The Qweak and MOLLER Experiments at Jefferson Lab – Weak Charge of the Proton and Electron

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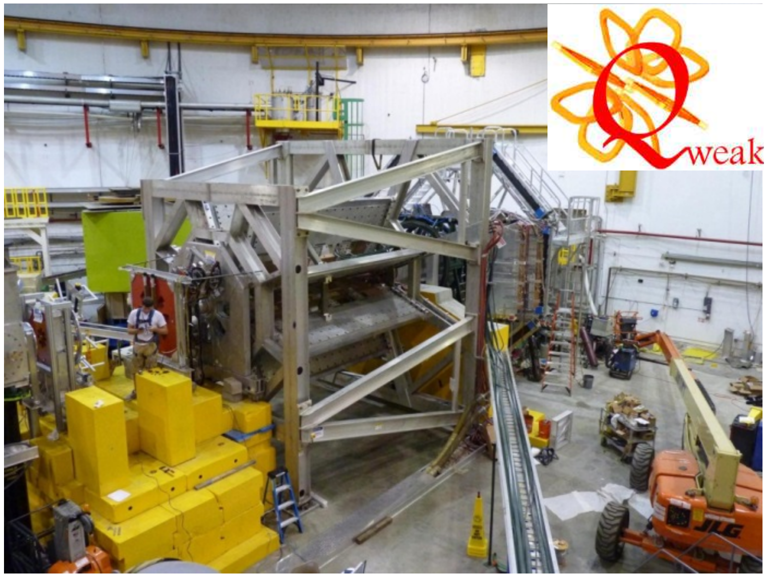
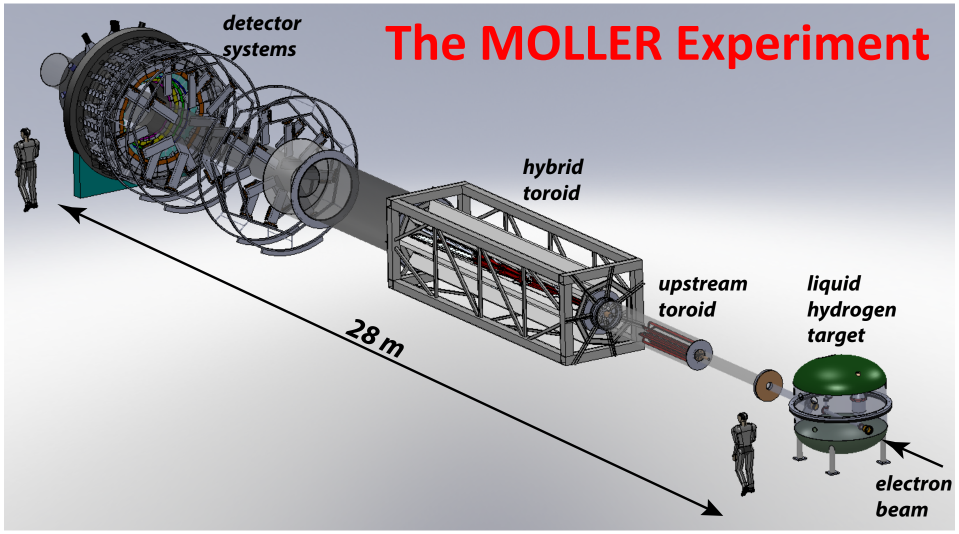




Jefferson Lab
Thomas Jefferson National Accelerator Facility
U.S. DEPARTMENT OF ENERGY
NSF
VT

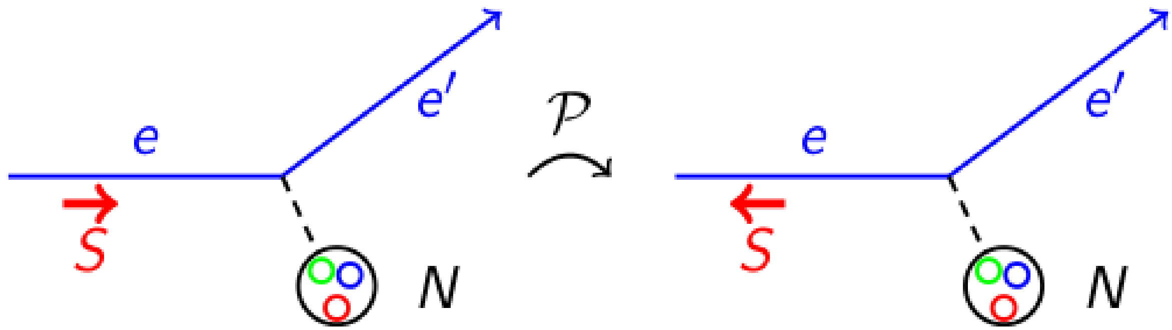
Outline

- Parity-Violating Electron Scattering: Formalism and Physics Motivation

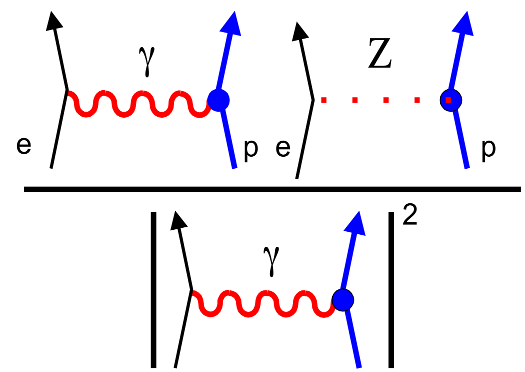
- The Qweak Experiment: Measurement of the Proton's Weak Charge

- The MOLLER Experiment: Measurement of the Electron's Weak Charge

Parity-Violating Electron Scattering – The Basics



$$A = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \quad \propto$$



- Longitudinally polarized electrons on unpolarized targets –
  e, p, d, ^{4}He, ^{9}Be, ^{12}C, ^{208}Pb
- Measure small parity-violating cross section asymmetry
  (~ 20 ppb – 100 ppm)
- **Elastic** and deep inelastic kinematics
- **Neutral weak current** – **Standard Model test** and select hadronic physics topics

Qweak and MOLLER Experiments at JLab

Qweak Experiment: parity-violating e-p elastic scattering to measure proton's weak charge

- last experiment in Hall C in "6 GeV era"
- data-taking 2010 – 2012 (~ 1 year total beam time)
- First results on proton's weak charge (based on 4% of the dataset) published in **Phys. Rev. Lett. 111, 141803 (2013)**
- Apparatus described in **NIM A781, 105 (2015)**
- Analysis of full dataset underway; final results expected early next year

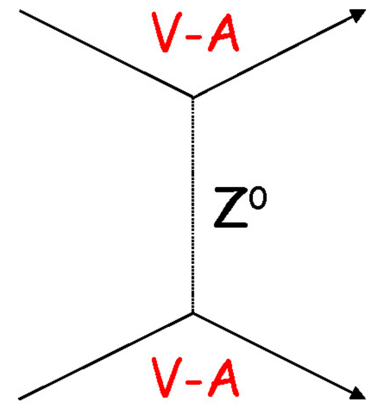
MOLLER (Measurement of a Lepton-Lepton Electroweak Reaction): parity-violating e-e elastic (Møller) scattering to measure electron's weak charge

- initiative for Hall A in "12 GeV era"
- approved by JLab PAC in Jan. 2009
- Successfully reviewed by JLab Director's Review in 2010 and DOE Science Review in 2014
- Aiming for factor of 5 improvement over previous measurement of SLAC E158
- See Moller white paper: **arXiv:1411.4088** for further details

Standard Model Weak Neutral Current Couplings

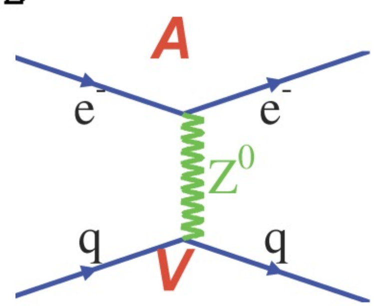
The Standard Model prescribes the couplings of the fundamental fermions to the Z boson:

fermions	$g_A^f = I_3$	$g_V^f = I_3 - 2Q\sin^2\theta_W$
ν_e, ν_μ	$\frac{1}{2}$	$\frac{1}{2}$
e-, μ-	$-\frac{1}{2}$	$-\frac{1}{2}+2\sin^2\theta_W$
u, c	$\frac{1}{2}$	$\frac{1}{2} - \frac{4}{3}\sin^2\theta_W$
d, s	$-\frac{1}{2}$	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_W$



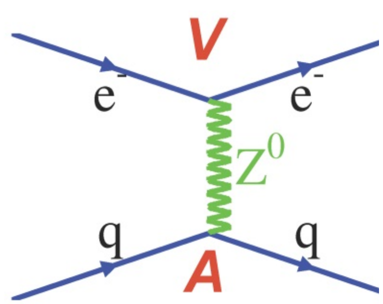
For low energy electroweak tests ($Q^2 << M^2_Z$), restrict to parity-violating e-q and e-e four-fermion contact interaction:

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



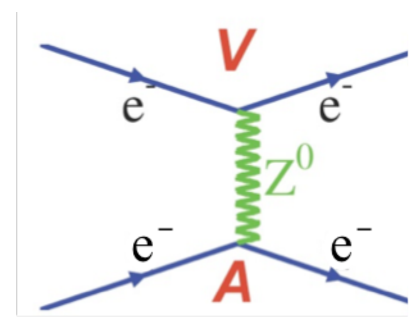
$$C_{1i} \equiv 2 g_A^e g_V^i$$

quark vector: C_{1u}, C_{1d}



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

quark axial-vector: C_{2u}, C_{2d}



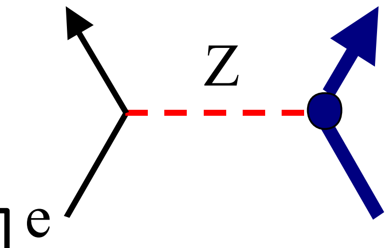
$$C_{ee} \equiv 2 g_V^e g_A^e$$

electron: C_{ee}

C_{1u} ,C_{1d} , C_{ee} : “Weak Charges”: neutral current analog to the electric charges

"Weak Charges" in Low Energy Neutral Current Tests

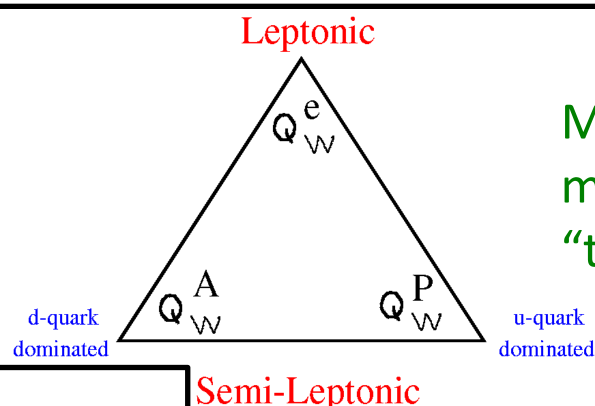
C_{1u}, C_{1d}, C_{ee} : "Weak Charges": neutral current analog to the electric charges



Electron's weak charge: $Q_W^e \equiv -2C_{ee} = -(1-4\sin^2\theta_W)$

parity-violating Møller scattering $\vec{e} + e \rightarrow e + e$

- published: SLAC E158 ~ 13% on Q^e_W
- **planned: JLAB MOLLER ~ 2.4% on Q^e_W**



Most precise low energy measurements define a weak charge "triad" (M. Ramsey-Musolf)

"Neutron's weak charge":

$$Q_W^A(Z,N) \equiv -2\left[C_{1u}(2Z+N) + C_{1d}(Z+2N)\right]$$
$$\approx Z\left(1-4\sin^2\theta_W\right) - N \approx -N$$

Atomic parity violation

- published: Cesium ~ 0.5% on Q^A_W
- planned: KVI Ra, FrPNC@TRIUMF ~ 0.2% on Q^A_W

Proton's weak charge:

$$Q_W^p \equiv -2\left[2C_{1u} + C_{1d}\right] = \left(1-4\sin^2\theta_W\right)$$

parity-violating elastic ep scattering

$\vec{e} + p \rightarrow e + p$

- **Running complete: JLab Qweak ~ 5% on Q^p_W**
- **Published: Qweak commissioning ~ 17% on Q^p_W**
- planned: Mainz MESA/P2 ~ 2.5% on Q^p_W

Q^e_W and Q^p_W are suppressed in Standard Model → increased sensitivity to new physics.

