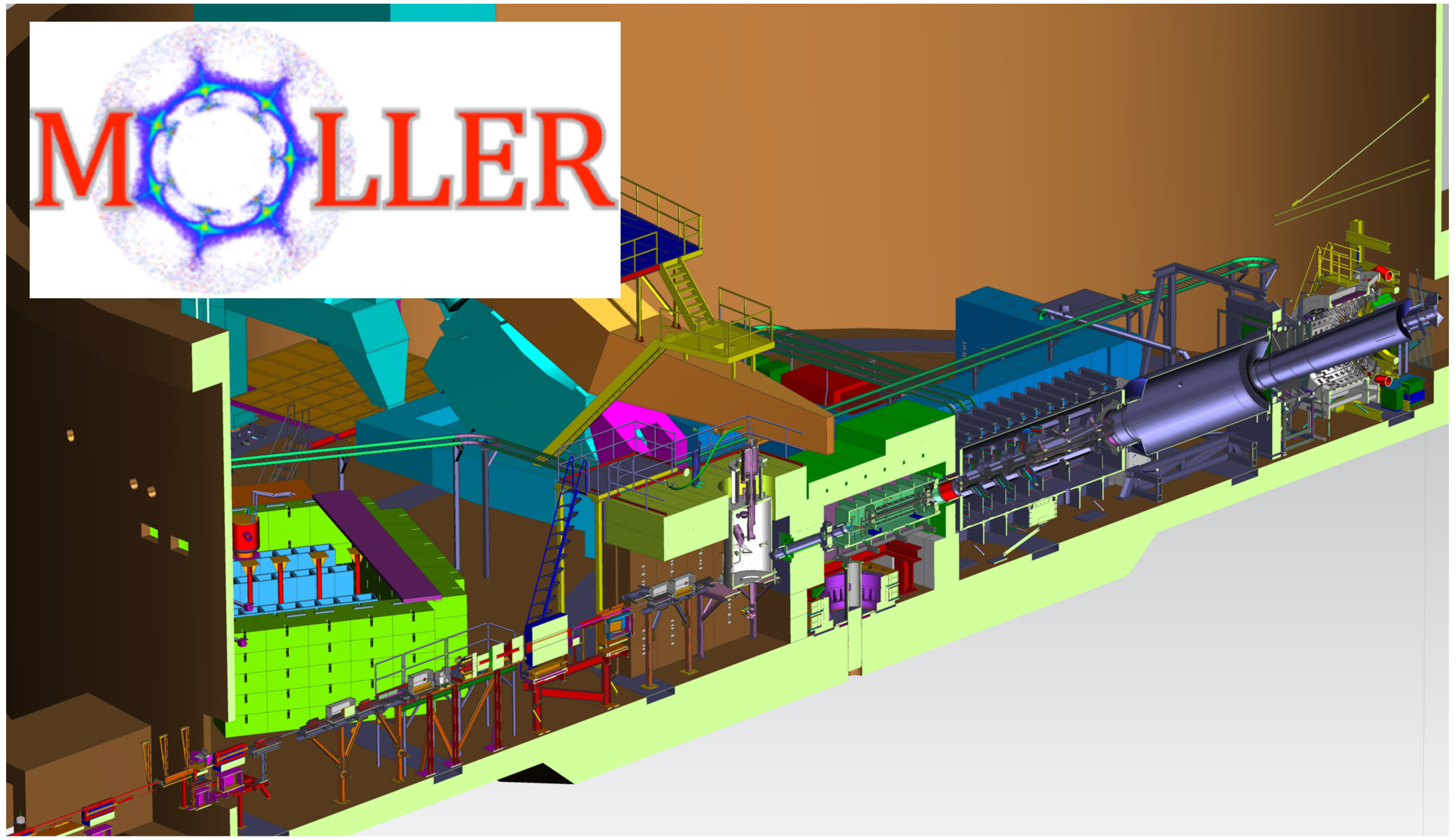
Measurement of Lepton Lepton Electroweak Reaction (MOLLER)

Overview of the MOLLER Experiment



Krishna Kumar
MOLLER Collaboration Spokesperson
UMass, Amherst

January 27, 2022

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

Outline

- **The MOLLER Science Discovery Reach**
  - Global Context
  - The observable and the experimental goal
  - Search for New Neutral Current Interactions
- **The MOLLER Apparatus**
  - Overview of a parity violating electron scattering asymmetry measurement
  - Overview of the MOLLER Apparatus
  - Snapshots of Recent Progress
- **The MOLLER Collaboration**

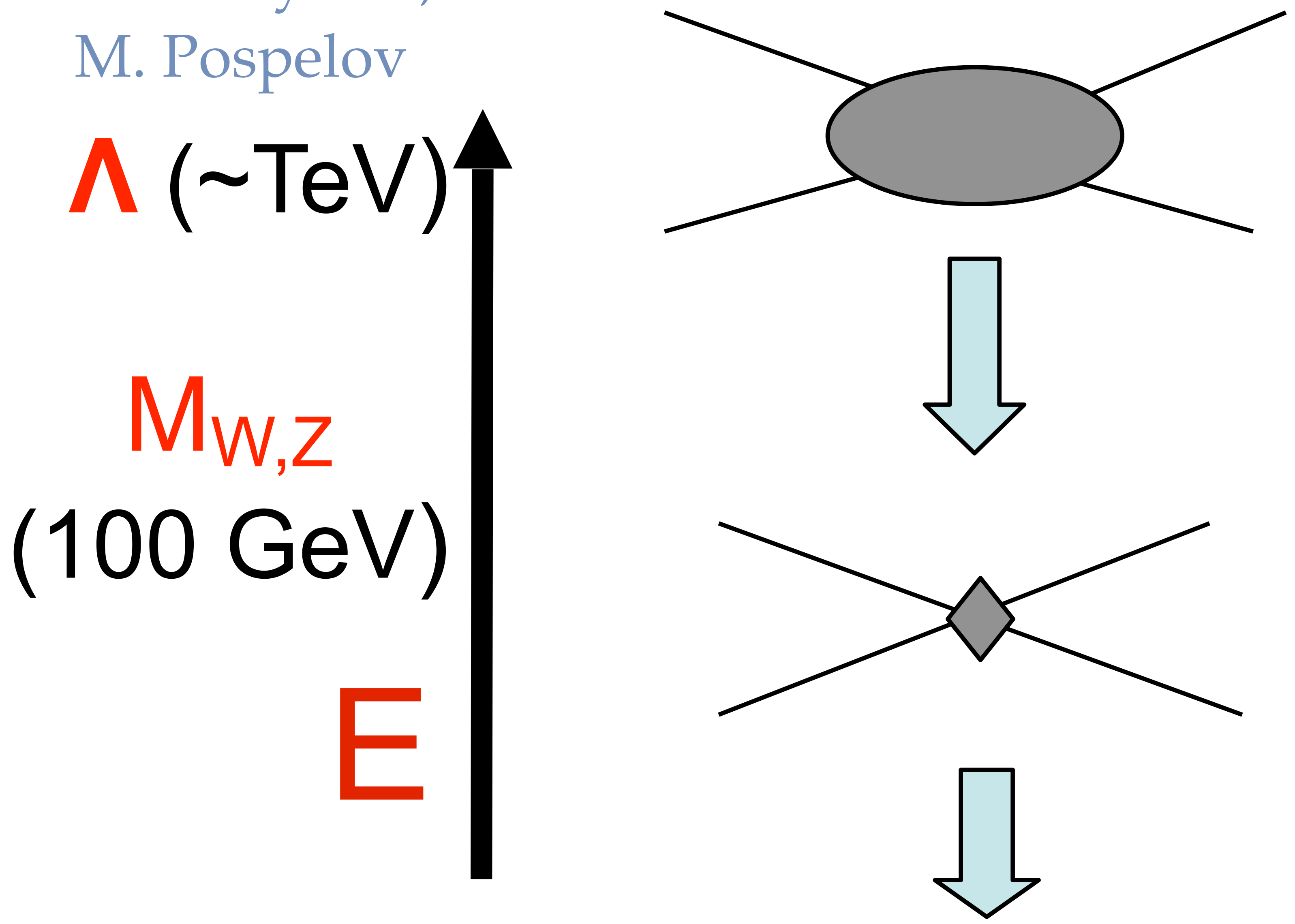
Physics Context for the Discovery Space of MOLLER

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

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

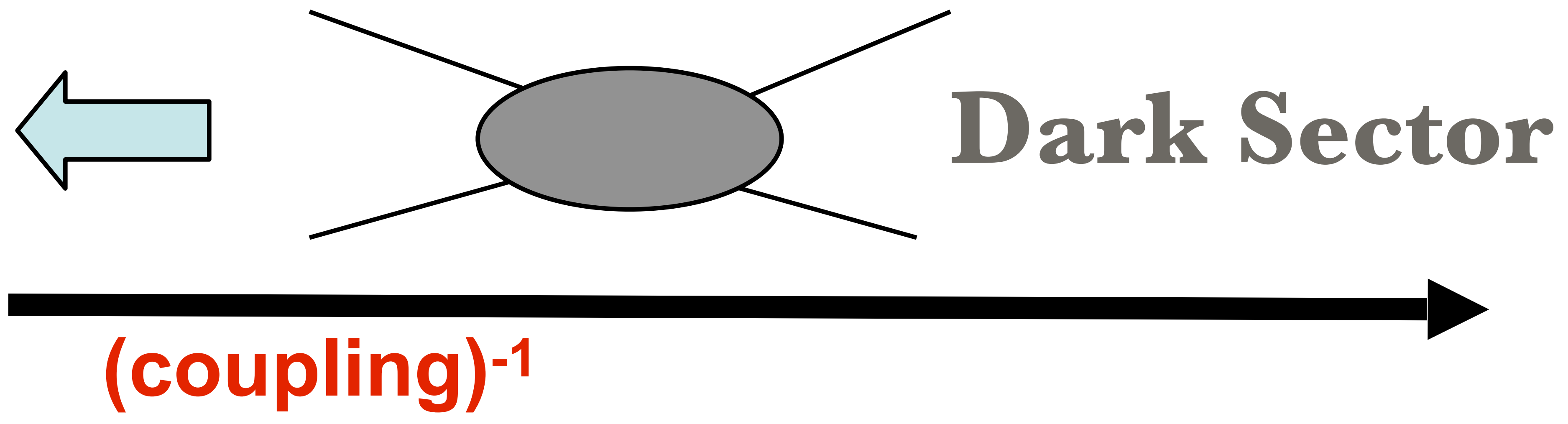
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

High Energy Dynamics

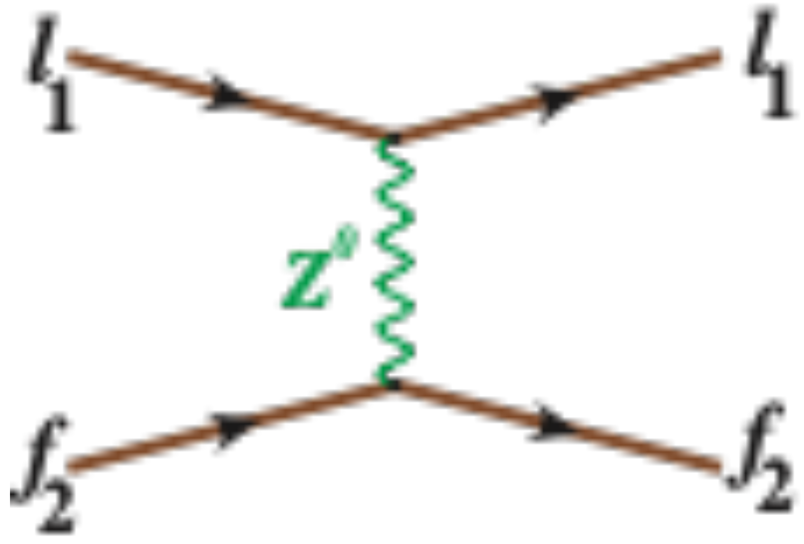


higher dimensional operators can be systematically classified

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

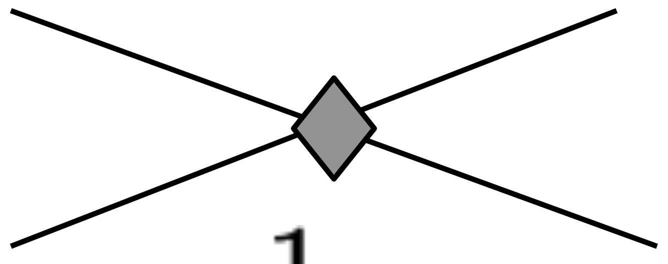


Leptonic and Semileptonic Weak Neutral Current Interactions



Search for new flavor diagonal neutral currents

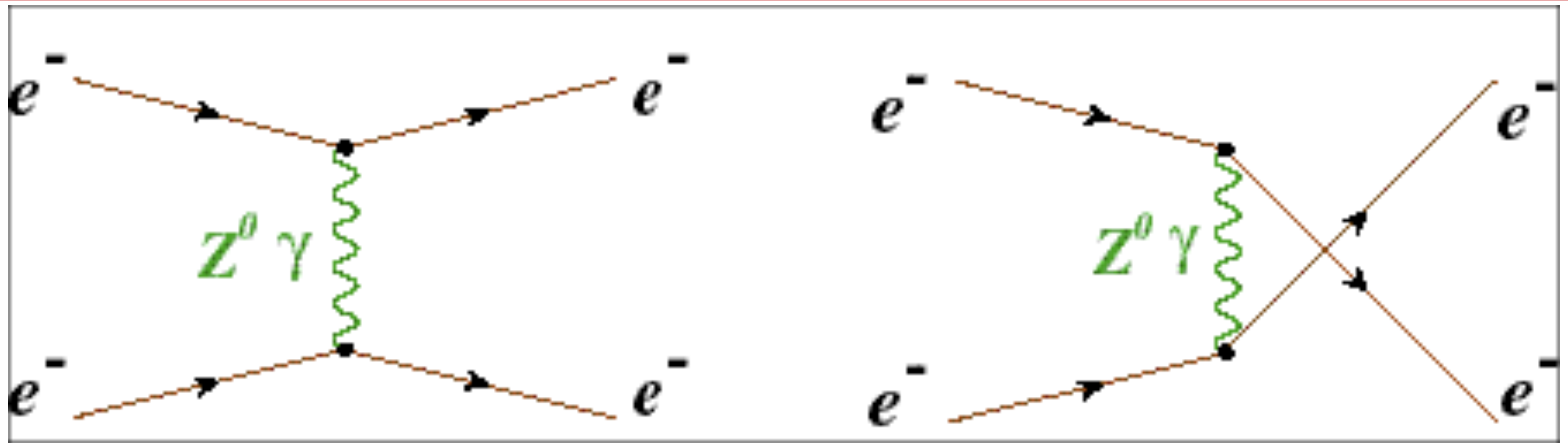
Tiny yet measurable deviations from precisely calculable SM processes



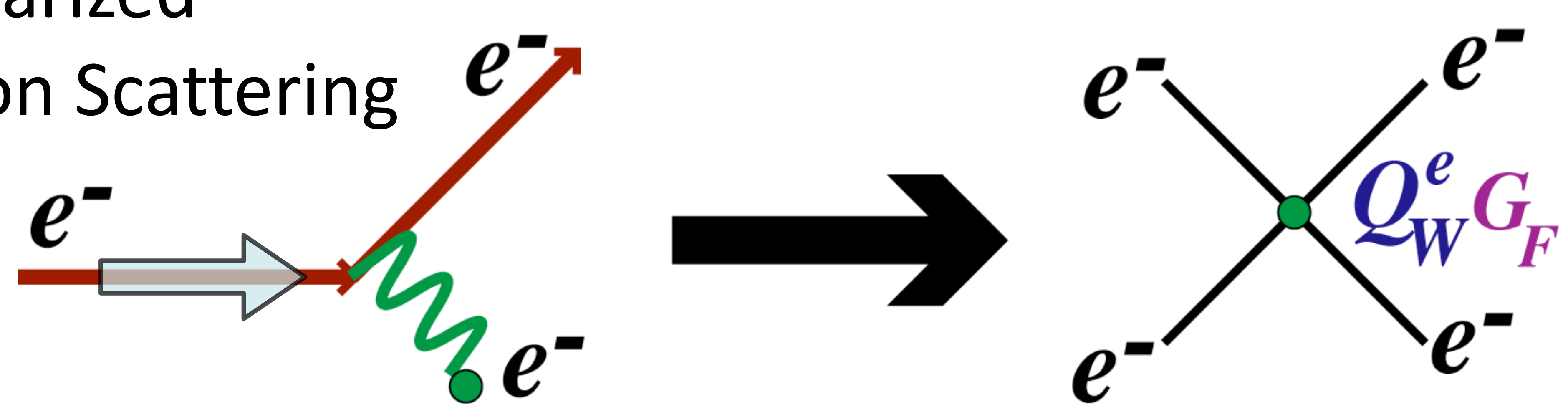
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ 10 TeV

Sensitivity of the Observable: PV Asymmetry in Møller Scattering



Fixed Target Polarized
Electron-Electron Scattering



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

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

11 GeV, 65 μA   90% beam polarization

A_{PV} ~ 32 ppb   δ(A_{PV}) ~ 0.8 ppb

δ(Q^e_W) = ± 2.1 % (stat.) ± 1.1 % (syst.)

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

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

New Physics

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

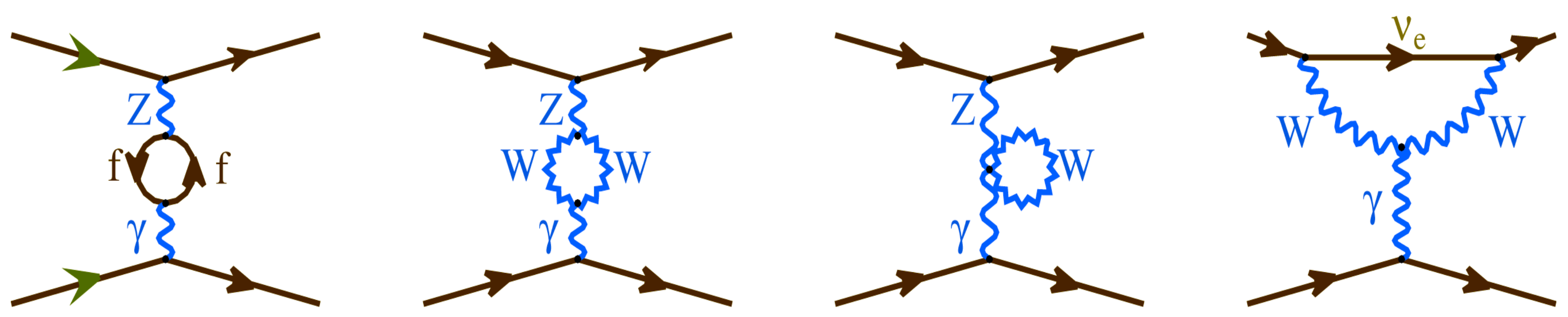
$$\frac{\Lambda}{\sqrt{|g^2_{RR} - g^2_{LL}|}} = 7.5 \text{ TeV}$$

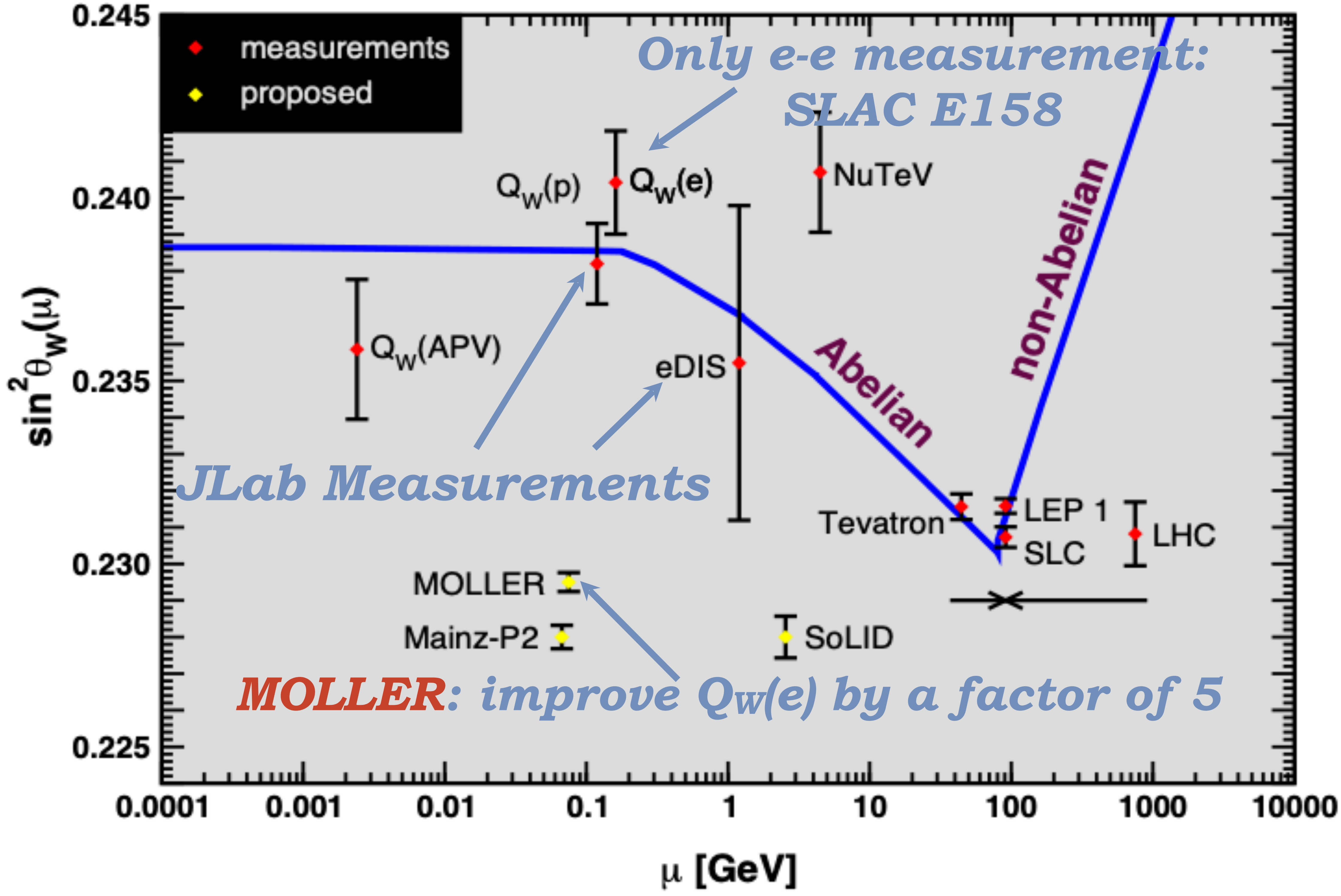
New purely leptonic interactions: MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

