A Z' with enhanced couplings to quarks: A bridge from CERN LEP 1, SLC, and CDF to LEP 2 anomalies

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In order to explain possible departures from the standard model (SM) predictions for $b\bar{b}$ and $c\bar{c}$ production at the Z peak, we propose the existence of a Z' vector boson with enhanced couplings to quarks. We first show that this proposal is perfectly consistent with the full set of LEP 1 and SLC results. In particular, Z-Z' mixing effects naturally explain the fact that Γ_b and Γ_c deviate from the SM in opposite directions. We then show that there is a predicted range for enhanced $Z'q\bar{q}$ couplings which explains, for a precise and interesting range of Z' masses, the excess of dijet events seen at CDF. A Z' with such couplings and mass would produce clean observable effects in $b\bar{b}$ and in total hadronic production at LEP 2. [S0556-2821(96)00813-2]

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I. INTRODUCTION

The precision measurements in the leptonic sector at the CERN e^+e^- collider LEP 1 and the SLAC Linear Collider (SLC) agree with the standard model (SM) predictions at the level of a few permille [1], which leads to drastic constraints on any type of new physics (NP) manifestation. As of today, the situation in the quark sector is slightly different. Through measurements of the $Z\to b\bar{b}$ and $Z\to c\bar{c}$ widths and asymmetries, LEP and SLC have given indications for possible departures from the SM predictions for b and c couplings at the level of a few percent. In the $b\bar{b}$ case such anomalies could be interpreted as a signal for NP in the heavy quark sector, driven, for example, by the large value of the top quark mass, whose effects already appear at standard level [2]. Several models of this type have been proposed [anomalous top quark properties [3,4], extended technicolor (ETC) models [5], anomalous gauge boson couplings [6], supersymmetric contributions, new Higgs bosons, gauginos, ... [7,8]. A common feature of all these explanations is that they fail to explain the possible existence of $c\bar{c}$ anomalies, which cannot be enhanced by the large top quark mass. So, it seems more difficult to describe the presence of anomalies in both $b\bar{b}$ and $c\bar{c}$ channels, without drastically modifying the fermionic sector, for example, through the mixing of quark multiplets with higher fermion representations as proposed in [9].

In this paper we would like to propose a simple explanation based on the existence of a *hadrophilic* Z' vector boson, i.e., one which would couple universally to quarks more strongly than to leptons. We shall not propose here a specific model, although the concept of Z' differently coupled to quarks and to leptons has already been considered in the past [10]. We shall be limited to extracting from LEP 1 or SLC experiments several suggestions about the required Z' properties. To achieve this, we shall first rely on a model-independent framework for the analysis of Z-Z' mixing effects. This is available from a previous work [11] in which the Z' couplings to each fermion-antifermion pair were left free. Working in this spirit, we will then derive in Sec. II experimental informations on the Z-Z' mixing angle θ_M and on the $Z'f\bar{f}$ couplings showing that, indeed, the anomalies in $b\bar{b}$ and $c\bar{c}$ productions can be described by such a hadrophilic Z'. In particular, from the absence of anomaly in the total hadronic width $\Gamma_{\rm had}$ at the Z peak we shall explain in a natural way the fact that the SM departures in Γ_b and in Γ_c have opposite signs.

The next relevant question to be answered is that of whether the values of the Z' couplings that we determined in this way do not contradict any already available experimental constraint. In particular, we shall focus in Sec. III on the significant excess of dijet events for large masses (above 500 GeV) at the Collider Detector at Fermilab (CDF) [12]. We shall show that this phenomenon could be naturally explained in terms of a hadrophilic Z', whose mass lies in the range between 800 GeV and 1 TeV and whose couplings are restricted by the request that the Z' behaves like a not too wide resonance, identifiable in different processes.

Our second step will then consist of examining in Sec. IV the consequences of this solution for other processes, in particular possible Z' effects in $e^+e^-\to f\bar{f}$ at LEP 2.

Here, the natural final channels to be considered in our case are the hadronic ones, where the Z' effect would depend on the product of Z' couplings to leptons times Z' couplings to quarks. In this paper, we shall consider the pessimistic case where the leptonic Z' couplings are not sufficiently strong to give rise to visible effects in the leptonic channel. Starting from this conservative assumption, we shall show that it would be still possible to observe effects in hadronic channels. We will proceed in two steps. First, in a model-independent way, we shall establish the domain of $Z'b\bar{b}$ couplings that would lead to visible deviations in the $b\bar{b}$ cross section σ_b and in the forward-backward asymmetry $A^b_{\rm FB}$. We shall show that this domain largely overlaps the ones suggested by our analysis of LEP 1 or SLC and CDF results. We shall then examine the total hadronic cross section $\sigma_{\rm had}$ at LEP 2 and we shall find again that the domain of

$Z'b\bar{b}$ and $Z'c\bar{c}$ couplings leading to visible effects contains the values selected by LEP 1 or SLC and CDF.

We can, therefore, conclude that, if a hadrophilic Z' is at the origin of the present observed anomalies, a quantitative study of these three hadronic observables at LEP 2 would allow to confirm this relatively simple explanation. In this case, it would become relevant and meaningful to construct a full and satisfactory theoretical model.

II. ANALYSIS OF LEP 1 AND SLC RESULTS IN TERMS OF Z-Z′ MIXING

We consider Z-Z' mixing effects at the Z peak in a model-independent way following the procedure given in Ref. [11]. As is well known, the two relevant effects consist in a modification of the Z couplings to fermions, proportional to a mixing angle $\equiv \theta_M$, and in a Z mass shift which induces a contribution to the δ_ρ parameter:

$$\delta_\rho^{Z'} \simeq \theta_M^2 \frac{M_{Z'}^2}{M_Z^2}. \tag{1}$$

The quantity $\delta_\rho^{Z'}$ is a *positive quantity* that can be extracted from the ratio $c_w^2 \equiv M_W^2/M_Z^2$ and its comparison to the quantities measured at the Z peak and defined in the conventional way [13].

From the latest available data [1] and under the assumption that no other significant contribution to δ_ρ (e.g., from one extra W') exists, we obtain, at two standard deviations,

$$0 \leqslant \delta_\rho^{Z'} \leqslant +0.005. \tag{2}$$

In this way we derive an upper value for the mixing angle:

$$|\theta_M| < \sqrt{0.005}\, \frac{M_Z}{M_{Z'}}. \tag{3}$$

Note that for our nextcoming qualitative analysis, values of $\delta_\rho^{Z'}$ not unreasonably larger than the limit of Eq. (2) would not modify our conclusions. We shall come back on this point later. We then normalize the $Z'f\bar{f}$ couplings,

$$-i\frac{e(0)}{2s_1c_1}\gamma^\mu[g'_{Vf} - g'_{Af}\gamma^5], \tag{4}$$

in the same way as the $Zf\bar{f}$ ones:

$$-i\frac{e(0)}{2s_1c_1}\gamma^\mu[g_{Vf} - g_{Af}\gamma^5] \tag{5}$$

with $g_{Vl} = -v_1/2$; $g_{Al} = -\frac{1}{2}$; $g_{Vf} = I_f^3 - 2s_1^2 Q_f$; $g_{Af} = I_f^3$; $v_1 = 1 - 4s_1^2$; $s_1^2 \equiv 1 - c_1^2 \simeq 0.2121$ from $s_1^2 c_1^2 = \pi\alpha(0)/\sqrt{2}G_\mu M_Z^2$.

