The Weak Charge of the Proton

Wouter Deconinck, University of Manitoba

July 29, 2021
HADRON 2021, Mexico City

University of Manitoba

Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Gauge couplings: g for $SU(2)_L$, g' for $U(1)_Y$
- Left-handed leptons in doublets, right-handed in singlets
- Fundamental symmetry of left and right helicity broken

Parity symmetry is violated

- Weak interaction violates parity
- Electromagnetic interaction satisfies parity
- Use parity-violation to measure electroweak parameters

Credit: Chris Parkes, CP Violation at LHCb

Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Gauge couplings: g for $SU(2)_L$, g' for $U(1)_Y$
- Left-handed leptons in doublets, right-handed in singlets
- Fundamental symmetry of left and right helicity broken

Electroweak symmetry breaking: $B_\mu, W_\mu^i \rightarrow A_\mu, Z_\mu^0, W_\mu^\pm$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 0.23129 \pm 0.00005 \, (\text{at } M_Z)^1 \approx \frac{1}{4}$$

$$\begin{aligned} A_\mu &= \cos\theta_W \cdot B_\mu + \sin\theta_W \cdot W_\mu^3 & &\text{(massless photon field)} \\ Z_\mu^0 &= -\sin\theta_W \cdot B_\mu + \cos\theta_W \cdot W_\mu^3 & &(M_W \approx 80.4\,\text{GeV}, M_Z \approx 91.2\,\text{GeV}) \end{aligned}$$

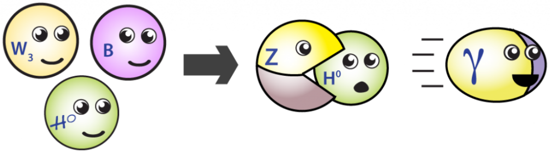
[1] *Review Particle Physics, J. Erler and A. Freitas, Chin. Phys. C, 40, 100001 (2016)*

Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Gauge couplings: g for $SU(2)_L$, g' for $U(1)_Y$
- Left-handed leptons in doublets, right-handed in singlets
- Fundamental symmetry of left and right helicity broken

Electroweak symmetry breaking: $B_\mu, W_\mu^i \rightarrow A_\mu, Z_\mu^0, W_\mu^\pm$



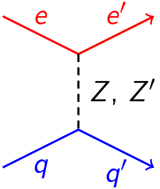
Credit: Flip Tanedo, Quantum Diaries

Electroweak Interaction

Glashow–Weinberg–Salam theory of weak interaction

- Gauge symmetry: $SU(2)_L \times U(1)_Y$
- Gauge couplings: g for $SU(2)_L$, g' for $U(1)_Y$
- Left-handed leptons in doublets, right-handed in singlets
- Fundamental symmetry of left and right helicity broken

Parity-violation neutral current



$$\mathcal{L}_{PV}^{EW} = -\frac{G_F}{\sqrt{2}} \quad [g_A^e\,(\bar{e}\gamma_\mu\gamma_5 e)\cdot\sum_i g_V^q\,(\bar{q}\gamma^\mu q)$$
$$+ \quad g_V^e\,(\bar{e}\gamma_\mu e)\cdot\sum_i g_A^q\,(\bar{q}\gamma^\mu\gamma_5 q)]$$

Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e\, g_V^q$ ($\gamma^\mu\gamma^5$ on e vertex)
- Weak axial quark coupling: $C_{2q} = 2g_V^e\, g_A^q$ ($\gamma^\mu\gamma^5$ on q vertex)

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$
e	-1	$Q_W^e = -2g_A^e g_V^e = -1 + 4\sin^2\theta_W \approx 0$

Weak vector charges of the proton and electron approximately zero

Accidental suppression of the weak vector charges in Standard Model makes them relatively more sensitive to new physics

Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e\, g_V^q$ ($\gamma^\mu\gamma^5$ on e vertex)
- Weak axial quark coupling: $C_{2q} = 2g_V^e\, g_A^q$ ($\gamma^\mu\gamma^5$ on q vertex)

Particle	Electric charge	Weak vector charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{1u} = +1 - \frac{8}{3}\sin^2\theta_W \approx +\frac{1}{3}$
d	$-\frac{1}{3}$	$-2C_{1d} = -1 + \frac{4}{3}\sin^2\theta_W \approx -\frac{2}{3}$
p(uud)	$+1$	$Q_W^p = 1 - 4\sin^2\theta_W \approx 0$
n(udd)	0	$Q_W^n = -1$
e	-1	$Q_W^e = -2g_A^e g_V^e = -1 + 4\sin^2\theta_W \approx 0$

Weak vector charge of the neutron is large

Dominance of neutron over proton weak charge means that parity-violating scattering is sensitive to neutron distributions

Several Electroweak Charges are Suppressed

Parity-violating electron scattering couplings

- Weak vector quark coupling: $C_{1q} = 2g_A^e g_V^q$ ($\gamma^\mu\gamma^5$ on e vertex)
- Weak axial quark coupling: $C_{2q} = 2g_V^e g_A^q$ ($\gamma^\mu\gamma^5$ on q vertex)

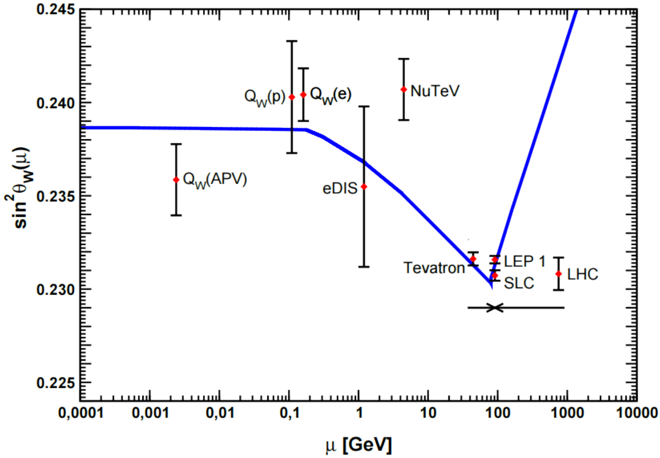
Particle	Electric charge	Weak axial charge ($\sin^2\theta_W \approx \frac{1}{4}$)
u	$+\frac{2}{3}$	$-2C_{2u} = -1 + 4\sin^2\theta_W \approx 0$
d	$-\frac{1}{3}$	$-2C_{2d} = +1 - 4\sin^2\theta_W \approx 0$

Weak axial charges of quarks approximately zero

Accidental suppression of the weak axial charges in deep-inelastic scattering of quarks

$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W} \frac{\Delta observable}{observable}$$

Weak Mixing Angle Runs With Energy Scale



(Width of curve indicates theoretical uncertainty in $\overline{\text{MS}}$.)

