

Measurement of Time-Dependent CP Asymmetries and Constraints on $\sin(2\beta + \gamma)$ with Partial Reconstruction of $B^0 \rightarrow D^{*\mp} \pi^\pm$ Decays

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We present a measurement of time-dependent CP -violating asymmetries in decays of neutral B mesons to the final states $D^{*\mp}\pi^\pm$, using approximately 82×10^6 $B\bar{B}$ events recorded by the $BABAR$ experiment at the PEP-II e^+e^- storage ring. Events containing these decays are selected with a partial

reconstruction technique, in which only the high-momentum π^\pm from the B decay and the low-momentum π^\mp from the $D^{*\mp}$ decay are used. We measure the amplitude of the asymmetry to be $-0.063 \pm 0.024(\text{stat}) \pm 0.014(\text{syst})$ and compute bounds on $|\sin(2\beta + \gamma)|$.

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The Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1] gives an explanation of CP violation and is under experimental investigation aimed at constraining its parameters. A crucial part of this program is the measurement of the angle $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ of the unitarity triangle related to the CKM matrix. The decay modes $B^0 \rightarrow D^{*\mp}\pi^\pm$ have been proposed for use in measurements of $\sin(2\beta + \gamma)$ [2], where $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$ is well measured [3]. In the standard model the decays $B^0 \rightarrow D^{*+}\pi^-$ and $\bar{B}^0 \rightarrow D^{*+}\pi^-$ proceed through the $\bar{b} \rightarrow \bar{u}cd$ and $b \rightarrow c\bar{u}d$ amplitudes A_u and A_c . The relative weak phase between the two amplitudes in the usual Wolfenstein convention [4] is γ . When combined with $B^0\bar{B}^0$ mixing, this yields a weak phase difference of $2\beta + \gamma$ between the interfering amplitudes.

The decay rate distribution for $B \rightarrow D^{*\pm}\pi^\mp$ is

$$\mathcal{P}_\eta^\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \times [1 \mp S^\zeta \sin(\Delta m \Delta t) \mp \eta C \cos(\Delta m \Delta t)], \quad (1)$$

where τ is the B^0 lifetime averaged over the two mass eigenstates, Δm is the $B^0 - \bar{B}^0$ mixing frequency, and Δt is the difference between the time of the $B \rightarrow D^{*\pm}\pi^\mp$ (B_{rec}) decay and the decay of the other B (B_{tag}) in the event. The upper (lower) sign in Eq. (1) indicates the flavor of the B_{tag} as a B^0 (\bar{B}^0), while $\eta = +1$ (-1) and $\zeta = +$ ($-$) for the B_{rec} final state $D^{*-}\pi^+$ ($D^{*+}\pi^-$). The parameters C and S^\pm are

$$C \equiv \frac{1 - r^{*2}}{1 + r^{*2}}, \quad S^\pm \equiv \frac{2r^*}{1 + r^{*2}} \sin(2\beta + \gamma \pm \delta^*). \quad (2)$$

Here δ^* is the strong phase difference between A_u and A_c and $r^* = |A_u/A_c|$. Since A_u is doubly CKM suppressed with respect to A_c , one expects $r^* \sim 2\%$.

In this Letter we report a study of CP -violating asymmetries in $B^0 \rightarrow D^{*\mp}\pi^\pm$ decays using the technique of partial reconstruction, which allows us to analyze a large sample of signal events. Additional information about the techniques used in this analysis appears in Refs. [5,6].

The data used in this analysis were recorded with the *BABAR* detector at the PEP-II storage ring, and consist of 76.4 fb^{-1} collected on the $\Upsilon(4S)$ resonance (on-resonance sample), and 7.6 fb^{-1} collected at an e^+e^- center-of-mass (c.m.) energy approximately 40 MeV below the resonance peak (off-resonance sample). Samples of simulated Monte Carlo (MC) events with an equivalent luminosity 3 to 4 times larger than the data are analyzed

through the same analysis chain. The *BABAR* detector is described in detail in Ref. [7].

