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Measurements of the branching fraction and time-dependent CP asymmetries of $B^0 \to J/\psi\pi^0$ decays

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We present measurements of the branching fraction and time-dependent *CP* asymmetries in $B^0 \to J/\psi\pi^0$ decays based on $(231.8 \pm 2.6) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ decays collected with the *BABAR* detector at the SLAC PEP-II asymmetric-energy *B* factory. We obtain a branching fraction $\mathcal{B}(B^0 \to J/\psi\pi^0) = (1.94 \pm 0.22(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-5}$. We also measure the *CP* asymmetry parameters $C = -0.21 \pm 0.26(\text{stat}) \pm 0.06(\text{syst})$ and $S = -0.68 \pm 0.30(\text{stat}) \pm 0.04(\text{syst})$.

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Charge conjugation-parity (*CP*) violation in the *B* meson system has been established by the *BABAR* [1] and Belle [2] collaborations. The standard model (SM) of electroweak interactions describes *CP* violation as a consequence of a complex phase in the three-generation Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [3]. Measurements of *CP* asymmetries in the proper-time distribution of neutral *B* decays to *CP* eigenstates containing a charmonium and K^0 meson provide a precise measurement of $\sin 2\beta$ [4], where β is $\arg[-V_{\rm cd}V^*_{\rm cb}/V_{\rm td}V^*_{\rm tb}]$ and the V_{ij} are CKM matrix elements.

The decay $B^0 \to J/\psi\pi^0$ is a *CP*-even Cabibbo-suppressed $b \to c\bar{c}d$ transition whose tree amplitude has the same weak phase as the $b \to c\bar{c}s$ modes *e.g.* the *CP*-odd decay $B^0 \to J/\psi K^0_S$. The $b \to c\bar{c}d$ penguin amplitude has a different weak phase than the tree amplitude. The tree and penguin amplitudes expected to dominate this decay are shown in Fig. 1.

If there is a significant penguin amplitude in $B^0 \to J/\psi\pi^0$, then one will measure values of the *CP* asymmetry coefficients *S* and *C* that are different from $-\sin 2\beta$ and 0, respectively [5]. The coefficient *S* denoting the interference between mixing and decay, and the direct *CP* asymmetry coefficient *C* are defined as

$$S \equiv \frac{2\mathcal{I}m\lambda}{1 + |\lambda|^2} \quad \text{and} \quad C \equiv \frac{1 - |\lambda|^2}{1 + |\lambda|^2}, \tag{1}$$

where λ is a complex parameter that depends on both the $B^0 - \bar{B}^0$ oscillation amplitude and the amplitudes describing B^0 and $\bar{B}^0$ decays to the $J/\psi\pi^0$ final state. An additional motivation for measuring *S* and *C* from $B^0 \to J/\psi\pi^0$ is that they can provide a model-independent constraint on the penguin dilution within $B^0 \to J/\psi K^0_S$ [6].

In this publication, we present an update of previous *BABAR* branching fraction and time-dependent *CP* violating asymmetry measurements of the decay $B^0 \to J/\psi\pi^0$ [7,8], which had been performed using 20.7 fb^{-1} and 81.1 fb^{-1} of integrated luminosity, respectively. Belle has also studied this mode and has published a branching fraction and later a time-dependent *CP*violating asymmetry result using 29.4 fb^{-1} and 140.0 fb^{-1} of integrated luminosity, respectively [9,10].

The data used in this analysis were collected with the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. This represents a total integrated luminosity of 210.6 fb^{-1} collected on or just below the $\Upsilon(4S)$ resonance (on-peak), corresponding to a sample of 231.8 ± 2.6 million $B\bar{B}$ pairs. An additional 21.6 fb^{-1} of data, collected at approximately 40 MeV below the $\Upsilon(4S)$ resonance, is used to study background from $e^+e^- \to q\bar{q}(q = u, d, s, c)$ continuum events.