Physics Potential of Precision Electron Weak Charge Measurement from MOLLER

The MOLLER experiment provides:

- **Excellent sensitivity to Beyond Standard Model (BSM) physics**

  High precision measurement $\delta(Q_W^e)/Q_W^e \sim \pm 2.4\%$

  of suppressed SM observable $Q_W^e = -\left(1 - 4\sin^2\theta_W\right) \sim -.046$

  ⟶ **sensitive to new neutral current amplitudes as weak as ~ 10^{-3} G_F**

  Most sensitive probe of new flavor and CP-conserving neutral current interactions over next decade

  - new TeV scale dynamics (Z', supersymmetry, doubly charged scalars,…)
  - weakly coupled MeV – GeV scale mediators (dark photons, …)

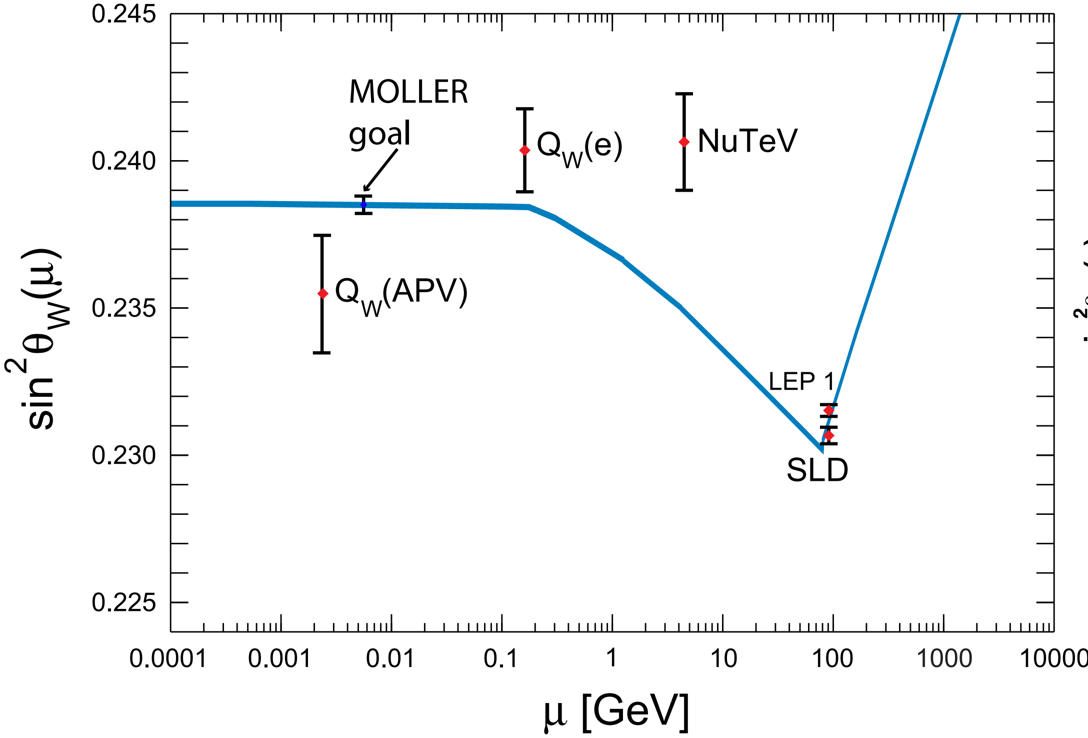
- **High precision benchmark point within the Standard Model**

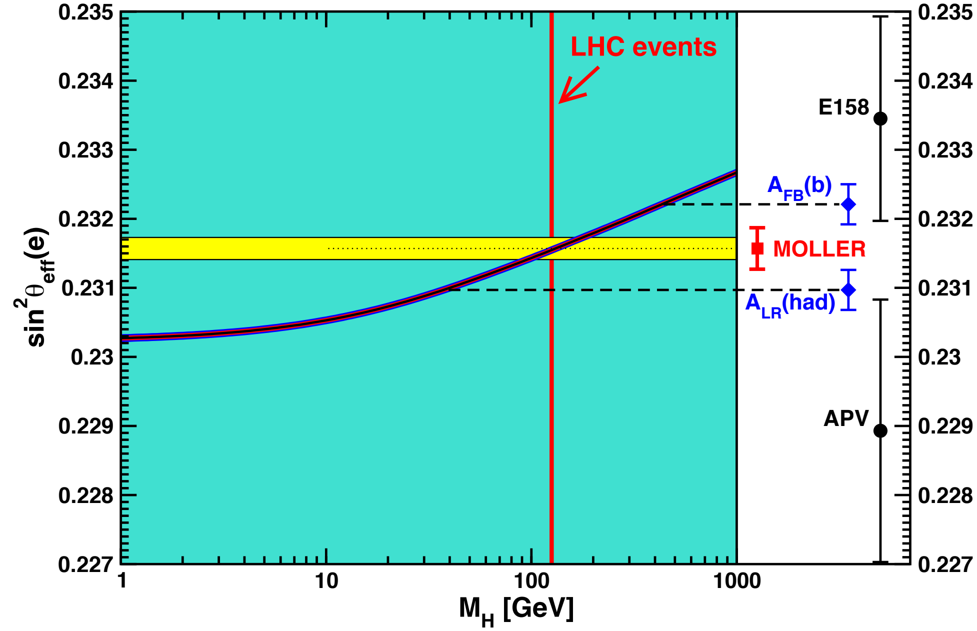
  $$\delta(\sin^2\theta_W) \sim \pm 0.00024\,(\text{stat.}) \pm 0.00013\ (\text{syst.})$$

  ~ 0.1% precision, comparable to sensitivity of best collider determinations

Other measurements on same timescale	$\delta(\sin^2\theta_W)$
Mainz MESA P2	~ ±0.00034
Final Tevatron	~ ±0.00041
LHC 14 TeV, 300 fb^{-1}	~ ±0.00036

Weak Mixing Angle – $\sin^2\theta_W$ – Potential MOLLER Impact





- Two most precise values of $\sin^2\theta_W$ at Z pole (SLC A_{LR} and LEP A^b_{fb}) disagree by 3σ
- MOLLER goal is $\delta(\sin^2\theta_W) \sim \pm 0.00024\,(\text{stat.}) \pm 0.00013\ (\text{syst.})$
  - comparable sensitivity to these two most precise collider values (±0.00029)
  - precise enough that result will have an impact on the central value of the world average
- MOLLER is the only method available in the next decade to directly address this issue at the same level of precision and interpretability
- **$\pm$ 10σ discovery potential at $Q^2 << M^2_Z$**

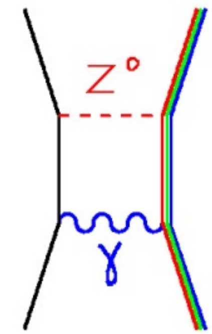
Energy Dependent Electroweak Radiative Corrections

→ For useful Standard Model test all electroweak radiative corrections need to be under good theoretical control

Proton weak charge: $Q_W^p = [1 + \Delta\rho + \Delta_e]\left[(1 - 4\sin^2\theta_W(0)) + \Delta_{e'}\right] + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$

Most significant radiative correction: γ-Z Box Diagram

- significant theory effort in past several years



Authors	Vector Y-Z rad. corr. for Q_W_p
Rislow & Carlson, PRD **83**, 113007 (2011)	0.0057±0.0009
Gorchtein, Horowitz, Ramsey-Musolf, PRC 84, 015502 (2011)	0.0054±0.0020
Hall, Blunden, Melnitchouk, Thomas, Young, arXiv:1504.0397	0.0054±0.0004

Electron weak charge:

$$Q_W^e = \left\{1 - 4\kappa(0)\sin^2\theta_W(m_Z)_{\overline{MS}} + \frac{\alpha(m_Z)}{4\pi\hat{s}^2} - \frac{3\alpha(m_Z)}{32\pi\hat{s}^2\hat{c}^2}(1-4\hat{s}^2)[1+(1-4\hat{s}^2)^2] + F_1(y, Q^2) + F_2(y, Q^2)\right\}$$

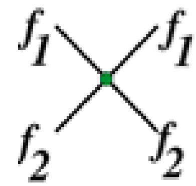
Purely leptonic process; electroweak radiative corrections under control at sub 1% level (1 loop, Czarnecki and Marciano, 2 loop: Aleksejevs, Barkanova)

Sensitivity to New Physics at TeV Scales

Model-independent way to quantify effects of potential new high energy dynamics (ie. heavy Z's, compositeness, extra dimensions,...) is expressing it in terms of neutral "contact" 4-fermi interactions:

$$\mathcal{L} = \mathcal{L}_{\mathtt{SM}} + \mathcal{L}_{\mathtt{new}}$$

Consider $f_1 f_1 \rightarrow f_2 f_2$ **or** $f_1 f_2 \rightarrow f_1 f_2$



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

Eichten, Lane and Peskin, PRL50 (1983)

mass scale Λ, coupling g **for each fermion and handedness combination**

Precision of current and future low energy experiments → mass reach of Λ/g in the multi-TeV region.

(See Erler, Horowitz, Mantry, Souder, Ann. Rev. Nucl. Part. Sci. **64** (2014) for detailed mass reach comparisons)

"Energy frontier" - like LHC

→ Make new particles ("X") directly in high energy collisions

"Precision frontier" – weak charge, g-2(μ), etc.

→ Measure indirect effects of new particles ("X") made virtually in low energy processes

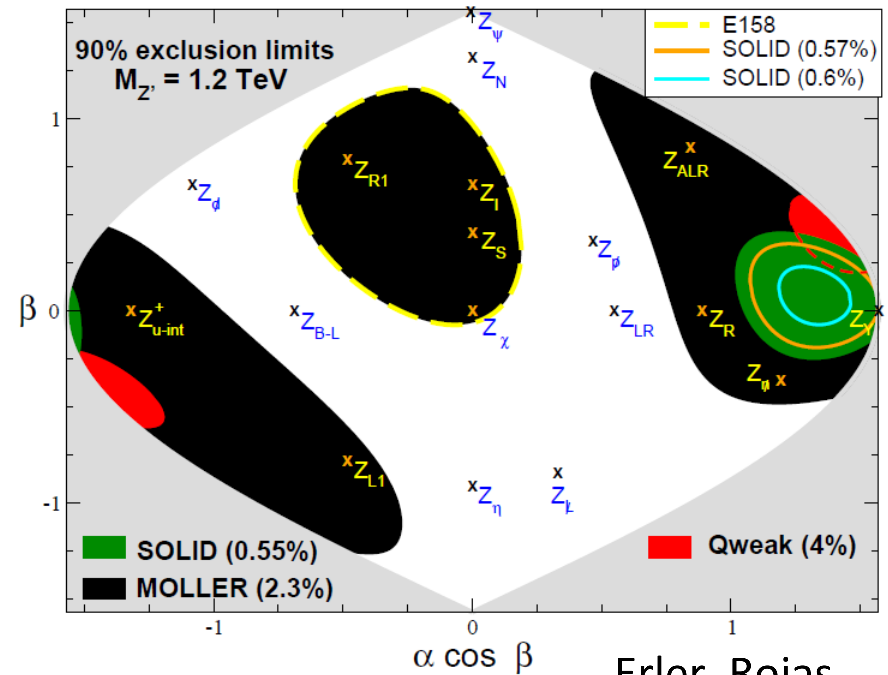
Qweak&MOLLER: TeV-Scale New Physics Reach Examples

Complementarity to Possible LHC Z'

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *For 'light' 1-2 TeV, Z' properties can be extracted*

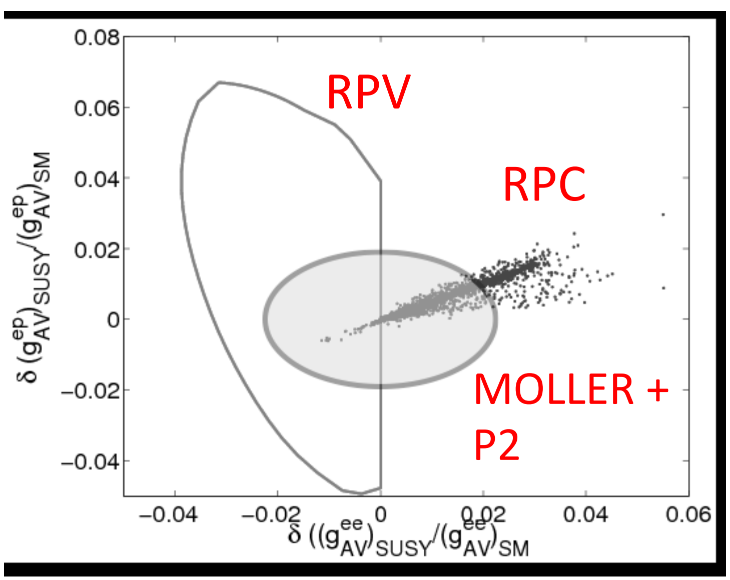
Suppose a 1 to 2 TeV heavy Z' is discovered at the LHC

- Can we point to an underlying GUT model?



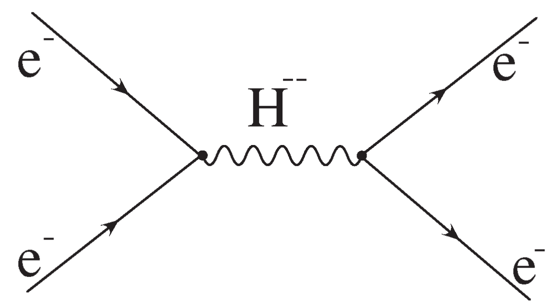
Erler, Rojas

RPC and RPV Supersymmetry



Includes LHC constraints;
Erler, Su arXiv: 1303.5522

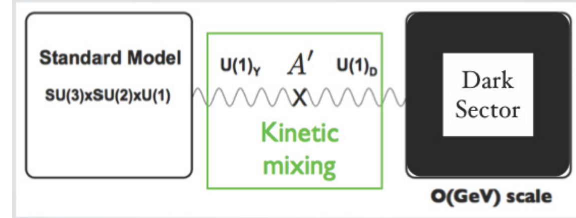
Doubly Charged Scalars



Naturally arise in many extended Higgs sector models; lepton number violating
MOLLER sensitivity: Λ > 5 TeV
(LEP-200 ~ 3 TeV)

