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Low Q^2 weak mixing angle measurements and rare Higgs decays

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A weighted average weak mixing angle θ_W derived from relatively low Q^2 experiments is compared with the standard model prediction obtained from precision measurements. The approximate 1.8 sigma discrepancy is fit with an intermediate mass (∼10–35 GeV) "dark" Z boson Z_d, corresponding to a $U(1)_d$ gauge symmetry of hidden dark matter, which couples to our world via kinetic and Z–Z_d mass mixing. Constraints on such a scenario are obtained from precision electroweak bounds and searches for the rare Higgs decays $H \to ZZ_d \to 4$ charged leptons at the LHC. The sensitivity of future anticipated low Q^2 measurements of $\sin^2\theta_W(Q^2)$ to intermediate mass Z_d is also illustrated. This dark Z scenario can provide interesting concomitant signals in low energy parity violating measurements and rare Higgs decays at the LHC over the next few years.

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Discovery of what appears to be a fundamental Higgs scalar [1,2] completes the basic standard model (SM) particle spectrum. In addition, comparing precision fine structure constant α, Fermi constant G_F, and Z boson mass (m_Z) values at the quantum loop level, employing the Higgs mass $m_H = 125$ GeV and top quark mass $m_t = 173.3(8)$ GeV gives the indirect SM weak mixing angle prediction [3,4]

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23124(12) \quad \text{SM prediction}, \tag{1}$$

where the modified minimal subtraction ($\overline{\rm MS}$) definition at scale $\mu = m_Z$ for the renormalized weak mixing angle θ_W has been employed [5]. The existing error in Eq. (1) stems from m_t, higher order loops (that overall double the error), and hadronic uncertainties, all of which are expected to be further reduced. That prediction agrees remarkably well with the average value [3] of the more direct Z pole measurements [6,7]

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.23125(16) \quad Z \text{ pole average}. \tag{2}$$

A comparison of these distinct precision methods severely constrains "new physics" extensions of the SM [3].

In contrast, low Q^2 determinations of the weak mixing angle (for a review, see Ref. [3]) currently allow considerable room for certain types of new physics, particularly Z' bosons (for earlier work along these lines, see for example Refs. [8–11]). Indeed, the three most precise measurements at lower $Q^2 \ll m_Z^2$ extrapolated, for comparison, to an $\overline{\rm MS}$ scale $\mu = m_Z$ give a somewhat disparate range of values [3]

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2283(20) \quad \text{APV}, \tag{3}$$

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2329(13) \quad \text{Moller E158}, \tag{4}$$

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2356(16) \quad \text{NuTeV} \tag{5}$$

from the measurements in Cs atomic parity violation (APV) at $\langle Q\rangle = 2.4$ MeV [12–15], SLAC Moller scattering experiment E158 at $\langle Q\rangle = 160$ MeV [16], and Fermilab neutrino deep inelastic scattering (DIS) experiment NuTeV at $\langle Q\rangle \approx 5$ GeV [17].

These measurements are illustrated in Fig. 1, after evolving back to their experimental Q values. There, we also show other less precise determinations of $\sin^2\theta_W(Q^2)$

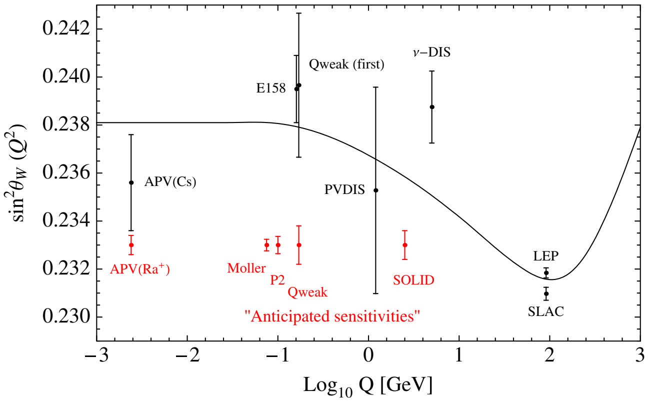

FIG. 1 (color online). Current measurements of the weak mixing angle at various Q [6,7,13–19] and future prospects [20–24]. The black curve represents the expected SM prediction for the running of $\sin^2\theta_W$ with Q [5]. Current measurements are given as black points with existing error bars. The red "anticipated sensitivities" are meant only to illustrate the possible uncertainties potentially obtainable from experiments under analysis and proposed.