This allows us to define the ratios

$$\xi_{Vf} \equiv \frac{g'_{Vf}}{g_{Vf}}, \quad \xi_{Af} \equiv \frac{g'_{Af}}{g_{Af}}, \tag{6}$$

which will significantly measure the magnitude of the $Z'f\bar{f}$ couplings. Keeping in mind the fact that g_{Vl} is depressed by $v_1 \simeq 0.1516$, we will consider as ‘‘natural’’ (i.e., nonenhanced) magnitudes $\xi_{Al} \simeq 1$, $\xi_{Vf} \simeq 1$, $\xi_{Af} \simeq 1$ for $f \neq l$, but $\xi_{Vl} \simeq 6$.

The total fermionic Z' width is given by

$$\Gamma_{Z'}^{\text{ferm}} = \frac{\alpha M_{Z'}}{12 s_1^2 c_1^2} \sum_f N_f \left(1 - \frac{4m_f^2}{M_{Z'}^2}\right)^{1/2} \left[\xi_{Vf}^2 g_{Vf}^2 \left(1 + \frac{2m_f^2}{M_{Z'}^2}\right) + \xi_{Af}^2 g_{Af}^2 \left(1 - \frac{4m_f^2}{M_{Z'}^2}\right)\right], \tag{7}$$

N_f being the lepton $(=1)$ or quark $(=3)$ color factor.

The Z-Z' mixing effects on Z peak observables (Z partial widths and asymmetries), due to $\delta_\rho^{Z'}$ and to the modifications of the Z couplings (of the form $\theta_M g'_{V,A}$) are analyzed in Appendix A. Using the most recent LEP and SLC data [1] we obtain information on Z' couplings. They are summarized below in the form of allowed bands, at two standard deviations, assuming that $|\theta_M|$ saturates the bound, Eq. (3), (so in a sense these are minimal bands) with the two possible signs $\eta_M = \pm 1$.

$Z'll$ couplings

$$\eta_M \xi_{Vl} \simeq (-2.25 \pm 6.25)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{LEP}),$$

$$\eta_M \xi_{Vl} \simeq (+1.75 \pm 6.25)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{SLC}), \tag{8}$$

$$\eta_M \xi_{Al} \simeq (-0.2 \pm 0.5)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right). \tag{9}$$

$Z'b\bar{b}$ couplings

$$\eta_M \xi_{Vb} \simeq (-3.45 \pm 20.72)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{LEP}),$$

$$\eta_M \xi_{Vb} \simeq (-24.24 \pm 25.98)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{SLC}), \tag{10}$$

$$\eta_M \xi_{Ab} \simeq (+4.58 \pm 9.84)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{LEP}),$$

$$\eta_M \xi_{Ab} \simeq (+14.54 \pm 12.47)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{SLC}), \tag{11}$$

$Z'c\bar{c}$ couplings

$$\eta_M \xi_{Vc} \simeq (-6.94 \pm 26.60)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{LEP}),$$

$$\eta_M \xi_{Vc} \simeq (-20.38 \pm 40.62)\left(\frac{M_{Z'}}{1\,\text{TeV}}\right)(\text{SLC}), \tag{12}$$

$$\eta_M \xi_{Ac} \simeq (-7.88 \pm 8.46)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{LEP}),$$

$$\eta_M \xi_{Ac} \simeq (-6.01 \pm 9.70)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{SLC}). \tag{13}$$

Because of the various uncertainties, both theoretical (the assumption about $|\theta_M|$) and experimental (disagreements for various measurements and large errors in the quark cases) we take these results just as indicative and we call the resulting values suggested Z' couplings. Several important remarks are nevertheless in order.

First, as expected, lepton couplings are strongly constrained: ξ_{Vl} and ξ_{Al} lie within the ''natural'' range mentioned above.

Second, on the contrary, there is room for very large values for quark couplings. In one case, from SLC data, a definite nonzero value for ξ_{Ab} is suggested. Obviously, the extreme quoted values are to be taken as purely indicative. *A priori* we would not trust values larger, for example, than the QCD strength ($\alpha_s \simeq 0.12$), which implies $|\xi_{Af}| < 7$ and $|\xi_{Vf}| < 7/v_f$, i.e., $|\xi_{Vb}| < 10$ and $|\xi_{Vc}| < 16$. We will conventionally define as ''reasonable'' the values of the couplings lying within this range. Further, restrictions can *a priori* be set by considering their effects on the total fermionic Z' width, Eq. (7). This will be discussed in the next section.

There is one more important information to be extracted from Z-Z' mixing effects at the Z peak. From the very precise measurement of Γ_{had} leading to

$$\frac{\delta\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{had}}} = +0.003 \pm 0.0017 \tag{14}$$

and Eq. (A7), one obtains

$$\eta_M[4v_c\xi_{Vc} + 12\xi_{Ac} + 12v_b\xi_{Vb} + 18\xi_{Ab}] = (10.6 \pm 15.4)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right), \tag{15}$$

where $v_f = 1 - 4|Q_f|s_1^2$. In practice, up to a small uncertainty, this relation reduces the four-parameter quark case to a three-parameter one. This result, valid for the most general type of Z', will introduce a quite useful simplification in our nextcoming calculations.

From Eq. (14) we can derive a strong correlation between $\delta\Gamma_b$ and $\delta\Gamma_c$ that is peculiar to our Z' hypothesis. Our universality assumptions $\delta^{Z'}\Gamma_u = \delta^{Z'}\Gamma_c$ and $\delta^{Z'}\Gamma_d = \delta^{Z'}\Gamma_s = \delta^{Z'}\Gamma_b$ allow us to rewrite Eq. (14) as

$$\frac{\delta\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{had}}} = 2\left(\frac{\delta\Gamma_c}{\Gamma_c}\right)\left(\frac{\Gamma_c}{\Gamma_{\mathrm{had}}}\right) + 3\left(\frac{\delta\Gamma_b}{\Gamma_b}\right)\left(\frac{\Gamma_b}{\Gamma_{\mathrm{had}}}\right) \tag{16}$$

leading to the conclusion

$$\frac{\delta\Gamma_b}{\Gamma_b} = -\left(\frac{2}{3}\right)\left(\frac{R_c}{R_b}\right)\left(\frac{\delta\Gamma_c}{\Gamma_c}\right) + \left(\frac{1}{3R_b}\right)\left(\frac{\delta\Gamma_{\mathrm{had}}}{\Gamma_{\mathrm{had}}}\right). \tag{17}$$

Numerically, the second term on the right-hand side is negligible in first approximation, which finally gives

$$\frac{\delta\Gamma_b}{\Gamma_b} \simeq -0.5\frac{\delta\Gamma_c}{\Gamma_c}. \tag{18}$$

Thus, in a natural way, the relative shifts in Γ_b and in Γ_c are predicted to be of opposite signs, with a ratio consistent with the experimental data and errors, which is a peculiar feature of the model, valid for all the values of its quark couplings that obey the universality request.

