**LETTER**

**Precision measurement of the weak charge of the proton**

The Jefferson Lab $Q_{\text{weak}}$ Collaboration*

Large experimental programmes in the fields of nuclear and particle physics search for evidence of physics beyond that explained by current theories. The observation of the Higgs boson completed the set of particles predicted by the standard model, which currently provides the best description of fundamental particles and forces. However, this theory’s limitations include a failure to predict fundamental parameters, such as the mass of the Higgs boson, and the inability to account for dark matter and energy, gravity, and the matter–antimatter asymmetry in the Universe, among other phenomena. These limitations have inspired searches for physics beyond the standard model in the post-Higgs era through the direct production of additional particles at high-energy accelerators, which have so far been unsuccessful. Examples include searches for supersymmetric particles, which connect bosons (integer-spin particles) with fermions (half-integer-spin particles), and for leptoquarks, which mix the fundamental quarks with leptons. Alternatively, indirect searches using precise measurements of well predicted standard-model observables allow highly targeted alternative tests for physics beyond the standard model because they can reach mass and energy scales beyond those directly accessible by today’s high-energy accelerators. Such an indirect search aims to determine the weak charge of the proton, which defines the strength of the proton’s interaction with other particles via the well known neutral electroweak force. Because parity symmetry (invariance under the spatial inversion ($x, y, z \rightarrow (-x, -y, -z)$) is violated only in the weak interaction, it provides a tool with which to isolate the weak interaction and thus to measure the proton’s weak charge. Here we report the value $0.0719 \pm 0.0045$, where the uncertainty is one standard deviation, derived from our measured parity-violating asymmetry in the scattering of polarized electrons on protons, which is $-226.5 \pm 9.3$ parts per billion (the uncertainty is one standard deviation). Our value for the proton’s weak charge is in excellent agreement with the standard model and sets multi-teraelectronvolt-scale constraints on any semi-leptonic parity-violating physics not described within the standard model. Our results show that precision-violating measurements enable searches for physics beyond the standard model that can compete with direct searches at high-energy accelerators and, together with astronomical observations, can provide fertile approaches to probing higher mass scales.

In the electroweak standard model, elastic scattering is mediated by the exchange of neutral currents (virtual photons and $Z^0$ bosons) between fundamental particles. A particle’s weak charge, $Q_{\text{weak}}$, is analogous to—but distinct from—its electric charge, $q$; the former quantifies the vector coupling of the $Z^0$ boson to the particle, whereas the latter quantifies the vector coupling of the photon to the particle. The proton’s weak charge $Q_{\text{weak}}^p$ is defined as the sum of the weak vector coupling constants $C_{1q}$ of the $Z^0$ boson to its constituent up ($u$) and down ($d$) quarks:

$$Q_{\text{weak}}^p = -2(C_{1u} + C_{1d})$$

(1)

The $Z^0$ exchange contribution to electron–proton scattering can be isolated via the weak interaction’s unique parity-violation signature (see Fig. 1). Interference between electromagnetic and weak scattering amplitudes leads to a parity-violation asymmetry $A_{\text{ep}}$ that can be measured with a longitudinally polarized electron beam incident on an unpolarized-proton target:

$$A_{\text{ep}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

(2)

Here, $\sigma_\pm$ represents the cross-section of the helicity-dependent elastic scattering $(\pm 0)$ of polarized electrons $(e)$ on protons $(p)$, integrated over the scattered-electron detector acceptance. Helicity $(\pm 1)$ indicates the spin direction of the electrons in the beam as either parallel $(+1)$ or anti-parallel $(-1)$ to their momenta.

Measuring $A_{\text{ep}}$ at a small four-momentum transfer $(Q^2)$ suppresses contributions from the proton’s extended structure relative to the proton’s weak charge $Q_{\text{weak}}^p$. However, $A_{\text{ep}}$ is small at small $Q^2$ values, making its measurement challenging. In the low-$Q^2$ limit, the parity-violation asymmetry can be expressed as:

$$A_{\text{ep}}/A_0 = Q_{\text{weak}}^p + Q^2 B(Q^2, \theta)$$

(3)

where $A_0 = -G_F Q^2/(4\pi \alpha \sqrt{2})$, $-Q^2$ is the four-momentum transfer squared, $B(Q^2, \theta)$ represents the proton’s extended structure defined in terms of electromagnetic, strange and axial form factors, $\theta$ is the (polar) scattering angle of the electron in the laboratory frame with respect to the beam axis, $G_F$ is the Fermi constant and $\alpha$ is the fine-structure constant.

The $Q_{\text{weak}}$ experiment (see Extended Data Fig. 1) used a beam of longitudinally polarized electrons accelerated to 1.16 GeV at the Thomas Jefferson National Accelerator Facility. Three sequential acceptance–defining lead collimators, matched to an eight-sector azimuthally symmetric toroidal magnet, selected electrons scattered from a liquid-hydrogen target at angles between 5.8° and 11.6°. In each magnet octant, elastically scattered electrons were directed to a quartz detector fronted by lead pre-radiators. Cherenkov light produced by the electromagnetic shower passing through the quartz was converted to a current by photomultiplier tubes at each end of the quartz bars. These currents were integrated for each 1-ms-long helicity state of the beam. For calibration purposes, and to confirm our understanding of the acceptance and backgrounds, drift chambers were periodically inserted upstream and downstream of the magnet to track individual particles during dedicated periods of low-current running.

To achieve a precision of less than 10 parts per billion (p.p.b.), this experiment pushed existing boundaries on many fronts: higher polarized-beam intensity (180 μA), faster beam-helicity reversal (960 s$^{-1}$), better GeV-scale beam polarimetry$^3$ precision (±0.6%), higher liquid-hydrogen target$^4$ luminosity $(1.7 \times 10^{39} \text{ cm}^{-2} \text{ s}^{-1})$ and cooling power (3 kW) and higher total detection rates (7 GHz). Following a brief commissioning period, the experiment was divided into two roughly six-month run periods, between which improvements were made primarily to polarimetry and helicity-related beam-monitoring and control instrumentation. Further details, including the

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backgrounds and corrections associated with each of the two halves of the experiment, are provided in Methods.

The asymmetry measurement results are $A_{\text{ep}} = -223.5 \pm 15.0$ (statistical) $\pm 10.1$ (systematic) p.p.b. in the first half of the experiment, and $A_{\text{ep}} = -227.2 \pm 8.3$ (statistical) $\pm 5.6$ (systematic) p.p.b. in the second half. These values are in excellent agreement with each other and consistent with our previously published commissioning result. Accounting for correlations in some systematic uncertainties between the two measurement periods, the combined result is $A_{\text{ep}} = -226.5 \pm 7.3$ (statistical) $\pm 5.8$ (systematic) p.p.b. The total uncertainty achieved (9.3 p.p.b.) sets a new level of precision for parity-violating electron scattering (PVES) from a nucleus.

The relationship between the measured asymmetries $A_{\text{ep}}$ and the proton’s weak charge $Q_P^e$ is expressed by equation (3), where the hadronic-structure-dependent term $B(Q^2, \theta)$ grows with the momentum transfer $Q^2$. Higher-$Q^2$ data from previous PVES experiments (see online references, Methods) were included in a global fit to constrain the proton-structure contributions for the short extrapolation from our datum to $Q^2 = 0$ in order to determine $Q_P^e$, the intercept of equation (3). The average $Q^2$ of this experiment (0.0248 GeV$^2$ c$^{-2}$) is much smaller than that of any other PVES experiments used in this fit, with correspondingly smaller contributions from the proton structure. The superior precision of the $Q_{\text{weak}}$ measurement tightly constrains the fit near $Q^2 = 0$, where the connection to $Q_P^e$ can be made.