Qweak & MOLLER: Sensitivity to MeV – GeV Scale Mediators

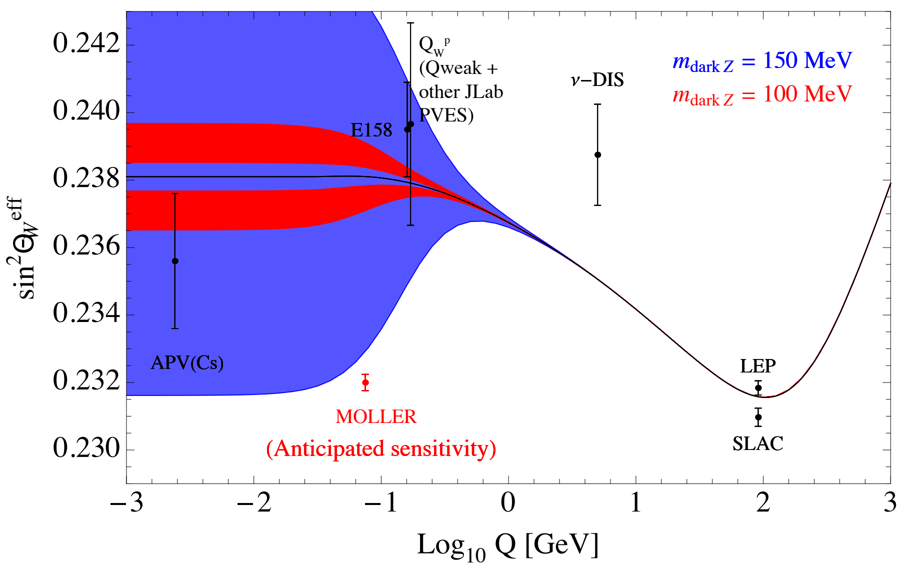
"Dark photon" – possible portal for new force to communicate with SM

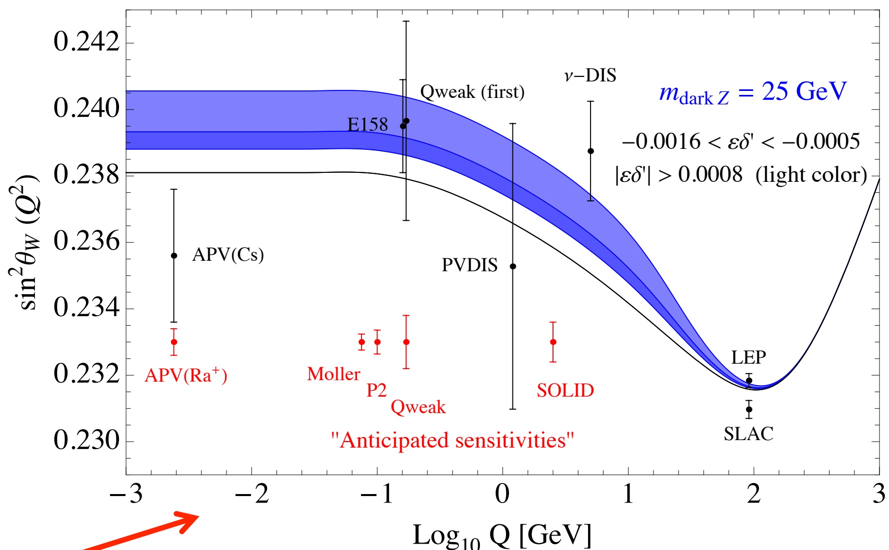


"Dark parity violation"

(Davoudiasl, Lee, Marciano, arXiv 1402.3620)

- New source of low energy parity violation through mass mixing between Z_0 and Z_d
- Complementary to direct searches for heavy dark photons; observable even if direct decay modes are "invisible"
- Example: possible deviations of $\sin^2\theta_W$ for dark photons respecting rare kaon decay constraints





Intermediate mass (~10 – 35 GeV) Z_d

(Davoudiasl, Lee, Marciano, arXiv 1507.00352)

- Relation to rare Higgs decays –

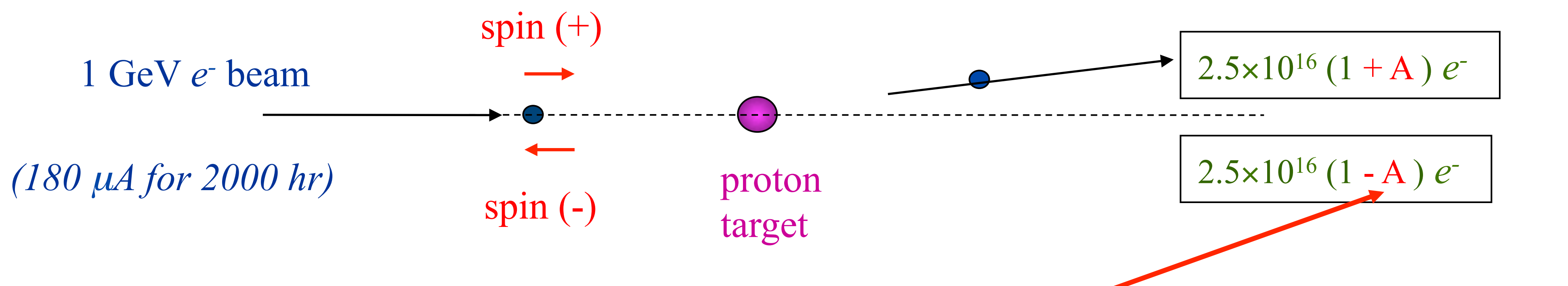
$$H \to Z\, Z_d \text{ or } H \to Z_d\, Z_d$$

The Q_{weak} Experiment at JLab: The Essentials

Elastic scattering of longitudinally polarized electrons on protons

$$\vec{e}^- + p \rightarrow e^- + p$$

(elastic) scattered e^- at small angle (~ 8^o)



Parity violating asymmetry:

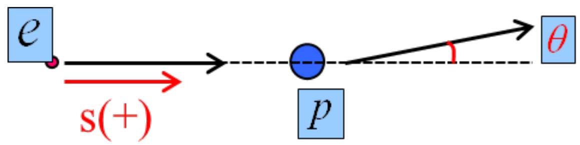
A ~ $- 2.3 \times 10^{-7}$ or -230 ppb (parts per billion)

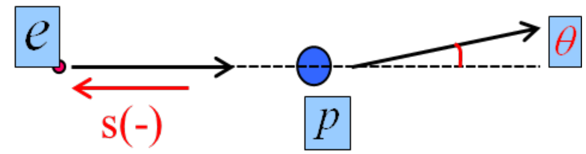
proportional to the proton's weak charge ("Qweak")

Requires:

- High polarization, high current polarized source **(record 180 µA , 89% polarized beam delivered routinely for Qweak)**
- High power cryogenic LH_2 target **(Qweak: world's highest power (3 kW), lowest density fluctuation target)**
- Large acceptance spectrometer with ability to separate elastic and background processes
- High count rate detectors/electronics

Parity-Violating Asymmetry for the Q_{weak} Experiment





The Qweak experiment at JLAB determines the proton's weak charge by measuring the parity-violating asymmetry in elastic scattering of longitudinally polarized electrons on proton.

$$A_{PV} = \frac{2M_{NC}}{M_{EM}} = \left[\frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\right]\left[\frac{\varepsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\varepsilon' G_M^\gamma G_A^Z}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}\right]$$

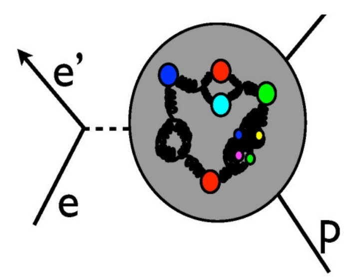
At forward scattering angles and low 4-momentum transfer:

$$A \equiv \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} \xrightarrow[\theta \to 0]{Q^2 \to 0} \left[\frac{-G_F}{4\pi\alpha\sqrt{2}}\right]\left[Q^2 Q^p_{weak} + Q^4 B(Q^2)\right]$$

proton's weak charge:
$Q^p_{weak} = 1 - 4\sin^2\theta_W$ at tree level

"Form factor" term due to finite proton size – hadronic structure (~ 30% for Qweak)

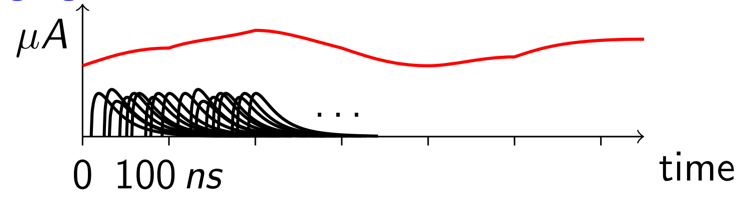
By running at a small value of Q^2 (small beam energy, small scattering angle) we minimize our sensitivity to the effects of the proton's detailed spatial structure.



Qweak Experimental Apparatus

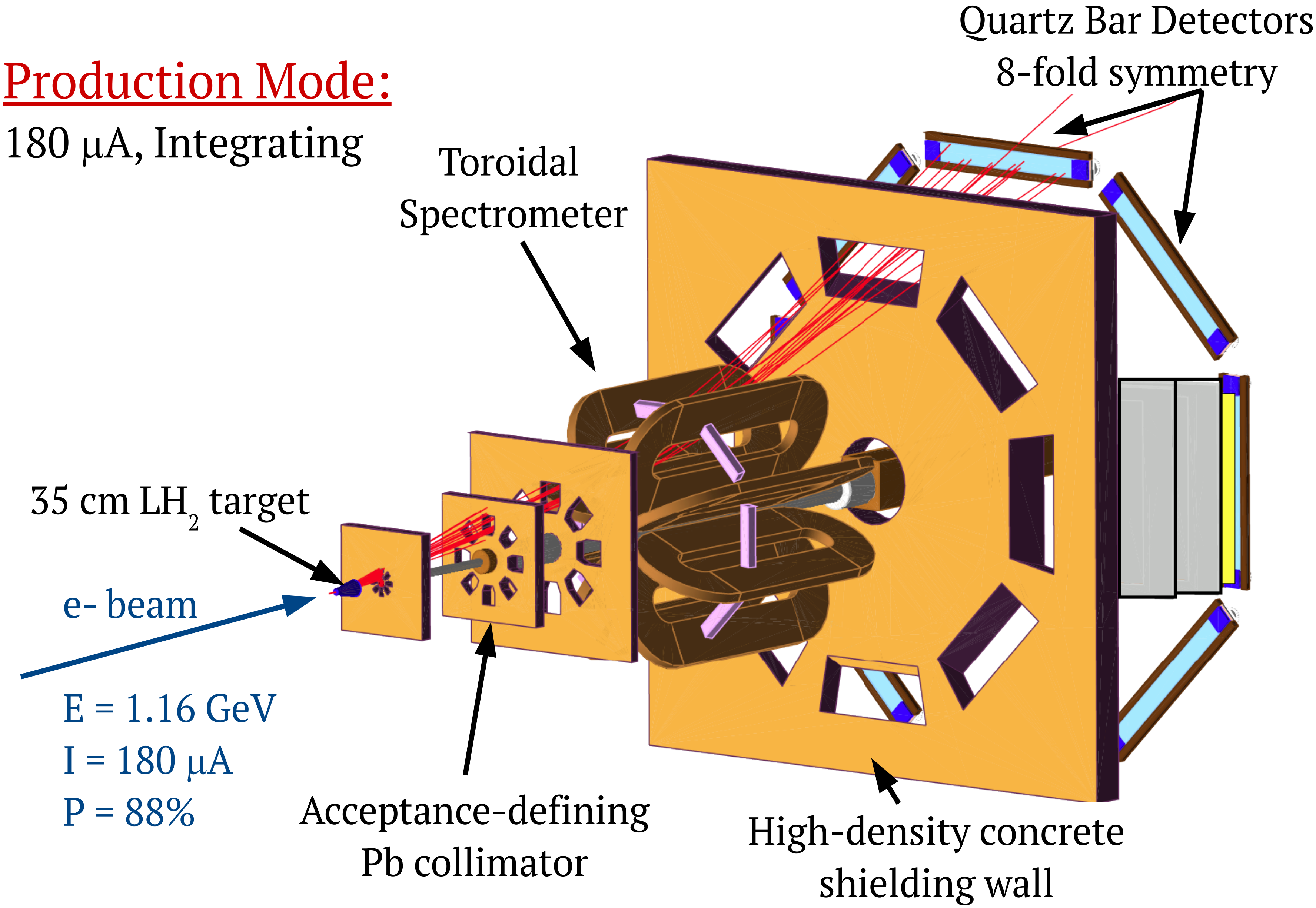
Production: ~ 800 MHz rates

must integrate PMT current



Production Mode:

180 μA, Integrating



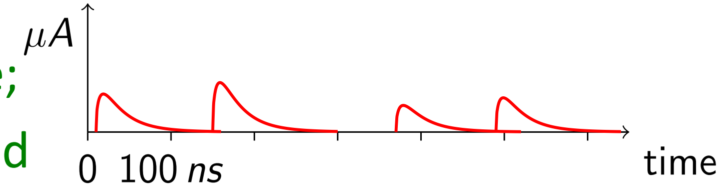
E = 1.16 GeV

I = 180 μA

P = 88%

Qweak Experimental Apparatus

Tracking (event) mode: low rate;
each event individually registered

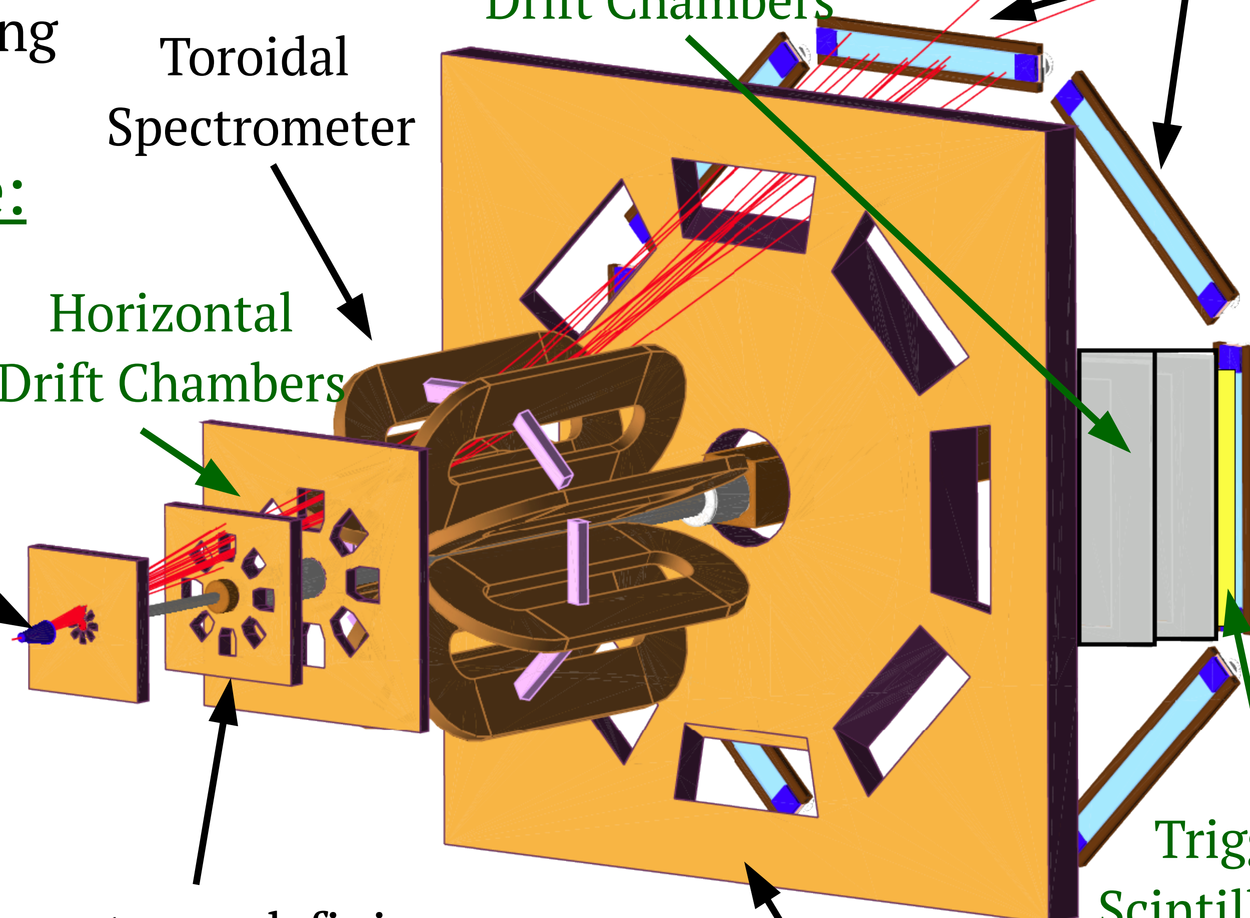


Production Mode:

180 μA, Integrating

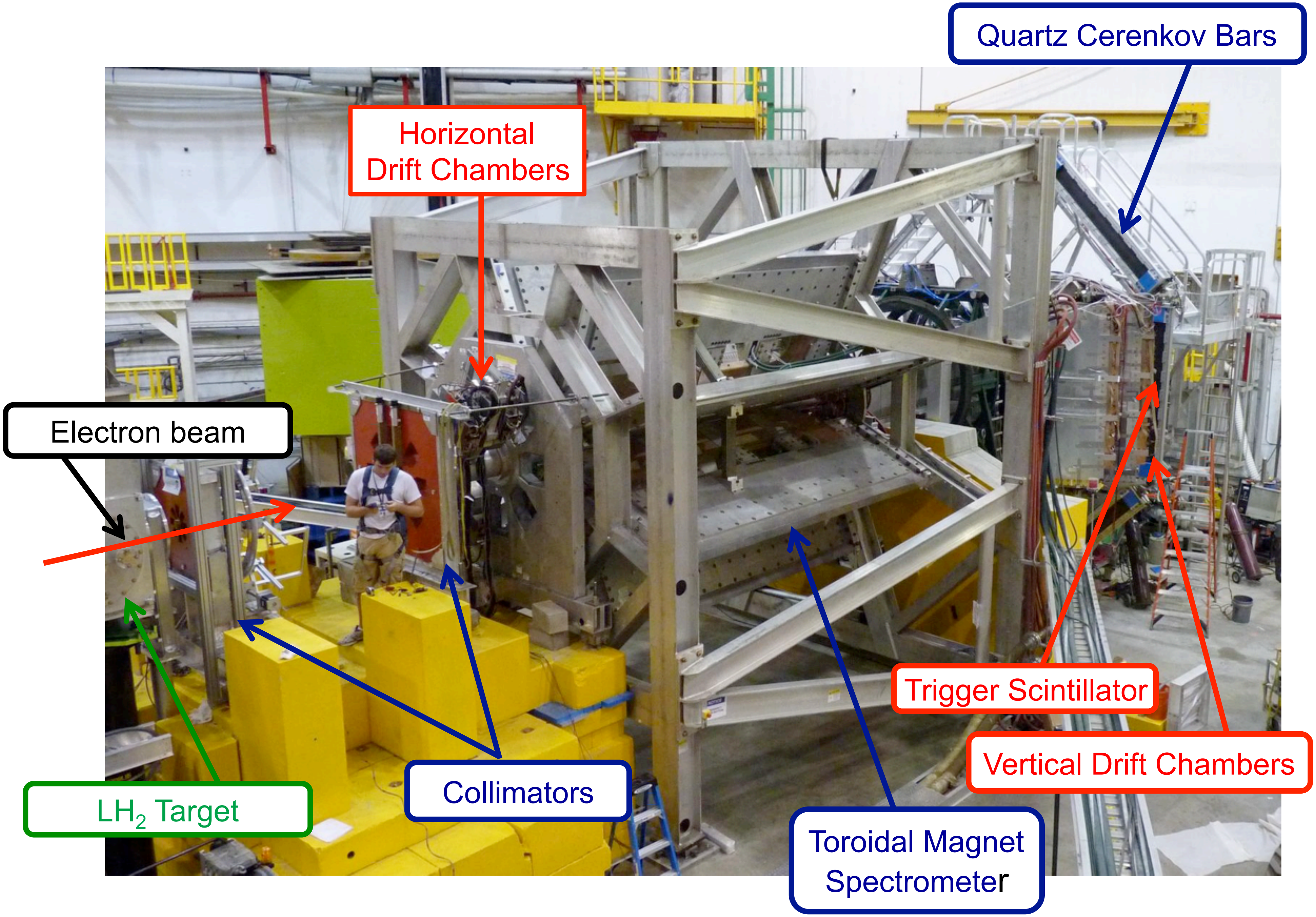
Tracking Mode:

50 pA, Counting
(Q^2 Systematics)



E = 1.16 GeV
I = 180 μA
P = 88%

Qweak Apparatus During Installation



Qweak Data Taking Periods and First Results

Qweak had ~ 1 calendar year of beam split into 3 running periods

Each period had its own “blinding factor” to avoid analysis bias:

- Run 0: January – February 2011 (commissioning data)
- Run 1: February – May 2011
- Run 2: November 2011 – May 2012

Run 0 results (about 1/25 of data set) published in PRL in Oct. 2013

PRL **111,** 141803 (2013) PHYSICAL REVIEW LETTERS week ending 4 OCTOBER 2013

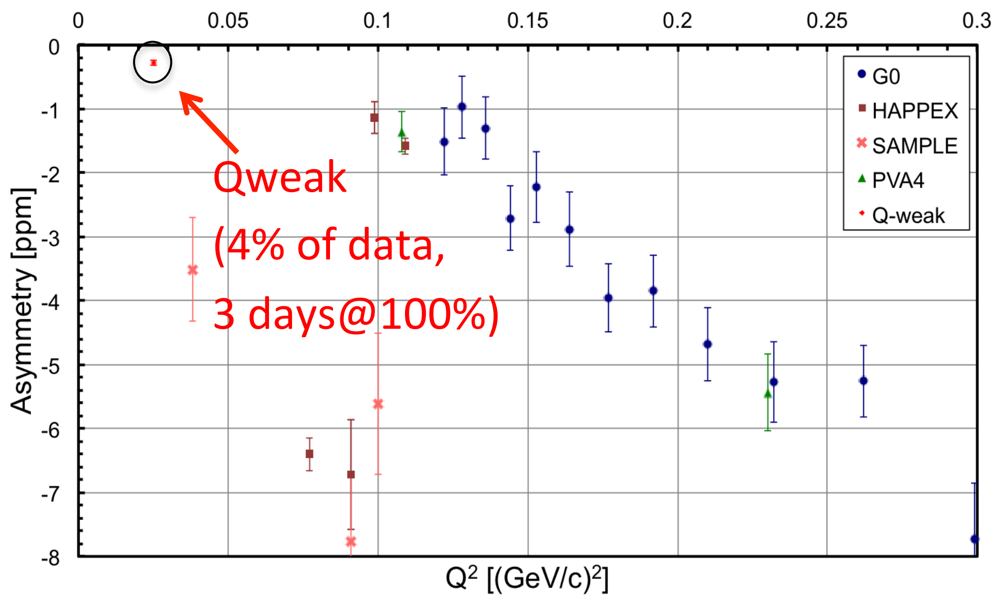
First Determination of the Weak Charge of the Proton

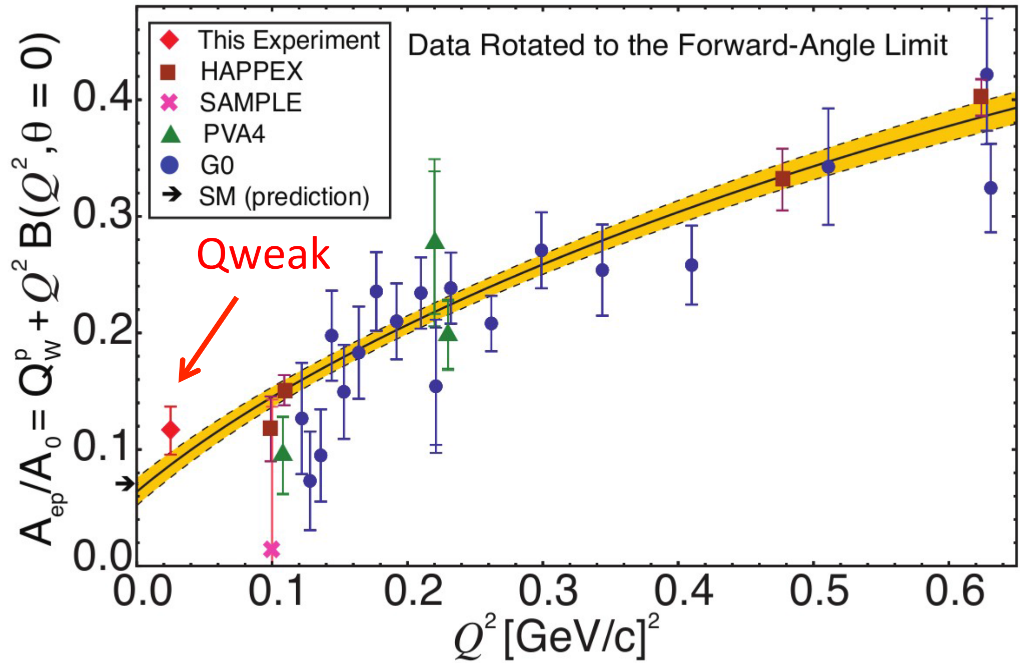
D. Androic,[1] D. S. Armstrong,[2] A. Asaturyan,[3] T. Averett,[2] J. Balewski,[4] J. Beaufait,[5] R. S. Beminiwattha,[6] J. Benesch,[5] F. Benmokhtar,[7] J. Birchall,[8] R. D. Carlini,[5,2,†] G. D. Cates,[9] J. C. Cornejo,[2] S. Covrig,[5] M. M. Dalton,[9] C. A. Davis,[10] W. Deconinck,[2] J. Diefenbach,[11] J. F. Dowd,[2] J. A. Dunne,[12] D. Dutta,[12] W. S. Duvall,[13] M. Elaasar,[14] W. R. Falk,[8] J. M. Finn,[2,*] T. Forest,[15,16] D. Gaskell,[5] M. T. W. Gericke,[8] J. Grames,[5] V. M. Gray,[2] K. Grimm,[16,2] F. Guo,[4] J. R. Hoskins,[2] K. Johnston,[16] D. Jones,[9] M. Jones,[5] R. Jones,[17] M. Kargiantoulakis,[9] P. M. King,[6] E. Korkmaz,[18] S. Kowalski,[4] J. Leacock,[13] J. Leckey,[2,‡] A. R. Lee,[13] J. H. Lee,[6,2,§] L. Lee,[10,8] S. MacEwan,[8] D. Mack,[5] J. A. Magee,[2] R. Mahurin,[8] J. Mammei,[13,‖] J. W. Martin,[19] M. J. McHugh,[20] D. Meekins,[5] J. Mei,[5] R. Michaels,[5] A. Micherdzinska,[20] A. Mkrtchyan,[3] H. Mkrtchyan,[3] N. Morgan,[13] K. E. Myers,[20,¶] A. Narayan,[12] L. Z. Ndukum,[12] V. Nelyubin,[9] Nuruzzaman,[11,12] W. T. H. van Oers,[10,8] A. K. Opper,[20] S. A. Page,[8] J. Pan,[8] K. D. Paschke,[9] S. K. Phillips,[21] M. L. Pitt,[13] M. Poelker,[5] J. F. Rajotte,[4] W. D. Ramsay,[10,8] J. Roche,[6] B. Sawatzky,[5] T. Seva,[1] M. H. Shabestari,[12] R. Silwal,[9] N. Simicevic,[16] G. R. Smith,[5] P. Solvignon,[5] D. T. Spayde,[22] A. Subedi,[12] R. Subedi,[20] R. Suleiman,[5] V. Tadevosyan,[3] W. A. Tobias,[9] V. Tvaskis,[19,8] B. Waidyawansa,[6] P. Wang,[8] S. P. Wells,[16] S. A. Wood,[5] S. Yang,[2] R. D. Young,[23] and S. Zhamkochyan[3]

