MOLLER Collaboration:
https://moller.jlab.org/DocDB/0007/000757/006/210619_MOLLER_Collaboration.pdf

The MOLLER Experiment

An Ultra-Precise Measurement of the Weak Mixing Angle using Møller Scattering

Krishna Kumar
University of Massachusetts, Amherst

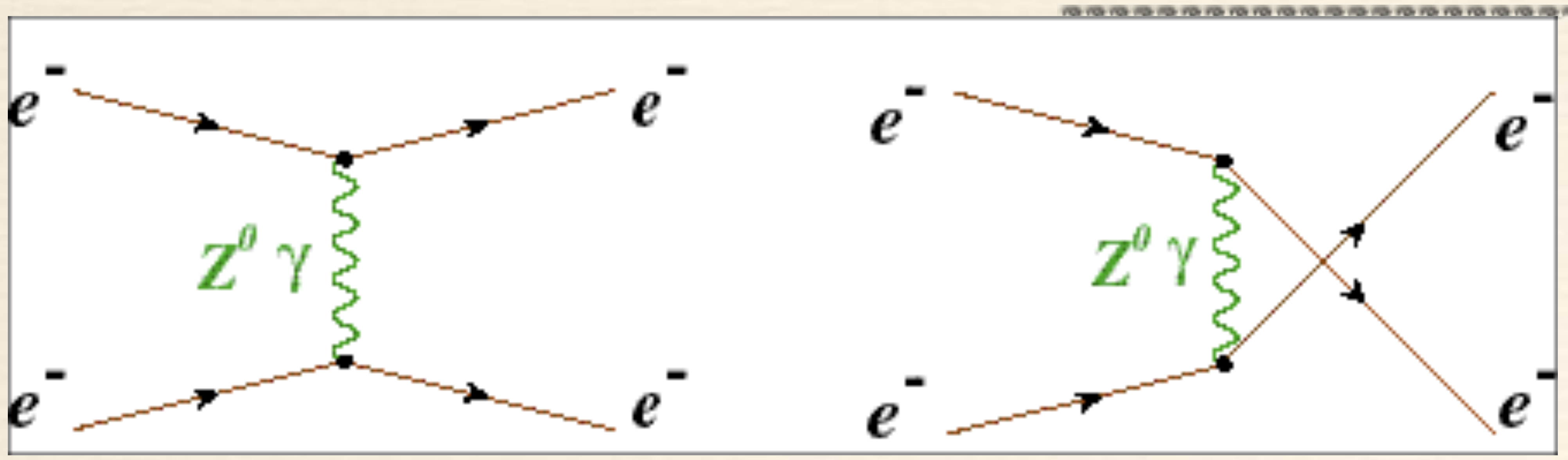
Spokesperson, MOLLER Collaboration

2021 JLab PAC 49 Meeting
July 22, 2021

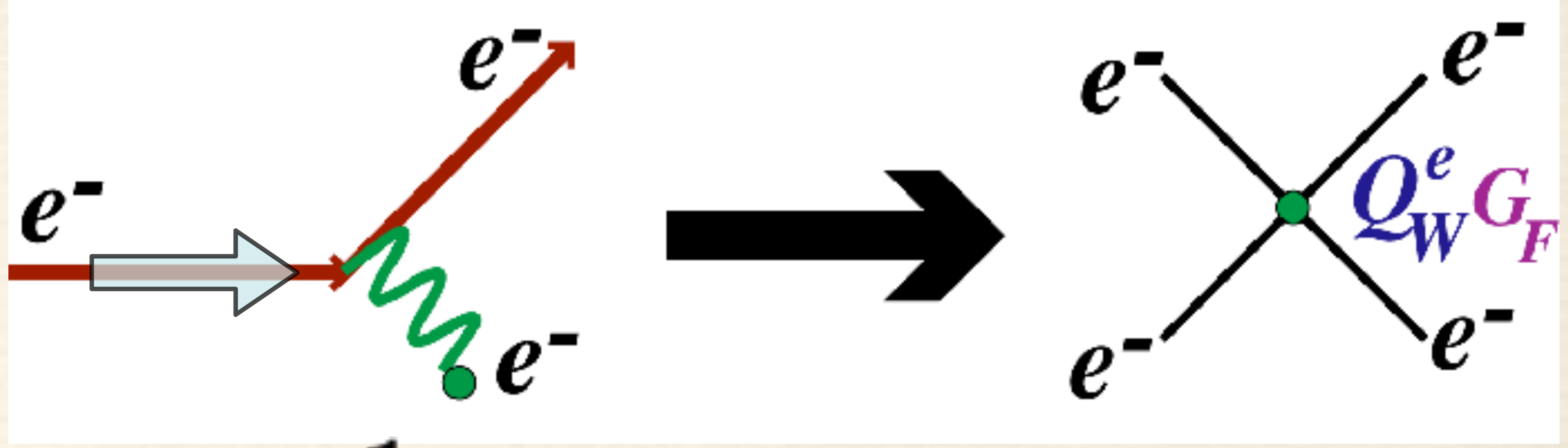
PAC 37 Beamtime Approval: 344 PAC Days

MOLLER Physics Goal

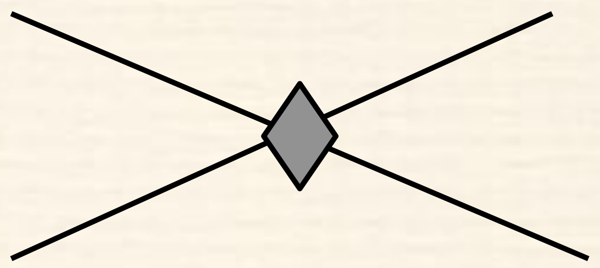
$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075}$$



Fixed Target Polarized Electron-Electron Scattering



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

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

11 GeV, 65 μA 90% beam polarization

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

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

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

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

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

→ ~ 0.1% **statistics limited!**

PAC 37 Request: 344 Production Days plus 13 Commissioning Weeks

Production beamtime of 344 days is the minimum required to achieve goal

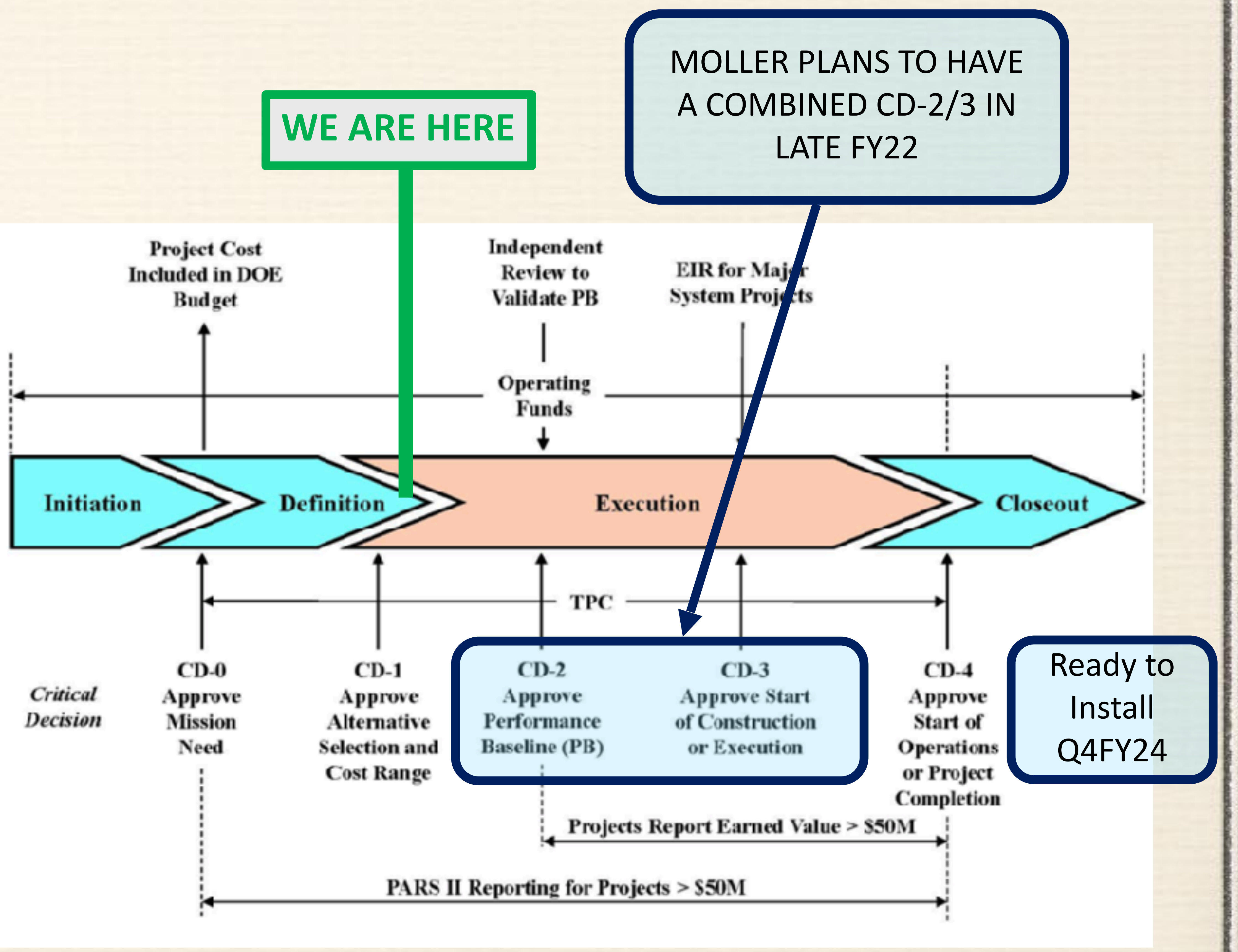
Timeline since PAC Approval

- First Director's Review took place in January 2010
- 2010-2018: Modest funding from DOE NP Research, JLab, NSF, NSERC
- Consistent Community Endorsement (including 2015 NSAC LRP)
- NP Office conducted a Science Review in September 2014
- A second Director's Review took place in December 2016
- CD-0 awarded in December 2016: but DOE MIE paused for 2 years
- Project Team Formed January '19: DOE project funding since June '19
- Director's Cost and Schedule Review in April 2019
- Internal Cost and Schedule Review in November 2019
- Review of the Conceptual Design Report in December 2019
- Director's Reviews in January 2020 and August 2020
- DOE Office of Project Assessment CD-1 Review: October 2020
- CD-1 Approval December 2020

Construction Launched with DOE, NSF and CFI/RM (Canada) Funding

- MOLLER construction funding from 3 sources
  - **DOE MIE received CD-1 December 2020 (US$ 48.2M)**
  - **NSF Physics Midscale awarded March 2021 (US$ 5.7M)**
  - **CFI/RM Innovation Fund awarded March 2021 (CAN$ 4.8M)**
- The MOLLER construction schedule as planned will have systems **ready for installation in Hall A in mid-2024**
- **Prominent element of the JLab and DOE-NP Plans**
  - **NSAC 2021 T. Hallman:**
    - *MOLLER: a “Must Do” Experiment to Point the Way to New Physics*
  - **Jlab 10-year Plan**
    - *Two exciting initiatives have emerged from our user community, which would significantly enhance the 12 GeV research capabilities. ... The MOLLER experiment aims to measure the weak charge of the electron and provide a special opportunity with the 12 GeV Upgrade to search for new flavor diagonal neutral currents. With the Higgs mass now known, a robust Standard Model theory prediction exists and allows for a unique discovery space for new physics, at a mass range even beyond that of a 500 GeV lepton collider. Starting the MOLLER experiment on a timely basis has scientific urgency to match these leptonic results with the hadronic constraints coming from the anticipated high-luminosity Large Hadron Collider (LHC) runs in the mid-2020s.*
  - **NP Report on the 2020 S&T Review of JLab:**
    - *The future experimental program is also well aligned with the 2015 NSAC Long Range Plan and the approved experiments comprise a backlog of over 5 years of CEBAF operations. There is an extensive plan for capital equipment projects matched to the experimental program and the Measurement of Lepton-Lepton Electroweak Reaction (Moller) and Solenoidal Large Intensity Device (SoLID) initiatives are aimed at maximizing the impact of the 12-GeV science program.*

MIE Project Manager: Jim Fast (JLab)



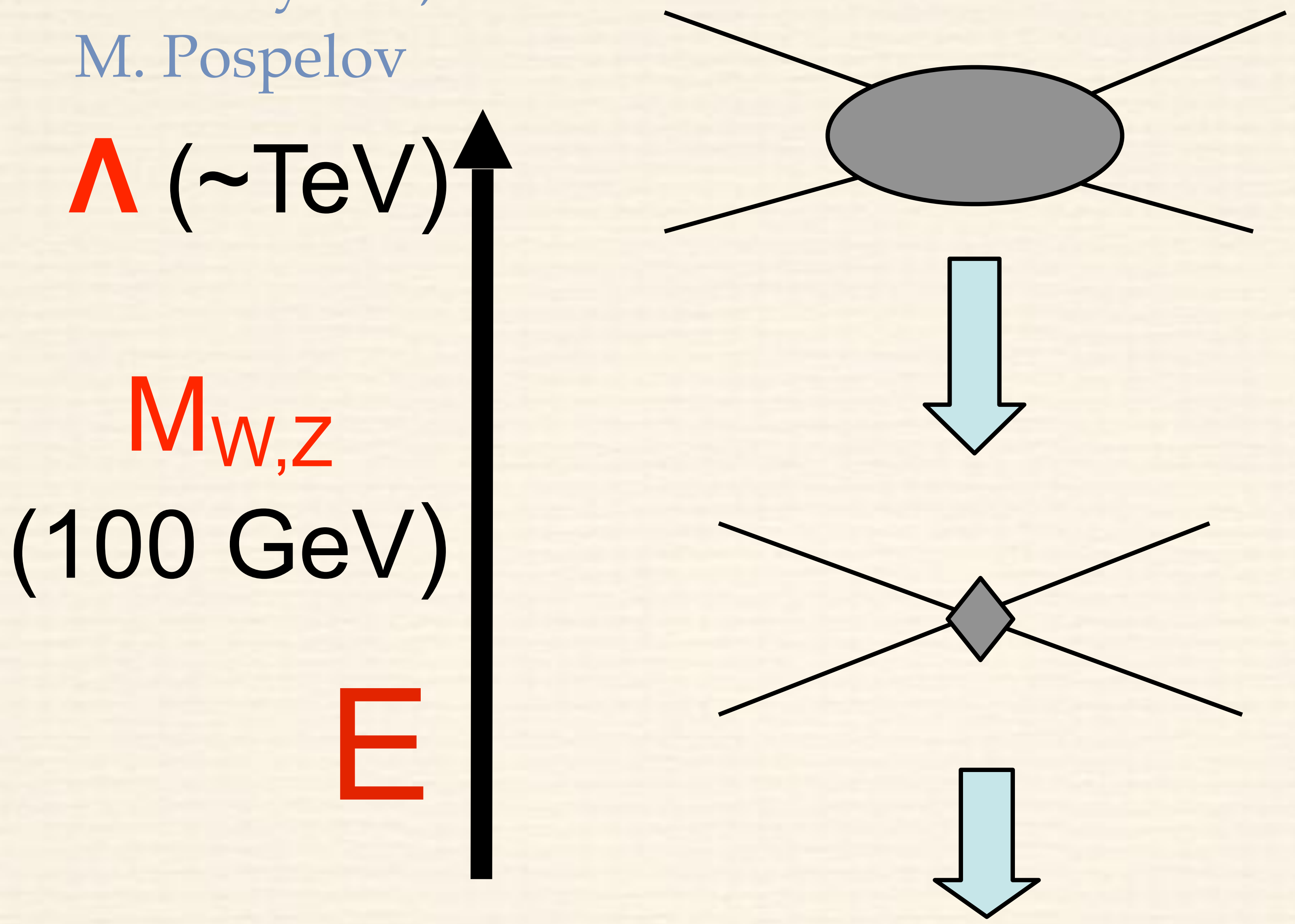
Physics Context for MOLLER

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

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

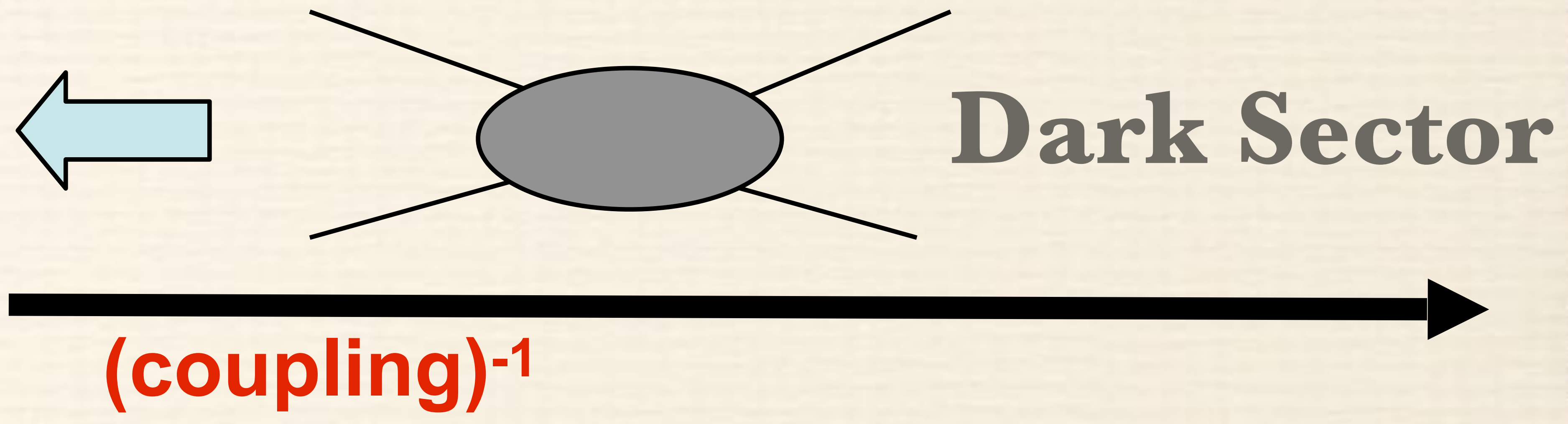
courtesy
V. Cirigliano,
H. Maruyama,
M. Pospelov

High Energy Dynamics

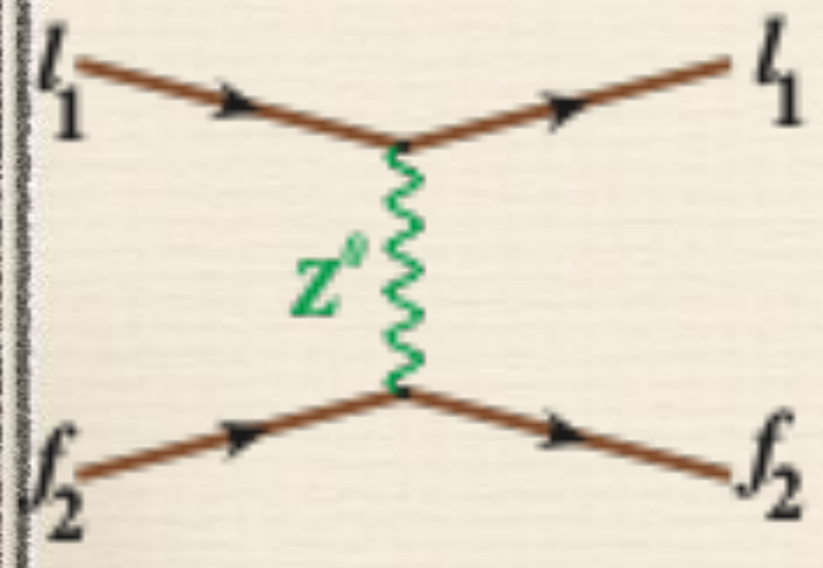


higher dimensional operators can be systematically classified

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

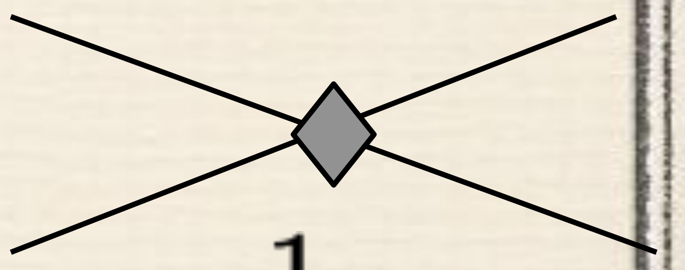


Leptonic and Semileptonic Weak Neutral Current Interactions



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

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

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

Conventional Collider Contact Interaction Analysis: → $g_{ij} = 4\pi\eta_{ij}$

Simultaneous fits to cross-sections and angular distributions

95% C.L. Limits

LEP200

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

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

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

E158 Reach (actual limits asymmetric)

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

LEP-200 insensitive

MOLLER Reach

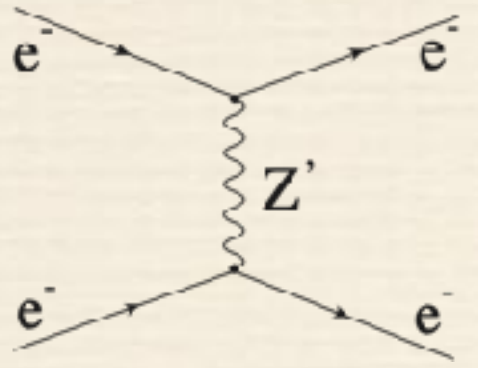
$\Lambda_{LL}^{ee} \sim 27$ TeV — $\Lambda_{RR-LL}^{ee} \sim 38$ TeV

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

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

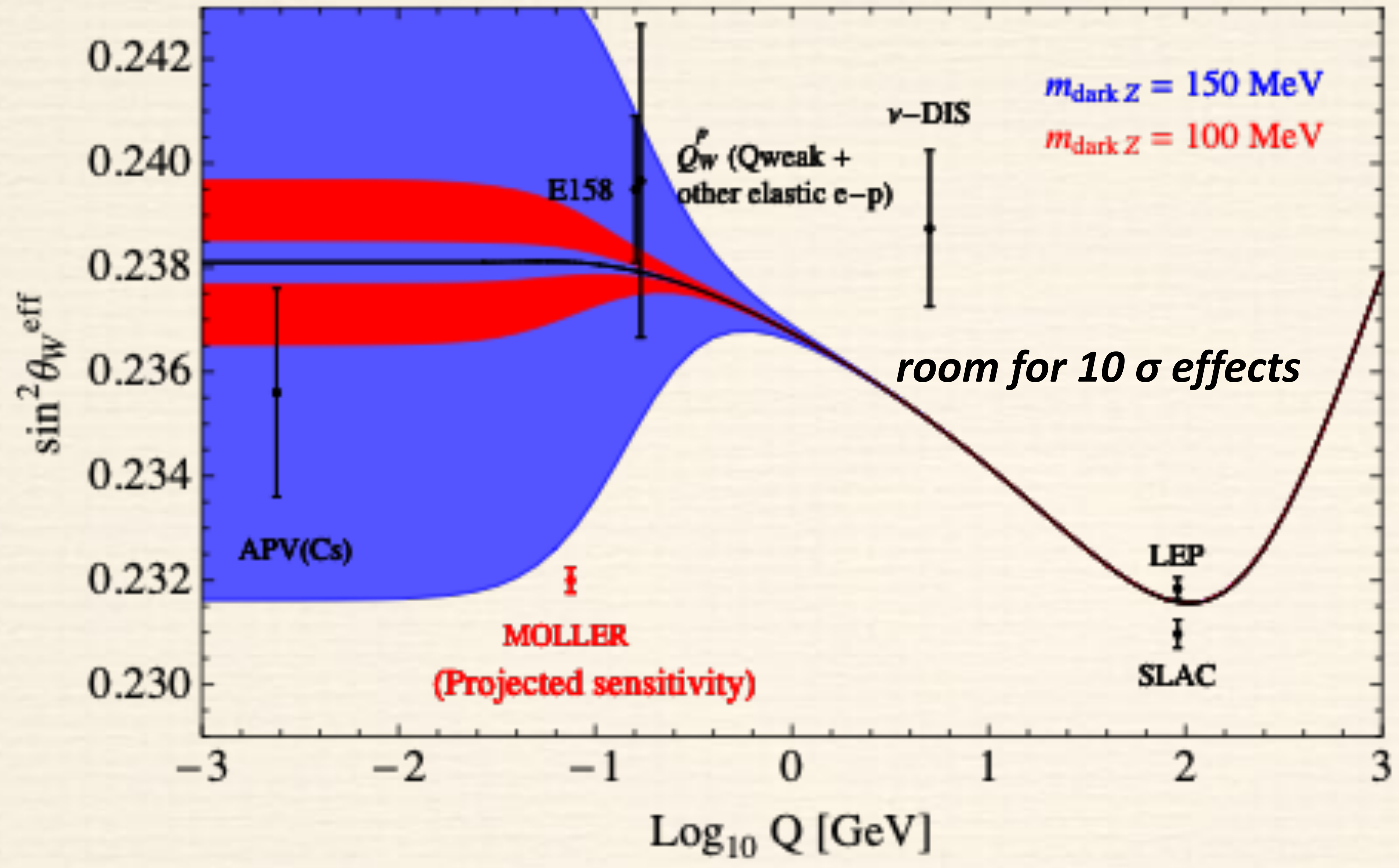
PV Møller Scattering: BSM Examples

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



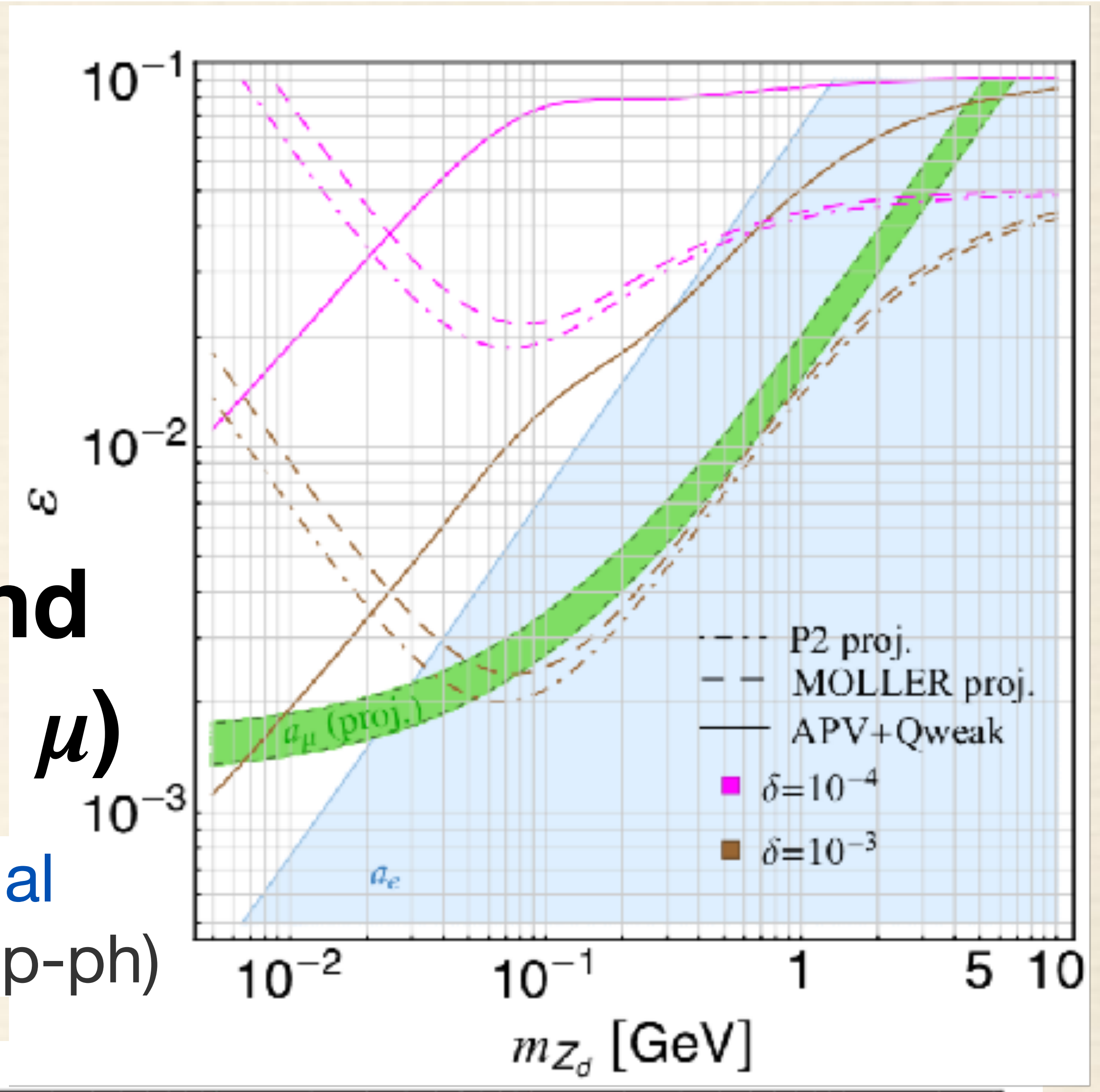
Heavy Photons (A' mixed with Z_0): The Dark Z

