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Testing the Standard Model by precision measurement of the weak charges of quarks

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In a global analysis of the latest parity-violating electron scattering measurements on nuclear targets, we demonstrate a significant improvement in the experimental knowledge of the weak neutral-current lepton–quark interactions at low energy. The precision of this new result, combined with earlier atomic parity-violation measurements, places tight constraints on the size of possible contributions from physics beyond the Standard Model. Consequently, this result improves the lower-bound on the scale of relevant new physics to $\sim 1\,\mathrm{TeV}$.

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The Standard Model has been enormously successful at predicting the outcomes of experiments in nuclear and particle physics. The search for new physical phenomena and a fundamental description of nature which goes beyond the Standard Model is driven by two complementary experimental strategies. The first is to build increasingly energetic colliders, such as the Large Hadron Collider (LHC) at CERN, which aim to excite matter into a new form. The second, more subtle approach is to perform precision measurements at moderate energies [1, 2, 3], where an observed discrepancy with the Standard Model will reveal the signature of these new forms of matter [4]. Here we show that the latest measurements of the parity violating electroweak force [5, 6, 7, 8, 9, 10, 11, 12] constrain the possibility of relevant physics beyond the Standard Model to the TeV energy scale and beyond. While the current data sets a much improved bound on the scale of new physics, the nature of such low-energy tests is that future results will play a complementary role in determining the structure of potential new interactions in the LHC era.

After three decades of experimental tests, the only indication of a flaw in the Standard Model lies in the recent discovery of neutrino oscillations [13]. That discovery has renewed interest in identifying other places where physics beyond the Standard Model might be found. In this work we report the results of a search for indirect signatures of new physics through precise measurements at low energy. This is possible because, within the electroweak theory, one can rigorously derive a low-energy effective interaction between the electron and the quarks. Any deviation from the predictions of that effective force is then an unambiguous signal of physics beyond the Standard Model. We show that recent, state-of-the-art measurements of parity-violating electron scattering (PVES) on nuclear targets [5, 6, 7, 8, 9, 10, 11, 12] yield a dramatic improvement in the accuracy with which we probe the weak neutral-current sector of the Standard Model at low energy.

For our purposes, the relevant piece of the weak force which characterises the virtual-exchange of a Z^0-boson between an electron and an up or down quark can be parameterised by the constants, $C_{1u(d)}$, which are defined through the effective four-point interaction by [14]

$$\mathcal{L}_{\rm NC}^{eq} = -\frac{G_F}{\sqrt{2}}\bar{e}\gamma_\mu\gamma_5 e\sum_q C_{1q}\bar{q}\gamma^\mu q\,. \qquad (1)$$

These effective couplings are known to high-precision within the Standard Model, from precision measurements at the Z-pole [15] and evolution to the relevant low-energy scale [16, 17]. There are also parity-violating contributions arising from the lepton vector-current coupling to the quark axial-vector-current, with couplings, C_{2q}, defined in a similar manner. Although the PVES asymmetries are also dependent on the C_{2q}'s, they cannot be extracted from these measurements without input from nonperturbative QCD.

As summarized by the Particle Data Group (PDG) [14], existing data, particularly the determination of atomic parity violation in Cesium [1], primarily constrains the *sum* of the up and down quark "charges", $C_{1u} + C_{1d}$. The analysis of the new high-precision PVES data presented here now permits us to extract an independent experimental constraint on the *difference*, $C_{1u} - C_{1d}$. Combining this constraint with previous experimental results leads to a significant improvement in the allowed range of values for C_{1u} and C_{1d}. This constraint is determined within the experimental uncertainties of the electroweak structure of the proton. The new range of values allowed for these fundamental constants is consistent with the predictions of the Standard Model and severely constrains relevant new physics — to a mass scale beyond ~1–5 TeV.

Much of the current experimental interest in precision PVES measurements on nuclear targets has been focussed on revealing the strange-quark content of the nucleon. Progress in revealing the strangeness form factors has seen a dramatic improvement over the past few years, with experimental results being reported by SAMPLE at MIT-Bates [5, 6], PVA4 at Mainz [7, 8] and the HAPPEX [9, 10] and G0 [11] Collaborations at Jefferson Lab. Depending on the target and kinematic configuration, these measurements are sensitive to different linear combinations of the strangness form factors, G_E^s and G_M^s, and the nucleon anapole form factor [18, 19]. Recently, we reported a global analysis [20] of these measurements to extract all form factors from data.

