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Constraining extra neutral gauge bosons with atomic parity violation measurements

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The discovery of a new neutral gauge boson Z' could provide the first concrete evidence of physics beyond the standard model. We explore how future parity violation experiments, especially atomic parity violation experiments, can be used to constrain Z' bosons. We use the recent measurement of the ^{133}Cs nuclear weak charge to estimate lower bounds on the mass of Z' bosons for a number of representative models and to put constraints on the couplings of a newly discovered Z' boson. We also consider how these constraints might be improved by future atomic parity violation experiments that will measure nuclear weak charges of multiple isotopes. We show how measurements of a single isotope and combining measurements into ratios and differences can be used to constrain the couplings of a Z' and discriminate between models. We include in our results the constraints that can be obtained from the experiments QWEAK and P2 that measure the proton weak charge. We find that current and future parity violation experiments could potentially play an important role in unravelling new physics if a Z' were discovered.

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I. INTRODUCTION

The Large Hadron Collider (LHC) has started to explore the TeV energy regime opening up the possibility of discovering new fundamental particles. One such particle, which arises in many models of physics beyond the standard model (SM) and should be relatively straightforward to discover, is a new, massive, spin-1, s-channel resonance (Z') [1–8]. Although such a resonance could arise as a Kaluza-Klein excitation of the photon or the SM Z [9–11], we restrict our attention to Z' s arising from an extended gauge symmetry. For these models, contributions to precision electroweak observables generally imply a mass bound $M_{Z'} \gtrsim 1$ TeV [12–14], and recent estimates [7,8] indicate that the LHC should be able to probe far beyond these bounds, up to $\sim$5 TeV once the LHC reaches its design energy and luminosity.

While direct detection of new particles is unambiguous, precision measurements provide a complementary approach to exploring new physics [15–17]. For example, precision electroweak (EW) measurements impose comparable or stronger bounds than direct detection on many Z' bosons [12–14], and EW constraints on oblique parameters [18] are difficult to avoid in other new physics scenarios. One important recent update to the EW observables is a better than 1% extraction of the ^{133}Cs weak charge [19] from atomic parity violation (APV) experiments [20]

$$Q_W({}^{133}_{55}\mathrm{Cs}) = -73.16(29)_{\mathrm{exp}}(20)_{\mathrm{th}}. \qquad (1)$$

The new determination is in perfect agreement with the SM prediction of $Q_W({}^{133}_{55}\mathrm{Cs}) = -73.16(3)$ [21]. It has since been noted that this measurement provides strong constraints on the S parameter [22], and it can act as the dominant observable in global analysis of precision measurements used to constrain models of new physics [23]. Thus, $Q_W({}^{133}_{55}\mathrm{Cs})$ has been measured to a precision that can significantly constrain new physics [15].

In this paper we examine the implications of APV experiments on the physics of Z' bosons. We consider both the $Q_W({}^{133}_{55}\mathrm{Cs})$ result and observables from a number of future APV experiments which are expected to perform measurements of weak charges along the isotope chains of Ba [24], Fr [25,26], Ra [27], and Yb [28]. For completeness, we also consider the implications of other experiments measuring parity violation: the QWEAK measurement of the proton weak charge at Jefferson Lab [29], the P2 experiment at Mainz [30], and the SoLID deep inelastic measurement at Jefferson Lab [31–33]. The presence of a Z' would result in an $\mathcal{O}(M_Z^2 g_{Z'}^2/M_{Z'}^2 g_Z^2)$ correction to a weak charge. This effect has been discussed in the literature [15,34–37], but only a small subset of Z' models were considered. We expand on these earlier studies by considering Z' s from the following classes of models: little Higgs (LH) [38–40], left-right symmetric (LR), technicolor (TC) [41–48], 3-3-1 [49], E_6 [1], and the ununified model (UUM) [50]. References [1–7] contain details of these models and their phenomenology.

Our analysis consists of two parts. We first examine how measurements in APV experiments including the $Q_W({}^{133}_{55}\mathrm{Cs})$ result can be used to bound the Z' mass for various models. Given the sensitivity of APV measurements to Z' physics, we also examine how they could be used to constrain the properties of a newly discovered Z'.

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We find that APV experiments can provide strong constraints on the u-and d-quark couplings of a new Z' that are otherwise difficult to obtain, and could provide valuable information that complements other measurements.

The paper is organized as follows: In Sec. II we outline the equations and conventions we use in our analysis. In the remaining subsections, we discuss mass bounds coming from $Q_W({}^{133}_{55}\mathrm{Cs})$, weak charge ratios in isotopes of Fr and Yb, and the proton weak charge, and other parity violation experiments. In Sec. III we examine how these measurements can constrain the couplings of a Z' and help distinguish between different models. We summarize our results in Sec. IV.