Finally, note that the values of these suggested Z' couplings grow linearly with the mass $M_{Z'}$. This is a natural consequence of assuming a given Z-Z' mixing effect on the Z peak observables. When $M_{Z'}$ grows, θ_M decreases. Consequently, for a given Z-Z' mixing effect the required Z' couplings increase.

Our model-independent analysis of the LEP 1 or SLC constraints on the Z' parameters is thus finished. In the next section, we shall investigate whether the large ''suggested'' $Z'q\bar{q}$ couplings are not ruled out by the data available from the hadronic colliders.

III. ANALYSIS OF CDF DIJET EVENTS IN TERMS OF A Z' RESONANCE

The CDF Collaboration has reported the observation of an excess of events with two-jet mass above 500 GeV, compared to the QCD prediction. The jets have been required to satisfy $|\eta| < 2$ (η being the pseudorapidity) and the events are required to have $|\cos\theta^\star| < \frac{2}{3}$, $\theta^\star$ being the parton scattering angle in the partonic center-of-mass frame. This kinematical restriction favors the appearance of NP since the QCD cross section is peaked around $|\cos\theta^\star| \simeq 1$. The two-jet production in hadronic collisions has been computed at next-to-leading order in QCD [14]. The aim of this section is that of investigating whether the observed dijet excess may, or may not, be explained in terms of a hadrophilic Z', that *a priori* represents in our opinion a reasonably natural possibility. In order to pursue this program we have to calculate the effect of the addition to the dominant QCD component of the weak contribution. In the SM this comes from W,Z and photon exchanges. In our analysis we will add the extra contribution due to the Z' with couplings taken within the range suggested by the LEP or SLC analysis. The practical calculation is rather lengthy and will be summarized in Appendix B.

The weak contribution being evaluated at leading order, we shall perform the calculation of the strong part at the same level. It has been shown in [14] that the difference between the order α_s^3 calculation and the Born calculation is small provided that we fix the arbitrary factorization M and renormalization μ scales to

$$M = \mu = \frac{0.5 M_{JJ}}{2\cosh(0.7\eta_\star)}, \tag{19}$$

where M_{JJ} is the dijet mass and $\eta_\star = |\eta_1 - \eta_2|/2$, η_i being the pseudorapidity of jet i. In the following we will use the prescription given in Eq. (19). The deviation from the QCD prediction appears as a resonance bump in the $700-1000$ GeV M_{JJ} mass range, suggesting, therefore, an indicative Z' mass range around $700-1000$ GeV. Since the bump is wide, the hadrophilic Z' cannot be narrow.

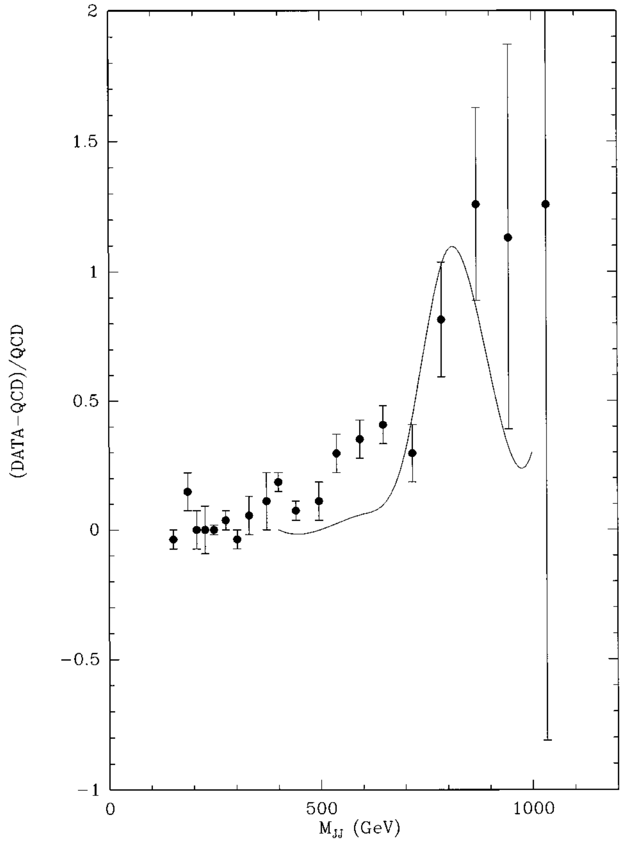

FIG. 1. Fractional difference between dijet CDF data [12] and QCD, compared to a hadrophilic Z' of mass $M_{Z'}=800$ GeV for $\xi_{Vb}=4$, $\xi_{Ab}=3$, $\xi_{Vc}=4$, and $\xi_{Ac}=3$.

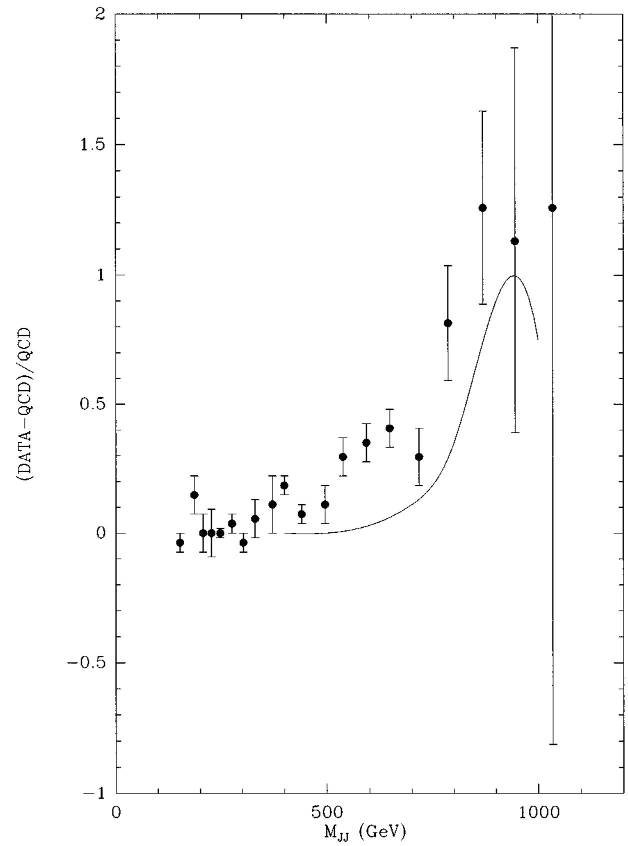

FIG. 2. Fractional difference between dijet CDF data [12] and QCD, compared to a hadrophilic Z' of mass $M_{Z'}=900$ GeV for $\xi_{Vb}=4$, $\xi_{Ab}=3$, $\xi_{Vc}=4$, and $\xi_{Ac}=3$.

