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Signature for intermediate bosons in $p\bar{p}$ collisions

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Intermediate vector bosons should be observable in the heavy-quark final states of high-energy $p\bar{p}$ collisions. Large-transverse-momentum like-sign dileptons would then provide a good $W^\pm$ signature. If the mass mixing between neutral B mesons is large, as usually predicted, the associated production of b quarks would give the most important background. In this case also, the Z^0 should be observable in the same channel. The cross sections for these processes are estimated. The $W^\pm$ signal turns out to be significantly large, especially in the forward-backward asymmetry between positive and negative dileptons.

I. INTRODUCTION

The intermediate vector bosons (IVB's) of weak interactions are expected to be discovered in high-energy $p\bar{p}$ colliding beams. The Z^0 peak should show up in the Drell-Yan dilepton cross section in spite of an important background from other sources of charged leptons.[1,2] The search for the charged $W^\pm$ bosons is a more difficult task because of the presence of a neutrino in the leptonic channel.[3] In any case it would be interesting to have additional signatures for IVB's. Their detection in the hadronic channel looks much less promising at first view, since the strong-interaction jet production is expected to exceed W and Z production by several orders of magnitude,[2,4] even if the uncertainties are large in these very-high-energy extrapolated quantum-chromodynamics (QCD) calculations. Therefore, a characteristic is needed which could make an adequate discrimination among hadronic jets in favor of those arising from W/Z decays. The associated production of two heavy-quark jets seems to provide for such a signature.[5] We shall call heavy the b and t quarks and we shall assume the standard six-quark sequential model[6,7] (the generalization to possible heavier quarks is straightforward, but a new up-down quark pair is unlikely in the 20–40 GeV mass region which is relevant to our discussion). To lowest order in QCD, the high-p_T heavy-quark associated production goes through the channels $\bar{u}u, \bar{d}d \to \bar{b}b, \bar{t}t$ and gluon-gluon $\to \bar{b}b, \bar{t}t$, which give only a small fraction of the strong-interaction cross section. Instead, about 25% of the produced W's and Z^0's would decay into heavy quarks. This justifies the choice of signature for IVB's if one is able to identify heavy-quark jets.

Many authors[1,5,8,9] have noticed that heavy quarks should be associated to hadronic jets surrounding fast leptons which originate from the semileptonic decay of the heavy hadrons. This signature for heavy quarks will be exploited in this paper, but we are aware that such a property has not been submitted to experimental verification yet. Then, in order to make quantitative predictions, both the lepton spectra and the branching ratios of the (hadronized) heavy-quark semileptonic decays are needed. There have been several estimates[7,8,10] of these quantities which are not very different either in the assumptions nor in the final results (experimental data for b-quark decays should be available rather soon).

In this paper we shall exploit in a systematic way the suggestion in Ref. 5 to look for like-sign dileptons as an improved signature for the charged IVB. The reason is that in the (direct) semileptonic decay of a b (t) quark a negative (positive) lepton l^- (l^+) is produced. Then, secondary like-sign leptons in the hadronic decay of the $W^\pm$,

$$W^+ \to \begin{cases} t \to l^+X \\ \bar{b} \to l^+X \end{cases}, \quad W^- \to \begin{cases} b \to l^-X \\ \bar{t} \to l^-X \end{cases} \quad (l^\pm = e^\pm, \mu^\pm),$$