II. NEW GAUGE BOSONS AND WEAK CHARGES

The nuclear weak charge of an isotope of element X with Z protons and N neutrons or $A = N + Z$ nucleons can be written [15] as

$$Q_W({}^A_ZX) = Q_W^0({}^A_ZX) + \Delta Q_W({}^A_ZX), \tag{2}$$

where a 0 superscript will denote a SM prediction, and a Δ will denote a new physics contribution. For the nuclear weak charge, the tree level SM prediction is given by [21]

$$\begin{aligned} Q_W^0({}^A_ZX) &= -4c_A^e[(2Z+N)c_V^u + (Z+2N)c_V^d] \\ &= -N + Z(1-4s_W^2), \end{aligned} \tag{3}$$

where $c^f_{A,V} \equiv c^f_L \mp c^f_R$ are the SM Z boson couplings to fermions and $s_W^2 \equiv \sin^2\theta_W$, with θ_W being the weak mixing angle [21].

At the sub-MeV energies of atomic physics, we can use the effective Lagrangian to describe the SM neutral current interaction between an electron e and a fermion f [15,21]. It has the following relevant parity-violating terms [51]:

$$\begin{aligned} \mathcal{L}^f_{\mathrm{PV}} &= -\frac{g_Z^2}{4M_Z^2}(c_A^e\bar{e}\gamma_\mu\gamma_5 e)(c_V^f\bar{f}\gamma^\mu f) \\ &\equiv \frac{g_Z^2}{16M_Z^2}Q_W^f(\bar{e}\gamma_\mu\gamma_5 e)(\bar{f}\gamma^\mu f), \end{aligned} \tag{4}$$

where $g_Z \equiv g_2/\cos\theta_W$ and g_2 is the gauge coupling constant of $\mathrm{SU}(2)_L$. It is understood that $\mathcal{L}_{\mathrm{PV}} = \sum_f \mathcal{L}^f_{\mathrm{PV}}$. Similarly, we can write the effective Lagrangian for the neutral current interaction of a Z' boson with mass $M_{Z'}$

$$\begin{aligned} \Delta\mathcal{L}^f_{\mathrm{PV}} &= -\frac{g_{Z'}^2}{4M_{Z'}^2}(\tilde{c}_A^e\bar{e}\gamma_\mu\gamma_5 e)(\tilde{c}_V^f\bar{f}\gamma^\mu f) \\ &= \frac{g_Z^2}{16M_Z^2}\left[-4\frac{M_Z^2}{M_{Z'}^2}\frac{g_{Z'}^2}{g_Z^2}\tilde{c}_A^e\tilde{c}_V^f\right](\bar{e}\gamma_\mu\gamma_5 e)(\bar{f}\gamma^\mu f), \end{aligned} \tag{5}$$

where $\tilde{c}^f_{A,V}$ and $g_{Z'}$ are defined for the $\bar{f}fZ'$ interactions in analogy with the SM quantities in Eq. (4).

It is straightforward to obtain the new physics contribution to the weak charge of a particle from Eq. (5), and for the proton and neutron we find

$$\begin{aligned} \Delta Q_W^p &= -4\frac{M_Z^2}{M_{Z'}^2}\frac{g_{Z'}^2}{g_Z^2}\tilde{c}_A^e(2\tilde{c}_V^u + \tilde{c}_V^d), \\ \Delta Q_W^n &= -4\frac{M_Z^2}{M_{Z'}^2}\frac{g_{Z'}^2}{g_Z^2}\tilde{c}_A^e(2\tilde{c}_V^d + \tilde{c}_V^u). \end{aligned} \tag{6}$$

The corrections to the weak charge of a given isotope can now be built from the above quantities

$$\Delta Q_W({}^A_ZX) = Z\Delta Q_W^p + N\Delta Q_W^n. \tag{7}$$

From Eqs. (6) and (7) it can be seen that a new neutral gauge boson does indeed modify weak charges by contributions of order $\mathcal{O}(M_Z^2 g_{Z'}^2/M_{Z'}^2 g_Z^2)$.

A. The weak charge of ^{133}Cs

Using Eq. (7), a precise determination of any weak charge can be readily translated into a bound on Z' physics. For example, the recent measurement of $Q_W({}^{133}_{55}\mathrm{Cs})$ can be used to obtain a mass bound on a model with fixed Z' couplings. We find, as in Ref. [19], that the Z' arising in the $E_6\chi$ model would result in a correction of $\Delta Q_W({}^{133}_{55}\mathrm{Cs}) \approx 65(M_Z/M_{Z'_\chi})^2$. The measurement of $Q_W({}^{133}_{55}\mathrm{Cs})$ given in Eq. (1) implies $M_{Z'_\chi} \gtrsim 1.3$ TeV at 84% C.L. Analogous mass bounds for various other Z' models are given in Table I.

