Acknowlegements:
The MOLLER Collaboration colleagues from whom I have borrowed pictures and ideas

Special thanks to Zuhal Demiroglu, Ciprian Gal and Kent Paschke for new material in this talk

Introduction to MOLLER

Context for Workshop Topics

Krishna Kumar
University of Massachusetts, Amherst

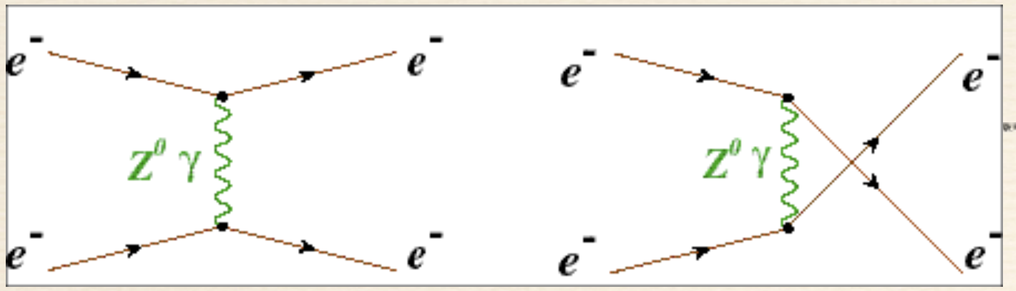
Precision Physics with MOLLER Workshop
November 5-6, 2026

Thanks to Jianwei Qiu and Wally Melnitchouk in taking the initiative to launch this workshop

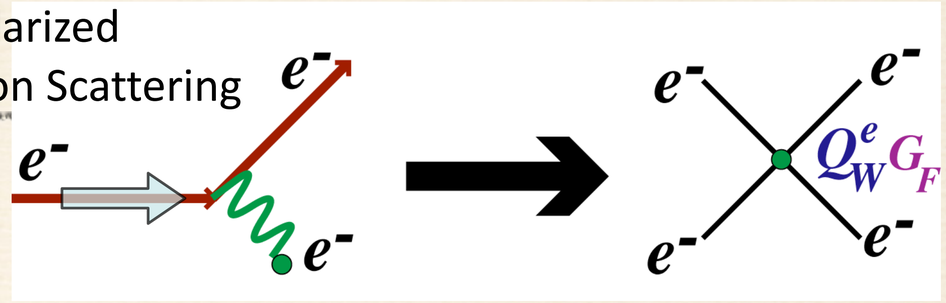
Outline

- **Introduction to the Main Observable**
  - *The Parity-Violating Asymmetry in electron-electron (Møller) scattering*
- **The MOLLER Experiment Fundamentals**
  - *Overview of the Apparatus*
  - *Spectrometer Design and Primary Irreducible Backgrounds*
  - *Relevant Detector Characteristics*
- **Context for Workshop Topics**
  - *PV electron-proton inelastic scattering at very forward angles and high W*
  - *High-order Calculations*
  - *Hyperon Backgrounds*
  - *Transverse Asymmetry (AT) Measurements*
- **Summary of Workshop Topics**

The MOLLER Physics Reach



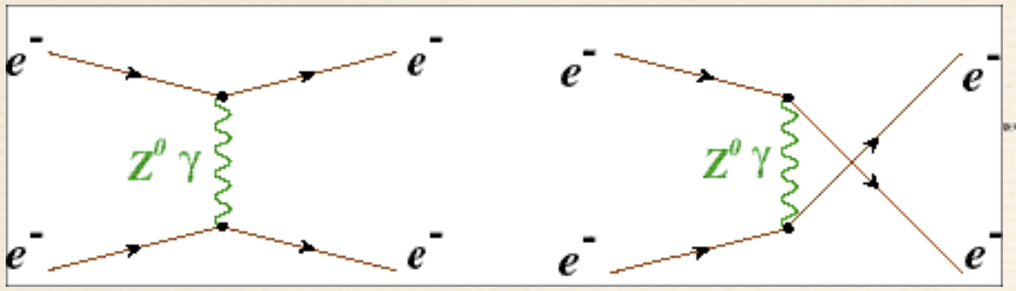
Fixed Target Polarized
Electron-Electron Scattering



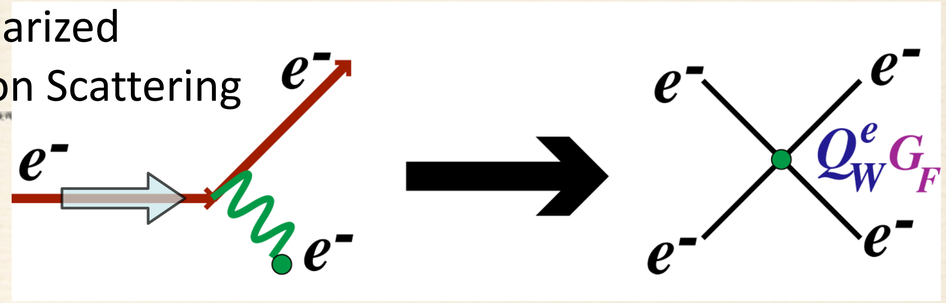
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE \frac{G_F}{\sqrt{2}\pi\alpha} \frac{16 \sin^2 \Theta}{(3 + \cos^2 \Theta)^2} Q_W^e$$

$$Q_W^e = 1 - 4 \sin^2 \theta_W \sim 0.075$$

The MOLLER Physics Reach



Fixed Target Polarized
Electron-Electron Scattering



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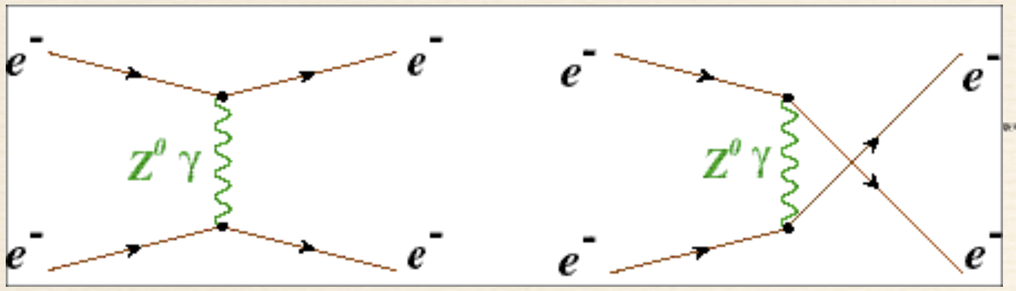
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11 GeV, 65 μA 90% beam polarization

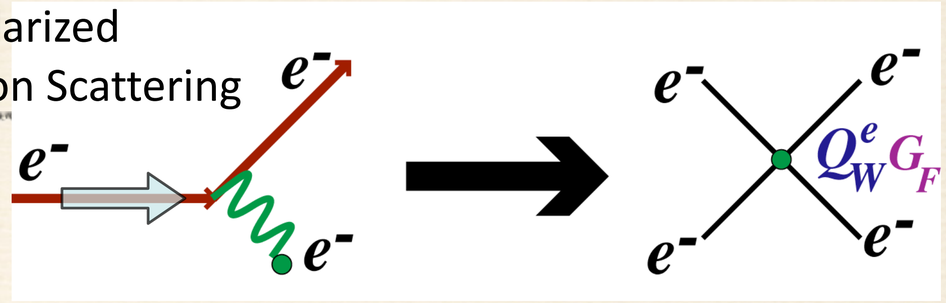
A_{PV} ~ 32 ppb *$\delta(A_{PV})$ ~ 0.8 ppb*

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

The MOLLER Physics Reach



Fixed Target Polarized
Electron-Electron Scattering



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

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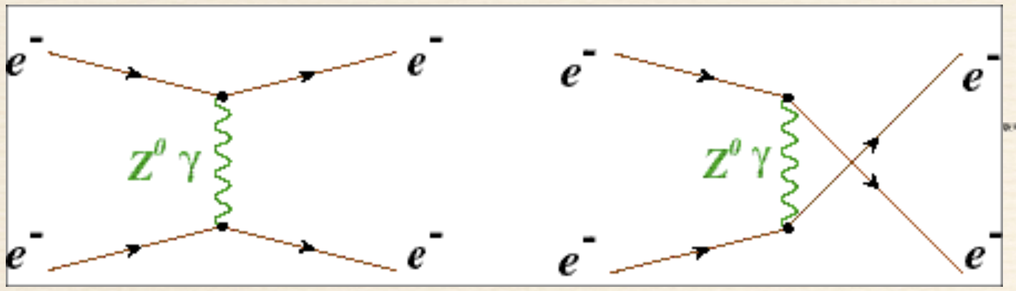
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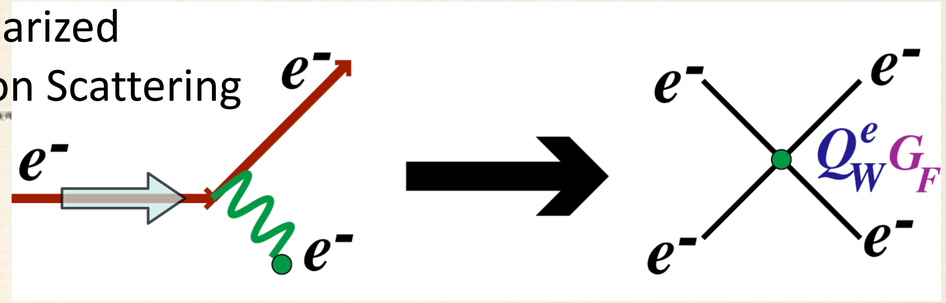
$\delta(\sin^2\theta_W) = \pm 0.00023$ (stat.) ± 0.00012 (syst.)

⇨ *~ 0.1%*

The MOLLER Physics Reach



Fixed Target Polarized
Electron-Electron Scattering



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

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

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

New Physics

11 GeV, 65 μA 90% beam polarization

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~ 0.1%

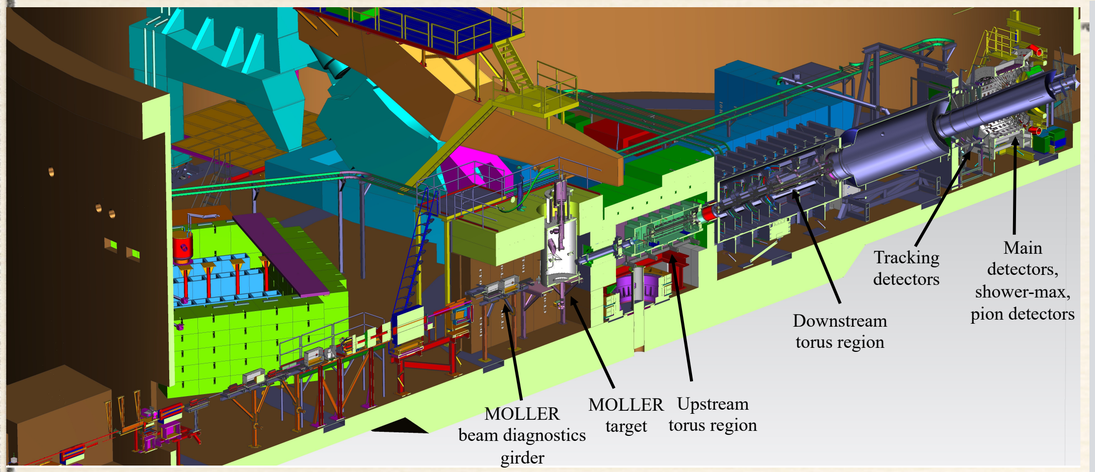
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

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

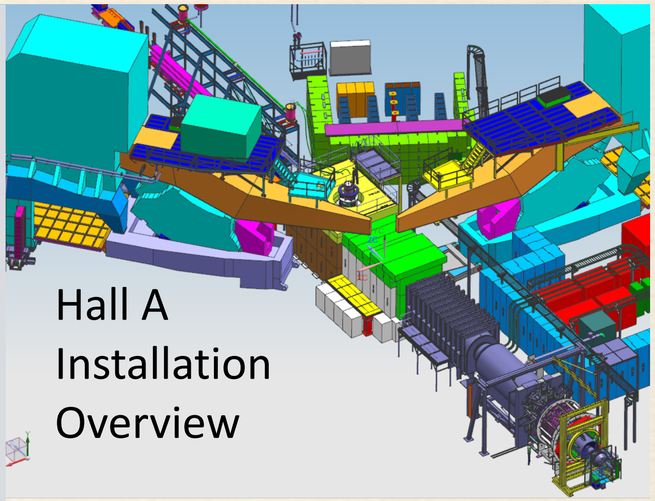
Sensitivity akin to a 500 GeV Lepton Collider

MOLLER Status

Engineering Design and most acquisitions complete, construction and assembly under way



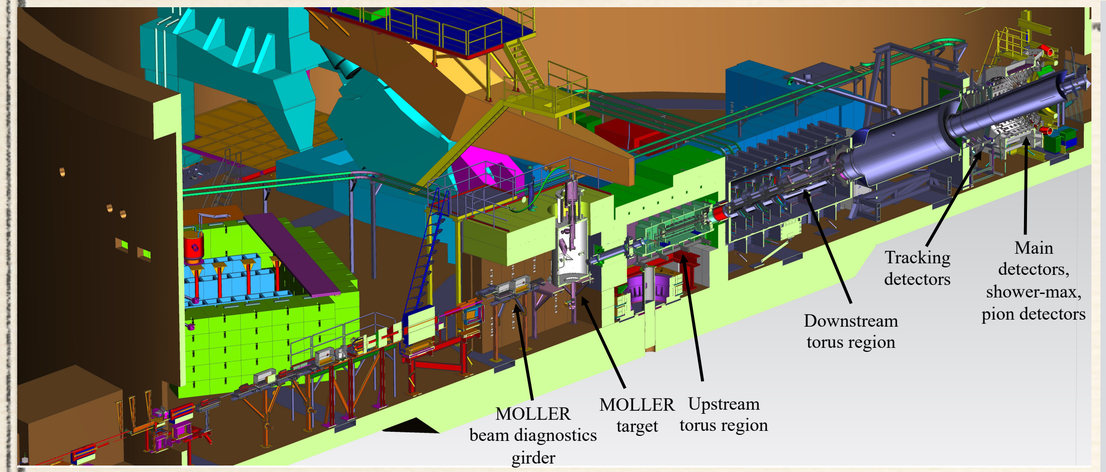
- **~ 50M$ MIE by US DOE NP**
- **~ 12M$: US NSF and Canada CFI/Research Manitoba**
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- **Construction: 2024-26**
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- **Start of Running: mid-2027**
- **Physics thru 2029 and beyond**



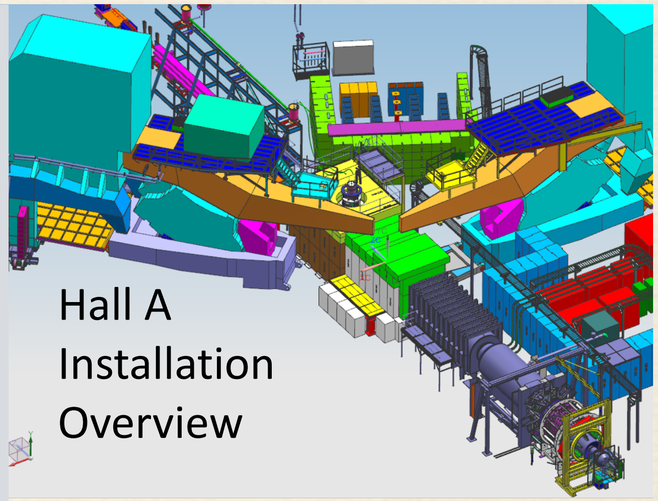
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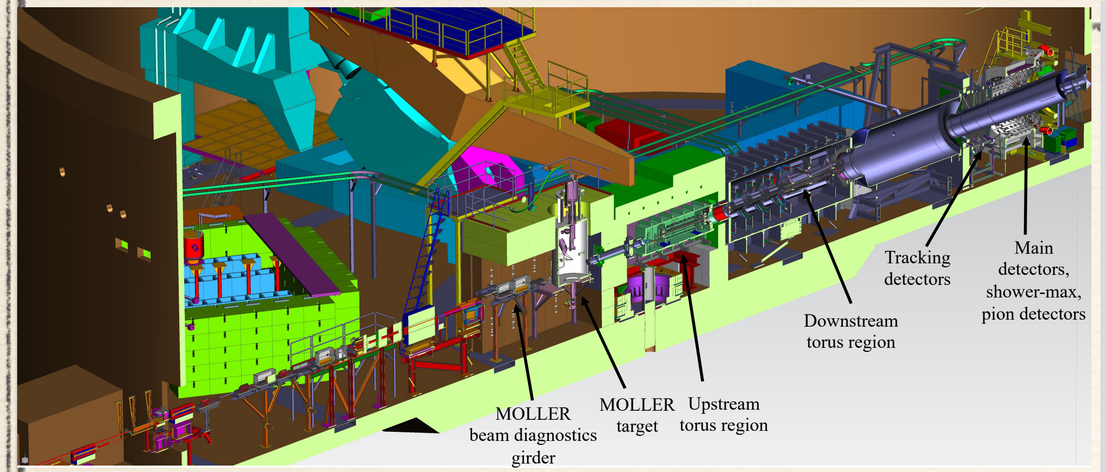
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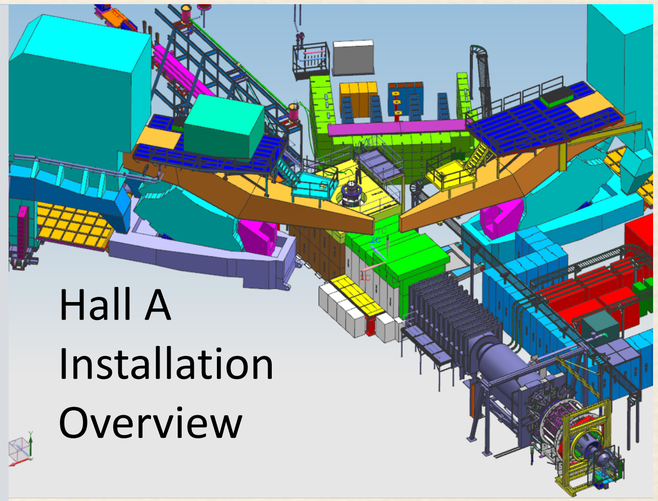
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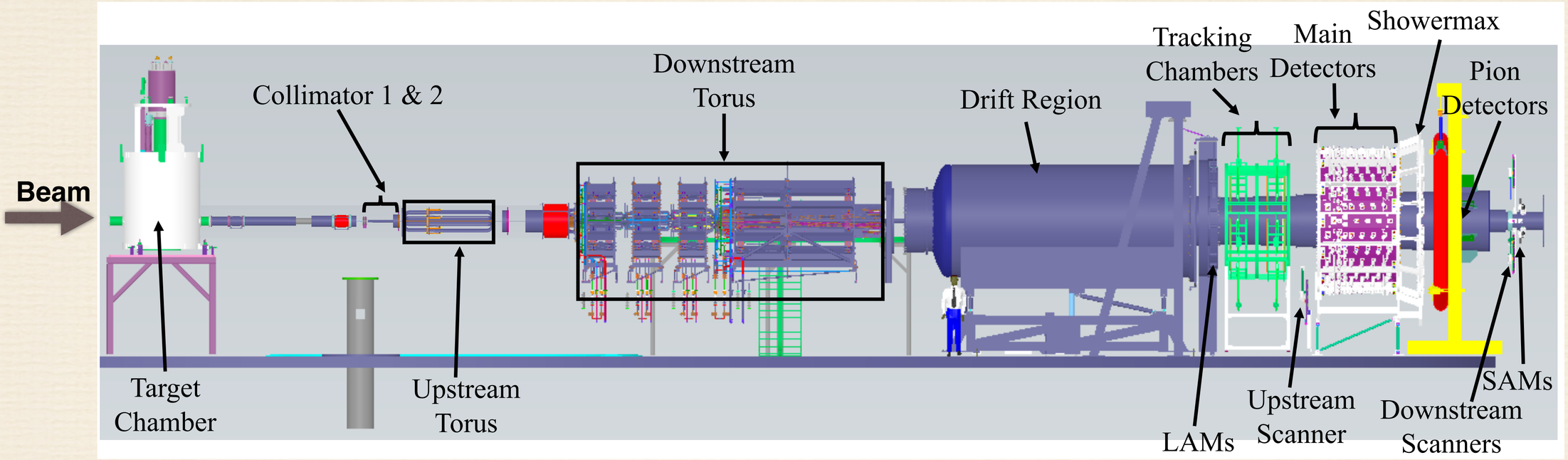
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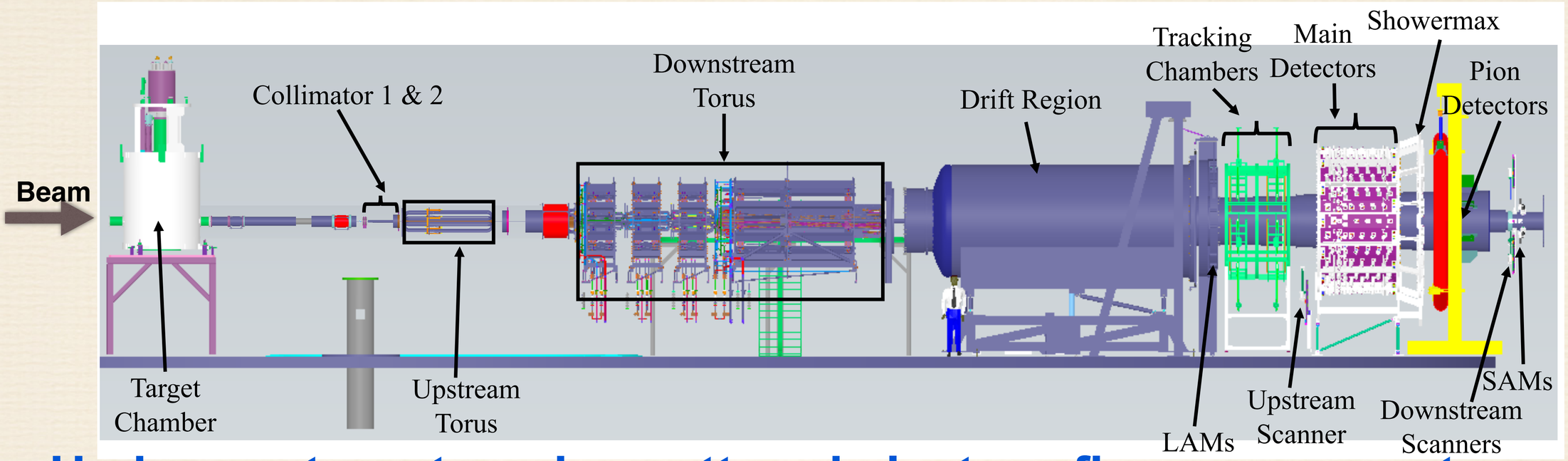
Physics in Summer 2027

- *Low power commissioning starting in June*
- *High power commissioning quickly followed by few days of 100% transverse running*
- *Demonstrate readiness for physics and take first longitudinal data as time permits*

Relevant Facts for Theory Discussion

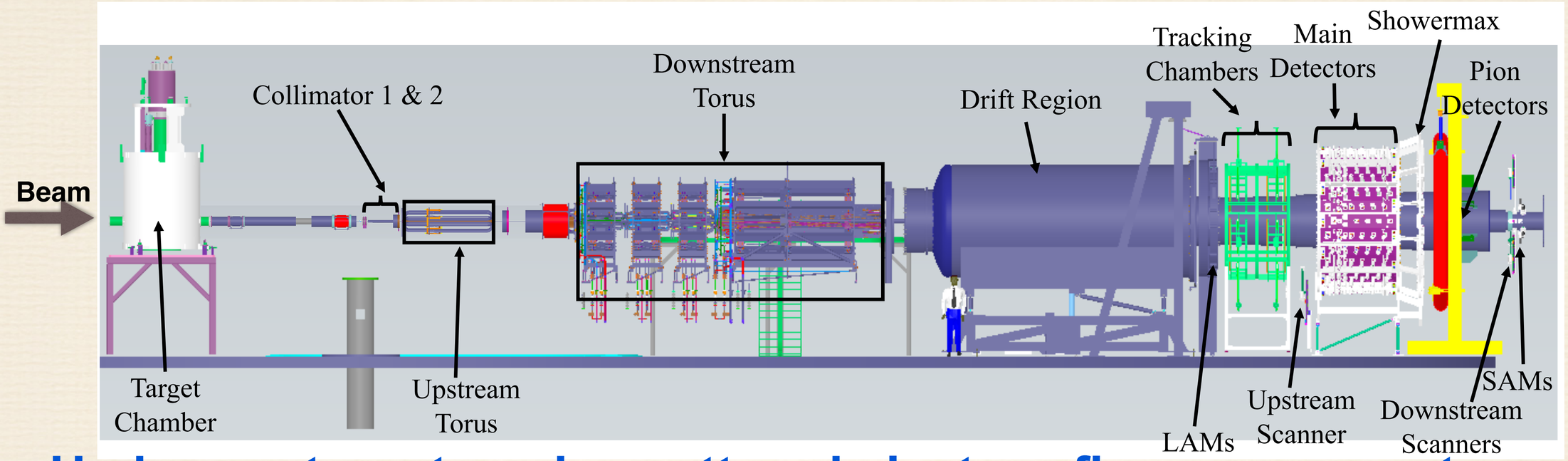


Relevant Facts for Theory Discussion



- **Hydrogen target: main scattered electron flux components**
  - ***Electron-electron (Møller) scattering***
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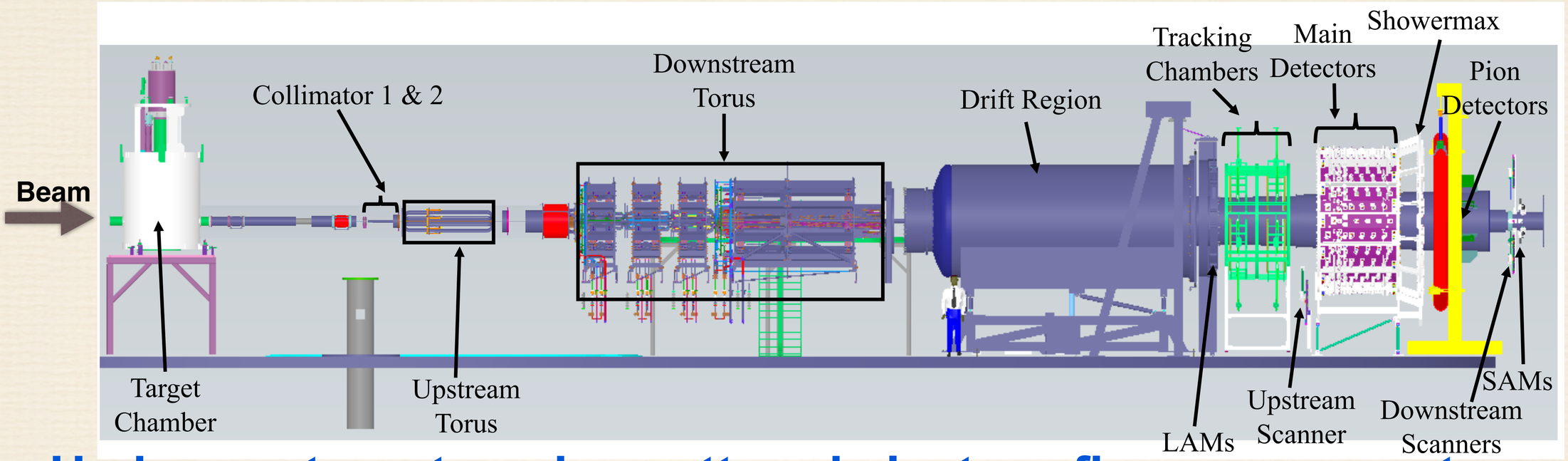
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Collimators and the magnetic spectrometer spatially separate these 3 components in the transverse plane

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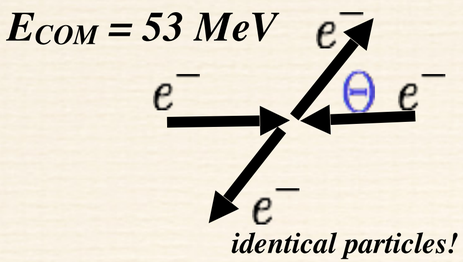
Collimators and the magnetic spectrometer spatially separate these 3 components in the transverse plane

- **Counting for Calibration, Flux Integration for Asymmetries**
  - *Relative rate in the full range of the acceptance can be determined with tracking detectors*
  - *Flux Integration for the asymmetry measurement: no event by event kinematic reconstruction*

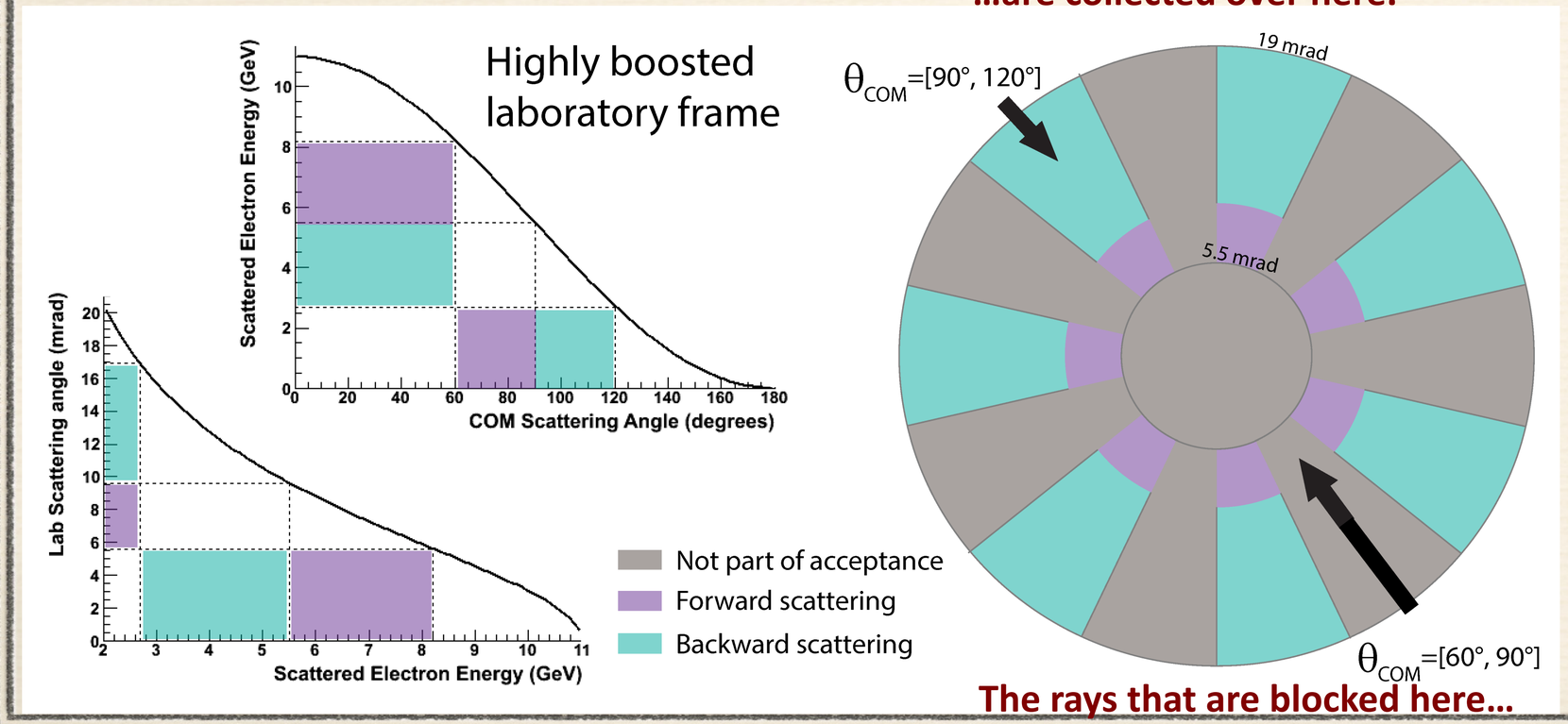
100% Møller-scattered Flux Acceptance

Incoming 11 GeV Electrons impinging on electrons at rest

- 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.

