Low $Q^{2}$ Weak Mixing Angle Measurements and Rare Higgs Decays

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A weighted average weak mixing angle $\theta_{W}$ 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 ($\sim 10 - 35$ GeV) “dark” Z boson $Z_{d}$, corresponding to a $U(1)_{a}$ 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 $H \rightarrow ZZ_{d} \rightarrow 4$ 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.

Discovery of what appears to be a fundamental Higgs scalar $h [1,2]$ completes the basic Standard Model (SM) particle spectrum. In addition, comparing precision fine structure constant $\alpha$, 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 $3,4$

$$\sin^{2} \theta_{W}(m_{Z})_{\overline{MS}} = 0.23124(12)$$

SM prediction, (1)

where the modified minimal subtraction ($\overline{MS}$) definition at scale $\mu = m_{Z}$ for the renormalized weak mixing angle $\theta_{W}$ 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 $[6,7]$

$$\sin^{2} \theta_{W}(m_{Z})_{\overline{MS}} = 0.23125(16)$$

$Z$ pole average. (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 3 most precise measurements at lower $Q^{2} \ll m_{Z}^{2}$ extrapolated, for comparison, to an $\overline{MS}$ scale $\mu = m_{Z}$ give a somewhat disparate range of values $3$

$$\sin^{2} \theta_{W}(m_{Z})_{\overline{MS}} = 0.2283(20) \text{ APV}, \quad (3)$$

$$\sin^{2} \theta_{W}(m_{Z})_{\overline{MS}} = 0.2329(13) \text{ Moller E158}, \quad (4)$$

$$\sin^{2} \theta_{W}(m_{Z})_{\overline{MS}} = 0.2356(16) \text{ NuTeV} \quad (5)$$

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

FIG. 1. Current measurements of the weak mixing angle at various $Q$ $[6,7,13,19]$ and future prospects $[20,21]$. 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.

These measurements are illustrated in Fig. 1 after evolving back to their experimental $Q$ values. There, we also show other less precise determinations of $\sin^{2} \theta_{W}(Q^{2})$ (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 their 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 $[20]$. The potential polarized electron scattering asymmetry improvements are currently on a more definite footing.
The weighted average from Eqs. 3-5

\[ \sin^2 \theta_W(m_Z)_{\text{SM}} = 0.2328(9) \]  
low \( Q^2 \) average (6)
is roughly 1.8 sigma higher than the SM prediction in Eq. 1

\[ \Delta \sin^2 \theta_W \simeq 0.0016(9) \]  
and gives about the same deviation relative to Eq. 2.

Of course, there are still outstanding issues regarding atomic parity violation theory \textsuperscript{27,29} and radiative corrections \textsuperscript{30} that warrant further scrutiny. In addition, NuTeV hadronic effects \textsuperscript{31} could shift the average somewhat \textsuperscript{32}. 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 \( m_{Z_d} \approx 10-35 \) \( \text{GeV} \) (the intermediate mass range bounded from below by the onset of severe constraints from low energy measurements and from above by \( m_H - m_{Z_d} \)) 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 \( \varepsilon \), and \( Z-Z_d \) mass matrix mixing, parametrized by \( \varepsilon_Z = (m_{Z_d}/m_Z)\delta \). Actually, for an intermediate mass \( Z_d \), the combination

\[ \delta' \simeq \delta + \frac{m_{Z_d}}{m_Z} \varepsilon \tan \theta_W \]  
proves important, as it governs the induced weak neutral current interactions of \( Z_d \) (throughout our discussion, we ignore higher order corrections in \( \varepsilon \) and \( \delta \)). It means the \( \delta \) is replaced by the more general \( \delta' \) of Eq. 3 for an intermediate mass \( Z_d \). For the usually considered case of \( m_{Z_d} \ll m_Z \), the second term in Eq. 3 is generally negligible and \( \delta' \approx \delta \) becomes a good approximation, but here it is retained. Depending on the relative sign of \( \delta \) and \( \varepsilon \), the \( Z-Z_d \) mass mixing or \( \delta' \) might increase or decrease as \( m_{Z_d} \) increases.

As a result of mixing, \( Z_d \) couples to the SM via \textsuperscript{33}

\[ \mathcal{L}_{\text{int}} = (-\varepsilon J_{\mu}^{em} - \frac{g}{2 \cos \theta_W} \frac{m_{Z_d} \delta'}{m_Z} J_{\mu}^{NC} + \ldots)Z_d^\mu, \]  
where the ellipsis represents other induced \( Z_d \) interactions such as the \( H Z Z_d \) coupling \textsuperscript{33,35,36} that we subsequently employ. As a consequence of Eq. 4, weak neutral current SM amplitudes at low \( Q^2 \) momentum

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.pdf}
\caption{BR(\( H \to ZZ_d \))/\( \delta'^2 \) with \( m_{Z_d} \). For the most part \( m_{Z_d} \lesssim 30 \) \( \text{GeV} \), the branching ratio into \( ZZ_d \) is almost independent of \( m_{Z_d} \). BR(\( H \to ZZ_d \)) \approx (16 - 18) \delta'^2.}  
\end{figure}

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

\begin{equation}
\rho_d = 1 + \delta'^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}. \end{equation}

\begin{equation}
\kappa_d = 1 - \delta'^2 m_{Z_d} \cot \theta_W \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}. \end{equation}
The above yields a low \( Q^2 \ll m_{Z_d}^2 \) shift

\[ \Delta \sin^2 \theta_W \simeq -\varepsilon \delta' \frac{m_{Z_d}^2}{m_{Z_d}} \cos \theta_W \sin \theta_W \]

\[ \simeq -0.42 \varepsilon \delta' \frac{m_{Z_d}^2}{m_{Z_d}}. \]  