We note that these mass bounds are derived using only the $Q_W({}^{133}_{55}\mathrm{Cs})$ measurement and a global fit including the precision EW data, etc. would improve these constraints [13,14]. However, by considering the $Q_W({}^{133}_{55}\mathrm{Cs})$ measurement on its own, we can compare its sensitivity to that of other Z' limits.

The simplest and anomaly free LH Z' s are particularly well constrained since they predict large, positive values for both ΔQ_W^p and ΔQ_W^n, which combine to give a large overall value for $AZ\Delta Q_W$. The opposite is true for the UUM, sequential SM, littlest Higgs, and models with an $\mathrm{SU}(2)\times\mathrm{SU}(2)$ group structure such as LR and extended TC. For these models ΔQ_W^p and ΔQ_W^n have opposite sign and the partial cancellation results in weak constraints from $Q_W({}^{133}_{55}\mathrm{Cs})$. Finally, APV experiments cannot constrain the $E_6\psi$ model, since it has $\tilde{c}_V^{u,d} = 0$ which implies no correction to any nuclear weak charge.

B. Future APV measurements

Improving the determination of $Q_W({}^{133}_{55}\mathrm{Cs})$ would require theoretical improvements in addition to the experimental efforts, and the mass bounds in the second column of Table I are not likely to be improved in the near future. However, the next generation of APV experiments is underway, in Ba [24], Fr [25,26], Ra [27], and Yb [28], each of which is well suited to APV experiments because they are expected to exhibit large parity violation, and there are multiple stable isotopes of each of these elements. We mention for completeness a proposal to measure the

TABLE I. Mass bounds from various APV observables. The second column contains the mass bounds from the actual measurement in Eq. (1) at 95% C.L. The remaining columns contain the masses that future APV experiments will be able to exclude, given a measurement that is in agreement with the SM prediction. All mass bounds are the expected 95% C.L. values.

Model	$Q_W(^{133}_{55}\mathrm{Cs})$ 0.48%	$Q_W(^{208}_{87}\mathrm{Fr})$ 0.1%	$\mathcal{R}_{\mathrm{Fr}}(121, 122)$ 0.3%	$\mathcal{R}_{\mathrm{Fr}}(121, 122)$ 0.1%	$\mathcal{R}_{\mathrm{Yb}}(98, 100)$ 0.3%	$\mathcal{R}_{\mathrm{Yb}}(98, 100)$ 0.1%	Q_W^p (QWEAK) 4.1%	Q_W^p (P2) 2.1%
$\mathrm{E}_6\eta$	485	997	339	585	337	581	356	497
$\mathrm{E}_6\chi$	969	1993	679	1170	674	1162	712	995
$\mathrm{E}_6\psi$	0	0	0	0	0	0	0	0
$\mathrm{E}_6 I$	1083	2228	759	1308	754	1299	796	1112
$\mathrm{E}_6 sq$	1110	2283	778	1340	772	1331	815	1139
$\mathrm{E}_6 N$	593	1220	416	716	413	712	436	609
Left Right (LR)	1033	2117	0	0	0	0	352	492
Alternate LR (ALR)	741	1527	701	1210	696	1202	772	1079
UUM	505	1012	953	1651	946	1640	1124	1570
SSM	1033	2117	0	0	0	0	352	492
TC1	520	1073	552	954	549	948	616	861
Littlest Higgs (LH)	505	1012	953	1651	946	1640	1124	1570
Simplest LH (SLH)	1589	3274	1409	2433	1400	2417	1541	2153
Anom. Free LH (AFLH)	1320	2718	1051	1812	1043	1800	1130	1579
331 2U1D	968	1993	770	1329	765	1320	829	1158
331 1U2D	1589	3274	1409	2433	1400	2417	1541	2153
ETC	245	490	461	800	458	794	544	760
TC2	872	1800	926	1601	920	1590	1034	1445

weak charges of an isotope chain of Cs [52] at the level of 0.2%. With multiple isotopes, a ratio can be exploited to largely cancel the required atomic and nuclear theory input [19,53,54]. Using measurements of weak charges along isotope chains, the following ratios can be defined [15]:

$$\mathcal{R}_X(N, N') = \frac{Q_W^{N'} - Q_W^N}{Q_W^{N'} + Q_W^N} \quad \text{or} \quad \mathcal{R}'_X(N, N') = \frac{Q_W^{N'}}{Q_W^N}, \tag{8}$$

where $Q_W^{N(N')}$ are the weak charges of two isotopes of element X. By circumventing large atomic theory uncertainty in this way, future APV experiments hope to probe the standard model at the sub-1% level.