(JLAB Qweak first result [18] and JLAB PVDIS [19]) as well as the very accurate Z pole values [6,7], future sensitivities (Ra$^+$ APV [20,21], JLAB Moller [22], MESA P2 [23], JLAB DIS experiment SOLID [24]), and the predicted SM running curve for comparison. Note that the Qweak result in our figures corresponds to only about 4% of their total collected data. Their statistical uncertainty may be significantly reduced in the near future making them the expectedly best low Q^2 determination. We return to this point later. Note, also, that the factor of 5 improvement envisioned for APV using single ionized Ra$^+$ trapped atoms as originally suggested in Ref. [25], although extremely well motivated, is still in a development stage [26]. The potential polarized electron scattering asymmetry improvements are currently on a more definite footing.

The weighted average from Eqs. (3)–(5),

$$\sin^2\theta_W(m_Z)_{\overline{\rm MS}} = 0.2328(9) \quad \text{low } Q^2 \text{ average}, \tag{6}$$

is roughly 1.8 sigma higher than the SM prediction in Eq. (1),

$$\Delta\sin^2\theta_W \simeq 0.0016(9), \tag{7}$$

and gives about the same deviation relative to Eq. (2).

Of course, there are still outstanding issues regarding atomic parity violation theory [27–29] that warrant further scrutiny. In addition, NuTeV hadronic effects [30] and radiative corrections [31,32] could shift the average somewhat [3]. However, here we take the current average in Eq. (6) at face value and examine its consequences for an intermediate mass dark $Z(Z_d)$ with $m_{Z_d} \sim 10$–35 GeV (the intermediate mass range bounded from below by the onset of severe constraints from low energy measurements and from above by m_H–m_Z) and coupling to the SM particles via kinetic and $Z - Z_d$ mass matrix mixing. Although the current 1.8 sigma discrepancy is far from compelling evidence for new physics, it does merit watching as low Q^2 measurements of $\sin^2\theta_W(Q^2)$ along with independent constraints on Z_d mixing improve.

We start our discussion of intermediate mass Z_d by briefly recalling its basic features. That scenario assumes a $U(1)_d$ gauge symmetry associated with a hidden dark sector. Its gauge boson, Z_d, couples to our world (SM) via kinetic mixing, parametrized by ε, and $Z - Z_d$ mass matrix mixing, parametrized by $\varepsilon_Z = (m_{Z_d}/m_Z)\delta$ [33].[1] Actually, for an intermediate mass Z_d, the combination

$$\delta' \simeq \delta + \frac{m_{Z_d}}{m_Z}\varepsilon\tan\theta_W \tag{8}$$

proves important, as it governs the induced weak neutral current interactions of Z_d (throughout our discussion, we ignore higher order corrections in ε and δ). It means the δ is replaced by the more general δ' of Eq. (8) for an intermediate mass Z_d. For the usually considered case of $m_{Z_d} \ll m_Z$, the second term in Eq. (8) [34] is generally negligible and $\delta' \simeq \delta$ becomes a good approximation, but here it is retained. Depending on the relative sign of δ and ε, the Z–Z_d mass mixing or δ' might increase or decrease as m_{Z_d} increases.

As a result of mixing, Z_d couples to the SM via [33]

$$\mathcal{L}_{\rm int} = \left(-e\varepsilon J^{em}_\mu - \frac{g}{2\cos\theta_W}\frac{m_{Z_d}}{m_Z}\delta' J^{\rm NC}_\mu + \cdots\right)Z^\mu_d, \tag{9}$$

where the ellipsis represents other induced Z_d interactions such as the HZZ_d coupling [33,35,36] that we subsequently employ. As a consequence of Eq. (9), weak neutral current SM amplitudes at low Q^2 momentum transfer are rescaled by ρ_d (that is $\rho_d G_F$ instead of G_F) and the SM weak mixing angle $\sin^2\theta_W(Q^2)_{\rm SM}$ is replaced by $\kappa_d\sin^2\theta_W(Q^2)_{\rm SM}$ [33,37,38] with

$$\rho_d = 1 + \delta'^2\frac{m^2_{Z_d}}{Q^2 + m^2_{Z_d}} \tag{10}$$

and

$$\kappa_d = 1 - \varepsilon\delta'\frac{m_Z}{m_{Z_d}}\cot\theta_W\frac{m^2_{Z_d}}{Q^2 + m^2_{Z_d}}. \tag{11}$$

