 GeV Lepton Collider

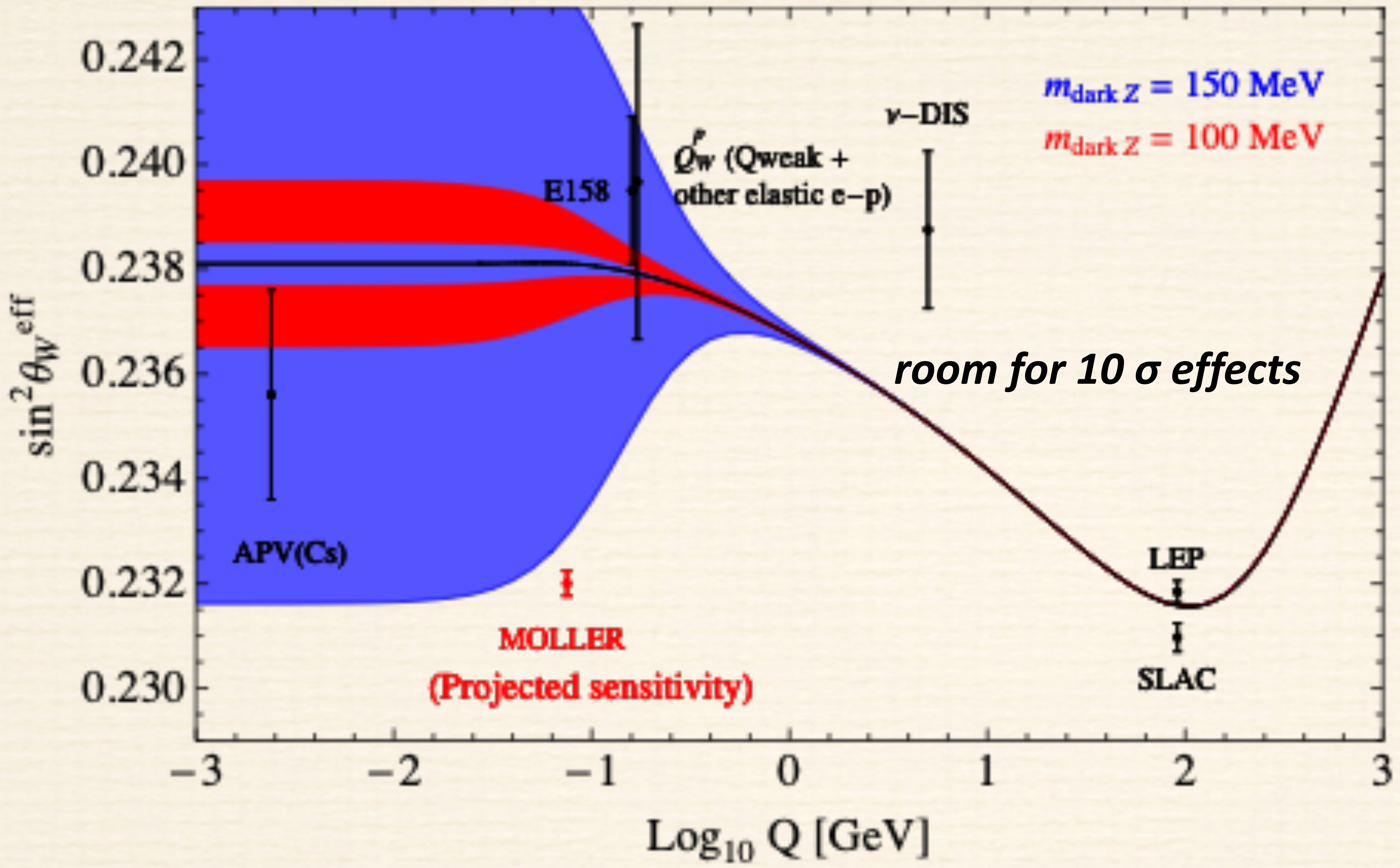
New Physics Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



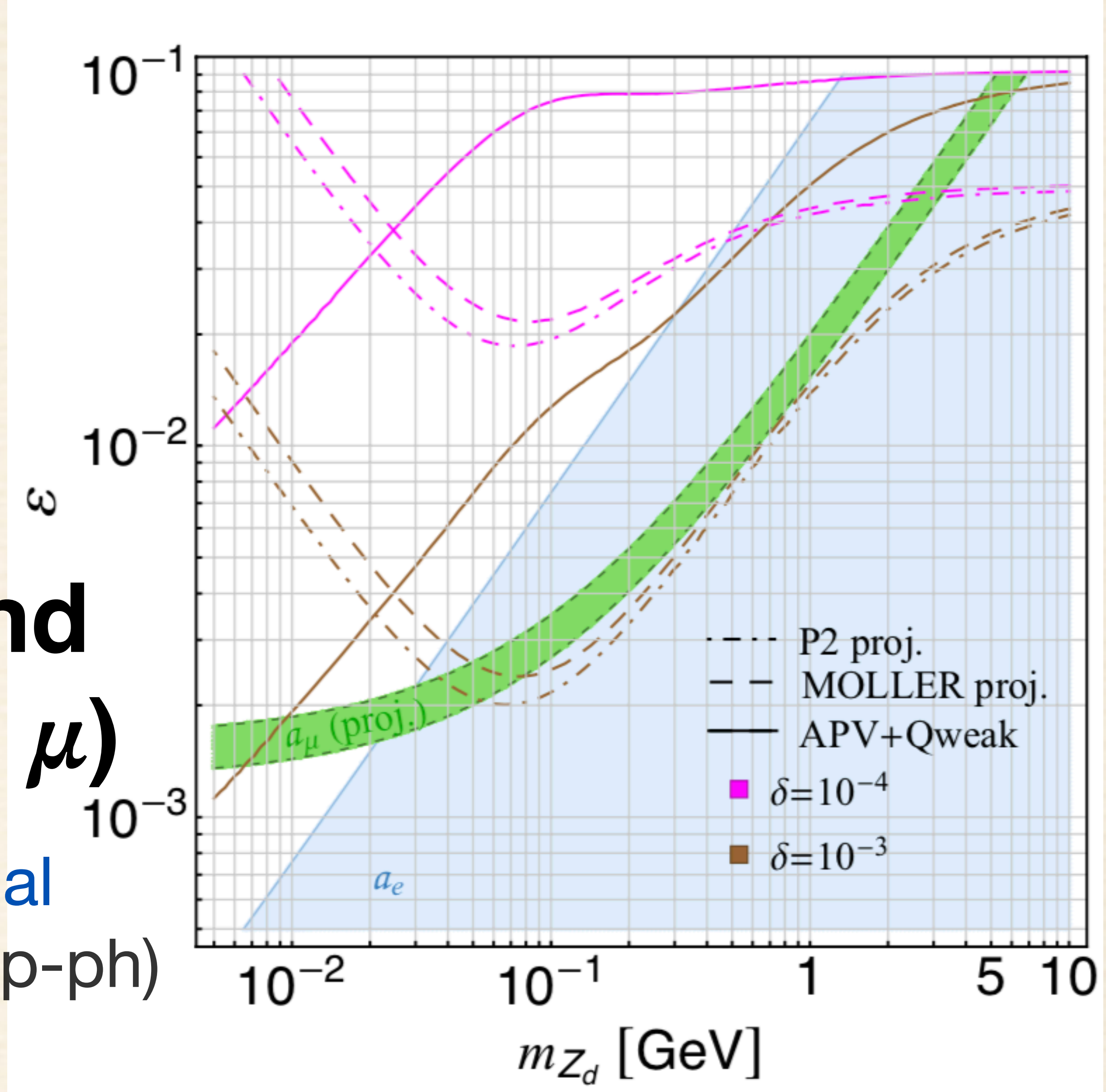
Heavy Photons (A' mixed with Z_0): The Dark Z

H. Davoudiasl, H-S. Lee and W. Marciano



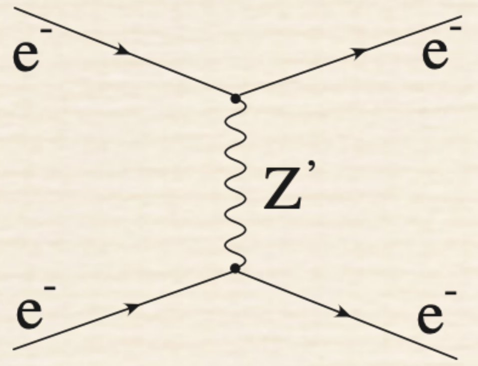
Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al 2104.03280 (hep-ph)



New Physics Examples

Many different scenarios give rise to effective 4-electron contact interaction amplitudes: significant discovery potential



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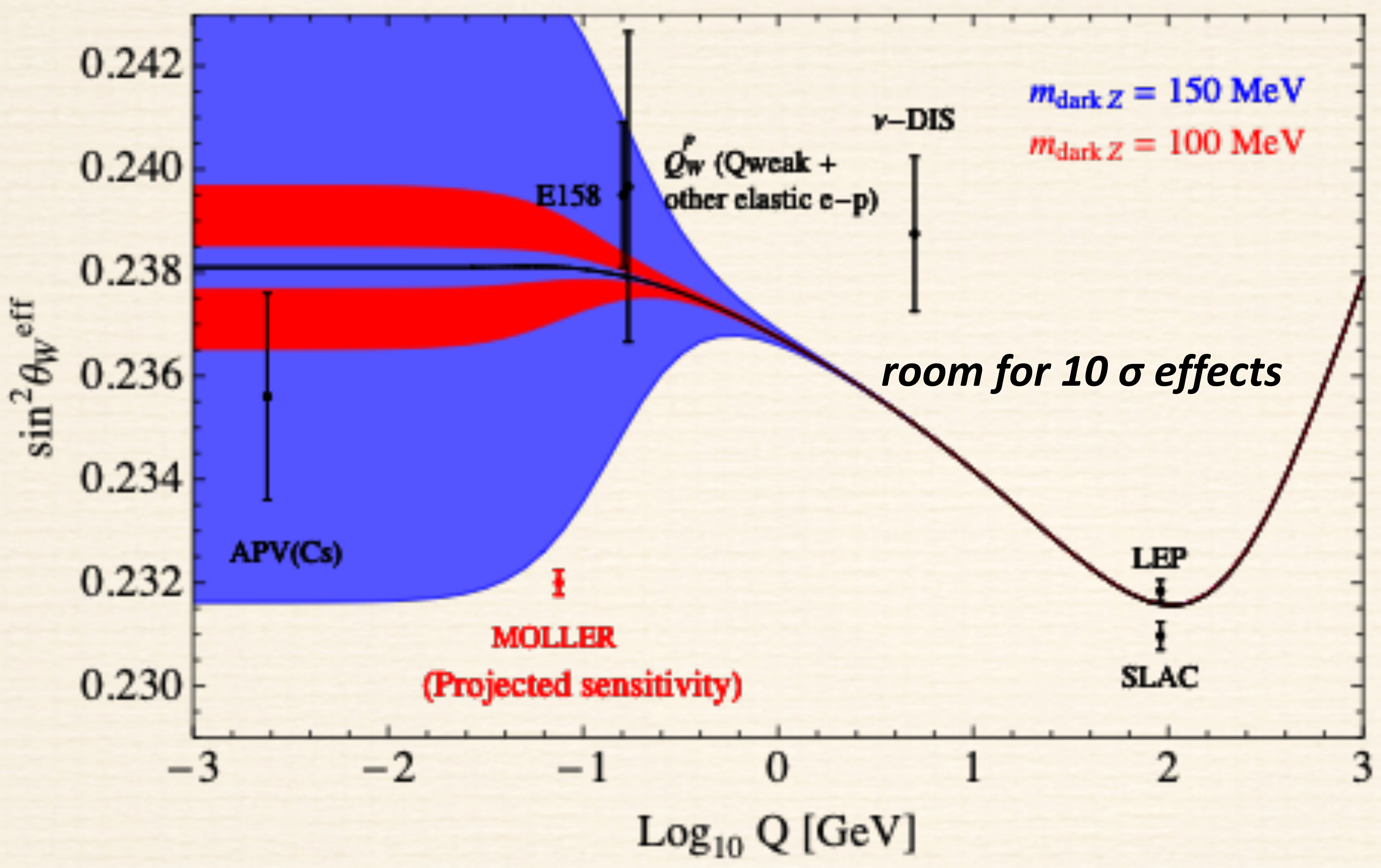

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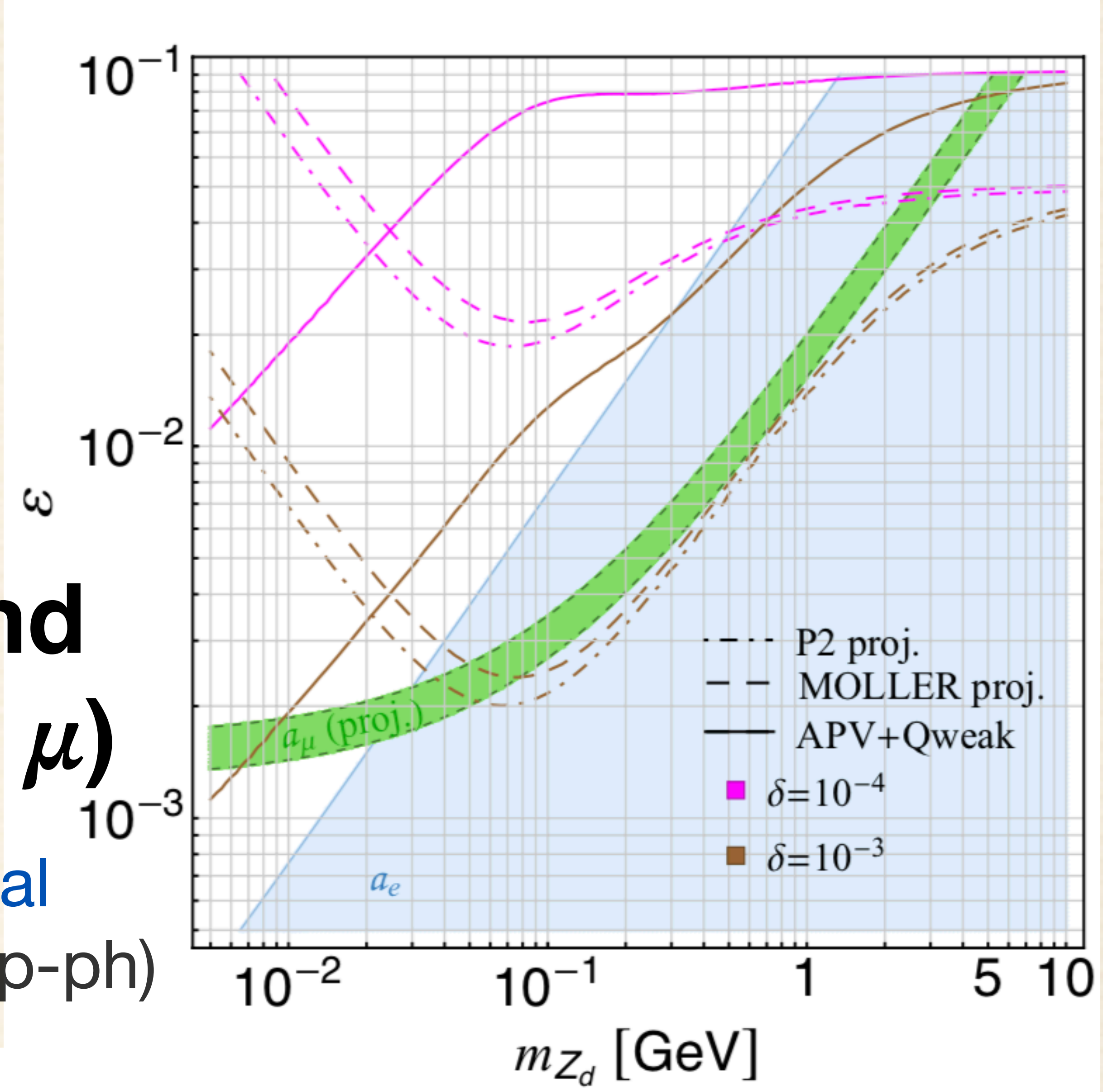
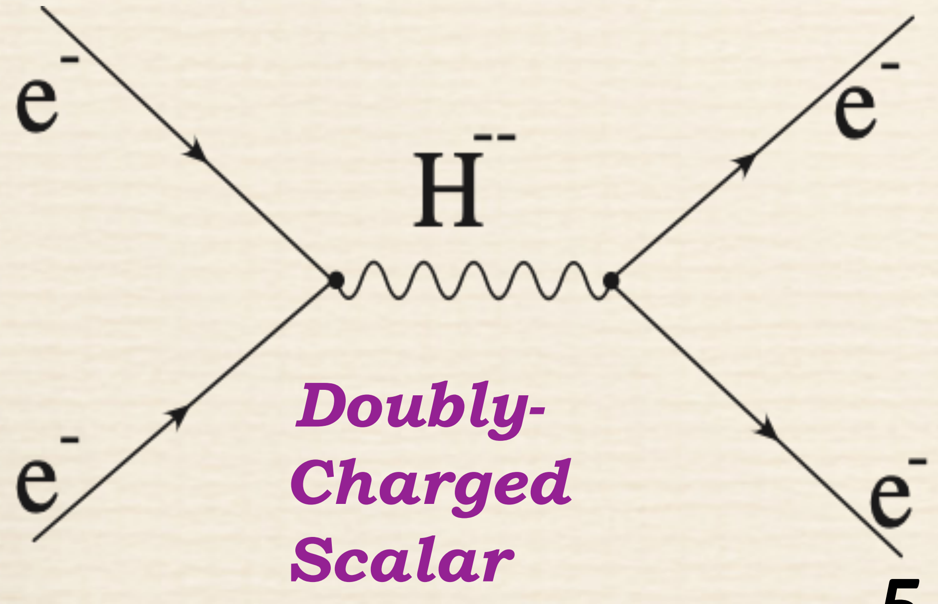


Lepton Number Violation



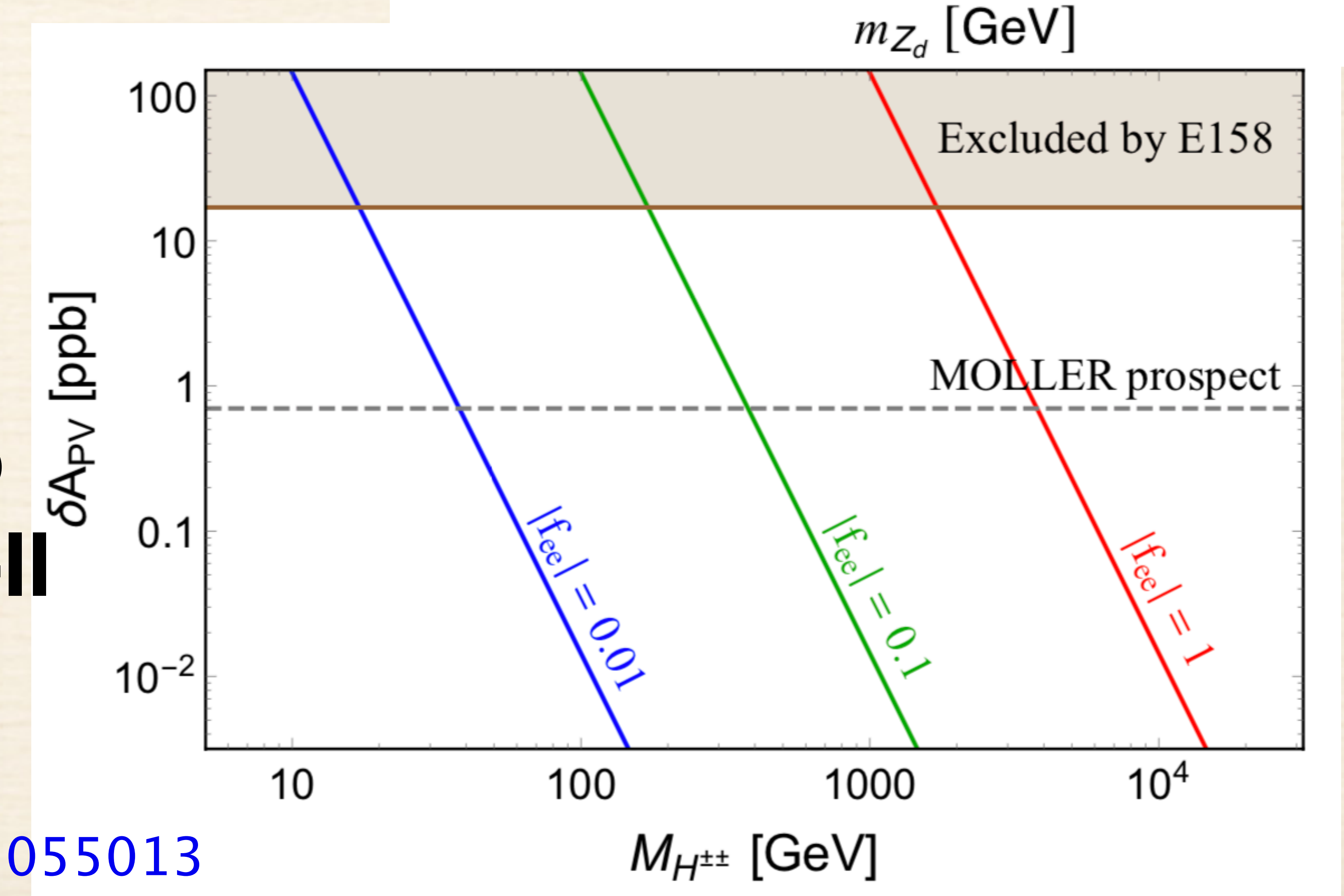
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\,\frac{|h_{ee}|^2}{(M_\Delta/1\ \text{TeV})^2}$$

Cirigliano et al
Phys.Rev. D70 (2004) 075007

5 σ for h_{ee} ~ 1 and M_Δ ~ 1 TeV

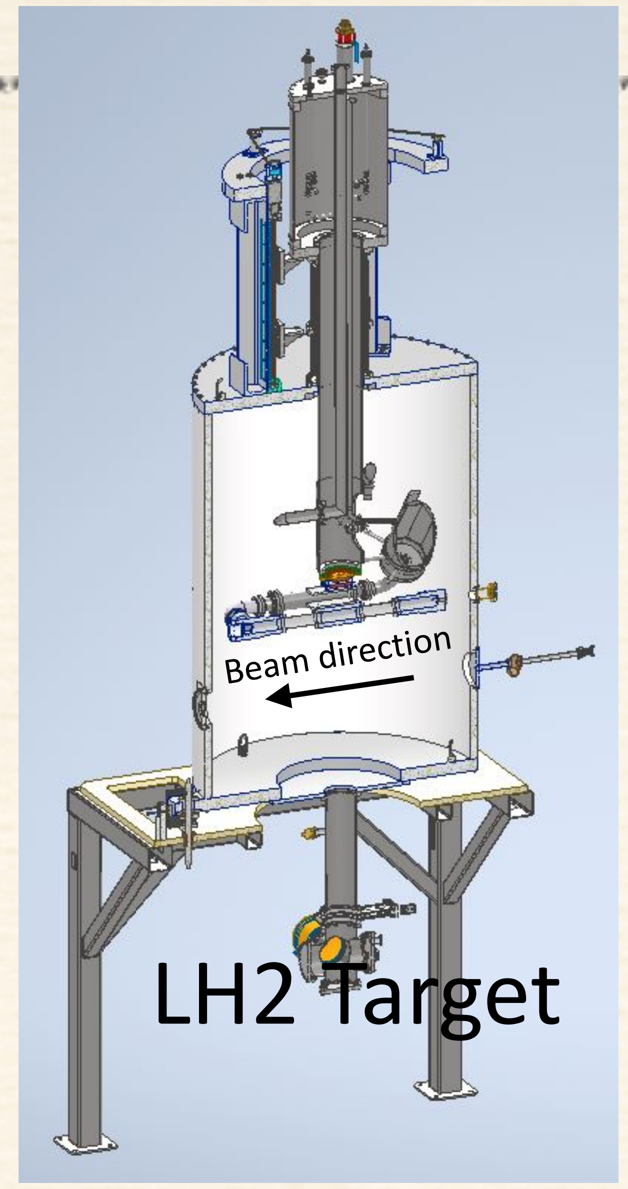
Specific Scenario for Type-II SeeSaw

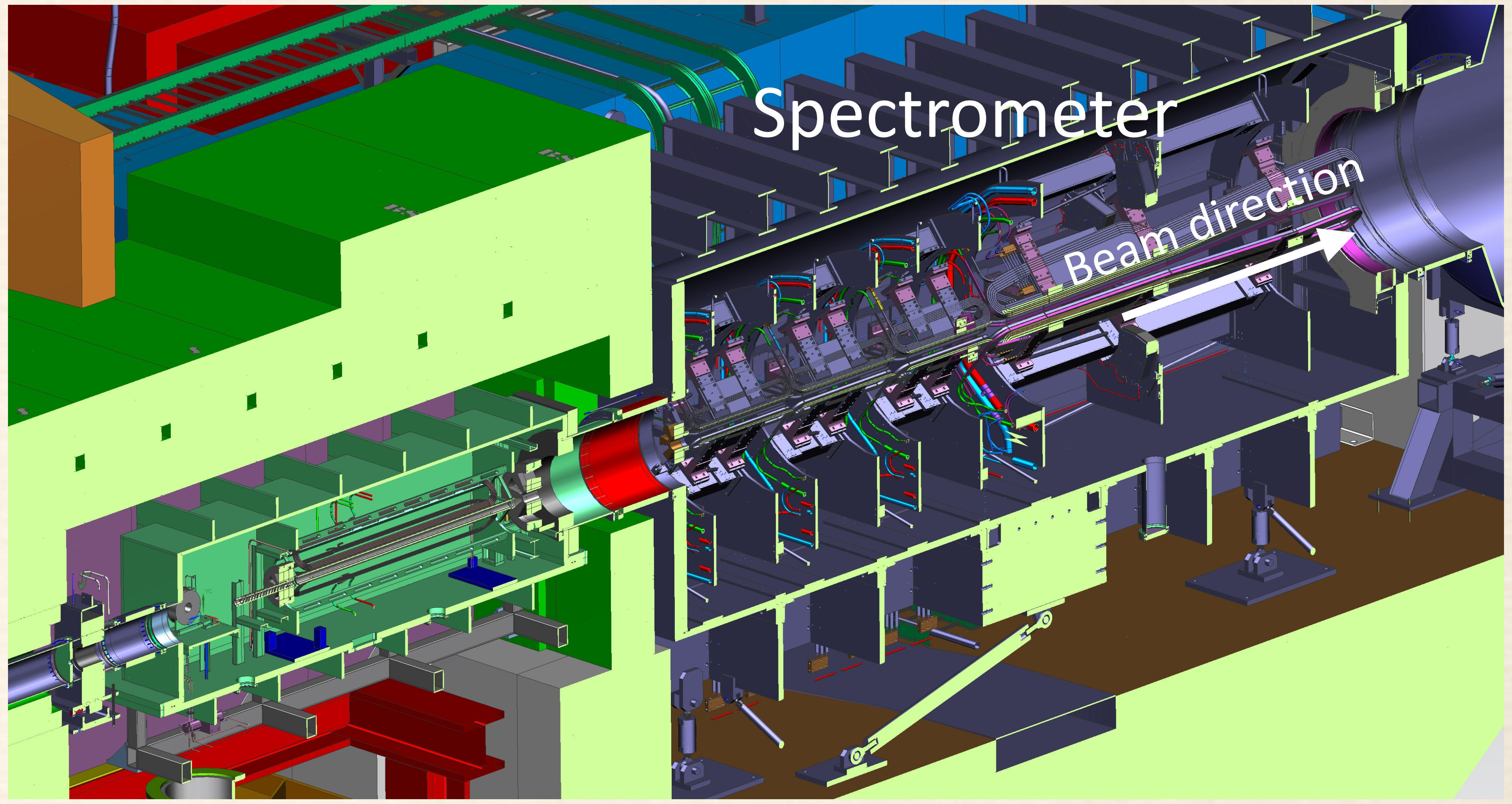
B. Dev et al
PhysRevD.98.055013

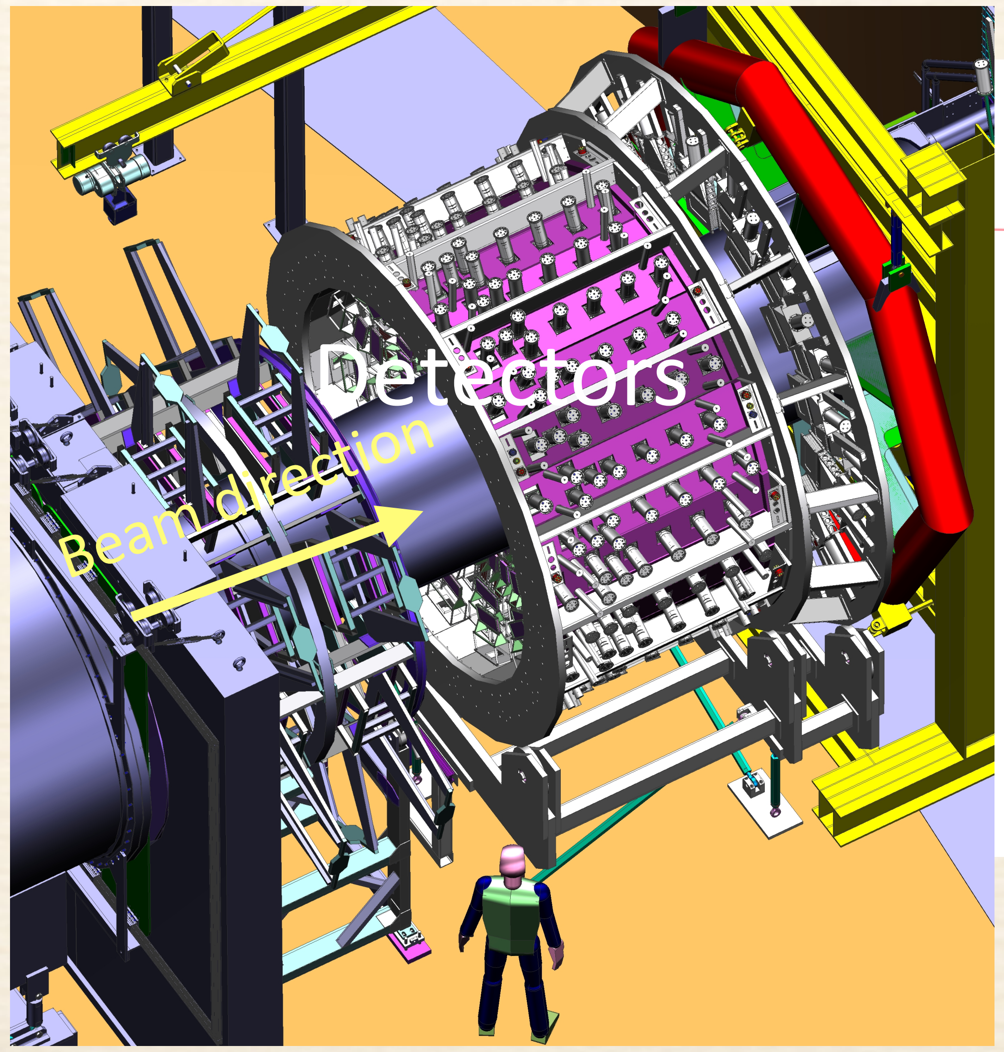


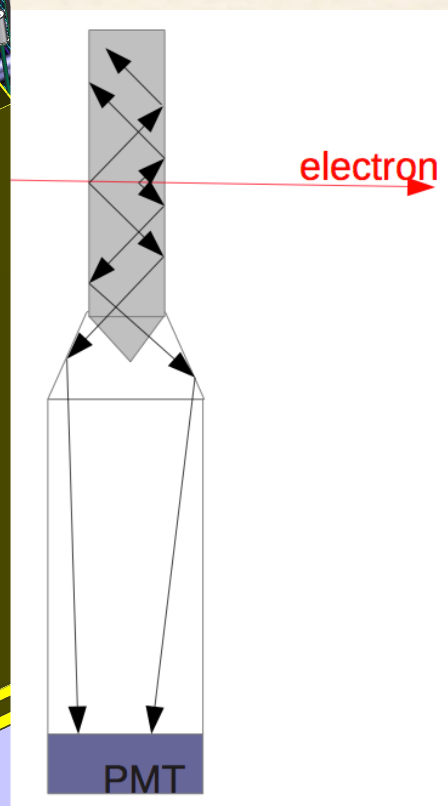
MOLLER Technical Challenges

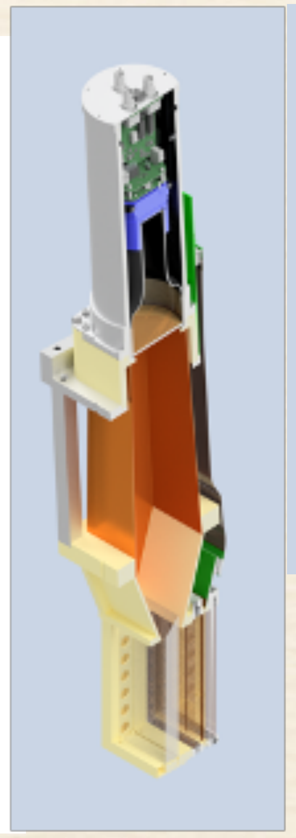
Evolutionary Improvements from Technology of Third Generation Experiments



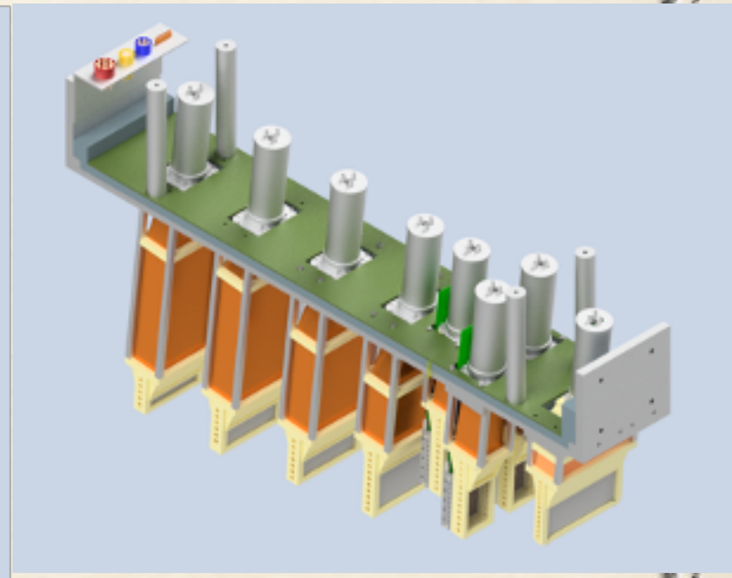








Single channel

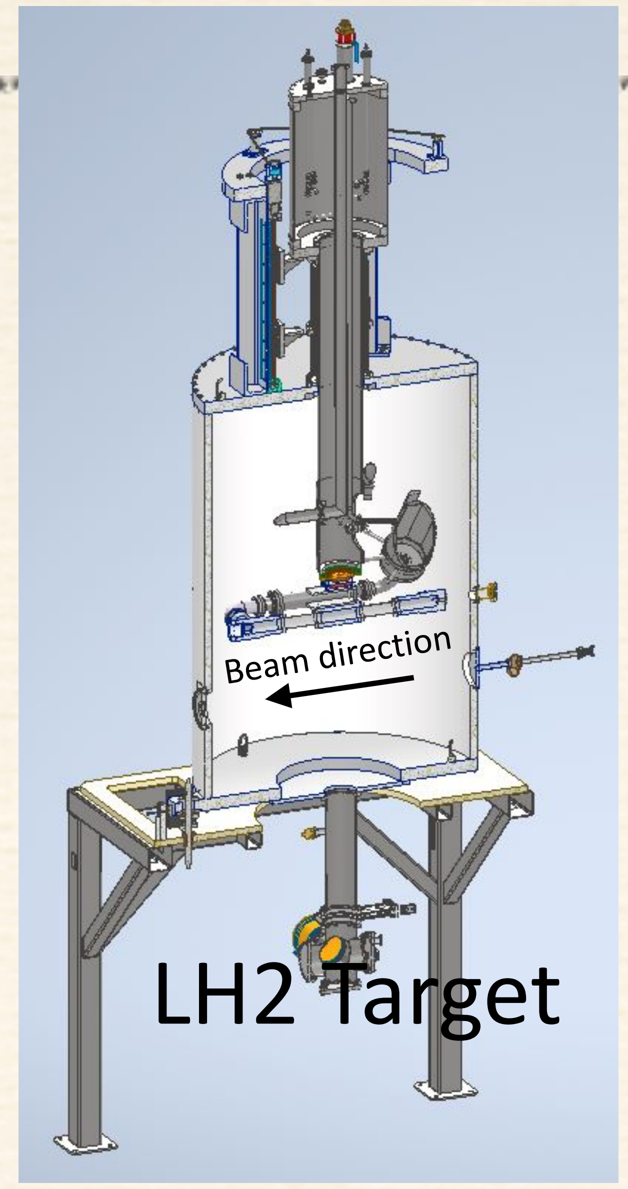


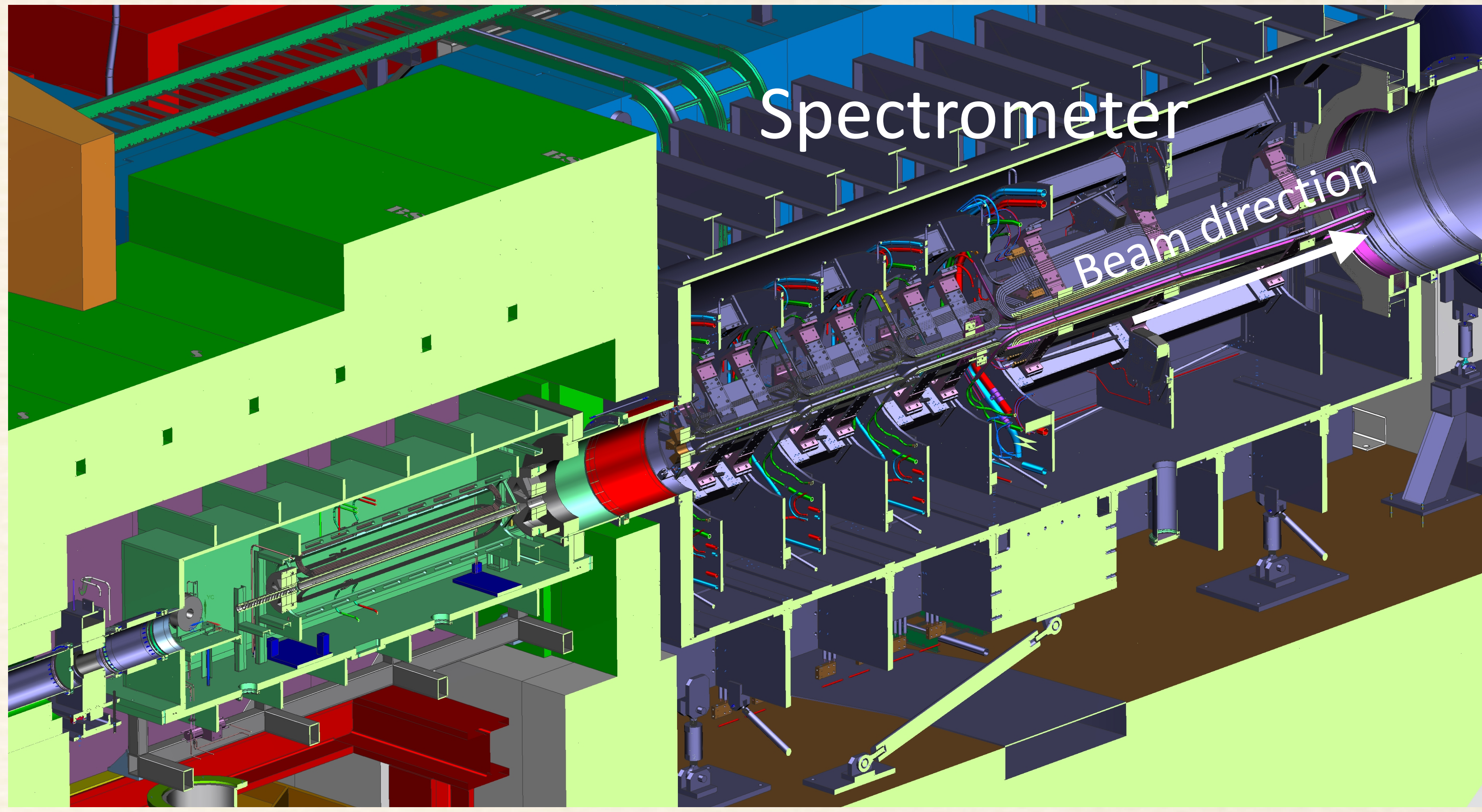
1/28th Segment

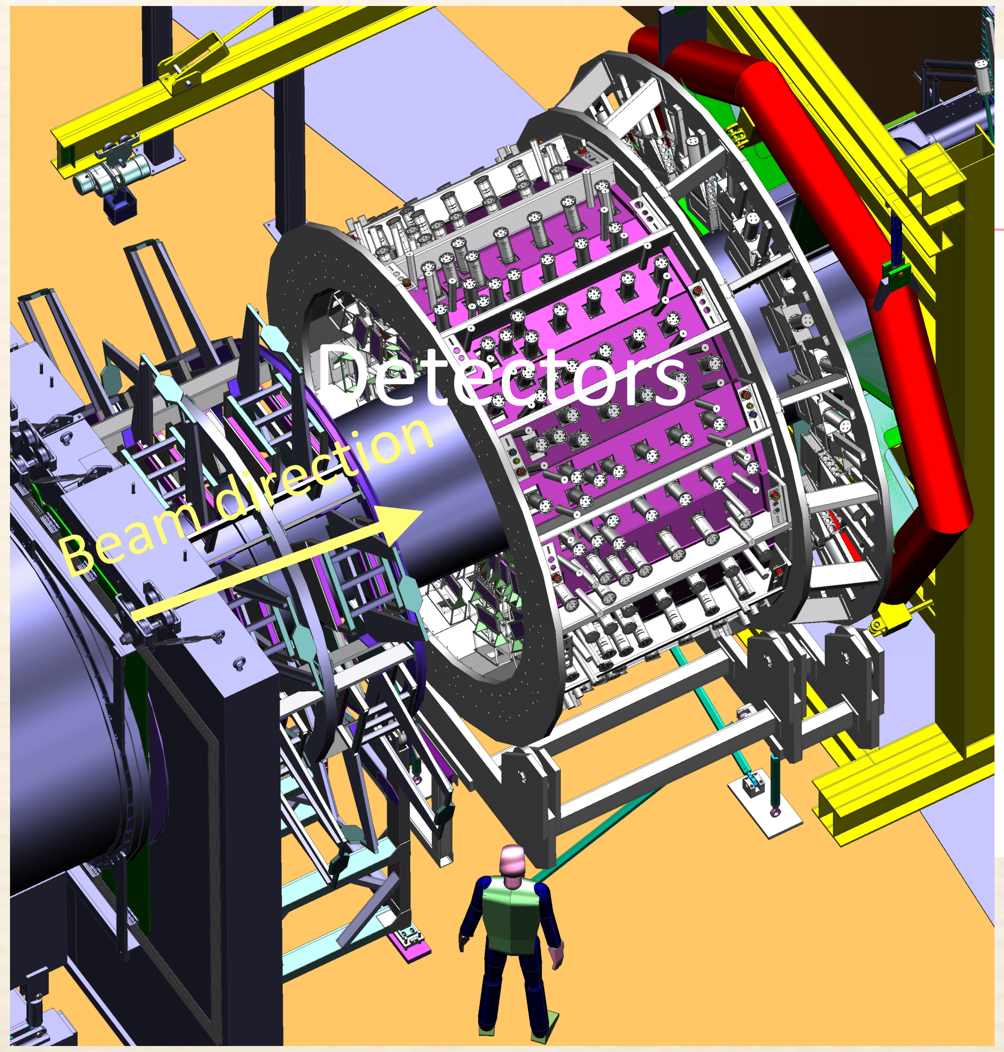
MOLLER Technical Challenges

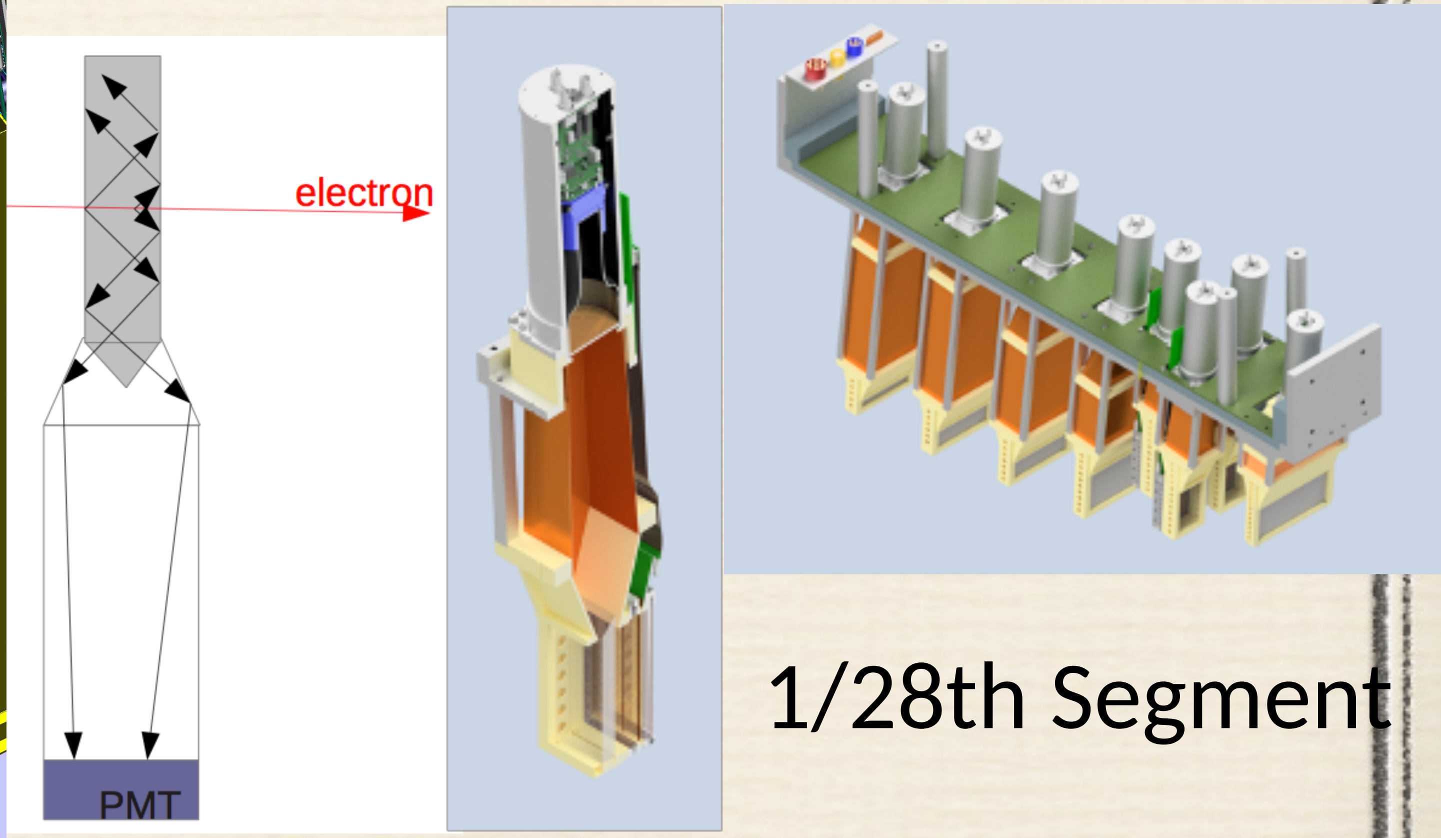
Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**









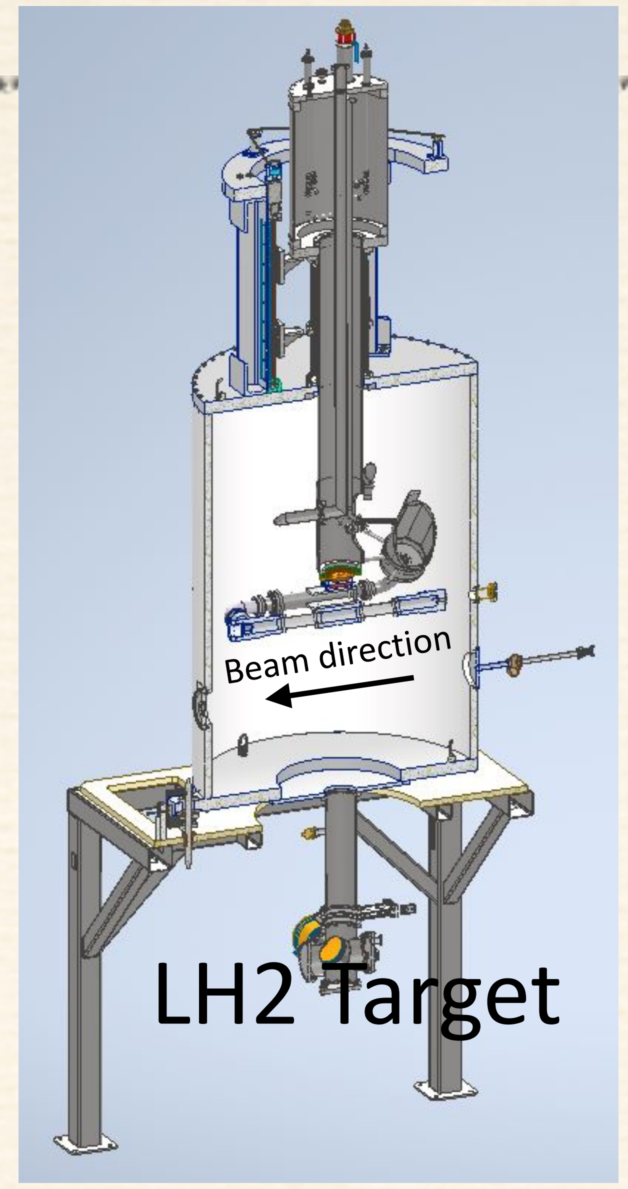
Single channel

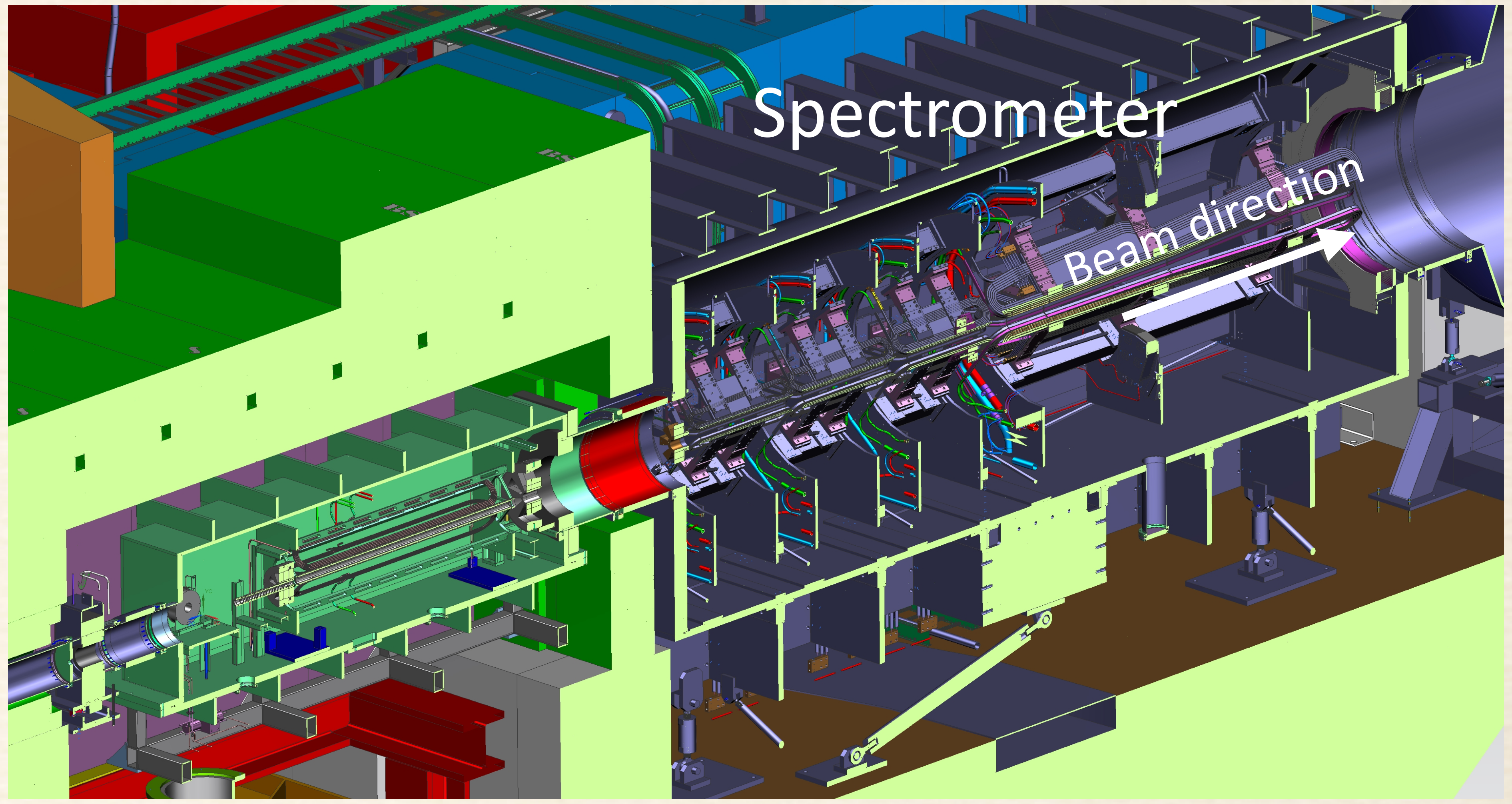
1/28th Segment

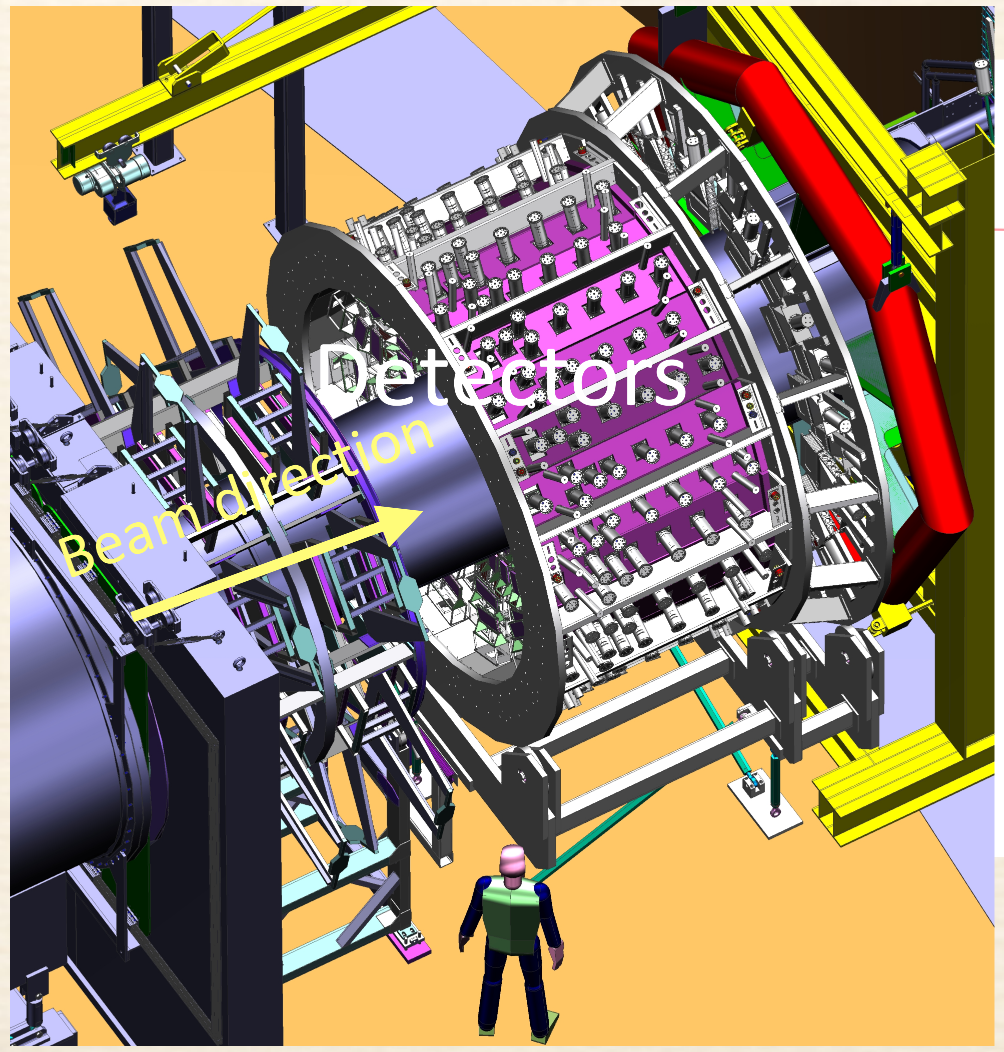
MOLLER Technical Challenges

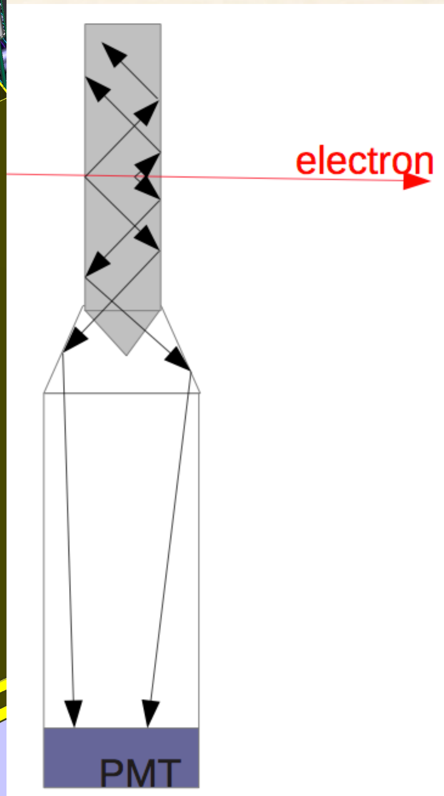
Evolutionary Improvements from Technology of Third Generation Experiments