Incorporating the new high-precision data, recently published by the HAPPEX Collaboration [12], into our global analysis [20], yields the most precise determination of the strange-quark currents to date, namely (at $Q^2 = 0.1\,\mathrm{GeV}^2$) $G_E^s = 0.002 \pm 0.018$ and $G_M^s = -0.01 \pm 0.25$ (correlation coefficient -0.96). Should one further impose constrain to theory estimates for the anapole form factor [19], as discussed below, these numbers shift by less than one standard deviation (with $G_E^s = -0.011 \pm 0.016$ and $G_M^s = 0.22 \pm 0.20$). Nevertheless, with the best fits constrained by data alone, we now ascertain that, at the 95% confidence level (CL), strange quarks contribute less than 5% of the mean-square charge radius and less than 6% of the magnetic moment of the proton. This new result offers further support for the latest theoretical quantum chromodynamics calculations [21, 22].

This determination of the strangeness form factors intimately relies on the accurate knowledge of the low-energy electroweak parameters of Eq. 1. Here we demonstrate that the latest PVES measurements are sufficient to probe new physics by testing the Q^2-evolution of the Standard Model.

Our global analysis of PVES measurements fits the world data with a systematic expansion of the relevant form factors in powers of Q^2. In this way one makes greatest use of the entire data set, notably the extensive study of the dependence on momentum transfer between 0.1 and $0.3\,\mathrm{GeV}^2$ by the G0 experiment [11]. We now allow the two coupling constants, C_{1u} and C_{1d}, to be determined by the data.

Most of the PVES data has been measured on a hydrogen target. For small momentum transfer, in the forward-scattering limit, the parity-violating asymmetry can be written as

$$A_{LR}^p \simeq A_0 \left[Q_{\mathrm{weak}}^p Q^2 + B_4 Q^4 + \ldots \right] , \tag{2}$$

where the overall normalisation is given by $A_0 = -G_\mu/(4\pi\alpha\sqrt{2})$. The leading term in this expansion directly probes the weak charge of the proton, related to the quark weak charges by $Q_{\mathrm{weak}}^p = G_E^{Zp}(0) = -2(2C_{1u} + C_{1d})$. (We note that in our earlier analysis [20], the full expressions for the relevant asymmetries were written in terms of radiative correction factors [23], related by $\xi_V^p = -2(2C_{1u} + C_{1d})$ and $\xi_V^n = -2(C_{1u} + 2C_{1d})$). The next-to-leading order term, B_4, is the first place that hadronic structure enters, with the dominant source of uncertainty coming from the neutral-weak, mean-square electric radius and magnetic moment. Under the assumption of charge symmetry this uncertainty naturally translates to the knowledge of the strangeness mean-square electric radius and magnetic moment. By considering different phenomenological parameterisations of the elastic form factors, we have confirmed that the potential uncertainties from this source have a negligible impact on our final result.

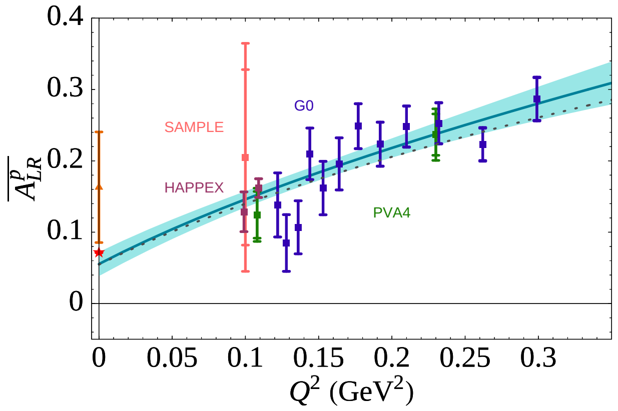

FIG. 1: Normalised, parity violating asymmetry measurements on a proton target, extrapolated to the forward-angle limit using our analysis of all world data on PVES (see text). The extrapolation to $Q^2 = 0$ measures the proton's weak charge, where the previous experimental knowledge (within uncertainties on the neutron weak charge) is shown by the triangular data point, and the Standard Model prediction by the star. The solid curve and shaded region indicate, respectively, the best fit and 1-σ bound, based upon our global fit to all electroweak data. The dotted curve shows the resulting fit if one incorporates the theoretical estimates [19] of the anapole form factors of the nucleon.

The extent of the data taken over the range $0.1 < Q^2 < 0.3\,\mathrm{GeV}^2$ allows a reliable extrapolation in Q^2 to extract the proton's weak charge. In Figure 1 we show the various proton-target measured asymmetries, extrapolated to zero degrees as explained below. The data is normalised as $\overline{A_{LR}^p} \equiv A_{LR}^p/(A_0 Q^2)$, such that the intercept at $Q^2 = 0$ projects onto Q_{weak}^p. The fit curve and uncertainty band is the result of the full global fits, where helium, deuterium and all earlier relevant neutral-weak current measurements [14, 24] are also incorporated.