Of the two observables in Eq. (8), we find that $\mathcal{R}_X(N, N')$ is the more sensitive probe of Z' physics. We therefore restrict our discussion to $\mathcal{R}_X(N, N')$ and suggest that future experiments measure this quantity. We consider the corrections arising from new physics, which can be represented by

$$\begin{aligned}\delta_{\mathcal{R}_X}^{(N,N')} &\equiv \frac{\mathcal{R}_X(N, N') - \mathcal{R}_X^0(N, N')}{\mathcal{R}_X^0(N, N')} \\ &= \frac{2Z[\Delta Q_W^n(1 - 4s_W^2) + \Delta Q_W^p]}{(N' + N)(1 - \Delta Q_W^n) - 2Z(1 - 4s_W^2 + \Delta Q_W^p)} \\ &\approx \left(\frac{2Z}{N' + N}\right)\Delta Q_W^p,\end{aligned} \tag{9}$$

where $\mathcal{R}_X^0(N, N')$ is the standard model prediction. The approximation follows by setting $1 - 4s_W^2 \approx 0$ and $\Delta Q_W^{p,n} \ll 1$, and agrees with the result of Ramsey-Musolf [15]. We use the exact formula to obtain our numerical results.

The $M_{Z'}$ dependence of Eq. (9) resides in the $\Delta Q_W^{p,n}$ terms and, as with ${}^A_Z Q_W$, a determination of $\mathcal{R}_X(N, N')$ can be translated into a mass bound on $M_{Z'}$. Since these experiments have not yet taken place, we derive expected mass bounds by assuming that a given experiment has made a measurement in agreement with the SM, with an error as given in Table I.

There is a subtlety when calculating mass bounds from $\delta_{\mathcal{R}}$. Some models counterintuitively predict a small value of $\delta_{\mathcal{R}}$ for small $M_{Z'}$, so that a measurement of $\mathcal{R}$ only excludes a mass region $M_{\min} < M_{Z'} < M_{\max}$. However, in every model we consider, $M_{\min}$ is small enough that it is already ruled out by other experiments and this issue can be safely ignored.

The mass bounds from $\mathcal{R}_X(N, N')$ are largest for the lightest isotopes as can be seen from Eq. (9). The values given in Table I are therefore calculated using the lighter isotopes to be studied for a given element. Furthermore, the mass bounds are not sensitive to small differences in proton number Z, which is apparent from the Fr and Yb mass bounds in Table I, so we do not also list those of Ba and Cs. Likewise, the stable isotopes of Ra and Fr have nearly identical atomic numbers and we find that the mass bounds from the two nuclei are very similar, so we only list those of Fr. Thus, we conclude that each of the future APV experiments is sensitive to the same region of parameter space and claim, very generally, that these experiments should aim to measure $\mathcal{R}$ with at least ~0.3% precision to probe new physics. We see in Table I that at this precision, future APV experiments for some models will begin to probe a higher mass region than the current measurement of $Q_W({}^{133}_{55}\mathrm{Cs})$.

Since the observables in Eq. (8) consist of weak charge ratios, there could be new physics models that might mimic the SM model prediction for $\mathcal{R}$ and thus remain unconstrained. For example, this happens in new physics scenarios that contribute to the nuclear weak charge in proportion to the SM prediction $\Delta Q_W^N \propto (Q_W^N)^0$. From Eq. (9) we can see that $\delta_{\mathcal{R}} = 0$ if $\Delta Q_W^p = -(1 - 4s_W^2)\Delta Q_W^n$. [This relation is lost if the approximate formula in Eq. (9) is used.] This defines a line in Z' coupling space

$$\tilde{c}_V^u = \frac{-3 + 8s_W^2}{3 - 4s_W^2}\tilde{c}_V^d \approx -\frac{1}{2}\tilde{c}_V^d \tag{10}$$

describing theories that are unconstrained by measurements of $\mathcal{R}$. The LR model and the sequential SM fall on this line, hence their trivial mass bounds in the fourth to seventh columns of Table I. This behavior is obvious for the Sequential SM Z', since it has couplings identical to the SM Z. However, it happens through a cancellation in the LR model, which has $\tilde{c}_A^f = -\beta c_A^f$ and $\tilde{c}_V^f = c_V^f/\beta$ where $\beta = \sqrt{1 - 2s_W^2}$. In this case, the product which governs the weak charge corrections $\tilde{c}_A^e \tilde{c}_V^{u,d} = -c_A^e c_V^{u,d}$ is indeed proportional to the SM prediction, hence the trivial mass bounds.

