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Relative rates of W and Z events at the $\bar{p}p$ collider and nonstandard physics

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We show that the data on the relative rates of W and Z events at the $\bar{p}p$ collider strongly disfavor a sequential charge $-\frac{1}{3}$ quark b' with $m_{b'} < 25$ GeV. $m_{b'}$ is not restricted at all only if b' is a $SU(2)_L$ singlet, as is the case, e.g., in string-inspired E_6 models. The same data indicate that the observation of weak gauginos in W/Z decays is unlikely.

The experimental data[1-3] on the rate of W vs Z events in $\bar{p}p$ collisions have been used to limit the possible number of neutrino species.[1-4] Recently it was argued[5] that within the standard model with three generations the same data favor $m_t < m_W$. In this paper we discuss, following procedures similar to Ref. 5, the implications of these data for an additional sequential or nonsequential charge $-\frac{1}{3}$ quark and also for the weak gauginos.

The absence of any guidelines regarding the possible number of quark-lepton generations has prompted many speculations[6] on the existence and properties of a fourth generation, viz., t', b', E, and ν_E. Many of these ideas can accommodate a light b', some even with $m_{b'} < m_t$. An excess of low-thrust events containing muons at the maximum energies of the DESY e^+e^- storage ring PETRA, reported by the Mark J and JADE Collaborations,[7] was interpreted as possible evidence of a low-mass b' quark ($m_{b'} \sim 23$ GeV) by some authors.[8] It was also argued that the current $\bar{p}p$ collider data are not inconsistent with such a b'. Subsequently possible signatures of a low-mass, charge $-\frac{1}{3}$ quark in e^+e^- reactions[9] as well as at the $\bar{p}p$ collider have been discussed.[10] However, our analysis of the ratio

$$R = \frac{\sigma(\bar{p}p \rightarrow WX)B(W \rightarrow l\nu)}{\sigma(\bar{p}p \rightarrow ZX)B(Z \rightarrow l^+l^-)} \tag{1}$$

shows that the current data do not favor such a light b'.

Within the standard model with four generations we get, for the theoretical estimate of R,

$$R_{\text{th}} = \frac{\sigma(\bar{p}p \rightarrow W^{\pm})\left(\frac{4}{3} + a\left[1 + P(Z \rightarrow E\bar{E})/3\right] + \tilde{\alpha}\{b[3 + P(Z \rightarrow b'\bar{b}')] + 2c + cP(Z \rightarrow t\bar{t})\}\right)}{\sigma(\bar{p}p \rightarrow Z)a\{1 + P(W \rightarrow E\bar{\nu}_E)/3 + \tilde{\alpha}[2 + P(W \rightarrow t\bar{b})]\}} \ . \tag{2}$$

a, b, c above are functions of $x \equiv \sin^2\theta_W$ given by $a(x) = 1 - 4x + 8x^2$, $b(x) = 1 - \frac{4}{3}x + \frac{8}{9}x^2$, $c(x) = 1 - \frac{8}{3}x + \frac{32}{9}x^2$, and $\tilde{\alpha} = 1 + \alpha_s(m_Z{}^2)/\pi$. We use $\alpha_s(m_Z{}^2) = 0.1$ and $x = 0.232$. The factor $P(M \rightarrow m_1 m_2)$ can be written as

$$P(M \rightarrow m_1 m_2) = \lambda^{1/2}\left[1, \frac{m_1{}^2}{M^2}, \frac{m_2{}^2}{M^2}\right] \left\{1 - \frac{m_1{}^2 + m_2{}^2}{2M^2} - \frac{(m_1{}^2 - m_2{}^2)^2}{2M^4} + \frac{3m_1 m_2}{M^2} \frac{\left[\dfrac{C_V{}^2}{C_A{}^2} - 1\right]}{\left[\dfrac{C_V{}^2}{C_A{}^2} + 1\right]}\right\} \ . \tag{3}$$

In Eq. (3) $C_V/C_A = 1 - \frac{8}{3}x$ for $Z \rightarrow t\bar{t}$, $1 - \frac{4}{3}x$ for $Z \rightarrow b'\bar{b}'$, and 1 for W decays. Here λ is the standard kinematic function for two-body decay. In the above we only assume that all the neutrinos are nearly massless and $m_W < (m_{t'} + m_{b'})$. Since b' does not contribute to the denominator of Eq. (2) it can, along with the data, bound $m_{b'}$ *from below*. Such discussions, of course, depend on m_t and m_E. An additional source of uncertainties is the theoretical estimate of $R_\sigma = \sigma(\bar{p}p \rightarrow W)/\sigma(\bar{p}p \rightarrow Z)$. To assess this uncertainty, we use three different choices of structure functions, those of Duke and Owens[11] (DO1 and DO2) and of Glück, Hoffman, and Reya[12] (GHR). Two new analyses[13,14] using the recent data[15] on deep-inelastic scattering, focusing on the ratio u_v/d_v where u_v, d_v are valence u,d quark densities in the proton, give