The *BABAR* detector is described in detail elsewhere [11]. Surrounding the interaction point is a 5 layer double-sided silicon vertex tracker (SVT) which measures the impact parameters of charged particle tracks in both the plane transverse to, and along the beam direction. A 40 layer drift chamber (DCH) surrounds the SVT and provides measurements of the transverse momenta for charged particles. Both the SVT and the DCH operate in the magnetic field of a 1.5 T solenoid. Charged hadron identification is achieved through measurements of particle energy loss (dE/dx) in the tracking system and the Čerenkov angle obtained from a detector of internally reflected Čerenkov light (DIRC). This is surrounded by a segmented CsI(Tl) electromagnetic calorimeter (EMC) which is used to pro-

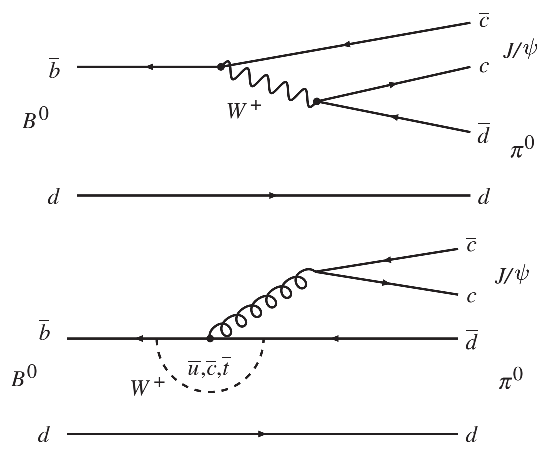

FIG. 1. Feynman diagrams of the color suppressed tree (top) and gluonic penguin (bottom) amplitudes contributing to the $B^0 \to J/\psi\pi^0$ decay.

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vide photon detection and electron identification, and is used to reconstruct neutral hadrons. Finally, the instrumented flux return (IFR) of the magnet allows discrimination of muons from pions.

We reconstruct $B^0 \to J/\psi \pi^0$ decays in $B\bar{B}$ candidate events from combinations of $J/\psi \to \ell^+\ell^-(\ell = e, \mu)$ and $\pi^0 \to \gamma\gamma$ candidates. A detailed description of the charged particle reconstruction and identification can be found elsewhere [7]. For the $J/\psi \to e^+e^-(J/\psi \to \mu^+\mu^-)$ channel, the invariant mass of the lepton pair is required to be between 3.06 and 3.12 GeV/c^2 (3.07 and 3.13 GeV/c^2). Each lepton candidate must also be consistent with the electron (muon) hypothesis. We form $\pi^0 \to \gamma\gamma$ candidates from clusters in the EMC with an invariant mass, $m_{\gamma\gamma}$ satisfying $100 < m_{\gamma\gamma} < 160\ \mathrm{MeV}/c^2$. These clusters are required to be isolated from any charged tracks, carry a minimum energy of 30 MeV, and have a lateral energy distribution consistent with that of a photon. Each π^0 candidate is required to have a minimum energy of 200 MeV and is constrained to the nominal mass [12]. Finally the $B^0 \to J/\psi\pi^0$ candidates (B_{rec}) are constrained to originate from the e^+e^- interaction point using a geometric fit.

We use two kinematic variables, $\mathrm{m_{ES}}$ and ΔE, in order to isolate the signal: $\mathrm{m_{ES}} = \sqrt{(E^*_{\mathrm{beam}})^2 - (p^*_B)^2}$ is the beam-energy substituted mass and $\Delta E = E^*_B - E^*_{\mathrm{beam}}$ is the difference between the B-candidate energy and the beam nergy. E^*_{beam} and p^*_B (E^*_B) are the beam energy and B-candidate momentum (energy) in the center-of-mass (CM) frame. We require $\mathrm{m_{ES}} > 5.2\ \mathrm{GeV}/c^2$ and $|\Delta E| < 0.3$ GeV.

A significant source of background is due to $e^+e^- \to q\bar{q}(q = u, d, s, c)$ continuum events. We combine several kinematic and topological variables into a Fisher discriminant ($\mathcal{F}$) [13] to provide additional separation between signal and continuum. The three variables L_0, L_2 and $\cos(\theta_H)$ are inputs to $\mathcal{F}$. L_0 and L_2 are the zeroth- and second-order Legendre polynomial moments; $L_0 = \sum_i |\mathbf{p}^*_i|$ and $L_2 = \sum_i |\mathbf{p}^*_i|/2(3\cos^2\theta_i - 1)$, where $\mathbf{p}^*_i$ are the CM momenta of the tracks and neutral calorimeter clusters that are not associated with the signal candidate. The θ_i are the angles between $\mathbf{p}^*_i$ and the thrust axis of the signal candidate and θ_H is the angle between the positively charged lepton and the B candidate in the J/ψ rest frame.

We use multivariate algorithms to identify signatures of B decays that determine (tag) the flavor of the decay of the other B in the event (B_{tag}) to be either a B^0 or $\bar{B}^0$. The flavor tagging algorithm used is described in more detail elsewhere [14]. In brief, we define seven mutually exclusive tagging categories. These are (in order of decreasing signal purity) Lepton, KaonI, KaonII, Kaon-Pion, Pion, Other, and No-Tag. The total effective tagging efficiency of this algorithm is $(30.5 \pm 0.4)\%$.