The above yields a low $Q^2 \ll m^2_{Z_d}$ shift

$$\begin{aligned}\Delta\sin^2\theta_W &\simeq -\varepsilon\delta'\frac{m_Z}{m_{Z_d}}\cos\theta_W\sin\theta_W \\ &\simeq -0.42\varepsilon\delta'\frac{m_Z}{m_{Z_d}}.\end{aligned} \tag{12}$$

Note that the effect of ρ_d in Eq. (10) on $\sin^2\theta_W(Q^2)$ is process dependent. Its largest effect is on the NuTeV result of Eq. (5), where an upward shift in the experimental $\sin^2\theta_W(m_Z)_{\overline{\rm MS}}$ of δ'^2 is induced if R_ν (the ratio of neutral current to charged current neutrino cross sections) is employed [31,32], and $\delta'^2/2$ if the Paschos-Wolfenstein relation [39] is used. Overall, ρ_d has little effect on the weighted average in Eq. (6). Nevertheless, including the effect of ρ_d in future more precise studies is warranted.

As can be seen from Eq. (12), the value of $\sin^2\theta_W(Q^2)$ in our framework depends on m_{Z_d}, ε, and δ'. Let us then consider next the current constraints on the latter two quantities over the m_{Z_d} range of interest here.

Recently, the ATLAS collaboration at the LHC has reported results for the rare Higgs decay $H \to ZZ_d \to \ell_1^+\ell_1^-\ell_2^+\ell_2^-$, with $\ell_{1,2} = e, \mu$ [40]. Assuming $Z - Z_d$ mass mixing parametrized by δ' and a dominantly SM-like Higgs

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[1] We note that a new Higgs doublet charged under $U(1)_d$, assumed in typical models of Z–Z_d mass mixing discussed in Ref. [33], can also lead to nonzero kinetic mixing, via loop effects.

boson of 125 GeV, one can show [33] that this decay has a branching ratio (roughly including Z_d phase space effects [36])

$$\mathrm{BR}(H \to ZZ_d) \approx (16-18)\delta'^2 \tag{13}$$

which is further reduced by Z and Z_d leptonic branching ratios. The on-shell branching ratio is given by [33,36]

$$\begin{aligned}\mathrm{BR}(H \to ZZ_d) = &\frac{1}{\Gamma_H}\frac{\sqrt{\lambda(m_H^2, m_Z^2, m_{Z_d}^2)}}{16\pi m_H^3}\left(\frac{g m_Z}{\cos\theta_W}\right)^2 \\ &\times\left(\delta'\frac{m_{Z_d}}{m_Z}\right)^2\left(\frac{(m_H^2 - m_Z^2 - m_{Z_d}^2)^2}{4m_Z^2 m_{Z_d}^2}+2\right)\end{aligned} \tag{14}$$

with $\lambda(x,y,z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ and $\Gamma_H(125\ \mathrm{GeV}) \simeq 4.1\ \mathrm{MeV}$ [41], which shows a rather m_{Z_d} independent value over most of the mass range (Fig. 2), resulting in Eq. (13).

The ATLAS bounds translate into constraints on δ' as a function of m_{Z_d}, but depend on the branching ratio for $Z_d \to \ell^+\ell^-$. For $\mathrm{BR}(Z_d \to 2\ell) \equiv \mathrm{BR}(Z_d \to 2e) + \mathrm{BR}(Z_d \to 2\mu) \approx 0.3$ [42], one finds (at 2 sigma) the nearly constant bound $|\delta'| \lesssim 0.02$, over the range of m_{Z_d} considered in our work. Here we note that in the presence of allowed dark decay channels (that is, decay into invisible particles), $\mathrm{BR}(Z_d \to 2\ell)$ can be much smaller than 0.3, which would weaken the constraint on δ'.