Weak Mixing Angle Measurements at Low Energy

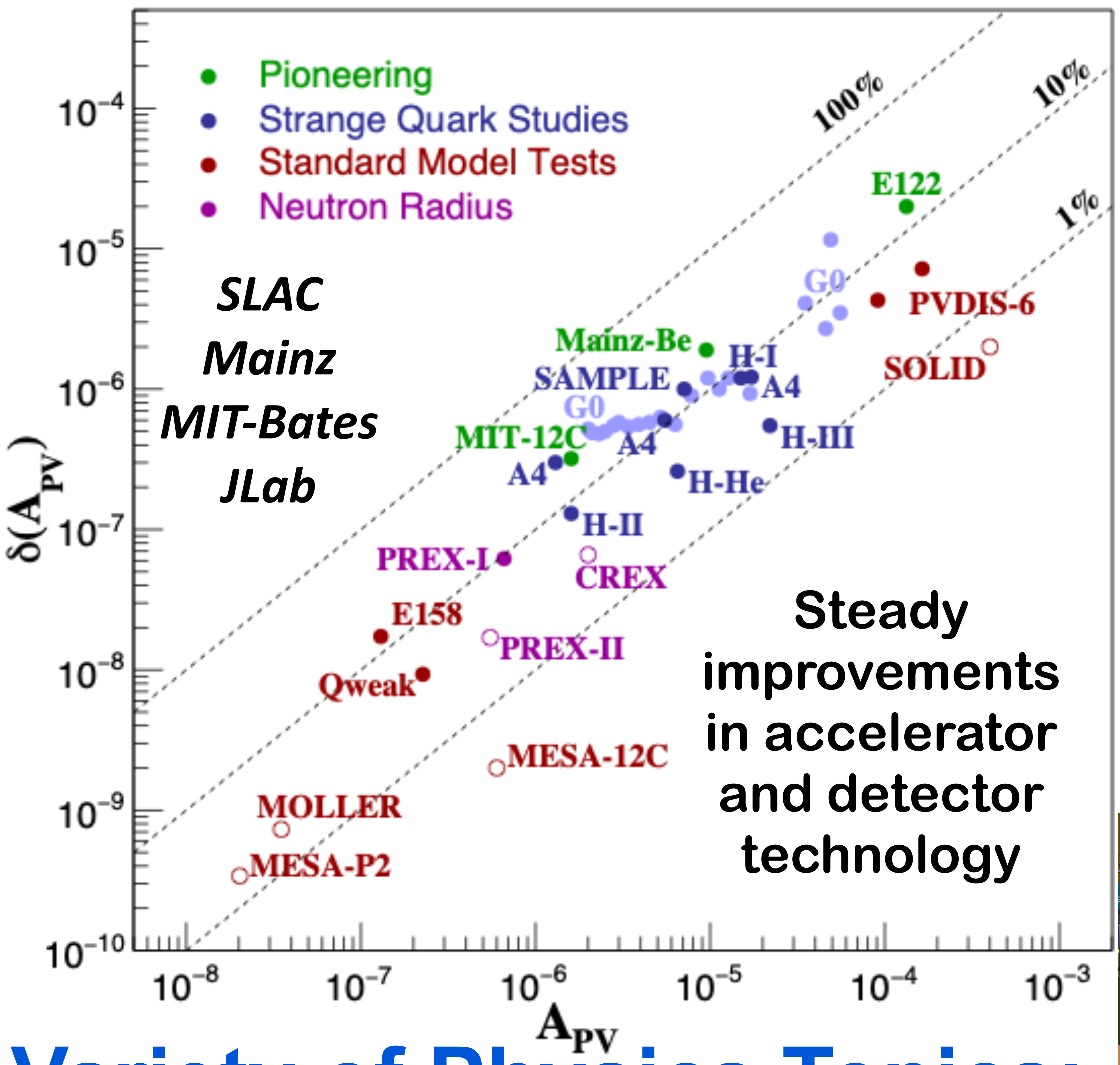
- **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- **PV elastic e-p scattering: Qweak**
  - theory robust at low beam energy
  - next generation: P2 (factor of 3 better)
- **PV Deep Inelastic Scattering: PVDIS**
  - theory robust for ^{2}H in valence quark region
  - factor of 5 improvement: SOLID

Czarnecki and Marciano (1995)





4th Generation Parity-Violating Electron Scattering Experiment at JLab



Variety of Physics Topics:

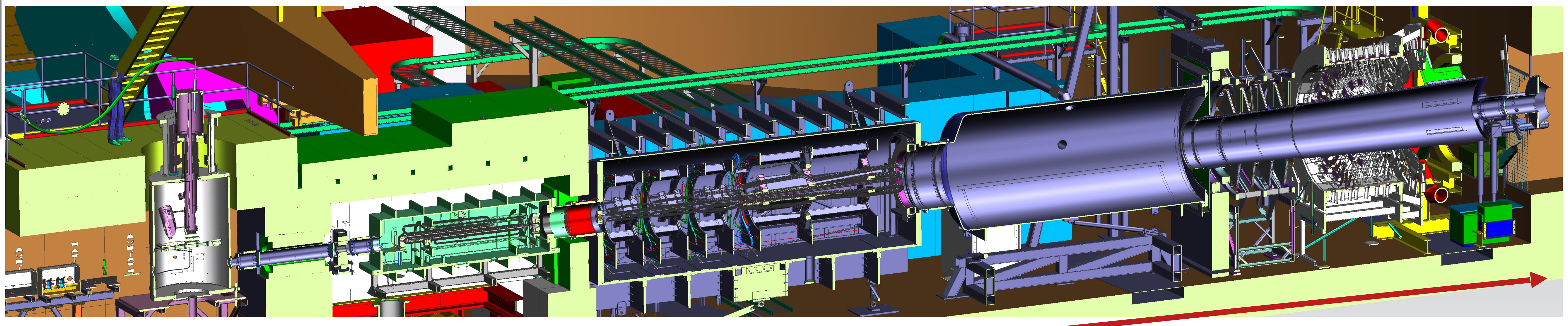
continuous interplay between hadron physics and electroweak physics

State of the Art

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

Unique opportunity leveraging 12 GeV Upgrade investment

MOLLER: *Special purpose installation in Hall A*



~ 30 m

Asymmetry Measurement Overview

Suppose instantaneous signal rate ~ 100 GHz and the beam helicity is reversed at 2 kHz

1 kHz Pulse Pair Width: ~100 ppm → 10 Billion Pairs: 1 ppb (average 10^7 s)

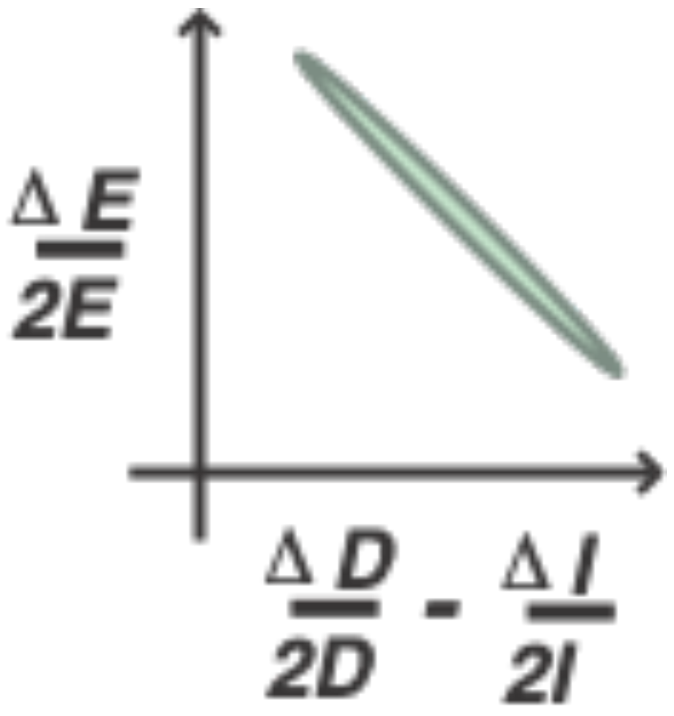
Detector D, Current I: F = D/I

$$\boxed{A_{pair} = \frac{F_R - F_L}{F_R + F_L}}$$

$$A_{pair} = \frac{\Delta F}{2F} + \Delta A$$

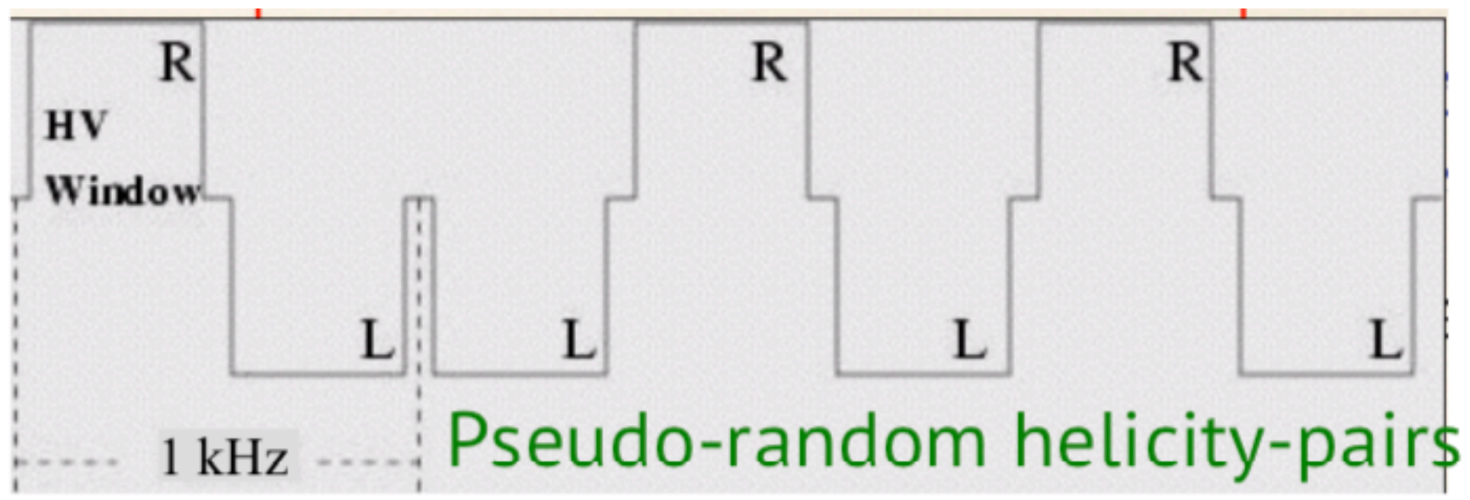
$$\left(A_{expt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

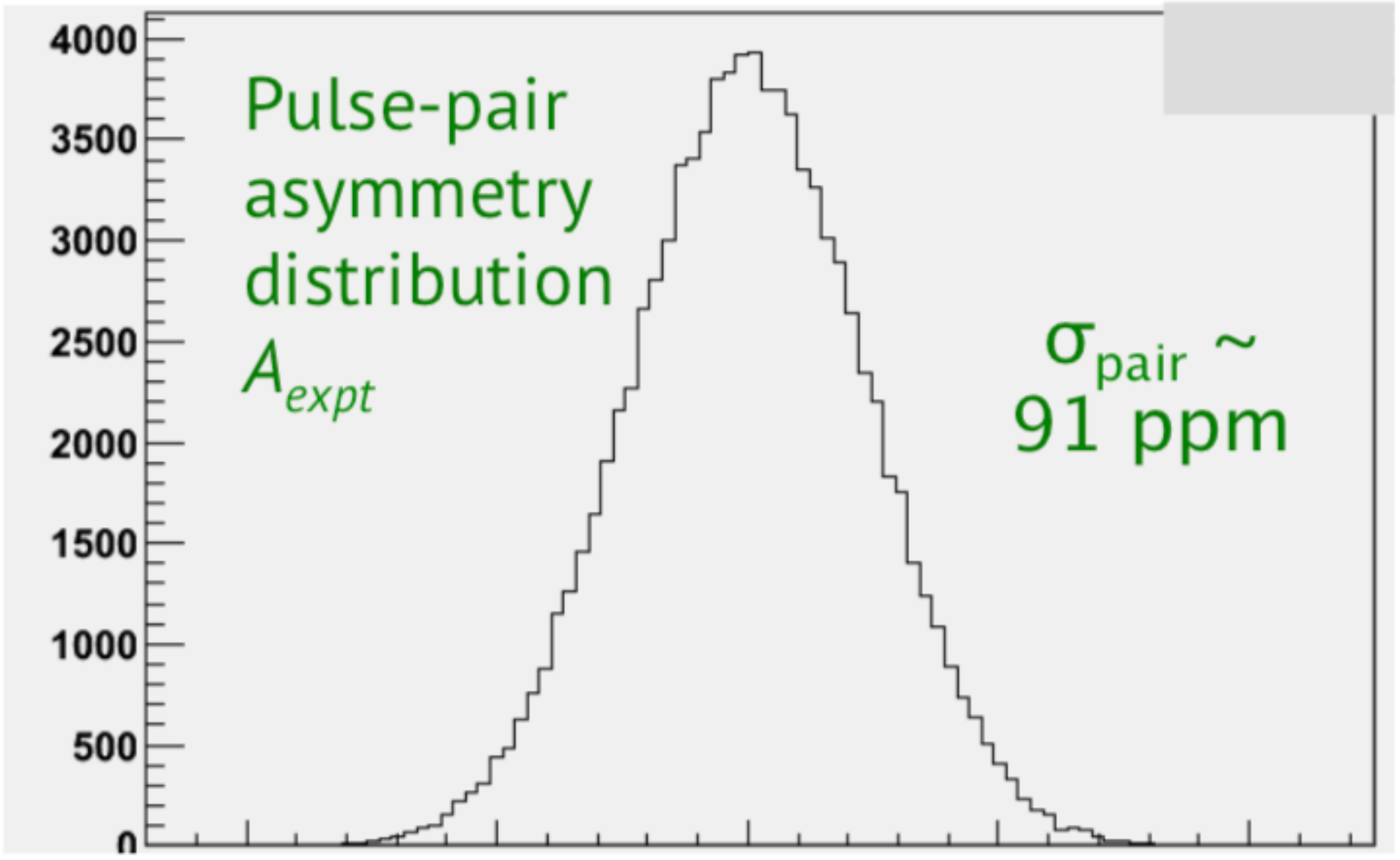
I order: $x, y, \theta_x, \theta_y, E$
II order: e.g. spot-size



Must minimize both random and helicity correlated fluctuations due to electron beam trajectory, energy and spot-size

After corrections, variance of A_{pair} must get as close to counting statistics as possible: ~ 100 ppm (1kHz pairs); central value then reflects A_{phys}





$$\sigma_{A_{expt}} = \frac{\sigma_{pair}}{\sqrt{N_{pair}}} = \frac{91\,\text{ppm}}{\sqrt{30\times10^9}} = 0.5\,\text{ppb}$$

Pulse-pair "width" σ_{pair} is the parameter that determines the statistical error

Projected Uncertainty Tables

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

Contributions to σ_{pair} - "Pair width"

Parameter	Random Noise (65 μA)
Statistical width (0.5 ms)	**~ 82 ppm**
Target Density Fluctuation	30 ppm
Beam Intensity Resolution	10 ppm
Beam Position Noise	7 ppm
Detector Resolution (25%)	21 ppm (3.1%)
Electronics noise	10 ppm
Measured Width (σ_{pair})	**91 ppm**

$$\sigma_{A_{cxpt}} = 0.54\,\text{ppb} \quad A_{cxpt} \sim 26\,\text{ppb} \quad \frac{\sigma_{A_{cxpt}}}{A_{cxpt}} = 2.1\%$$

$$A_{PV} = \frac{\frac{A_{cxpt}}{P_b} - f_{bkgd}A_{bkgd}}{1 - f_{bkgd}}$$

Uncertainty budget for A_{PV}

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

All systematics required at sub-1% level

$$\boxed{\text{Combined}\ \frac{\delta A_{PV}}{A_{PV}} = 2.4\%}$$

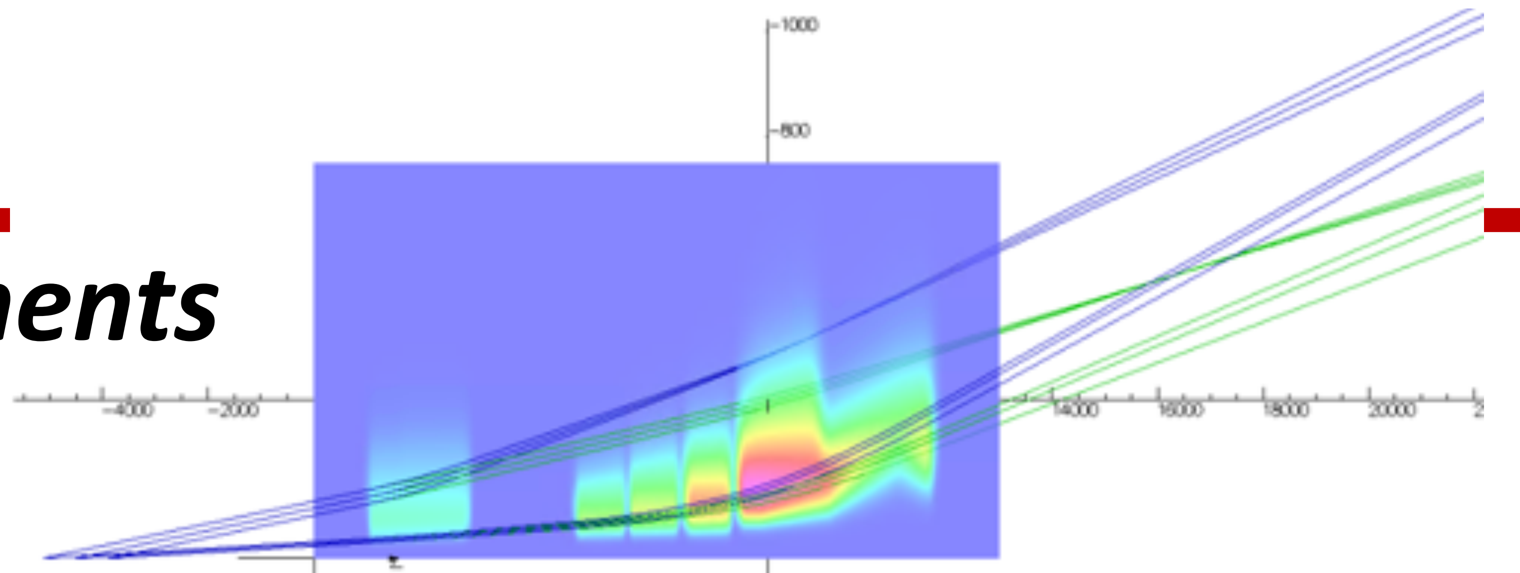
Experimental design driven by these goals:

Statistical error: Measure A_{expt} with precision ~ 2%

Systematic error: Measure and/or minimize all systematic error sources so their individual contributions are < 1%, resulting in statistics limited experiment

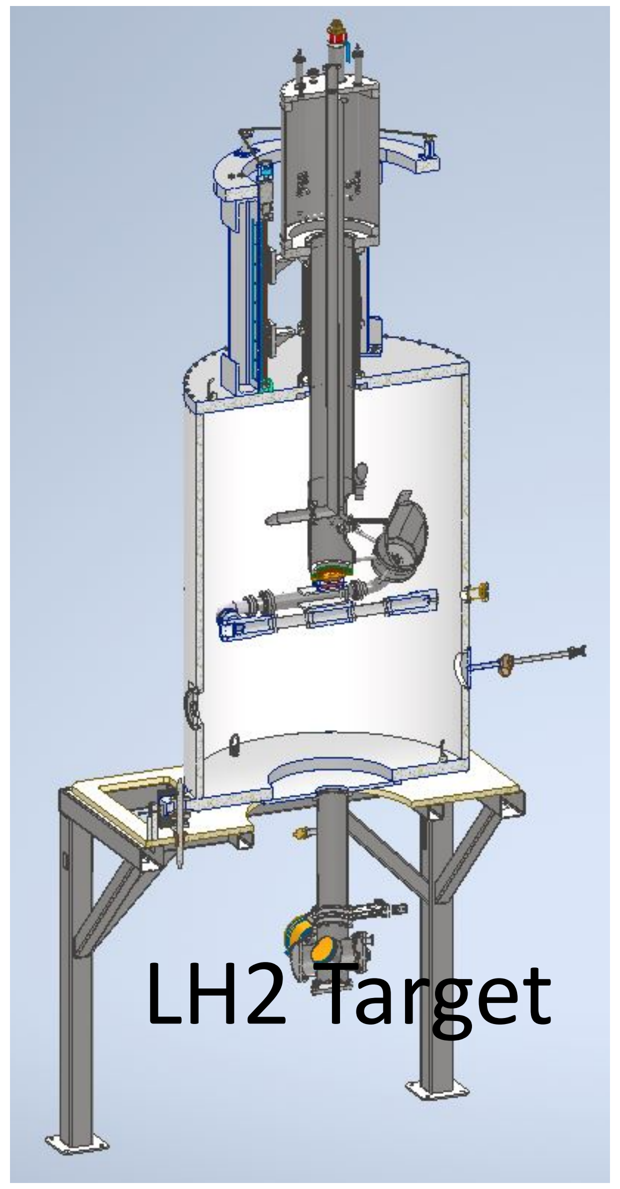
MOLLER Apparatus Characteristics From 30000 ft

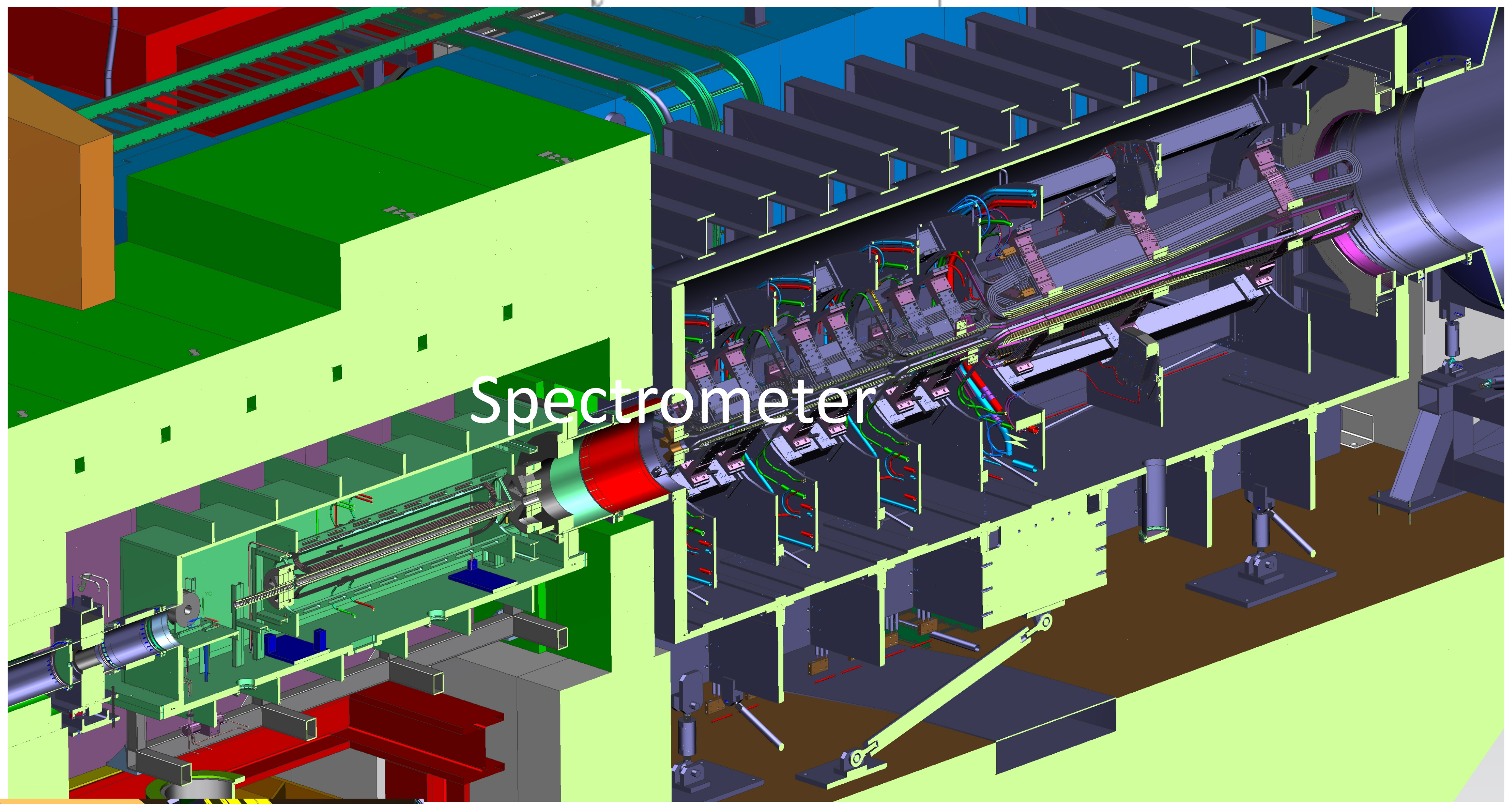
Evolutionary Improvements from Technology of Third Generation Experiments