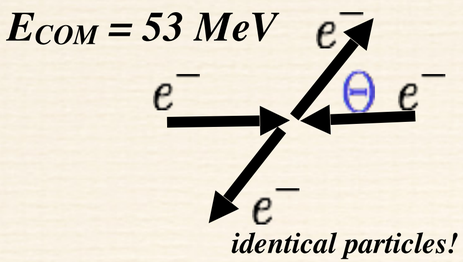


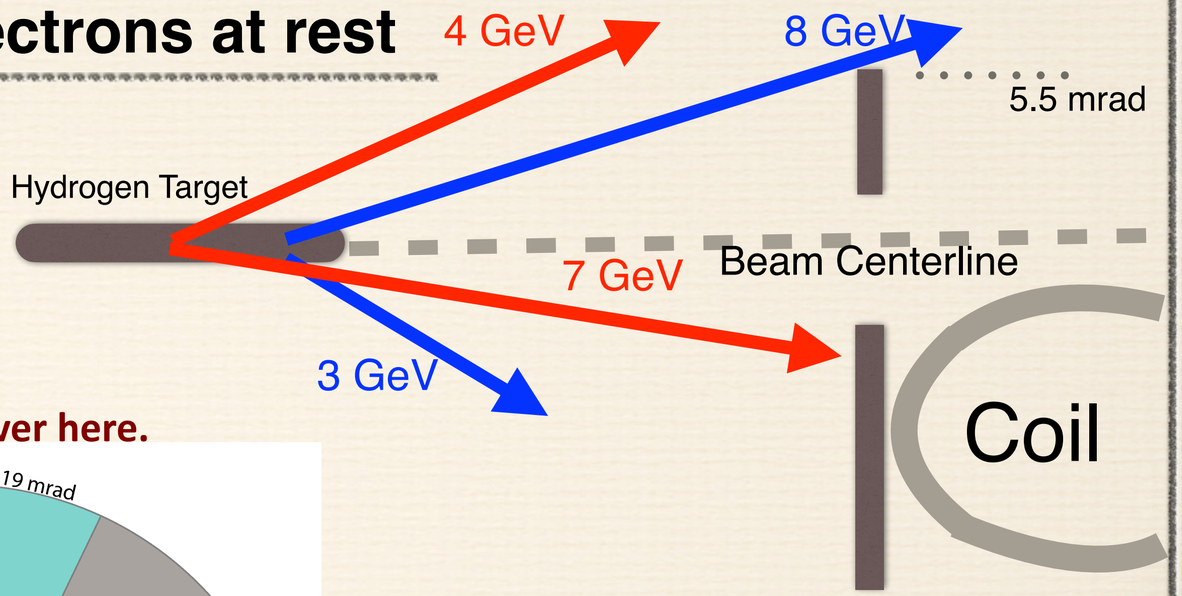
The rays that are blocked here…

100% Møller-scattered Flux Acceptance

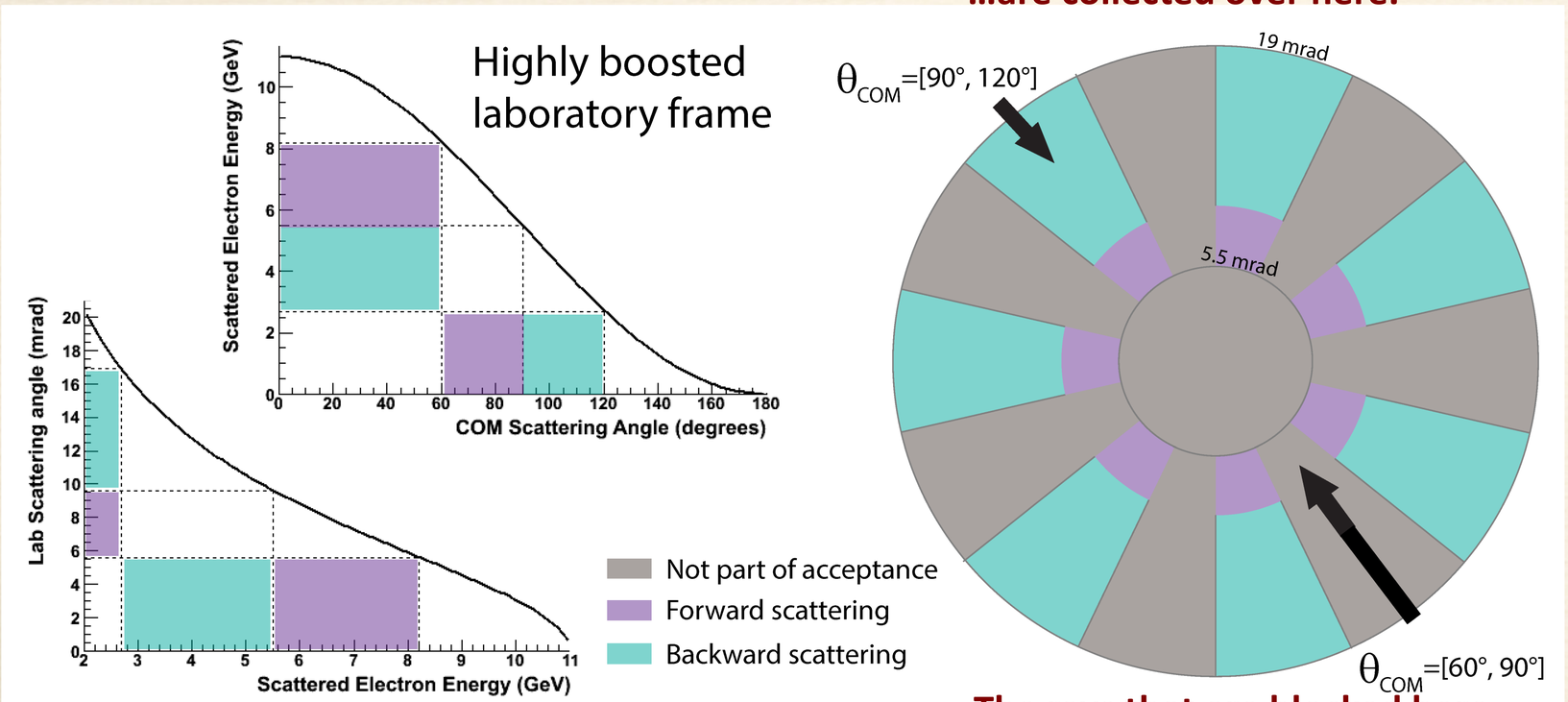
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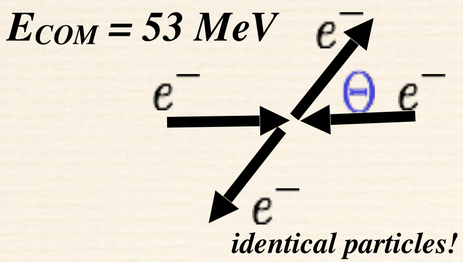


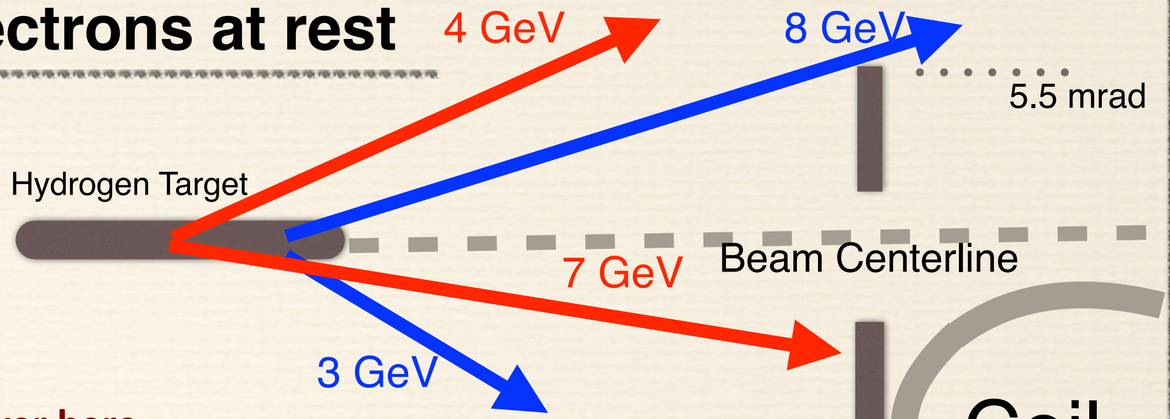
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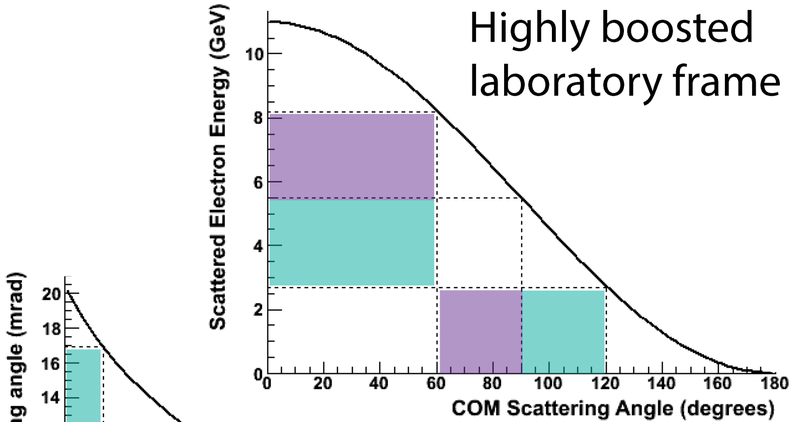
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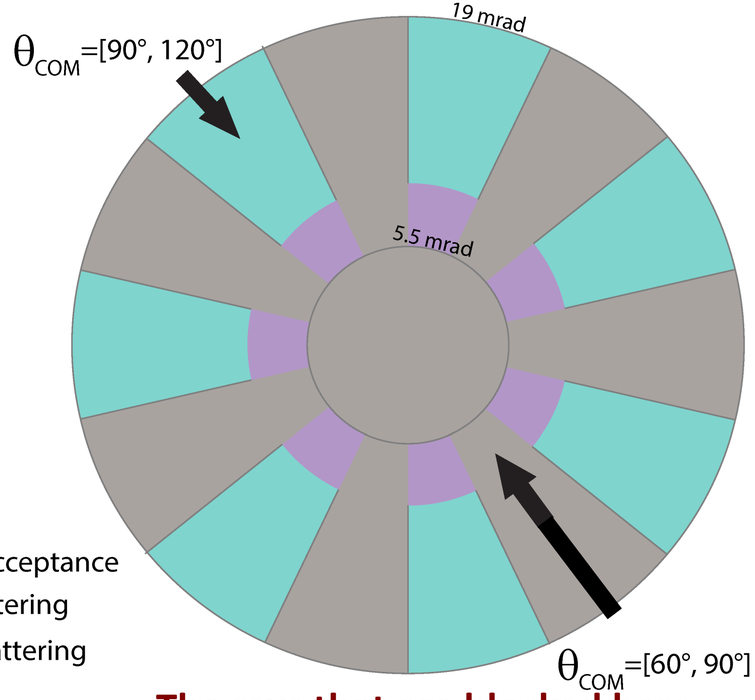
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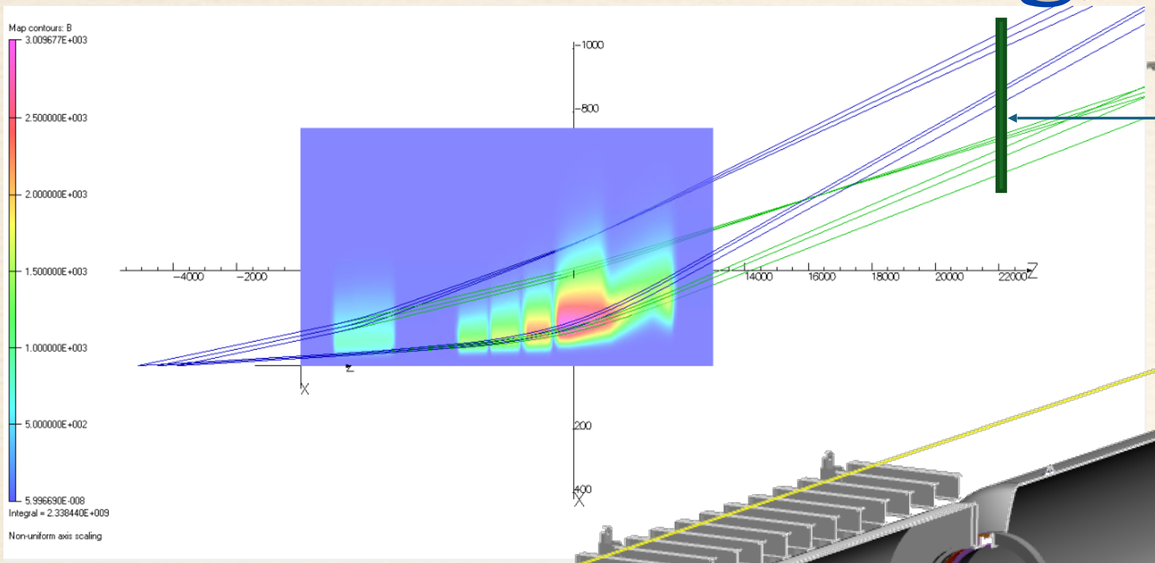


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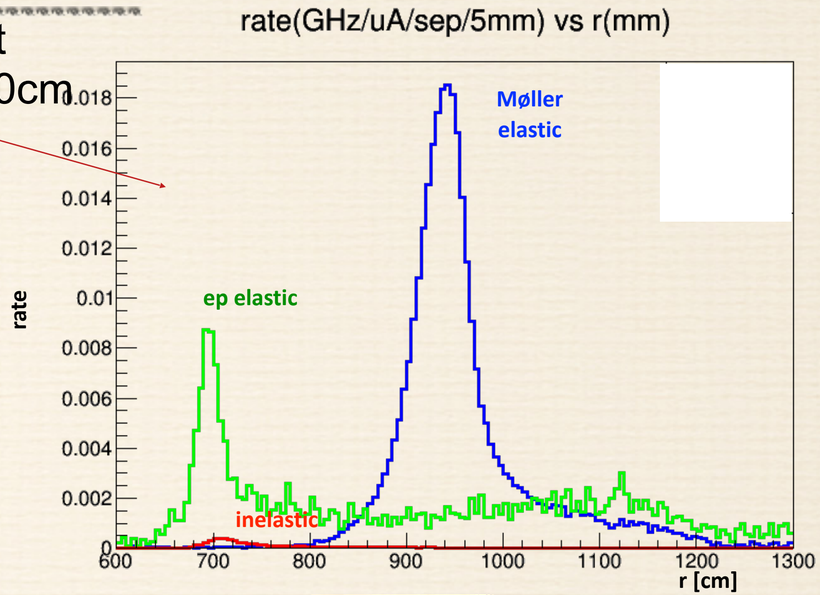
Summary of kinematic acceptance

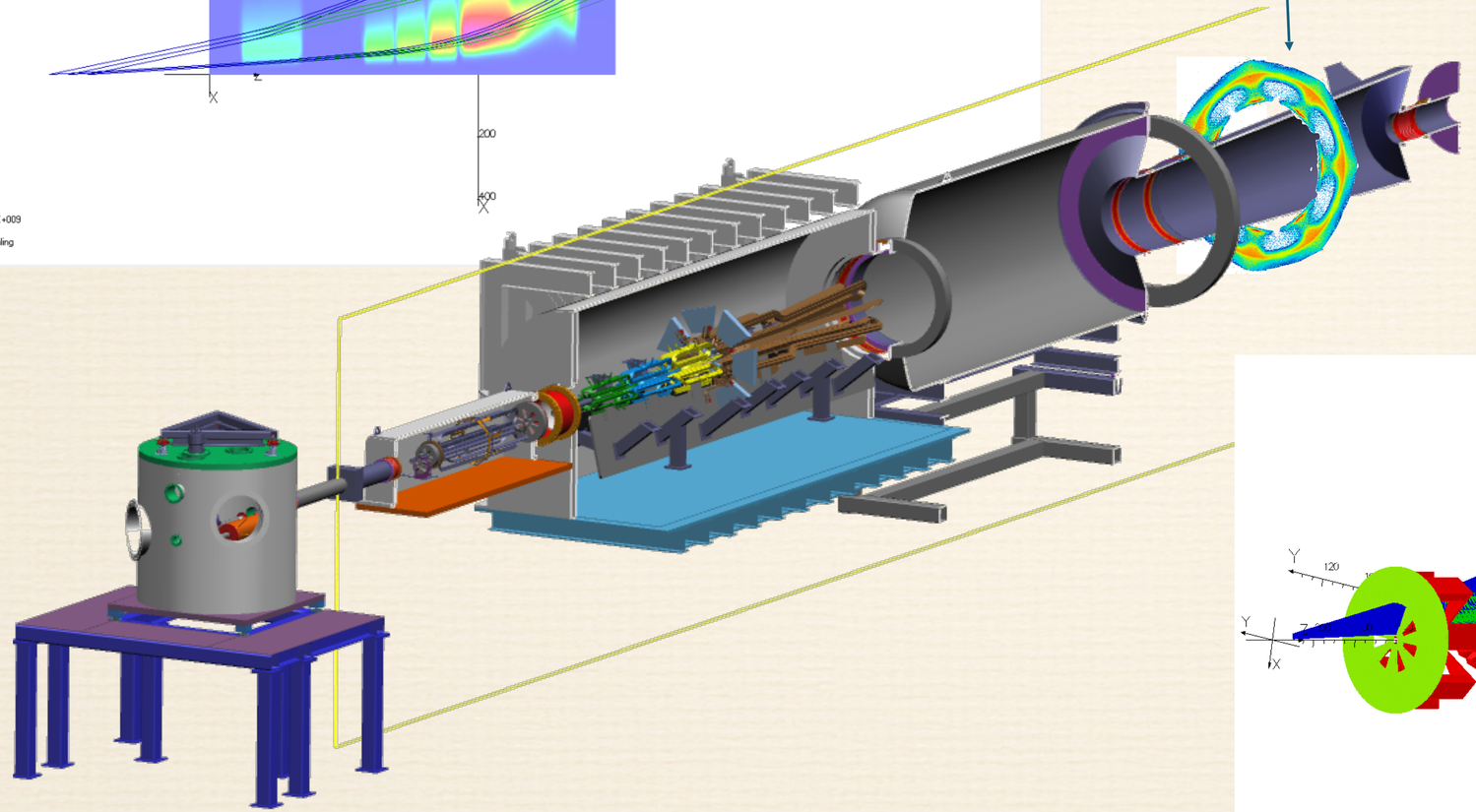
- **Momentum Range**
  - *2 to 8 GeV*
  - *Both radial and azimuthal separation*
- **Lab scattering angle**
  - *5.5 to 19 mrad*
  - *Some azimuthal separation*

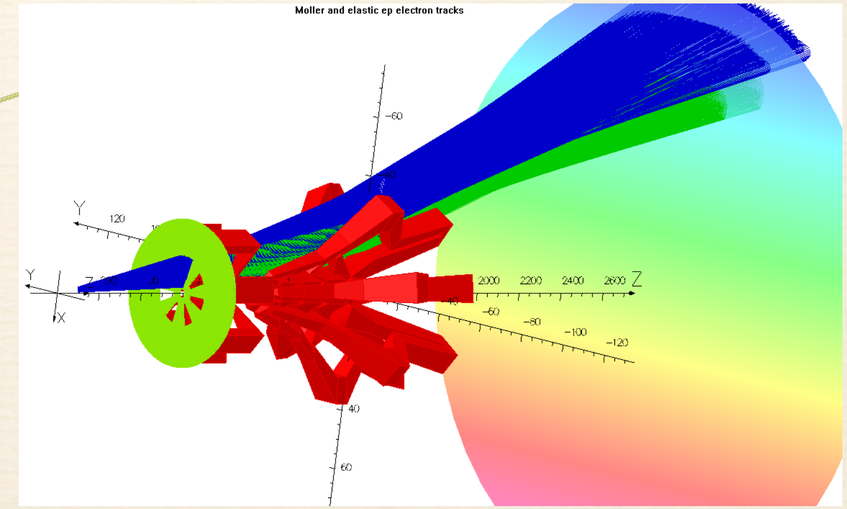
Radial Focusing, Azimuthal Defocusing

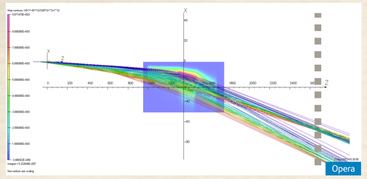


Flux distribution at detector plane z=2650cm



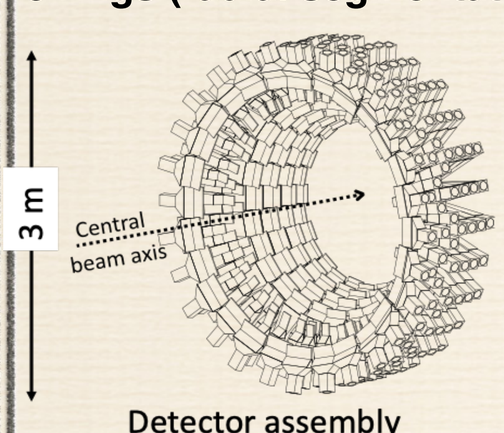


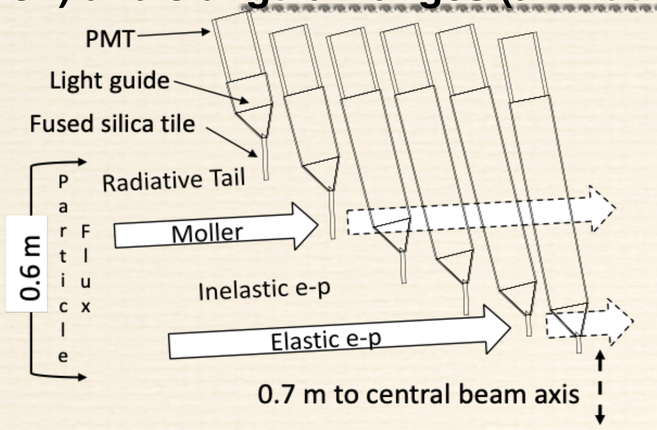


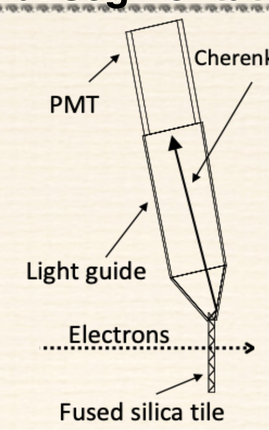


Capturing the Scattered Flux

6 rings (radial segmentation) and 3 angular ranges (azimuthal segmentation)

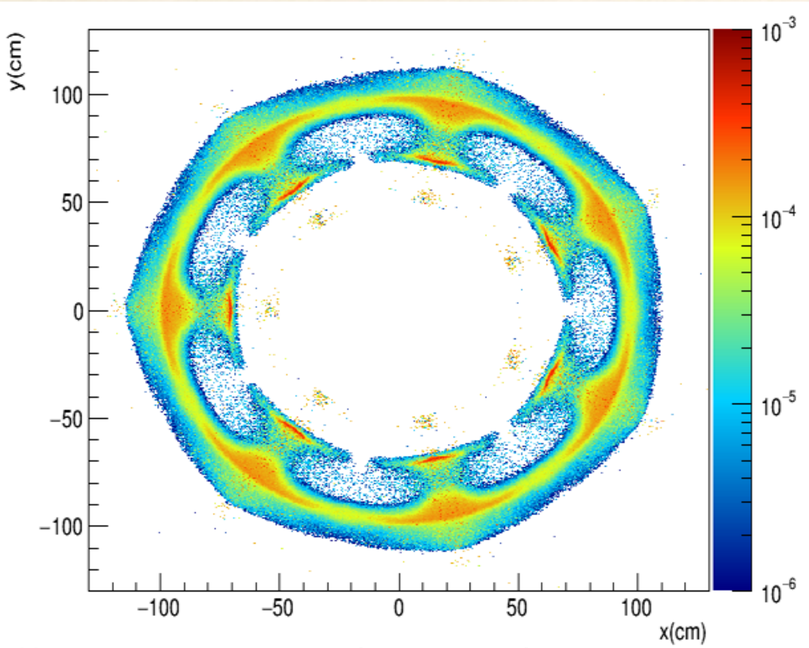




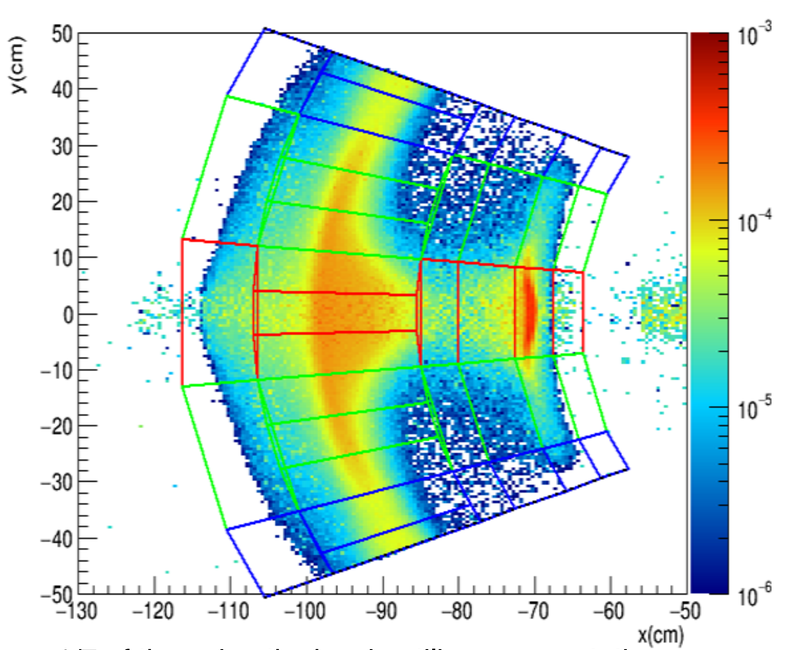


Combined charged particle flux over the full radial and azimuthal range measured periodically by tracking detectors with mm² resolution

- **Asymmetries are measured in larger "pixels"**
- **by symmetry, there are 18 tiles with distinct E' and θ_{lab} acceptances for the 3 main processes**

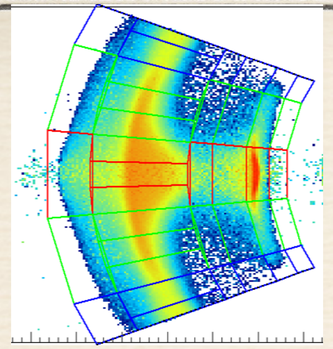


Heat map on transverse plane 26.5 m from target center



1/7 of the azimuth showing tiling segmentation

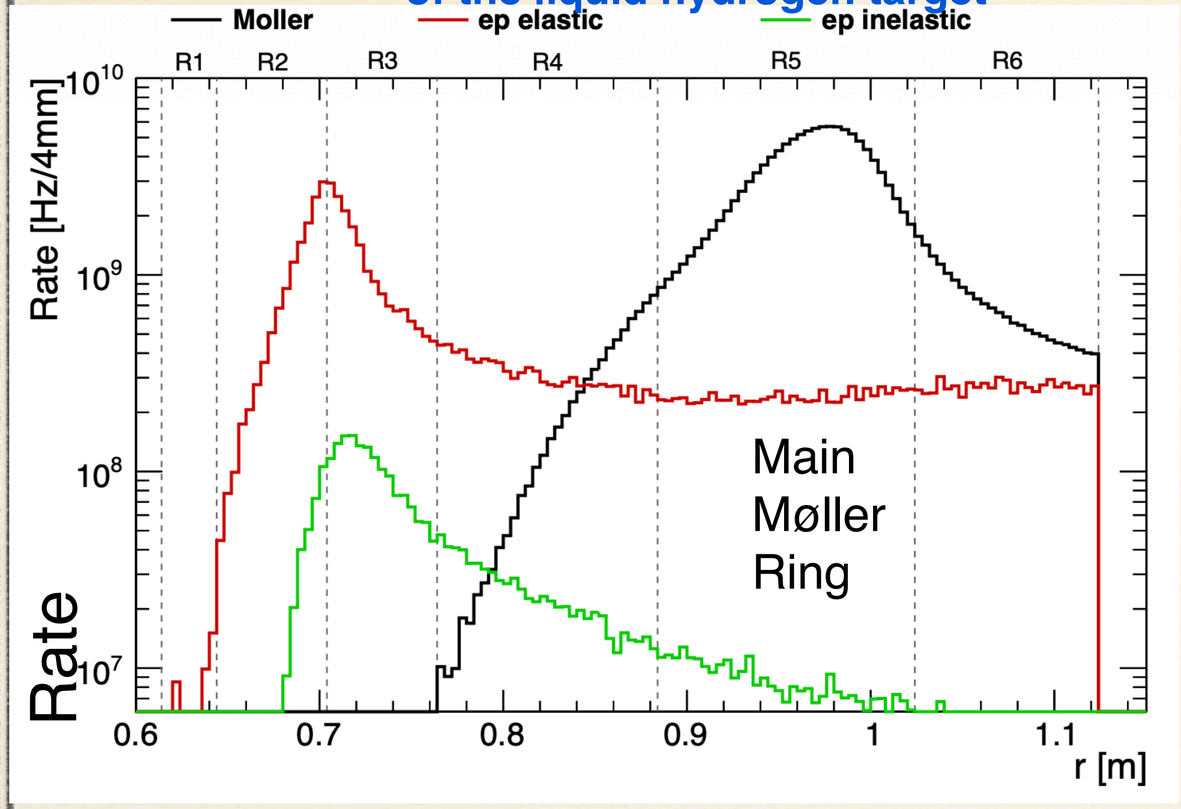




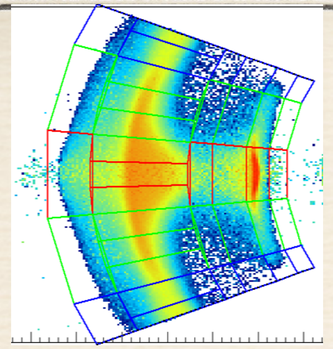
Inclusive Electron Rate Distributions

Inclusive 11 GeV electron scattering off hydrogen

Radial distributions 26.5 m downstream of the liquid hydrogen target



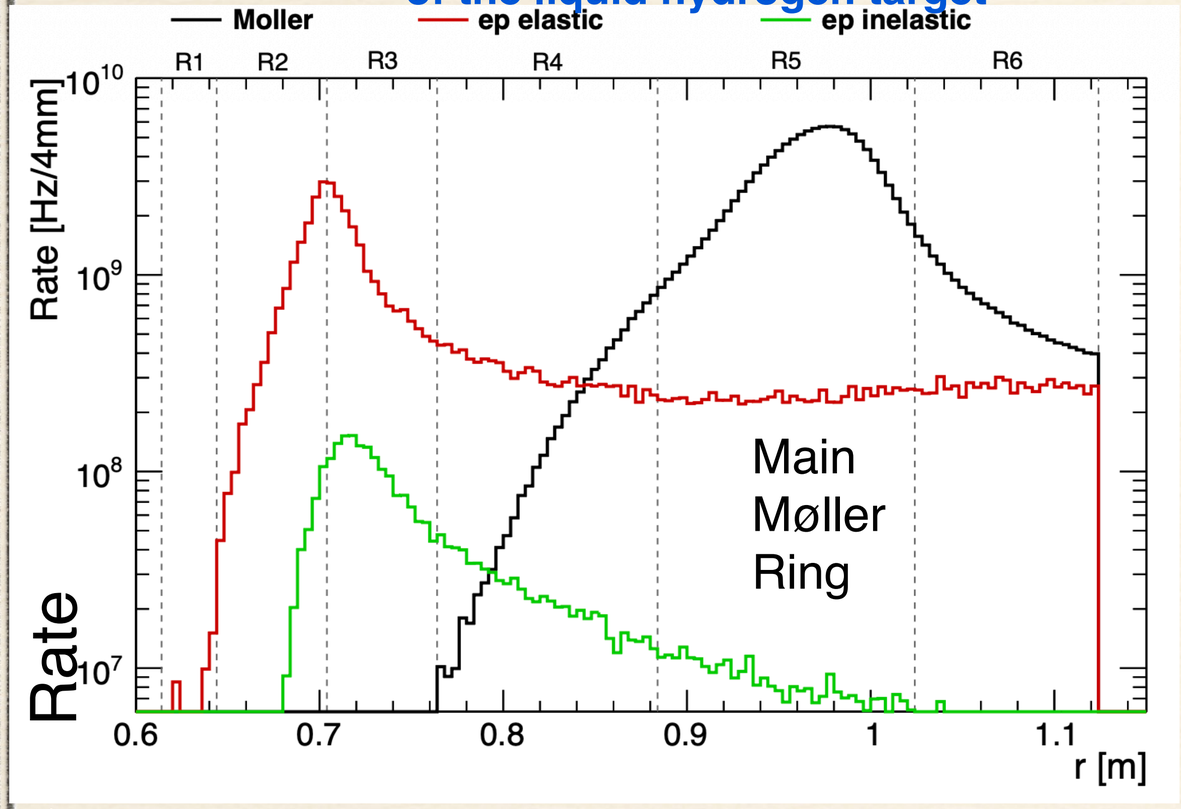
- Black: e-e scattering
- Red: elastic e-p scattering
- Green: inelastic e-p scattering



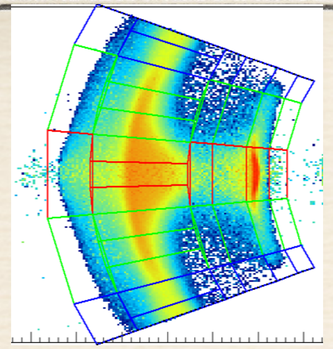
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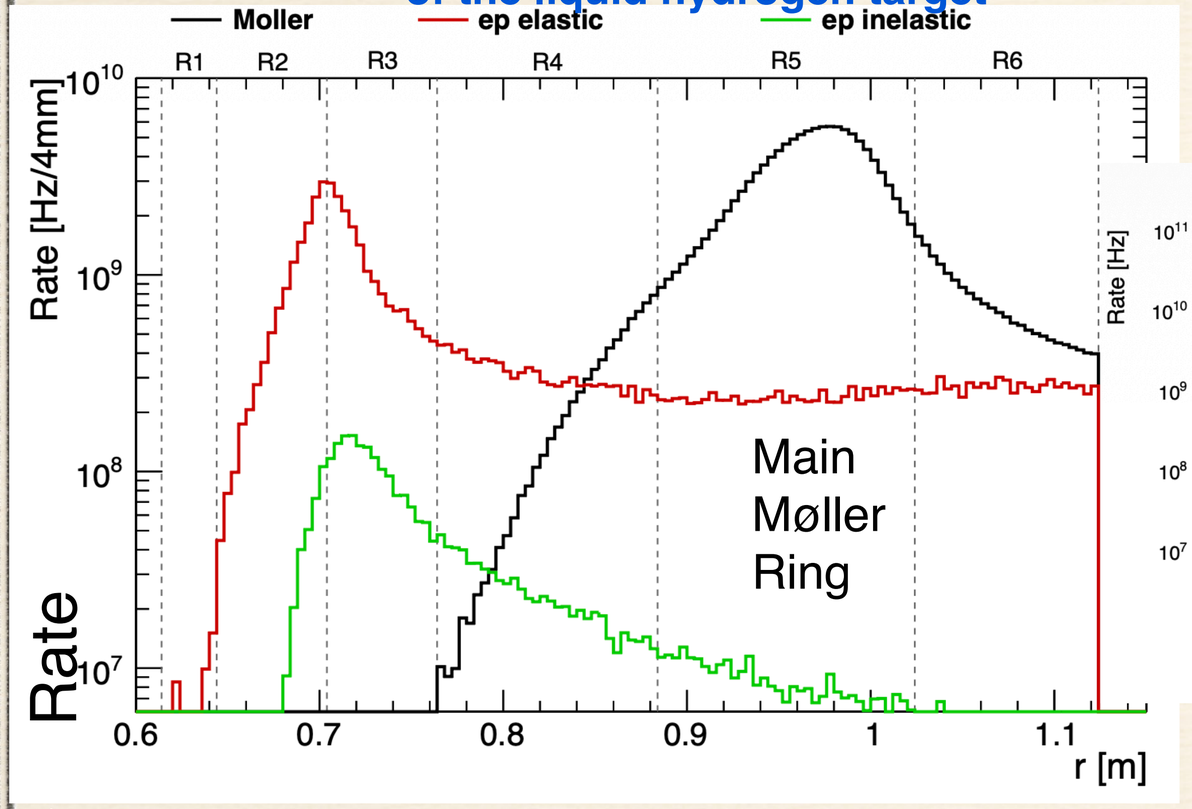
- Black: e-e scattering $e^- + e^- \rightarrow e^- + e^- : A_{PV} = 5 \times 10^{-6} \times Q^2 \ (\mathrm{GeV})^2$
- Red: elastic e-p scattering $e^- + p \rightarrow e^- + p : A_{PV} = 1 \times 10^{-5} \times Q^2 \ (\mathrm{GeV})^2$
- Green: inelastic e-p scattering $e^- + p \rightarrow e^- + X : A_{PV} = 8 \times 10^{-5} \times Q^2 \ (\mathrm{GeV})^2$



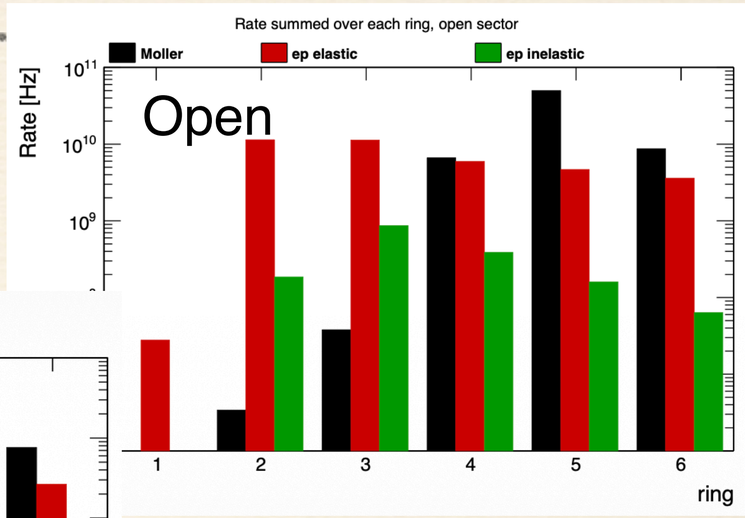
Inclusive Electron Rate Distributions

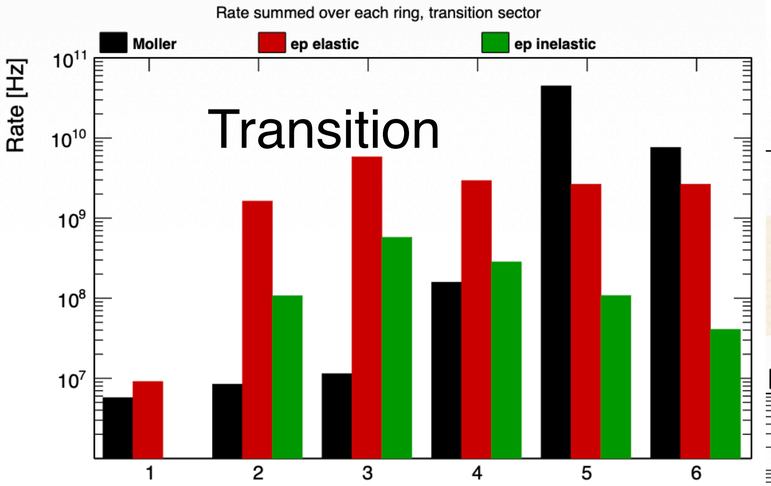
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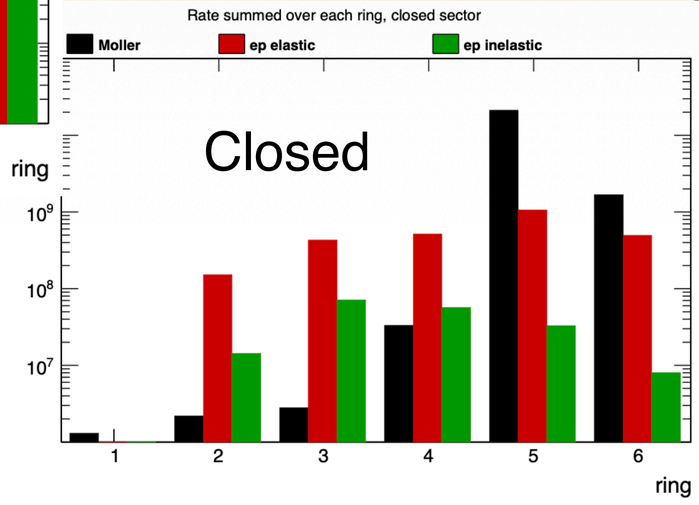
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Azimuthal separation into Open, Closed and Transition sectors