Extraction of Qweak from e-p Asymmetry

Run 0 Results (1/25th of total dataset) – published in PRL **111**, 141803 (2013)

$$A_{ep} = -279 \pm 35(\mathrm{stat}) \pm 31(\mathrm{syst})\ \mathrm{ppb} \quad \text{at} \quad \langle Q^2 \rangle = 0.0250\ (\mathrm{GeV}/c)^2$$





Global fit of world PVES data up to Q^2 = 0.63 GeV^2 is done to extract the proton's weak charge

$$A_{ep}/A_0 = Q^p_W + Q^2 B(Q^2, \theta), \qquad A_0 = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right].$$

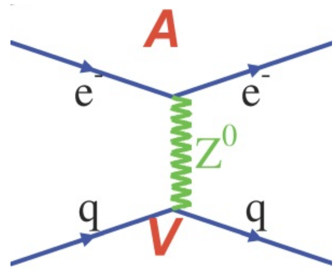
$$Q^p_W(\mathrm{PVES}) = 0.064 \pm 0.012 \qquad Q^p_W(\mathrm{SM}) = 0.0710 \pm 0.0007$$

First determination of proton's weak charge in good agreement with Standard Model

Implications of First Proton Weak Charge Measurement

Improved precision on quark vector coupling constants

$$Q_W^p = -2(2C_{1u} + C_{1d})$$



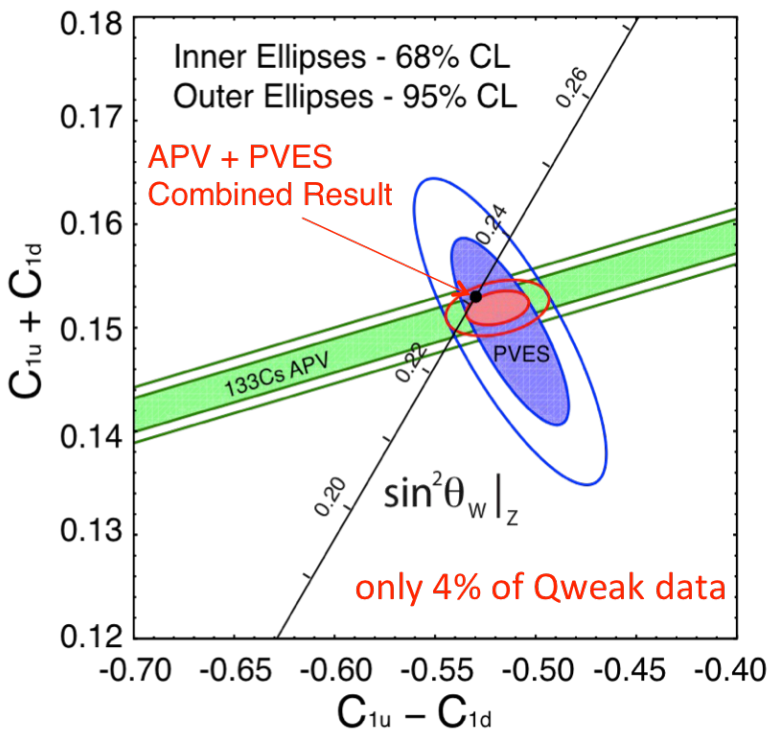
$$C_{1i} \equiv 2 g_A^e g_V^i$$

$$C_{1u} = -0.1835 \pm 0.0054$$
$$C_{1d} = 0.3355 \pm 0.0050$$

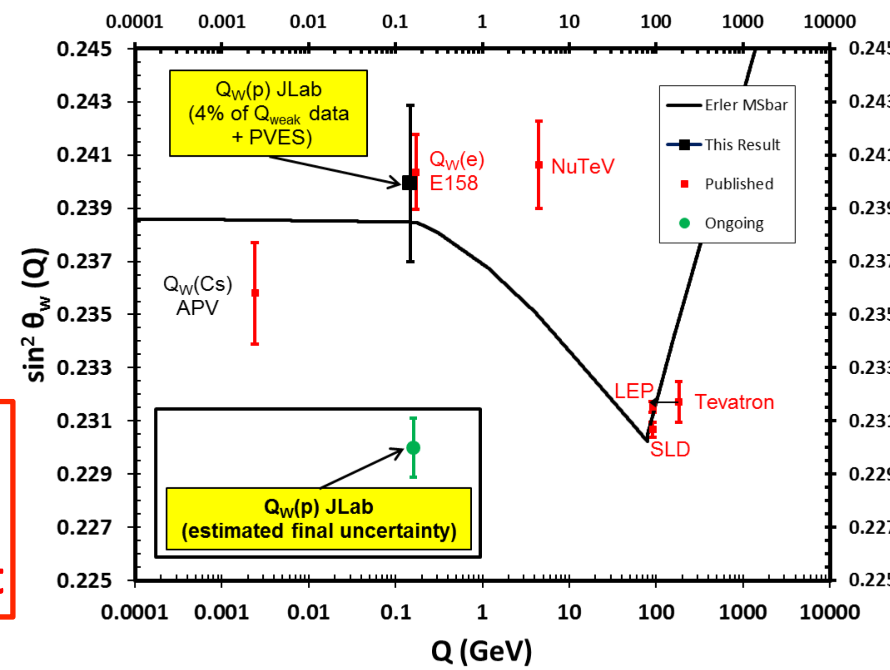
Combining this result with the most precise atomic parity violation experiment we can also extract, for the first time, the **neutron's weak charge**:

$$Q_W^n(\text{SM}) = -0.9890 \pm 0.0007$$

$$Q_W^n(\text{PVES+APV}) = -0.975 \pm 0.010$$



First contribution of proton weak charge to "weak charge triad" in running plot



Qweak First Result – Correction/Error Summary

$$A_{ep} = R_{total}\left[\frac{\frac{A_{msr}}{P} - \sum_{i=1}^{4} A_i f_i}{1 - \sum_{i=1}^{4} f_i}\right]$$

A_{msr} : Includes corrections for helicity-correlated differences in beam parameters

P : Beam polarization

A_i, f_i : Background asymmetry and signal fraction

R_{total} : Radiative corrections and non-uniform Q^2

Corrections and uncertainty contributions for initial result

	Correction Value (ppb)	Contribution to ΔA_{ep} (ppb)	
Normalization Factors Applied to A_{Raw}			
Beam Polarization $1/P$	-21	5	
Kinematics R_{tot}	5	9	
Bckgrnd Dilution $1/(1-f_{tot})$	-7	-	
Asymmetry corrections			
Beam Asymmetries κA_{reg}	-40	13	
Transverse Polarization κA_T	0	5	
Detector Linearity κA_L	0	4	
Backgrounds	$\kappa P f_i A_i$	$\delta(f_i)$	$\delta(A_i)$
Target Windows (b_1)	-58	4	8
Beamline Scattering (b_2)	11	3	23
Other Neutral bkg (b_3)	0	1	< 1
Inelastics (b_4)	1	1	< 1

Largest uncertainty contributions for initial result

- False asymmetries from helicity-correlated differences in beam parameters **(13 ppb)**
- Backgrounds from beamline scattering **(23 ppb)**

Status of Full Qweak Dataset Analysis – Beam Corrections

Data analysis in progress for the full dataset

Example: Status of corrections for helicity-correlated beam parameters

(sensitivity of detector asymmetries to beam position variations)

- “Regression”: **Natural jitter** of beam parameters
- “Dithering”: Occasional “large” **driven variation** of each beam parameter

- Corrections based on the two methods are in excellent agreement for this subset of our data

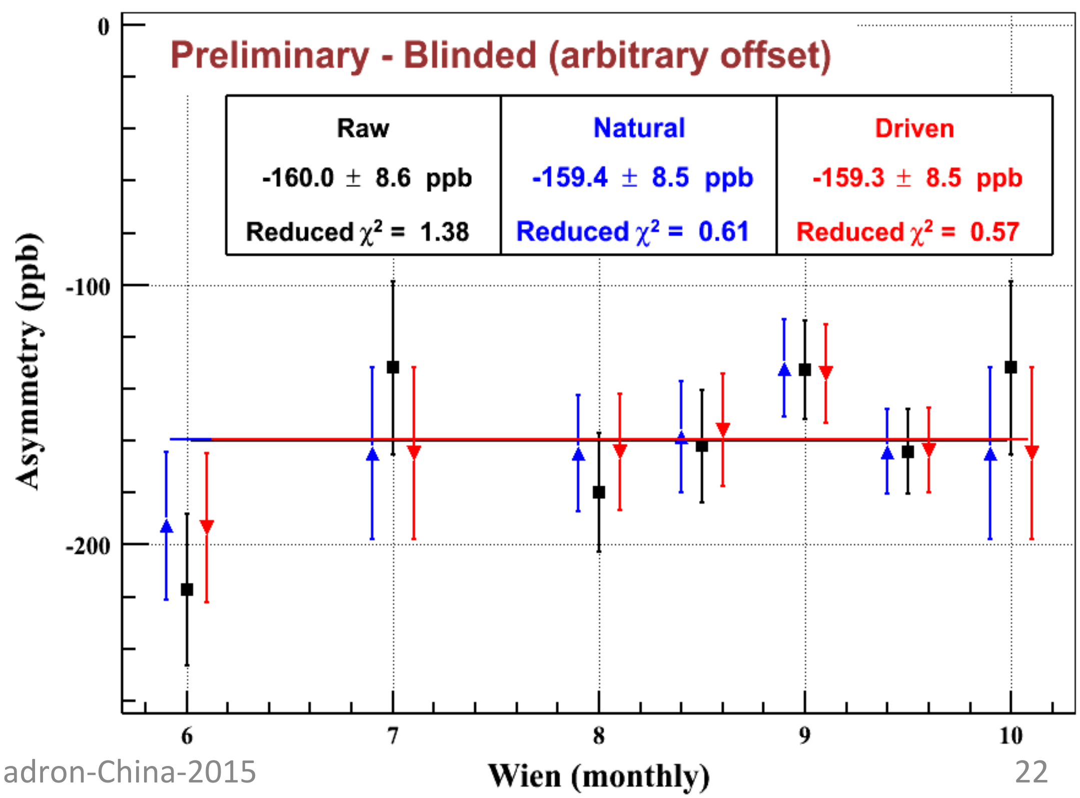
$$A_{corr} = \sum_{i=1}^{5} \left(\frac{\partial A}{\partial x_i}\right) \Delta x_i$$

$$(x, x', y, y', E)$$

- Includes about 77% of Run 2 dataset (~ 50% of overall dataset)
- Asymmetries have no corrections other than beam parameter corrections

Excellent consistency between regression and dithering observed

Run2 measured asymmetry

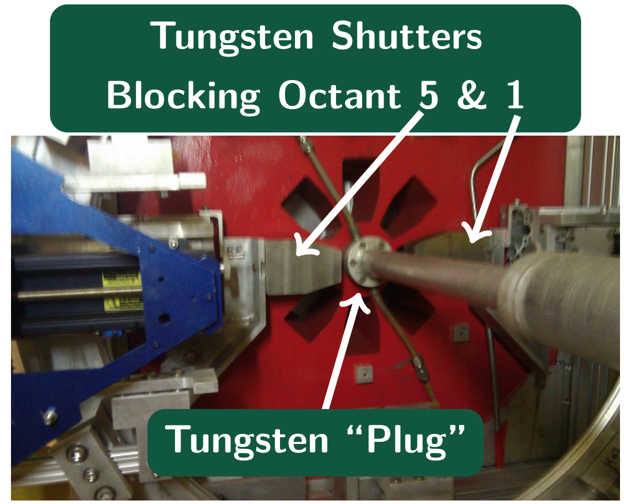


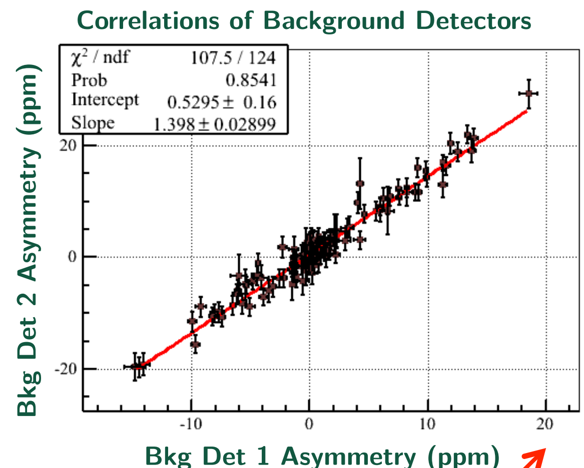
Status of Full Qweak Dataset Analysis – Beamline Backgrounds

- Highest contribution to **systematic uncertainty** for Run 0 results.
- Background from electrons scattering on beamline or tungsten plug collimator.
  - Thought to be associated with large helicity-correlated false asymmetries in the beam halo.
- Yield fraction on Main Detector **measured directly** by blocking scattered electron on octants 1 & 5. Where the contribution was

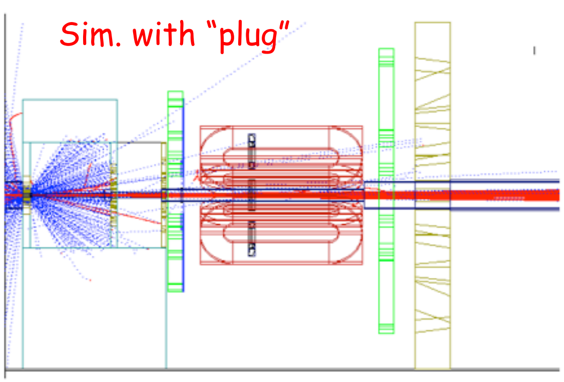
$$f_{b_2}^{\mathrm{MD}} \approx 0.19\,\%.$$

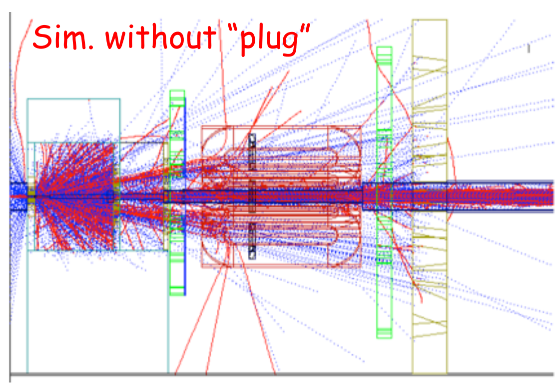
- Dedicated background detectors in various locations monitored this component and measured highly correlated asymmetries.
- Scaling of background asymmetries was also consistent with expectation from dedicated measurement.