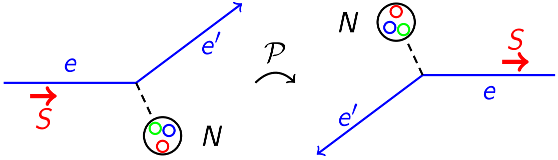
Flipping Electron Spin to Access Electroweak Observables

Parity transformation: Inversion of spatial vectors $\vec{x} \rightarrow -\vec{x}$

Tests using parity-violating electron scattering

- Polarized electrons (spin $\vec{S}$) on unpolarized target
- We could invert $\vec{r} \rightarrow -\vec{r}$, $\vec{p} \rightarrow -\vec{p}$, and keep $\vec{S} = \vec{S}$,

Parity-violating asymmetry A_{PV} between $\pm$ helicity scattering yields



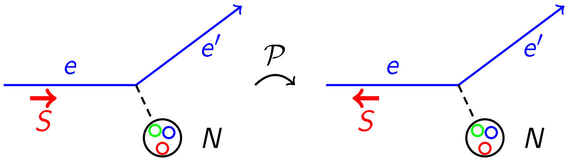
Flipping Electron Spin to Access Electroweak Observables

Parity transformation: Inversion of spatial vectors $\vec{x} \rightarrow -\vec{x}$

Tests using parity-violating electron scattering

- Polarized electrons (spin $\vec{S}$) on unpolarized target
- We could invert $\vec{r} \rightarrow -\vec{r}$, $\vec{p} \rightarrow -\vec{p}$, and keep $\vec{S} = \vec{S}$, but instead we leave $\vec{r}$, $\vec{p}$ unchanged and flip the spin $\vec{S}$

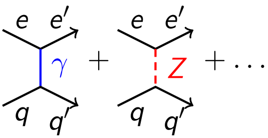
Parity-violating asymmetry A_{PV} between $\pm$ helicity scattering yields



Parity-Violating Asymmetries are Typically Small

Asymmetry between + and − incoming electron helicity

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \quad \text{with} \quad \sigma = \left| \; \cdots \; \right|^2$$



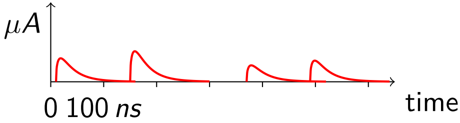
Interference of exchange of photon ($\mathcal{P}$-even) and weak boson ($\mathcal{P}$-odd)

$$\mathcal{M}^{EM} \propto \frac{1}{Q^2} \qquad \mathcal{M}^{NC}_{PV} \propto \frac{1}{M_Z^2 + Q^2}$$

$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \frac{\mathcal{M}^{NC}_{PV}}{\mathcal{M}^{EM}} \propto \frac{Q^2}{M_Z^2} \propto G_F Q^2 \approx \mathcal{O}(\text{ppm}, \text{ppb}) \text{ when } Q^2 \ll M_Z^2$$

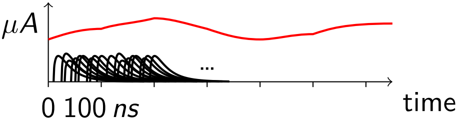
Strategy to Measure Parts-Per-Billion: Integration

Event or counting mode



- Each event individually detected, digitized and read-out
- Selection or rejection possible based on event characteristics
- 100 ns pulse separation limits rate to 10 MHz per detector segment; at least 1 day for 1 ppm precision

Integrating or current mode



- Very high event rates possible, as long as detectors are linear
- But no rejection of background events possible after the fact
- Q_{Weak} segment rates 800 MHz; MOLLER segment rates up to 2.5 GHz; P2 up to 0.5 THz

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

- Access to weak vector quark charges, measurements of $\sin^2\theta_W$

Electroweak measurements with electrons (Møller scattering)

- Access to weak electron charge, measurements of $\sin^2\theta_W$

Electroweak measurements with quarks (deep-inelastic scattering)

- Access to weak axial quark charges, measurements of $\sin^2\theta_W$, measurements of weak structure functions

Electroweak measurements with nuclei (elastic scattering)

- Access to neutron distributions, measurements of neutron skin thickness

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

- Access to weak vector quark charges, measurements of $\sin^2\theta_W$

Electroweak measurements with electrons (Møller scattering)

- Access to weak electron charge, measurements of $\sin^2\theta_W$

Electroweak measurements with quarks (deep-inelastic scattering)

- Access to weak axial quark charges, measurements of $\sin^2\theta_W$, measurements of weak structure functions

Electroweak measurements with nuclei (elastic scattering)

- Access to neutron distributions, measurements of neutron skin thickness

Determination of the Weak Charge of the Proton

Electroweak measurements with protons (elastic scattering)

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

In the forward elastic limit $Q^2 \to 0$, $\theta \to 0$ (plane wave):

$$A_{PV}(p) \xrightarrow{Q^2 \to 0} \frac{-G_F Q^2}{4\pi\alpha\sqrt{2}} \left[Q_W^p + Q^2 \cdot B(Q^2) \right] \propto Q_W^p \text{ when } Q^2 \text{ small}$$

Weak charge is intercept at $Q^2 \to 0$ of normalized asymmetry $A_{PV}(p)/A_0$

$$A_{PV}(p)/A_0 \xrightarrow{Q^2 \to 0} Q_W^p \xrightarrow{LO} -1 + 4\sin^2\theta_W$$

Determination of the Weak Charge of the Proton

Qweak Experiment

- First experiment with direct access to proton's weak charge
- Experiment collected data between 2010 and 2012 with toroidal spectrometer and integrating quartz detectors

First determination based on subset of data

- First measurement was published in 2013 based on commissioning data[1] (4% compared to the independent full data set)

Precision final results are now published

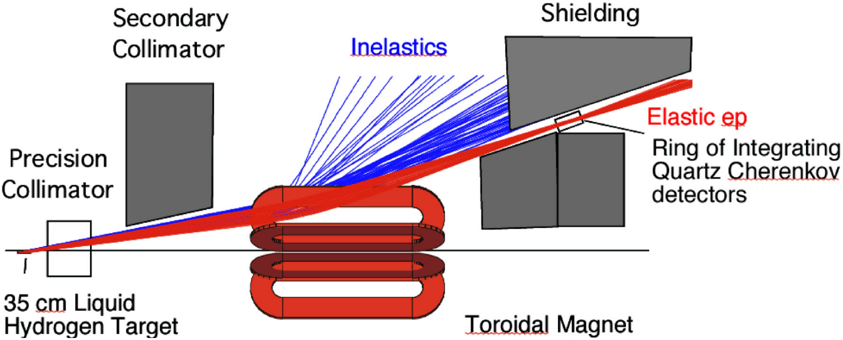
- Precision measurement of weak charge in Nature[2] in 2018
- Agrees with the Standard Model; exclusion limits for new physics

[1] *First Determination of the Weak Charge of the Proton, Phys. Rev. Lett. 111, 141803 (2013)*
[2] *Precision Measurement of the Weak Charge of the Proton, Nature 557, p207-211 (2018)*