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PV Electron-Proton Inelastic Scattering

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

first principles: using electroweak neutral current structure functions

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

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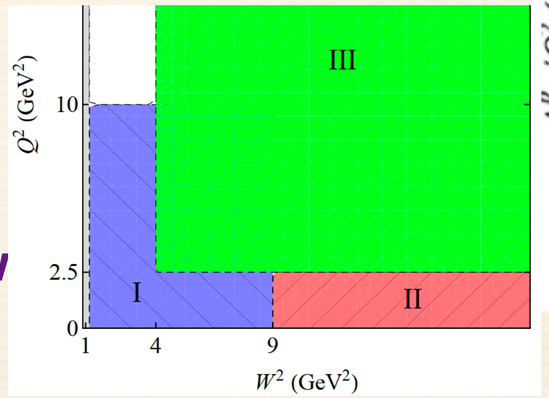
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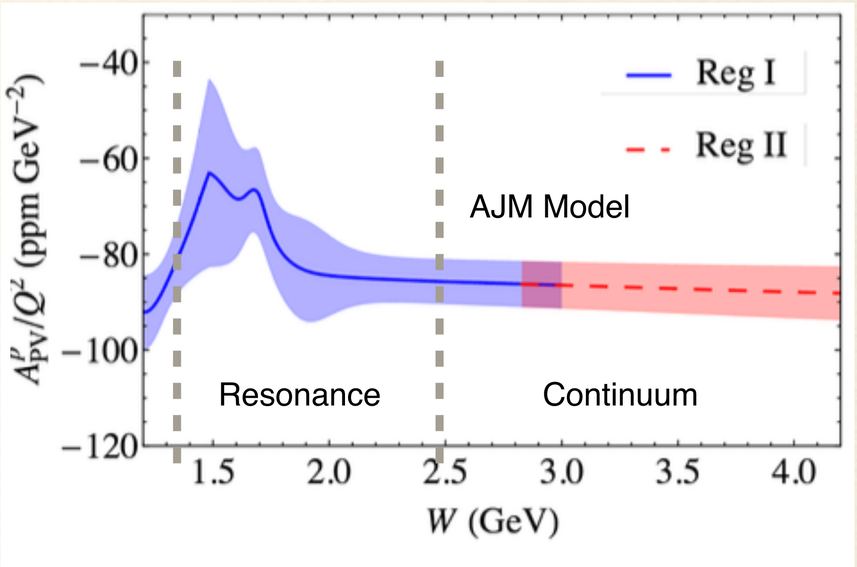
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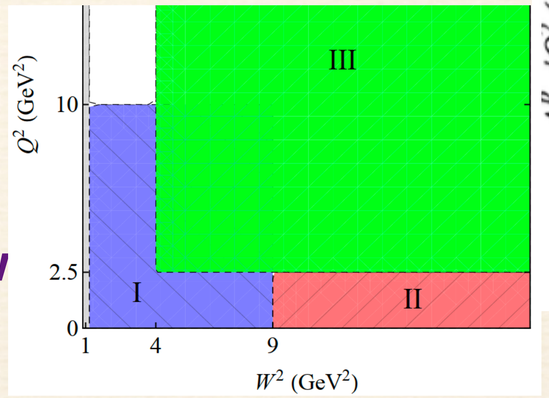


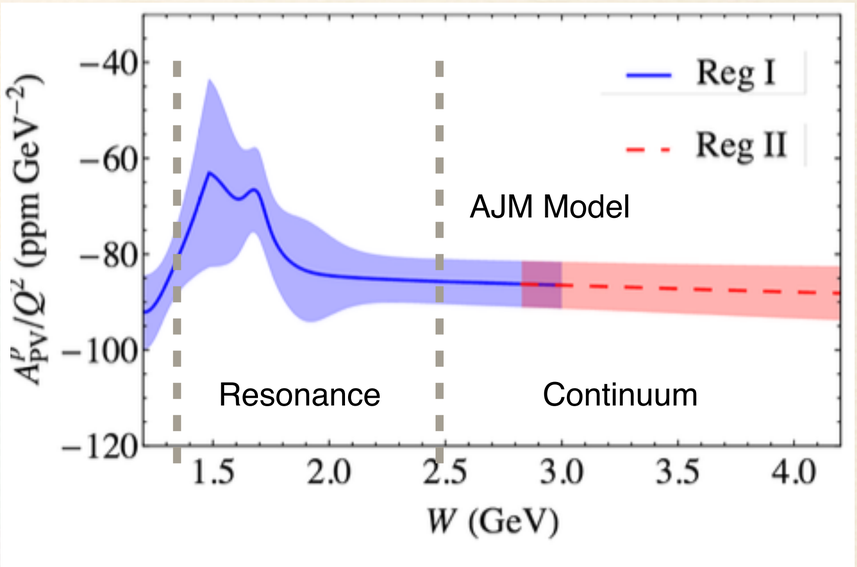
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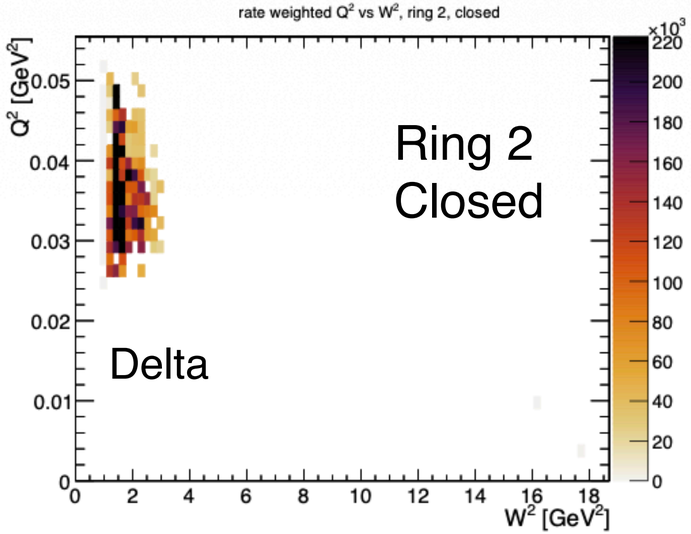


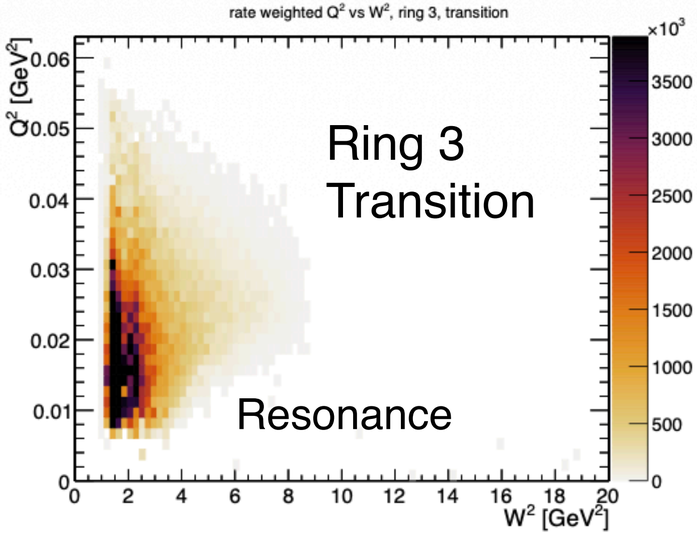
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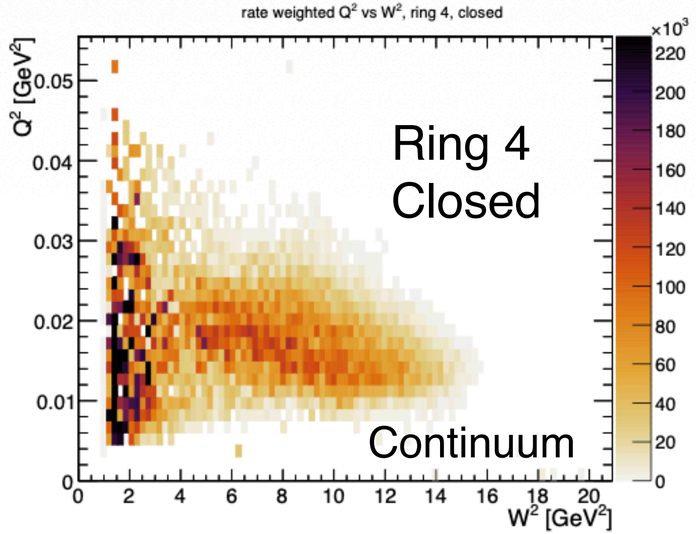
Key question for workshop: **Assumption in MOLLER: A_{PV}/Q^2 ~ F(W) roughly constant in 3 separate W regions: Delta, Resonance, Continuum**

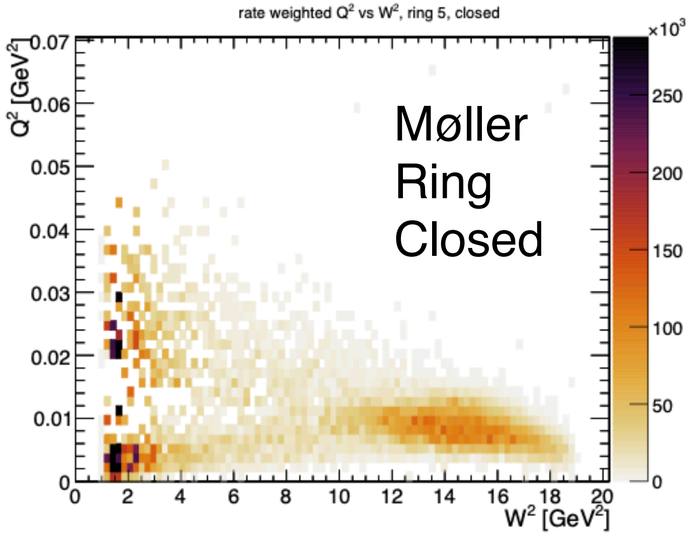
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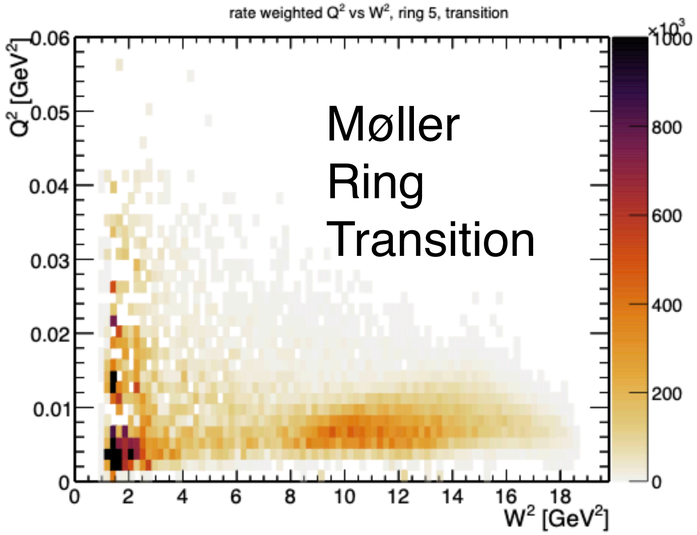
Kinematic Distributions in Various Tiles in Q^2-W^2 space

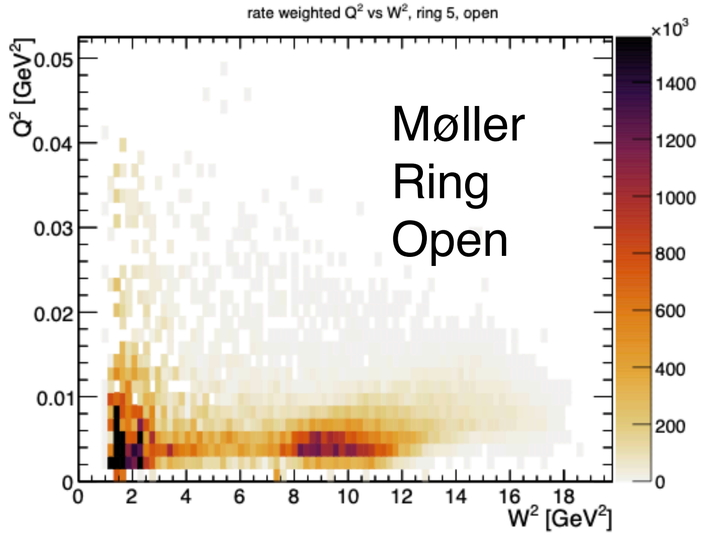




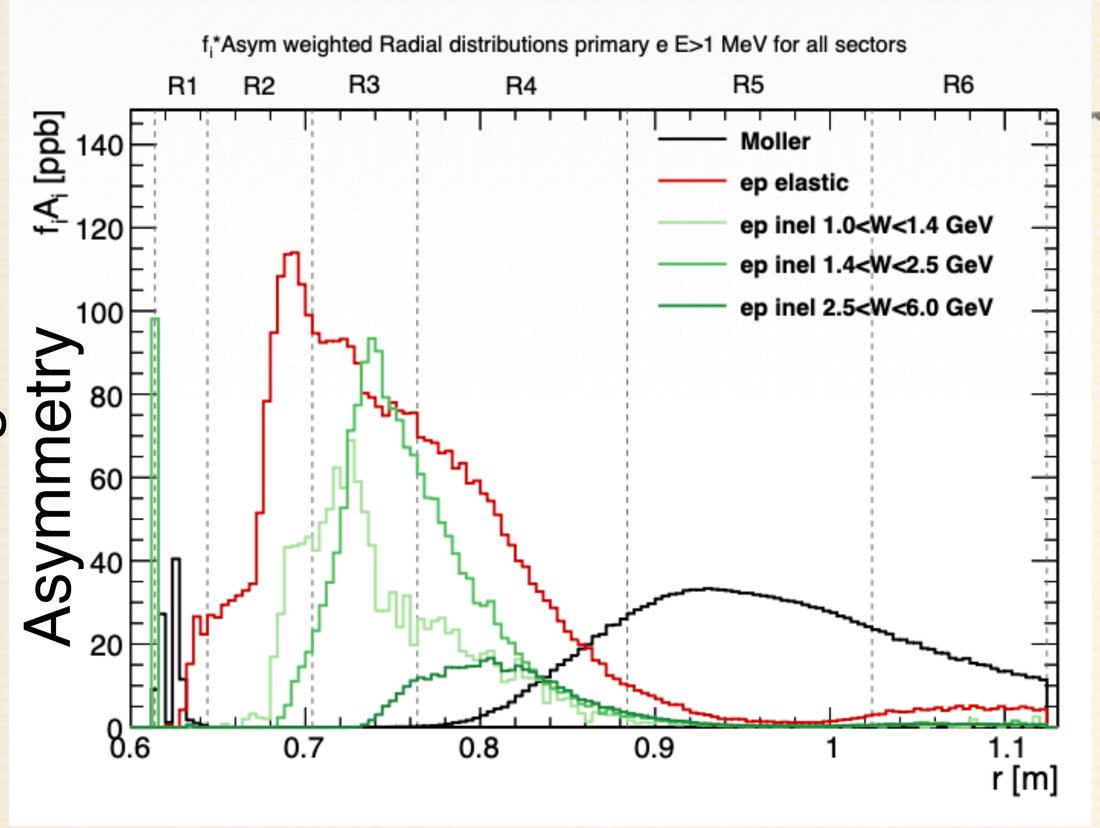








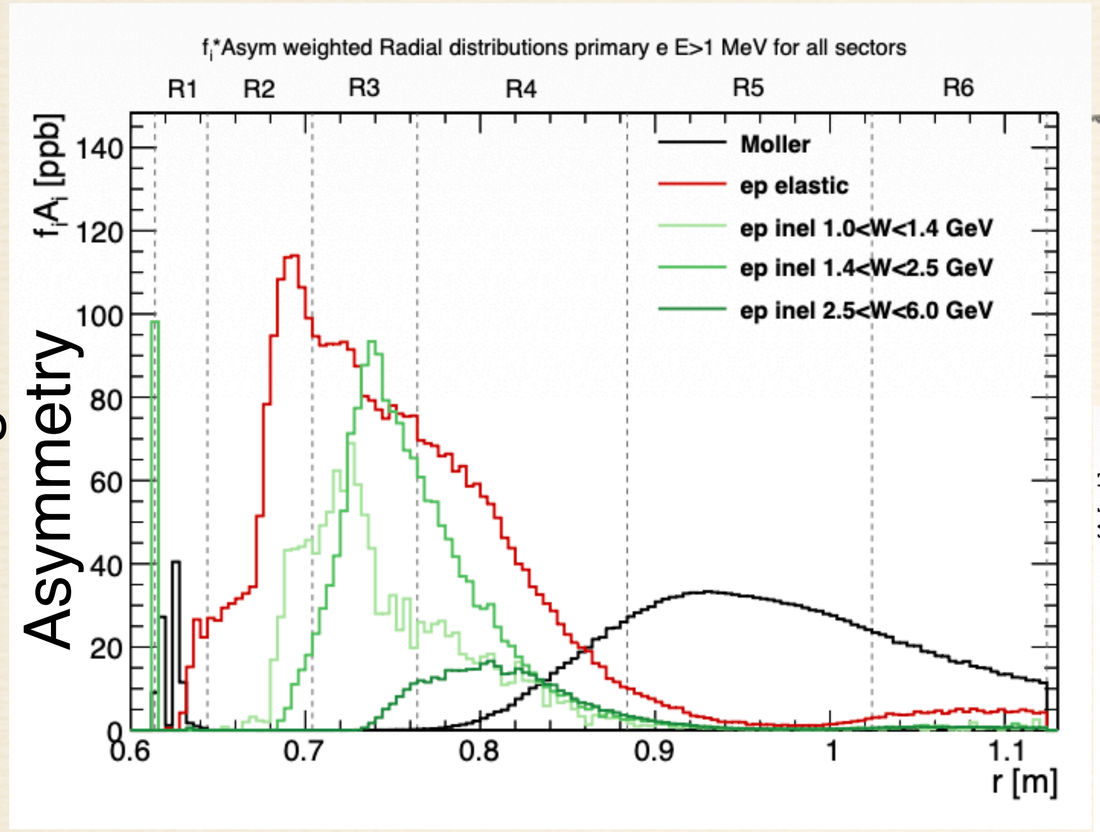
Simultaneous Extraction

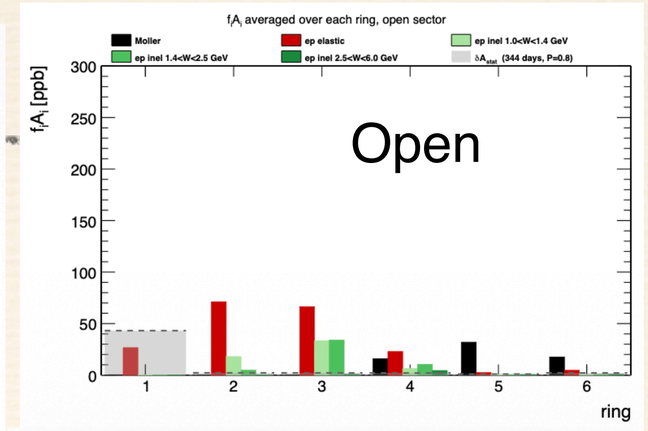


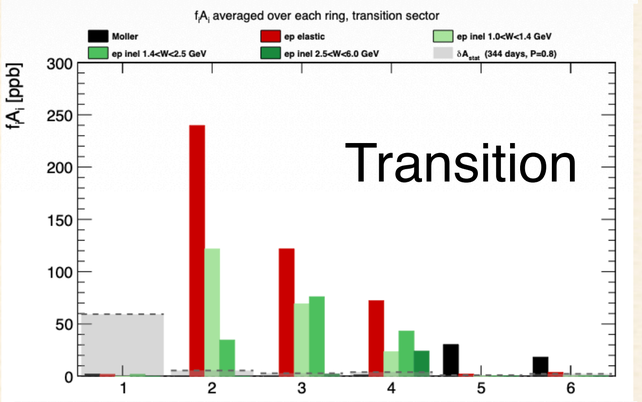
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- “Pre-subtract” Al and pion asymmetry contributions
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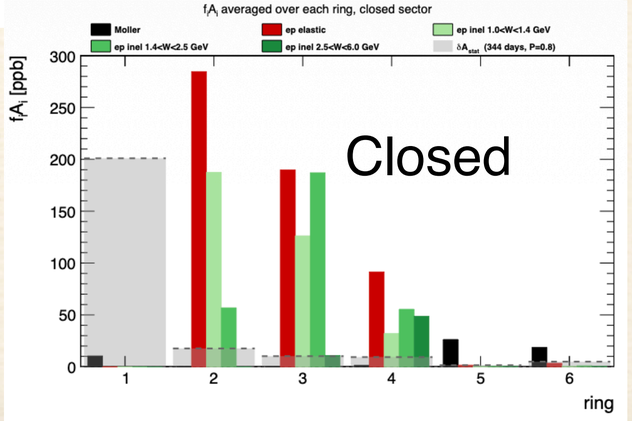
Simultaneous Extraction

Rate-weighted Asymmetry





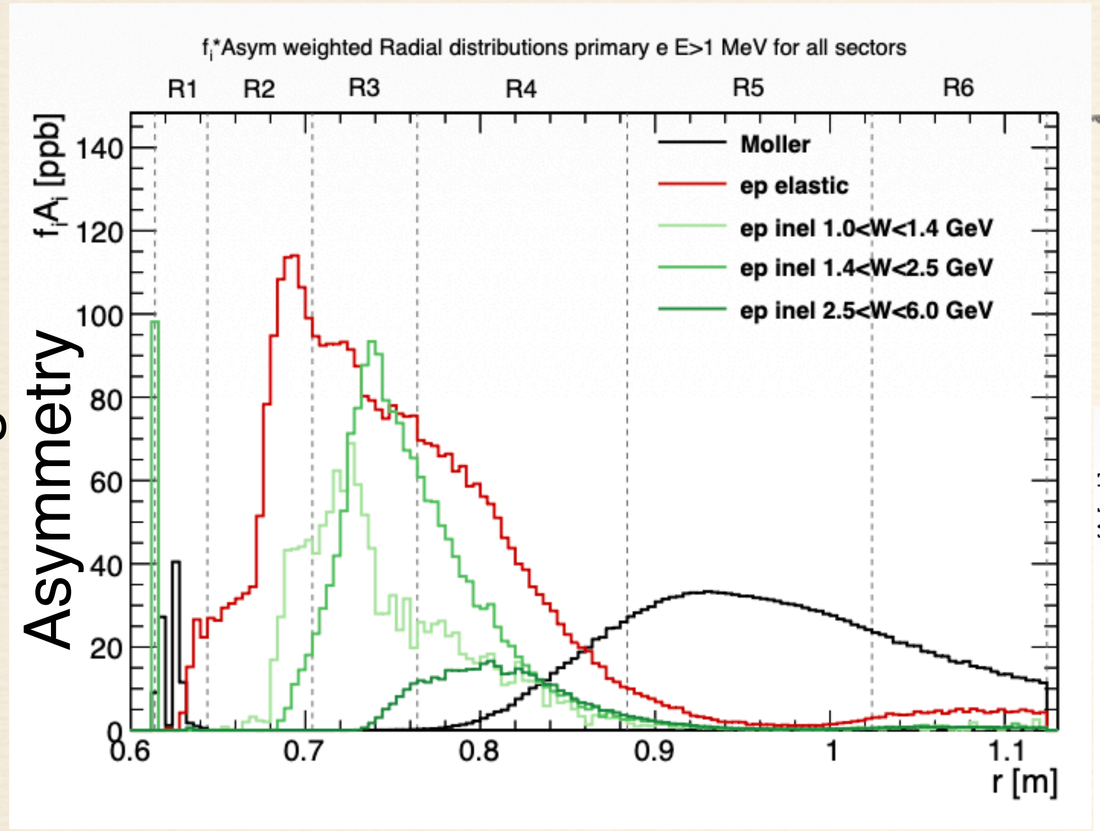


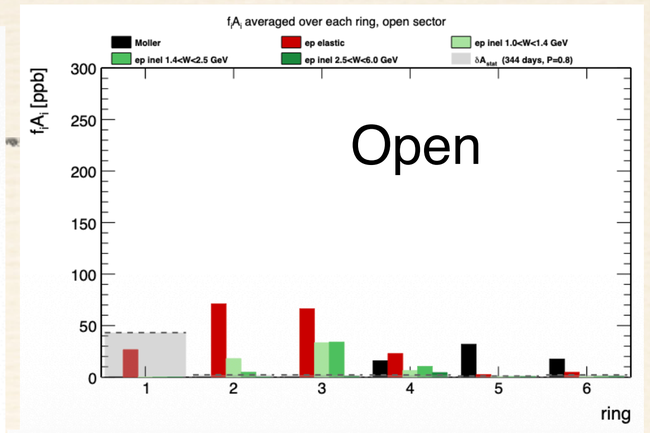


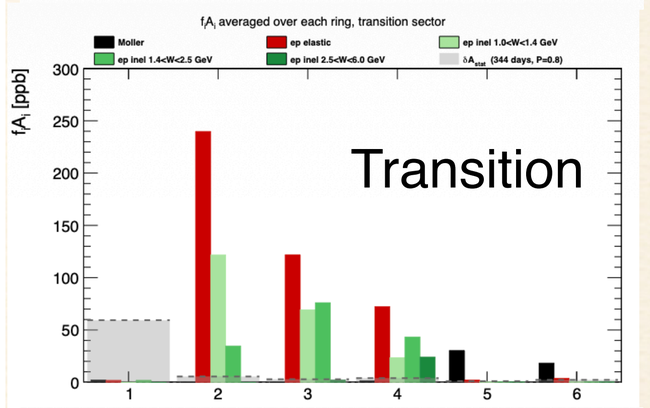
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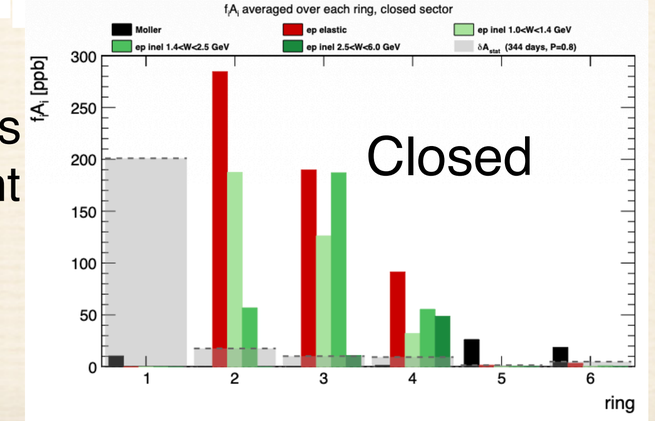
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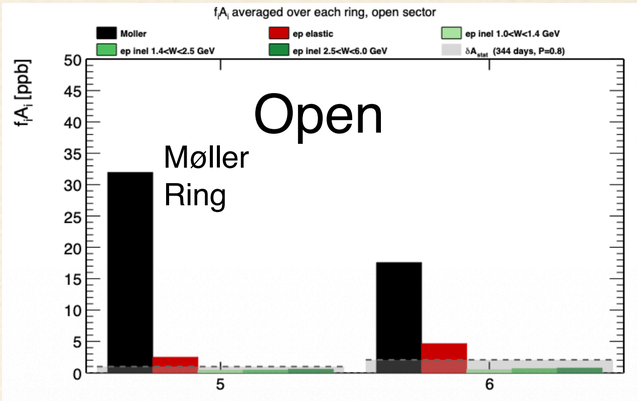
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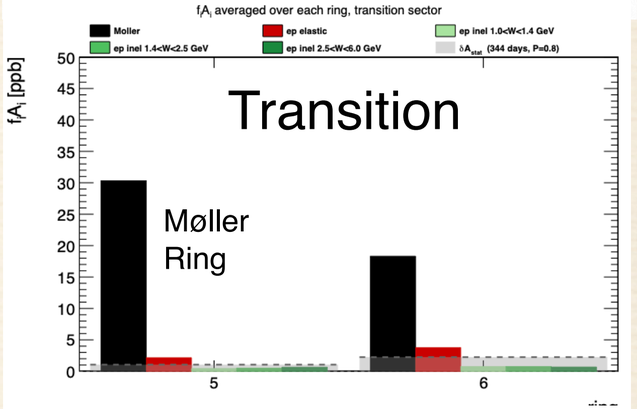


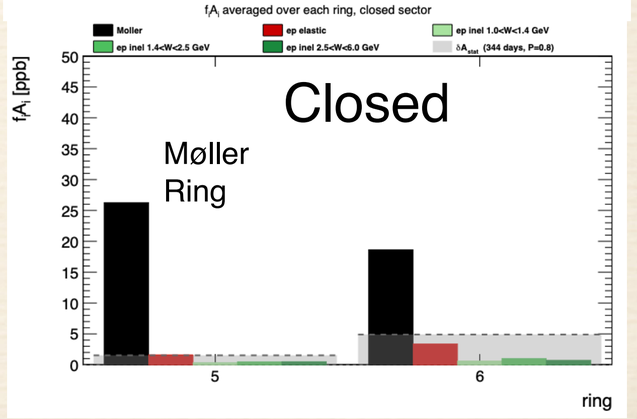








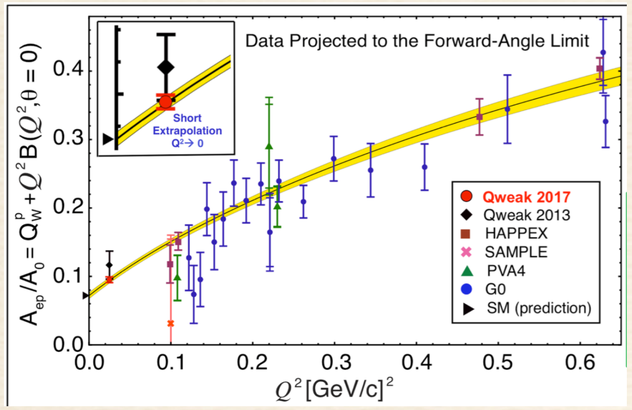




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MOLLER Proton Weak Charge Measurement

Nature 557 (2018) no.7704, 207-211

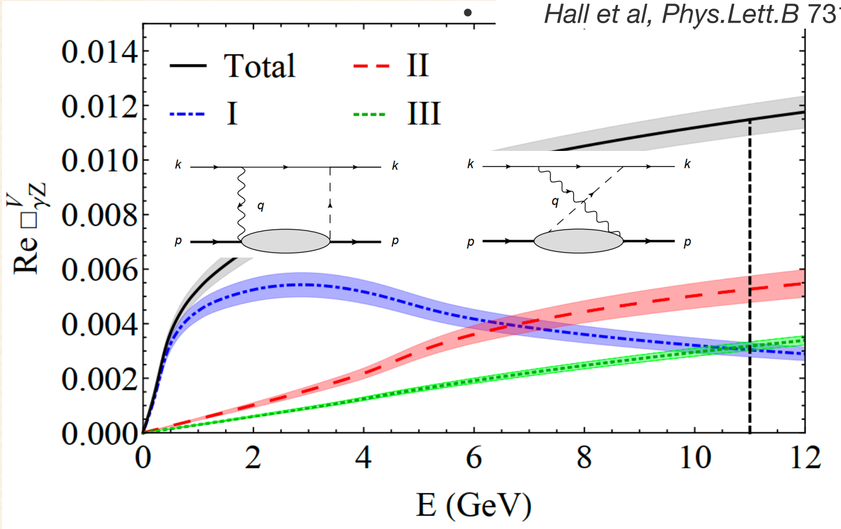


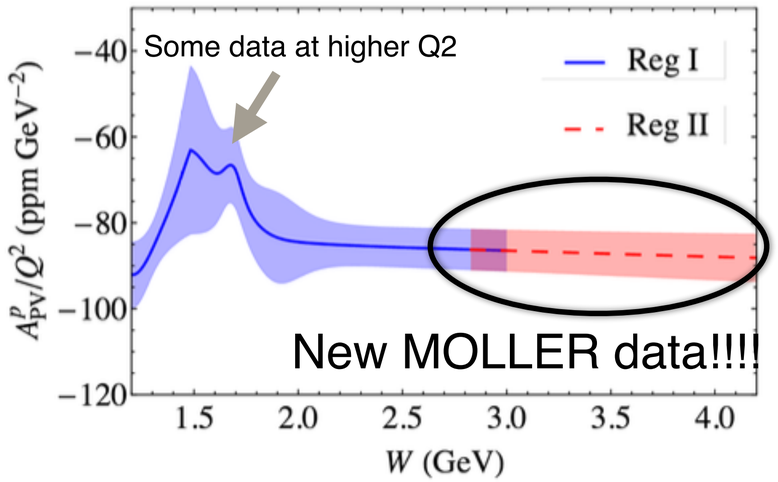
SM: 0.0708 ± 0.0003

Quantity		Value	Error
Q_W^p	Qweak	0.0719	0.0045
$\sin^2\theta_W$		0.2382	0.0011

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

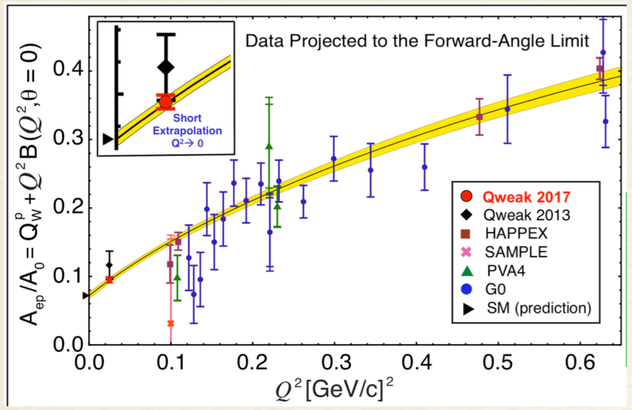
Hall et al, Phys.Lett.B 731 (2014) 287-292, *Phys.Lett.B* 733 (2014)





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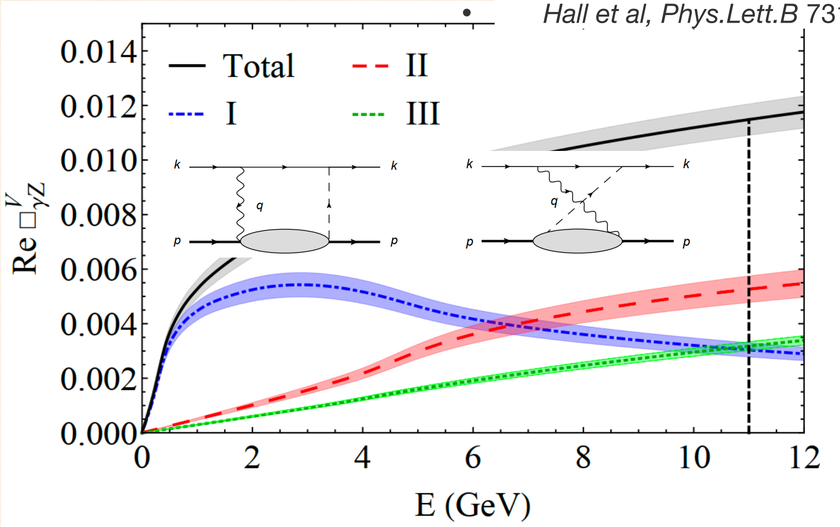


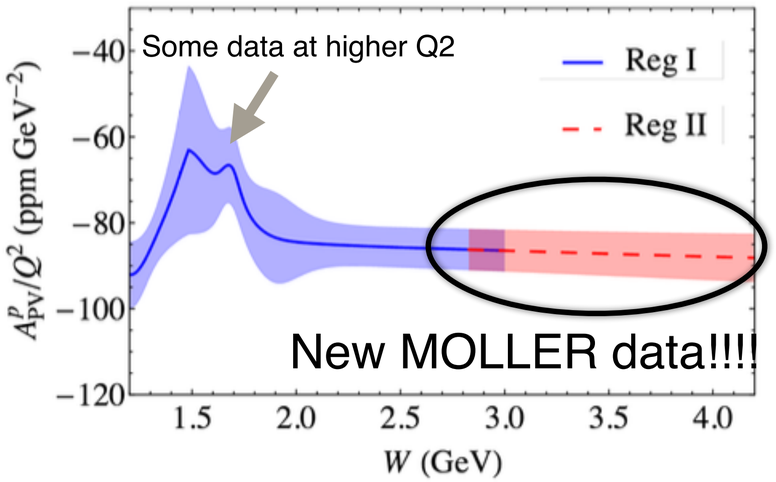
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Mock Fit Extraction with Monte Carlo Trial Data

