Parity-Violating Electron Scattering as a Test of the Standard Model

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Virginia Tech
Blacksburg, Virginia, USA

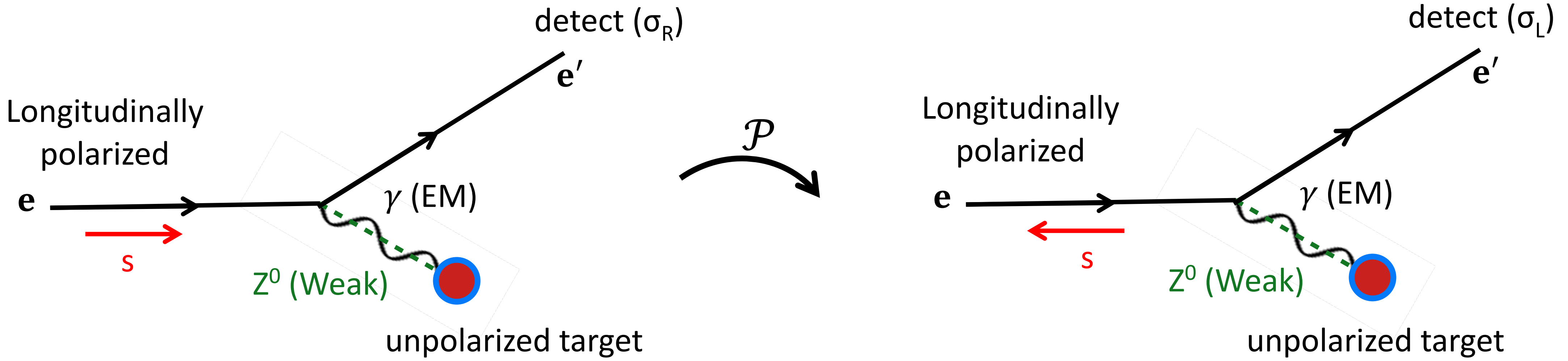
14th Conference on the Intersections of Particle and Nuclear Physics

Outline

- Parity-violating electron scattering (PVeS) introduction
- History of PVeS experiments
- Electron scattering off electrons, protons, and quarks
  - Program to Search for New Neutral Current Interactions Beyond the Standard Model
  - Brief Review of Past Measurements
  - The Future: MOLLER, P2 and SoLID
- Summary and outlook

Parity-Violation in Electron Scattering

- Scattering of longitudinally polarized electrons from unpolarized targets.



- **We change electron's helicity to mimic parity operation.**

- **Asymmetry (A_{PV}) of the detected rates between the beam's opposite helicity states.**

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad \text{where } \sigma \sim |\mathcal{M}_\gamma + \mathcal{M}_{Z^0}|^2$$

- At $Q^2 \ll (M_{Z^0})^2$, A_{PV} is dominated by the interference between the weak and electromagnetic amplitudes.

$$A_{PV} \approx \frac{2\mathcal{M}_\gamma (\mathcal{M}_{Z^0})^*}{|\mathcal{M}_\gamma|^2} \sim 10^{-5}.\, Q^2 \text{ to } 10^{-4}.\, Q^2$$

PVeS Technique (SLAC E122 Experimental Blueprint)

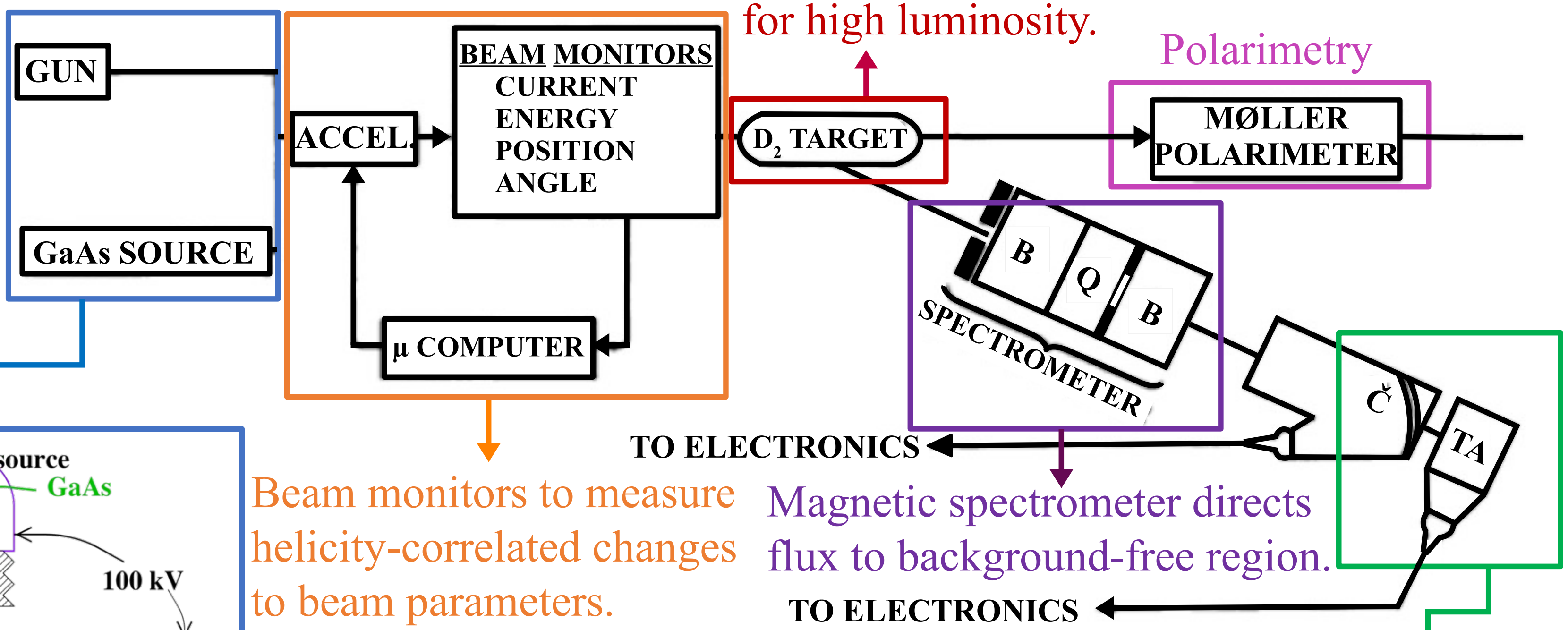
First observation of PV in weak neutral current

Published:
Phys. Lett. 77B, 347 (1978)
Phys. Lett. 84B, 524 (1979)

$\sin^2\theta_W = 0.224 \pm 0.020$

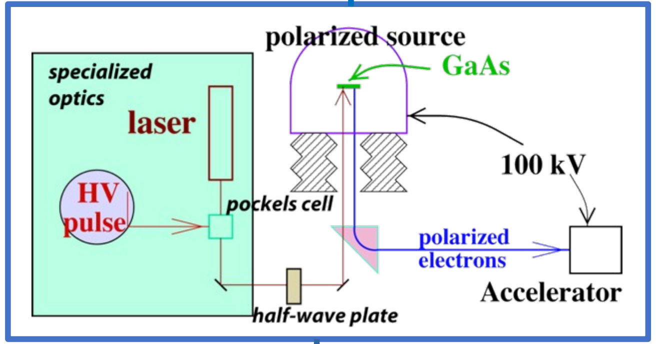
High-power cryotarget for high luminosity.

Polarimetry

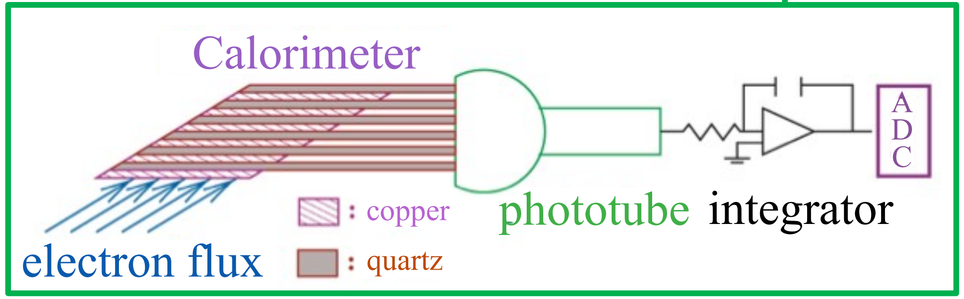


Beam monitors to measure helicity-correlated changes to beam parameters.

Magnetic spectrometer directs flux to background-free region.

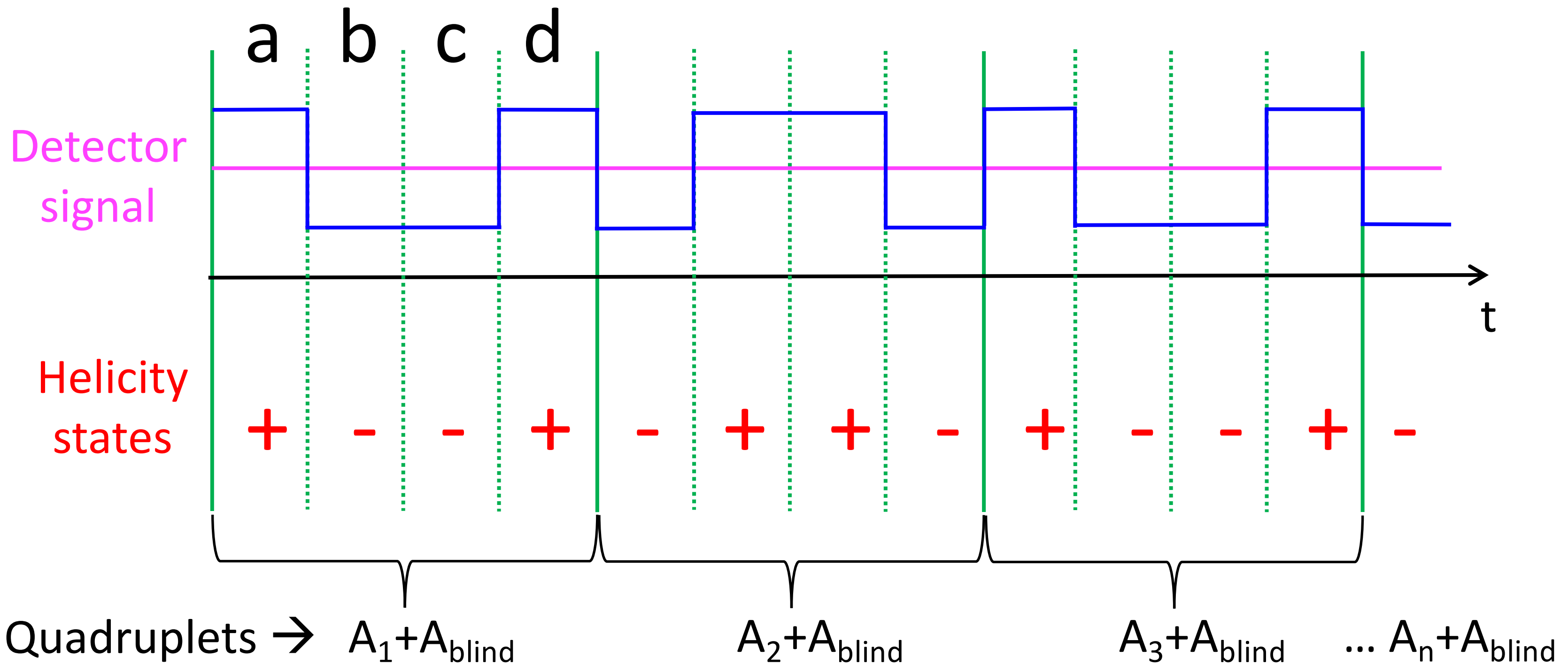


High intensity beam using new GaAs photocathode.