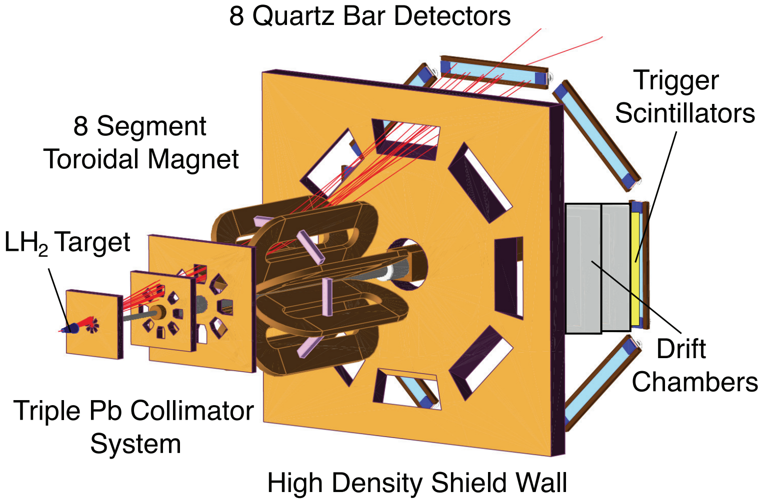
The Q_{Weak} Experiment

Schematic overview

- Elastic electron scattering on protons in liquid hydrogen target
- Magnetic field to bend the scattered electrons by energy
- Collimator system to select elastic events only
- Lower energy inelastic events bent away from the detectors

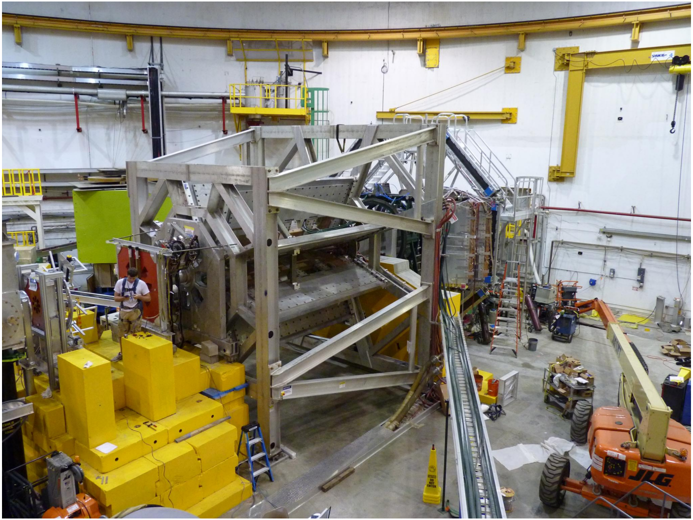


Determination of the Weak Charge of the Proton



[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton



[1] *The Qweak Apparatus, NIM A 781, 105 (2015)*

Determination of the Weak Charge of the Proton

Pushing the envelope of intensity (more detected electrons)

- Higher beam current (180 μA versus usually $< 100\,\mu$A)
- Longer cryo-target (35 cm versus 20 cm, 2.5 kW in 20 K LH2)
- Higher event rates up to 800 MHz (integrating mode)
- Typical luminosity of $1.7 \times 10^{39}\,\text{cm}^{-2}\,\text{s}^{-1}$, $\int \mathcal{L} dt = 1\,\text{ab}^{-1}$

Pushing the envelope of precision (better measurements)

- Electron beam polarimetry precision of 1% at 1 GeV
- Helicity-correlated asymmetries at ppb level (beam position at nm level)
- Precise determination of Q^2 since $A_{PV} \propto Q^2$
- Isolate elastic scattering from background processes (f_i, A_i)
  - This is why we must measure various background asymmetries

Determination of the Weak Charge of the Proton

Intercept of A_{PV} at $Q^2 \to 0$ gives weak charge ($Q^2 = 0.025\,\text{GeV}^2$)

$$\overline{A_{PV}} = \frac{A_{PV}}{A_0} = Q_W^p + Q^2 \cdot B(Q^2, \theta = 0) \quad \text{with} \quad A_0 = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}$$

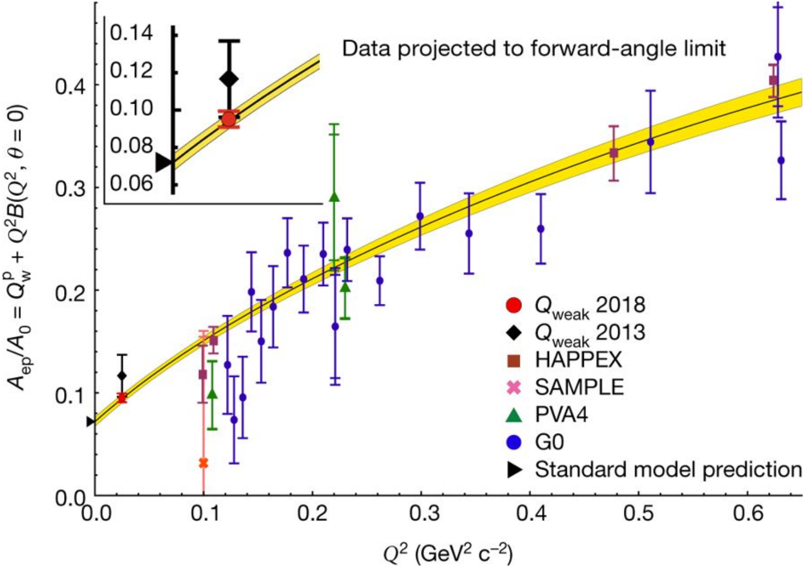
Global fit[1] of all parity-violating electron scattering with full data set[2]

- Fit of parity-violating asymmetry data on H, D, ^{4}He, $Q^2 < 0.63\,\text{GeV}^2$
- Free parameters were C_{1u}, C_{1d}, strange charge radius ρ_s and magnetic moment μ_s ($G^s_{E,M} \propto G_D$), and isovector axial form factor $G_A^{Z,T=1}$
- $Q_W^p(PVES) = 0.0719 \pm 0.0045$, $\sin^2\theta_W(Q^2) = 0.2382 \pm 0.0011$
- $\rho_s = 0.19 \pm 0.11$, $\mu_s = -0.18 \pm 0.15$, $G_A^{Z,T=1} = -0.67 \pm 0.33$
- After combination with atomic parity-violation on Cs:
  - $C_{1u} = -0.1874 \pm 0.0022$
  - $C_{1d} = 0.3389 \pm 0.0025$