Background detector asymmetries up to **20 ppm**

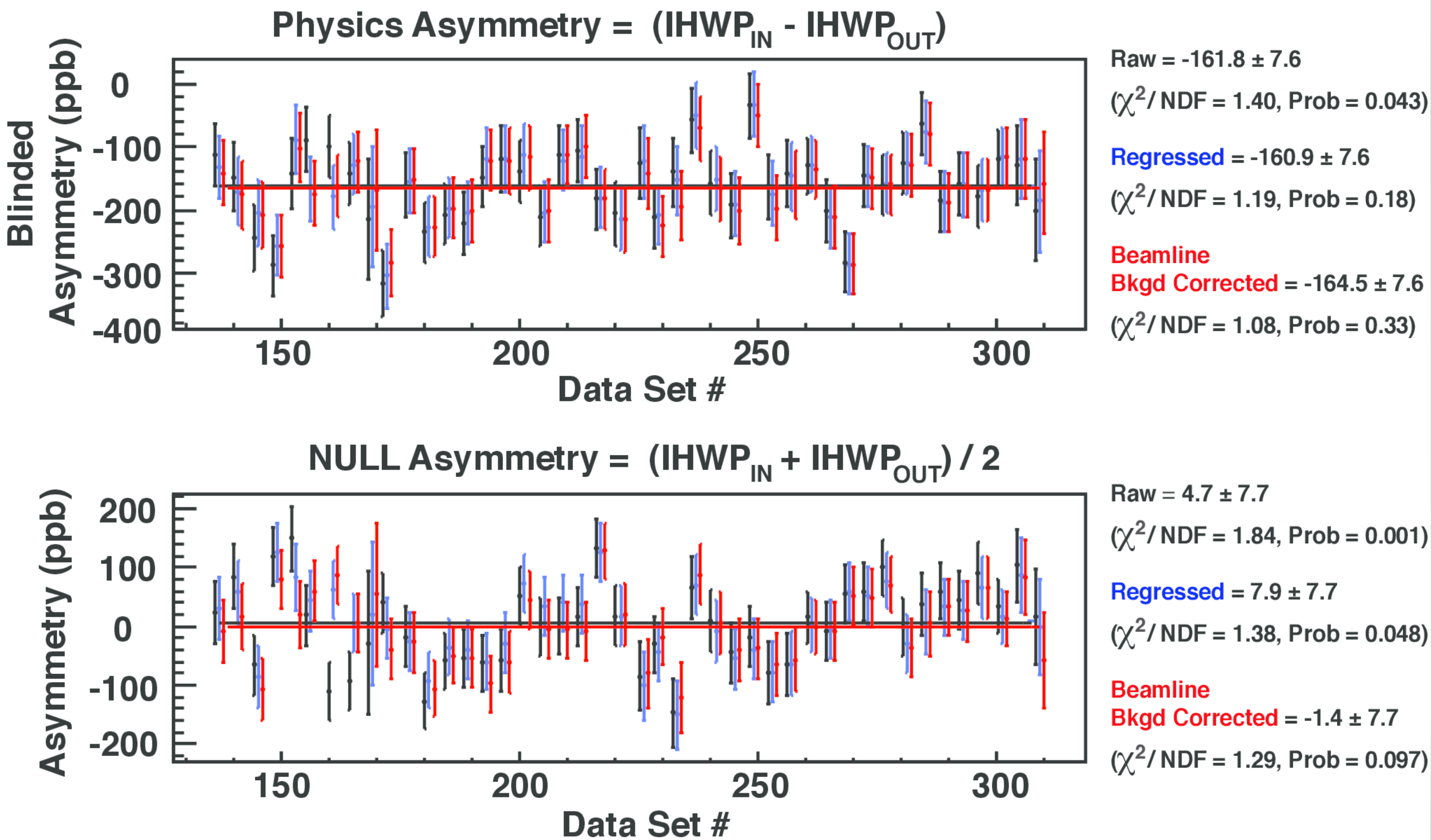




Status of Full Qweak Dataset Analysis – Beamline Backgrounds

Qweak Run 2 - Blinded Asymmetries

(statistics only - not corrected for beam polarization, Al target windows, ΔQ^2, etc.)



Inclusion of beamline background correction improves the statistical consistency of both the Physics and "NULL" asymmetry

The MOLLER Experiment at JLab: The Essentials

Elastic scattering of longitudinally polarized electrons on unpolarized electrons

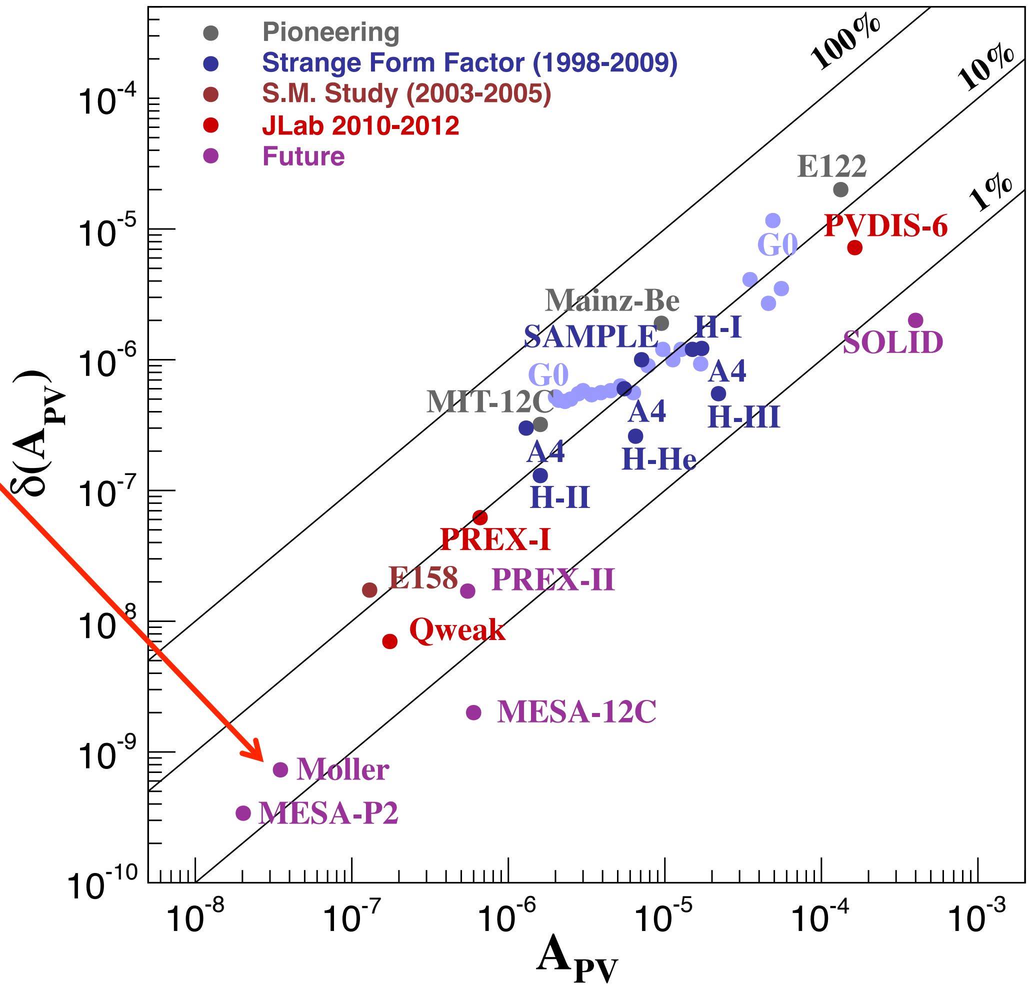
⟶ Parity-Violating Møller scattering $\vec{e} + e \rightarrow e' + e'$

Parity violating asymmetry:

$A_{PV} \sim$ 35 × 10^{-9} or 35 ppb (parts per billion)

$\delta A_{PV} \sim \pm$ 0.7 ppb (2.4% precision)

⟶ next generation in size and precision of asymmetry for parity-violating electron scattering experiments



proportional to the electron's weak charge Q^e_W

- precisely predicted in Standard Model

At tree level $$Q_W^e = -\left(1 - 4\sin^2\theta_W\right)$$

2.4% precision on Q^e_W 0.1% on $\sin^2\theta_W$

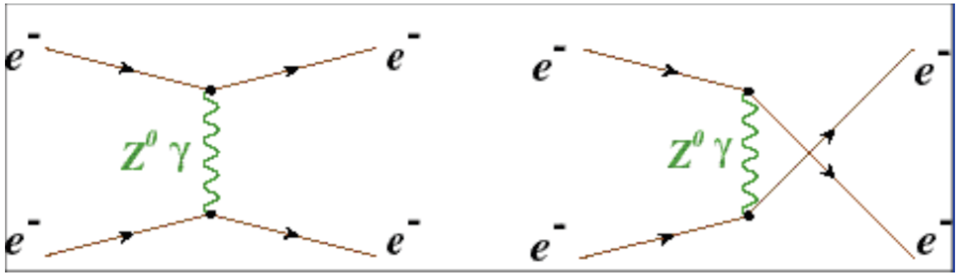
MOLLER experiment approved by JLAB PAC in Jan. 2009

Successfully reviewed by JLab Director's Review in 2010 and DOE Science Review in 2014

Will be factor of 5 improvement over previous measurement of SLAC E158

Parity Violating Asymmetry in Møller Scattering

Under assumption of 126 GeV Higgs SM boson, the parity-violating asymmetry in Møller scattering is predicted at the sub-1% level of theoretical accuracy:



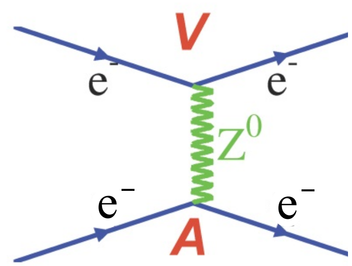
At tree level in Standard Model:

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{A_\gamma A_Z}{A_\gamma^2} = m_e E_{lab} \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4 sin^2\theta}{(3 + cos^2\theta)^2} Q_W^e,$$

Derman and Marciano (1978)

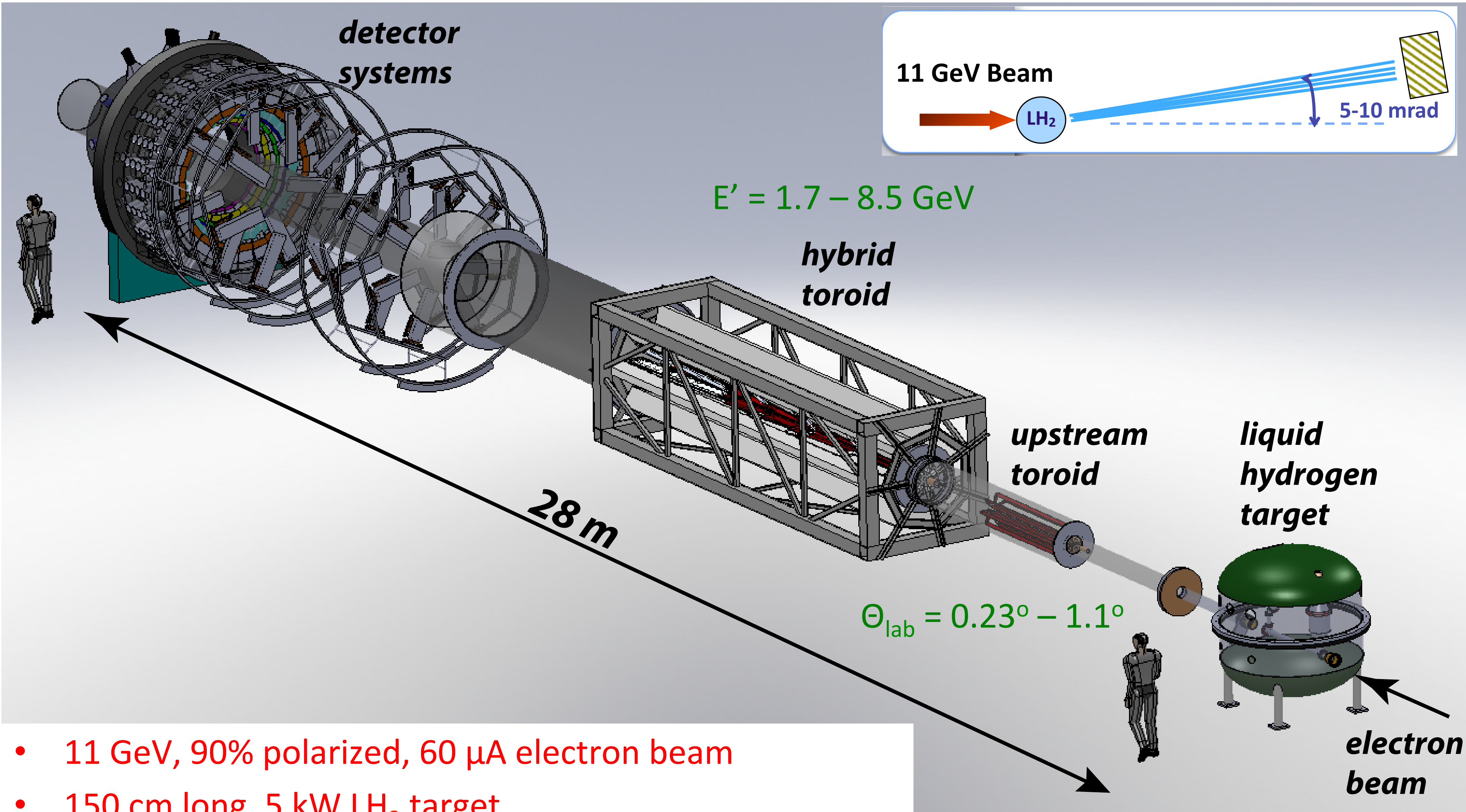
At tree level electron's weak charge is given by:

$$Q_W^e = -4 g_V^e g_A^e = -\left(1 - 4\sin^2\theta_W\right)$$



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

MOLLER Experiment: Conceptual Overview



- 11 GeV, 90% polarized, 60 µA electron beam
- 150 cm long, 5 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