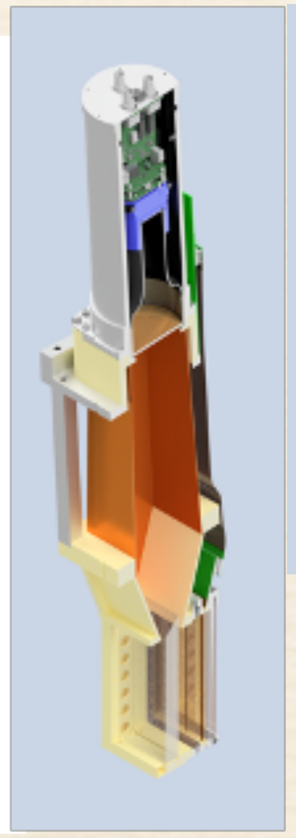
- **High intensity polarized electron source**
- **~ 134 GHz scattered electron rate**











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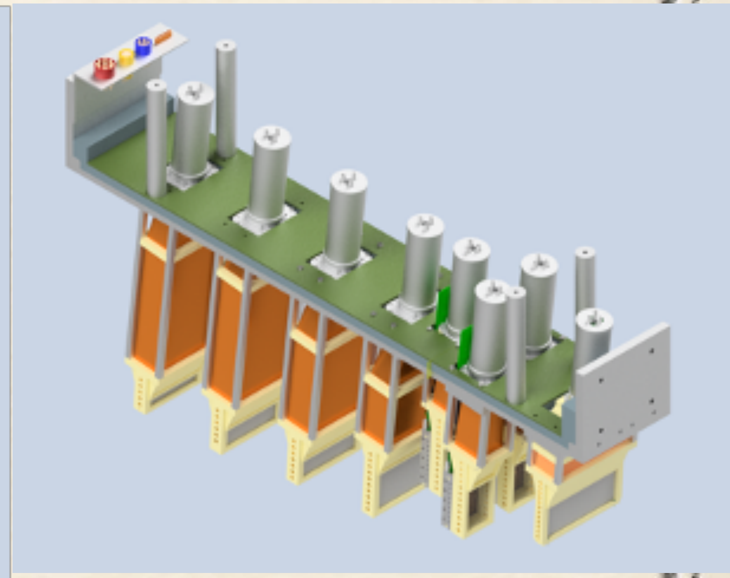
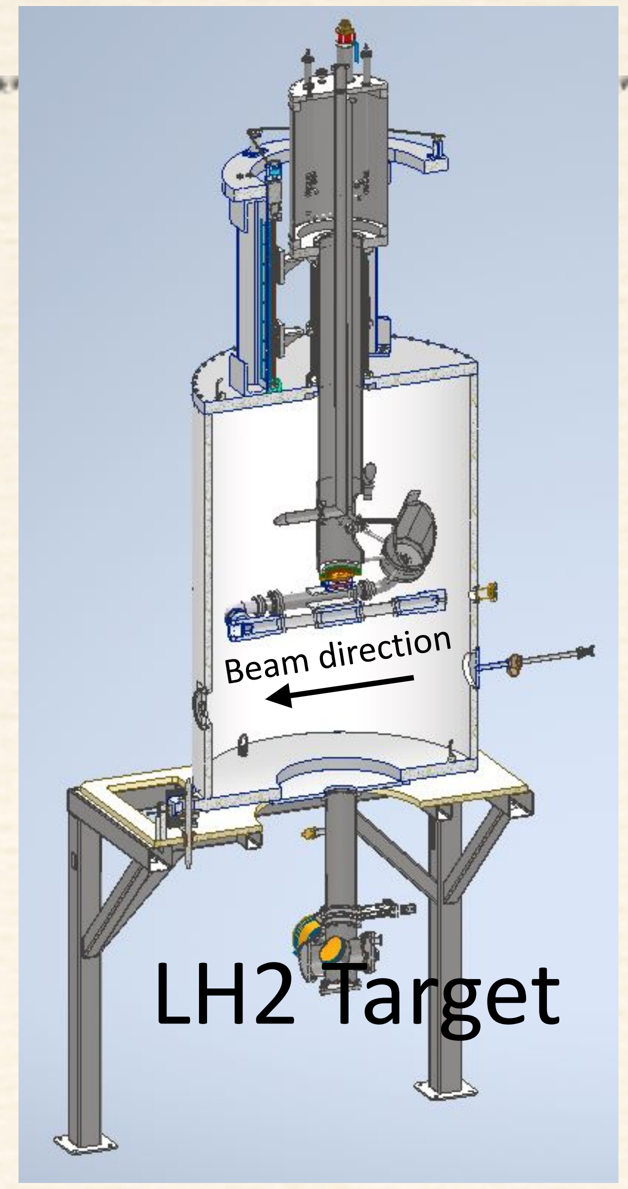


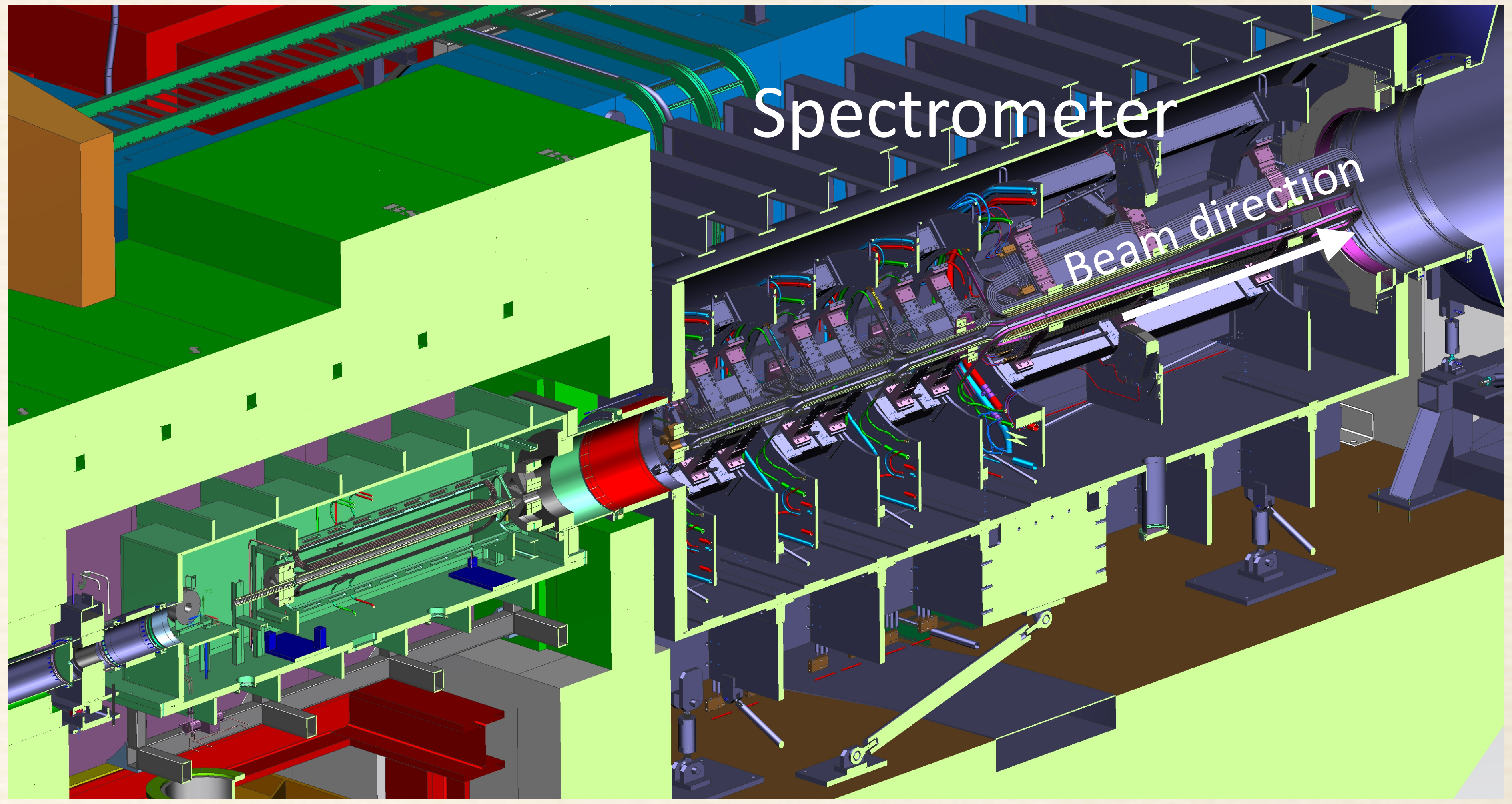
1/28th Segment

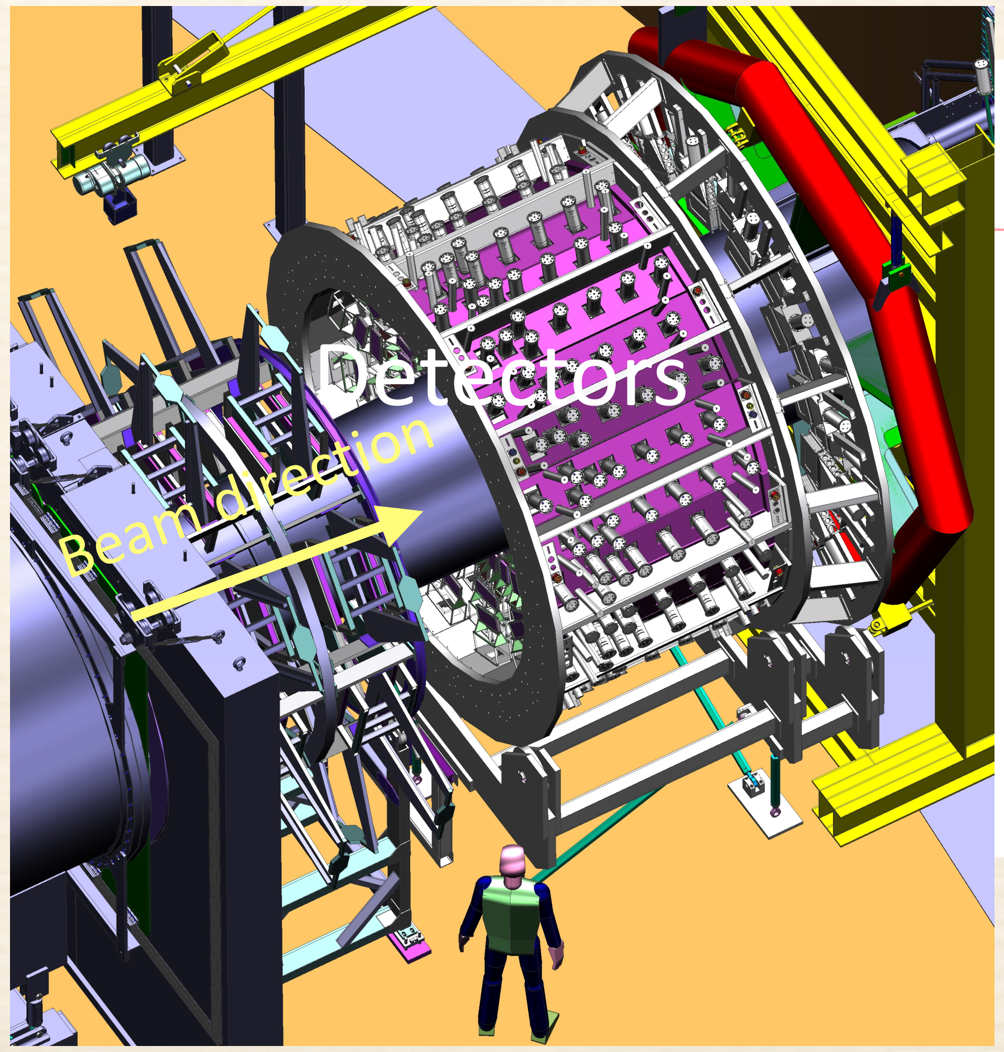
MOLLER Technical Challenges

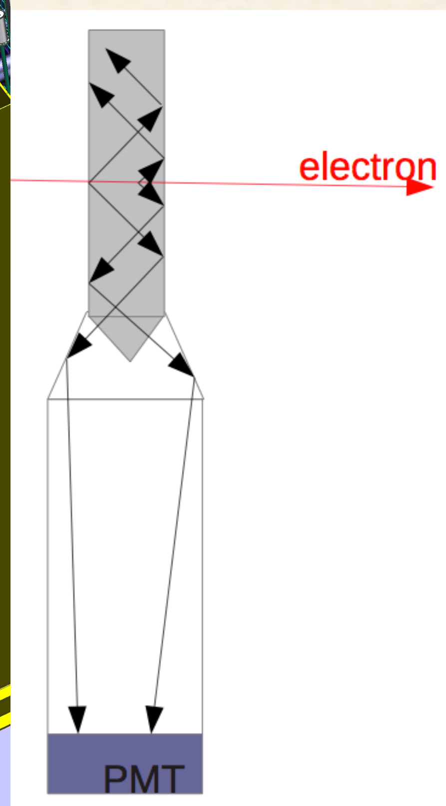
Evolutionary Improvements from Technology of Third Generation Experiments

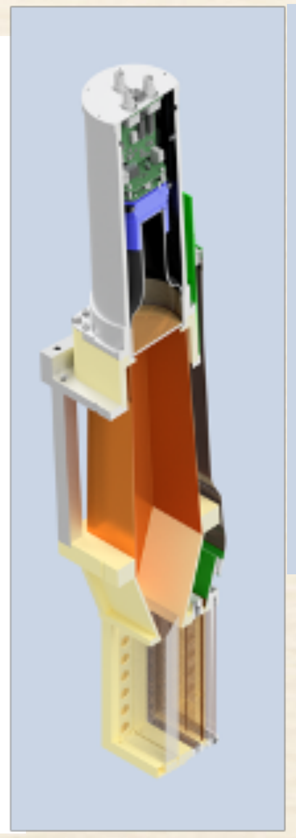
- **High intensity polarized electron source**
- **~ 134 GHz scattered electron rate**
- **1 nm control of beam centroid on target**











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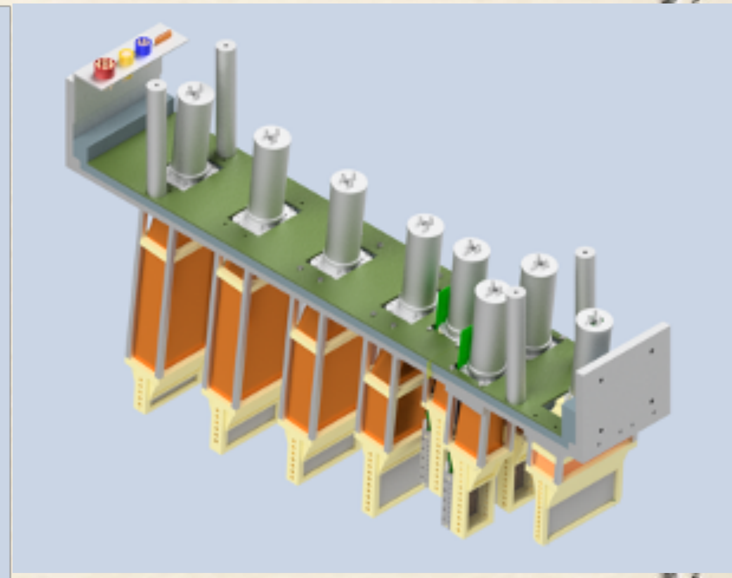

1/28th Segment

MOLLER Technical Challenges

Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**
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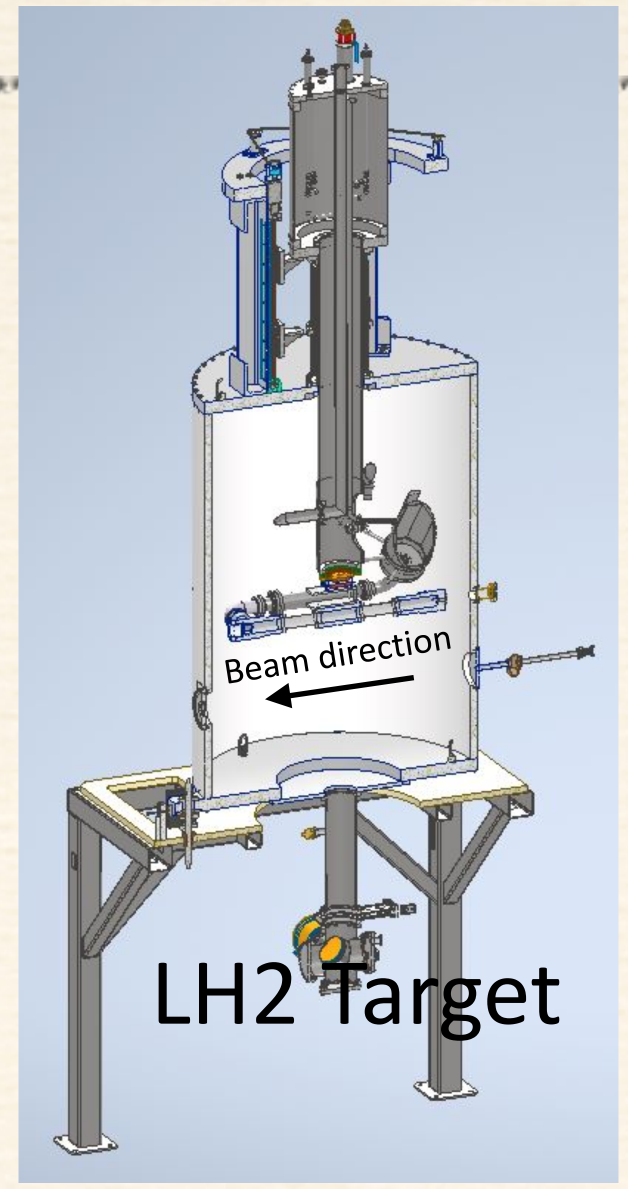
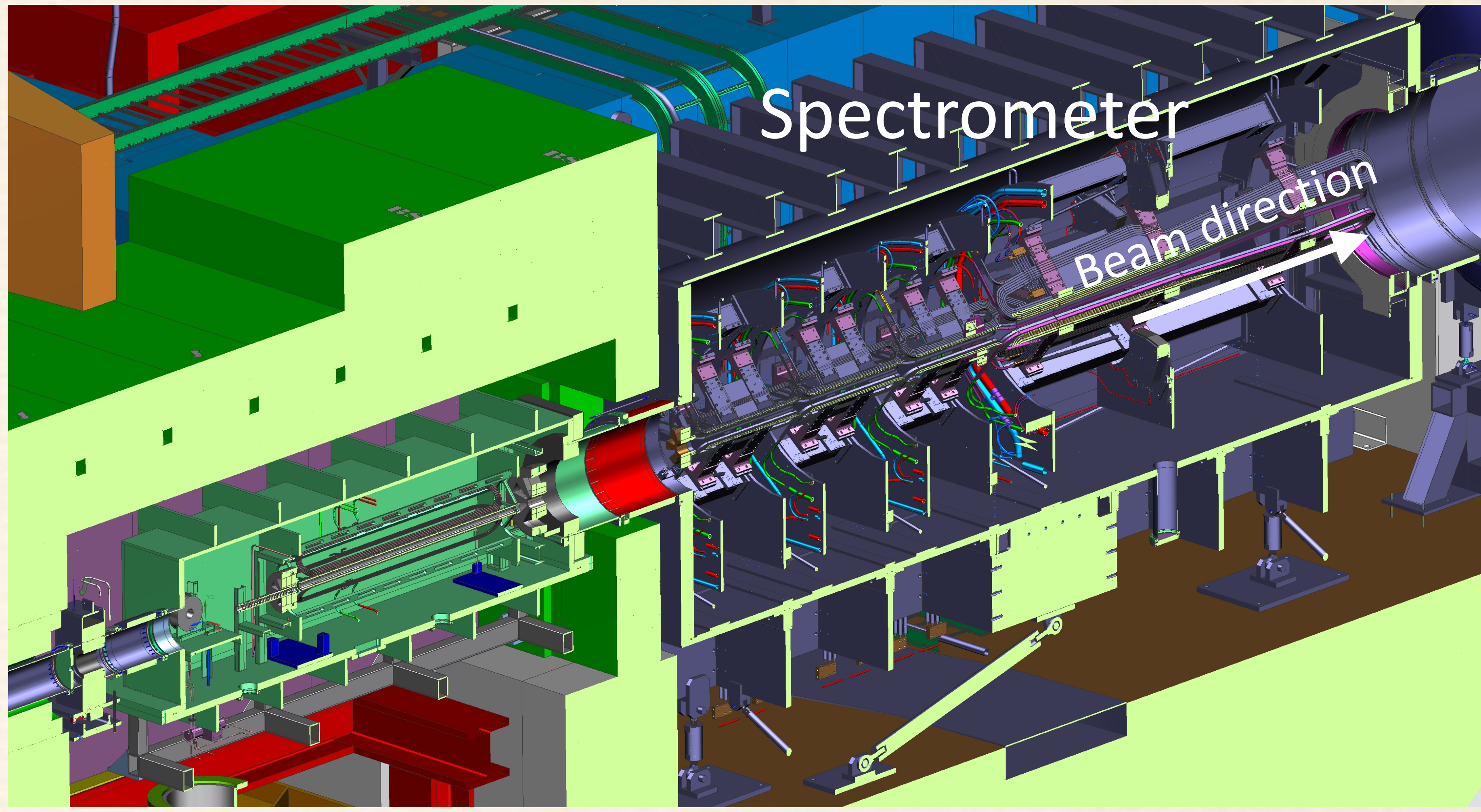
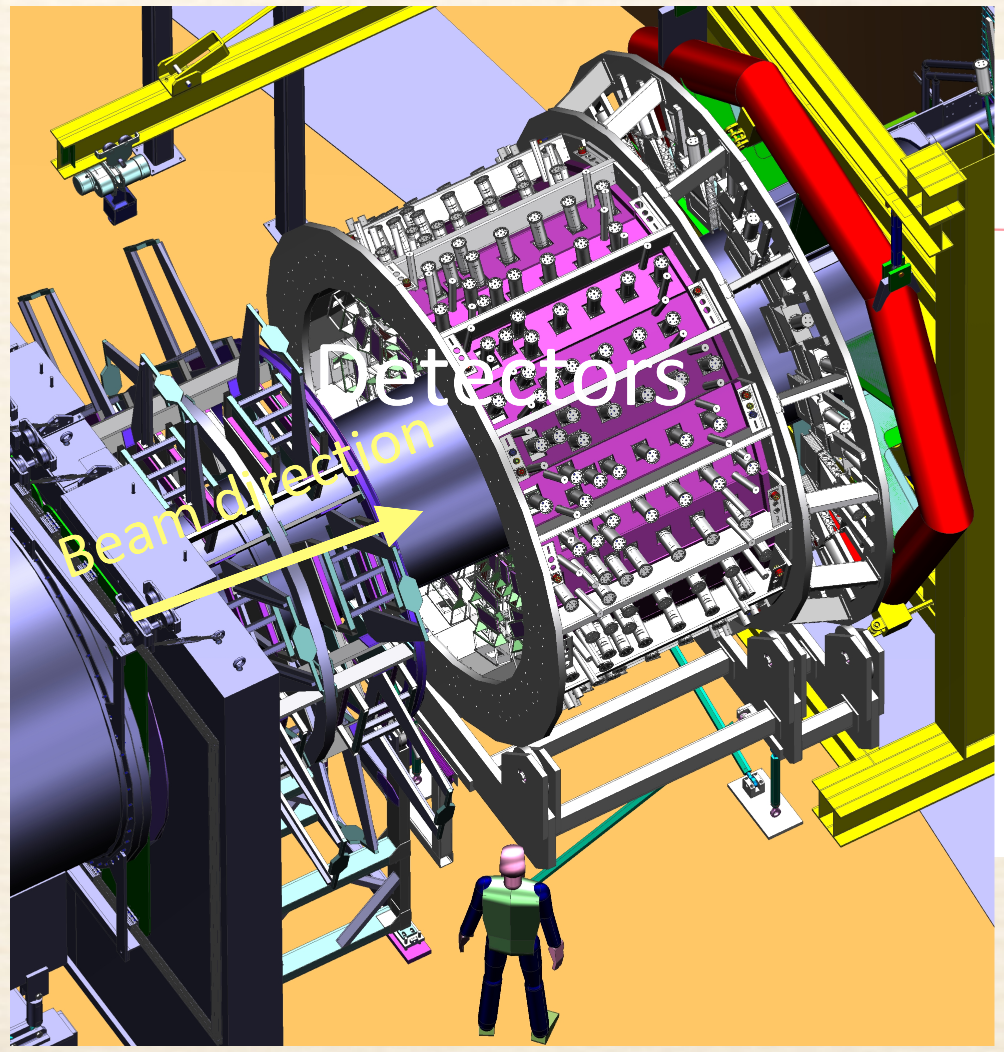
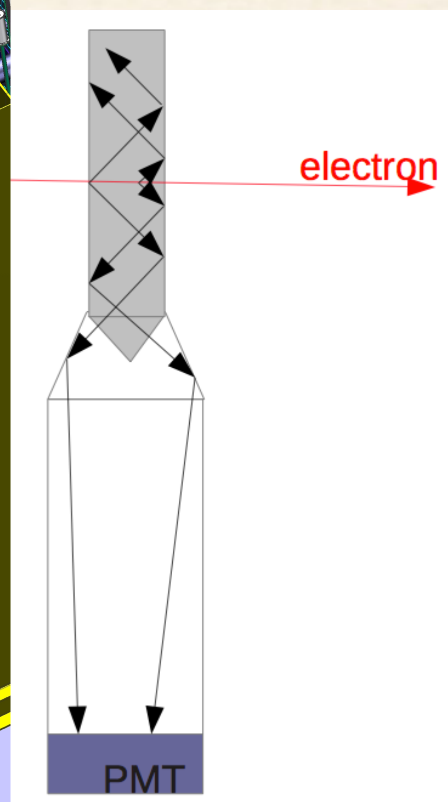
- **~ 9 gm/cm² liquid hydrogen target**









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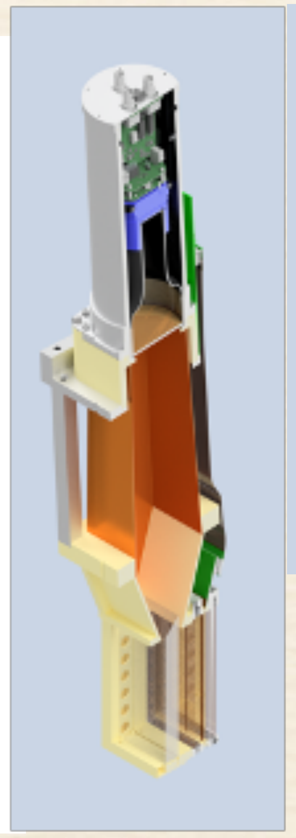

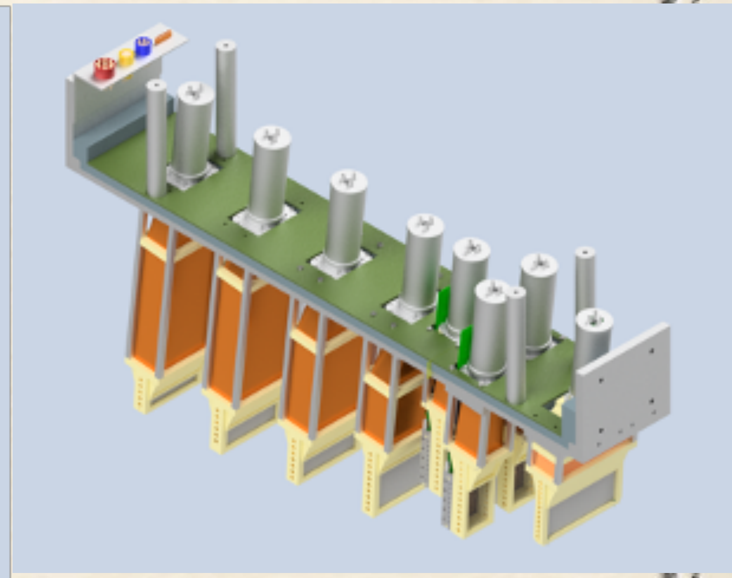

1/28th Segment

MOLLER Technical Challenges

Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**
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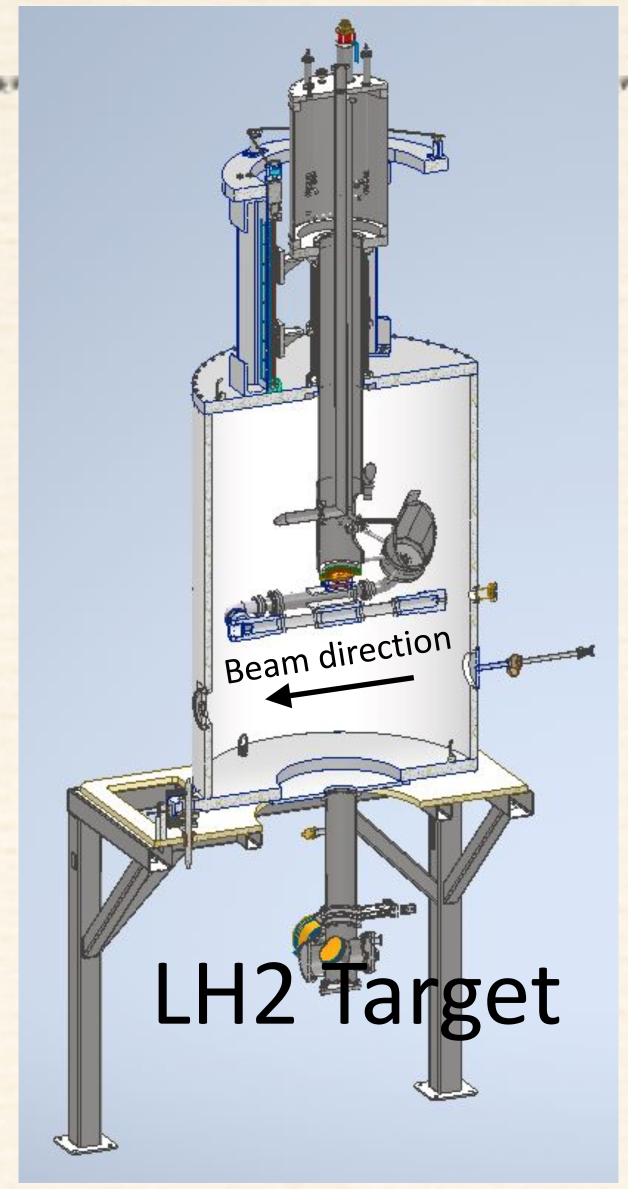
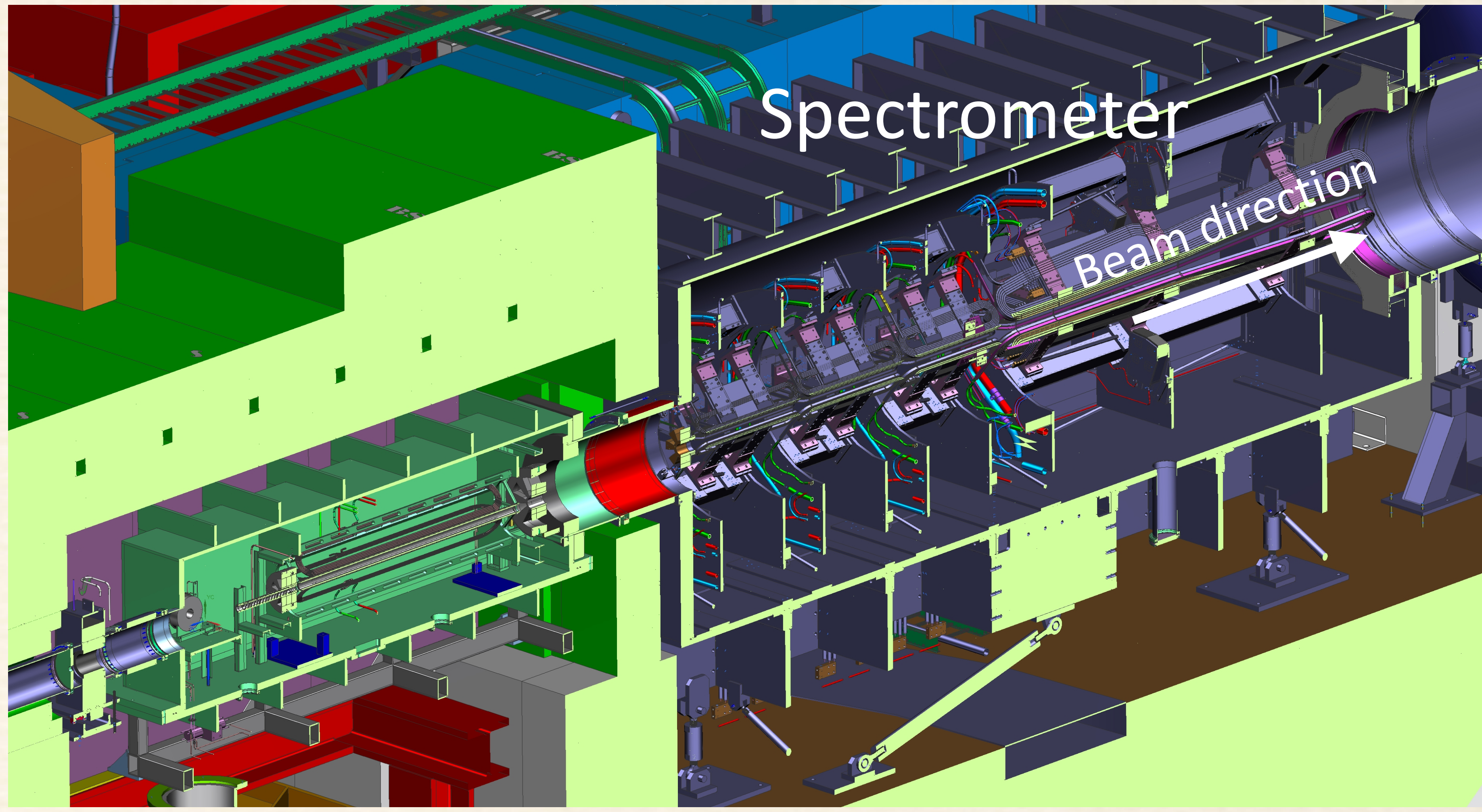
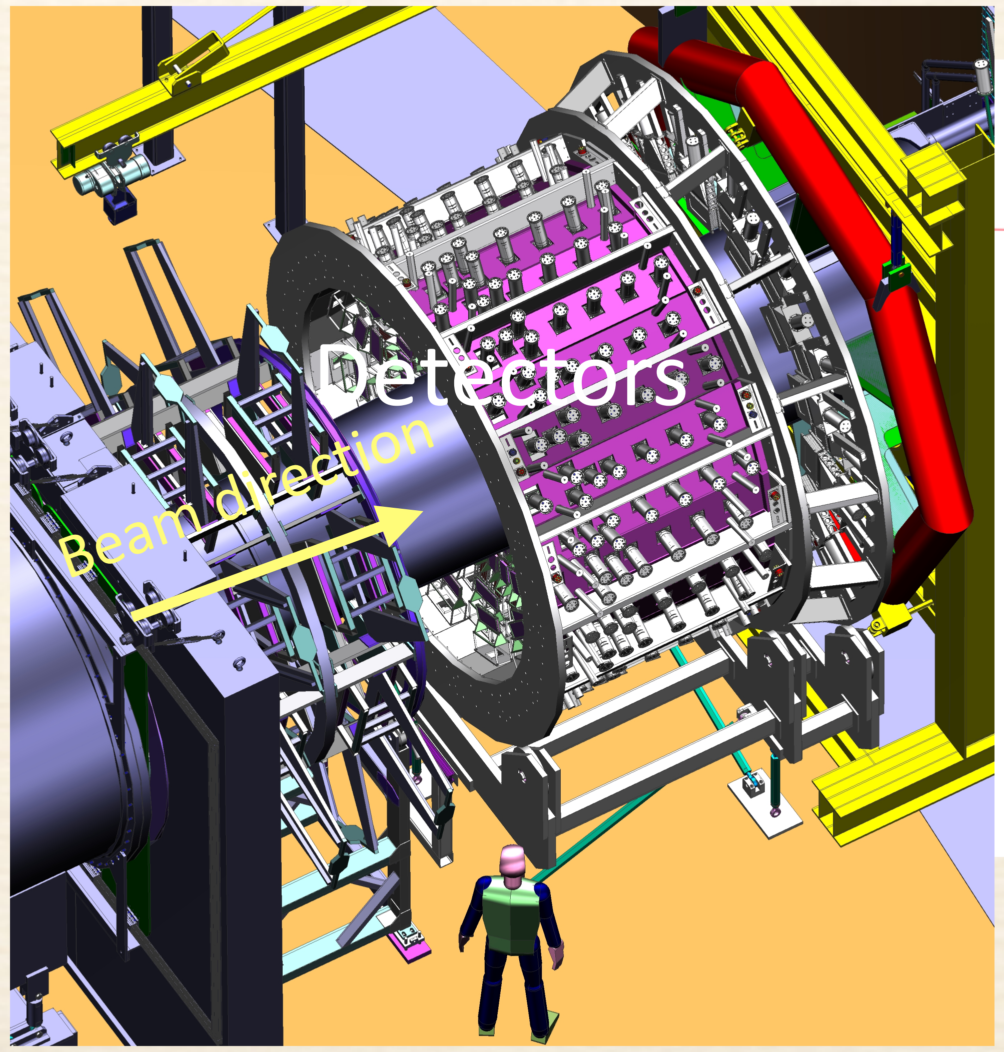
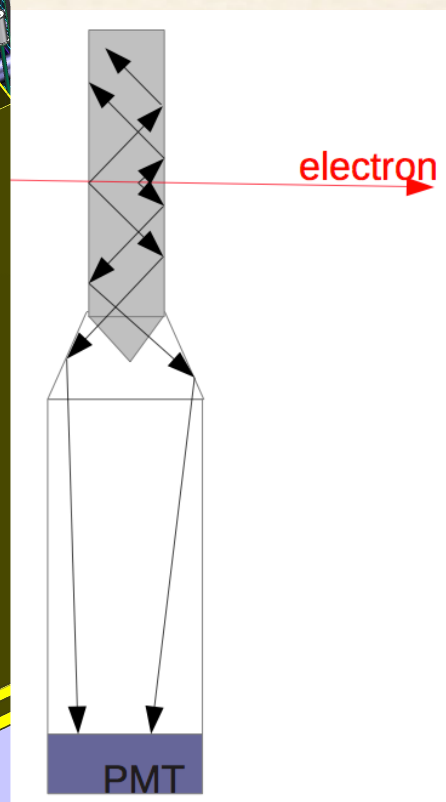
  - **1.25 m: ~ 3.7 kW @ 70 μA**









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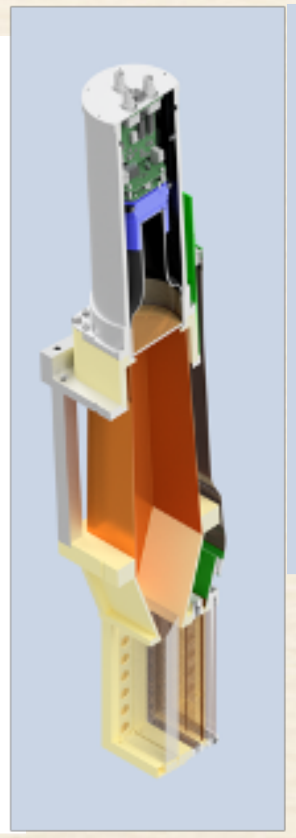

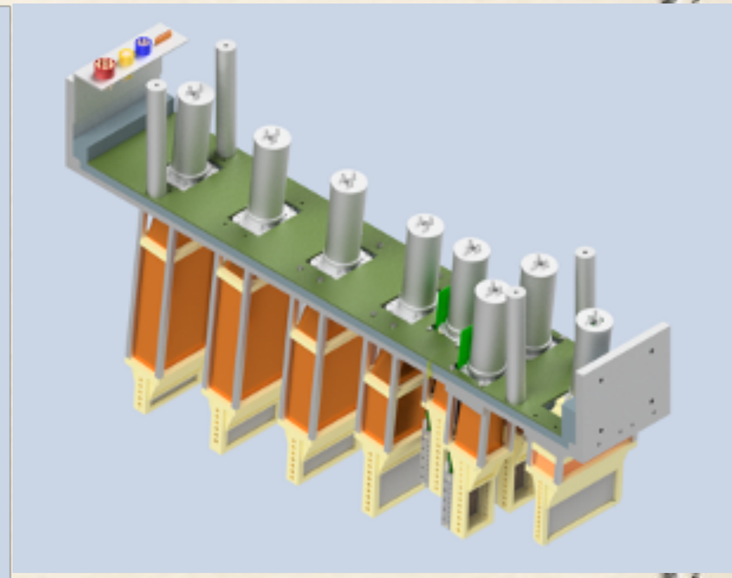

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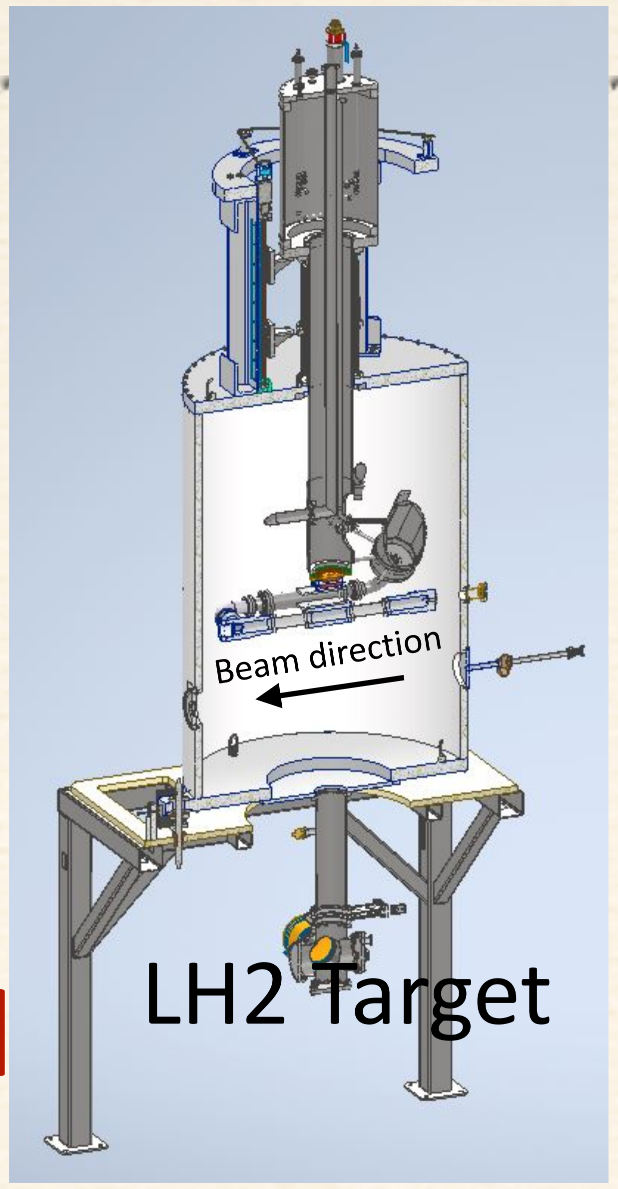
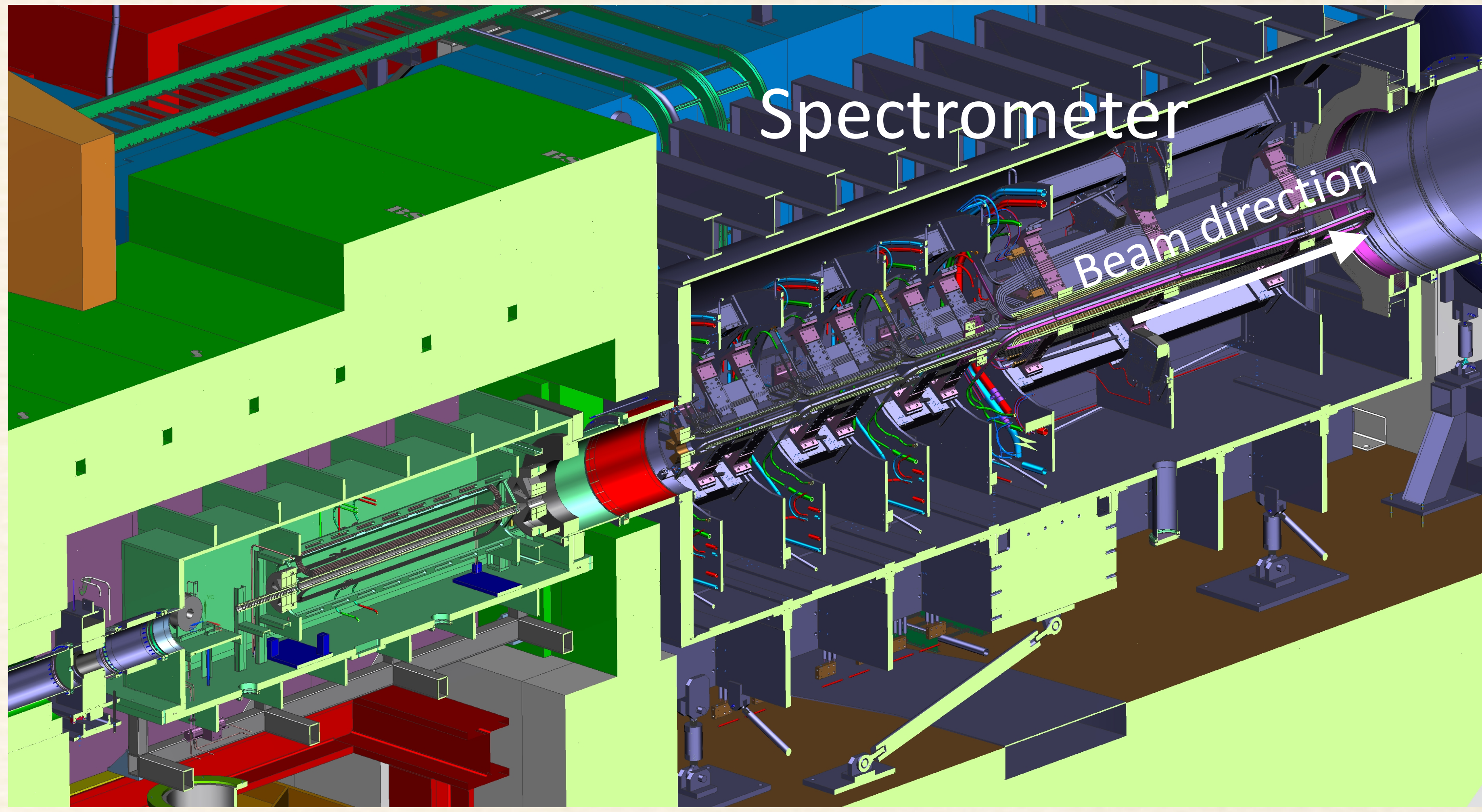
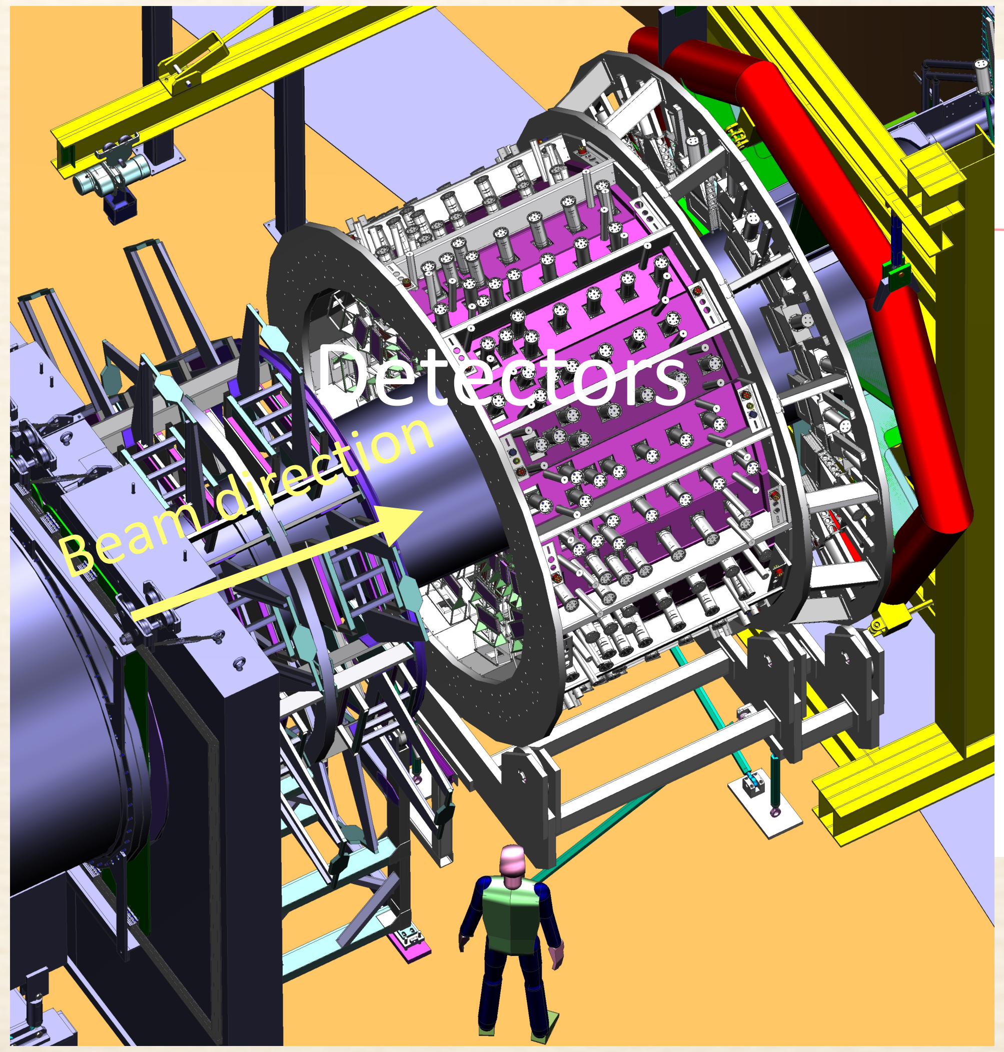
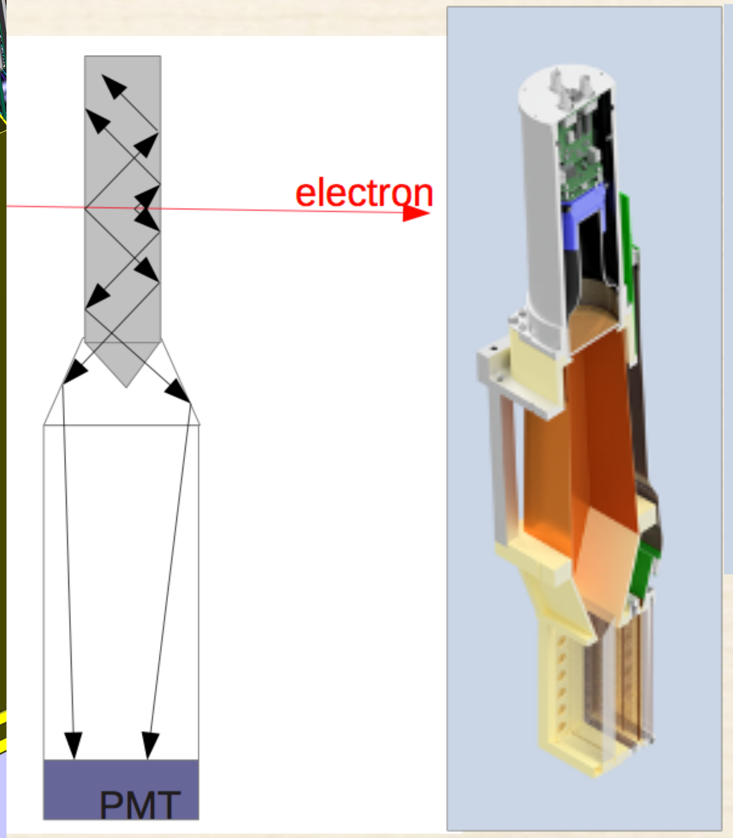
- **Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad**









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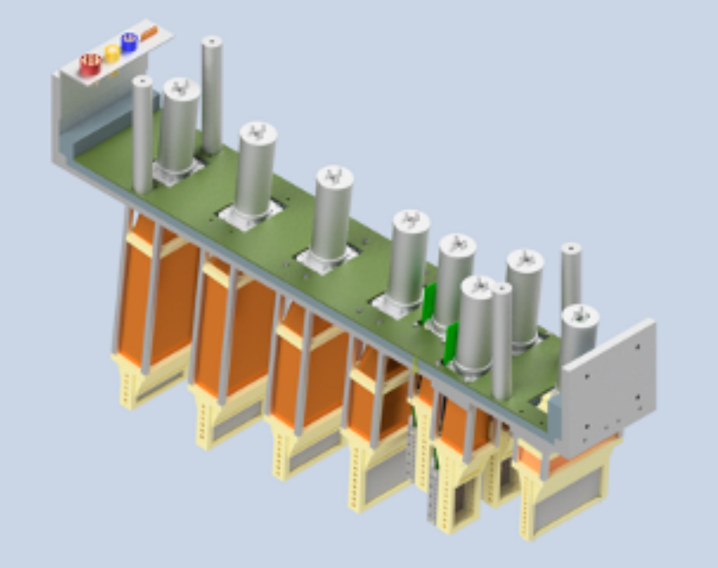