The decay rate f_+ (f_-) of neutral decays to a CP eigenstate, when B_{tag} is a $B^0(\bar{B}^0)$, is

$$f_\pm(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 \pm S\sin(\Delta m_d \Delta t) \mp C\cos(\Delta m_d \Delta t)], \tag{2}$$

where Δt is the difference between the proper decay times of the B_{rec} and B_{tag} mesons, $\tau_{B^0} = 1.536 \pm 0.014$ ps is the B^0 lifetime and $\Delta m_d = 0.502 \pm 0.007\ \mathrm{ps}^{-1}$ is the $B^0 - \bar{B}^0$ oscillation frequency [12]. The decay width difference between the B^0 mass eigenstates is assumed to be zero.

The time interval Δt is calculated from the measured separation Δz between the decay vertices of B_{rec} and B_{tag} along the collision axis (z). The vertex of B_{rec} is reconstructed from the lepton tracks that come from the J/ψ; the vertex of B_{tag} is constructed from the remaining tracks in the event that do not belong to B_{rec}, with constraints from the beam spot location and the B_{rec} momentum. We accept events with $|\Delta t| < 20$ ps whose uncertainty are less than 2.5 ps.

After all of the selection criteria mentioned above have been applied, the average number of candidates per event is approximately 1.1, indicating some events still have multiple candidates. In these events, we randomly choose one candidate to be used in the fit. This selection is unbiased. Overall, the true signal candidate is correctly identified 91.7% of the time. After this step, the signal efficiency is 22.0% and a total of 1318 on-peak events are selected.

In addition to signal and continuum background events, there are also $B\bar{B}$-associated backgrounds present in the data. We divide the B backgrounds into the following types: (i) $B^0 \to J/\psi K^0_S$, where $K^0_S \to \pi^0\pi^0$ (ii) inclusive neutral B meson decays, and (iii) inclusive charged B meson decays. When normalized to the integrated luminosity, Monte Carlo (MC) studies predict $153 \pm 9, 68 \pm 14$ and 314 ± 63 events of these background types, respectively. The inclusive neutral B meson decays exclude signal and $B^0 \to J/\psi K^0_S$ events. The inclusive B decay backgrounds are dominated by contributions from $B \to J/\psi X$ (inclusive charmonium final states). In particular the inclusive charged B meson decay backgrounds are dominated by $B^+ \to J/\psi\rho^+$ decays. The $B^0 \to J/\psi K^0_S$ background was studied separately since it contributes a significant amount of neutral B background, has a large asymmetry, and has the almost same tagging efficiency and resolution as the signal.

The signal yield, S and C are simultaneously extracted from an unbinned maximum-likelihood (ML) fit to the B candidate sample, where the discriminating variables used in the fit are m_{ES}, ΔE, $\mathcal{F}$, and Δt. The signal yield is fitted using known tagging efficiencies [14]. The continuum yield for the seven mutually-exclusive tagging categories, is also allowed to vary in the ML fit.

The probability density function (PDF) for signal m_{ES} distribution takes the form of a Gaussian with a low side exponential tail [15]. We parameterize the m_{ES} distribution for continuum and neutral inclusive B background with an Argus phase space distribution [16]. As there are significant correlations between $m_{\rm ES}$ and ΔE for the charged inclusive B and the $B^0 \to J/\psi K^0_S$ backgrounds, we parameterize these variables with two-dimensional nonparametric PDFs as described in Ref. [17]. The ΔE distribution for signal events is modeled by a Gaussian with an exponential tail on the negative side to account for energy leakage in the EMC, plus a polynomial contribution. The ΔE distributions for the continuum and the neutral inclusive B background are described by second and third-order polynomials, respectively. The $\mathcal{F}$ distributions for the signal and the backgrounds are described by bifurcated Gaussians with different widths above and below the peak value.

The signal decay rate distribution of Eq. (2) is modified to account for dilution coming from incorrectly assigning the flavor of $B_{\rm tag}$ and is convolved with a triple Gaussian resolution function, whose core width is about 1.1 ps [18]. The decay rate distribution for B backgrounds is similar to that for signal. The inclusive B backgrounds are assigned an effective lifetime instead of their respective B lifetimes to account for their misreconstruction. This effective lifetime is determined from MC simulated data. The potential CP asymmetry of the inclusive B background is evaluated by allowing the parameters of S and C for this background to vary. The decay rate distribution for $B^0 \to J/\psi K^0_S$ is the same as that for signal and reflects the known level of CP violation in that decay. The continuum background is modeled with a prompt lifetime component convolved with a triple Gaussian resolution function. The core Gaussian parameters and fractions are allowed to vary in the ML fit. The other two Gaussians have means fixed to zero, and widths of 0.85 ps and 8.0 ps, respectively.

