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Fitting precision electroweak data with exotic heavy quarks

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The 1999 precision electroweak data from CERN LEP and SLC persist in showing some slight discrepancies from the assumed standard model, mostly regarding b and c quarks. We show how their mixing with exotic heavy quarks could result in a more consistent fit of all the data, including two unconventional interpretations of the top quark.

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Precision measurements of electroweak parameters at the Z resonance have been available for many years [1,2]. Their updated values in 1999 as reported at Tampere [3] and at Stanford [4] are consistent with the expectations of the minimal standard model, including all radiative corrections to one-loop order. However, certain slight discrepancies persist, mostly regarding b and c quarks. In this article, we show how their mixing with exotic heavy quarks could result in a more consistent fit of all the data, including two unconventional interpretations of the top quark.

The most telling sign that there may be something beyond the minimal standard model in precision electroweak measurements is the observation [4] that the two most precise measurements of $\sin^2\theta_{eff}$ are 3.0 standard deviations apart. One is the left-right asymmetry A_{LR} (which directly measures A_e) from the SLAC Linear Collider (SLC) that gives [4]

$$\sin^2\theta_{eff}(A_{LR}) = 0.23101 \pm 0.00028, \tag{1}$$

and the other is the forward-backward asymmetry $A_{FB}^{0,b}$ of b quarks from the CERN e^+e^- collider LEP which gives [3]

$$\sin^2\theta_{eff}(A_{FB}^{0,b}) = 0.23236 \pm 0.00036. \tag{2}$$

We note that Eq. (1) is consistent with the forward-backward asymmetry of leptons measured at LEP which gives [3]

$$\sin^2\theta_{eff}(A_{FB}^{0,l}) = 0.23107 \pm 0.00053, \tag{3}$$

whereas Eq. (2) is consistent with the A_b measurement at SLC, i.e., $A_b = 0.905 \pm 0.026$ versus the extracted value [4] of $A_b = 0.881 \pm 0.020$ from the value of $A_{FB}^{0,b}$ used. This points to the possibility that there is new physics in the decay $Z \to b\bar{b}$.

Specifically, consider the effective left-handed and right-handed couplings of the b quark to the Z boson in the standard model:

$$g_{bL}^{SM} = \left(1 + \frac{\epsilon_1}{2}\right)\left(-\frac{1}{2}(1+\epsilon_b) + \frac{1}{3}\sin^2\theta_{eff}\right), \tag{4}$$

$$g_{bR}^{SM} = \left(1 + \frac{\epsilon_1}{2}\right)\frac{1}{3}\sin^2\theta_{eff}, \tag{5}$$

where the radiative corrections [2] ϵ_1 and ϵ_b are functions of m_t and m_H. Note the important fact [5] that ϵ_b (which has a strong quadratic dependence on m_t) contributes only to g_{bL}^{SM}. On the other hand, the measured quantity $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is proportional to $g_{bL}^2 + g_{bR}^2$, whereas $A_{FB}^{0,b}$ and A_b are proportional to $(g_{bL}^2 - g_{bR}^2)/(g_{bL}^2 + g_{bR}^2)$. From the 1999 data reported at Tampere [3] and at Stanford [4],

$$R_b = 0.21642 \pm 0.00073, \quad A_{FB}^{0,b} = 0.0984 \pm 0.0020,$$
$$A_b = 0.905 \pm 0.026, \tag{6}$$

the couplings g_{bL} and g_{bR} can be extracted [6]:

$$g_{bL} = -0.4163 \pm 0.0020, \quad g_{bR} = 0.0996 \pm 0.0076. \tag{7}$$

Using $m_t = 174$ GeV, $m_H = 100$ GeV, and $\alpha(m_Z)^{-1} = 128.9$, the standard model yields [7]

$$g_{bL}^{SM} = -0.4208, \quad g_{bR}^{SM} = 0.0774. \tag{8}$$

Note that $g_{bL}^2 + g_{bR}^2$ is almost exactly equal to $(g_{bL}^{SM})^2 + (g_{bR}^{SM})^2$, but g_{bL} and g_{bR} are each over two standard deviations away from g_{bL}^{SM} and g_{bR}^{SM}, respectively.

As we already pointed out last year [5], since ϵ_b depends only on the left-handed partner of the b quark, this may be an indication that m_t is actually much greater than 174 GeV and the observed ''top'' quark events are due to an exotic quark Q_4 of charge $-4/3$. In this scenario, the singlet b_R mixes with the exotic quark Q_1 in the doublet $(Q_1, Q_4)_R$ so that

$$\begin{aligned} g_{bR} &= \left(1 + \frac{\epsilon_1}{2}\right)\left[\frac{1}{3}\sin^2\theta_{eff}\cos^2\theta_b + \left(\frac{1}{2} + \frac{1}{3}\sin^2\theta_{eff}\right)\sin^2\theta_b\right] \\ &= \left(1 + \frac{\epsilon_1}{2}\right)\left(\frac{1}{3}\sin^2\theta_{eff} + \frac{1}{2}\sin^2\theta_b\right). \end{aligned} \tag{9}$$

Since $\sin^2\theta_{eff}/3$ is small to begin with, a reasonably small $\sin^2\theta_b$ is sufficient to make g_{bR} fit the data. (If radiative corrections to g_{bR} from new physics were invoked, an unreasonably large effect of about 30% would be needed.) In the following we will update our analysis using the 1999 data. We will also address the new possibility that slight discrepancies in $Z\rightarrow c\bar{c}$ may be due to yet another exotic quark [8] and offer a second alternative interpretation of the ''top'' quark events.