1/28th Segment

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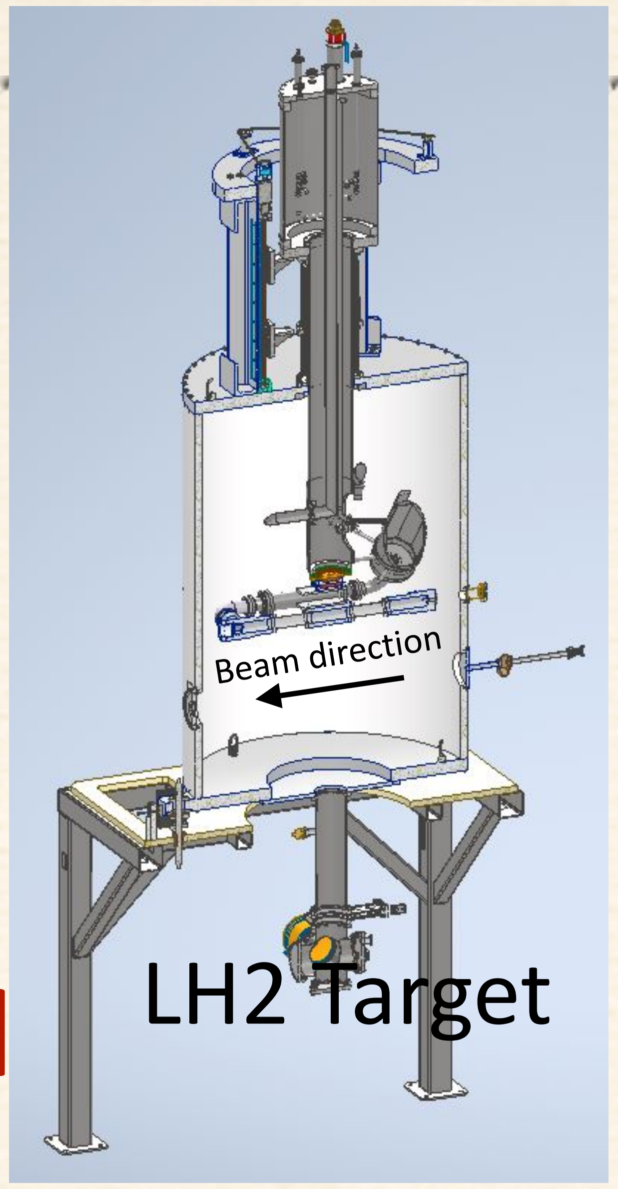
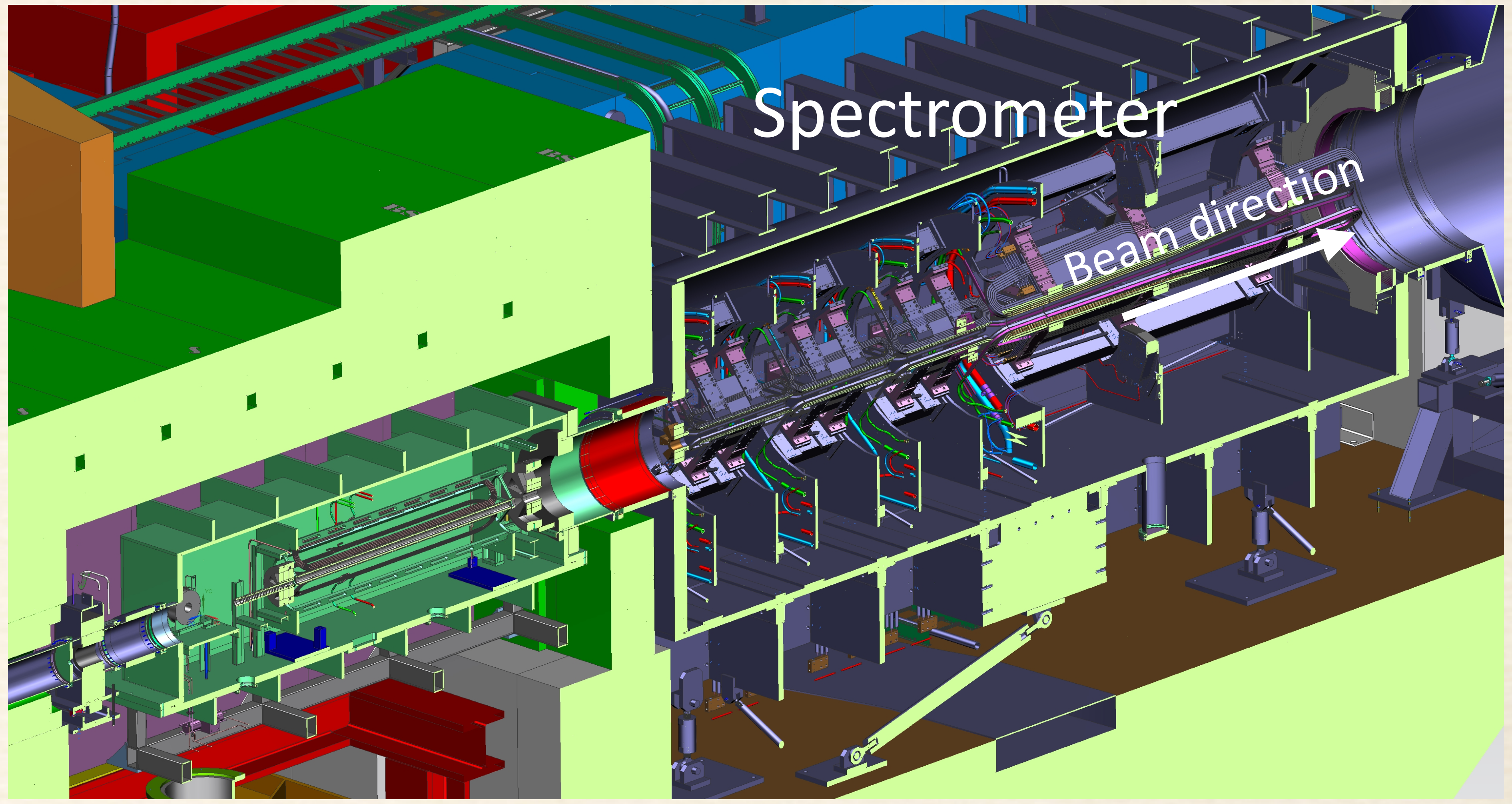
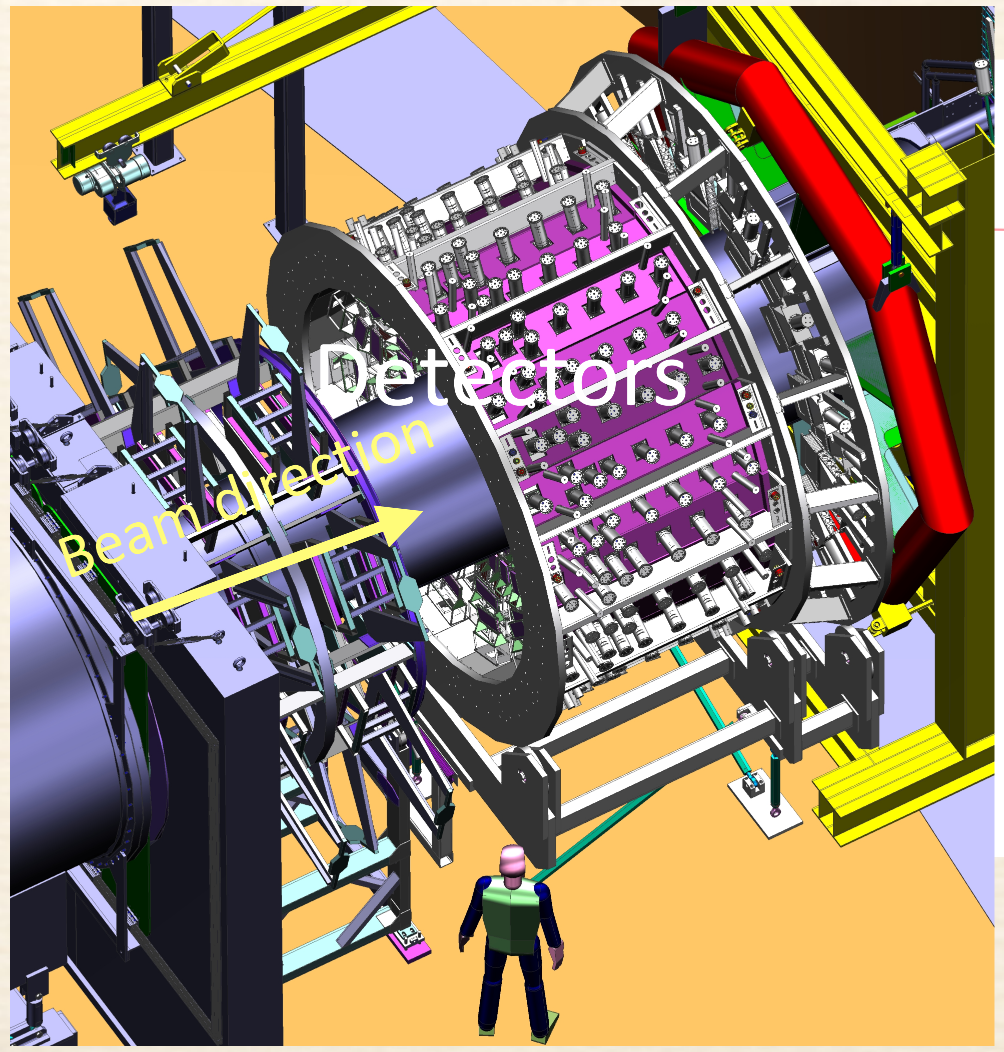
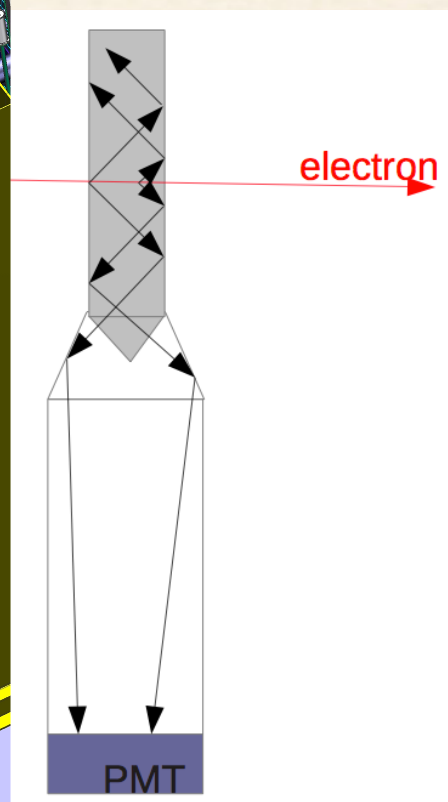
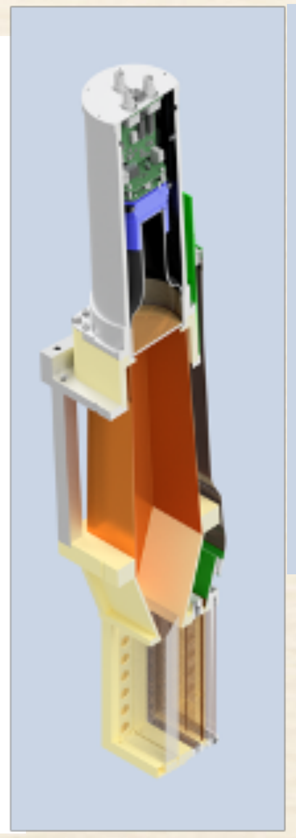
  - **•novel toroidal spectrometer assemblies**



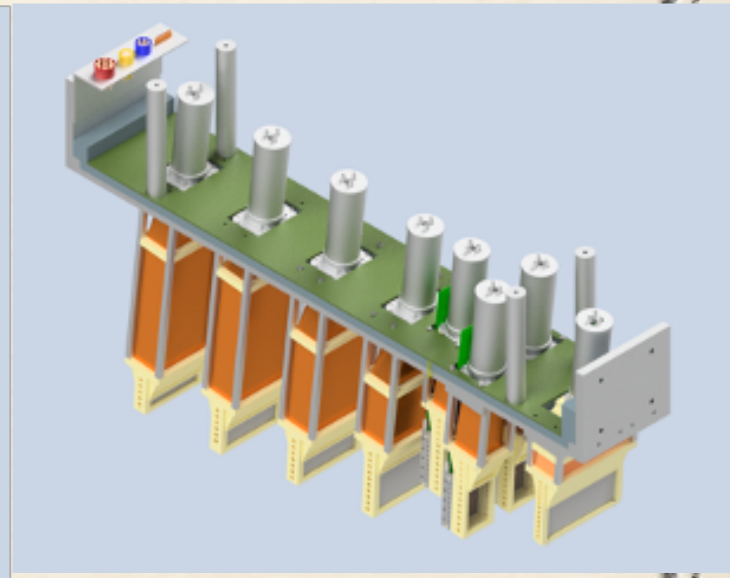








Single channel

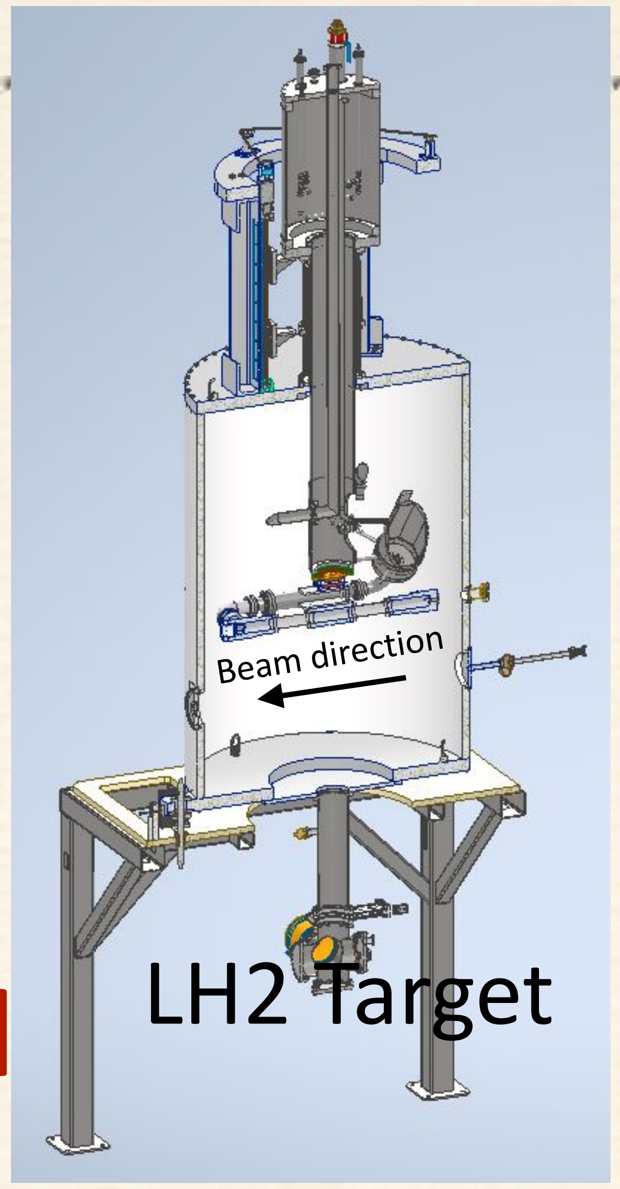


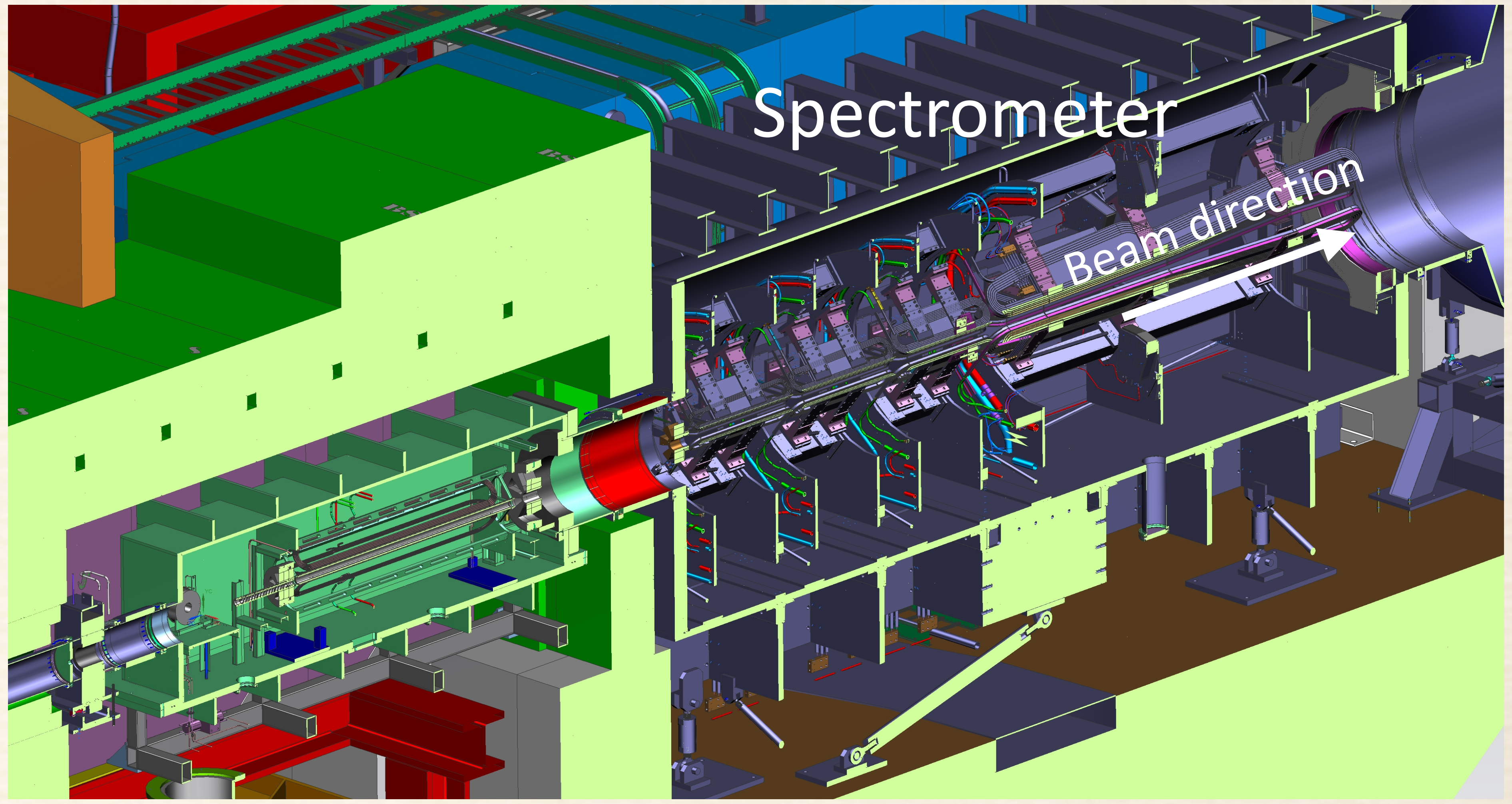
1/28th Segment

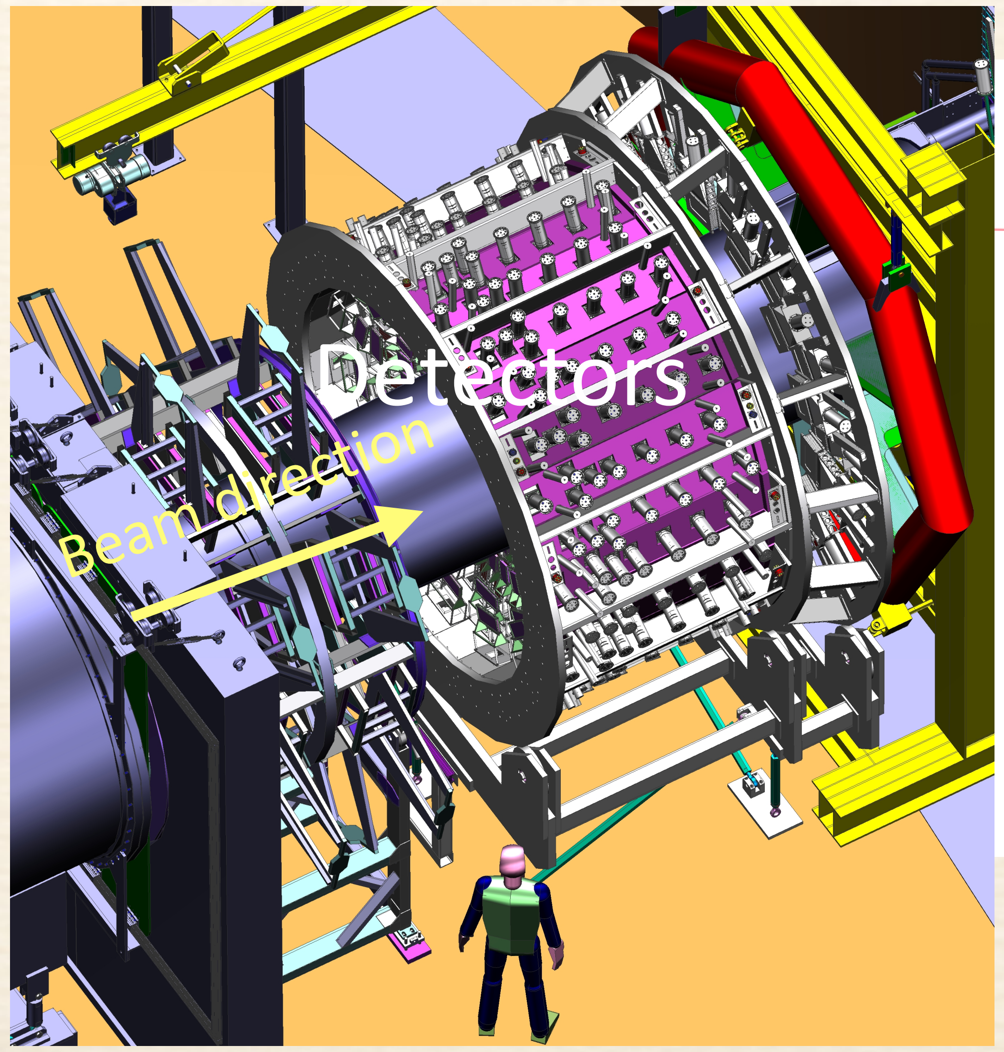
MOLLER Technical Challenges

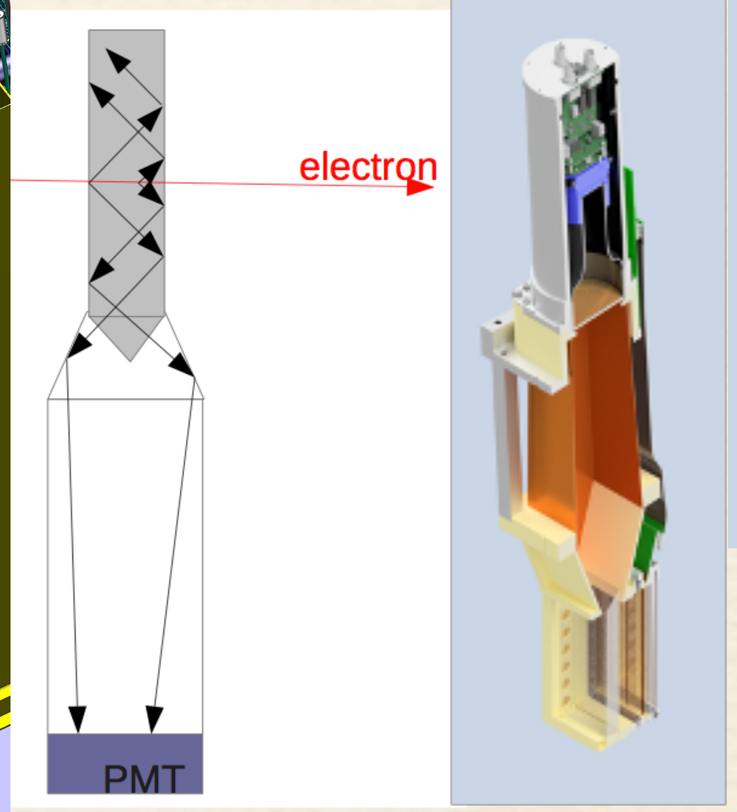
Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**
- **~ 134 GHz scattered electron rate**
- **1 nm control of beam centroid on target**
- **~ 9 gm/cm² 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**









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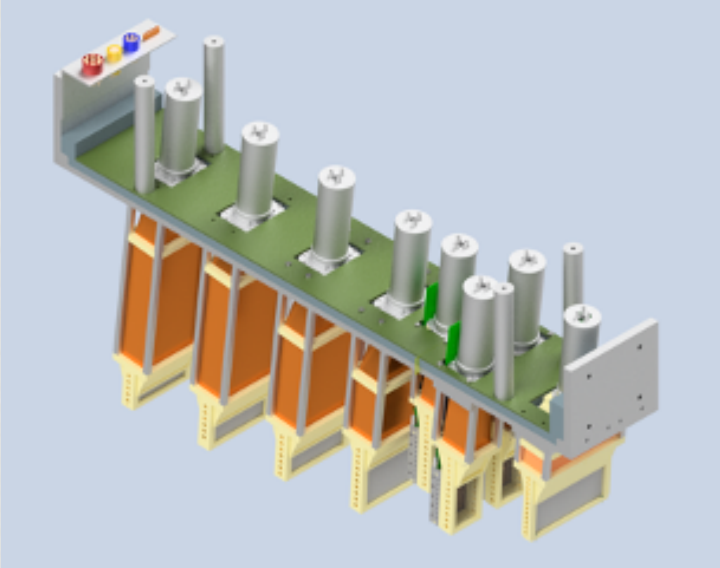

1/28th Segment

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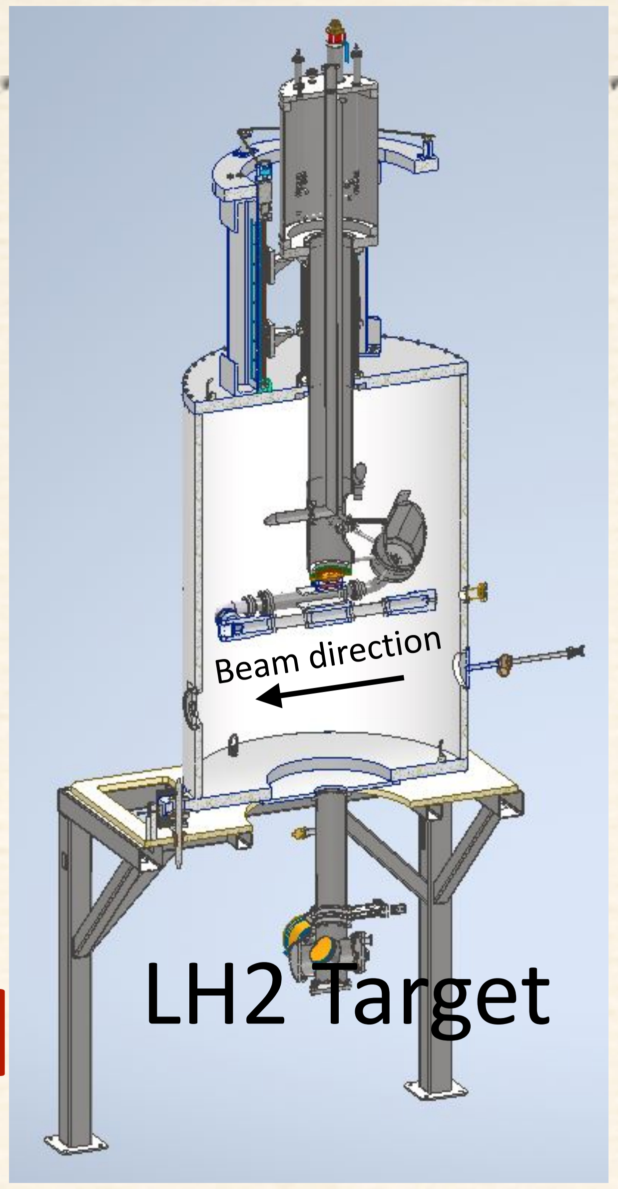
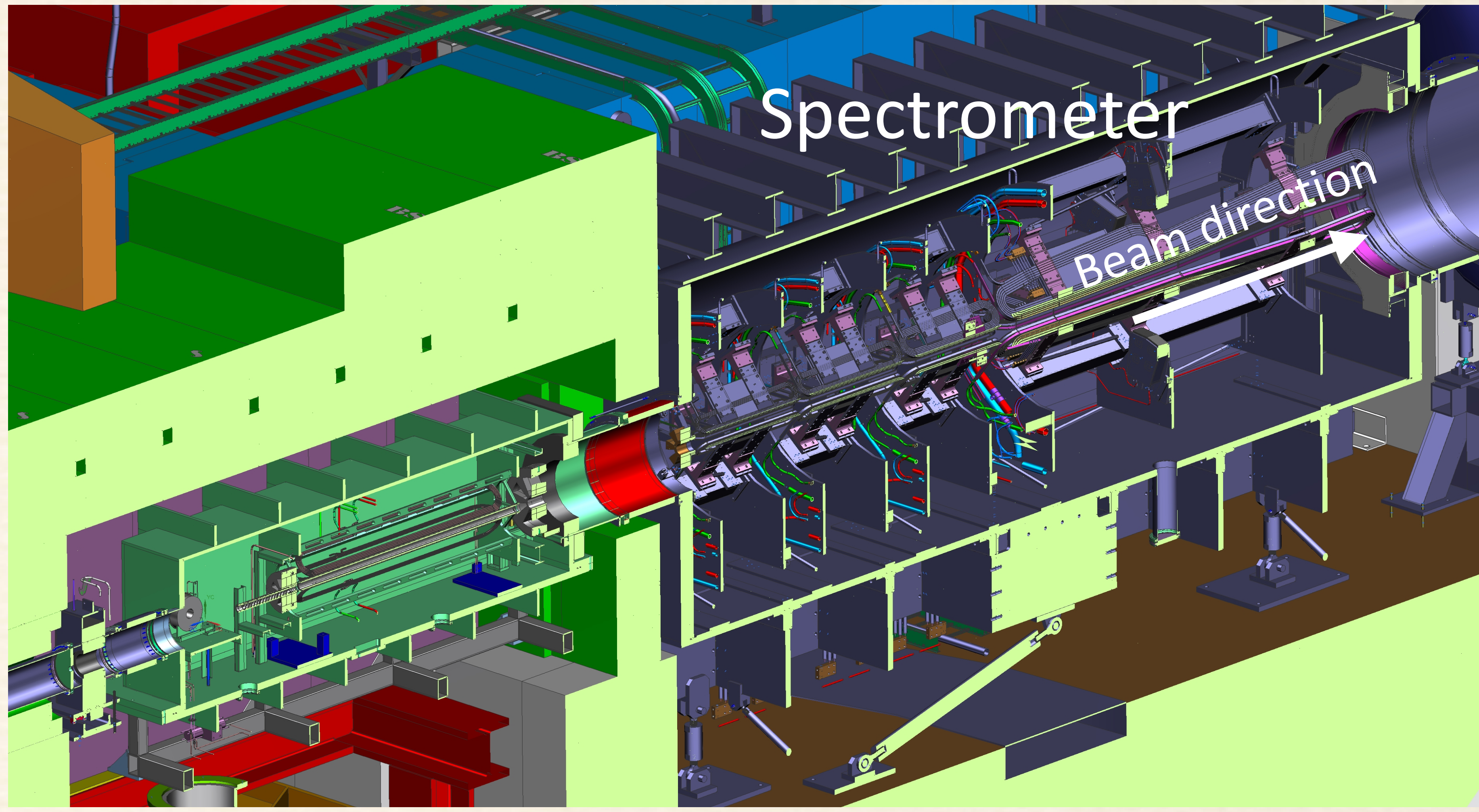
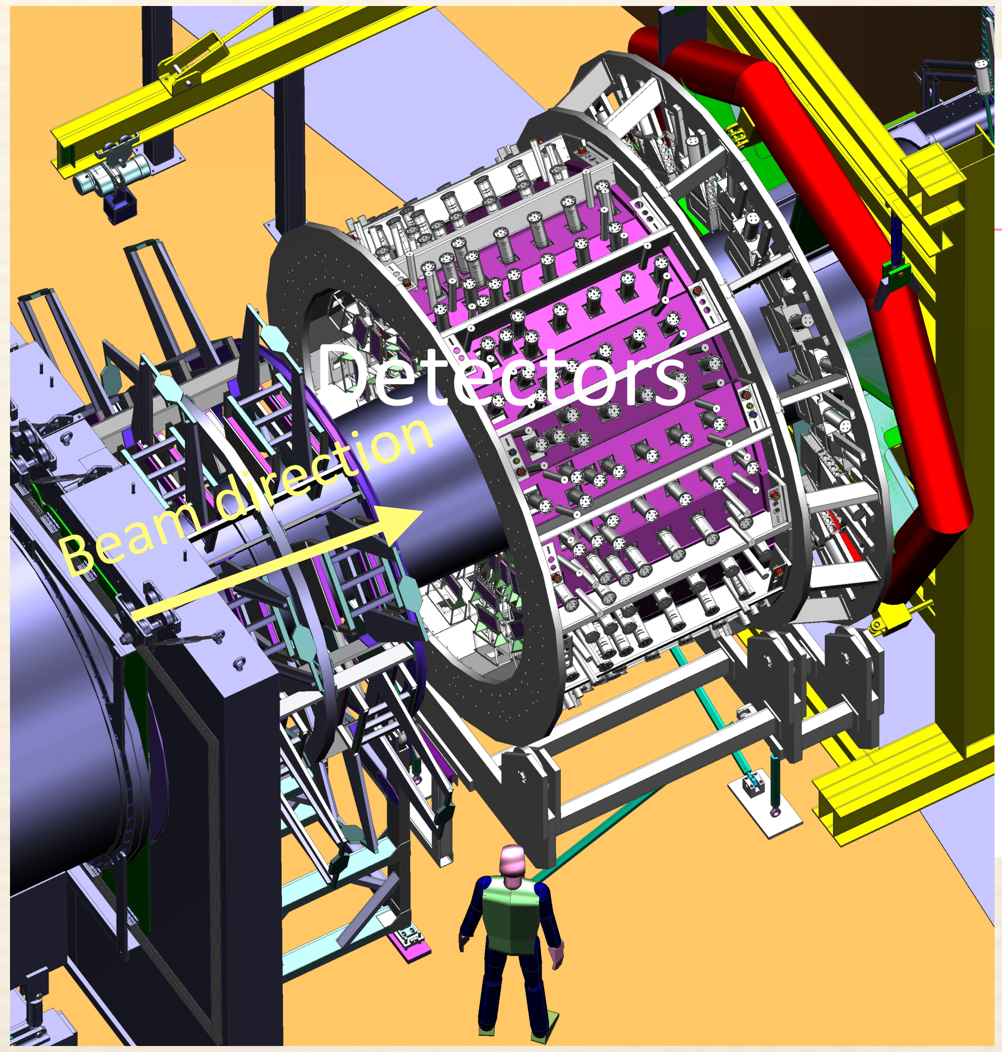
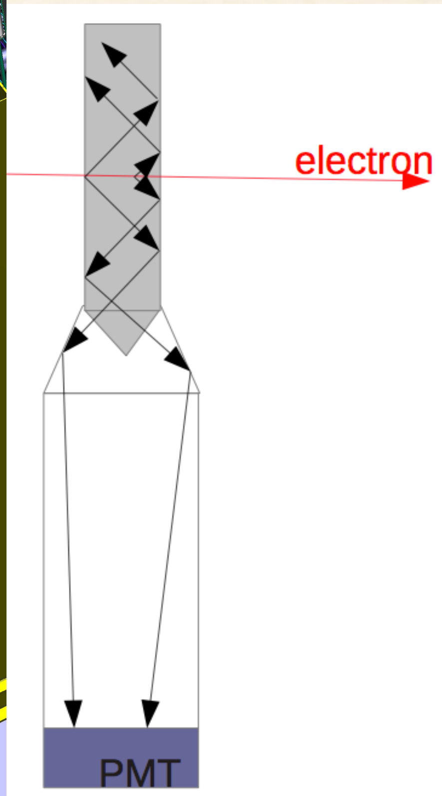
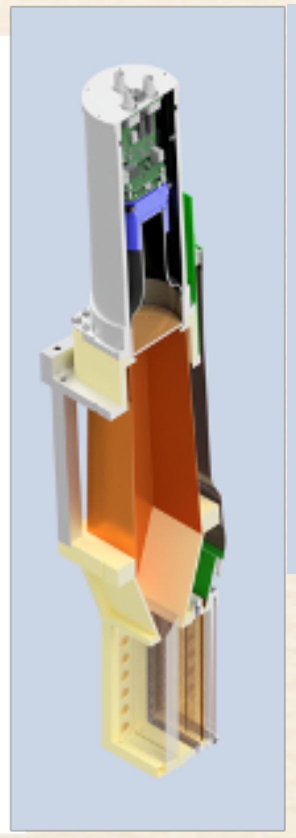
- **Robust & Redundant 0.4% beam polarimetry**











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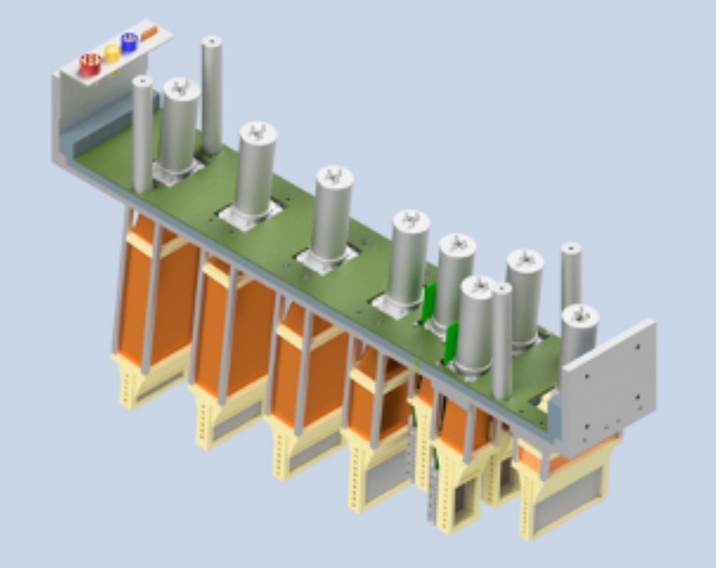

1/28th Segment

MOLLER Technical Challenges

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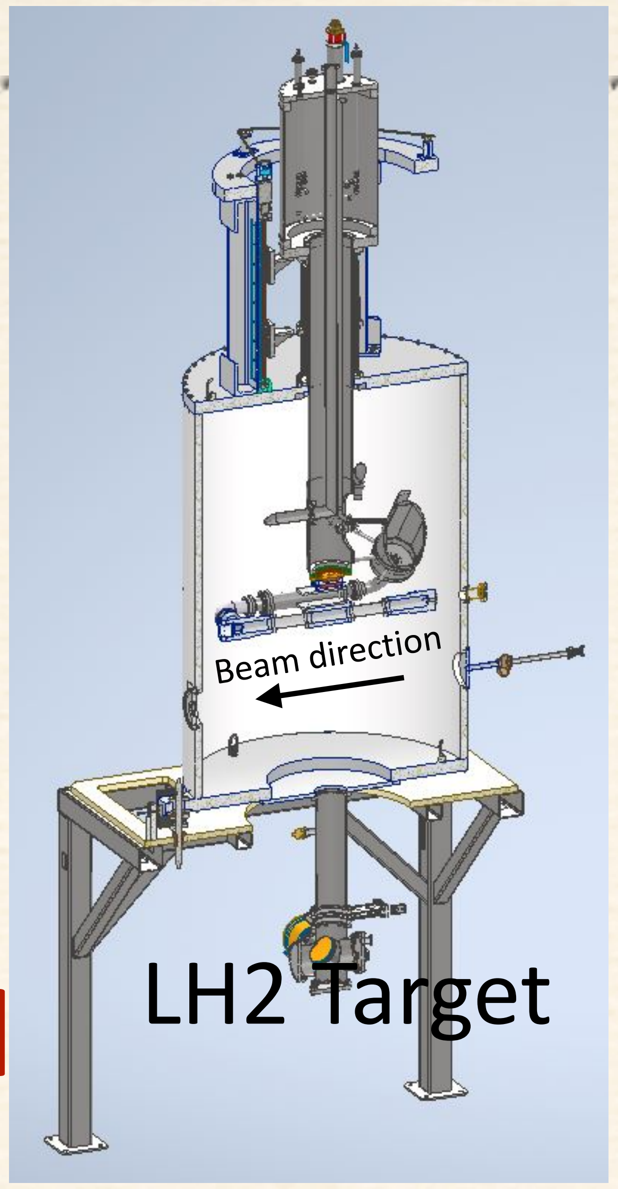
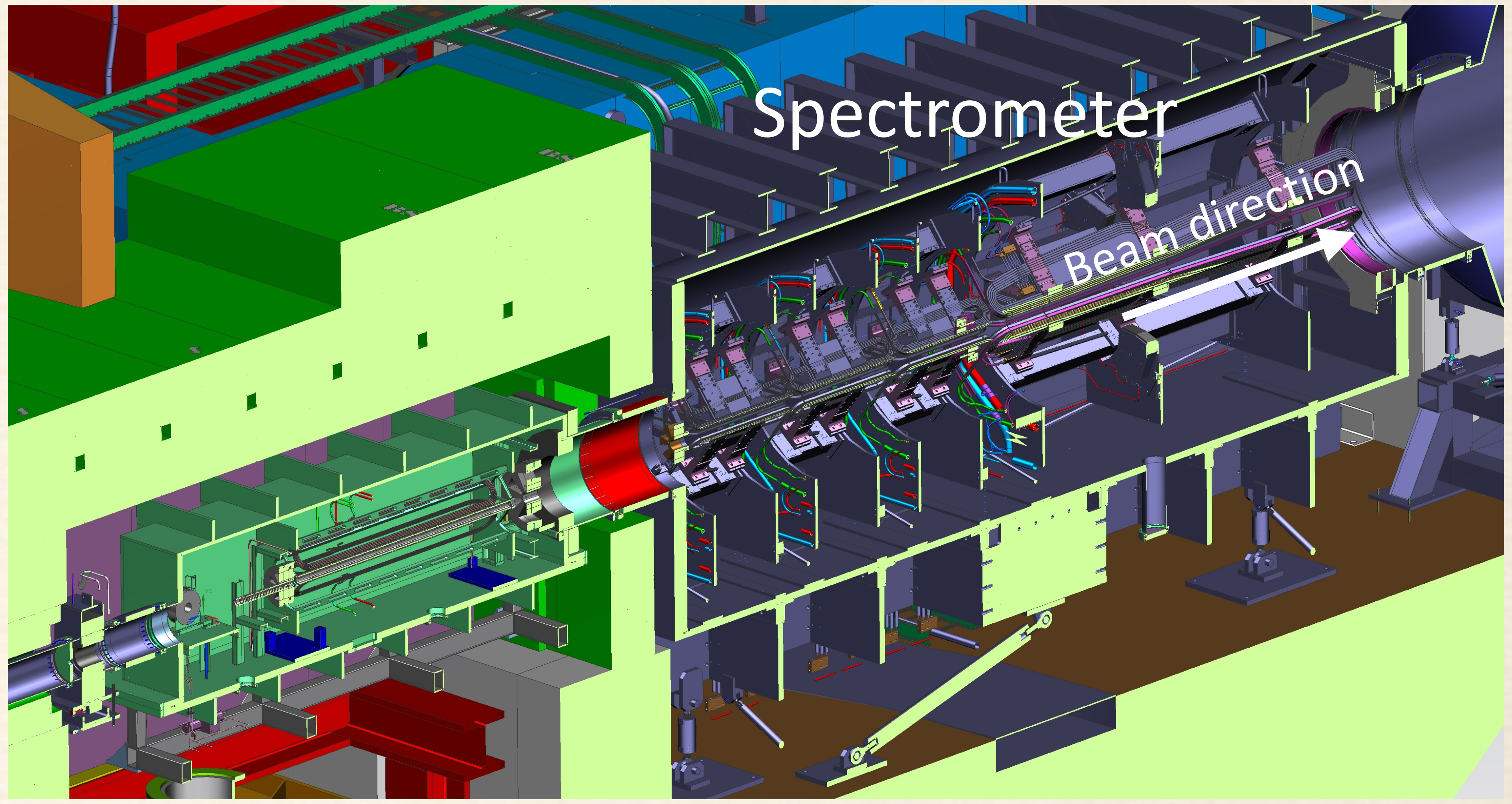
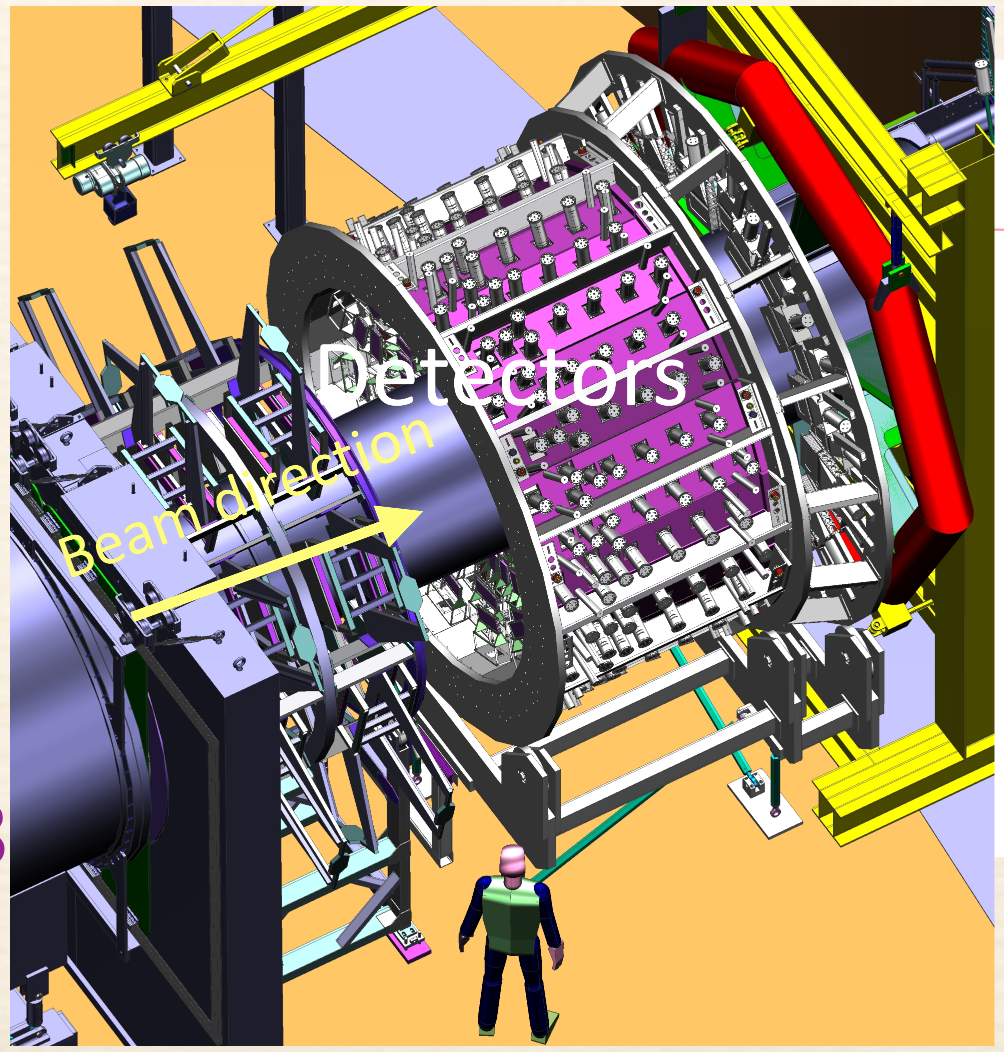
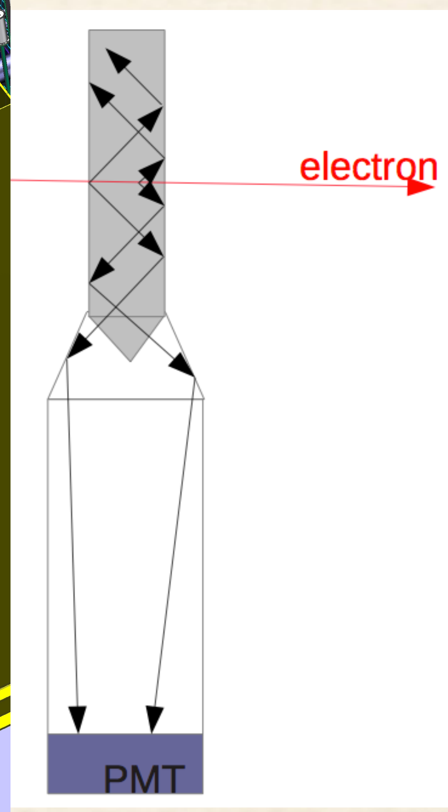
- Robust & Redundant 0.4% beam polarimetry

- **MOLLER Collaboration Team**
  – ~ 180 scientists from more than 30 institutions (3 countries)
  – Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  – Final Technical Design Report is public









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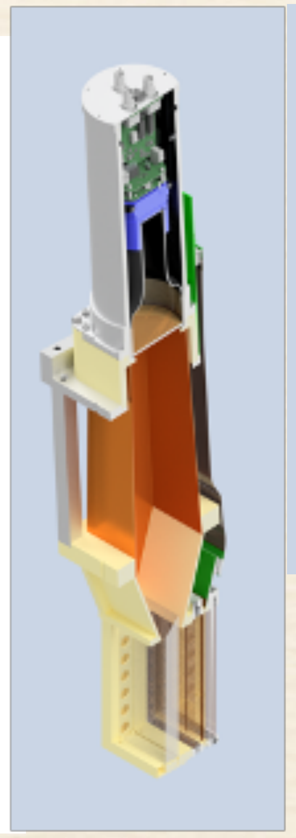
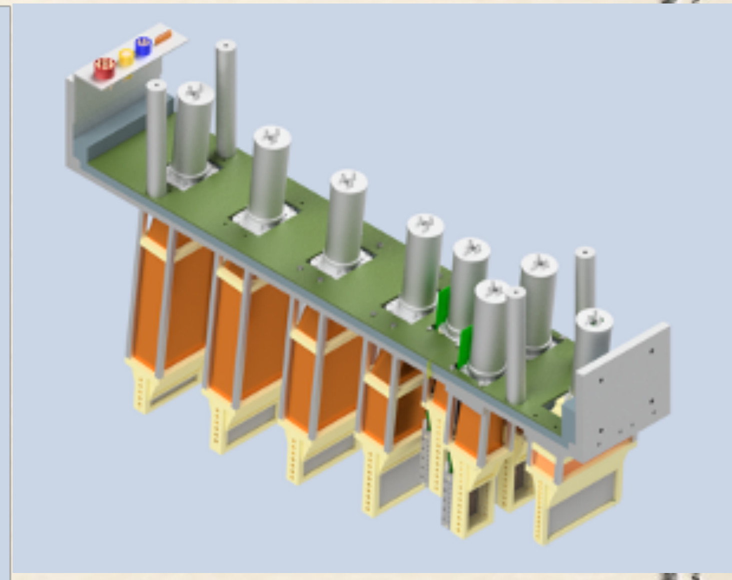
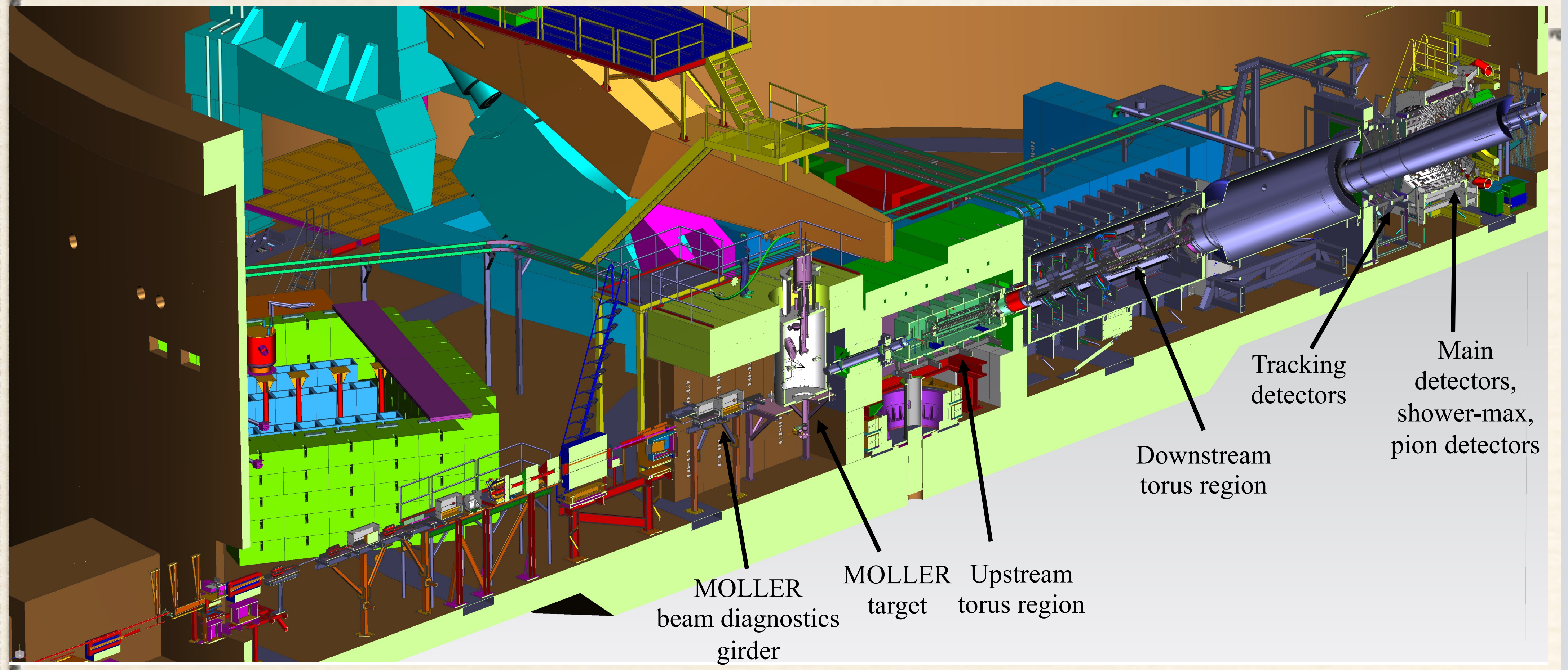




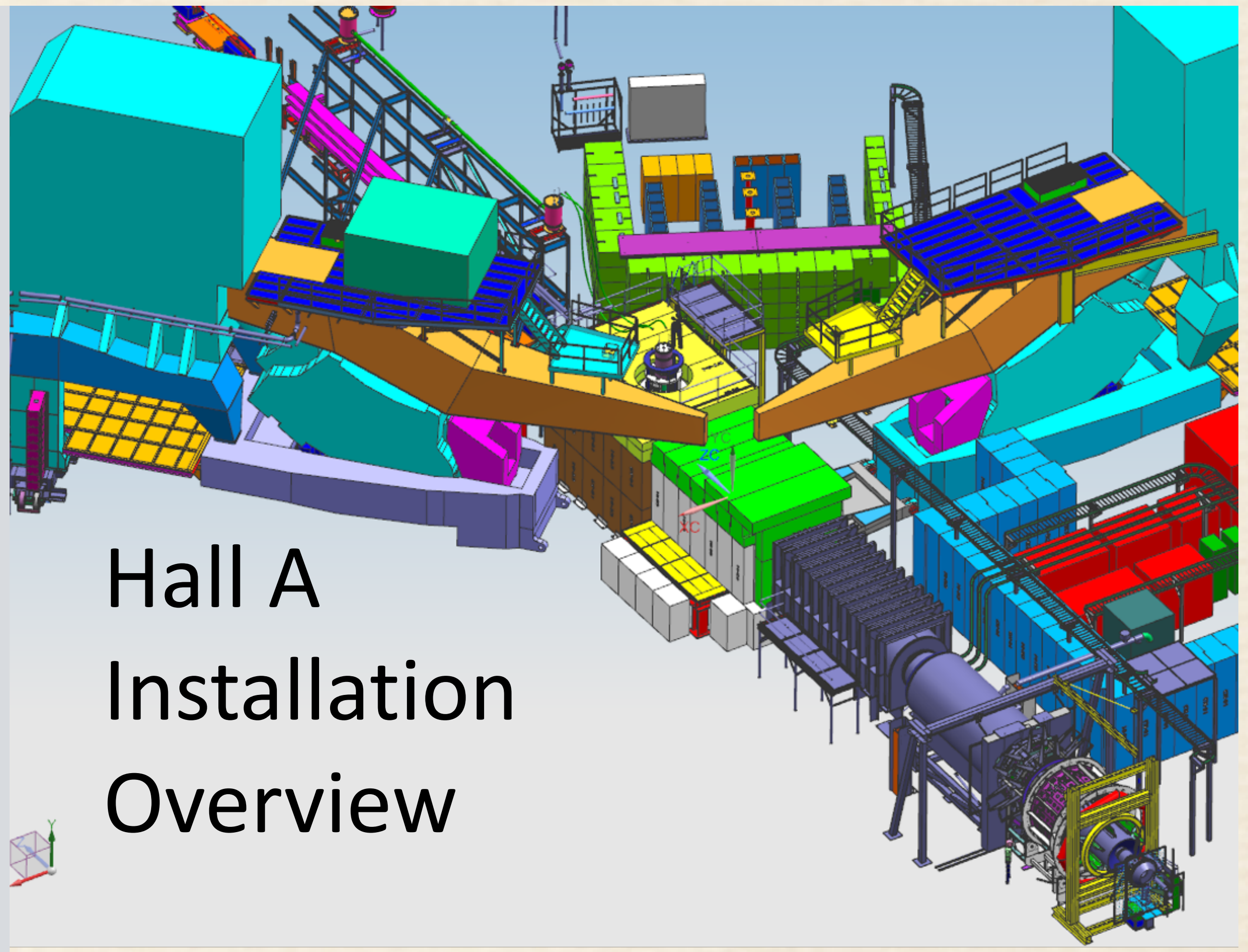
1/28th Segment

MOLLER Status

Engineering Design complete, acquisitions ongoing and construction has begun



- ~ 50M$ MIE by US DOE NP
- ~ 12M$: US NSF and Canada CFI/Research Manitoba
- CD-1 granted in Dec 2020
- CD-2/3 granted May 2024
- Construction: 2024-25
- Installation 2025-2026
- Commissioning: Early 2027
- Physics thru 2029 and beyond



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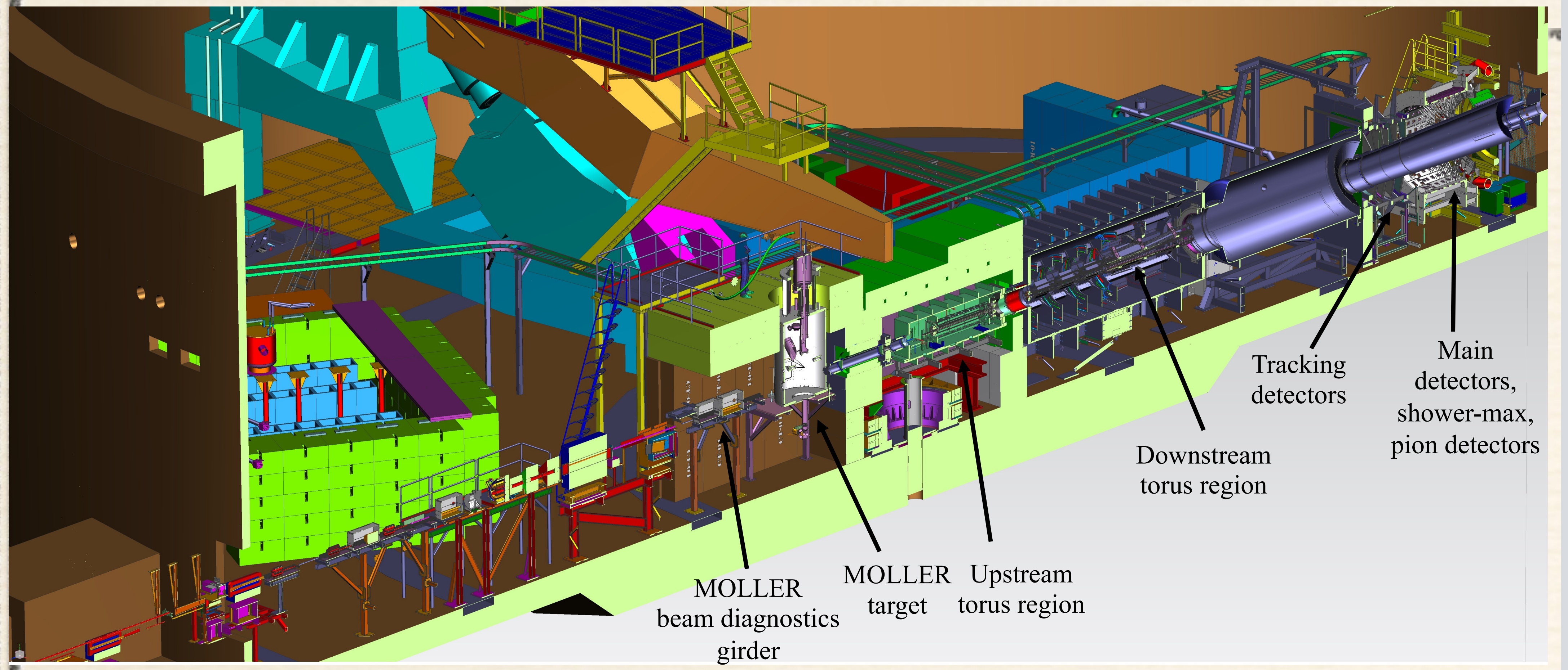