The results from the ML fit are 109 ± 12(stat) signal events, with $S = -0.68 \pm 0.30$(stat) and $C = -0.21 \pm 0.26$(stat). The fit yields the following numbers of continuum events: $\rm N_{Lepton} = 17 \pm 5$, $\rm N_{KaonI} = 38 \pm 8$, $\rm N_{KaonII} = 101 \pm 12$, $\rm N_{KaonPion} = 102 \pm 12$, $\rm N_{Pion} = 115 \pm 12$, $\rm N_{Other} = 94 \pm 11$, and $\rm N_{NoTag} = 227 \pm 17$. Figure 2 shows the distributions of $m_{\rm ES}$, ΔE, and $\mathcal{F}$ for the data. In these plots the signal has been enhanced by selecting $|\Delta E| < 0.1$ GeV for the $m_{\rm ES}$ plot, $\rm m_{ES} > 5.275\ GeV/\mathit{c}^2$ for the ΔE plot and by applying both of these criteria for the $\mathcal{F}$ plot. After applying these requirements to the signal (background) samples that are used in the fit, they are reduced to a relative size of 83.1% (24.3%), 85.0% (21.1%) and 73.1% (2.8%) for the $m_{\rm ES}$, ΔE, and $\mathcal{F}$ distributions, respectively.

Figure 3 shows the Δt distribution for signal B^0 and $\bar{B}^0$ tagged events. The signal has been enhanced using the same $m_{\rm ES}$ and ΔE cuts as for Fig. 2. The time-dependent decay rate asymmetry $[N(\Delta t) - \bar{N}(\Delta t)]/[N(\Delta t) + \bar{N}(\Delta t)]$ is also shown, where N ($\bar{N}$) is the decay rate for $B^0(\bar{B}^0)$ tagged events and the decay rate takes the form of Eq. (2).