Using the 1999 $Z\rightarrow l^-l^+$ data assuming lepton universality [3,4], i.e.,

$$\Gamma_l = 83.96 \pm 0.09 \ \text{MeV}, \quad A_{FB}^{0,l} = 0.01701 \pm 0.00095, \tag{10}$$

together with [3]

$$m_W = 80.394 \pm 0.042 \ \text{GeV}, \quad m_Z = 91.1871 \pm 0.0021 \ \text{GeV}, \tag{11}$$

we find

$$\epsilon_1 = (4.7 \pm 1.1)\times 10^{-3}, \quad \epsilon_2 = (-7.2 \pm 2.4)\times 10^{-3},$$
$$\epsilon_3 = (3.6 \pm 1.7)\times 10^{-3}, \tag{12}$$

which agree very well with previous values [2,5] and also with the standard model, i.e., [6]

$$\epsilon_1^{SM} = 5.4\times 10^{-3}, \quad \epsilon_2^{SM} = -7.6\times 10^{-3}, \quad \epsilon_3^{SM} = 5.2\times 10^{-3}. \tag{13}$$

Using Eqs. (3), (4) and (7), we then obtain

$$\epsilon_b = (-15.3 \pm 4.0)\times 10^{-3}. \tag{14}$$

This implies that

$$m_t = 271^{+33}_{-38} \ \text{GeV}, \tag{15}$$

where we have approximated ϵ_b by its leading contribution, $-G_F m_t^2/4\pi^2\sqrt{2}$. To explain g_{bR} of Eq. (7) and thus also Eq. (2), we use Eq. (9) and find

$$\sin^2\theta_b = 0.045 \pm 0.015. \tag{16}$$

In the standard model, ϵ_1 and ϵ_b are fixed by $m_t = 174$ GeV and θ_b is absent, so the experimental discrepancy from $Z\rightarrow b\bar{b}$ data is forced into a value of $\sin^2\theta_{eff}$ given by Eq. (2) which is 3.0 standard deviations away from the true value given by Eqs. (1) and (3).

Our interpretation of the data so far is that b_R is not purely $I_3=0$ as in the standard model, but has a small $I_3=1/2$ component from mixing with the exotic $(Q_1,Q_4)_R$ doublet. We also take the viewpoint that b_L is as given by the standard model and the measured g_{bL} is a direct indication of the mass of its partner, defined as the t quark. This results in Eq. (15). At this point, we need to revise our assessment of the agreement of Eq. (12) with Eq. (13), namely that in the presence of new physics, $\epsilon_{1,2,3}$ receive additional contributions, hence a change in the value of m_t may be suitably compensated. Details have already been discussed in our previous paper [5].

Consider now the 1999 $Z\rightarrow c\bar{c}$ data:

$$R_c = 0.1674 \pm 0.0038, \quad A_{FB}^{0,c} = 0.0691 \pm 0.0037,$$
$$A_c = 0.630 \pm 0.026, \tag{17}$$

from which the couplings g_{cL} and g_{cR} can be extracted [6]:

$$g_{cL} = 0.341 \pm 0.005, \quad g_{cR} = -0.164 \pm 0.005, \tag{18}$$

whereas the standard model yields [6]

$$g_{cL}^{SM} = 0.347, \quad g_{cR}^{SM} = -0.155. \tag{19}$$

Although the deviations here are small, there is a hint that g_{cR} may be too large in magnitude and g_{cL} too small. To explain both, we take the analog of Eq. (9) and let c mix with a heavy quark Q_2, where Q_{2L} is a singlet but $(Q_5,Q_2)_R$ is an exotic doublet, so that

$$g_{cR} = \left(1+\frac{\epsilon_1}{2}\right)\left(-\frac{2}{3}\sin^2\theta_{eff} - \frac{1}{2}\sin^2\theta_{cR}\right), \tag{20}$$

$$g_{cL} = \left(1+\frac{\epsilon_1}{2}\right)\left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{eff} - \frac{1}{2}\sin^2\theta_{cL}\right). \tag{21}$$

Using Eqs. (3), (12) and (18), we then obtain

$$\sin^2\theta_{cR} = 0.02 \pm 0.01, \quad \sin^2\theta_{cL} = 0.01 \pm 0.01. \tag{22}$$

This opens up the possibility that Q_2 may also mix with t (and not just with c) so that the Tevatron ''top'' quark events are due to Q_2 rather than t which is heavier. This second interpretation is of course much more speculative because it is not directly related to the data. Note that the $\epsilon_{1,2,3}$ contributions of Q_2 and Q_5 may be handled in the same way as those of Q_1 and Q_4, as discussed by us in Ref. [5].

In conclusion, we have shown in this article that the 1999 precision electroweak data at LEP and SLC still support the possibility [5] that b_R mixes with Q_{1R} of the exotic heavy quark doublet $(Q_1,Q_4)_R$. Hence the ''top'' quark events may be due to Q_4 which has charge $-4/3$, whereas the true t quark is heavier, as evidenced by the value of ϵ_b extracted from g_{bL}. Experimentally, $t\rightarrow bW^+$ and $\bar{Q}_4\rightarrow \bar{b}W^+$ are not distinguishable at the Tevatron at present because the b or $\bar{b}$ jet charge is not easily measured, but that will become possible in the near future. We also propose here a second, more speculative idea that the ''top'' quark events may be due to a heavy quark Q_2 of charge 2/3, where Q_{2L} is a singlet but $(Q_5,Q_2)_R$ is an exotic doublet. In both scenarios, the lifetime of the ''top'' quark is enhanced by the inverse square of a reduced coupling and the single production of ''top'' quark at the Tevatron is suppressed.

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