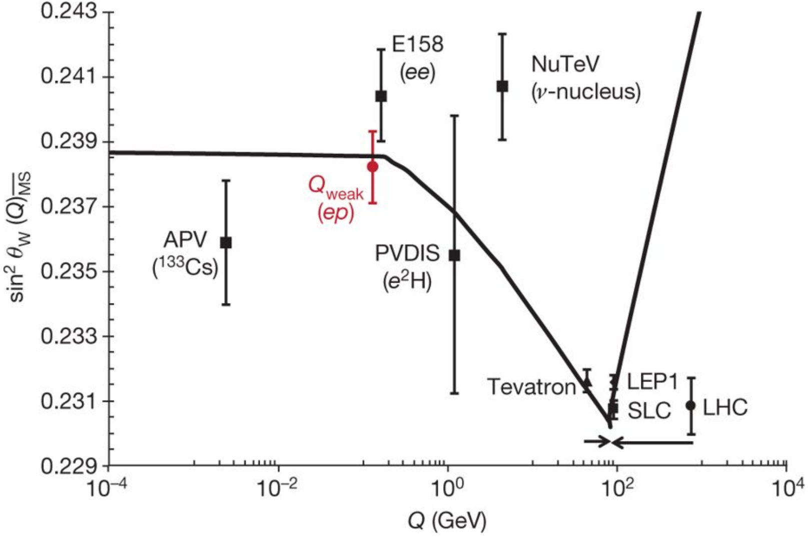
[1] *R. Young, R. Carlini, A.W. Thomas, J. Roche, Phys. Rev. Lett. 99, 122003 (2007)*

[2] *Precision Measurement of the Weak Charge of the Proton, Nature 558 (2018)*

Determination of the Weak Vector Charge of the Proton



Determination of the Weak Vector Charge of the Proton



Sensitivity to New Physics

Effective four-point interactions of some higher mass scale[1]

$$\mathcal{L}^{PV}_{e-q} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e \sum_q C_{1q}\bar{q}\gamma^\mu q + \frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^V_q \bar{q}\gamma^\mu q$$

Limits on new physics energy scale when uncertainty ΔQ^p_W

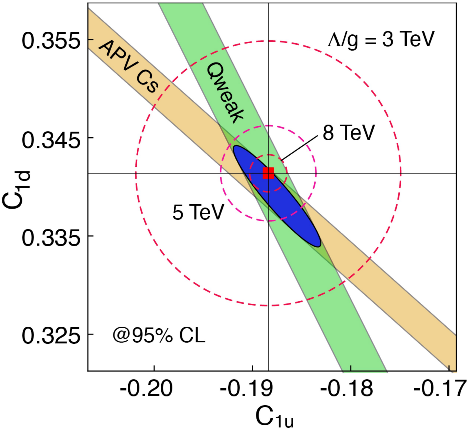
$$\frac{\Lambda}{g} = \frac{1}{2}\left(\sqrt{2}G_F \Delta Q^p_W\right)^{-1/2}$$

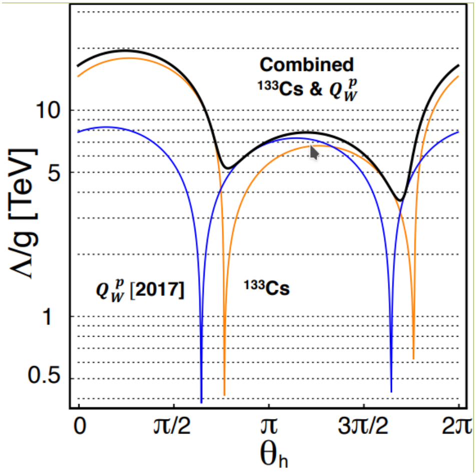
Assuming that we have an arbitrary flavor dependence of the new physics:

$$h^u_V = \cos\theta_h \quad h^d_V = \sin\theta_h$$

[1] J. Erler, A. Kurylov, M. Ramsey-Musolf, PRD 68, 016006 (2003)

Sensitivity to New Physics





$$\Lambda_-/g = 8.4\,\text{TeV and } \Lambda_+/g = 7.4\,\text{TeV}$$

Determination of the Weak Charge of the Proton

Background treatment in integrating experiments

- Measured asymmetry A_{msr} corrected for all background contributions
  - with their own parity-violating asymmetry A_i (ppm-level)
  - and their dilution in the measured asymmetry f_i (%-level)

$$A_{PV} = R_{total} \frac{\frac{A_{msr}}{P} - \sum f_i A_i}{1 - \sum f_i}$$

Example of a background: Aluminum target walls

- Dominant correction to the asymmetry: background from scattering of the thin aluminum entrance and exit windows of the hydrogen target
  - Dilution $f_1 \approx 2.5\%$: directly measured with empty target, slightly different for run1 and run2
  - Effective Al alloy asymmetry $A_1 = 1515 \pm 77\,\text{ppb}$: directly measured with thick “dummy” target of identical alloy as hydrogen target windows

Measurements on Al Alloy Allow for Physics Results Too

Parity-Violating Asymmetry $A_{PV}(^{27}\mathrm{Al})$

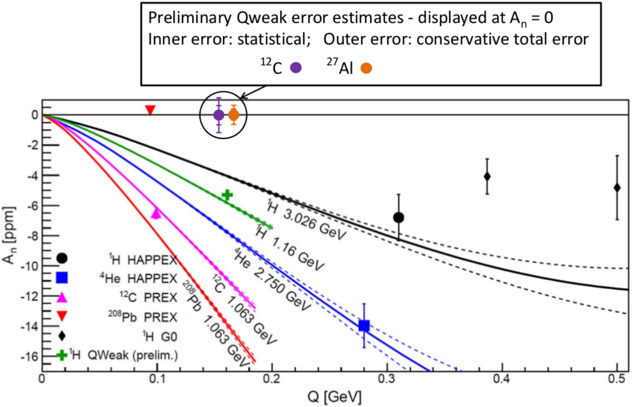
- Extraction of neutron distribution radius R_n in aluminum
  - Precision of 4% on A_{PV} of pure ^{27}Al translates to 2% on R_n
  - $R_n(^{27}\mathrm{Al})$ helps benchmark theory important for nuclear astrophysics
- Part of larger program with CREX/PREX-II in Summer 2019

Parity-Conserving Transverse Asymmetries $B_n(^{27}\mathrm{Al})$, $B_n(\mathrm{C})$

- Surprisingly small Pb transverse asymmetry in PREX-I[1]
- Qweak has several data sets which speak to this observable:
  - Elastic scattering on hydrogen: already presented
  - Elastic scattering on aluminum, carbon: new results
- Aluminum adds new data between carbon (where data agrees with A/Z scaling) and lead (where there is disagreement)