$$R_\sigma = 3.41 \pm 0.08 \ \ (\text{Ref. } 13) \ ,$$

$$R_\sigma = 3.36 \pm 0.09 \ \ (\text{Ref. } 14) \ .$$

Since one gets $R_\sigma = 3.41$ for the DO1 structure functions, we see that in the following discussion, bounds given for DO1 are the most representative.

The recent UA1 data[16] imply a limit on m_E, viz., $m_E > 41$ GeV. In this mass range R_{th} increases with m_E. Hence the most conservative lower bound on $m_{b'}$

will be given by using $m_E = 41$ GeV. Solid lines in Fig. 1 show R_{th} calculated with $m_t = 40$ GeV and $m_E = 41$ GeV, along with the data. The value of R_{exp}, as well as the upper limit on it at the 90% confidence level, is taken from Ref. 3. Therein these are obtained by combining UA1 and UA2 data in Refs. 1 and 2, respectively. As can be seen the combined UA1, UA2 data disfavor a light b'. Increasing m_E only worsens the case for a low $m_{b'}$, as can be seen from the dashed line.

Increasing m_t has a similar effect on these considerations. Figure 2 shows the region in the m_t-$m_{b'}$ plane allowed at the 90% confidence level. The solid lines correspond to $m_E = 41$ GeV. For DO1 and DO2 structure functions, a light b' is disfavored even for m_t as low as that barely allowed by e^+e^- annihilation data, viz., 23 GeV. With $m_E > 60$ GeV, similar stringent lower bounds on $m_{b'}$ are obtained even with GHR distributions. Again $m_{b'} > 25$ GeV is indicated for $m_t = 23$ GeV (see the dashed curve). The above bounds become even more restrictive, if we include the effect of recently reported[17] bounds on the top-quark mass from the $\bar{p}p$ collider data, viz., $m_t > 45$ GeV at the 90% C.L. This limit is indicated by the vertical dotted line in Fig. 2. In light of this discussion it is clear that the possibility of a b' with mass small enough to be produced at the current DESY PETRA energies is strongly disfavored. With the choice of DO1 or DO2 even the usual mass hierarchy $m_{b'} < m_t$ is disfavored at the 90% confidence level (Fig. 2). Unfortunately uncertainties, both in R_{exp} and R_{th}, make it impossible to make any stronger statement.

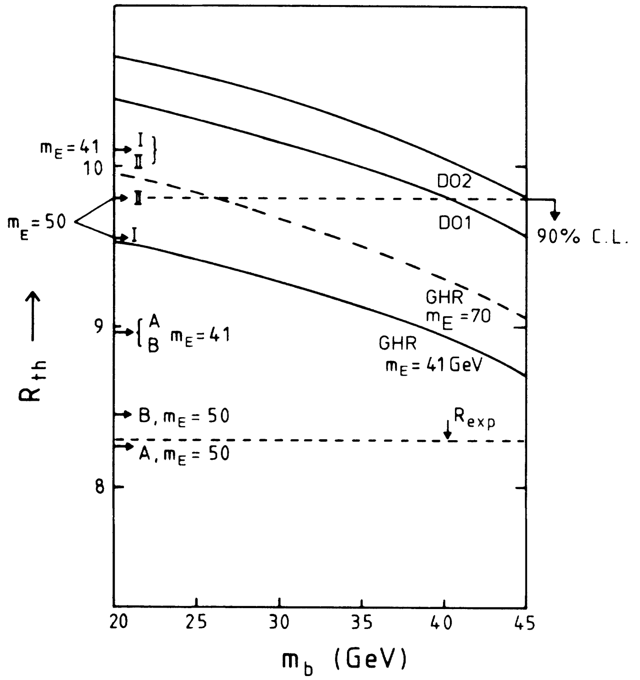

FIG. 1. Value of R_{th} [Eq. (2)] as a function of $m_{b'}$, for different choices of structure functions and heavy-lepton masses m_E. The solid lines correspond to $m_E = 41$ GeV in both the figures. The dashed horizontal lines represent the experimental value of R [Eq. (1)] and upper bound on it at the 90% level of confidence as obtained in Ref. 3. For the explanation of various arrows see text.