Flux integration measures high rate without dead-time.

PVeS Technique Contd.



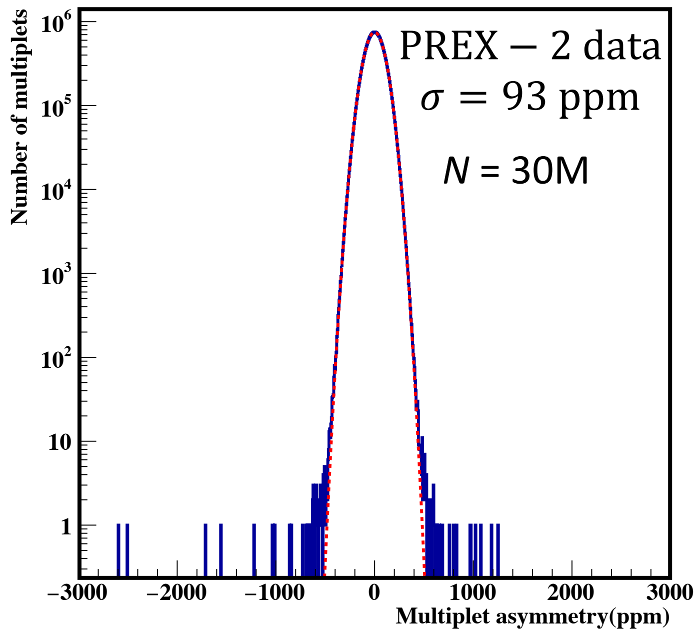
$$A_1 = \frac{(a+d)-(b+c)}{a+b+c+d}$$

Measure flux F for each helicity window

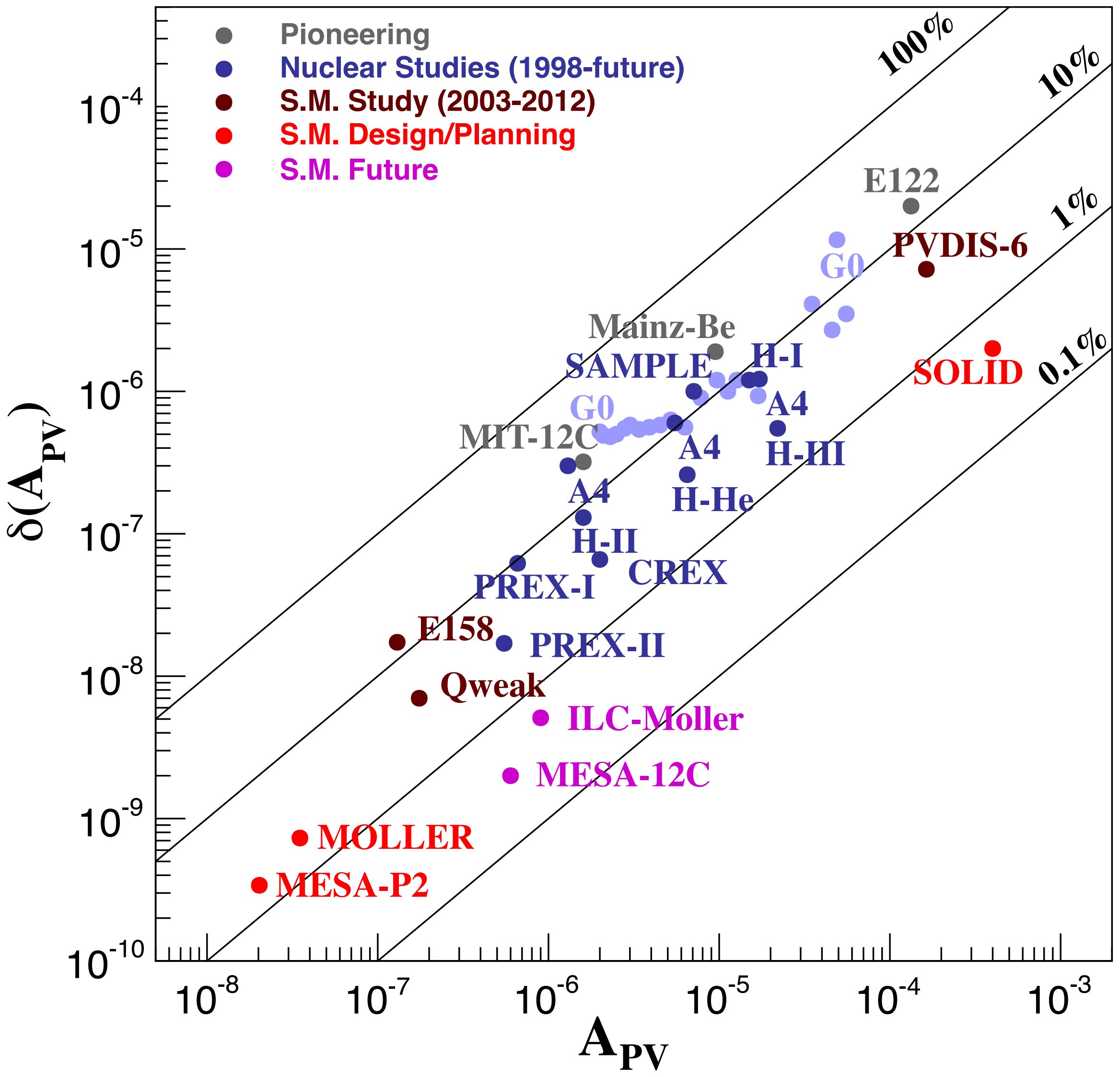
$$A_{pair} = \frac{F_R - F_L}{F_R + F_L}$$

For N window pairs: $A \pm \frac{\sigma}{\sqrt{N}}$

For MOLLER, N = 30B



Historical Perspective of PVeS



- E122 – 1st PVeS exp. (late 70's) at SLAC
- E158 – PV in Møller scattering at SLAC (2005)
- Significant improvement over time:
  - ➢ Photocathodes
  - ➢ Polarimetry
  - ➢ Cryotargets
  - ➢ Beam stability to nanometer level
  - ➢ Low noise electronics
  - ➢ Radiation-hard detectors

PVeS has become a precision tool!

- Beyond standard model searches
- Strange quark form factors
- Neutron skin of a heavy nucleus
- QCD structure of the nucleon

State-of-the-art:

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

Modern Electroweak Physics

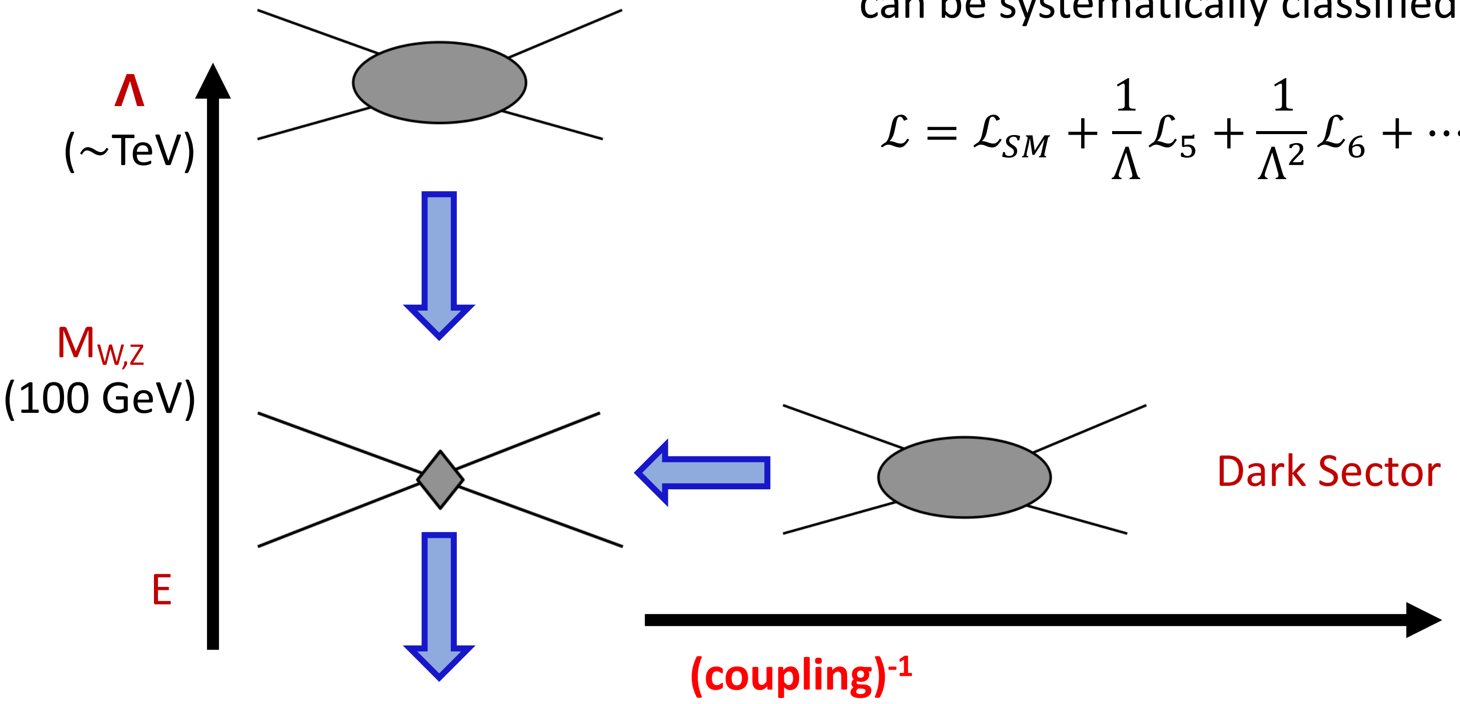
- Unraveling "New Dynamics" in the early universe
  - How did nuclear matter form and evolve?
- Nuclear Physics Initiatives:
  - Low Energy → $Q^2 \ll M_Z^2$