The parameters of the global fit include the strange charge radius $\rho_s$ and strange magnetic moment $\mu_s$ (which characterize the strength of the proton’s electric and magnetic strange-quark form factors) and the strength of the neutral weak ($Z^0$ exchange) isovector $(T = 1)$ axial form factor $g_A^{Z0(T = 1)}$. The EM form factors $G_{EL}$ and $G_{M0}$ used in the fit were taken from ref. 9; uncertainties in this input were accounted for in the result for $Q_P^e$ and in its uncertainty.

The $ep$ asymmetries shown in Fig. 2 were corrected for the energy-dependent part of the $\gamma Z^0$ box weak radiative correction and its uncertainty. No other electroweak radiative corrections need to be applied to determine $Q_P^e$. However, ordinary electromagnetic radiative corrections (bremsstrahlung) were accounted for in the asymmetries used in the fit, including our datum. Details of the fitting procedure, as well as a description of the corrections applied to the asymmetry for this experiment, are described in Methods.

The global fit is shown in Fig. 2 together with the $ep$ data, expressed as $A_{\text{ep}}(Q^2, \theta = 0)/A_0$. To isolate the $Q^2$ dependence for this figure, the $\theta$ dimension was projected to 0° by subtracting [$A_{\text{calc}}(Q^2, \theta) − A_{\text{calc}}(Q^2, \theta = 0)$] from the measured asymmetries $A_{\text{ep}}(Q^2, \theta)$, as described in refs. 3–8. Here $A_{\text{calc}}$ refers to the asymmetries determined from the global fit. The fit includes all relevant PVES data for the scattering of polarized electrons on protons ($ep$), deuterons ($e^+H$) and $^4$He ($e^+\text{He}$); see Methods. The PVES database provides a data-driven (as opposed to a more theoretical) constraint on the nucleon structure uncertainties in the extrapolation to $Q^2 = 0$. We consider this to be the best method to provide our main result (denoted in Table 1 as $Q_{\text{weak}}$ experiment).

### Table 1 | Results extracted from the asymmetry measured in the $Q_{\text{weak}}$ experiment

| Method              | Quantity | Value   | Error   |
|---------------------|----------|---------|---------|
| PVES fit            | $Q_P^e$  | 0.0719  | 0.0045  |
| $\rho_s$            |          | 0.20    | 0.11    |
| $\mu_s$             |          | -0.19   | 0.14    |
| $g_A^{Z0(T = 1)}$   |          | -0.64   | 0.30    |
| PVES fit + APV      | $Q_P^e$  | 0.0718  | 0.0044  |
| $C_1$               |          | 0.1874  | 0.0022  |
| $C_{1\text{d}}$    |          | 0.3389  | 0.0025  |
| $C_1$ correlation   |          | -0.9318 |         |
| PVES fit + LQCD     | $Q_P^e$  | 0.0685  | 0.0038  |
| $Q_{\text{weak}}$ datum only | $Q_P^e$ | 0.0706  | 0.0047  |
| Standard model      | $Q_P^e$  | 0.0708  | 0.0003  |

*PVES fit* refers to a global fit incorporating the $Q_{\text{weak}}$ result and the PVES database, as described in Methods. When combined with APV4–10 (to improve the $C_{1\text{d}}$ precision), this method is denoted as ‘PVES fit + APV’. If the strange form factors in the global fit (without APV) are constrained to match LQCD calculations11, we label the result as ‘PVES fit + LQCD’. The method labelled ‘$Q_{\text{weak}}$ datum only’ uses the $Q_{\text{weak}}$ datum, together with electromagnetic3 and axial10 form factors from the literature in lieu of the global fit. Uncertainties are 1 s.d.
other determinations described above, which employ the entire PVES database (see Table 1, ‘Qweak datum only’). The uncertainty of the $Q_w^0$ result in this case includes an additional uncertainty (4.6 p.p.b.) due to the calculated form factors, but is only 4% larger than the uncertainty of the global fit result, which uses the entire PVES database. The dominant correction, from the electromagnetic form factors (23.7%), is well known in the low-$Q^2$ regime of the $Q_{weak}$ experiment.

The $Q_w^0$ determinations described above can be used to test the prediction of the standard model for $\sin^2\theta_W$, the fundamental
The low-energy precision frontier continues to offer an exciting landscape to search for BSM physics. The results of this experiment are consistent with the standard model and place important limits on new beyond-standard-model physics. Future experiments propose to provide even more precise (and much more challenging) determinations of $Q^2_W$ at lower $Q^2$ (ref. 31) and of $Q^2_w$ (ref. 32) by taking the techniques and lessons learned in this experiment to the next level.

Online content

Any Methods, including any statements of data availability and Nature Research reporting summaries, along with any additional references and Source Data files, are available in the online version of the paper at https://doi.org/10.1038/s41586-018-0096-0.

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METHODS

Here we describe the formalism connecting the experimentally measured asymmetry $A_{ep}$ to the proton’s weak charge $Q^p_w$, the experimental method used to determine $A_{ep}$, some measures of the data quality, and the electroweak radiative corrections needed to extract the weak mixing angle from $Q^p_w$.

Formalism. The $Q_{weak}$ experiment measured the parity-violating asymmetry $A_{ep}$, which is the normalized difference between the elastic-scattering cross-sections ($\sigma_+$) of longitudinally polarized electrons with positive $(\sigma_+)$ and negative $(\sigma_-)$ helicity from unpolarized protons:

$$A_{ep} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

The extended structure of the proton can be represented using form factors. Assuming charge symmetry, the single-boson exchange (‘tree’-level) expression for the asymmetry can be written in terms of the proton and neutron electromagnetic form factors $G^p_{E1}$, $G^p_{M1}$, $G^n_{E1}$ and $G^n_{M1}$, the strange electric and magnetic form factors $G^s_{E1}$ and $G^s_{M1}$, and the neutral weak axial form factor $G_A^0$ as:

$$A_{ep} = \frac{\alpha p + \alpha s + \alpha A}{\varepsilon (G_E^p)^2 + \tau (G_M^p)^2}$$

with

$$\alpha p = -G^p_{Q1} Q\nu \lambda^2$$
$$\alpha s = G^s_{Q1} (G_E^p)^2 + \tau G^s_{M1} G^s_{M1}$$
$$\alpha A = -G^p_{Q2} - \tau G^s_{M1} G^s_{M1}$$
$$\alpha L = -(1 - 4\sin^2 \theta W) G^p_{M1} G^s_{M1}$$
$$Q^p_w = 2(2C_{1e} + C_{1d})$$

where the subscripts $v$, $s$ and $A$ refer to the vector, strange and axial contributions to the asymmetry, respectively.

$$\varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$$

$$\tau = \frac{2}{1 + (1+\tau)\tan^2(\theta/2)}$$

are kinematical quantities and $\tau = Q^2/(4\Delta^2)$, where $\Delta$ is the proton mass.

By taking the limits $\theta = 0$ and $Q^2 = 0$, equation (6) is reduced to equation (3).

Although similar relationships apply for parity-violating elastic scattering from $^4$He and quasi-elastic scattering from $^2$H, these involve different linear combinations of $G_{E1}$ and $G_{M1}$ and the various form factors $^{15,16}$. Global fit. Using equation (6), a global fit was made to a database that included all relevant PVES data up to $Q^2 = 0.63$ GeV$^2$–c$^{-2}$: 28 electron–proton scattering results obtained by the G0$^{06,37}$, HAPPEX$^{38,41}$, SAMPLE$^{42}$, PVA$^{44-46}$ and Q$^{weak}$ collaborations, including the present result, two $^4$He elastic scattering results (HAPPEX$^{40,46}$) and five $^2$H quasi-elastic scattering results (G0$^{07}$, PVA$^{44,45}$ and SAMPLE$^{38}$).