The best current bounds on ε for the relevant mass range are given by the precision electroweak constraints, along with the noncontinuous bounds from the $e^+e^- \to$ hadron cross-section measurements at various experiments [43]. The Drell-Yan dilepton resonance searches at the LHC experiments (such as in Refs. [44,45]) have the potential to give a better bound than precision electroweak constraints

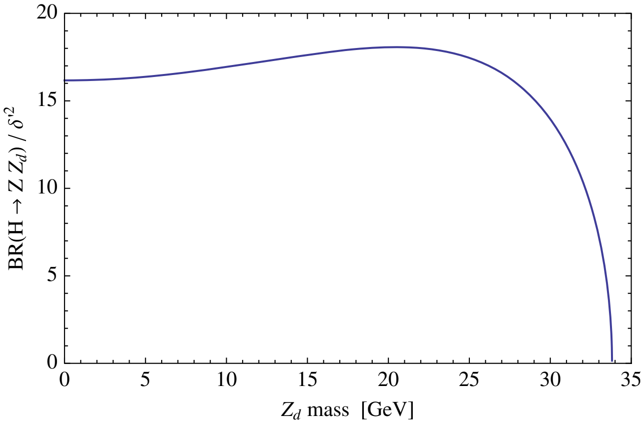


FIG. 2 (color online). $\mathrm{BR}(H \to ZZ_d)/\delta'^2$ with m_{Z_d}. For the most part ($m_{Z_d} \lesssim 30$ GeV), the branching ratio into ZZ_d is almost independent of m_{Z_d}. $\mathrm{BR}(H \to ZZ_d) \approx (16-18)\delta'^2$.

[46]. When combined with bounds on ε from precision measurements and production constraints [43,47], one finds $|\varepsilon| \lesssim 0.03$, for kinetic mixing alone. However, in our scenario, where a separate source of mass mixing is also considered [33], that bound can be somewhat relaxed, via partial cancellation with δ' dependent contributions to the Z–Z_d mixing angle [33], roughly yielding $|\varepsilon| \lesssim 0.04$. (See also Refs. [47,48] for less severe bounds on ε from a recasting of a CMS analysis of run 1 data, sensitive to $H \to ZZ_d$.)

Given the above discussion, a simple combination of the upper bounds on ε and δ' suggests

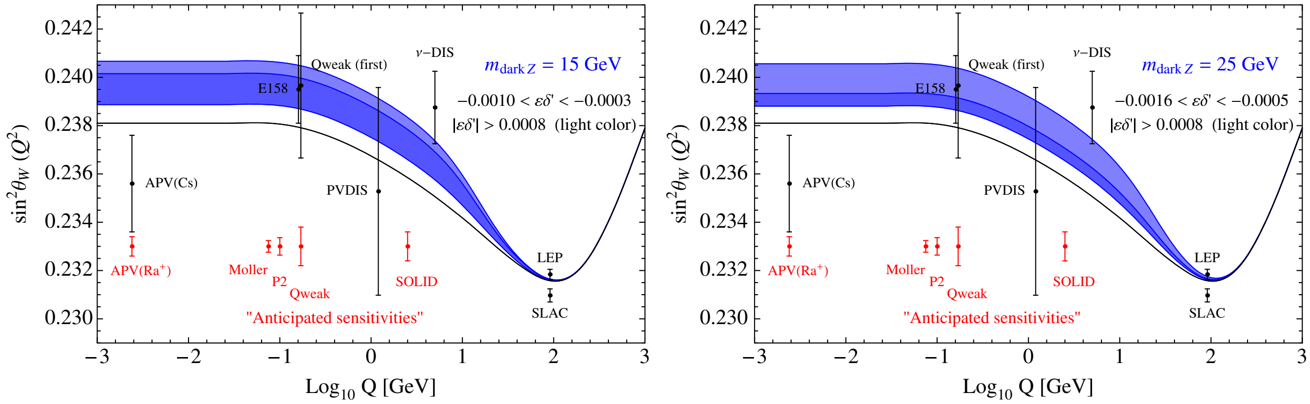
$$|\varepsilon\delta'| \lesssim 0.0008. \tag{15}$$

We use the above bound as a rough guide for the allowed region of parameter space in our discussion below.