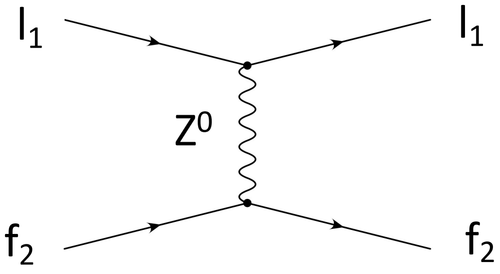
High Energy Dynamics:

Higher dimensional operators can be systematically classified

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

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





Leptonic and semileptonic weak neutral current interactions

Search for new flavor diagonal neutral currents

Tiny yet measurable deviations from precisely calculable SM processes

must reach Λ ~ 10 TeV

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

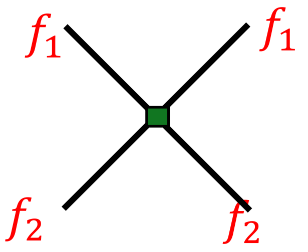
$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

Weak Neutral Current Couplings

In GWS model, the weak neutral current $V-A$ couplings to the Z^0 are:

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

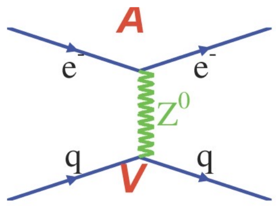
+ New Physics



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

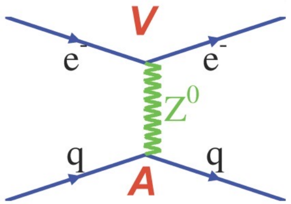
For $Q^2 \ll M_{Z^0}^2$, restrict to $e-q$ and $e-e$ four-fermion contact interactions:

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



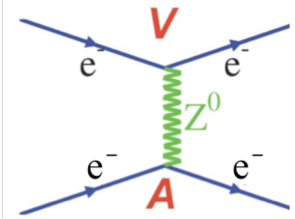
$C_{1i} \equiv 2g_A^e g_V^i$

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



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

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



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

electron: C_{ee}

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

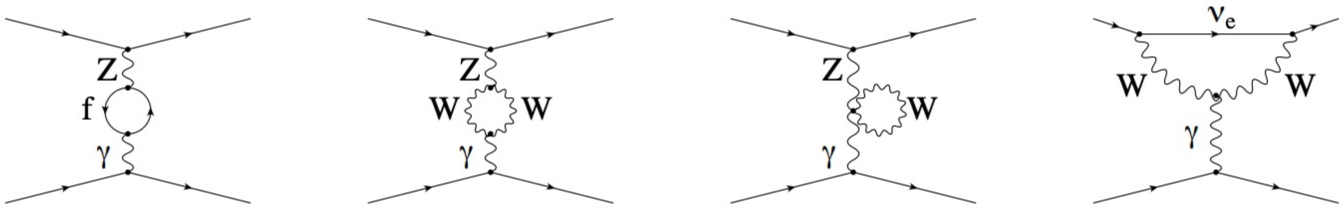
$C_{2q} \propto \left(g_{RR}^{eq}\right)^2 - \left(g_{RL}^{eq}\right)^2 + \left(g_{LR}^{eq}\right)^2 - \left(g_{LL}^{eq}\right)^2$ ➔ PV deep inelastic scattering

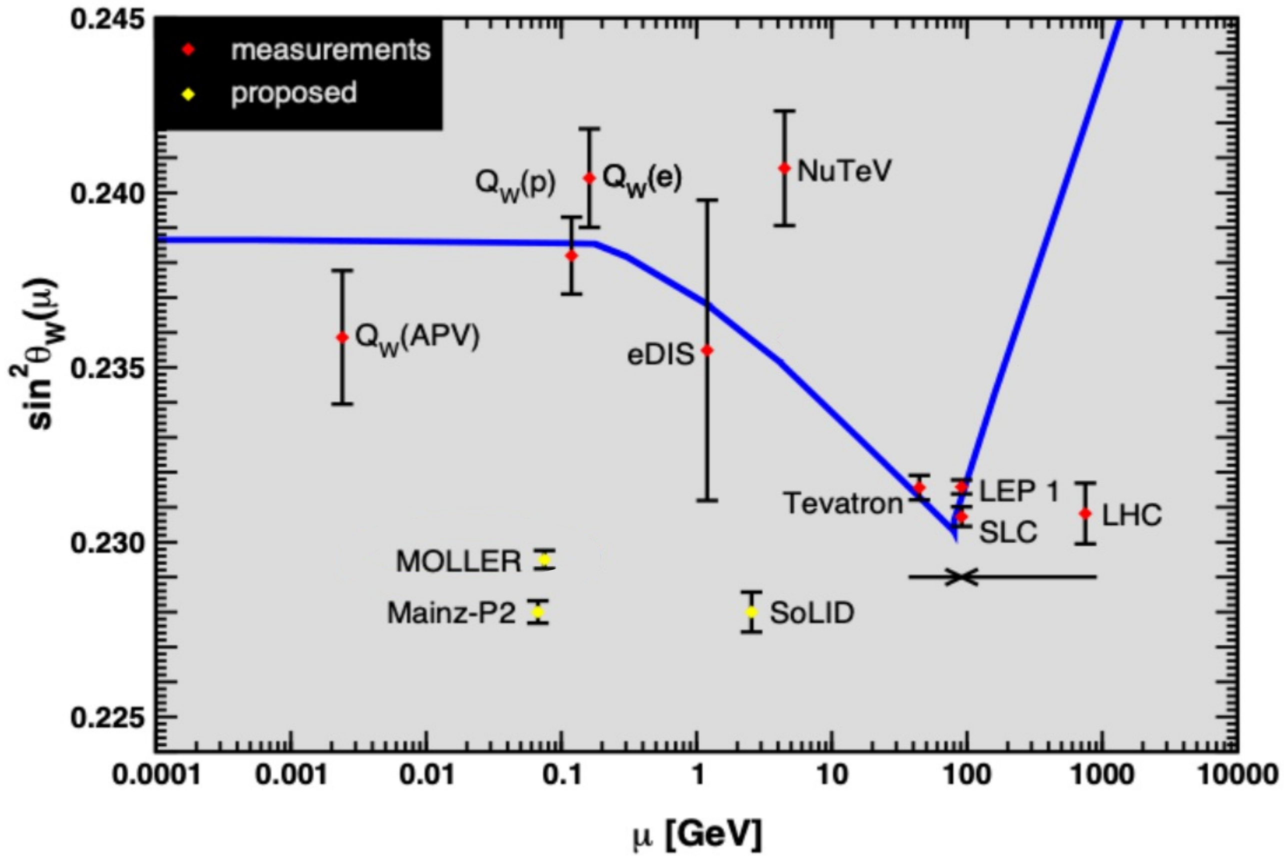
$C_{ee} \propto \left(g_{RR}^{ee}\right)^2 - \left(g_{LL}^{ee}\right)^2$ ➔ PV Møller scattering

Running of the Weak Mixing Angle $\sin^2\theta_W$ – *Standard Model Test*

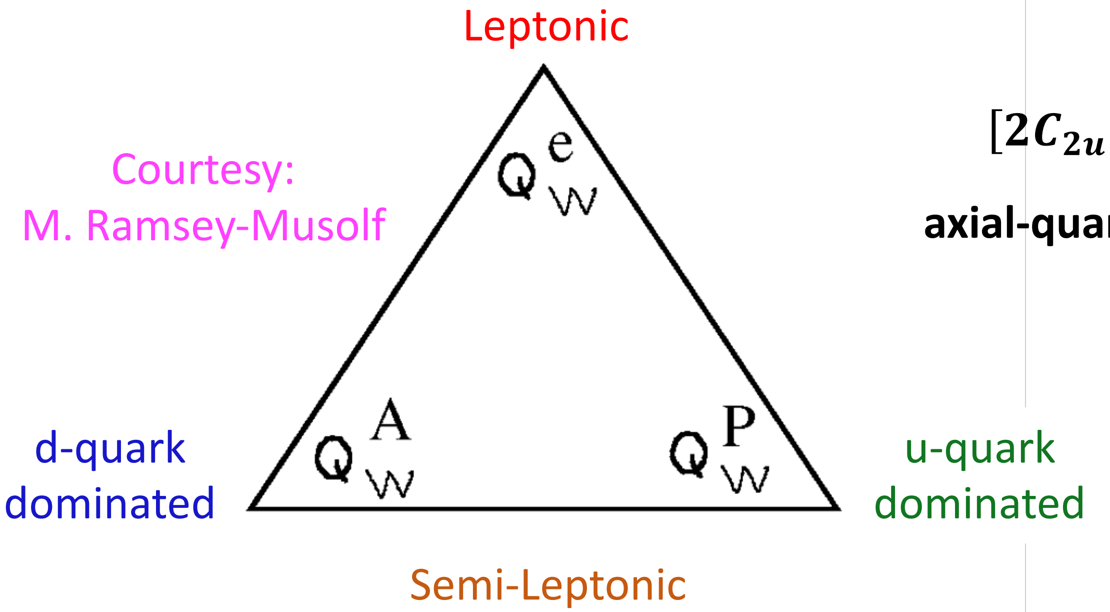
- Atomic Parity Violation (APV): ^{133}Cs
- Neutrino Deep Inelastic Scattering: NuTeV
- Parity-Violating Møller Scattering: E158 at SLAC
  - statistics limited; theory robust
  - next generation: MOLLER; factor of 5 improvement
- Parity-Violating e-p Scattering: Qweak
  - theory robust at low beam energy
  - next generation: P2; factor of 3 improvement
- Parity-Violating Deep Inelastic Scattering: PVDIS
  - theory robust for ^{2}H in valance quark region
  - next generation: SoLID; factor of 5 improvement

Electroweak radiative corrections cause the running of $\sin^2\theta_W$





Low Energy Weak Neutral Current – *Sensitivity to New Physics Models*



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

axial-quark couplings

vector-quark couplings

SUSY Loops → Q_W^e and Q_W^P: same absolute shift, smaller for others

GUT Z' → High for $Q_W(Cs)$, Q_W^e (relative), smaller for others

Leptophobic Z' → axial-quark couplings (C_2's) only

RPV SUSY → Different for all four in sign and magnitude

Leptoquarks → semi-leptonic only; different sensitivities

Lepton Number Violation → Q_W^e only

Fixed Target vs Collider Complementarity for Leptons

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

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

Simultaneous fits to cross-sections and angular distributions

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

95% C.L.

