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Increasing R_b and decreasing R_c with new heavy quarks

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If the b and c quarks mix with new heavy quarks of weak isospin $I_3=-1$ and 0, respectively, then the $Z\to b\bar{b}(c\bar{c})$ rate is necessarily greater (smaller) than that of the standard model. This may be the reason for the R_b excess and R_c deficit observed at CERN LEP. A possible consequence of this scenario is the prospective discovery of a new quark x with the dominant decay $x\to ch$, then $h\to b\bar{b}$, where h is a neutral Higgs boson.

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It has been known for some time [1] that the experimentally measured $Z\to b\bar{b}(c\bar{c})$ rate is greater (smaller) than that of the standard model. With the recent observation of the top quark [2] at the Fermilab Tevatron and more precision data [3] from the four experiments at the CERN e^+e^- collider LEP, the two discrepancies have become even sharper, as summarized below.

	Measurement	SM	Pull
R_b	0.2219 ± 0.0017	0.2156	3.7
R_c	0.1543 ± 0.0074	0.1724	−2.5

Here $R_b\equiv\Gamma(Z\to b\bar{b})/\Gamma(Z\to\text{hadrons})$, $R_c\equiv\Gamma(Z\to c\bar{c})/\Gamma(Z\to\text{hadrons})$, SM stands for the standard-model fit with $m_t=178$ GeV and $m_H=300$ GeV, and "pull" is defined as the difference between measurement and fit in units of the measurement error. If these results are taken at face value, physics beyond the standard model is indicated. Previous attempts in this direction have dealt mostly with R_b. Its excess has been interpreted as due to one-loop corrections of the $Zb\bar{b}$ vextex coming from extensions of the standard model, such as the two-Higgs-doublet model [4], or the minimal supersymmetric standard model [5], or the $SU(3)^3\times SU(2)_L\times U(1)_Y$ model [6]. However, the first two scenarios are in potential conflict with top quark decay [7] and all three fail to account for the large R_c deficit.

The purpose of this Rapid Communication is to point out that the R_b excess and the R_c deficit are naturally explained by the mixing of the b and c quarks with new heavy quarks of weak isospin $I_3=-1$ and 0, respectively. The idea is very simple. Consider first the mixing of the c quark with a new heavy isosinglet quark x of charge 2/3 [8]. Since both c_R and x_R are singlets, we can define x_R to be that which appears in the gauge-invariant mass term $\bar{x}_L x_R$. We then have both $\bar{c}_L c_R \bar{\phi}^0$ and $\bar{c}_L x_R \bar{\phi}^0$ Yukawa terms, where (ϕ^+,ϕ^0) is the usual Higgs doublet of the standard model. As a result, the mass matrix linking $(\bar{c}_L,\bar{x}_L)$ to (c_R,x_R) is given by

$$\mathcal{M}=\begin{pmatrix} m_c & m_{cx} \\ 0 & M_x \end{pmatrix}. \tag{1}$$

The c_L-x_L mixing is then $\theta_x\sim m_{cx}/M_x$, whereas the c_R-x_R mixing is $m_c m_{cx}/M_x^2$ which is certainly negligible. The physical $Z\to c\bar{c}$ rate becomes proportional to

$$[(\tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W)\cos^2\theta_x+(-\tfrac{2}{3}\sin^2\theta_W)\sin^2\theta_x]^2+(-\tfrac{2}{3}\sin^2\theta_W)^2=(\tfrac{1}{2}\cos^2\theta_x-\tfrac{2}{3}\sin^2\theta_W)^2+(-\tfrac{2}{3}\sin^2\theta_W)^2, \tag{2}$$

which is clearly a decreasing function of θ_x for small θ_x. Similarly, the physical $Z\to b\bar{b}$ rate becomes proportional to

$$[(-\tfrac{1}{2}+\tfrac{1}{3}\sin^2\theta_W)\cos^2\theta_y+(-1+\tfrac{1}{3}\sin^2\theta_W)\sin^2\theta_y]^2+(\tfrac{1}{3}\sin^2\theta_W)^2=[-\tfrac{1}{2}(1+\sin^2\theta_y)+\tfrac{1}{3}\sin^2\theta_W]^2+(\tfrac{1}{3}\sin^2\theta_W)^2, \tag{3}$$