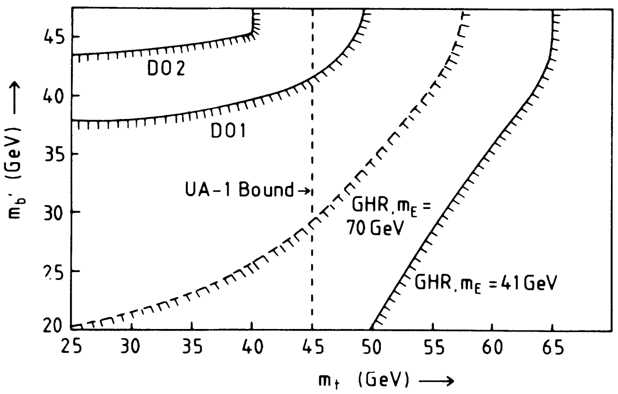

FIG. 2. Allowed regions in $m_{b'}$-m_t plane at the 90% confidence level for different choices of structure functions and values of heavy-lepton masses. The dashed line indicates the bound obtained by UA1 Collaboration as reported in Ref. 17.

It should be noted that for each choice of structure functions there is a limiting m_t, indicated by the vertical line in Fig. 2. Beyond this R_{th} becomes inconsistent with the data even for $m_{b'} \geq m_Z/2$. Also note that the contribution of the lepton E to the denominator in Eq. (2) increases significantly the range of allowed m_t values, for $m_E < 60$–65 GeV, even with four generations, as compared to the ones discussed earlier.[2,5]

In the discussion above we considered the case of a sequential, charge $-\frac{1}{3}$ quark which occurs in an $SU(2)_L$ doublet. However, models with $SU(2)_L$-singlet nonsequential, charge $-\frac{1}{3}$ quarks also exist. As a matter of fact the superstring-inspired E_6 models[18] contain three such exotic quarks, one for each quark-lepton generation. This occurs in the **27** of E_6 along with other exotic fermions. The particle content of the **27** of E_6 is

$$\begin{bmatrix} \nu \\ e \end{bmatrix}_L, \quad \begin{bmatrix} u \\ d \end{bmatrix}_L, \quad u_R,\; d_R,\; e_R,\; \nu_R\;,$$

$$\begin{bmatrix} N \\ E \end{bmatrix}_L, \quad \begin{bmatrix} N' \\ E \end{bmatrix}_R, \quad b'_L,\; b'_R,\; \nu''_L\;.$$

To assess the implications of the ratio R for the extra fermions written in the second row above we consider the possibility that one generation of these is light. This contains three extra neutrals N, N', ν''_L, a charged lepton E, and a charge $-\frac{1}{3}$ quark b'. ν''_L will couple to ordinary gauge bosons Z and W only through mixing. If the masses m_E, $m_{b'}$, m_N, and $m_{N'}$ are small enough, they can contribute to the numerator of the ratio R, through $Z \to E\bar{E}$, $Z \to N\bar{N}$, $Z \to N'\bar{N}'$, and $Z \to b'\bar{b}'$. The denominator can receive contributions through $W \to EN$ and $W \to EN'$.

Both E and b' couple to Z with pure vector coupling. This slows down the damping of the phase-space factor of Eq. (3) with increasing m_1 and m_2. This gives rise to interesting behavior of R as a function of m_E and m_N. This is discussed elsewhere.[19]

The b' in this case is an $SU(2)_L$ singlet. Therefore, its coupling to Z is suppressed by x compared to $Z \to \nu\bar{\nu}$ coupling. In this case in Eq. (2) the coefficient of

$P(Z \to b'\bar{b}')$ is $\frac{8}{9}x^2$ instead of the factor b which occurs for a sequential charge $-\frac{1}{3}$ quark. As a result the contribution of b' to the numerator is indeed minimal in spite of the vector coupling.

As an example, values of R_{th} predicted for two different possibilities, (i) both $m_N, m_{N'} > m_Z/2$, (ii) either of $m_N, m_{N'} < m_Z/2$ for DO2 (GHR) structure functions, with $m_t = 40$ GeV, are denoted in Fig. 1 by arrows labeled I, II (A,B), respectively. The contributions are labeled by arrows as they are almost independent of $m_{b'}$.

From this we can see that in this case a light b' ($m_{b'} \sim 23$ GeV) is allowed irrespective of all the other masses or choices of structure functions. Thus the data on R_{exp} do not restrict the mass of a charge $-\frac{1}{3}$ quark at all only if it is an $SU(2)_L$ singlet.