should be the most energetic, while in the associated production of heavy quarks through either strong interactions or Z^0 production, the most energetic dileptons have opposite signs, corresponding to the decays $t \to l^+X$ ($\bar{t} \to l^-X$), $b \to l^-X$ ($\bar{b} \to l^+X$). In Ref. 5 the like-sign dilepton cross sections in high-energy $p\bar{p}$ collisions have been estimated. It has been assumed there that in the case of $t\bar{t}$ and $b\bar{b}$ final states, the like-sign dileptons arise from the cascade decay (i.e., $t \to b \cdots \to l^- \cdots$, $b \to c \cdots \to l^+ \cdots$) of either quark, which produce less energetic leptons. The results in Ref. 5 show a clear W bump in the invariant-mass distribution of the two jets surrounding the leptons. The strong-interaction background seems very efficiently suppressed by requiring the lepton energies to be higher than some value to be chosen around 5 GeV. These results are encouraging enough to deserve a more systematic study in several aspects. First of all, it is now well established that the t-quark threshold is beyond the energy range of the existent e^+e^- colliding rings. For such large masses of the t quark, the usual estimates[7,8,11,12] predict a large mass mixing between the neutral B mesons. In this case, a wrong-sign lepton could be directly produced from an initial b quark through B-$\bar{B}$ mixing. Like-sign dileptons would then arise from $b\bar{b}$ pairs because of mass mixing, which would not be suppressed by the cut in the lepton energy which has been exploited in Ref. 5. Here we investigate this question and, at the same time, we improve the calculations of Ref. 5 in many respects. Thus, scaling violations are taken into account in both the quark and the gluon structure functions. Also, heavy-quark fragmentation functions replace the trivial δ function, $\delta(1-z)$, which has been used in Ref. 5. The mass ratios m_c/m_b and m_b/m_t are included in the determination of the leptonic spectra in b and t decays. Finally, we introduce a cut on the transverse momenta (p_T) of the triggering leptons instead of a minimum value for the lepton energies. In this way, the important background from forward and backward gluon-gluon annihilation into $b\bar{b}$ is strongly reduced.

An interesting consequence of the B-$\bar{B}$ mixing is the proportional amount of like-sign dileptons from the decay of produced Z^0's into $b\bar{b}$ pairs. Therefore, both the $W^\pm$ and the Z^0 bumps would be observable in the mass distribution of the heavy-quark jets.

An elegant way to pick up the charged-$W^\pm$ contribution is by looking for the asymmetry[5] in rapidity between l^+l^+ and l^-l^- dileptons. Indeed, it is an experimental fact[13] that u quarks are more energetic than d quarks inside the proton. Therefore, a u from the p together with a $\bar{d}$ from the $\bar{p}$ mostly produce W^+'s in the direction of the p. Conversely, most of the W^-'s come out along the $\bar{p}$ beam. This introduces an asymmetry between the rapidity distributions of l^+l^+ events (from W^+) and l^-l^- events (from W^-). Strong interactions and Z^0 production do not contribute to this asymmetry, which then vanishes everywhere but around the W mass. (Notice that this asymmetry is not due to C violation in W decay, whose effects are lost since we consider like-sign dileptons.)

II. RESULTS

All of the quantities discussed below, and illustrated in the figures, are for like-sign dileptons produced in $p\bar{p}$ collisions around $\sqrt{s}=500$ GeV. We assume that the invariant mass (M) of the whole system of large-p_T particles is measured in each event (M is then the center-of-mass energy of the produced heavy-quark pair). To select the heavy-quark final states, both lepton transverse momenta are required to be larger than some minimum value, denoted by $p_T^{\min}$.

The production of heavy quarks in $p\bar{p}$ collisions has been estimated in the parton model. We need structure functions at $Q^2 \sim M_W^2$, much higher than the Q^2 values in currently available data. We have chosen the Q^2-dependent parametrization of Buras and Gaemers[14] as fitted by the CERN-Dortmund-Heidelburg-Saclay (CDHS) experiment.[15] Although these structure functions do not take into account higher-order QCD effects and are valid in a limited x region, they can be considered good enough for our purposes. For the gluon distribution we assume the usual form, $xg(x)=0.5(1+n_g)(1-x)^{n_g}$, but the power $n_g(Q^2)$ is poorly known.[16] By assuming $n_g=5$ at $Q^2\sim 2$ GeV^2, Buras and Gaemers[14] arrive at a value $n_g\approx 20$ at $Q^2\sim M_W^2$. In the numerical results presented here we have taken $n_g=15$ in order to avoid underestimating the gluon contribution. Other reasonable choices of n_g will modify the gluon-gluon annihilation contribution to the M distributions presented below, but for $M\sim M_W$ and $s\approx 500$ GeV, the effects are not very important.

In the calculation of the heavy-quark production cross section at the parton level we have just included the lowest-order contributions from (a) QCD diagrams[4,17] and (b) Weinberg-Salam sequential model with three families and $\sin^2\theta_W=0.23$ for weak interactions. Nonleading QCD corrections have been left out of account, so that, for instance, the transverse momenta of the produced IVB are neglected. It looks plausible that QCD radiative corrections would mostly affect in a similar way both the strong and the weak contributions, in which case our results would remain at least qualitatively unaltered.