LEP-200

$\Lambda_{LL}^{ll} \sim 12.8$ TeV

$\Lambda_{RR}^{ll} \sim 12.2$ 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

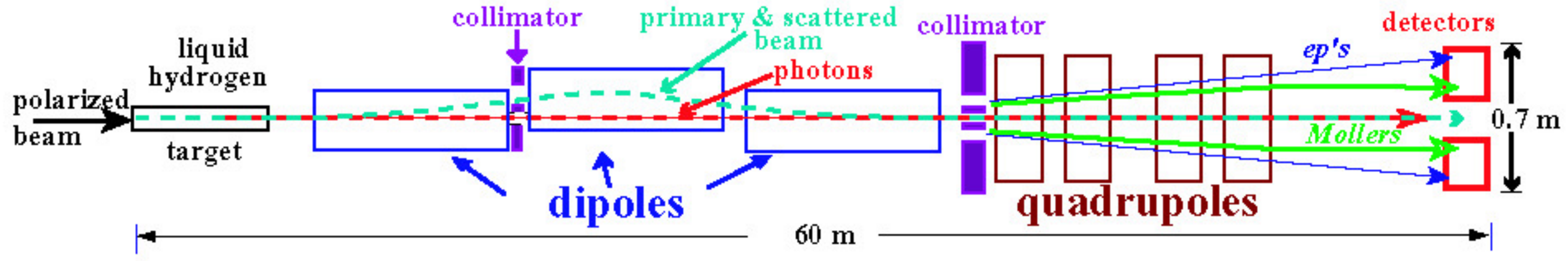
MOLLER Reach

$\Lambda_{LL}^{ee} \sim 27$ 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

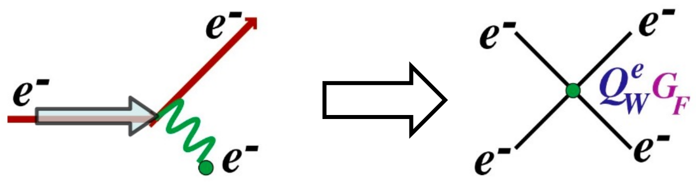
E158 Experiment at SLAC: First Measurement of Q_W^e



Measured at SLAC End Station A

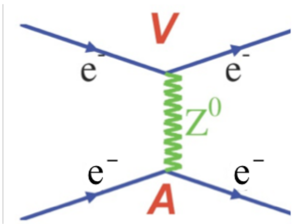
Parameter	Value
E	48 GeV
θ	$4-7$ mrad
Q^2	$0.026\ (\mathrm{GeV}/c)^2$

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



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

$$Q_W^e \equiv -2C_{ee} = -(1-4\sin^2\theta_W)$$



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

electron: C_{ee}

Published: PRL 95 081601 (2005)

$$A_{PV} = -131 \pm 14\ (\mathrm{stat.}) \pm 10(\mathrm{syst.})\ \mathrm{ppb}$$

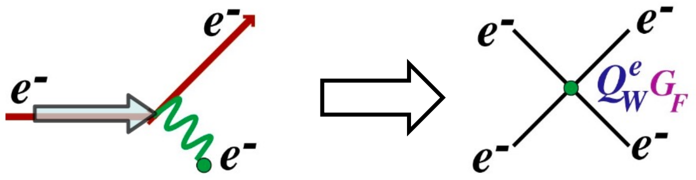
$$Q_W^e = -0.0369 \pm 0.0052$$

$$\sin^2\theta_W^{eff} = 0.2397 \pm 0.0010\ (\mathrm{stat.}) \pm 0.0008(\mathrm{syst.})$$

MOLLER Experiment at JLab

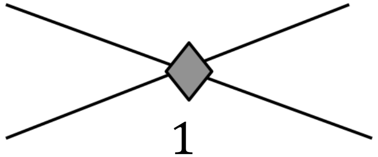
- MOLLER: Measurement Of Lepton Lepton Electroweak Reaction
  - **will have a factor of 5 improvement over E158 measurement**

PV Møller scattering: $\vec{e} + e \rightarrow e + e$



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{4\sin^2\theta}{(3+\cos^2\theta)^2}Q_W^e$$

+



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

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

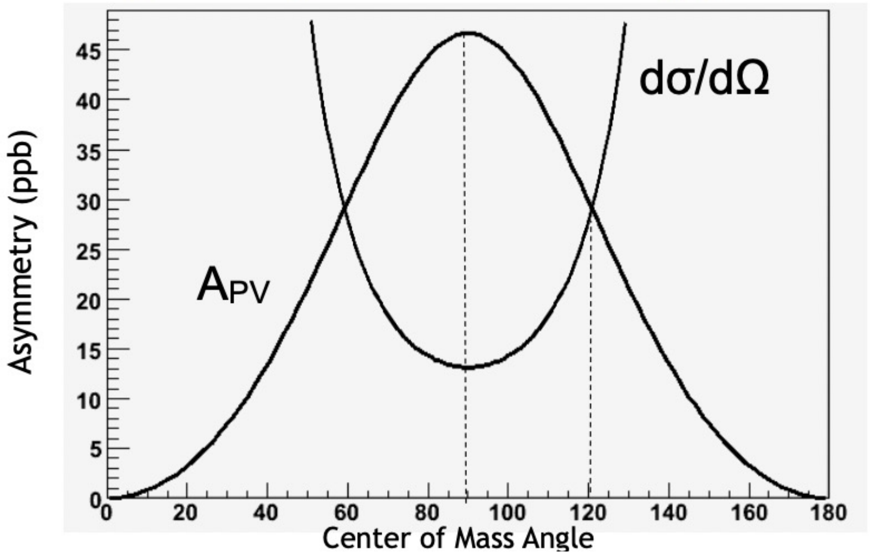
Parameter	Value
E	11 GeV
E'	2 – 9 GeV
θ_{CM}	60° – 90°
Target	125 cm long LH_2
Max. Luminosity	2.4×10^{39} cm^{-2} sec^{-1}
Moller Rate @ 65 μA	134 GHz
Run Time	344 PAC-days
Polarization	≈ 90 %
$< A_{PV} >$	33 ppb

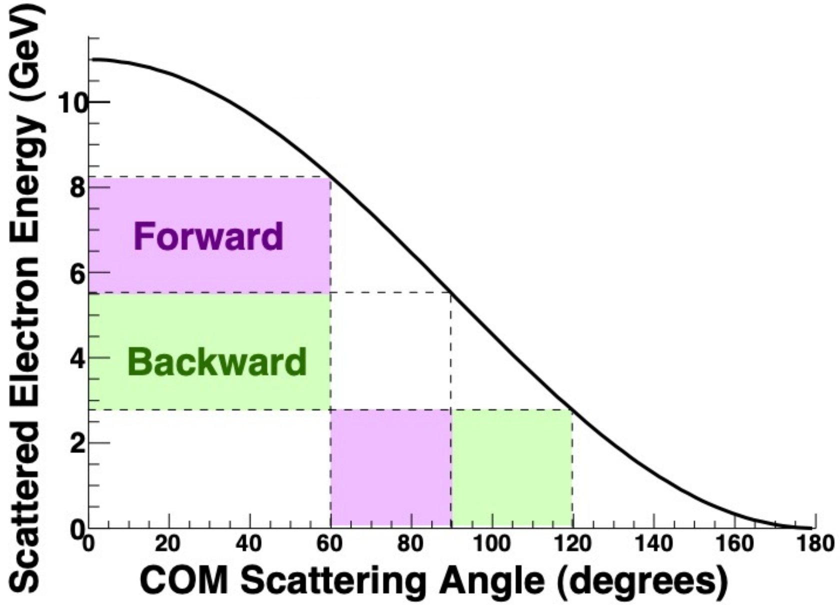
$$\mathcal{L}_{e_1e_2} = \sum_{i,j=L,R}\frac{g_{ij}^2}{2\,\Lambda^2}\bar{e}_i\gamma_\mu e_i\bar{e}_j\gamma^\mu e_j$$

Sensitive up to:

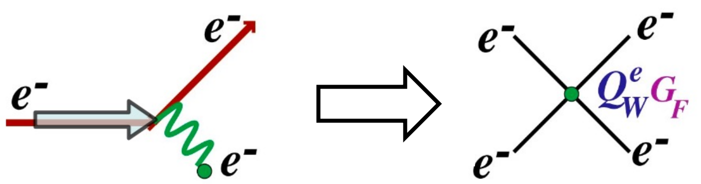
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5\text{ TeV}$$