The results of our investigation are shown in Figs. 1 and 2. As one can see, the observed dijet excess can be satisfactorily explained for $M_{Z'}$ around 800–900 GeV and for reasonable $Z'q\overline{q}$ values, i.e., $|\xi_{Af}|$ and $|\xi_{Vf}|\simeq 3$. We have checked that these values satisfy the correlation constraint due to $\Gamma_{\rm had}$, Eq. (15), and lead to an acceptable enhancement of the Z' width, Eq. (7). Note that $|\xi_{Af}|$ and $|\xi_{Vf}|$ cannot be simultaneously too small (i.e., all $\simeq 1$–2), otherwise the width would be too narrow. To fix a scale in our analysis we allow the Z' width to lie in the range $\Gamma_{Z'}\simeq$ 150–200 GeV. Larger values of the $Z'q\overline{q}$ couplings would lead to an unreasonably wide resonance and the observed peak would be much less pronounced.

The excess of dijet events could also be explained by a hadrophilic Z' of mass $M_{Z'}=700$ GeV or even 1 TeV provided that its quark couplings are all suitably larger, i.e., for $|\xi_{Af}|$ and $|\xi_{Vf}|$ values between 3 and 5. For what concerns possible effects at LEP 2 these situations would lead to more dramatic consequences. For this reason, we shall rather concentrate our analysis on the configuration of Figs. 1 and 2, which corresponds from this point of view to a more conservative attitude.

A few technical comments about our calculation are now appropriate. We have used the Kwiecinski-Martin-Roberts-Stirling (KMRS) set B of parton distributions [15]. The uncertainty due to our imperfect knowledge of the structure functions is small since we calculate a ratio. The dominant weak contribution is due to the Z' pole. We are, therefore, not sensitive to the sign of $Z'q\overline{q}$ couplings and the SM weak vector bosons contributions are quite negligible in the high dijet mass range we are interested in.

This concludes our confrontation of hadrophilic Z' hypothesis to existing data. We shall now investigate the future prospects from LEP 2.

IV. Z' EFFECTS IN HADRONIC PRODUCTION AT LEP 2

In this section, we shall examine possible visible consequences of our assumption that a hadrophilic Z' exists, with ‘‘suggested’’ couplings and mass derived by an overall analysis of LEP or SLC and CDF data. As rather natural experimental quantities to be considered for this purpose, we shall concentrate our attention on the three hadronic observables that will be measured in a very near future at LEP 2, i.e., the $b\overline{b}$ cross section $\sigma_b(q^2)$, the $b\overline{b}$ forward-backward asymmetry $A_{{\rm FB},b}(q^2)$, and the total hadronic production cross section $\sigma_h(q^2)$, where $\sqrt{q^2}$ is the total center-of-mass energy that will vary in the range (chosen for theoretical and experimental reasons [16]) 140 GeV$\leqslant\sqrt{q^2}\leqslant$190 GeV. The calculated shifts on these three quantities due to a Z' will depend on products of Z' quark couplings with Z' lepton couplings. For the latter ones, we have seen from our previous investigation that no special ‘‘suggestion’’ exists that motivates some anomalously large values. In fact, a more detailed investigation of the constraints on the Z' lepton couplings derived from LEP or SLC would lead to the conclusion that Z' signals in the leptonic channel at LEP 2 are not forbidden, but are also not specially encouraged. In particular, in the extreme configuration of a saturation of the bound on $|\theta_M|$, the lepton couplings would lie in a domain which corresponds roughly to the domain of nonobservability for the various leptonic observables at LEP 2, which has been derived very recently in another detailed paper [17]. Following a conservative attitude, we shall assume therefore that the leptonic Z' couplings lie in the previous domain of nonobservability at LEP 2. With this input, we shall look for possible effects in the LEP 2 hadronic channels, motivated by the suggested anomalously large Z' quark couplings. Of course, should an effect be produced in the leptonic channel, the corresponding situation in the hadronic one would become more favorable than that in the configuration that we shall consider from now on.

The treatment of the Z' shifts on various observables can be performed in various ways. We shall follow in this paper a theoretical approach that has been proposed very recently [18], in which this effect can be formally considered as a one-loop Z' correction of ''box'' type to the SM quantities containing conventional γ and Z exchanges. These corrections enter in a not universal way in certain gauge-invariant combinations of self-energies, vertices, and boxes that have been called $\tilde{\Delta}\alpha(q^2)$, $R(q^2)$, $V_{\gamma Z}(q^2)$, and $V_{Z\gamma}(q^2)$, whose contributions to the various observables have been completely derived and thoroughly discussed in Sec. II of Ref. [18]. We shall not repeat here the derivations of these contributions, and defer the interested reader to the aforementioned reference. For our purposes, it will be sufficient to remember that the relevant one-loop corrected expressions of an observable O_{lf} of the process $e^+e^-\to f\bar{f}$ (where f is a certain quark) will be of the type

$$O_{lf}(q^2)=O_{lf}^{(\mathrm{Born})}[1+a_{lf}\tilde{\Delta}_{\alpha}^{(lf)}(q^2)+b_{lf}R^{(lf)}(q^2)+c_{lf}V_{\gamma Z}^{(lf)}(q^2)+d_{lf}V_{Z\gamma}^{(lf)}(q^2)], \quad (20)$$

where $(a,b,c,d)_{lf}$ are certain numerical constants given in Ref. [18] for the various relevant cases and $O_{lf}^{(\mathrm{Born})}$ is a certain suitably defined ''effective'' Born approximation. For the case $f=b$, the Z' contributions to the four one-loop corrections turn out to be

$$\tilde{\Delta}_{\alpha}^{(lb)}(q^2)=-z_{2l}z_{2b}, \quad R^{(lb)}(q^2)=z_{1l}z_{1b}\chi^2, \quad (21)$$

$$V_{\gamma Z}^{(lb)}(q^2)=z_{1l}z_{2b}\chi^2, \quad V_{Z\gamma}^{(lb)}(q^2)=z_{2l}z_{1b}\chi^2, \quad (22)$$

where we use the reduced couplings

$$z_{1b}=\xi_{Ab}\sqrt{\frac{q^2}{M_{Z'}^2-q^2}}, \quad (23)$$

$$z_{2b}=\left(\frac{3v_b}{4s_1c_1}\right)(\xi_{Vb}-\xi_{Ab})\sqrt{\frac{q^2}{M_{Z'}^2-q^2}}, \quad (24)$$

and $\chi^2=(q^2-M_Z^2)/q^2$.