For the fit, we followed the procedure introduced by Young et al.$^{17}$, as used in refs.$^{18,19}$. We used six parameters in the fit; namely, $G_{10}$, $G_{20}$ and four parameters that characterize the strange and axial form factors: the strange radius $\rho_s$, the strange magnetic moment $\mu_s$, and the magnitudes of $G_{E1}^s$ and $G_{M1}^s$. The parameterizations chosen for the strange form factors were $G_{E1}^s = \rho_s Q^2 G_{M1}^s$ and $G_{M1}^s = \mu_s G_{E1}^s$, with the dipole form factor $G_{E1}^s = (1 - Q^2/\lambda_s^2)^2$, where $\lambda_s = 1$ GeV–c$^{-1}$. Young et al.$^{17}$ examined the consequences of using more elaborate $Q^2$ dependences for $G_{E1}^s$ and $G_{M1}^s$ and found that they were not required for the data. More recent analyses have come to the same conclusion.$^{19,40,41}$ LQCD calculations$^{19,42}$ have also found similar shapes for $G_{E1}^s$ and $G_{M1}^s$. The neutron’s axial form factor $G_A^0$ enters the fit through the inclusion of $^2$H data in the database. For the isovector combination $G_{E1}^{T=1/2} = (G_{E1}^p - G_{E1}^n)/2$, the dipole form $G_{E1}^p$ was again adopted, with the normalization factor as the parameter. Because the isoscalar combination $G_{E1}^{T=0} = (G_{E1}^p + G_{E1}^n)/2$ is known from the theory to be small, it was constrained in the fit to the theoretical value$^{43}$ $G_{E1}^{T=0} = -0.08 \pm 0.26$, reducing the effective number of parameters to five. The unconstrained isovector combination $G_{E1}^{T=1}$ presented in Table 1 was constructed from the values of $G_{E1}^p$ and $G_{E1}^n$ determined in the fit, which were $G_{E1}^p = -0.59 \pm 0.34$ and $G_{E1}^n = 0.68 \pm 0.44$ with a covariance of $-0.0265$.

The electromagnetic form factors $G_E^p$, $G_M^p$, $G_E^n$ and $G_M^n$ were taken from ref.$^{4}$. If, instead, we use any one of the several alternative parameterizations for these form factors$^{15,18}$, the fitted result for $Q_{weak}$ changes by less than 1%. We have incorporated this range as a systematic uncertainty.

Each of the experimental asymmetries $A_{ep}$ used in the fit needed to be corrected for the one electroweak radiative correction with considerable energy dependence, the $\gamma$Z-box diagram$^1$. Three independent theoretical groups have calculated this correction, with results in excellent mutual agreement.$^{10,13,54}$ We have adopted the most recent, which was obtained from a data-driven calculation of the vector$^{10} (0.0054(4))$ and axial-vector$^{12,12} (0.0007/2))$ contributions, multiplied by a small $Q^2$ correction$^{13} (0.978(12))$; the numerical values given here are in terms of the effect on the reduced asymmetry $A_{ep}/A_0$. The total correction to our datum is $0.0046(5)$, corresponding to a 6.4% $\pm$ 0.6% correction to $Q_{weak}^p$. If, instead, we use the calculations of either ref.$^{13}$ or ref.$^{33}$, the extracted value of $Q_{weak}^p$ is essentially unchanged, and the effect on its uncertainty is negligible.

The fit was done using linear $\chi^2$ minimization, with a resulting $\chi^2/d.o.f.$ of 1.25 for 29 degrees of freedom (d.o.f.).

Apparatus. The $Q_{weak}$ experiment was performed using a custom apparatus installed in Hall C at the Thomas Jefferson National Accelerator Facility. A complete description of the apparatus and critical aspects of the accelerator can be found in ref.$^4$. Here we highlight some of the most important details illustrated in Extended Data Fig. 1.

The electron beam was longitudinally polarized and its helicity was reversed at a rate of 960 Hz in a pseudorandom sequence of ‘helicity quartets’ $(++)$ or $(-+--)$. The quartet pattern minimized noise due to slow linear drifts, and the rapid helicity reversal limited noise due to fluctuations in the target density and beam properties. As a test for possible false asymmetries, two methods were used to reverse the beam helicity on a slower timescale than the rapid helicity reversal. About every 8 h, the helicity of the laser beam that was used to generate the polarized electron beam was reversed by insertion of a half-wave plate in its path. The helicity of the electron beam in the accelerator’s injector region was reversed monthly using a ‘double Wien’ spin rotator$^{20}$. Non-vanishing correlations between the properties of the electron beam (intensity, position, angle, and energy) and its helicity lead to false contributions to the measured asymmetry. These helicity-correlated beam properties were suppressed by carefully setting up the helicity-defining optics and active-feedback systems in the polarized injector laser system.

The electron beam transport line was instrumented to allow the correction of residual helicity-correlated beam properties. Beam monitors upstream of the experimental apparatus provided continuous, non-invasive measurement of the electron beam’s intensity, position, angle and energy. The response of the experimental apparatus to changes in the beam properties was periodically measured using a beam modulation system that generated controlled variations in the beam’s position and angle using magnets and in its energy using a radio-frequency accele-

ratory cavity. Finally, the electron beam’s polarization was measured with two independent polarimeters upstream of the $Q_{weak}$ apparatus.

The experiment usually ran with a 180$^\circ$-A beam of 1.16 GeV, $~88$% longitudinally polarized electrons incident on a 34.4-cm-long liquid hydrogen target placed in an aluminium cell and maintained at 20 K. A set of three lead collimators restricted the polar scattering angle acceptance to the range $5.8^\circ \leq \theta \leq 11.6^\circ$ with an azimuthal angle coverage of 49$^\circ$ of $\pi$. A resistive toroidal magnet between the target and detectors separated the elastically scattered electrons of interest from irreducible backgrounds arising from inelastic and Møller scattering. The resulting scattered electrons were detected in eight synthetic-quartz Cherenkov detectors, each 200 cm $\times$ 18 cm $\times$ 1.25 cm, arranged in an azimuthally symmetric pattern about the beam axis. Fourfold azimuthal symmetry was important to minimize and characterize the effects of helicity-correlated beam properties and residual transverse beam polarization. These ‘main’ detectors were equipped with 2-cm-thick Pb pre-radiators that amplified the electron signal and suppressed low-energy backgrounds. Light was collected from the detectors by photomultiplier tubes (PMTs) at each end. The high rates of $~800$ MHz per detector required a current-mode readout, in which the PMT anode current was converted to a voltage that was digitized and integrated about every millisecond. Photographs of the apparatus are shown in Extended Data Fig. 1.

The collimator–magnet configuration and carefully designed shielding were effective in minimizing reducible sources of background, such as direct line-of-sight (neutral) tracks originating in the target and secondary scattering from the beampipe. The residual diffuse background was monitored by background detectors placed in the super-elastic region, a dark box with a bare PMT and a dark box with a PMT attached to a light guide. A symmetric array of four smaller detectors (‘upstream luminosity monitors’) placed on the upstream face of the defining (middle) collimator was effective in monitoring residual backgrounds from the tungsten beam collimator that shielded the downstream region from small-angle-scattered particles.