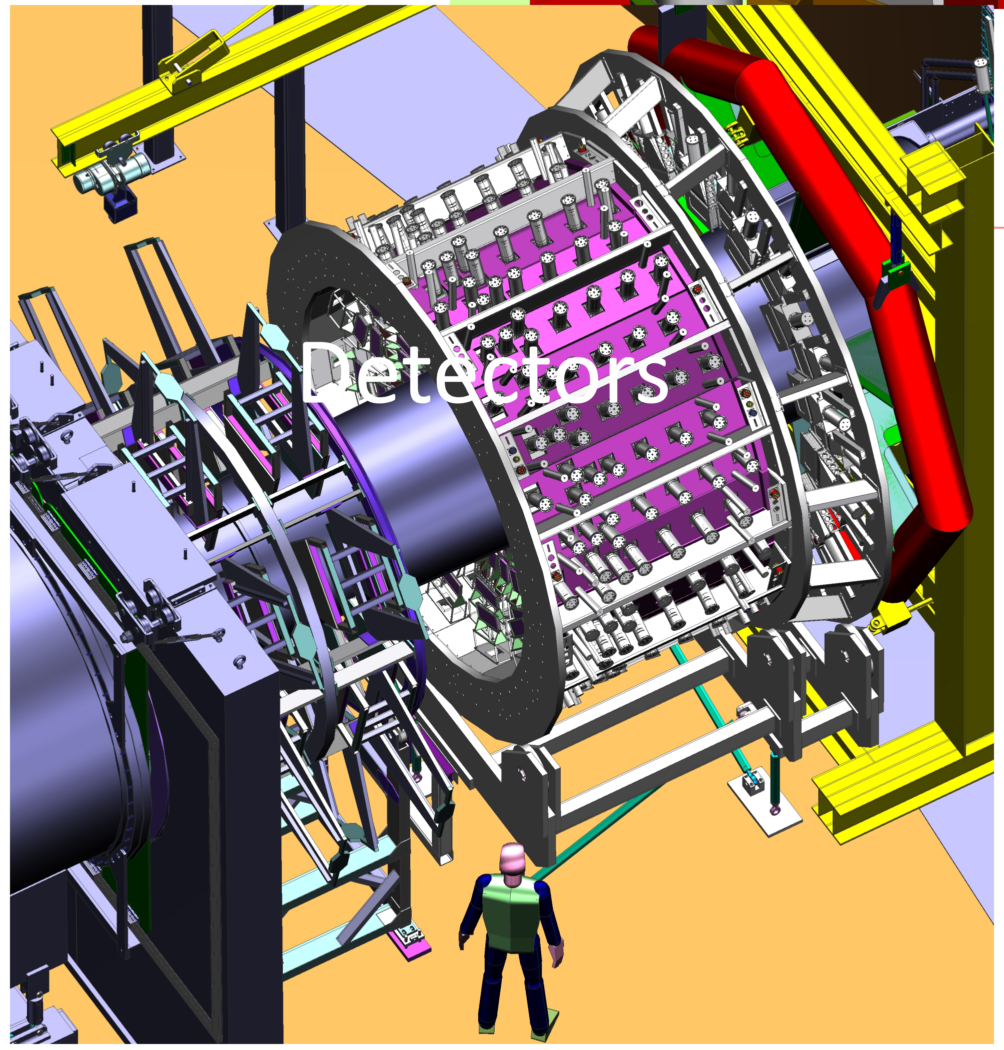


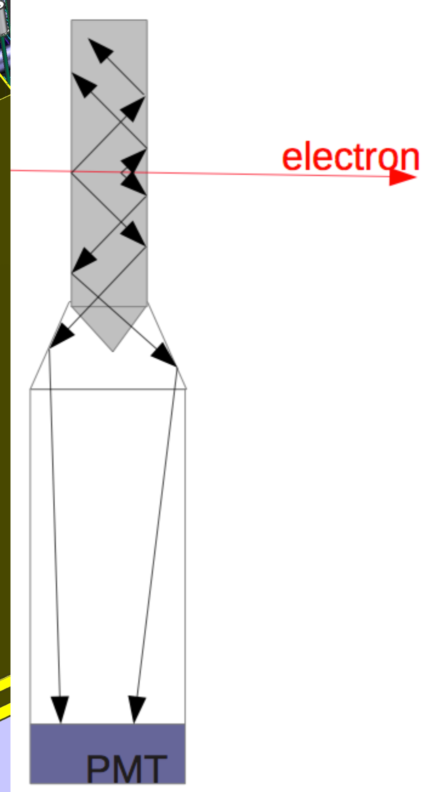
- High intensity polarized electron source
- ~ 134 GHz scattered electron rate
- 1 nm control of beam centroid on target
- ~ 9 gm/cm² liquid hydrogen target
  - 1.25 m: ~ 4 kW @ 70 μA
- Full Azimuthal acceptance w/ θ_{lab} ~ 5 mrad
  - novel toroidal spectrometer assemblies
  - radiation hard, segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry

- **MOLLER Collaboration Team**
  - Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158
  - Technical Design Report Draft is being internally reviewed
  - To be updated with final design details to ArXiv by Mar '23

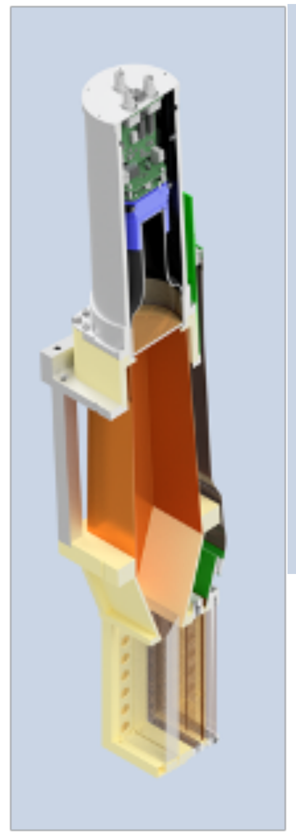


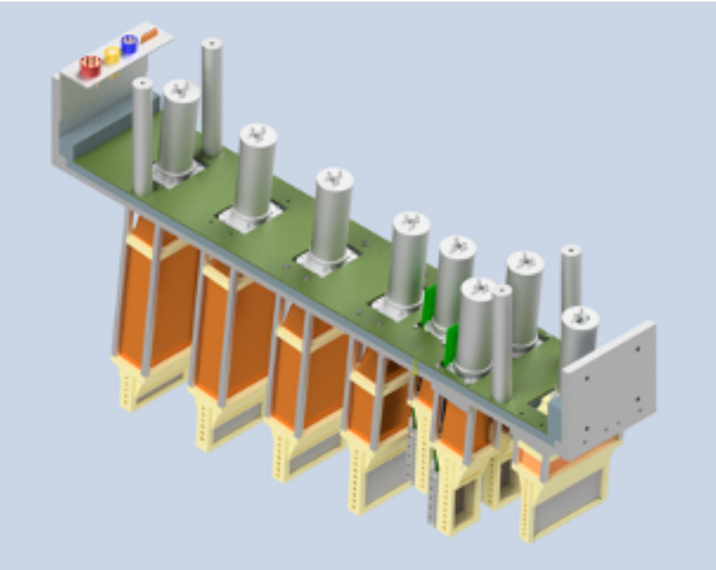






Single channel

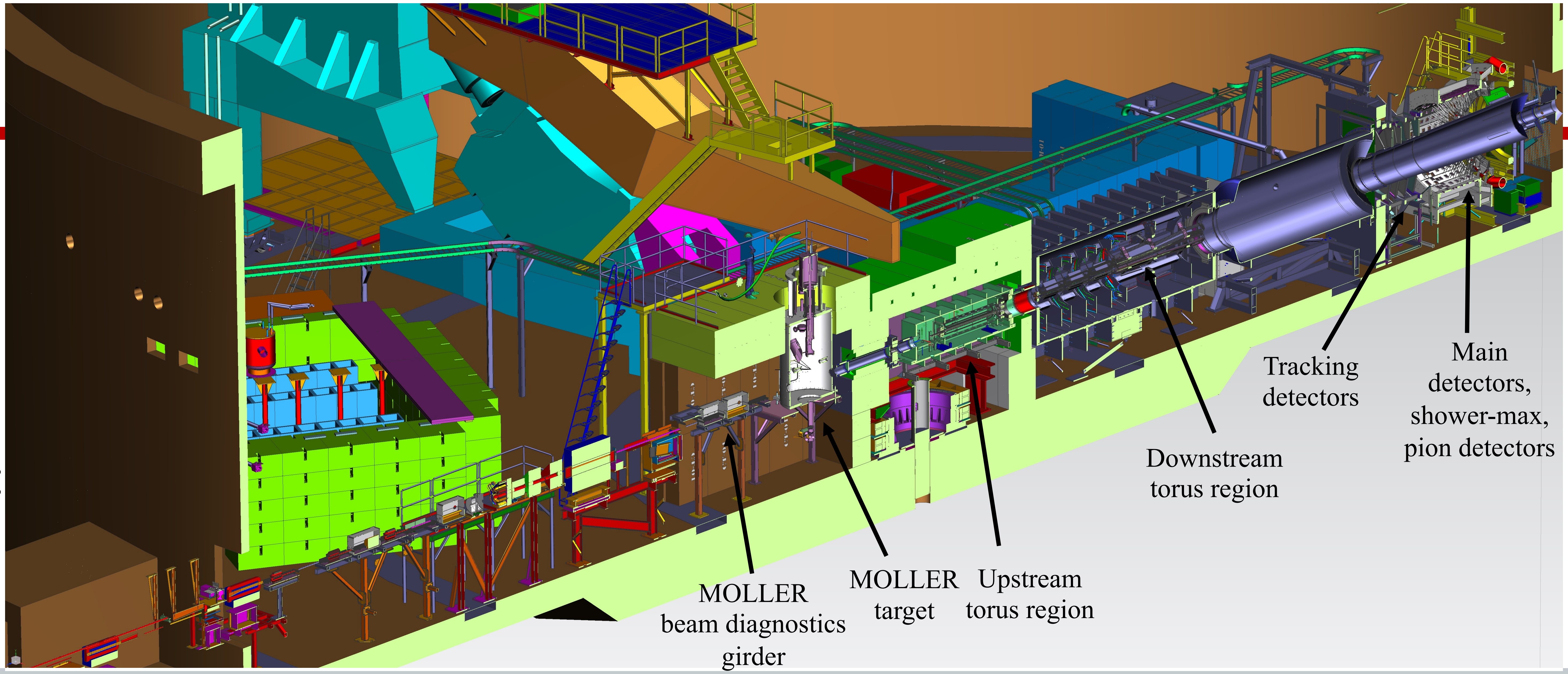


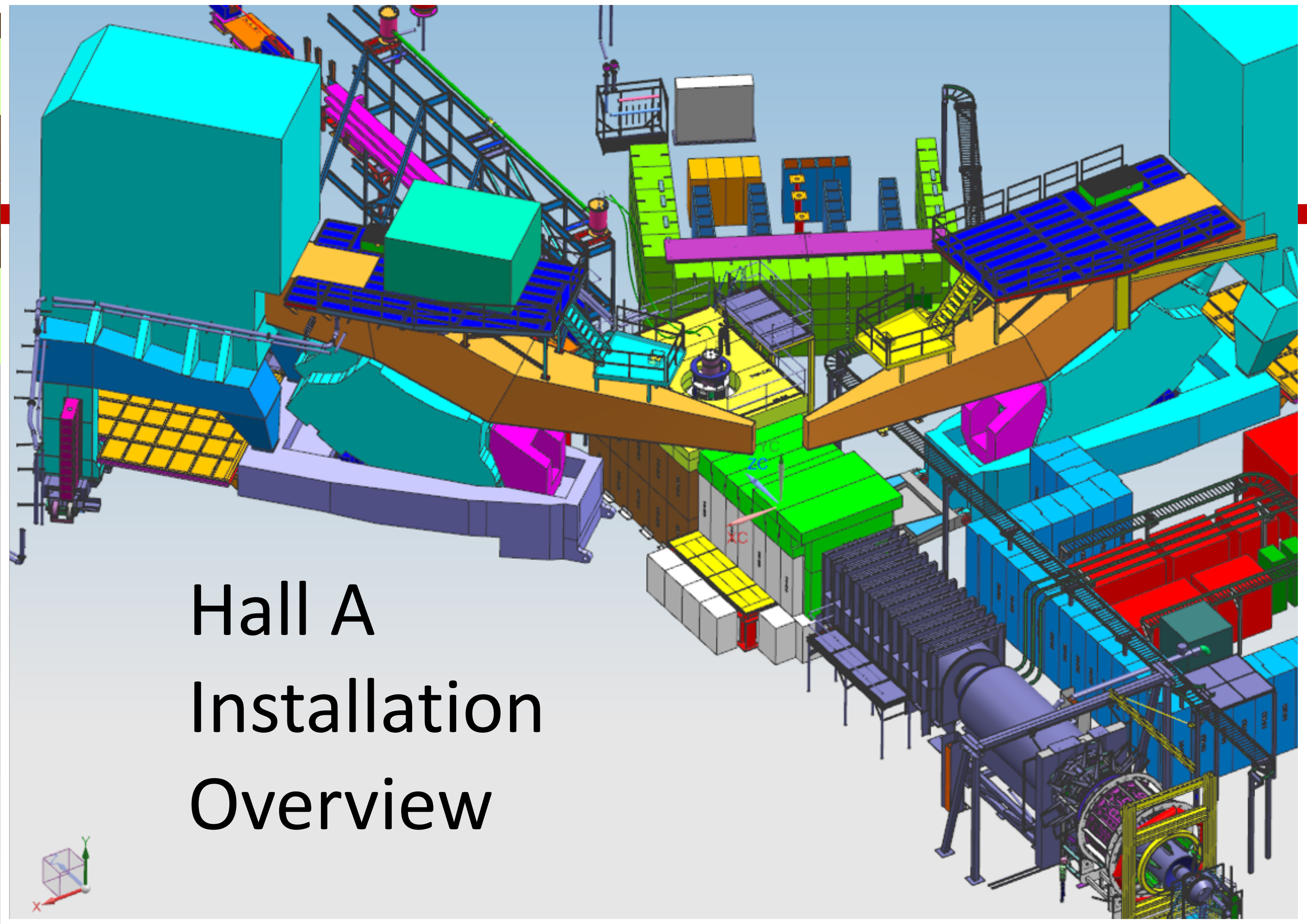


1/28th Segment

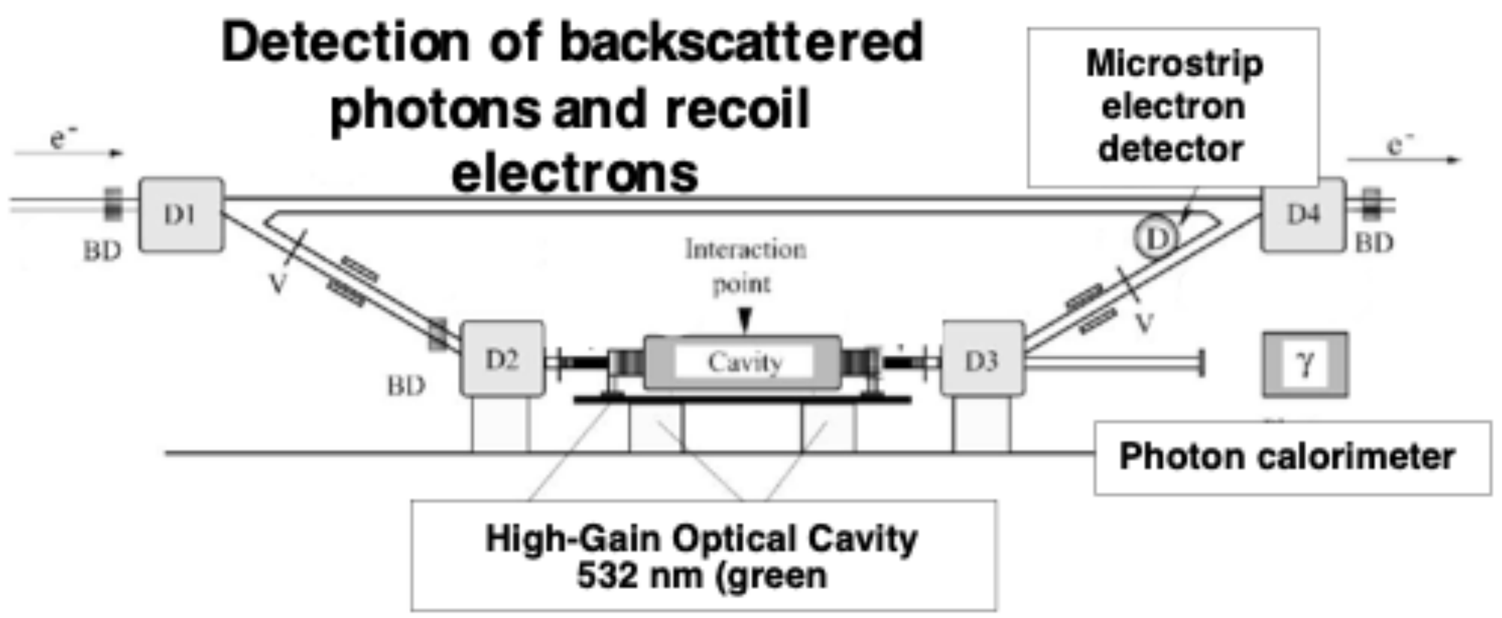
CAD

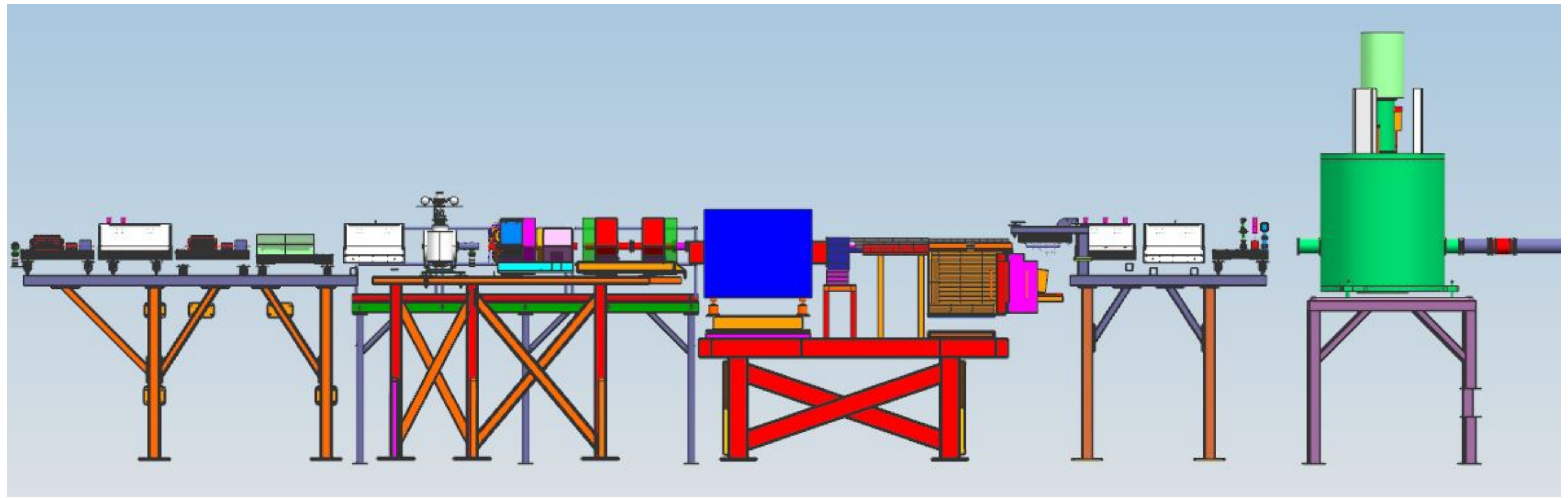
Tremendous amount of engineering design work over the past 2 years!