[1] *Abrahamyan et al., PRL 109, 192501 (2012)*

Potential to Elucidate the Behavior Between Carbon and Lead

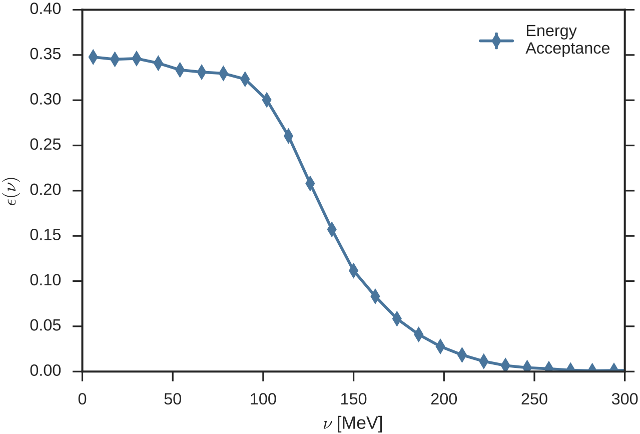


- $B_n \propto AQ/Z$: Gorchtein, Horowitz, Phys. Rev. C77, 044606 (2008)
- HAPPEX, PREX: Abrahamyan *et al.*, PRL 109, 192501 (2012)

Two Primary Challenges in these Ancillary Results

- Spectrometer not designed with narrow energy acceptance to separate elastic state from excited states in nuclei
- Target not made of pure aluminum but alloy instead (carbon is cleaner)

Spectrometer Energy Acceptance Approximately 150 MeV



- Non-elastic scattering processes dilute the asymmetry measurement
- Corrections required for nuclear excited states, GDR, ...

Correction for 20% ppm-level Non-Elastic Asymmetries

f_i: Background Fraction

$$f_i = \frac{y_i}{\sum_i y_i}$$

where y_i is the detector signal yield

- Using Geant4 Monte Carlo simulation to determine y_i
- Cross-section parameterization in simulation from empirical fit[1]

Process	f[%]	∂f[%]	$\partial f/f$[%]
Quasi	12.75	1.14	8.91
Inelastic	7.38	0.70	9.50

A_i: Background Asymmetry

- Quasi-elastic:
  - Theoretical support from C. Horowitz and Z. Lin
  - Initial calculation agrees well with "free nucleon" estimate

$$A_{QE} = -0.34 \pm 0.34\,\text{ppm}$$

- Inelastic:
  - Have statistics dominated ($\partial A/A = 71\,\%$) measurement of this asymmetry

$$A_{IN} = 1.61 \pm 1.15\,\text{ppm}$$

[1] *P. Bosted, V. Mamyan, arXiv:1203.2262v2*

Aluminum Alloy Has About 10% Higher-Z Contaminants

Aluminum alloy elements [w%]

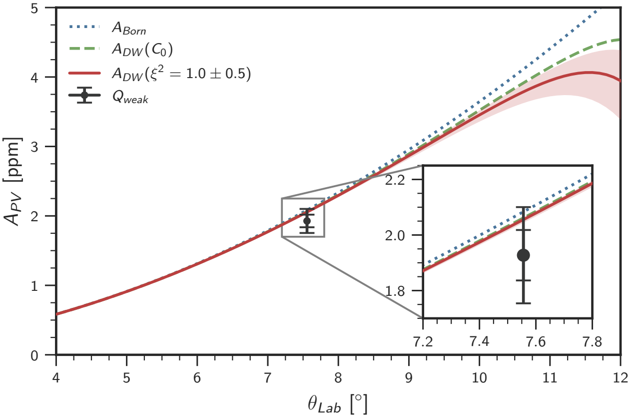
Element	Run 1	Run 2
Al	89.53	89.23
Zn	5.90	5.87
Mg	2.60	2.63
Cu	1.50	1.81
Cr	0.19	0.19
Fe	0.14	0.11
Si	0.08	0.09
Mn	0.04	0.04
Ti	0.02	0.03

Correction method

- Only most common isotopes of Zn, Mg, Cu, Cr, Fe, and Si
- Only elastic scattering from contaminants
- Modified luminosity calculation
    - Zn, Mg, Cu, Cr, Fe, Si: cross sections and asymmetries using distorted wave model[1]
    - Mn, Ti: Born approximation cross section model with Fourier-Bessel form factor fits

[1] *C. Horowitz, Z. Lin, private communication*

Measured Parity-Violating Asymmetry Agrees With Theory

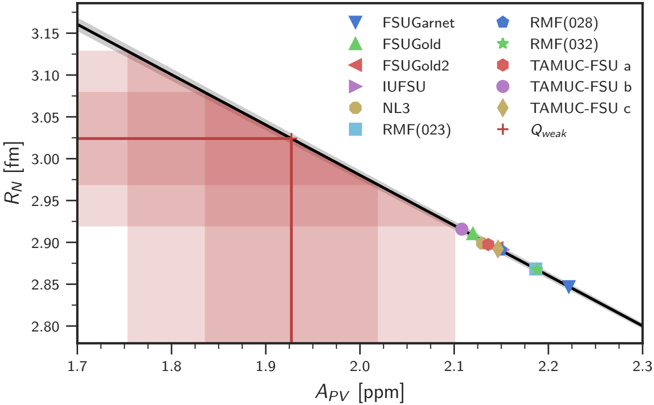


Distorted wave calculation[1] prediction of 2.1 ppm at 1.16 GeV

$A_{PV} = 1.927 \pm 0.173(\text{tot.})\,[0.091(\text{stat.}) \pm 0.148(\text{sys.})]\,\text{ppm} \quad \Delta A/A \approx 9\%(\text{tot.})$

[1] *C. J. Horowitz Phys. Rev. C 89, 045503 (2014)*

Determined Neutron Distribution Radius Agrees with Proton's



Extraction of R_n based on collection of nuclear models

- $R_n = 3.024 \pm 0.104\,\text{fm}$ and $R_n - R_p = 0.092 \pm 0.104\,\text{fm}$
- Neutron 'skin' consistent with expected range 0.004–0.024 fm

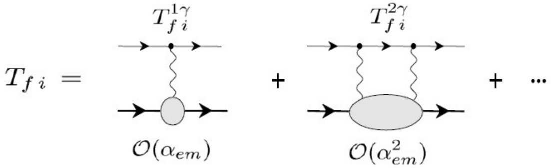
Beam Normal Asymmetry is the Size of Azimuthal Variation

Beam normal single spin asymmetries B_n

- Measurement of $A_T(\phi)$ with transversely polarized beam (H or V)
- Parity-conserving T-odd transverse asymmetry of order ppm