Finally, a tracking system consisting of drift chambers located before and after the magnet was deployed periodically to verify the acceptance-weighted kinematic distribution of the beam forward to help define the backgrounds. These measurements were done in special run periods at very low beam currents (0.1–200 nA) and using conventional individual pulse counting.
Data from the experiment’s short commissioning run (4% of the size of the dataset reported here) have been previously published. Here we report the combined result from two run periods (referred to as Run 1 and Run 2), each about six months in duration. Because improvements were made to the apparatus between the two run periods and their beam conditions were different, we report the corrections and systematic uncertainties for each run period separately. To prevent possible biases in the analysis, the main-detector asymmetries were blinded by an additional shift in asymmetry that was different for each run period. When the data analysis was complete, the asymmetries were unblinded, revealing the results presented here.

Data analysis. The raw asymmetry \( A_{\text{raw}} \) was formed from the normalized cross-section difference of equation (5) over the sum of the beam–charge normalized detector PMT signals, summed over the 8 detectors. The measured asymmetry \( A_{\text{raw}} \) was calculated from \( A_{\text{raw}} \) by correcting for a variety of effects that could cause false asymmetries:

\[
A_{\text{raw}} = A_{\text{beam}} + A_{t} + A_{\text{bcm}} + A_{\text{bb}} + A_{\text{bias}}
\]

The methods for determining each of these corrections and their uncertainties are discussed below.

Transverse asymmetry correction, \( A_{t} \). A small (~2%) residual transverse component of the incident beam polarization resulted in a transverse asymmetry \( A_{t} \), which is driven by a parity-conserving two-photon-exchange amplitude. To determine this correction, we measured the transverse asymmetry using a maximally transversely polarized incident beam, which we used to calculate an upper bound on the broken symmetry of the spectrometer–detector system (~1.3%). By combining these effects with the measured residual transverse polarization components of the beam during data-taking with a nominally longitudinally polarized beam, we determined the correction to be \( A_{t} = 0.0 \pm 0.1 \) p.p.b. and \( A_{t} = 0.0 \pm 0.7 \) p.p.b. for Run 1 and Run 2, respectively.

Beam current monitor correction, \( A_{\text{bcm}} \). The beam current was measured non-invasively with radio-frequency resonant cavities to allow a precise relative comparison of the beam charge in each helicity state. Two such beam current monitors (BCMs) were used in Run 1, while three BCMs were used in Run 2 after the installation of an additional monitor and improvement of the low-noise digital demodulation electronics. The correction \( A_{\text{bcm}} \) is zero by definition because in each period we normalize the integrated detector signals to the average of the BCM signals. The systematic uncertainty on this correction is determined from the variation in the reported charge asymmetry for the BCMs in each analysis, resulting in \( \Delta A_{\text{BCM}} = \pm 4.4 \) p.p.b. and \( \Delta A_{\text{BCM}} = \pm 2.1 \) p.p.b. for Run 1 and Run 2, respectively.

Beamline background asymmetry correction, \( A_{\text{bb}} \). False asymmetry caused by secondary events scattered from the beamline and the tungsten beam collimator is referred to as the beamline background asymmetry \( A_{\text{bb}} \). Such events were determined to be predominantly due to low-energy neutral particles and contributed a small amount to the signal (0.19%) but had a large asymmetry, which is believed to be associated with a helicity-dependent intensity or position variation in the extended halo around the main accelerated beam. Although their contribution was only a small component of the main detector signal, it dominated the asymmetry measurement of the background detectors, which were highly correlated (see Extended Data Fig. 2b). A direct correlation between the main-detector asymmetry from these events and the background asymmetries measured by the background detectors was shown by blocking two of the eight openings in the first of the three Pb collimators with 5.1-cm-thick tungsten plates (see Extended Data Fig. 2a). To correlate this false asymmetry, a correlation factor was extracted (separately for Run 1 and Run 2) between the asymmetries of the main detector array and the upstream luminosity monitor array, as shown in Extended Data Fig. 2c. The correlation factor was combined with the measured upstream luminosity monitor asymmetry, averaged every 6 min, to correct the main-detector asymmetry in that interval. The resulting net corrections for Run 1 and Run 2 were \( A_{\text{bb}} = 3.9 \pm 4.5 \) p.p.b. and \( A_{\text{bb}} = -2.4 \pm 1.1 \) p.p.b., respectively, where the uncertainty includes contributions from the statistical error on the determination of the correlation, as well as systematic errors extracted by allowing the correlation factor to vary randomly within a reasonable range over different time periods.

Correction for helicity-correlated beam properties, \( A_{\text{beam}} \). Residual non-vanishing correlations in the properties of the electron beam were accounted for through the correction \( A_{\text{beam}} \). Five beam properties—the transverse beam position and angle (horizontal \( X \), \( \chi \); vertical \( Y \), \( \psi \)), as well as the energy—were monitored continuously as described above. The run-averaged helicity-correlated values of these parameters are presented in Extended Data Table 1. Using the measured helicity-correlated beam differences \( \Delta X_{i} \) and the sensitivity of the measured asymmetry to variations in the beam parameters \( \partial A / \partial X_{i} \), the corrections for the 7th beam parameter were combined into the total correction:

\[
A_{\text{beam}} = -\sum_{i=1}^{5} \frac{\partial A}{\partial X_{i}} \Delta X_{i}
\]

The detector sensitivities \( \partial A / \partial X_{i} \) were measured routinely by varying the beam parameters using the beam modulation system described above. This system created small perturbations of the beam parameters about their nominal values with a sinusoidal driving function at 125 Hz. Furthermore, an accelerator fast-feedback system with an operational frequency range that included 125 Hz was used, driving the beam position and angle parameters with a sinusoidal pattern that was 90° out of phase with respect to the beam modulation system. The result was that the beam parameters were driven in more than one way, allowing for redundant measurements of the detector sensitivities using different combinations of the driven signals. The spread in those results was the dominant component of the systematic uncertainty for this correction. Typical values of the sensitivities are shown in Extended Data Table 1. For a perfectly symmetric apparatus, the position and angle sensitivities would be zero. For this apparatus, the sensitivities show that the horizontal plane had a larger broken symmetry than the vertical plane. The resulting corrections were \( A_{\text{beam}} = 18.5 \pm 4.1 \) p.p.b. and \( A_{\text{beam}} = 0.0 \pm 1.1 \) p.p.b. for Runs 1 and 2, respectively. The considerably smaller correction in Run 2 was due to smaller position and angle helicity-correlated differences during that period.

Rescattering bias, \( A_{\text{resc}} \). When comparing the measured asymmetry in the two PMTs (‘left’ and ‘right’) that read out the signal at each end of the eight main detectors, we found a consistent difference of about ±300 p.p.b., as shown in Extended Fig. 3a. Here, ‘right’ is the beam direction \( \hat{r} \) crossed with the radial direction \( \hat{r} \times \hat{r} \). This effect is due to the left/right analysing power of the multiple scattering of transversely (radially) polarized electrons through the Pb pre-radiators of the main detectors. For perfect symmetry, this parity-conserving effect cancels when forming the parity-violating asymmetry of interest. Properly accounting for the minor broken symmetries of the as-built apparatus leads to a correction, \( A_{\text{resc}} \), referred to as rescattering bias.

A schematic of the physical model for this effect is shown in Extended Data Fig. 3a. Scattered electrons, which are initially fully longitudinally polarized, acquire some transverse polarization through precession as they transport through the spectrometer’s magnetic field.

The effect was modelled using a detailed Geant4 simulation of the transport of the detected electrons through the spectrometer and the Pb radiator, including electromagnetic showering and Mott scattering. An asymmetry in the distribution of electrons penetrating the radiator develops owing to the analysing power of low-energy Mott scattering. A possible analysing power for high-energy scattering due to non-Born processes was also considered, but reasonable models for those processes showed a negligible contribution.