Then one has to describe the hadronization of the heavy quarks into heavy hadrons. We have used the (Q^2-independent fragmentation functions of Ref. 8 which try to take account of the quark masses. For $Q^2\sim M_W^2 \gg m_b^2$, these flavor-conserving fragmentation functions could eventually become broader as a consequence of scaling violations. But our results are rather independent of this fact since a good approximation is even obtained with a δ function,

$$D_{Q\to H}(z)=\delta(z-z_Q),$$

$$z_Q=(z_{Q\to H})_{\max}=M_H/(M_H+2).$$

Then a change $z_Q\to z'_Q$ essentially corresponds to rescale the cut in the lepton transverse momenta, $p_T^{\min}\to(z'_Q/z_Q)p_T^{\min}$. The lepton spectra in the semileptonic heavy-hadron decay have been calculated in the usual parton picture[7-11] (i.e., the free-heavy-quark-decay approximation) without the QCD corrections which are expected to be small for hadrons with b and t constituents. In the Appendix, we present the general expressions of the cross sections at the parton level for the production of heavy-quark jets including a like-sign dilepton with the lepton transverse momenta larger than $p_T^{\min}$.

For convenience, the cross sections are normalized to the product of inclusive semileptonic branching ratios, $B^2 \equiv B(b \to l^- \cdots)B(t \to l^+ \cdots)$. Notice that, in view of the selection of high-p_T leptons, only the branching ratios for direct semileptonic decays are relevant to our calculations. With this normalization the strong-interaction and Z^0 contributions, which involve $\bar{B}-B$ mixing, will be proportional to the ratio: $R = B(b \to l^+ \cdots)/B(t \to l^- \cdots)$. The values of B^2 and R will depend on the t-quark mass (especially for R) as well as on the generalized Cabibbo angles.[7-11] If one adopts the standard assumptions in the calculation of the B-$\bar{B}$ mixing and the heavy-quark branching ratios[7] together with the phenomenological constraints[7,18] on the parameters (m_t and Cabibbo angles), one gets the predictions for direct semileptonic decay ($l = e + \mu$):

$$B(b \to l^- \cdots) = 28\text{–}30\%\,,$$

$$B(t \to l^+ \cdots) = 24\text{–}26\%\,.$$

If one also assumes $B(b \to c \cdots) \geqslant B(b \to u \cdots)$, it follows that

$$0.1 \lesssim R = \frac{B(b \to l^+ \cdots)}{B(t \to l^+ \cdots)} \lesssim 0.4\,.$$

In the presentation of our result we take $R = 0.4$ so that, from the point of view of the mass mixing, the contributions from strong and Z^0 interactions shown in the figures below are upper bounds.

The predicted cross section for l^+l^+ or l^-l^- events with $M > 50$ GeV are shown in Fig. 1, as a function of the cut $p_T^{\min}$ on the lepton transverse momenta. As already anticipated, this cut reduces the large yields of $gg \to b\bar{b}$ in the forward and backward directions. Since the like-sign dileptons arising from the cascade decay of a heavy quark are strongly suppressed by this cut in p_T, as already shown in Ref. 5, their contributions are not included in the figures.

The various cross sections for the production of a l^+l^+ (l^-l^-) pair, associated to a hadronic system of mass M, are given in Fig. 2. The overall cross sections are presented in Fig. 3 for several values of $p_T^{\min}$. These estimates indicate that even in the presence of a large B-$\bar{B}$ mixing (its maximum value being assumed in the figures), the $W^\pm$ bump should still show up in the hadronic mass distribution of like-sign dilepton events with a reasonable choice of $p_T^{\min}$. As a consequence of a large B-$\bar{B}$ mixing, the Z^0 bump would also appear beside the $W^\pm$ bump.