Because each measurement has been performed at various scattering angles, the data points displayed in Fig. 1 have been rotated to the forward-angle limit using the global fit of this analysis, with the outer error bar on the data points indicating the uncertainty arising from the $\theta \to 0$ extrapolation. The dominant source of uncertainty in this $\theta \to 0$ extrapolation lies in the determination of the anapole form factor of the nucleon. The experimentally-constrained uncertainty on the anapole form factor is relatively large compared to estimates based upon chiral perturbation theory supplemented with a vector meson dominance model [19]. Further constraining our fits to this theoretical estimate yields the dotted curve in Fig. 1, where the discrepancy with the experimentally determined fit is always less than one standard deviation — and yields negligible impact on the weak charge extraction. In particular, the dotted curve changes our final lower-bound on the scale of new physics, Λ/g, reported below, by less than 1 part in 10^3.

This new constraint on the proton's weak charge provides an essentially orthogonal constraint to combine with the precise atomic parity-violation measurement on Cesium [1, 25] — which primarily constrains the isoscalar combination of the weak quark charges. The combined analysis, which involves fitting both the hadronic structure (strangeness and anapole) and electroweak parameters ($C_{1u,d}$, $C_{2u,d}$), displays excellent agreement with the data, with a reduced $\chi^2 = 21/23$. The new improvement is displayed in Fig. 2, where the previous experimental knowledge is summarised by the dotted ellipse [14, 24]. This is to be compared with the solid contour obtained by combining all earlier data with the powerful new constraint of the PVES data (indicated by the filled ellipse). Although the principal constraint from the PVES data is the proton's weak charge, the results are also sensitive to the isoscalar combination of the C_{1q} parameters through the helium measurements — resulting in the ellipse in Fig. 2.

The area of the allowed phase space of the effective couplings has been reduced by a factor of 5, where the combined analysis produces $C_{1u} + C_{1d} = 0.1526 \pm 0.0013$ and $C_{1u} - C_{1d} = -0.513 \pm 0.015$ (correlation +0.49). Since these numbers are dominated by the atomic parity violation and forward-angle PVES measurements, the correlations with the C_{2q} parameters are small. Further, we note that the new allowed region is in excellent agreement with the latest Standard Model values [14, 17], $C_{1u} + C_{1d} = 0.1529 \pm 0.0001$ and $C_{1u} - C_{1d} = -0.5297 \pm 0.0004$.

The dramatic increase in precision shown by the solid contour in Fig. 2 yields a new constraint on physics beyond the Standard Model. Whatever the dynamical origin, new physics can be expressed in terms of an effective contact interaction [17],

$$\mathcal{L}^{eq}_{\rm NP} = \frac{g^2}{\Lambda^2}\bar{e}\gamma_\mu\gamma_5 e \sum_q h^q_V \bar{q}\gamma^\mu q\,. \qquad (3)$$

With the characteristic energy scale, Λ, and coupling strength, g, we set the isospin dependence by $h^u_V = \cos\theta_h$ and $h^d_V = \sin\theta_h$. In Fig. 3 we display the bounds on the size of such an interaction, where new physics is ruled out at the 95% CL below the curve. Whereas previous data constrained a lower bound on relevant new physics $\Lambda/g > 0.4\,$TeV, consistent with direct searches at Fermilab, our new result lifts this limit to $0.9\,$TeV. Note that this limit applies to a generic class of quark-lepton parity-violating contact interactions, arising from integrating out all heavy, new-physics, degrees of freedom. The possibility of cancellations between conspiring new physics at lower energies cannot be ruled out by this analysis — yet our results do then necessitate such a cancellation for any proposed lower-energy new-physics scenarios. We further note that our determined limit involves the ratio, Λ/g, hence these results directly imply a "weak" coupling for any potential discovery of new physics at a relatively low energy.