In the partial reconstruction of a $B^0 \rightarrow D^{*\mp}\pi^\pm$ candidate (B_{rec}), only the hard (high-momentum) pion track π_h from the B decay and the soft (low-momentum) pion track π_s from the decay $D^{*-} \rightarrow \bar{D}^0\pi_s^-$ are used. Applying kinematic constraints consistent with the signal decay mode, we calculate the four momentum of the D , obtaining its flight direction to within a few degrees and its invariant mass m_{miss} [6]. Signal events peak in the m_{miss} distribution at the nominal D^0 mass M_D^0 with a rms of $3 \text{ MeV}/c^2$.

In addition to $B^0 \rightarrow D^{*\mp}\pi^\pm$ events, the selected event sample contains the following kinds of events: $B^0 \rightarrow D^{*\mp}\rho^\pm$; $B\bar{B}$ background peaking in m_{miss} , composed of pairs of tracks coming from the same B meson, with the π_s originating from a charged D^* decay, excluding $B^0 \rightarrow D^{*\mp}\rho^\pm$ decays; combinatoric $B\bar{B}$ background, defined as all remaining $B\bar{B}$ background events; and continuum $e^+e^- \rightarrow q\bar{q}$, where q represents a $u, d, s,$ or c quark. We suppress the combinatoric background with selection criteria based on the event shape and the D^* helicity angle. We reject π_h candidates that are identified as leptons or kaons. All candidates must satisfy $1.81 < m_{\text{miss}} < 1.88 \text{ GeV}/c^2$. Multiple candidates are found in 5% of the events. In these instances, only the candidate with the m_{miss} value closest to M_{D^0} is used.

To perform this analysis, Δt and the flavor of the B_{tag} must be determined. We measure Δt using $\Delta t = (z_{\text{rec}} - z_{\text{tag}})/(\gamma\beta c)$, where z_{rec} (z_{tag}) is the decay position of the B_{rec} (B_{tag}) along the beam axis (z) in the laboratory frame, and the e^+e^- boost parameter $\gamma\beta$ is continuously calculated from the beam energies. To find z_{rec} we fit the π_h track with a beam spot constraint in the plane perpendicular to the beams. We obtain z_{tag} from a beam-spot-constrained vertex fit of all other tracks in the event, excluding all tracks within 1 rad of the D momentum in the CM frame. The Δt error $\sigma_{\Delta t}$ is calculated from the results of the z_{rec} and z_{tag} vertex fits.

We tag the flavor of the B_{tag} using lepton or kaon candidates. The lepton CM momentum is required to be greater than $1.1 \text{ GeV}/c$ to suppress ‘‘cascade’’ leptons that originate from charm decays. If several flavor-tagging tracks are present in either the lepton or kaon tagging category, the only track of that category used for tagging is the one with the largest value of θ_T , the CM angle between the track momentum and the D momentum. The tagging track must satisfy $\cos\theta_T < C_T$, where $C_T = 0.75$ ($C_T = 0.50$) for leptons (kaons), to minimize the impact of tracks originating from the D decay. If both

a lepton and a kaon satisfy this requirement, the event is tagged with the lepton only.

The analysis is carried out with a series of unbinned maximum-likelihood fits, performed simultaneously on the on- and off-resonance data samples and independently for the lepton-tagged and kaon-tagged events. The probability density function (PDF) depends on the variables m_{miss} , Δt , $\sigma_{\Delta t}$, F , s_t , and s_m , where F is a Fisher discriminant formed from 15 event-shape variables that provide discrimination against continuum events [6], $s_t = 1$ (-1) when the B_{tag} is identified as a B^0 (\bar{B}^0), and $s_m = 1$ (-1) for “unmixed” (“mixed”) events. An event is labeled unmixed if the π_h is a π^- (π^+) and the B_{tag} is a B^0 (\bar{B}^0), and mixed otherwise.

The PDF for on-resonance data is a sum over the PDFs of the different event types, $\mathcal{P} = \sum_i f_i \mathcal{P}_i$, where the index $i = \{D^* \pi, D^* \rho, \text{peak, comb, } q\bar{q}\}$ indicates one of the event types described above, f_i is the relative fraction of events of type i in the data sample, and \mathcal{P}_i is the PDF for these events. The PDF for off-resonance data is $\mathcal{P}_{q\bar{q}}$. The parameter values for \mathcal{P}_i are different for each event type, unless indicated otherwise. Each \mathcal{P}_i is a product of the PDFs $\mathcal{M}_i(m_{\text{miss}})$, $\mathcal{F}_i(F)$, and $\mathcal{T}'_i(\Delta t, \sigma_{\Delta t}, s_t, s_m)$, defined below.