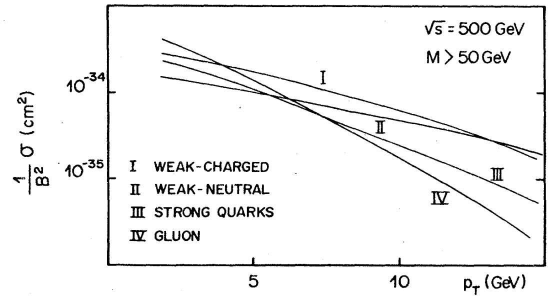

FIG. 1. Cross sections for $p\bar{p} \to l^+l^+X$, integrated over the invariant mass of the hadronic jets $M > 50$ GeV, and over both the lepton transverse momenta, $p_T > p_T^{\min}$, versus $p_T^{\min}$. The following contributions are separately shown: (I) $W^\pm$ pole, (II) Z^0 pole, (III) strong-interaction $q\bar{q}$ annihilation, and (IV) gluon-gluon annihilation. The results are given in units of the product B^2 of semileptonic branching ratios and the contributions (II–IV) are plotted for their maximum value, $R = 0.4$ (see text).

An interesting way of disentangling the $W^\pm$ pole from the Z^0 pole and from the strong-interaction background is to look for the asymmetry in rapidity between positive and negative dileptons.[5] The variable y is defined here as the rapidity of the final two-jet system in the $p\bar{p}$ center-of-mass frame. By defining N^{++} (N^{--}) as the number of l^+l^+ (l^-l^-) events for a given rapidity y and an invariant two-jet mass M, the asymmetry is defined as

$$A(y,M) = \frac{N^{++}(y,M) - N^{--}(y,M)}{N^{++}(y,M) + N^{--}(y,M)} = -A(-y,M)\,.$$

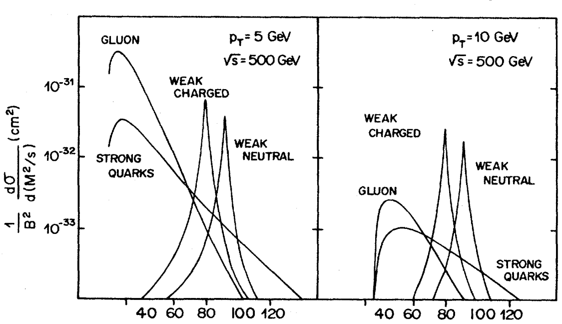

FIG. 2. Distribution of the ($p\bar{p} \to l^+l^+X$) cross section in the hadronic mass M (= center-of-mass energy of the two-jet final system). The various contributions are as in Fig. 1, integrated over lepton transverse momenta $> p_T^{\min}$, with $p_T^{\min} =$ 5 and 10 GeV, respectively, and with $R = 0.4$ (see text). Notice the suppression of the strong-interaction contributions when $p_T^{\min}$ increases.

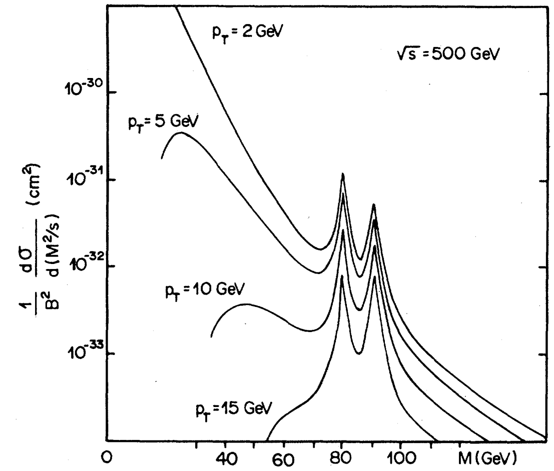

FIG. 3. Overall cross section, obtained by adding together the contributions in Fig. 2, versus M, for several values of $p_T^{\min}$ ($R=0.4$).

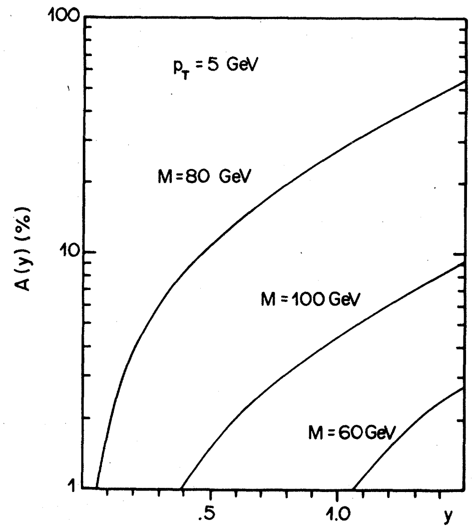

FIG. 4. Asymmetry $A(y) = -A(-y)$ between positive (l^+l^+) and negative (l^-l^-) dileptons in $p\bar{p}$ collisions at $\sqrt{s} = 500$ GeV, versus the rapidity y of the final hadronic jets in the $p\bar{p}$ center-of-mass frame. The asymmetry is large around $M \approx M_W$. The curves are obtained for $p_T^{\min} = 5$ GeV and $R = 0.4$ (see text).