From these expressions we have computed the relative shifts $\delta\sigma_b(q^2)/\sigma_b$ and $\delta A_{\mathrm{FB},b}(q^2)/A_{\mathrm{FB},b}$ due to a Z', assuming, as previously discussed, that the lepton couplings lie in the domain of nonobservability at LEP 2. As has been shown in [17], this corresponds to the limitations on the leptonic ratios

$$|\xi_{Vl}|\lesssim\left(\frac{0.22}{v_1}\right)\sqrt{\frac{M_{Z'}^2-q^2}{q^2}}, \quad (25)$$

$$|\xi_{Al}|\lesssim(0.18)\sqrt{\frac{M_{Z'}^2-q^2}{q^2}}. \quad (26)$$

The calculation of the shifts has been performed without taking into account the potentially dangerous effects of QED radiation. From our previous experience [17] we know that, provided that suitable experimental cuts are imposed, the realistic results will not deviate appreciably from those calculated without QED convolution. This is particularly true if one is interested in large effects, as in our case. We defer the reader to Ref. [17] for a complete disussion of this point.

From now on, we shall concentrate on the configuration $q^2=(175\ \mathrm{GeV})^2$ since, for the purposes of Z' searches, it has been shown in [17] that within the three planned realistic LEP 2 phases this is the most convenient one. In this case, we can rewrite for sufficiently large $M_{Z'}$ (which we are assuming) Eqs. (25) and (26) as

$$|\xi_{Vl}|\lesssim 8.02\left(\frac{M_{Z'}}{1\ \mathrm{TeV}}\right), \quad |\xi_{Al}|\lesssim 1.01\left(\frac{M_{Z'}}{1\mathrm{TeV}}\right). \quad (27)$$

In Figs. 3 and 4 we present our results for the $Z'b\bar{b}$ couplings rescaled by the factor $M_{Z'}/1\ \mathrm{TeV}$. The observability regions of Fig. 3 correspond to a relative Z' effect in $\delta\sigma_b/\sigma_b$ of at least five percent (dark area) and ten percent (gray area). In Fig. 4, numerical effects of five and ten per-

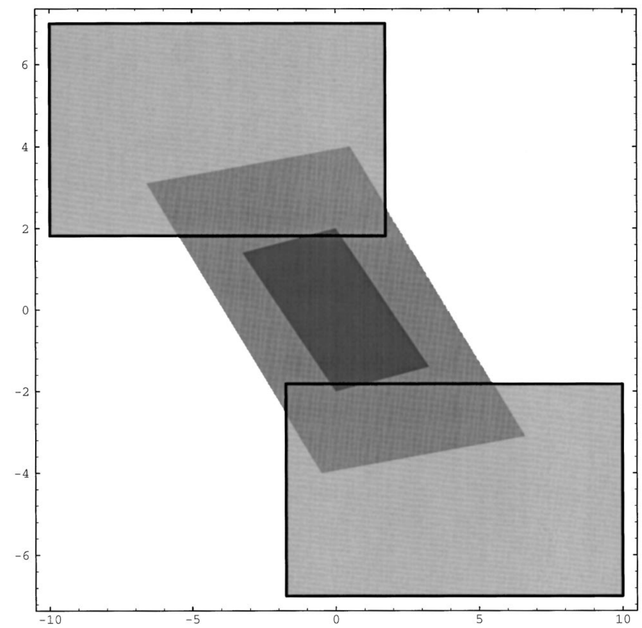

FIG. 3. Domains in $Z'bb$ vector and axial coupling ratios scaled by the factor $(M_{Z'}/1\ \mathrm{TeV})$. Observability limits from σ_b at LEP 2 with two possible accuracies, 5% (central dark), 10% (central gray). Upper and lower rectangles correspond to the more restrictive SLC suggested domains, Eqs. (10) and (11).

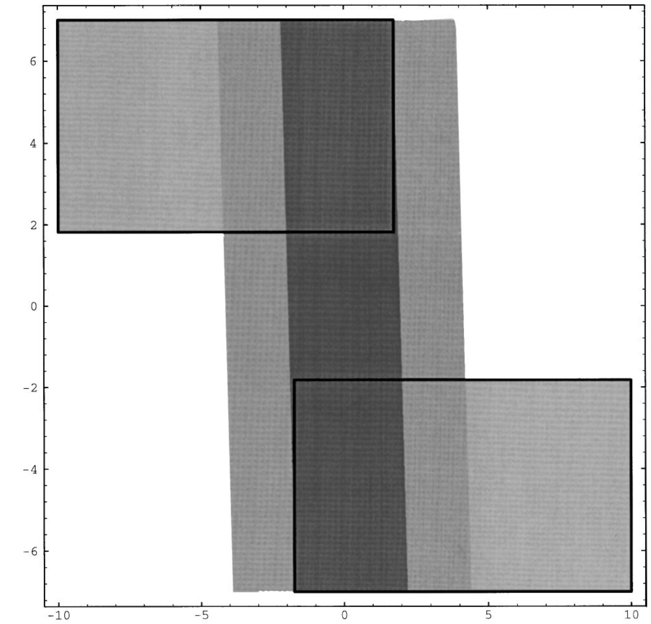

FIG. 4. Domains in $Z'bb$ vector and axial coupling ratios scaled by the factor $(M_{Z'}/1\ \text{TeV})$. Observability limits from A_{FB}^{b} at LEP 2 with two possible accuracies, 5% (central dark), 10% (central gray). Upper and lower rectangles correspond to the more restrictive SLC suggested domains, Eqs. (10) and (11).