Highest figure of merit at θ_{CM} = 90°





MOLLER Experiment at JLab

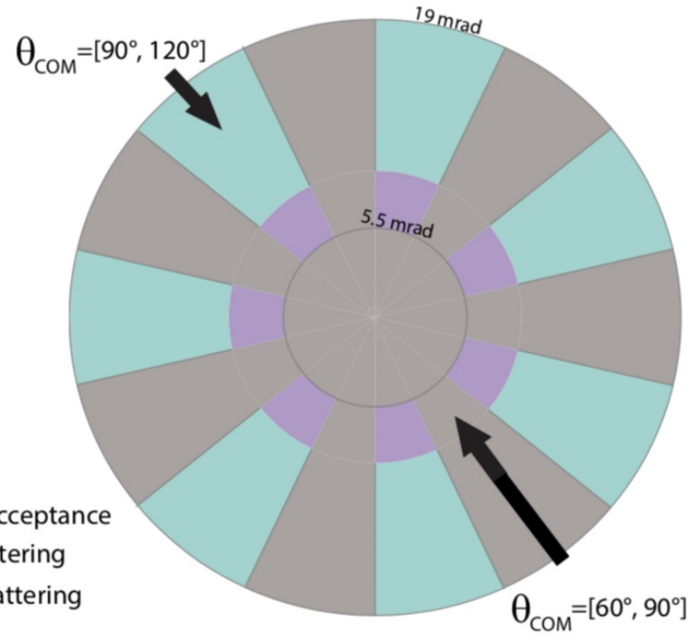


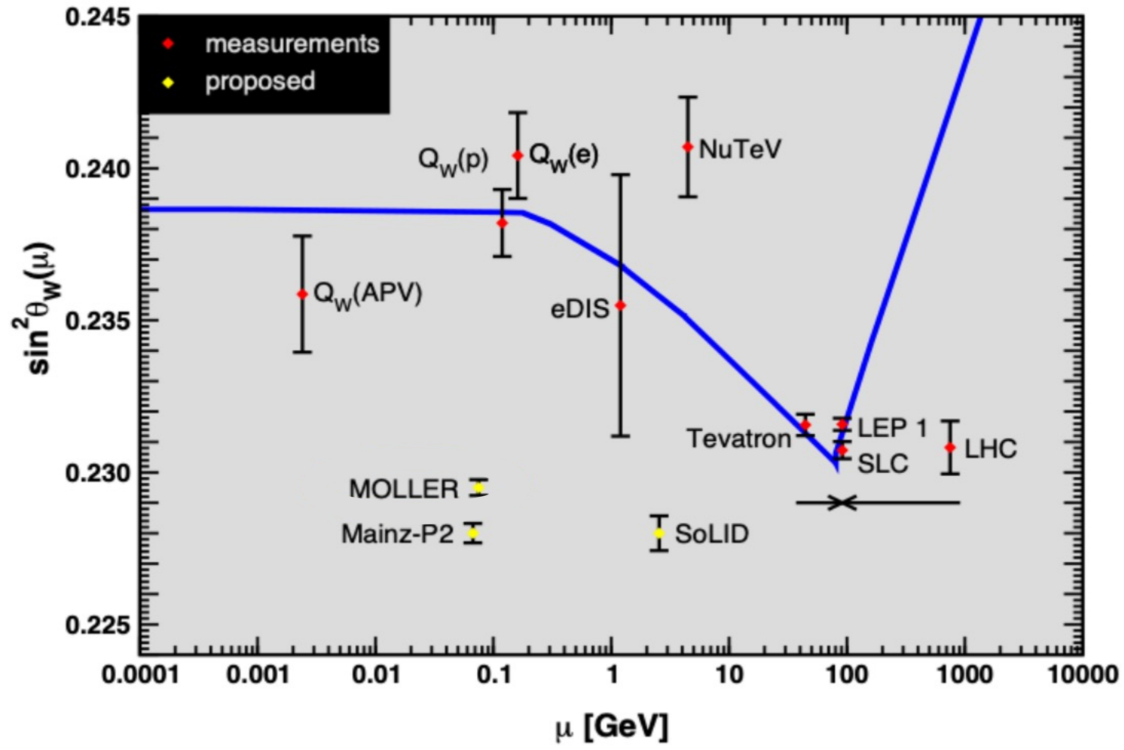
$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\,\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

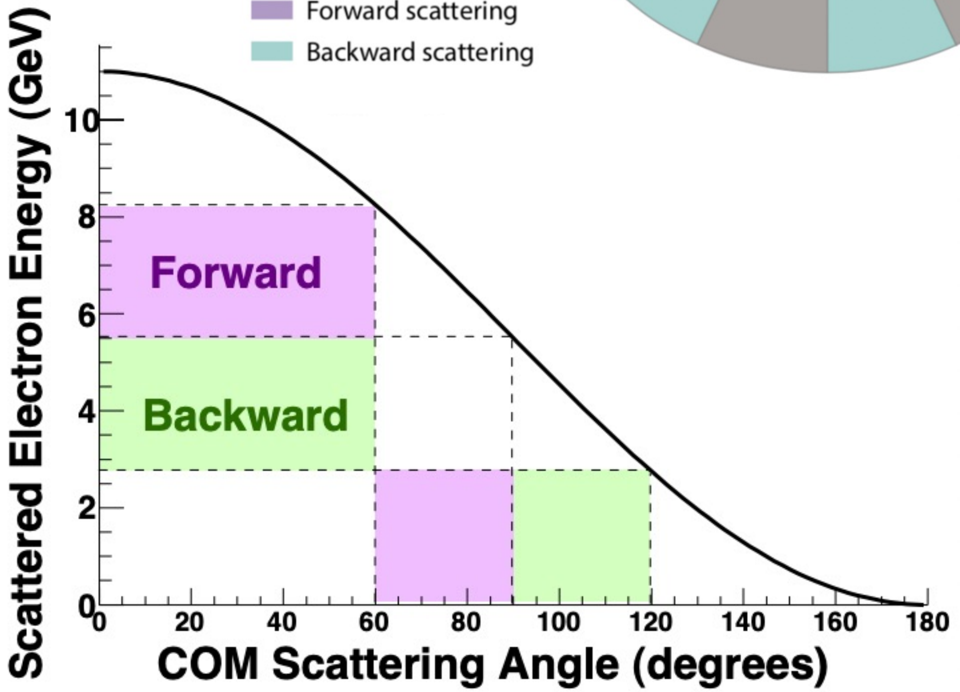
Sensitive up to: $\dfrac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5$ TeV

MOLLER precision:

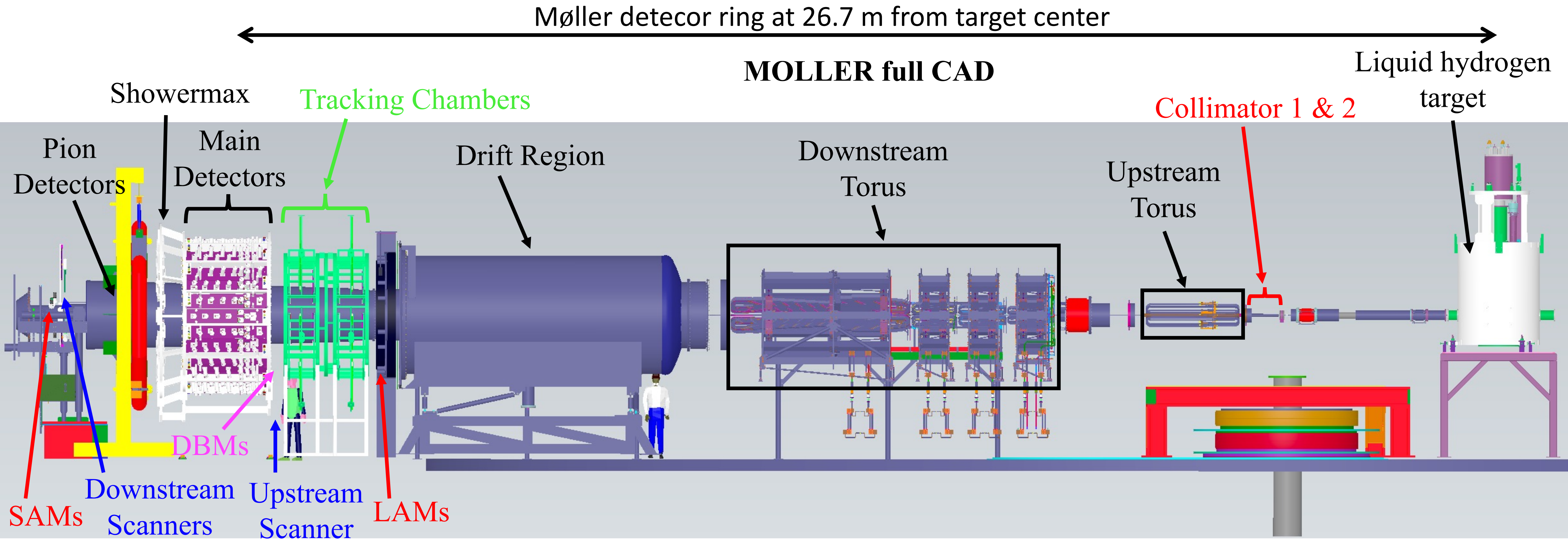
$\delta(\sin^2\theta_W) = \pm 0.00023\ (\text{stat.}) \pm 0.00012\ (\text{syst.}) \Longrightarrow 0.1\ \%$