Beamline, Target and Polarimetry



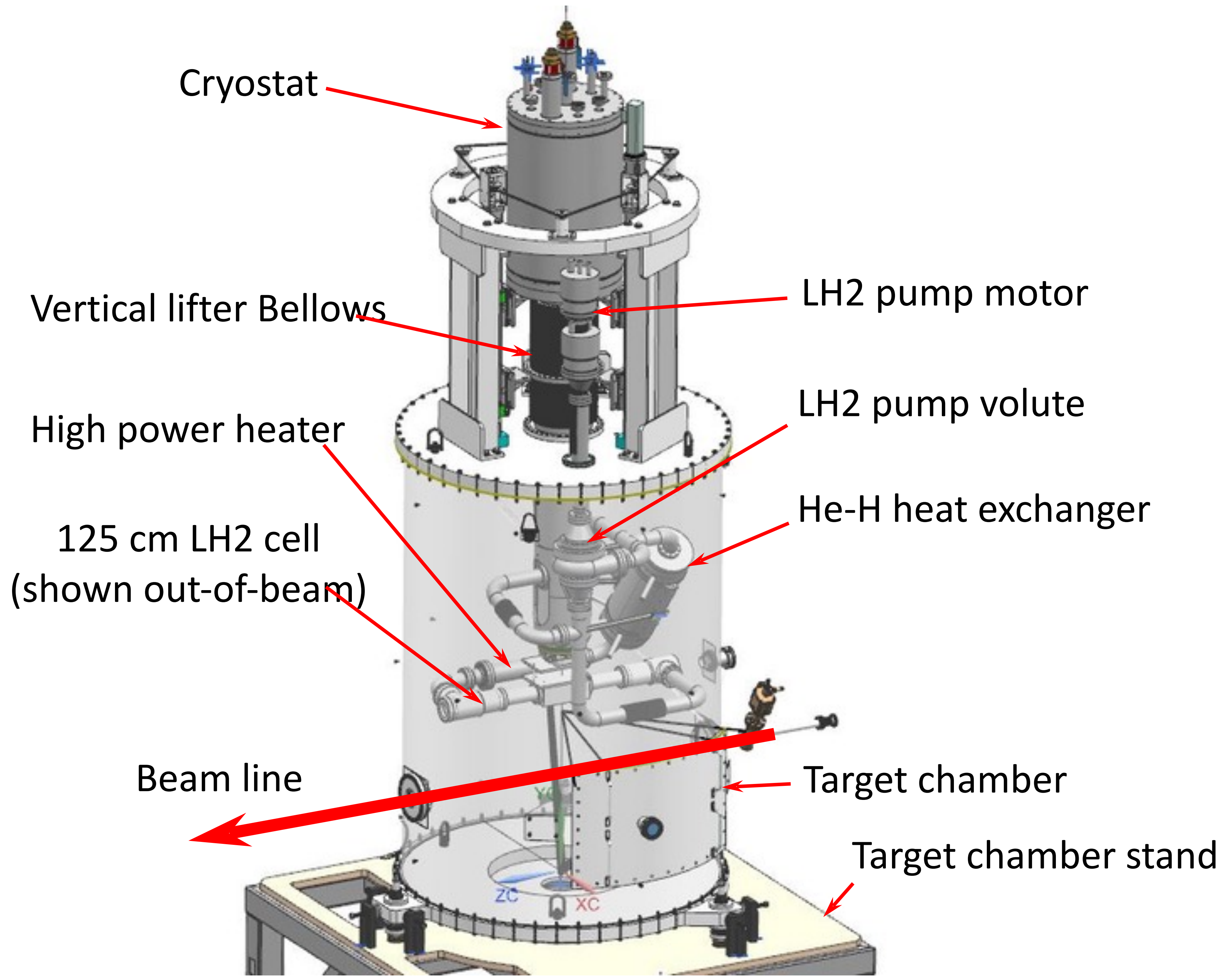


Beamline and Beam Monitoring

- Redundant position, angle, intensity monitoring
- Intensity, position monitor resolution requirements

Electron Beam Polarimetry

- Two independent measurements
- Compton: continuous monitor
- Møller: invasive at low beam current



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)

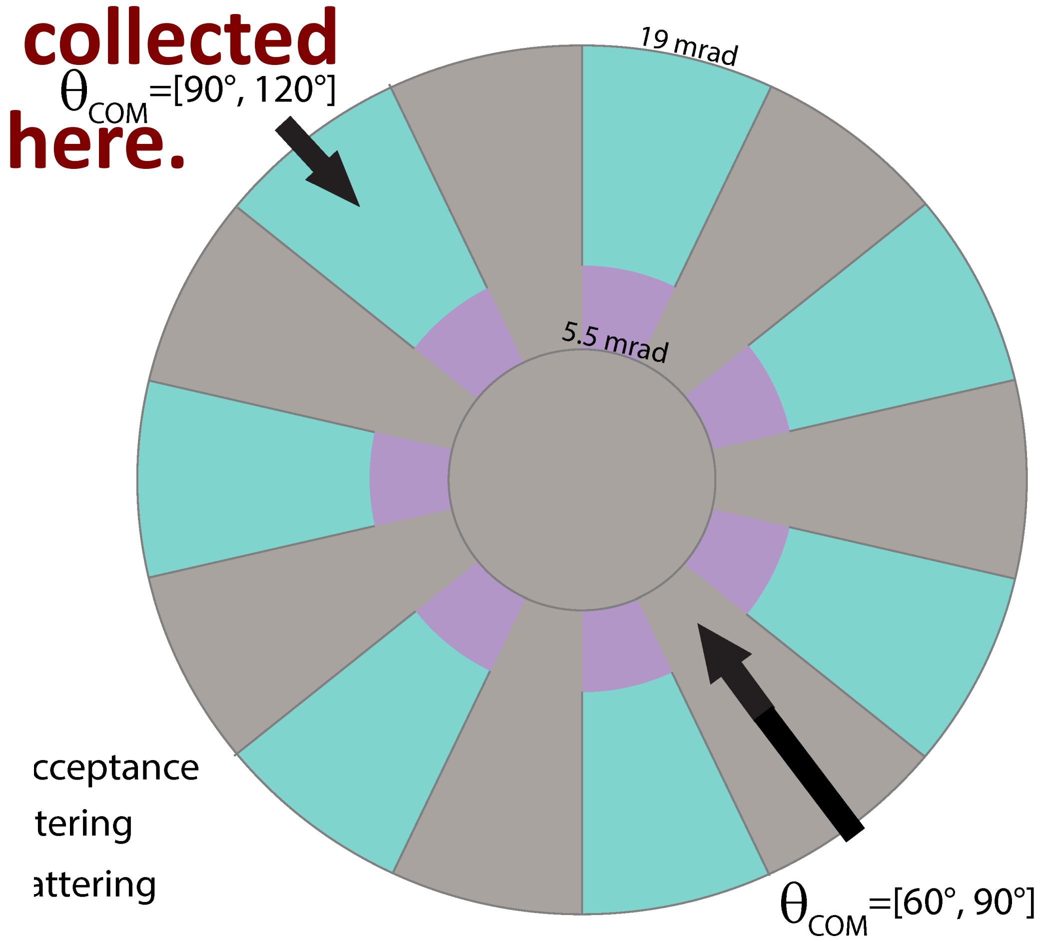
Main requirement: minimize target density fluctuations ($\Delta\rho/\rho$):

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

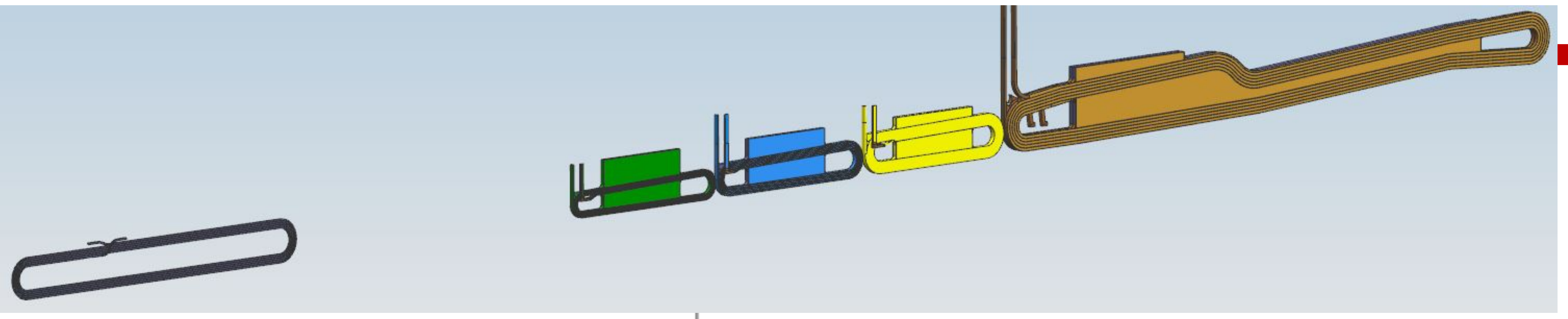
Spectrometer Acceptance and Collimation

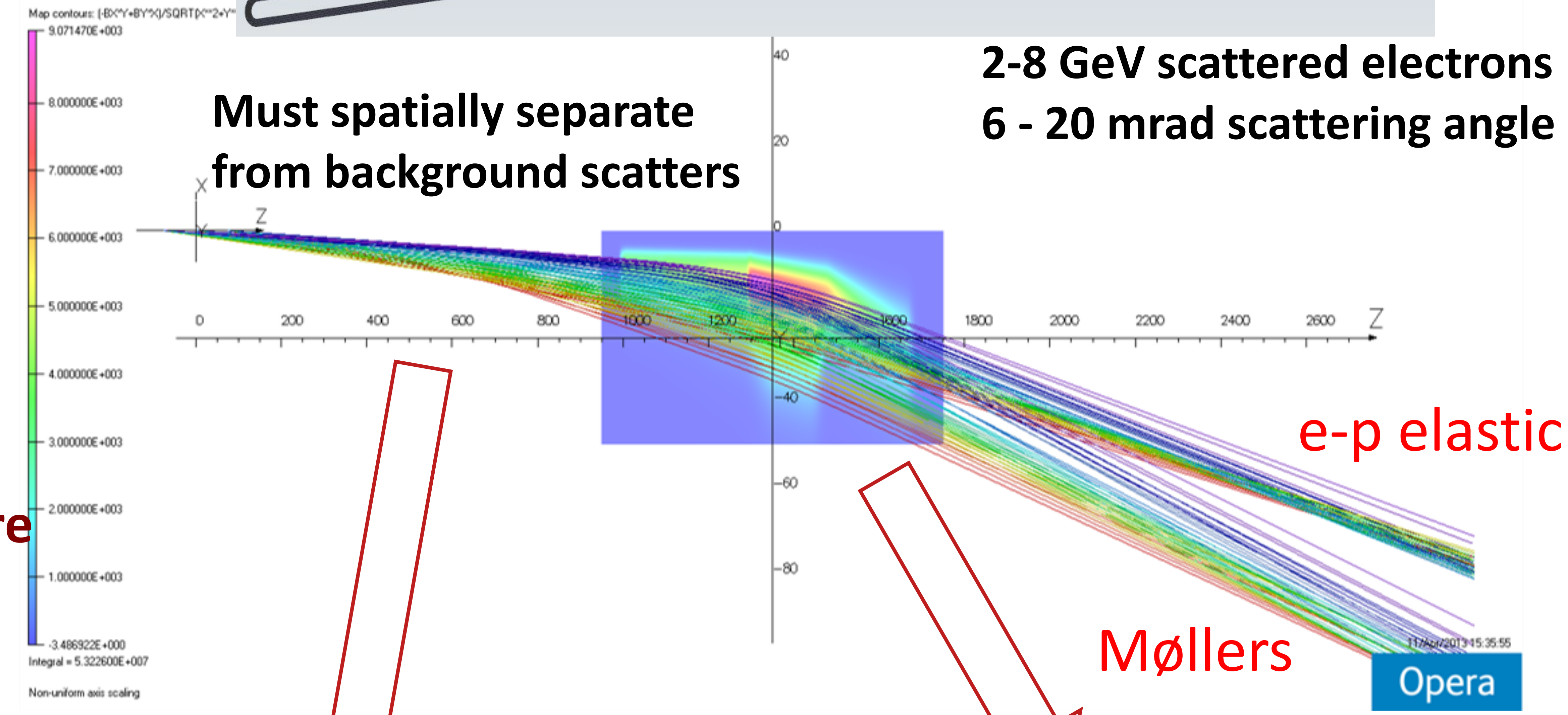
- Accept all Møller scattered electrons in range $\Theta_{CM} = 50^o – 130^o$
- **Exploit identical particle nature for 100% azimuthal acceptance**; needs odd number of coils

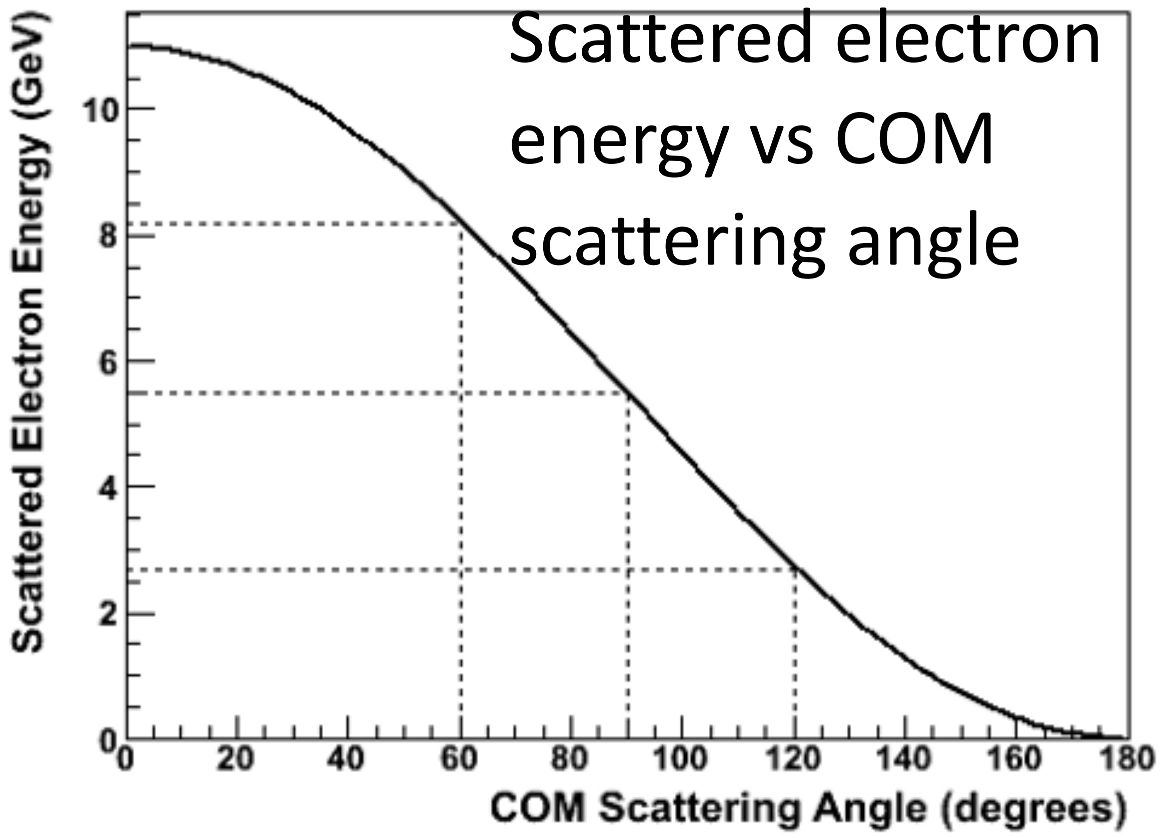
…are collected over here.