The m_{miss} PDF \mathcal{M}_i for each event type i is the sum of a bifurcated Gaussian $B(x) \propto \exp[-(x - \mu)^2/2\sigma_x^2]$, where $\sigma_x = \sigma_L(\sigma_R)$ for $x \leq \mu$ ($x > \mu$), and an ARGUS function [6]. The Fisher PDF \mathcal{F}_i is a bifurcated Gaussian. The parameter values for $\mathcal{F}_{D^* \pi}$, $\mathcal{F}_{D^* \rho}$, $\mathcal{F}_{\text{peak}}$, and $\mathcal{F}_{\text{comb}}$ are identical.

The Δt PDF, $\mathcal{T}'_i = \int d\Delta t_{\text{tr}} \mathcal{T}_i(\Delta t_{\text{tr}}, s_t, s_m) \mathcal{R}_i(\Delta t - \Delta t_{\text{tr}}, \sigma_{\Delta t})$, is a convolution, where \mathcal{T}_i is the distribution of the true decay-time difference Δt_{tr} and \mathcal{R}_i is a three-Gaussian resolution function that accounts for detector resolution and effects such as systematic offsets in the measured positions of vertices [6].

The PDF $\mathcal{T}_{D^* \pi}(\Delta t_{\text{tr}}, s_t, s_m)$ for signal events corresponds to Eq. (1) with $O(r^2)$ terms neglected, and with additional parameters that account for imperfect flavor-tagging:

$$\mathcal{T}_{D^* \pi} = \frac{e^{-|\Delta t_{\text{tr}}|/\tau}}{4\tau} \left\{ \alpha(1 + s_m \kappa) + (1 - \alpha)[(1 - s_t \Delta \omega) + s_m(1 - 2\omega) \cos(\Delta m \Delta t_{\text{tr}}) - S \sin(\Delta m \Delta t_{\text{tr}})] \right\}, \quad (3)$$

where the mistag rate ω is the probability to misidentify the flavor of the B_{tag} averaged over B^0 and \bar{B}^0 , $\Delta \omega$ is the B^0 mistag rate minus the \bar{B}^0 mistag rate, α is the probability that the tagging track is a daughter of the signal D meson, $\kappa = 1 - 2\rho$, where ρ is the probability that the daughter of the D results in a mixed flavor event, and $S = s_t(1 - 2\omega)S^\zeta$.

The B_{tag} may undergo a $b \rightarrow u\bar{c}d$ decay, and the kaon produced in the subsequent charm decay might be used for tagging. This effect is not described by Eq. (3). To

account for it, we use a different parametrization [8] for kaon tags, in which the coefficient of the $\sin(\Delta m \Delta t_{\text{tr}})$ term $S = [(1 - 2\omega)(s_t a + s_m c) + s_t s_m b(1 - s_t \Delta \omega)]$, where $a \equiv 2r^* \sin(2\beta + \gamma) \cos \delta^*$, $b \equiv 2r' \sin(2\beta + \gamma) \cos \delta'$, and $c \equiv 2 \cos(2\beta + \gamma)(r^* \sin \delta^* - r' \sin \delta')$. Here r' (δ') is the effective magnitude ratio (strong phase difference) between the $b \rightarrow u\bar{c}d$ and $b \rightarrow c\bar{u}d$ amplitudes in the tagside decays. This parametrization is good to first order in r^* and r' .

