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 $U(1)_d$ 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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proves important, as it governs the induced weak neutral current interactions of $Z_d$ (throughout our discussion, we ignore higher order corrections in $\epsilon$ and $\delta$). It means the $\delta$ is replaced by the more general $\delta'$ 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 $\delta' \approx \delta$ becomes a good approximation, but here it is retained. Depending on the relative sign of $\delta$ and $\epsilon$, 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 [33]

$$\mathcal{L}_{\text{int}} = \left( -eeJ^m_\mu - \frac{g}{2\cos\theta_W} \frac{m_{Z_d}}{m_Z} \delta' f^\text{NC}_\mu + \cdots \right) Z_d^\mu,$$

(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 $\rho_d$ (that is $\rho_d G_F$ instead of $G_F$) and the SM weak mixing angle $\sin^2\theta_W(Q^2)_{\text{SM}}$ is replaced by $\kappa_d \sin^2\theta_W(Q^2)_{\text{SM}}$ [33,37,38] with

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

(10)

and

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

(11)

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

$$\Delta\sin^2\theta_W = -e\delta' \frac{m_{Z_d}}{m_{Z_d}} \cos\theta_W \sin\theta_W$$

$$= -0.42e\delta' \frac{m_{Z_d}}{m_{Z_d}}.$$  

(12)

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 $\sin^2\theta_W(m_{Z_d})_{\text{MS}}$ of $\delta^2$ is induced if $R_\nu$ (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, $\rho_d$ 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 $m_{Z_d}$, $\epsilon$, 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 $H \rightarrow ZZ_d \rightarrow \ell^+\ell^-\ell'^+\ell'^-$, with $\ell_{1,2} = e, \mu$ [40]. Assuming $Z-Z_d$ mass mixing parametrized by $\delta'$ and a dominantly SM-like Higgs
boson of 125 GeV, one can show [33] that this decay has a branching ratio (roughly including \(Z_d\) phase space effects [36])

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

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

\[
\text{BR}(H \to ZZ_d) = \frac{1}{16πm_H^2} \left( \frac{gm_Z}{\cos θ_W} \right)^2 \left( \delta \frac{m_{Z_d}}{m_Z} \right)^2 \left( \frac{m_Z^2 - m_{Z_d}^2}{4m_Z^2m_{Z_d}^2} + 2 \right)
\]

with \(\lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2yz - 2zx\) and \(Γ_H(125 \text{ GeV}) \approx 4.1 \text{ MeV}\) [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 \(δ^\prime\) as a function of \(m_{Z_d}\), but depend on the branching ratio for \(Z_d \to ℓ^+ ℓ^-\). For \(\text{BR}(Z_d \to 2ℓ^+) \equiv \text{BR}(Z_d \to 2ℓ^-) \approx 0.3\) [42], one finds (at 2 sigma) the nearly constant bound \(|δ^\prime| ≲ 0.02\), 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), \(\text{BR}(Z_d \to ℓ^+ ℓ^-)\) can be much smaller than 0.3, which would weaken the constraint on \(δ^\prime\).

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 \(e^+ e^-\) → 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 [46]. When combined with bounds on \(ε\) from precision measurements and production constraints [43,47], one finds \(|ε| ≲ 0.03\), 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 \(δ^\prime\) dependent contributions to the \(Z-Z_d\) mixing angle [33], roughly yielding \(|ε| ≲ 0.04\). (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 \(δ^\prime\) suggests

\[
|εδ^\prime| ≲ 0.0008.
\]

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 \(εδ^\prime\) in Eq. (12) will shift the SM prediction in Eq. (1) towards the low \(Q^2\) experimental \(sin^2 θ_W(m_{Z_d})\) 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 \(-0.0010 < εδ^\prime < -0.0003\). A similar 1-σ band is presented in Fig. 3(b) for \(m_{Z_d} = 25\) GeV with \(-0.0016 < εδ^\prime < -0.0005\). In each case, the lighter shaded upper part of the band corresponds to \(|εδ^\prime| > 0.0008\) 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 \(sin^2 θ_W(Q^2)\) 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 \(sin^2 θ_W(Q^2)\), the Qweak polarized \(ep\) asymmetry experiment at JLAB, which measures weak nuclear charge of proton \(Q^p_{\text{weak}}\), 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 ±0.0005 and, assuming the same central value as the current published result, could yield a 3-σ 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
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 $\epsilon \delta$ 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 $\sin^2 \theta_W(m_Z)_{\overline{MS}}$ 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 $pp \rightarrow Z_dX$ or as a final state in rare Higgs decays. Besides the $H \rightarrow ZZ_d$ mode that we have discussed, searching for the mode $H \rightarrow Z_dZ_d$, mediated by Higgs-dark Higgs mixing [34], is well motivated. In fact, we note that the ATLAS 8 TeV search for $H \rightarrow Z_dZ_d$ 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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[45] S. Chatrchyan et al. (CMS Collaboration), Measurement of the differential and double-differential Drell-Yan cross...