Only the $W^\pm$ production contributes to the difference in the numerator, so that $A(y, M)$ vanishes outside the W bump. The predicted y dependence of the asymmetry is presented in Fig. 4, at $M = M_W$ and, for comparison, for M above and below the W peak. A better way to visualize this asymmetry is by adding together the events with $y > y_0$, where $y_0 \sim 0.5$, and by plotting the asymmetry versus the invariant mass M. This is shown in Fig. 5, with a neat W bump. For $p_T^{\min} \geq 2$ GeV (such that cascade decays are well excluded) the asymmetries in Figs. 4 and 5 have only a small dependence on the cut $p_T^{\min}$.

III. CONCLUDING REMARKS

We conclude that, in principle, IVB's could be observed in the hadronic final states of $p\bar{p}$ colliders by requiring high-p_T like-sign dileptons, even if the B-$\bar{B}$ mixing turns out to be large. Furthermore, the $W^\pm$ bump could be isolated by measuring the asymmetry in rapidity between positive and negative dileptons. It is clear that this study can also be extended to opposite-sign dileptons, but the strong-interaction background would become more important. By asking for high-p_T dileptons one selects the heavy-quark decay modes of the IVB. It would be interesting to study the properties of these particular hadronic jets, such as charge (and strangeness) distributions and correlations,[4] multilepton distributions and rates,[7,19] and acoplanarities of the dileptons.

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APPENDIX

We write here an explicit expression of the cross section for the process

$$aa' \to Q_1\bar{Q}_2 \quad \begin{matrix} \nearrow H_1 \ldots \to l_1 \ldots , \\ \\ \searrow \bar{H}_2 \ldots \to l_2 \ldots , \end{matrix} \tag{A1}$$

where a and a' are initial partons and Q_1 and $\bar{Q}_2$ are the produced heavy quarks which hadronize into H_1, $\bar{H}_2$. The semileptonic decay of the heavy hadrons then produce two leptons, l_1, l_2. We define M as the center-of-mass energy of the initial partons (or the final $Q_1\bar{Q}_2$ pair). We assume a common cut $p_T^{\min}$ on the transverse momenta p_{T1}, p_{T2} of the leptons, so that the cross sections are integrated over $p_{T1}, p_{T2} \geq p_T^{\min}$. In the results below, we neglect the angle between l_1 (l_2) and Q_1 ($\bar{Q}_2$) since the heavy quarks are highly relativistic and the angular dependences will be integrated out. [This collinear approximation could seem ore questionable for W production when Q_1 (or $\bar{Q}_2$) is a t ($\bar{t}$) quark, but in this case the noncollinearity of the lepton, due to the relatively large m_t mass, will not greatly affect the final-lepton angular distribution, which is rather flat.]

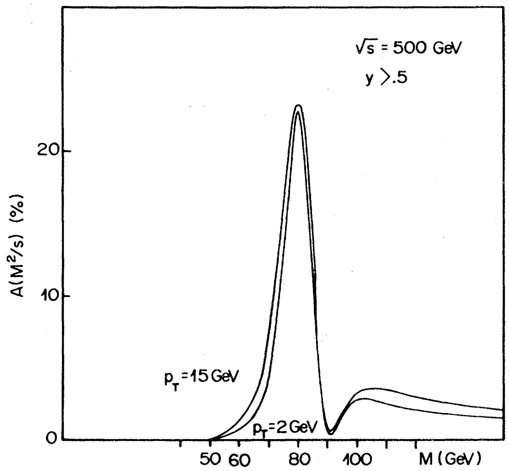

FIG. 5. Asymmetry between positive and negative dileptons integrated over $y>0.5$, versus M (hadronic invariant mass), in $p\bar{p}$ collisions at $\sqrt{s}=500$ GeV. Notice that for $p_T^{\min} \geqslant 2$ GeV the results are almost independent of $p_T^{\min}$. The figure corresponds to $R=0.4$: the peak becomes slightly higher and broader for smaller values of R (see text).