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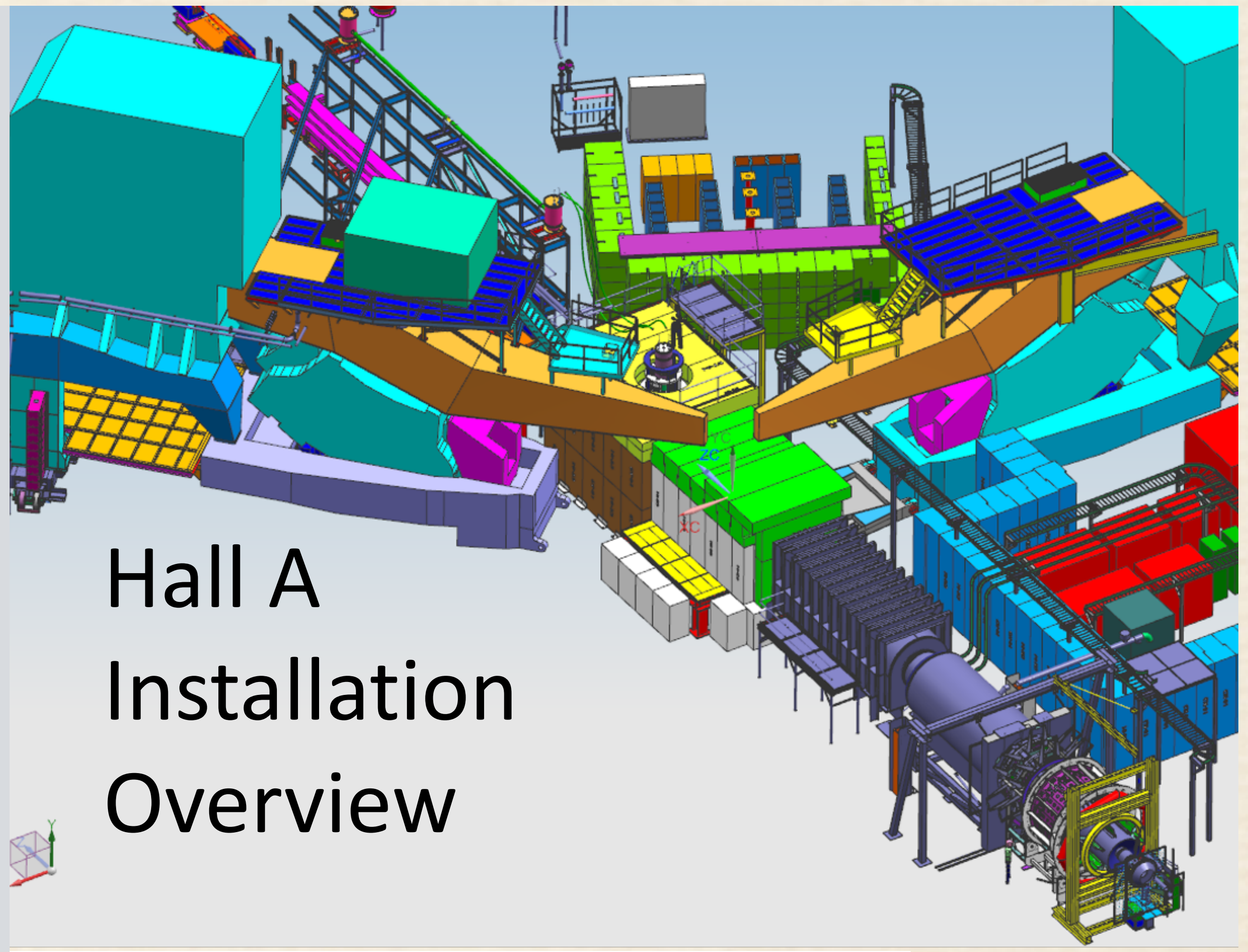
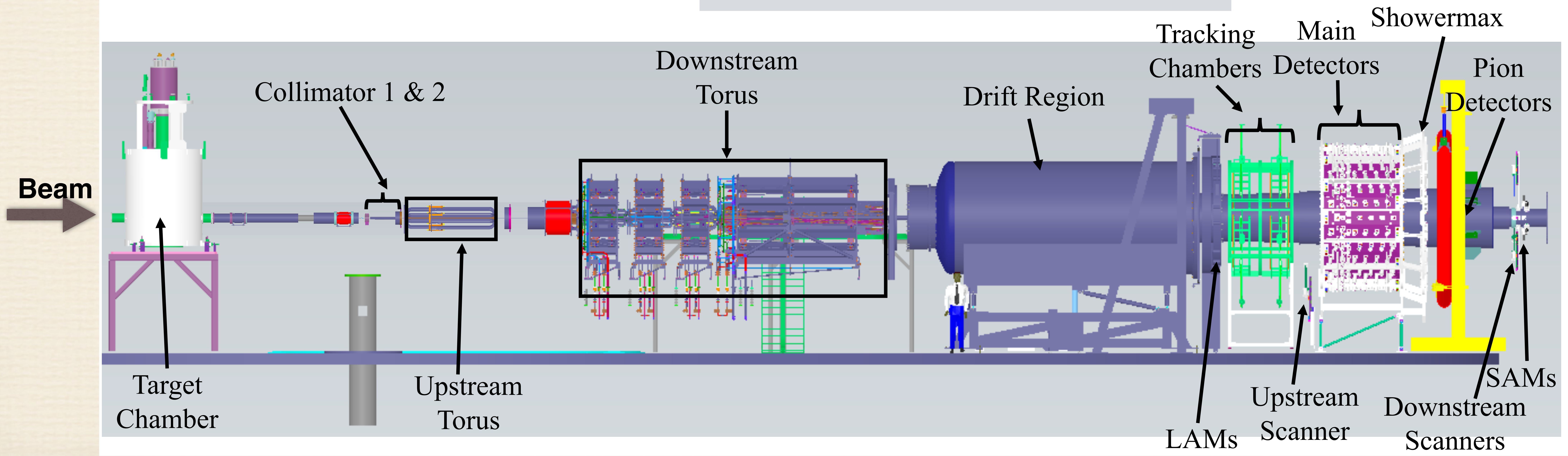
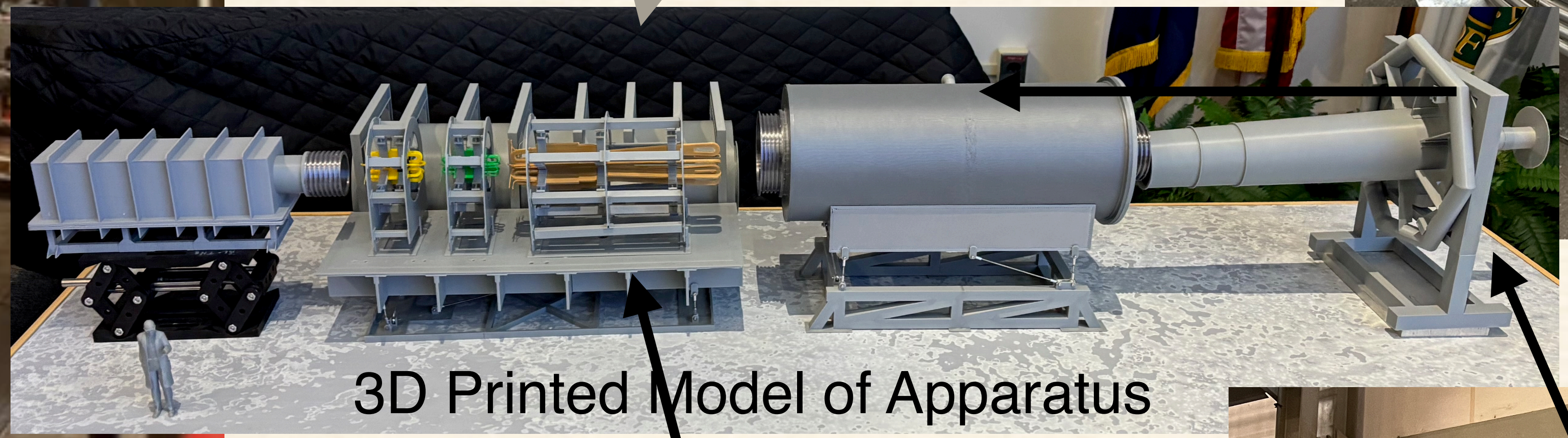
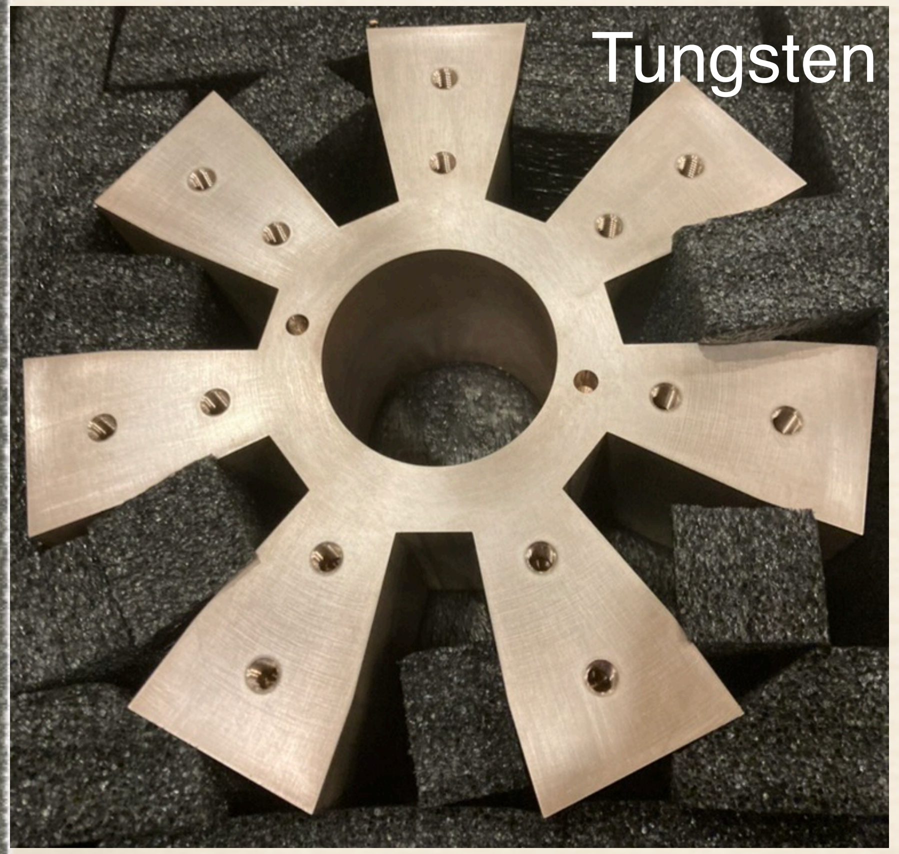
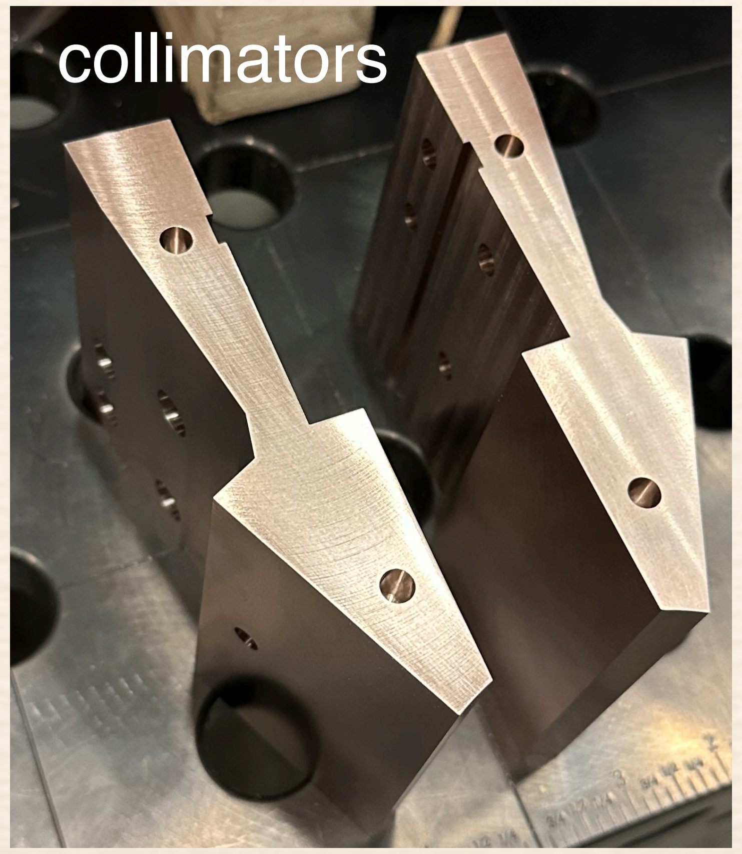


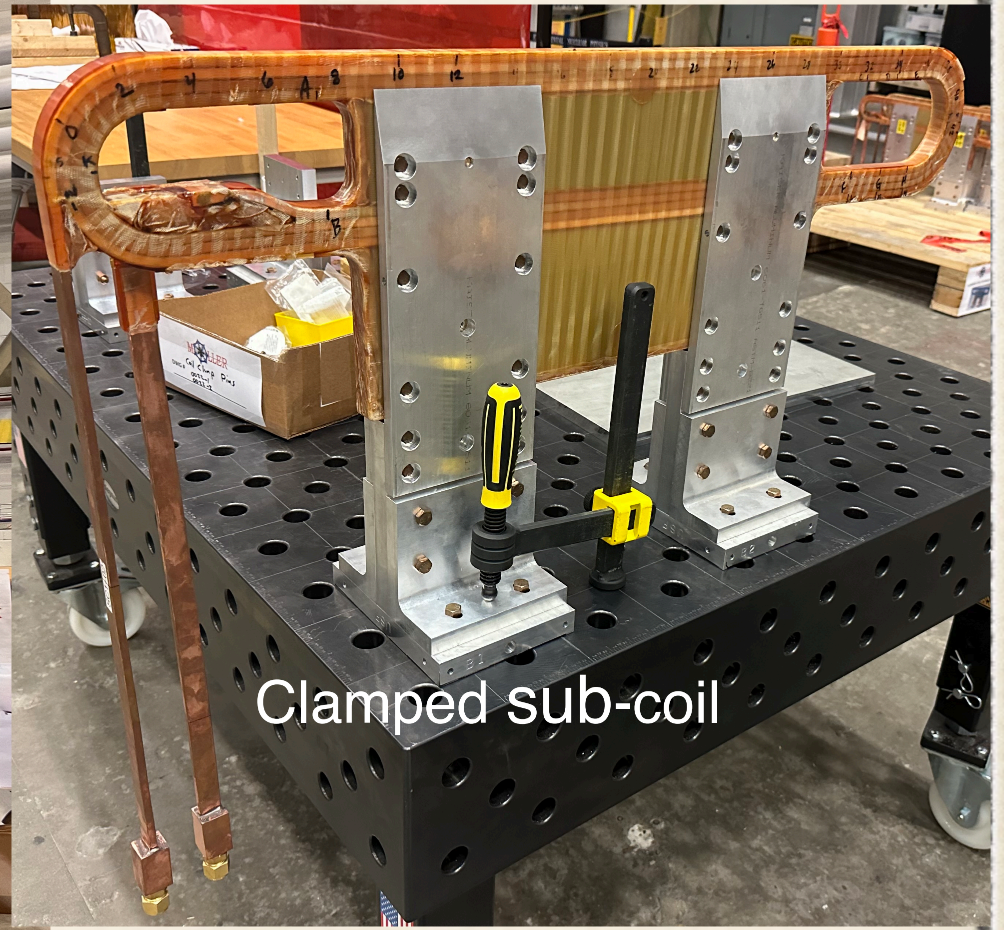


MOLLER Under Construction!







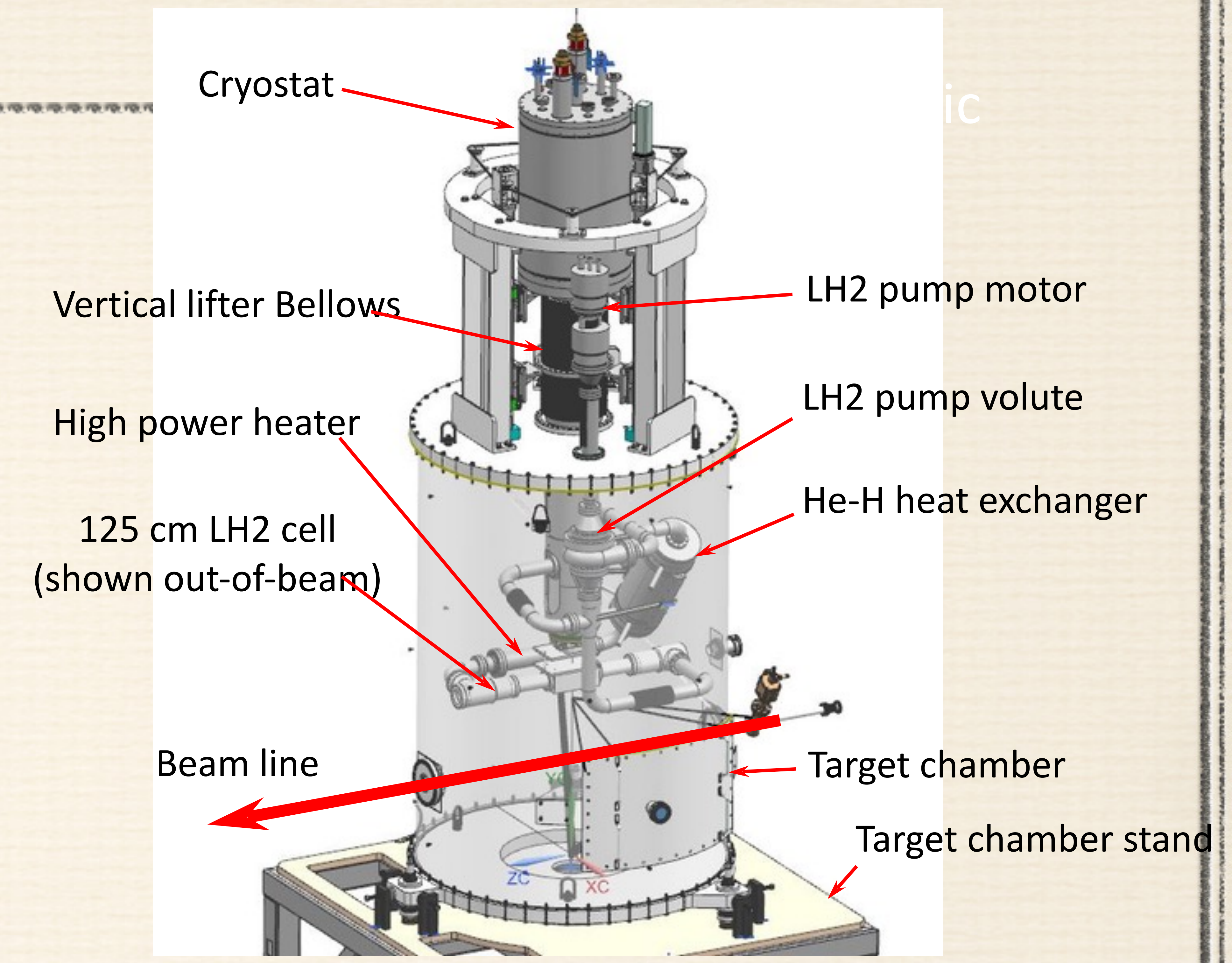


Liquid Hydrogen Target

- 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 ($\Delta\rho/\rho$):

Γ_{target} < 30 ppm for 70 µA, 5x5 mm^2 raster, 1.92 kHz flip



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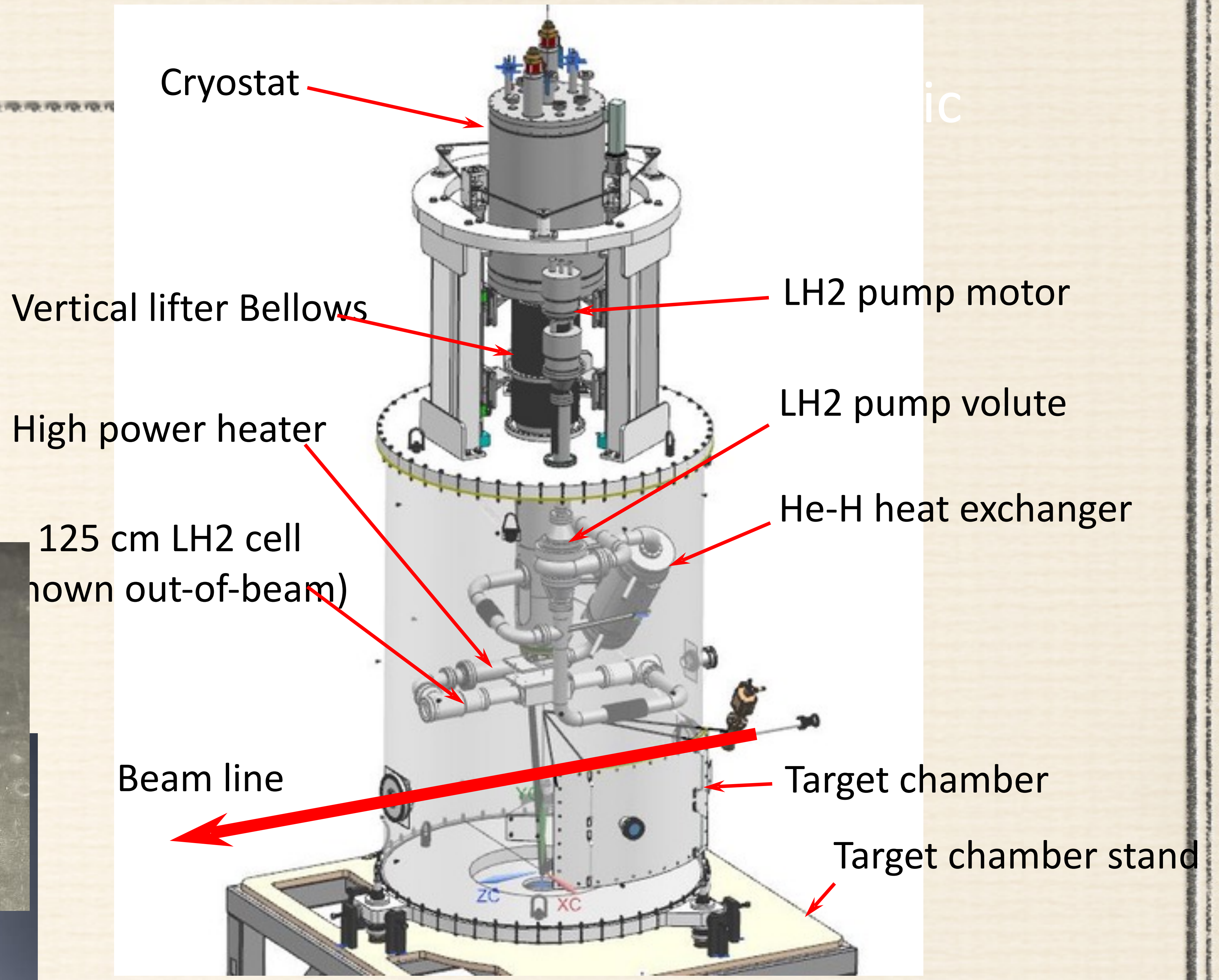
Test fit of scattering chamber completed

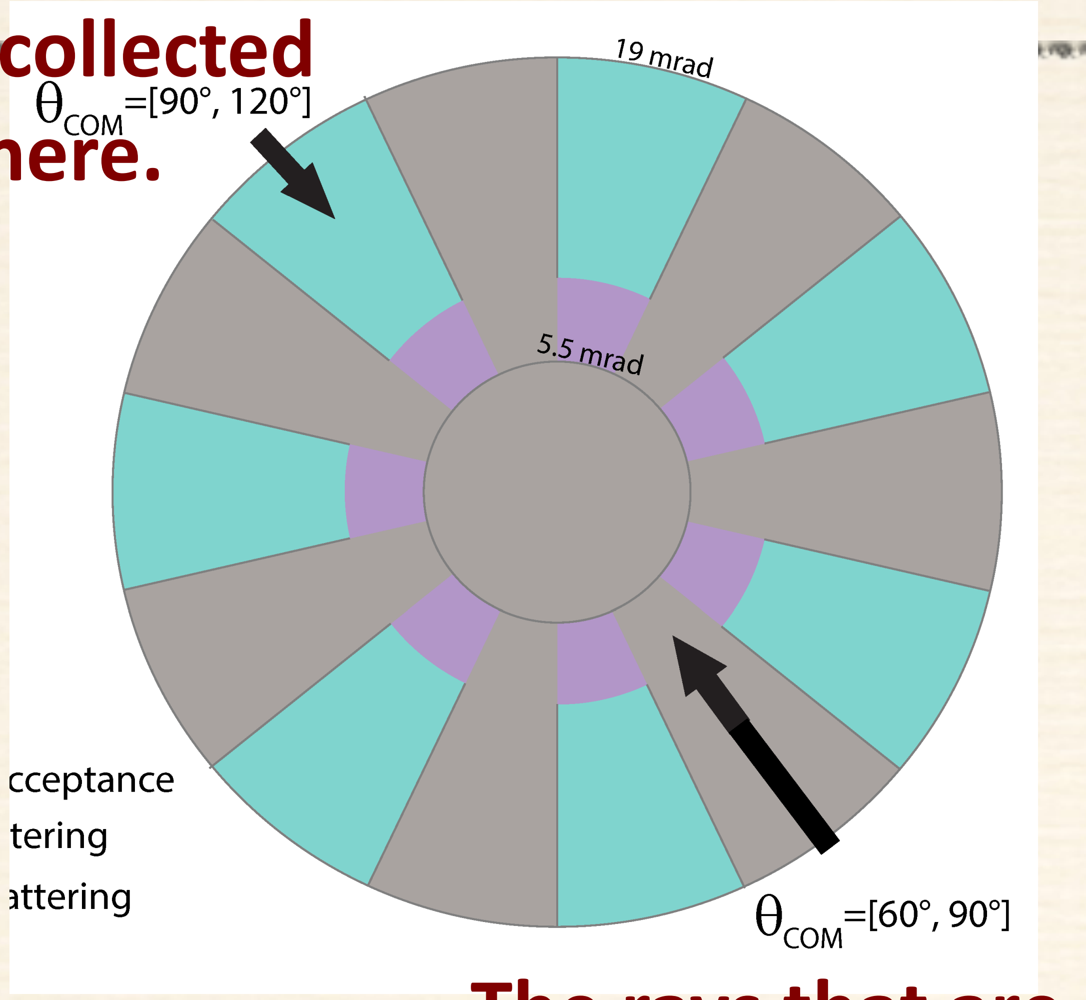


Cryostat components

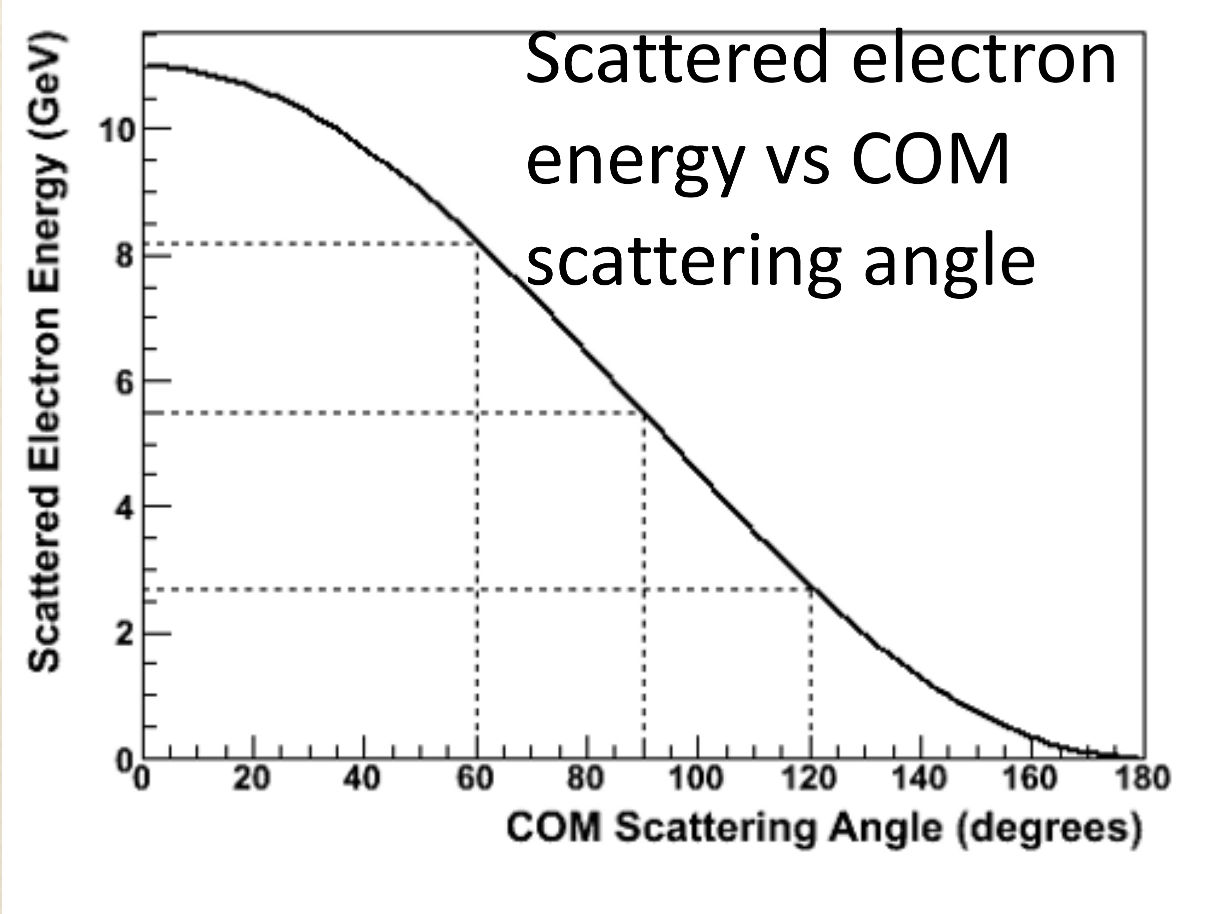
Spectrometer Design

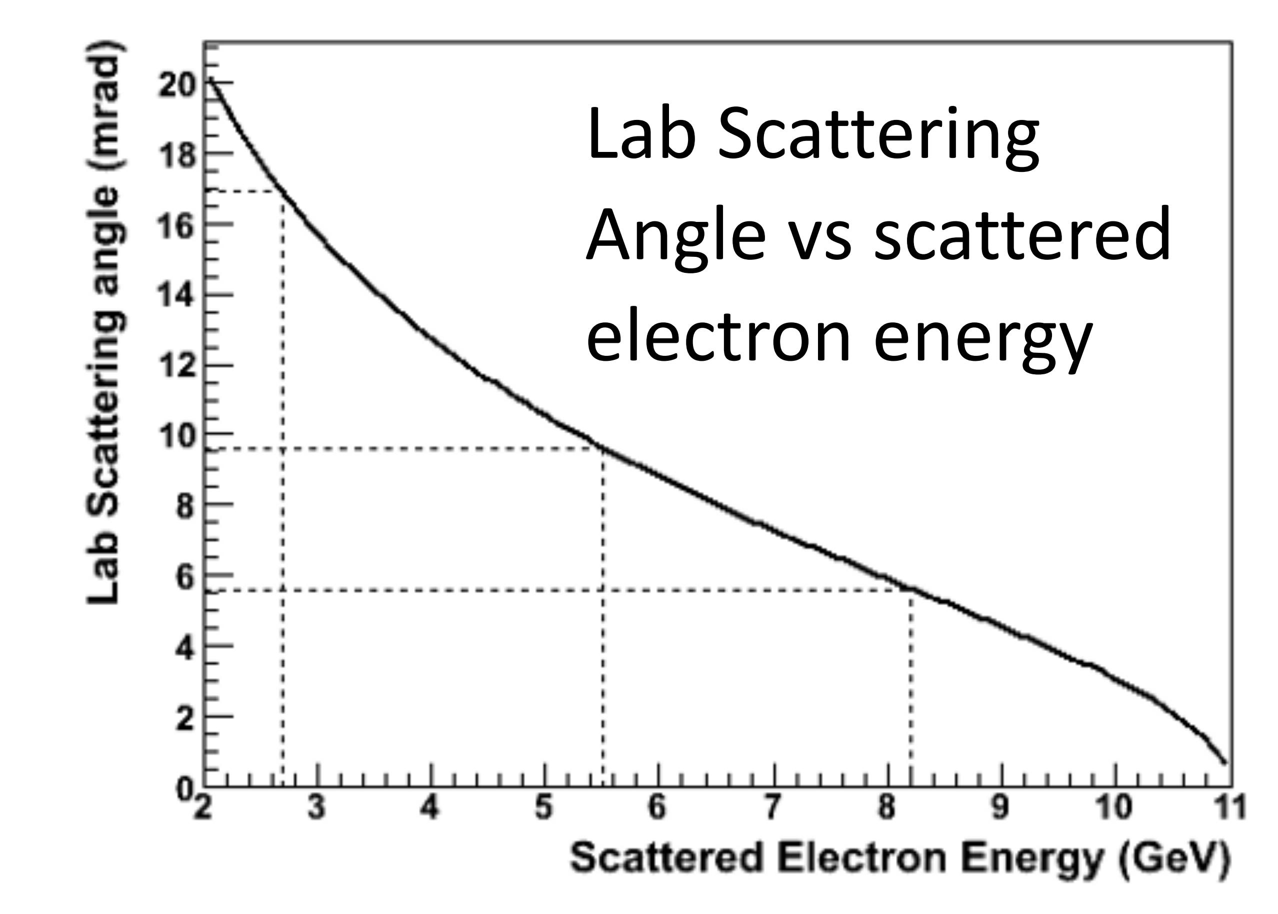
- Accept all Møller scattered electrons in range $\Theta_{CM} = 50^o – 130^o$
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

...are collected over here.



The rays that are blocked here...





UPSTREAM TORUS

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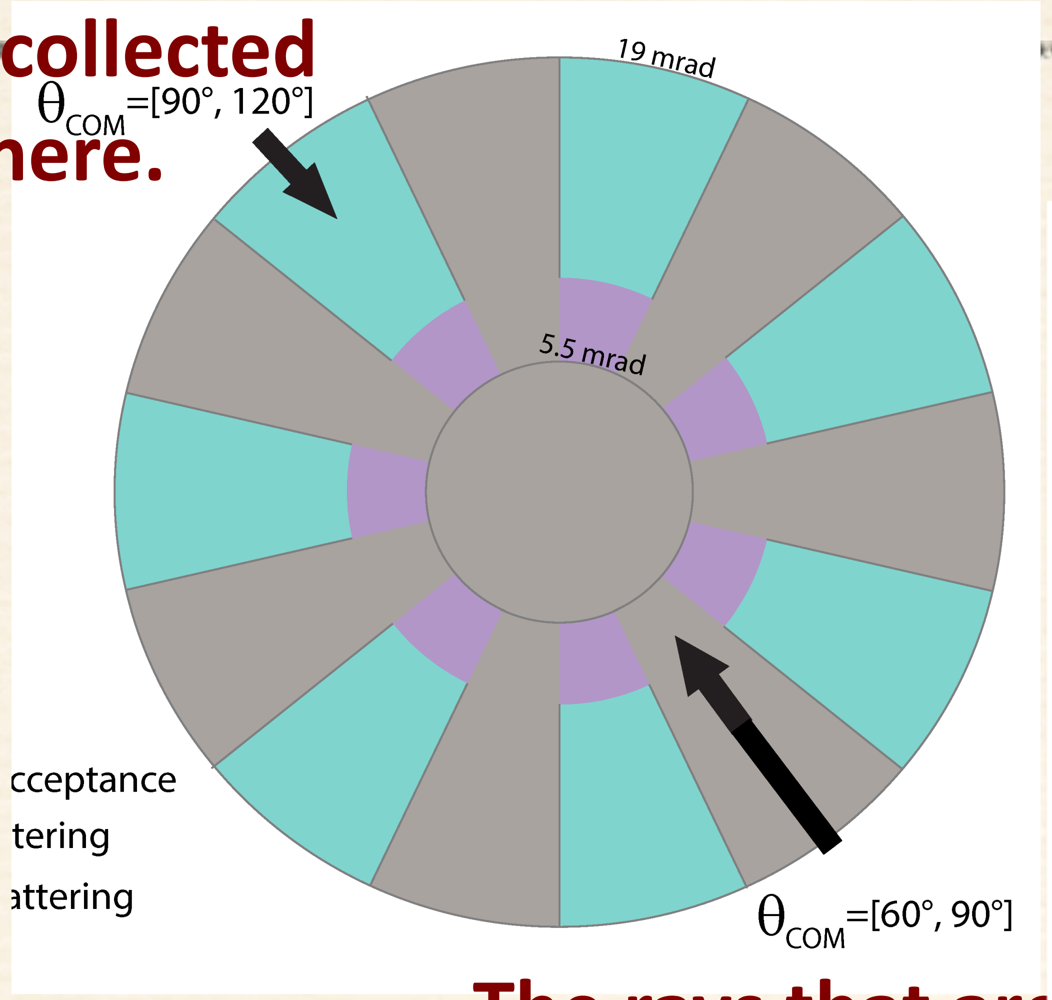

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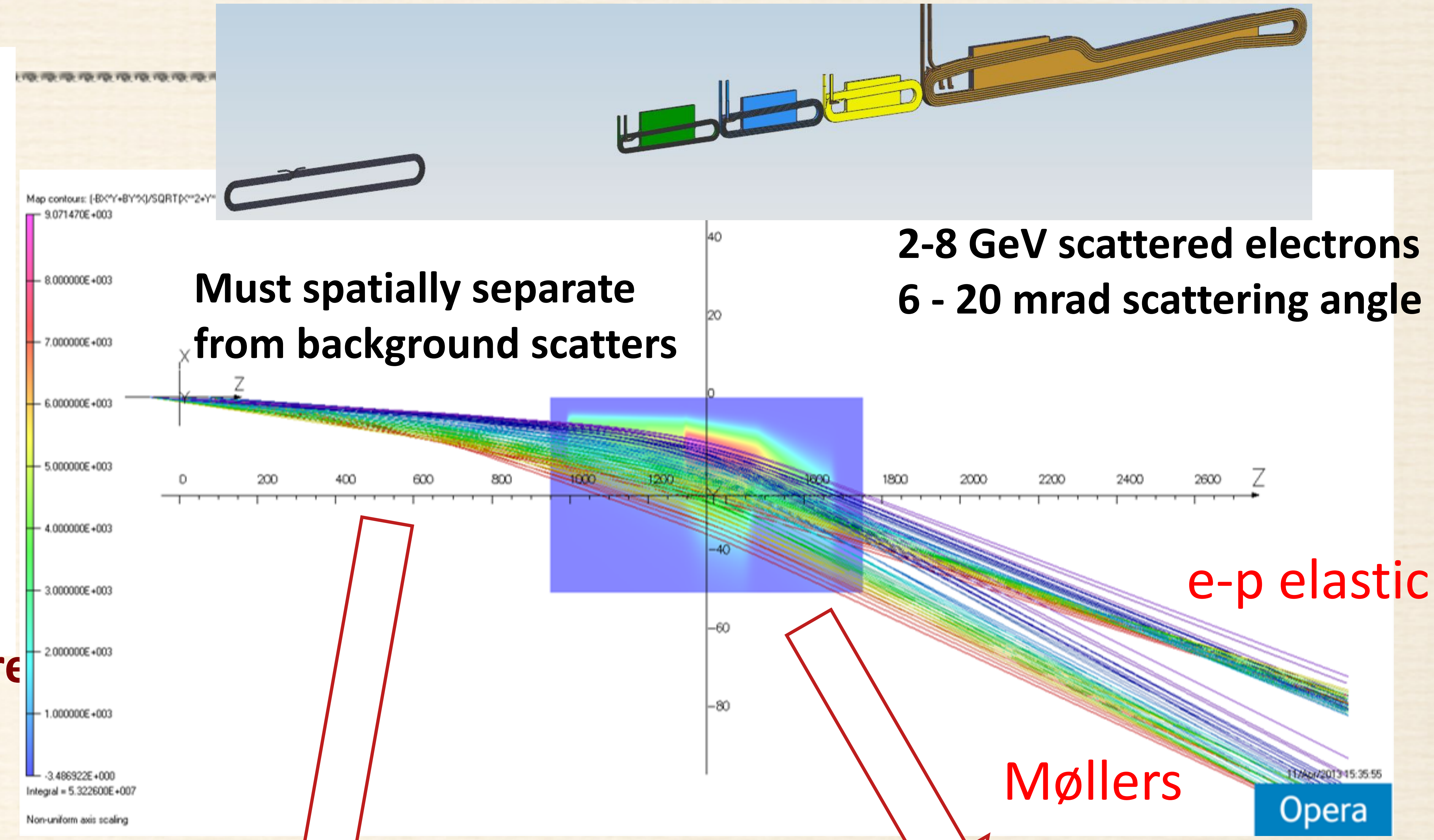
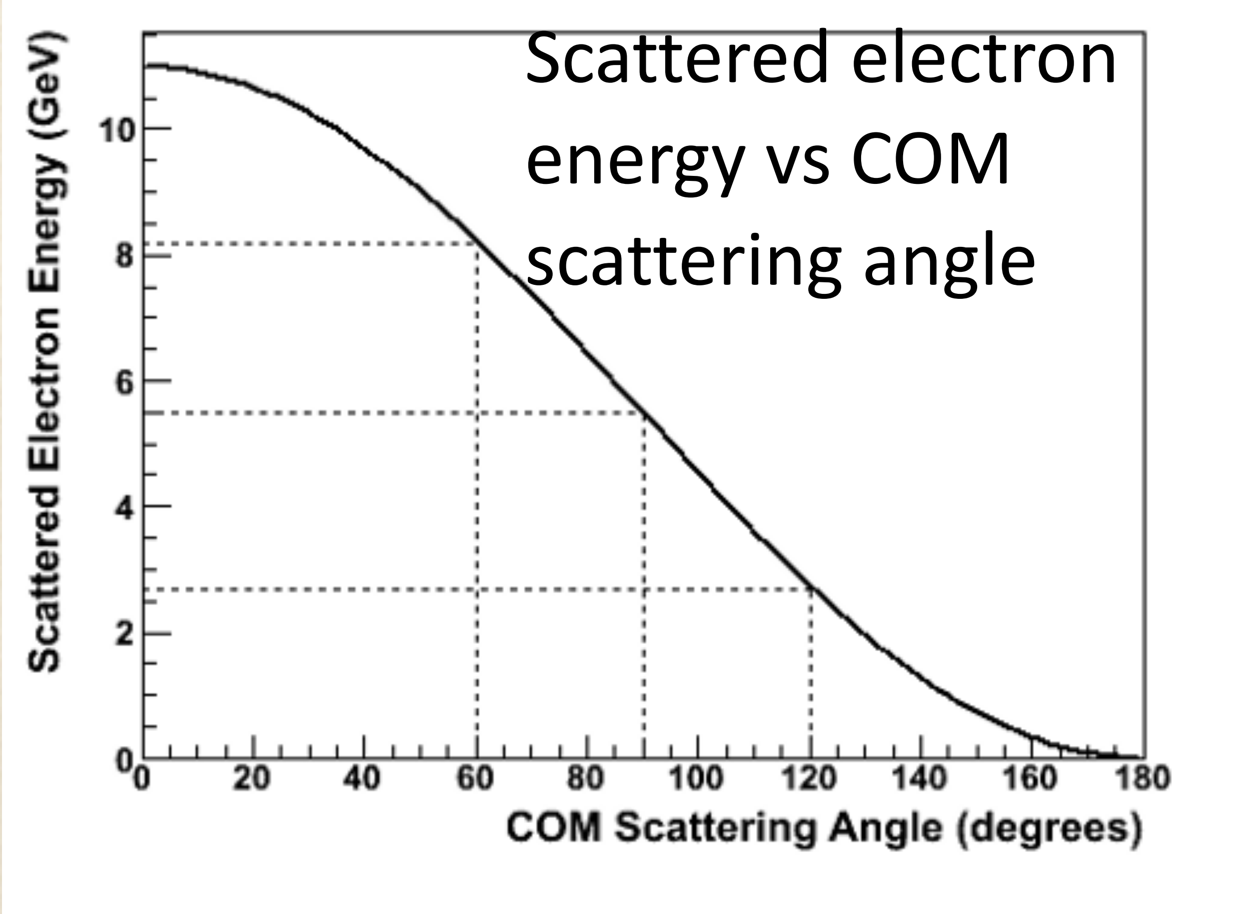
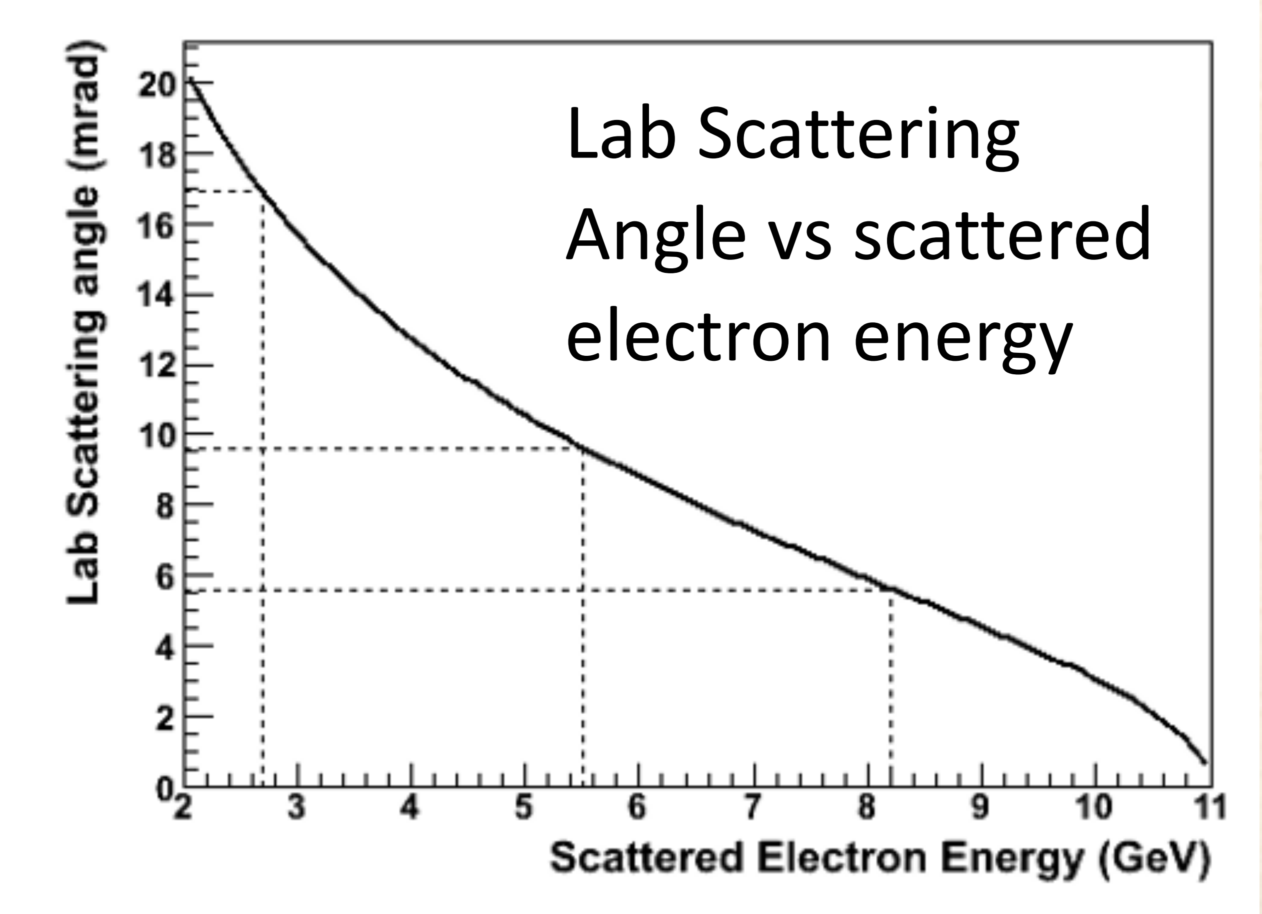
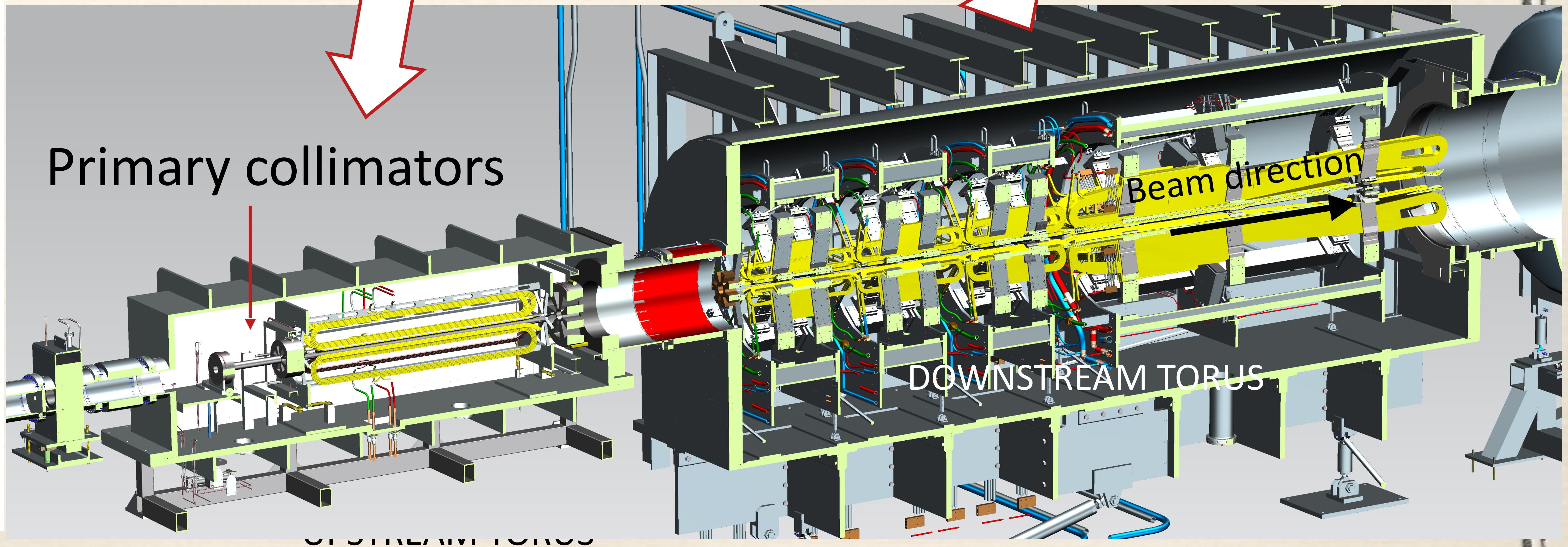
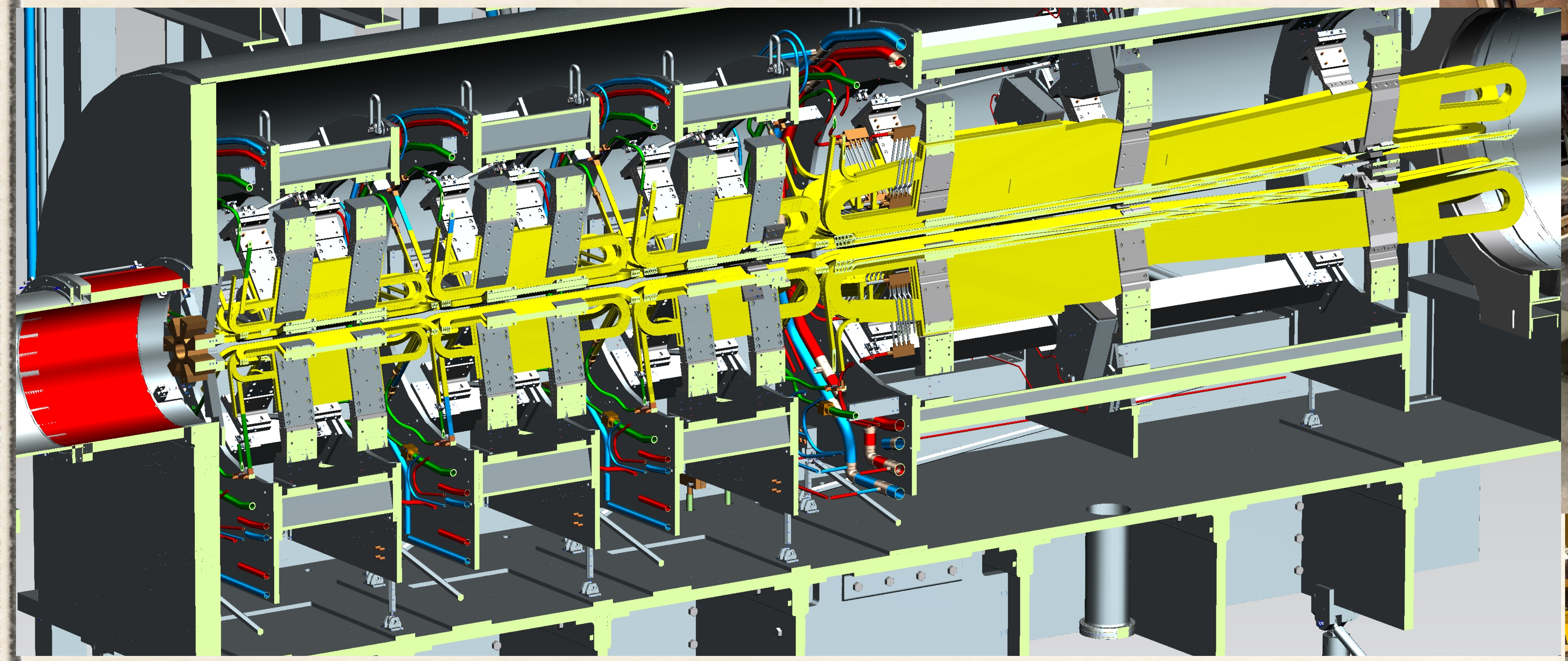