The CP parameters (S^\pm , a , b , and c) of $\mathcal{T}_{D^* \rho}$, T_{peak} , and T_{comb} are set to 0 and are later varied to evaluate systematic uncertainties. Otherwise, the PDF $\mathcal{T}'_{D^* \rho}$ for $B^0 \rightarrow D^{*\mp} \rho^\pm$ events is taken to be identical to $\mathcal{T}'_{D^* \pi}$. The $B\bar{B}$ background PDFs $\mathcal{T}_{\text{comb}}$ and $\mathcal{T}_{\text{peak}}$ have the same functional form as Eq. (3), with independent parameter values. The parameters of $\mathcal{T}'_{\text{peak}}$ are determined from a fit to the MC simulation sample. The PDF $\mathcal{T}_{q\bar{q}}$ for the continuum background is the sum of two components, one with a finite lifetime and one with zero lifetime.

The analysis proceeds in three steps:

(1) The parameters of \mathcal{M}_i and the value of $f_{D^* \pi}/(f_{D^* \pi} + f_{D^* \rho})$ are obtained from the MC simulation with the branching fractions $\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+)$ and $\mathcal{B}(B^0 \rightarrow D^{*-} \rho^+)$ from Ref. [9]. Using these parameter values, we fit the data with $\mathcal{P}_i = \mathcal{M}_i(m_{\text{miss}}) \mathcal{F}_i(F)$, to determine $f_{q\bar{q}}$, f_{comb} , $f_{D^* \rho} + f_{D^* \pi}$, the parameters of $\mathcal{M}_{q\bar{q}}$, and the parameters of \mathcal{F}_i for both continuum and $B\bar{B}$ events. This fit yields 6400 ± 130 ($25\,160 \pm 320$) signal events for the lepton- (kaon-) tagged sample. The fit results for the $\mathcal{M}_i(m_{\text{miss}})$ PDFs are shown in Fig. 1. The fit is repeated to determine the signal yields requiring first $\cos \theta_T < C_T$ and then $\cos \theta_T > C_T$, in order to measure the values of α and ρ . We find $\alpha = (1.0 \pm 0.1)\%$ [$(5.6 \pm 0.2)\%$] for lepton- (kaon-) tagged events.

(2) We fit the events in the sideband $1.81 < m_{\text{miss}} < 1.84 \text{ GeV}/c^2$ to obtain the parameters of $\mathcal{T}'_{\text{comb}}$.

(3) Using the parameter values obtained in the previous steps, we fit the data in the signal region

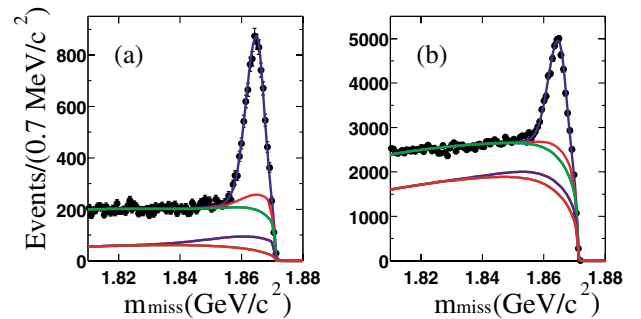


FIG. 1 (color online). The m_{miss} distributions for (a) lepton-tagged and (b) kaon-tagged events. The curves show, from bottom to top, the cumulative contributions of continuum, peaking $B\bar{B}$, combinatoric $B\bar{B}$, $B^0 \rightarrow D^{*+} \rho^-$, and $B^0 \rightarrow D^{*+} \pi^-$ events.

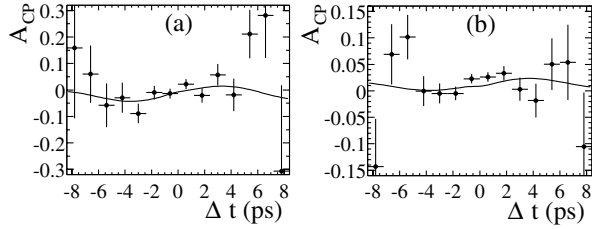


FIG. 2. The asymmetry \mathcal{A}_{CP} for (a) lepton-tagged and (b) kaon-tagged events. The curves show the projection of the PDF from the unbinned fit.

$1.845 < m_{\text{miss}} < 1.880 \text{ GeV}/c^2$, determining the parameters of $\mathcal{T}'_{D^*\pi}$ and $\mathcal{T}'_{q\bar{q}}$.