Processes	Expected A (ppb)	σ_A (ppb)	$\frac{\sigma_A}{\lvert A\rvert}$ (%)
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

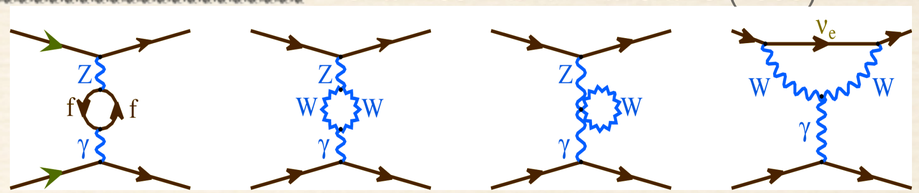
Process	Correction (%)	Systematic Error (%)
e-p elastic	1.14	0.08
e-p inelastic ($W < 1.4$ GeV)	-1.34	0.22
e-p inelastic ($1.4 < W < 2.5$ GeV)	-1.54	0.11
e-p inelastic ($W > 2.5$ GeV)	-1.66	0.35
e-Al elastic	0.87	0.09
e-Al other	< 0.10	< 0.10

A_{PV} in Møller Scattering: Theory

The Standard Model Prediction: Remarkably Well-Known

Czarnecki and Marciano (1995)

$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}} + \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2] + F_1(y,Q^2)+F_2(y,Q^2)\}$$

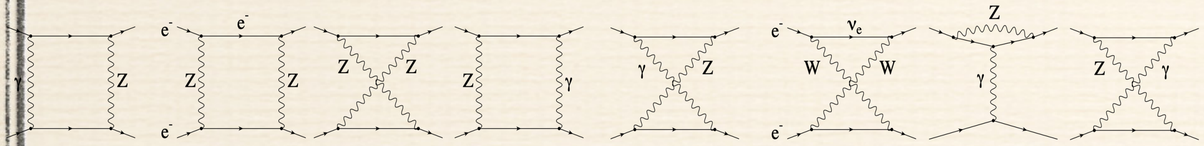


κ(0) known to 1% of itself
Erler and Ferro-Hernandez (2018)

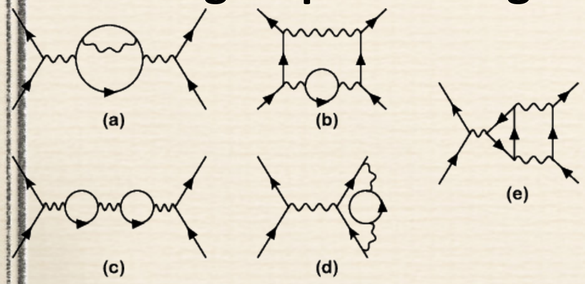
$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045$$

$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

δ(Q^e_W) ≲ 0.4%



2 groups working on 2-loop Calculations

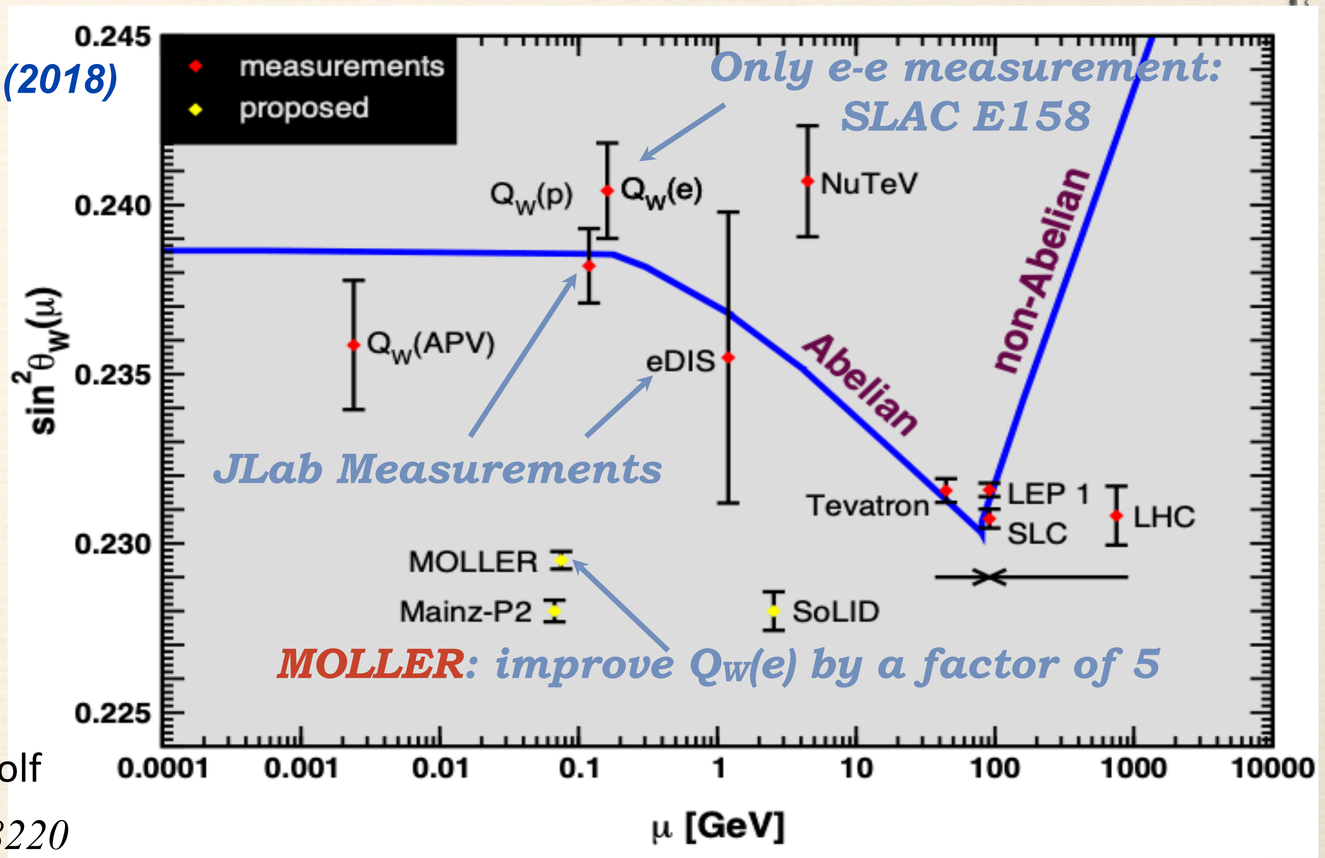


Aleksejevs and Barkanova

Series of publications

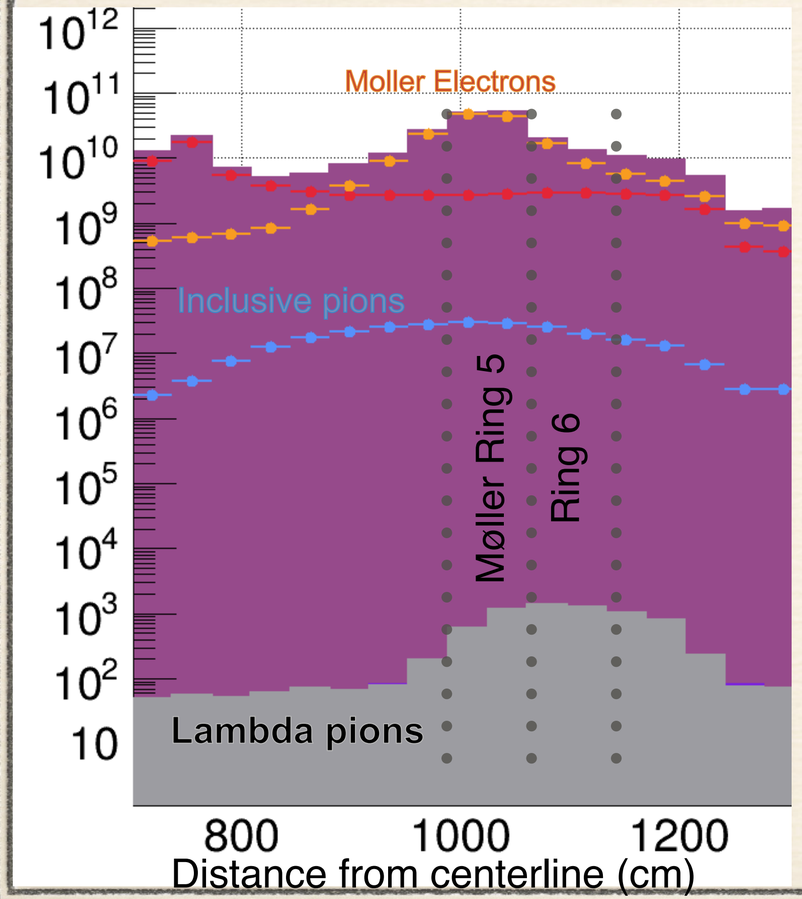
Du, Freitas, Patel and Ramsey-Musolf

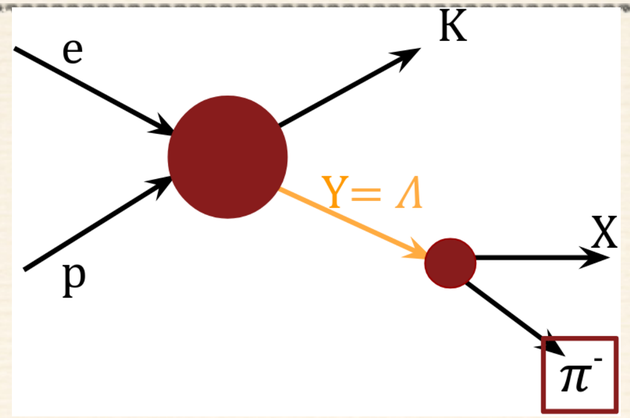
closed-fermion loops: arXiv:1912.08220



Pions from Hyperons

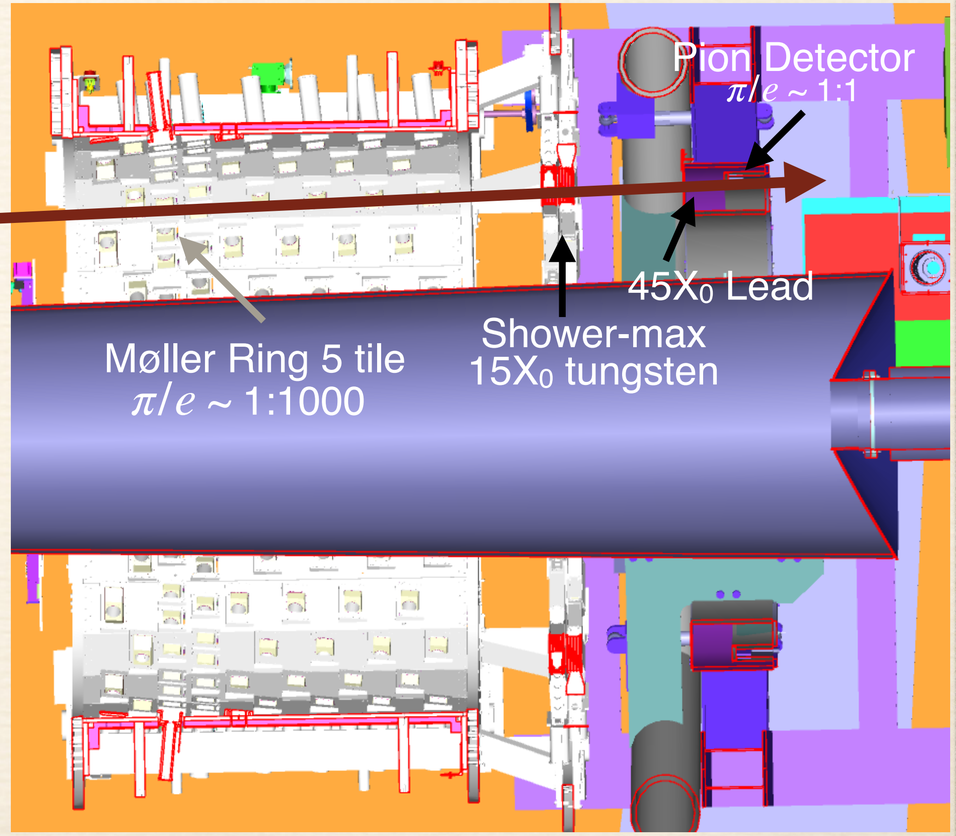
11 GeV electrons can electro- and photo-produce hyperons in the 1.25 m long liquid hydrogen target





- **Current MOLLER simulation estimate is that rate is ~ 10^{-8}**
- **A. Hurley will present the estimate of the correction**
- **J. Stevens will follow with the physics perspective, discussion of assumptions and future possibilities to improve on estimates**

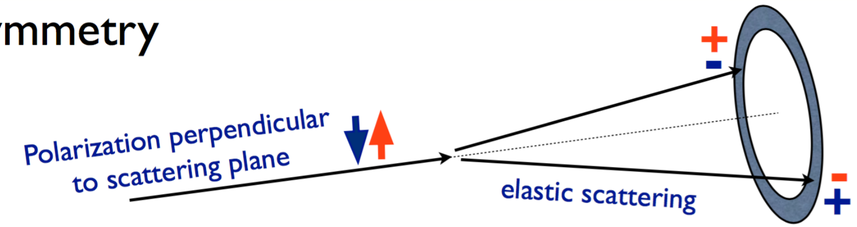
Since the pions are produced in a weak decay, they could have large PV analyzing power! 10%?



Sometimes called the Transverse Asymmetry A_T

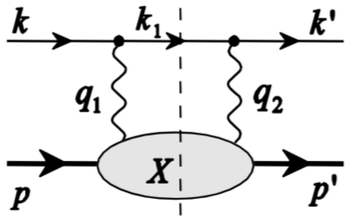
Beam Normal Single Spin Asymmetry

B_n asymmetry



time-reversal invariance forces this SSA to vanish for one-photon exchange

arises from an interference between the one-photon exchange (Born) amplitude and the imaginary part of the two-photon exchange amplitude



intermediate states on-shell

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\mathrm{Im}(T_{2\gamma} \cdot T_{1\gamma}^*)}{|T_{1\gamma}|}$$

Asymmetry is very small

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

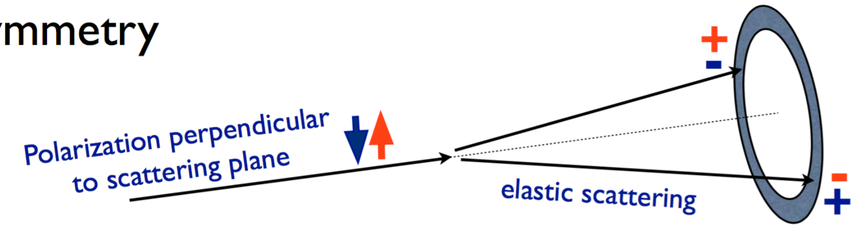
2-photon

ultra-relativistic

Sometimes called the Transverse Asymmetry A_T

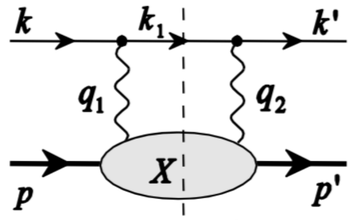
Beam Normal Single Spin Asymmetry

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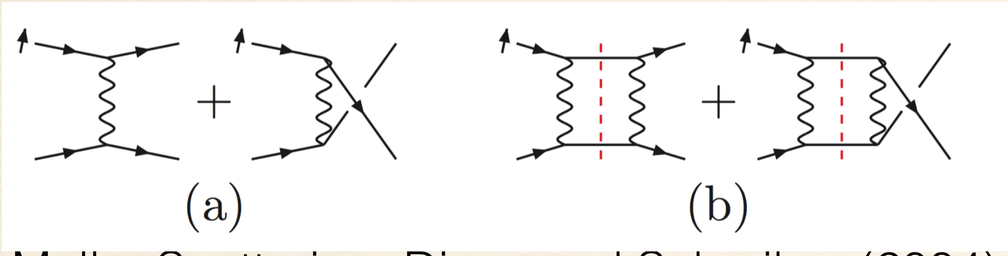
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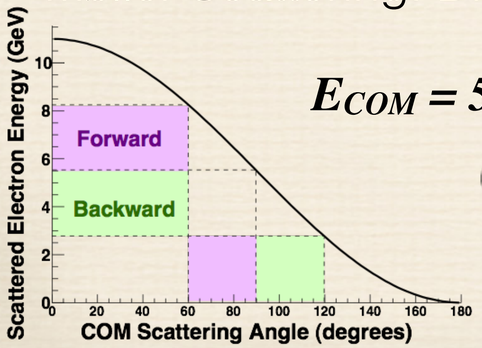
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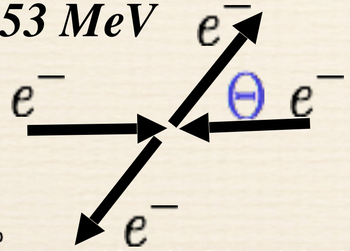
B_n must vanish at 90 degrees in the COM for Møller scattering



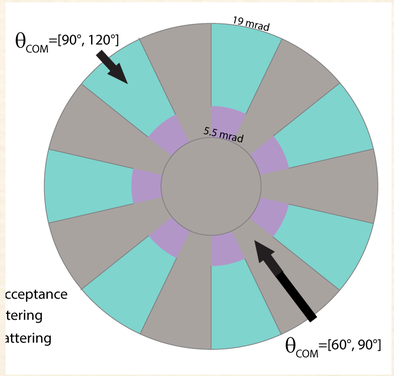
Møller Scattering: Dixon and Schreiber (2004)



$E_{COM} = 53\ MeV$



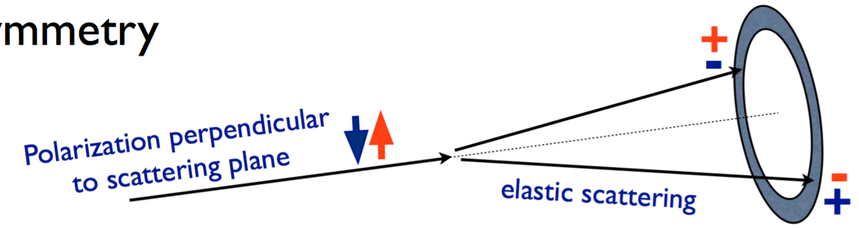
identical particles!



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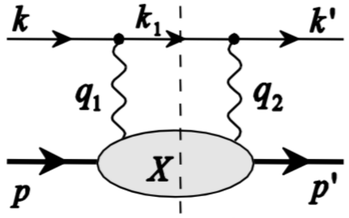
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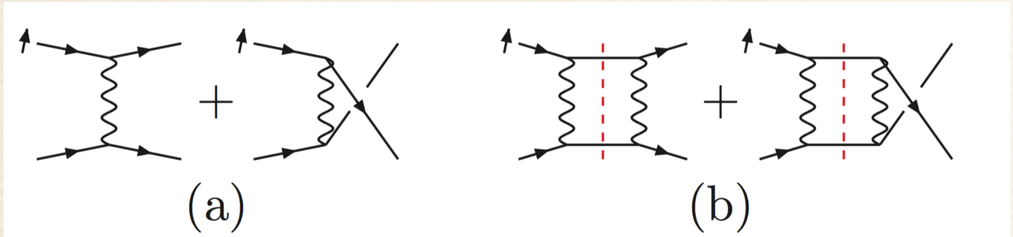
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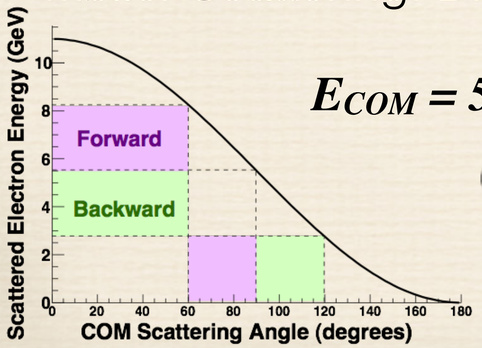
2-photon

ultra-relativistic

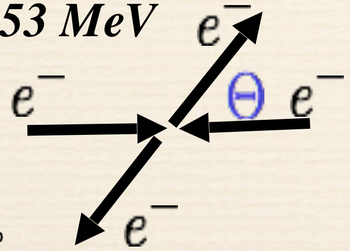
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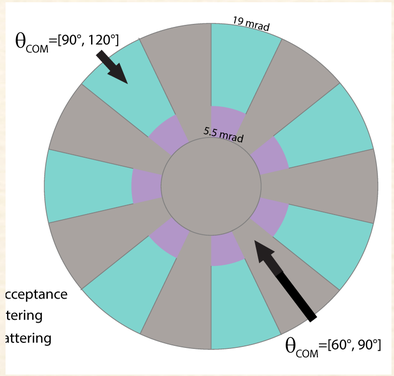
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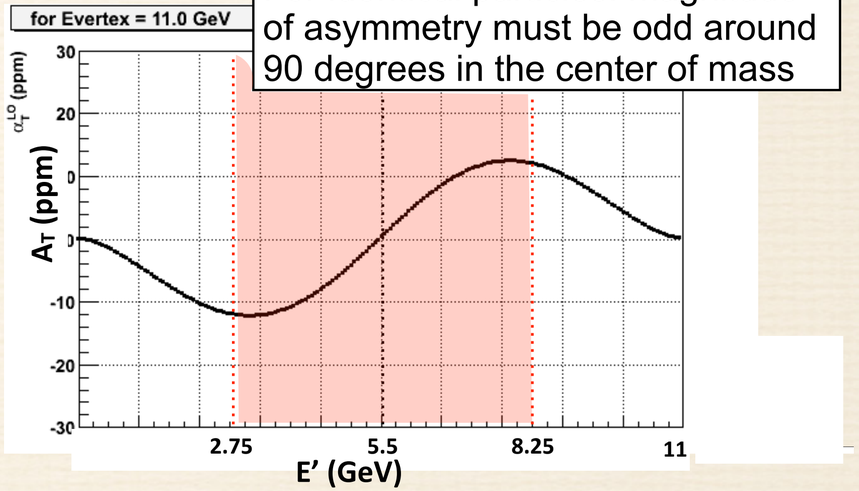
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identical particles!



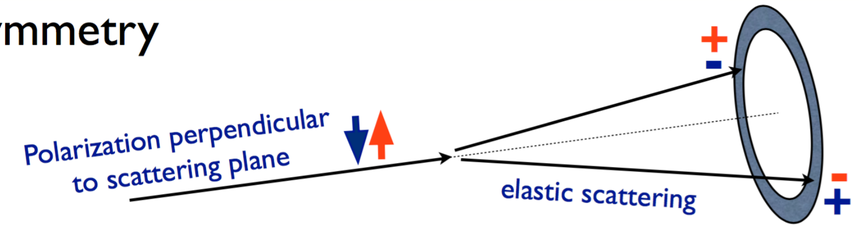
For identical particles: magnitude of asymmetry must be odd around 90 degrees in the center of mass



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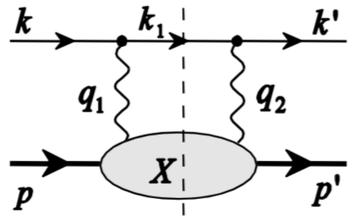
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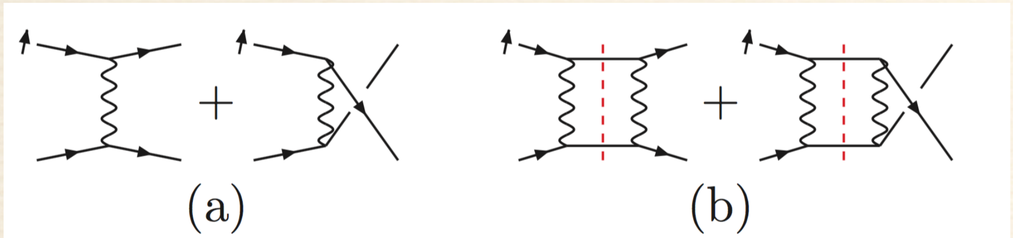
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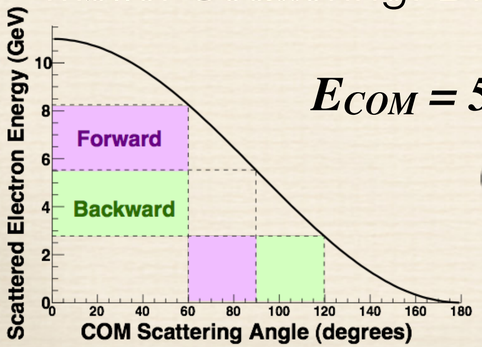
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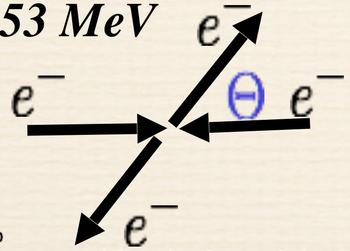
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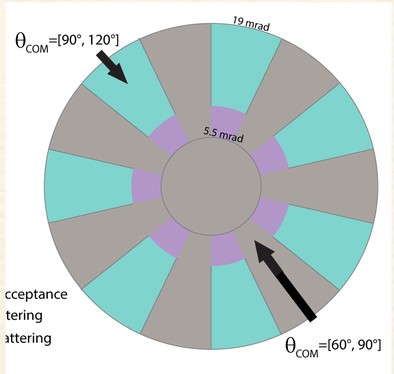
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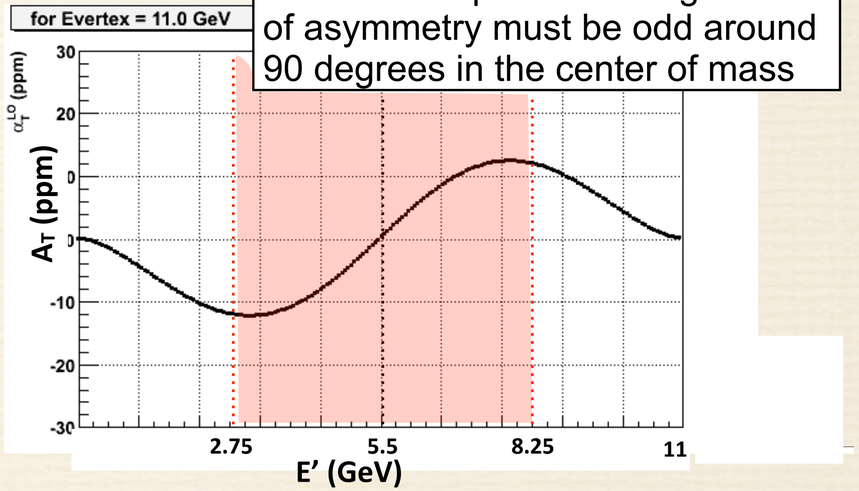
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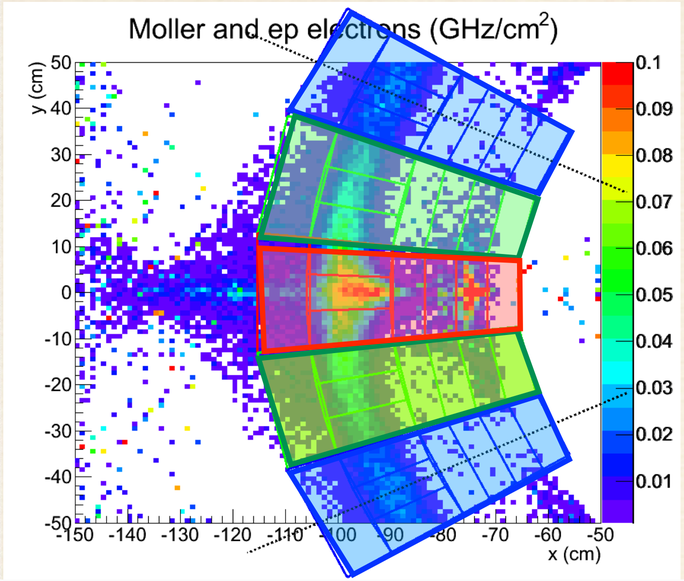
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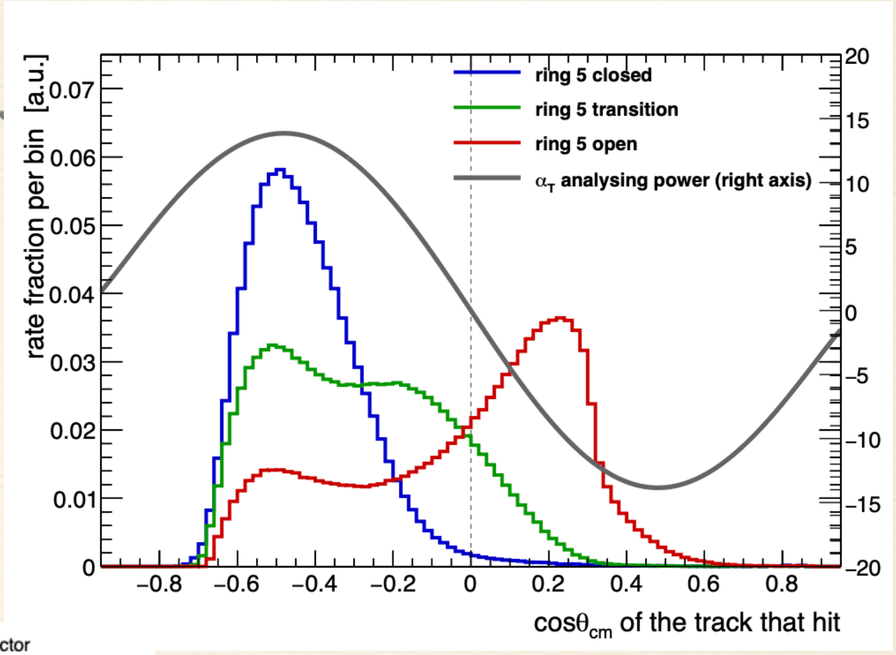
Dramatic demonstration of the quantum mechanics of identical particles in action!

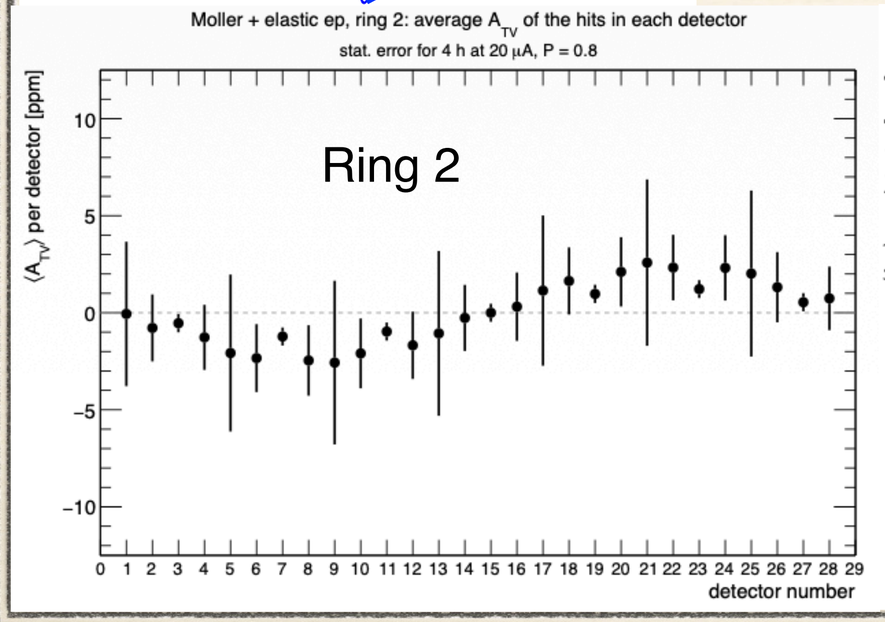
Simultaneous measurements of both e-e and e-p AT!

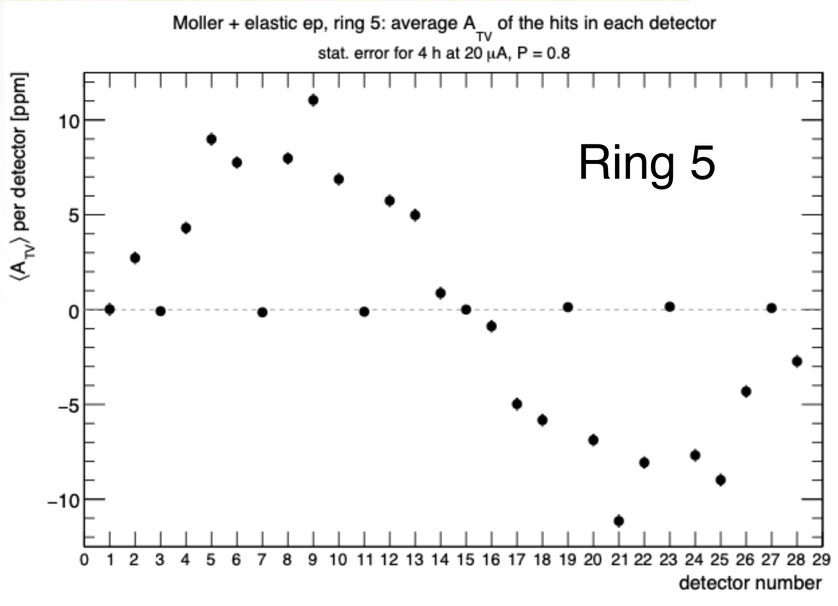
Very Cool First Physics within HOURS!