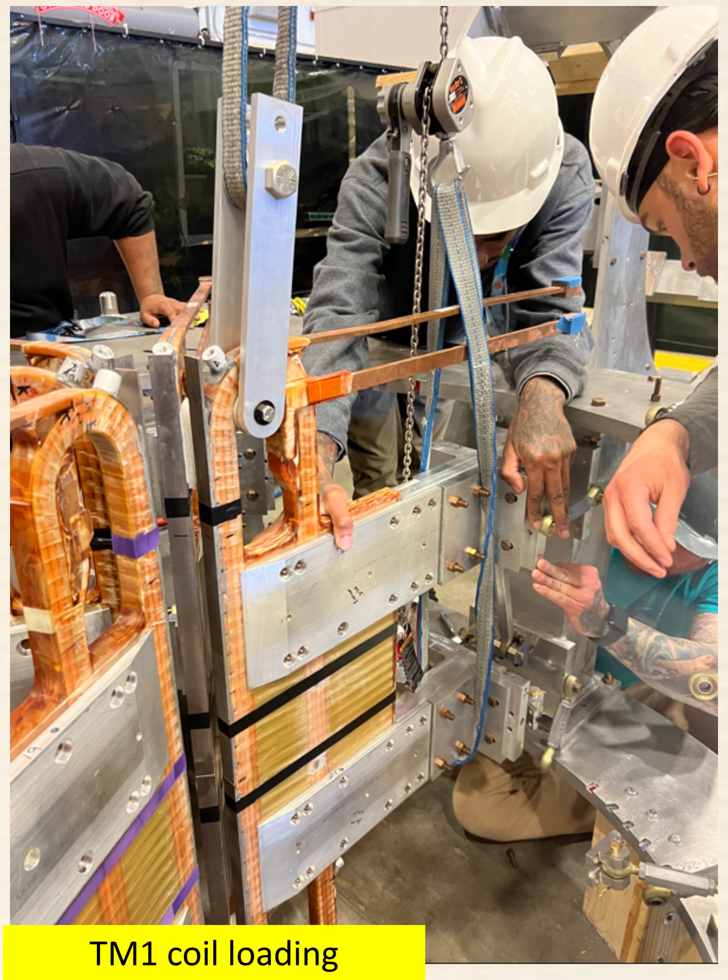


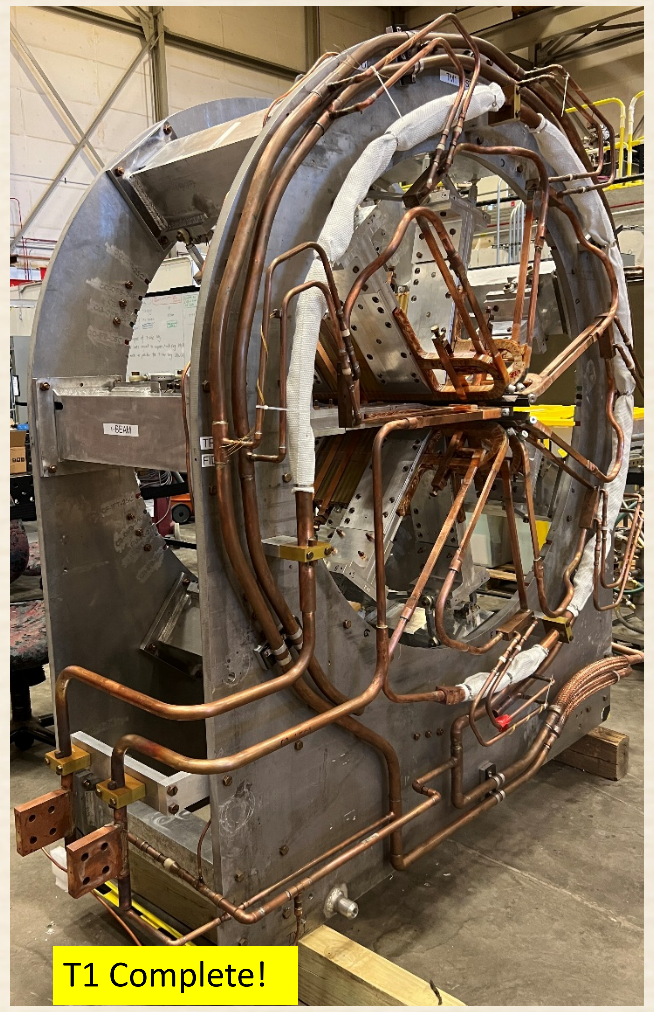


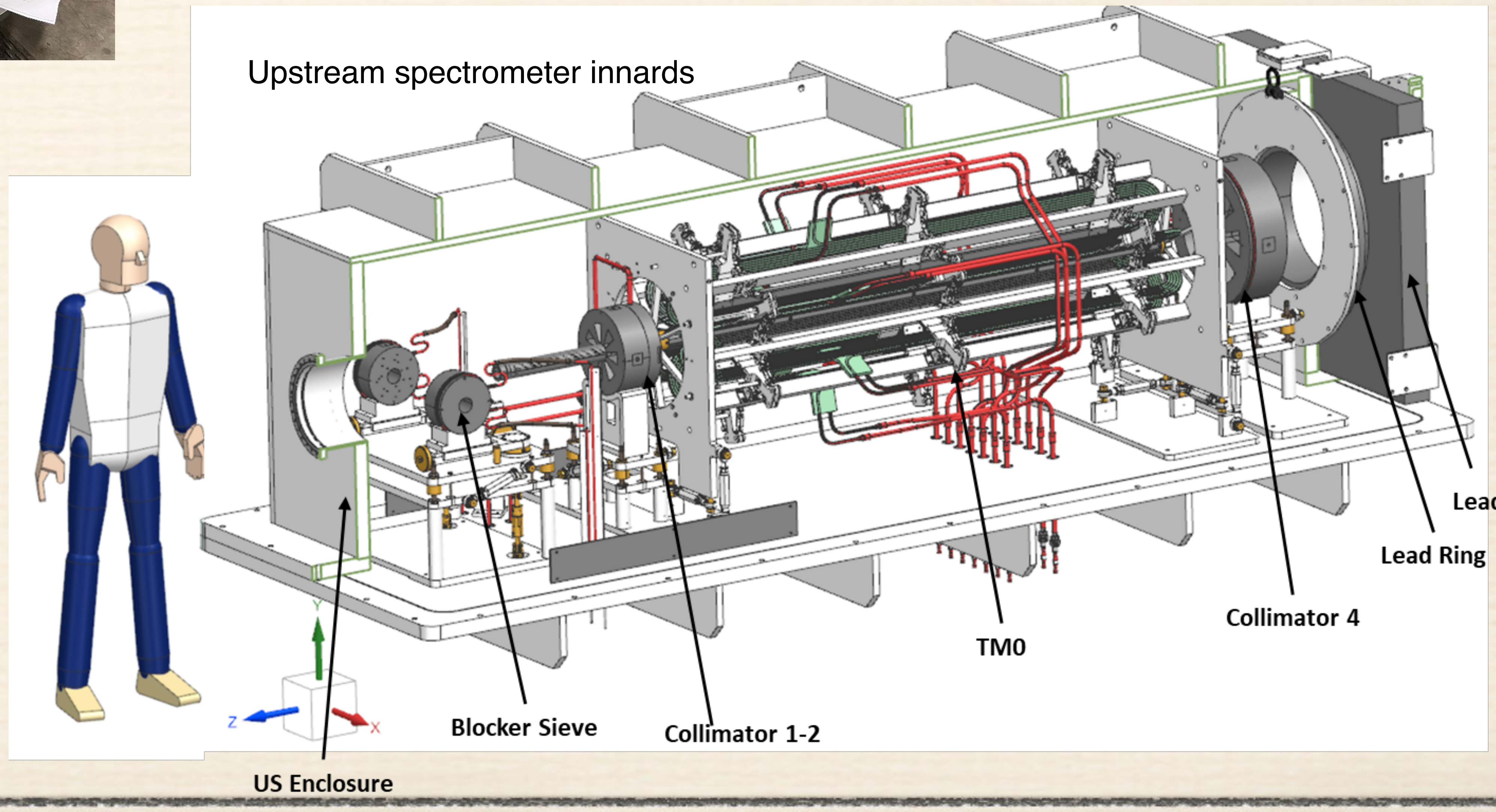


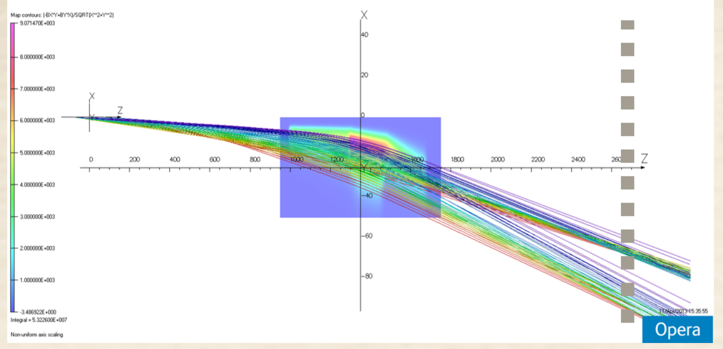
Spectrometer Construction





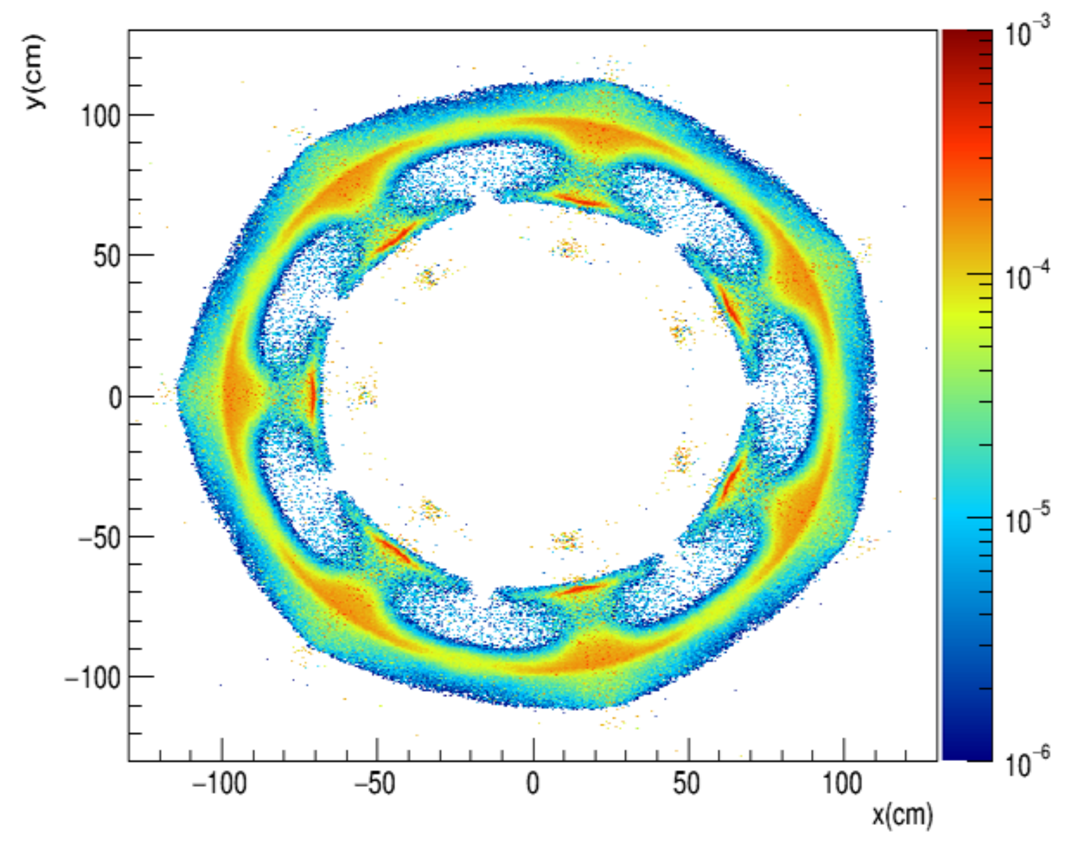




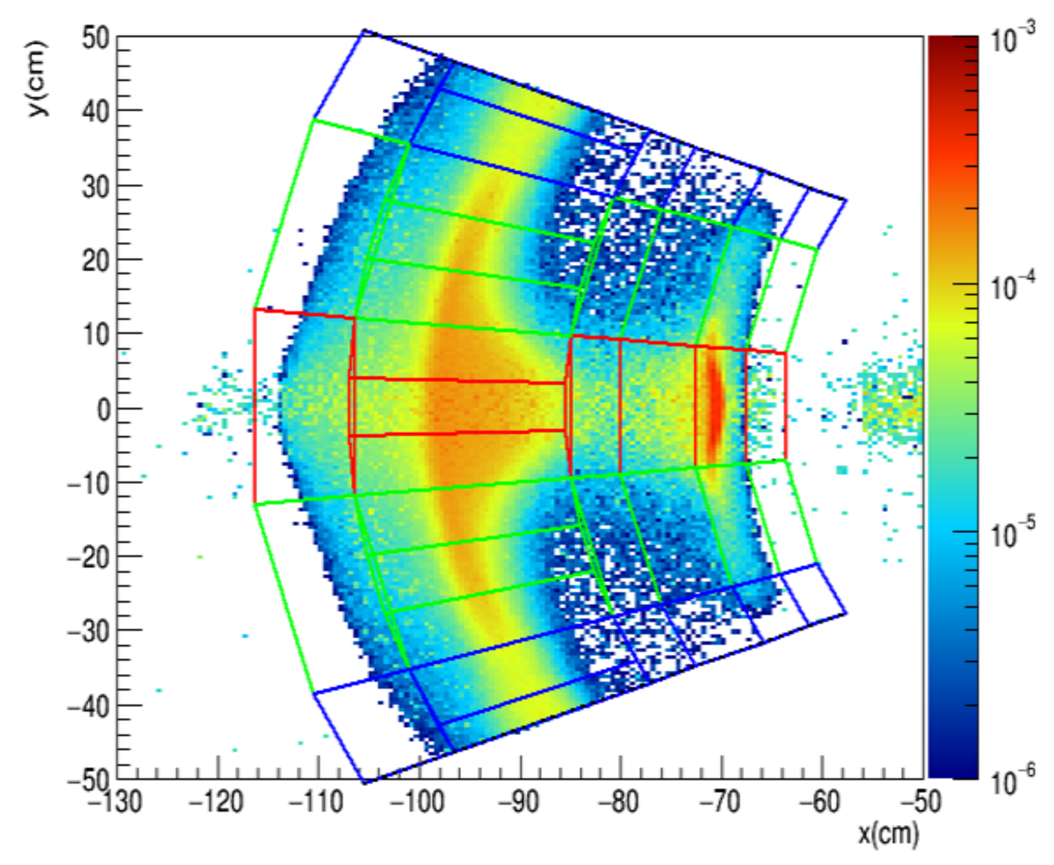


Capturing the Scattered Flux

Heat map on transverse plane 26.5 m from target center

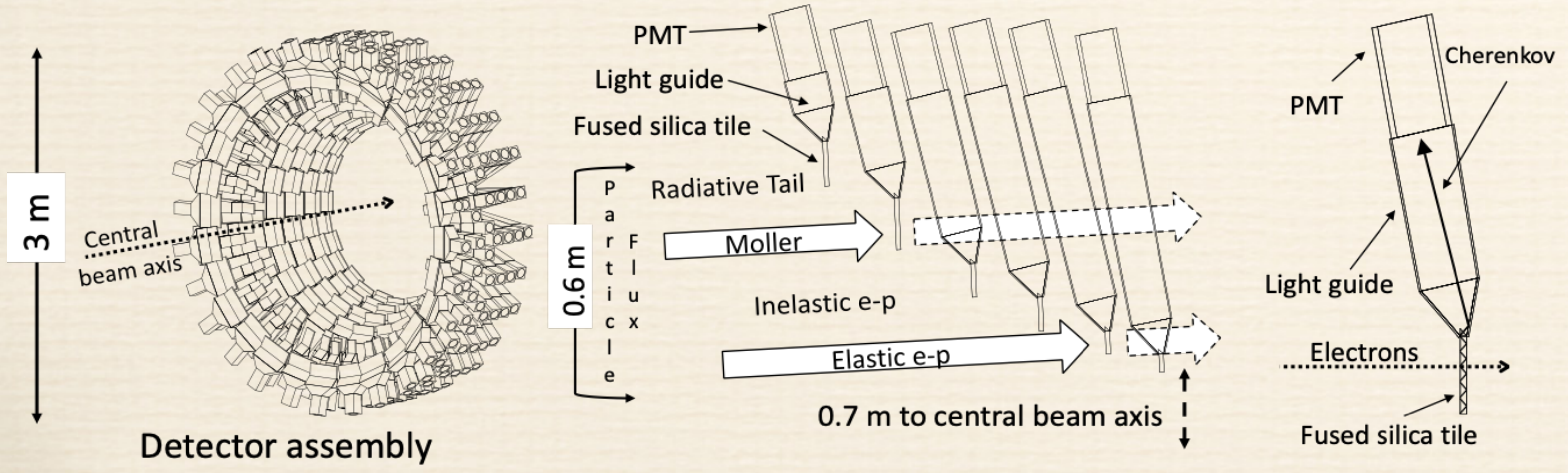


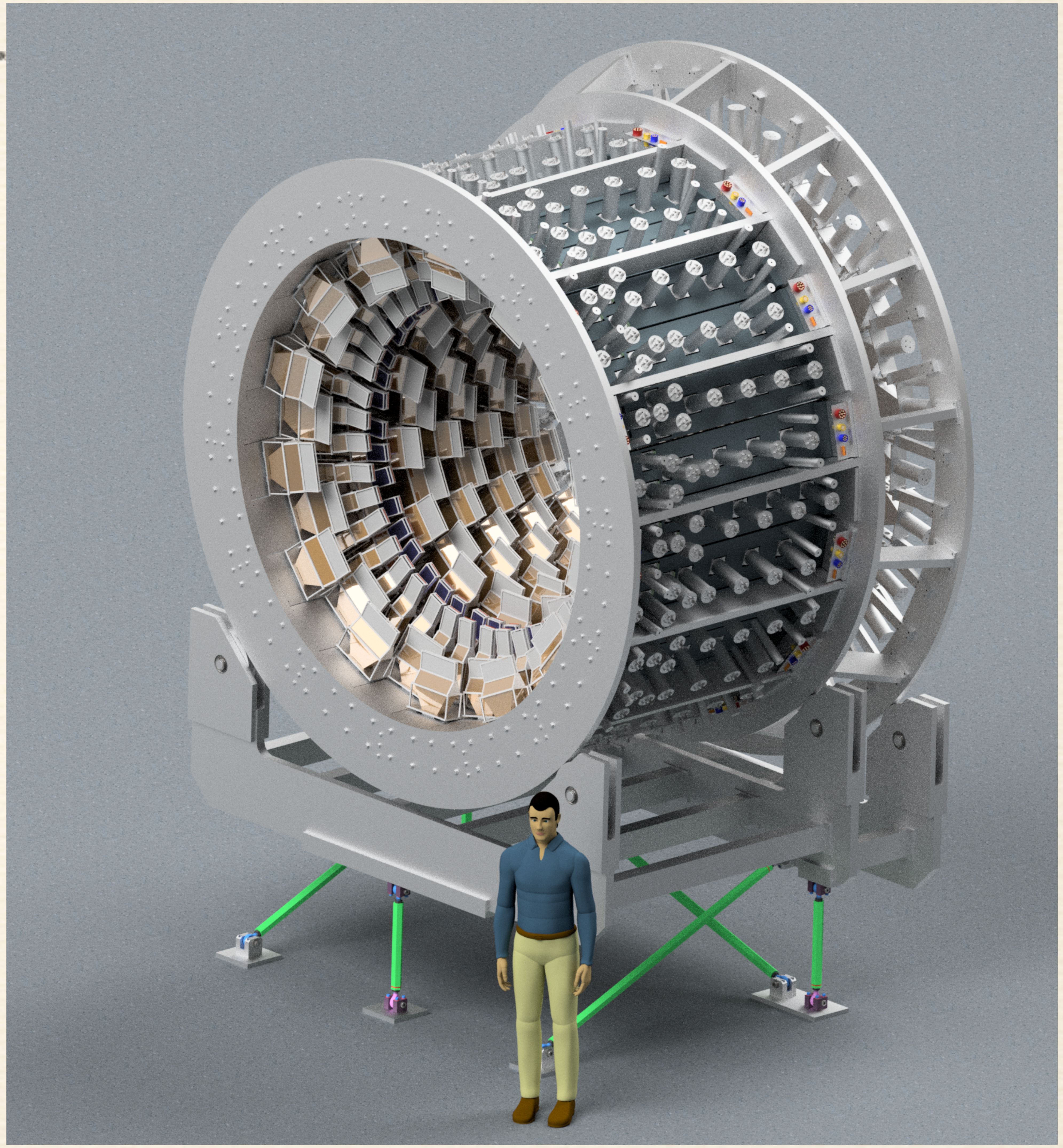
1/7 of the azimuth showing tiling segmentation



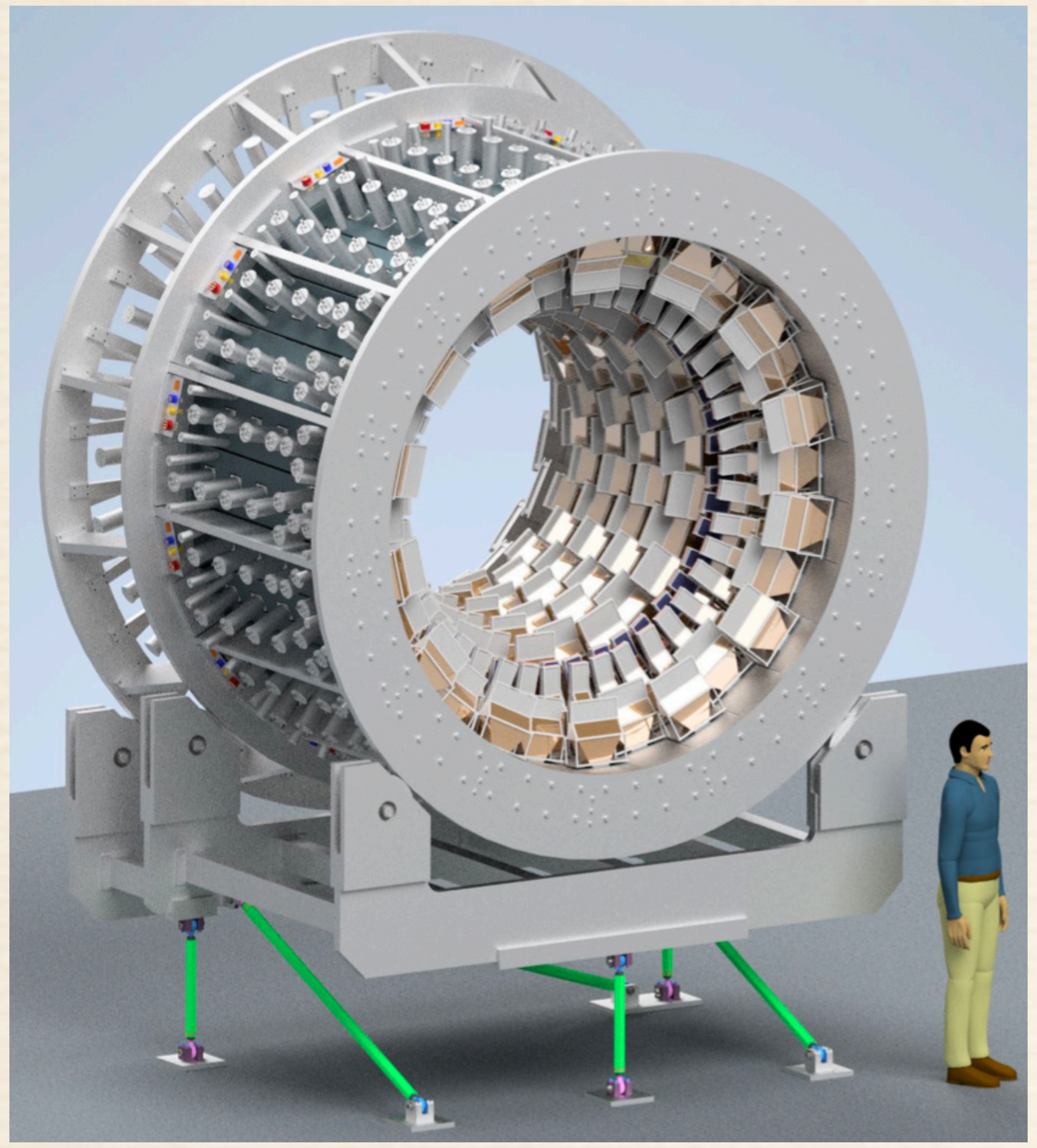
Wide variation in flux intensity and weights of different scattering processes: 1) e-e, 2) elastic e-p, 3) inelastic e-p

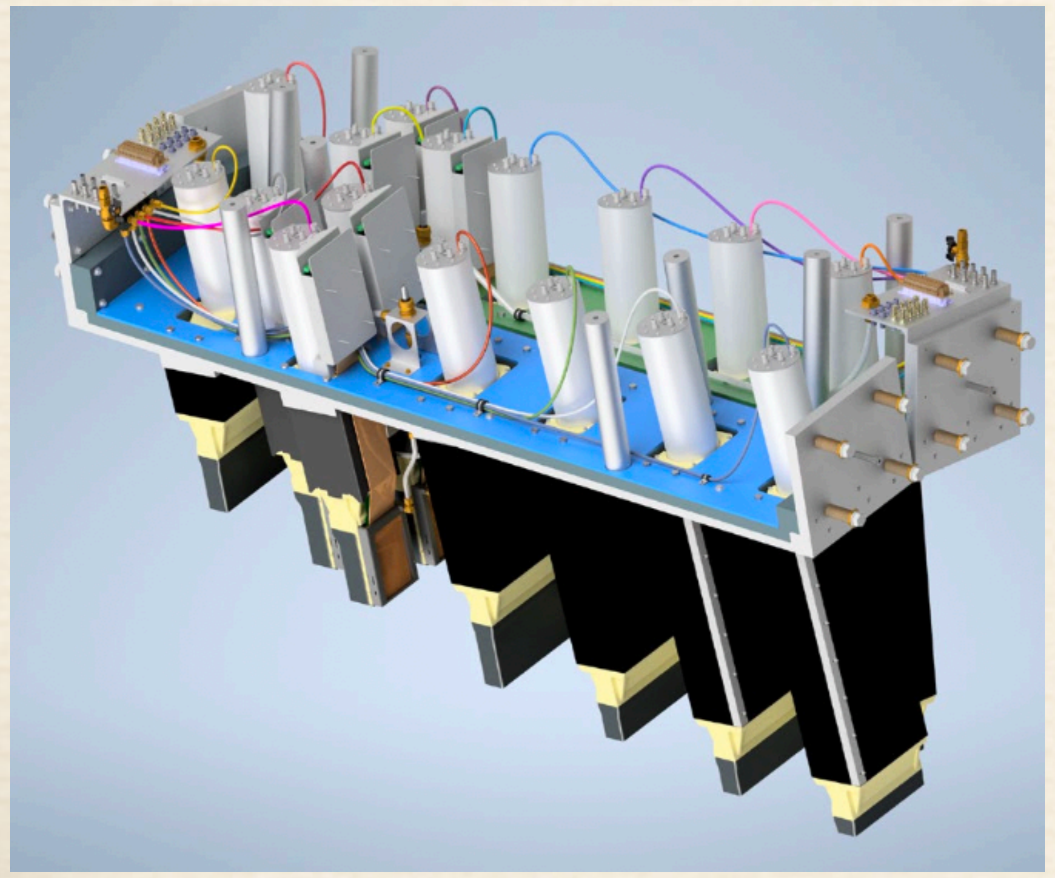
Both radial and azimuthal segmentation in scattered flux measurements required

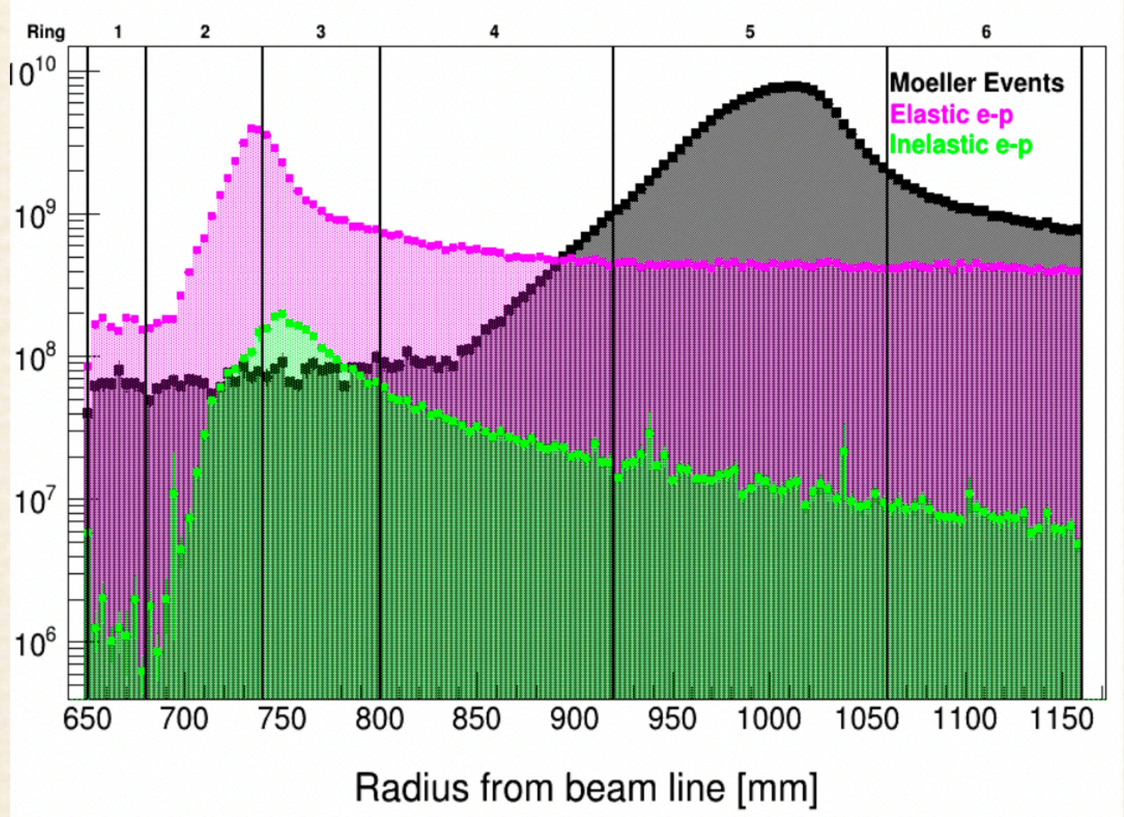




Integrating Detector Assembly







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University of Massachusetts
Bartoszek Engineering

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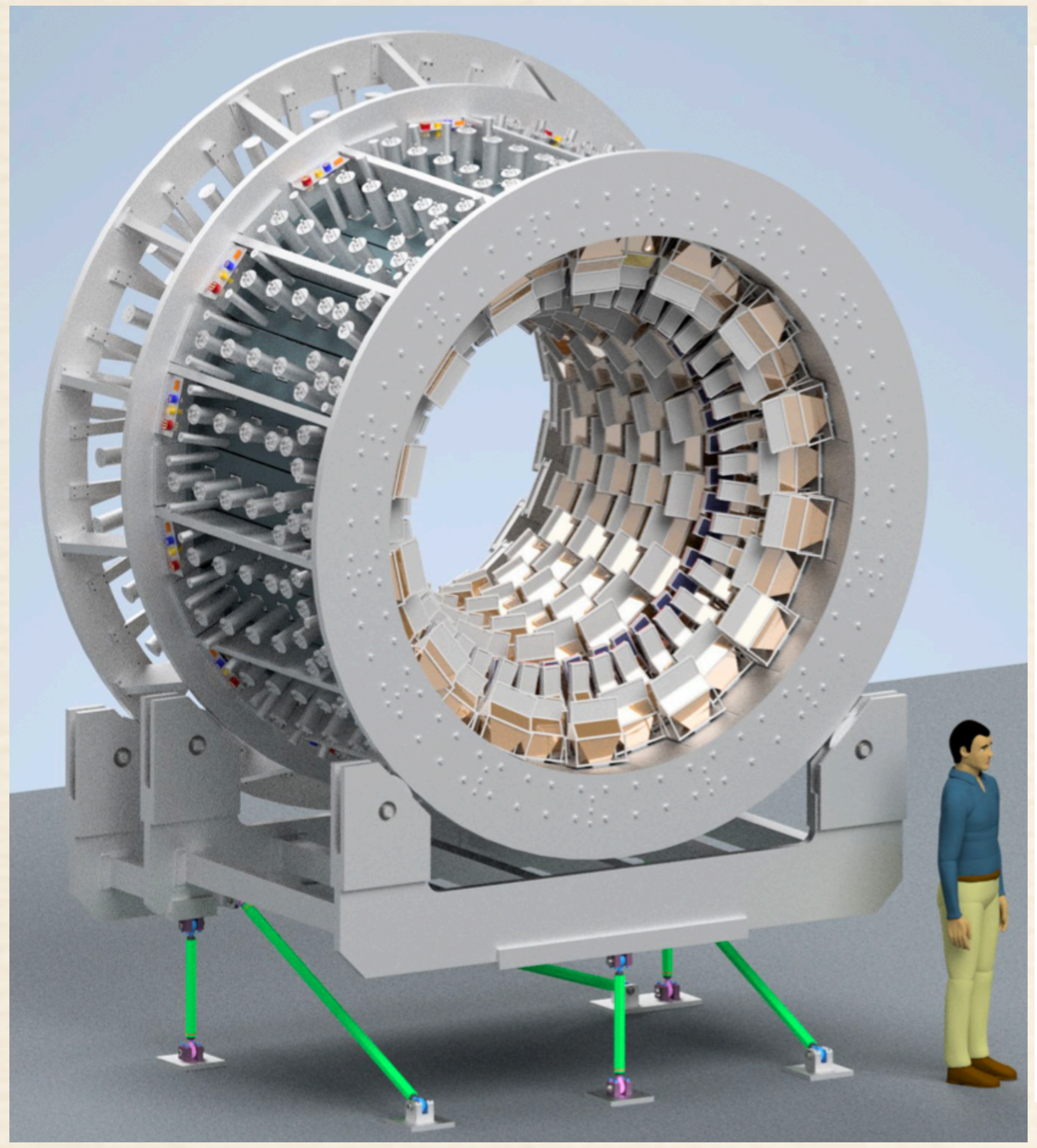

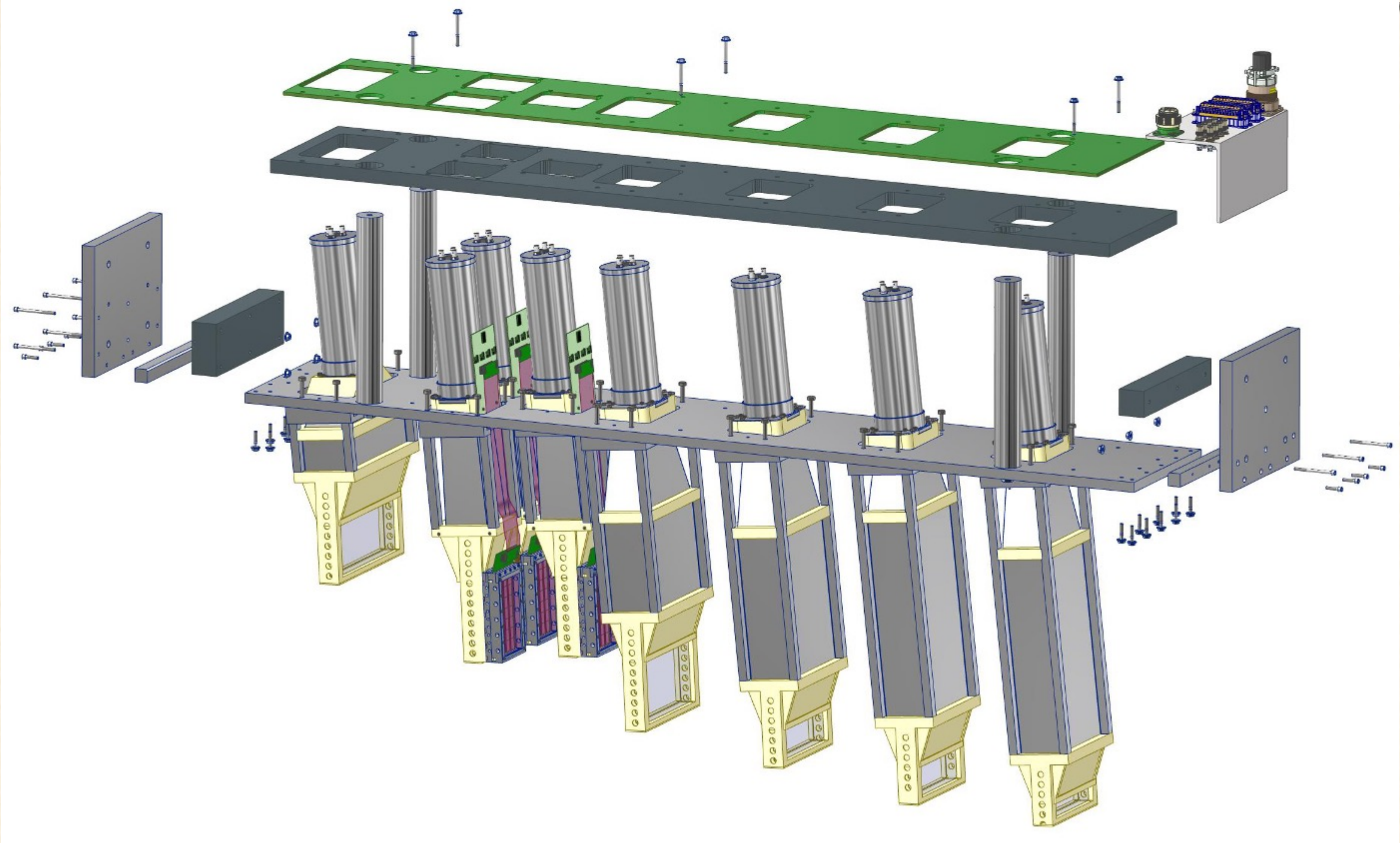

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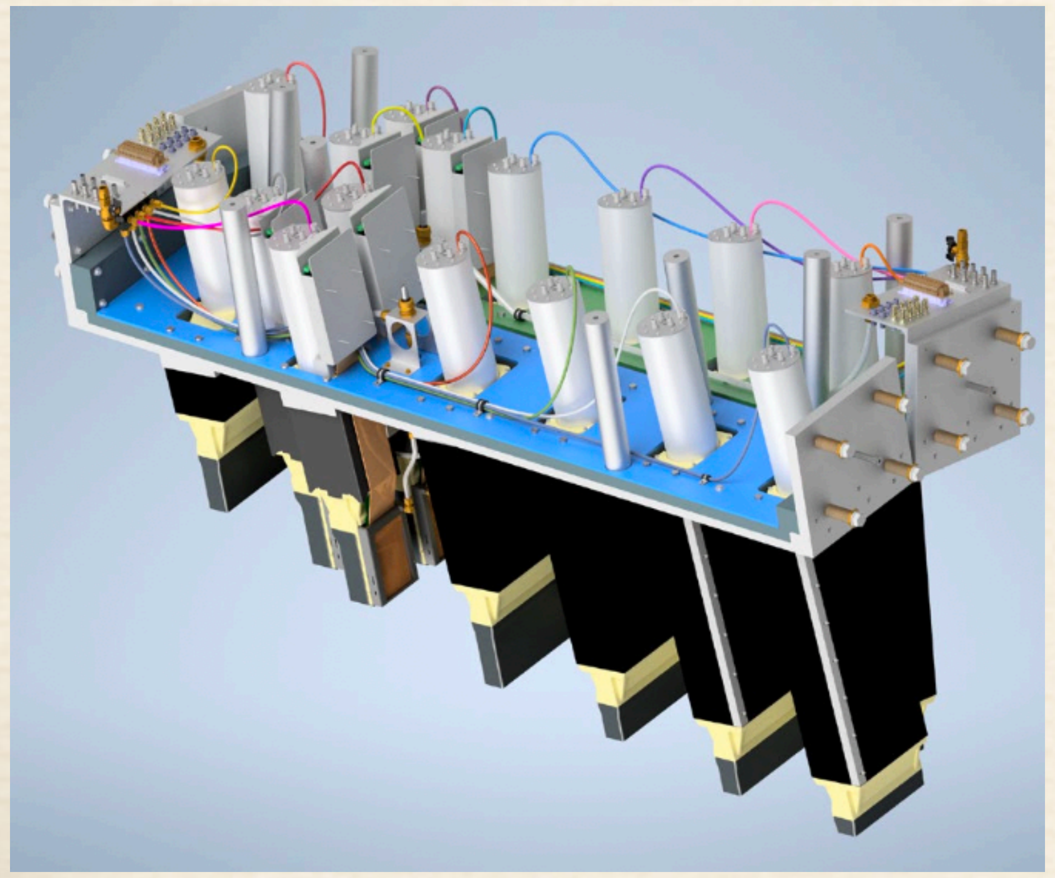

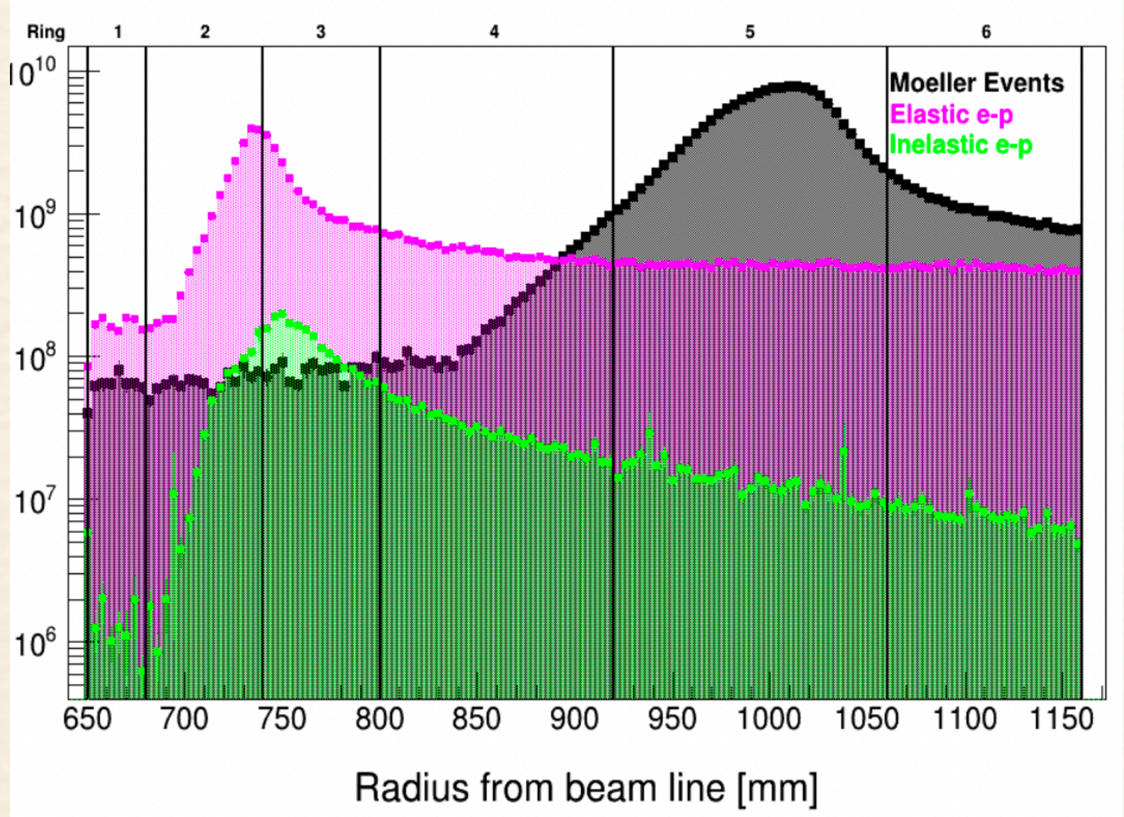

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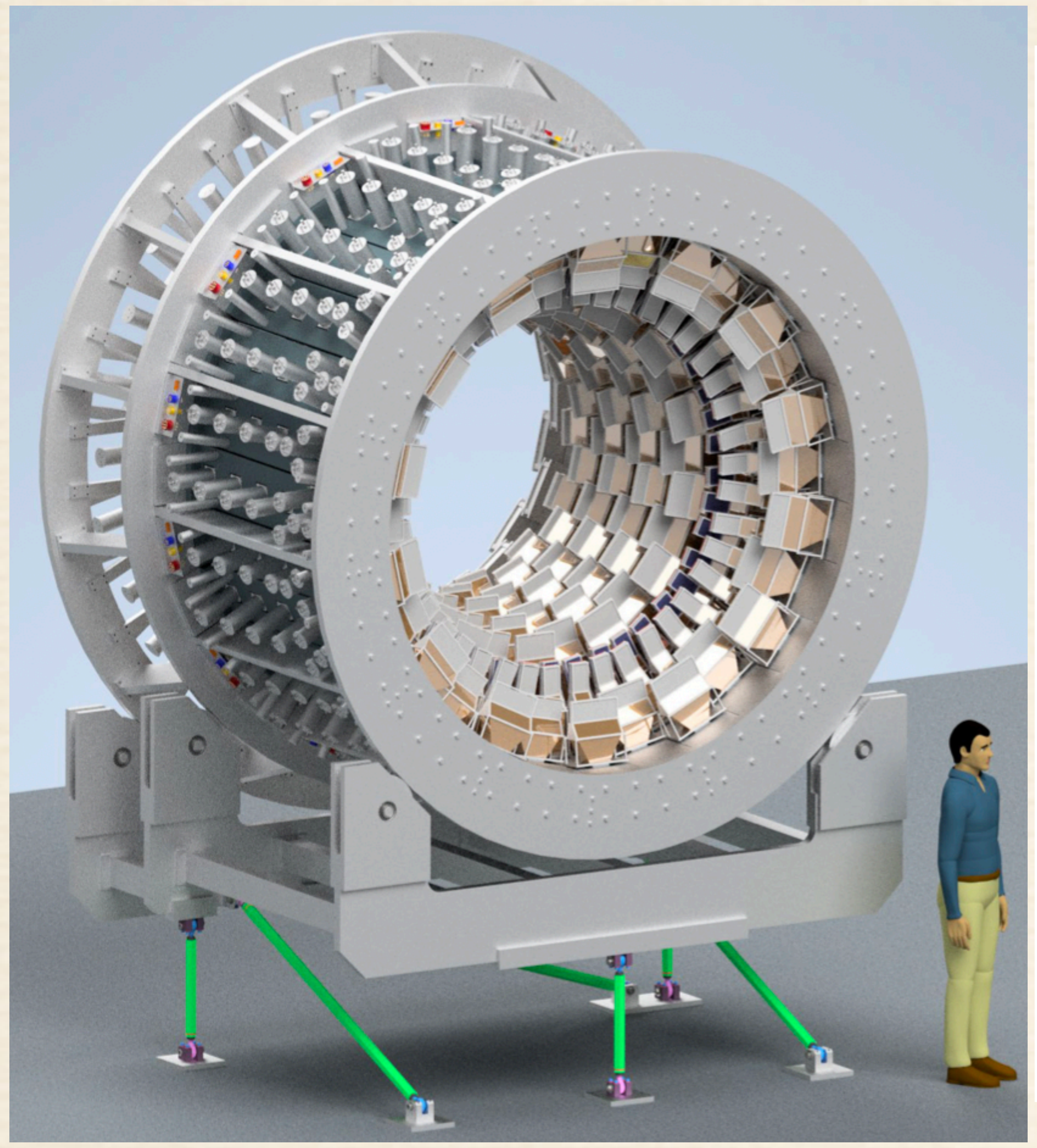

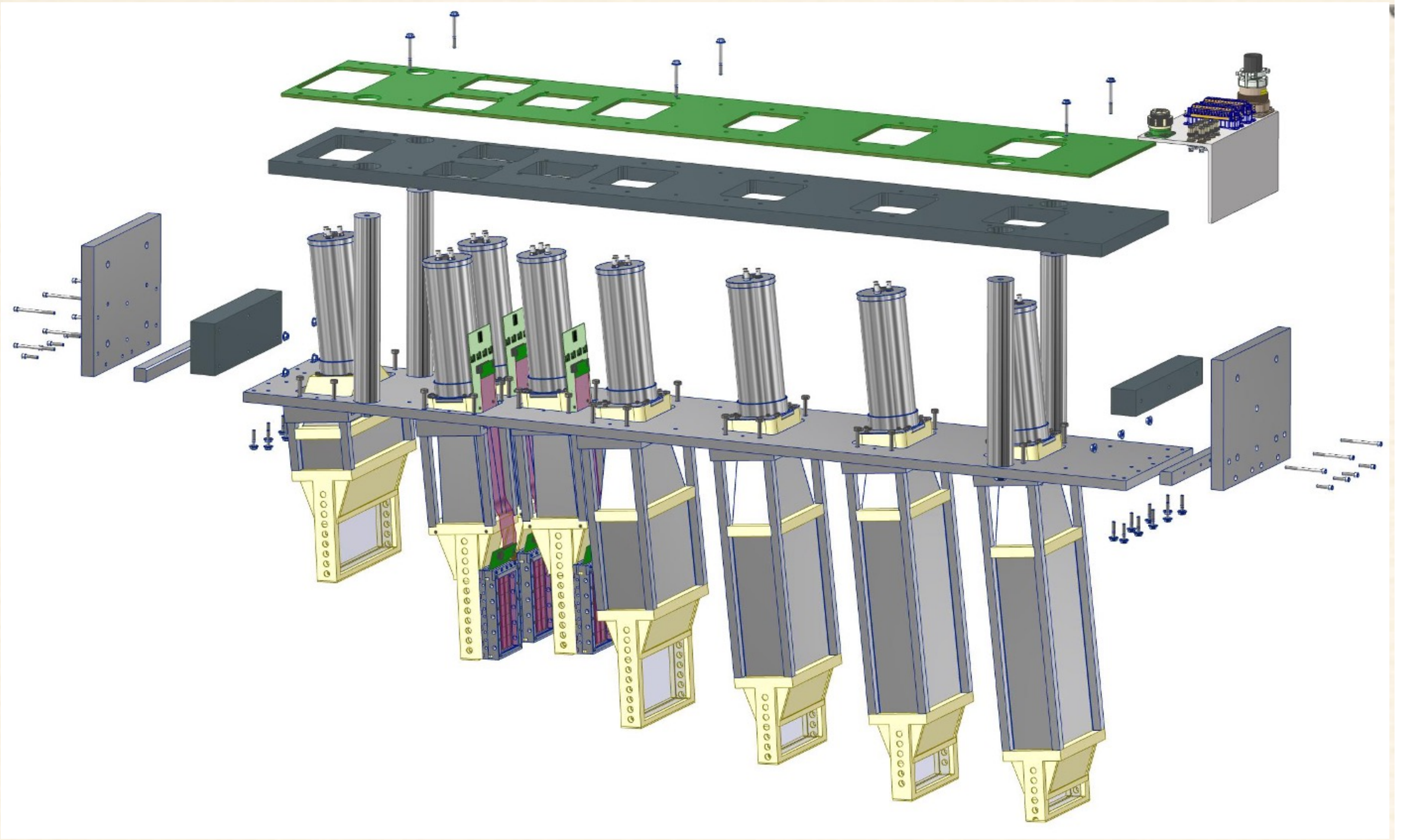

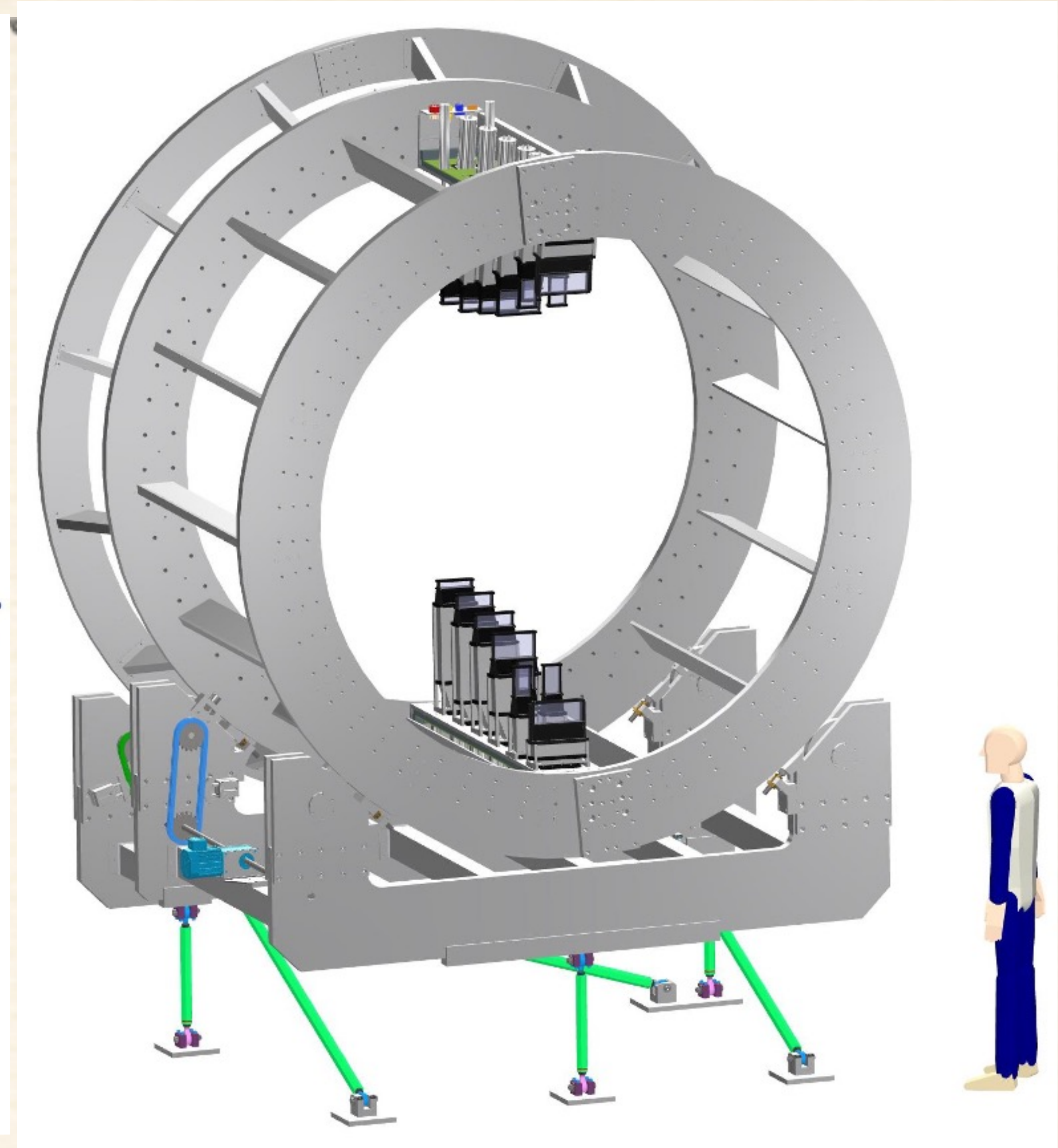

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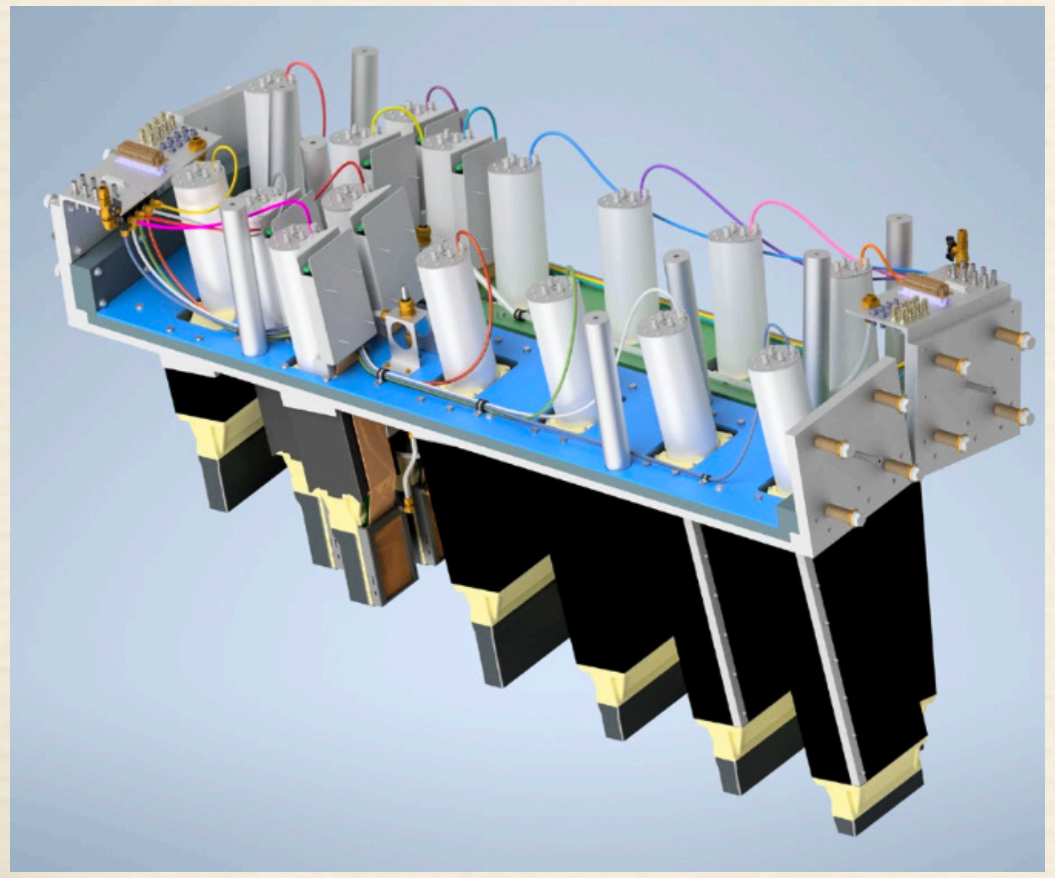

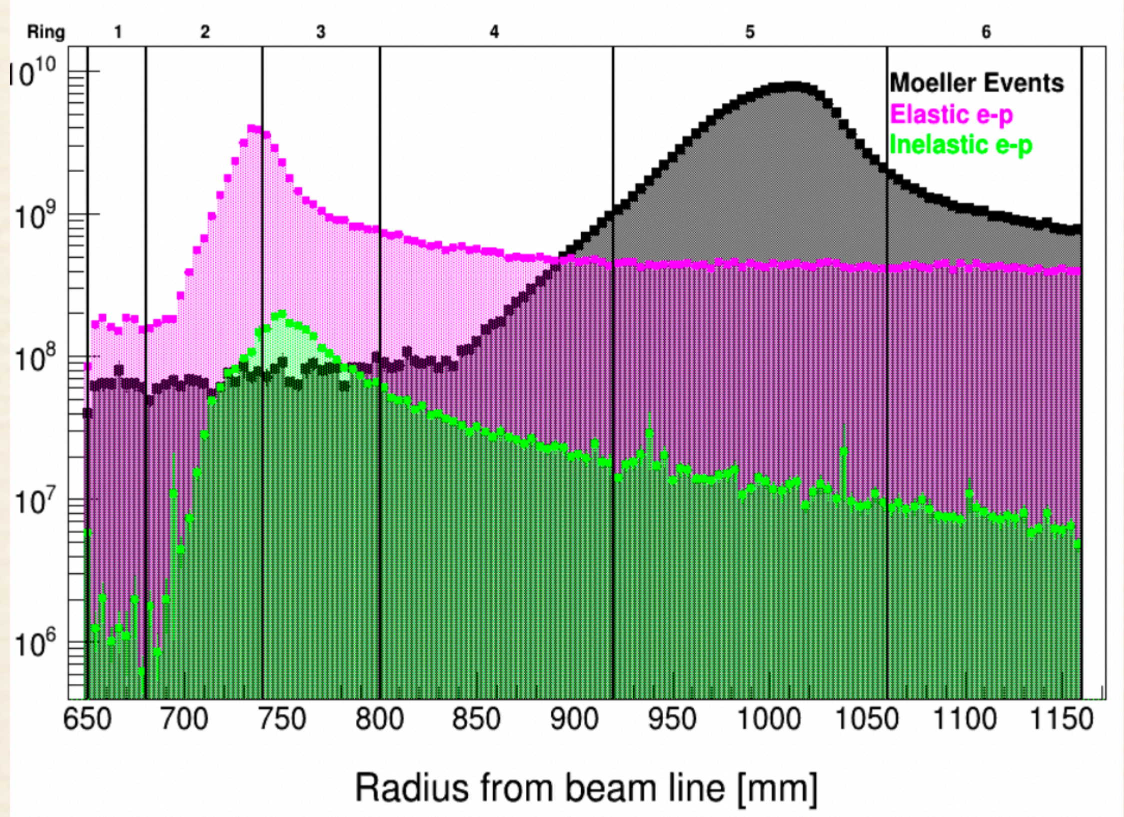

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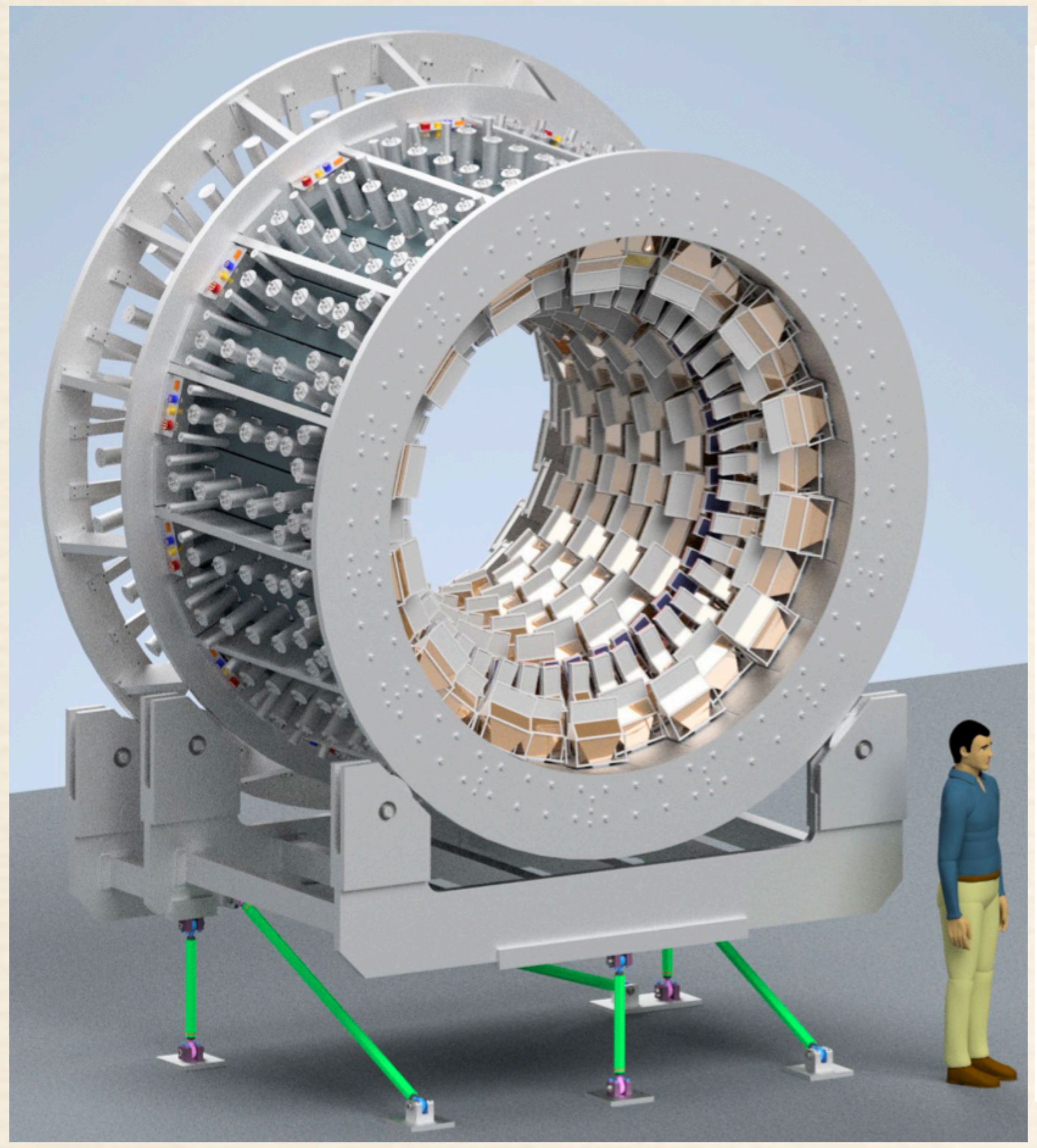