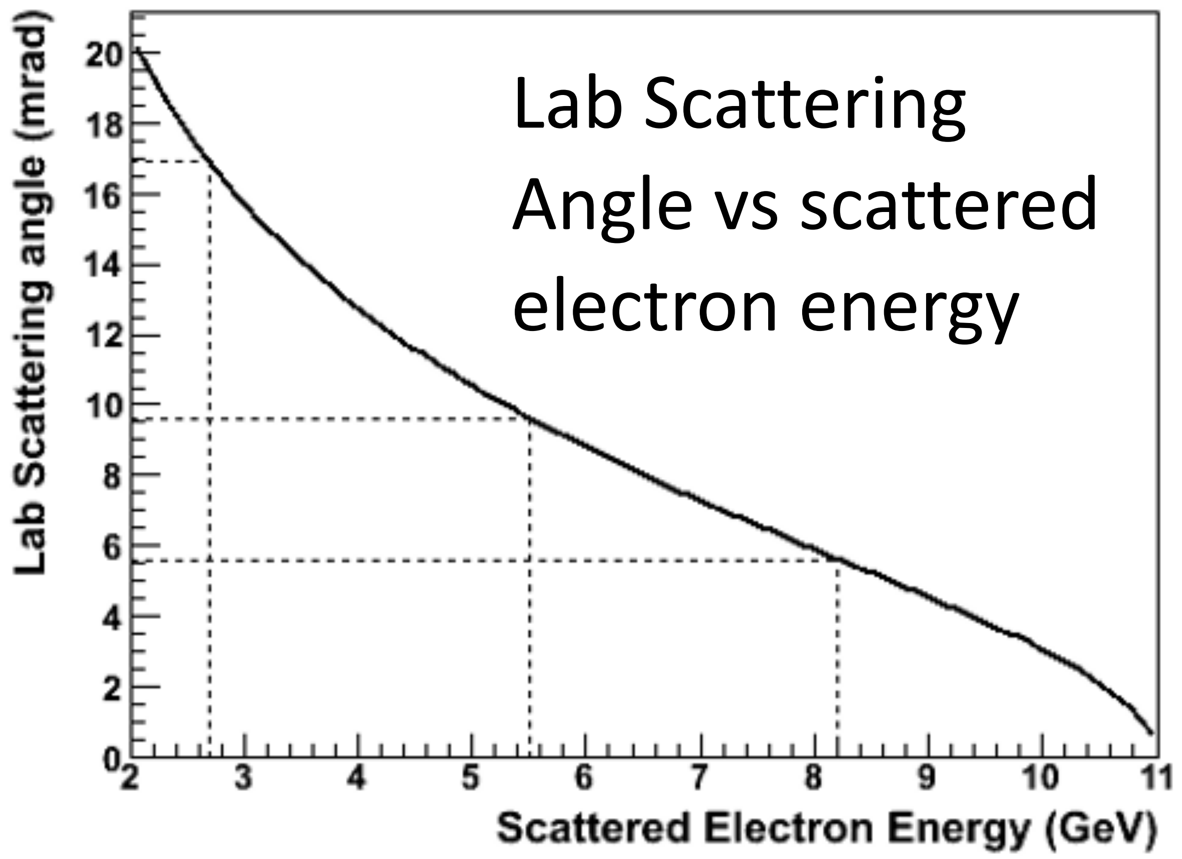


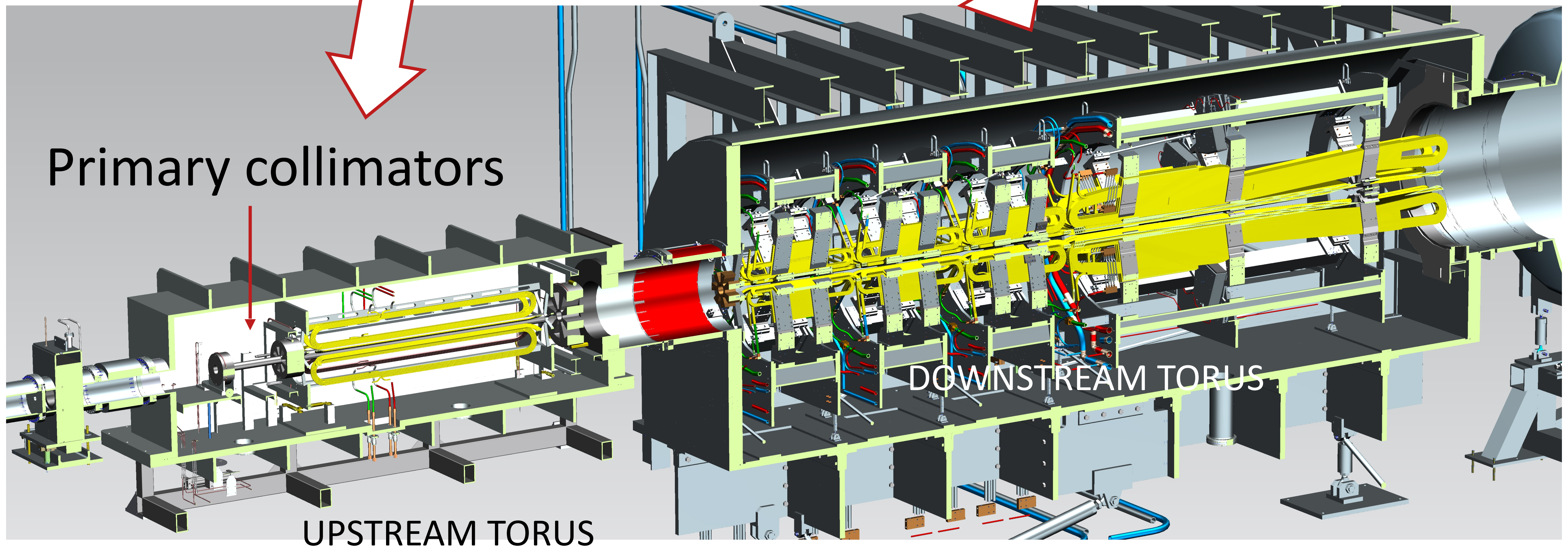
The rays that are blocked here…



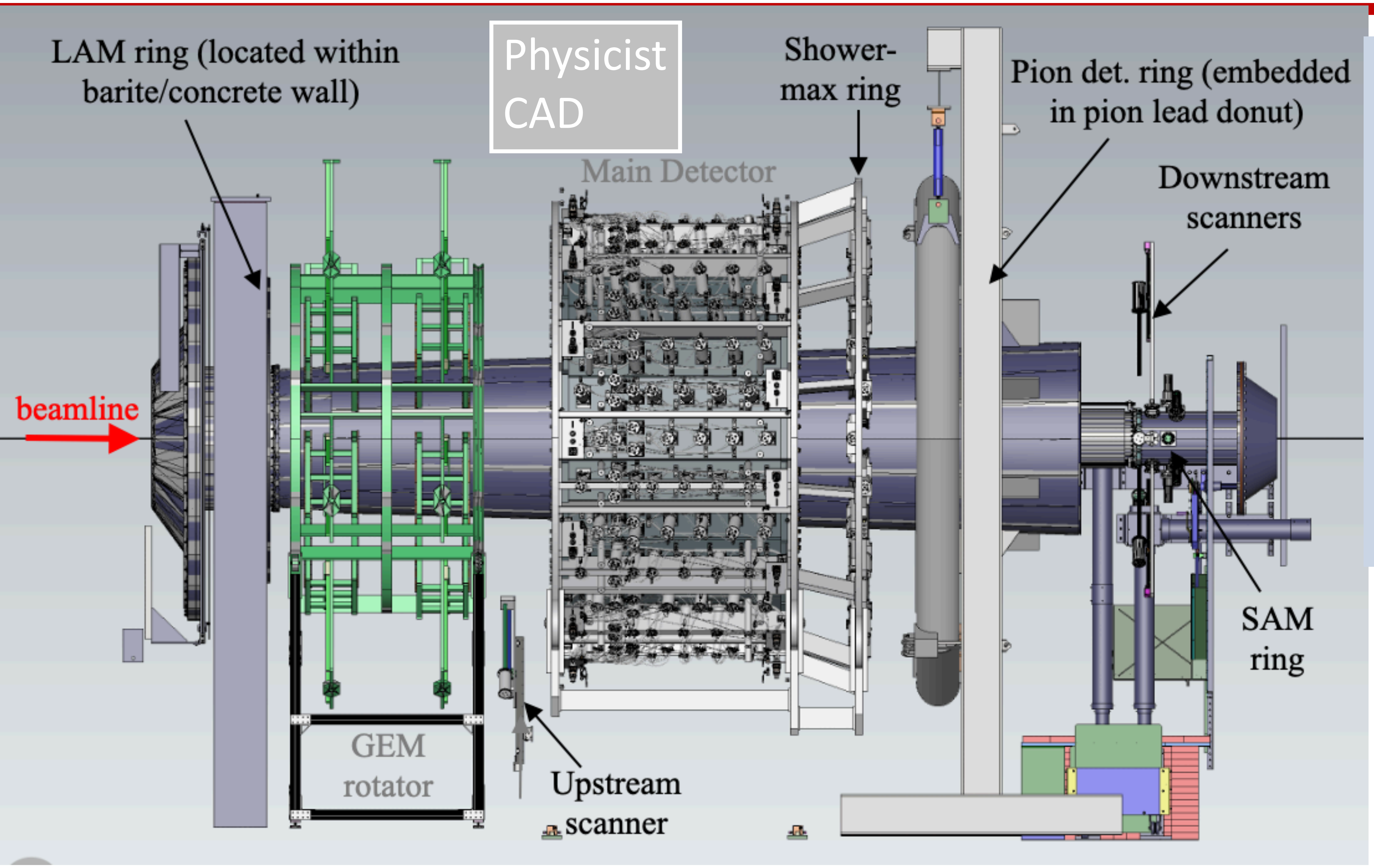


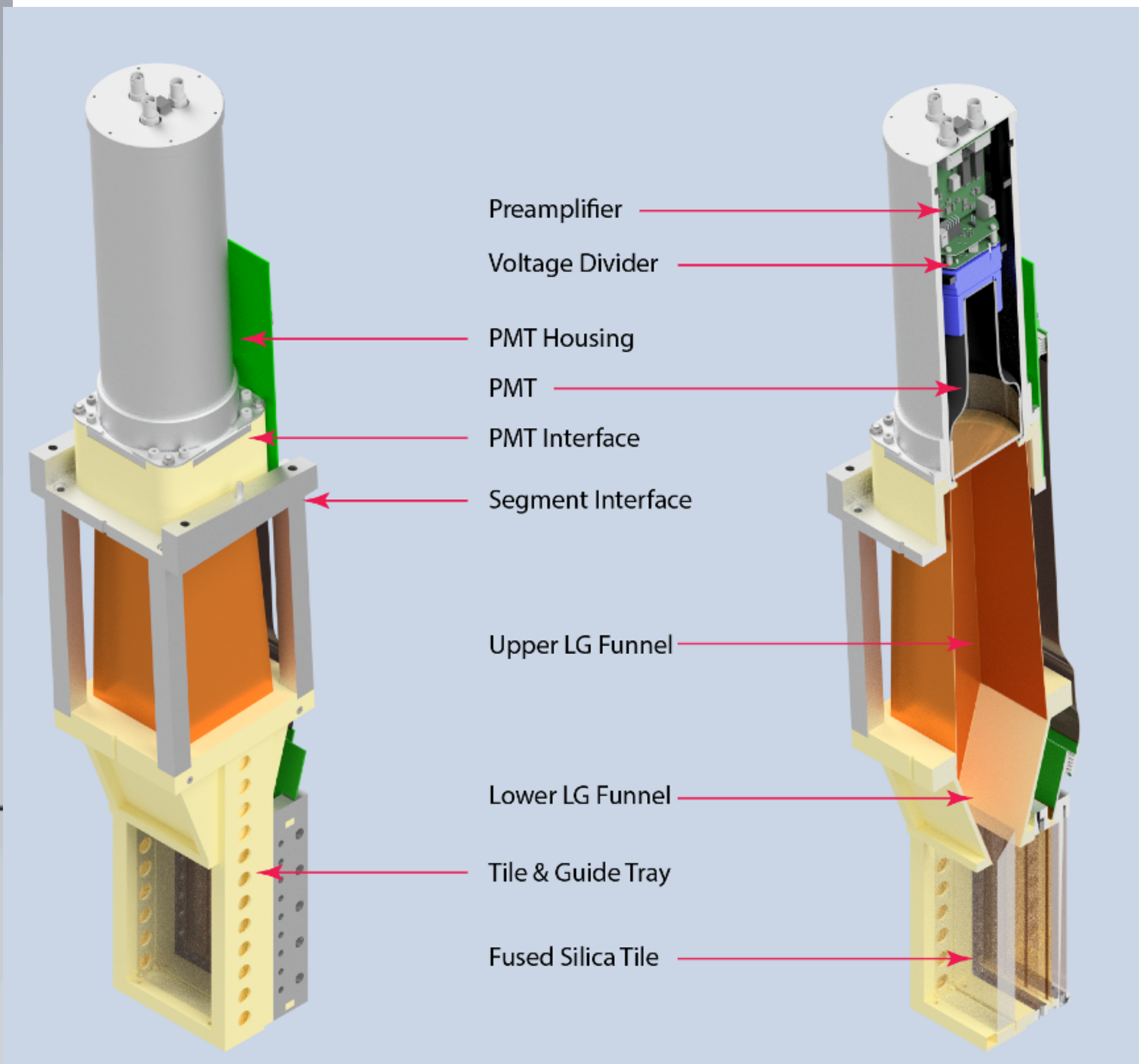




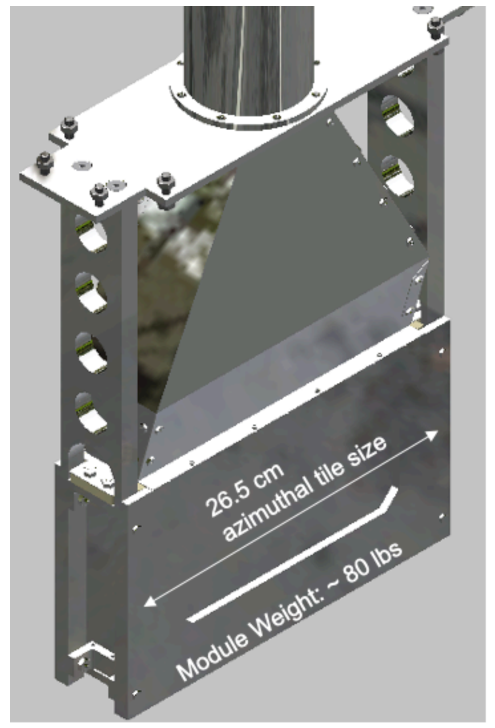


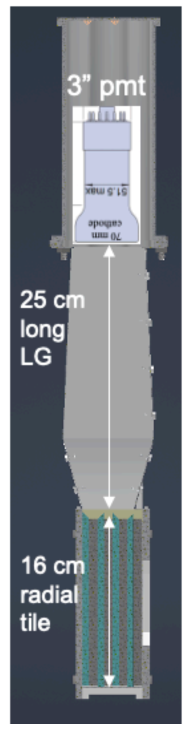
Primary and Auxiliary Integrating and Tracking Detectors

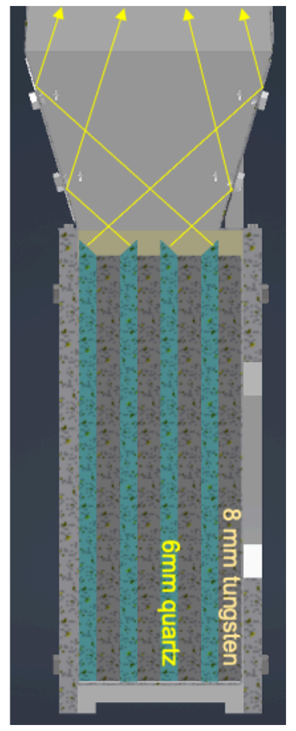




Requirement for Ring 5:
Detector resolution < 25%
excess noise < 4%







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

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

- 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*

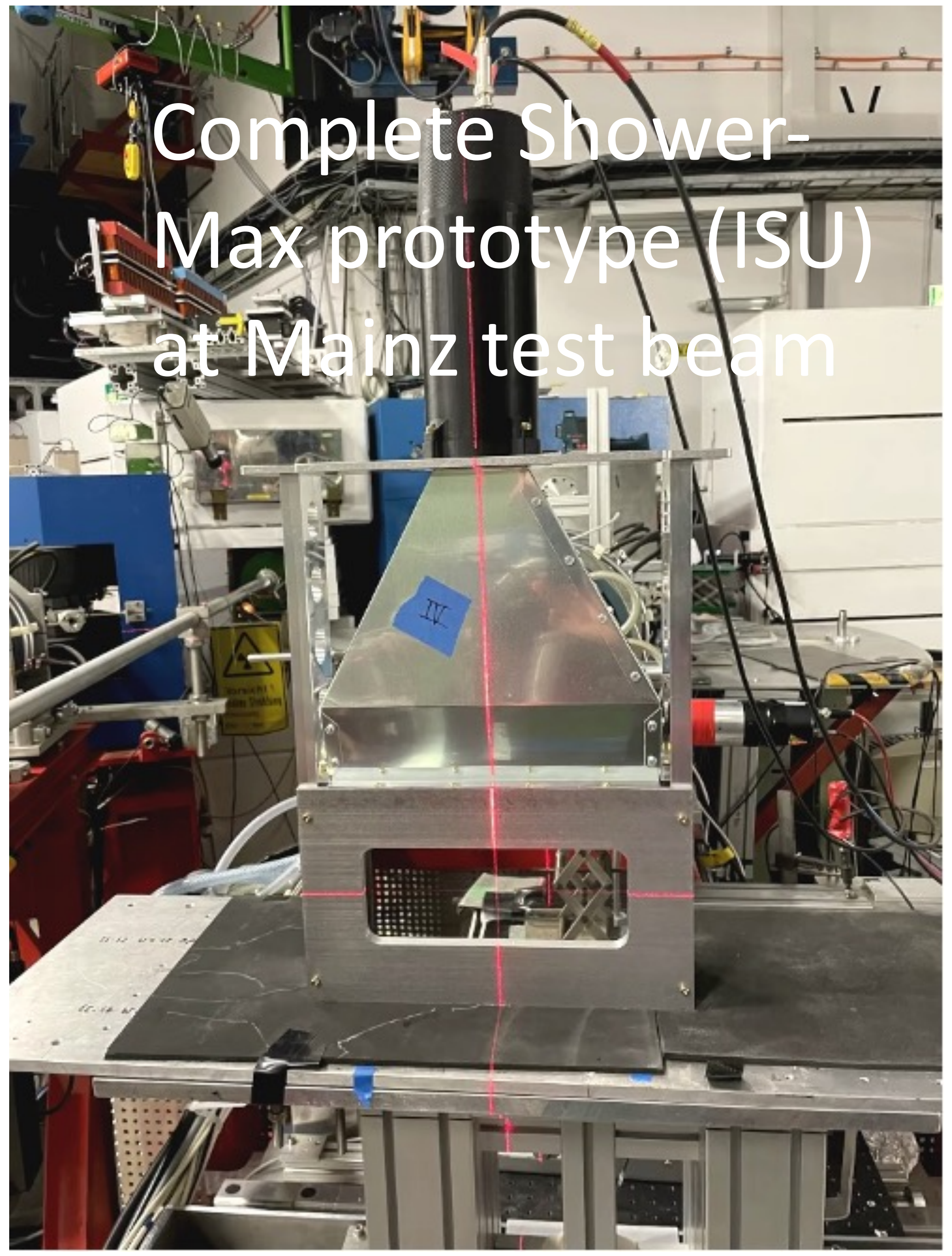
Pre-Production Prototypes being actively tested!


Prototype Frame for DS Magnet

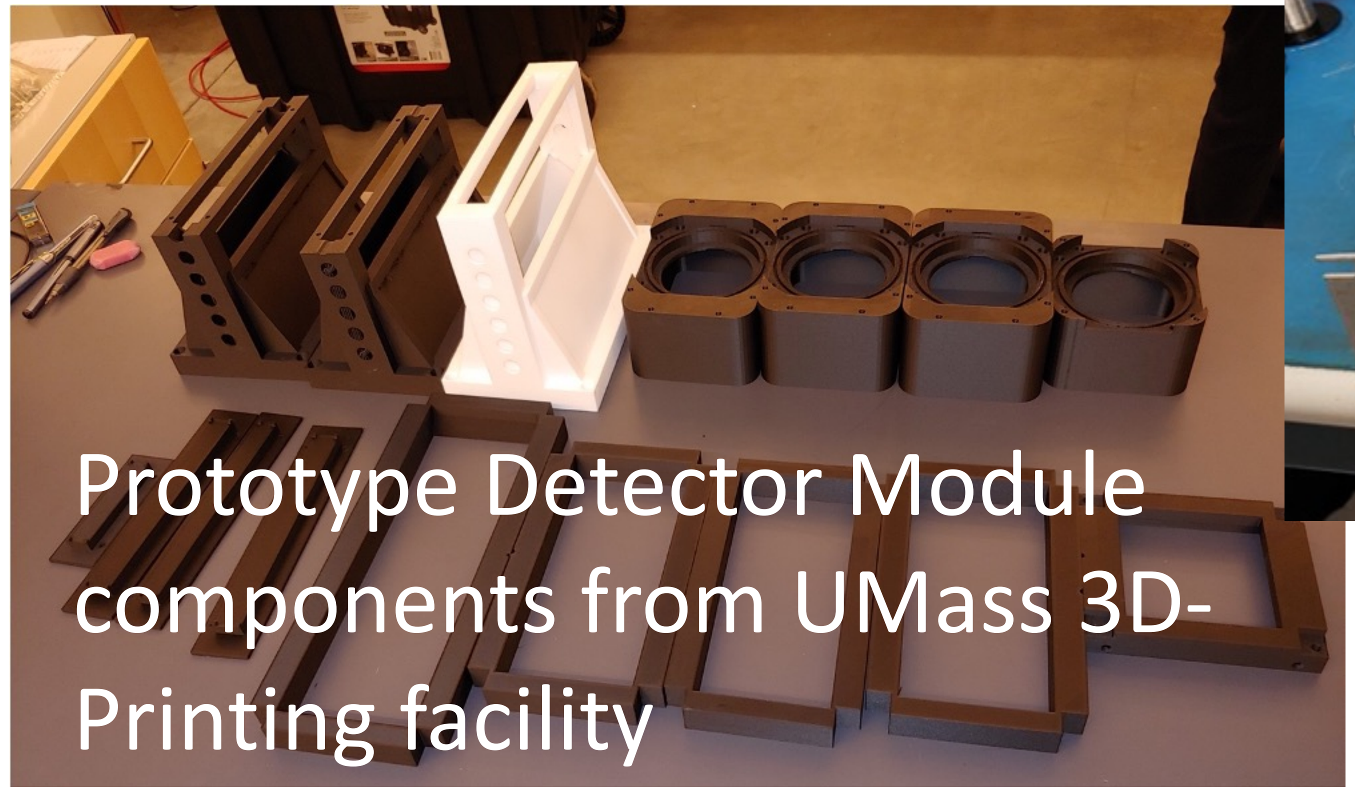
Set of 4 downstream magnet coils fabricated; tests validate design/ fabrication process

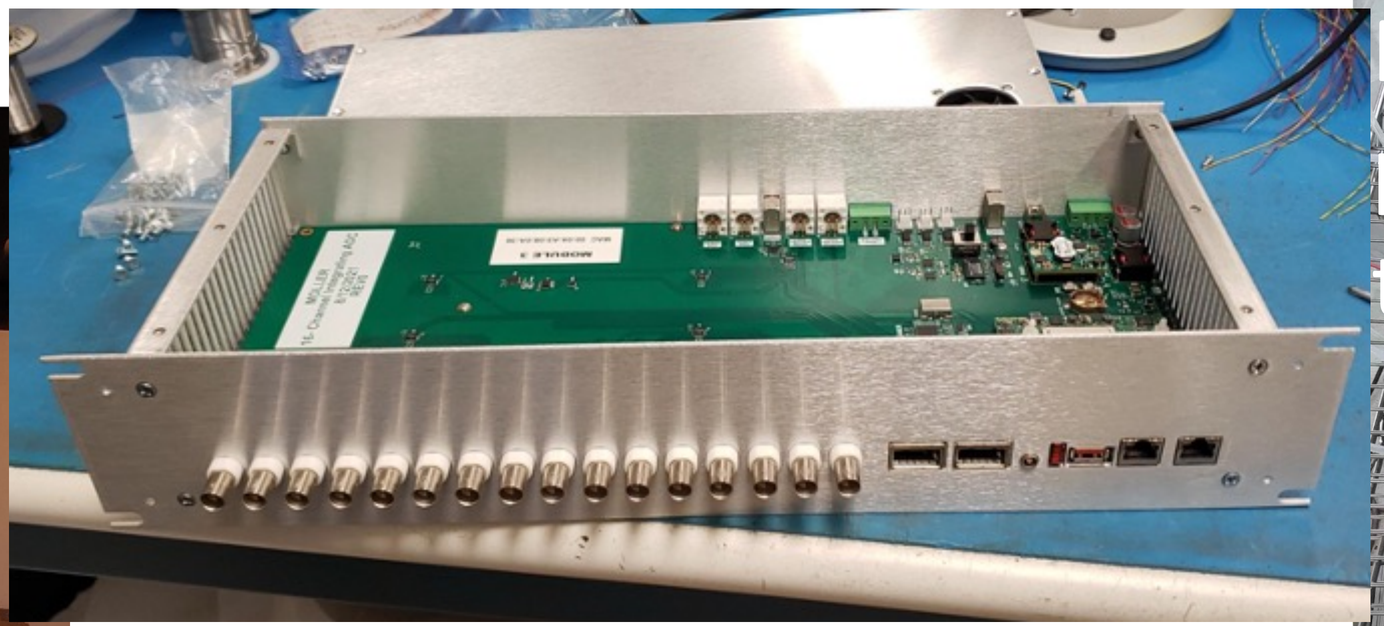

Complete Ring 5 (Manitoba) and Ring 6 (UMass) prototypes at Mainz test beam

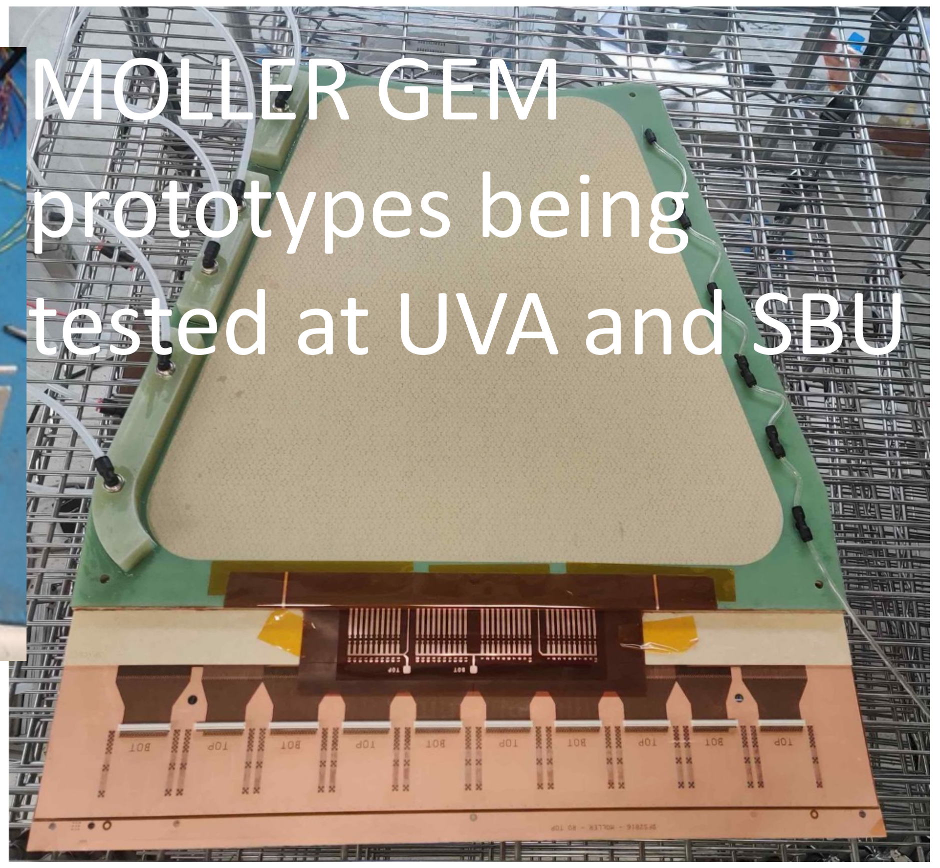

Full PMT/Base/ Preamplifier and container (Manitoba)


Complete Shower-Max prototype (ISU) at Mainz test beam


Ring 1 (Manitoba) Prototype at Mainz Test Beam (Thanksgiving 2022)


Prototype Detector Module components from UMass 3D-Printing facility


Complete 16 channel Integrating ADC Module (U. Manitoba/TRIUMF)


MOLLER GEM prototypes being tested at UVA and SBU

MOLLER Collaboration: ~ 180 authors, 34 institutions, 4 countries

Spokesperson: K. Kumar, UMass, Amherst

Executive Board Chair and Deputy Spokesperson: M. Pitt, Virginia Tech

Other Executive Board Members

D. Armstrong (William & Mary), J. Fast (JLab), M. Gericke (Manitoba), M. Jones (JLab), J. Mammei (Manitoba), K. Paschke (UVa), P. Souder (Syracuse U.)

MOLLER Working Groups

Polarized Source
Beam Instrumentation
Hydrogen Target
Spectrometer
Integrating Detectors
Tracking Detectors
Hall Integration
Polarimetry
Electronics/DAQ/Offline
Simulations
Physics Extraction

R. Beminiwattha, J. Butler, V. Berdnikov, S. Covrig, M. Dion, C. Gal, P. King, Y. Kolomensky, N. Liyanage, D. McNulty, D. Meekins, R. Michaels, J. Napolitano, C. Palatchi, R. Wines, C. Zorn

Technical Board

Institutional Board of PI's:

Jim Napolitano, Chair

MOLLER Project Personnel

J. Fast, MOLLER Project Manager

Project Leads

Control Account Managers

Technical Leads

The MOLLER experiment is in an exciting phase in its evolution!