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

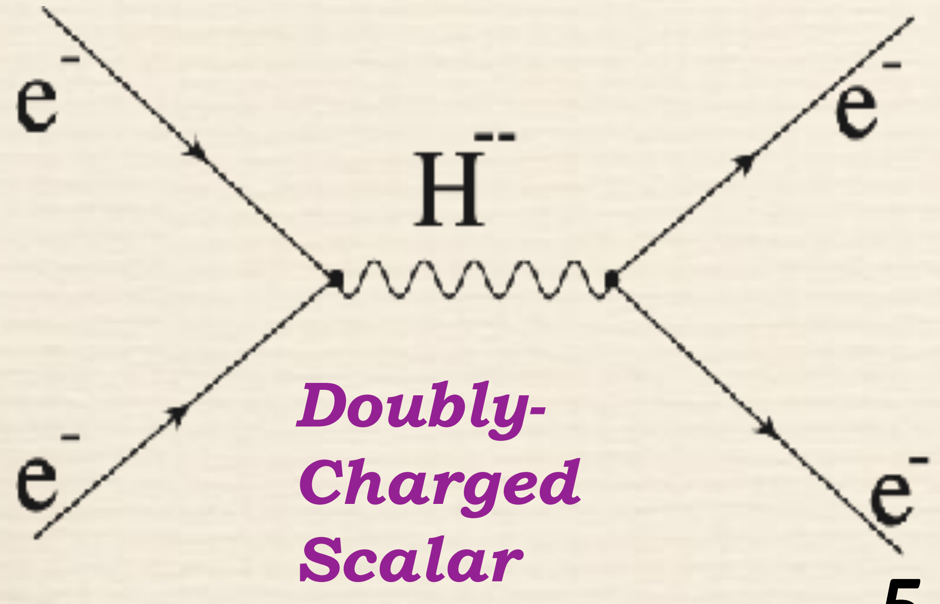


Specific Scenario folding in Cs APV and g-2 (e and μ)

M. Caddedu et al
2104.03280 (hep-ph)



Lepton Number Violation



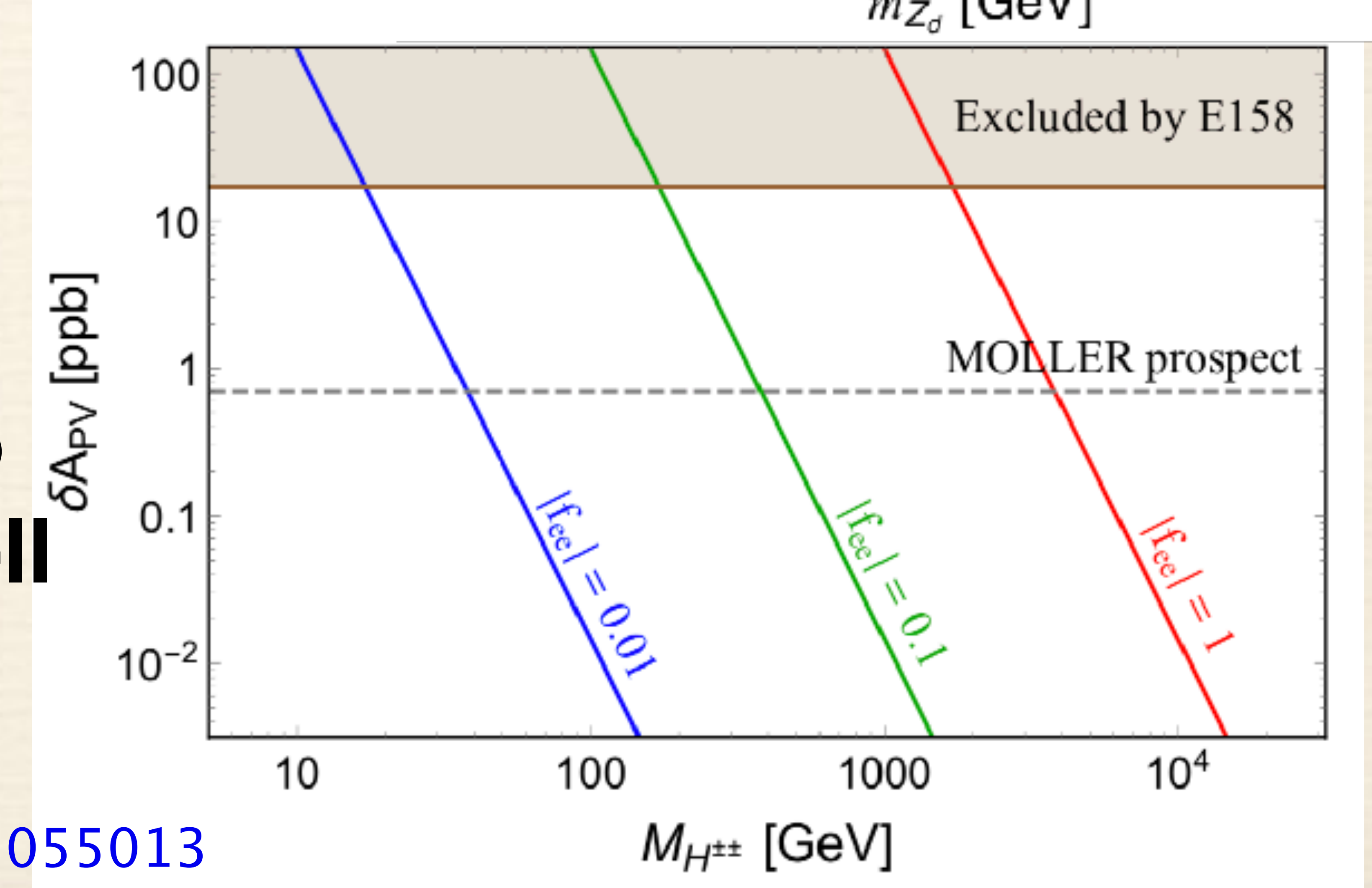
$$\left|\frac{\Delta Q_W^e}{Q_W^e}\right| = 0.14\frac{|h_{ee}|^2}{(M_\Delta/1\ \mathrm{TeV})^2}$$

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

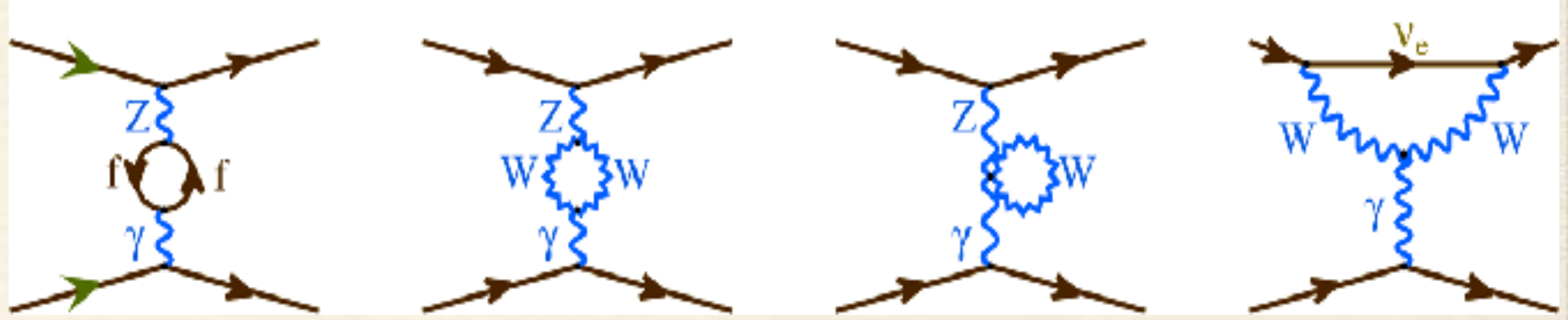
B. Dev et al
PhysRevD.98.055013

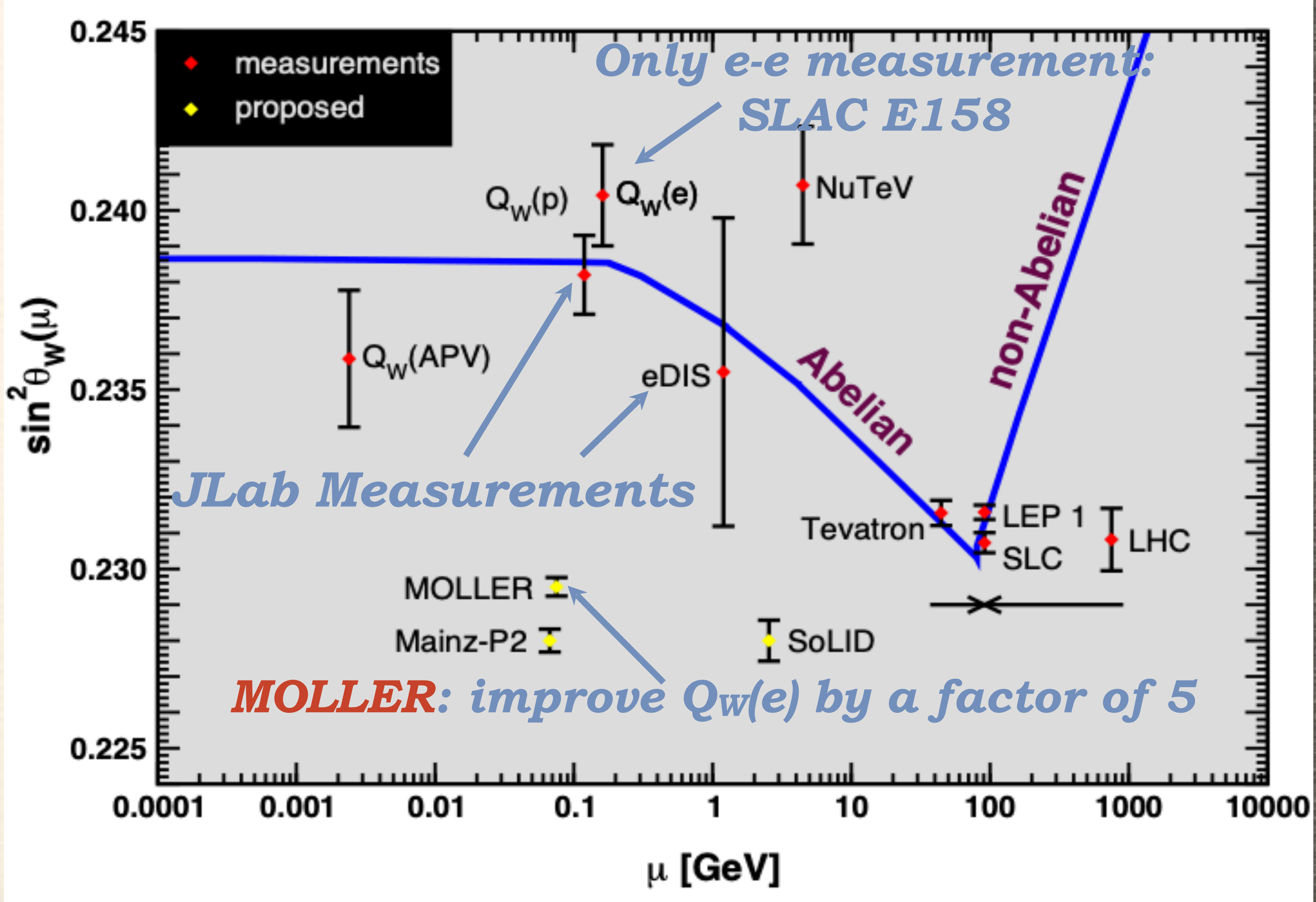


The Weak Mixing Angle at Low Q^2

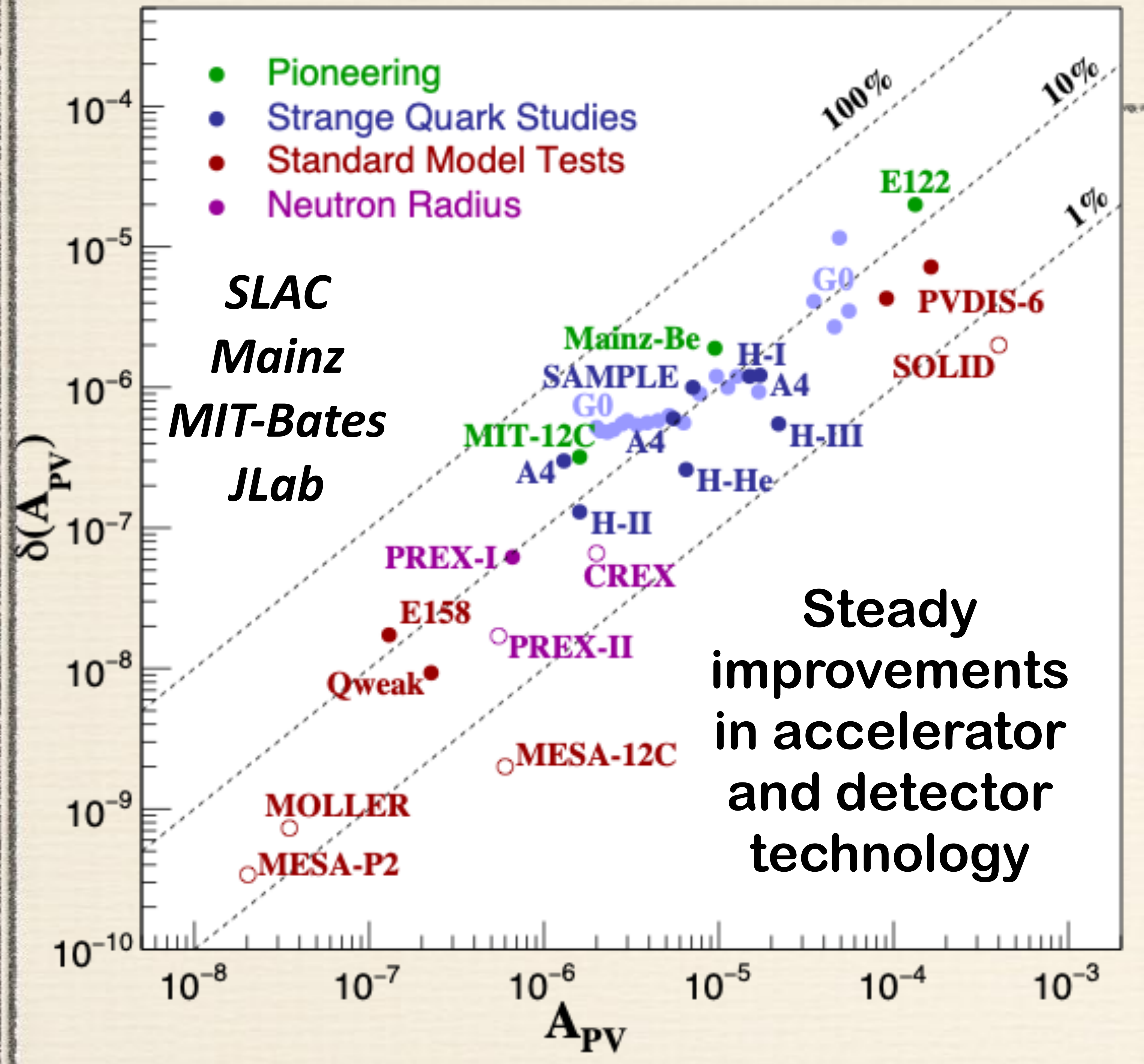
- **Atomic Parity Violation: Cs-133**
  - future measurements and theory challenging
- **Neutrino Deep Inelastic Scattering: NuTeV**
  - future measurements and theory challenging
- **PV Møller Scattering: E158 at SLAC**
  - statistics limited, theory robust
  - next generation: MOLLER (factor of 5 better)
- **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 ^2H in valence quark region
  - factor of 5 improvement: SOLID

Czarnecki and Marciano (1995)



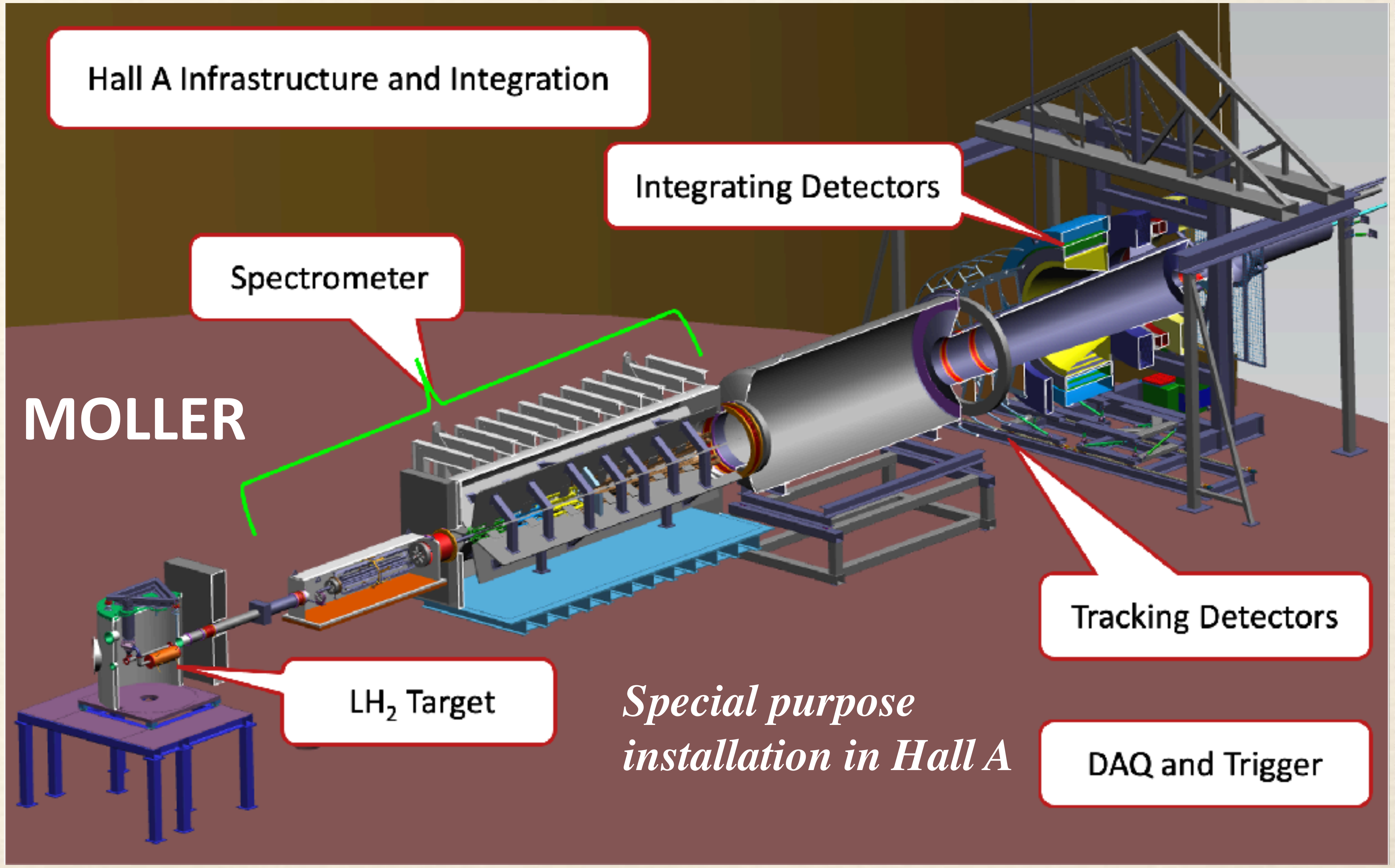


4th Generation PVES at JLab



State of the Art →

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



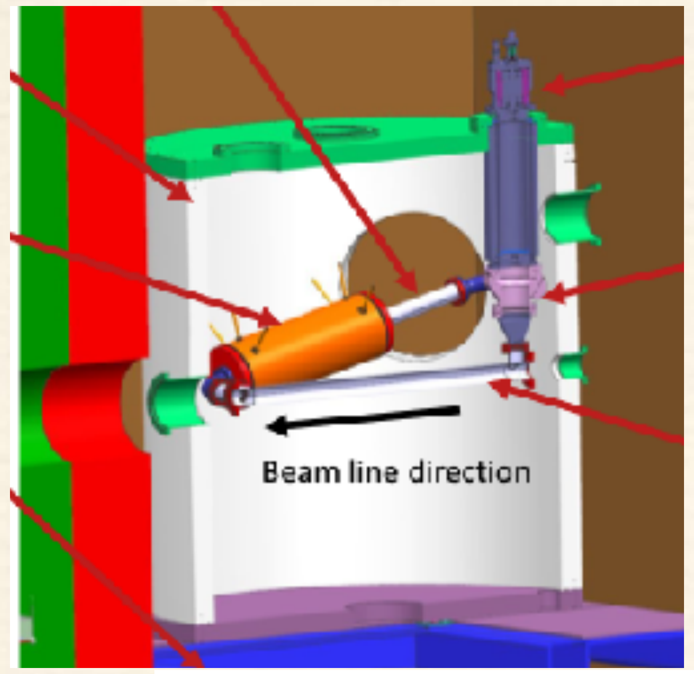
Variety of Physics Topics:

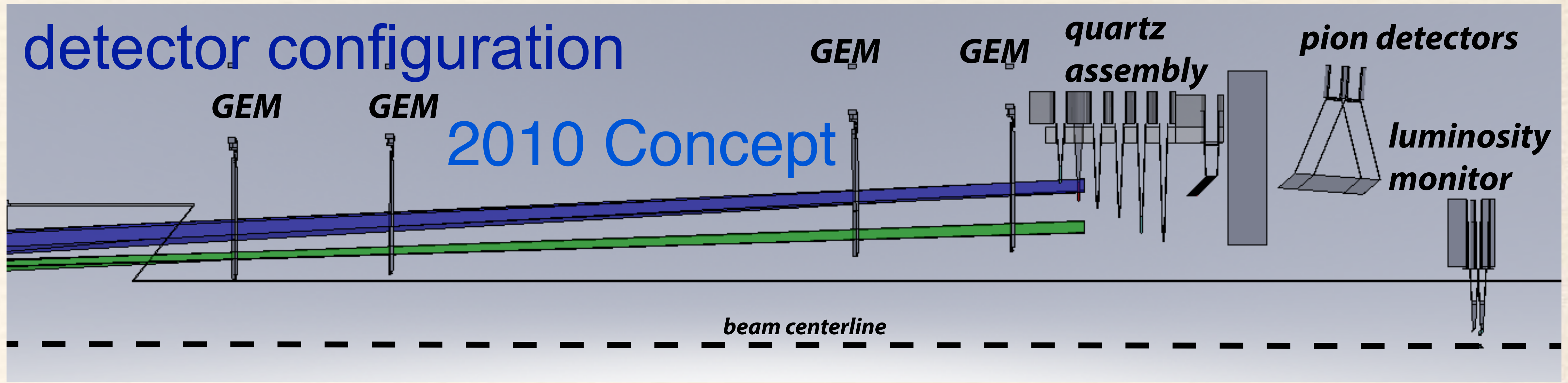
continuous interplay between hadron physics and electroweak physics