- **Ring 5 (Møller): Closed sectors select all backward electrons, Transition sectors selects majority backward electrons, Open sectors have roughly equal forward and backward electrons**
- **Ring 2 dominated by elastic e-p**

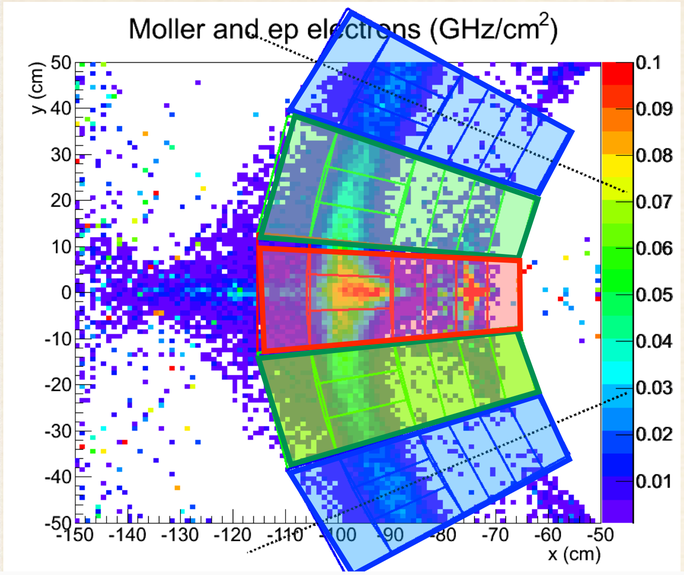




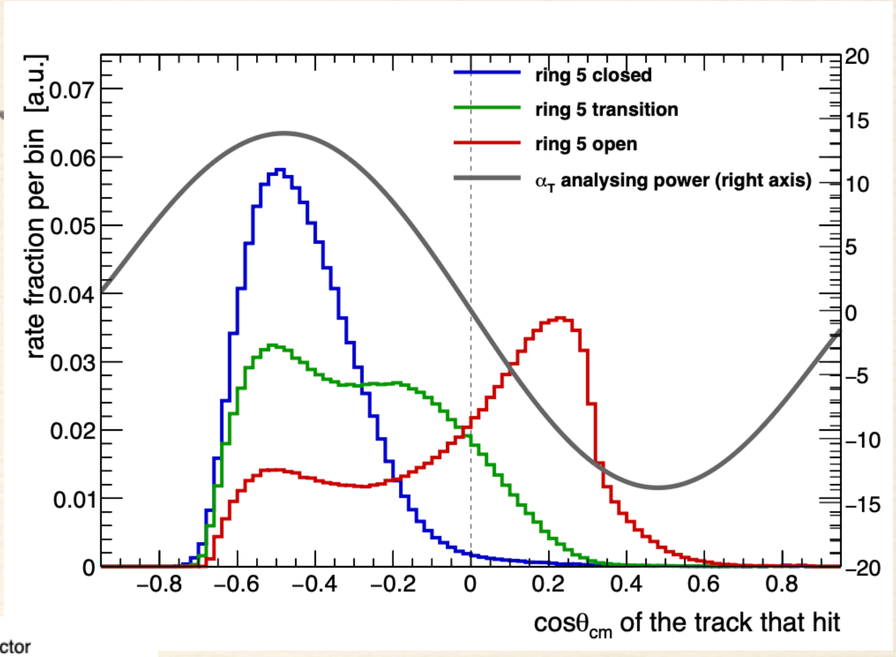


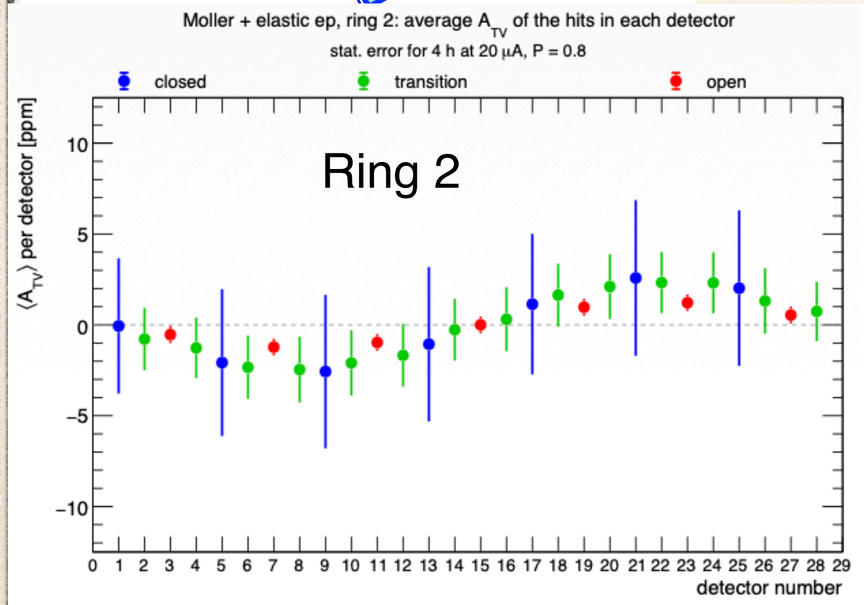
*Projections for a **4 hour** run at **20 microamps** with 100% transverse polarization:*
ring 5 dominated by A_T(ee) and ring 2 dominated by A_T(ep)

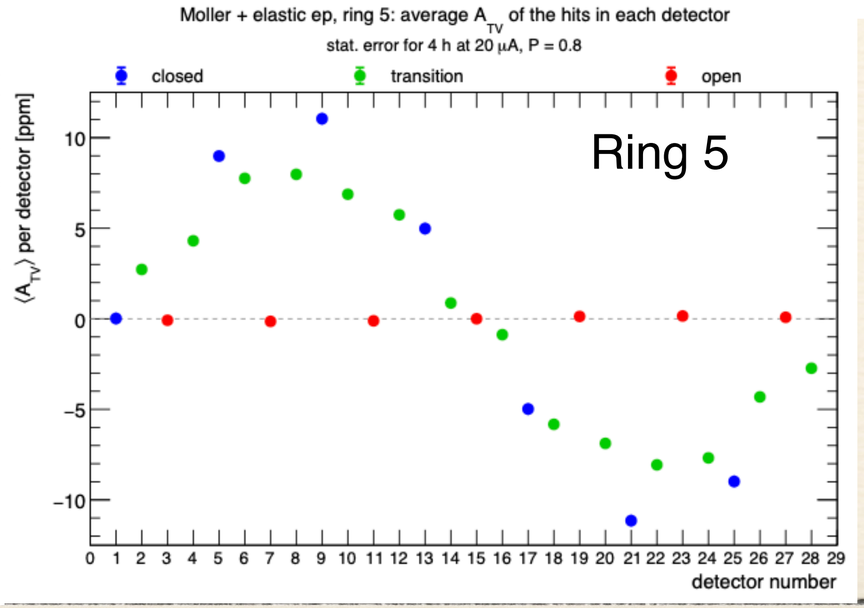
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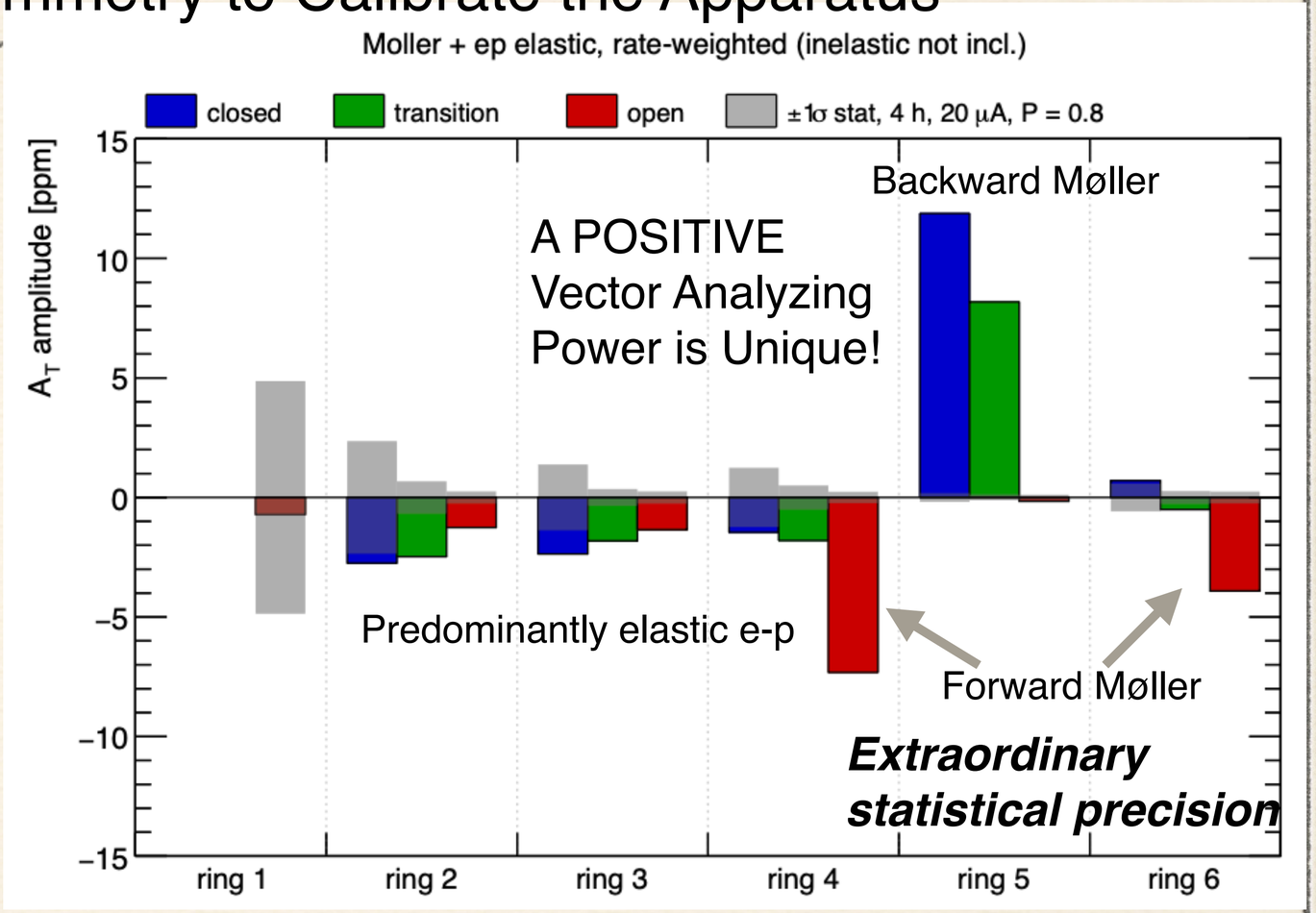
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Deconvolution for A_T

Use the Beam Normal Asymmetry to Calibrate the Apparatus

- set up for physics running
- convert to vertical polarization
- run a few hours to few days
- extract A_T with precision & accuracy much better than 0.5%

demonstrate complete understanding of apparatus:
simultaneous test of beam polarization, radiative corrections, detector acceptance, backgrounds



Is Møller B_n theory good to 0.1% with Dixon/Schreiber work?

What is A_T for INELASTIC e-p scattering?
What is A_T for pion production?

Summary of Workshop Topics

✦ Hadron Physics

- ★ **Gamma-Z Structure Functions at low Q and high W**
- ★ **Beam Normal Asymmetry in Inclusive Inelastic Scattering**
- ★ **Beam Normal Asymmetry in Pion Production**
- ★ **Polarized Hyperon Asymmetry**

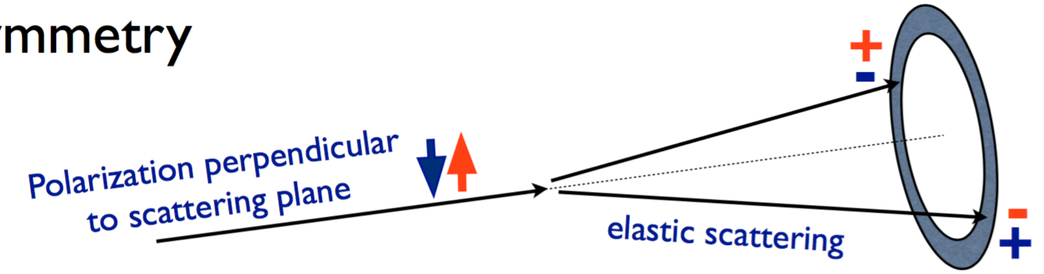
✦ Electroweak Physics

- ★ **Electroweak radiative corrections**
  - *Weak mixing angle running: lattice vs data-driven*
  - *Leading 2-loop done, complete 2-loop now being completed*
- ★ **Beam Normal Møller Asymmetry (intrinsically 1-loop effect)**
  - *Experimental measurement is expected to be made at the sub-0.5% level: need commensurate higher-order calculation*

Backup

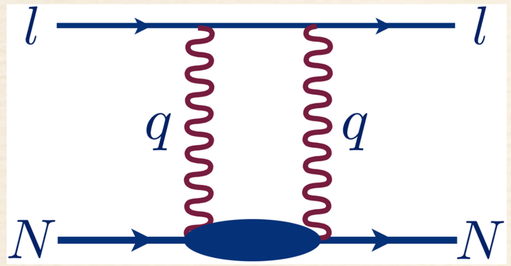
PREX/CREX B_n Measurements on Nuclei

B_n asymmetry



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

$$A(\phi) = A_n(\theta,\ E_{beam})\,P_n\cos(\phi) \qquad A_n = \frac{2A_{Born}\mathcal{I}(A^*_{2\gamma})}{|A_{Born}|^2}$$



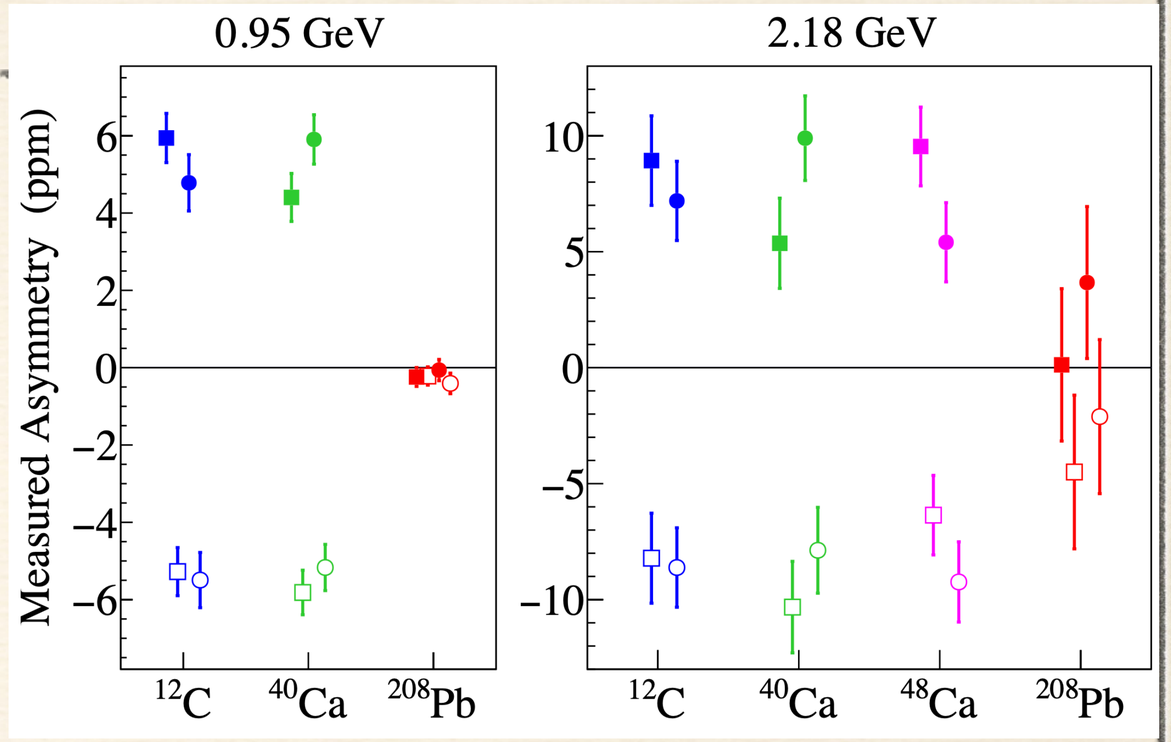
Two-Photon Exchange (TPE)

Asymmetry is very small

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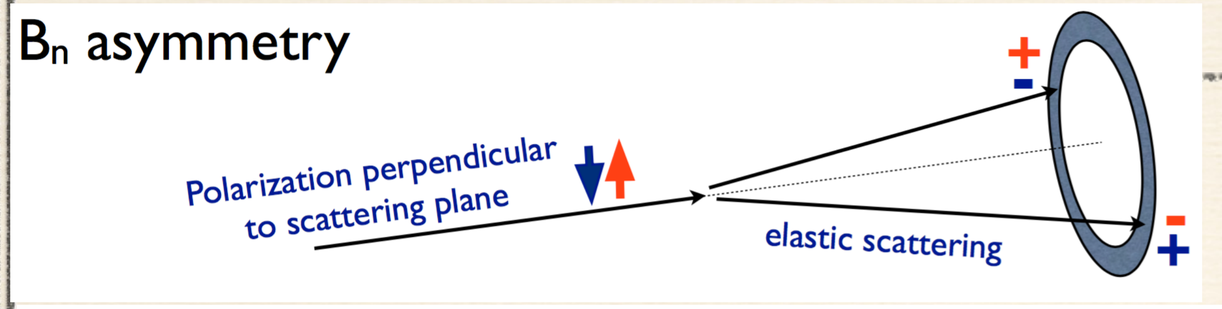
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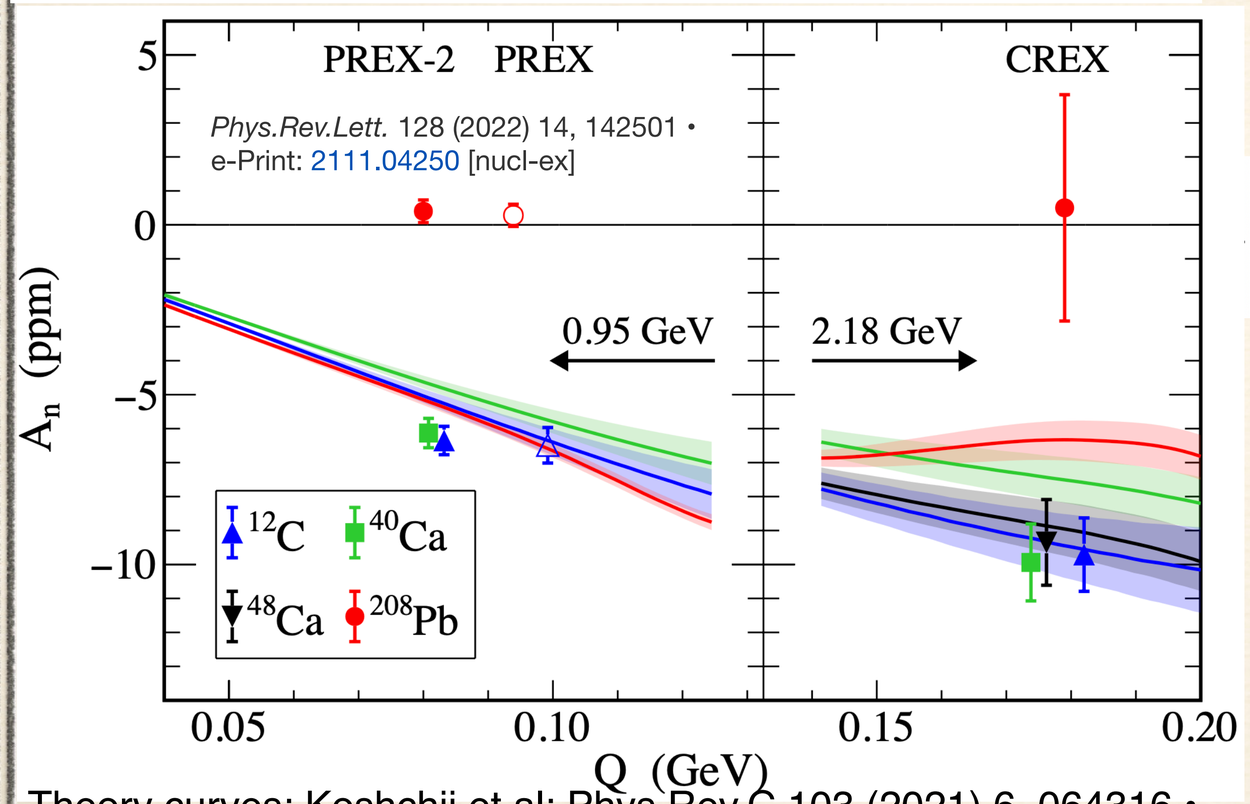
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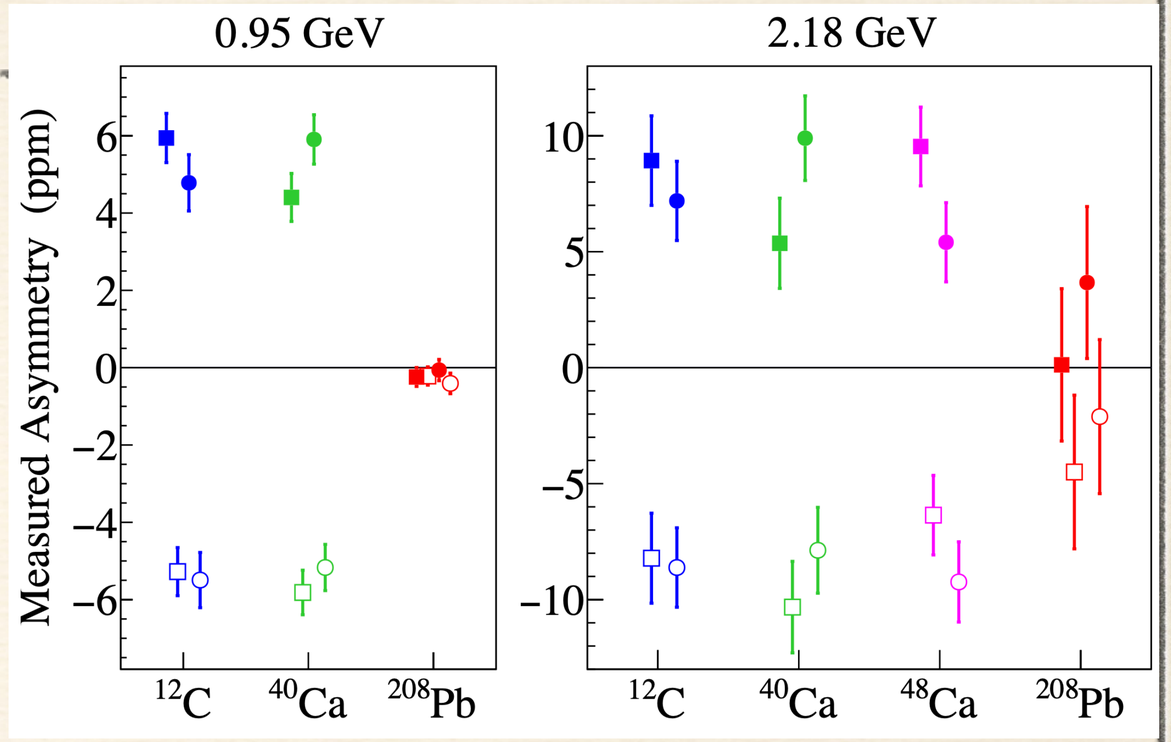
- **High Beam Energy**
- **Very Forward Angle**
- **Clean Separation of Inelastics**
- **Tremendous Statistics**

PREX/CREX B_n Measurements on Nuclei



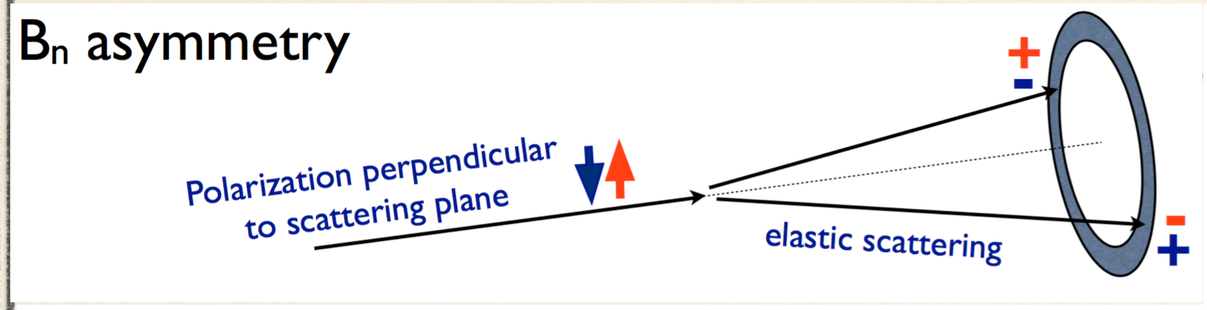


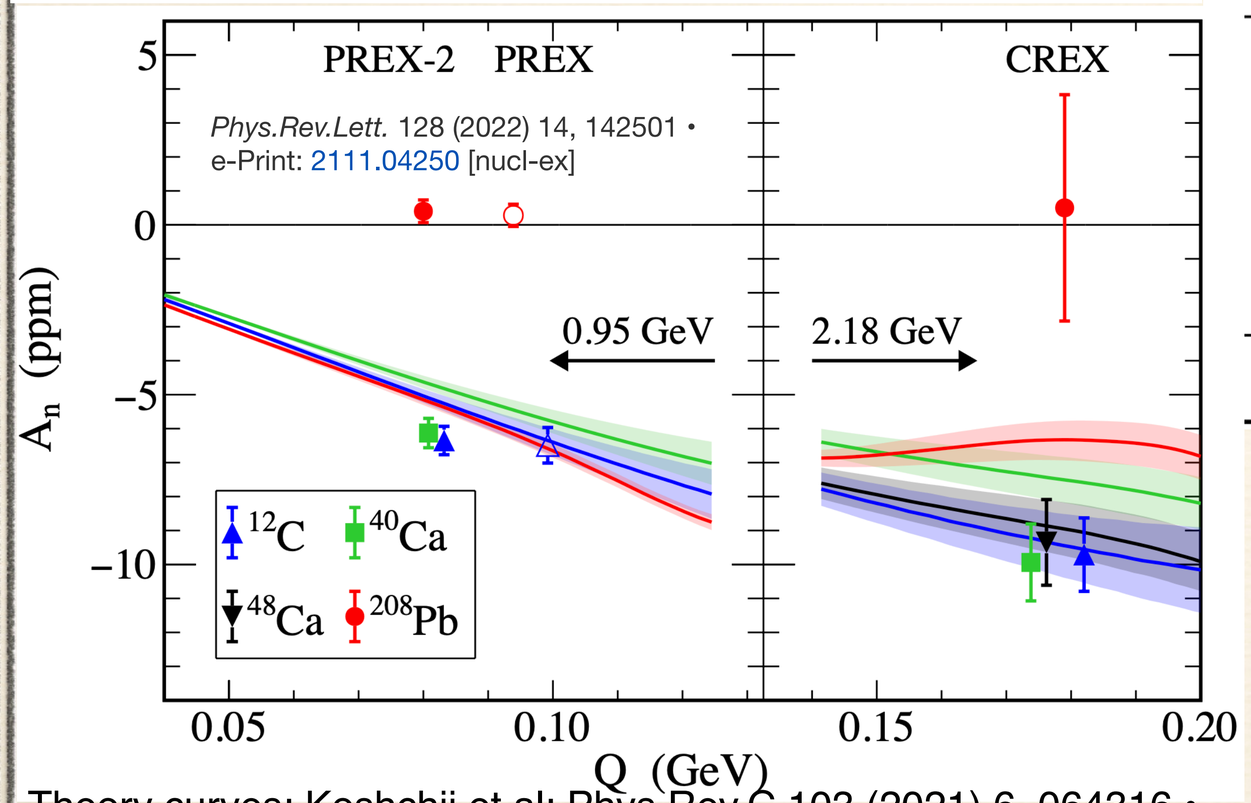
Theory curves: Koshchii et al: Phys.Rev.C 103 (2021) 6, 064316 • e-Print: 2102.11809 • DOI: 10.1103/PhysRevC.103.064316



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PREX/CREX B_n Measurements on Nuclei





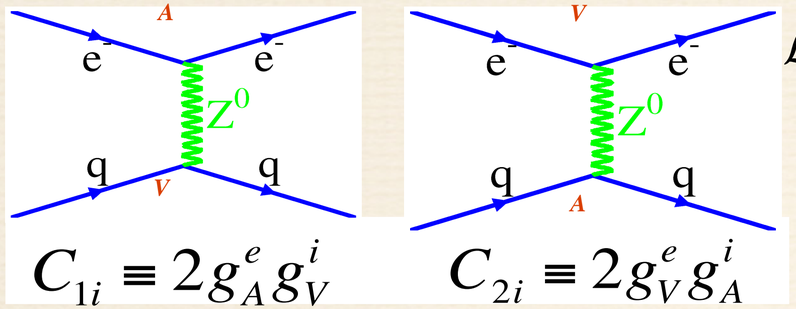
E_{beam} (GeV)	Target	A_n (ppm)	$A_{avg}^{Z\leq 20}$ (ppm)	$\frac{A_n - A_{avg}^{Z\leq 20}}{uncert}$
0.95	^{12}C	-6.3 ± 0.4	-6.2 ± 0.2	
0.95	^{40}Ca	-6.1 ± 0.3		
0.95	^{208}Pb	0.4 ± 0.2		21 σ
2.18	^{12}C	-9.7 ± 1.1	-9.7 ± 0.6	
2.18	^{40}Ca	-10.0 ± 1.1		
2.18	^{48}Ca	-9.4 ± 1.1		
2.18	^{208}Pb	0.6 ± 3.2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

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

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

Weak Neutral Current (WNC) Couplings

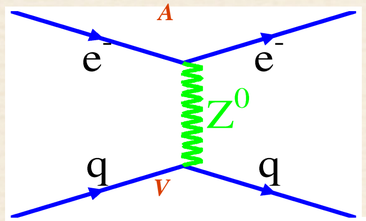


$C_{1i} \equiv 2 g_A^e g_V^i$

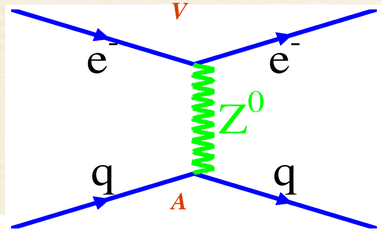
$C_{2i} \equiv 2 g_V^e g_A^i$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}} [\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)]$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$



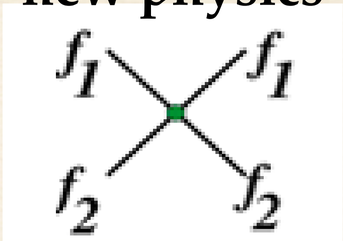
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$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
C_{2d}	$=$	$\frac{1}{2}-2\sin^2\theta_W$	$\approx$	0.04

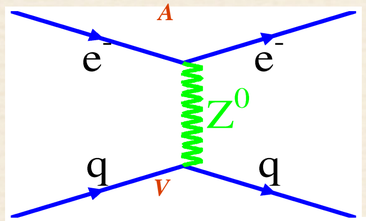
+

new physics

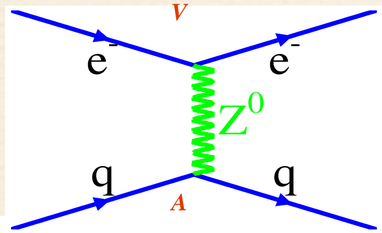


$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$



$C_{2i} \equiv 2 g_V^e g_A^i$

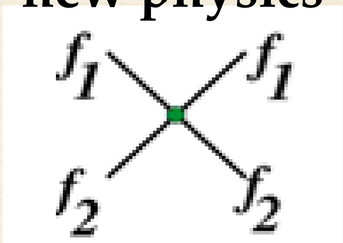
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

C_{1u}	$=$	$-\frac{1}{2}+\frac{4}{3}\sin^2\theta_W$	$\approx$	-0.19
C_{1d}	$=$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$\approx$	0.35
C_{2u}	$=$	$-\frac{1}{2}+2\sin^2\theta_W$	$\approx$	-0.04
C_{2d}	$=$	$\frac{1}{2}-2\sin^2\theta_W$	$\approx$	0.04

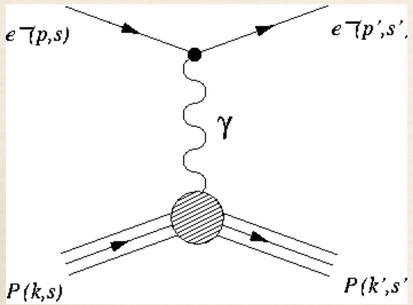
$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2$$ ⇨ ***PV elastic e-N scattering, Atomic parity violation***

+

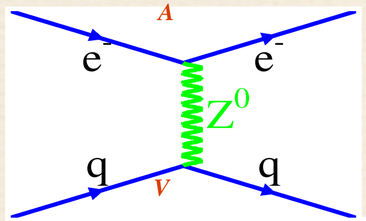
new physics



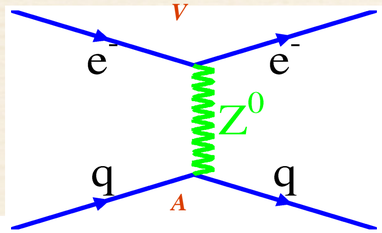
$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$



Weak Neutral Current (WNC) Couplings



$C_{1i} \equiv 2 g_A^e g_V^i$



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$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

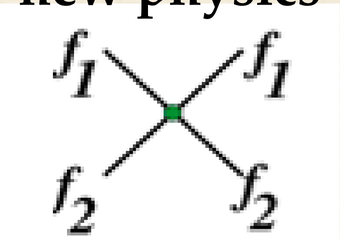
PV elastic e-N scattering, Atomic parity violation

$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$

PV deep inelastic scattering

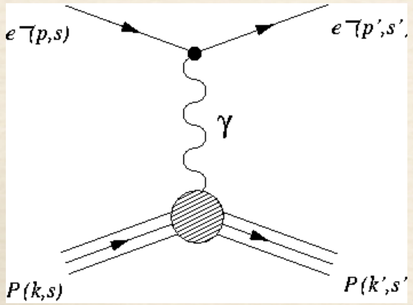
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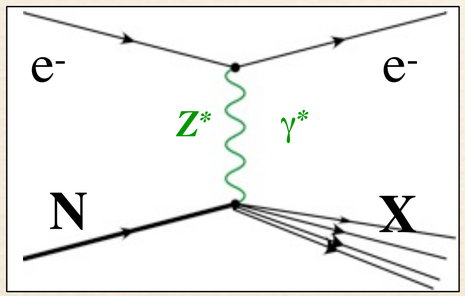
new physics



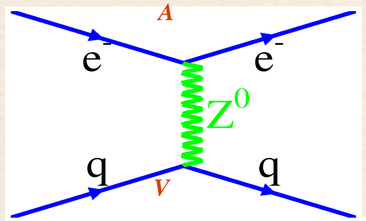
$$\mathcal{L}_{f_1 f_2} =$$

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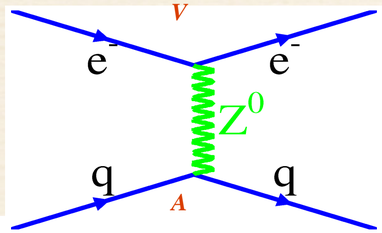




Weak Neutral Current (WNC) Couplings



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$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)] + C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

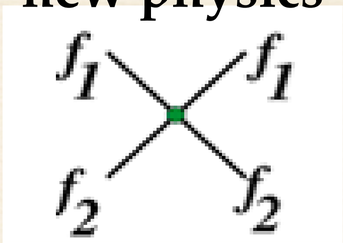
$$\begin{array}{lcll} C_{1u} & = & -\frac{1}{2}+\frac{4}{3}\sin^2\theta_W & \approx -0.19 \\ C_{1d} & = & \frac{1}{2}-\frac{2}{3}\sin^2\theta_W & \approx 0.35 \\ C_{2u} & = & -\frac{1}{2}+2\sin^2\theta_W & \approx -0.04 \\ C_{2d} & = & \frac{1}{2}-2\sin^2\theta_W & \approx 0.04 \end{array}$$

$$C_{1q} \propto (g_{RR}^{eq})^2 + (g_{RL}^{eq})^2 - (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV elastic e-N scattering, Atomic parity violation***

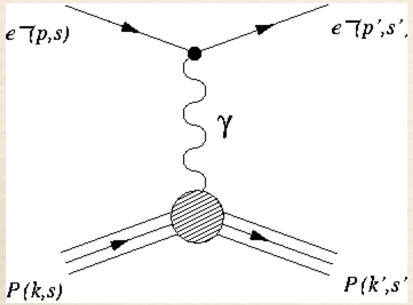
$$C_{2q} \propto (g_{RR}^{eq})^2 - (g_{RL}^{eq})^2 + (g_{LR}^{eq})^2 - (g_{LL}^{eq})^2 \Rightarrow$$ ***PV deep inelastic scattering***

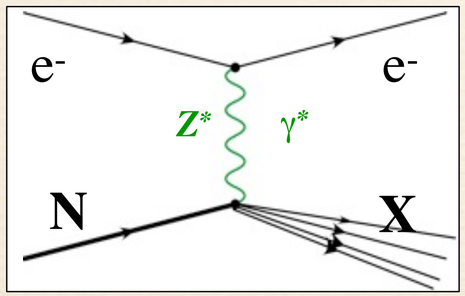
$$C_{ee} \propto (g_{RR}^{ee})^2 - (g_{LL}^{ee})^2 \Rightarrow$$ ***PV Møller scattering***

+ new physics

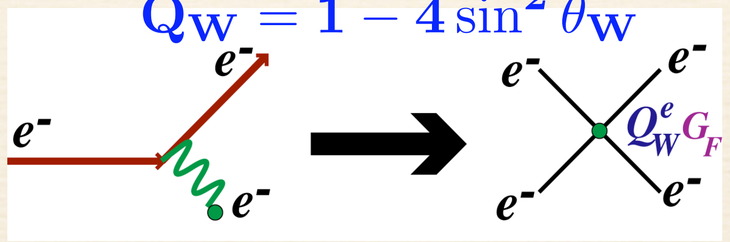


$$\mathcal{L}_{f_1 f_2} =$$





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



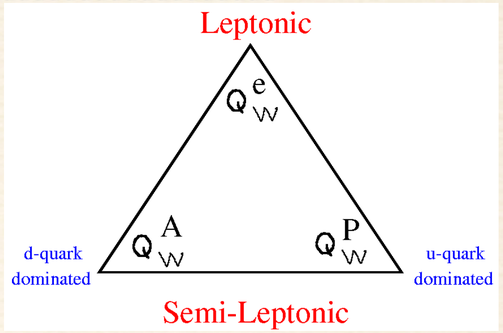
$$\sum_{i,j=L,R} \frac{(g_{ij}^{12})^2}{\Lambda_{ij}^2} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma_\mu f_{2j}$$