- ✦ **A long early road to realize the experiment! (2007-2016)**
  - ★ Concept developed ~ 2007, PAC approval ~ 2009, beamtime allocation and rating ~ 2011
  - ★ Intense pre-conceptual design activity to validate the experimental strategy
- ✦ **CD-0 awarded in December 2016**
- ✦ **Project team formed in January 2019**
  - ★ First DOE OPC Funds in Summer 2019
  - ★ Jim Fast took over project leadership in Summer 2020
- ✦ **MIE Project is now ballistic with a fantastic collaborative team**
  - ★ CD-1 awarded in December 2021
  - ★ IRA Funds (31M$) committed in Fall 2022
  - ★ Anticipate CD3A in a couple of months and CD2/CD3 by the end of the summer
  - ★ Installation envisioned for Nov '24 thru calendar '25

Starting this Fall, we will adiabatically pivot to a more conventional preparation phase:

- **Software development**
- **Installation and equipment checkout**
- **Experiment commissioning**

Historically, parity violation experiments have had multiple graduate students from different institutions write theses on the same final physics measurements

PREX/CREX had 14 graduate students and Qweak had 27 graduate students

We welcome new PI's, especially those with interested graduate students and postdocs

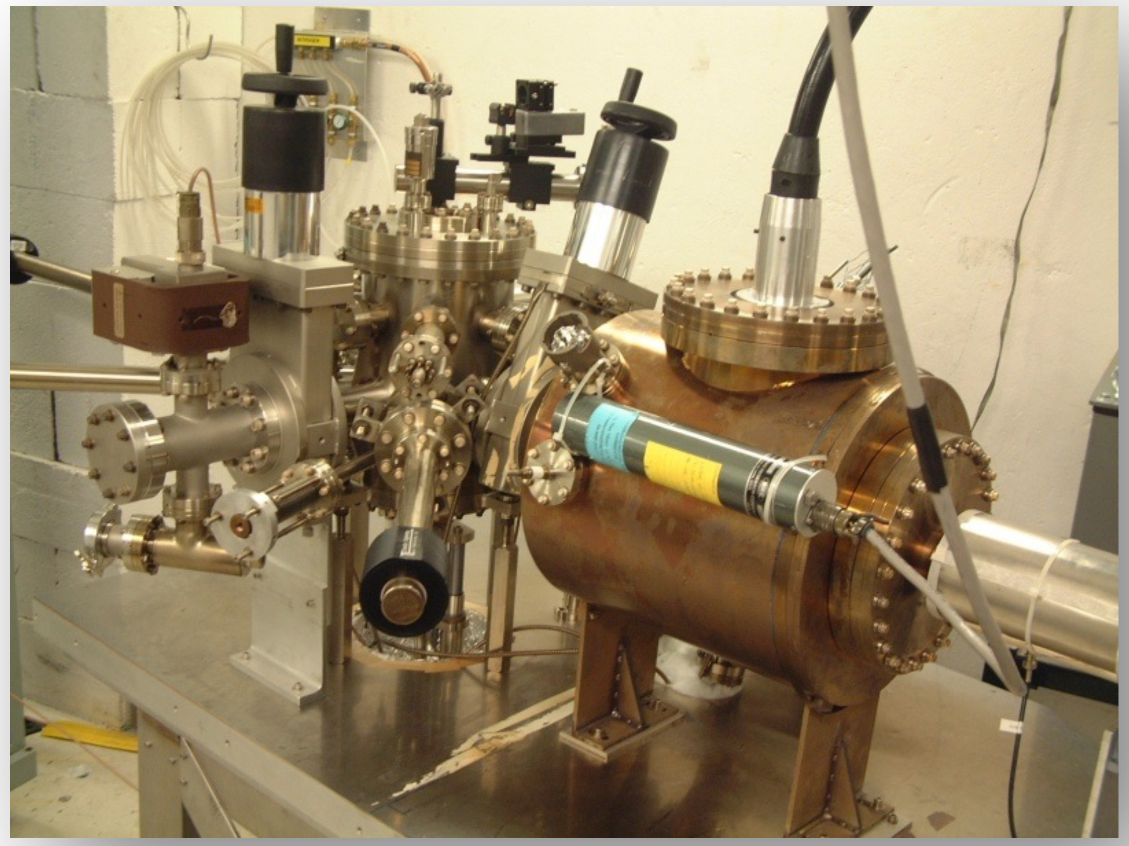
Summary

- MOLLER represents an outstanding opportunity to take advantage of the unique instrument (11 GeV CEBAF beam) enabled by the 12 GeV upgrade
- The science case remains compelling; the plan is to run physics at about the time that precision results from high luminosity phases of 14 TeV LHC are becoming available
- The science goals cannot be accomplished in existing or planned facilities worldwide
- Rapidly maturing engineering design and prototyping efforts have led to readiness for CD-3A and CD-2/CD-3 soon thereafter
- An enthusiastic and well-experienced international collaboration with an integrated project team has achieved a mature engineering design and is launching into construction and installation of the apparatus and DAQ/analysis software development, followed by commissioning, data collection and physics analysis
- We welcome new collaborators to help us make the next exciting and challenging phases of the MOLLER experiment a success

Backup

The CEBAF Polarized Electron Beam: Essential Characteristics

Highly intense, stable, high energy electron beam with longitudinal beam polarization



Record Performance (2012): 180 μA at 89% polarization

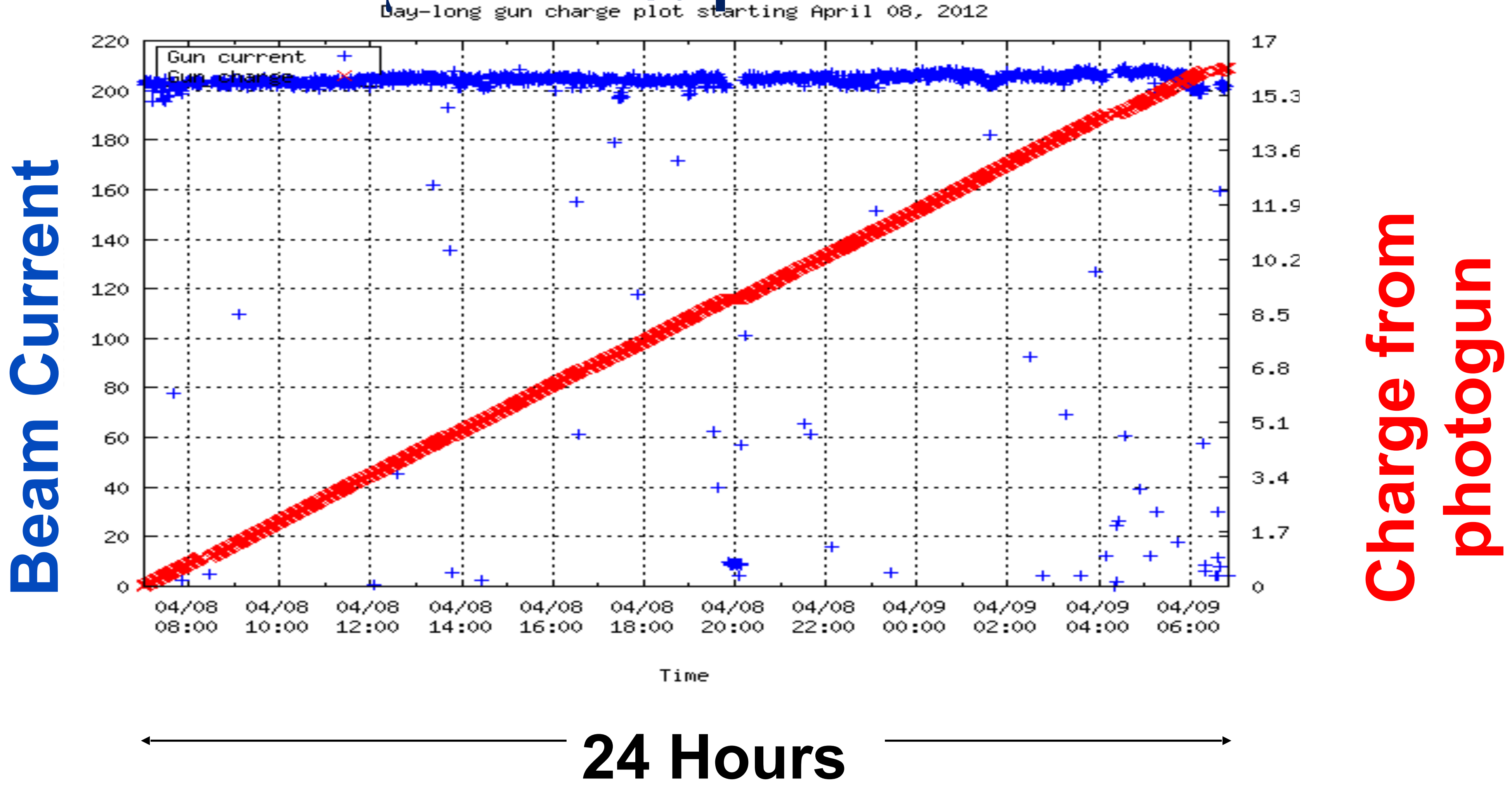


Figure of merit rises linearly with beam energy: experiment not viable below a few GeV with current state-of-the-art

MOLLER will plan to use 1.96 kHz reversal to reverse the electron beam helicity

CEBAF beam properties: 2 kHz time scale (~ppm, microns) AND days (~ppb, nm) must be carefully tuned, actively monitored and maintained with proper diagnostics

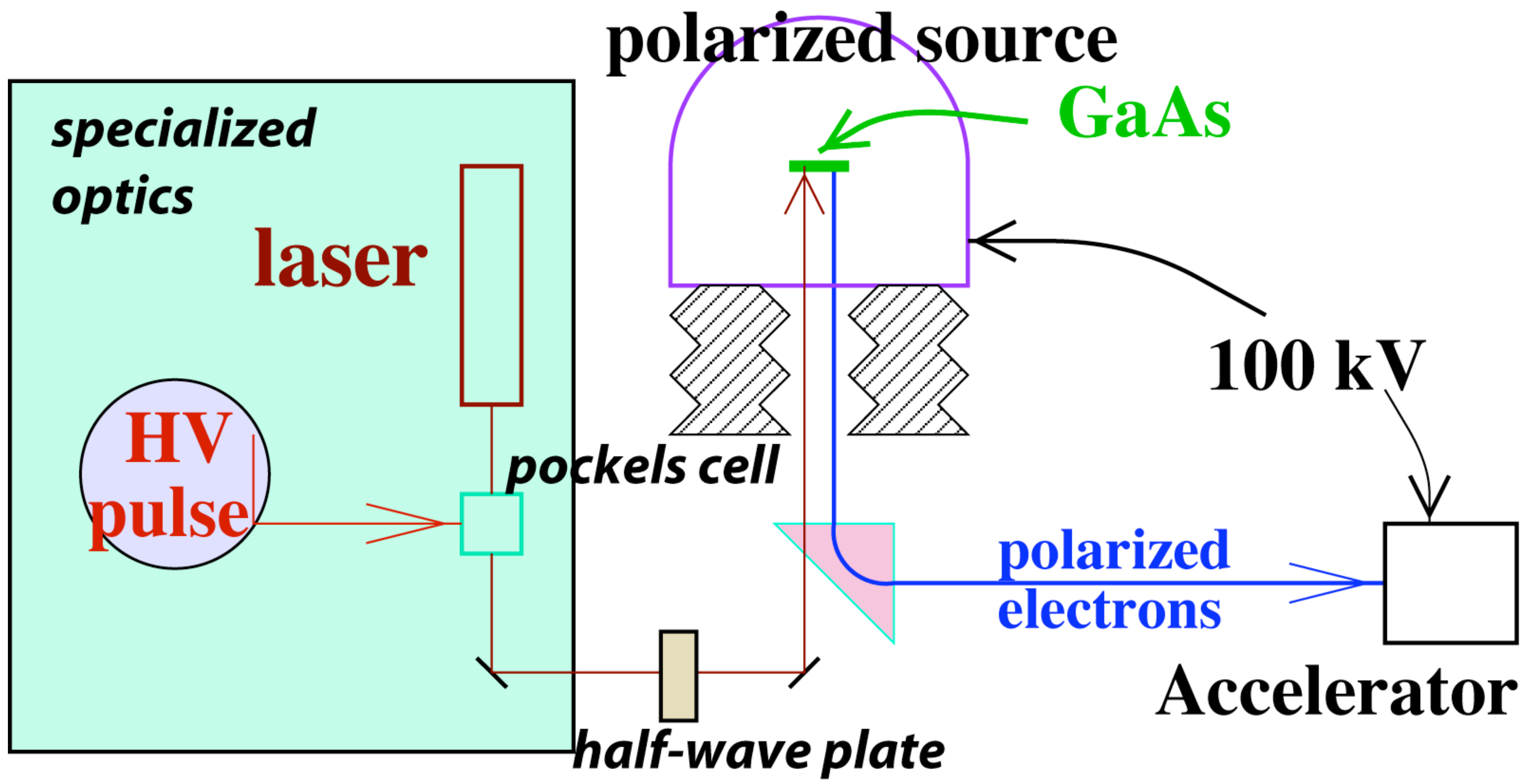
Systematic control likely impossible without a "cold" "CW" machine

Extensive operation experience in manipulating injector characteristics to control systematics

10's of ppb beam charge asymmetry and ~ 1 nm control of position asymmetry

Møller PV measurement cannot be done elsewhere; JLab's beam characteristics are unique

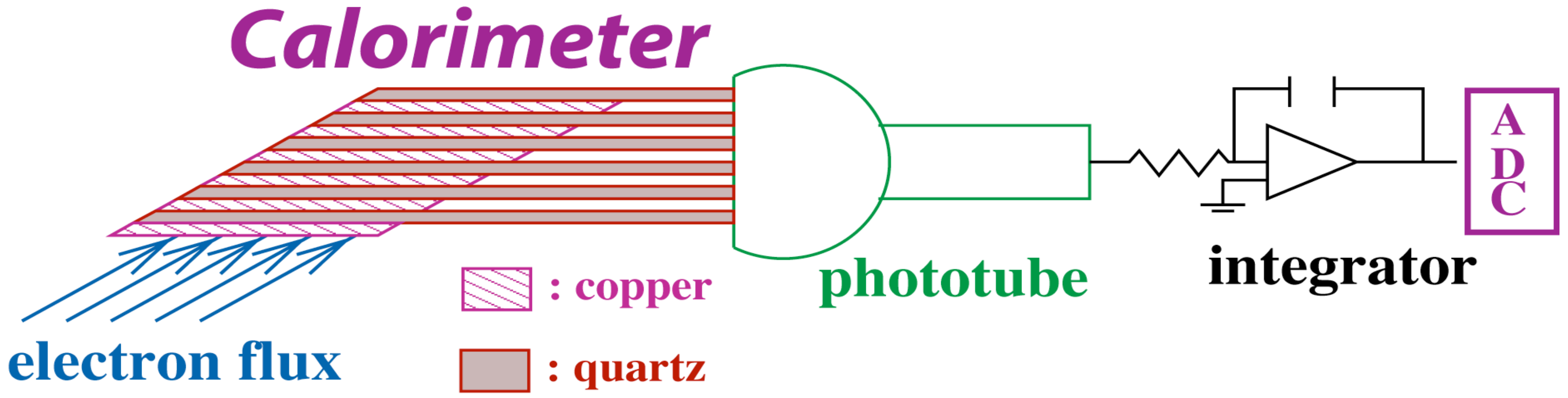
Conceptual Overview of the Experimental Technique



·Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency

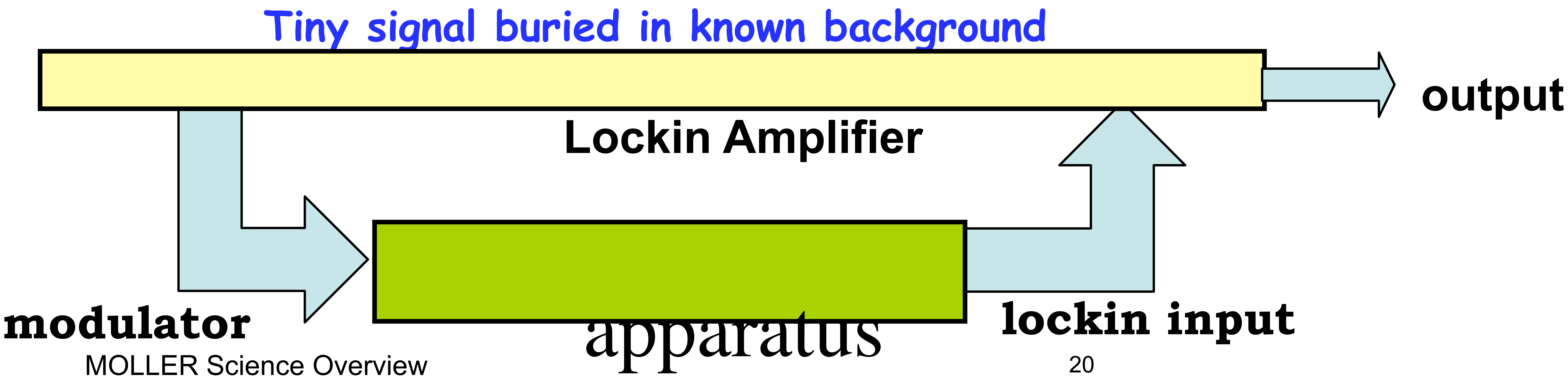
·Rapid helicity reversal: polarization sign flips > 100 Hz to minimize the impact of drifts

·Helicity-correlated beam motion: under sign flip, beam stability at the sub-micron level



"Flux Integration": very high rates

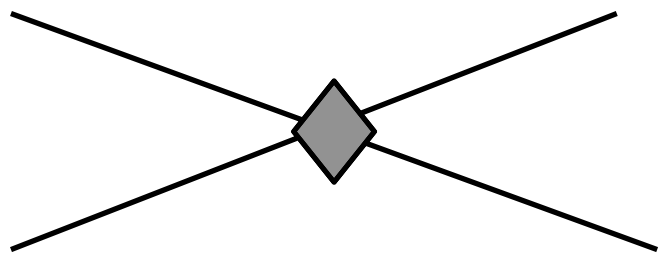
direct scattered flux to background-free region



Apparatus:

beam, target, spectrometer, detectors and accelerator all interconnected!

Can MOLLER physics be done elsewhere in the world?



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

Search for New Interactions: carefully chosen low energy experiments complement direct searches

LHC and future EIC sensitive to new lepton-hadron interactions

New purely leptonic interactions: MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

There are no concrete plans anywhere worldwide to build a next generation lepton collider or neutrino factory, both billion dollar class facilities that would take a decade or more to realize.

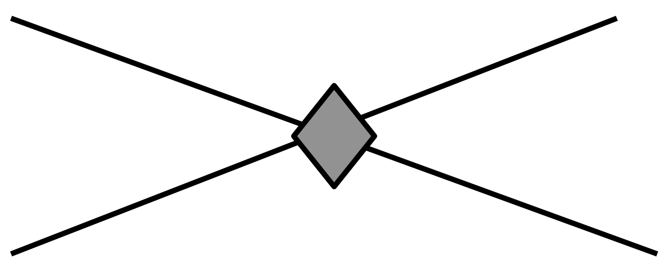
If the MOLLER measurement is not carried out, purely leptonic interactions will remain unexplored for at least another decade

Three other aspects:

- Cleanliness of Theoretical Prediction
- Electroweak Physics
- New “Low” Energy Physics

Comparison with High Energy Colliders

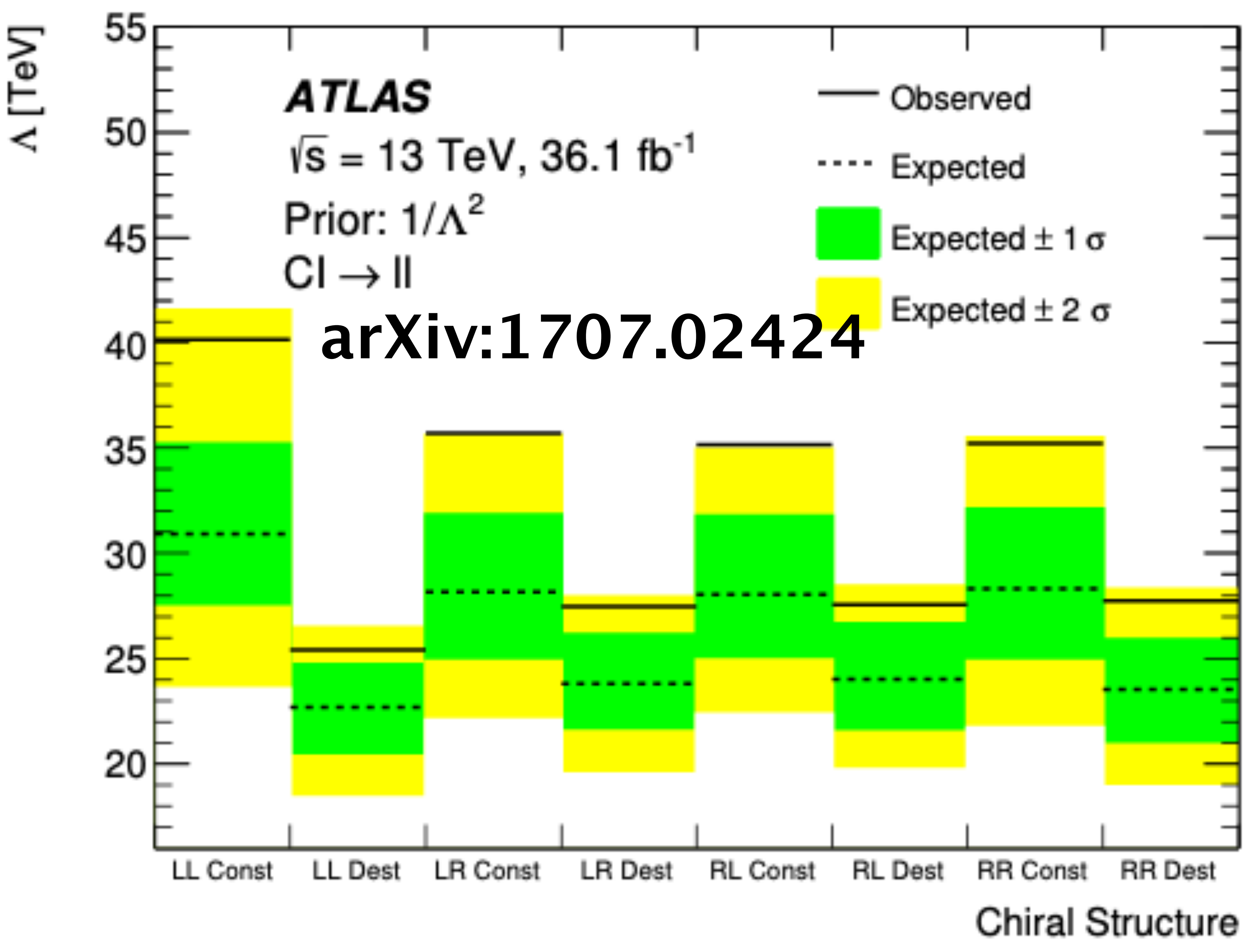
Carefully chosen low energy experiments complement direct searches



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

Lacking any direct evidence for new particles besides the Higgs, both colliders and fixed target experiments search for new physics by looking for deviations from Standard Model predictions

LHC searching for lepton-hadron interactions



LEP200 searched for lepton-lepton interactions

95% C.L.

e^+e^- Collisions	LEP200 Reach	$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim \mathbf{8.3}$ TeV
Fixed Target	E158 Reach	$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim \mathbf{12}$ TeV
	MOLLER Reach	$\Lambda_{\mathrm{LL}}^{\mathrm{ee}} \sim \mathbf{27}$ TeV

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

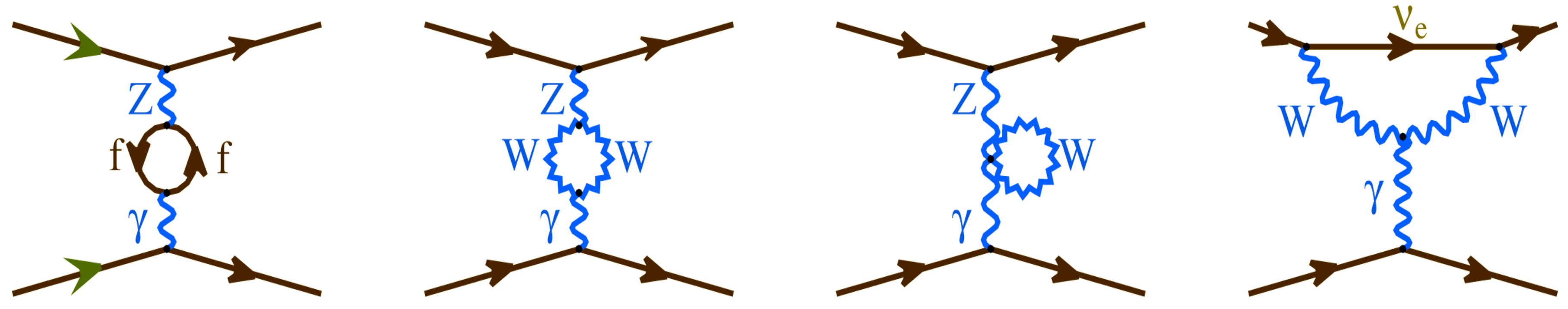
Theory Prediction and Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

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

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

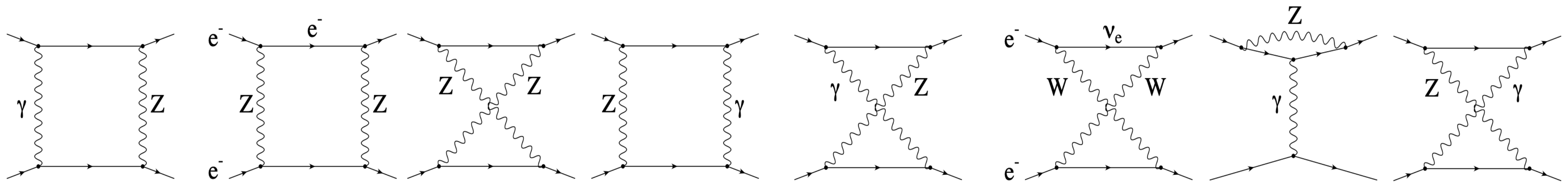
Czarnecki and Marciano (1995)