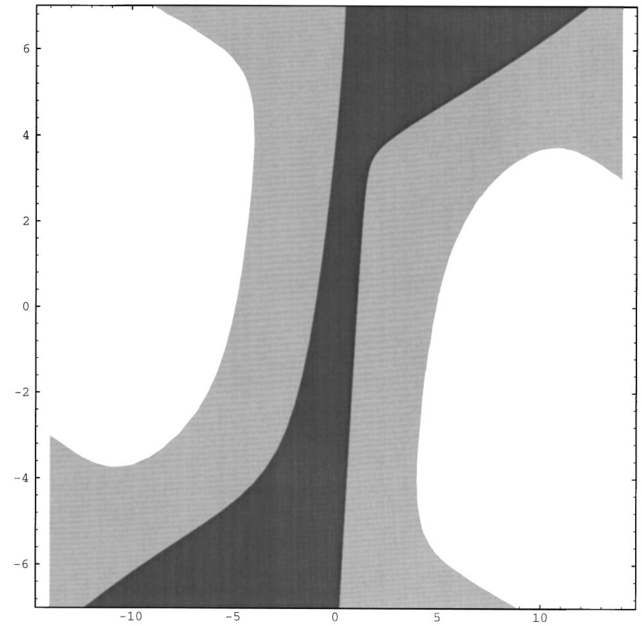

FIG. 5. Domains in $Z'cc$ vector and axial coupling ratios scaled by the factor $(M_{Z'}/1\ \text{TeV})$. Constraint due to the $Z'bb$-$Z'cc$ correlation, Eq. (15) and the observability of a 5% effect on σ_{had} at LEP 2, for $|\xi_{Vb}|<2$, $|\xi_{Ab}|<1.5$ (white domain), for $|\xi_{Vb}|<4$, $|\xi_{Ab}|<3$ (gray + white domain).

cent on the relative forward-backward asymmetry $\delta A_{\text{FB},b}/A_{\text{FB},b}$ are depicted. Following the analysis presented in Table II of Ref. [17], these Z' effects would be visible in the chosen LEP 2 configuration. Note that we have restricted the variation domain of variables in the figures to values that we called ‘‘reasonable’’ in Sec. II, i.e., that contain, in fact, the strip $|\xi_{Ab}|=|\xi_{Vb}|\simeq 3$ suggested by our previous CDF analysis. Note that we did not fix the $M_{Z'}$ value. To be consistent with our preferred CDF choice $M_{Z'}\simeq 800-900$ GeV, we should, in fact, rescale the values of the couplings shown in Figs. 3 and 4 by a (scarcely relevant) 10–20% factor.

As one can see from an inspection of the two figures, values of the couplings lying in the neighborhood of the ‘‘suggested’’ representative set of couplings $|\xi_{Ab}|=|\xi_{Vb}|\simeq 3$ would produce in both cases a large effect. In other words, a hadrophilic Z' with such couplings and mass should not escape indirect experimental detection in the final $b\bar{b}$ channel at LEP 2.

We discuss now the possible Z' effects on the total hadronic cross section σ_{had} (hereafter denoted σ_5) at LEP 2.

For up quarks we use the reduced couplings

$$z_{1c}=\xi_{Ac}\sqrt{\frac{q^2}{M_{Z'}^2-q^2}}, \tag{28}$$

$$z_{2c}=\left(\frac{3v_c}{8s_1c_1}\right)(\xi_{Vc}-\xi_{Ac})\sqrt{\frac{q^2}{M_{Z'}^2-q^2}}, \tag{29}$$

and the quantities corresponding to Eqs. (21) and (22) with the replacement of b by c. The expression of $\sigma_5(q^2)$ is taken from Ref. [18] and we considered the relative shift $\delta\sigma_5/\sigma_5$ expressed in terms of the eight quantities corresponding to Eqs. (21) and (22) for up quarks (c) and down quarks (b). *A priori* they depend on four Z' couplings ξ_{Vb}, ξ_{Ab}, ξ_{Vc}, ξ_{Ac}. We imposed the strong correlation Eq. (15) implied by the absence of effect in Γ_{had}, which practically reduces the freedom to a small domain around a three independent quark parameter case. As above, we kept the leptonic Z' couplings inside the nonobservability domain at LEP 2, Eq. (27).

With these inputs we looked for visible effects in $\sigma_5(q^2)$. The results are shown in Fig. 5, demanding $\delta\sigma_5(q^2)/\sigma_5$ larger than 5%. Following the experimental analysis of Ref. [17], this relative shift would represent a spectacular effect. One sees from this figure that indeed values of couplings $|\xi_{Ab}|=|\xi_{Vb}|=|\xi_{Ac}|=|\xi_{Vc}|\simeq 3$, lying around the suggested CDF ones, would be able to generate a clean and impressive effect both in the $b\bar{b}$ and in the total hadronic observables. This would represent, in our opinion, a spectacular confirmation of the Z' origin of the apparent LEP or SLC and CDF anomalies.

V. CONCLUSIONS

In order to explain possible $b\bar{b}$ and $c\bar{c}$ anomalies observed in LEP 1 and SLC experiments at the Z peak, we used a model-independent description of Z-Z' mixing effects starting with arbitrary mixing angle and $Z'ff$ couplings. With this description, using the full set of LEP 1 or SLC data at the Z peak, we have derived ‘‘suggested’’ Z' couplings to leptons and quarks. The presence of anomalous effects in hadronic channels at the Z peak as opposed to very stringent constraints in leptonic channels would be explained by a Z' more strongly coupled to quarks than to leptons, a hadrophilic Z'. We notice, as a support to our assumption, that the absence of effect in Γ_{had} leads naturally to the prediction of effects with opposite signs in Γ_b and in Γ_c, in agreement with experimental data.

We considered the consequences of this hypothesis for other processes. We have first investigated the observed excess of high mass dijet events at CDF. This excess can be naturally explained by the hadrophilic Z' provided that its couplings to quarks are reasonable, its mass range lies around 800–900 GeV, and its width is relatively large ($\Gamma_{Z'} \simeq 200$ GeV).

We have also examined the observability of hadrophilic Z' effects at LEP 2. We have checked that for leptonic channels, the ''suggested'' strongly constrained leptonic couplings do not particularly motivate Z' effects at LEP 2.

On the contrary, the suggested $Z'b\bar{b}$ couplings would produce large effects in $e^+e^- \to b\bar{b}$ (cross section and forward-backward asymmetry) at LEP 2. Within the assumption that the Z' leptonic couplings are such that no effect is seen in leptonic observables, we have established model-independent observability domains in the space of vector and axial $Z'b\bar{b}$ couplings. These domains correspond to visible effects if the $Z'b\bar{b}$ couplings have a reasonably enhanced magnitude. There is a large overlap with the domains suggested by LEP 1 or SLC and CDF. So the existence of a hadrophilic Z' producing LEP 1 or SLC and CDF anomalies could be confirmed by such measurements at LEP 2.

We have then analyzed what information the total hadronic cross section could bring on $Z'c\bar{c}$ couplings. The interesting feature is the strong correlation imposed by the absence of effect in Γ_{had} at the Z peak. With this constraint included in the analysis of σ_{had} at LEP 2, we have determined the observability domains in the space of vector and axial $Z'c\bar{c}$ couplings. We have established them in correlation with various ranges of ''reasonable'' $Z'b\bar{b}$ couplings. It appears that visible effects would also be present in σ_{had} for similar ''reasonable'' values of $Z'c\bar{c}$ couplings. Should this happen, a deeper theoretical analysis on the origin of such a hadrophilic Z' would become mandatory.