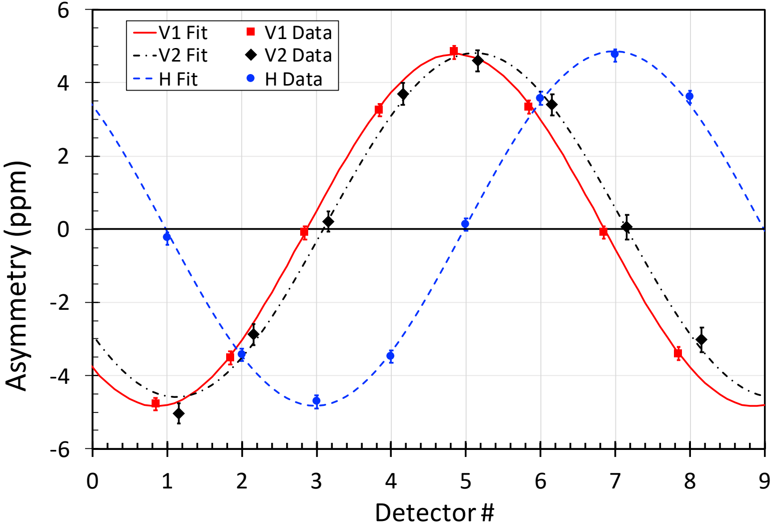
$$A_T(\phi) = \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)} = B_n S \sin(\phi - \phi_S) = B_n(P_V \cos\phi + P_H \sin\phi)$$

$$B_n = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \frac{2\Im(T^{1\gamma *} \cdot Abs T^{2\gamma})}{|T^{1\gamma}|^2} \propto \frac{A \cdot Q}{Z} \approx \mathcal{O}(\alpha \frac{m}{E}) \approx \text{ppm}$$



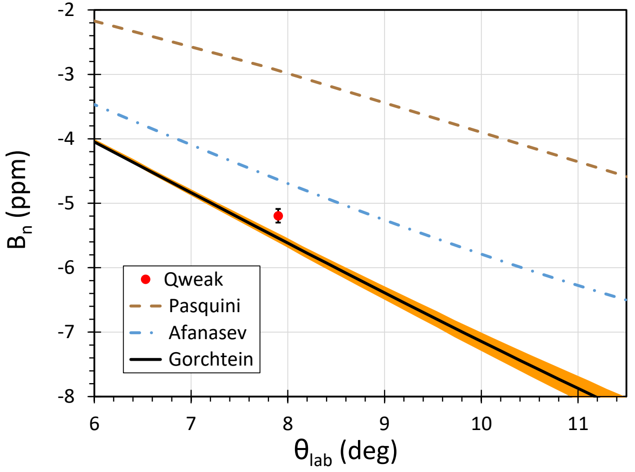
Beam Normal Asymmetry is the Size of Azimuthal Variation

Aluminum azimuthal asymmetry for Hydrogen



Beam Normal Asymmetry on H is Consistent with Theory

Beam normal asymmetry for Hydrogen[1]



[1] *Phys.Rev.Lett. 125 (2020) 11, 112502*

Beam Normal Asymmetry on C is Consistent with PREX-I

$B_n(\mathrm{C}) = -10.68 \pm 0.90(\mathrm{stat}) \pm 0.57(\mathrm{syst})$ ppm in elastic scattering

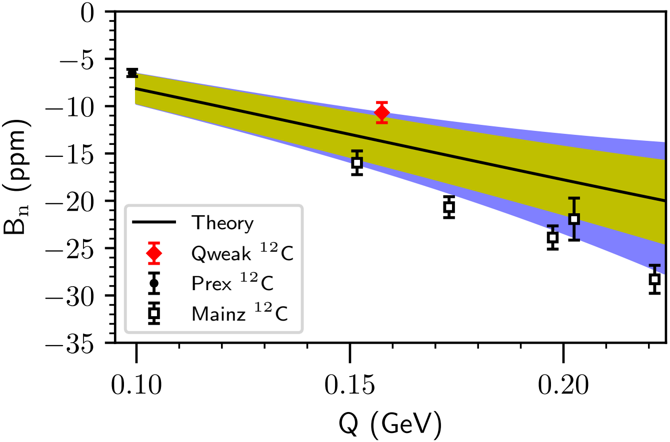
- Target consists of 99% ^{12}C, no significant contaminations
- Correction for contribution from quasi-elastic scattering, but no attempts at separation of nuclear excited states and GDR
- $B_n(\mathrm{C})$ is a quantity that applies not to a purely elastic state

J^P	E [MeV]	weight [%]
0^+	0	71.6 ± 7.9
2^+	4.44	3.5 ± 0.3
0^+	7.65	10.3 ± 2.1
3^-	9.64	11.6 ± 1.4
GDR	(24)	1.9 ± 0.4

- Scaling PREX-I to $E_b = 1.165$ GeV and $Q^2 = 0.0270 \pm 0.0079$ GeV^2 leads to expected $B_n(\mathrm{C}) = -10.8 \pm 0.3$ ppm (ground state)

Beam Normal Asymmetry on C is Consistent with Mainz

Consistent with both PREX-I[1] and 2018 Mainz[2] measurements



[1] *Abrahamyan et al., PRL 109, 192501 (2012)*

[2] *A. Esser, Phys. Rev. Lett. 121, 022503 (2018)*

Beam Normal Asymmetry on Al is More Complicated

Quasi-elastic scattering

- Free nucleon approximation and some heuristics related to isoscalar/isovector impact on sign of asymmetry
- More detailed quasi-elastic implementation per Horowitz, Phys. Rev. C 47, 826 (1992), which Z. Lin has adapted to ^{27}Al

Contaminants in Al alloy

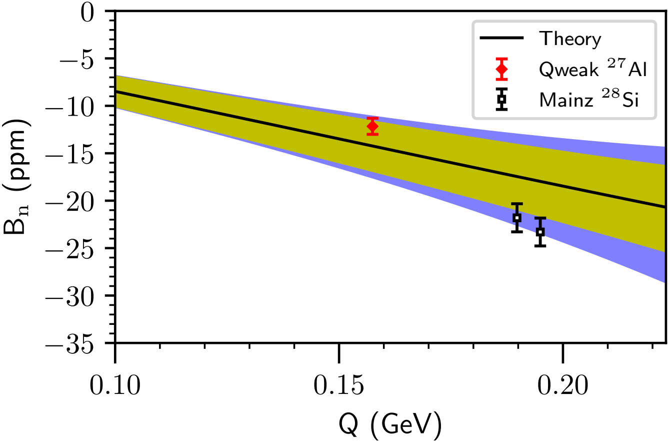
- Similar approach as C. Horowitz, Phys. Rev. C89, 045503 (2014)
- Implementation into Q_{Weak} Monte Carlo to determine contributions

Nuclear excited states

- Fitted nuclear excited state form factors using MIT Bates data
  - R.S. Hicks, A. Hotta, J.B. Flanz, H. deVries, Phys. Rev. C21, 2177 (1980)
  - P.J Ryan, R.S. Hicks, A. Hotta, J. Dubach, G.A. Peterson, D.V. Webb, Phys. Rev. C27, 2515 (1983)