Consequently, we suggest that a measurement of $\mathcal{R}_X$ in a given element be accompanied by an extraction of $Q_W({}^A_Z X)$. The two quantities $Q_W({}^A_Z X)$ and $\mathcal{R}_X$ are complementary, since $Q_W({}^A_Z X)$ is sensitive to both ΔQ_W^n and ΔQ_W^p, whereas $\mathcal{R}_X$ is predominantly sensitive to ΔQ_W^p, to the extent that the approximations in Eq. (9) are valid. This suggestion assumes that atomic and nuclear theory uncertainties are not overwhelming [19,53,54], despite the fact that the rationale for using ratios of isotopes was to reduce the impact of atomic and nuclear theory uncertainties in the extraction Q_W from the APV observables because these uncertainties are large. Nonetheless, let us optimistically consider the case in which the theoretical uncertainties could be reduced to the same level of precision as the experimental measurements so that Q_W could be determined from APV measurements to a combined uncertainty of, for example, 0.1%. The mass bounds that could be obtained from a measurement of $Q_W({}^{208}_{87}\mathrm{Fr})$ at this precision are included in Table I. We see that one could approximately double the $M_{Z'}$ bounds obtained from ^{133}Cs. One would obtain comparable results for the other isotopes being studied. We emphasize that the key to these results is reducing the theoretical uncertainty.

If this reduction in theoretical uncertainty is possible, then it also becomes interesting to consider a combination of Q_W from different isotopes that would cancel the proton contribution, thereby isolating the neutron contribution. We define a quantity

$$D_X(N, N') = Q_W^{N'} - Q_W^N \tag{11}$$

from which the correction arising from new physics is given by

$$\delta_{D_X}^{N,N'} = \frac{D_X(N, N') - D_X^0(N, N')}{D_X^0(N, N')} = -\Delta Q_W^n. \tag{12}$$

Note that δ_D is independent of N and N'. D_X would constrain the Z' couplings in a manner that would complement the other weak charge constraints as we will show below.

C. Proton weak charge

In addition to the APV observables, we have included the bounds that can be extracted from measurements of the proton weak charge Q_W^p by the QWEAK experiment at Jefferson Lab [29] which has recently started taking data. The new physics correction to the weak charge of the proton is given by

$$\delta_p \equiv \frac{\Delta Q_W^p}{(Q_W^p)^0} = -4\frac{M_Z^2}{M_{Z'}^2}\frac{g_{Z'}^2}{g_Z^2}\frac{\tilde{c}_A^e(2\tilde{c}_V^u + \tilde{c}_V^d)}{1 - 4s_W^2}, \tag{13}$$

and we see that this observable is sensitive to the same physics as the APV observables. In the eighth column of Table I we list expected bounds from QWEAK that assume a measurement of Q_W^p in agreement with the SM prediction at 4.1% precision. These expected bounds are generally comparable to the actual bounds obtained from $Q_W({}^{133}_{55}\mathrm{Cs})$ although in a few cases (UUM, LH, ETC, TC2) they surpass the $Q_W({}^{133}_{55}\mathrm{Cs})$ bounds and will not be exceeded by APV measurements until $\mathcal{R}$ is measured at the highest precision in the future. However, the P2 experiment at the MAMI facility in Mainz is under development with the goal of measuring the proton weak charge Q_W^p to 2.1% precision [30]. The bounds that could be extracted from measurement of Q_W^p by the P2 experiment are also included in Table I.

D. Other future parity-violating experiments

In addition to the measurements described above there are two additional experiments under construction at the Jefferson Lab. The Moller experiment is a high precision measurement of parity violation in $e^- e^-$ scattering [55]. The Moller collaboration estimates that they can measure the combination of electron couplings $c_A^e c_V^e$ to 7%. We do not include bounds that could be obtained on Z' masses from the Moller experiment in Table I as for most, although not all models, they fall below the bounds obtained by the $Q_W({}^{133}_{55}\mathrm{Cs})$ measurement. However it is important to note, as pointed out by Li *et al.*, that the Moller experiment could provide important information on determining Z' couplings, complementary to LHC measurements [56,57]. We do not include these in our analysis on couplings because we are focusing on constraints on quark couplings to Z''s.

The SoLID experiment measures the left-right asymmetry obtained from deep inelastic scattering of longitudinally polarized electrons on a deuterium target [31–33]. The SoLID collaboration estimates that they will be able to measure the combination of couplings

$$2C_{1u} - C_{1d} \propto 2c_A^e c_V^u - c_A^e c_V^d \tag{14}$$

to a precision of, at best, 0.6%. The bounds that can be obtained from this level of precision are generally lower than other measurements that we have considered so we do not include them in Table I. We mention an interesting exception, that of a leptophobic Z', that can arise, in for example, E_6 scenarios [58]. The leptophobic Z' can contribute to the SoLID asymmetry through photon-Z' mixing. In any case, the u-and d-quark couplings appear in a different linear combination than appears elsewhere, so the SoLID measurement can potentially be useful for constraining the couplings of a Z'. This will be explored in the next section.