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APPENDIX A: Z-Z' MIXING EFFECTS ON Z PEAK OBSERVABLES

From the analysis of Ref. [11] we can derive the shifts to the SM predictions for the various Z peak observables, partial Z decay widths [$\Gamma_f \equiv \Gamma(Z \to f\bar{f})$], and asymmetry factors A_f. Forgetting systematically terms that are numerically negligible, we get

$$\frac{\delta\Gamma_l}{\Gamma_l} = \delta_\rho^{Z'} + 2\,\theta_M \xi_{Al}, \tag{A1}$$

$$\delta A_l = 3\,\delta_\rho^{Z'} + 2\,\theta_M v_1 \xi_{Vl}, \tag{A2}$$

$$\frac{\delta\Gamma_u}{\Gamma_u} = \frac{8}{5}\delta_\rho^{Z'} + \frac{3}{5}\theta_M[v_u\xi_{Vu} + 3\,\xi_{Au}], \tag{A3}$$

$$\frac{\delta\Gamma_d}{\Gamma_d} = \frac{19}{13}\delta_\rho^{Z'} + \frac{6}{13}\theta_M[2v_d\xi_{Vd} + 3\,\xi_{Ad}], \tag{A4}$$

$$\frac{\delta A_u}{A_u} = \frac{12}{5}\delta_\rho^{Z'} + \frac{4}{5}\theta_M[3v_u\xi_{Vu} - \xi_{Au}], \tag{A5}$$

$$\frac{\delta A_d}{A_d} = \frac{15}{52}\delta_\rho^{Z'} + \frac{5}{26}\theta_M[3v_d\xi_{Vd} - 2\,\xi_{Ad}]. \tag{A6}$$

Assuming universality with respect to the three families of quarks, we also get

$$\frac{\delta\Gamma_h}{\Gamma_h} = \frac{89}{59}\delta_\rho^{Z'} + \frac{3}{59}\theta_M[4v_u\xi_{Vu} + 12\xi_{Au} + 12v_d\xi_{Vd} + 18\xi_{Ad}]. \tag{A7}$$

We can solve this set of equations and express the Z' couplings in terms of θ_M, $\delta_\rho^{Z'}$, and the experimental values for the shifts to the observables. The values that we shall give below will always correspond to the upper bound, Eq. (3), for $|\theta_M|$, with the two possible signs $\eta_M = \pm 1$ and to experimental data taken at two standard deviations.

Lepton couplings are obtained as

$$\xi_{Vl} = \frac{1}{2v_1\theta_M}[\,\delta A_l - 3\,\delta_\rho^{Z'}], \tag{A8}$$

$$\xi_{Al} = \frac{1}{2\,\theta_M}\left[\frac{\delta\Gamma_l}{\Gamma_l} - \delta_\rho^{Z'}\right]. \tag{A9}$$

The experimental measurement $\Gamma_l = 83.93 \pm 0.14$ MeV agrees with the SM prediction involving the ϵ_i parameters which depend on m_t and M_H [13]. Taking $m_t = 180 \pm 12$ GeV and $M_H = 65$–1000 GeV, we get at most a total relative shift $\delta\Gamma_l/\Gamma_l = \pm 3 \times 10^{-3}$. Combining with $\delta_\rho^{Z'}$ given in Eq. (2) and the upper bound for $|\theta_M|$ in Eq. (3), we obtain

$$\eta_M \xi_{Al} \simeq (-0.2 \pm 0.5)\left(\frac{M_{Z'}}{1\ \text{TeV}}\right). \tag{A10}$$

Concerning A_l, there is a disagreement between the LEP average $A_l(\text{LEP}) = 0.147 \pm 0.004$ and the SLC result $A_{LR}(\text{SLD}) = 0.1551 \pm 0.004$, whereas the SM prediction is $A_e(\text{SM}) = 0.144 \pm 0.003$. We then consider both cases. Combining these results with $\delta_\rho^{Z'}$ in Eq. (A8), we obtain

$$\eta_M \xi_{Vl} \simeq (-2.25 \pm 6.25)\left(\frac{M_{Z'}}{1\text{TeV}}\right)(\text{LEP}), \tag{A11}$$

$$\eta_M \xi_{Vl} \simeq (+1.75 \pm 6.25)\left(\frac{M_{Z'}}{1\text{TeV}}\right)(\text{SLC}). \tag{A12}$$

b-quark couplings are obtained from

$$\xi_{Vb}=\frac{1}{30v_b\theta_M}\left[\frac{325}{13}\frac{\delta A_b}{A_b}+\frac{10\delta\Gamma_b}{\Gamma_b}-5\delta_\rho^{Z'}\right], \quad \text{(A13)}$$

$$\xi_{Ab}=\frac{1}{10v_b\theta_M}\left[\frac{-8\,\delta A_b}{A_b}+\frac{5\,\delta\Gamma_b}{\Gamma_b}-5\,\delta_\rho^{Z'}\right]. \quad \text{(A14)}$$

We used for the $b\bar{b}$ anomaly the shift $\delta\Gamma_b/\Gamma_b=+0.03\pm0.008$, but for A_b we have different results from LEP and from SLC to be compared with the SM result $A_b(\mathrm{SM})=0.934$. From A_{FB}^b at LEP, $A_b=0.916\pm0.034$, we obtain $\delta A_b/A_b=-0.02\pm0.04$ and

$$\eta_M\xi_{Vb}\simeq(-3.45\pm20.72)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{LEP}), \quad \text{(A15)}$$

$$\eta_M\xi_{Ab}\simeq(+4.58\pm9.84)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{LEP}). \quad \text{(A16)}$$

Using the SLD result, $A_b=0.841\pm0.053$, we obtain $\delta A_b/A_b=-0.1\pm0.05$ and

$$\eta_M\xi_{Vb}\simeq(-24.24\pm25.98)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{SLC}). \quad \text{(A17)}$$

$$\eta_M\xi_{Ab}\simeq(+14.54\pm12.47)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{SLC}). \quad \text{(A18)}$$

For c-quark couplings the solutions are

$$\xi_{Vc}=\frac{1}{10v_c\theta_M}\left[\frac{15\,\delta A_c}{4A_c}+\frac{5\,\delta\Gamma_c}{3\Gamma_c}-\frac{35}{3}\delta_\rho^{Z'}\right], \quad \text{(A19)}$$

$$\xi_{Ac}=\frac{1}{10\theta_m}\left[-\frac{5\,\delta A_c}{4A_c}+\frac{5\,\delta\Gamma_c}{\Gamma_c}-5\,\delta_\rho^{Z'}\right]. \quad \text{(A20)}$$