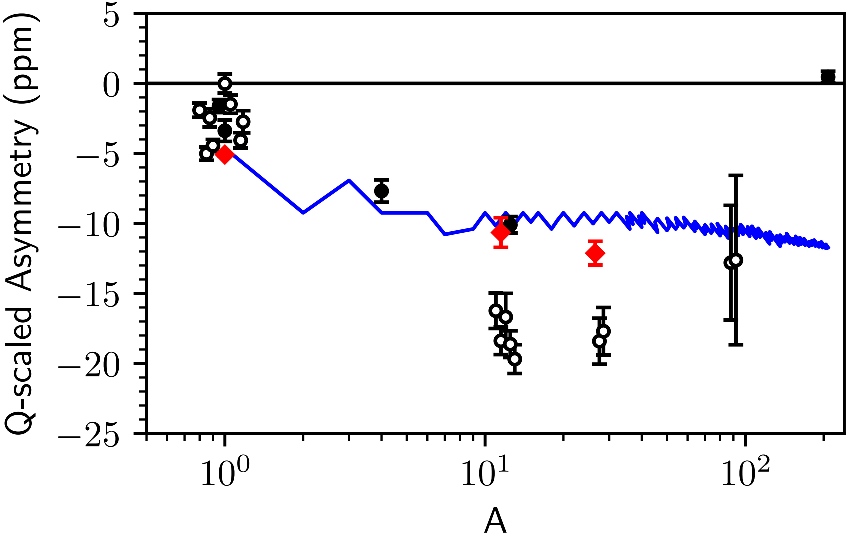
Beam Normal Asymmetry on Al compared to Mainz Si

Consistent with Mainz[1] measurements

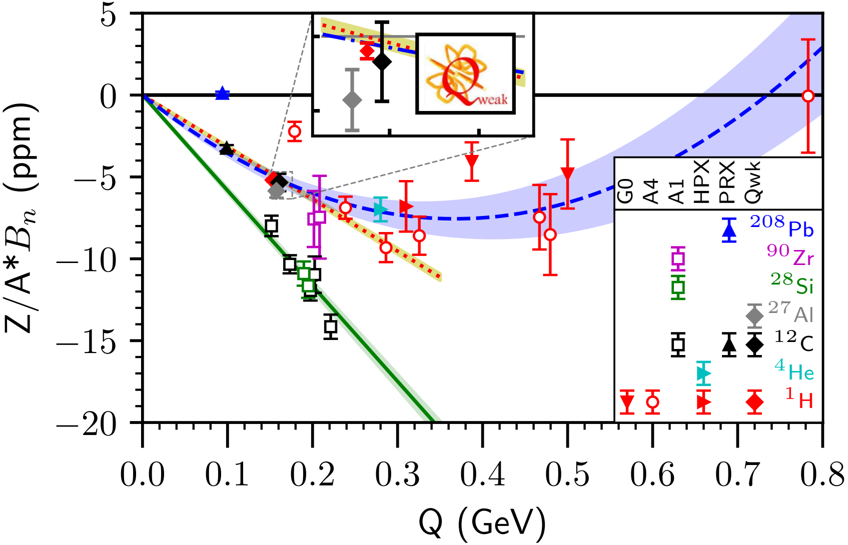


[1] *A. Esser et al., Phys. Lett. B 808, 135664 (2020)*

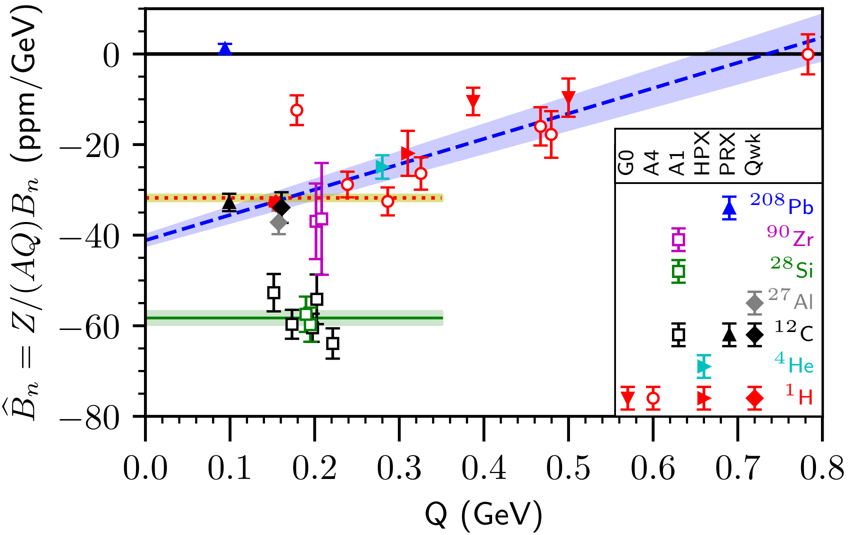
Beam Normal Asymmetry World Data vs. Atomic Mass



Beam Normal Asymmetry World Data vs. Momentum Transfer



Reduced Beam Normal Asymmetry vs. Momentum Transfer



Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

- Access to weak vector quark charges, measurements of $\sin^2\theta_W$

Electroweak measurements with electrons (Møller scattering)

- Access to weak electron charge, measurements of $\sin^2\theta_W$

Electroweak measurements with quarks (deep-inelastic scattering)

- Access to weak axial quark charges, measurements of $\sin^2\theta_W$, measurements of weak structure functions

Electroweak measurements with nuclei (elastic scattering)

- Access to neutron distributions, measurements of neutron skin thickness

Parity-Violating Asymmetry to Access Electroweak Parameters

Electroweak measurements with protons (elastic scattering)

- Access to weak vector quark charges, measurements of $\sin^2\theta_W$

Electroweak measurements with electrons (Møller scattering)

- Access to weak electron charge, measurements of $\sin^2\theta_W$

Electroweak measurements with quarks (deep-inelastic scattering)

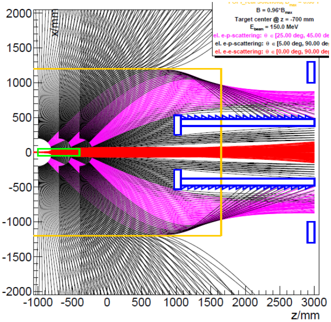
- Access to weak axial quark charges, measurements of $\sin^2\theta_W$, measurements of weak structure functions

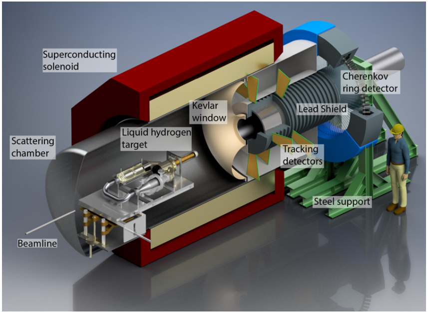
Electroweak measurements with nuclei (elastic scattering)

- Access to neutron distributions, measurements of neutron skin thickness

New Experiment: P2 Experiment in Mainz[1]