which is clearly an increasing function of θ_y. To be more precise, we have assumed an isotriplet $y\equiv(y_1,y_2,y_3)$ of quarks which transforms as (3; 2/3) under the standard $SU(2)\times U(1)$ with $Q=I_3+Y$ in both its left-handed and right-handed projections. The extended model is thus anomaly-free and we have a gauge-invariant mass term $\bar{y}_{1L}y_{1R}+\bar{y}_{2L}y_{2R}+\bar{y}_{3L}y_{3R}$ as well as the Yukawa term $\bar{y}_{1R}t'_L\phi^+ +\bar{y}_{2R}(t'_L\phi^0+b_L\phi^+)/\sqrt{2}+\bar{y}_{3R}b_L\phi^0$, where $t'=V^*_{tb}t+V^*_{cb}c+V^*_{ub}u$. Hence b mixes with y_3 and t' with y_2. We assume that $M_y>m_t$.

To fit the updated LEP measurements [3], we need

$$\sin^2\theta_x=0.045\pm0.019, \tag{4}$$

$$\sin^2\theta_y=0.0127\pm0.0034. \tag{5}$$

These numbers are perfectly consistent with the experimentally known entries of the 3×3 weak charged-current mixing matrix [9]. The precisely measured entries $|V_{ud}|$ and $|V_{us}|$ are not affected. Others can be reinterpreted without contradiction. For example, the experimental value $|V_{cd}|$

may be written as $|V'_{cd}|\cos\theta_x$ and $|V_{cb}|$ as $|V'_{cb}|\cos\theta_x(\cos\theta_y\cos\theta'_y+\sqrt{2}\sin\theta_y\sin\theta'_y)$, where $\sin\theta'_y\simeq\sin\theta_y/\sqrt{2}$. In this notation, V' is again a unitary matrix.

As the result of explaining the experimental values of R_b and R_c, a discrepancy in the total hadronic width is now exposed. If we keep α_s at 0.123 ± 0.006, then there is a missing ΔR of 0.0118 ± 0.0070 where the negative correlation between R_b and R_c has been taken into account. For a smaller value of α_s as indicated in deep-inelastic scattering or the upsilon spectrum or lattice calculations, the discrepancy would be even worse. One possible explanation is that $M_x<M_Z-m_c$ so that Z decays into $c\bar{x}+x\bar{c}$ with a rate proportional to $\sin^2\theta_x\cos^2\theta_x/2$. To obtain $\Delta R>0.0048$, we would need $M_x<72$ GeV. In that case, $x\bar{x}$ production at the Tevatron would be plentiful and easily identifiable unless x decays predominantly into hadrons. Actually, this may well happen here because the decay chain $x\rightarrow ch$, then $h\rightarrow b\bar{b}$, where h is the standard-model Higgs boson, is dominant if kinematically allowed, and the existence of the heavy quark x would be hidden at the Tevatron from a search of its semileptonic decay modes. Since the present experimental lower bound of m_h is about 65 GeV (which comes from trying to detect $Z\rightarrow h+\text{leptons}$), there is only a narrow window of opportunity for this scenario to be correct. On the other hand, if there are two Higgs doublets, then h is in general a linear combination of two states; hence, the hZZ coupling would be reduced and the experimental bound on m_h would be lowered accordingly.

If M_x is indeed less than 72 GeV, then it can be confirmed in the near future at LEP, which will gradually step up in energy to about 190 GeV. The $e^-e^+\rightarrow x\bar{x}$ cross section (not including radiative corrections) is given by

$$\sigma=\frac{8\pi\alpha^2}{9s}\sqrt{1-\frac{4M_x^2}{s}}\left(1+\frac{2M_x^2}{s}\right)\times\left\{\left|1-\frac{s(1-2\sin^2\theta_W)}{2\cos^2\theta_W(s-M_Z^2+iM_Z\Gamma_Z)}\right|^2+\left|1+\frac{s\tan^2\theta_W}{s-M_Z^2+iM_Z\Gamma_Z}\right|^2\right\}, \tag{6}$$

which is about 4 pb at $\sqrt{s}=160$ GeV for $M_x=70$ GeV. This increase in the hadronic rate should be detectable across the $x\bar{x}$ threshold. The decay of x will be dominantly into ch, then $h\rightarrow b\bar{b}$, as discussed in the previous paragraph. Such a signature should be easily identifiable at LEP2.