We define collinear momenta $p^+ = E + p_\parallel$ and for each inclusive transition $a \to b$ we introduce the longitudinal fraction $z_{b/a} = p_b^+/p_a^+$, as well as the fragmentation function $D_{b/a}(z_{b/a})$, normalized to 1. The cross section for the process (A1), such that $p_{T1}, p_{T2} \geqslant p_T^{\min}$, is given by

$$\sigma(M, p_T^{\min}) = \int_{\xi_{\min}}^{1} d\xi\, \xi^4 \left(\frac{d\hat{\sigma}^{aa' \to Q_1 \bar{Q}_2}(M,\xi)}{d\xi}\right) \times R_{l_1/Q_1}\left(\frac{p_T^{\min}}{\mu_1 \xi}\right) R_{l_2/\bar{Q}_2}\left(\frac{p_T^{\min}}{\mu_2 \xi}\right), \qquad \text{(A2)}$$

where ξ is $|\sin\theta^*|$, θ^* being the angular direction of Q_1 (or $\bar{Q}_2$) in the initial parton center-of-mass frame, and

$$\mu_1 \approx \frac{M}{2}\,, \quad \mu_2 \approx \frac{M}{2}\left(1 - \frac{m_t^2}{M^2}\right), \quad \text{if } Q_1 = t,\quad Q_2 = b$$

(or vice versa), (A3)

$$\mu_1 = \mu_2 = \frac{M}{2}\,, \quad \text{if } Q_1 = Q_2 = b\,.$$

The leptonic distributions $R_{l/Q}(x)$ are defined by

$$R_{l/Q}(x) = \int_x^{\xi_{\max}} d\xi \int_\xi^1 \frac{dz}{z}\, D_{l/H}\left(\frac{\xi}{z}\right) D_{H/Q}(z)\,. \qquad \text{(A4)}$$

If the flavor-conserving $Q \to H$ fragmentation function is approximated by a δ function, $D_{H/Q}(z) \approx \delta(z - z_Q)$ $(z_Q < 1)$, one obtains by using the leptonic spectra which are given, e.g., in Ref. 8, the expressions

$$\begin{aligned} R_{l^+/t}(z_t x) &= 1 + [12r^2(1-x)\ln(1-x) - 2x(1 - 6r - 3r^2 + 2r^3 - 6r^2 \ln r) - 6r^2x^2 + 2(1-2r)x^3 - x^4]/\mathfrak{F}(r) \quad [x \leqslant (1-r)] \\ &= 0 \quad [x \geqslant (1-r)]\,, \\ R_{l^-/b}(z_b x) &= 1 + \frac{1}{\mathfrak{F}(r')}\Big[12r'^2 \ln(1-x) + 2r'^2(r'-3)x\ln(1-x) - 2r'^3(1-x)^{-1} + 4r'^2 - 2r'^3 \\ &\qquad - x\left(\frac{5}{3} - 9r' - 3r'^2 + \frac{r'^3}{3} - 2r'^2(r'-3)\ln r'\right) + (1-r')x^3 - \frac{x^4}{3}\Big] \quad [x \leqslant (1-r')] \\ &= 0 \quad [x \geqslant (1-r')]\,, \qquad \text{(A5)} \\ \mathfrak{F}(r) &= 1 - 8r + 8r^3 - r^4 - 12r^2 \ln r, \quad r = (m_b^2/m_t^2)\,, \quad r' = (m_c^2/m_b^2) \end{aligned}$$

(in the limit $r, r' \to 0$, these expressions reproduce those in Ref. 5. In this case, the parameter $\xi_{\min}$ in (A2) becomes $\xi_{\min} = p_T^{\min}/\min[(1-r_i)z_i\mu_i]$, $i = 1, 2$. Now, more general fragmentation functions $D_{H/Q}(z_Q)$ can be easily introduced as weight functions of the results in (A5).

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