Conceptual Design Extensively Vetted

Intensive Progress towards a Complete Engineering Design

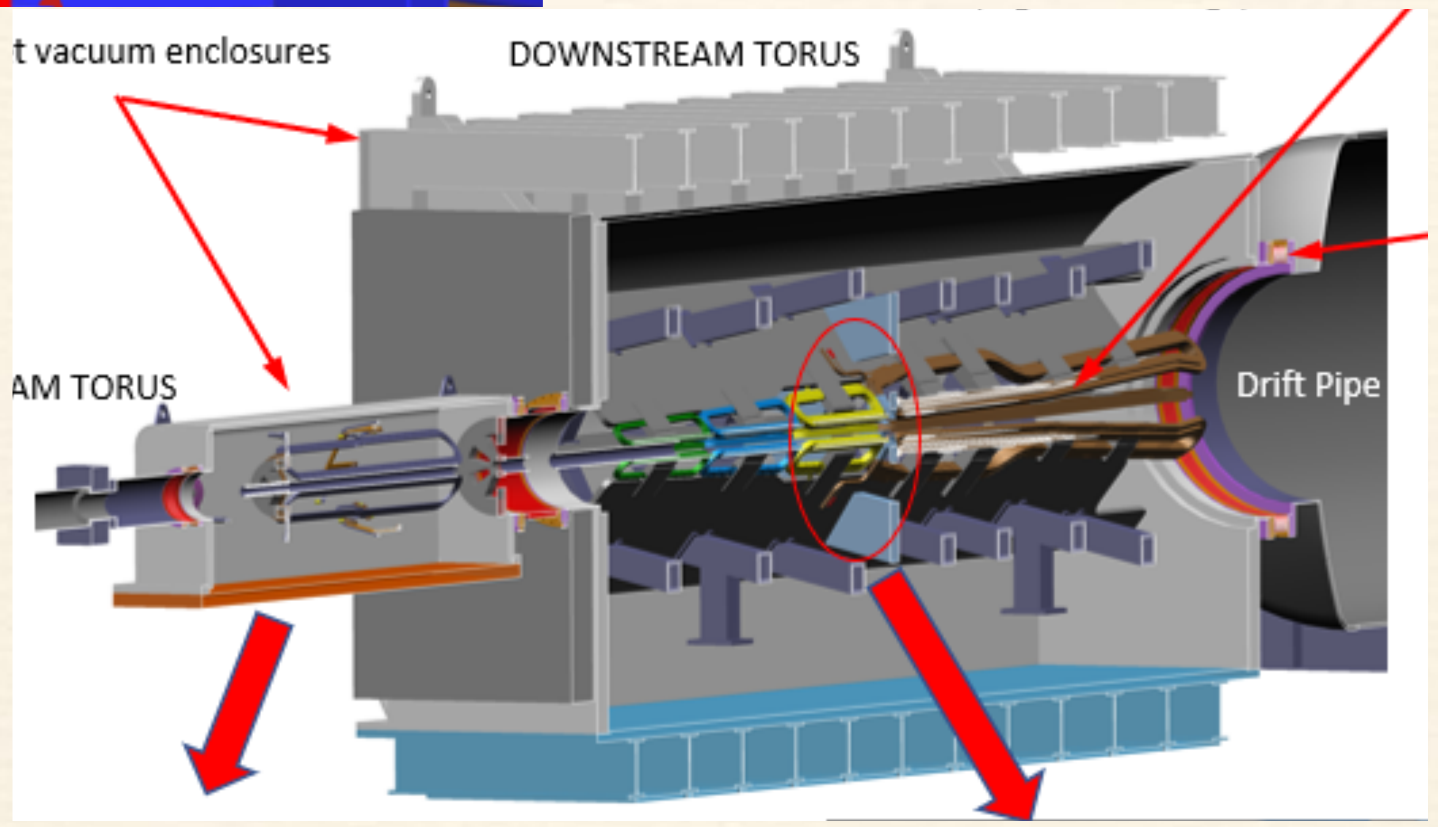
- Ongoing JLab Construction Project
- goal: Installation start Summer 2024

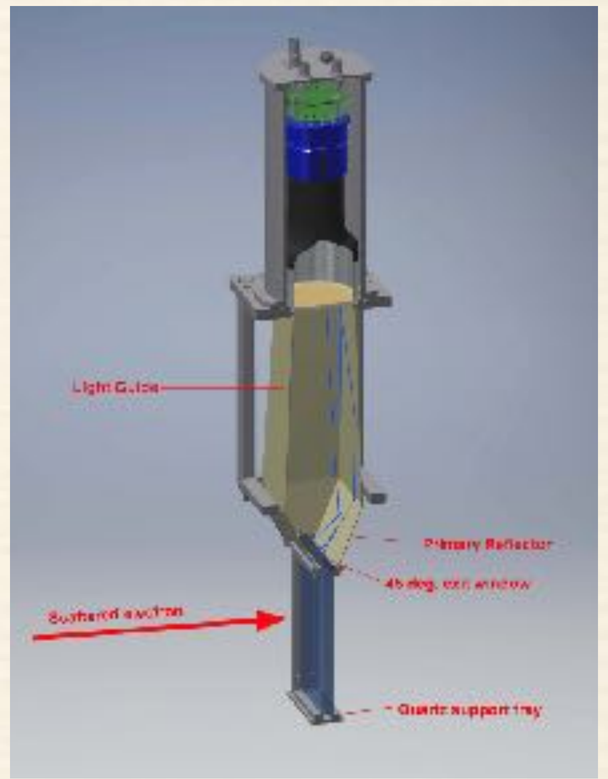


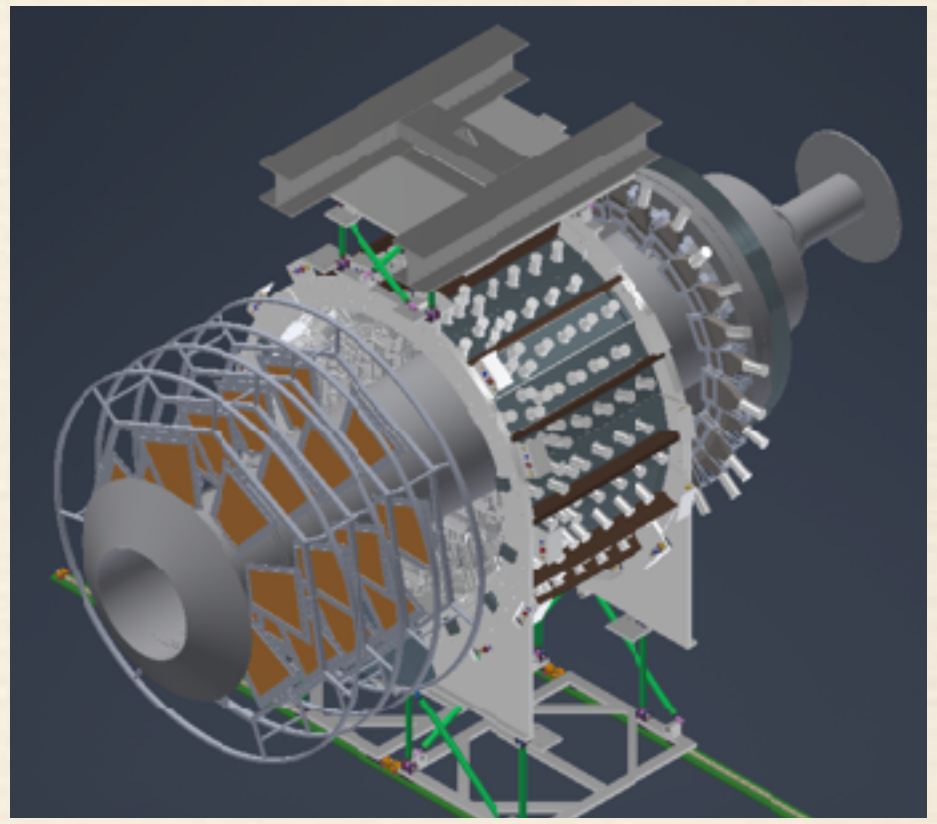


Technical Challenges

Evolutionary Improvements from Technology of Third Generation Experiments







- ~ 150 GHz scattered electron rate
- 1 nm control of beam centroid on target
- 9 gm/cm^2 liquid hydrogen target
  - 1.25 m: ~ 4 kW @ 65 µA
- Full Azimuthal acceptance w/ θ_{lab} ~ 6 mrad
  - novel toroidal spectrometer pair
  - radiation hard, highly segmented integrating detectors
- Robust & Redundant 0.4% beam polarimetry

- **MOLLER Collaboration**
  - 182 scientists, 37 institutions, 5 countries
  - Experience from SAMPLE, A4, HAPPEX, G0, PREX, Qweak, E158

Beamtime and Summary

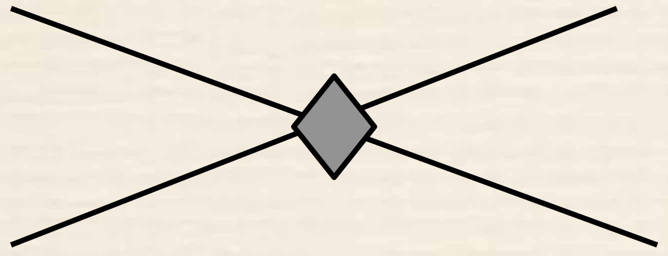
65 µA, 90% polarization

Run Period	1 kHz Width	PAC Days (prod)	Stat Error (ppb)	Stat Error (%)	Eff %	Notional Calendar Weeks Production	Notional Commissioning Weeks	Notional Total Weeks
I	101	14	2.96	11.4	40	5	6	11
II	96	95	1.08	4.2	50	27	3	30
III	91	235	0.65	2.5	60	56	4	60
Total		**344**	**0.55**	**2.1**			**13**	**101**

- ✦ **MOLLER Physics Motivation Remains Compelling**
  - ★ Discovery space unmatched for neutral current interactions at $Q^2 \ll M_Z^2$
  - ★ Multiple review panels: MOLLER must be supported to achieve stated goal
  - ★ This purely leptonic measurement cannot be done elsewhere in the world
- ✦ **MOLLER Construction Project well under way**
  - ★ Intense & coherent effort among physics collaboration and project personnel
- ✦ **We are looking forward to first physics in late 2025**

Backup

MOLLER Physics Elsehwere?



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

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

MOLLER Collaboration: ~ 182 authors, 37 institutions, 5 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) C. Keppel (JLab), F. Maas (Mainz), 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

Technical Board

MOLLER Project Personnel

J. Fast, MOLLER Project Manager

Project Leads

Control Account Managers

Technical Leads

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)

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

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

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

- **If LHC sees ANY anomaly in Runs 2 or 3**
  - **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**
  - **…**

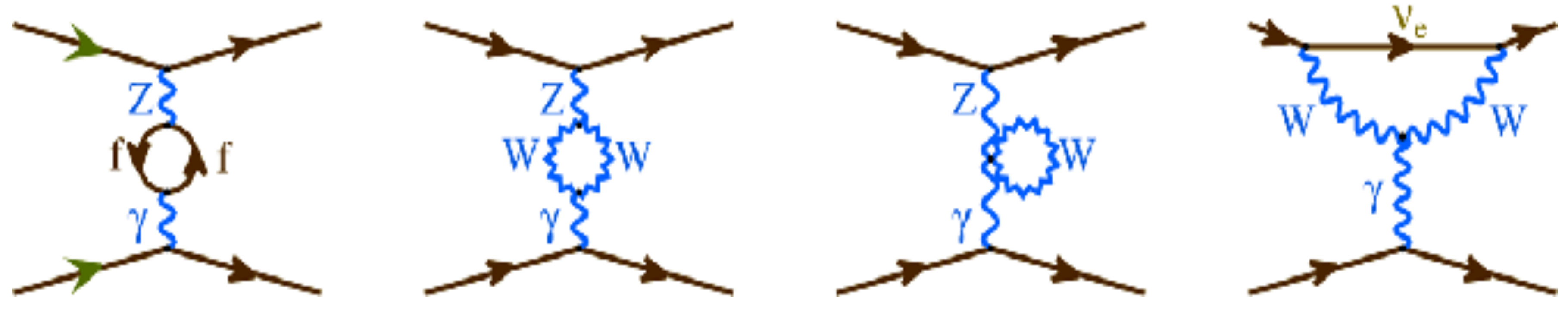
Most sensitive discovery reach over the next decade for CP-/flavor-conserving or LNV scattering amplitudes

Radiative Corrections

The Standard Model Prediction: Remarkably Well-Known

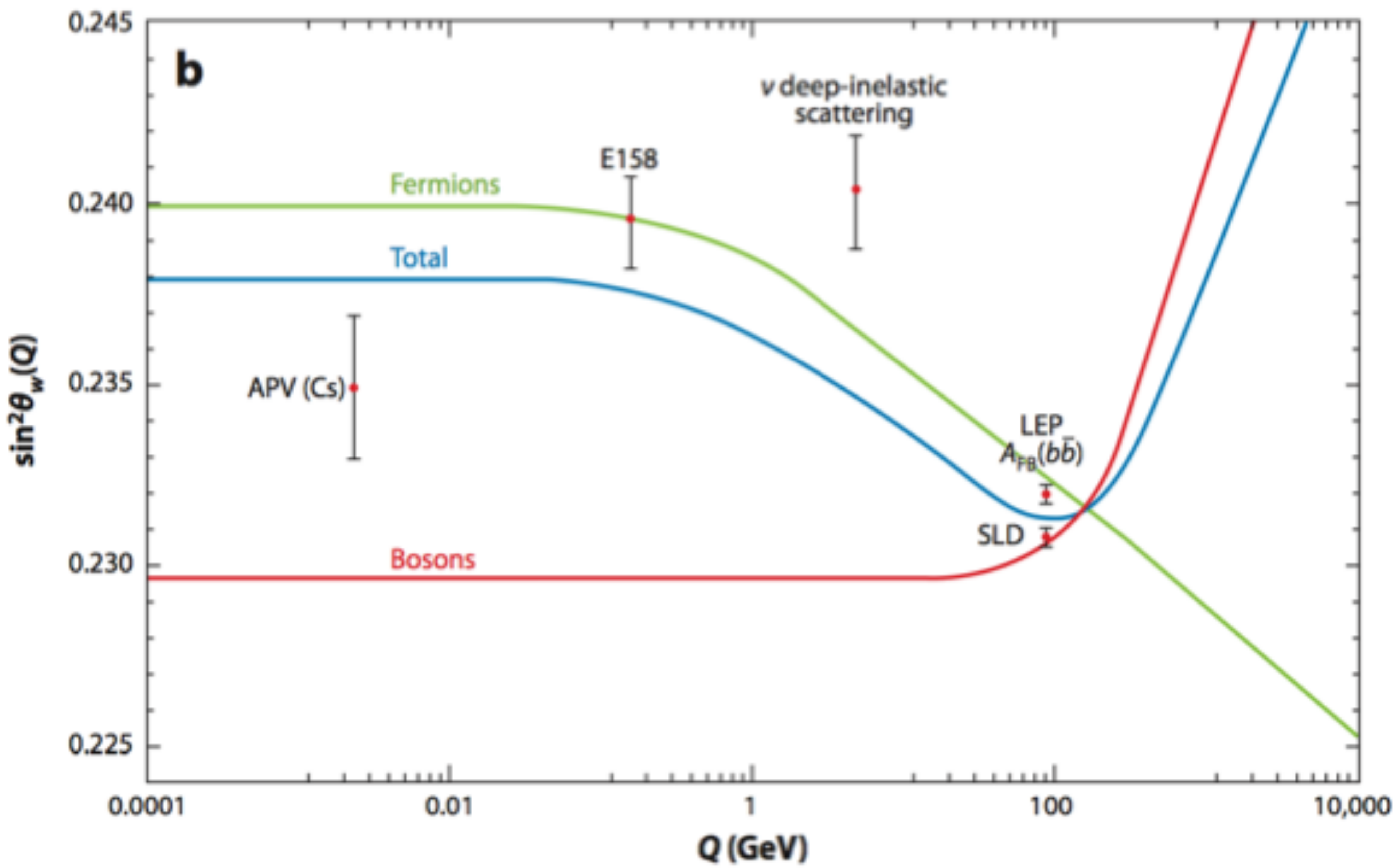
$$A_{PV} = \frac{\rho G_F Q^2}{\sqrt{2}\pi\alpha}\frac{1-y}{1+y^4+(1-y)^4}\{1-4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{\rm MS}}$$
$$+ \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2]$$
$$+ F_1(y,Q^2)+F_2(y,Q^2)\Big\}$$

Czarnecki and Marciano (1995)



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

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



The small size of the coupling, further reduced by radiative corrections, will be a recurring theme: it eases the pressure on "normalization" errors

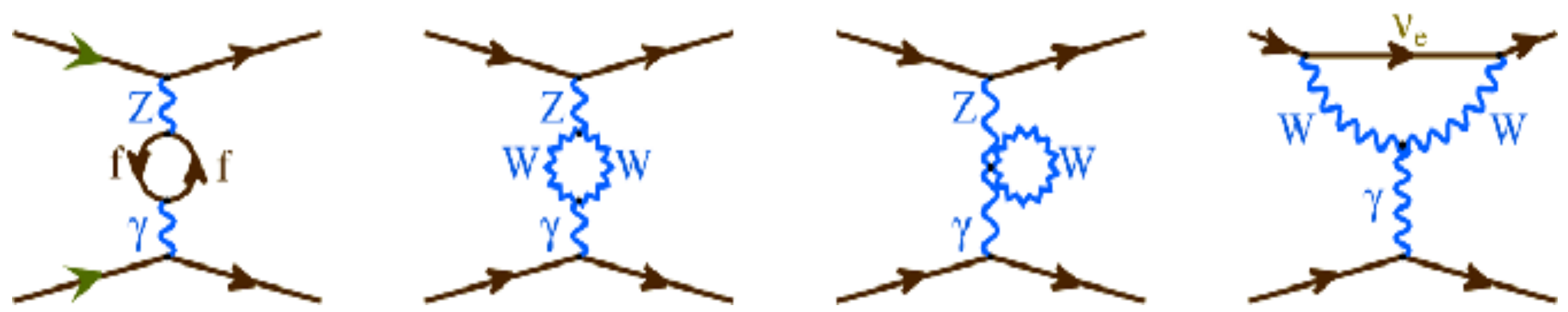
Theory Prediction and Radiative Corrections

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)

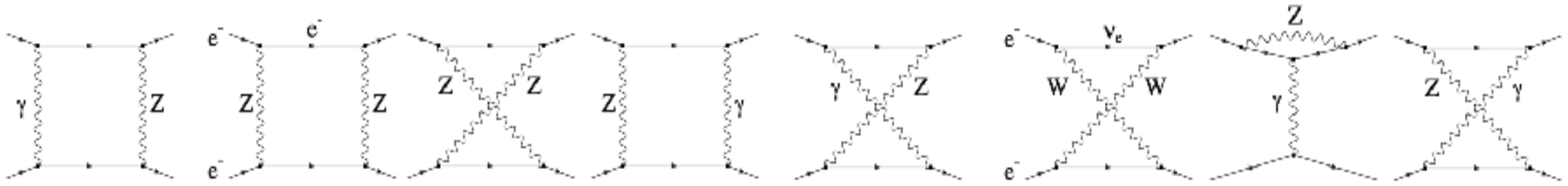
Czarnecki and Marciano (1995)

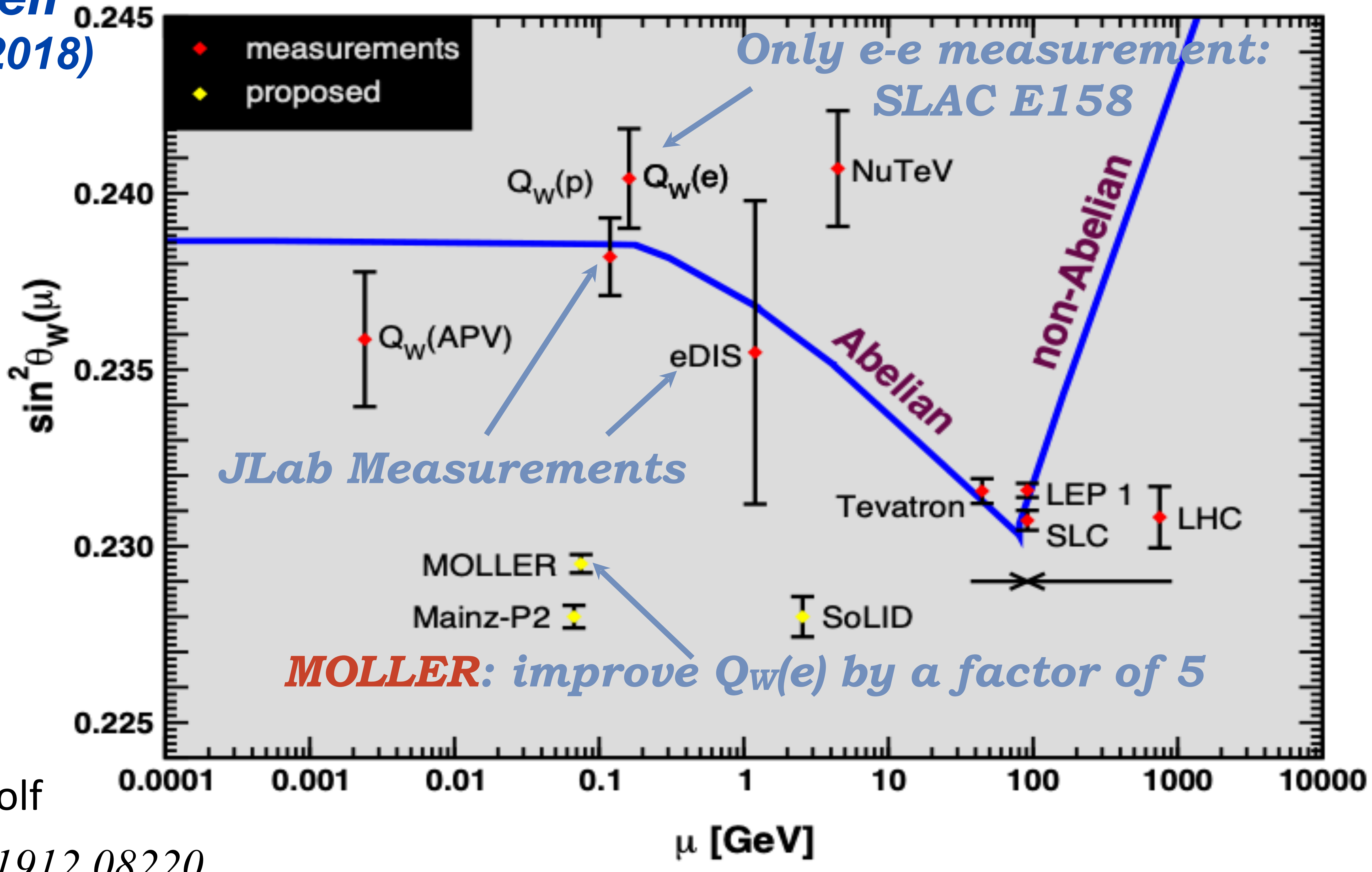


$$\mathbf{Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075 \Longrightarrow 0.045}$$

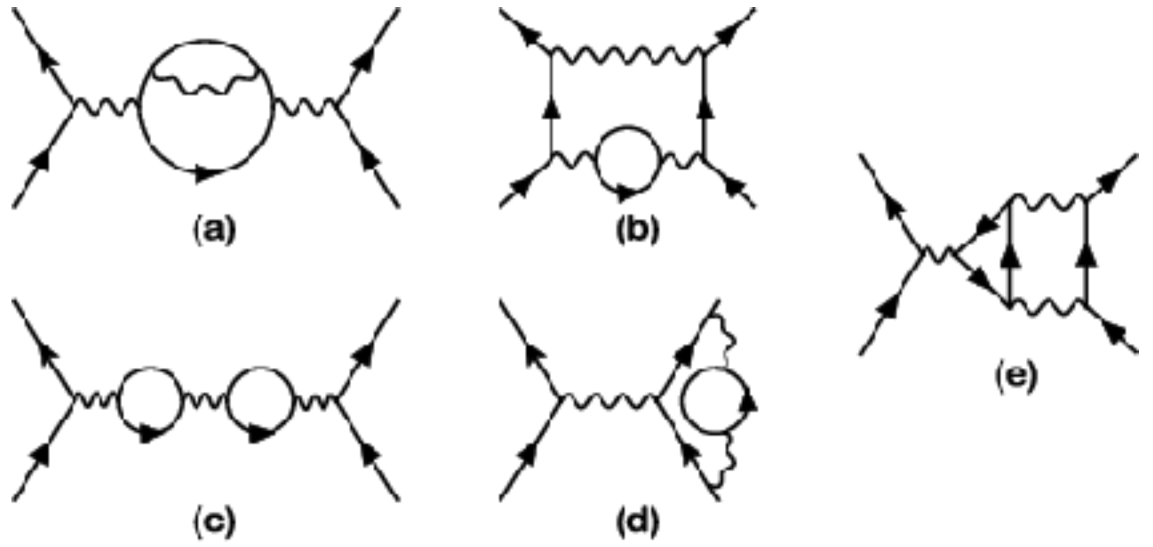
$$\frac{\delta(Q_W)}{Q_W} \sim 10\% \Longrightarrow \frac{\delta(\sin^2\theta_W)}{\sin^2\theta_W} \sim 0.5\%$$

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





2 groups working on 2-loop Calculations

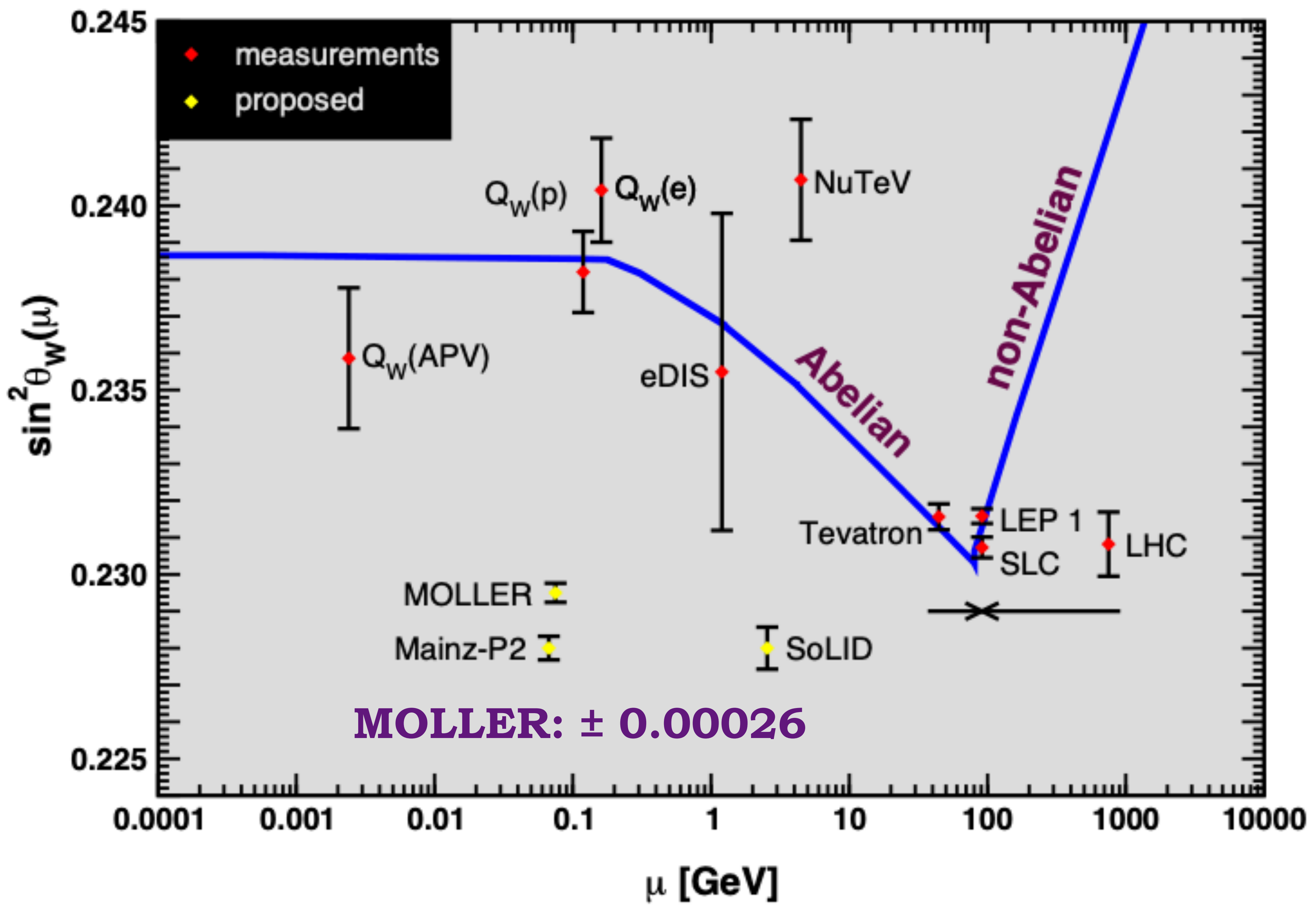


Aleksejevs and Barkanova
Series of publications

Du, Freitas, Patel and Ramsey-Musolf
Recent closed-fermion loops: arXiv:1912.08220