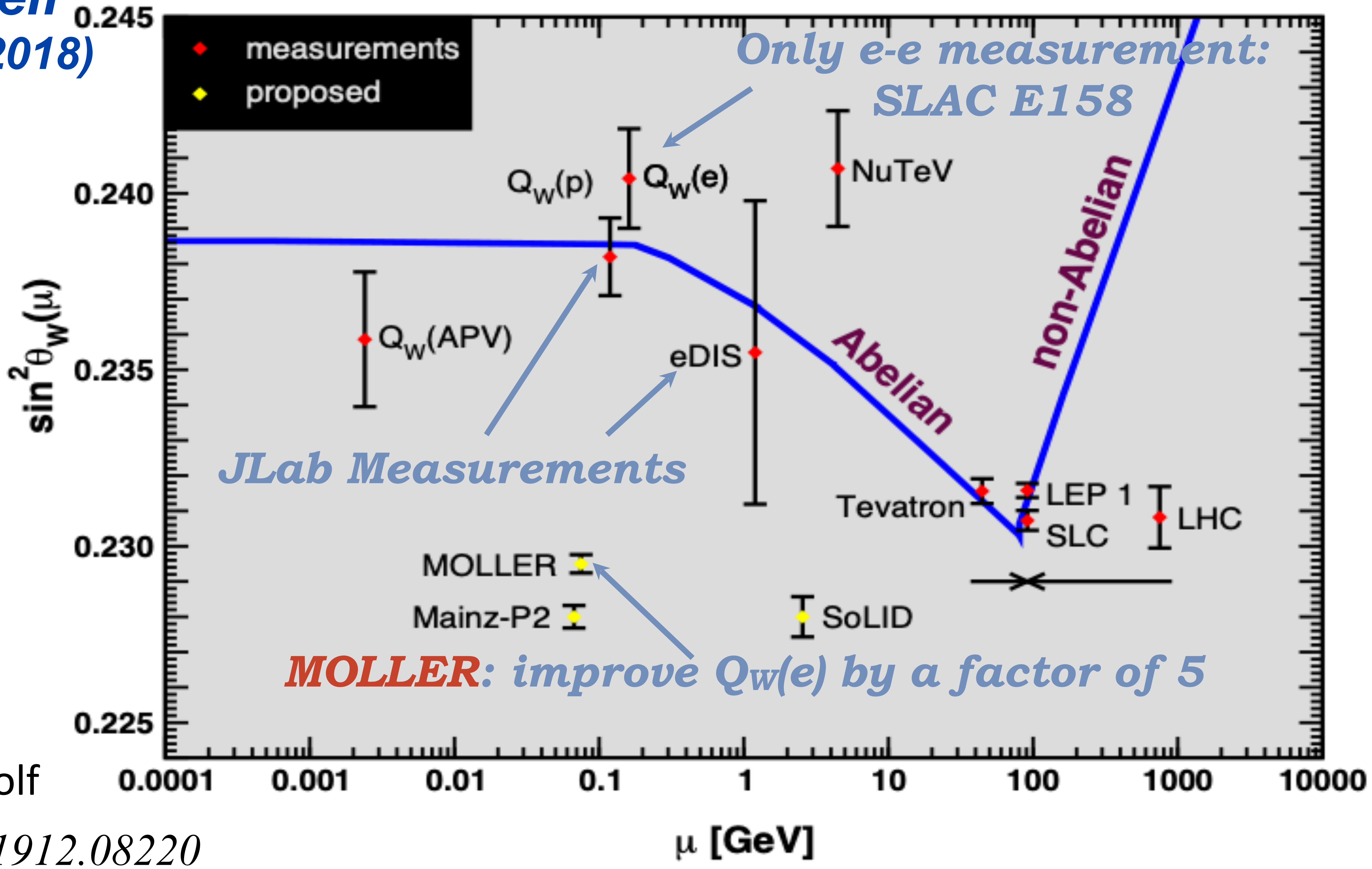


$$\mathbf{Q^e_W = 1-4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

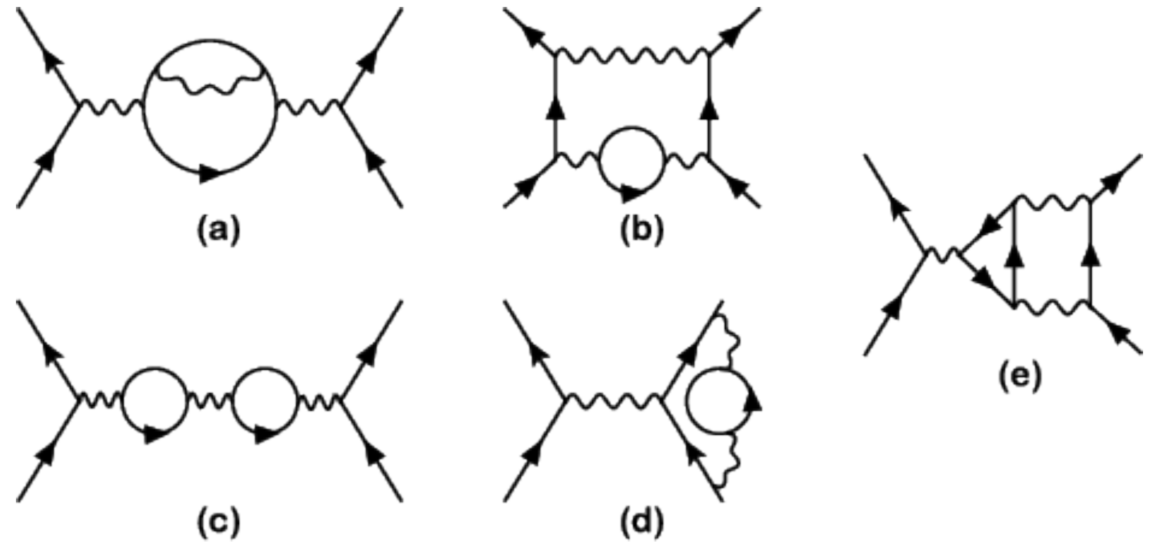
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

$\delta(Q^e_W) \lesssim 0.4\%$





2 groups working on 2-loop Calculations



Aleksejevs and Barkanova

Series of publications

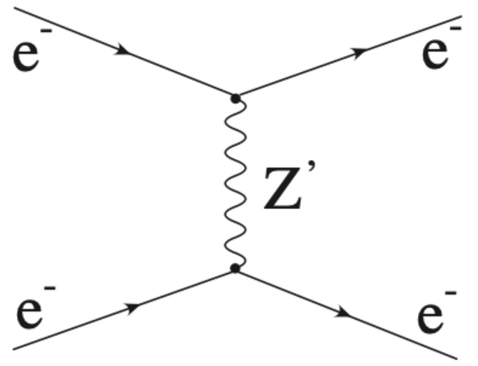
Du, Freitas, Patel and Ramsey-Musolf

Recent closed-fermion loops: arXiv:1912.08220

New (Low Energy) Physics Examples

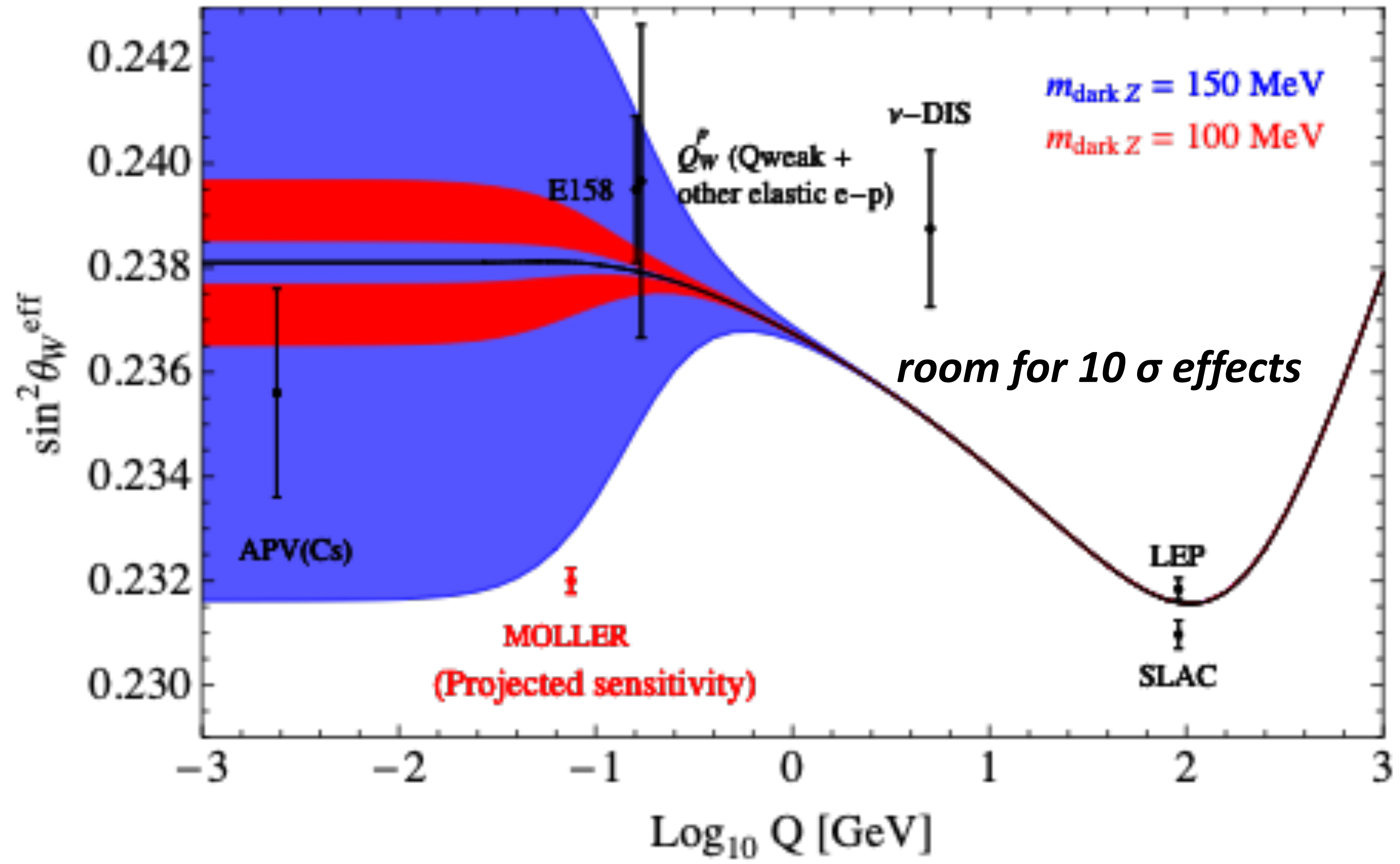
Unique Opportunity: Purely Leptonic Reaction at $Q^2 << M_Z^2$

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



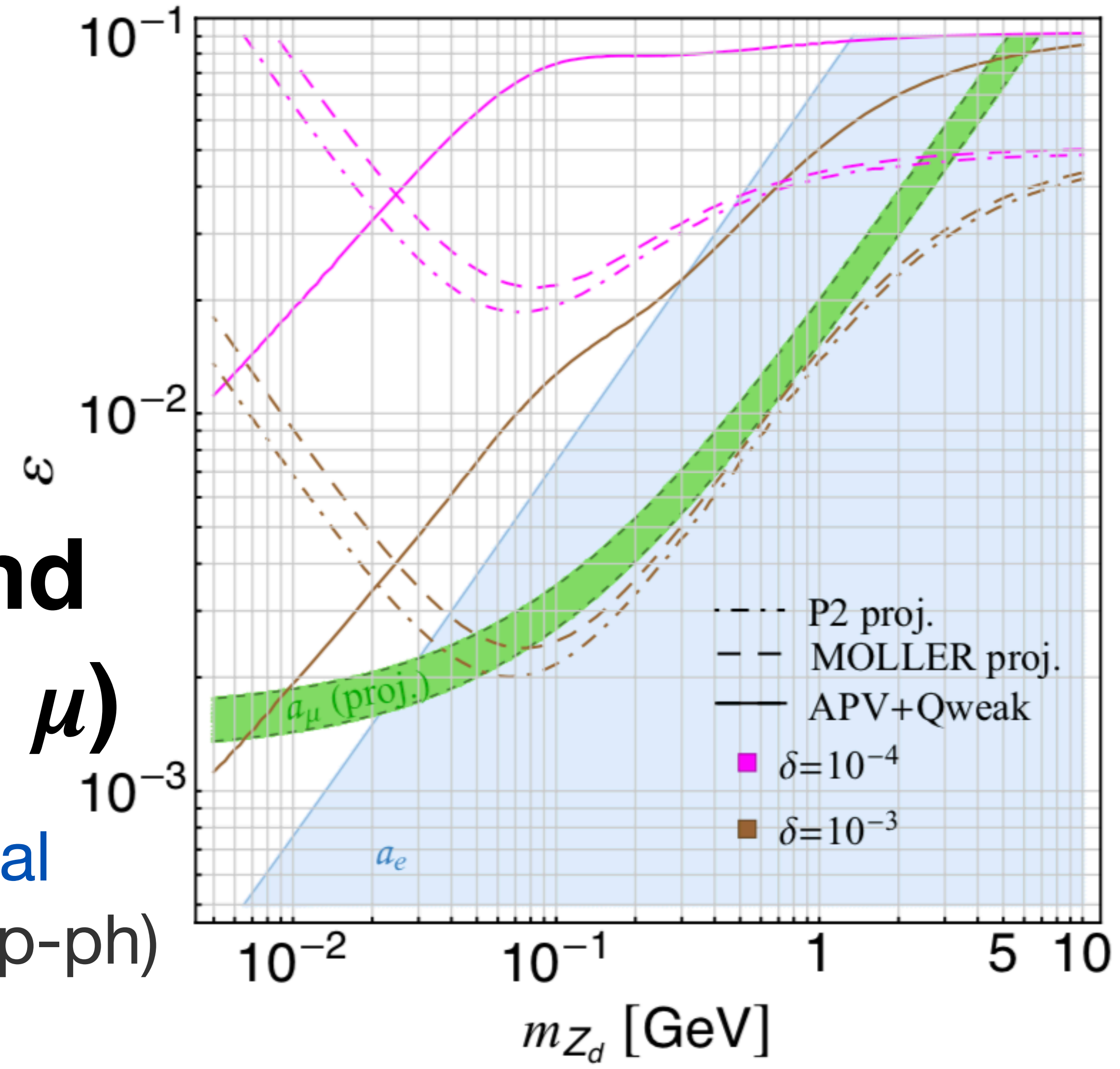
Heavy Photons (A' mixed with Z_0): The Dark Z

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

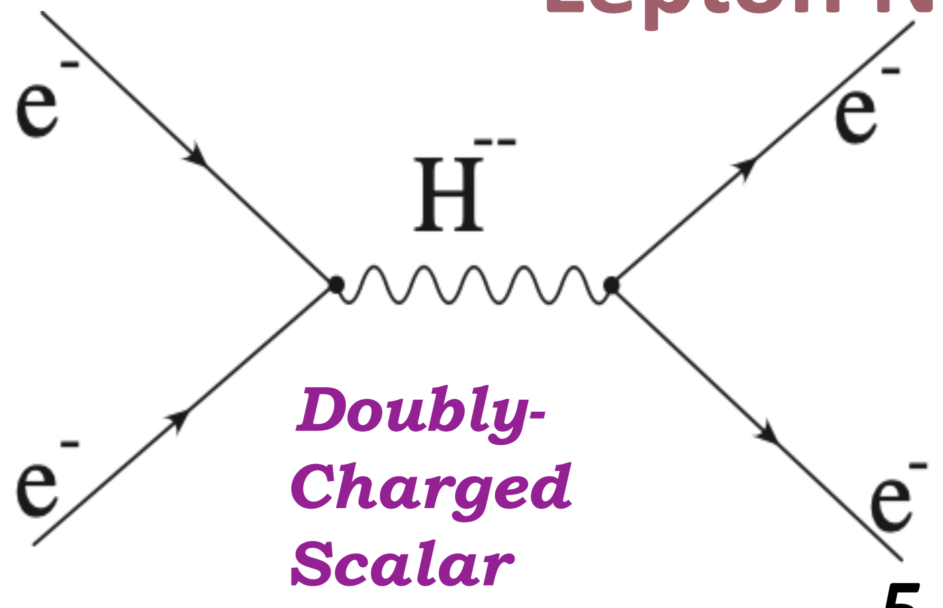


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



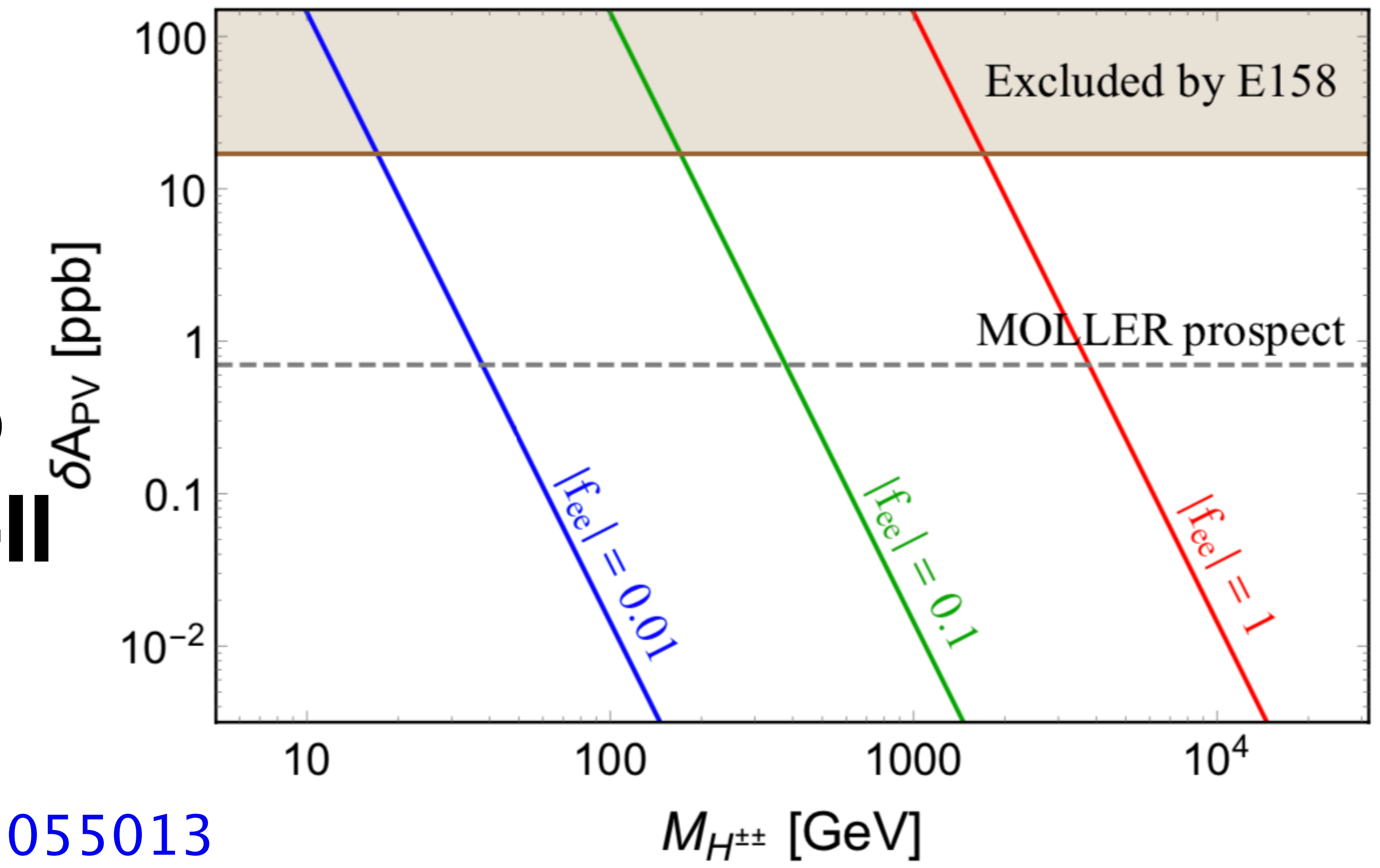
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\,\frac{|h_{ee}|^2}{(M_\Delta/1\ \text{TeV})^2}$$

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



Global Context Summary

best contact interaction reach for leptons at low OR high energy: similar to LHC reach with semi-leptonic amplitudes

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

$$\delta(\sin^2\theta_W) = \pm\, 0.00023\ (\text{stat.}) \pm 0.00012\ (\text{syst.}) \Rightarrow \sim 0.1\%$$

Best projected uncertainties among projects being considered over next 10 years worldwide

- **If LHC sees ANY anomaly in the mid-2020s**
  - The unique MOLLER discovery space becomes pressing, with a few others (e.g. g-2 anomaly)
- **Discovery scenarios beyond LHC signatures**
  - Hidden weak scale scenarios
  - Lepton Number Violating Amplitudes
  - Light Dark Matter Mediators
  - …

Most sensitive discovery reach over the next decade for CP-/flavor-conserving or LNV scattering amplitudes

Alternatives Analysis Summary Table

	Reaction	$\sin^2\theta_W$ Precision	Technical Requrements	Feasibliity	Cost	Possible Timeline	Comments
MOLLER	**ee-ee**	**0.1%**	**11 GeV, polarimetry**	**reviewed**	**~ 40M$**	**2025**	
Other Møller	ee-ee	0.5%?	> 10 GeV e-e collider with spin	unknown	>> 100M$	N/A	Possible JLEIC figure-8 modification
Other PVES	ee-qq	0.15 - 0.25 %	MESA P2 JLab SOLID	likely studied	30 - 70 M$	2024 2027	additional hadronic uncertainties studied
Hadron Collider	qq-ee	0.1% 0.3%	> 300 inv. fb at LHC > 250 inv. fb at EIC	likely likely	-	2025 2030s	Requires pdf uncertainty reduction
Lepton Collider	ee-$\mu\mu$	0.1%?	> 500 GeV electron-positron collider	studied	> 1B$	> 2035	No current plans to move forward
Neutrino DIS	$\nu\nu$-qq $\nu\mu$-q_1q_2	0.2%?	fine-grained large calorimeter + ν beam	studied	> 100 M$	~ 2030	DUNE Near-Detector upgrade, QCD uncertainties
Elastic Neutrino	νe-νe $\nu\nu$-qq	0.5%?	Reactor neutrino experiments	studied	unknown	unknown	Requires upgrades of existing plans
Atomic PV	ee-qq	0.3%?	Ra+, Cs, Fr or Th beams, custom apparatus	studies ongoing	unknown	unknown	Feasibility studies ongoing (Mainz, TRIUMF, KVI, Purdue)

Sensitivity to 4-Lepton Contact Interactions from Low Energy and Colliders

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

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

Model	η^f_{LL}	η^f_{RR}	η^f_{LR}	η^f_{RL}
$LL^\pm$	±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: → $|g^2_{RR} - g^2_{LL}| = 4\pi$

Simultaneous fits to cross-sections and angular distributions

LEP200

95% C.L. Limits

$\Lambda^{ee}_{LL} \sim 8.3$ TeV $\Lambda^{ll}_{LL} \sim 12.8$ TeV

$\Lambda^{ee}_{RR} \sim 8.2$ TeV $\Lambda^{ll}_{RR} \sim 12.2$ TeV

$\Lambda^{ee}_{VV} \sim 17.7$ TeV $\Lambda^{ll}_{VV} \sim 22.2$ TeV

E158 Reach (actual limits asymmetric)