For a given m_{Z_d}, a negative $\varepsilon\delta'$ in Eq. (12) will shift the SM prediction in Eq. (1) towards the low Q^2 experimental $\sin^2\theta_W(m_Z$ weighted average in Eq. (6). That effect is illustrated in Fig. 3(a), where for $m_{Z_d} = 15$ GeV the blue band corresponds to a 1-σ fit to Eq. (7) or $-0.0010 < \varepsilon\delta' < -0.0003$. A similar 1-$\sigma$ band is presented in Fig. 3(b) for $m_{Z_d} = 25$ GeV with $-0.0016 < \varepsilon\delta' < -0.0005$. In each case, the lighter shaded upper part of the band corresponds to $|\varepsilon\delta'| > 0.0008$ which is in some tension with constraints from precision measurements and the rare Higgs decay search by ATLAS, as explained above. Future improved sensitivity at the LHC should cover most of the bands in Figs. 3(a) and 3(b). For other m_{Z_d} values, the 1-σ bands are about the same as our Fig. 3 representative examples; however, for larger $m_{Z_d} > 25$ GeV, the darker parts of the bands allowed by current constraints narrow. This can be seen from a comparison of Figs. 3(a) and 3(b) that shows how smaller values of m_{Z_d} can accommodate a shift in $\sin^2\theta_W(Q^2)$ more easily, over the currently allowed parameter space [as suggested by the m_{Z_d} dependence in Eq. (12)].

In the case of low Q^2 determinations of $\sin^2\theta_W(Q^2)$, the Qweak polarized ep asymmetry experiment at JLAB, which measures weak nuclear charge of proton (Q^p_{weak}), is expected to reach an uncertainty of ± 0.0007 after all existing data are analyzed in the near future. This would reduce the uncertainty on the weighted average in Eq. (6) to ± 0.00055 and, assuming the same central value as the current published result, could yield a $\sim 3\sigma$ deviation from the SM result in Eq. (1). It will be interesting to watch that outcome. We note that the weak mixing angle extracted from the Qweak experiment will exhibit some dependence on nucleon form factors including strangeness matrix element effects [49,50]. For that reason, lattice gauge theory improvements in those hadronic matrix elements are strongly warranted.

Future experiments, primarily polarized ee Moller scattering at JLAB and polarized ep scattering (P2) at MESA in Mainz, are expected collectively to further reduce the



(a) (b)

FIG. 3 (color online). Effective weak mixing angle running as a function of Q^2 shift (the blue band) due to an intermediate mass Z_d for (a) $m_{Z_d} = 15$ GeV and (b) $m_{Z_d} = 25$ GeV for one sigma fit to $\varepsilon\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that is in some tension with precision constraints (see text for more details).

weighted average uncertainty on $\sin^2\theta_W(m_Z)_{\overline{\text{MS}}}$ at low Q^2 below ± 0.0002, becoming competitive with Z pole measurements. Together, low Q^2 precision studies combined with improved $H \to ZZ_d$ searches at the LHC will squeeze the intermediate mass Z_d scenario with some possibility of uncovering its existence.

The intermediate mass Z_d is an interesting viable alternative to the "light" dark photon often considered in the literature [51]. In addition to the parity violation at low Q^2 that we have explored, it can give rise to potential signals at the LHC, both in direct Drell-Yan production $pp \to Z_d X$ or as a final state in rare Higgs decays. Besides the $H \to ZZ_d$ mode that we have discussed, searching for the mode $H \to Z_d Z_d$, mediated by Higgs-dark Higgs mixing [34], is well motivated. In fact, we note that the ATLAS 8 TeV search for $H \to Z_d Z_d$ has two interesting but tentative candidate events (each at 1.7σ), roughly in the mass range ∼20–25 GeV [40]. Further data from run 2 at the LHC will be needed to clarify whether these events could be identified as intermediate mass Z_d states that connect our world to an as yet unknown dark sector of nature. Such a discovery would certainly revolutionize elementary particle physics and perhaps provide a new window into the world of dark matter.

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