Asymmetries obtained from this simulation (and from a variety of analytic effective models that reproduced the key features of the simulation) were combined with scattered electron flux distributions and tailored parameterizations of the Cherenkov–light yield for each detector to estimate \( A_{\text{resc}} \) and its uncertainty. The light yield varied strongly with the arrival angle and position of the electron on the detector. The light-yield parameterizations were developed to match the observed light-yield distribution by tuning the optical parameters in a Geant4 optical-photon transport simulation. The largest systematic uncertainty was associated with the optical modelling of the individual as-built detectors. This uncertainty was determined from the range of predicted \( A_{\text{resc}} \) values, which was obtained by varying the optical parameters in the simulation while maintaining reasonable agreement with the measured light yield distributions. The predicted \( A_{\text{resc}} \) values for each detector are shown in Extended Data Fig. 3c. The resulting averaged correction and its systematic uncertainty are \( A_{\text{resc}} = 4.3 \pm 3.0 \) p.p.b.

This result was consistent to within 1 p.p.b. with a simpler, independent calculation based on a phenomenological approach, which used the measured position distributions of the electron flux on the pre-radiators and the measured dependence of the asymmetry on the position of the electron on the detector. The results obtained using the measured distributions from the experiment’s tracking system were compared with those obtained from the simulation. In this approach, the effect of the position differences was scaled to match the observed left/right asymmetry. The sensitivity to various models for the position dependence of the asymmetries was found to be small.

Determination of \( A_{\text{ep}} \). The measured asymmetry \( A_{\text{ep}} \) was then corrected for incomplete beam polarization, the effects of various background processes, electromagnetic radiative corrections and the finite acceptance of the detector, to obtain the fully corrected electron–proton asymmetry \( A_{\text{ep}} \) using:
(8) where $R_{\text{tot}} = R_1 R_2 R_{\text{det}} R_{\text{Q}} f_1 f_2$ are dilutions to the signal and $A$ are false or background process asymmetries. The components of equation (8) are discussed below.

1. $R_{\text{det}}$. The electromagnetic radiative correction factor $R_{\text{det}} = 1.010 \pm 0.005$ accounts for the effect of internal and external bremsstrahlung of the incident electron, which can depolarize the electron and modify the momentum transfer $Q^2$ at the scattering vertex. $R_{\text{det}}$ was determined using a Geant3 simulation by comparing results with and without bremsstrahlung enabled in the simulation.

2. $R_{\text{Q}}$. The Cherenkov detector analogue response that is, the summed optical signal detected by the two PMTs attached at each end of each detector) varied as a function of the arrival location of the scattered electron on the detector. The magnetic optics of the spectrometer also caused a correlation of the electron arrival location with $Q^2$ and, therefore, with the asymmetry. The correlation between the detector's analogue response and the $Q^2$ value of each track was determined using the tracking-system drift chambers, and the resulting correction to the measured asymmetry was $R_{\text{Q}} = 0.9893 \pm 0.0021$.

3. $R_{\text{asc}}$. Owing to the finite acceptance of the spectrometer and the effect of radiative energy losses, $A_{\text{raw}}$ represents an average over a range of $Q^2$ values. Because the asymmetry varies strongly with $Q^2$, we used a simulation to correct the averaged asymmetry $(A(Q^2))$ to the asymmetry that would arise from point scattering at the central $(Q^2)$. $A(Q^2)$, using:

$$A(Q^2) = \frac{A_{\text{raw}}(Q^2)}{A(Q^2)} \times 0.977 \pm 0.002$$

4. $R_{\text{Q}}$. The central $(Q^2)$ for the experiment was determined from a Geant4 simulation that was benchmarked with measurements from the tracking system. The $(Q^2)$ value was not identical for Run 1 and Run 2 because of minor differences in the beam energy, target location and magnetic field of the spectrometer, with Run 1 having a higher $(Q^2)$. The global fit of $A_{\text{Q}}$ versus $Q^2$ (see Fig. 2) was used to determine the sensitivity of the asymmetry to small changes in $(Q^2)$. Run 2 was chosen as the reference for $(Q^2)$, and the Run 1 asymmetry was scaled from its measured $(Q^2)$ value using $R_{\text{Q}} = 0.9928$ ($R_{\text{Q}} = 1$ for Run 2, by definition). The determination of the central $(Q^2)$ value has a 0.45% relative uncertainty, dominated by the uncertainties on the locations of the collimator, target and main detector and that of the beam energy determination. To simplify the global fitting, we decided to quote $(Q^2)$ as exact and used the sensitivity $A_{\text{Q}}/(Q^2)$ to determine an effective error contribution to the asymmetry. This error on $(Q^2)$ was 0.0055 for both run periods. The acceptance-averaged $Q^2$, scattering angle and incident electron energy were $(Q^2) = 0.0248$ GeV$^2$ c$^{-2}$, $\theta = 7.90^\circ$ and $E_0 = 1.149$ GeV, respectively.

5. Beam polarization, $P$. To achieve a reliable determination of the beam polarization ($P$) at <1% accuracy, two different techniques with precisely calculated analysing powers were employed for redundancy. An existing Moller polarimeter$^{30}$ in experimental Hall C was used invisibly 2–3 times a week. It measured the parity-conserving cross-section asymmetry in the scattering of polarized beam electrons from polarized electrons in an iron foil target at low (typically smaller than or equal to ~2μA) beam currents. A newly installed, non-invasive Compton polarimeter$^{31}$ monitored the beam polarization continuously at the full-production beam current of 180μA. This device measured the parity-conserving asymmetry in the scattering of Compton electrons from circularly polarized laser photons. For each run period, the averaged beam-polarization-corrected asymmetry was computed in two ways: by correcting each ~6 min period of data-taking for the polarization measured during that interval, and by using an overall average beam polarization for the whole run period. Because the two methods gave the same result to a small fraction of the quoted uncertainty, for simplicity the results obtained using the overall average beam polarization are quoted here. The overall average beam polarizations for the two running periods were $P_{\text{run}1} = (87.66 \pm 1.05)%$ and $P_{\text{run}2} = (88.71 \pm 0.55)%$, where the uncertainties are predominantly systematic. For Run 1, the uncertainty was larger for two reasons: the Compton polarimeter was still being commissioned, so it was not used for this determination, and the Moller uncertainty was larger than usual owing to the need to correct for the effects of an intermittent short circuit in one of the quadrupole magnets of the polarimeter. For Run 2, both polarimeters were fully functional and agreed well with each other, as shown in Extended Data Fig. 4. A dedicated direct comparison of the Moller and Compton polarimeters under identical beam conditions at low beam current was also performed. The two techniques agreed within the uncertainties for that measurement, $dP/P = 1%$ and $dP/P = 0.73%$ for the Compton and Moller polarimeters, respectively.