These measurements are discussed in more detail in Ref. [15].

E. Comparison with direct detection

We can compare this section's mass bounds to direct search limits obtained by the LHC experiments. The ATLAS Collaboration has obtained Z' mass bounds based on dilepton resonance searches in $\mu^+\mu^-$ and e^+e^- final states for the $\sqrt{s} = 7$ TeV run with 5.0 fb^{-1} and 4.9 fb^{-1} integrated luminosity for the two final states [59]. They find $M(Z'_{\mathrm{SSM}}) > 2.21$ TeV, $M(Z'_\eta) > 1.84$ TeV, $M(Z'_\chi) > 1.96$ TeV, and $M(Z'_\psi) > 1.76$ TeV. The CMS Collaboration has presented some limits which include results for $\sqrt{s} = 8$ TeV with 3.6 fb^{-1} together with $\sqrt{s} = 7$ TeV [60]. They find $M(Z'_{\mathrm{SSM}}) > 2.59$ TeV and $M(Z'_\psi) > 2.26$ TeV. The LHC limits clearly exceed those obtained from $Q_W({}^{133}_{55}\mathrm{Cs})$. However, future APV experiments could be sensitive to larger Z' masses in, for example, the simplest LH, anomaly free LH, and 331 (1U2D) models, and could remain competitive with direct LHC searches until the LHC reaches its design energy and luminosity [7].

III. BOUNDS ON THE COUPLINGS

If a Z' boson with mass $M_{Z'}$ were discovered at the LHC, weak charge measurements could be used to constrain its couplings. Since the mass would be fixed, APV and QWEAK experiments would constrain the coupling combinations $(\tilde{d}, \tilde{u}) \equiv (g_{Z'}^2/g_Z^2)\tilde{c}_A^e \tilde{c}_V^{(d,u)}$. For example, the $Q_W({}^{133}_{55}\mathrm{Cs})$ measurement constrains at 68% C.L. the $\tilde{u}$ and $\tilde{d}$ couplings of a 2.5 TeV Z' to lie within a band in parameter space, as shown in Fig. 1(a).

We also include in Fig. 1(a) the constraints one could obtain from the expected QWEAK measurement of Q_W^p. We assume that Q_W^p is measured to have its SM value with the stated experimental error, and plot the expected 68% C.L. bounds on $\tilde{u}$ and $\tilde{d}$ for a 2.5 TeV Z'. Additionally, we show the region of the $\tilde{u} - \tilde{d}$ parameter space that would be constrained at 68% C.L. by combining the APV measurement of $Q_W({}^{133}_{55}\mathrm{Cs})$ and the QWEAK of Q_W^p. We obtain this contour by calculating the χ^2 obtained by comparing the SM values to a scan of the $\tilde{u} - \tilde{d}$ parameter space. In addition, we plot the predicted value of $\tilde{u}$ and $\tilde{d}$ for each of the models we consider. We see that these measurements would not in themselves be able to identify a 2.5 TeV Z'.

We next consider how approved future experiments will constrain the Z' couplings which we show in Fig. 1(b). We include constraints one could obtain from a measurement of $\mathcal{R}_X(N, N')$ using isotopes of Fr as a representative example, the expected P2 measurement of Q_W^p, and the measurement of the coupling combination $2C_{1u} - C_{1d}$ by the SoLID experiment. As before, we assume that $\mathcal{R}_{\mathrm{Fr}}$, Q_W^p, and $2C_{1u} - C_{1d}$ are found to have their SM values with the stated experimental error, and plot the expected 68% C.L. bounds on $\tilde{u}$ and $\tilde{d}$ for a 2.5 TeV Z'. We also calculate the expected constraints based on $\mathcal{R}_{\mathrm{Yb}}$ but they are almost identical to those of Fr so we do not show them in the figure. The final contour in Fig. 1(b) shows the 68% C.L. region found by combining the experimental precision for all five of these measurements: Q_W of ${}^{133}_{55}\mathrm{Cs}$, Q_W^p from QWEAK and P2, the couplings from SoLID, and the $\mathcal{R}_{\mathrm{Fr}}$ measurement. We do not show the constraints derived from measurement by the SoLID experiment as they fall outside the range of the figure but do include them in the combined fit as they do improve the constraints slightly.