MOLLER Equipment



~ 48M$ MIE by US DOE; also NSF, CFI funding

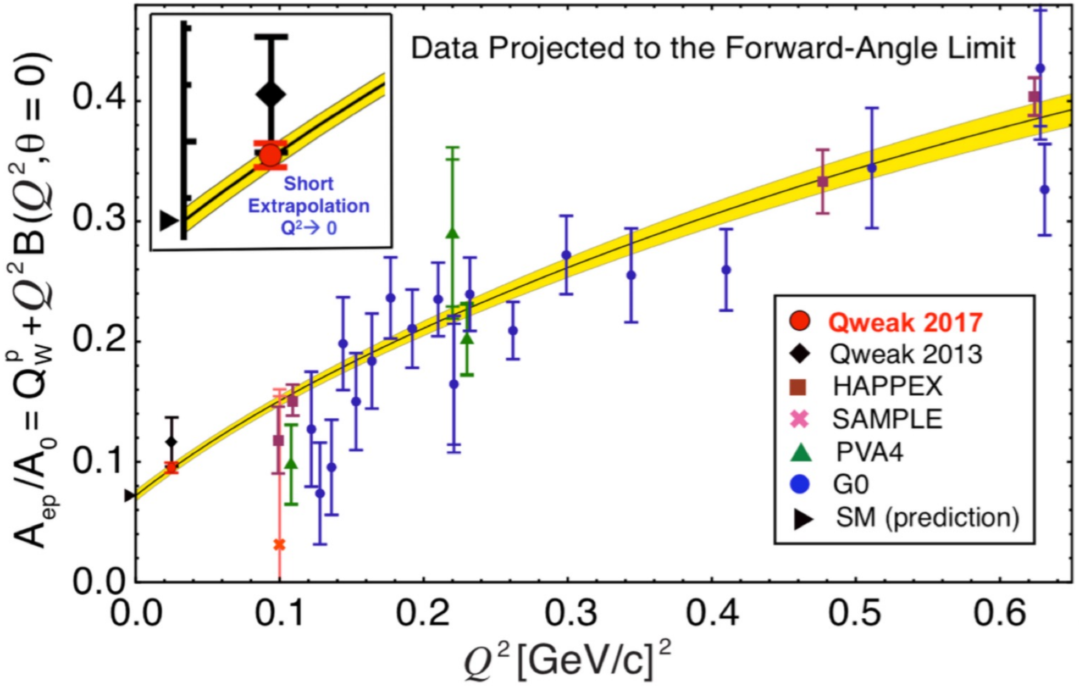
CD-1 granted in Dec 2020

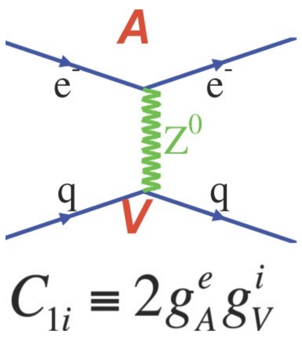
CD-2 early in calendar year 2023

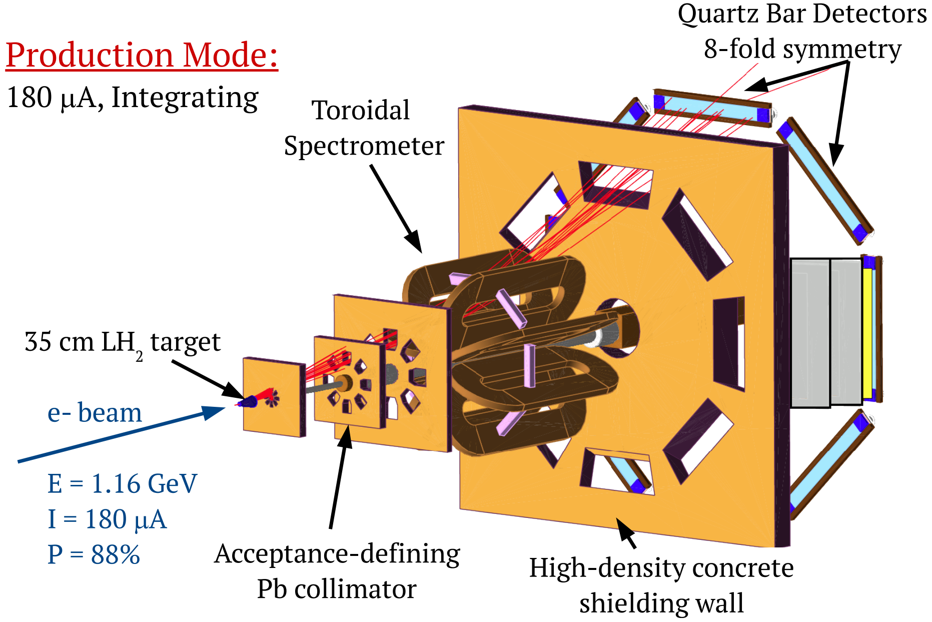
Construction: 2023 - 24

Qweak Experiment at JLab (First Measurement of Q_W^P) and AVP

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







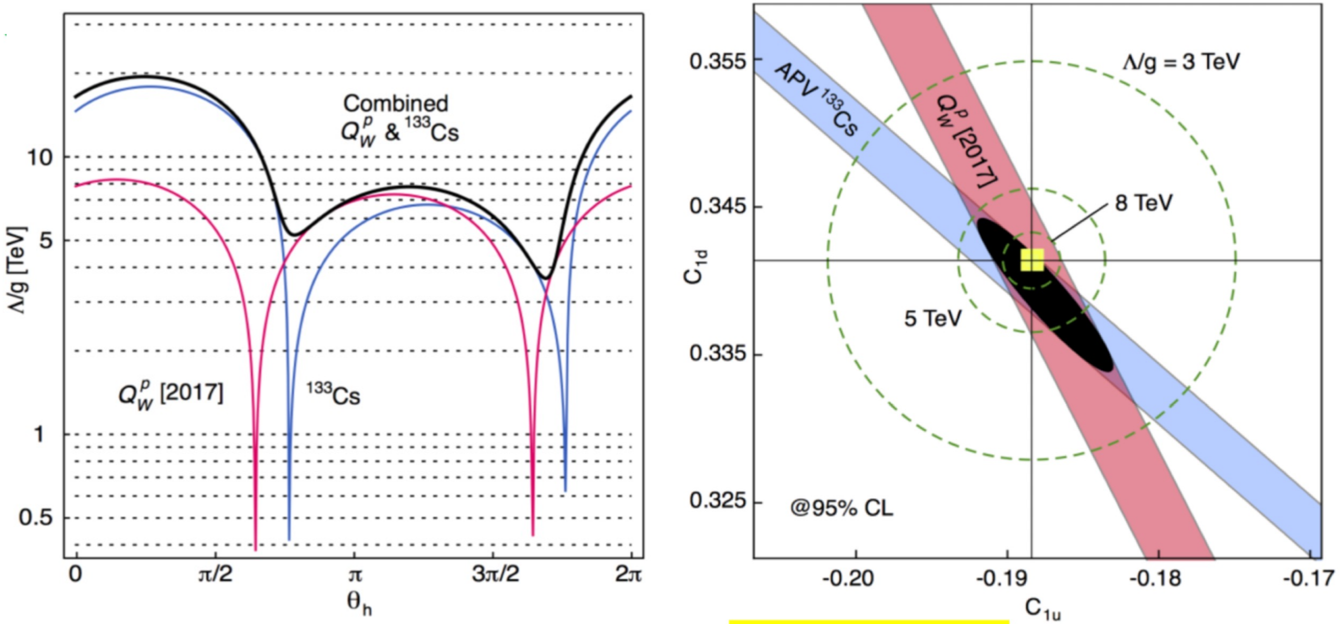
Parity-Violating e-p scattering: $\vec{e}^- + p \rightarrow e + p$

$$A_{PV}^{ep} = -226.5 \pm 7.3\ (\text{stat.}) \pm 5.8\ (\text{syst.})\ \text{ppb}$$

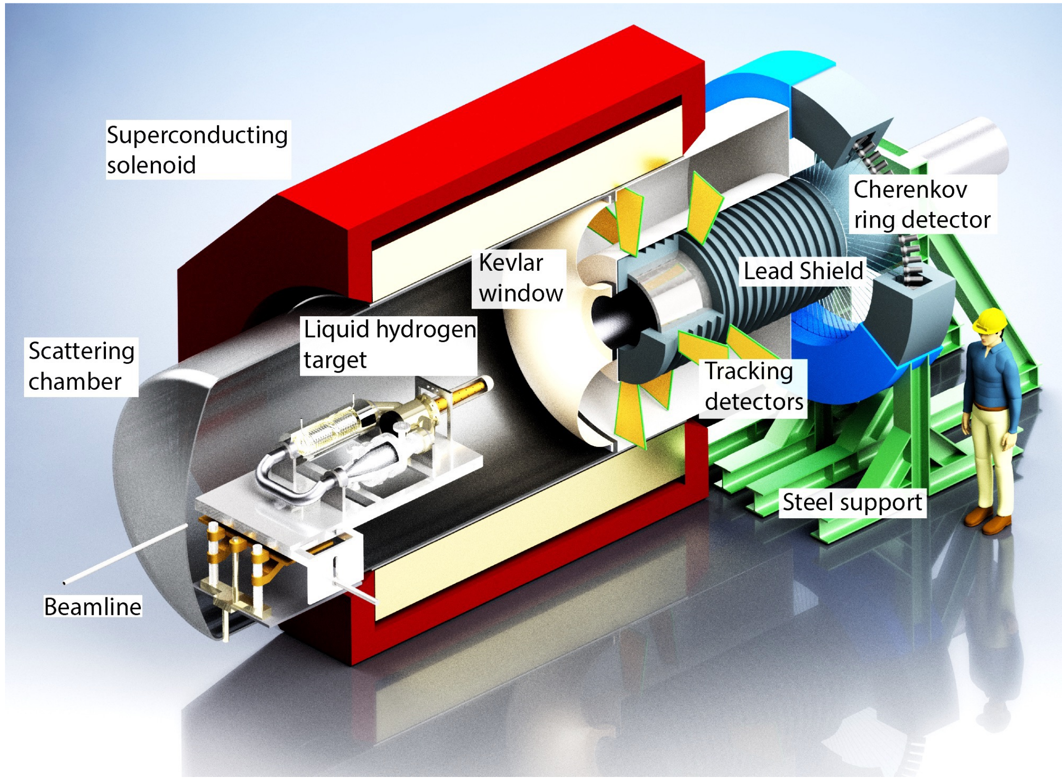
$$A_{PV}^{ep} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}[Q_W^P + Q^2 B(Q^2, \theta)]$$