Physics backgrounds (target windows). The entrance (0.11-mm-thick) and exit (0.13-mm-thick) windows of the hydrogen target were made of aluminium 7075 alloy. Electrons scattered from these windows caused the dominant background process ($f_1 A_1 = 37$ p.p.b. for Run 1 and $f_2 A_2 = 38$ p.p.b. for Run 2). The parity-violating electron asymmetry for electrons scattered from aluminium is observed to be nearly an order of magnitude larger than that for scattering from hydrogen owing to the much larger weak charge of the aluminium nucleus$^{34}$. Therefore, even the small fraction of the detected yield arising from the windows required a substantial correction to the measured asymmetry. The aluminium asymmetry was determined in dedicated data-taking runs using an aluminium target made from the same block of material as the target windows but with a thickness (3.7 mm) to match the radiation length of the hydrogen target. The ranges of scattering angles accepted from the upstream and downstream windows were different, which required a small kinematical correction to the measured alloy asymmetry to yield the asymmetry from the target windows $A_1 = 1.515 \pm 0.077$ p.p.m. (see Extended Data Fig. 5). The uncertainty is dominated by statistics but includes systematic uncertainties arising from the kinematical correction, among others. The fraction of the measured yield arising from the target windows, $f_2 = (2.471 \pm 0.056)%$ (Run 1) and $f_2 = (2.516 \pm 0.059)%$ (Run 2), was measured with a low beam current on an evacuated target cell, and a simulation was used to correct for radiative effects due to the liquid hydrogen.

Physics backgrounds (beamline background dilution). As described above (see Beamline-background asymmetry correction, $A_{\text{beam}}$), a component of the background came from scattering sources in the beamline. The dilution from this source was measured$^{26}$ to be $f_2 = (0.193 \pm 0.064)%$ by blocking two of the eight openings in the first collimator to eliminate the electron elastic-scattering signal from the target. The uncertainty accounts for variations in the $f_2$ value between detectors and under different beam conditions.

Physics backgrounds (neutral background). A possible contribution from low-energy neutral backgrounds arising from secondary interactions of the primary scattered electrons in the collimators and magnet structure was bounded$^{45}$ to $f_2 < 0.30\%$ by subtracting $f_2$ from the total neutral background measured by the main detector after vetoing charged particles using thin scintillators. The asymmetry for this background was estimated$^{46}$ from a Geant4 simulation of the contributing processes to be $A_1 = 0.39 \pm 0.16$ p.p.m., with the dominant contribution coming from secondary interactions of electrons elastically scattered from protons.

Physics backgrounds (inelastic electrons). An unavoidable background component comes from inelastically scattered electrons that have excited the target protons to the $\Delta(1322)$ resonance, a small fraction of which enter the acceptance of the spectrometer. The fraction of the yield from inelastically scattered electrons was estimated using simulation to be $f_2 = (1.82 \pm 0.37) \times 10^{-4}$. To determine the correction to the asymmetry owing to these events, we measured the parity-violating asymmetry in the energy region near the $\Delta(1322)$ resonance during a dedicated study with a reduced spectrometer current to concentrate these electrons on the detectors. Scaling this asymmetry up to the $Q^2$ value of the elastic peak gives an inelastic asymmetry of $A_{\text{inel}} = -3.0 \pm 1.0$ p.p.m. at the elastic peak. Backgrounds from other sources and other beam conditions are negligible.

Summary of corrections to the asymmetry and their uncertainties. The separate and combined measured asymmetries for Runs 1 and 2 are presented in Extended Data Table 2. Also shown is the breakdown of these uncertainties in terms of descending fractional significance. Extended Data Table 3 presents the numerical values of the raw asymmetry, $A_{\text{raw}}$ along with all systematic and acceptance correction factors used to derive the observed measured asymmetry, $A_{\text{obs}}$, and physics asymmetries, $A_{\text{ph}}$, using equations (7) and (8). Correlated uncertainties, accounted for when the two runs were combined, are also listed.

The fully corrected asymmetry is $A_{\text{obs}} = -223.5 \pm 15.0$ (statistical) $\pm 10.1$ (systematic) p.p.b. for Run 1 and $A_{\text{obs}} = -227.2 \pm 8.3$ (statistical) $\pm 5.6$ (systematic) p.p.b. for Run 2. The combined asymmetry is $A_{\text{obs}} = -226.5 \pm 7.3$ (statistical) $\pm 5.8$ (systematic) p.p.b.

Data quality. Two representative tests of the consistency and the quality of the corrected asymmetries are presented below.

Null result. The $Q_{\text{min}}$ experiment employed signal phase locking on three independent techniques of polarized-beam helicity reversal that were used to isolate the scattering asymmetry. These were the rapid (960 Hz) reversal, the insertion of a half-wave plate in the source laser optical path at 8-9 h intervals and the Wien-filter reversal at monthly intervals. The half-wave plate technique is based on a mechanical action and thus is unable to induce any false asymmetries electrically or magnetically. The Wien-filter reversal rejects false asymmetries induced by beam-size (or focus) modulation. By constructing an out-of-phase, or null, asymmetry $A_{\text{null}}$ from the latter two slow-reversal techniques, we can determine whether there are unaccounted-for false asymmetries. The full dataset-weighted null is $A_{\text{null}} = -1.75 \pm 6.51$ p.p.b., which is consistent with zero, as expected.

Asymmetry measurements. A plot of the observed main-detector asymmetry versus polarimeter phase is shown in Extended Data Fig. 6. Run 1 and Run 2 were separated by a six-month accelerator shutdown, during which numerous modifications were made to the experimental apparatus and accelerator. These included upgrading the electronics associated with the beam current measurement.
and increasing the number of associated RCMs. An electrically isolated helicity phase-locked beam-position stabilization system was enabled in the 6-MeV region of the injector during Run 2. This greatly improved the helicity-correlated stability of the beam delivered to the experiment. There were also radio-frequency-associated electronics and superconducting-cavity upgrades performed within the accelerator, unrelated to this experiment, as well as extensive upgrades to both beam polarimeters. As a consequence, the contributions of many beam-related systematic effects meaningfully changed between the two run periods. However, the resulting fully corrected physics asymmetries of the two run periods agree well. This is evidence that within the experiment's precision, the observed set of identified systematic effects is complete and their associated correction algorithms behave in a deterministic manner.

**Electroweak radiative corrections and extraction of \( \sin^2 \theta_W \).** The weak mixing angle is obtained from the proton's weak charge, taking into account energy-independent electroweak radiative corrections using

\[
4 \sin^2 \theta_W(0) = 1 - \frac{Q^p_W - \Delta q_{\text{WW}} - \Delta q_{\text{ZZ}} - \Delta q_{\text{ZZ}(0)}}{(\rho + \Delta_e)} + \Delta_e^\prime
\]

(9)

Here, \( \Delta q_{\text{WW}} \) and \( \Delta q_{\text{ZZ}} \) are the WW and ZZ boson box diagram radiative corrections, \( \rho \) is the renormalization of the ratio of neutral-current (Z) to charged-current (W±) interactions at low energy, \( \Delta_e \) is the electron vertex correction to the axial Zee interaction, \( \Delta_{q_{\text{ZZ}}}(0) \) refers to the remaining energy-independent piece of the Z-boson box diagram (the energy-dependent piece was discussed in 'Global fit').

The accidental suppression of the proton's weak charge in the standard model means that \( Q^p_W \) is unusually sensitive to \( \sin^2 \theta_W \). To see this quantitatively, our determination of \( Q^p_W \) to a precision of 0.25% results in a \( \sin^2 \theta_W \) precision of 0.46%. By contrast, the higher relative precision (0.59%) of the weak charge measurement on \(^{127}\text{Cs} \), which is dominated by the neutron's weak charge, which is not suppressed in the standard model, leads to a \( \sin^2 \theta_W \) uncertainty of 0.81%, almost twice the uncertainty of our result.

The radiative corrections appearing in equation (9) are described in ref. 1 but were re-evaluated using the more recent input found in refs. 2,11. Although \( Q^p_W \) in equation (6) is defined in the Thomson limit (\( Q < m_e \), where \( m_e \) is the electron mass) at \( Q = 0 \), it is determined from data in the scattering limit (\( Q \gg m_e \)). We chose to use radiative corrections in the Thomson limit from ref. 1 to calculate \( \sin^2 \theta_W(0) \) from \( Q^p_W \). Extended Table Data 4 lists these corrections,\(^{1,2,5,10,17}\).