In view of the nontrivial role played by m_E in the above discussion for a sequential as well as nonsequential b' quark, it is clear that the W and Z decays into weak gauginos, $W \to \tilde{Z}\,\tilde{W}$, $W \to \tilde{W}\,\tilde{\gamma}$, and $Z \to \tilde{W}\,\tilde{W}$, when allowed, will affect R_{th}. As a result values of R_{exp} can also be used to limit values of $m_{\tilde{W}}$ and $m_{\tilde{Z}}$. Unfortunately, the couplings of the weak gauginos with W and Z are model dependent. In the usually studied $N=1$ supergravity models, with equal vacuum expectation values for the two Higgs scalars, R_{th} as a function of $m_{\tilde{W}}$ has been calculated[20] for $m_{\tilde{\gamma}} = 0$ and 8 GeV. They use DO1 structure functions and $40 < m_t < 50$ GeV. They find that for $30 < m_{\tilde{W}} < 47$ GeV R lies considerably above the standard-model (SM) value (rising up to ~ 10.6 for $m_{\tilde{W}} \sim 40$ GeV). Beyond this range it lies close to the SM value independent of $m_{\tilde{W}}$. This along with the combined UA1 and UA2 data shows that the data disfavor the range $36 < m_{\tilde{W}} < 47$ GeV at the 90% confidence level with DO1 structure functions. Values of $m_{\tilde{W}} < 35$ GeV, though allowed by data on R, are unlikely in view of the large monojet cross sections (~ 50–60 pb) (Ref. 20) predicted at CERN energies in this case. This would mean that UA1 should have seen 30–40 monojet events with large missing energy, which is not the case.[16] The range $35 < m_{\tilde{W}} < 45$ GeV is precisely the region where large cross sections ~ 150 pb (Ref. 20) (with a background of ~ 300 pb) were expected at Fermilab Tevatron. Beyond $M_{\tilde{W}} = M_Z/2$ the predicted monojet cross sections, due to $\tilde{W}\tilde{\gamma}$ production, at the Tevatron are as small as ~ 25–30 pb for realistic mass values: $m_{\tilde{\gamma}} \sim 15$ GeV (Ref. 21). Thus the considerations above imply that the experimental observation of weak gauginos in $\bar{p}p$ colliders is quite unlikely. Our study of the behavior of the ratio R_{th} in this case, as a function of m_t, implies that the situation gets worse with increasing values of m_t. It follows from this that the supersymmetric decays of W/Z are unlikely to affect R_{th} so as to make $m_t > m_W$ possible. The cases for E_6 models we have looked at imply similar conclusions for them also. This will be discussed in detail elsewhere.[19]

The analysis presented here may have serious implications for four-generation model buildings. The smallness of the quark mixing angles has been used to argue[22] that the mass matrices for charge $-\frac{1}{3}$ quark (M_D) and charge $\frac{2}{3}$ quark (M_U) be related by

$$M_U = \alpha M_D + M' ,$$

where α is a constant and M' a perturbation. Neglecting the perturbation implies proportionality of the eigenvalues of M_U and M_D. The obvious violation of such a proportionality for the light up and down quarks has been argued as being due to stronger effects of the perturbation M' for lighter-quark systems. If $m_t \sim 40$ GeV, the second and third generations satisfy this proportionality approximately. This, along with the restriction $(m_{t'} - m_{b'}) \lesssim 310$ GeV (Ref. 23) then implies[24]

$$m_{b'} = \left[\frac{m_{t'} m_b}{m_t} \right] \lesssim \left[310 \frac{m_b}{m_t} \right] \left[1 - \frac{m_b}{m_t} \right]^{-1} . \qquad (4)$$

For $m_t > 40$ GeV, at least for DO1 and DO2 structure functions, the upper limits implied by Eq. (4) and limits from Fig. 2 are in conflict. A recent analysis[25] based on $O(\alpha)$ radiative corrections to the parameter Δr (Ref. 26) would reduce $(m_{t'} - m_{b'})_{\max}$ to 180. This would lower the upper bound in Eq. (4). In this case the lower bounds implied even with GHR functions (for $m_E > 60$ GeV) are in conflict with this upper bound. While the various uncertainties in the analysis do not allow a much stronger conclusion, it is clear that such studies of mass correlations already restrict the four-generation models quite strongly.

Thus we see that, in spite of the various uncertainties, the data on R at the collider are already restrictive enough to give us some indications about the physics beyond the standard model.

Since the submission of this paper for publication, there has been a recent report by Barger *et al.*[27] also discussing limits on the masses of b', L, and t. They arrive at similar though slightly less restrictive conclusions.

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