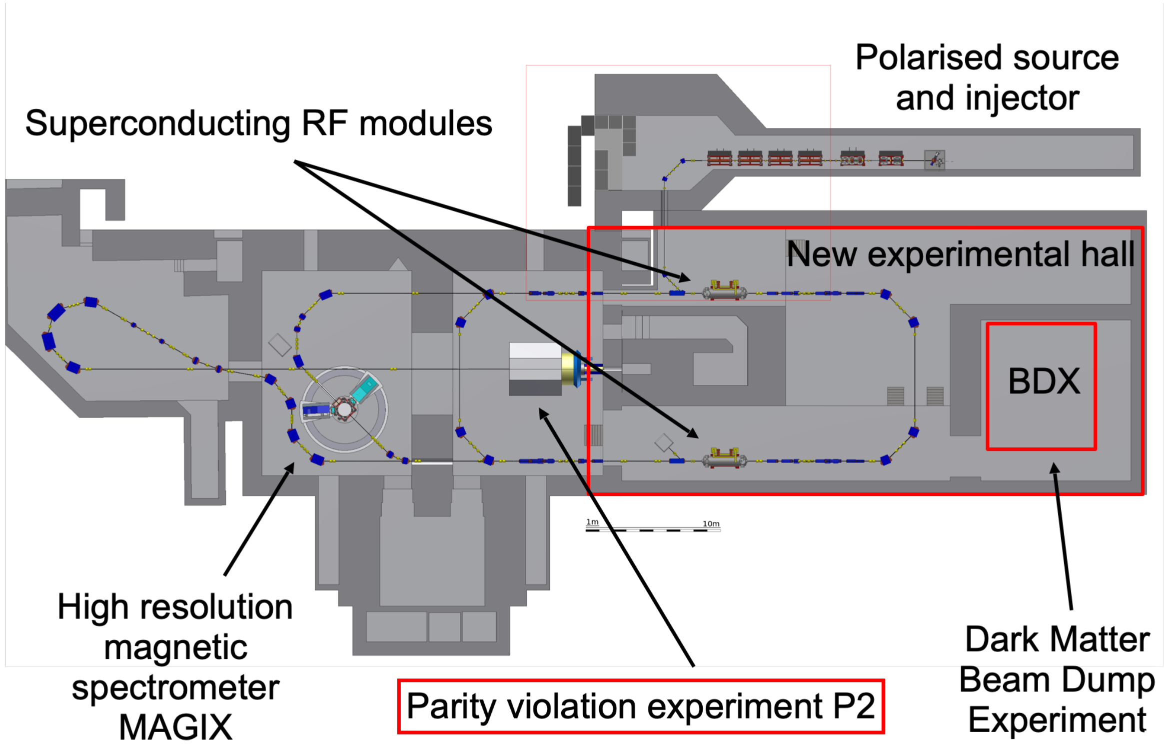
$$Q_W^P = -2[2C_{1u} + C_{1d}] = 1 - 4\sin^2\theta_W$$
$$= 0.0719 \pm 0.0045$$

$$\sin^2\theta_W = 0.2382 \pm 0.0011$$



P2 Experiment at MESA





Parity violating e-p elastic scattering at

$$Q^2 = 4.5\times10^{-3}\left(\frac{\text{GeV}}{\text{c}}\right)^2$$

Measures the weak charge of proton

$$A_{PV} = -24.03 \pm 0.50\ (\text{stat.}) \pm 0.29(\text{syst.})\ \text{ppb}$$

$$\delta(Q_W^P) = 1.8\%$$

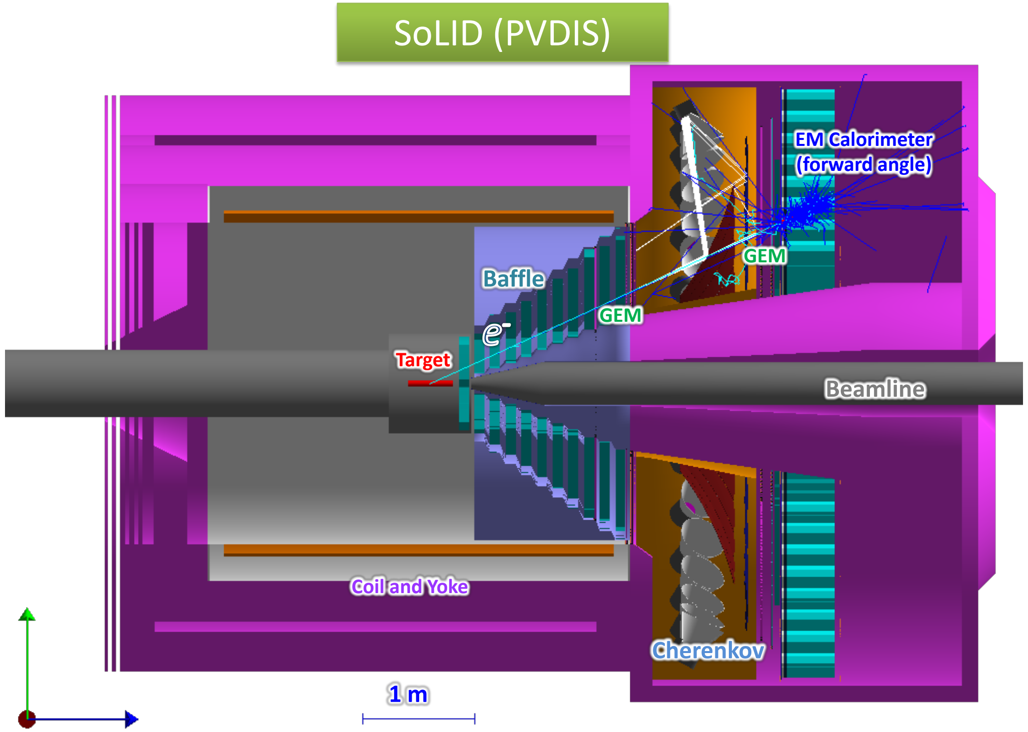
$$\delta(\sin^2\theta_W) = 0.16\ \%$$

Construction 2021-23
Pilot experiments: 2024

Physics Program in 2025-30 with proton, 12C and 208Pb targets

Most precise measurement of parity violating e-p, e-C, and e-Pb scattering

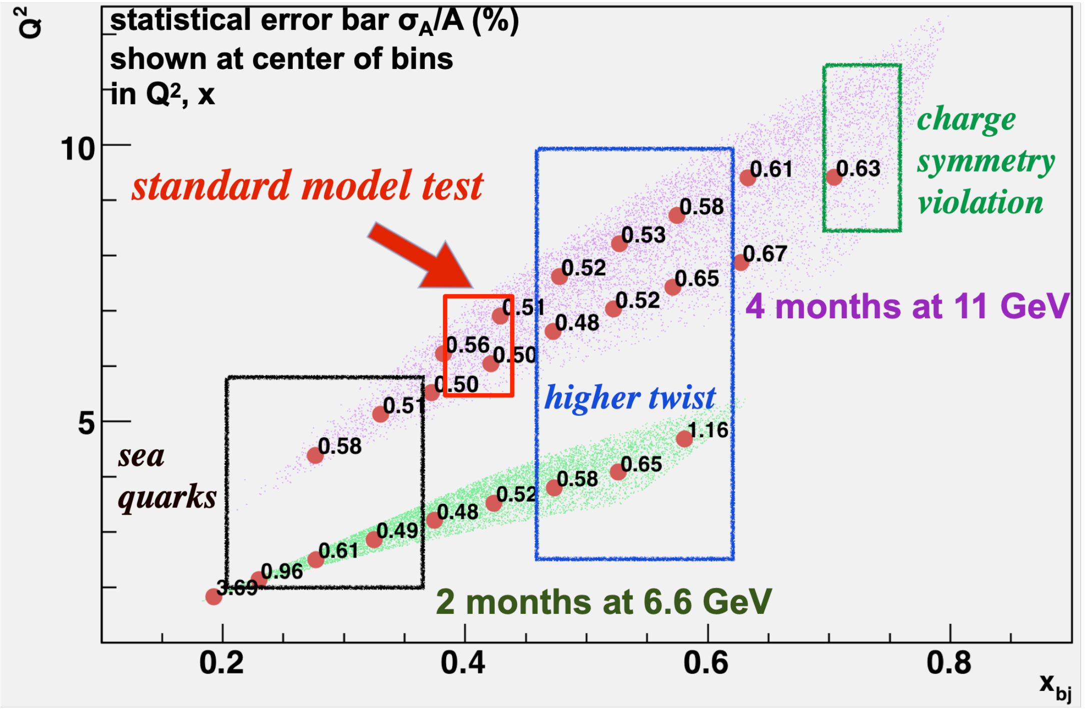
SoLID (PVDIS) Experiment at JLab



electron-deuteron parity-violating deep inelastic scattering

Strategy:

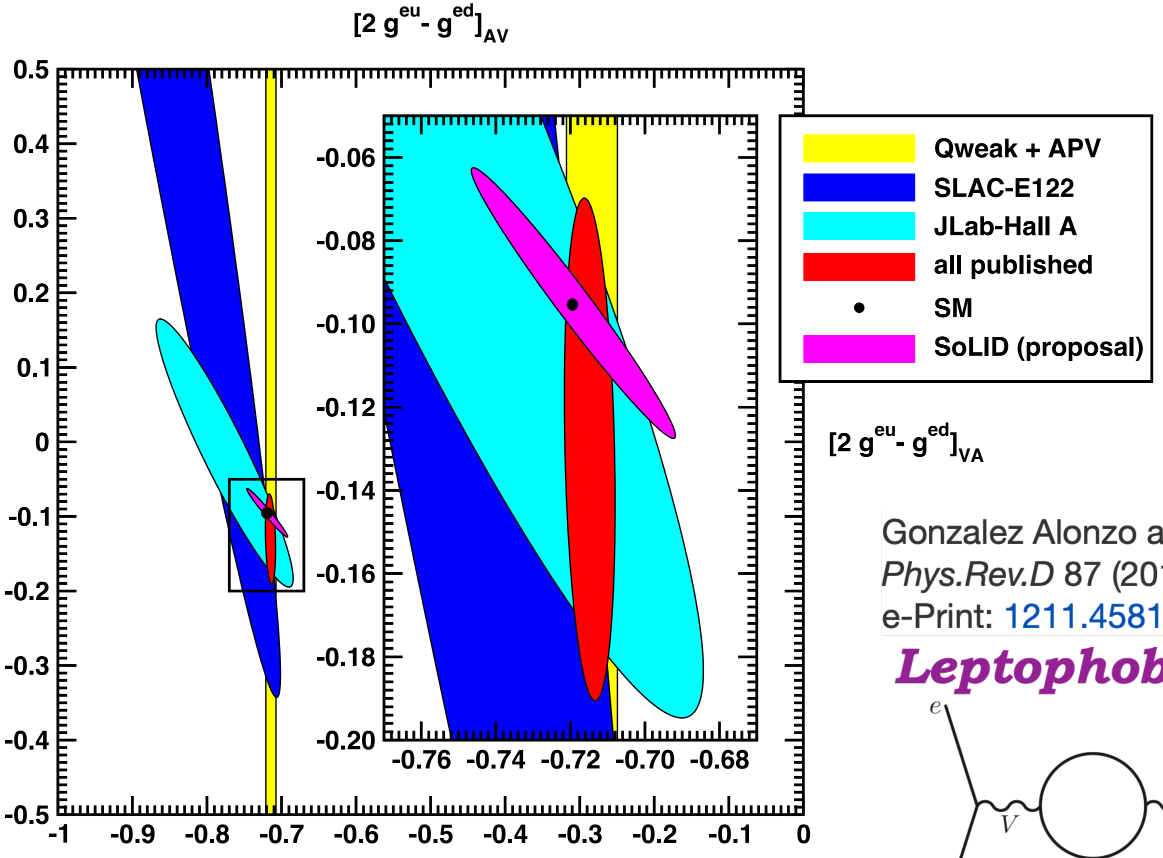
- sub-1% precision over broad kinematic range
- sensitive Standard Model test
- detailed study of hadronic structure contributions