The Weak Mixing Angle

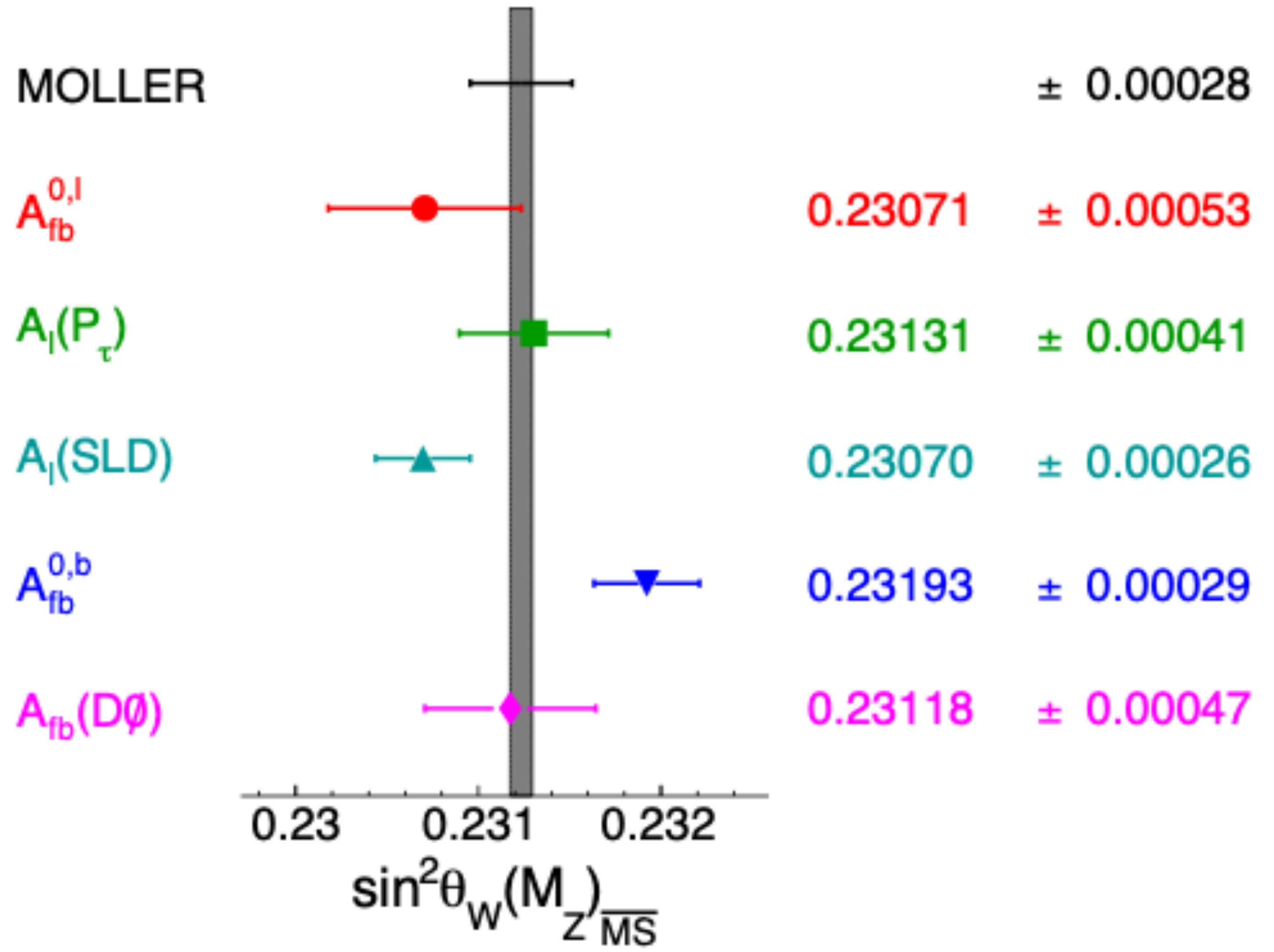
MOLLER Projection: ***δ(sin²θ_W) = ± 0.00023 (stat.) ± 0.00012 (syst.)***



± 10σ discovery potential at $Q^2 \ll M_Z^2$

Mainz P2: 0.00031 (projected)

Z resonance measurements:
no interference term



Tevatron: 0.00033 (combined)

LHC (combined) : ~ 0.00036

systematics-dominated (pdf uncertainties)

LHC (combined) and MOLLER/P2 (combined) will provide two combinations with uncertainties ~ 0.0002 in mid-2020's

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

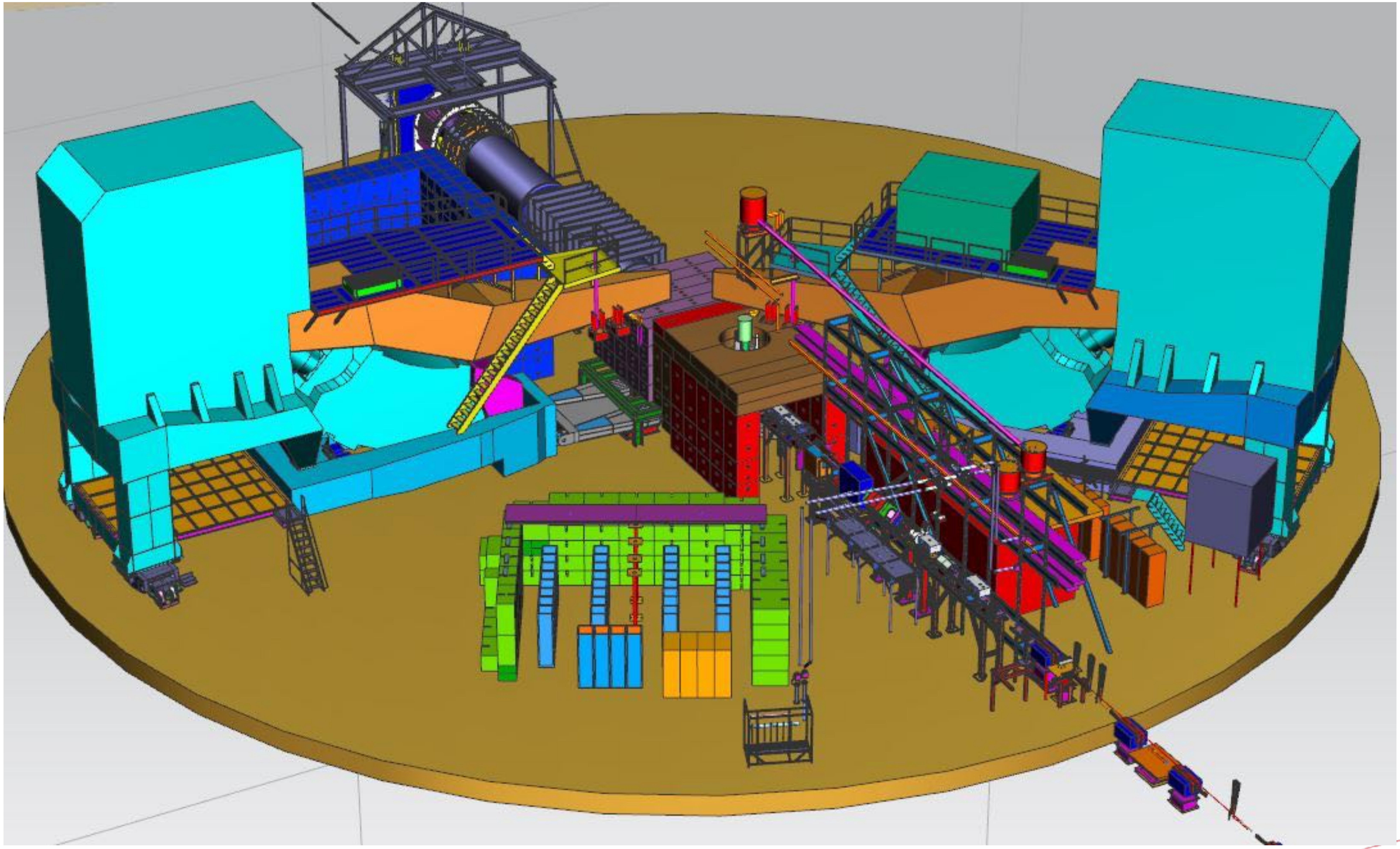
$$\text{Combined}\ \frac{\delta A_{PV}}{A_{PV}} = 2.4\%$$

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

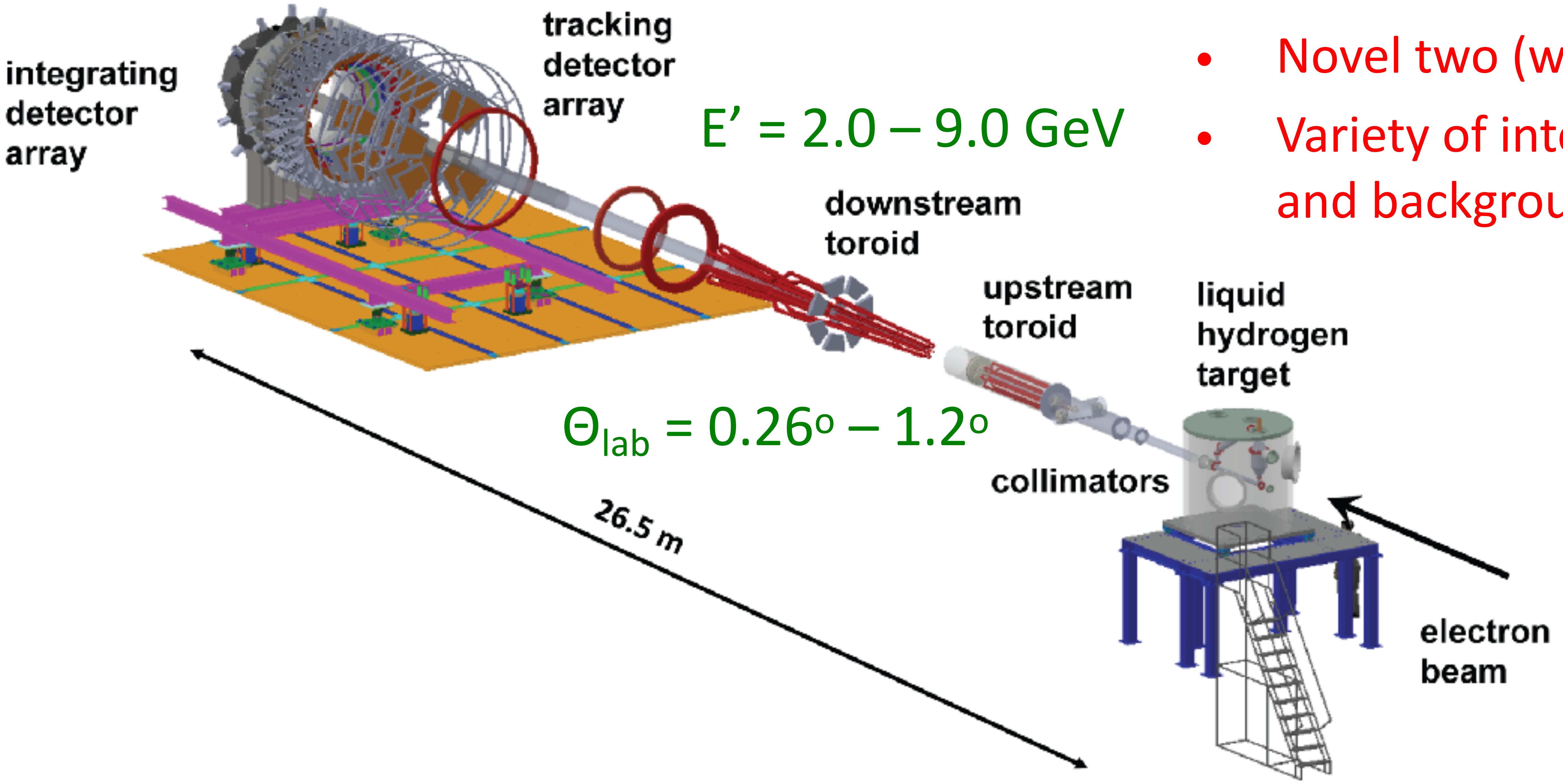
Hall A Layout



MOLLER Experiment: Conceptual Design Overview

- 11 GeV, 90% polarized, 65 μA electron beam
- 125 cm long, 4 kW LH_2 target
- Precision collimation (“2-bounce” design minimizes backgrounds)
- Novel two (warm) toroid spectrometer
- Variety of integrating and counting detectors for main measurement and backgrounds

Schematic layout



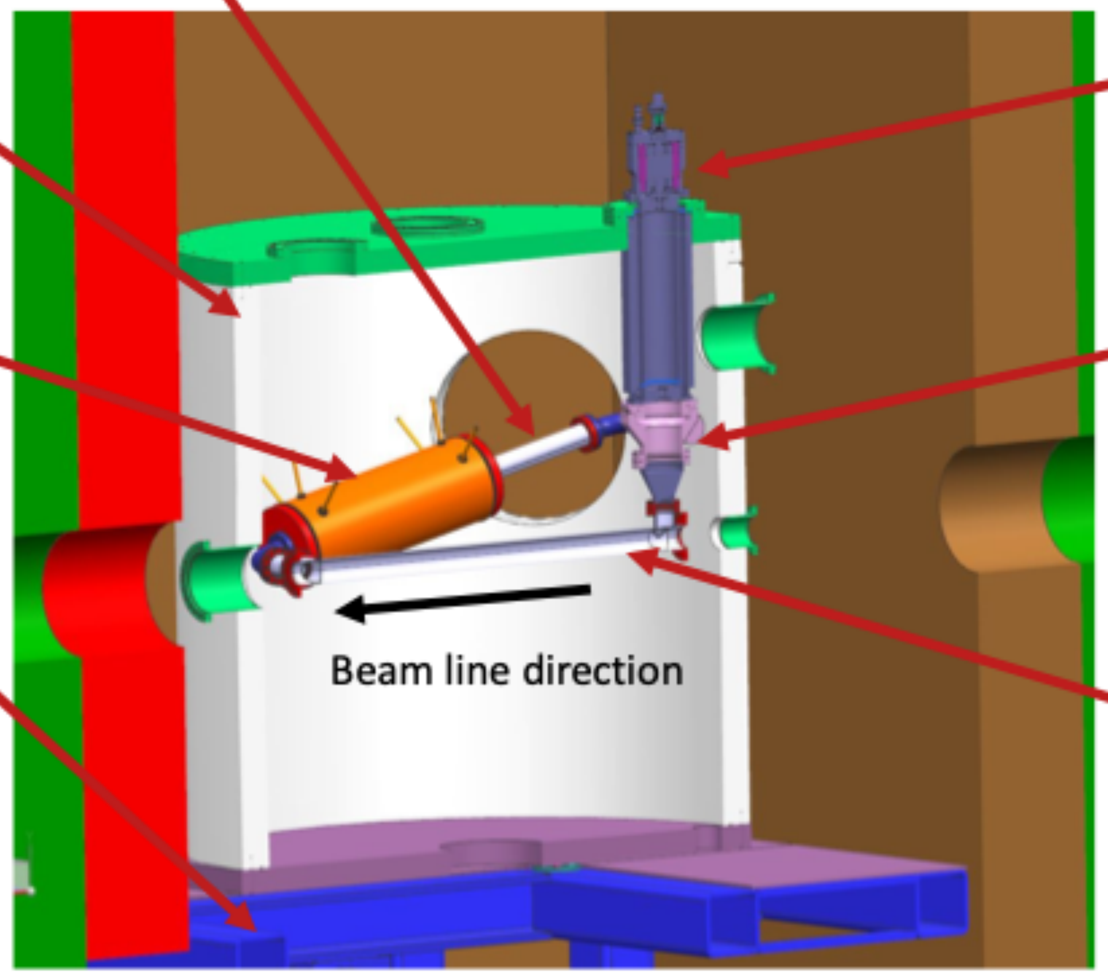
Subsystems:

- WBS 1.02: Liquid Hydrogen Target
- WBS 1.03: Spectrometer: Collimation, 2 toroids
- WBS 1.04: Integrating Detectors
- WBS 1.05: Tracking Detectors
- WBS 1.06: Hall A Integration: Shielding, Electrical/Cryo utilities
- WBS 1.07: Data acquisition and trigger
- Dependencies: Polarized beam, Beamline instrumentation, Polarimetry

In the following, the subsystems are presented along with relevant threshold and objective KPP’s

High Power Liquid Hydrogen Cryotarget

- MOLLER requirement: up to 70 µA on 125 cm LH_2 target - 4.0 kW power
- Build on Q_{weak} success of using CFD (computational fluid dynamics) for target design
- Q_{weak} target successfully operated up to 2.9 kW (compared to previous high of ~ 1.0 kW)



Main requirement: minimize target density fluctuations (Δρ/ρ) (``target boiling noise'')

$$\Gamma_{stat} = \sqrt{\Gamma^2_{count} + \Gamma^2_{target}} \quad \text{want } \Gamma_{target} << \Gamma_{count}$$

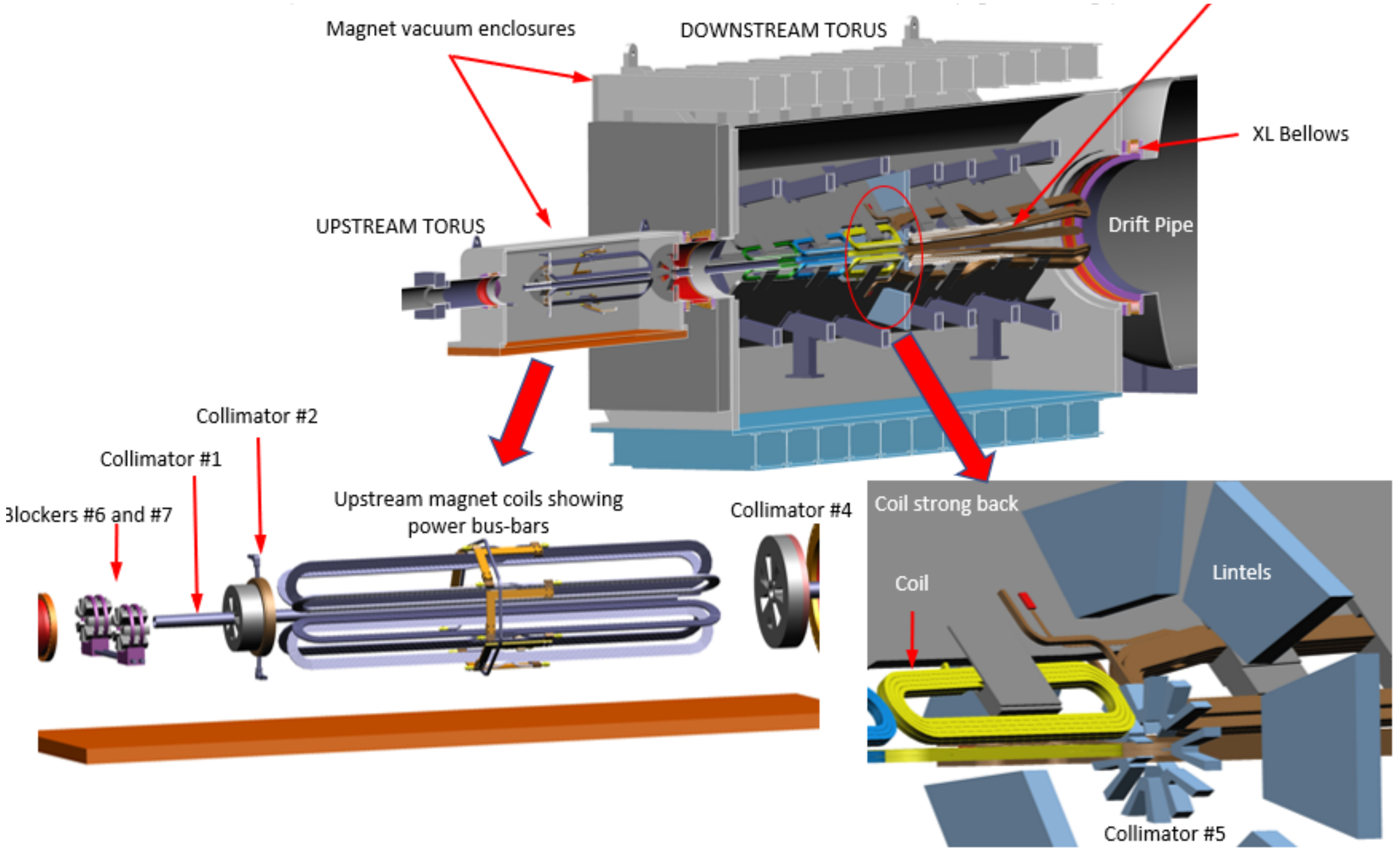
Projection for MOLLER based on G0 and Q_{weak} experience

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

WBS Element	KPP	Threshold Criteria	Objective Criteria
1.02 Liquid Hydrogen Target	Cryogenic liquid hydrogen and solid target systems installed in Hall A and operated successfully	Demonstrate liquid hydrogen target operation with ≥2kW load from heater	Demonstrate liquid hydrogen target operation with ≥4kW load from heater

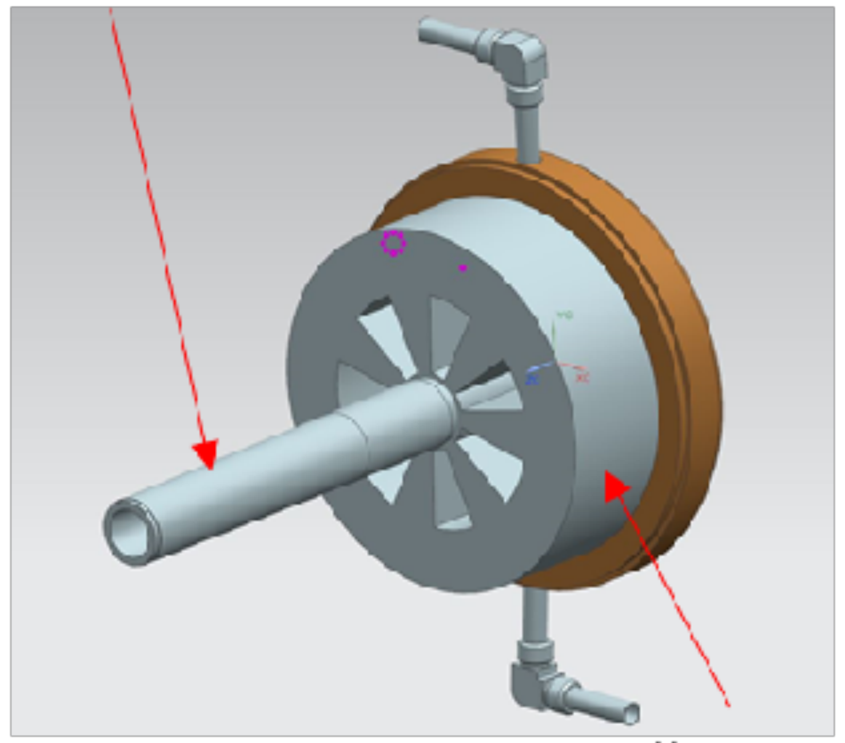
Collimation and Shielding

- Collimation system requirements:
  - define Møller electron acceptance
  - block detector line-of-sight to target and localize backgrounds
  - shield the toroid coils
- Designed to achieve “two-bounce” criteria for low energy neutral backgrounds
- Most critical required tolerances:
  - ±200 µm machining tolerance on defining inner edge
  - ±1 mm positioning tolerance for most critical collimators
- Employs water-cooled tungsten and copper collimators



Collimator	Power @65uA, 1.25m Tgt
1: beam interceptor	4000 W
2: primary	700 W
4: cleanup	70 W
5+Lintel: photon blocker	40 W