To compare our result for \( \sin^2 \theta_W(0) \), given by equation (9), with that of refs. 1,4, we added a correction of 2\( \rho \)/\( (\rho + \Delta_e) \), consistent with the definition of \( \rho \), as discussed in ref. 10. The result is \( \sin^2 \theta_W(0) = 0.2384 \pm 0.0011 \) in the MS scheme\(^{10} \). Shifting this to the \( Q = 0.158 \) GeV of the Qweak experiment (a correction of \(-0.00012\)) results in \( \sin^2 \theta_W(0) = 0.2382 \pm 0.0011 \).

**Data availability.** The 200 TB of raw data acquired in this work are stored at the Jefferson Laboratory data silo. The derived data supporting the findings of this study are available from the corresponding authors upon request.

**Code availability.** The software used for data management and analysis consisted of commercial and publicly available codes, plus experiment-specific software. Jefferson Laboratory's data management plan is available at https://scicomp.jlab.org/DataManagementPlan.pdf. The experiment-specific software is stored in a version management system (SVN & GIT) and archived at the data storage facilities of Jefferson Laboratory, in accordance with existing US regulations. Requests for this material should be addressed to the corresponding authors.
Extended Data Fig. 1 | Apparatus. **a**, Schematic of critical accelerator components and the $Q_{\text{weak}}$ apparatus$^4$. The electron beam is generated at the photocathode, accelerated by the Continuous Electron Beam Accelerator Facility (CEBAF) and sent to experimental Hall C, where it is monitored by beam position monitors and beam current monitors. The insertable half-wave plate (IHWP) provides slow reversal of the electron beam helicity. The data acquisition system records the data. **b**, Computer-aided design drawing of the experimental apparatus. **c**, The $Q_{\text{weak}}$ apparatus, before the final shielding configuration was installed. **d**, Interior of the hut shielding the detectors, showing two of the Cherenkov detectors (right) and a pair of tracking chambers (left).
**Extended Data Fig. 2 | Beamline background.** Determination of $A_{bb}$, the false asymmetry arising from beamline background events. Uncertainties are 1 s.d. **a**, Correlation of the main detector asymmetry to that of the upstream luminosity monitors, measured when the signal from elastically scattered electrons in the main detectors was blocked at the first collimator. **b**, Correlation of asymmetries from the upstream luminosity monitors with one of the other background detectors (a bare PMT located in the detector shield house). **c**, Correlation of the unblocked main detector asymmetry to that of the upstream luminosity monitor for Run 2. Our $A_{bb}$ determination was based on this slope.
Extended Data Fig. 3 | Rescattering bias. a, Schematic illustrating the precession of longitudinally polarized electrons through the spectrometer magnet, generating sizeable transverse spin components upon arrival at the detector array (spin directions indicated by red and blue arrows for the two electron helicity states). An end-view of the detector array, indicating the right (R) and left (L) PMT positions, is shown on the left. b, Difference between the asymmetry measured by the two (R and L) PMT tubes versus the detector number (Run 2 data). c, Calculated rescattering bias $A_{\text{bias}}$ versus detector number, with the eight-detector-averaged value shown by the red lines. Uncertainties (1 s.d.) are systematic.
Extended Data Fig. 4 | Electron beam polarization. Measurements from the Compton (closed blue circles) and Möller (open red squares) polarimeters during Run 2. Inner error bars denote statistical uncertainties and outer error bars show the statistical and point-to-point systematic uncertainties added in quadrature. Normalization, or scale-type, uncertainties are shown by the solid blue (Compton) and red (Möller) bands. All uncertainties are 1 s.d. The yellow band shows the derived polarization values used in the evaluation of the parity-violating asymmetry $A_{ep}$. The time dependence of the reported polarization is driven primarily by the continuous Compton measurements, with a small-scale correction (0.21%, not included in this figure) determined from an uncertainty-weighted global comparison of the Compton and Möller polarimeters.
Extended Data Fig. 5 | Asymmetry from aluminium. Parity-violating asymmetry from the aluminium alloy target versus the dataset number. All uncertainties are 1 s.d. The labels 'IN' and 'OUT' refer to the state of the insertable half-wave plate at the electron source, which generated a 180° flip of the electron spin when IN. The subscripts denote the setting of the Wien filter, with L and R corresponding to the presence and absence, respectively, of an additional 180° rotation of the spin direction of the electron beam. A period in which a further 180° flip was generated through $(g_e - 2)$ precession ($g_e$, electron gyromagnetic ratio) via a modified accelerator configuration during Wien 6 is indicated. The combinations OUT–R and IN–L with no $(g_e - 2)$ spin flip reveal the physical sign of the asymmetry. Solid lines represent the time-averaged values, and the horizontal dashed line indicates zero asymmetry. The vertical dashed lines delineate particular data subsets with a given Wien filter setting.
Extended Data Fig. 6 | Asymmetry from the proton. Observed parity-violating asymmetry $A_{ep}$ after all corrections, versus the dataset number (acquired in the double-Wien-filter configuration). The Wien filter reversed the beam helicity at approximately monthly intervals. The subscripts denote the setting of the Wien filter as L or R, corresponding to the presence or absence, respectively, of a 180° rotation of the spin direction of the electron beam. IN and OUT refer to the state of the insertable half-wave plate at the electron source, generating an additional 180° flip of the spin when IN. A period in which a further 180° flip was generated through $(g_e - 2)$ precession via a modified accelerator configuration is indicated. The combinations OUT–R and IN–L with no $(g_e - 2)$ flip reveal the physical sign of the asymmetry. Solid lines represent the time-averaged values and the dashed line indicates zero asymmetry. The uncertainties (1 s.d.) shown are those of the corresponding $A_{msr}$ values (see text) only—that is, they do not include time-independent uncertainties—so as to illustrate the time stability of the results. The weighted mean and $P$-value of the upper OUT–L and IN–R data are $226.9 \pm 10.2$, $P = 0.59$ (upper solid line), respectively. For the opposite combination, OUT–R and IN–L, we find a weighted mean of $-226.1 \pm 10.5$ and $P = 0.36$ (lower solid line).
Extended Data Table 1 | Helicity-correlated beam parameter differences and sensitivities

| Beam Parameter | Run 1 $\Delta X_i$   | Run 2 $\Delta X_i$   | Typical $\partial A / \partial X_i$ |
|----------------|-----------------------|-----------------------|-------------------------------------|
| $X$            | $-3.5 \pm 0.1$ nm     | $-2.3 \pm 0.1$ nm     | $-2$ ppb/nm                        |
| $X'$           | $-0.30 \pm 0.01$ nrad | $-0.07 \pm 0.01$ nrad | $50$ ppb/nrad                      |
| $Y$            | $-7.5 \pm 0.1$ nm     | $0.8 \pm 0.1$ nm      | $< 0.2$ ppb/nm                     |
| $Y'$           | $-0.07 \pm 0.01$ nrad | $-0.04 \pm 0.01$ nrad | $< 3$ ppb/nrad                     |
| Energy         | $-1.69 \pm 0.01$ ppb  | $-0.12 \pm 0.01$ ppb  | $-6$ ppb/ppb                       |