Requirements:

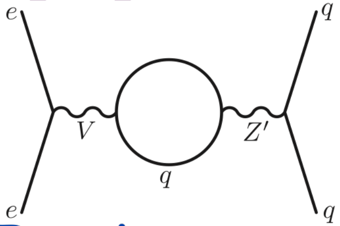
- High luminosity with E > 10 GeV
- Large scattering angles (for high x and y)
- Better than 1% errors for small bins
- x_{bj} range 0.20 – 0.75
- $W^2 > 4$ GeV^2
- Q^2 range a factor of 2 for each x except for very high x
- Moderate running times

SoLID and P2: New Reach on e-q Couplings

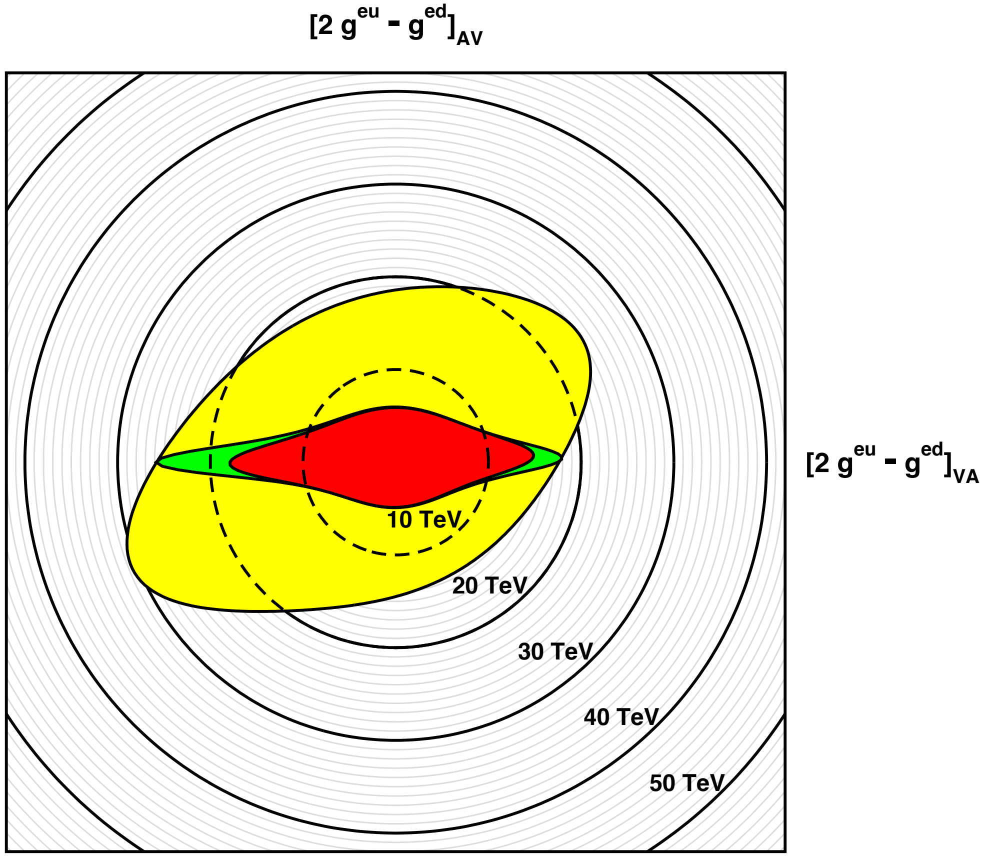


Gonzalez Alonzo and Ramsey-Musolf
Phys.Rev.D 87 (2013) 5, 055013
e-Print: 1211.4581

Leptophobic Z'



SOLID can improve sensitivity: 100-200 GeV range

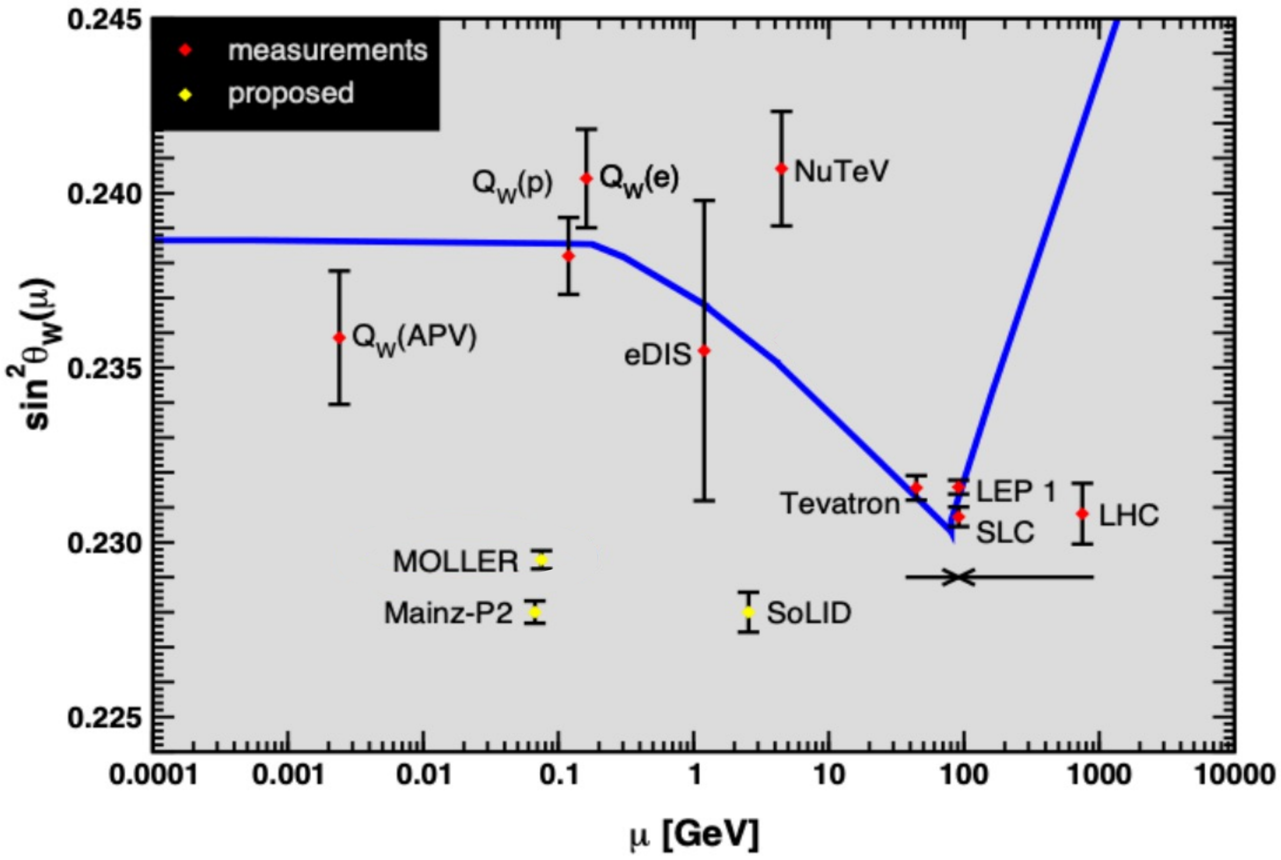


All data
All data + P2
All data + P2 +SoLID

Recent paper explores Z' sensitivity of P2 over a range of masses
B. Dev et al: *JHEP* 06 (2021) 039

Summary and Outlook

- **PVeS has become a precision tool for:**
  - Beyond standard model searches
  - Neutron skin of a heavy nucleus
  - QCD structure of the nucleon
- **Technical progress over time has enabled unprecedented precision**
- **Complementary to collider measurements**



Thank You
🙏

Low Energy Weak Neutral Current – *Standard Model Test*

$C_{1u}, C_{1d}, C_{ee} \rightarrow$ "weak charges" neutral current analog to the electric charge

Q_W^e and Q_W^P are suppressed in SM: increased sensitivity to "New Physics" dynamics

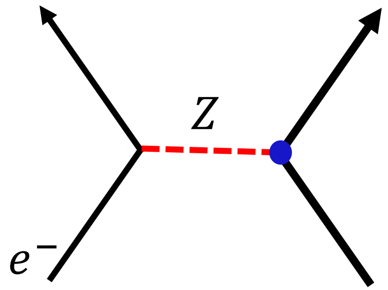
Electron's weak charge:

$$Q_W^e = -2C_{ee} = -(1 - 4\sin^2\theta_W)$$

Parity-Violating Møller scattering:

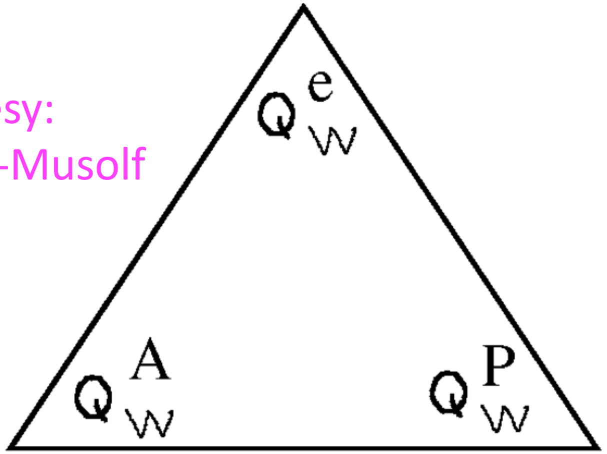
$$\vec{e}^- + e \rightarrow e + e$$

Published: SLAC E158 $\sim 13\%$ on Q_W^e



Leptonic

Courtesy:
M. Ramsey-Musolf



d-quark dominated

u-quark dominated

Semi-Leptonic

Neutron's weak charge:

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

Atomic parity violation (APV)

Published: ^{133}Cs $\sim 0.6\%$ on Q_W^A

Proton's weak charge:

$$Q_W^P = -2[2C_{1u} + C_{1d}] = 1 - 4\sin^2\theta_W$$

Parity-violating elastic e-p scattering:

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

Published: Qweak $\sim 6\%$ on Q_W^P