Experimental data are less precise than for the b quarks. We have $\delta\Gamma_c/\Gamma_c=-0.1\pm0.05$ but for the asymmetry there is again a discrepancy between LEP and SLC. At LEP, from A_{FB}^c, $A_c=0.67\pm0.06$, whereas at SLC $A_c=0.606\pm0.09$, to be compared with the SM prediction $A_c=0.67\pm0.002$. So with $\delta A_c/A_c=0\pm0.1$ at LEP, one obtains

$$\eta_M\xi_{Vc}\simeq(-6.94\pm26.60)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{LEP}), \quad \text{(A21)}$$

$$\eta_M\xi_{Ac}\simeq(-7.88\pm8.46)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{LEP}), \quad \text{(A22)}$$

whereas with $\delta A_c/A_c=-0.1\pm0.15$ at SLC,

$$\eta_M\xi_{Vc}\simeq(-20.38\pm40.62)\left(\frac{M_{Z'}}{1\,\mathrm{TeV}}\right)(\mathrm{SLC}), \quad \text{(A23)}$$

$$\eta_M\xi_{Ac}\simeq(-6.01\pm9.70)(M_{Z'}/1\ \mathrm{TeV})(\mathrm{SLC}). \quad \text{(A24)}$$

Note that all above results correspond to the upper bound, Eq. (3), for $|\theta_M|$ and to experimental data taken with two standard deviations.

APPENDIX B: DIJET-INVARIANT MASS DISTRIBUTION IN HADRONIC COLLISIONS

The observable that we consider is the dijet-invariant mass (M_{JJ}) distribution:

$$\frac{d\sigma}{dM_{JJ}}=\frac{M_{JJ}^2}{2S}\int_{-\eta}^{\eta}d\eta_1\int_{\eta_{\min}}^{\eta_{\max}}d\eta_2 \times\sum_{ij}\frac{1}{\cosh^2(\eta^\star)}f_i(x_1,M^2)f_j(x_2,M^2)\frac{d\sigma_{ij}}{d\hat{t}}, \quad \text{(B1)}$$

where the $f_i(x,M^2)$ are the parton distribution evoluted at scale M^2; η has been defined in Sec. III, η_1 and η_2 are the pseudorapidities of jets 1 and 2, $\eta_{\min}=\max[-\eta,\ln M_{JJ}/\sqrt{s}-\eta_1]$, $\eta_{\max}=\min[+\eta,-\ln M_{JJ}/\sqrt{s}-\eta_1]$, whereas $d\sigma_{ij}/d\hat{t}$ is the partonic cross section for the subprocess $ij\to2$ jets. The momenta fractions carried by initial partons read

$$x_1=\frac{M_{JJ}}{\sqrt{S}}\exp(\eta_B) \quad \text{(B2)}$$

and

$$x_2=\frac{M_{JJ}}{\sqrt{S}}\exp(-\eta_B) \quad \text{(B3)}$$

where $\eta_B=(\eta_1+\eta_2)/2$.

The expression for the partonic cross sections can be found in [19]. The pure QCD terms for $gg\to gg$, $qg\to qg$, $gg\to q\bar{q}$, $q\bar{q}\to gg$ as well as the QCD and γ, Z, and W exchange contributions to the subprocess $qq\to qq$ are given in Eqs. (A1)–(A6) of [19]. The subprocess $q\bar{q}\to q\bar{q}$ is obtained by performing the crossing $s\leftrightarrow u$. The QCD and W,Z,γ exchange contributions to $qq'\to qq'$ are given by Eqs. (A7)–(A14) of [19]. By crossing $s\leftrightarrow u$, one obtains the $q\bar{q}'\to q\bar{q}'$ subprocess and by crossing $s\leftrightarrow t$ and then $t\leftrightarrow u$ the $q\bar{q}\to q'\bar{q}'$ subprocess. One has also to add the pure W exchange processes involving four distinct quarks: $qq'\to q''q'''$, $q\bar{q}'''\to q''\bar{q}'$, as given by Eqs. (A15) and (A16) of [19].

We have now to add the Z' contribution to these various subprocesses. The $Z'Z'$, $Z'\gamma$, $Z'W$, and $Z'g$ squared matrix elements can be directly obtained from the ZZ, $Z\gamma$, ZW, and Zg ones given in [19], by performing the replacement of g_{Vq} by $\xi_{Vq}g_{Vq}$ and of g_{Aq} by $\xi_{Aq}g_{Aq}$. More precisely one has to replace the C_L and C_R Z couplings to left-handed and right-handed quarks by

$$C'_{q,L}=\frac{1}{2}(g'_{Vq}+g'_{Aq})=\frac{1}{2}(\xi_{Vq}g_{Vq}+\xi_{Aq}g_{Aq}), \quad \text{(B4)}$$

$$C'_{q,R}=\frac{1}{2}(g'_{Vq}-g'_{Aq})=\frac{1}{2}(\xi_{Vq}g_{Vq}-\xi_{Aq}g_{Aq}). \quad \text{(B5)}$$

The contribution due to the interference between the Z and the Z' is the only one that cannot be directly read off from their expressions. We have computed it explicitly. For the subprocess $qq\to qq$, we obtain (using the same notation as in [19])

$$T_{ZZ'}=2\alpha_Z^2\Big\{s^2\Big[\frac{1}{t_Zt_{Z'}}+\frac{1}{u_Zu_{Z'}}+\frac{1}{3}\Big(\frac{1}{t_Zu_{Z'}}+\frac{1}{u_Zt_{Z'}}\Big)\Big]\times(C_{q,L}^2C'^{\,2}_{q,L}+C_{q,R}^2C'^{\,2}_{q,R})+2C_{q,L}C'_{q,L}C_{q,R}C'_{q,R}\Big(\frac{u^2}{t_Zt_{Z'}}+\frac{t^2}{u_Zu_{Z'}}\Big)\Big\}. \tag{B6}$$

For the subprocess $qq'\to qq'$, we obtain

$$T_{ZZ'}=2\alpha_Z^2\Big[\frac{s^2}{t_Zt_{Z'}}(C_{q,L}C'_{q,L}C_{q',L}C'_{q',L}+C_{q,R}C'_{q,R}C_{q',R}C'_{q',R})+\frac{u^2}{t_Zt_{Z'}}(C_{q,L}C'_{q,L}C_{q',R}C'_{q',R}+C_{q,R}C'_{q,R}C_{q',L}C'_{q',L})\Big]. \tag{B7}$$

For subprocesses involving antiquarks the same crossings, as previously given, have to be performed.

The complete expression for $d\sigma_{ij}/d\hat{t}$ is then obtained by summing over the quark flavors (we have not considered top quark production since its decay involves also a W leading to a different topology) and adding to $(d\sigma_{ij}/d\hat{t})(s,t,u)$ the crossed contribution $(d\sigma_{ij}/d\hat{t})(s,u,t)$ due to the indiscernability of jets.

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