Finally, in Fig. 1(c) we show the bounds on $\tilde{d}$ and $\tilde{u}$ from $Q_W({}^{208}_{87}\mathrm{Fr})$ and $D_{\mathrm{Fr}}(N, N')$, in both cases assuming a hypothetical 0.1% combined theoretical and experimental uncertainty. We also show the 68% C.L. region found by combining the expected experimental precision for these two measurements plus the five already described above.

In Fig. 1(d) we show the 68% C.L. regions for the three cases described above: (i) The APV measurement of $Q_W({}^{133}_{55}\mathrm{Cs})$ and the QWEAK measurement of Q_W^p. (ii) These two measurements plus $\mathcal{R}_{\mathrm{Fr}}$, Q_W^p from P2, and the constraints from the SoLID experiment. (iii) All of these plus $Q_W({}^{208}_{87}\mathrm{Fr})$ and $D_{\mathrm{Fr}}(N, N')$. One can see how successive improvements in the experimental and theoretical uncertainties can improve the constraints on Z' couplings if one were to be discovered. Theoretical uncertainties are the dominant uncertainties in $Q_W({}^{208}_{87}\mathrm{Fr})$ and $D_{\mathrm{Fr}}(N, N')$. Thus, reducing the theoretical uncertainties needed to obtain $Q_W({}^{208}_{87}\mathrm{Fr})$ from the APV measurement can result in a significant improvement in determining the Z' couplings. We conclude that when APV measurements of $Q_W({}^{133}_{55}\mathrm{Cs})$ and future measurements of $\mathcal{R}$ and Q_W^p are combined with measurements from the LHC and other low energy precision experiments [56], they could add useful information about a Z' boson's u and d couplings that are not easily obtained elsewhere.