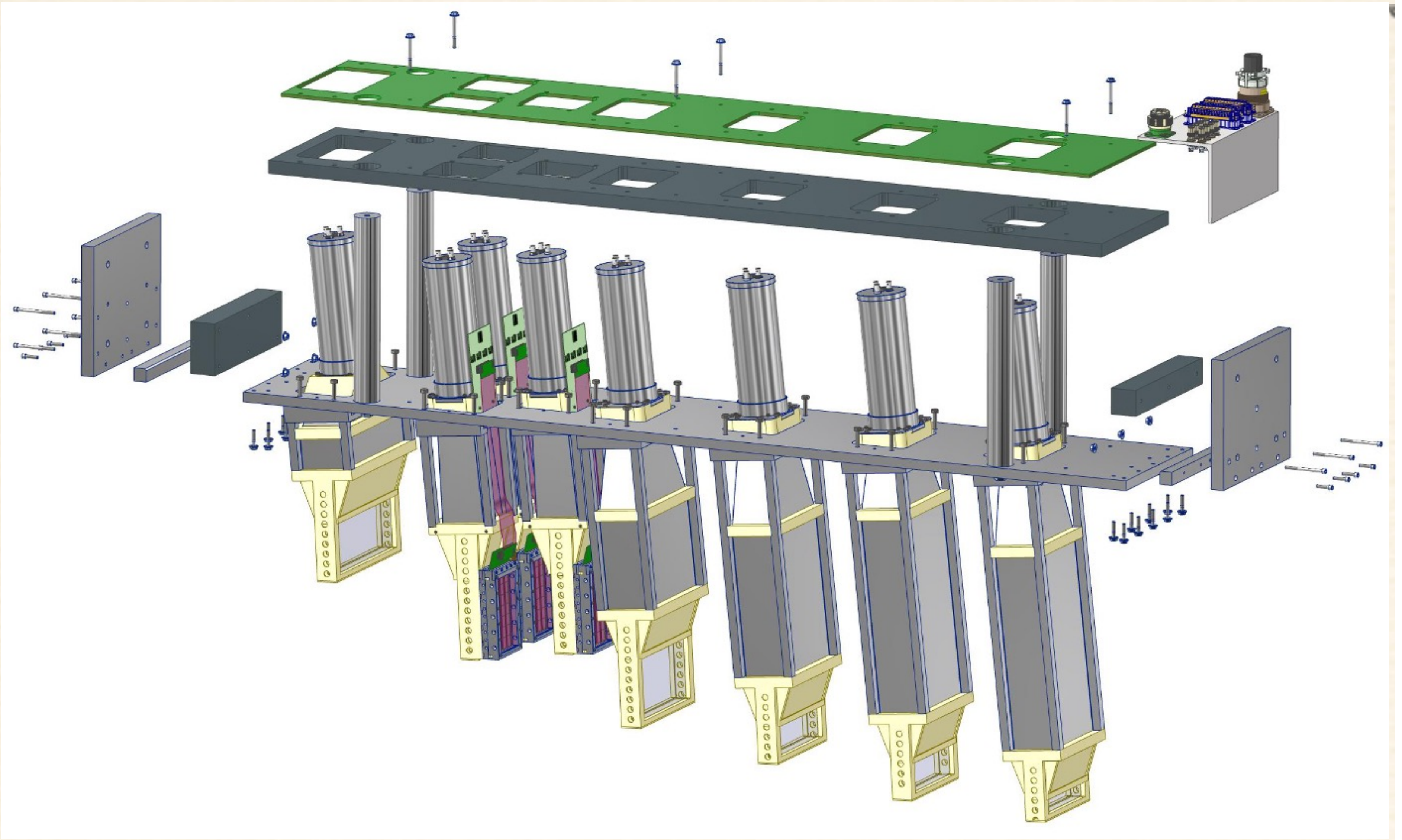

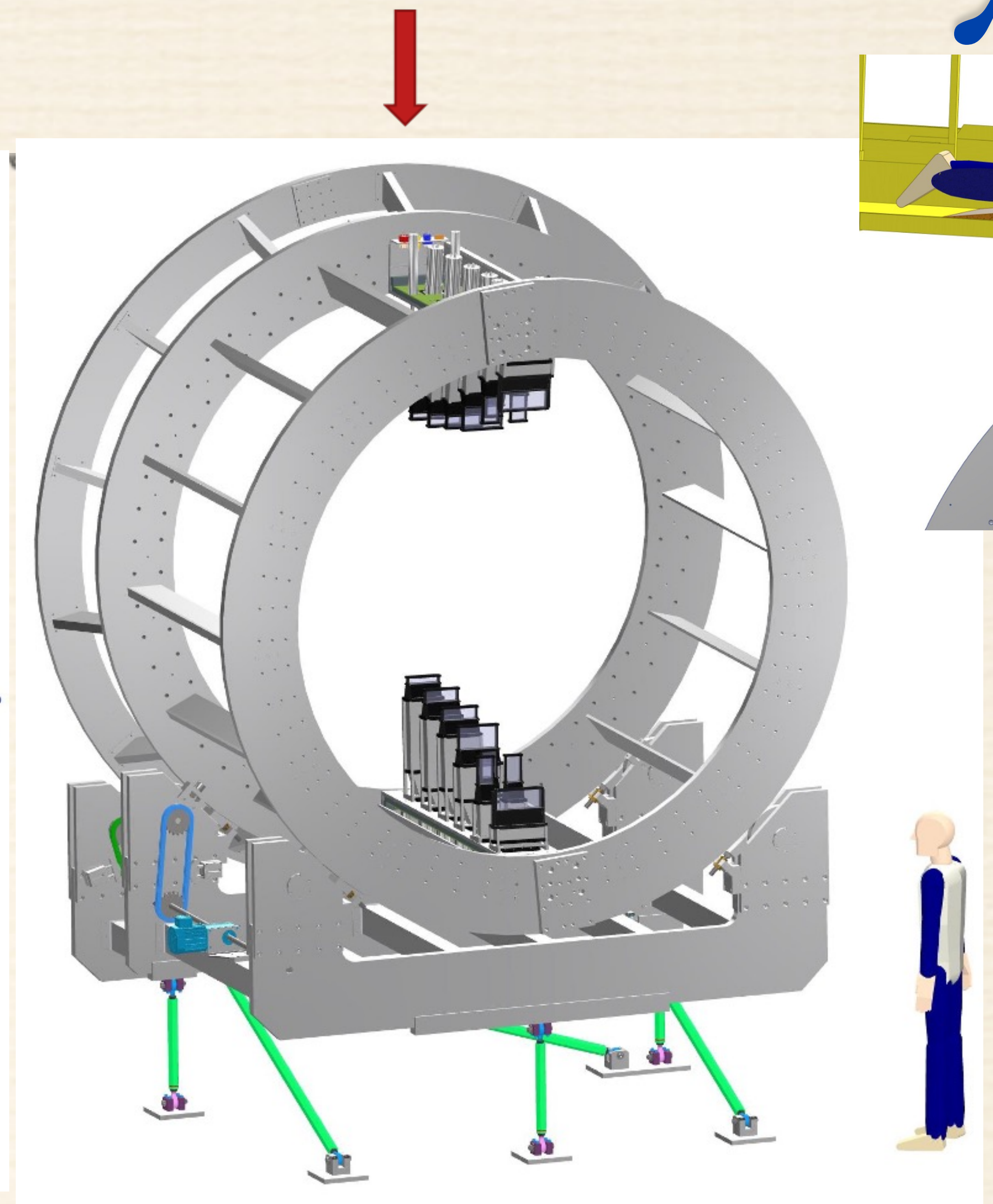

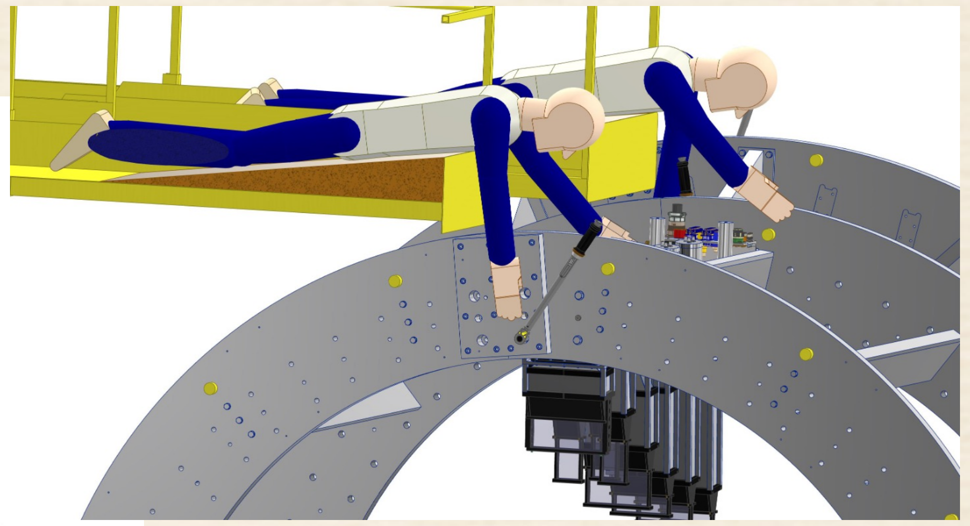

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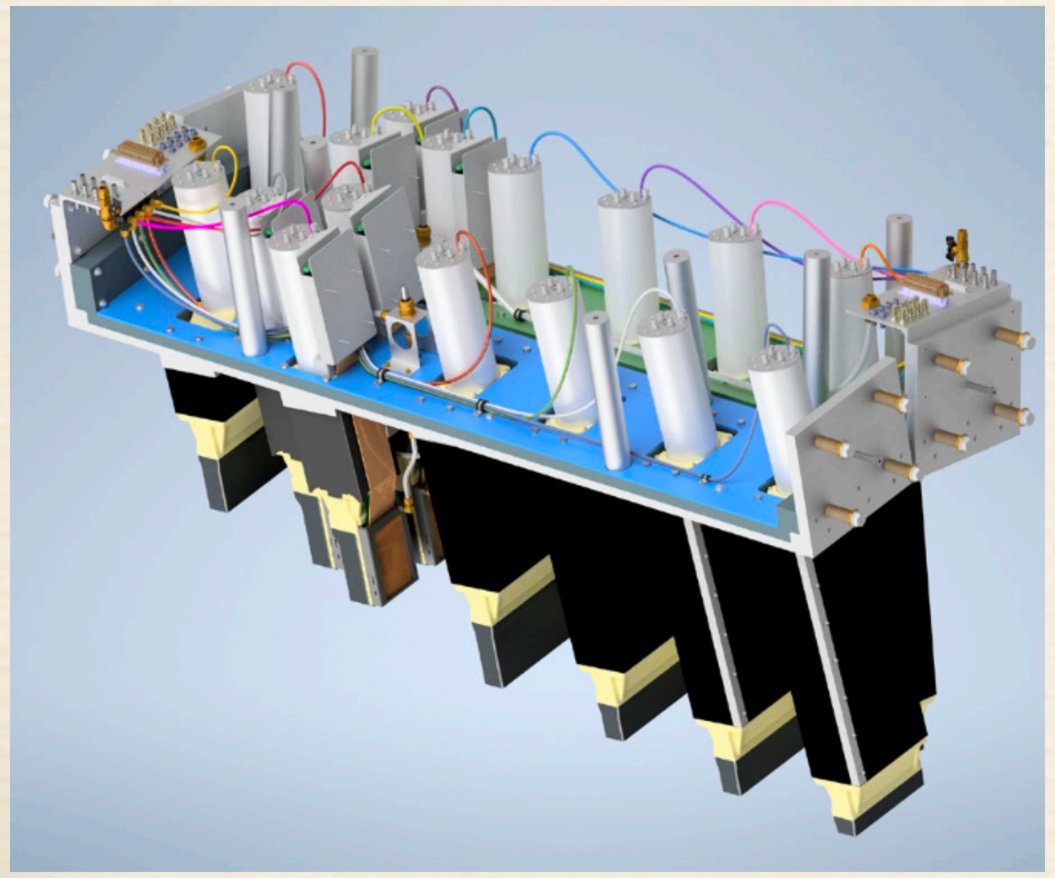
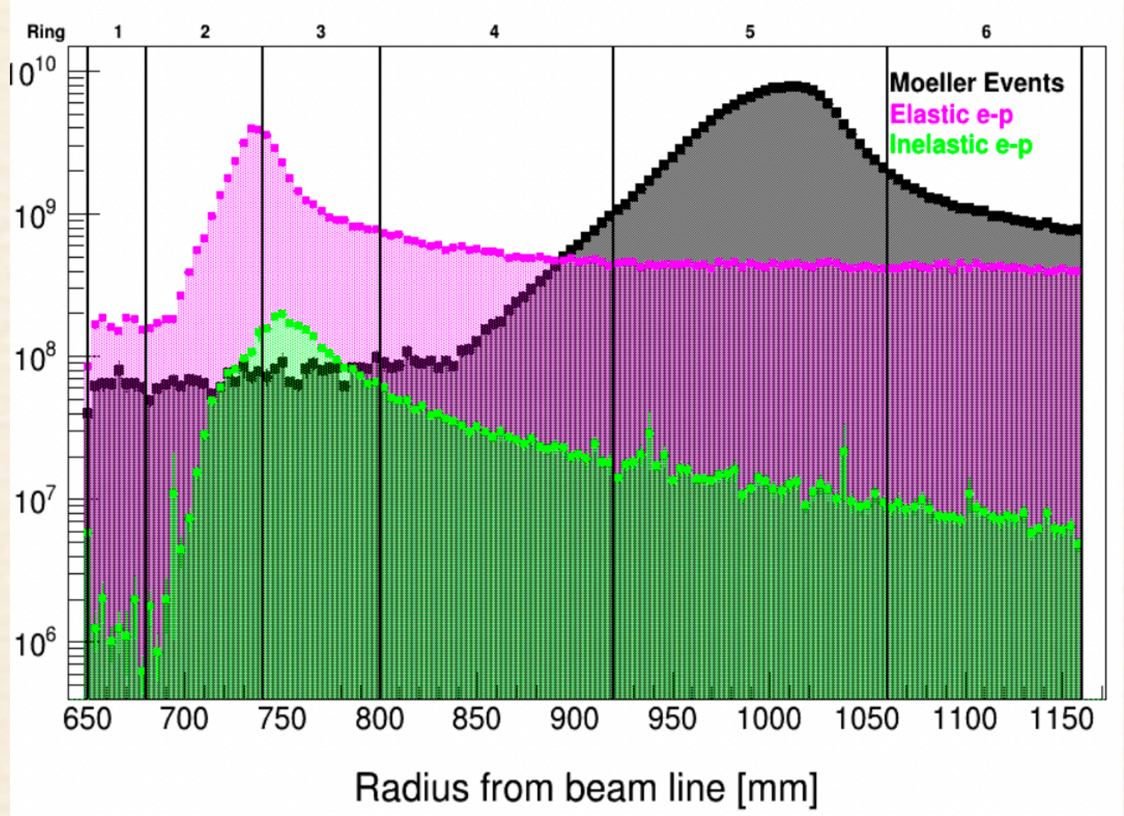
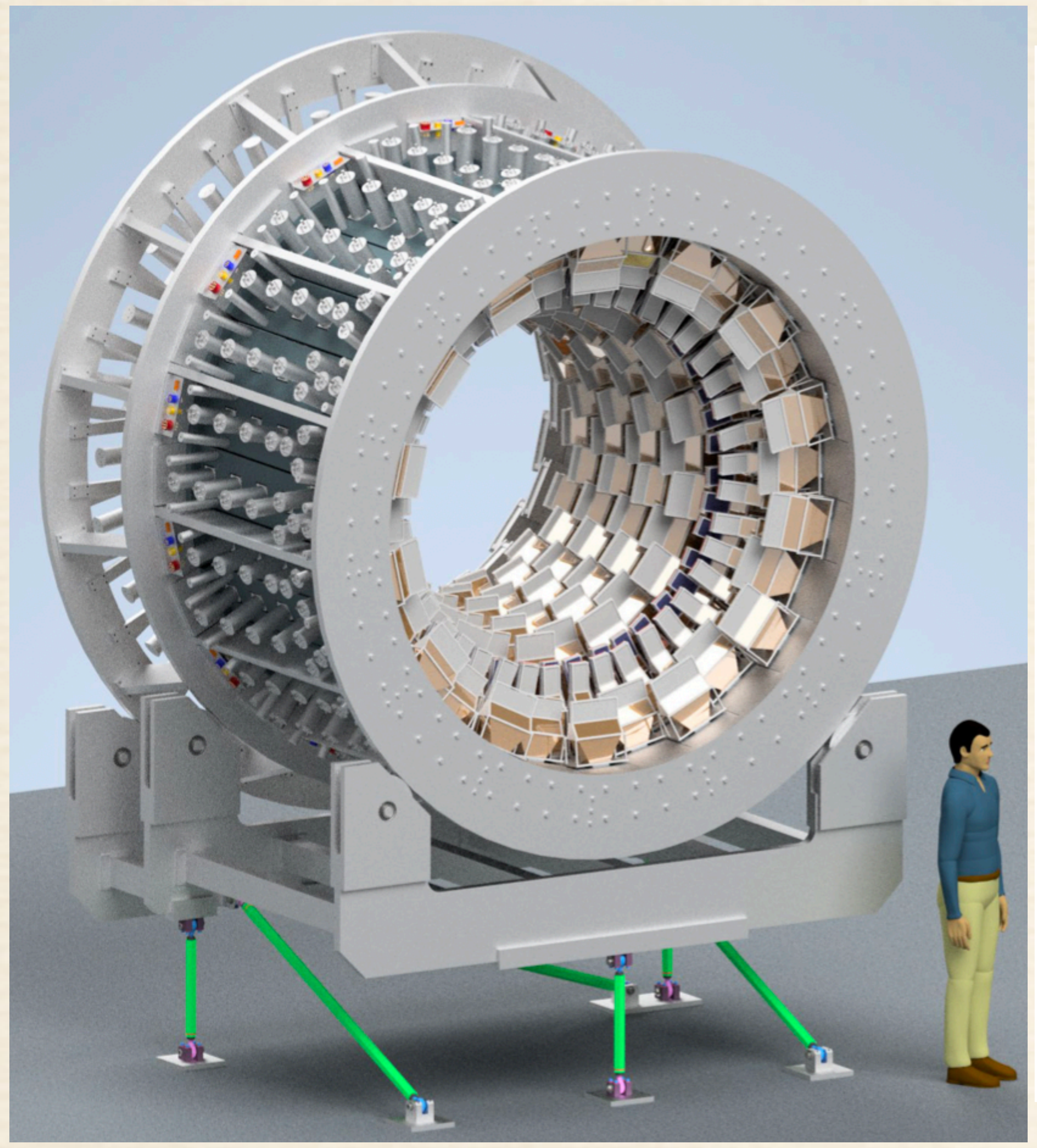
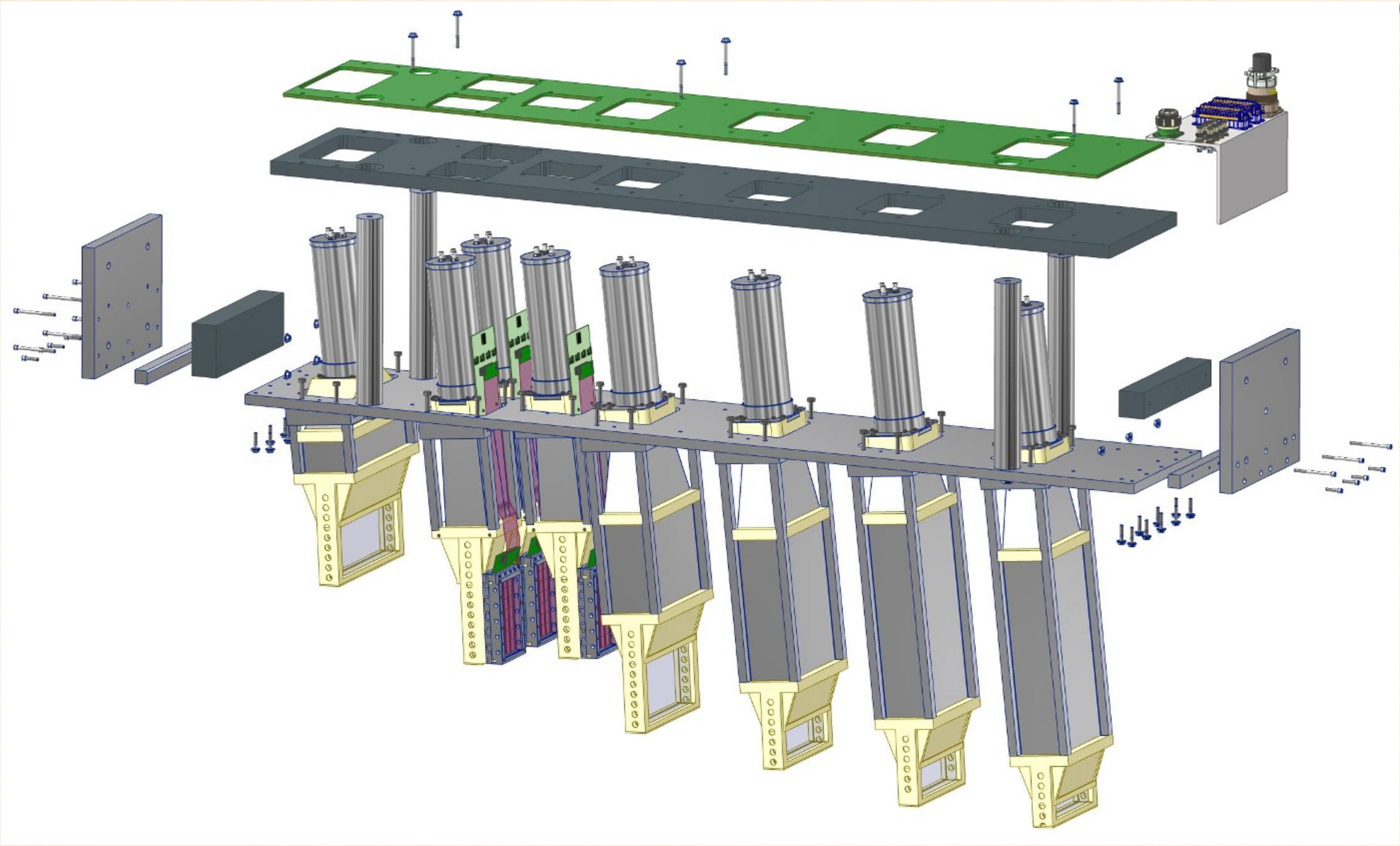
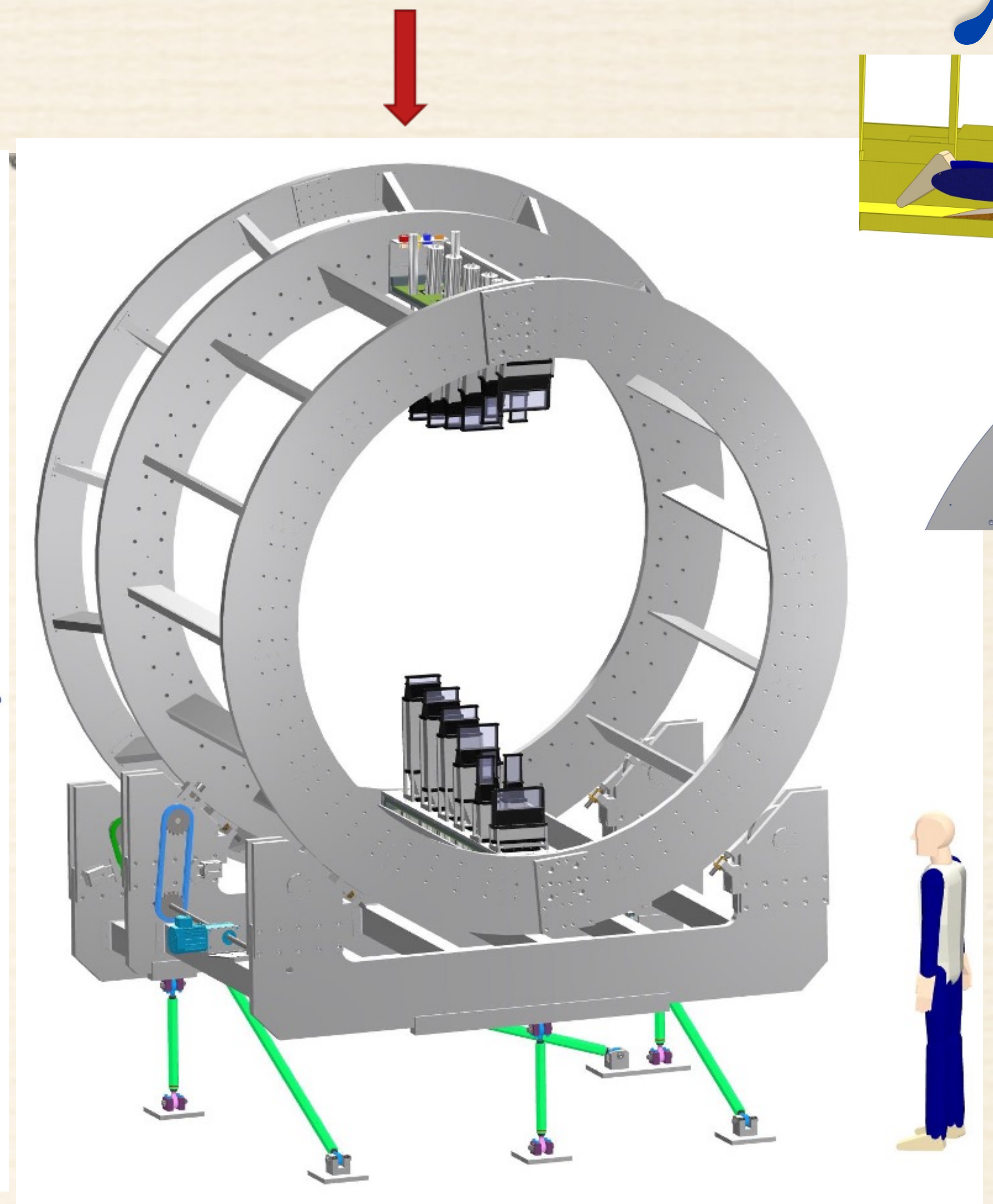


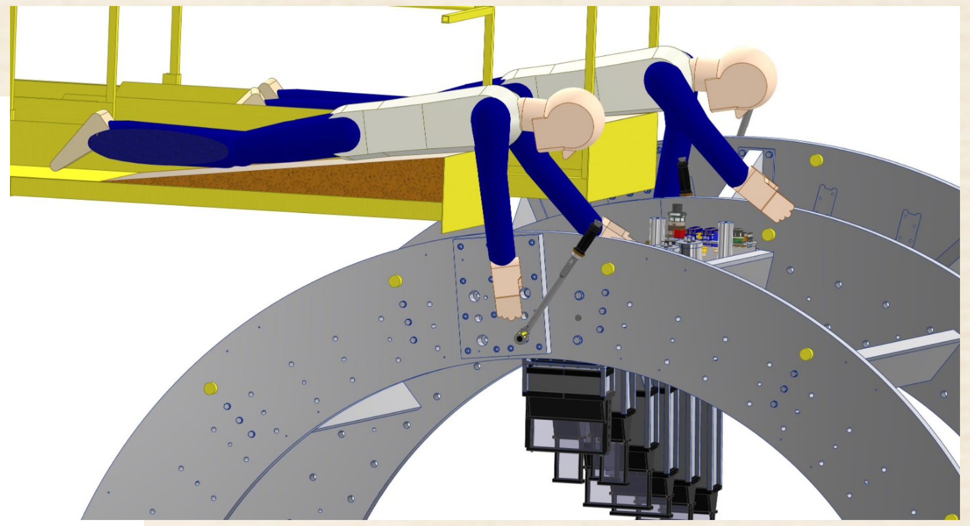


Integrating Detector Assembly

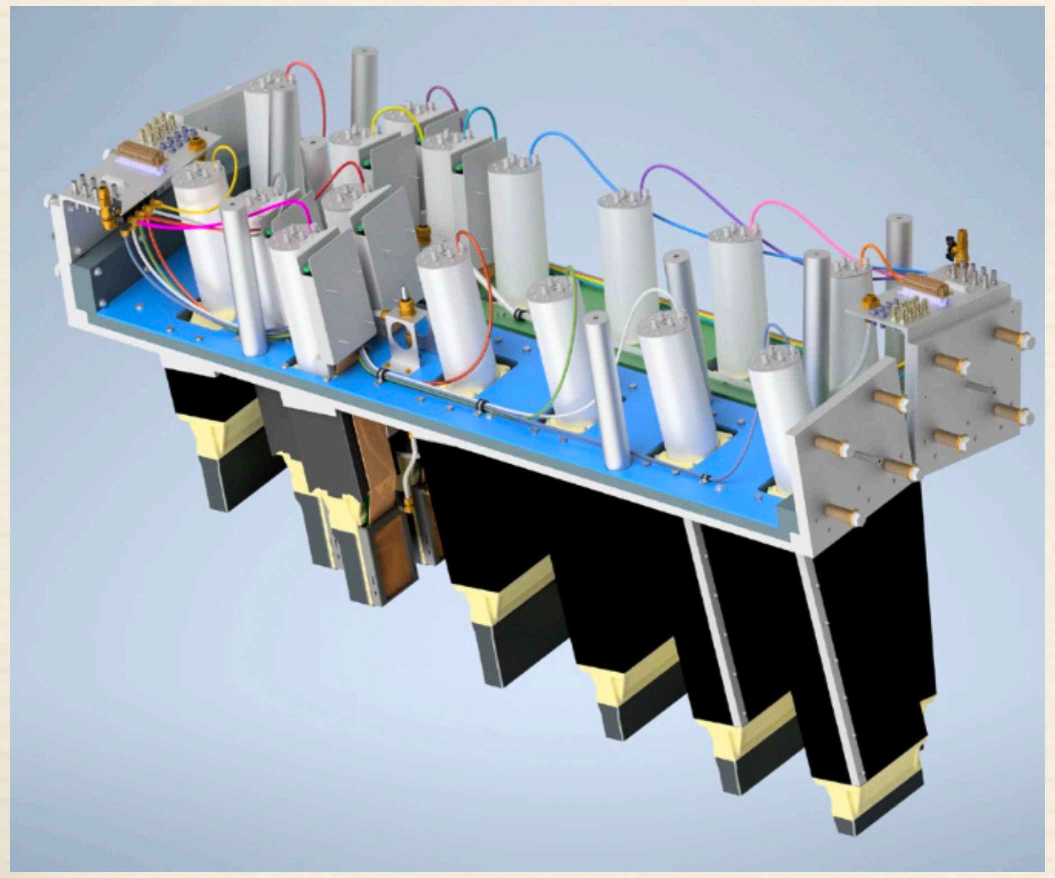


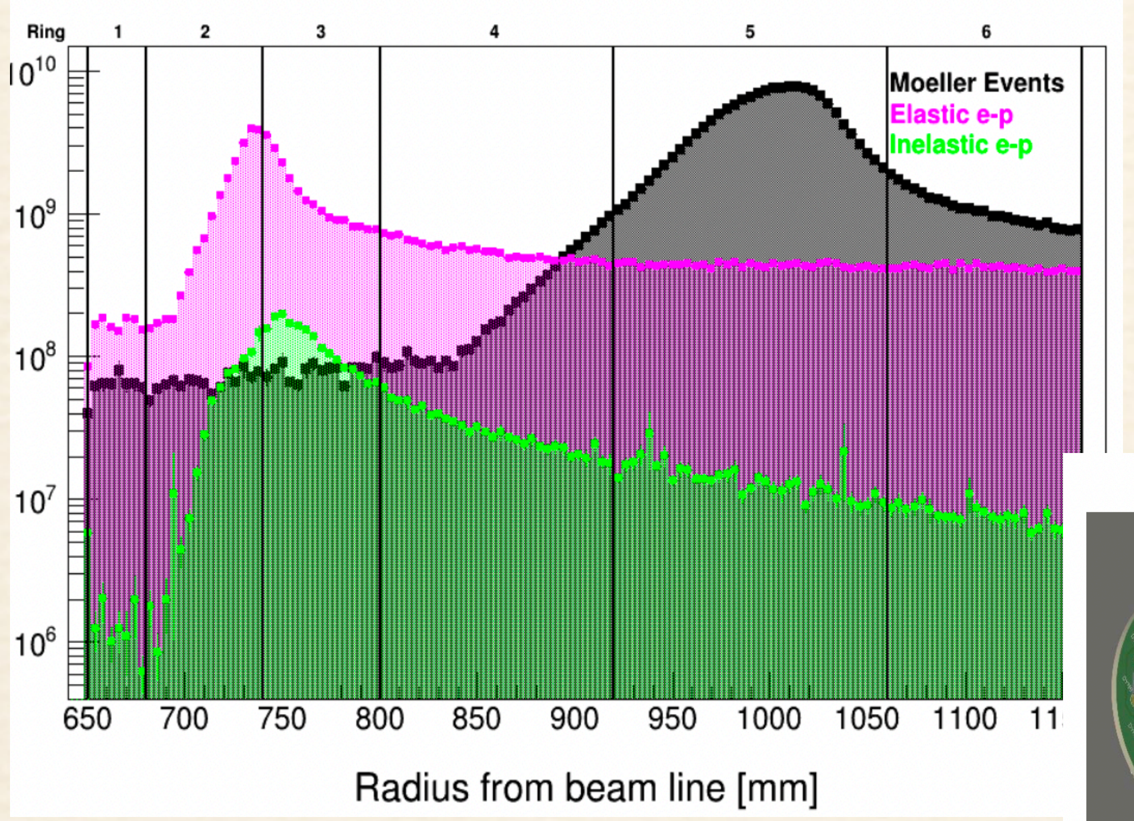


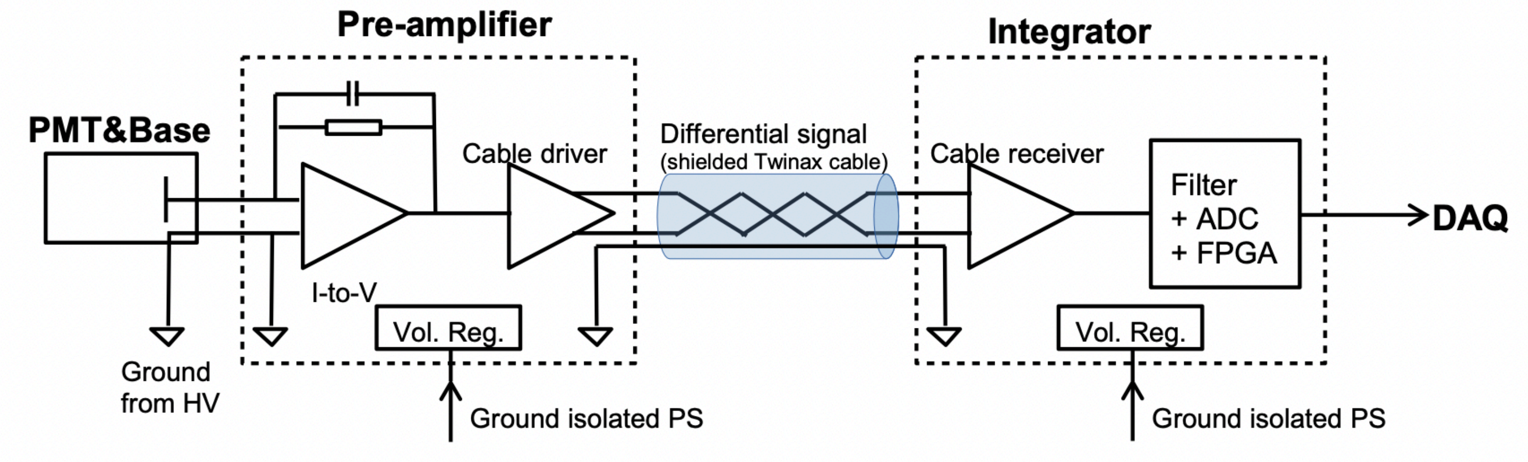


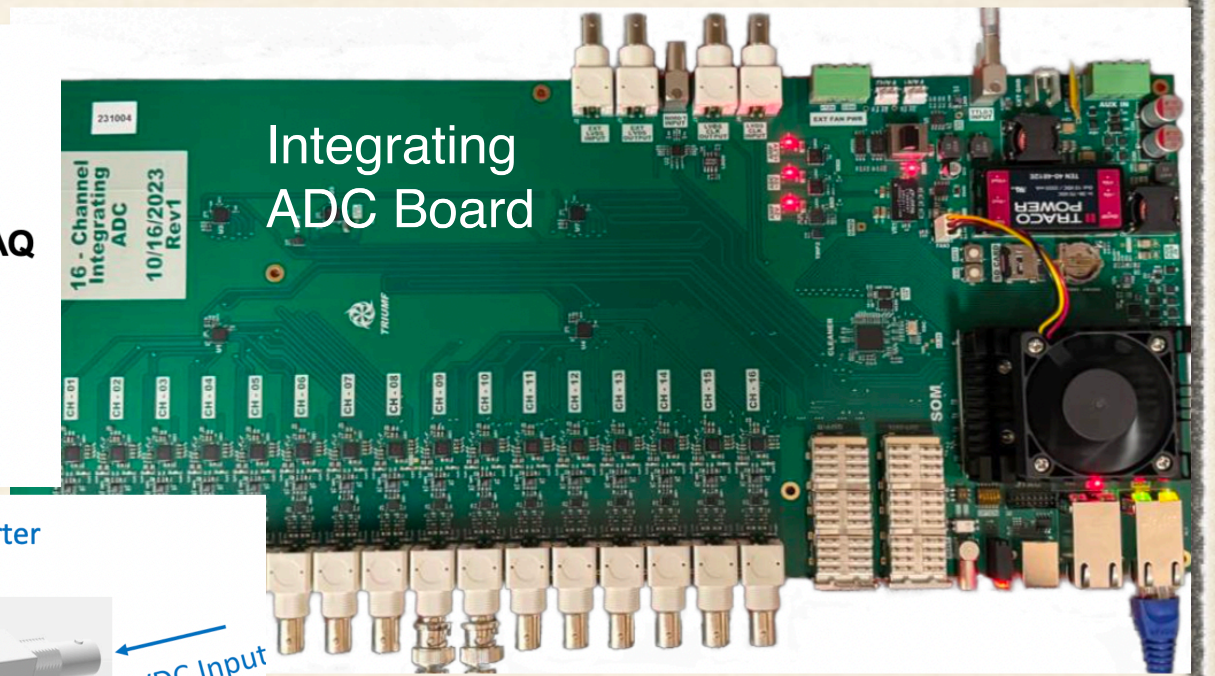


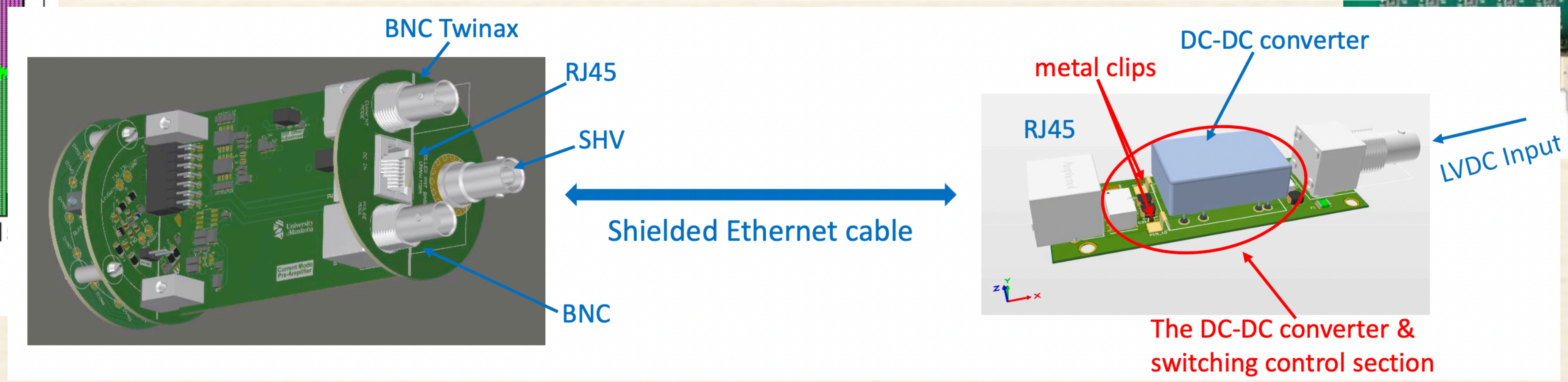
Idaho State University
University of Manitoba
University of Massachusetts
Bartoszek Engineering



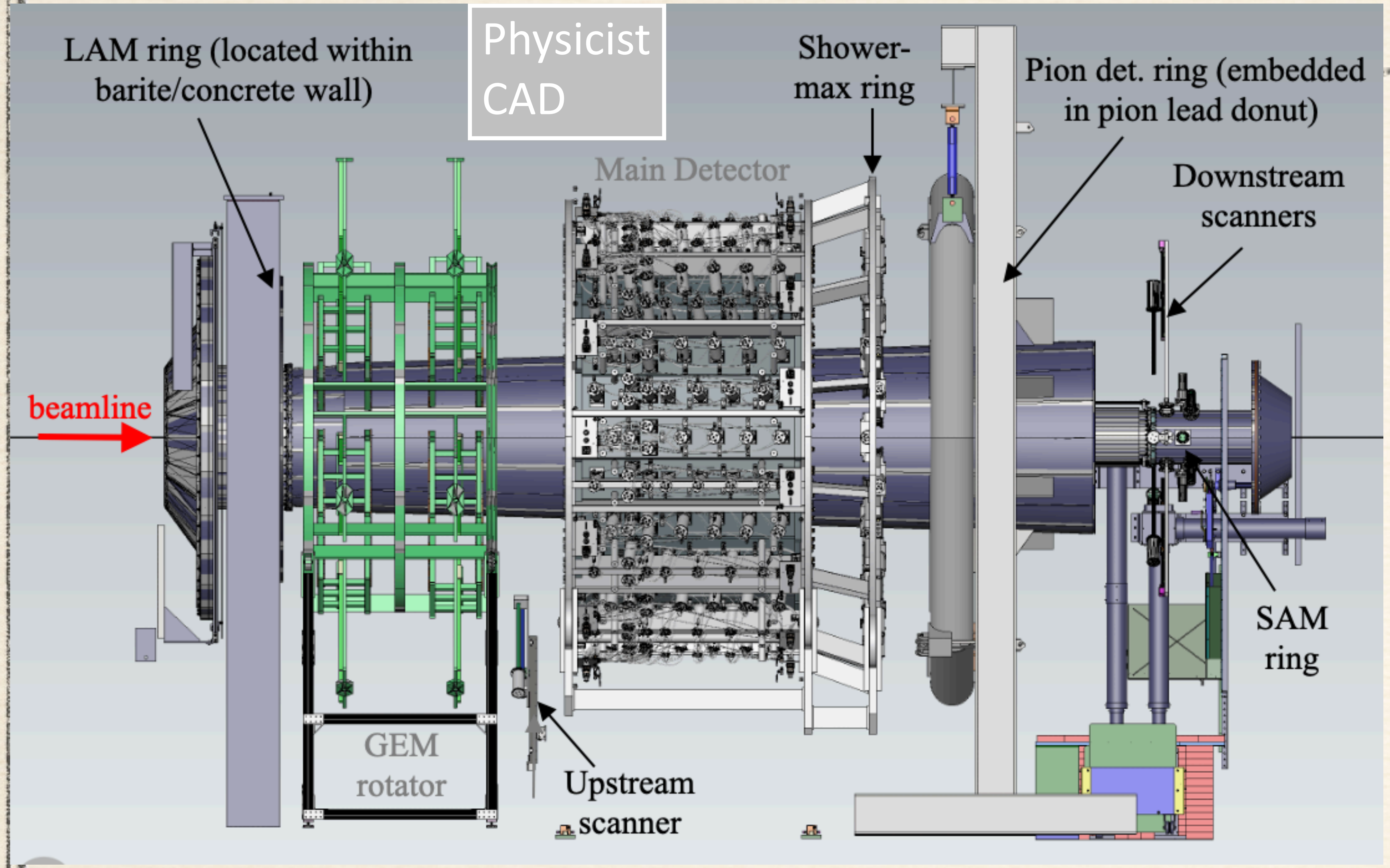








MOLLER Detection Overview



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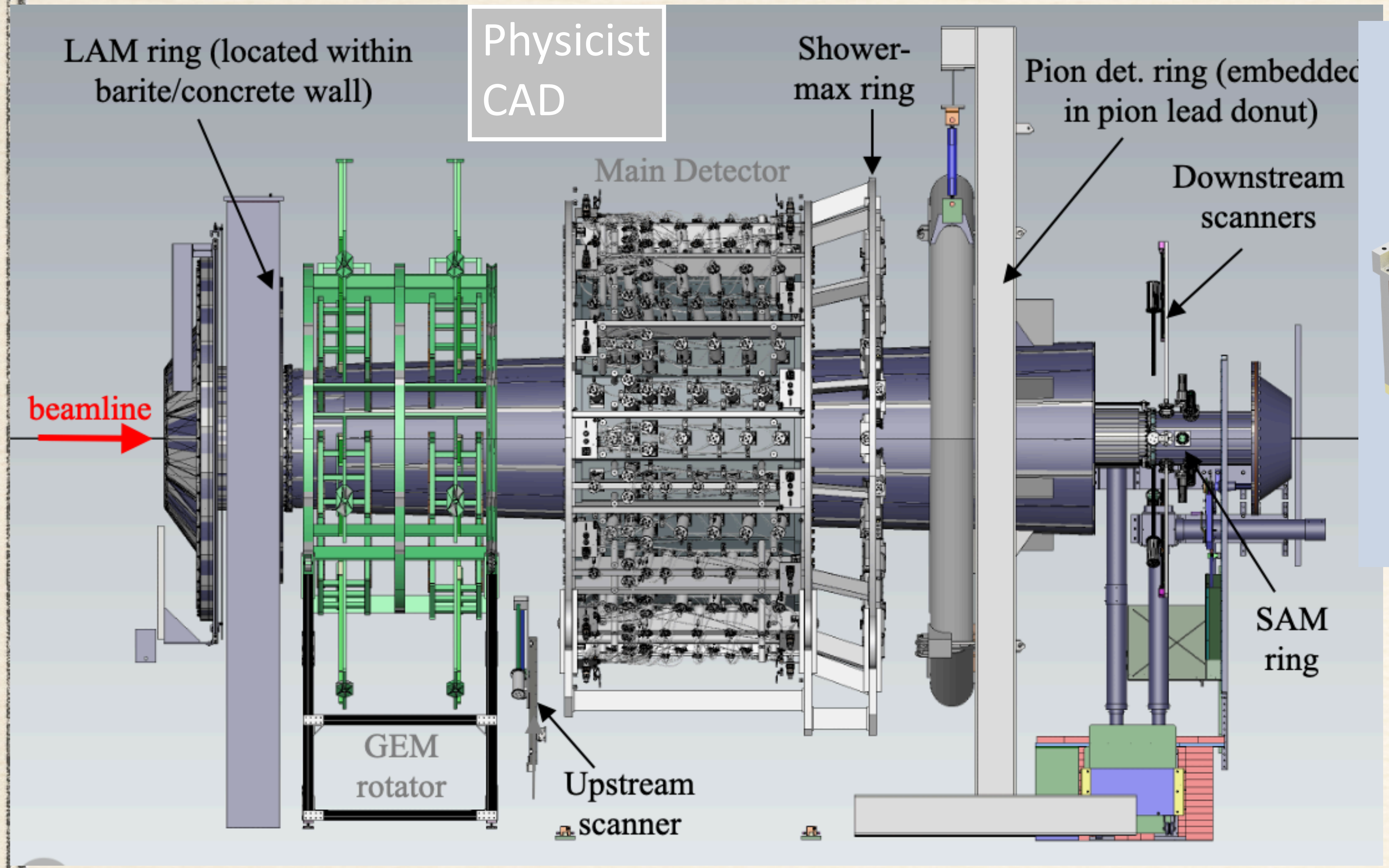
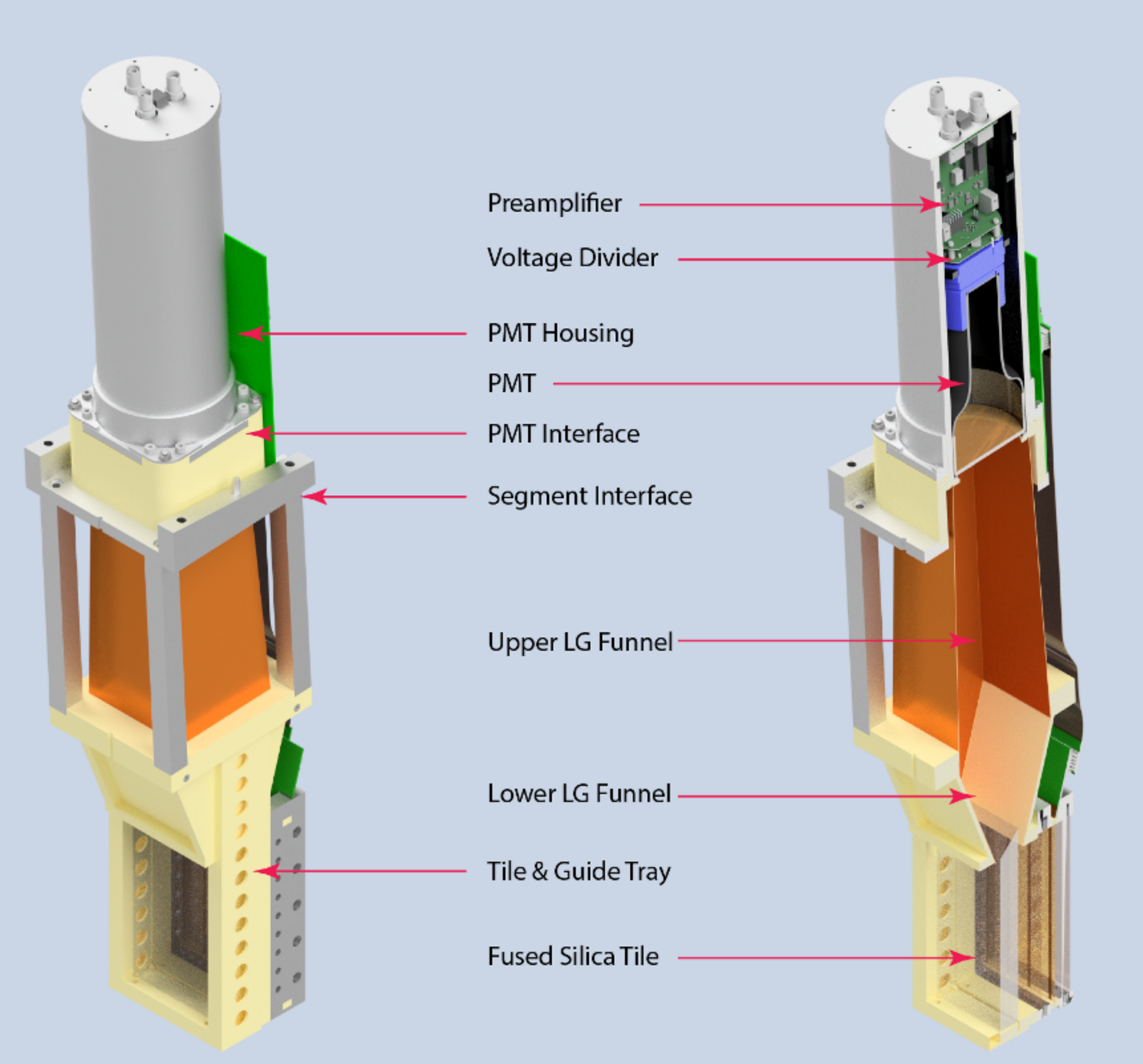
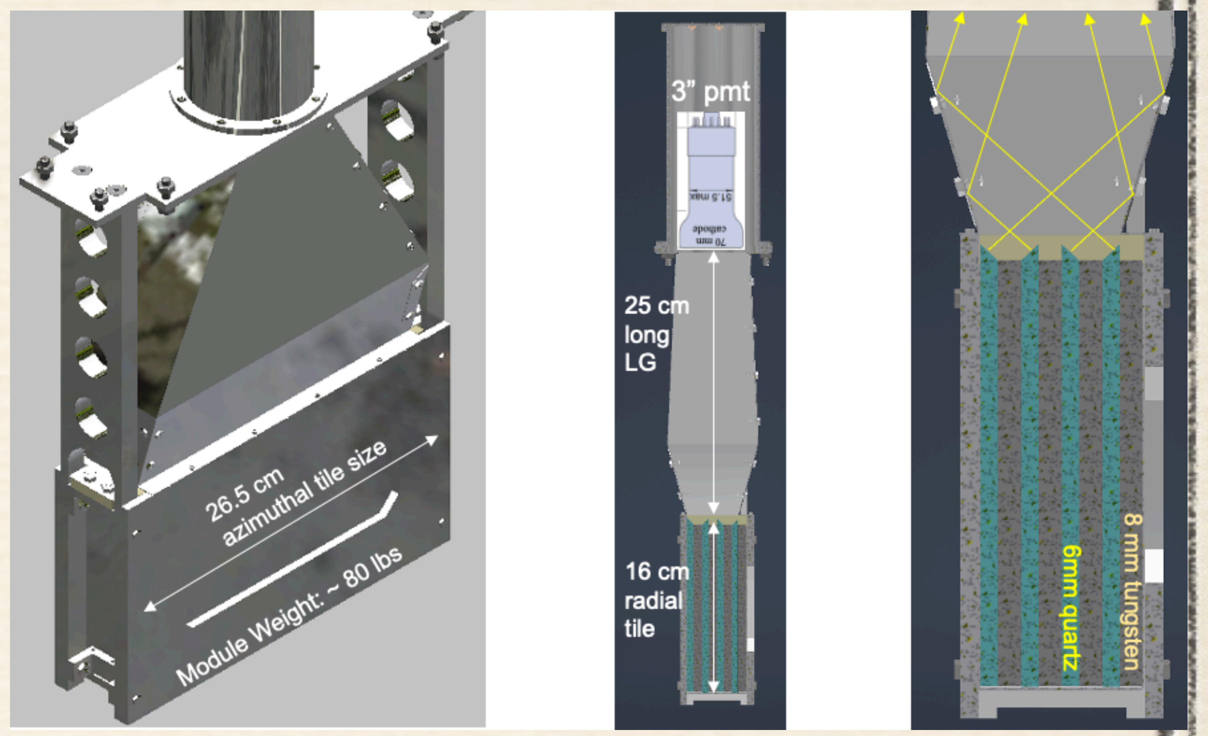




Requirement for Ring 5:

Detector resolution < 25%

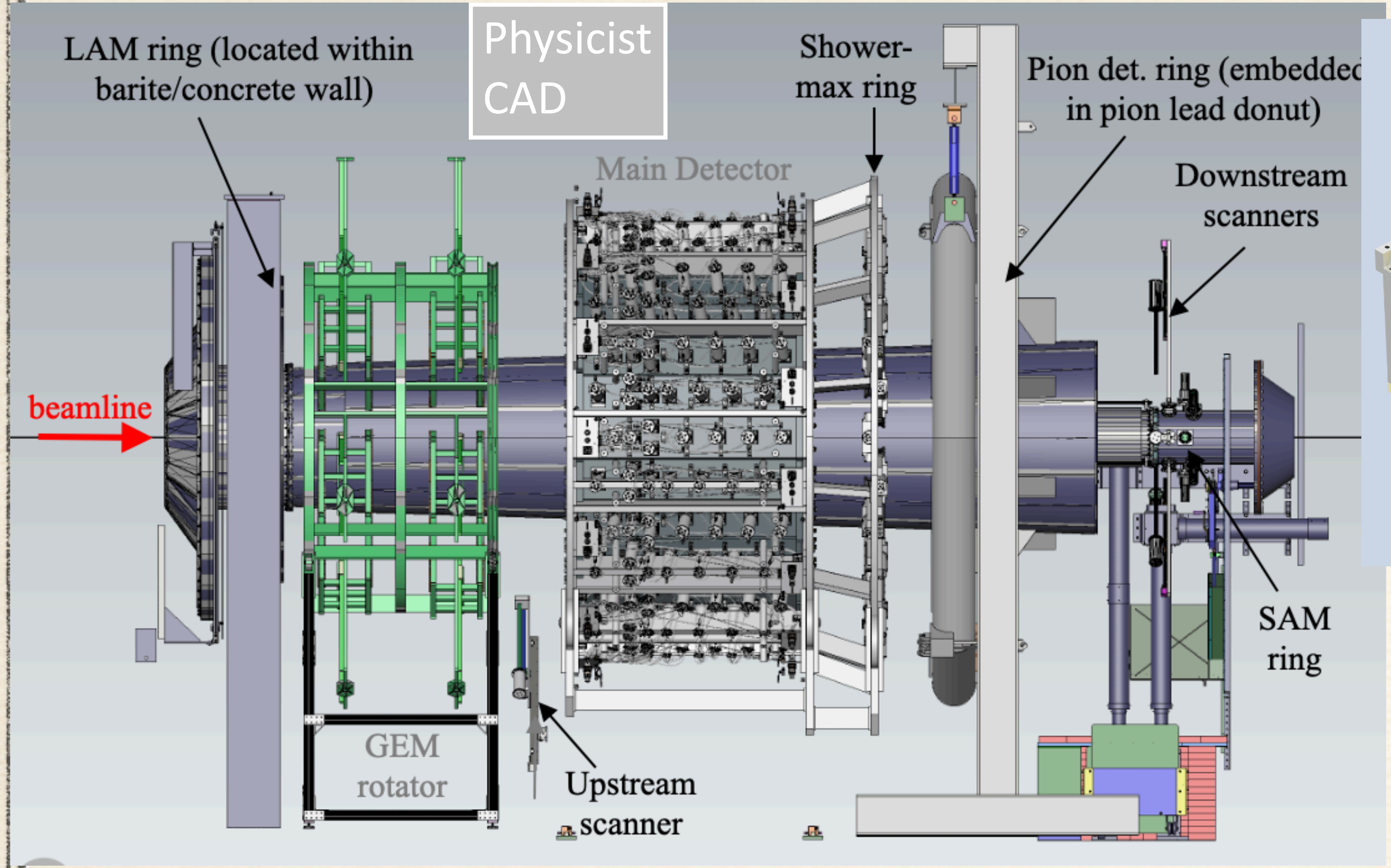
excess noise < 4%

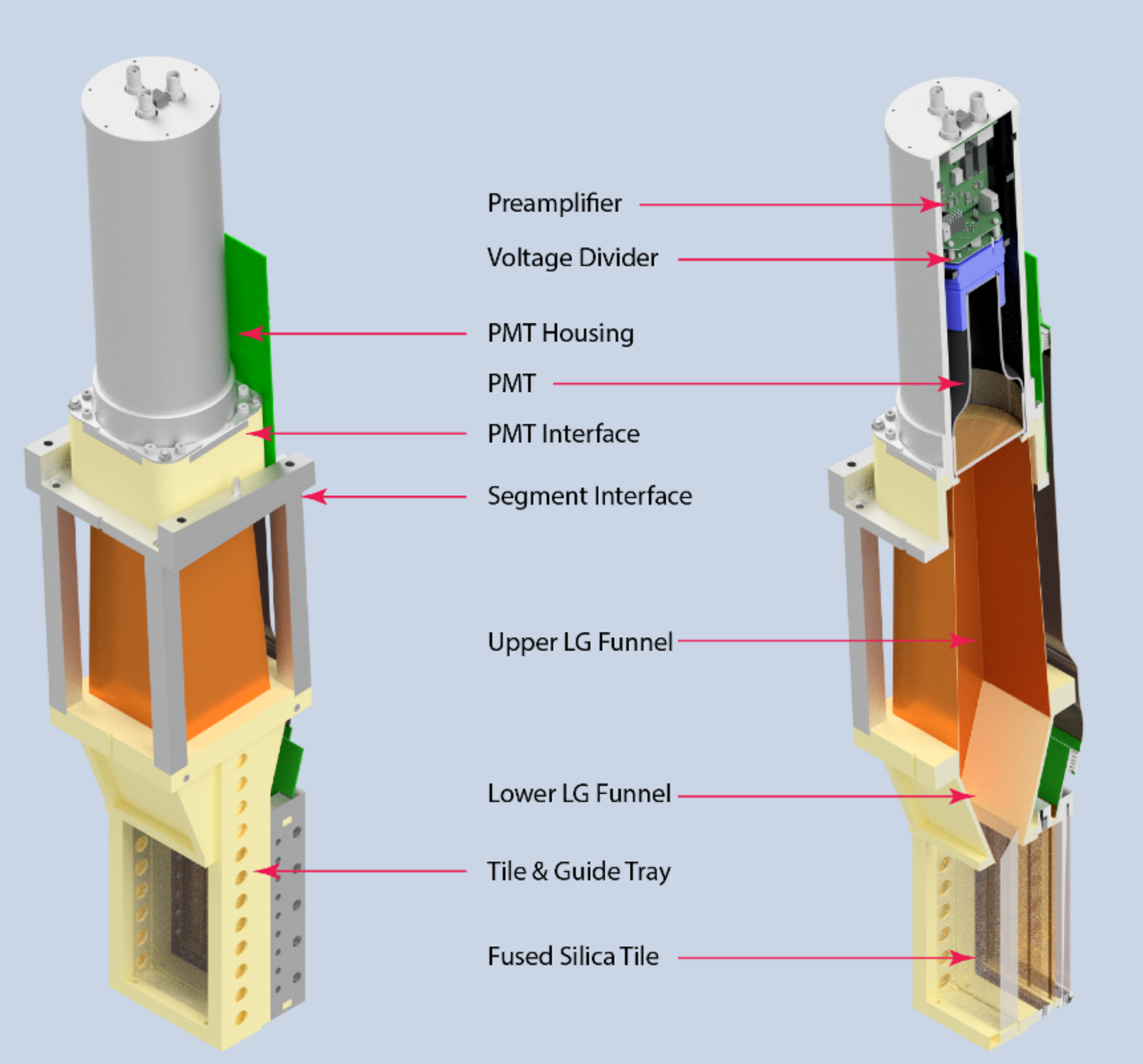


Integrating (current mode) detectors:

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

MOLLER Detection Overview





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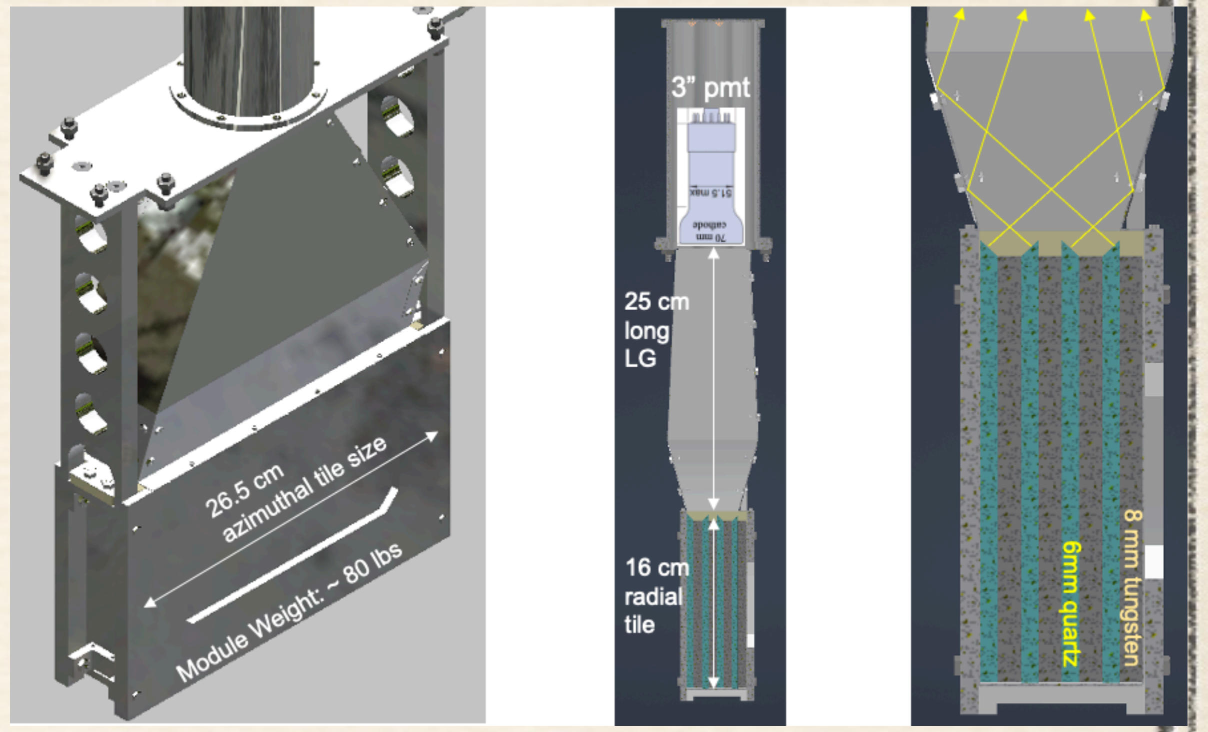
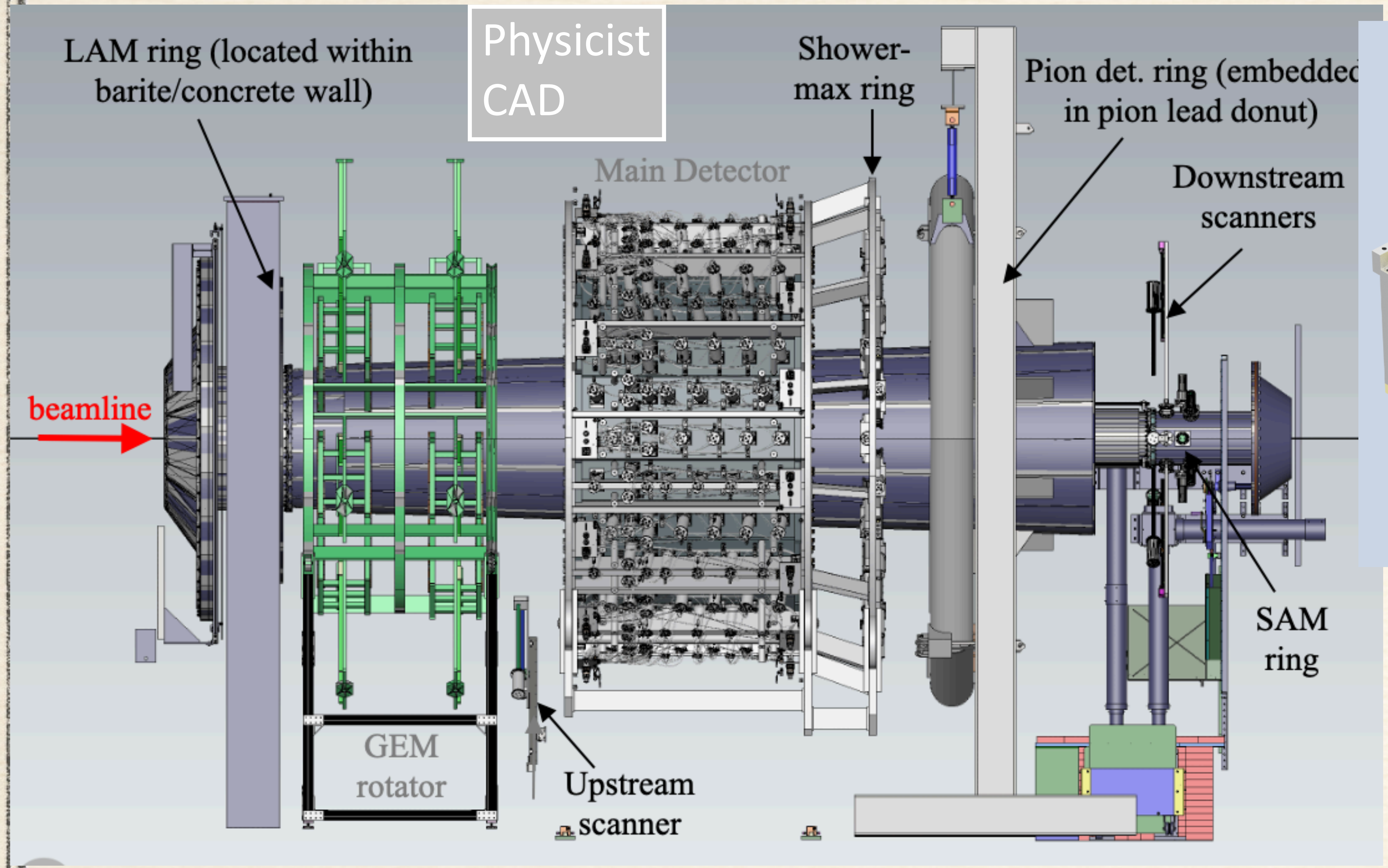


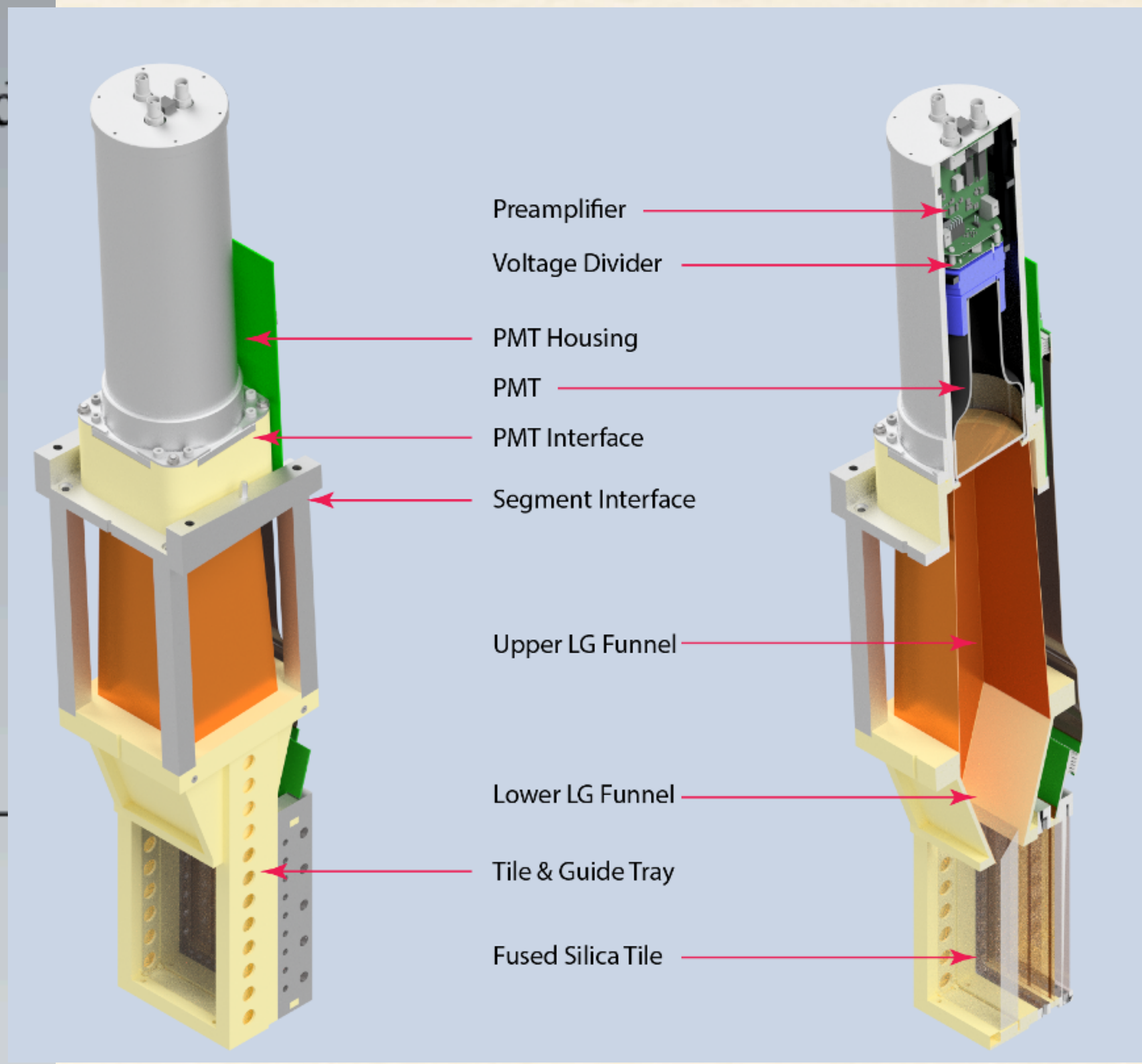
Integrating (current mode) detectors:
asymmetry measurements of both signal and background, and beam and target monitoring

Tracking (counting mode) detectors:
spectrometer calibration, electron scattering angle distribution, and background measurements

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

MOLLER Detection Overview





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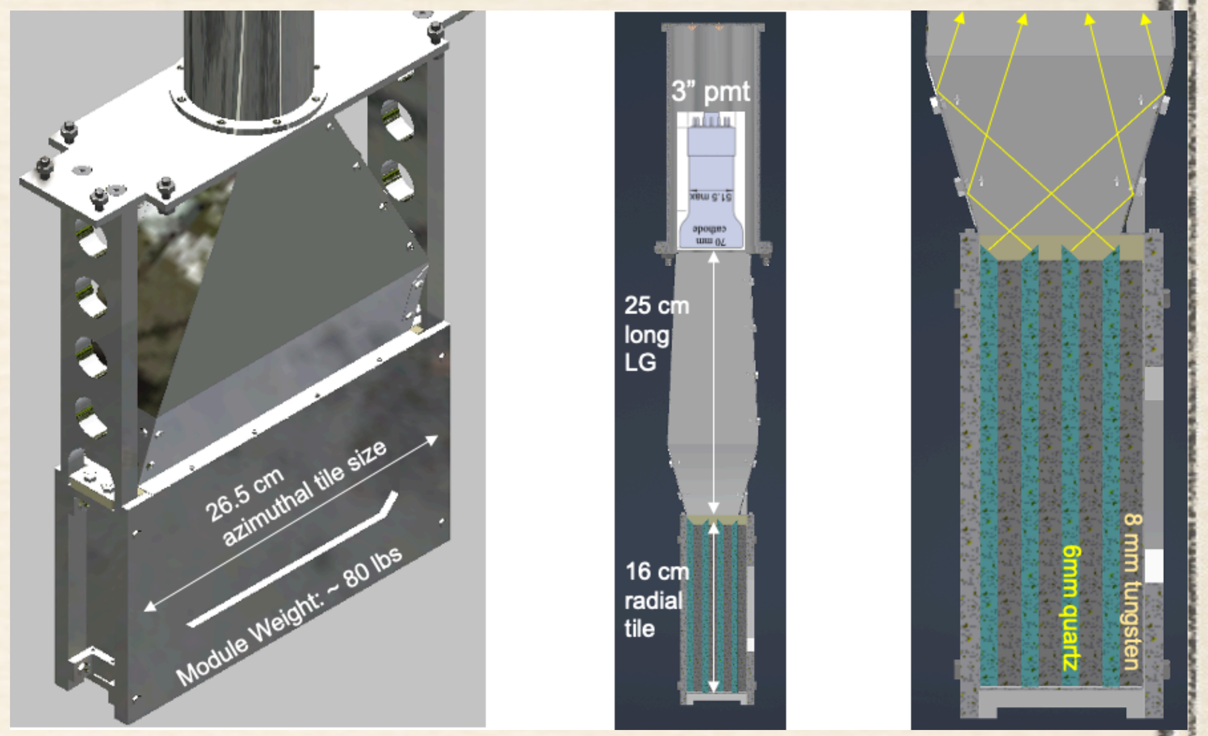

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Readout Electronics:

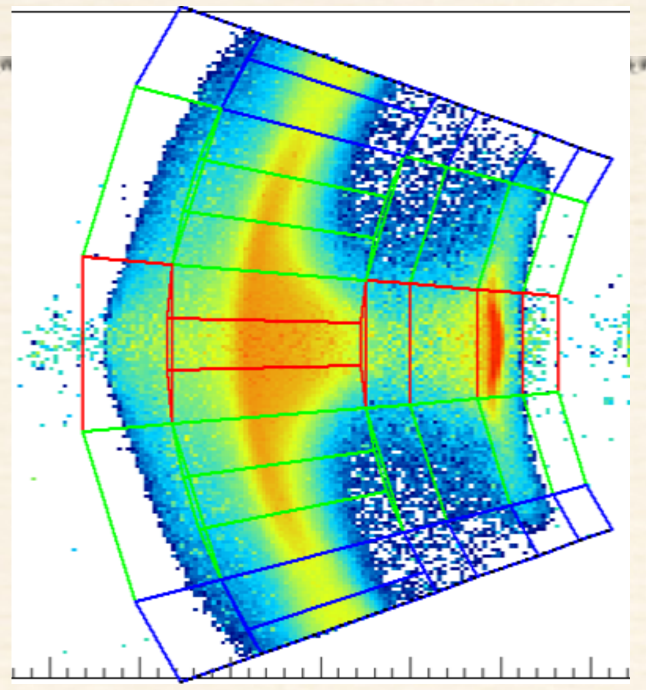
- Integration mode DAQ & trigger
  – *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  – *input rates between 10~kHz and 300~kHz*

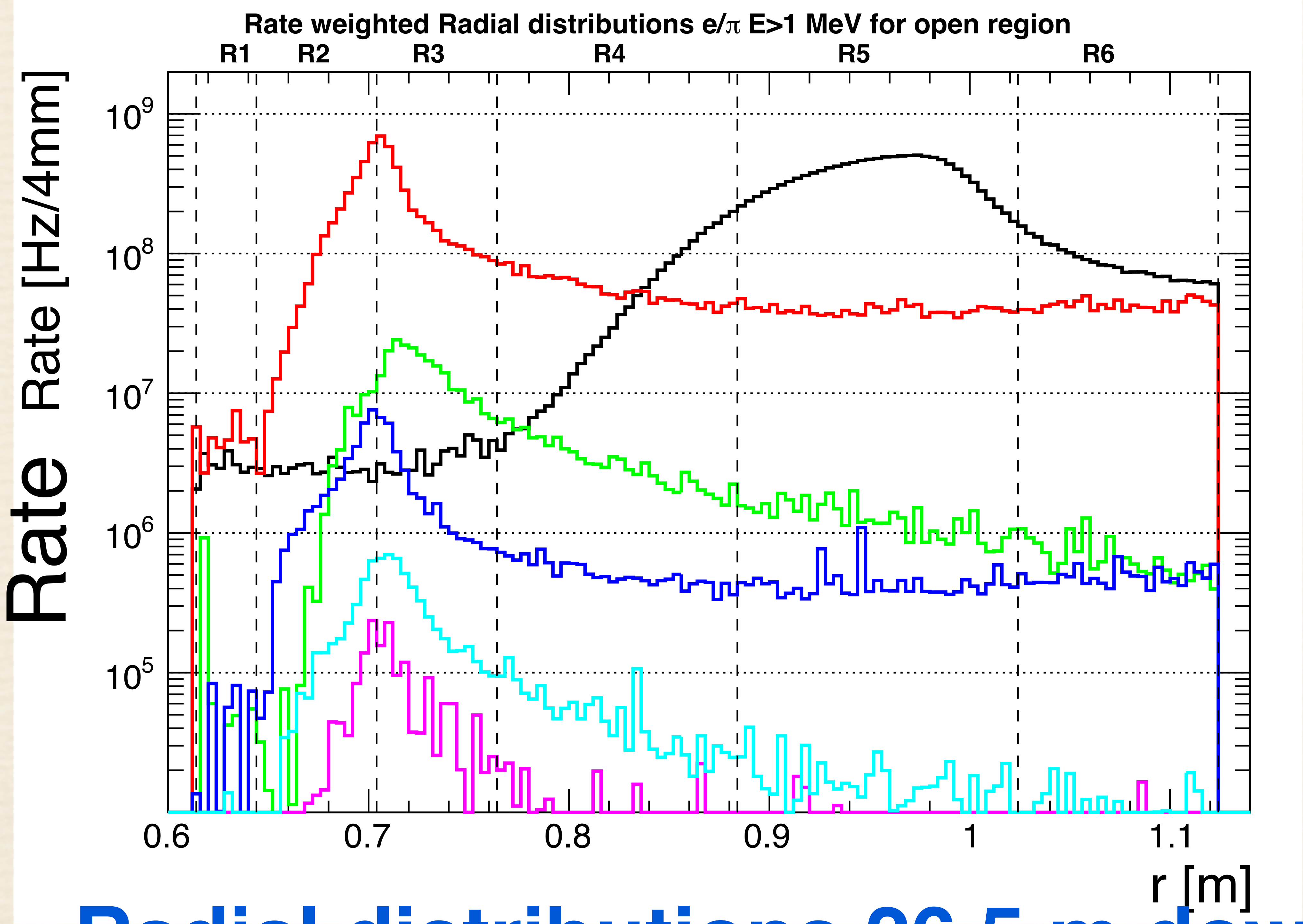
Lepton-Nucleus Topics

Extracting MOLLER Physics

Inclusive 11 GeV electron scattering off hydrogen

- ✦ 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





Radial distributions 26.5 m downstream of the liquid hydrogen target

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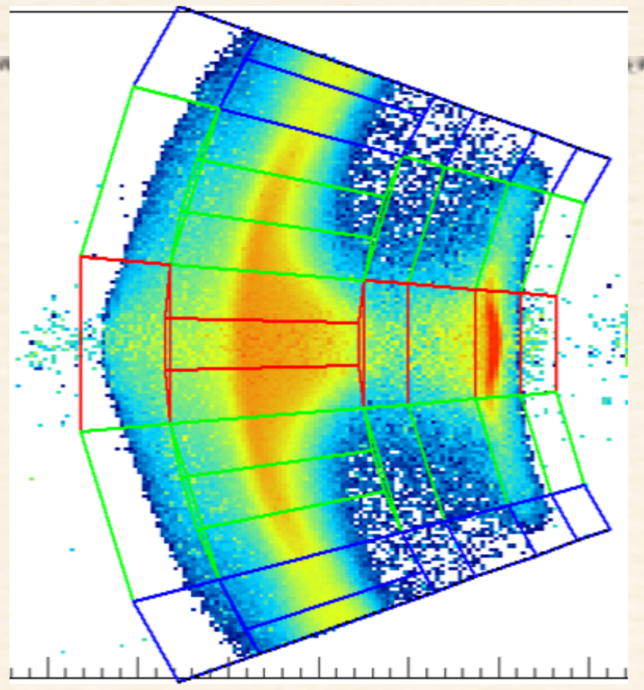
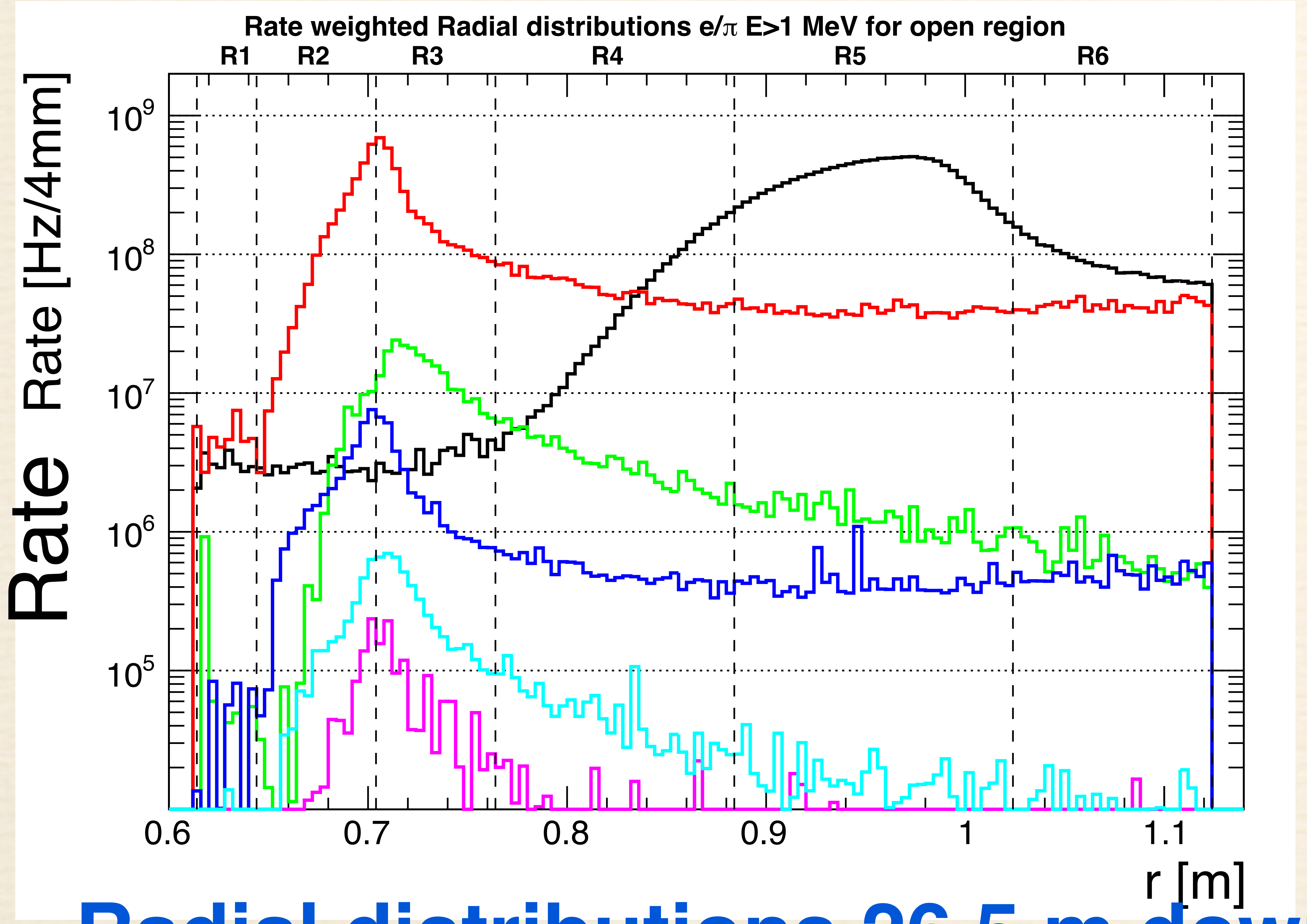
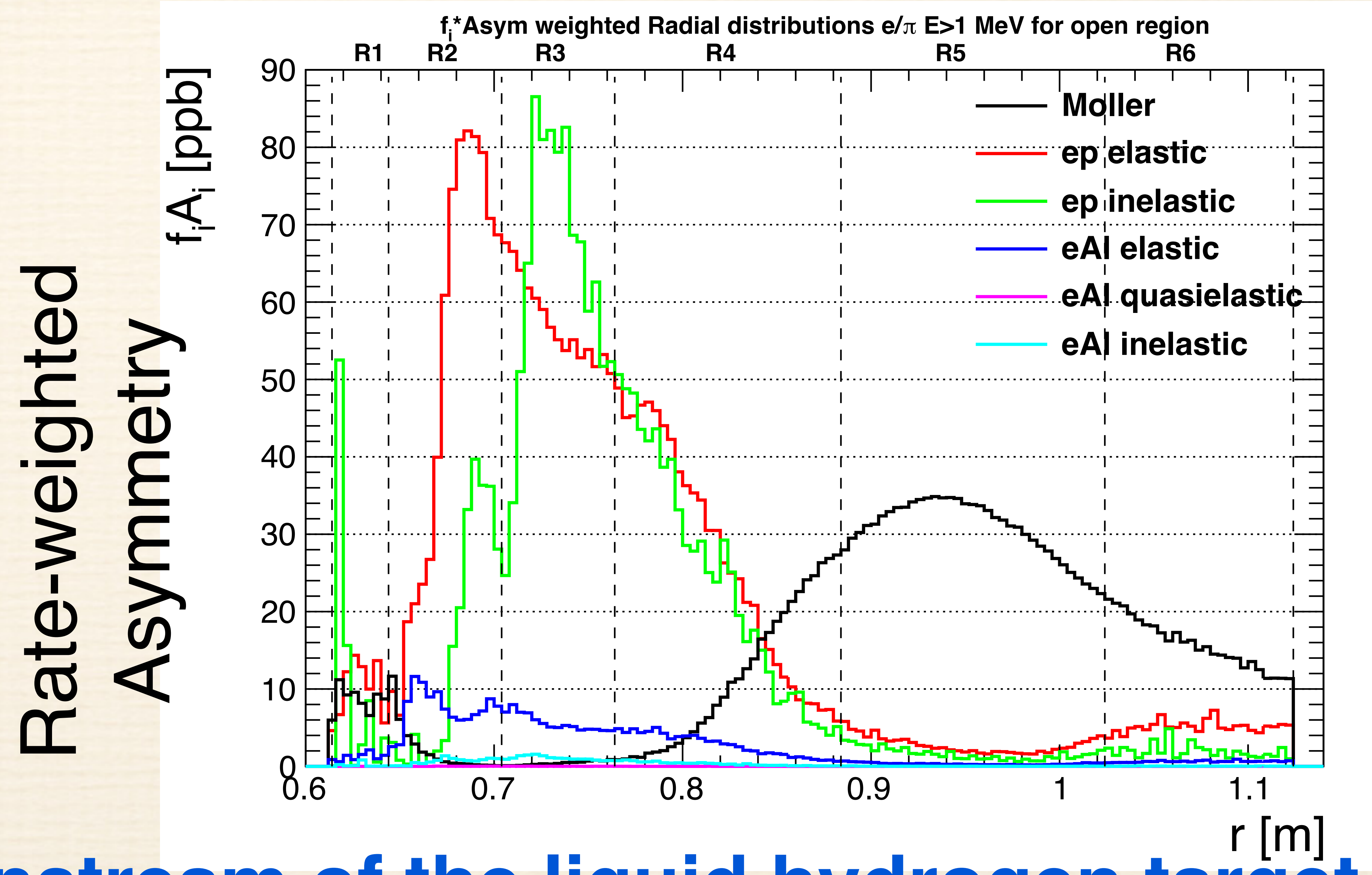


- 16 different tile asymmetries
- “Pre-subtract” Al and pion asymmetry contributions
- Simultaneous fit to 16 measurements with different contributions of e-e, e-p elastic, ep-inelastic
- Extract the “weak charge” for e-e, e-p elastic and inelastic e-p for 3 different W ranges





Radial distributions 26.5 m downstream of the liquid hydrogen target

PV Electron-Proton Inelastic Scattering

Deep inelastic scattering

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

first principles: using electroweak neutral current structure functions

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

At high Q^2, one can use quark pdf's and standard model couplings. At forward angles, the prediction is $A_{PV}/Q^2 \sim 8.5 \times 10^{-5}$. However, for very low Q^2, one needs a model as a function of W.

MOLLER kinematics:	**E_{beam} = 11 GeV, $6 < \theta_{lab} < 20$ mrad, E' = 3 to 8 GeV** **$Q^2 \sim$ 0.001 - 0.02 GeV^2, W^2 from 1 to 20 GeV^2**	**Diffractive Regime (VMD or Pomeron Physics)**

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Assumption: A_{PV}/Q^2 ~ F(W) is constant in 3 W regions

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Mock Fit Extraction with Monte Carlo Trial Data Fit

Processes	Expected A (ppb)	σ_A (ppb)	$\frac{\sigma_A}{\|A\|}$ (%)
Moller	-35.20	0.64	1.8
ep-elastic	-19.67	1.82	9.2
ep-inelastic (1)	-439.94	80.6	18.3
ep-inelastic (2)	-433.96	38.3	8.8
ep-inelastic (3)	-384.59	91.5	23.8
eAl-elastic	297.27	83.01	27.9

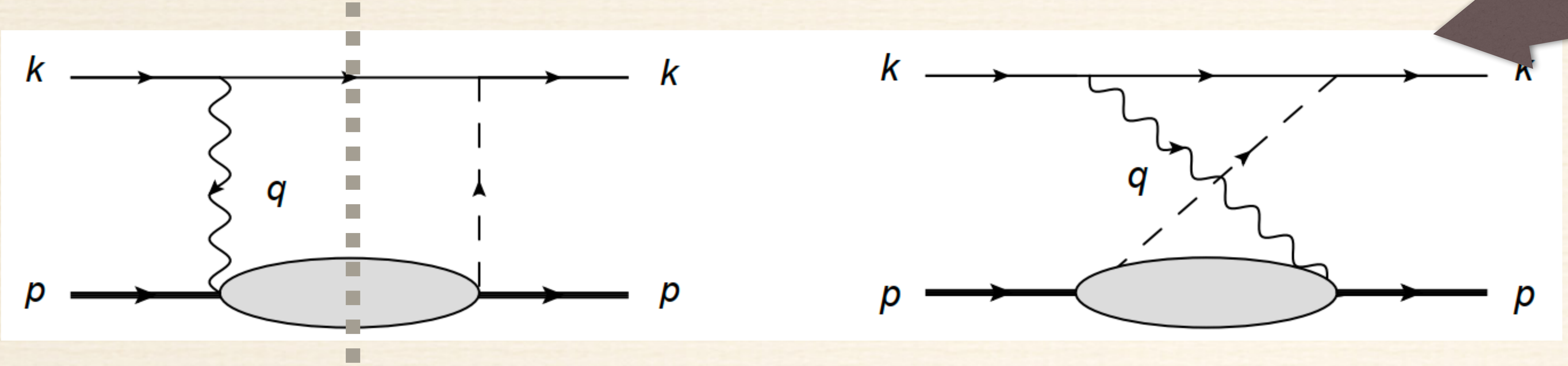
Corrections for Ring-5 Tiles after Fit Extraction

Process	Correction (%)	Systematic Error (%)
e-p elastic	1.14	0.08
e-p inelastic ($W < 1.4$ GeV)	-1.34	0.22
e-p inelastic ($1.4 < W < 2.5$ GeV)	-1.54	0.11
e-p inelastic ($W > 2.5$ GeV)	-1.66	0.35
e-Al elastic	0.87	0.09
e-Al other	< 0.10	< 0.10

The Box Diagram Connection

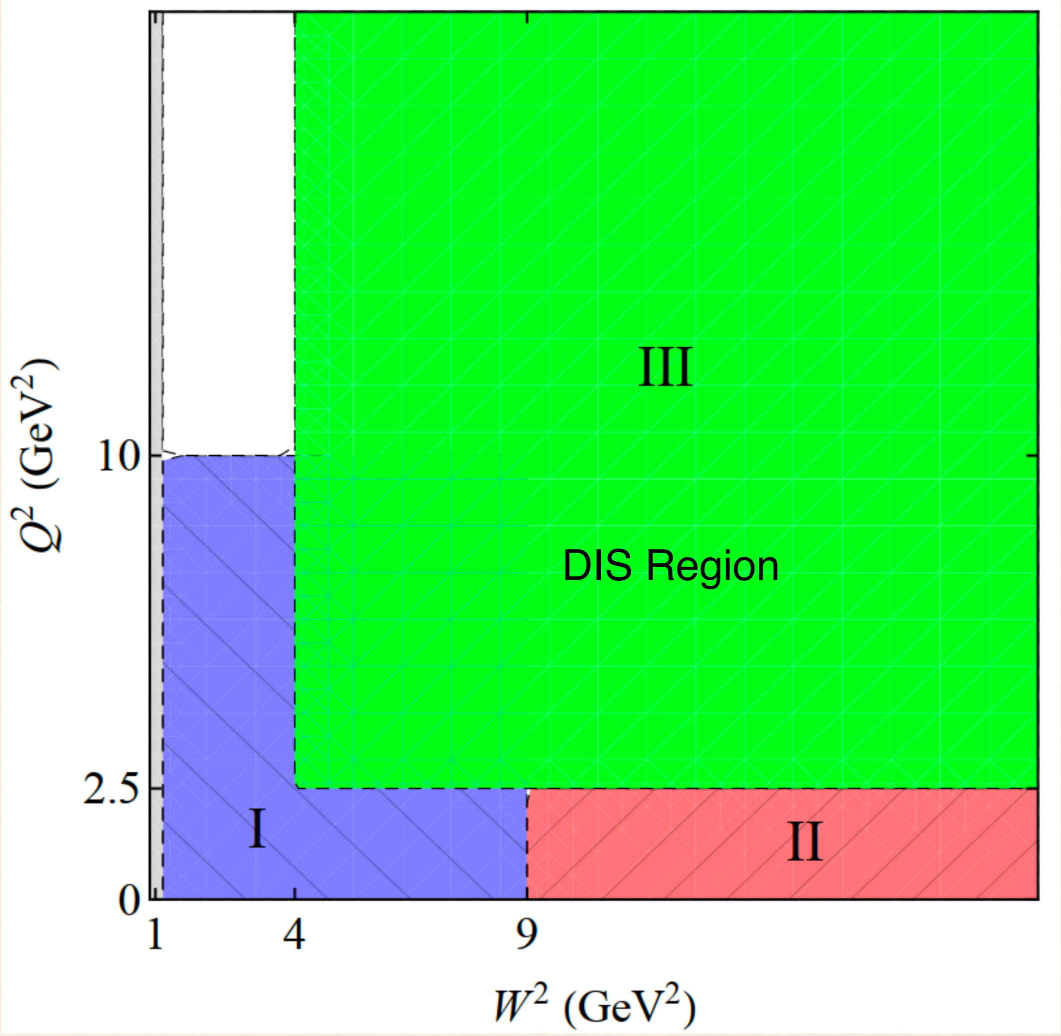
Radiative corrections to the theoretical prediction of the weak charge of the proton

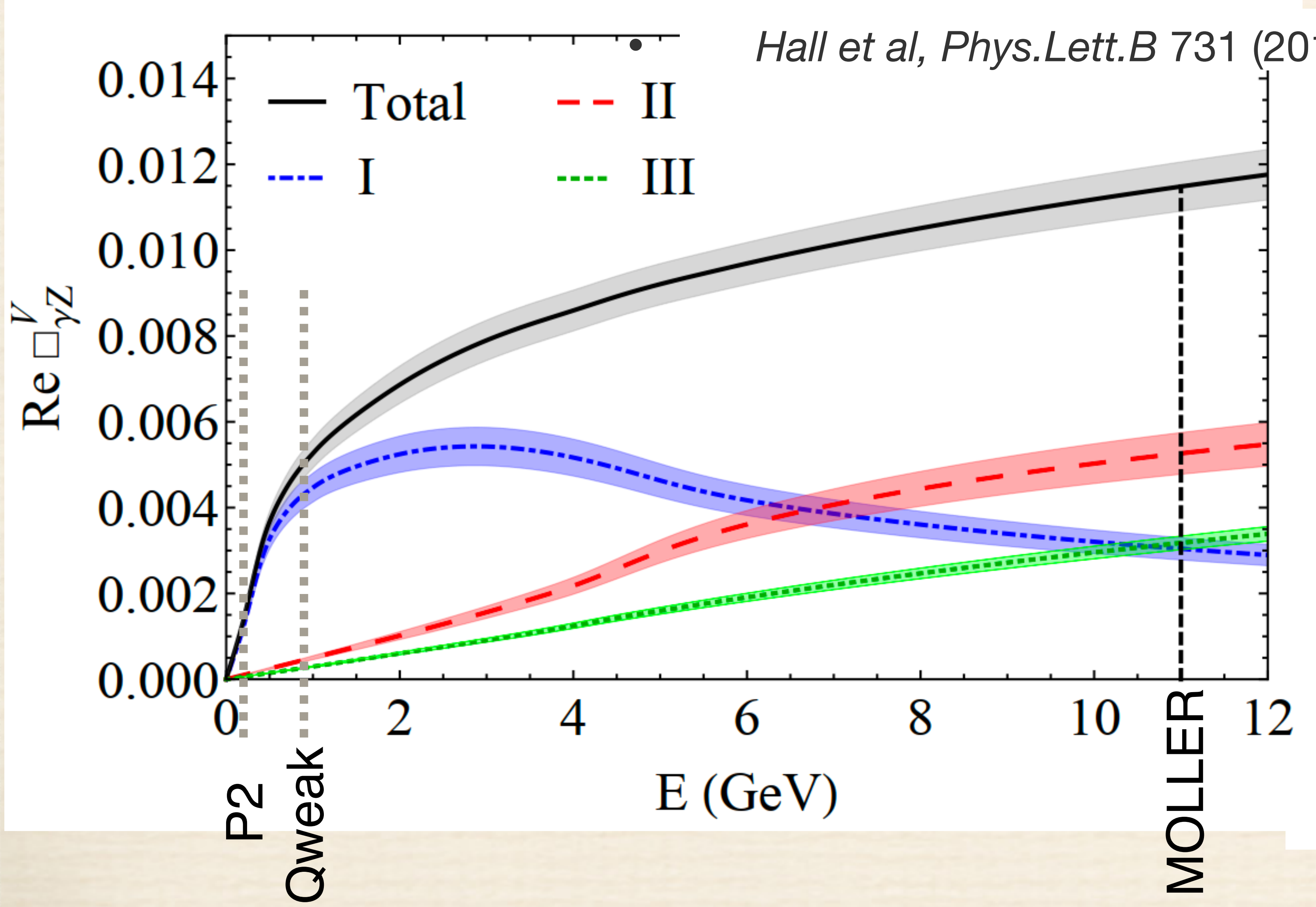
$$Q_W^p = (1 + \Delta\rho + \Delta_e)\left(1 - 4\sin^2\theta_W(0) + \Delta_e'\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$$



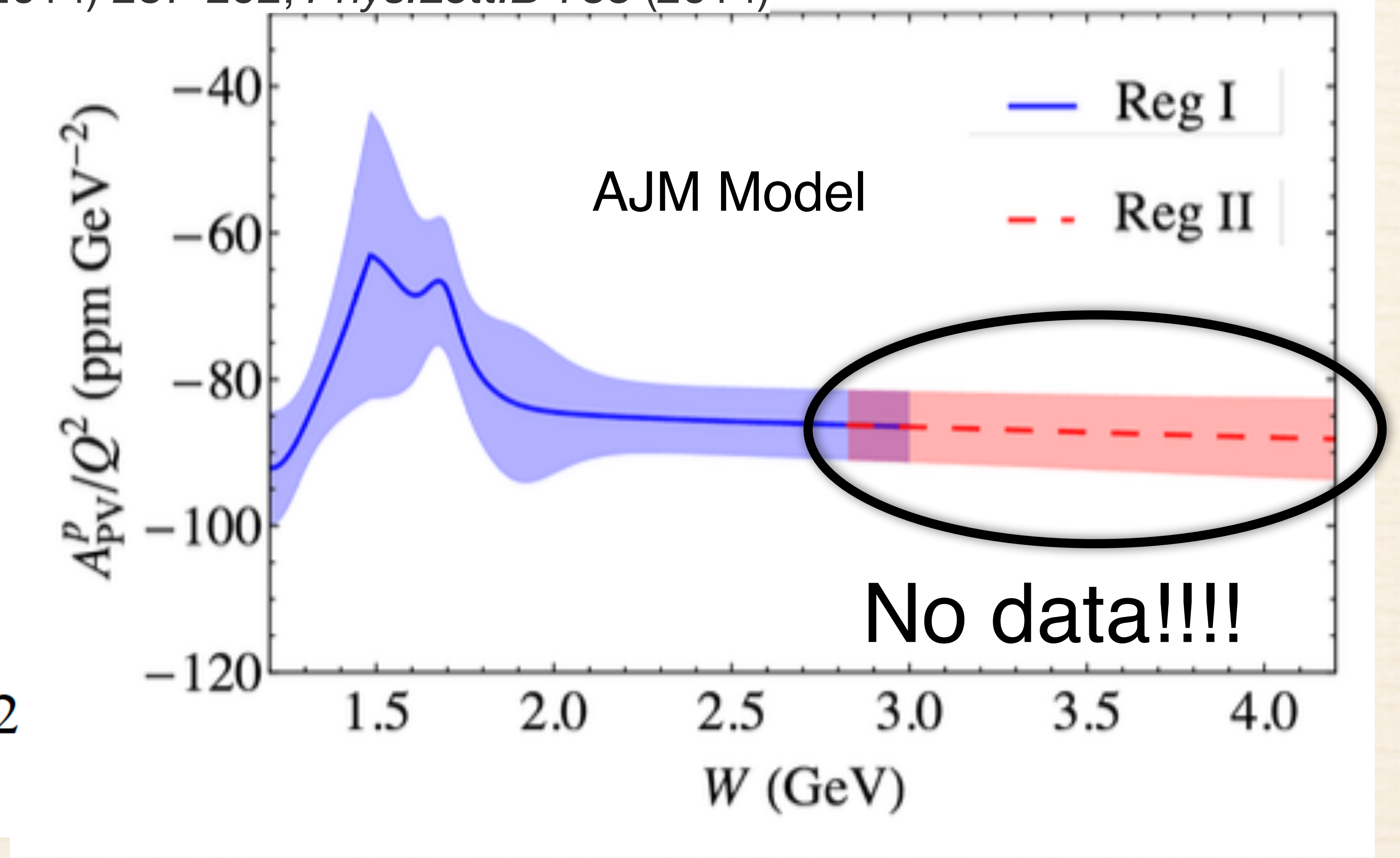
$F_{1,2}^{\gamma Z}(Q^2, W^2)$

In 3 different kinematic regimes





Hall et al, Phys.Lett.B 731 (2014) 287-292, *Phys.Lett.B* 733 (2014)



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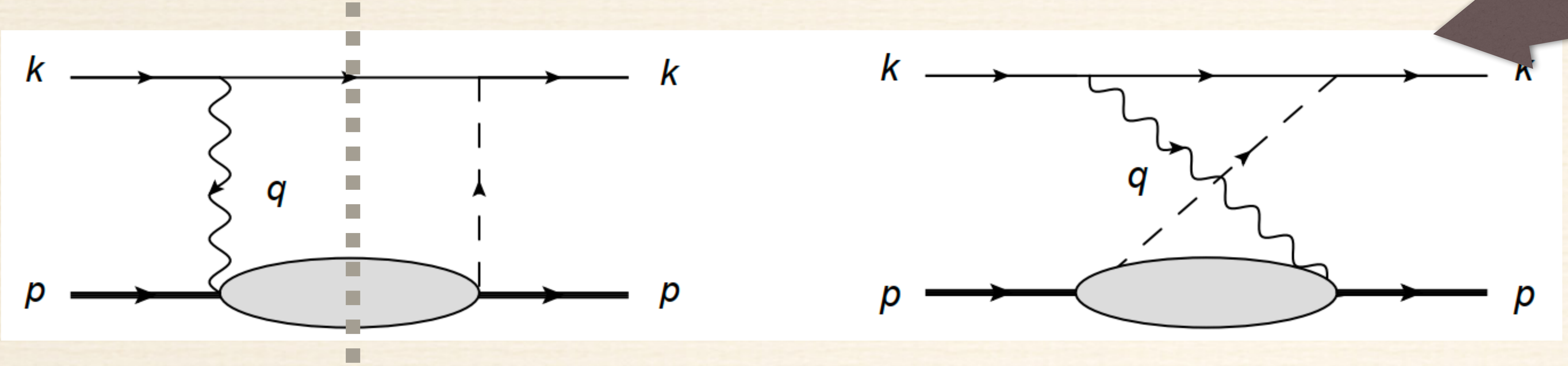

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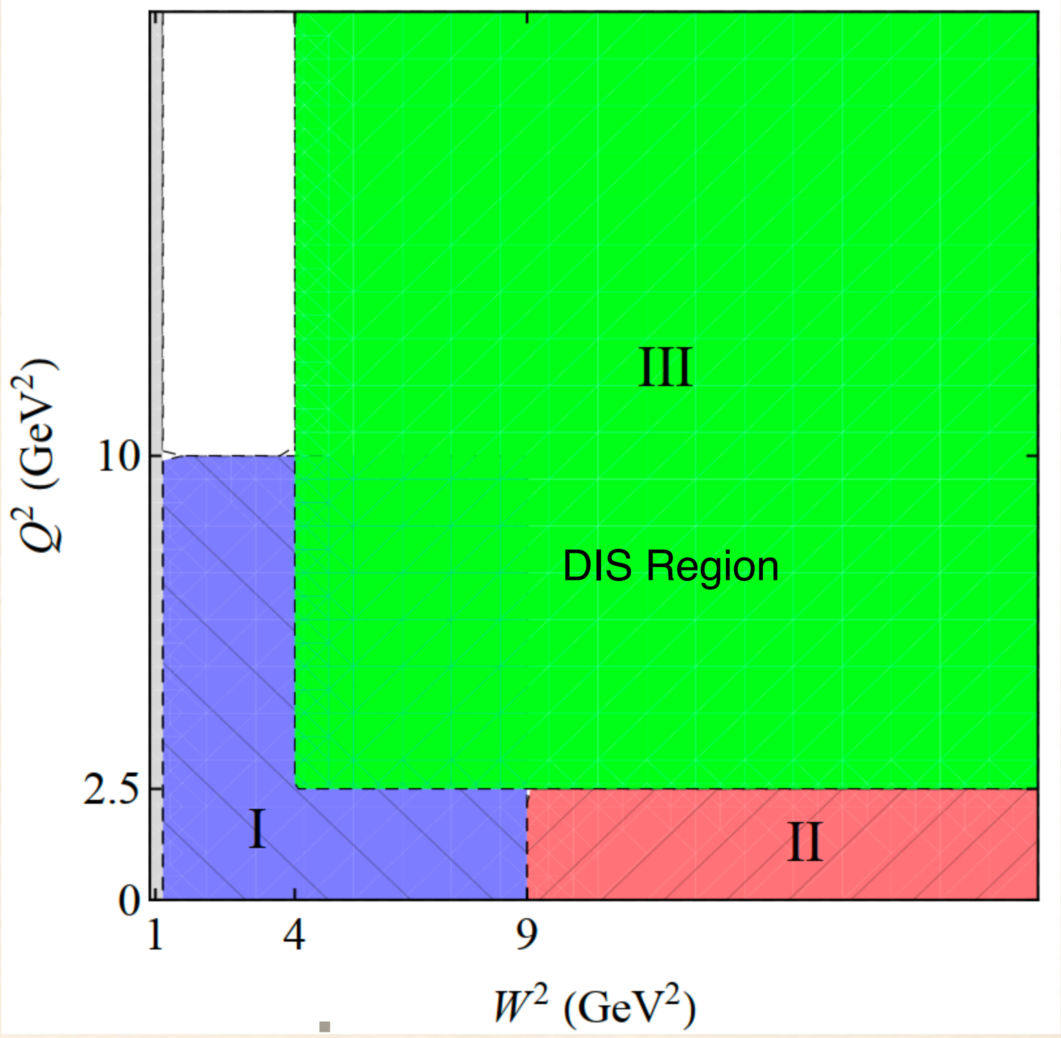

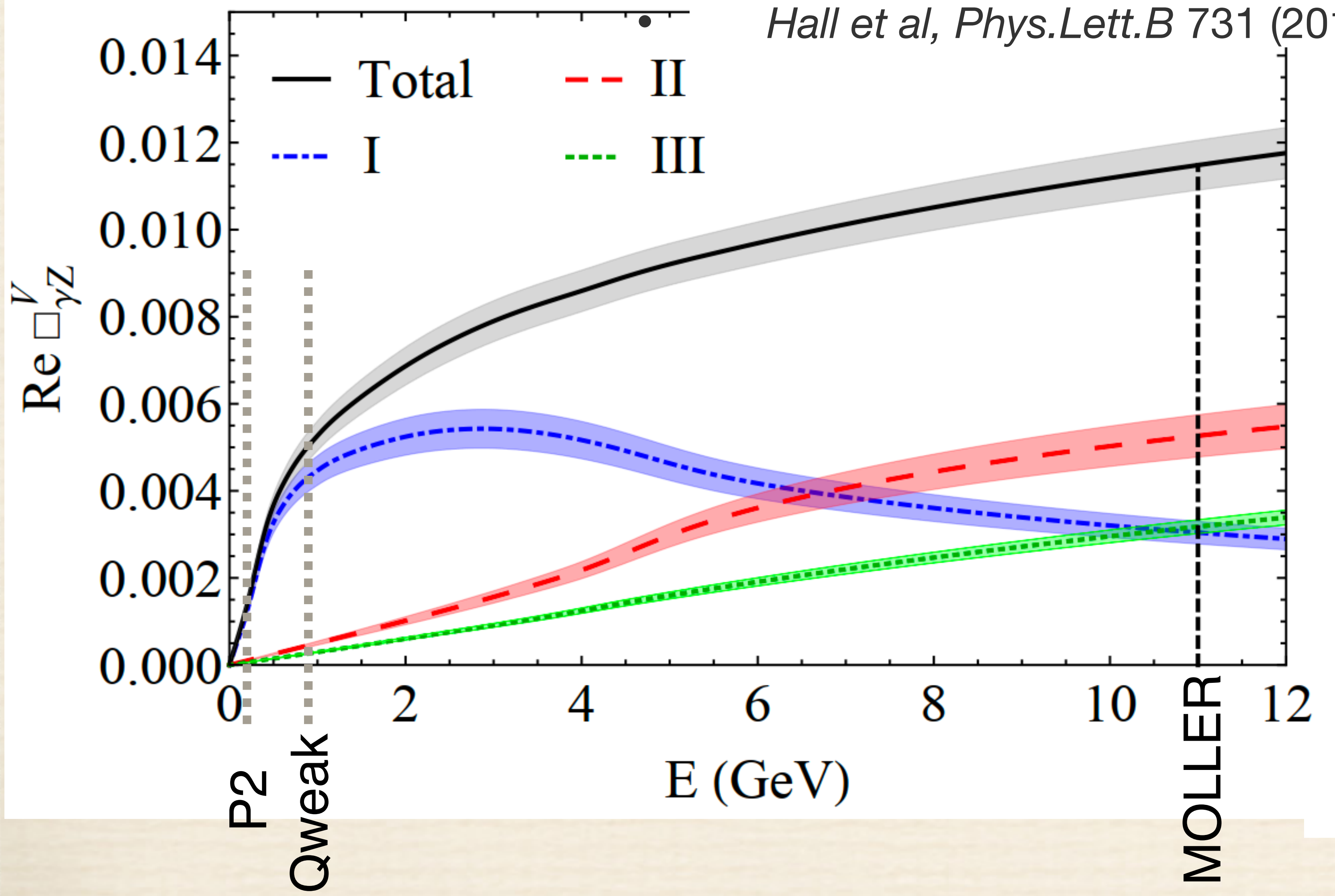

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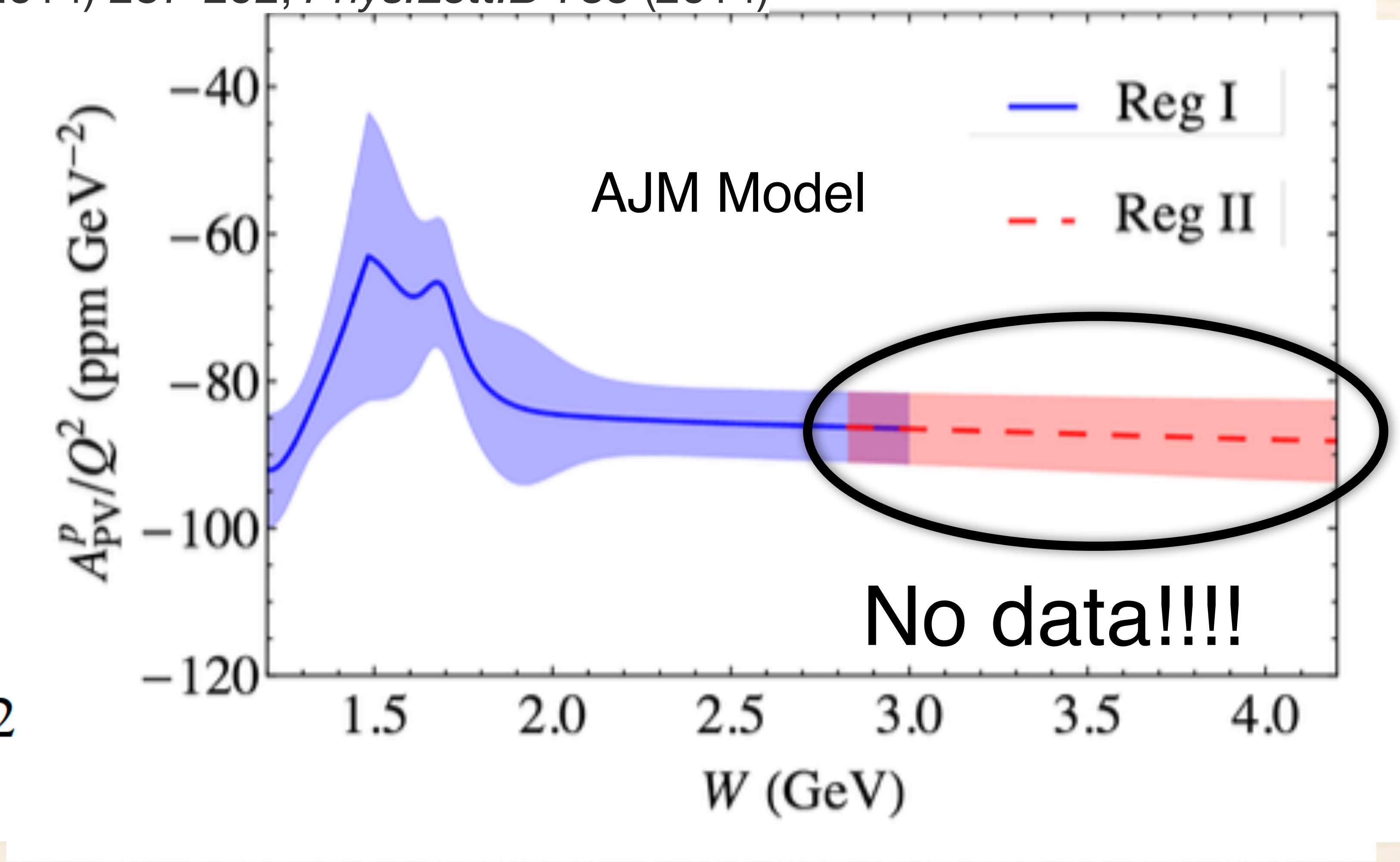