The beam parameter differences and typical detector sensitivities for the five measured beam parameters for Run 1 and Run 2. Uncertainties are 1 s.d.
### Extended Data Table 2 | Asymmetries and their corrections

| Period                      | Asymmetry (ppb) | Stat. Unc. (ppb) | Syst. Unc. (ppb) | Tot. Uncertainty (ppb) |
|-----------------------------|-----------------|------------------|------------------|------------------------|
| Run 1                       | -223.5          | 15.0             | 10.1             | 18.0                   |
| Run 2                       | -227.2          | 8.3              | 5.6              | 10.0                   |
| Run 1 and 2 combined with correlations | -226.5          | 7.3              | 5.8              | 9.3                    |

| Quantity                      | Run 1 error (ppb) | Run 1 fractional | Run 2 error (ppb) | Run 2 fractional |
|-------------------------------|-------------------|------------------|-------------------|------------------|
| BCM Normalization: $A_{BCM}$  | 5.1               | 25%              | 2.3               | 17%              |
| Beamline Background: $A_{BB}$ | 5.1               | 25%              | 1.2               | 5%               |
| Beam Asymmetries: $A_{beam}$  | 4.7               | 22%              | 1.2               | 5%               |
| Rescattering bias: $A_{bias}$ | 3.4               | 11%              | 3.4               | 37%              |
| Beam Polarization: $P$        | 2.2               | 5%               | 1.2               | 4%               |
| Target windows: $A_{t}$       | 1.9               | 4%               | 1.9               | 12%              |
| Kinematics: $R_{Q^2}$         | 1.2               | 2%               | 1.3               | 5%               |
| Total of others               | 2.5               | 6%               | 2.2               | 15%              |
| Combined in quadrature        | 10.1              |                  | 5.6               |                  |

Top, corrected asymmetries $A_{ep}$ for the Run 1 and Run 2 datasets, and the combined value, with their statistical (Stat. Unc.), systematic (Syst. Unc.) and total (Tot.) uncertainties (1 s.d.), in parts per billion (ppb). Bottom, fractional quadrature contributions ($\sigma_i/\sigma_{tot}$)² to the systematic uncertainty (1 s.d.) on $A_{ep}$ for Run 1 and Run 2. Only error sources with fractional contribution $\geq 5\%$ in one of the runs are shown.
Extended Data Table 3 | Raw asymmetries and their corrections

| Quantity     | Run 1                      | Run 2                      | Correlation |
|--------------|----------------------------|----------------------------|-------------|
| $A_{\text{raw}}$ | $-192.7 \pm 13.2$ ppb     | $-170.7 \pm 7.3$ ppb      |             |
| $A_T$        | $0 \pm 1.1$ ppb            | $0 \pm 0.7$ ppb            | 0           |
| $A_L$        | $1.3 \pm 1.0$ ppb          | $1.2 \pm 0.9$ ppb          | 1           |
| $A_{\text{BCM}}$ | $0 \pm 4.4$ ppb            | $0 \pm 2.1$ ppb            | 0.67        |
| $A_{\text{BB}}$ | $3.9 \pm 4.5$ ppb          | $-2.4 \pm 1.1$ ppb         | 0           |
| $A_{\text{beam}}$ | $18.5 \pm 4.1$ ppb         | $0.0 \pm 1.1$ ppb          | 0           |
| $A_{\text{bias}}$ | $4.3 \pm 3.0$ ppb          | $4.3 \pm 3.0$ ppb          | 1           |
| $A_{\text{msr}}$ | $-164.6 \pm 15.5$ ppb      | $-167.5 \pm 8.4$ ppb       |             |
| $P$          | $87.66 \pm 1.05$ %         | $88.71 \pm 0.55$ %         | 0.19        |
| $f_1$        | $2.471 \pm 0.056$ %        | $2.516 \pm 0.059$ %        | 1           |
| $A_1$        | $1.514 \pm 0.077$ ppm      | $1.515 \pm 0.077$ ppm      | 1           |
| $f_2$        | $0.193 \pm 0.064$ %        | $0.193 \pm 0.064$ %        | 1           |
| $f_3$        | $0.12 \pm 0.20$ %          | $0.06 \pm 0.12$ %          | 1           |
| $A_3$        | $-0.39 \pm 0.16$ ppm       | $-0.39 \pm 0.16$ ppm       | 1           |
| $f_4$        | $0.018 \pm 0.004$ %        | $0.018 \pm 0.004$ %        | 1           |
| $A_4$        | $-3.0 \pm 1.0$ ppm         | $-3.0 \pm 1.0$ ppm         | 1           |
| $R_{\text{RC}}$ | $1.010 \pm 0.005$          | $1.010 \pm 0.005$          | 1           |
| $R_{\text{Det}}$ | $0.9895 \pm 0.0021$        | $0.9895 \pm 0.0021$        | 1           |
| $R_{\text{Acc}}$ | $0.977 \pm 0.002$          | $0.977 \pm 0.002$          | 1           |
| $R_{Q^2}$    | $0.9928 \pm 0.0055$        | $1.0 \pm 0.0055$           | 1           |
| $R_{\text{tot}}$ | $0.9693 \pm 0.0080$        | $0.9764 \pm 0.0080$        | 1           |
| $\Sigma f_i$ | $2.80 \pm 0.22$ %          | $2.78 \pm 0.15$ %          | 1           |

The raw measured asymmetries $A_{\text{raw}}$ for the two run periods, and all the corrections (including for false asymmetries, backgrounds, beam polarization and detector acceptance) that were applied to extract the final asymmetry $A_{\text{msr}}$ from $A_{\text{raw}}$ (see text). The $f_i$ values are dilutions to the signal, $A_i$ are false or background process asymmetries, $P$ is the beam polarization and $R_i$ are multiplicative factors. The net multiplicative correction $R_{\text{tot}}$ and the total dilution are also indicated, as well as the values of $A_{\text{msr}}$, the asymmetry after the corrections for the false asymmetries (see equation (7)). The correlations used to combine the two runs are provided in the final column. Uncertainties are 1 s.d.
Extended Data Table 4 | Radiative corrections

| Term          | Expression                                                                 | Value   | Reference |
|---------------|---------------------------------------------------------------------------|---------|-----------|
| $\rho_{NC}$   | $1 + \Delta_{\rho}$                                                      | 1.00066 | 1, 2      |
| $\Delta_\epsilon$ | $-\alpha / 2\pi$                                                        | -0.001161 | 1, 2     |
| $\Delta'_\epsilon$ | $-\frac{\alpha}{3\pi} (1 - 4\hat{s}^2) \left[ \ln \left( \frac{M_Z^2}{m_e^2} \right) + \frac{1}{6} \right]$ | -0.001411 | 1, 2     |
| $\hat{\alpha}$ | $\equiv \alpha(M_Z)$                                                     | 1/127.95 | 1, 2      |
| $\hat{s}^2$   | $= 1 - \hat{c}^2 \equiv \sin^2 \theta_W(M_Z)$                           | 0.23129 | 1, 2      |
| $\alpha_s(M_W^2)$ | $\frac{\hat{\alpha}}{4\pi \hat{s}^2} \left[ 2 + 5 \left( 1 - \frac{\alpha_s(M_W^2)}{\pi} \right) \right]$ | 0.12072 | 67       |
| $\Box_{WW}$   | $\frac{\hat{\alpha}}{4\pi \hat{s}^2 \hat{c}^2} \left[ \frac{9}{4} - 5\hat{s}^2 \right] \left( 1 - 4\hat{s}^2 + 8\hat{s}^2 \right) \left( 1 - \frac{\alpha_s(M_Z^2)}{\pi} \right)$ | 0.01831 | 1, 2      |
| $\Box_{ZZ}$   | Axial-vector hadron piece of $\Box_{\gamma Z}$: $\text{Re} \Box_{\gamma Z}^A$ | 0.0044 | 11       |

Numerical values used for the electroweak radiative corrections in equation (9).