Projected Uncertainty Budget and Experimental Challenges

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

All systematics required at sub-1% level

Statistics: High power beam, target; large acceptance; minimize random noise sources

Beam quality: Minimize helicity-correlated beam properties; small random fluctuations

Polarimetry: Redundant, high-precision polarimetry

Backgrounds: Novel spectrometer, “2 bounce” collimation, auxiliary detectors

Tracking: kinematic factor, backgrounds

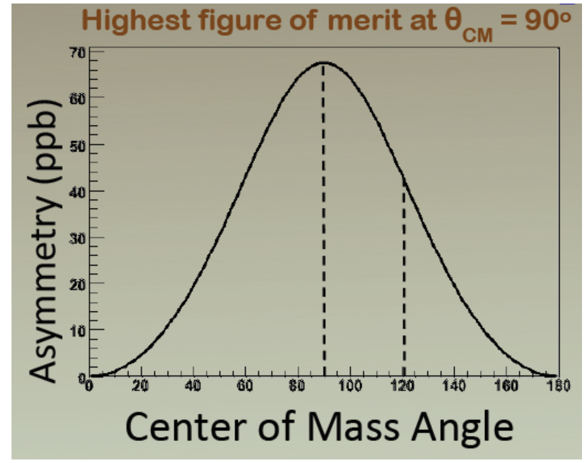
Builds on experience from previous PVES experiments like E158 and Qweak

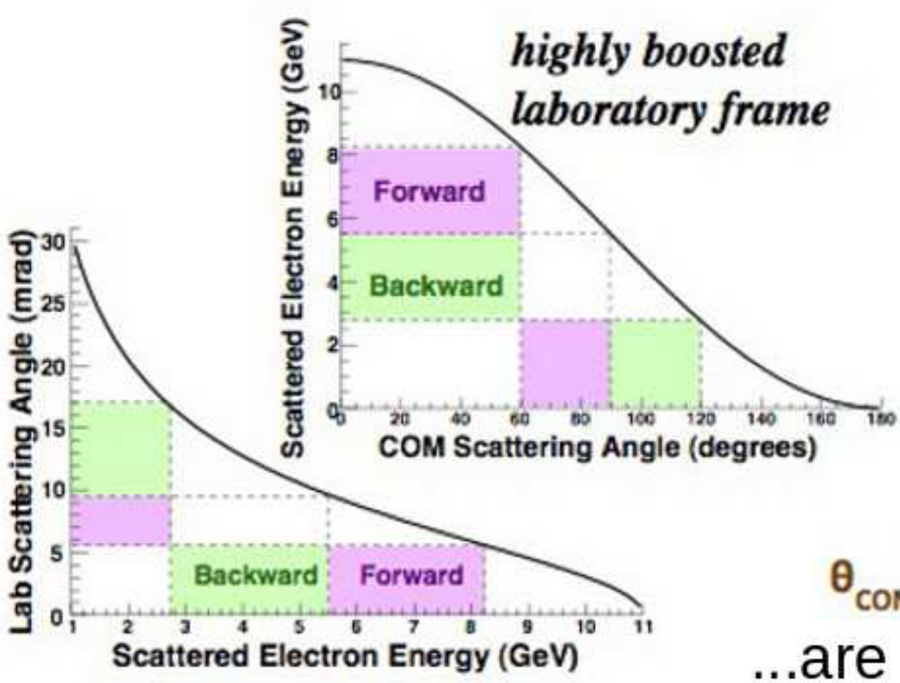
Spectrometer – Kinematics and Azimuthal Acceptance

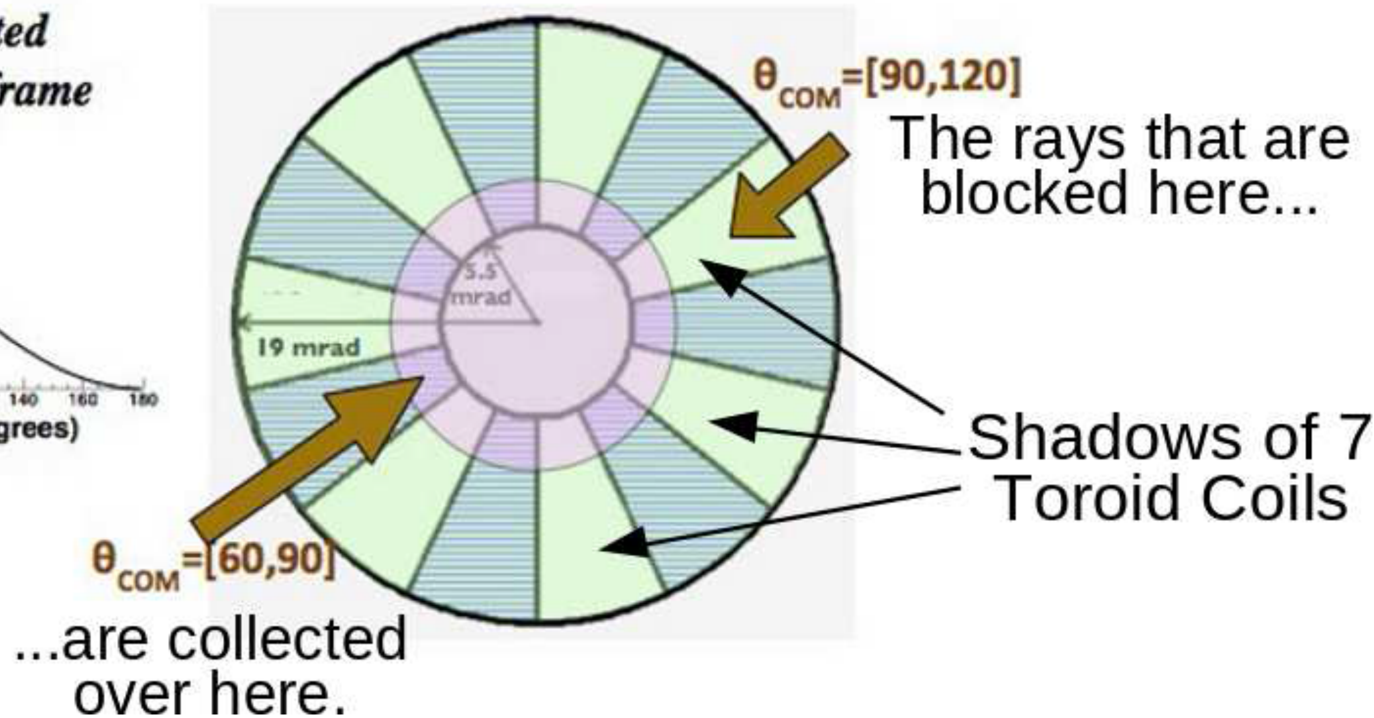
Optimized spectrometer:

50% azimuth, 100% acceptance

FOM optimized at 90° in COM

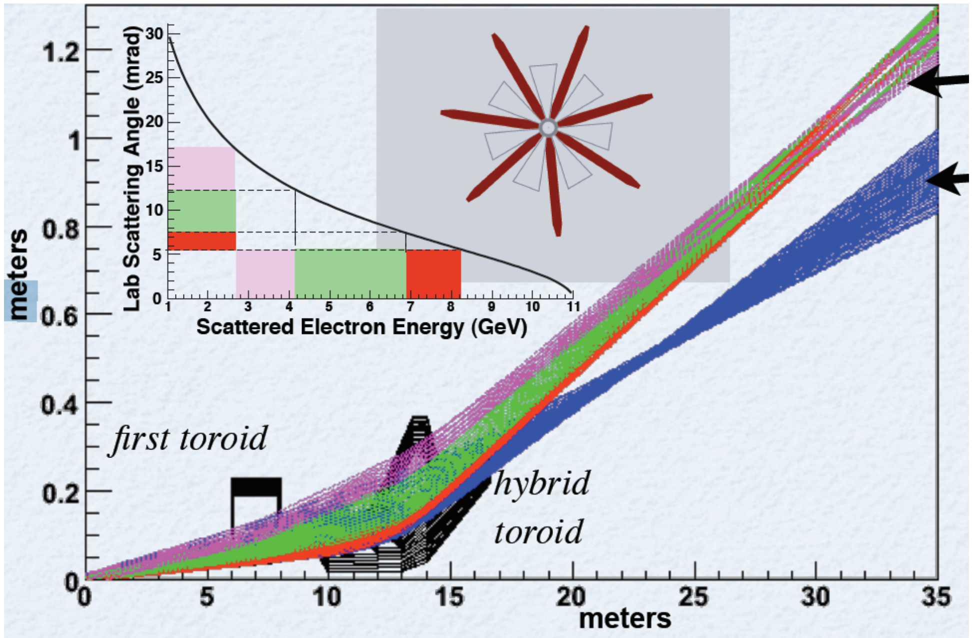




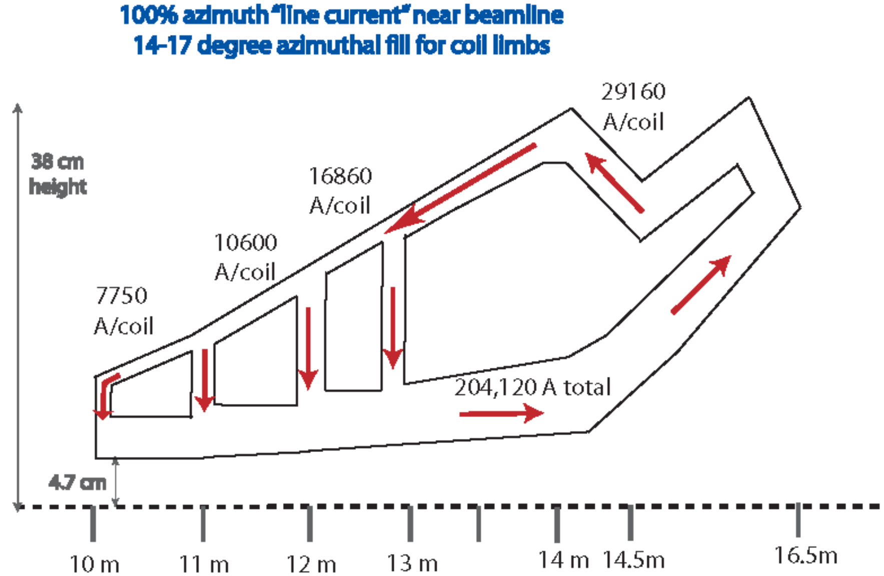


- Accept all Møller scattered electrons in range Θ_{CM} = 60° – 120°
- Exploit identical particle nature for 100% acceptance; needs odd number of coils

Spectrometer – Signal/Background Separation



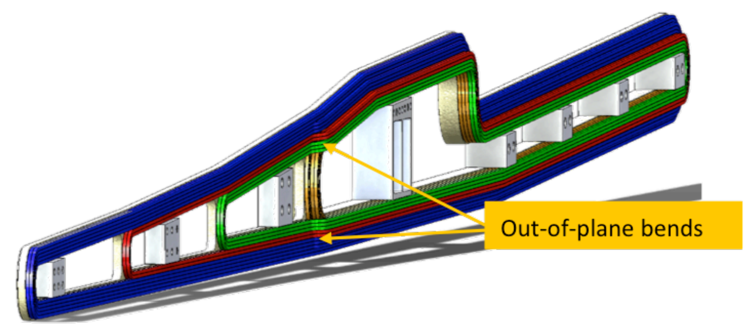
Downstream "hybrid" toroid



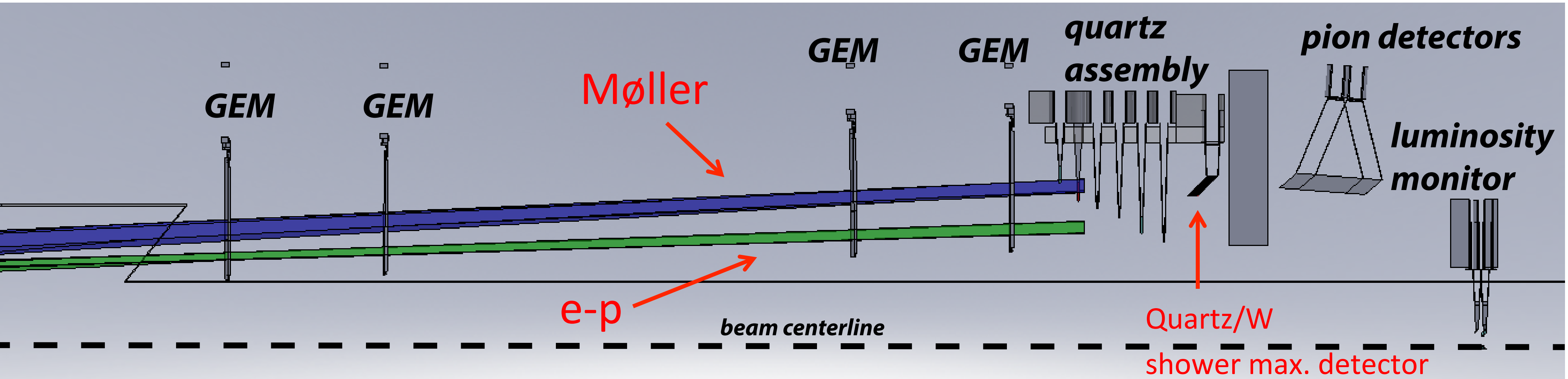
Spectrometer employs a novel two toroid design