Note that the effect of \( \rho_d \) 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 \( \sin^2 \theta_W(m_Z)_{\text{SM}} \) of \( \delta'^2 \) is induced if \( R_{e} \) (the ratio of neutral current to charged current neutrino cross sections) is employed \textsuperscript{31,32}, and \( \delta'^2/2 \) if the Paschos-Wolfenstein relation \textsuperscript{39} is used. Overall, \( \rho_d \) has little effect on the weighted average in Eq. (6). Nevertheless, including the effect of \( \rho_d \) 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 \( m_{Z_d}, \varepsilon, \) and \( \delta' \). 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 \( \ell_{1,2} = e, \mu \). Assuming \( Z-Z_d \) mass mixing parametrized by \( \delta' \) and a dominantly SM-like Higgs boson of 125 GeV, one can show \textsuperscript{33} that this decay has a branching ratio (roughly including \( Z_d \) phase space effects \textsuperscript{36})

\[ \text{BR}(H \to ZZ_d) \approx (16 - 18) \delta'^2 \]  

\begin{equation}
\text{BR}(H \to ZZ_d) \approx (16 - 18) \delta'^2. \end{equation}

\begin{superscript}{1}\text{We note that a new Higgs doublet charged under } U(1)_d, \text{ assumed in typical models of } Z-Z_d \text{ mass mixing discussed in Ref. [33], can also lead to non-zero kinetic mixing, via loop effects.}\end{superscript}
FIG. 3. 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 1 sigma fit to $\delta'$ in Eq. (12). The lightly shaded area in each band corresponds to choice of parameters that is in tension with precision constraints (see text for more details).

which is further reduced by $Z$ and $Z_d$ lepton branching ratios. The on-shell branching ratio is given by\(^{33,36}\)

$$\text{BR}(H \rightarrow ZZ_d) = \frac{1}{\Gamma_H} \sqrt{\lambda(m_H^2, m_Z^2, m_{Z_d}^2)} \left( \frac{g m_Z}{\cos \theta_W} \right)^2 \times \left( \delta \frac{m_{Z_d}}{m_Z} \right)^2 \left( \frac{(m_H^2 - m_Z^2 - m_{Z_d}^2)^2}{4m_Z^2 m_{Z_d}^2} + 2 \right)$$

with $\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx$ and $\Gamma_H(125 \text{ GeV}) \approx 4.1 \text{ MeV}$\(^{11}\), 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 $\delta'$ as a function of $m_{Z_d}$, but depend on the branching ratio for $Z_d \rightarrow \ell^+ \ell^-$. For $\text{BR}(Z_d \rightarrow 2\ell) \equiv \text{BR}(Z_d \rightarrow 2\ell) \equiv 0.3$\(^{15}\), one finds (at 2 sigma) the nearly constant bound $|\delta'| < 0.02$, 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), $\text{BR}(Z_d \rightarrow 2\ell)$ can be much smaller than 0.3, which would weaken the constraint on $\delta'$.

The best current bounds on $\varepsilon$ for the relevant mass range are given by the precision electroweak constraints, along with the non-continuous bounds from the $e^+ e^- \rightarrow$ hadron cross-section measurements at various experiments\(^{13}\). The Drell-Yan dilepton resonance searches at the LHC experiments (such as in Refs.\(^{14,15}\)) have the potential to give a better bound than precision electroweak constraints\(^{16}\). When combined with bounds on $\varepsilon$ from precision measurements and production constraints\(^{13,47}\), 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 $\delta'$ dependent contributions to the $Z-Z_d$ mixing angle\(^{33}\), roughly yielding $|\varepsilon| \lesssim 0.04$. (See also Refs.\(^{47,15}\) for less severe bounds on $\varepsilon$ from a recasting of a CMS analysis of Run 1 data, sensitive to $H \rightarrow ZZ_d$.)

Given the above discussion, a simple combination of the upper bounds on $\varepsilon$ and $\delta'$ suggests

$$|\varepsilon \delta'| \lesssim 0.0008.$$  \hspace{1cm} (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 $\sin^2 \theta_W(m_Z)_{\text{CMS}}$ 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-$\sigma$ fit to Eq. (7) or $-0.0016 < \varepsilon \delta' < -0.0003$. 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 (b). For other $m_{Z_d}$ values, the 1-$\sigma$ 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 (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 $e p$ asymmetry experiment at JLAB, which measures weak nuclear charge of proton ($Q^p_{\text{weak}}$), is expected to reach an uncertainty of $\pm 0.0007$ after all existing data are analyzed in the near future. This would reduce the uncertainty on the weighted average in Eq. (6) to $\pm 0.00055$ 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 $e e$ Moller scattering at JLAB and polarized $e p$ scattering (P2) at MESA in Mainz, are expected collectively to further reduce the weighted average uncertainty on $\sin^2 \theta_W (m_Z^2)_{\text{SM}}$ at low $Q^2$ below $\pm 0.0002$, becoming competitive with $Z$ pole measurements. Together, low $Q^2$ precision studies combined with improved $H \rightarrow ZZ_d$ 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 $pp \rightarrow Z_d X$ or as a final state in rare Higgs decays. Besides the $H \rightarrow Z Z_d$ mode that we have discussed, searching for the mode $H \rightarrow Z_d Z_d$, mediated by Higgs-dark Higgs mixing [34], is well motivated. In fact, we note that the ATLAS 8 TeV search for $H \rightarrow Z_d Z_d$ has two interesting but tentative candidate events (each at 1.7 $\sigma$), roughly in the mass range $\sim 20 - 25$ 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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