Collimator #1



Collimator #2

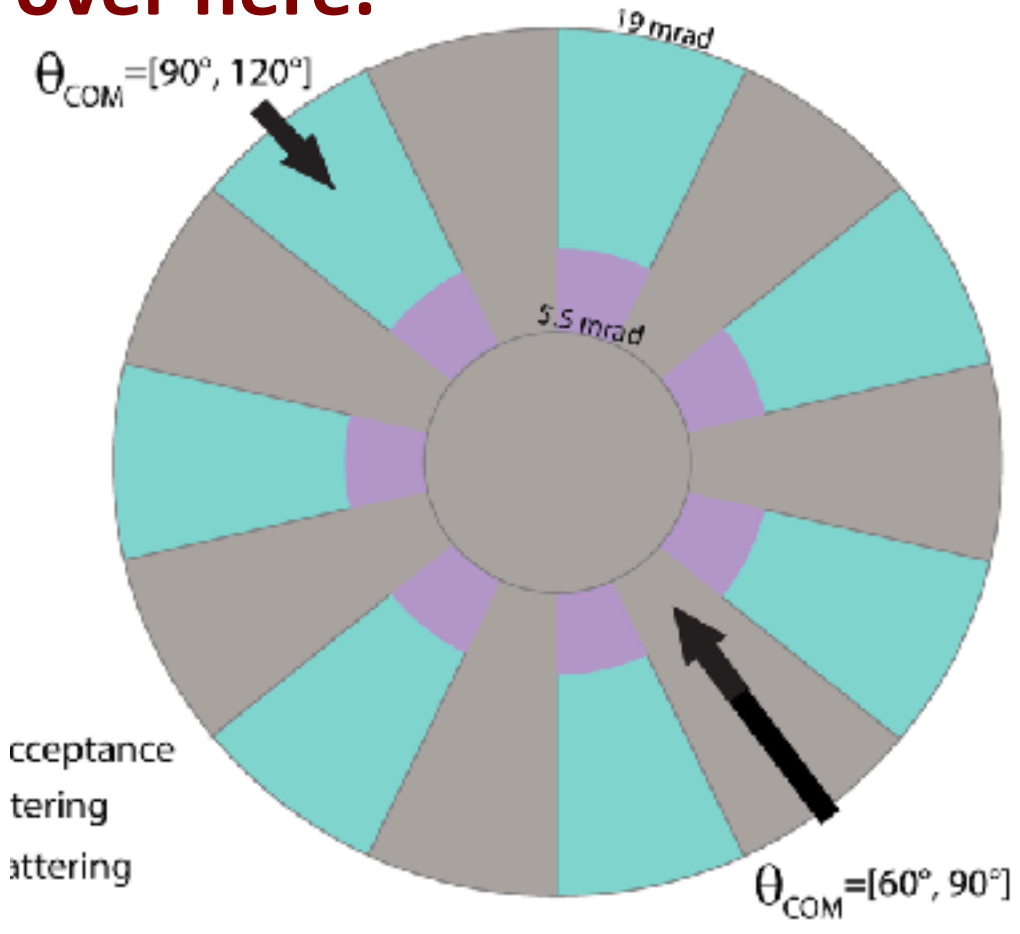
WBS 1.03 Spectrometer

Jefferson Lab

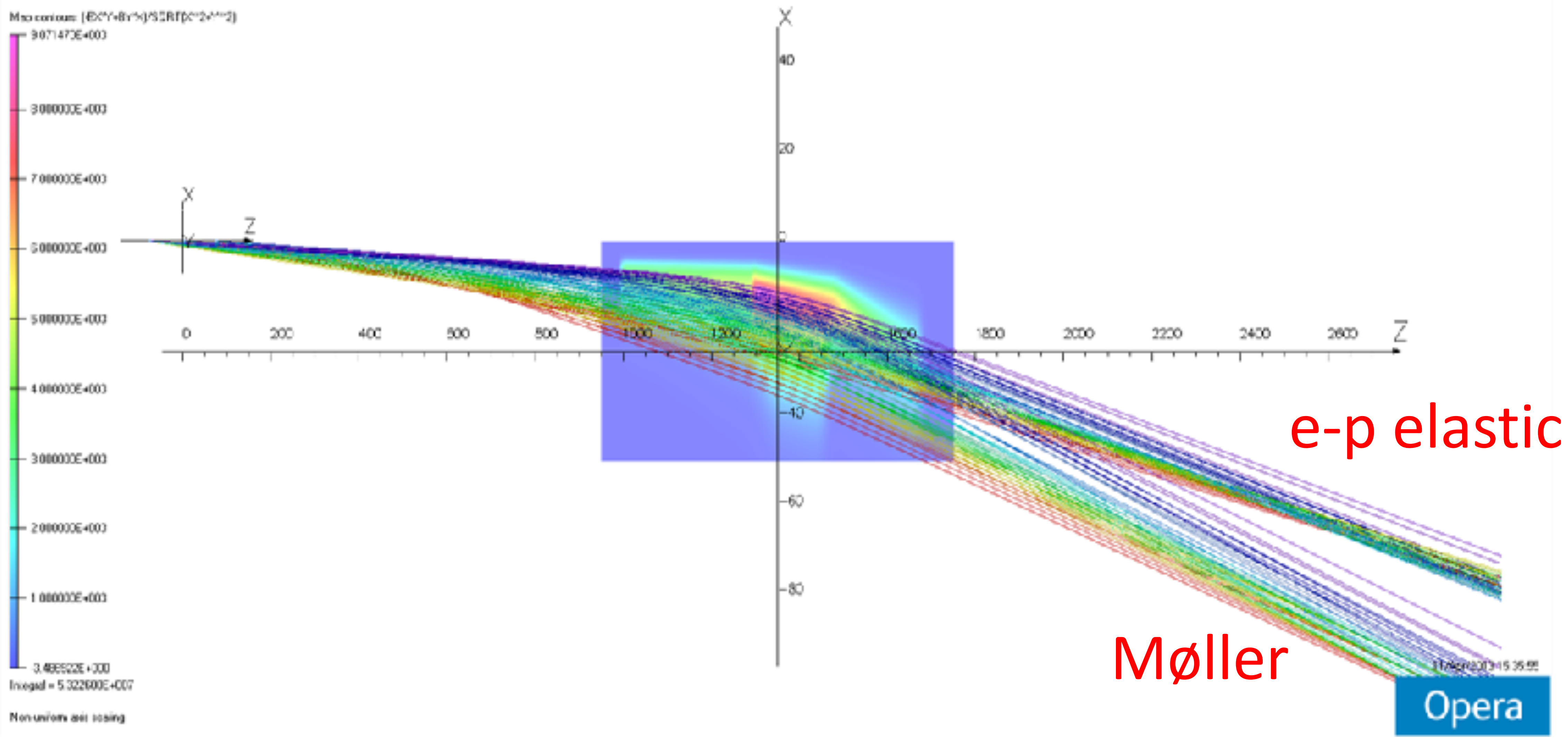
Spectrometer: Kinematics, Azimuthal Acceptance, Signal/Background Separation

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

…are collected over here.

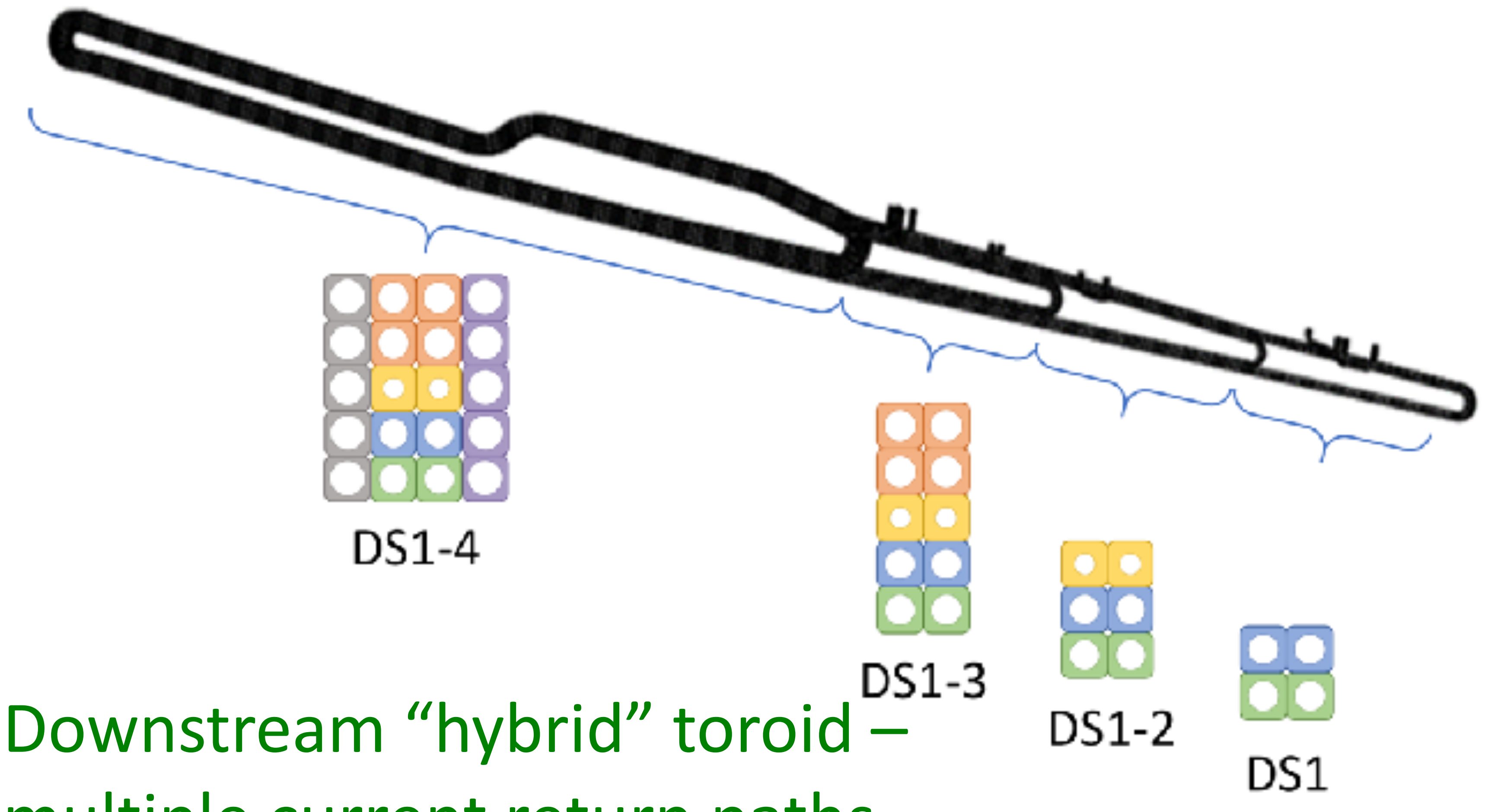


The rays that are blocked here…



Spectrometer employs a novel two toroid design

- Upstream toroid has conventional "racetrack" geometry
- **Downstream "hybrid" toroid novel design** inspired by the need to focus Møller electrons with wide scattered energy range E' = 2.0 – 9.0 GeV while separating them from Mott (e-p) scattering background - requires long, skinny magnet with multiple current return paths for needed field integral ~ 1 T-m



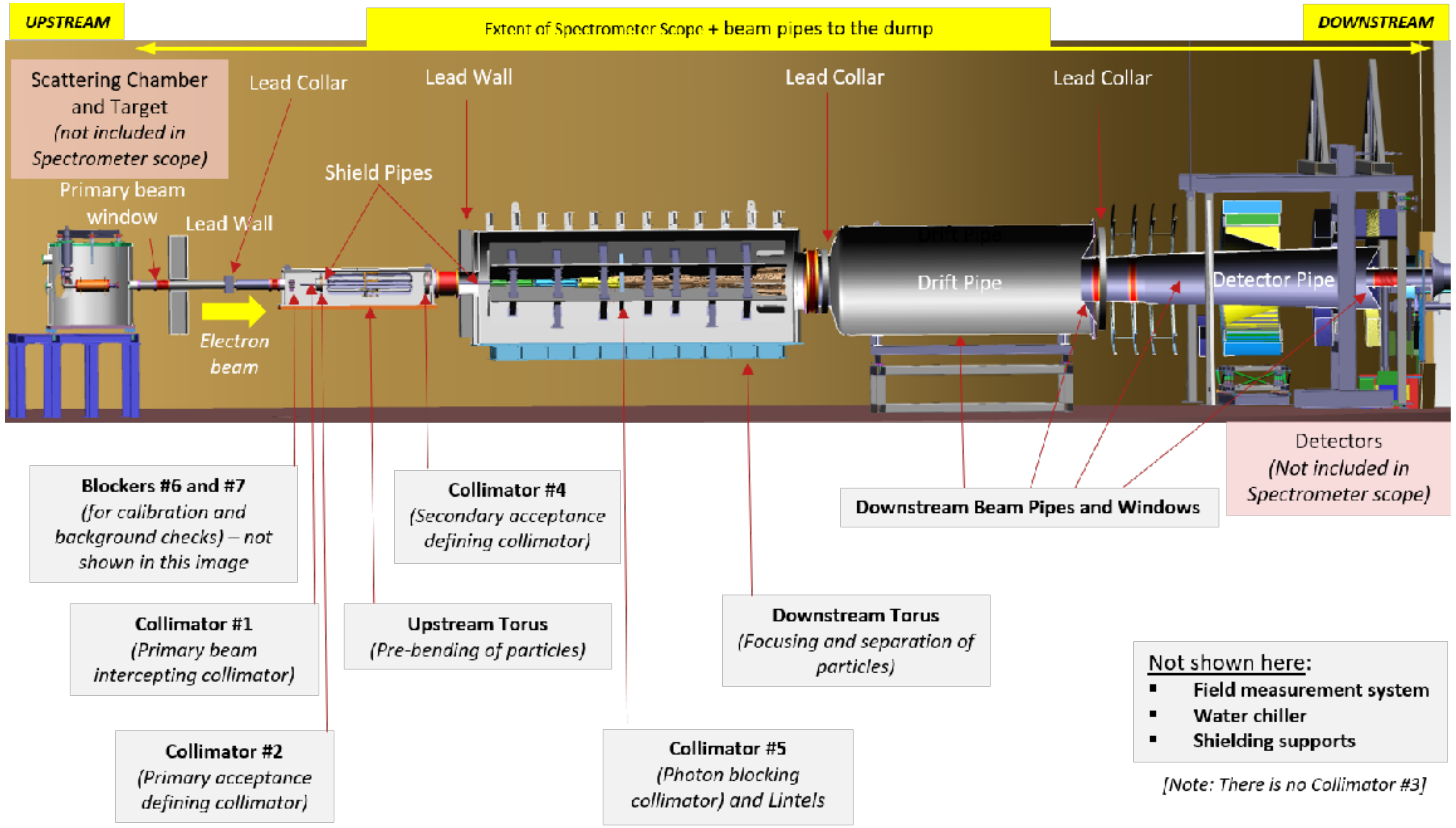
Downstream "hybrid" toroid – multiple current return paths

WBS 1.03 Spectrometer

Spectrometer – Subsystem Overview and Requirements

Subsystem consists of:

- Two resistive, water-cooled magnets
- Water-cooled tungsten and copper collimators
- Magnet strongbacks, supports, and enclosures
- Magnet power supplies
- Beampipes and windows
- Closed loop water cooling system
- Field measurement system



Requirements developed for fabrication and assembly tolerances, coil currents and stability, movement during operation, keep-out information, and radiation dose limits.

Example for coil and support envelopes shown.

#	Physics Requirement	Allowed Values	
		downstream	upstream
1	Envelope for an individual coil, strongback and supports, relative to the beam centerline and nominal center lines of coils	$z = \pm$ 25mm r = +3mm / -1 mm ϕ = 3 mm outer radius, 1 mm inner radius	

WBS Element	KPP	Threshold Criteria	Objective Criteria
1.03 Spectrometer	Upstream and downstream magnetic spectrometers installed in Hall A and shown to be operable.	Demonstrate post-installation operation at ≥88% of design operating current[1] and magnetic field strength stability <100 ppm over 24 hours.	Demonstrate post-installation operation at design operating current, allowing for operation at ≥10% over-current above the nominal operating current

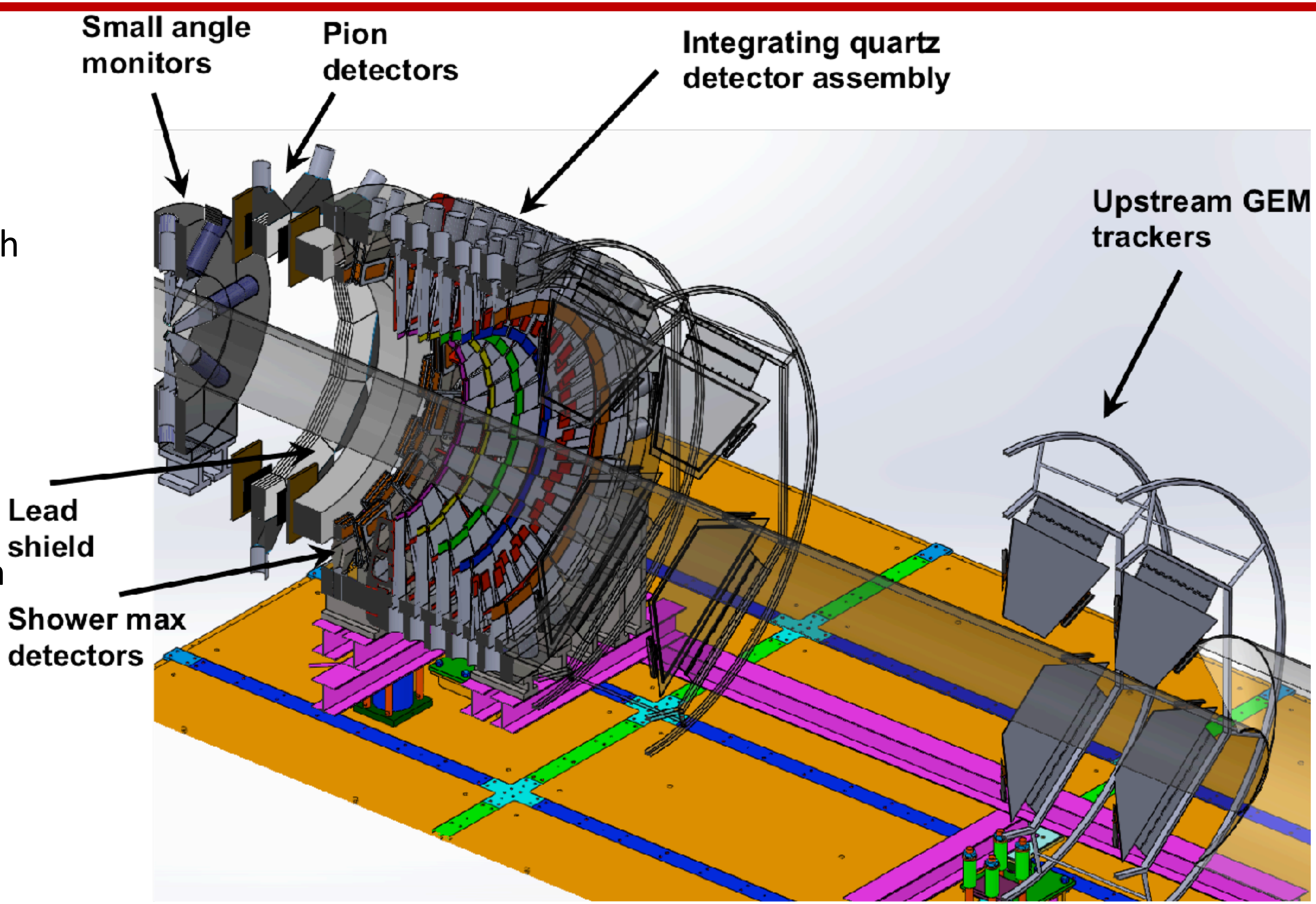
Detectors Overview

- **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



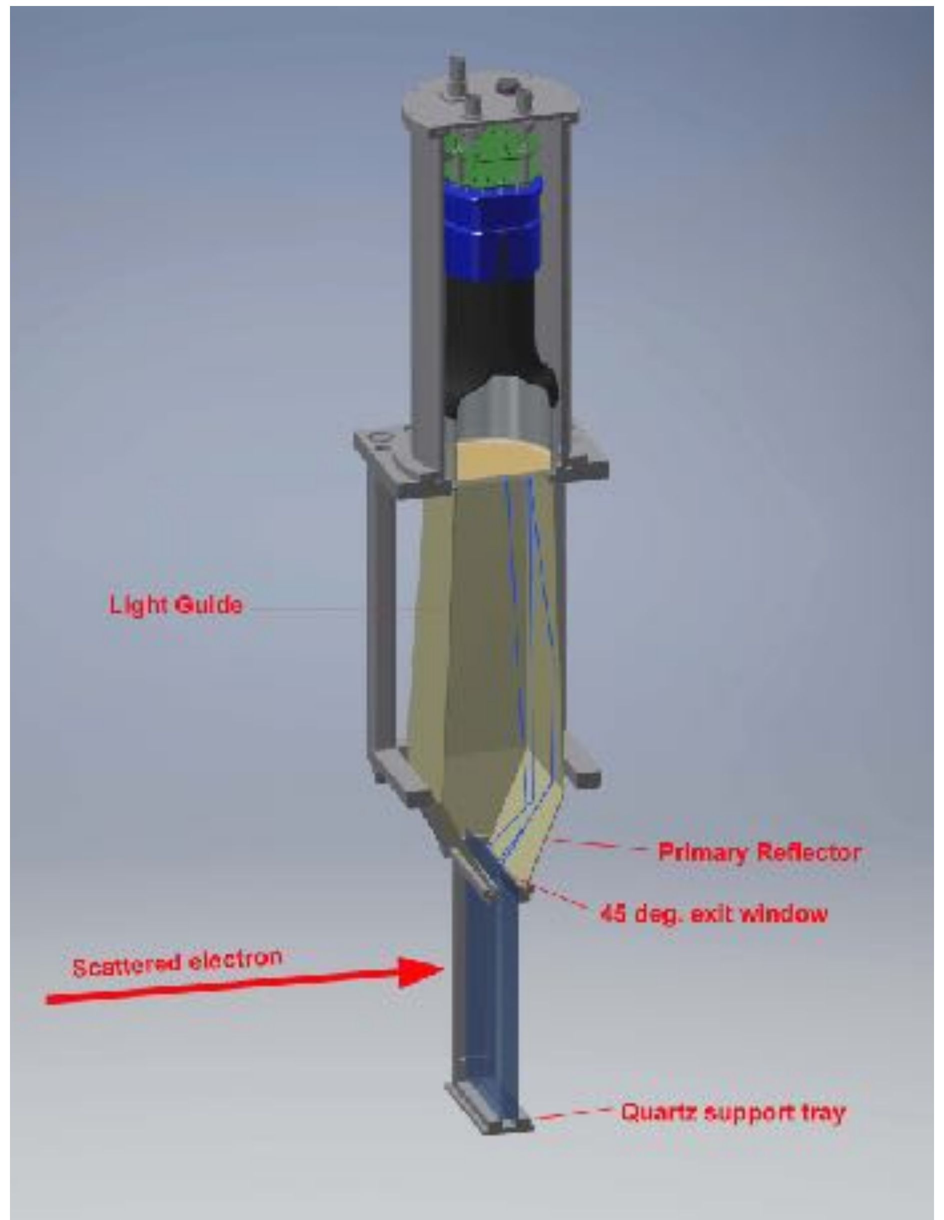
Basic Detector Element – Quartz Cherenkov Detector

Basic **integrating quartz detector** element has 3 parts:

- Active detection volume: artificial fused silica ("quartz")
- Light guide: air-core light guide with walls of highly reflective material
- Quartz window photomultiplier tube

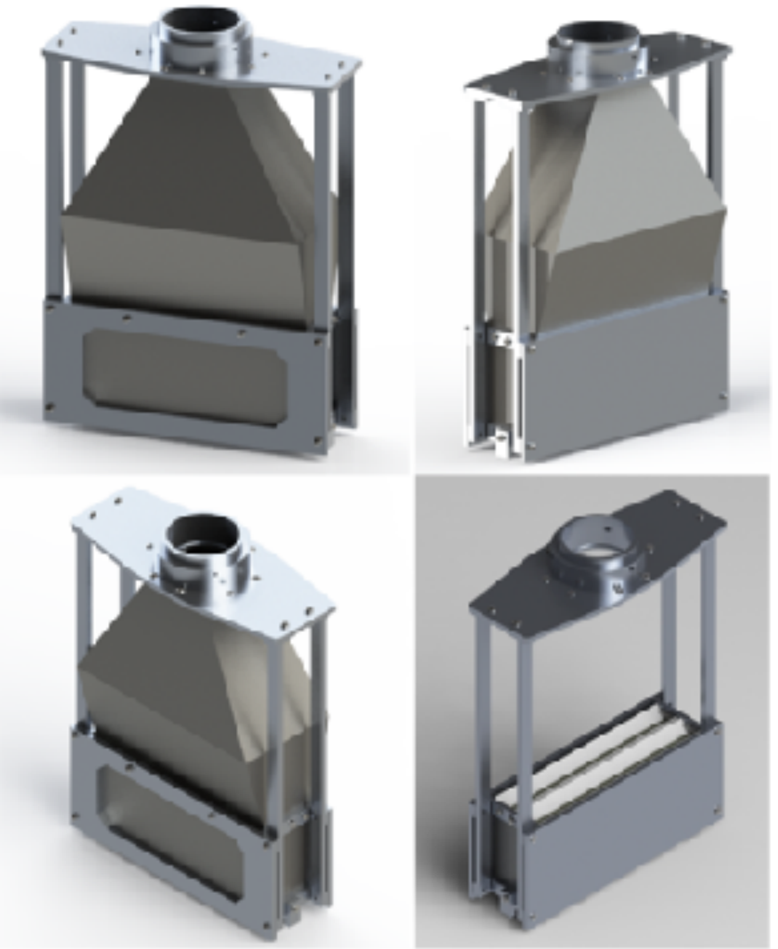
Motivations:

- Quartz: radiation hard, negligible scintillation response, reduced sensitivity to neutral backgrounds
- Air-core light guides: reduced events from light guide hits



Shower-max detector:

- Quartz/tungsten stack
- Less sensitive to soft photon and charged hadron backgrounds



Key requirement:

Detector resolution < 25%

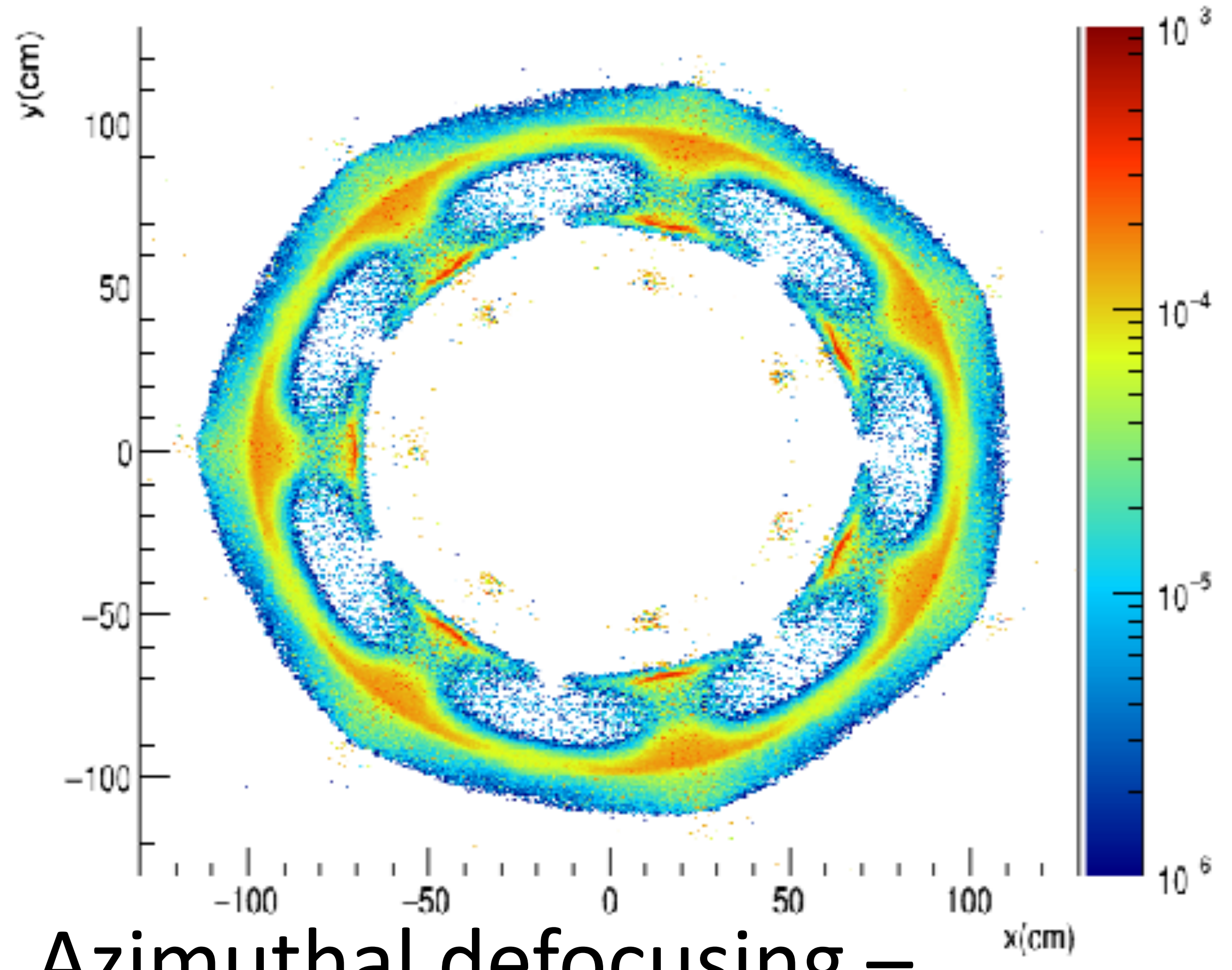
for detector excess noise < 4%

Flux integration technique implemented with precision custom integrating electronics

WBS 1.04 Integrating Detectors

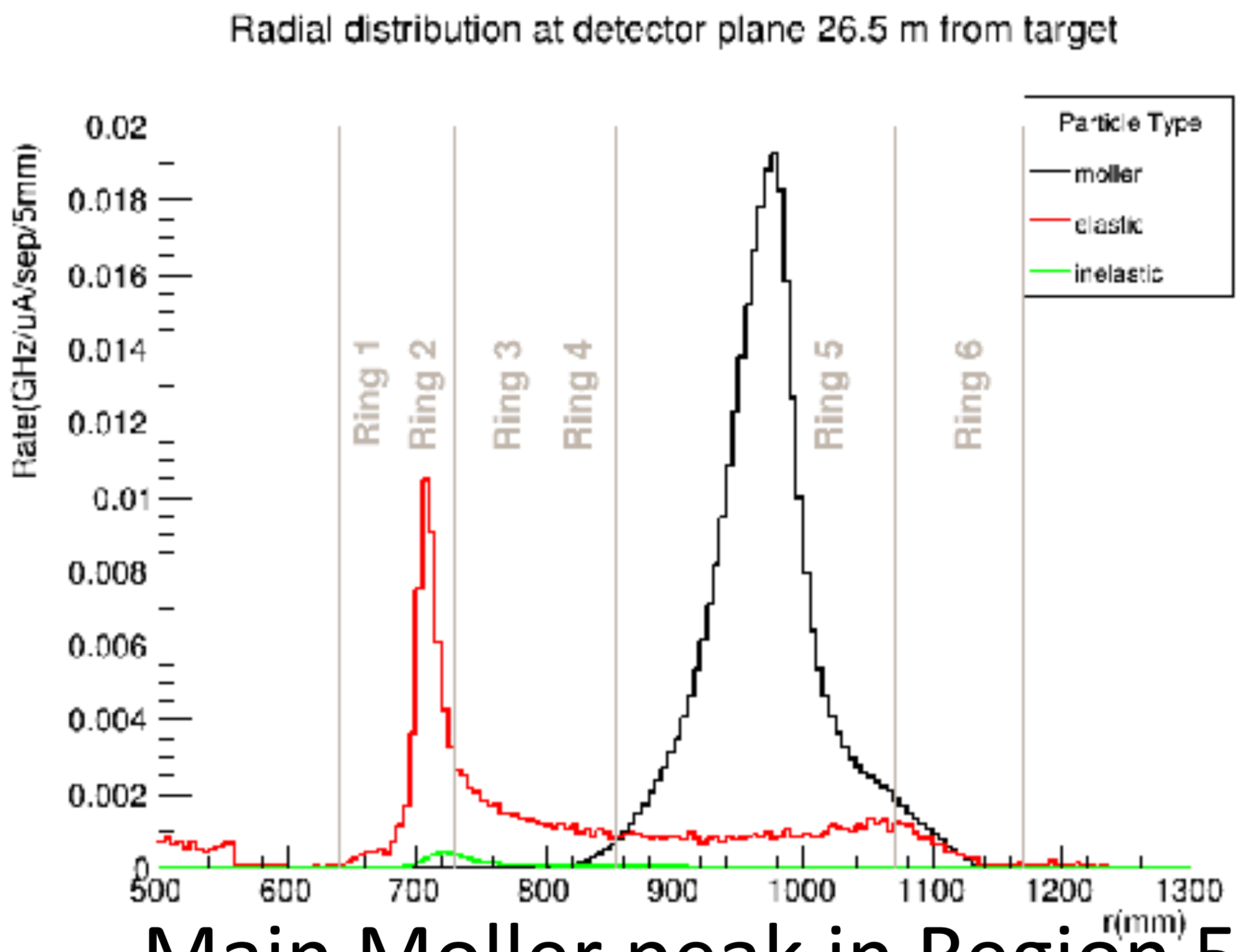
Detector Plane Segmentation

Quartz Cherenkov detectors will have radial and azimuthal segmentation

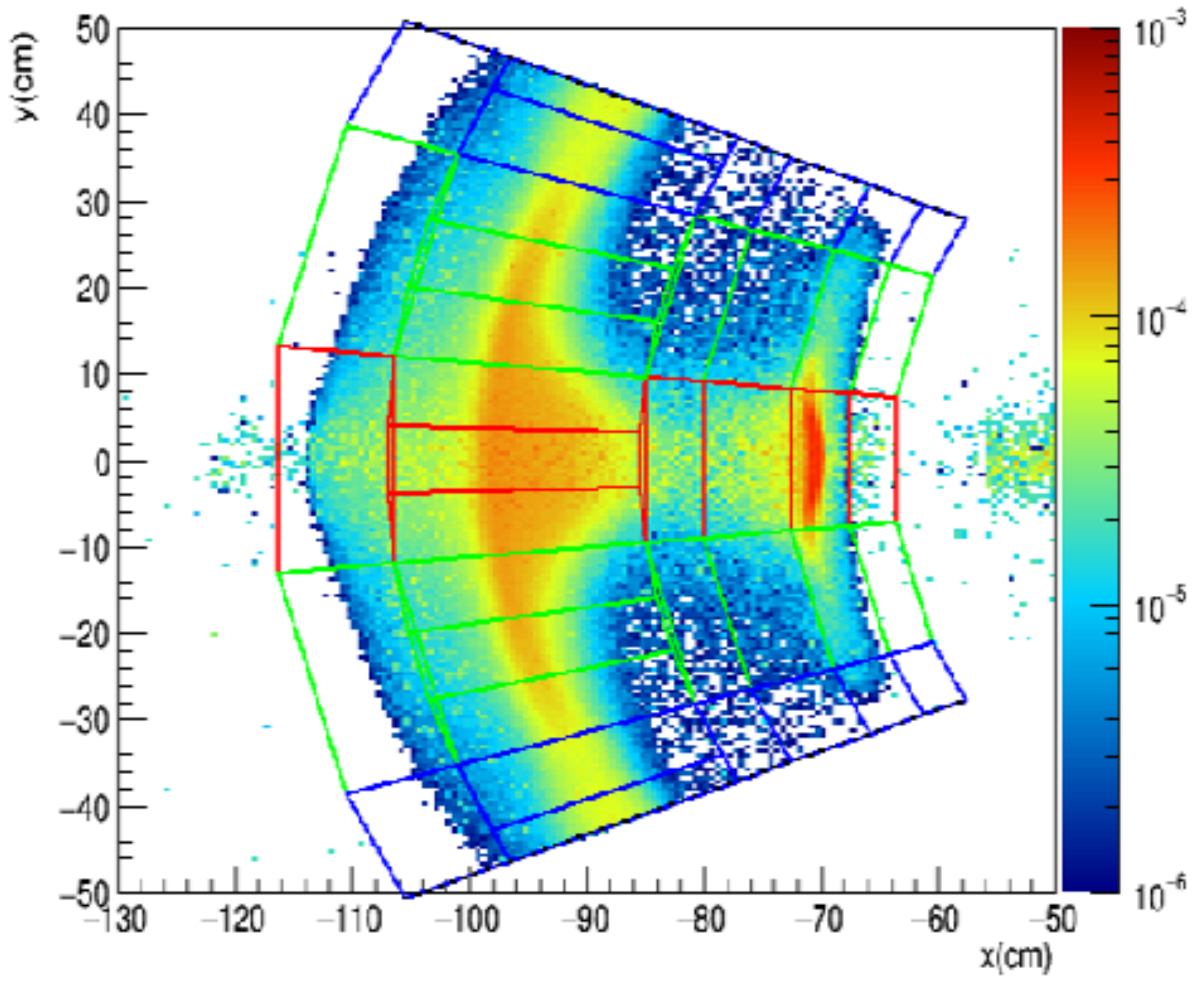


Azimuthal defocusing –

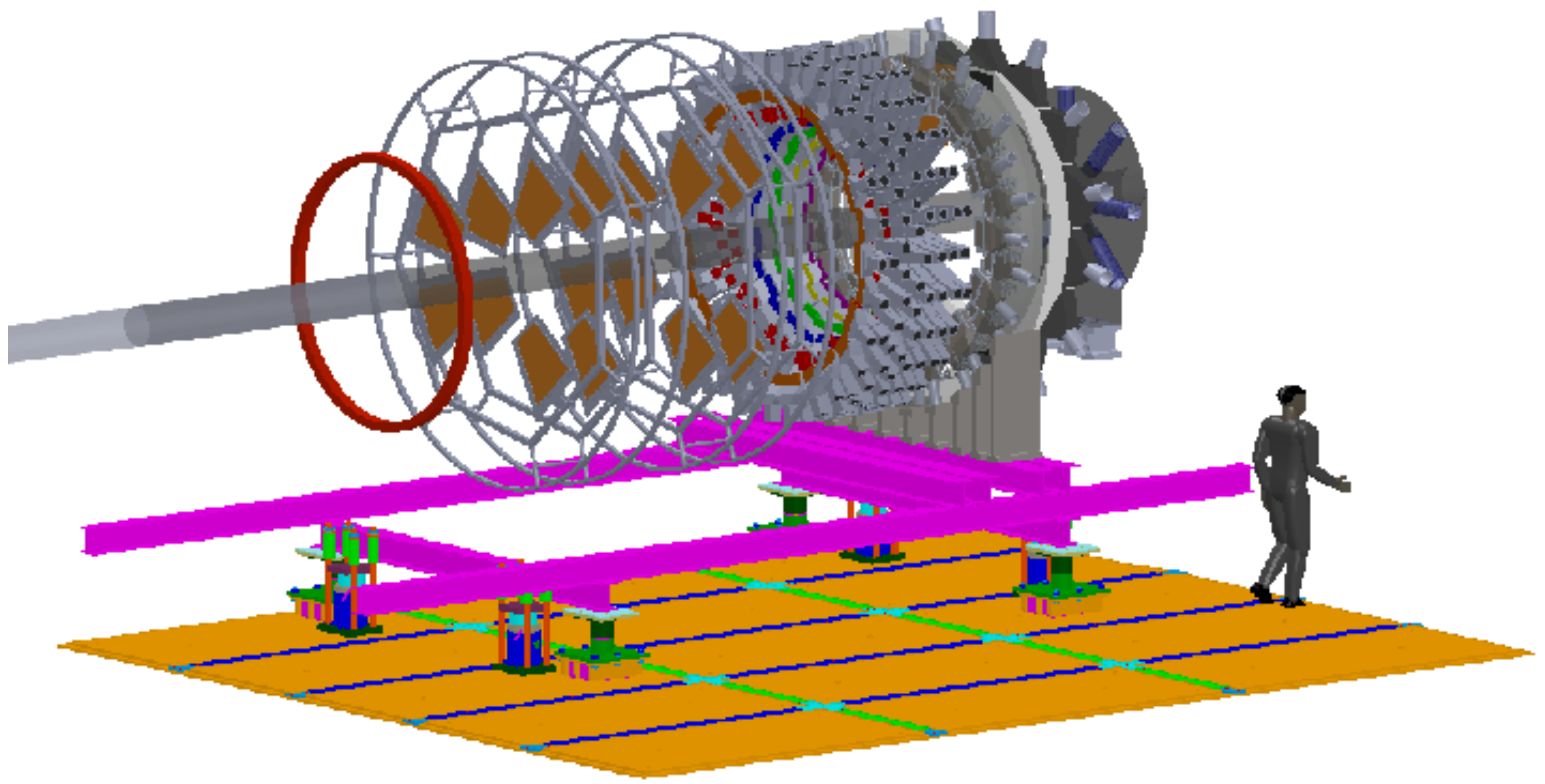
Different φ, different θ_{CM} bins



Main Moller peak in Region 5



Proposed Segmentation



28 azimuthal channels per radial bin

Moller peak (region 5): 84 azimuthal channels per radial bin

224 total channels

Rate per channel ~ few MHz – GHz

(overall rate ~ 148 GHz)

Segmentation needed for proper evaluation of background contributions

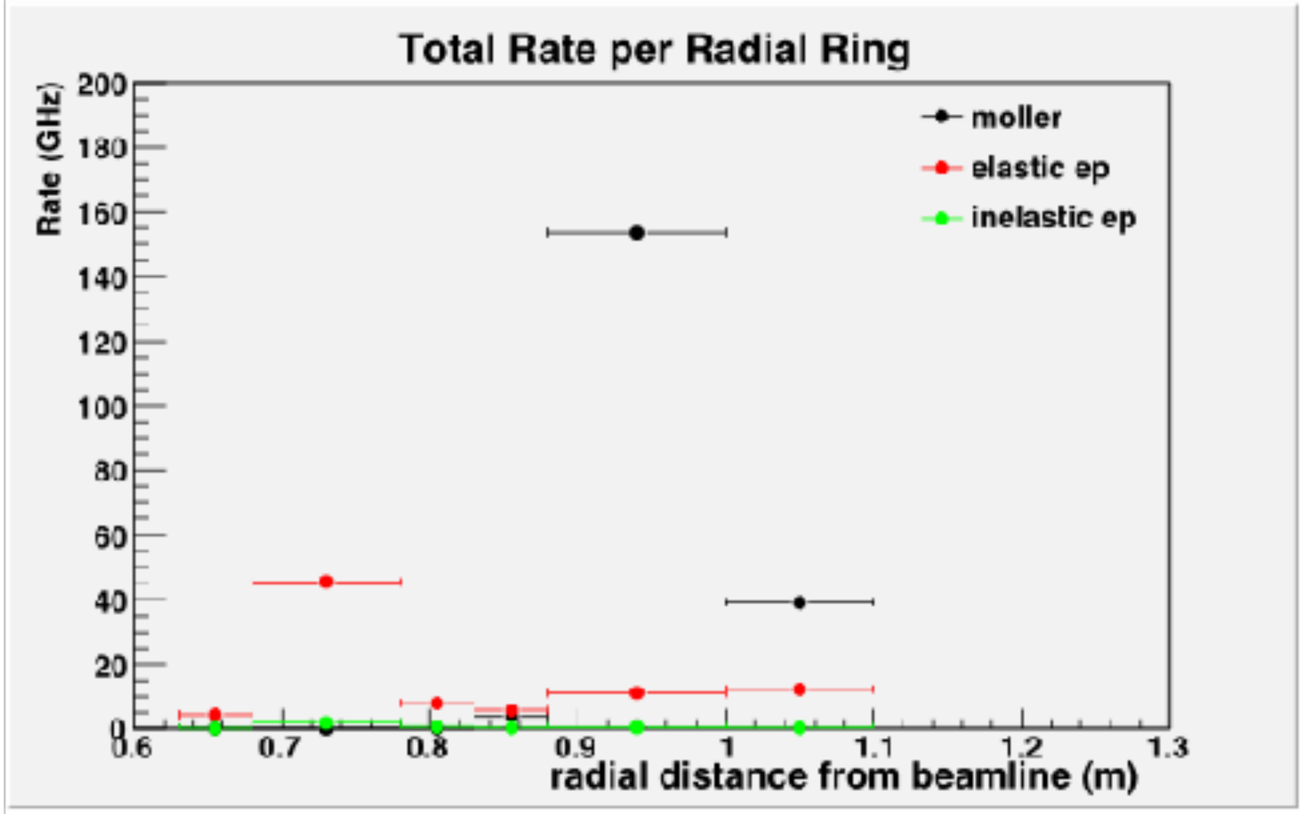
WBS Element	KPP
1.04 Integrating Detectors	Installation and successful operation of 224 thin quartz and 28 Shower Max detector modules with light guides, PMTs and front-end electronics.

Threshold Criteria	Objective Criteria
Measured response of >70% (>30%) of the Ring-5 (other rings) channels is ≥ 20 (≥10) photo-electrons for β = 1 particles	Threshold plus measured response of all (>80%) Ring-5 (other rings) channels is ≥ 25 (≥15) photo-electrons for β = 1 particles

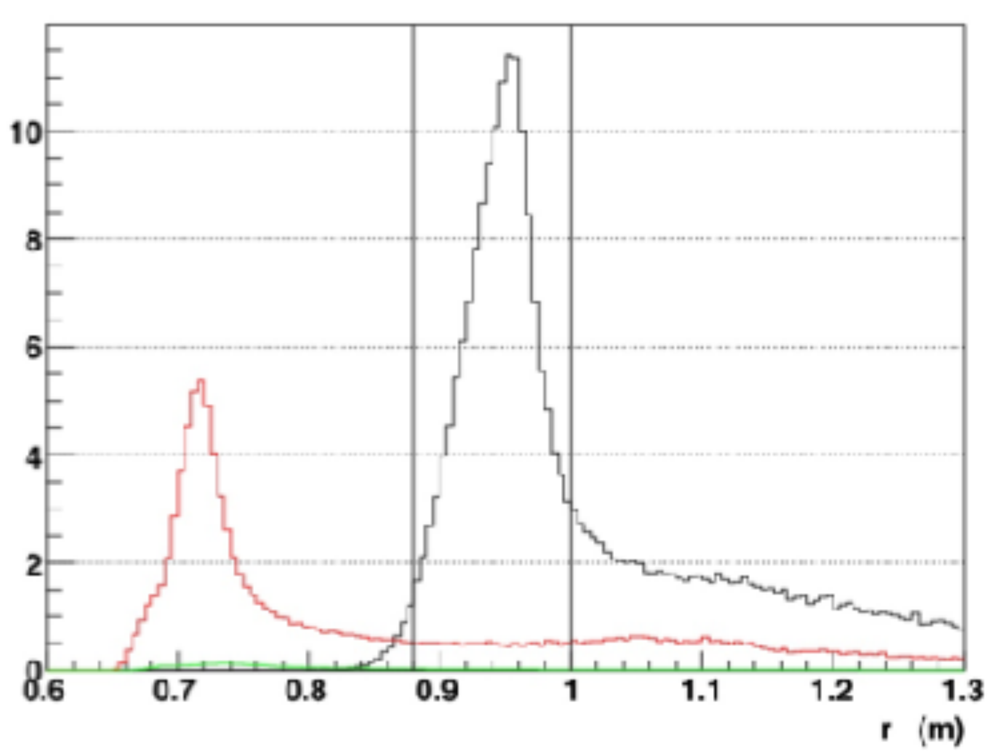
Event Mode Tracking Detectors

Event mode tracking will be done at low (few nA) beam current for:

- weighted kinematic factor in asymmetry $A \equiv \frac{mG_F}{\sqrt{2}\pi\alpha}\frac{4E\sin^2\theta}{(3+\cos^2\theta)^2}$.
- verification of spectrometer optics
- background determination



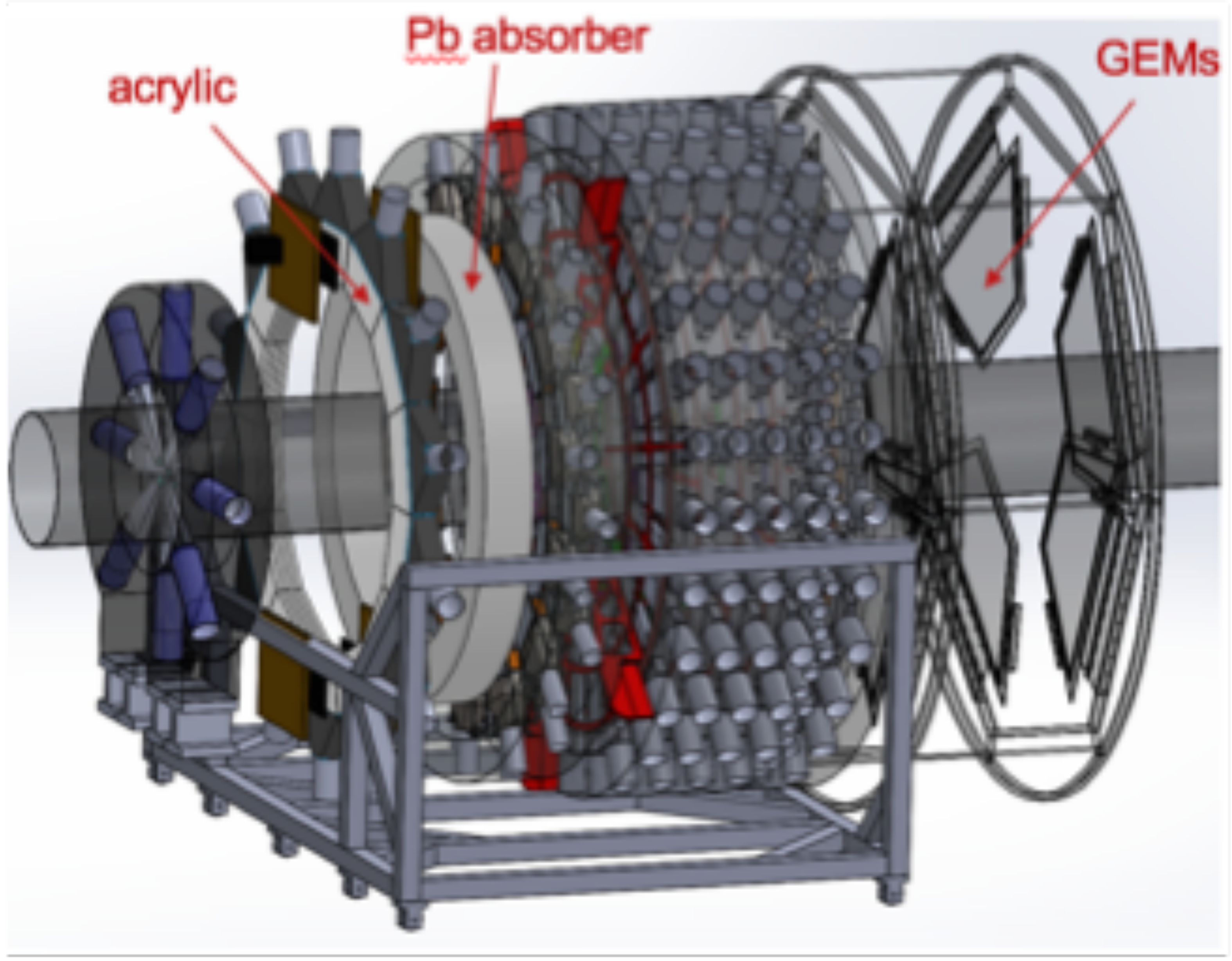
What the main detectors "see"
(assuming perfect gain matching)



What a tracking system would see

Subsystem consists of:

- Gas electron multiplier (GEM) detectors
- Trigger scintillators
- Rotating support wheels for GEMs and trigger scintillators
- Pion detectors (acrylic Cherenkov detectors)



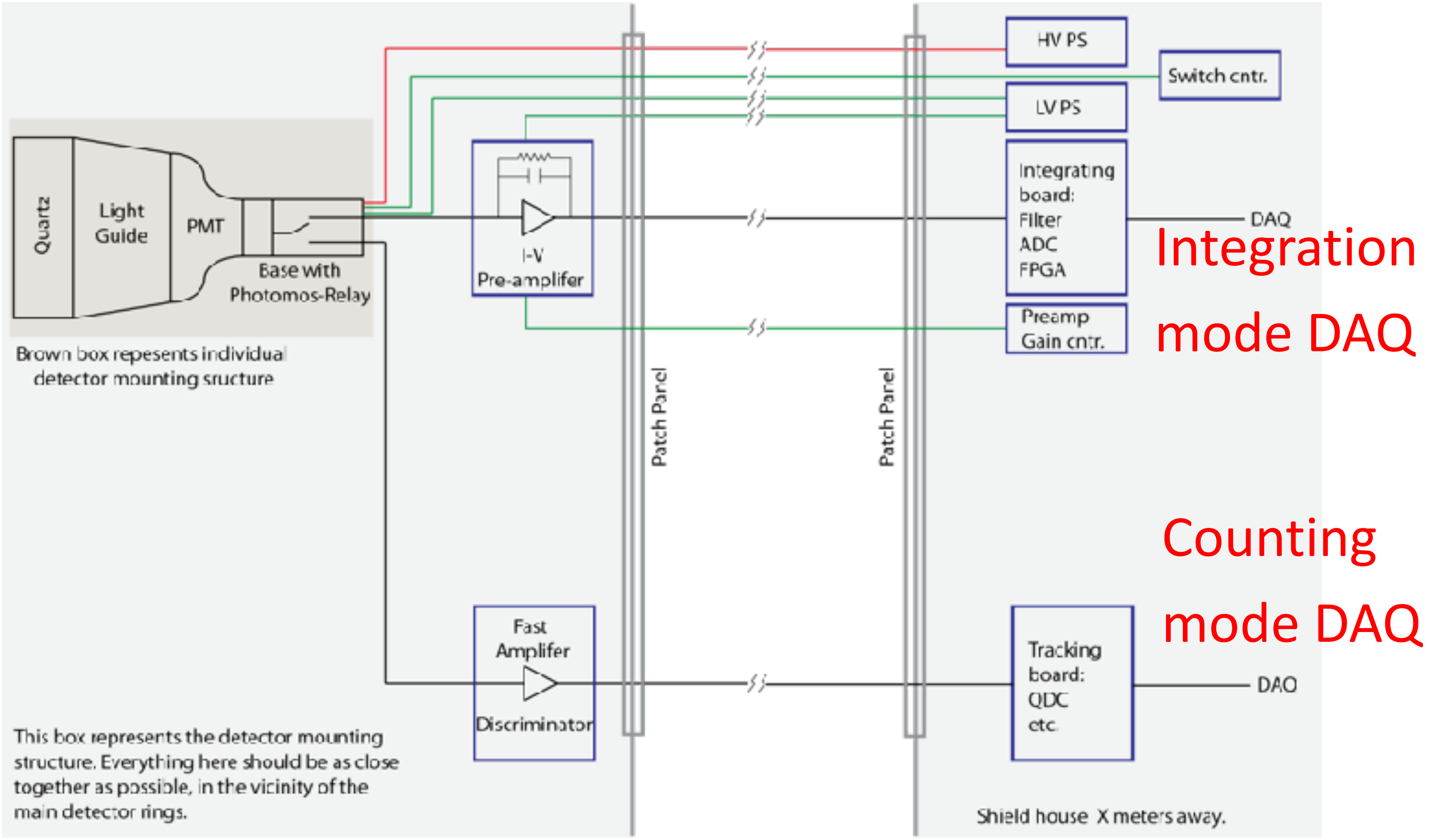
WBS Element	KPP
1.05 Tracking Detectors	Installation and successful operation of 16 gaseous electron multiplier (GEM) tracking detectors.