PVES New Physics Reach

Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4\pi$)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

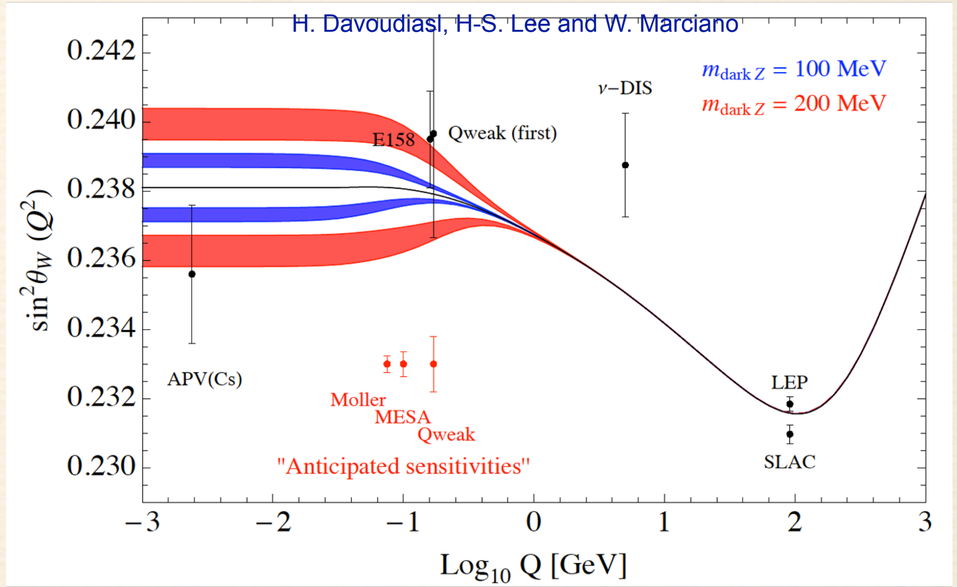
J. Erler



Courtesy: M. Ramsey-Musolf

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings



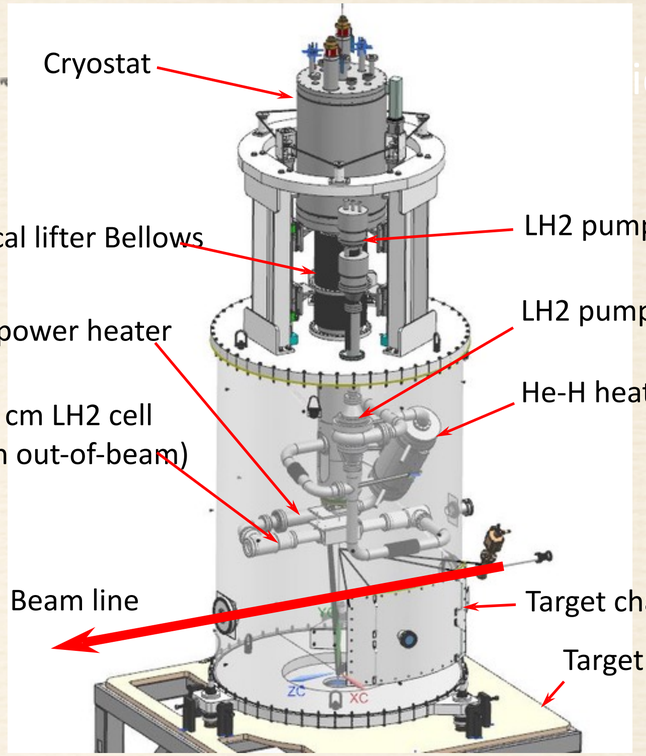
✦Complementary to collider Drell-Yan Searches
✦Unique sensitivity to low energy dark Z's

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 (Δρ/ρ):

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



Liquid Hydrogen Target

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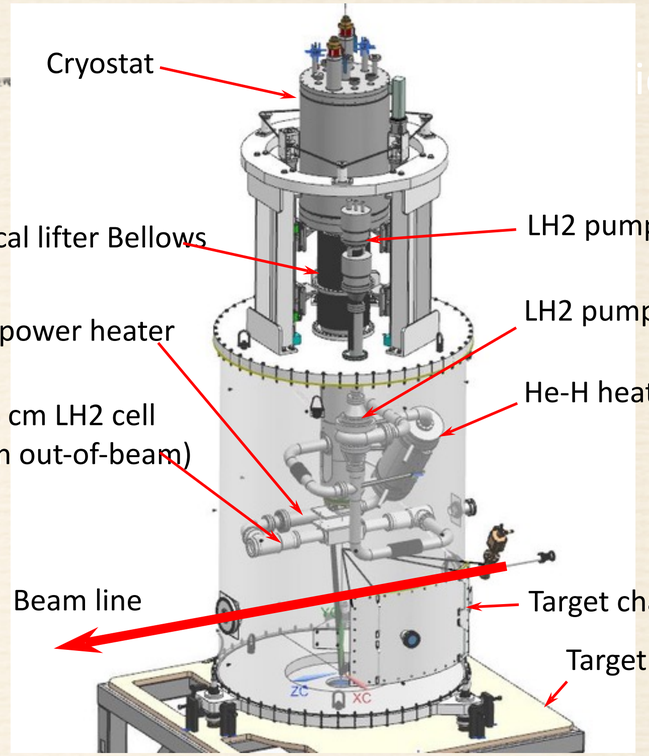
Main requirement: minimize target density fluctuations (Δρ/ρ):

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



Test fit of scattering chamber completed

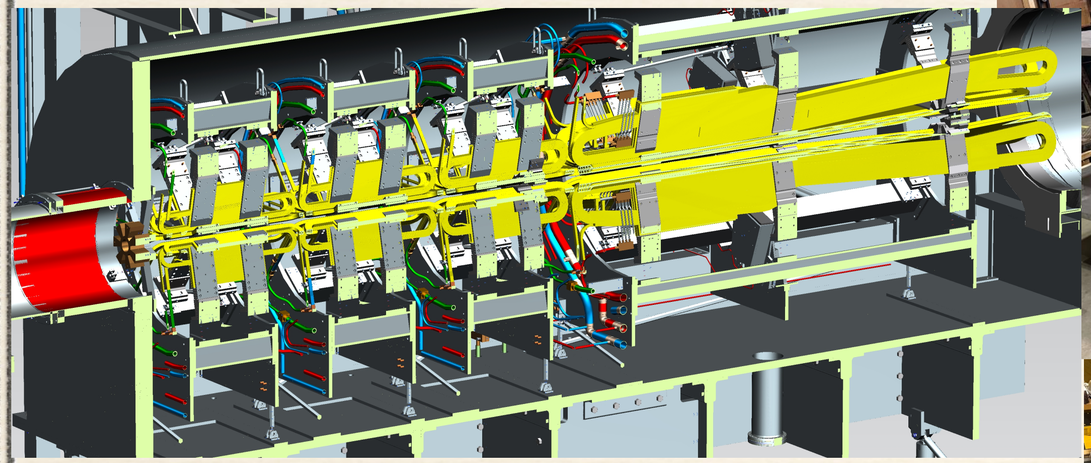






Cryostat components

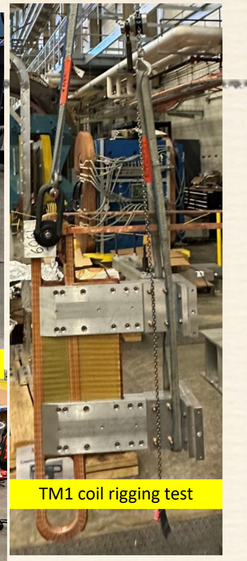
Spectrometer Construction



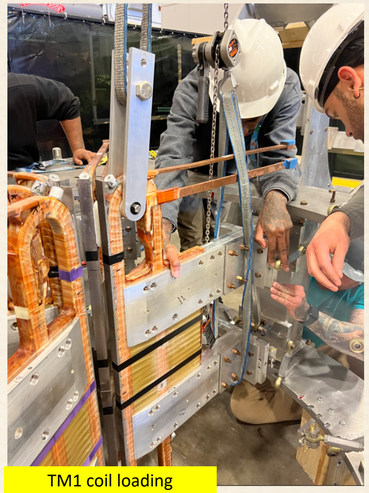


TM2 frame ready for loading

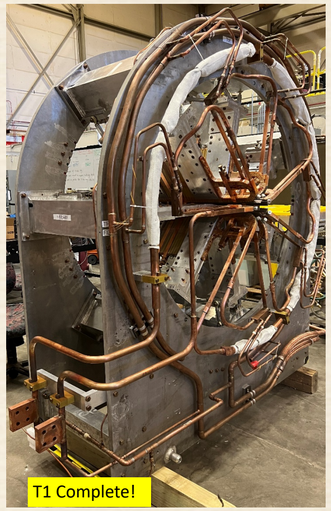




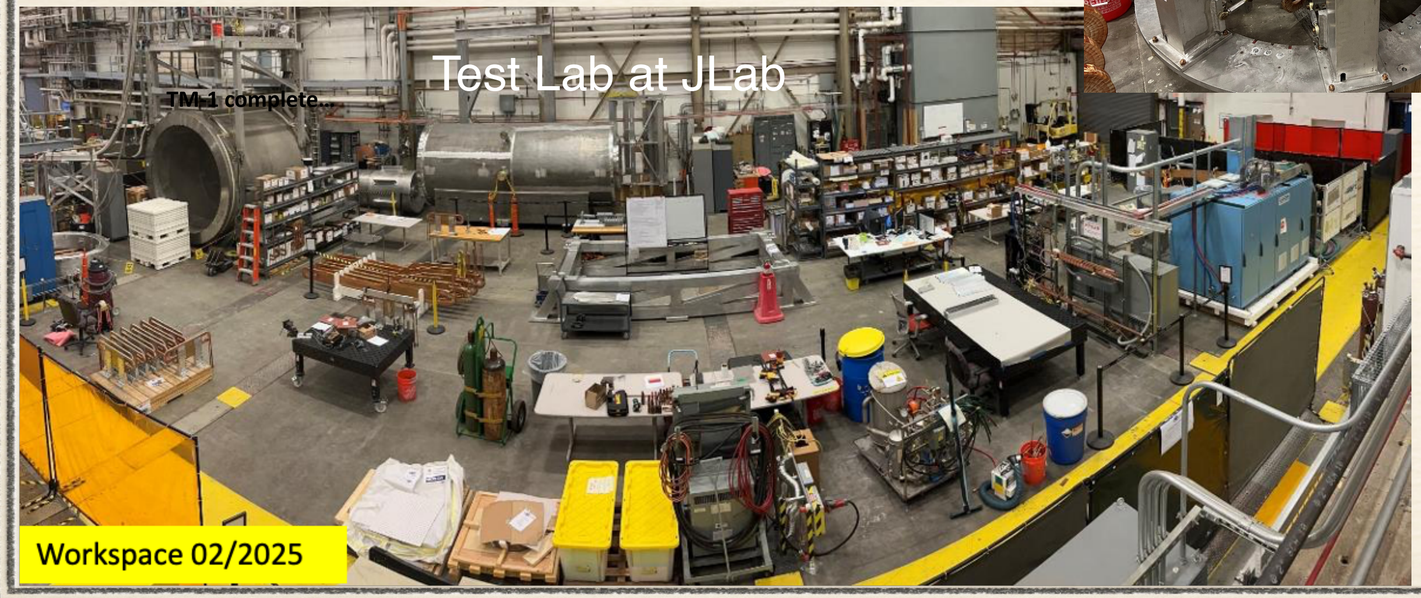
TM1 coil rigging test

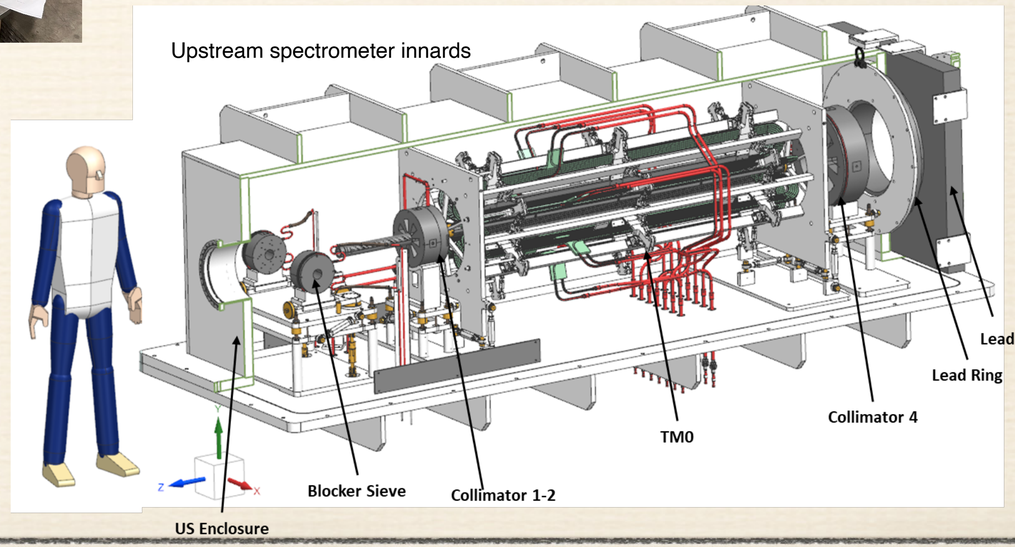


TM1 coil loading

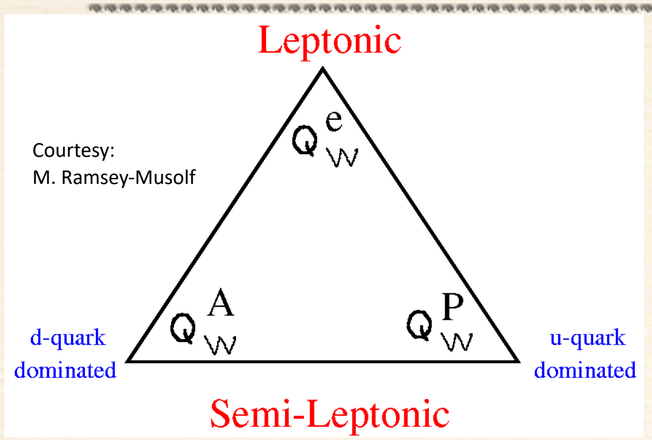


T1 Complete!





PVES Standard Model Tests: Complementarity



vector-quark couplings

$$[2C_{2u} - C_{2d}]$$

axial-quark couplings

SUSY Loops	➡	Q_W^e and Q_W^p:same absolute shift, smaller for others
GUT Z'	➡	High for Q_W(Cs), Q_W^e(relative), smaller for others
Leptophobic Z'	➡	axial-quark couplings (C_2's) only
RPV SUSY	➡	Different for all four in sign and magnitude
Leptoquarks	➡	semi-leptonic only; different sensitivities
Lepton Number Violation	➡	Q_W^e only

Fixed Target vs Collider Complementarity

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

$$\simeq \frac{246.22\ \text{GeV}}{\sqrt{0.023 Q_W^e}} = 7.5\ \text{TeV}.$$

Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
$LL^{\pm}$	± 1	0	0	0
$RR^{\pm}$	0	± 1	0	0
$LR^{\pm}$	0	0	± 1	0
$RL^{\pm}$	0	0	0	± 1
$VV^{\pm}$	± 1	± 1	± 1	± 1
$AA^{\pm}$	± 1	± 1	∓ 1	∓ 1
$VA^{\pm}$	± 1	∓ 1	± 1	∓ 1

Conventional Collider Contact Interaction Analysis: ➡ $\left|g_{RR}^2 - g_{LL}^2\right| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

95% C.L. Limits

LEP200

$\Lambda_{LL}^{ee} \sim 8.3$ TeV $\quad \Lambda_{LL}^{ll} \sim 12.8$ TeV

$\Lambda_{RR}^{ee} \sim 8.2$ TeV $\quad \Lambda_{RR}^{ll} \sim 12.2$ TeV

$\Lambda_{VV}^{ee} \sim 17.7$ TeV $\quad \Lambda_{VV}^{ll} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda_{LL}^{ee} \sim 12$ TeV $\quad \Lambda_{RR-LL}^{ee} \sim 17$ TeV

LEP-200 insensitive

Fixed Target vs Collider Complementarity

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{\sqrt{2}G_F|\Delta Q_W^e|}}$$

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Model	η_{LL}^f	η_{RR}^f	η_{LR}^f	η_{RL}^f
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$LR^{\pm}$	0	0	± 1	0
$RL^{\pm}$	0	0	0	± 1
$VV^{\pm}$	± 1	± 1	± 1	± 1
$AA^{\pm}$	± 1	± 1	∓ 1	∓ 1
$VA^{\pm}$	± 1	∓ 1	± 1	∓ 1

Conventional Collider Contact Interaction Analysis: $\Rightarrow \left|g_{RR}^2 - g_{LL}^2\right| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

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LEP200

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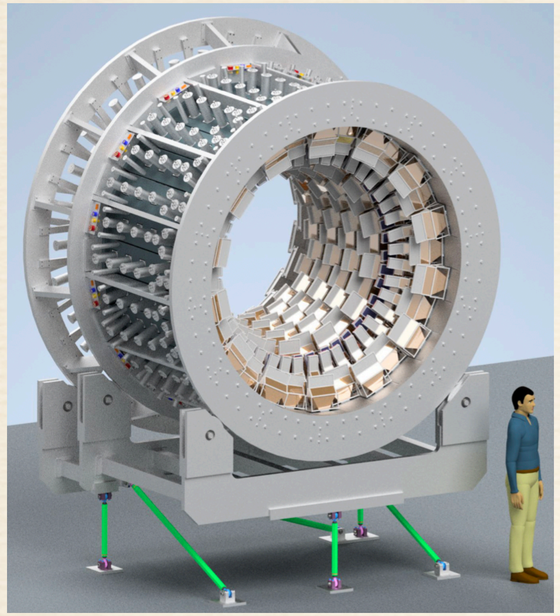
LEP-200 insensitive

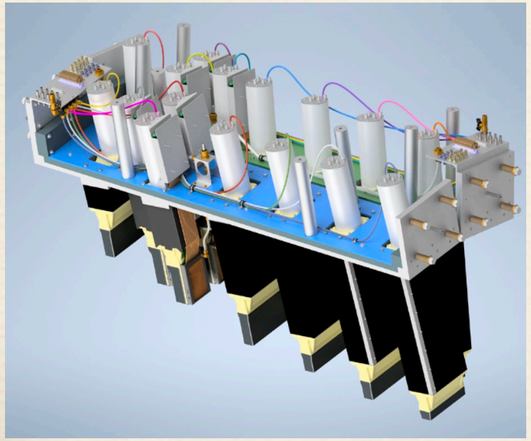
MOLLER Reach

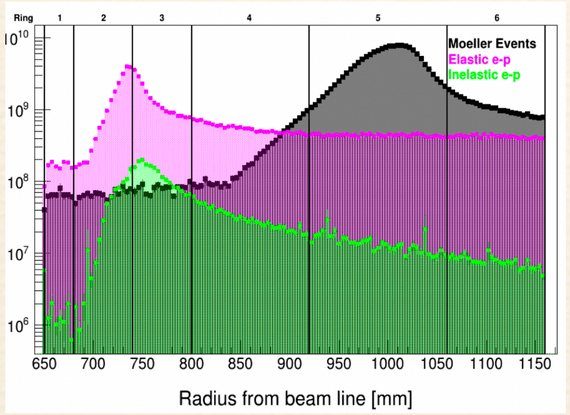
$\Lambda_{LL}^{ee} \sim 27$ TeV $\quad \Lambda_{RR-LL}^{ee} \sim 38$ TeV

MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

Integrating Detector Assembly

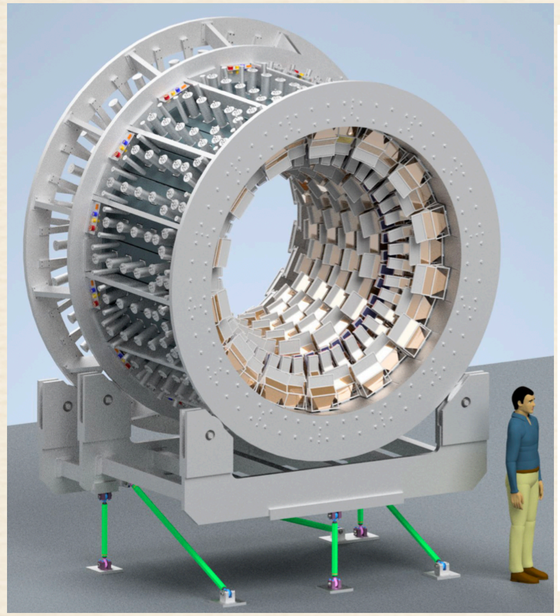


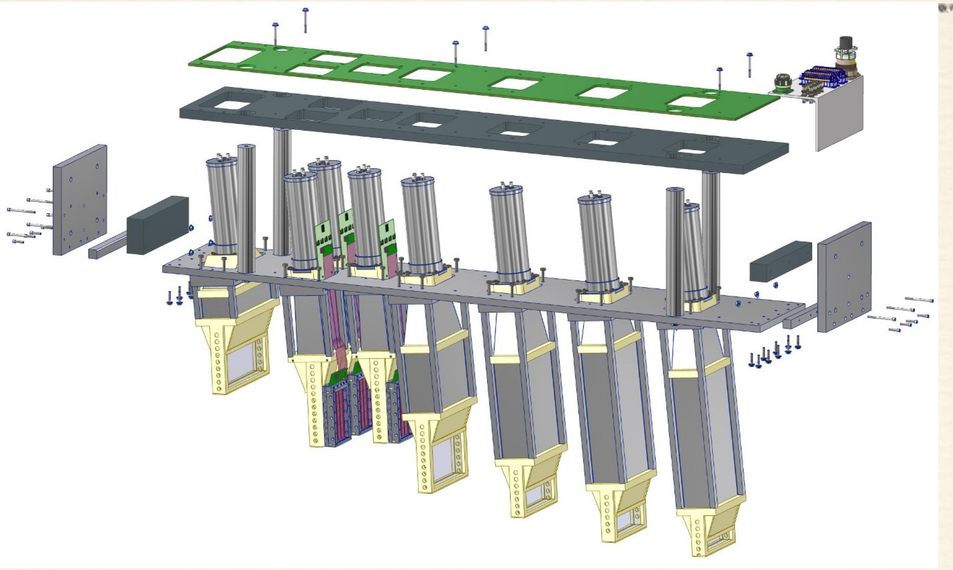


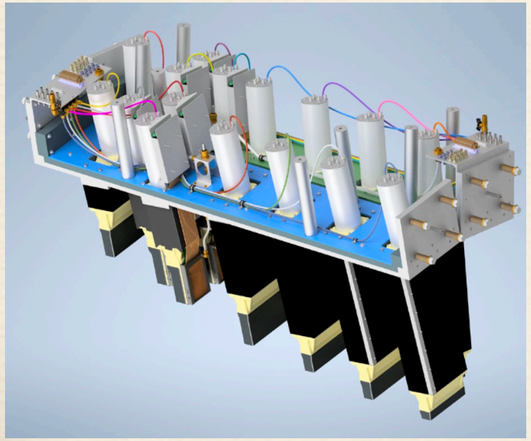


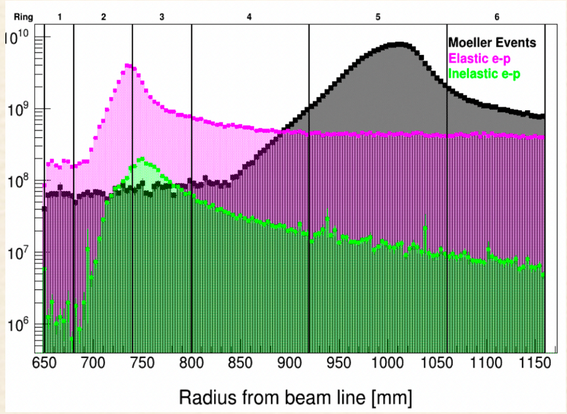
Idaho State University
University of Manitoba
University of Massachusetts
Bartoszek Engineering

Integrating Detector Assembly



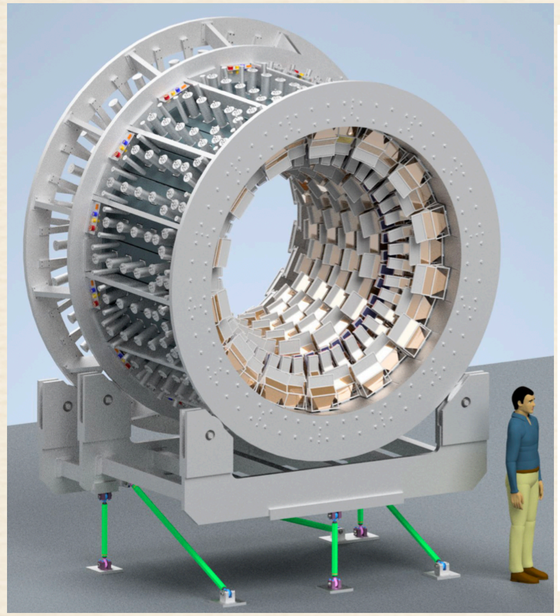


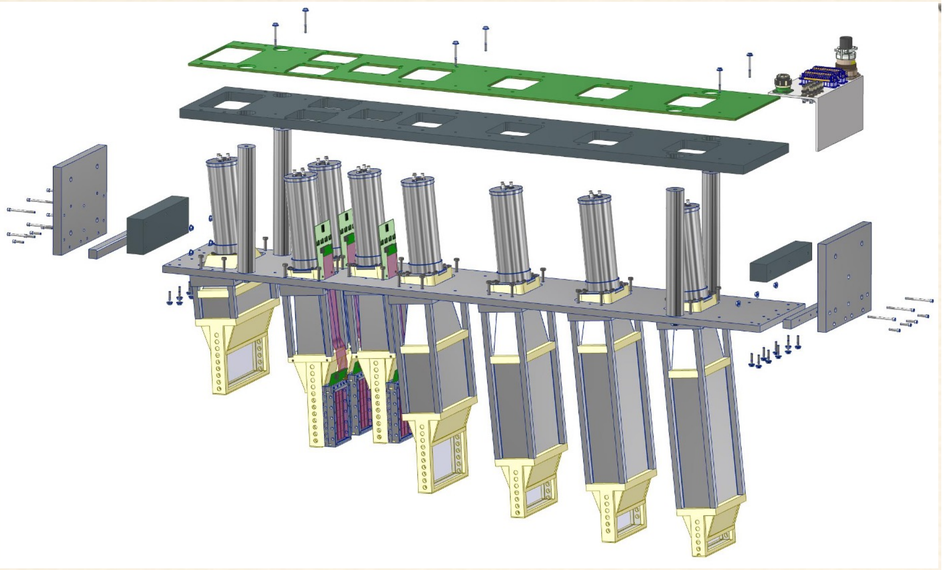


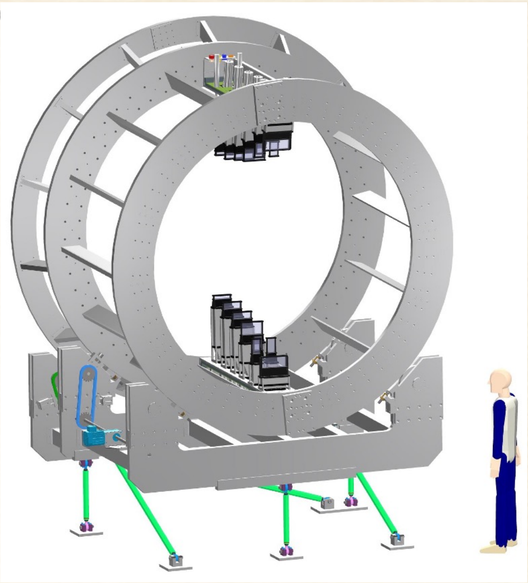


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Bartoszek Engineering

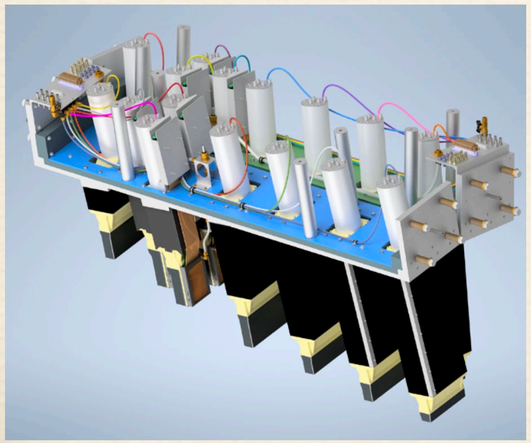
Integrating Detector Assembly

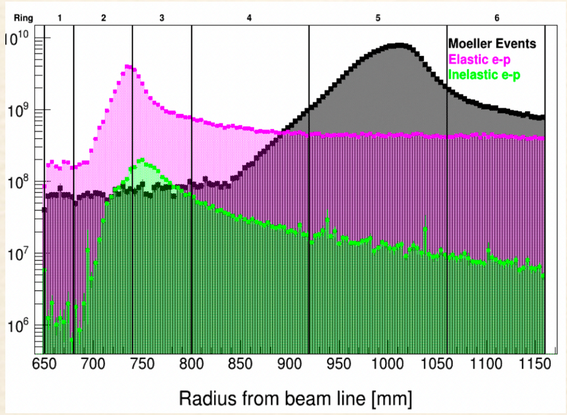




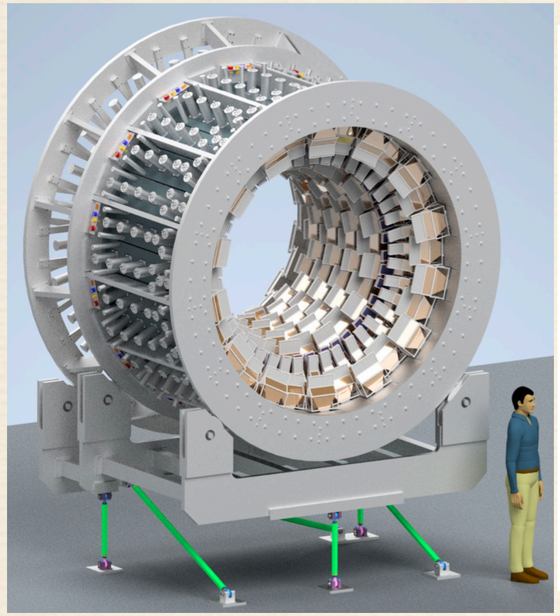


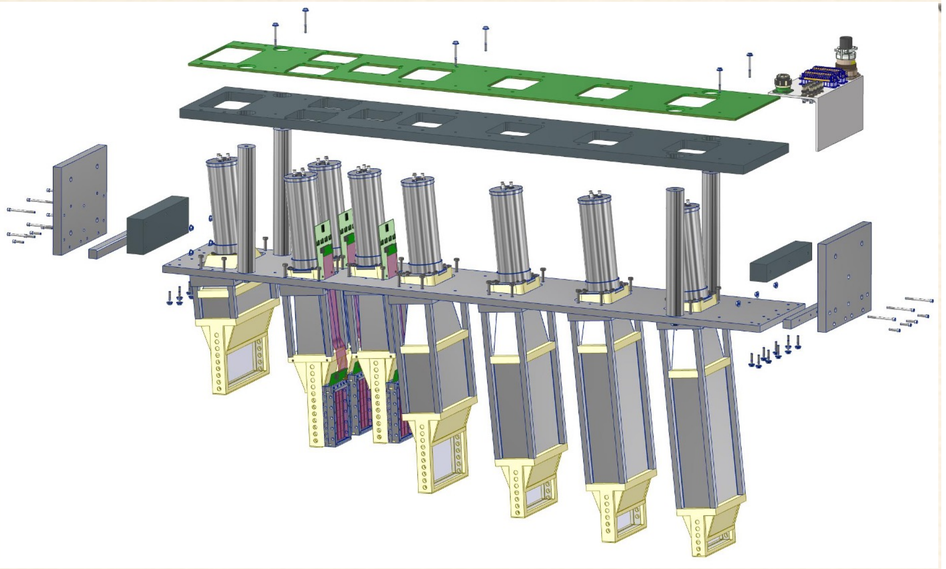
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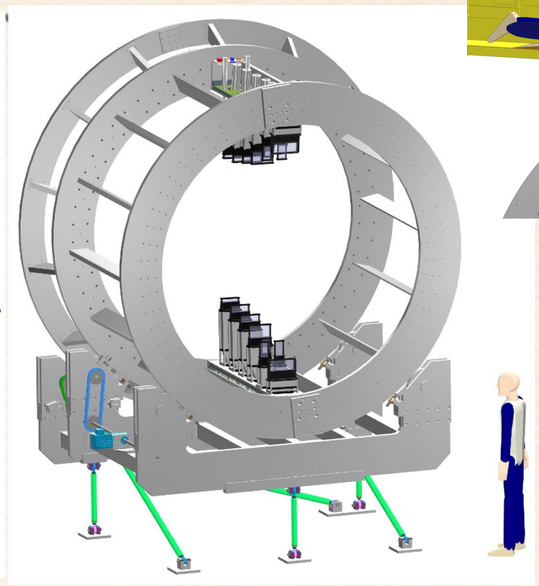


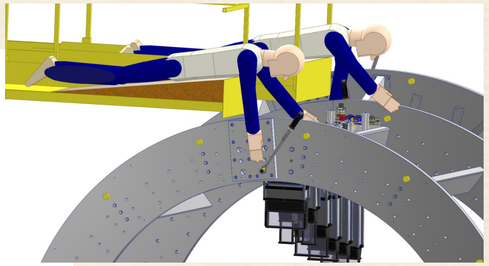


Integrating Detector Assembly

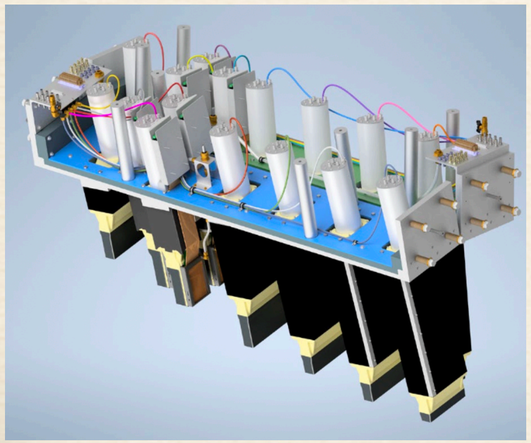


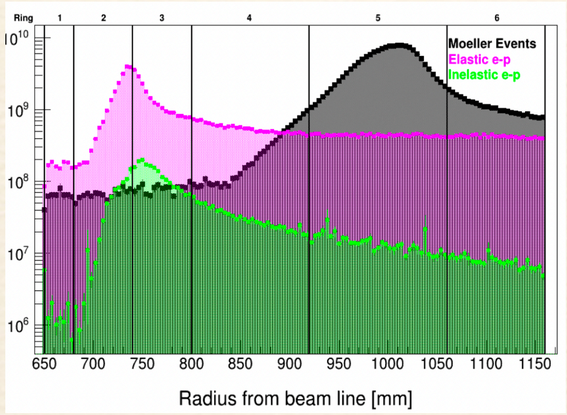




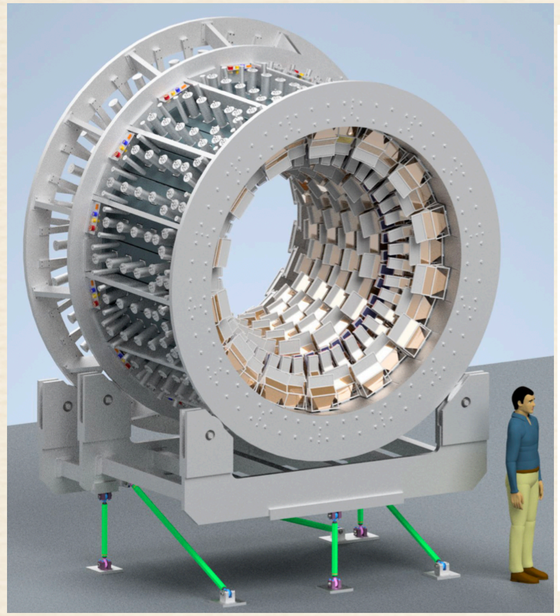


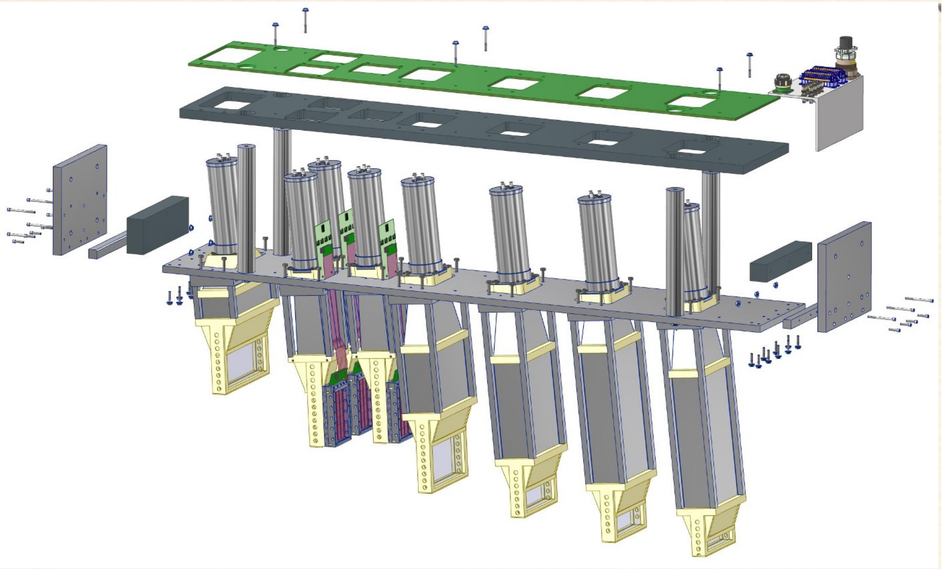
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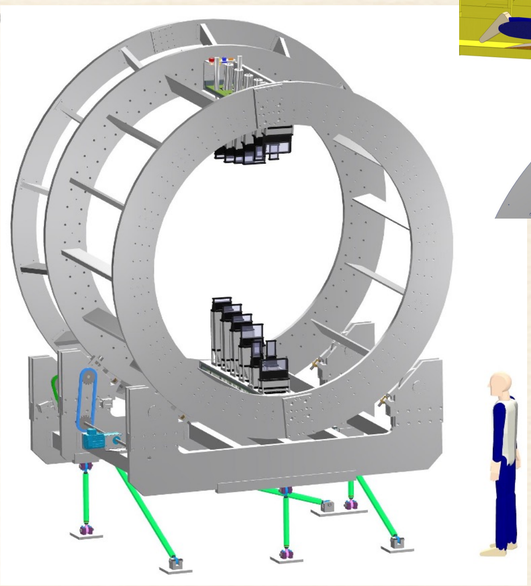