$\Lambda^{ee}_{LL} \sim 12$ TeV $\Lambda^{ee}_{RR-LL} \sim 17$ TeV

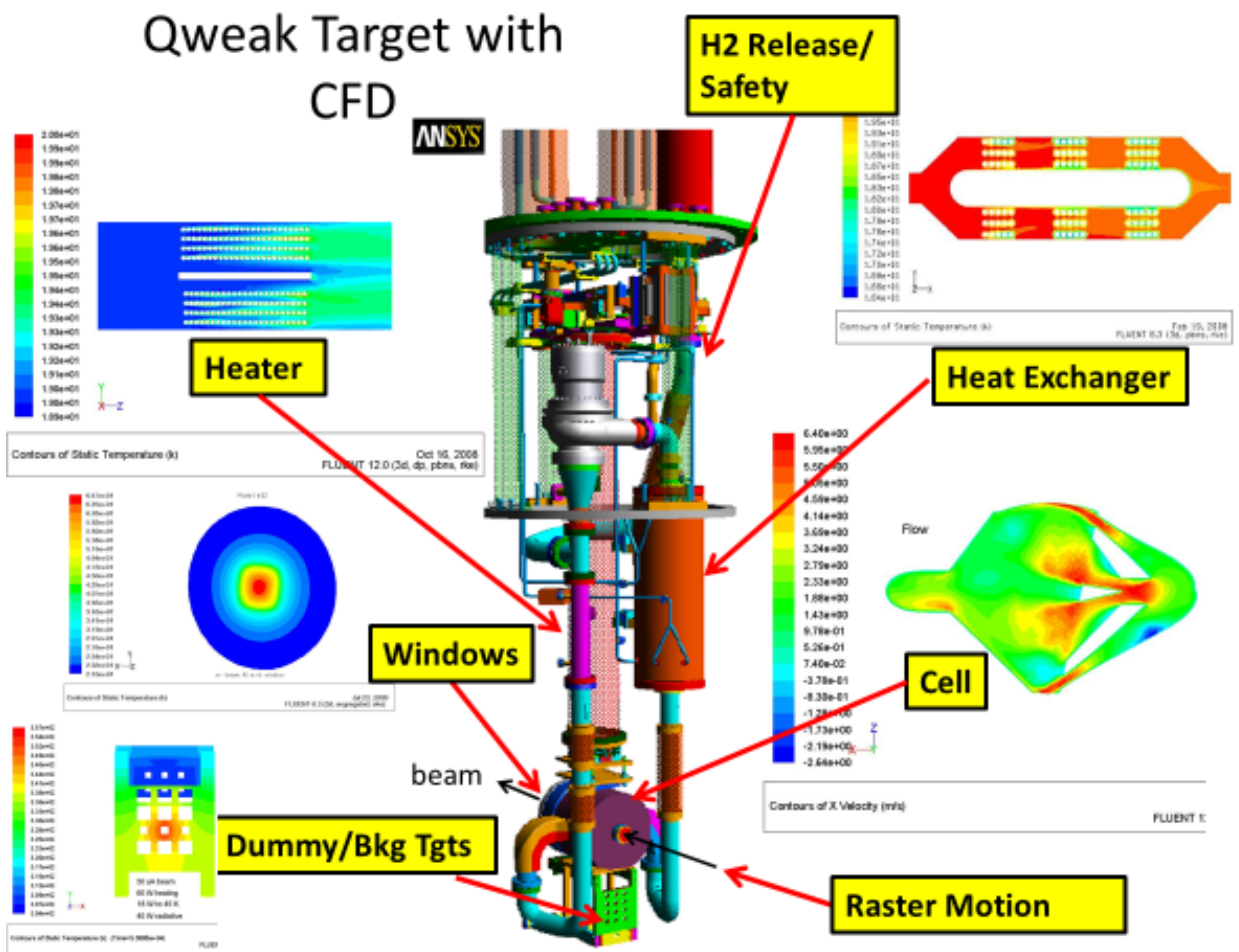
LEP-200 insensitive

MOLLER Reach

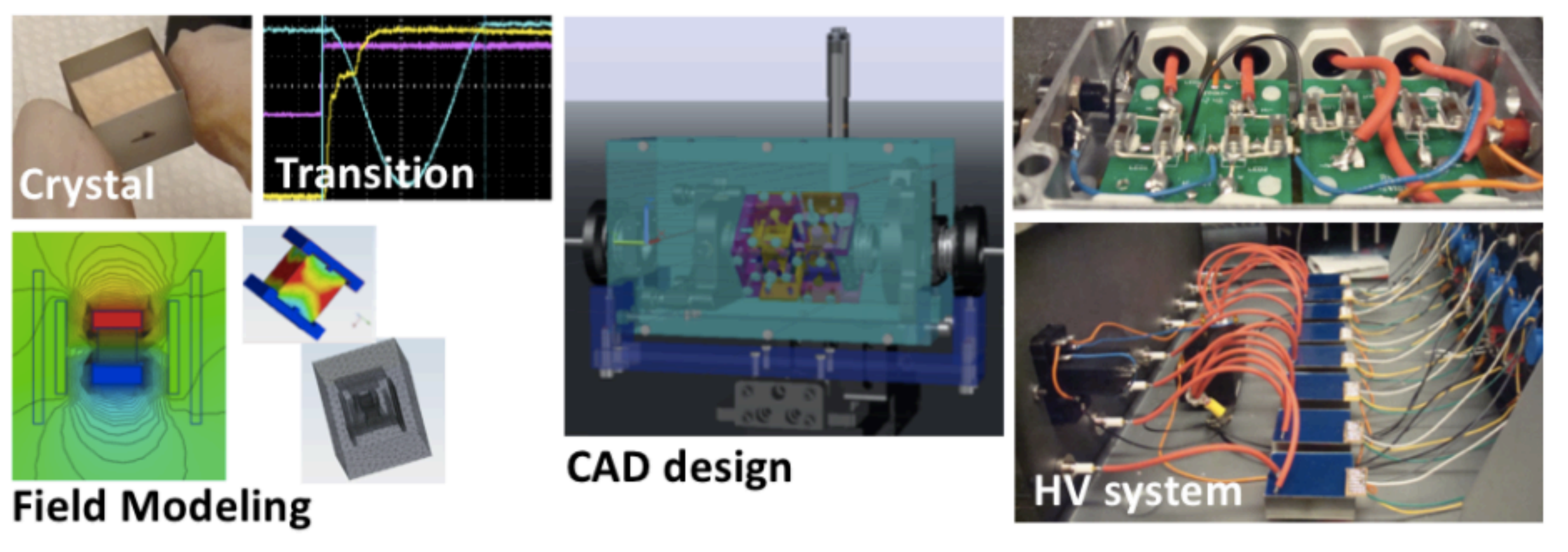
$\Lambda^{ee}_{LL} \sim 27$ TeV $\Lambda^{ee}_{RR-LL} \sim 38$ TeV

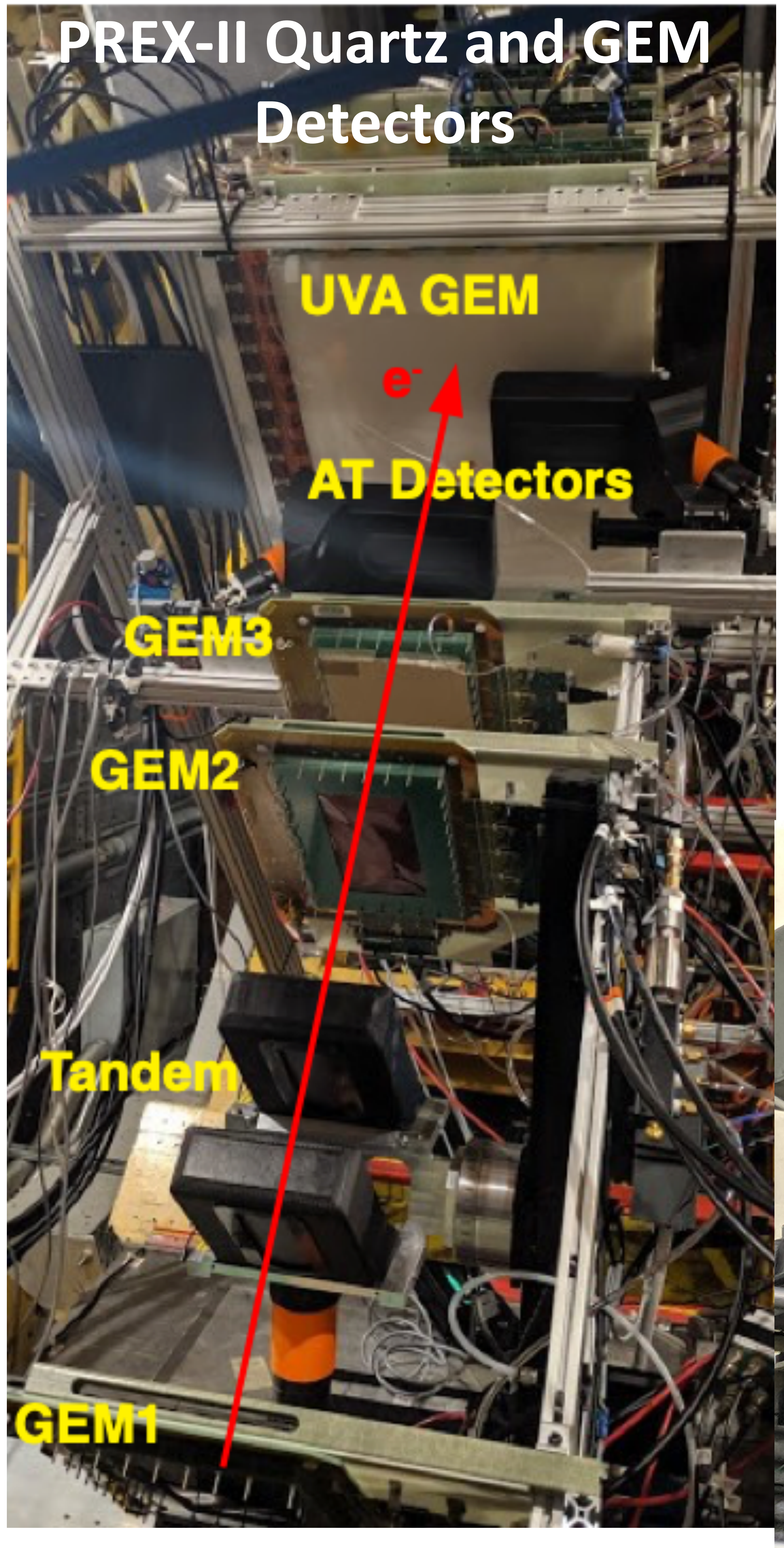
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider

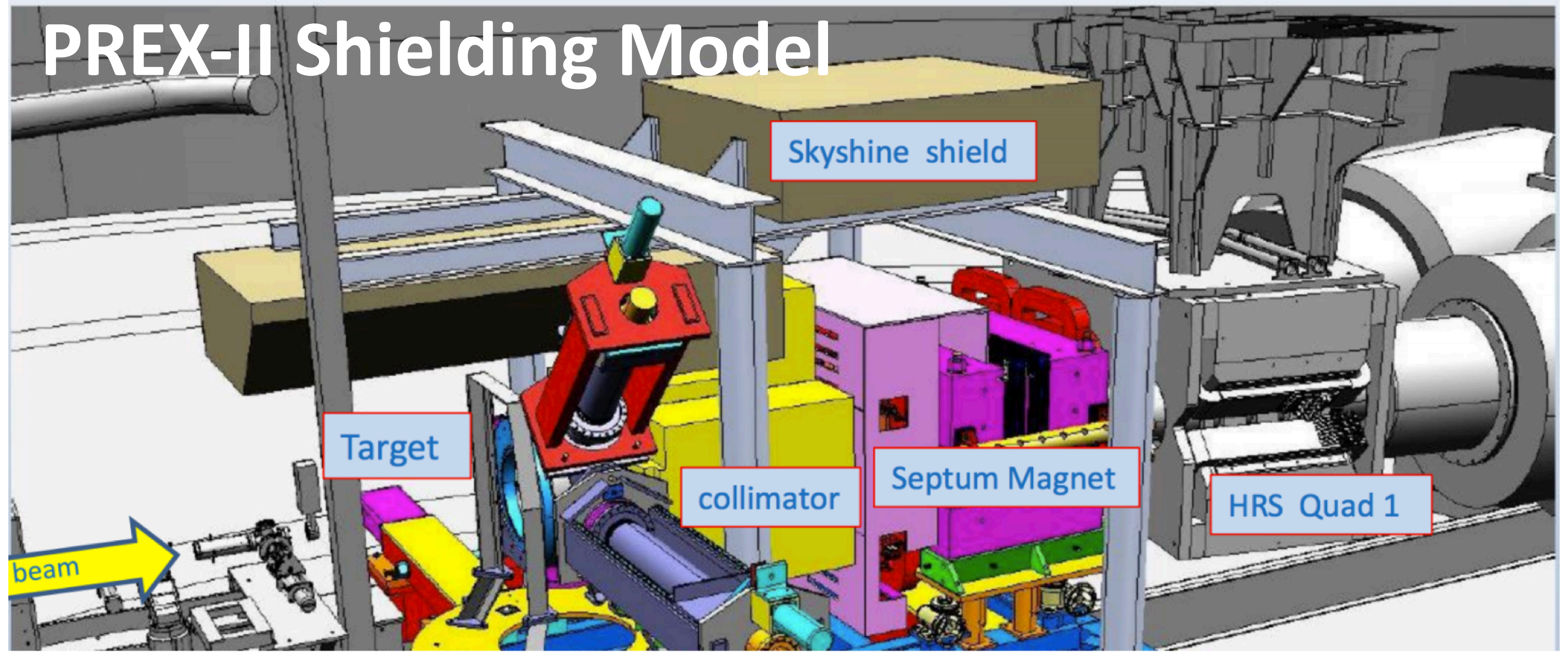
Relevant Technical and Operational Experience from 3rd Generation Experiments



RTP Pockels Cell: Improved control of beam fluctuations



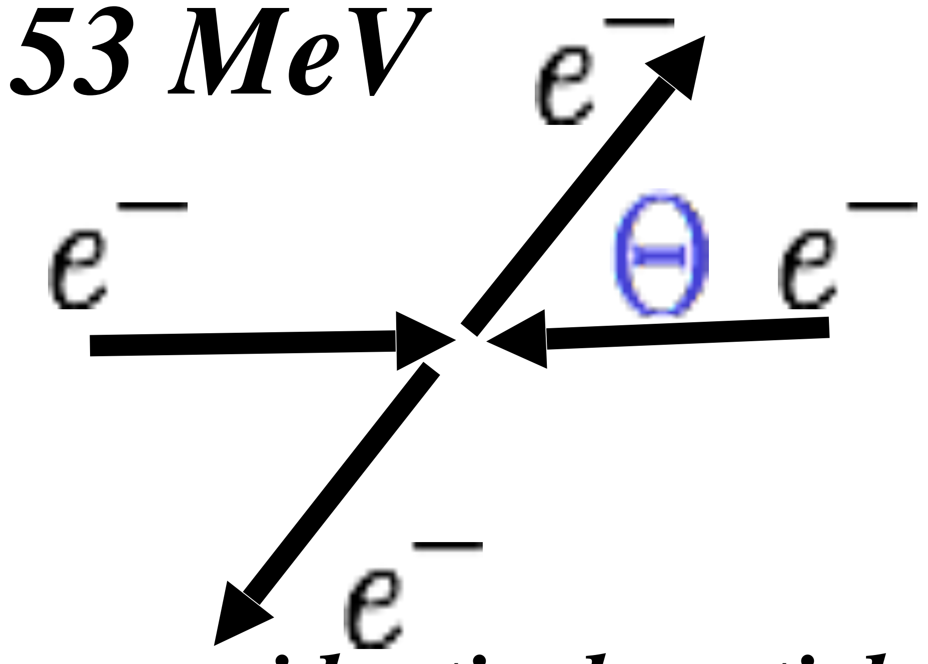




Radiation Shielding: Close collaboration between collaboration physicists, engineers and Radiation Safety

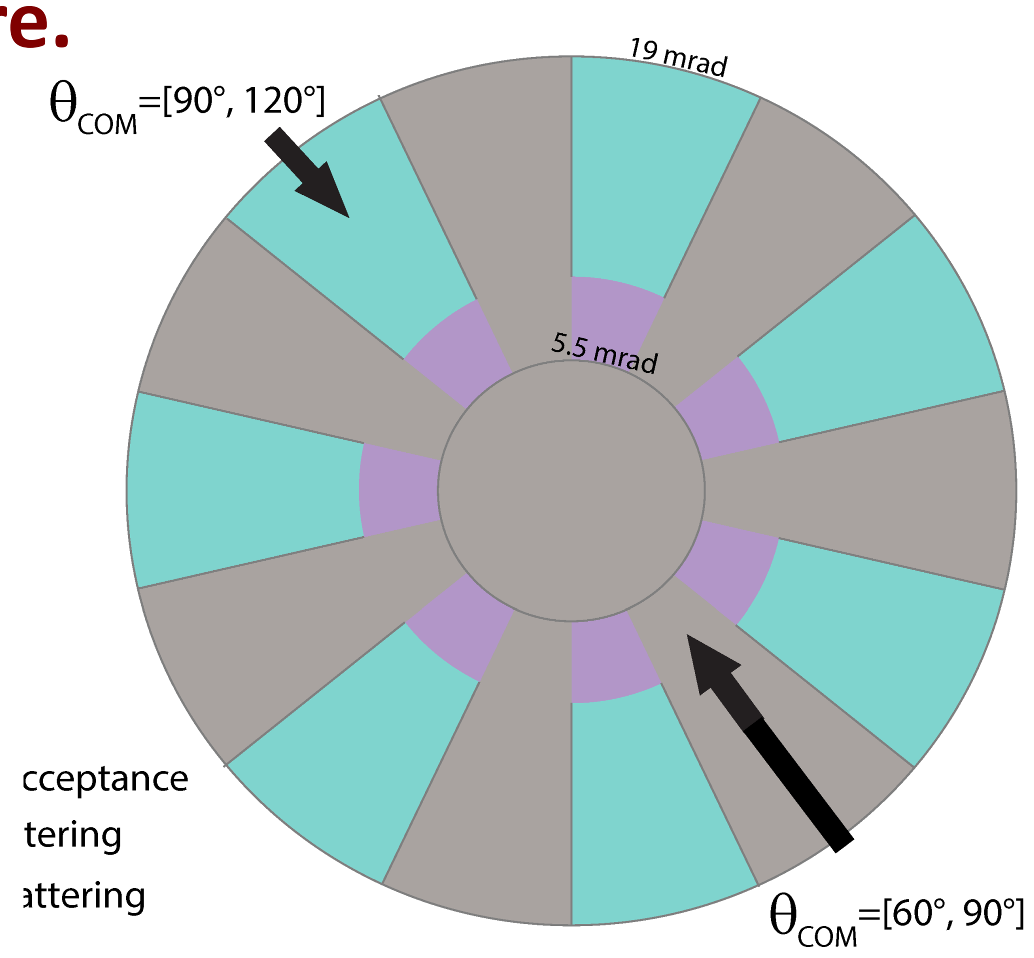
100% Azimuthal Acceptance for Møller Scattering

E_{COM} = 53 MeV

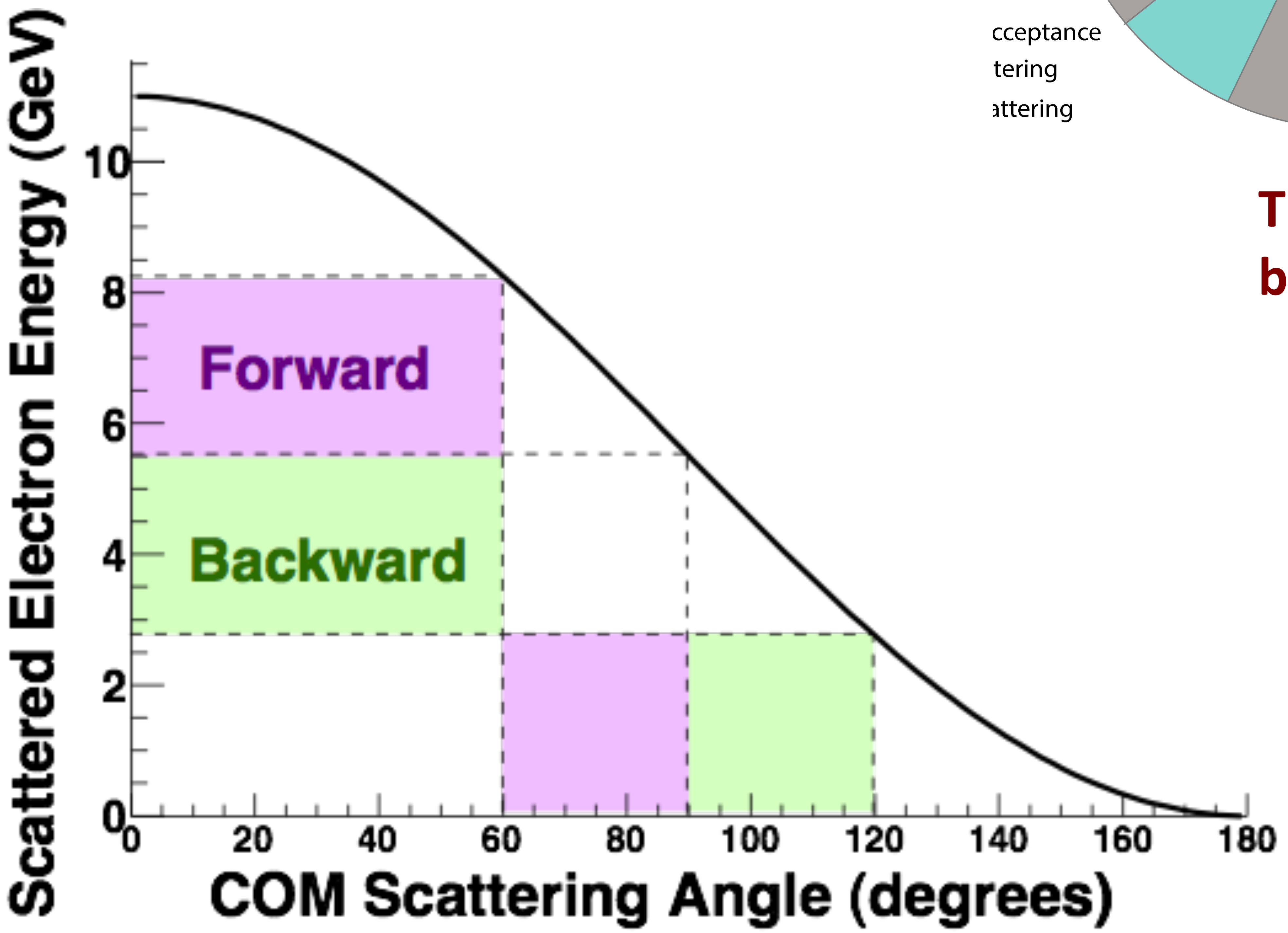


identical particles!

...are collected over here.



The rays that are blocked here...



Odd number of coils: both forward & backward Møllers in same phi-bite