With $c-x$ and $b-y$ mixing, the forward-backward asymmetries of $c\bar{c}$ and $b\bar{b}$ production at LEP are also affected. Taking the central value $\sin^2\theta_x=0.045$, the predicted value of $A_{\rm FB}^c$ is about 6% below that of the standard model:

g_V^c	g_A^c	$A_{\rm FB}^c$	$A_{\rm FB}^c$(LEP)
0.1685	0.4775	0.0685	0.0725 ± 0.0058

In the case of $A_{\rm FB}^b$, taking the central value $\sin^2\theta_y=0.0127$, its predicted value is only about 0.2% above that of the standard model:

g_V^b	g_A^b	$A_{\rm FB}^b$	$A_{\rm FB}^b$(LEP)
-0.3519	-0.5064	0.1022	0.0999 ± 0.0031

It is seen that both asymmetries agree well with the experimental measurements.

Tree-level flavor-changing neutral-current (FCNC) effects are present in this model. It has been assumed that the new quarks x, y_3, and y_2 mix only with c, b, and t', respectively. Hence there is necessarily a contribution to D^0-$\bar{D}^0$ mixing from the interaction

$$\mathscr{H}_{\rm int}=\frac{-g}{2\cos\theta_W}\cos\theta_x\sin^2\theta'_yZ_\mu(V'_{ub}V'^*_{cb}\bar{u}_L\gamma^\mu c_L+V'^*_{ub}V'_{cb}\bar{c}_L\gamma^\mu u_L), \tag{7}$$

which results in a value of $\Delta m_D/m_D\sim10^{-18}$, well below the experimental bound of 7×10^{-14} [9]. In the above, we have used the central values given in Eqs. (4) and (5) as well as $|V_{cb}|=0.040$, $|V_{ub}/V_{cb}|=0.08$, and $f_D=200$ MeV. Note that if d and s also mix with y_3, then there would be also tree-level FCNC contributions to K-$\bar{K}$ and B-$\bar{B}$ mixing.

There will be a definite impact on planned B physics measurements. The famous unitarity triangle based on the standard-model condition

$$V_{ud}^*V_{ub}+V_{cd}^*V_{cb}+V_{td}^*V_{tb}=0 \tag{8}$$

will be modified to read

$$V_{ud}^*V_{ub}+V_{cd}^*V_{cb}/\cos^2\theta_x+V_{td}^*V_{tb}=0. \tag{9}$$

The oblique radiative corrections S, T, and U are affected only to the extent that the new heavy quarks x and y mix with the usual ones. Since the mixings are small, these changes are much smaller than the experimental uncertainties.

In conclusion, it has been suggested in this Rapid Communication that if both the R_b excess and the R_c deficit at LEP are due to new physics, a simple explanation is that the b and c quarks mix with new heavy quarks of weak isospin $I_3=-1$ and 0, respectively. To keep the total hadronic rate from Z decay at about the standard-model level which does agree with data, the new quark x may have to be light enough so that $Z\rightarrow c\bar{x}+x\bar{c}$ is possible at LEP, and $e^-e^+\rightarrow x\bar{x}$ possible at LEP2. For x to have evaded detection at the Tevatron, it must decay dominantly into hadrons. In this scenario, that means $x\rightarrow ch$, where h is a neutral Higgs boson which then decays into $b\bar{b}$. This may be detectable already at LEP from $Z\rightarrow c\bar{x}+x\bar{c}$ because its branching fraction has to be greater than about 3×10^{-3} and should rise above the expected QCD background. In fact, it may already contaminate the $Z\rightarrow b\bar{b}$ and $Z\rightarrow c\bar{c}$ samples used to determine R_b and R_c. Of course, there may be other decay modes such as $x \rightarrow sh^+$, where h^+ is a charged Higgs boson which then decays into $c\bar{s}$ or $\nu_\tau \tau^+$. The signal would then be diluted. In any case, the production and detection of $x\bar{x}$ at LEP2 would not be a problem if kinematically allowed.

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