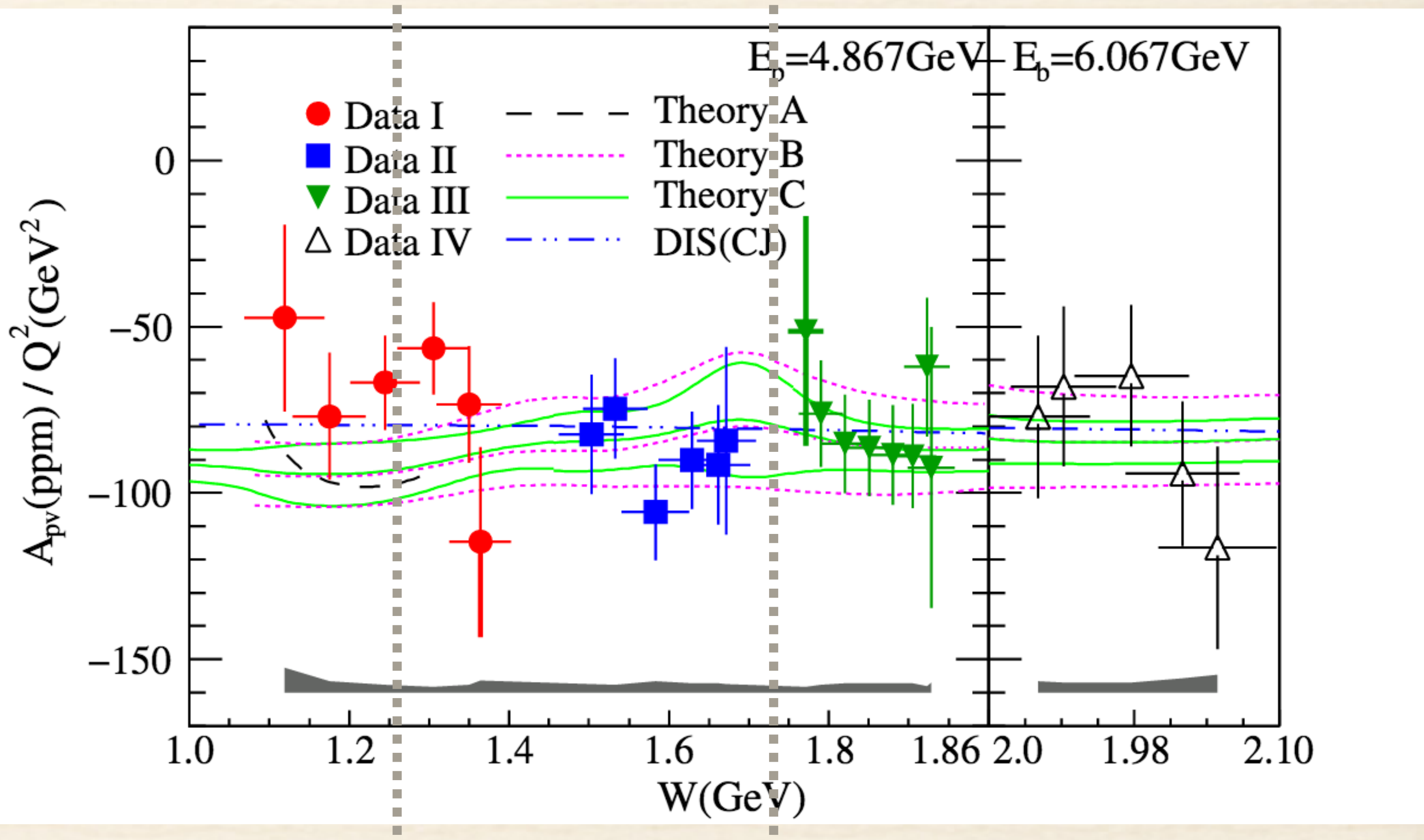

Matsui et al, Gorschein et al, AJM, CJ, compared to PVDIS measurements

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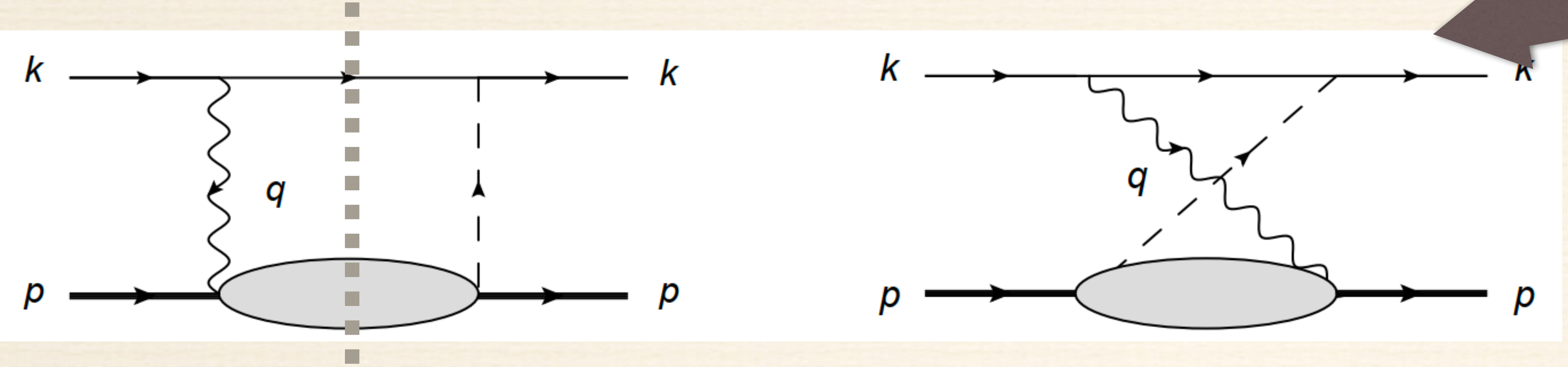

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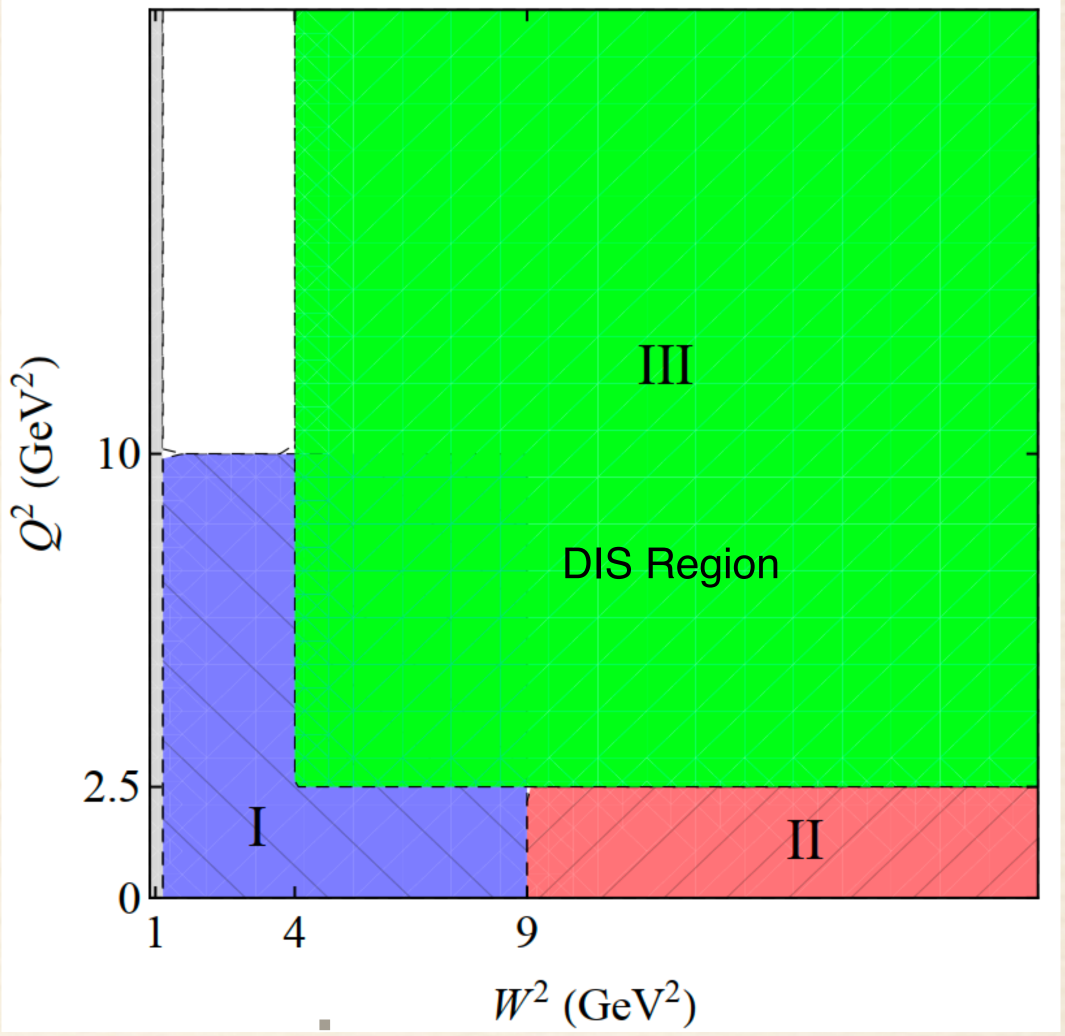

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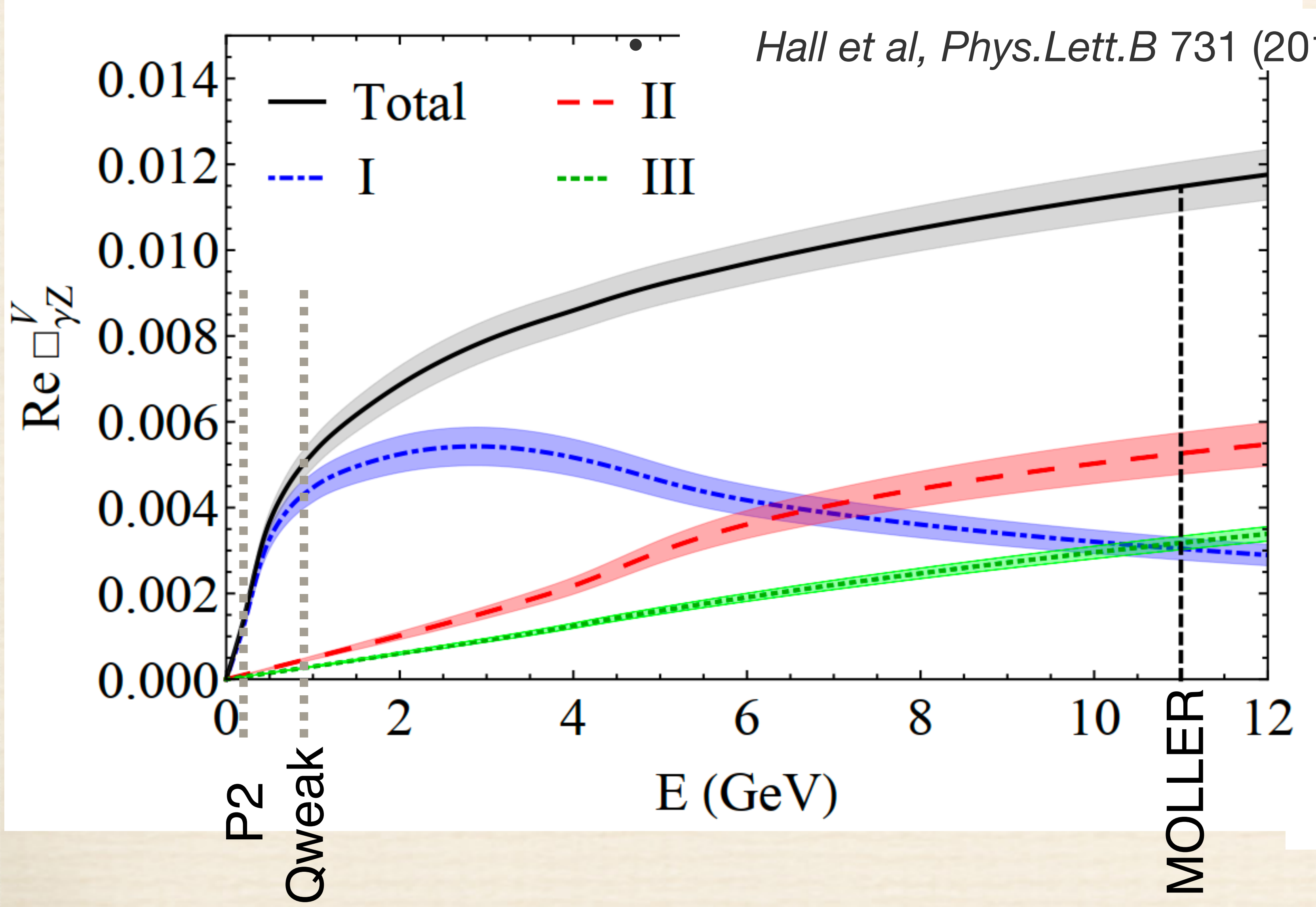
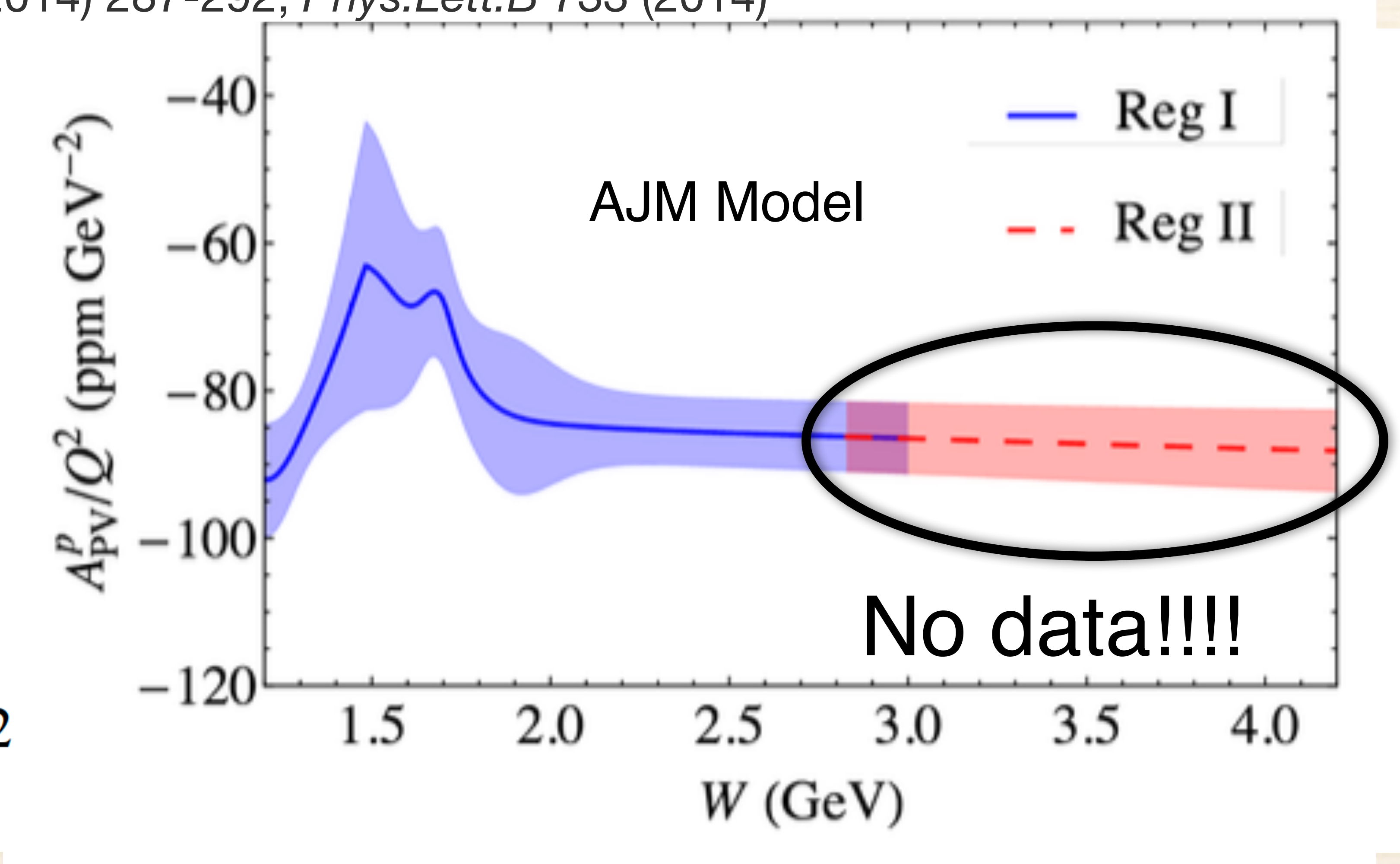
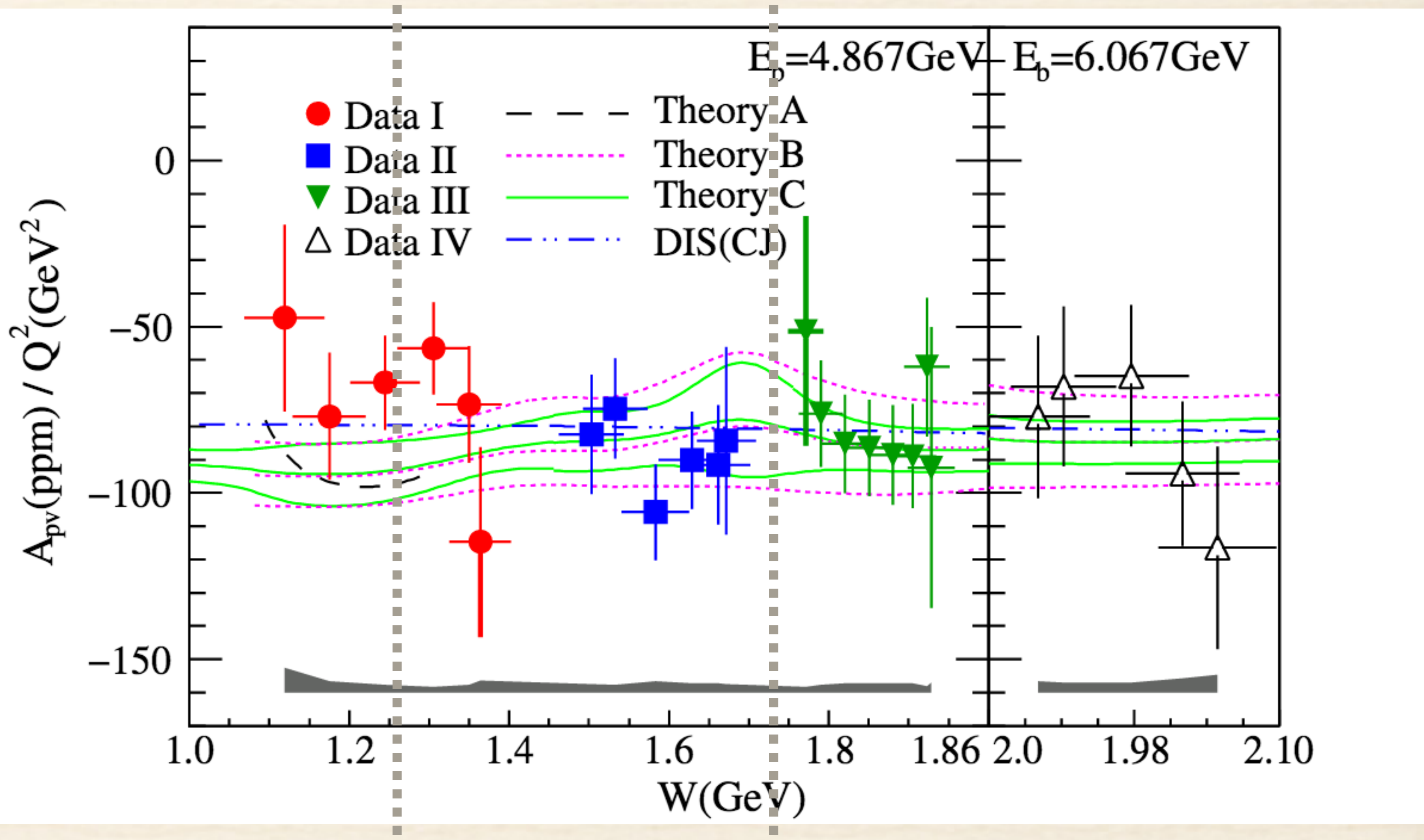


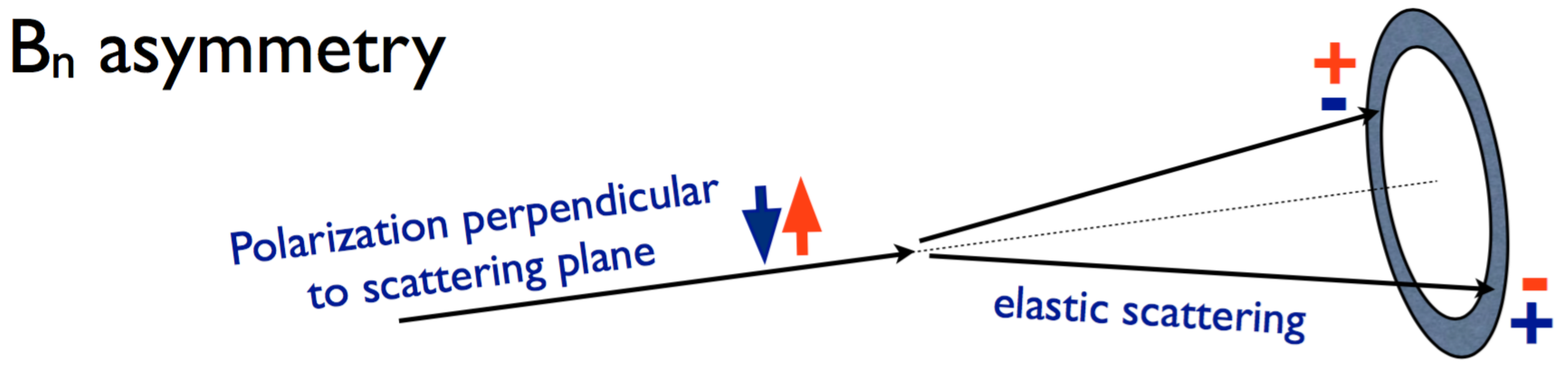




Matsui et al, Gorschein et al, AJM, CJ, compared to PVDIS measurements

There is no data on $F_1^{\gamma Z}$ in Region II! MOLLER will make the first ever measurement!

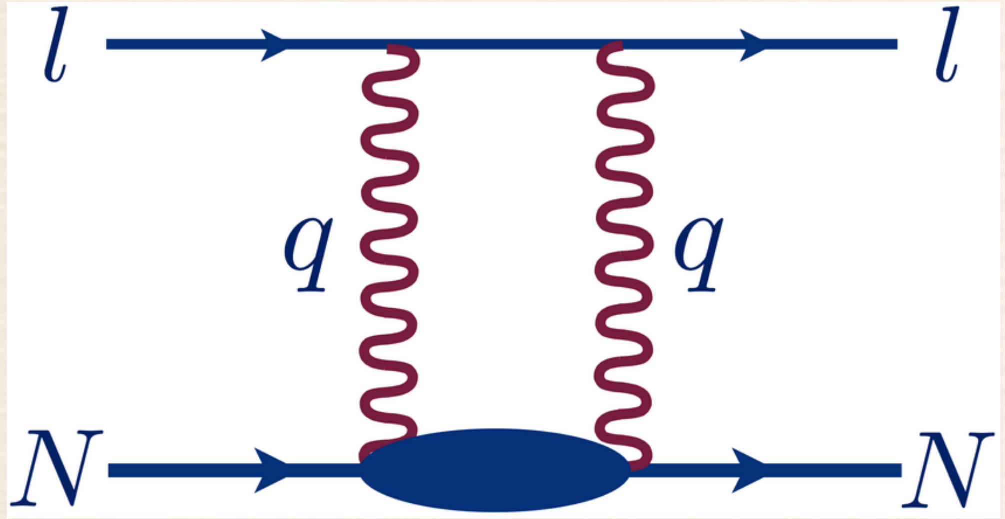
PREX/CREX B_n Measurements on Nuclei



- The asymmetry arises from two-photon exchange. A single-photon exchange contribution vanishes under time-reversal symmetry.

$$A(\phi) = A_n(\theta,\ E_{beam}) P_n \cos(\phi)$$

$$A_n = \frac{2A_{Born}\mathcal{I}(A^*_{2\gamma})}{|A_{Born}|^2}$$



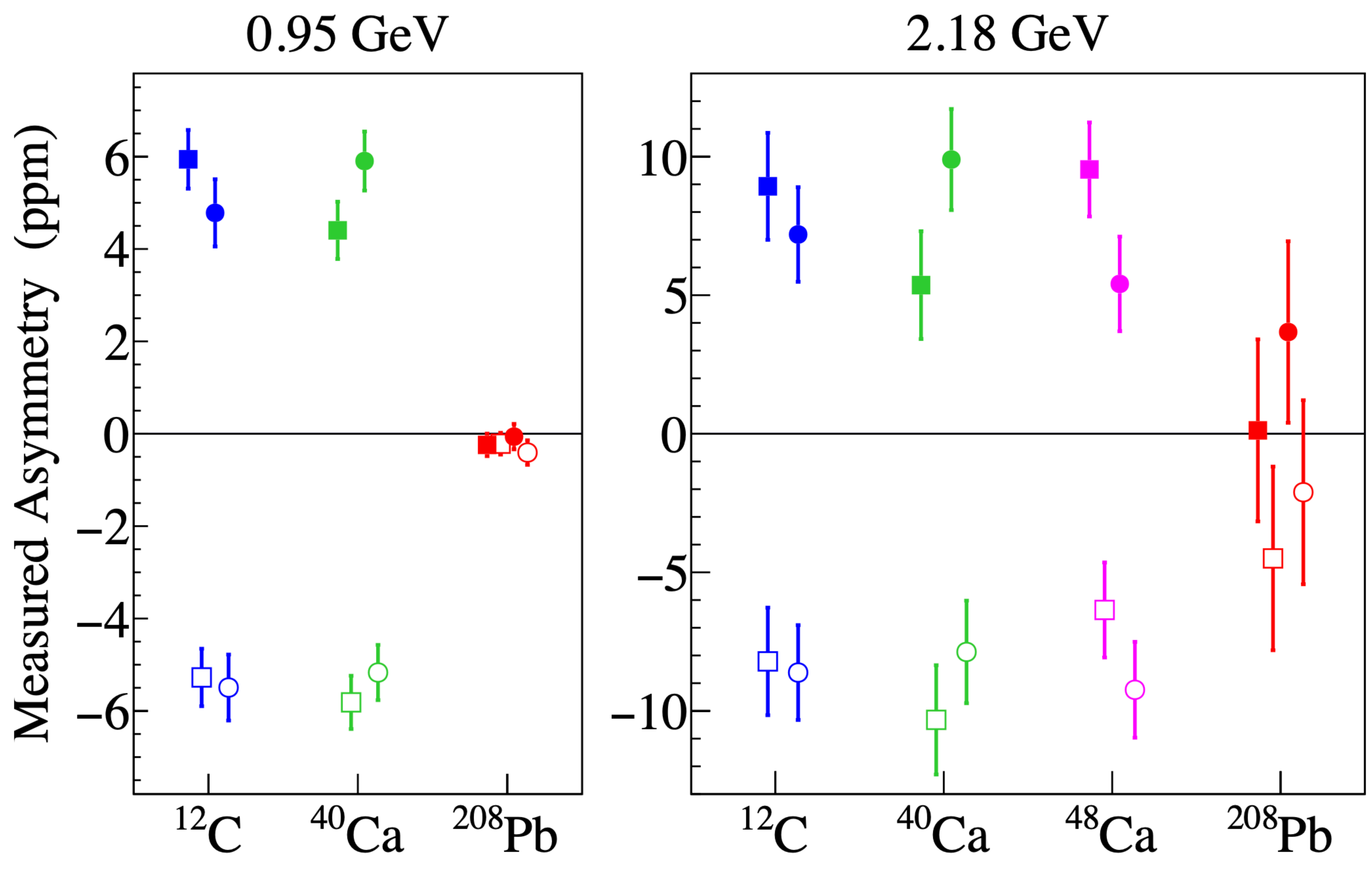
Two-Photon Exchange (TPE)

Asymmetry is very small

$$B_n \sim \alpha_{\rm em}\frac{m_e}{E_e} \sim 10^{-6} - 10^{-5}$$

2-photon

ultra-relativistic



- ✦ **High Beam Energy**
- ✦ **Very Forward Angle**
- ✦ **Clean Separation of Inelastics**
- ✦ **Tremendous Statistics**

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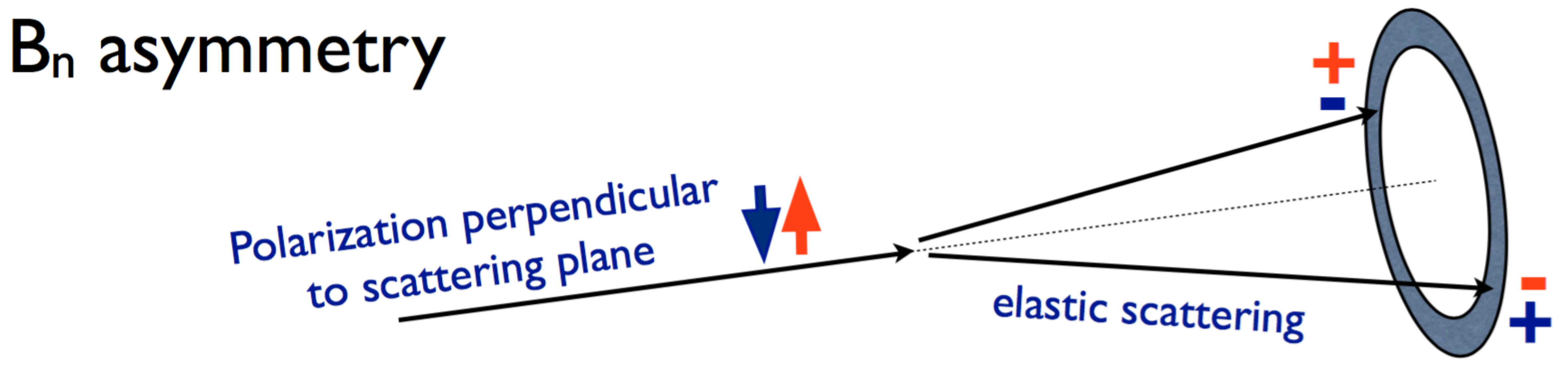

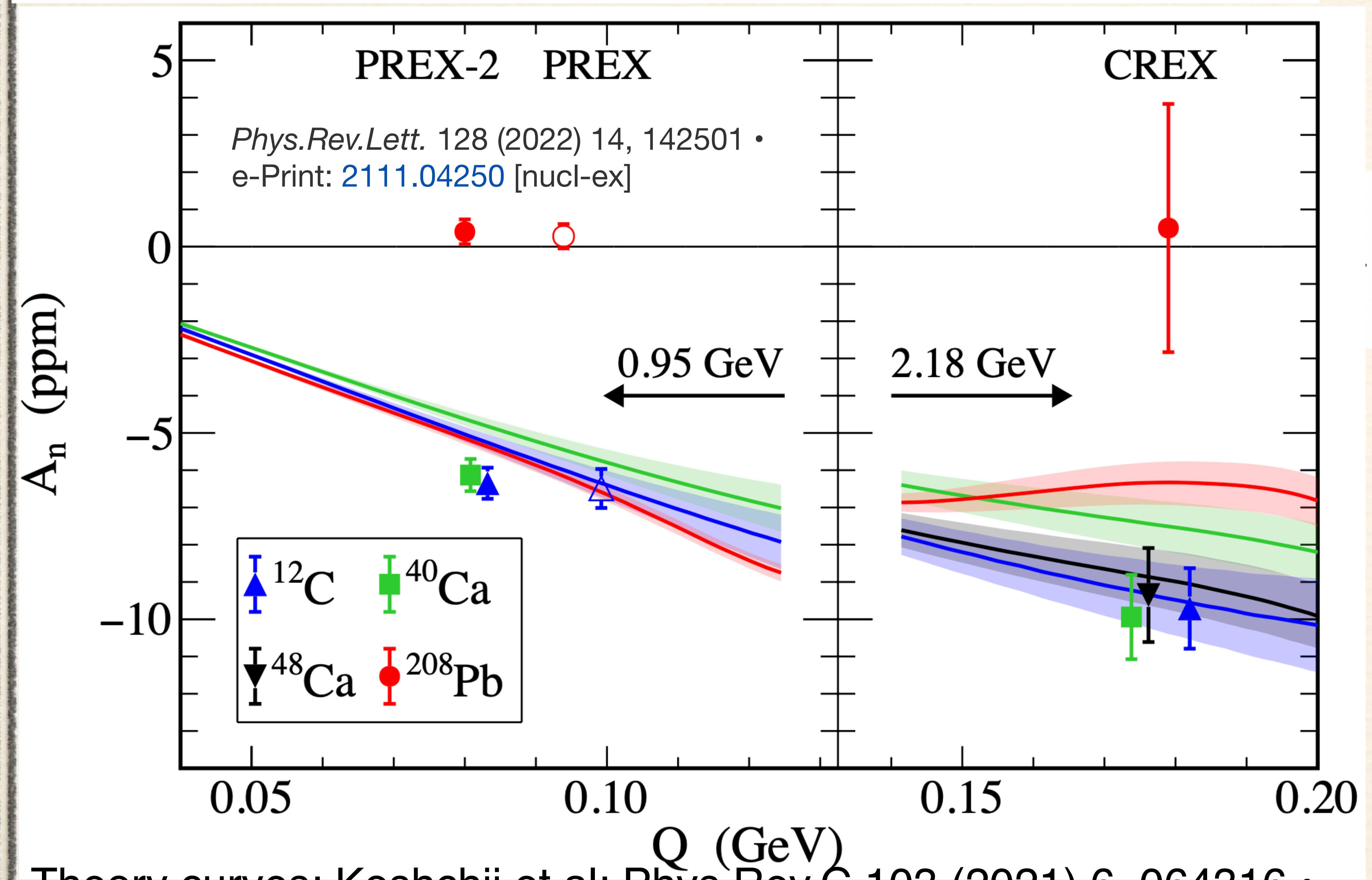

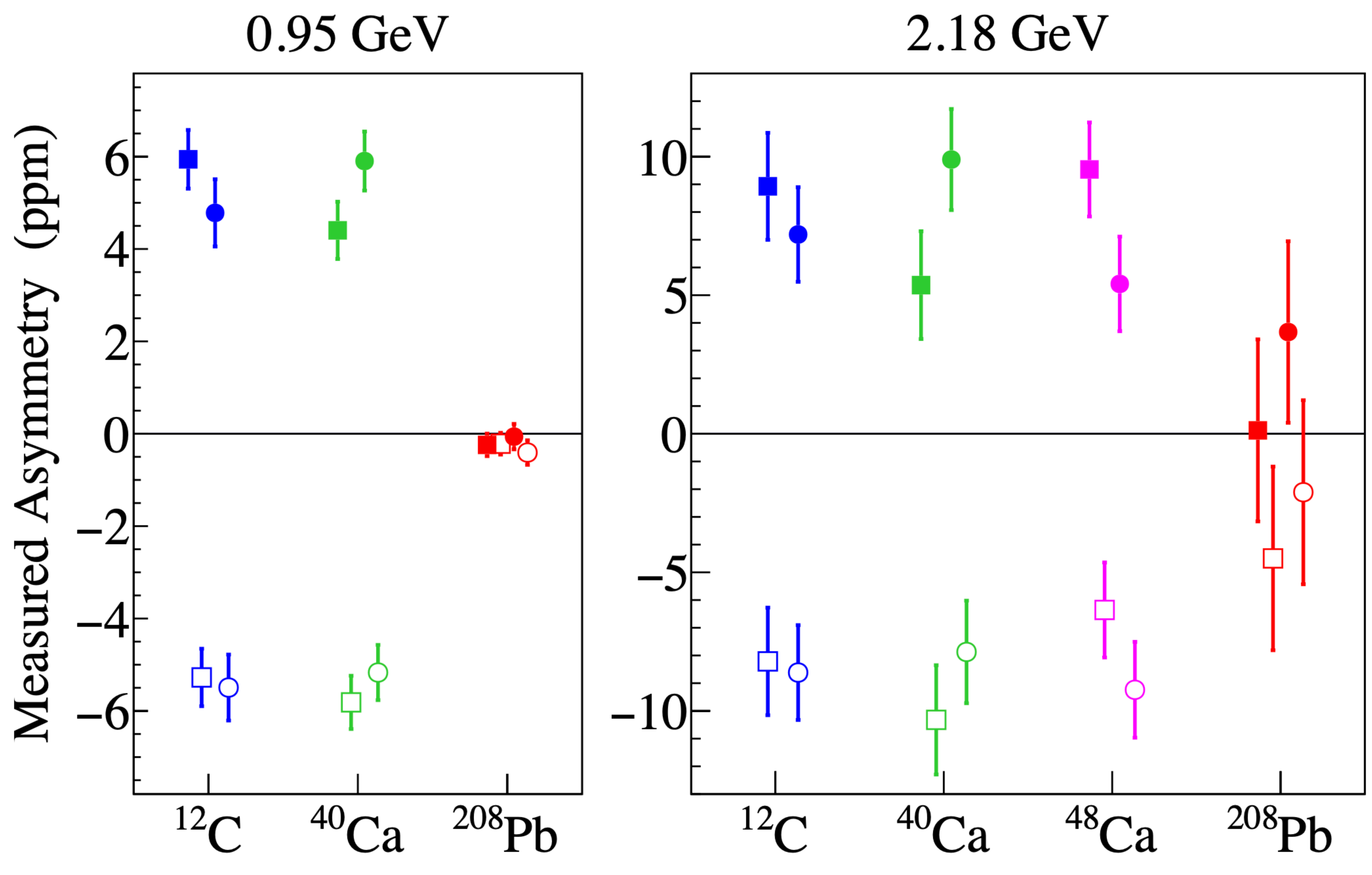

Theory curves: Koshchii et al: Phys.Rev.C 103 (2021) 6, 064316 •
e-Print: 2102.11809 • DOI: 10.1103/PhysRevC.103.064316

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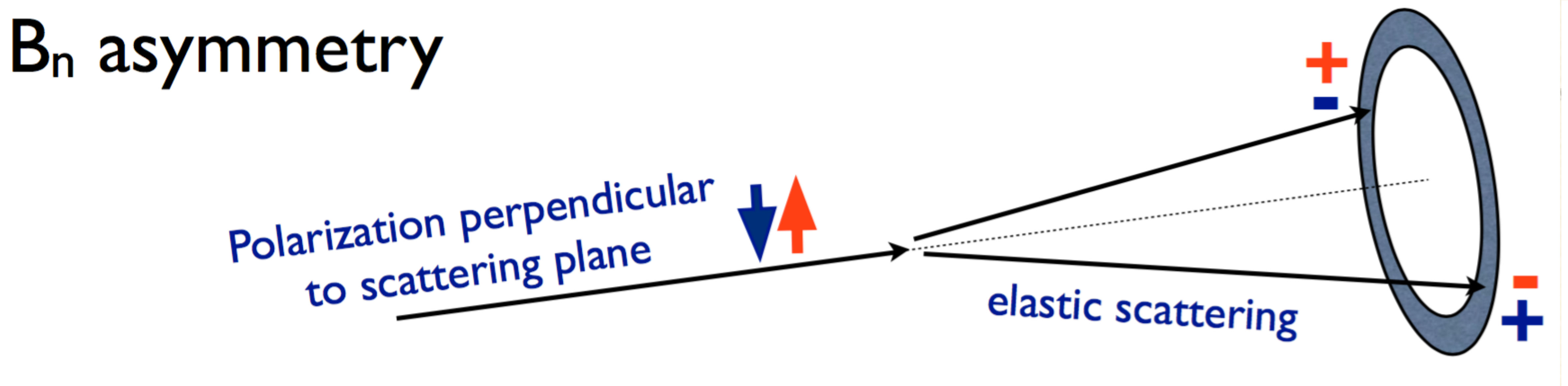

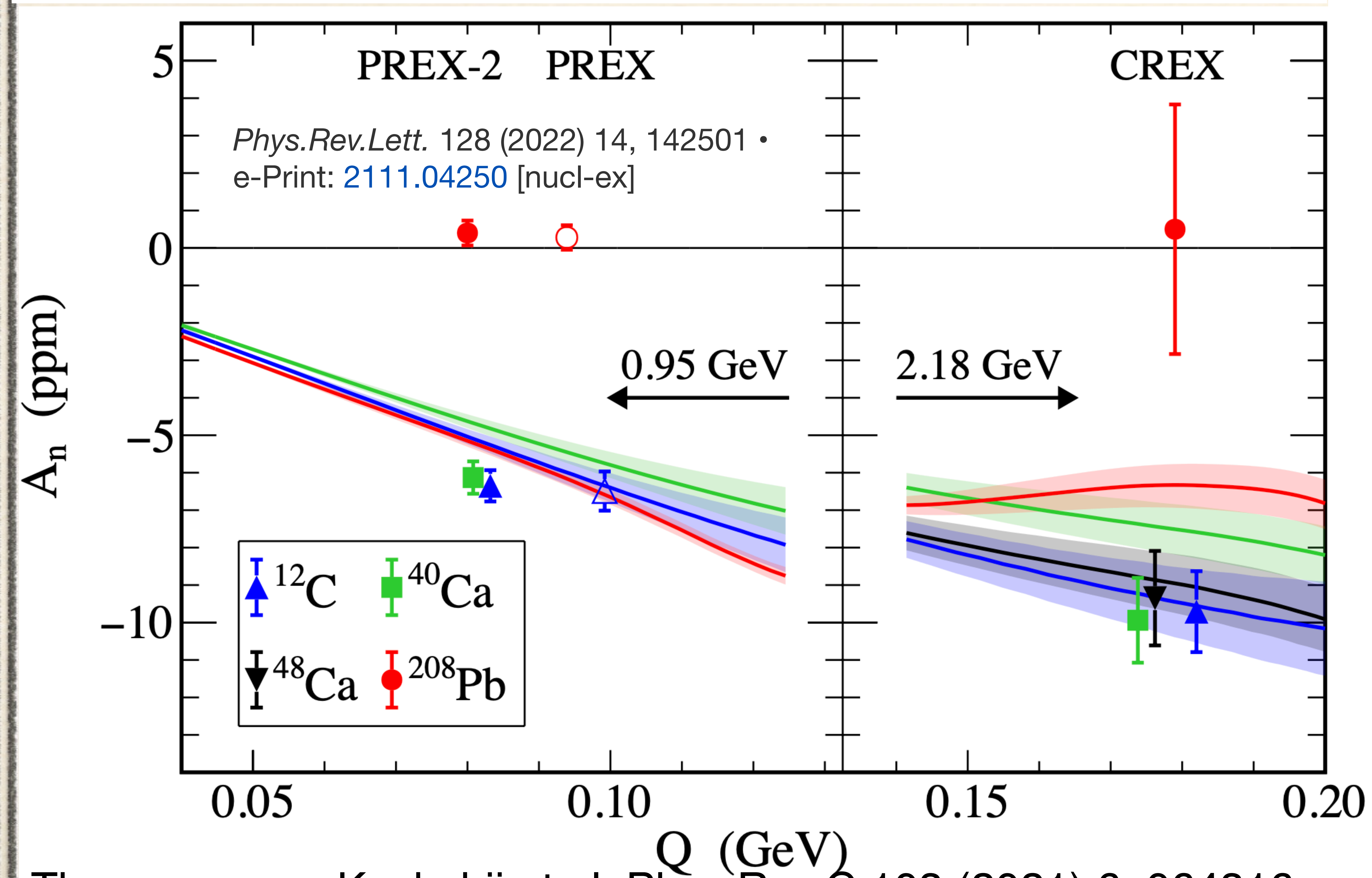

E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{\text{uncert}}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		$21\ \sigma$
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
2.18	^{40}Ca	-10.0 ± 1.1		
2.18	^{48}Ca	-9.4 ± 1.1		
2.18	^{208}Pb	0.6 ± 3.2		$3.2\ \sigma$

Theory curves: Koshchii et al: Phys.Rev.C 103 (2021) 6, 064316 •
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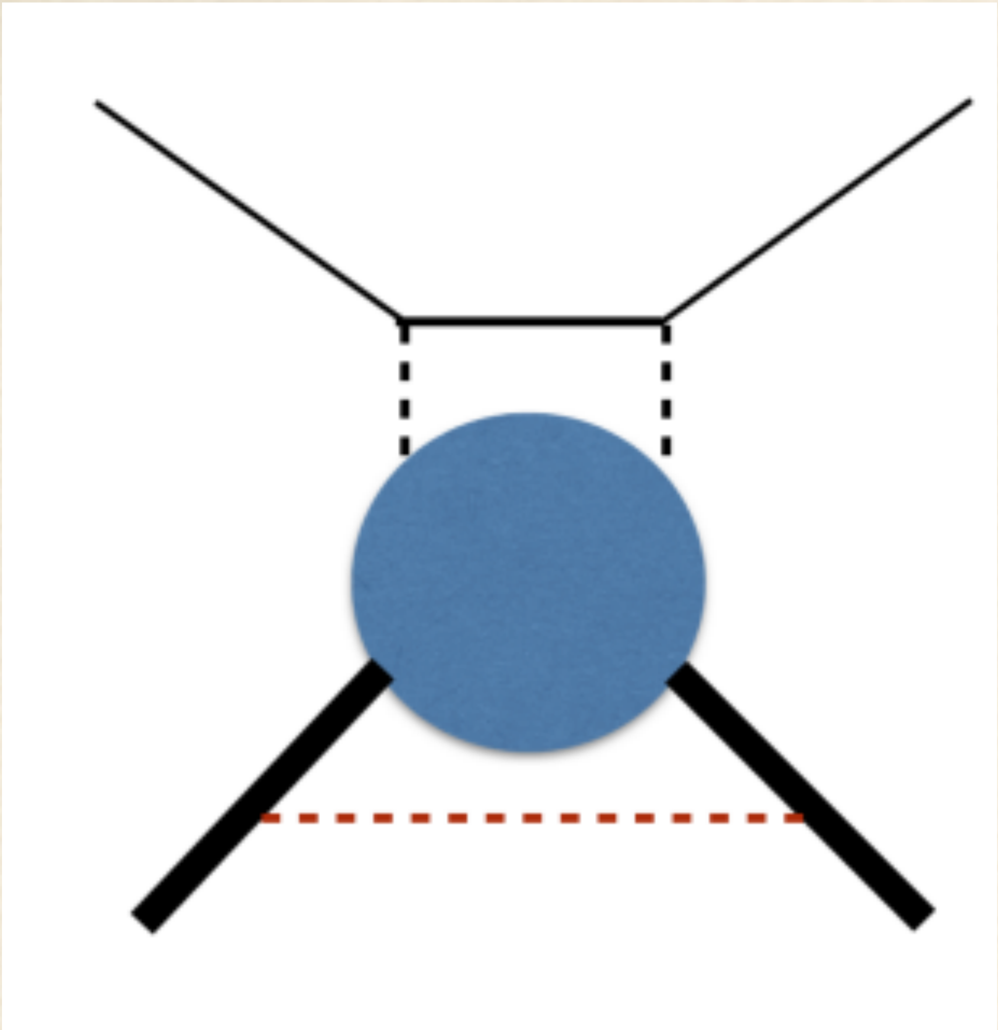


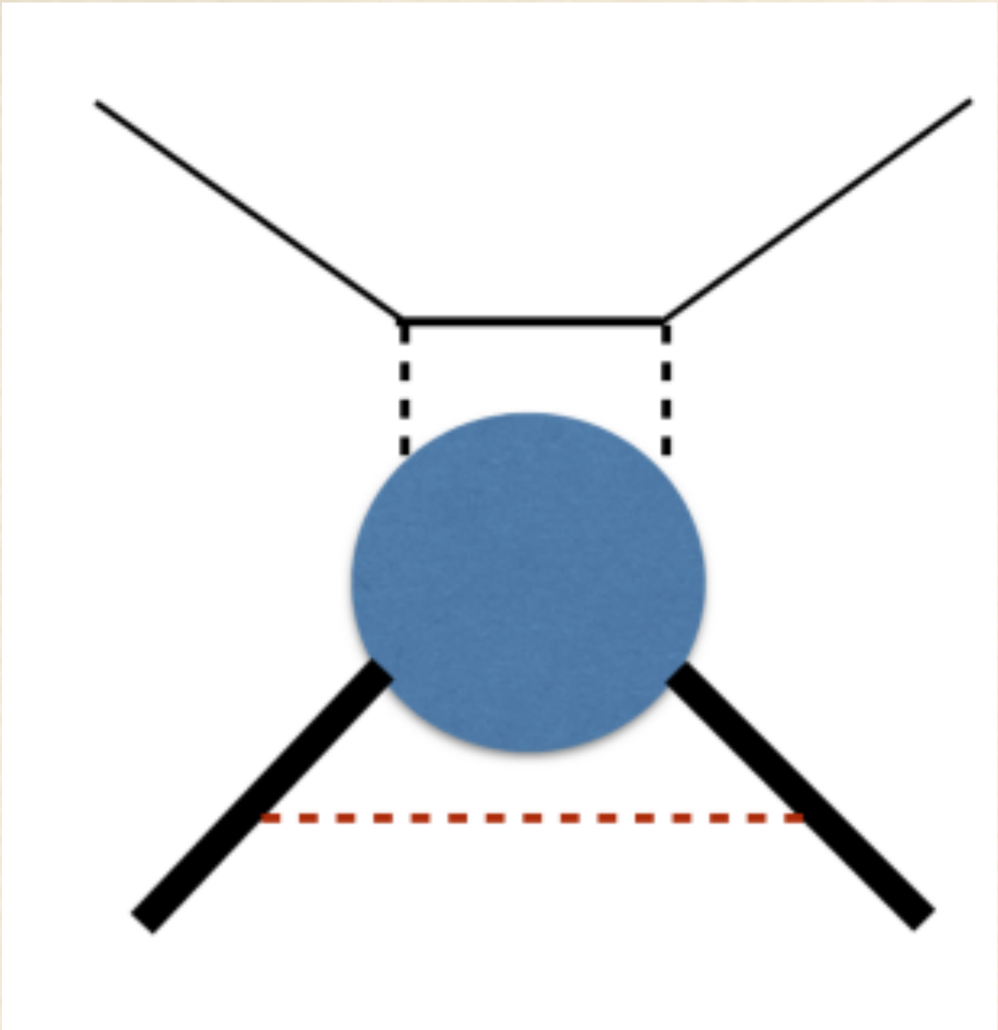
Hall C Proposal PR-12-24-007

C. Gal (contact), C. Ghosh, S. Park (co-spokespersons)

$$A_n \approx A_0(Q)(1 - C \cdot Z^2\alpha),$$

- A fit to the small amount of data available at forward angles produces a C=0.02 which is consistent with Mainz Zr-90 data

- One possible explanation would be that another physics process produces a transverse asymmetry with the opposite sign as the TPE that is present in high Z (or A) nuclei



Hall C Proposal PR-12-24-007

C. Gal (contact), C. Ghosh, S. Park (co-spokespersons)

$$A_n \approx A_0(Q)(1 - C \cdot Z^2\alpha),$$

- A fit to the small amount of data available at forward angles produces a C=0.02 which is consistent with Mainz Zr-90 data

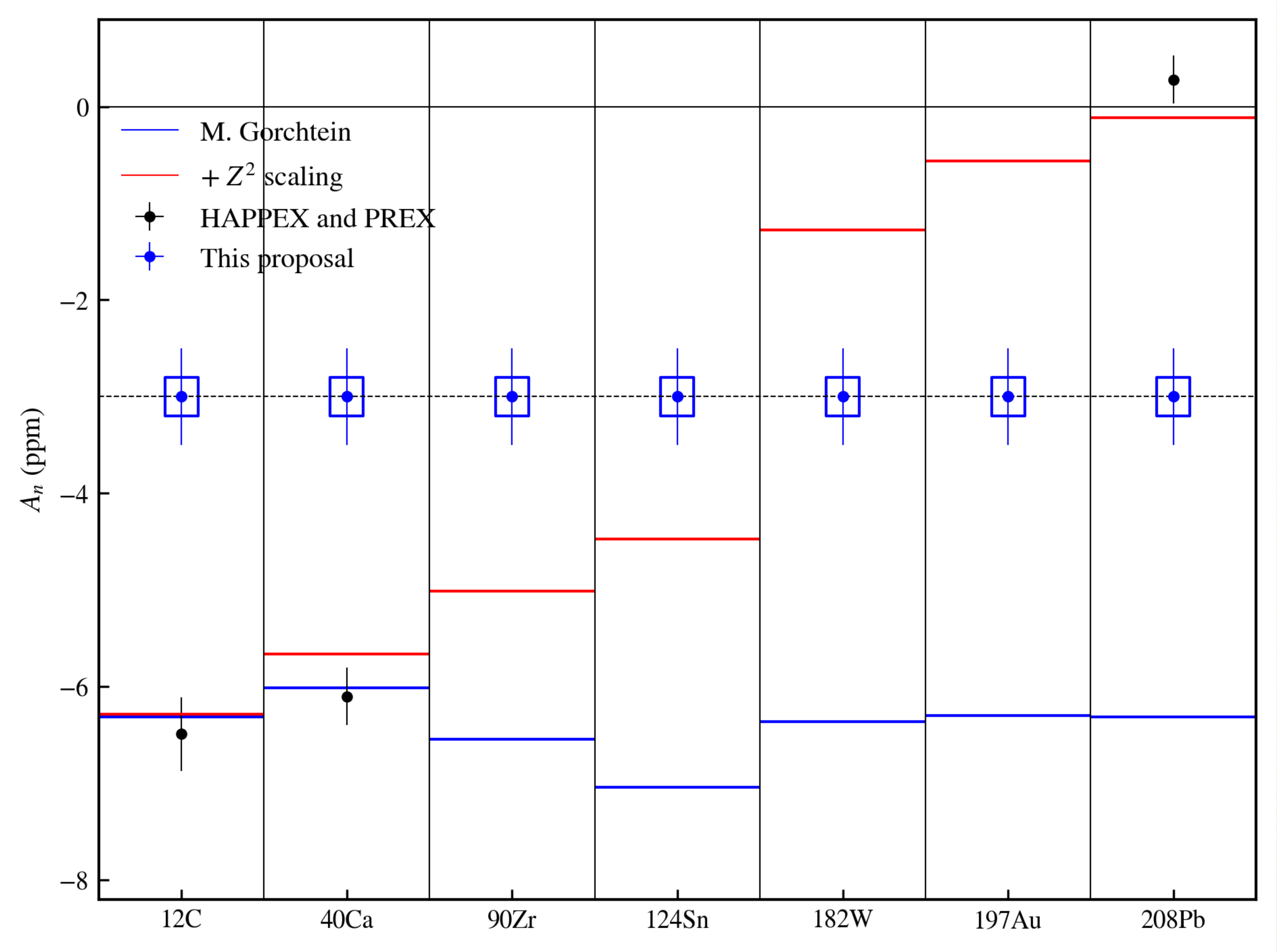
- One possible explanation would be that another physics process produces a transverse asymmetry with the opposite sign as the TPE that is present in high Z (or A) nuclei

- We propose to measure the beam normal single spin asymmetry using targets with a broad range of Z (6 ≤ Z ≤ 90)
- The experiment aims to measure the asymmetries with an absolute uncertainty of 0.5 ppm (stat) ± 0.2 ppm (syst)
- New data on intermediate to heavy nuclei will allow us study nuclear dependence of the asymmetry

E_{beam} (GeV)	1.0
θ_{lab} (deg)	5.5
Q^2 (GeV^2)	0.0092
Beam current (μA)	30
Statistical uncertainty	0.5 ppm
Systematic uncertainty	0.2 ppm

Projected Results

9 Approved PAC days: 2-3 days commissioning, ~ 5 days production data



- TPE calculations suggest 6-7 ppm asymmetries for all targets at the proposed kinematics
- Empirical determination of asymmetry suppression assuming Z² corrections
  $A_n \approx A_0(Q)(1 - C \cdot Z^2\alpha)$
- Lack of data for Z > 40 makes it almost impossible to test models for the missing contributions
- The precision proposed in this experiment will allow studying the nuclear dependence of the asymmetry

MOLLER Summary

- ✦ MOLLER is unique probe of TeV-scale purely leptonic interactions
- ✦ There is also sensitivity (e.g. lepton number violation) to low energy physics, quite apart from dark-Z's etc
- ✦ If the current schedule is maintained (US DOE funding for JLab must continue to be healthy), then we could publish an E158-level result by summer 2028, and reach our ultimate sensitivity by 2030 ($\pm 0.00023 \pm 0.00012$)
- ✦ CMS at LHC released a new number (± 0.00031) with pdf uncertainty (± 0.00027): Window of opportunity for MOLLER and P2 until HL-LHC
- ✦ MOLLER will also explore electroweak nucleon structure in a novel kinematic regime; auxiliary measurements at MOLLER and Hall-C might produce surprises involving low energy QCD dynamics