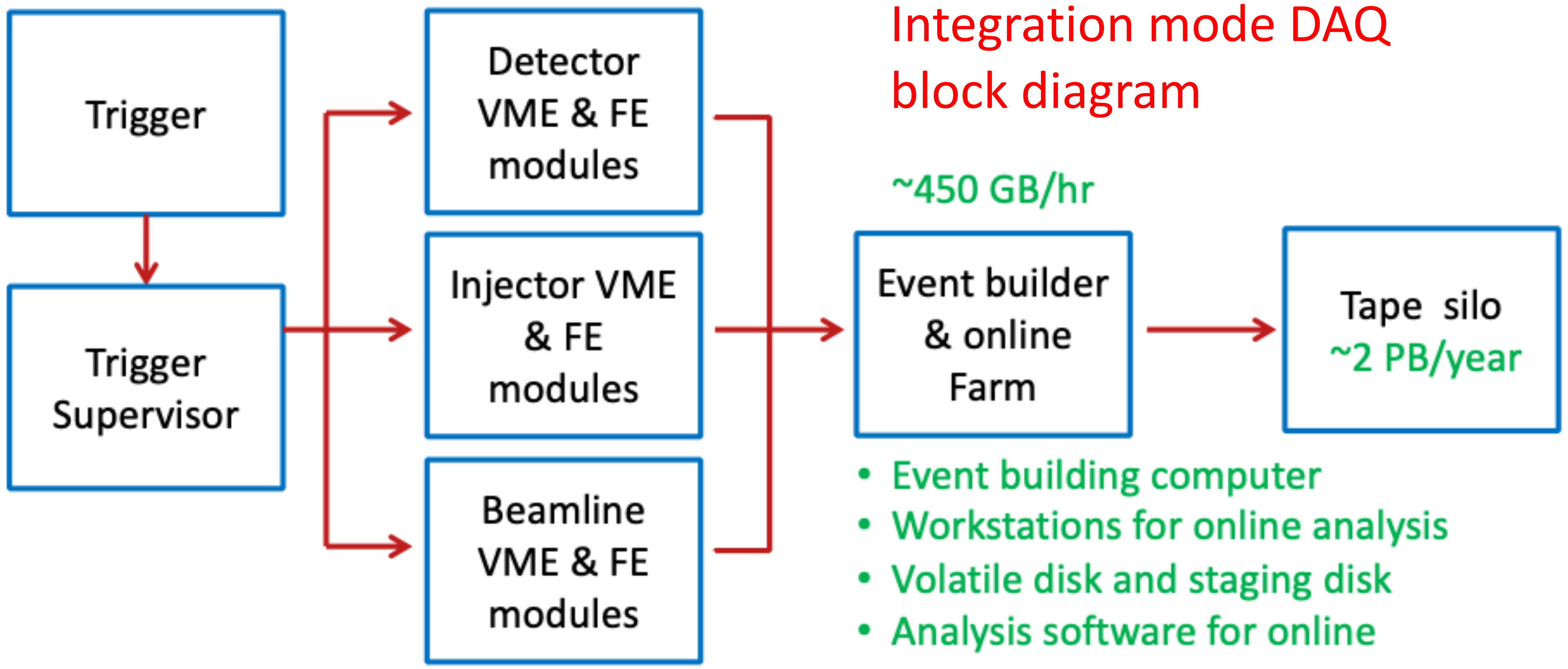
Threshold Criteria	Objective Criteria
All modules installed and operating with single-plane hit efficiency > 90% for >75% of GEM modules	Threshold plus single-plane hit efficiency >90% for all GEM modules. Single-plane track position residual width s <1mm

Jefferson Lab

Data Acquisition and Trigger

One of the inputs to DAQ: Schematic layout of integrating detector channel, including both integrating and tracking mode electronic chains.





- Integration mode DAQ & trigger
  - Collect and transfer 100% of the helicity windows, without deadtime
  - Allow adjustment of gate timing for each integrator
- Counting mode DAQ & trigger
  - Support trigger decisions based on input rates between 10~kHz and 300~kHz
  - Flexible definitional of triggers using the trigger scintillators, the quartz detectors, or pulser

WBS Element	KPP	Threshold Criteria	Objective Criteria
1.07 Data Acquisition and Trigger	A DAQ and trigger system for readout of detector systems in both counting (low rate) and integrating (high rate) modes installed and stress-tested successfully.	Demonstrate integrating mode readout rate of ≥0.96 kHz (pulser test).	Demonstrate integrating mode readout rate of 1.92 kHz (pulser test).
		Stress-test data transfer rate to Mass-Storage System with ≥500 Mbit/sec pulser test	Stress-test data transfer rate to Mass-Storage System with ≥1 Gbit/sec pulser test

Jefferson Lab

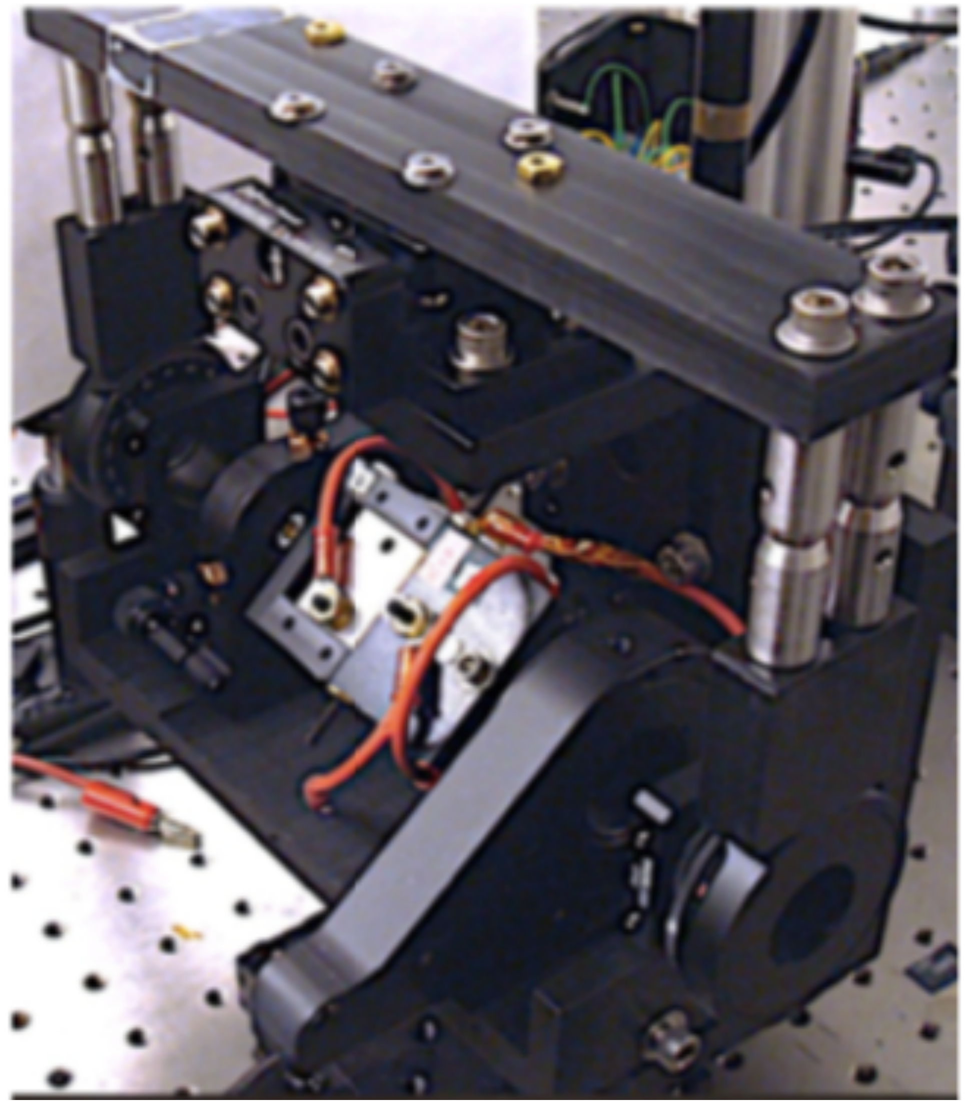
Polarized Source/Beam, Beam Monitoring, Beam Polarimetry

Polarized source/beam

- up to 70 µA at ~90% polarization
- Random and helicity-correlated beam fluctuation requirements

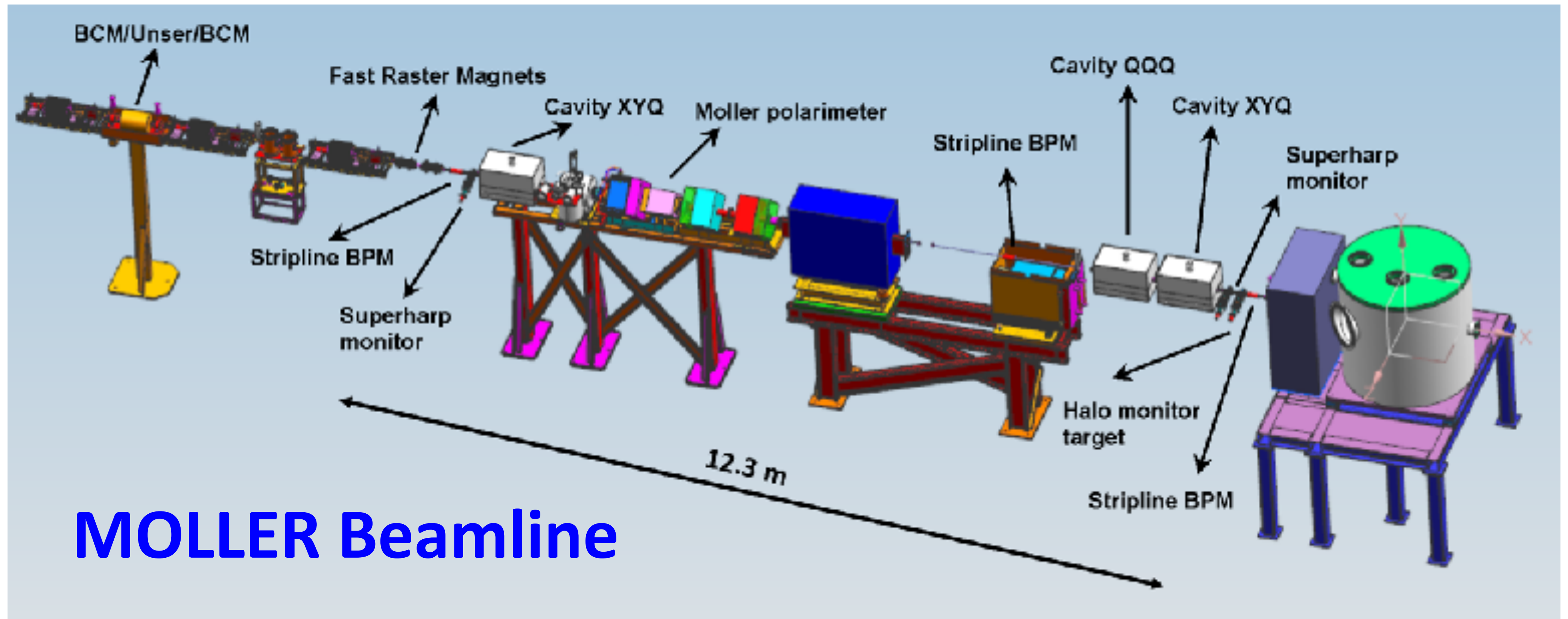
$$\left(A_{cxpt}\right)_i = \left(\frac{\Delta F}{2F} - \frac{\Delta I}{2I}\right)_i - \sum_j \left(\alpha_j \left(\Delta X_j\right)_i\right)$$

RTP Pockels Cell



Beamline and Beam Monitoring

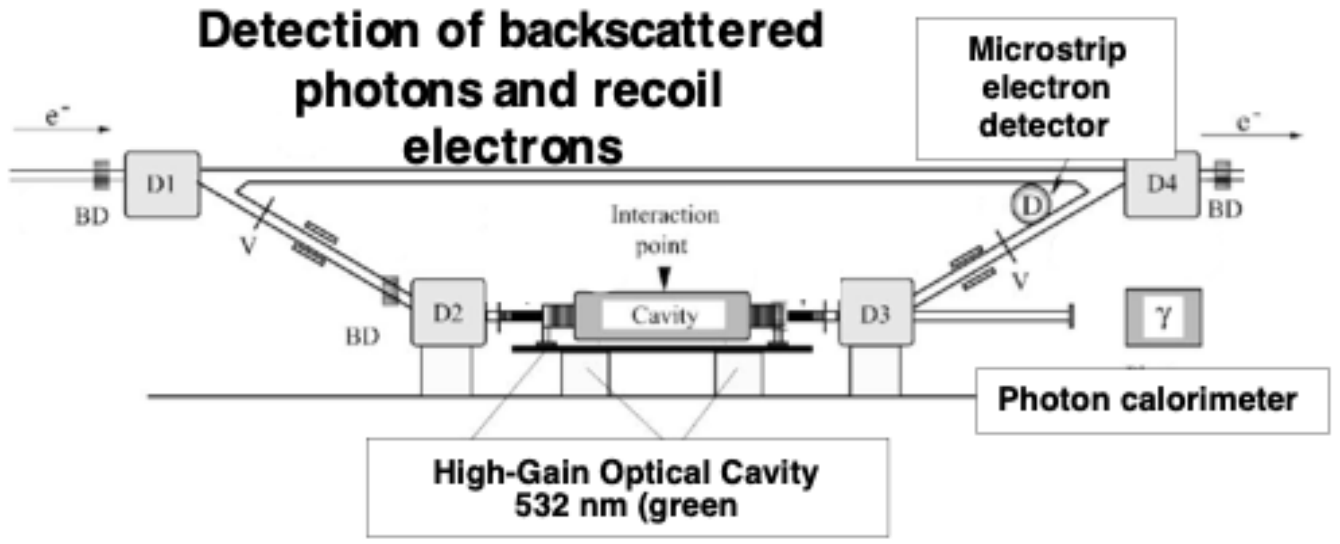
- Redundant position, angle, intensity monitoring
- Intensity, position monitor resolution requirements



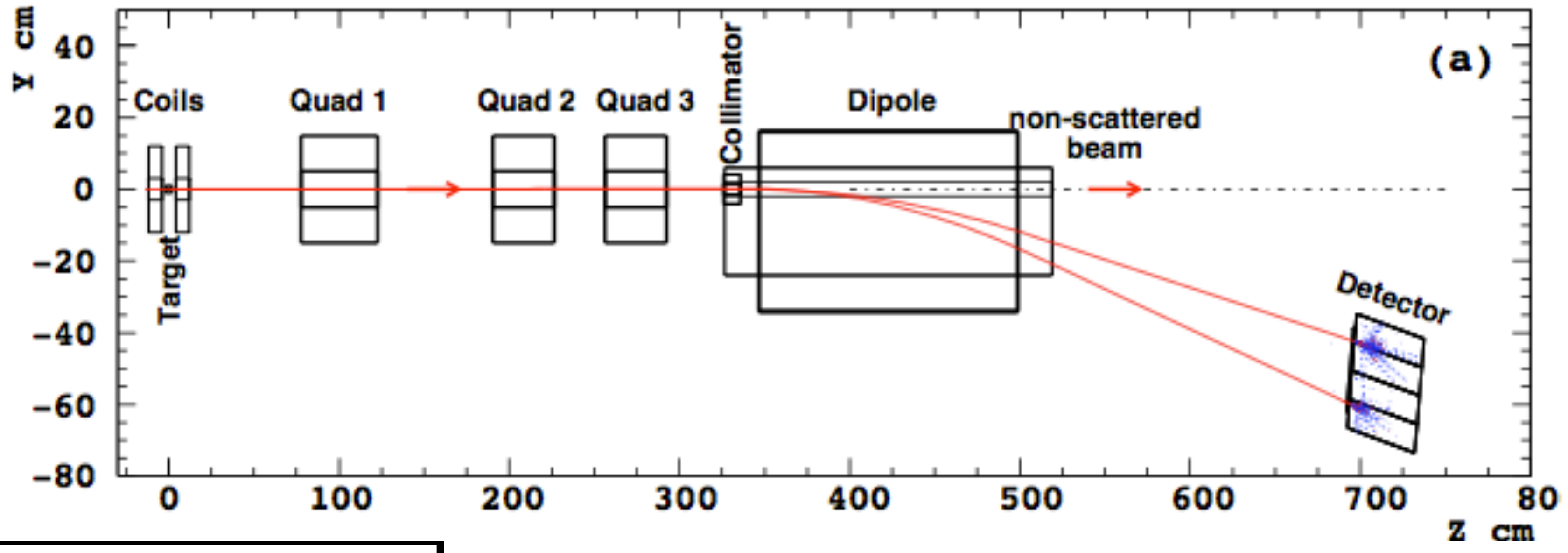
Electron Beam Polarimetry

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

Compton

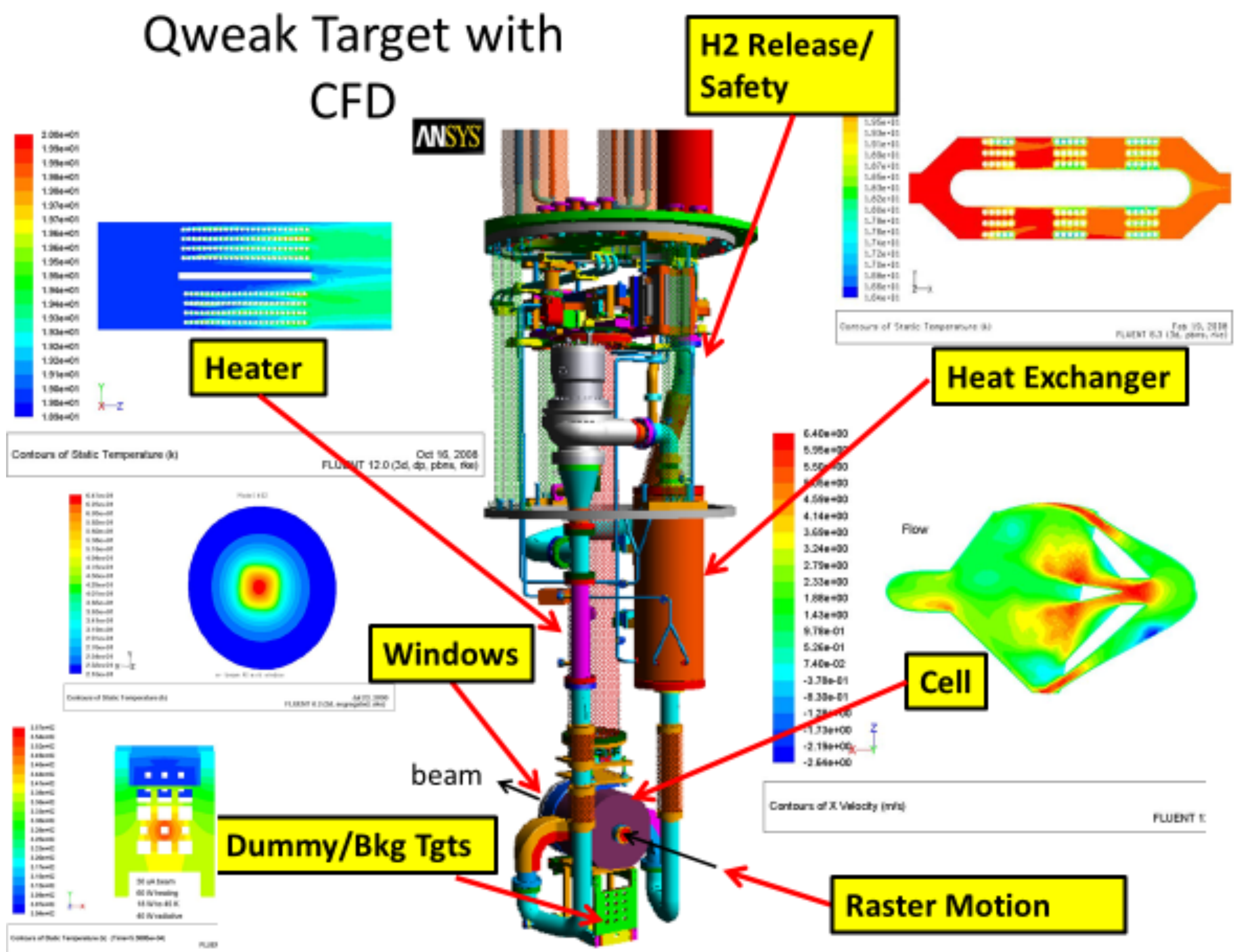


Møller

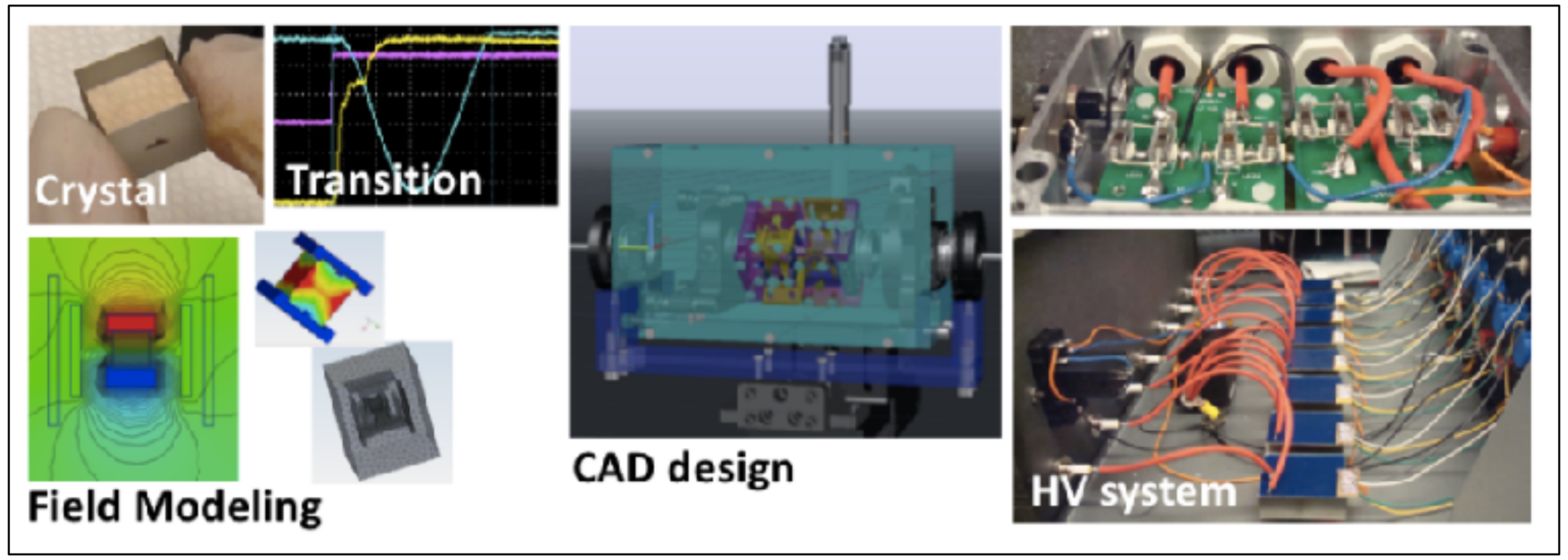


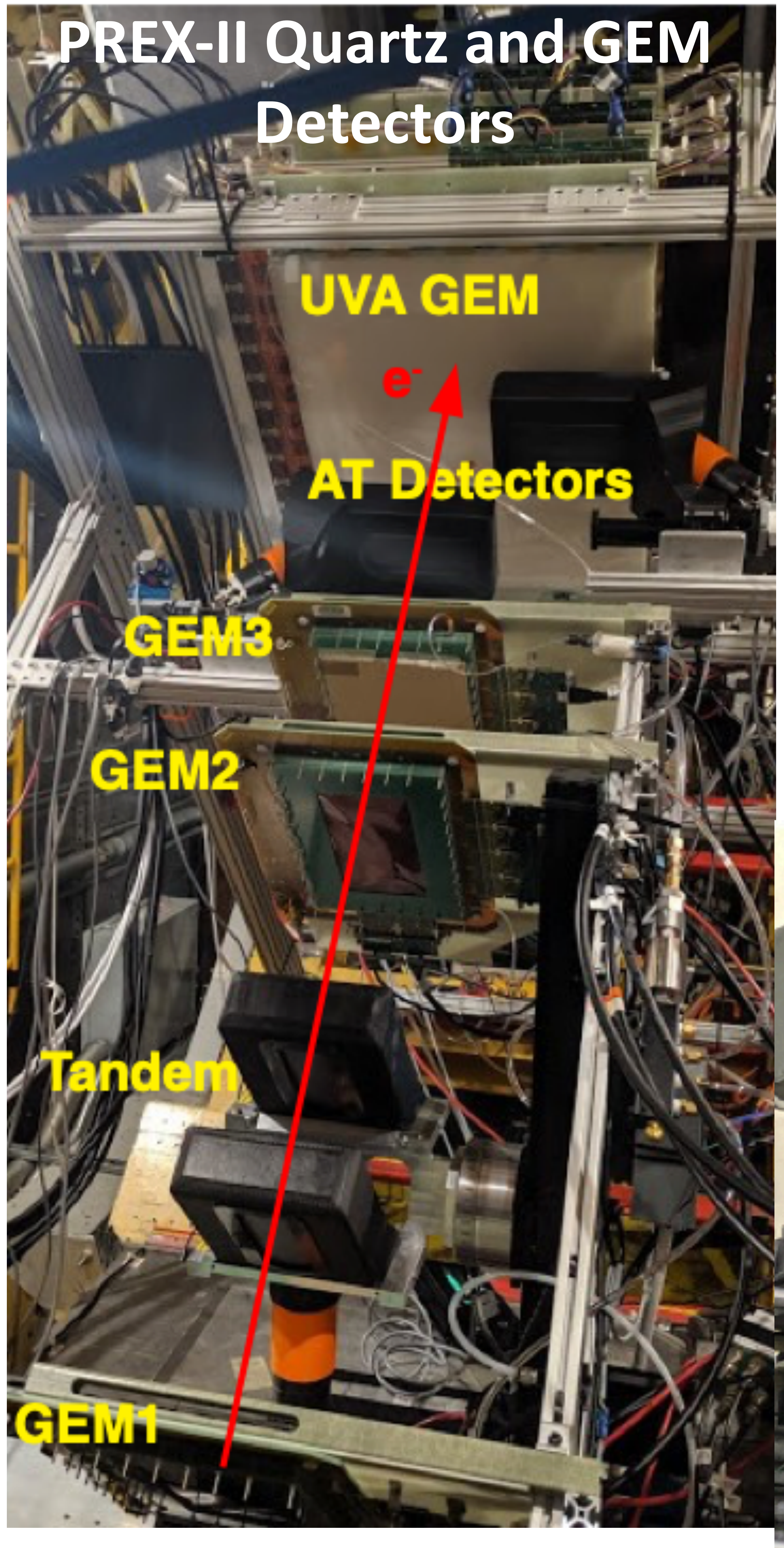
Project Dependencies, WBS 1.04 Tracking Detectors, WBS 1.06 Infrastructure