We use the MC samples to verify the entire analysis procedure, as well as the validity of using the same non- CP parameters in $\mathcal{T}'_{D^*\rho}$ and $\mathcal{T}'_{D^*\pi}$ and of using the $\mathcal{T}'_{\text{comb}}$ parameters obtained from the sideband in the signal region. For lepton-tagged events, we find a bias of ∓ 0.012 in S^\pm , due to the assumption that events tagged with direct and cascade leptons are described by the same resolution function. The results presented below are corrected for this bias.

The CP parameters S^\pm for lepton tags and (a, b, c) for kaon tags are determined in step 3 to be $S^+ = -0.078 \pm 0.052 \pm 0.021$, $S^- = -0.070 \pm 0.052 \pm 0.019$, $a = -0.054 \pm 0.032 \pm 0.017$, $b = -0.009 \pm 0.019 \pm 0.013$, and $c = +0.005 \pm 0.031 \pm 0.017$, where the first error is statistical and the second is systematic. The time-dependent, CP -violating asymmetry $\mathcal{A}_{CP} = (N_{B^0\text{tag}} - N_{\bar{B}^0\text{tag}})/(N_{B^0\text{tag}} + N_{\bar{B}^0\text{tag}})$ is shown in Fig. 2. In the absence of background and experimental effects, $\mathcal{A}_{CP} = 2r^* \sin(2\beta + \gamma) \cos\delta^* \sin(\Delta m \Delta t)$. The signal-region fit determines also the mistag rate $\omega = 0.102 \pm 0.008$ ($\omega = 0.217 \pm 0.006$) and the mixing frequency $\Delta m = 0.521 \pm 0.017(\text{stat})\text{ps}^{-1}$ [$\Delta m = 0.478 \pm 0.012(\text{stat})\text{ps}^{-1}$], consistent with the world average [9], for lepton (kaon) tagged events.

The systematic uncertainties on the CP parameters are summarized in Table I. They include (1) the statistical errors obtained from the fits of steps 1 and 2; (2) uncertainties due to the unknown values of the CP parameters in the background, the uncertainty in the ratio of branch-

TABLE I. The systematic uncertainties on the CP -violation parameters.

Source	Error ($\times 10^{-3}$) in				
	S^+	S^-	a	b	c
(1) Step 1 & 2 statistics	1.7	0.9	1.0	0.5	0.6
(2) Backgrounds	12.1	10.0	13.7	8.4	14.2
(3) Fit procedure	6.6	5.3	5.2	1.7	0.8
(4) Detector effects	9.4	7.3	3.7	9.1	3.5
(5) MC statistics	12.8	12.8	8.0	4.0	9.0
Total	21	19	17	13	17

ing fractions $\mathcal{B}(B^0 \rightarrow D^{*-}\pi)/\mathcal{B}(B^0 \rightarrow D^{*-}\rho)$, the modeling of $\mathcal{T}'_{\text{peak}}$, and possible biases introduced by the presence of background; (3) the uncertainty in the cascade lepton bias and possible biases due to the τ and Δm parameters; (4) uncertainties in the measurement of the beam spot position, the detector z length scale, and detector alignment; and (5) the statistical error in the parameters determined from the MC sample.

Combining a and $(S^+ + S^-)/2$, accounting for correlated errors, we obtain

$$2r^* \sin(2\beta + \gamma) \cos\delta^* = -0.063 \pm 0.024 \pm 0.014. \quad (4)$$

This measurement deviates from zero by 2.3 standard deviations. It can be used to provide bounds on $|\sin(2\beta + \gamma)|$ [10]. We use two methods for interpreting our results in terms of constraints on $|\sin(2\beta + \gamma)|$. Both methods involve minimizing a χ^2 function that is symmetric under the exchange $\sin(2\beta + \gamma) \rightarrow -\sin(2\beta + \gamma)$, and applying the method of Ref. [11].