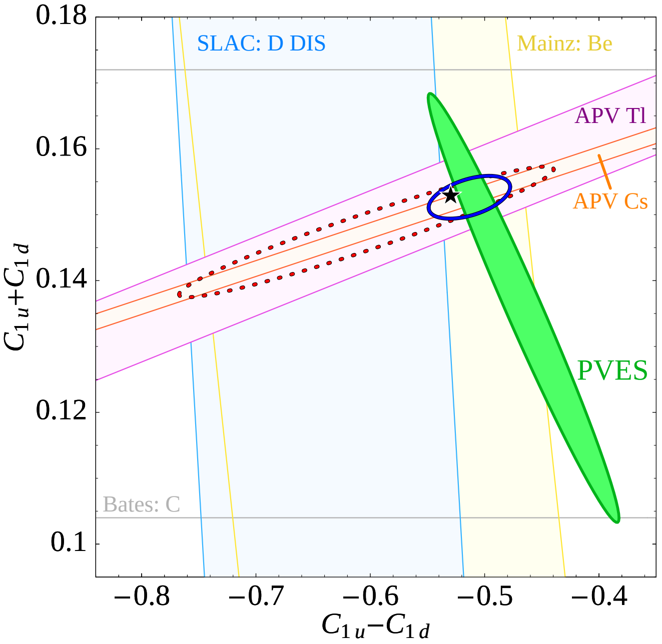

FIG. 2: Knowledge of the neutral weak effective couplings of Eq. (1). The dotted contour displays the previous experimental limits (95% CL) reported in the PDG [14] together with the prediction of the Standard Model (black star). The filled ellipse denotes the new constraint provided by recent high-precision PVES scattering measurements on hydrogen, deuterium and helium targets (at 1 standard deviation), while the solid contour (95% CL) indicates the full constraint obtained by combining all results. All other experimental limits shown are displayed at 1 standard deviation.

To conclude, let us briefly summarize our main findings. Our systematic analysis of the world data on PVES has shown that the effect of the hadronic form factors can be separated from the low-energy, effective weak charges C_{1u} and C_{1d}. Combining the resulting constraint with that obtained from the study of atomic parity violation data, one finds an extremely tight range of allowed values for **both** C_{1u} and C_{1d} — see the solid contour in Fig. 2. Not only is the result in excellent agreement with the predictions of the Standard Model, but the reduction in the range of allowed values of C_{1u} and C_{1d} is such that it severely limits the possibilities of relevant new physics (beyond the Standard Model) below a mass scale ∼1–5 TeV.

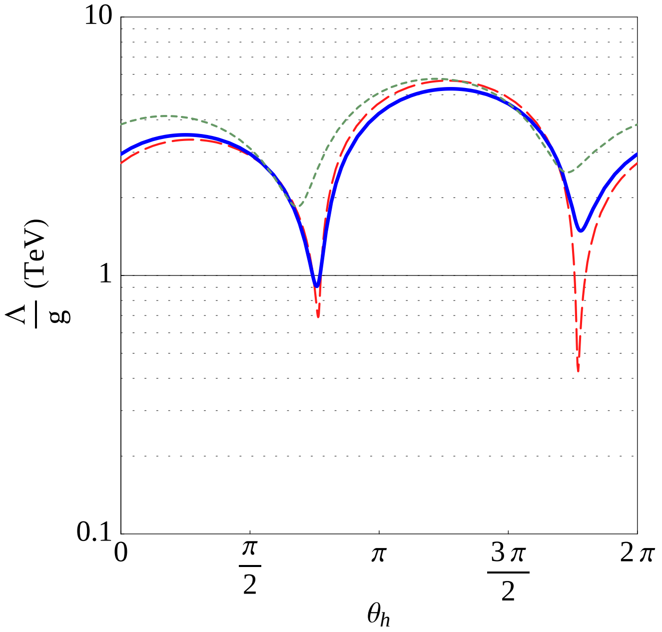

FIG. 3: Constraints on new physics beyond the Standard Model in terms of the mass scale versus the flavour mixing angle. New physics is ruled out at the 95% CL below the curves. The long-dashed curve shows the limits before this work, corresponding to the dotted ellipse of Fig. 2. The solid curve shows the new limits based on the solid contour in Fig 2. The short-dashed curve displays the reach of the future proton weak charge measurement to be performed at Jefferson Lab, *assuming* agreement with the Standard Model is observed.

The success of this analysis makes evident the significance of what can be achieved with future high-precision measurements, such as Q-weak, the proton PVES experiment planned at Jefferson Lab. Supplementing our current analysis with data of the accuracy expected from that experiment (under the assumption of agreement with the Standard Model) yields a reduction of the allowed region of $C_{1u,1d}$ by a further factor of 5. The potential impact of this is shown in Fig. 3, where over most of the range of θ_h, this would raise the lower bound on the mass of a possible Z' by roughly 1 TeV. Of course, it is also possible that Q-weak could discover a deviation from the Standard Model which would constrain both the mass–coupling ratio and flavor dependence of the relevant new physics, such as a new Z'. In the event of a discovery at the LHC, then measurements such as Q-weak will play a key role in determining the characteristics of the new interaction.

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