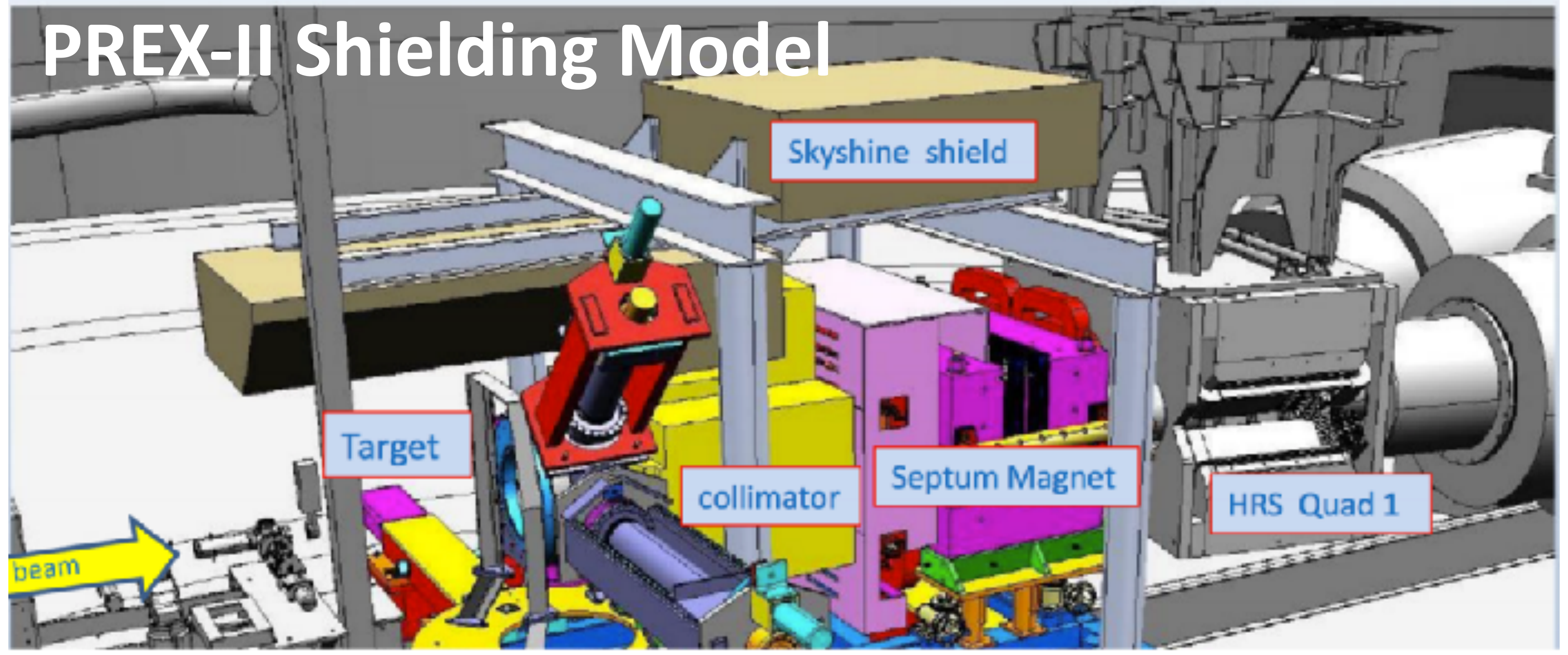
Relevant Technical and Operational Experience from 3rd Generation Experiments



RTP Pockels Cell: Improved control of beam fluctuations

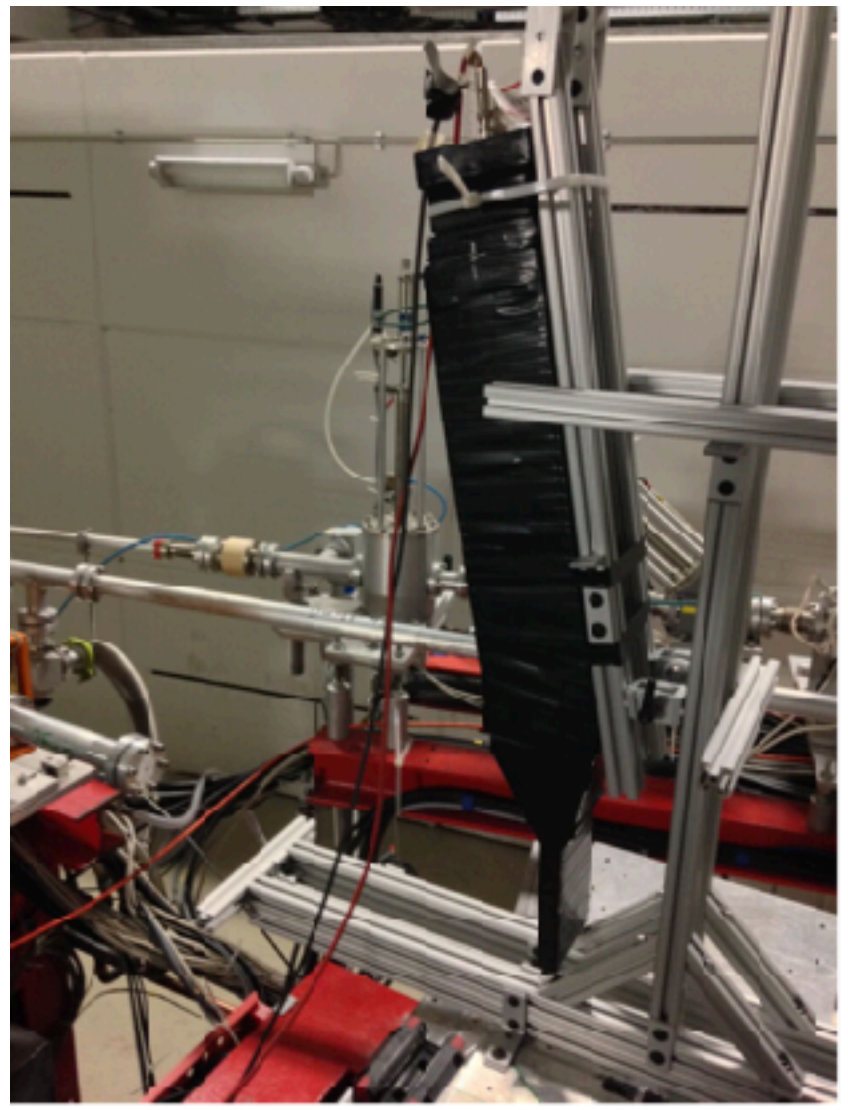


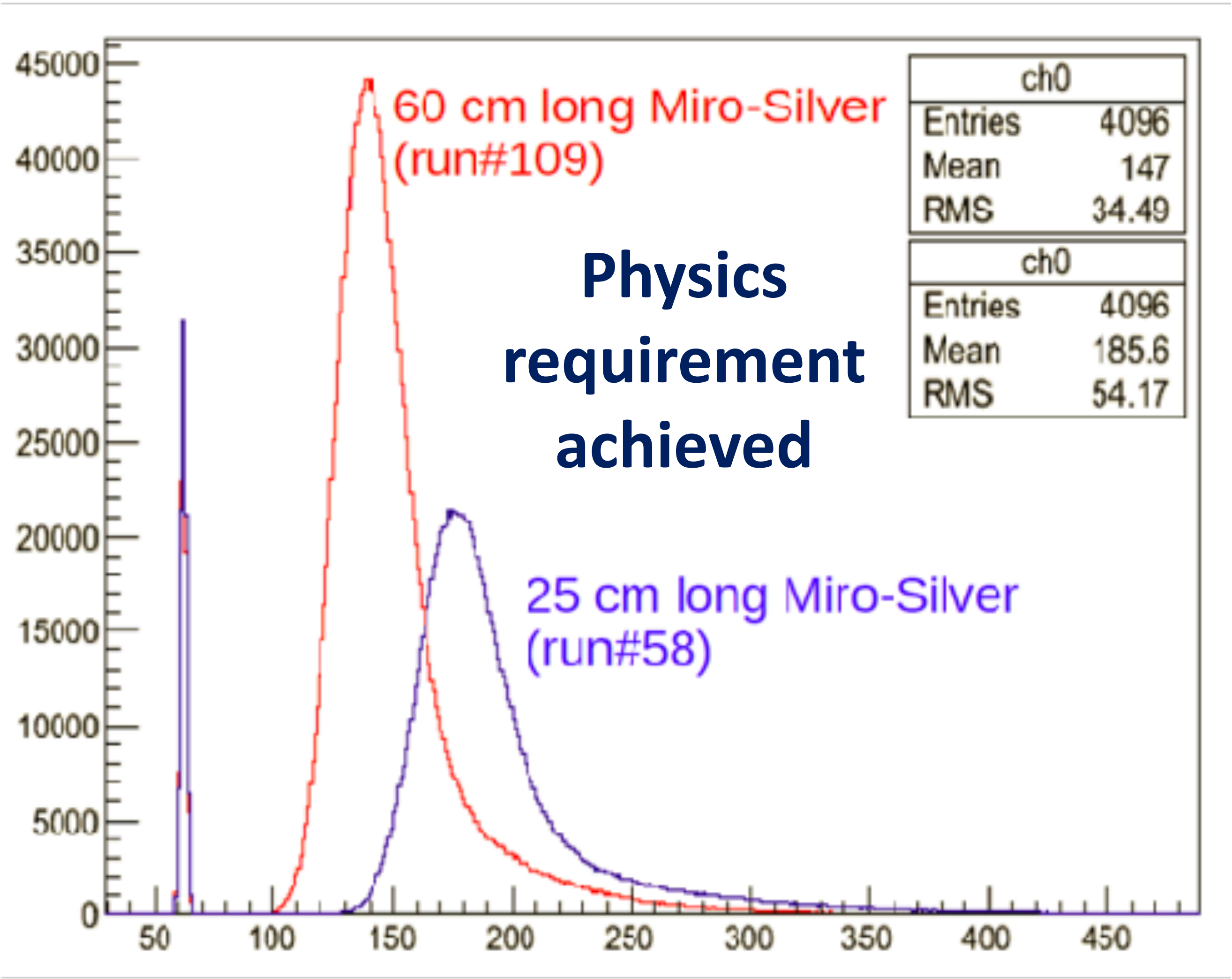


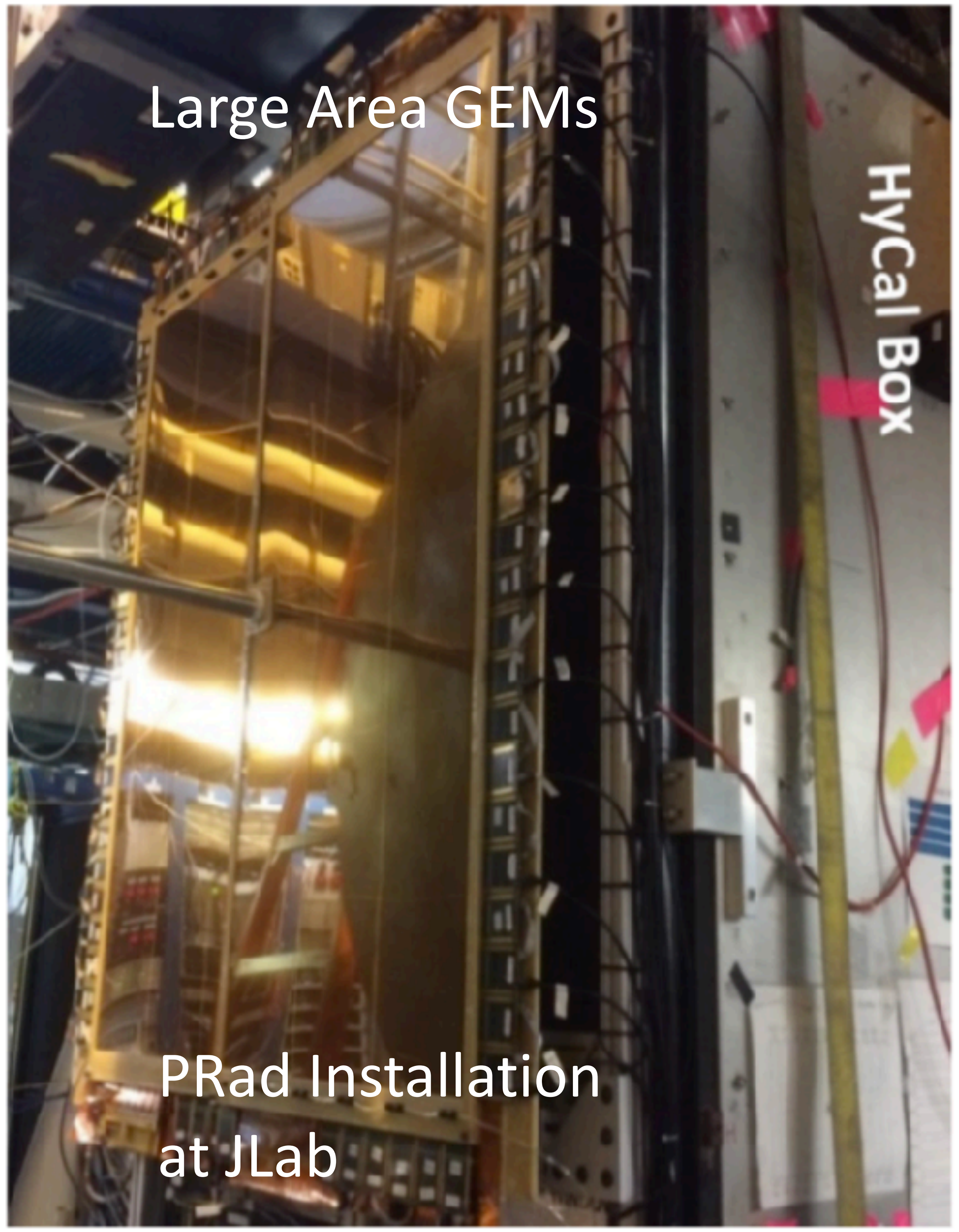


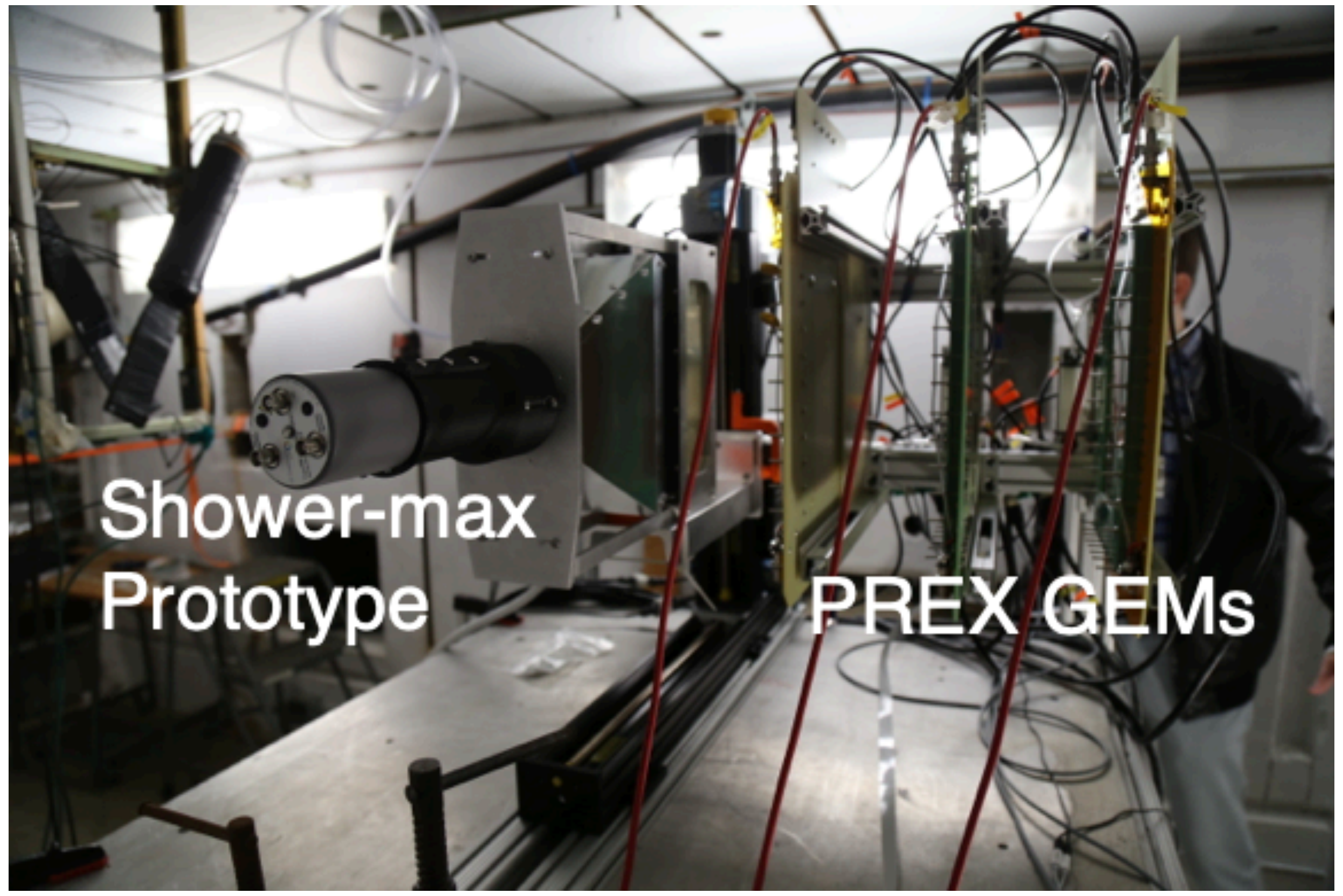
Radiation Shielding: Close collaboration between collaboration physicists, engineers and Radiation Safety

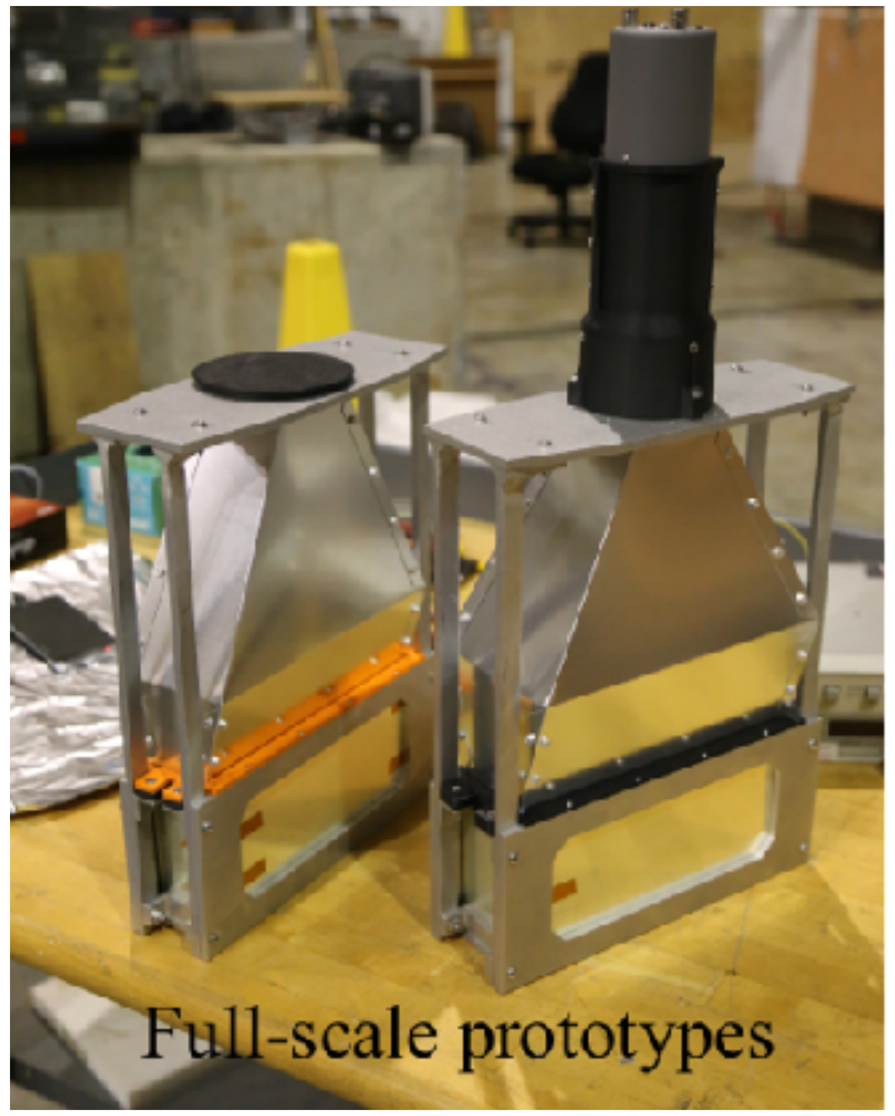
Significant Prototyping and Validation from R&D Efforts











Backups - Institutional Commitments

Institutional commitments to MOLLER from organizations external to Jefferson Lab:

- **GEM detectors, trigger scintillators, rotator**: Virginia, William and Mary, Louisiana Tech
- **Pion detectors:** William and Mary, Louisiana Tech, Manitoba
- **Prototype testing:** Mainz, Manitoba, UMass Amherst, Stony Brook, Idaho State
- **Main detectors/shower-max detectors/ detector mechanics**: Manitoba, UMass Amherst, Syracuse, Idaho State
- **Polarized beam:** Virginia
- **Moller polarimetery:** Temple, Syracuse, Stony Brook, Virginia
- **Compton:** Virginia, Carnegie Mellon, Manitoba, Mississippi State
- **DAQ:** Ohio, Manitoba, TRIUMF, UC Berkeley/LBNL
- **Integrating mode electronics:** Manitoba, TRIUMF
- **Simulations:** Louisiana Tech, UMass Amherst, Stony Brook, Virginia, William and Mary, Manitoba, Idaho State, Temple
- **Data Handling/Analysis:** Ohio, Manitoba, Virginia, UMass Amherst, Syracuse, UC Berkeley/LBNL
- **Scanner detectors:** Virginia Tech
- **Beam Monitoring Instrumentation:** Virginia Tech, UC Berkeley/LBNL, Virginia
- **Scattered Beam Monitors:** Virginia Tech, Idaho State, UMass Amherst, Syracuse
- **Beam Modulation:** Syracuse, Virginia, Virginia Tech

Backups – MOLLER Collaboration Working Groups

MOLLER Collaboration Working Groups institutional membership:

- **Polarized Source :** Virginia, Jefferson Lab
- **Beam Instrumentation:** Virginia Tech, Virginia, UC Berkeley/LBNL, Syracuse, Jefferson Lab
- **Hydrogen Target:** Jefferson Lab, Mississippi State, Cal State LA
- **Spectrometer:** Jefferson Lab, Manitoba, MIT, UMass Amherst
- **Integrating Detectors:** Manitoba, Idaho State, UMass Amherst, Syracuse, Stony Brook
- **Tracking Detectors:** William and Mary, Virginia, Muskingum, Louisiana Tech
- **Hall Integration:** Jefferson Lab, Stony Brook, UMass Amherst, Syracuse, Idaho State
- **Polarimetry:** Virginia, Temple, Jefferson Lab, Carnegie Mellon, Manitoba, Syracuse, Stony Brook, Mississippi State
- **Electronics/DAQ/Offline:** Jefferson Lab, Ohio, Virginia, UC Berkeley/LBNL, Manitoba, Hendrix
- **Simulations:** Louisiana Tech, UMass Amherst, Stony Brook, Virginia, William and Mary, Manitoba, Idaho State
- **Physics Extraction:** UC Berkeley/LBNL, UNAM, UMass Amherst, Memorial U.