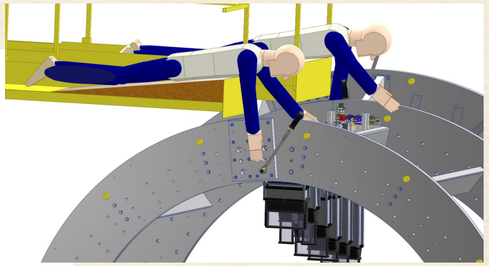


Integrating Detector Assembly

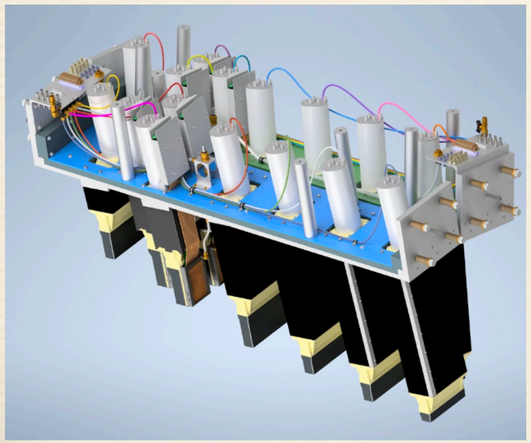


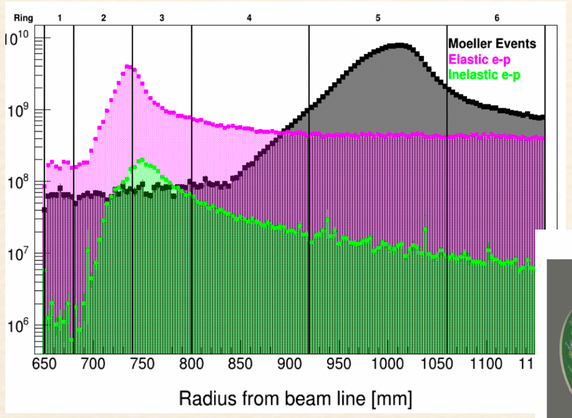


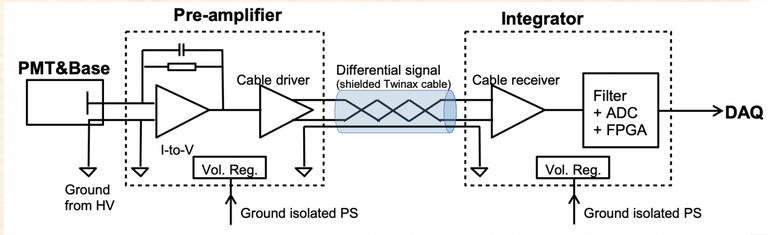


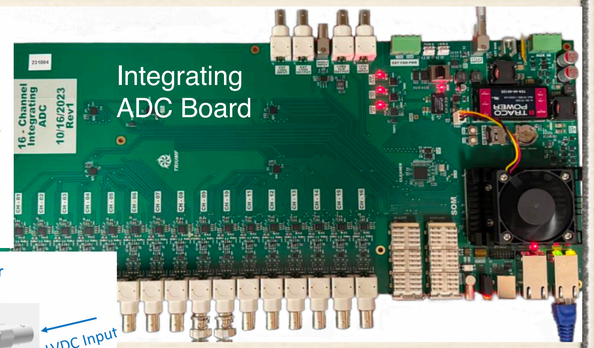


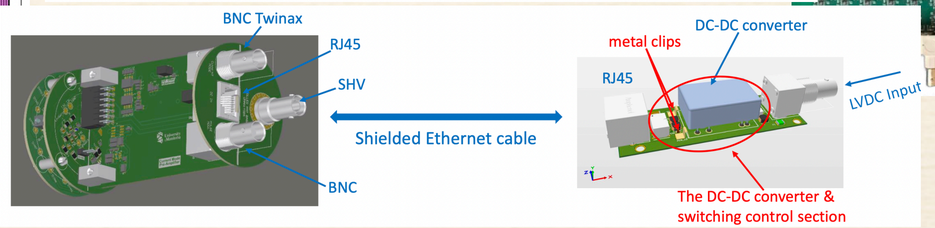
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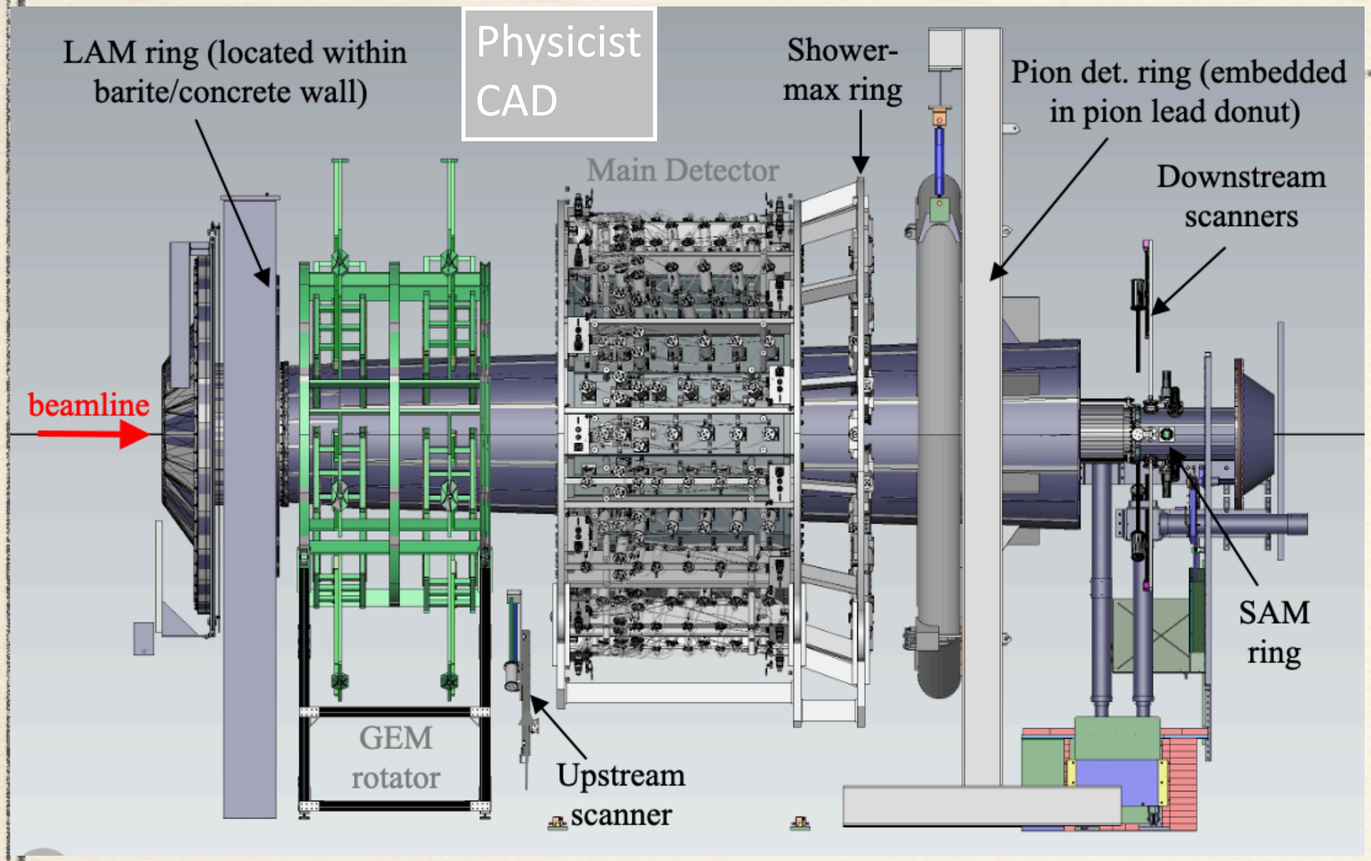




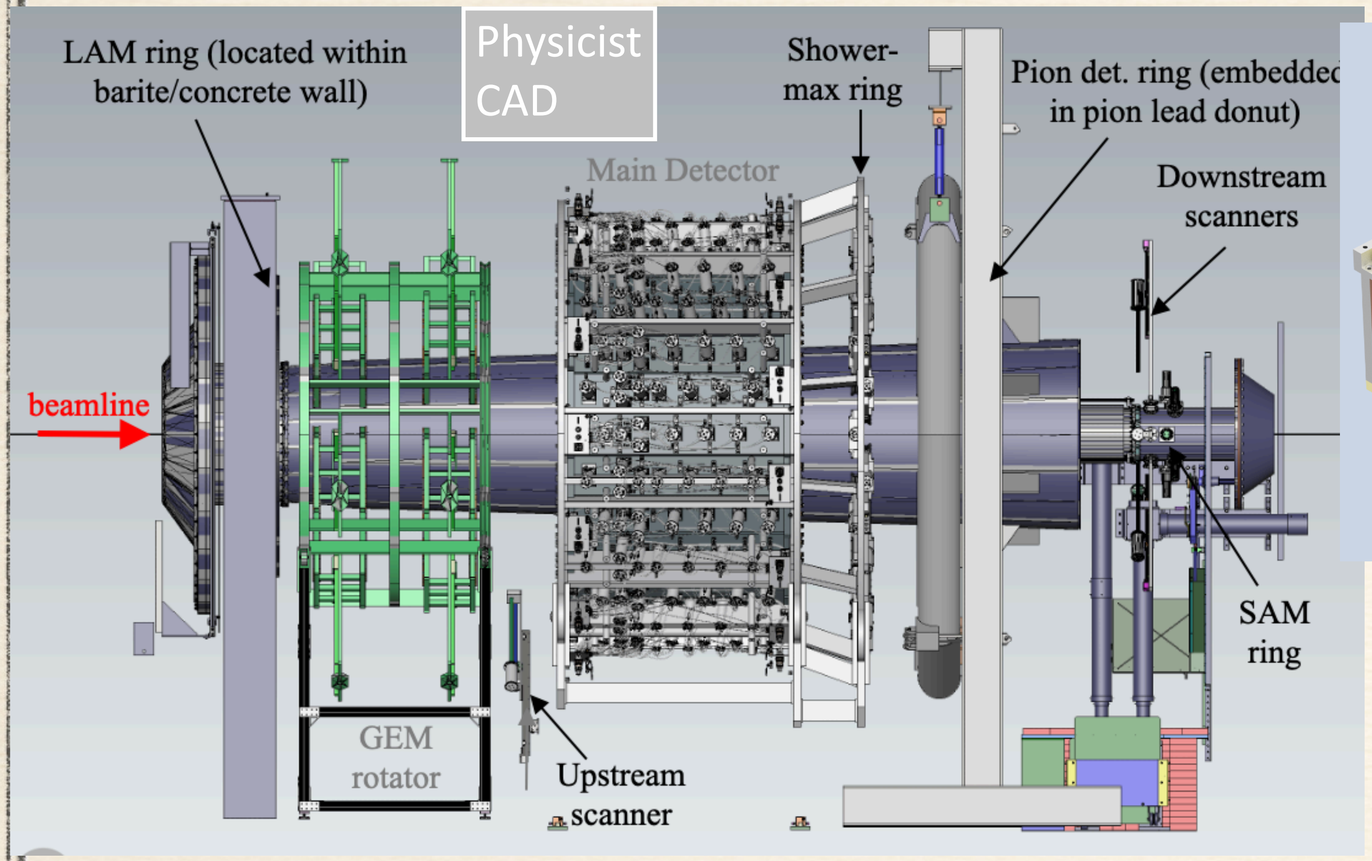


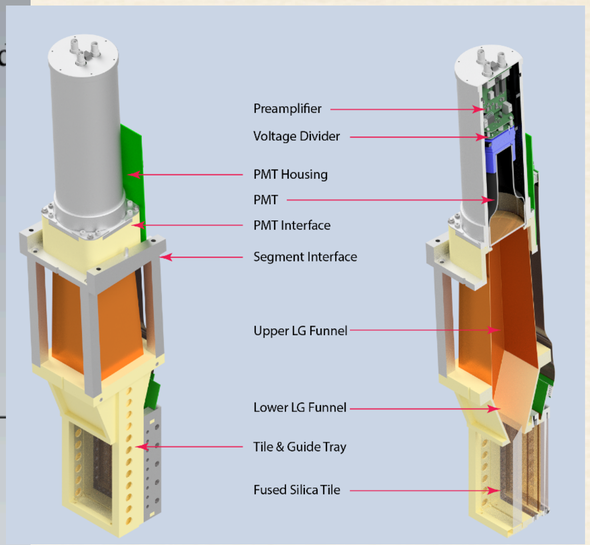


MOLLER Detection Overview



MOLLER Detection Overview

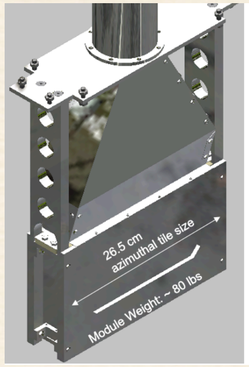




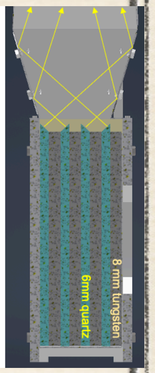
Requirement for Ring 5:

Detector resolution < 25%

excess noise < 4%



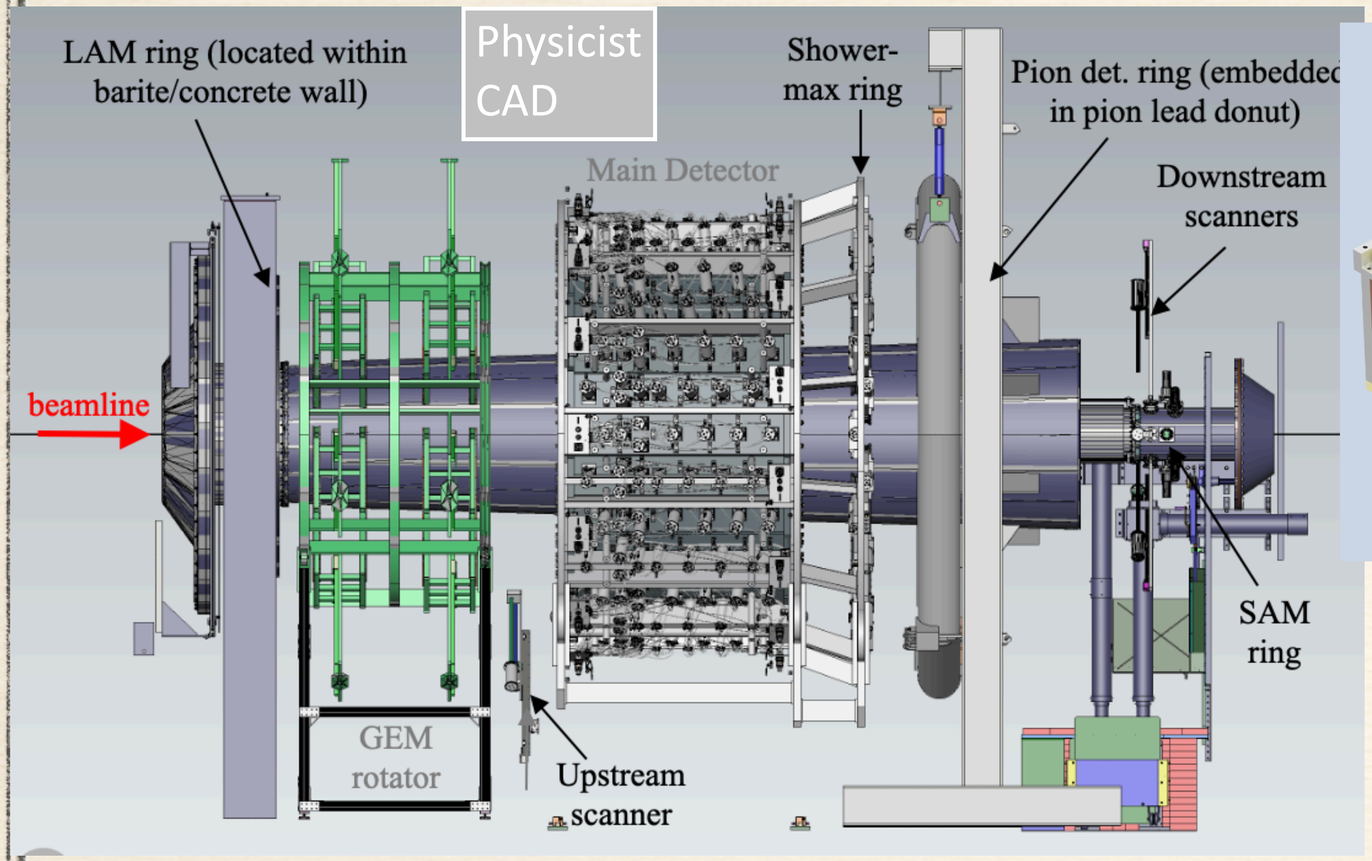


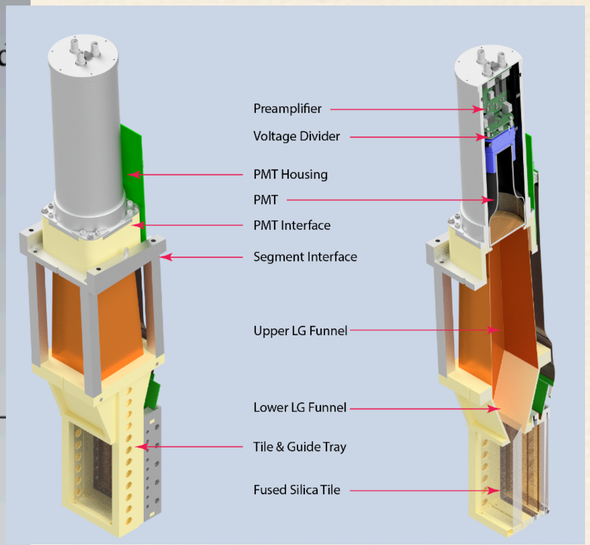


Integrating (current mode) detectors:

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

MOLLER Detection Overview

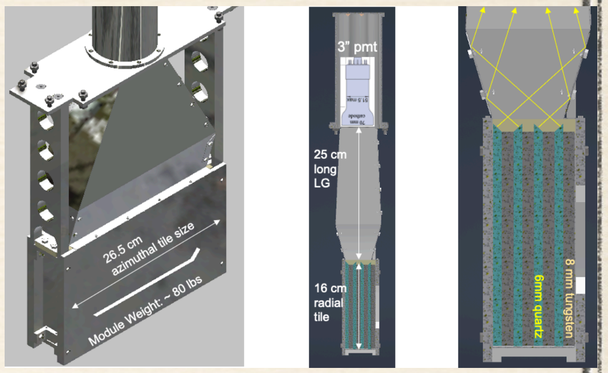




Requirement for Ring 5:

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Integrating (current mode) detectors:

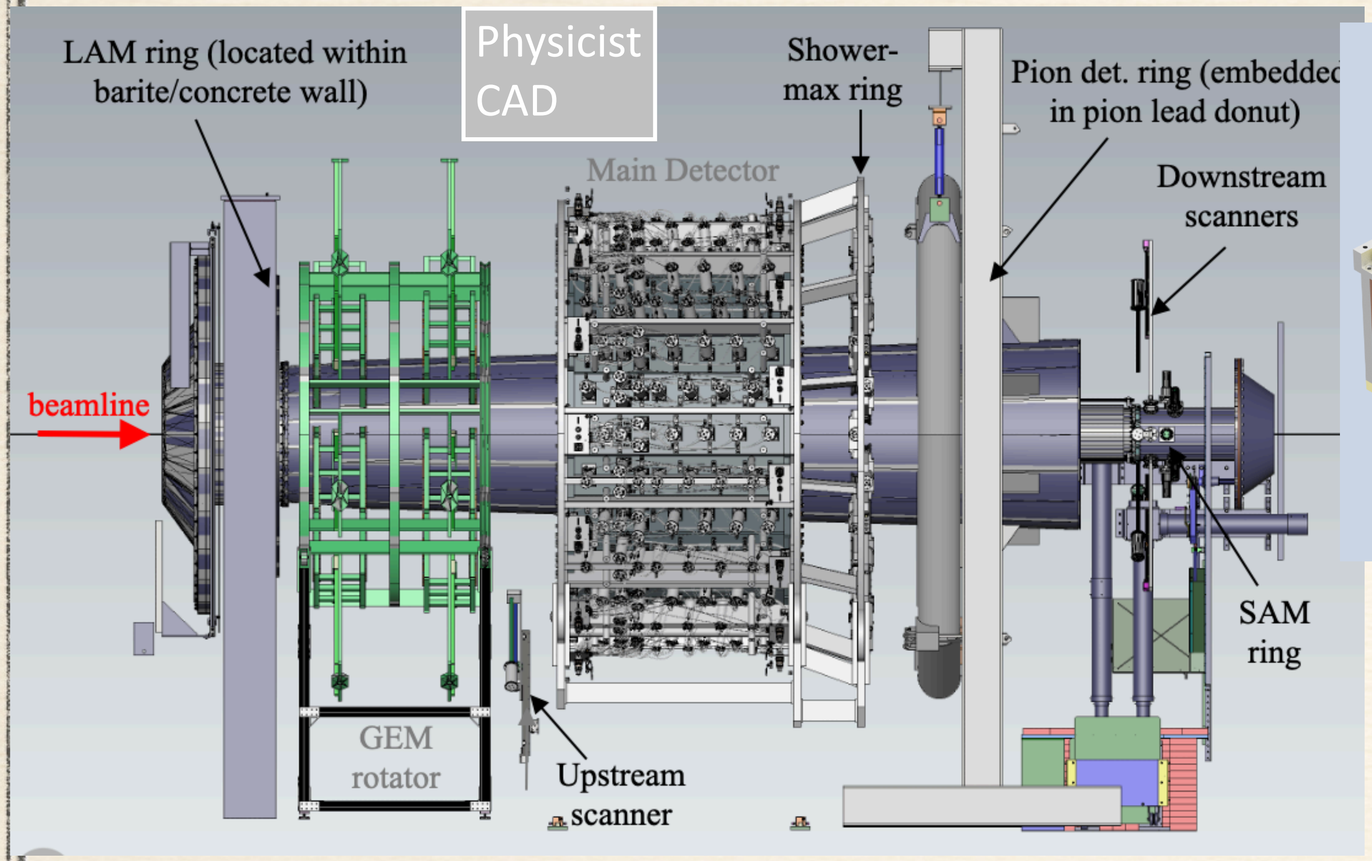
asymmetry measurements of both signal and background, and beam and target monitoring

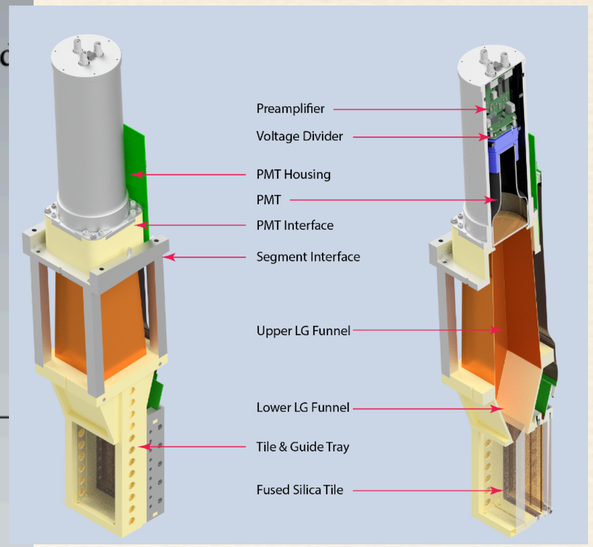
Tracking (counting mode) detectors:

spectrometer calibration, electron scattering angle distribution, and background measurements

- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

MOLLER Detection Overview

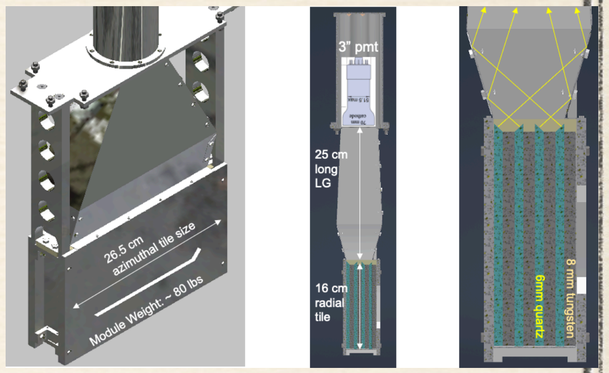




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Integrating (current mode) detectors:

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

Tracking (counting mode) detectors:

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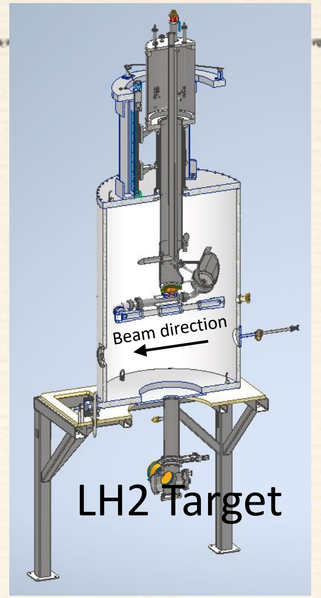
- Gas electron multipliers (GEM) detectors
- "Pion" acrylic Cherenkov detectors

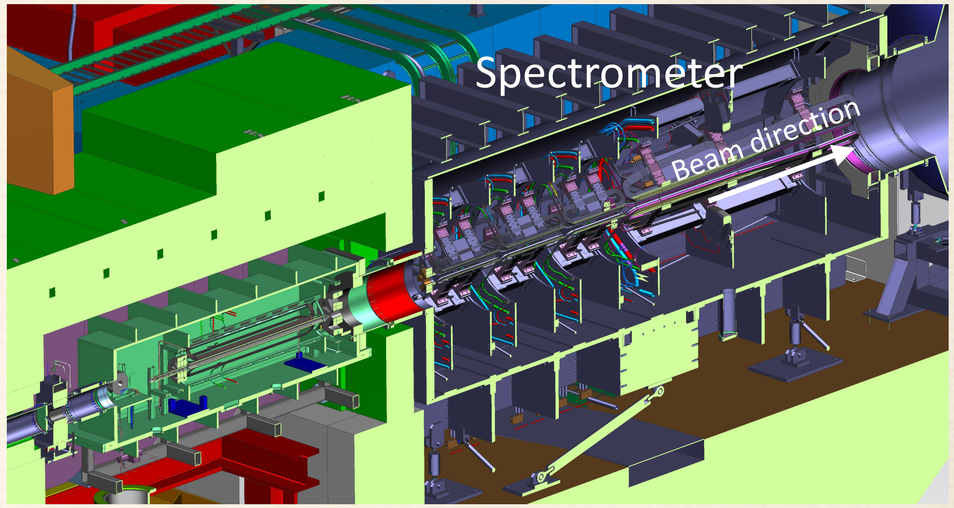
Readout Electronics:

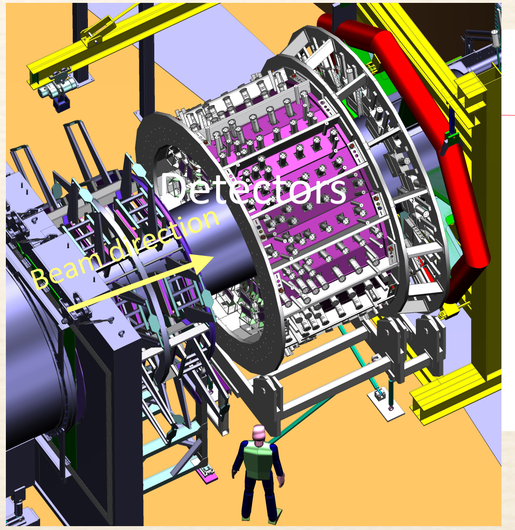
- Integration mode DAQ & trigger
  - *Collect & analyaize100% of the helicity windows*
- Counting mode DAQ & trigger
  - *input rates between 10~kHz and 300~kHz*

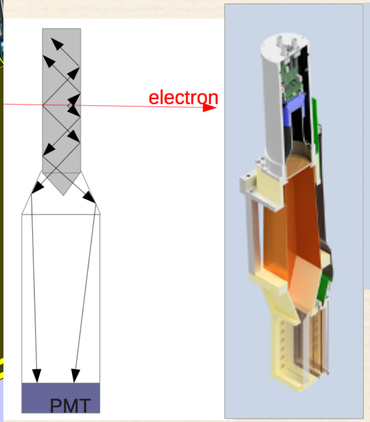
MOLLER Technical Challenges

Evolutionary Improvements from Technology of Third Generation Experiments

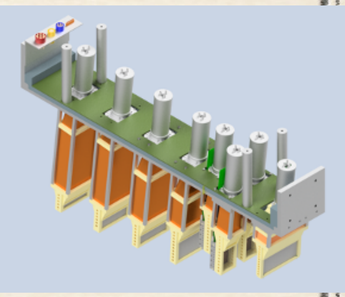








Single channel

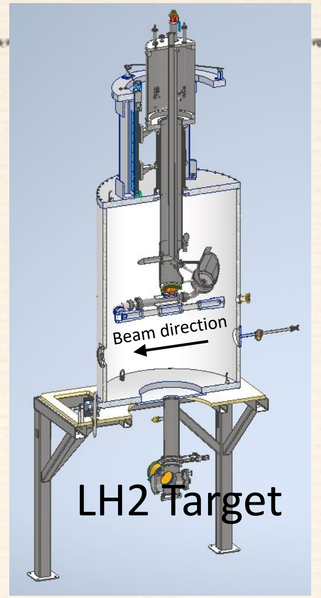


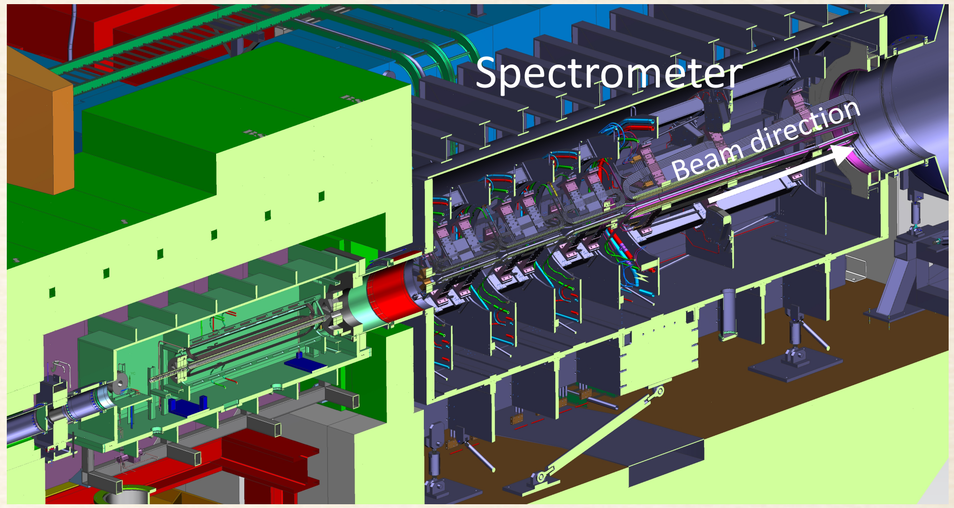
1/28th Segment

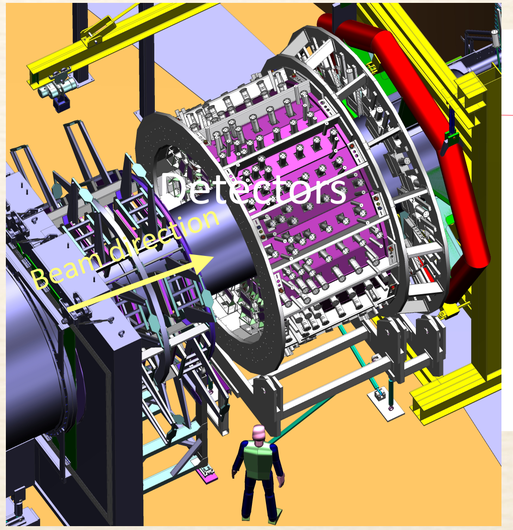
MOLLER Technical Challenges

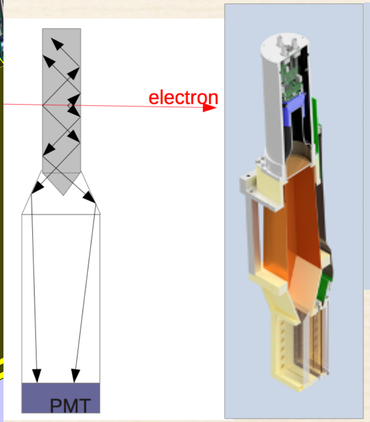
Evolutionary Improvements from Technology of Third Generation Experiments