- 155 MeV energy-recovery superconducting accelerator MESA
- Projected precision of $\sin^2\theta_W$ to ± 0.0003 at $Q^2 = 0.0045\,\mathrm{GeV}^2$
- Accelerator commissioning, experiment data taking, target for operations in 2023
- Electron polarimetry at 0.5% precision with atomic hydrogen Møller



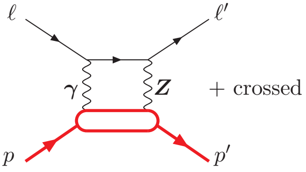


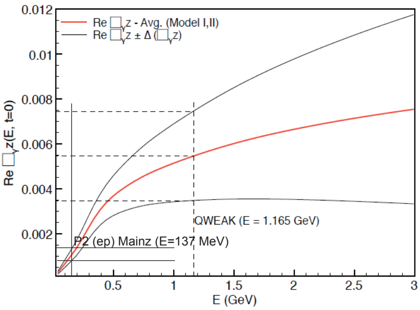
[1] *Becker, D. et al. Eur. Phys. J. A (2018) 54: 208*

P2: High Precision Measurement of Proton's Weak Charge

Radiative corrections on weak charge

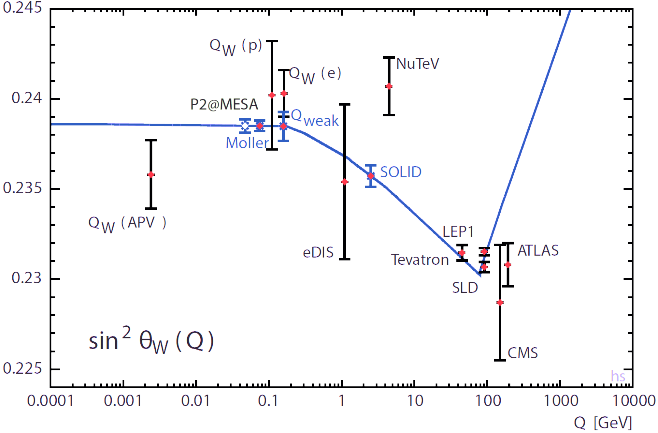
- $Q_W^p = (\rho_{NC} + \Delta_e)(1 - 4\sin^2\theta_W(0) + \Delta'_e) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}$
- $\Box_{\gamma Z}$: relatively large correction and uncertainty[1]
- Improving measurements of Q_W^p benefits from smaller beam energies





[1] M. Gorchtein, C. J. Horowitz, M. J. Ramsey-Musolf, Phys. Rev. C 84, 015502 (2011)

Weak Mixing Angle Runs With Energy Scale



Summary

Qweak Experiment

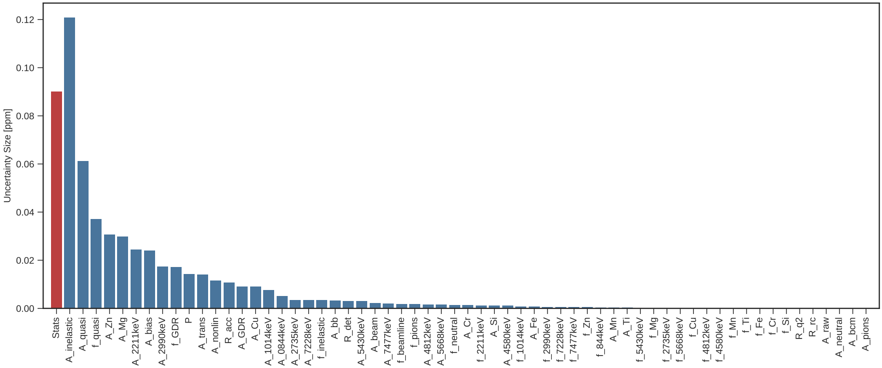
- Weak charge imposes new lower limit on new physics
- $A_{PV}(^{27}\text{Al})$ agrees with theoretical calculations
- $B_n(\text{C})$ (including mixture of pure elastic and excitations) agrees with PREX-I and Mainz measurements and $A \cdot Q/Z$ scaling
- $B_n(^{27}\text{Al})$ adds beam-normal measurement between carbon and lead

P2 Experiment

- Proton's weak charge measurement in Mainz, Germany
- Gearing up for commissioning and operations

Systematics Dominated by Inelastic Asymmetry Uncertainty

Statistical and Systematic Uncertainties

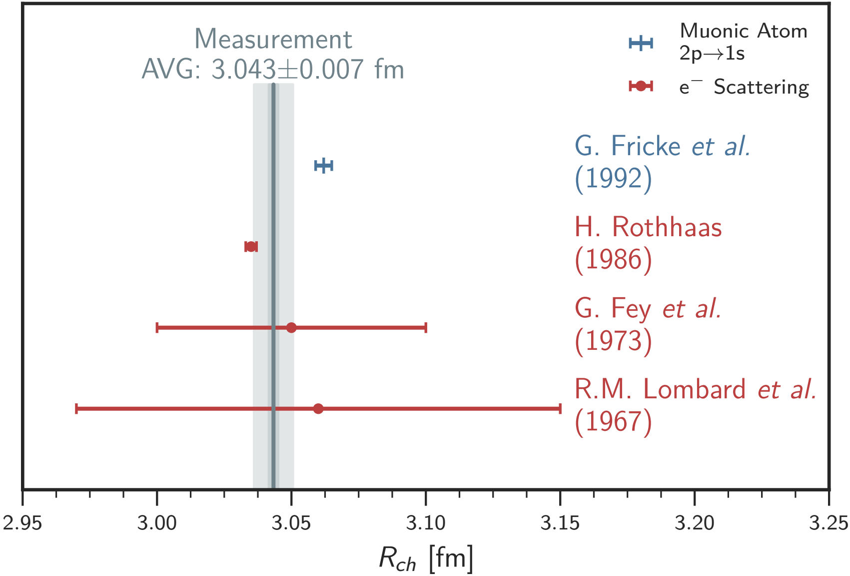


- Only $A_{inelastic}$ is larger than the statistical (red) uncertainty.

Systematics Dominated by Inelastic Asymmetry Uncertainty

Top five largest uncertainty contributions

Quantity	Error [ppm]
Statistics	0.090
A_{IN}: Inelastic Asym.	0.121
A_{QE}: Quasi-elastic Asym.	0.061
f_{QE}: Quasi-elastic Fraction	0.037
A_{Zn}: Zinc Asym.	0.031
A_{Mg}: Magnesium Asym.	0.030
⋮	⋮
Combined (quadrature)	0.180



Measurement
AVG: 3.043±0.007 fm
Muonic Atom
2p→1s
e⁻ Scattering
G. Fricke et al.
(1992)
H. Rothhaas
(1986)
G. Fey et al.
(1973)
R.M. Lombard et al.
(1967)
2.95
3.00
3.05
3.10
3.15
3.20
3.25
Rch [fm]