In the first method we make no assumption regarding the value of r^* . For different values of r^* we minimize the function $\chi^2 = \sum_{j,k=1}^3 \Delta x_j V_{jk}^{-1} \Delta x_k$, where Δx_j is the difference between the result of our measurement and the expression of S^+ , S^- , and a as functions of r^* , δ^* and $\sin(2\beta + \gamma)$. The measurement error matrix V is nearly diagonal, and accounts for correlations between the measurements due to correlated statistical and systematic uncertainties. The parameters determined by this fit are $\sin(2\beta + \gamma)$, which is limited to lie in the range $[-1, 1]$, and δ^* . We then generate many parametrized MC experiments with the same sensitivity as reported here for different values of $\sin(2\beta + \gamma)$ and with $\delta^* = 0$, which yields the most conservative lower limits. The fraction of these experiments in which $\chi^2(\sin(2\beta + \gamma)) - \chi^2_{\text{min}}$ is smaller than in the data is interpreted as the confidence level (C.L.) of the lower limit on $|\sin(2\beta + \gamma)|$. The resulting 95% C.L. lower limit is shown as a function of r^* in Fig. 3. This limit is always the more conservative of the two possibilities implied by the ambiguity $|\sin(2\beta + \gamma)| \leftrightarrow |\cos\delta^*|$.

The second method assumes that r^* can be estimated from the Cabibbo angle, the ratio of branching fractions

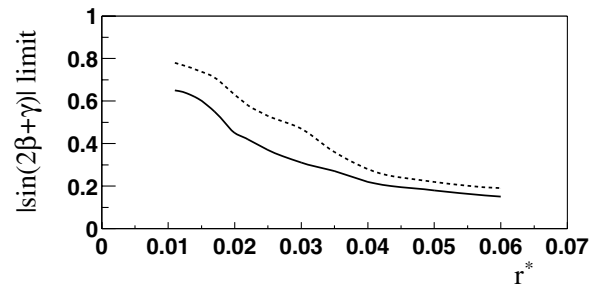


FIG. 3. 95% C.L. lower limit on $|\sin(2\beta + \gamma)|$ as a function of r^* . The solid curve corresponds to this analysis; the dashed curve includes the results of Ref. [12] for $B^0 \rightarrow D^{*\mp} \pi^\pm$ only.

$\mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-)/\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+)$ [13], and the ratio of decay constants $f_{D^*}/f_{D_s^*}$ [14], yielding $r_0^* = 0.017_{-0.007}^{+0.005}$. We attribute an additional non-Gaussian 30% relative error to the theoretical assumptions involved in obtaining this value. We minimize $\tilde{\chi}^2 = \chi^2 + \Delta^2(r^*)$, where $\Delta^2(r^*) = 0$ for $|r^* - r_0^*|/r_0^* \leq 0.3$ and is an offset quadratic function outside this range [15], corresponding to a χ^2 contribution with the uncertainties on r_0^* given above. The parameters $\sin(2\beta + \gamma)$, δ^* , and r^* are determined in this fit. This method yields the limits $|\sin(2\beta + \gamma)| > 0.87(0.56)$ at 68 (95)% C.L.

Combining this measurement with the *BABAR* results for fully reconstructed $B^0 \rightarrow D^{*\mp} \pi^\pm$ and $B^0 \rightarrow D^\mp \pi^\pm$ [12], taking into account correlations between the measurements, we find, using the second method, $|\sin(2\beta + \gamma)| > 0.87(0.58)$ at 68 (95)% C.L. We use the same value of $r = |A_u/A_c|$ for $B^0 \rightarrow D^\mp \pi^\pm$ decays as Ref. [12] [Eq. (6)]. Because of the relatively low value of the asymmetry in $B^0 \rightarrow D^\mp \pi^\pm$ [Eq. (5), Ref. [12]], including this mode in the combination leads to almost no change in the lower limits. The lower limit on $|\sin(2\beta + \gamma)|$ obtained with the first method, including the results of Ref. [12] for $B^0 \rightarrow D^{*\mp} \pi^\pm$ only, is shown in Fig. 3. The results of Ref. [12] for $B^0 \rightarrow D^\mp \pi^\pm$ were not included to avoid any assumption on the value of r .

We have studied time-dependent *CP*-violating asymmetries in $B^0 \rightarrow D^{*\mp} \pi^\pm$ using partial reconstruction. We interpret our results as a limit on $|\sin(2\beta + \gamma)|$ that can be used to set a constraint on the unitarity triangle.

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