- **High intensity polarized electron source**

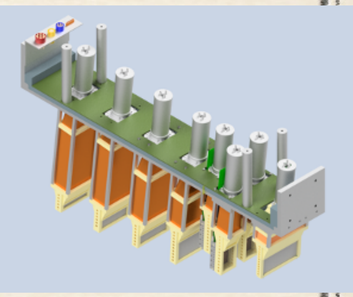








Single channel

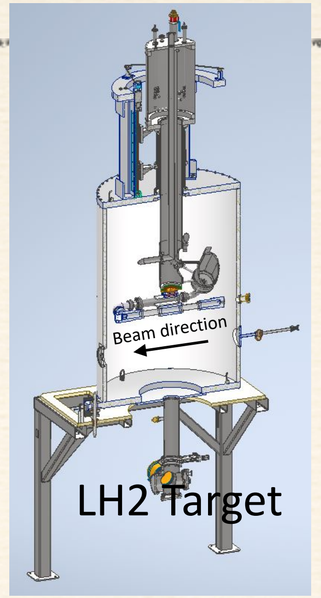


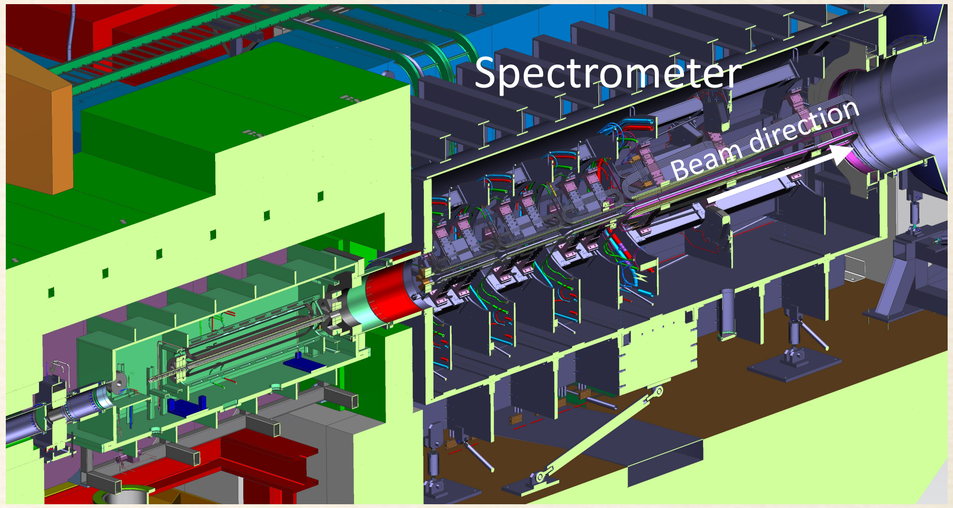
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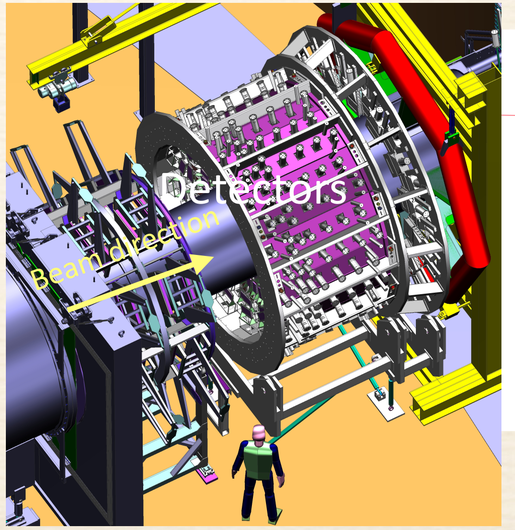
MOLLER Technical Challenges

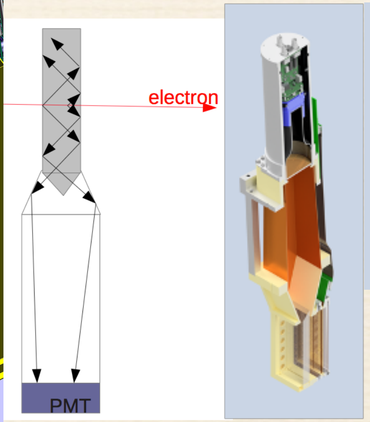
Evolutionary Improvements from Technology of Third Generation Experiments

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

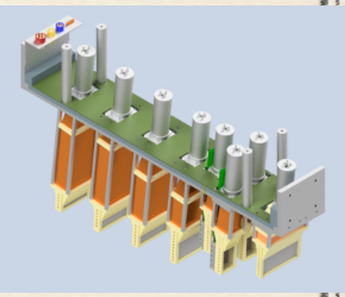








Single channel

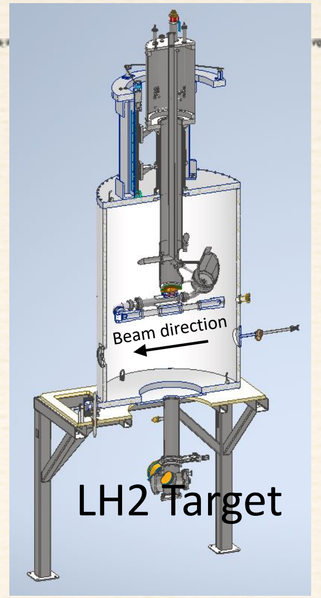


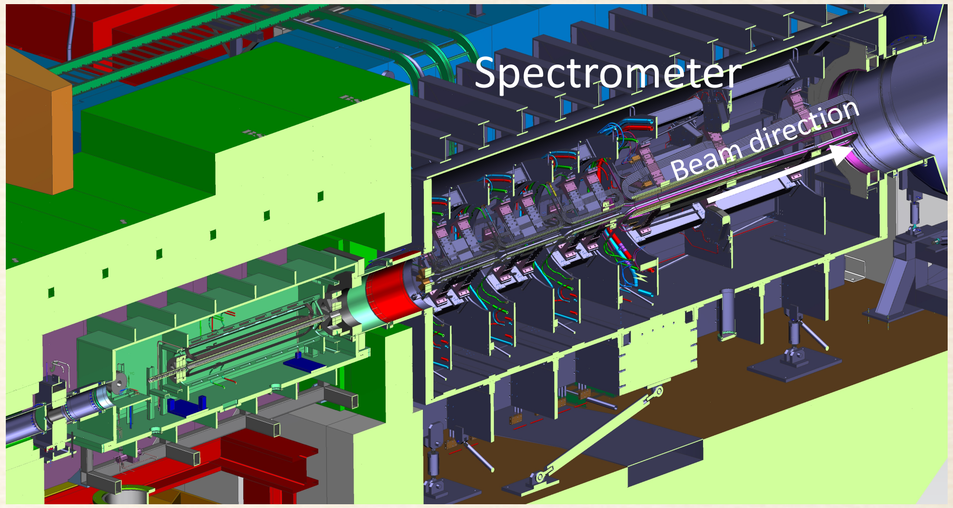
1/28th Segment

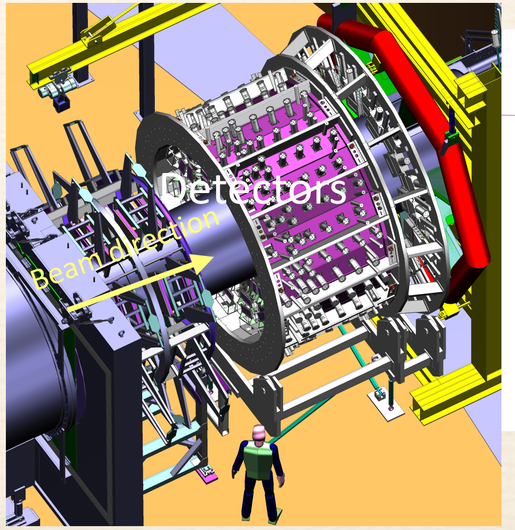
MOLLER Technical Challenges

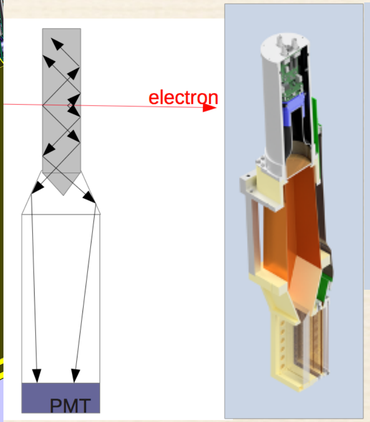
Evolutionary Improvements from Technology of Third Generation Experiments

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

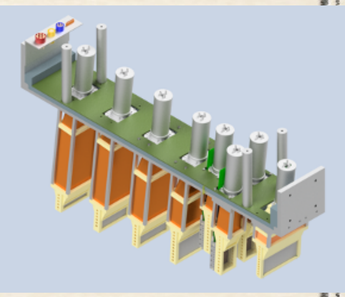








Single channel

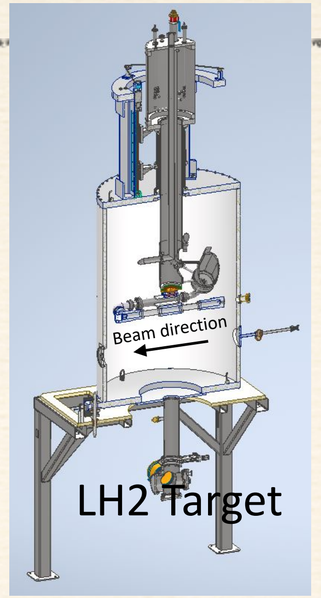


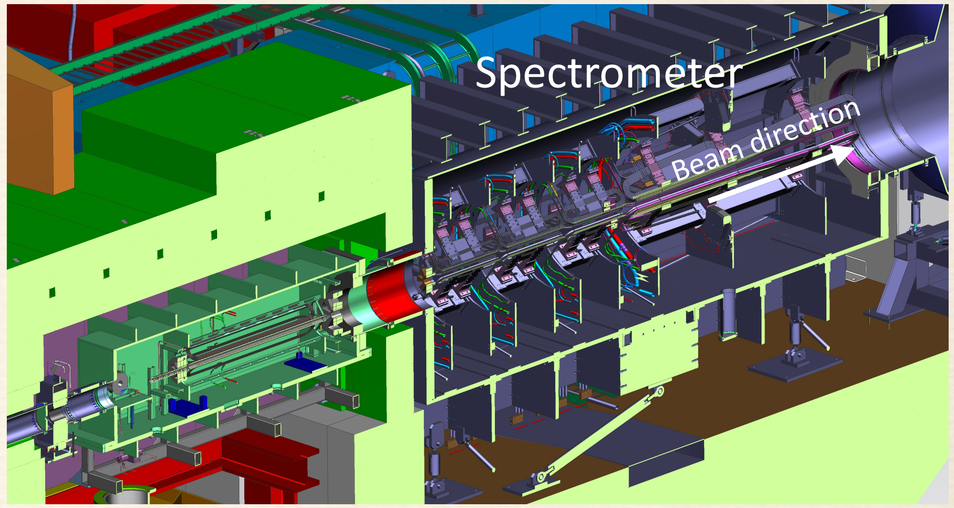
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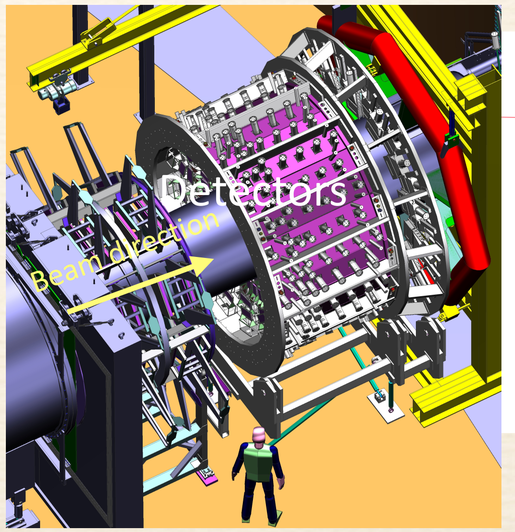
MOLLER Technical Challenges

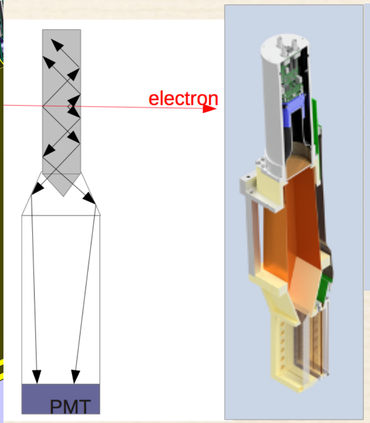
Evolutionary Improvements from Technology of Third Generation Experiments

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

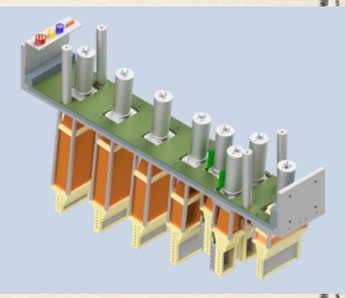








Single channel

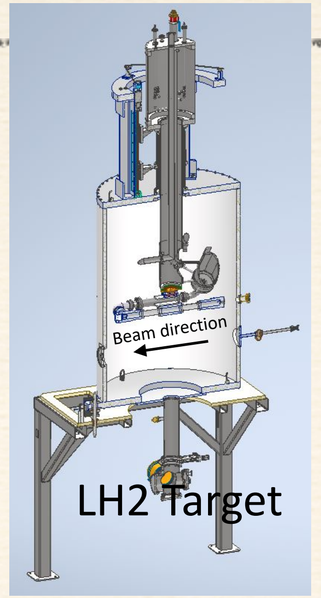


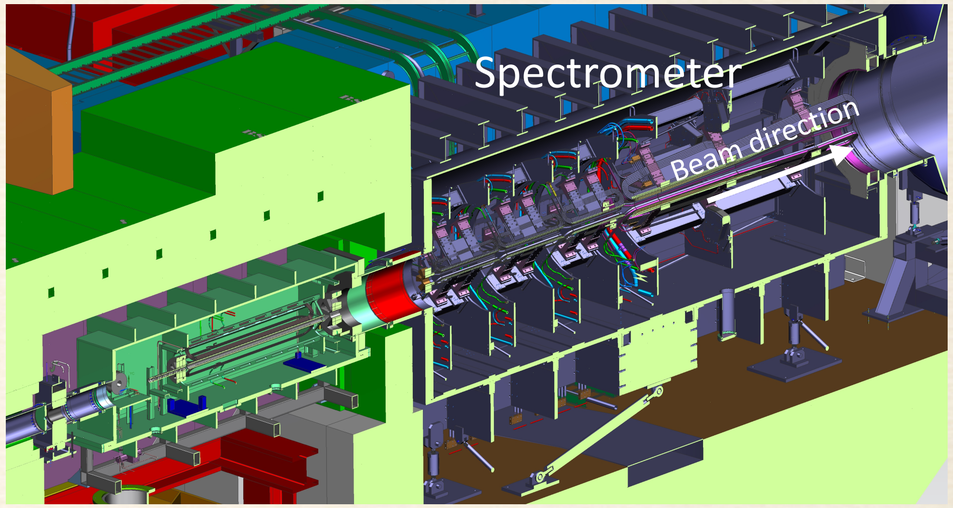
1/28th Segment

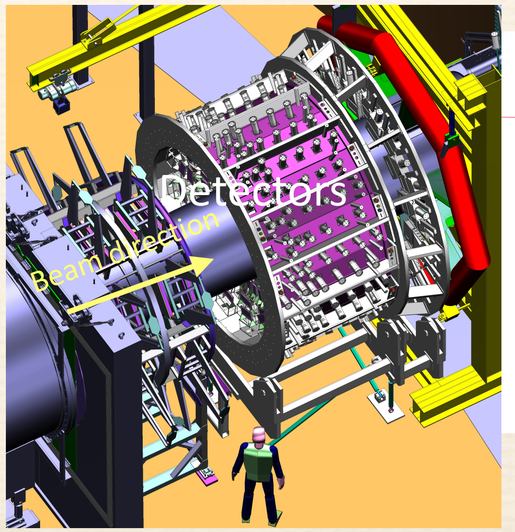
MOLLER Technical Challenges

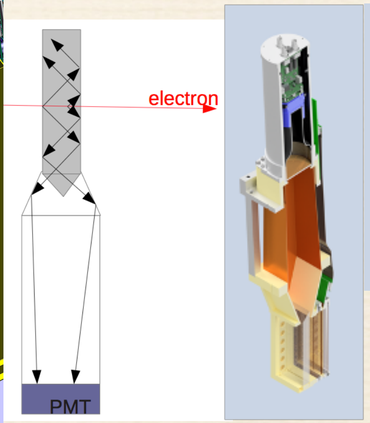
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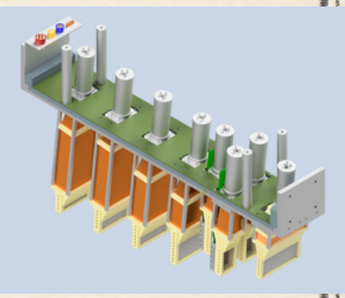








Single channel

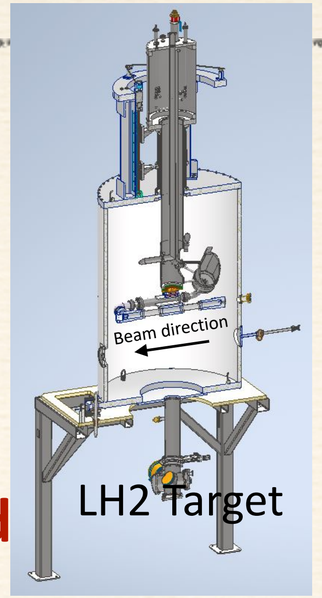


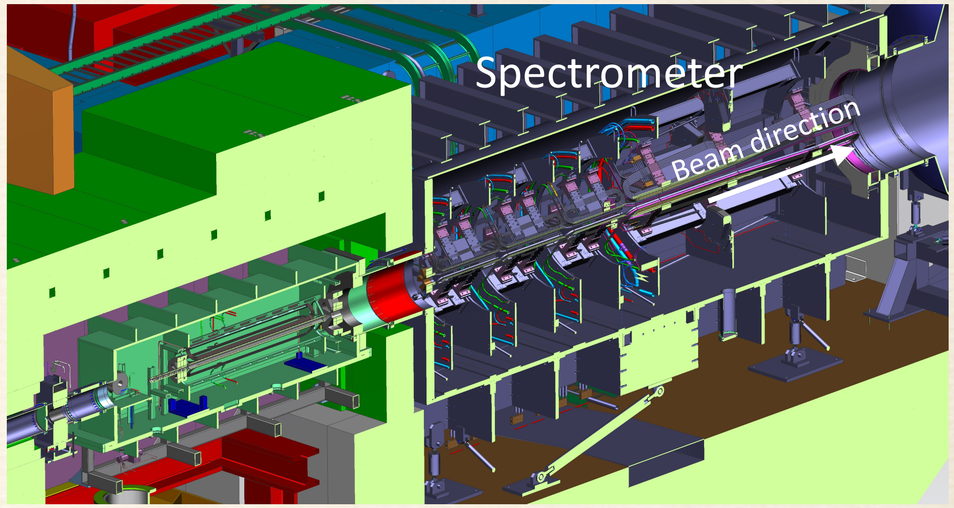
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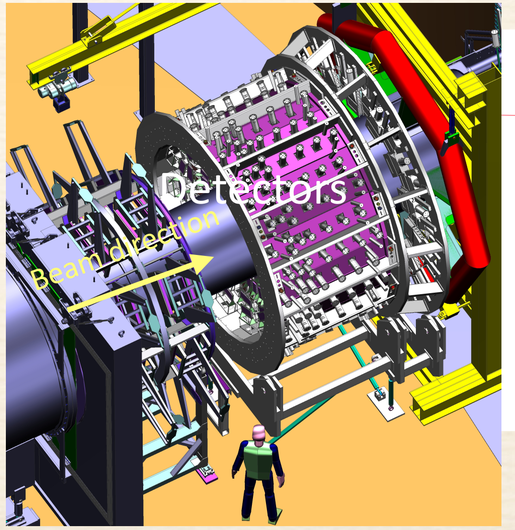
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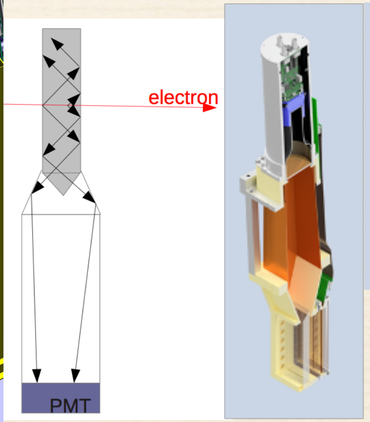
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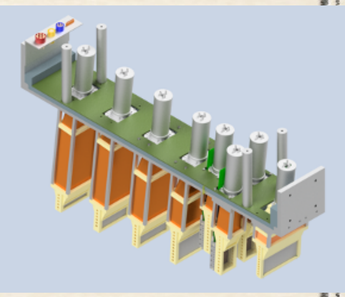








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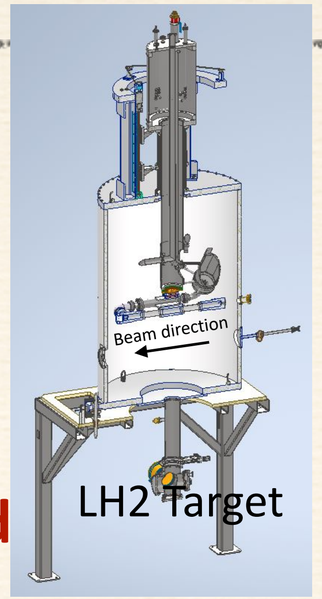


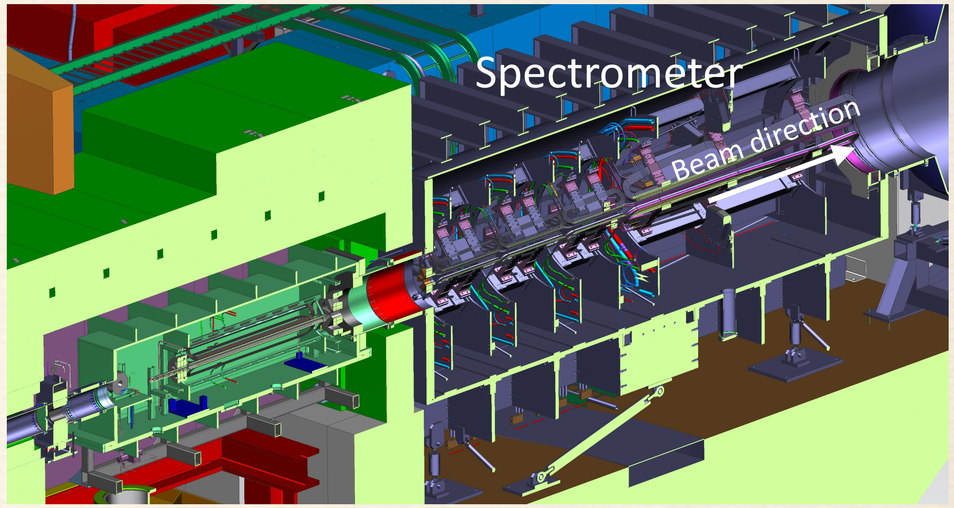
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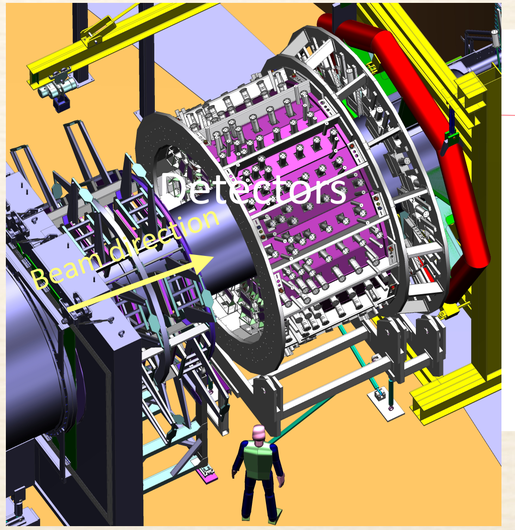
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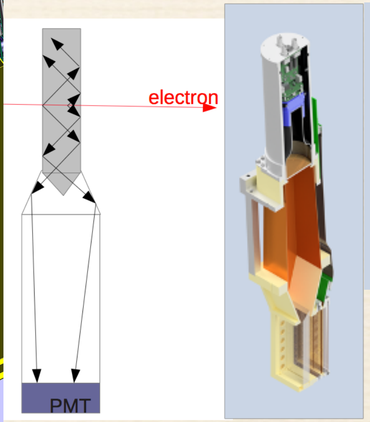
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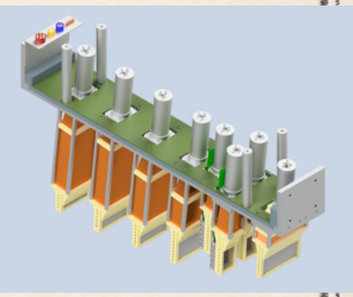








Single channel

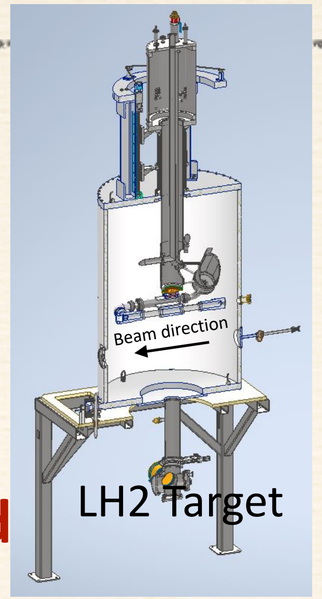


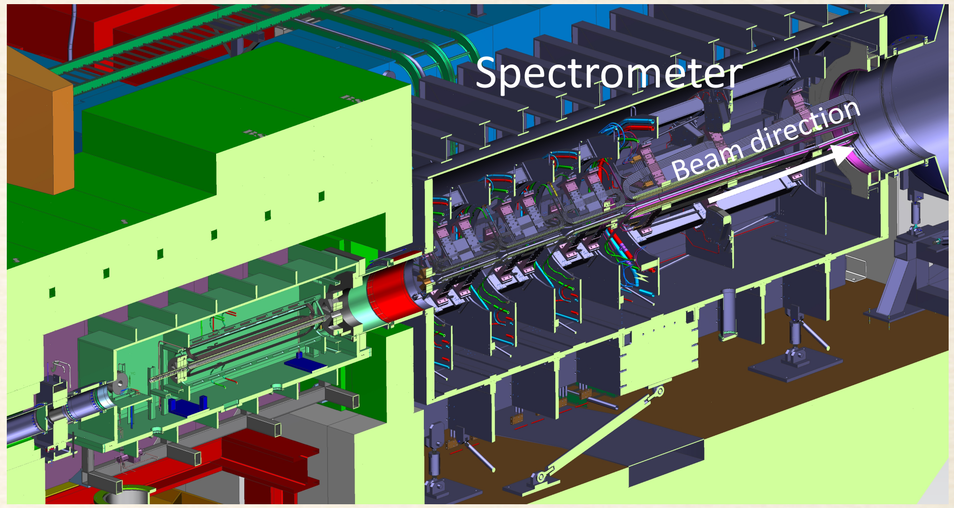
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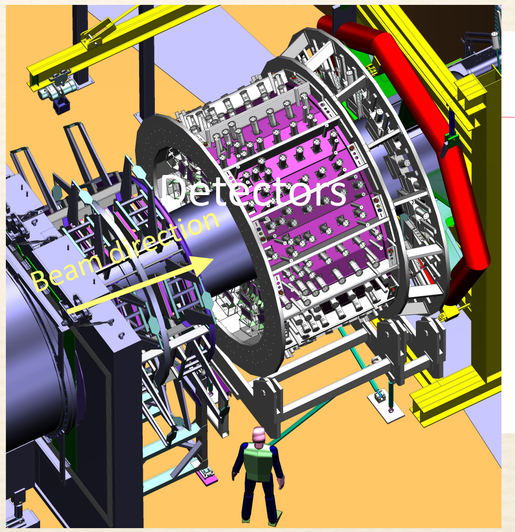
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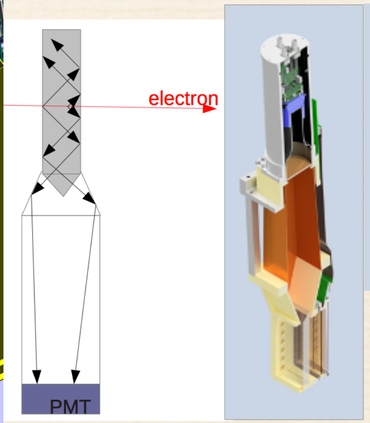
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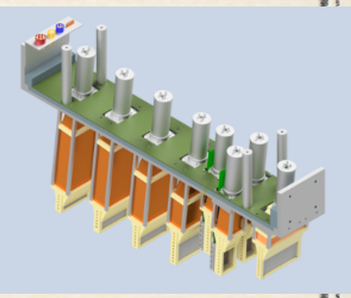








Single channel

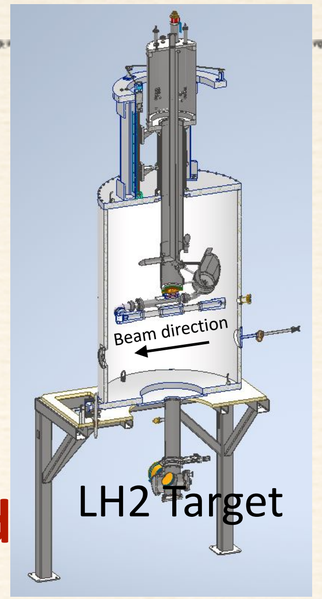


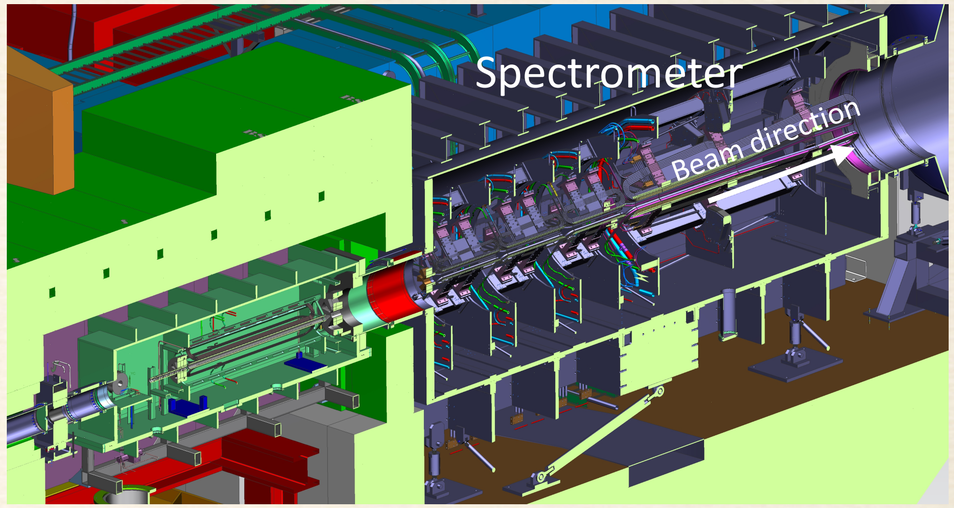
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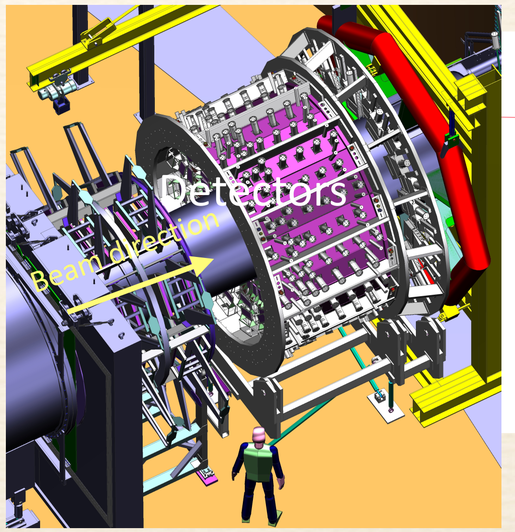
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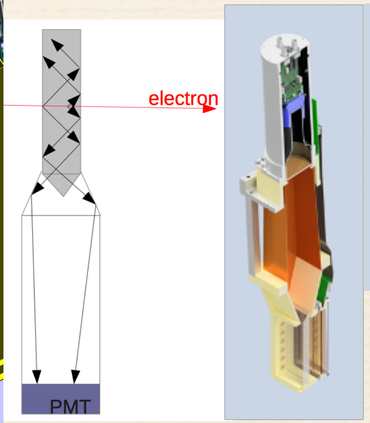
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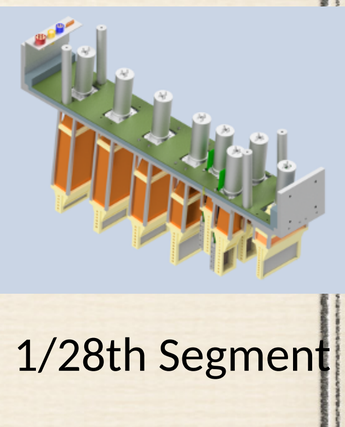








Single channel

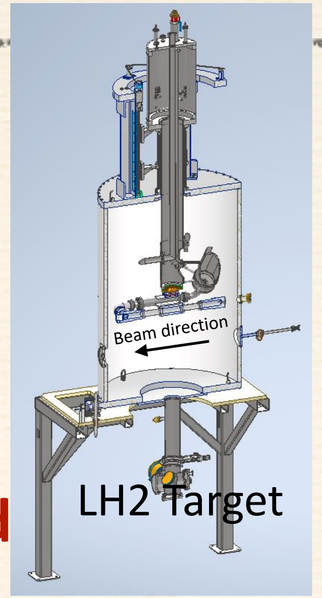


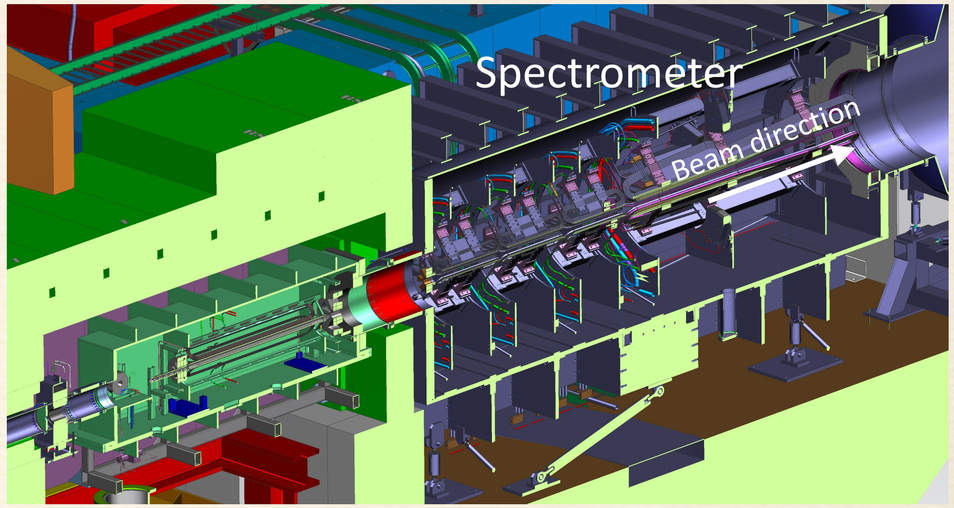
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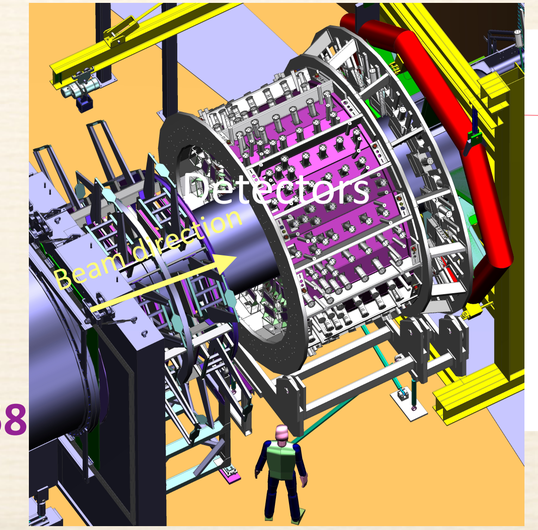
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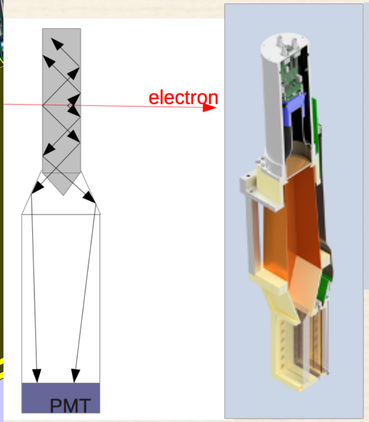
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- **MOLLER Collaboration Team**
  - **~ 180 scientists from more than 30 institutions (3 countries)**
  - **Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158**
  - **Final Technical Design Report is public**

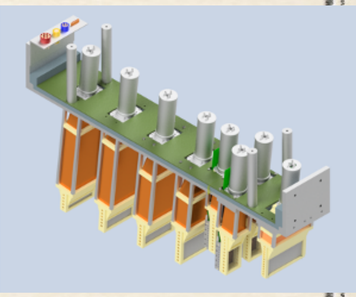








Single channel



1/28th Segment

MOLLER Under Construction!