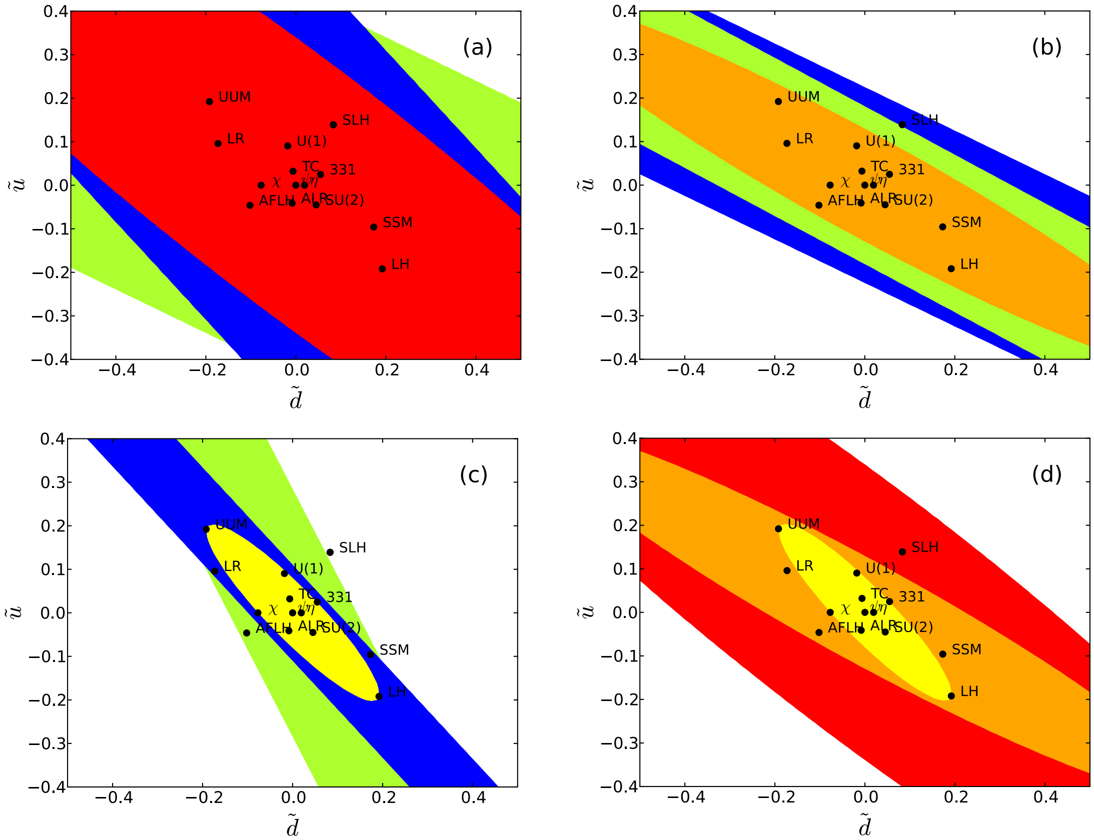

FIG. 1 (color online). Allowed 68% C.L. regions for the couplings $\tilde{d}$ and $\tilde{u}$ for a 2.5 TeV Z'. It is assumed that all measurements are in agreement with the SM. In (a) the blue (dark grey) band corresponds to the region allowed by the ^{133}Cs weak charge measurement with 0.48% precision; the green (light grey) band corresponds to the allowed regions expected from the QWEAK measurement of Q_W^p with 4.1% precision; and the red (medium grey) oval is the region allowed by a combined fit of $Q_W(^{133}\mathrm{Cs})$ and Q_W^p. In (b) the blue (dark grey) region is the region that would be constrained by the P2 measurement of Q_W^p with 2.1% precision; the green (light grey) band is the region allowed by the $\mathcal{R}_{\mathrm{Fr}}(121, 122)$ measurement with 0.1% precision; and the orange (medium grey) oval is the region allowed by a combined fit using the SoLID results, Q_W^p from P2 and QWEAK, $\mathcal{R}_{\mathrm{Fr}}(121, 122)$, and $Q_W(^{133}\mathrm{Cs})$. In (c) the blue (dark grey) band is the region that would be constrained by a ^{208}Fr weak charge measured to the precision of 0.1%; the green (medium grey) band is the region that would be constrained by a D_{Fr} measured to 0.1%; and the yellow (lightest grey) oval is the region that would constrained from a combined fit to $Q_W(^{208}\mathrm{Fr})$, D_{Fr}, and the other five measurements. (d) collects the combined fits from (a), (b), and (c) to show how successive measurements can improve the constraints on Z' couplings.

Finally, it is worth pointing out the generality of the results in Fig. 1. While we have focused on Z' physics, the combinations $g_Z^2\tilde{d}$ and $g_Z^2\tilde{u}$ are just the overall dimensionless couplings that appear in the new physics effective Lagrangian of Eq. (5). We explicitly include the factor of g_Z^2 because we normalized $\tilde{u}$, $\tilde{d}$ to the SM Z coupling strength. $M_{Z'}$ is just the overall mass scale, so the constraints in Fig. 1 can be immediately recast into constraints on other parity-violating new physics scenarios. If some other new physics described by the effective Lagrangian

$$\Delta\mathcal{L}_{\mathrm{NP}}^f = -\frac{(g_Z^2\tilde{f})}{4\Lambda^2}(\bar{e}\gamma_\mu\gamma_5 e)(\bar{f}\gamma^\mu f) \qquad (15)$$

were discovered at a mass scale $\Lambda = 2.5$ TeV, then the normalized couplings $\tilde{f}$ in the u and d sector would also be constrained exactly as shown in Fig. 1. A Z' boson is a particular case, with $\Lambda = M_{Z'}$ and $\tilde{f} = (g_{Z'}^2/g_Z^2)\tilde{c}_A^e\tilde{c}_V^{(d,u)}$.

IV CONCLUSION

Extra neutral gauge bosons Z' s arise in many extensions of the standard model. In this paper we explored the constraints that atomic parity violation experiments can place on Z' s. While this subject has been studied previously, we consider a large collection of models, and we explore a number of new experiments which plan to observe APV in different isotopes of Ba, Fr, Ra, and Yb. These new experiments allow the measurement of weak charge ratios along isotope chains which will abate difficulties associated with atomic theory uncertainties.

We have two main results: the constraints that APV measurements can put on a Z' mass for a given model, and the constraints that APV measurements can put on Z' couplings if one were to be discovered at the LHC. We also include the bounds expected from the QWEAK measurement of the proton weak charge and future measurements by the P2 and SoLID experiments. We find that the current 0.48% precision measurement of $Q_W(^{133}_{55}\mathrm{Cs})$ constrains Z' masses to be above ~500 GeV to ~1600 GeV at 95% C.L. depending on the model. Future APV experiments which will measure isotope ratios for Fr and Yb could yield bounds close to ~2 TeV for the UUM, LH, SLH, and AFLH models. While bounds from the LHC's direct searches already exceed the $Q_W(^{133}_{55}\mathrm{Cs})$ limits on most models, we found that future APV limits could still be competitive for some models, such as variations of the little Higgs models [7].

We also considered the constraints that APV experiments could put on Z' couplings if a Z' were discovered, which will be an important step in better understanding the underlying physics. We found that measurements at QWEAK and the APV experiments could be used to distinguish between some but not all models. Future measurements by the P2 and SoLID experiments will also provide useful input. The addition of $Q_W({}_{87}{}^{A}\mathrm{Fr})$ and D_{Fr} at 0.1% precision would result in better discrimination, highlighting the importance of improving both theoretical and experimental uncertainties. Regardless, current and future APV experiments will provide information complementary to other measurements [56] and would be an important addition to fits used to constrain a newly discovered Z'.

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