- Upstream toroid has conventional geometry
- **Downstream "hybrid" toroid novel design** inspired by the need to focus Møller electrons with wide scattered energy range E' = 1.7 – 8.5 GeV while separating them from Mott (e-p) scattering background

MIT-Bates engineers have produced a buildable coil design and have designed coil carriers, mounting struts, frame, and vacuum chamber for the hybrid torus



Detectors Overview

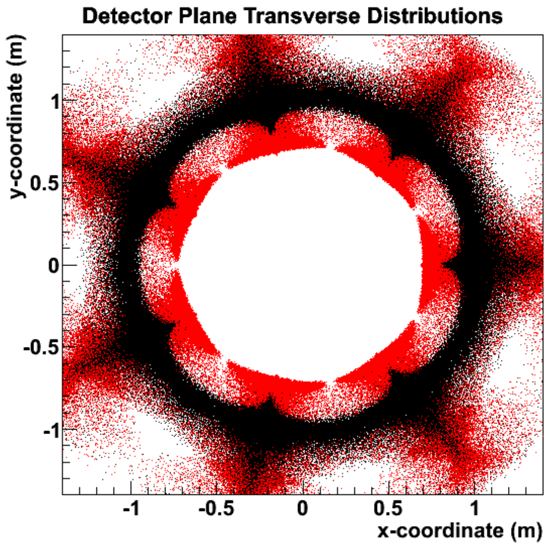


- **Integrating (current mode) detectors**: asymmetry measurements of both signal and background, and beam and target monitoring.
- **Tracking (counting mode) detectors**: spectrometer calibration, electron scattering angle distribution and background measurements.

Quartz	A_{PV} measurements for Møller, elastic and inelastic e-p events
Quartz/W	Shower max. detector, provides a second, independent measurement of Møller peak
Pion detector	Pb-glass and two GEM planes for hadronic dilution/asymmetries
Lumis	monitor for target density fluctuations, false asymmetries
GEMS	backgrounds, kinematics, spectrometer diagnostics

Detector Plane Segmentation

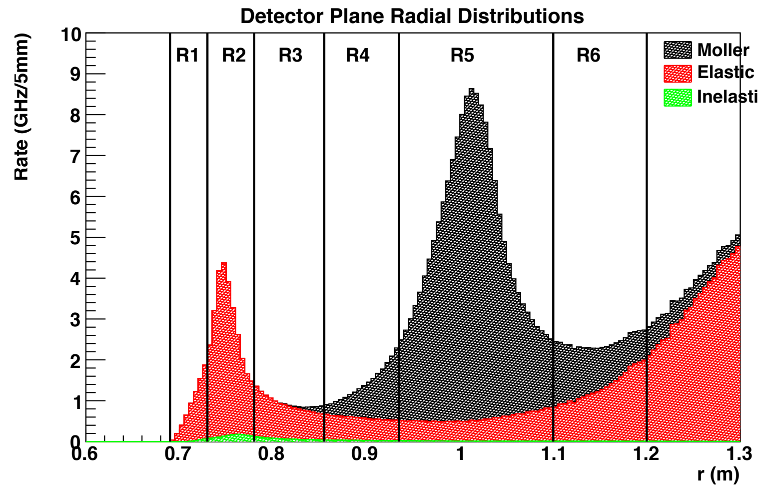
Quartz Cerenkov detectors will have radial and azimuthal segmentation



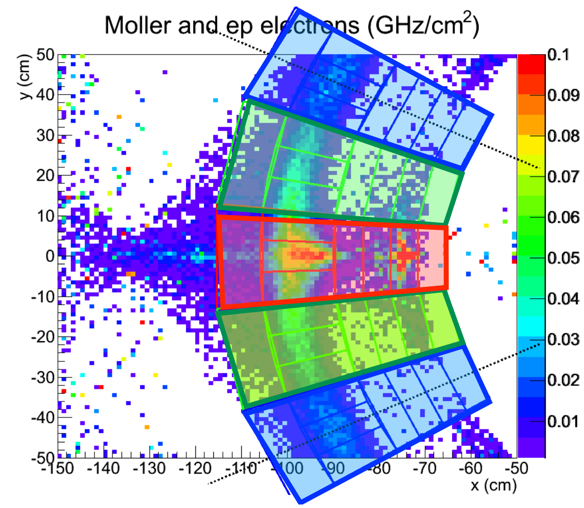
Azimuthal defocusing –

Different φ, different θ_{CM} bins

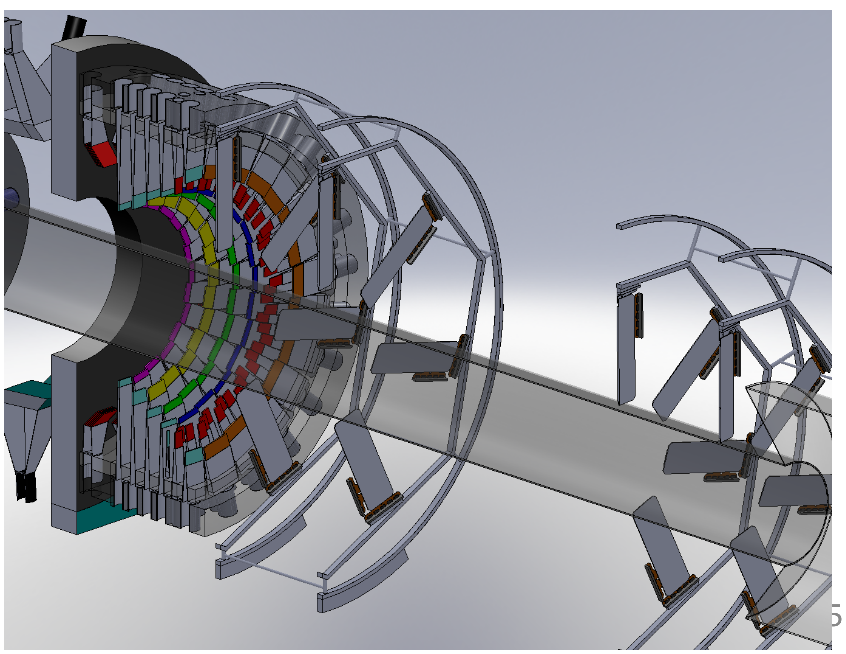
Detector Plane Radial Distribution



Main Moller peak in Region 5



Proposed Segmentation



28 azimuthal channels per radial bin

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

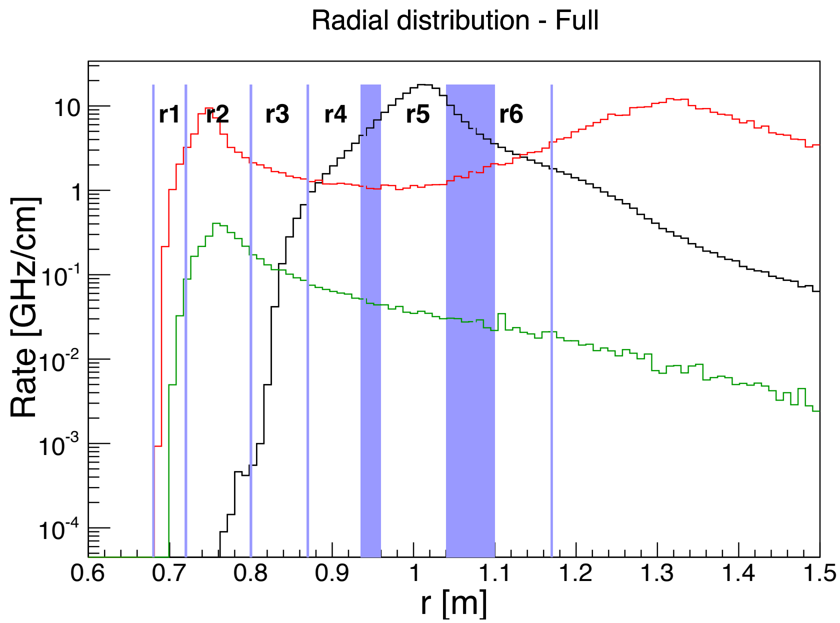
224 total channels

Rate per channel ~ few MHz – GHz

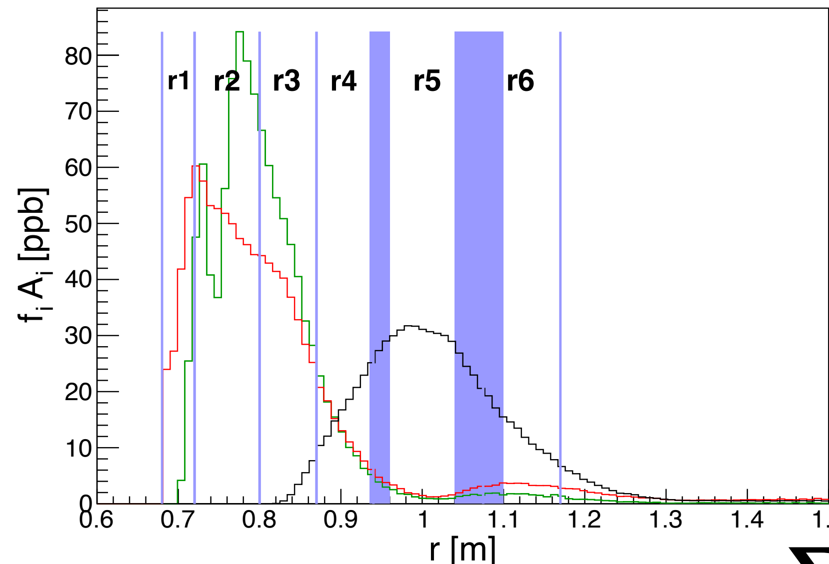
(**overall rate ~ 159 GHz**)

Measurement of Background Asymmetries/Dilutions

Radial rate distribution



Radial f_i A_i distribution: Contributions to A_{PV}



$$A_{meas} = \sum_i f_i A_i$$

Color coding: Møller: black, elastic e-p: red, inelastic e-p:green

Radial binning of measurements – measurement of background asymmetries under "Møller peak"

- Elastic e-p: ~8.9% of signal; asymmetry well known
- Inelastic e-p: <0.5% of signal but asymmetry ~ x20 larger and not well known

⟶ The asymmetry weighted inelastic contribution dominates rings 2 and 3, so it will be measured there

MOLLER Complementarity to LHC

- **If LHC sees ANY anomaly in Runs 2 or 3 (~2022)**
  - **The unique discovery space provided by MOLLER will become a pressing need, like other sensitive probes (eg. *g-2* anomaly)**

- **If LHC observes no anomaly in next decade, MOLLER sensitive to discovery scenarios beyond LHC signatures**
  - **Hidden weak scale scenarios (eg. compressed supersymmetry)**
  - **Lepton number violating amplitudes**
  - **Light dark matter mediators**
  - **…**

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

Timeline: Past and Future

Past:

- JLab PAC approval Jan. 2009, JLab Director's review Jan. 2010
- JLab PAC37 Ranking/Beam Allocation Jan. 2011 (A rating, 344 PAC days)
- DOE Science Review of MOLLER Experiment – Sept. 2014
  - Report received at lab recently; excerpts:
  - *"… NP concludes that the proposed MOLLER experiment has very strong scientific merit. …. Purely leptonic … is well motivated … would be of high scientific impact … "*
  - *"… theoretical cleanliness … makes it unique among the low-Q^2 probes of the SM"*
  - *"Significant progress … in design of the liquid hydrogen target...; novel design of the hybrid toroidal magnetic spectrometer is impressive."*
  - *"…experimental collaboration is strong with world-class experience in previous PV electron scattering experiments."*
  - *"…collaboration is bold in setting the new goal…, thorough in examining possible systematic effects."*
  - *"The panelists believe the experiment has the potential to be a flagship effort for JLAB and the NP community."*

Next Steps:

- JLab Director's Technical Feasibility/Cost/Schedule Review planned for Fall 2015
- DOE Technical Feasibility review potentially late in 2015

Summary

- Parity-violating electron scattering provides stringent low energy tests of the Standard Model

- **Qweak Experiment:** Parity-violating elastic e-p scattering

  - First result: PRL **111**,141803 (2013)

  - based on just 4% of data taken

  - first determination of proton's weak charge

  $Q_W^p\text{(PVES)} = 0.064 \pm 0.012 \qquad Q_W^p\text{(SM)} = 0.0710 \pm 0.0007$

  - final result using full dataset expected early next year

- **MOLLER Experiment:** Parity-violating elastic e-e scattering

  - new initiative being developed for Jlab

  - anticipated 0.1% precision on weak mixing angle

  - sensitive down to 10^{-3} G_F ; mass scales to $\Lambda/g \sim 7.5$ TeV

  - best discovery reach for flavor and CP conserving process over next decade

The Qweak Collaboration

97 collaborators **23 grad students**
10 post docs **23 institutions**

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[10] TRIUMF
[11] Hampton University
[12] Mississippi State University
[13] Virginia Polytechnic Institute & State Univ
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Spokespersons **Project Manager** **Grad Students**

Funded by DOE, NSF, NSERC

The MOLLER Collaboration

~ 35 institutions, ~ 115 people

The MOLLER Collaboration

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