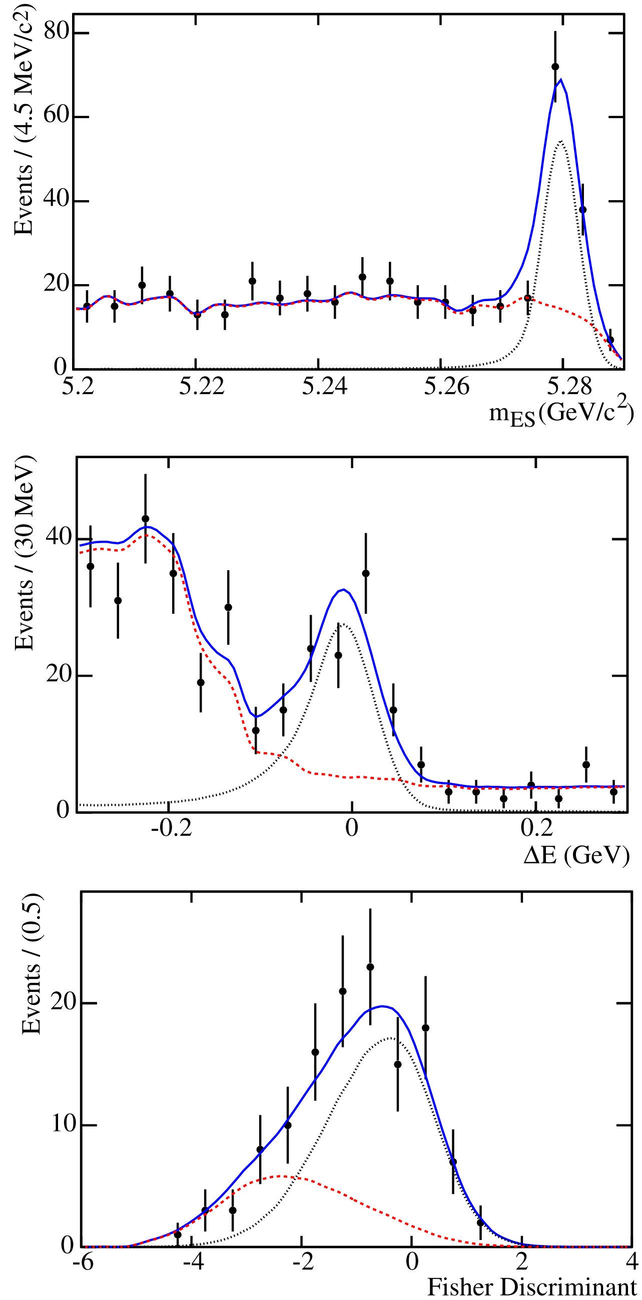

FIG. 2 (color online). Signal enhanced distributions of $m_{\rm ES}$ (top), ΔE (center) and $\mathcal{F}$ (bottom) for the data (points). The solid line represents the total likelihood, the dashed line is the sum of the backgrounds and the dotted line is the signal. The undulations in the background model are the result of limited MC statistics available for defining the two-dimensional nonparametric PDFs.

Table I summarizes the systematic uncertainties on the signal yield, S and C. These include the uncertainty due to the PDF parameterization (including the resolution function), evaluated by varying the signal and the background PDF parameters within uncertainties of their nominal values. the effect of SVT misalignment; the uncertainties

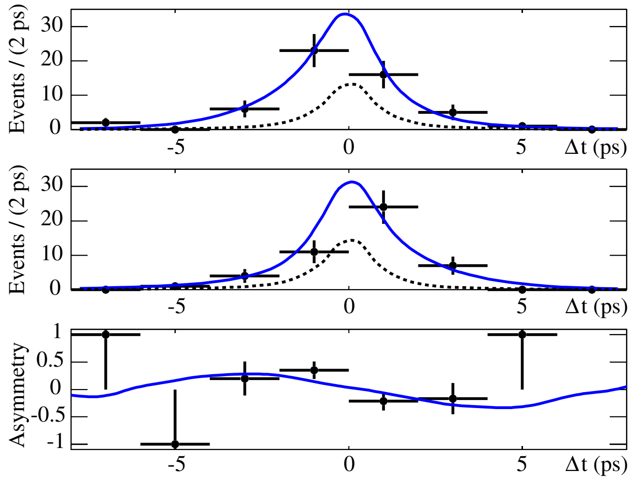

FIG. 3 (color online). The Δt distribution for a sample of signal enhanced events tagged as B^0 (top) and $\bar{B}^0$ (middle). The dotted lines are the sum of backgrounds and the solid lines are the sum of signal and backgrounds. The time-dependent *CP* asymmetry (see text) is also shown (bottom), where the curve is the measured asymmetry.

associated with the Lorentz boost, the z-scale of the tracking system, and the event-by-event beam spot position.

The uncertainty coming from the fit bias is estimated by performing ensembles of mock experiments using signal MC which is generated using the GEANT4-based [19] *BABAR* MC simulation, embedded into MC samples of background generated from the likelihood. The deviation from input values is added in quadrature to the error on the deviation in order to obtain a conservative fit bias uncertainty. Most, but not all of the inclusive charmonium final states which dominate the inclusive B background, are precisely known from previous measurements. Their yields are then fixed in the fit. As a crosscheck, the yields for inclusive B backgrounds that are not well known are allowed to vary. The deviation from the nominal result is taken as a systematic uncertainty. We include an additional systematic uncertainty to account for neglecting the small correlation between m_{ES} and ΔE in signal and neutral inclusive B background events.

TABLE I. Contributions to the systematic errors on the signal yield, S and C, where the signal yield errors are given in numbers of events. The total systematic uncertainty is the quadratic sum of the individual contributions listed. Additional systematic uncertainties that are applied only to the branching fraction are discussed in the text.

Contribution	Signal yield	S	C
PDF parameterization	$+3.21 - 2.88$	± 0.013	± 0.012
SVT misalignment	–	± 0.002	± 0.002
Boost and z-scale	$+0.08 - 0.16$	± 0.004	± 0.001
Beam spot position	–	± 0.007	± 0.002
Fit bias	± 3.00	± 0.026	± 0.016
Inclusive B background yields	± 3.52	± 0.003	± 0.020
$m_{ES} - \Delta E$ correlations	± 2.92	± 0.020	± 0.002
CP content of B background	$+0.13 - 0.11$	± 0.012	± 0.049
CP background lifetime	± 0.67	± 0.010	± 0.010
Tagging efficiency asymmetry	± 0.02	± 0.000	± 0.020
Tag-side interference	–	± 0.004	± 0.014
Fisher data/MC comparison	± 0.70	± 0.004	± 0.004
Total	$+6.42 - 6.26$	± 0.040	± 0.063

In order to evaluate the uncertainty coming from *CP* violation in the B background, we have allowed the S and C parameters to vary in a fit for the neutral inclusive B background, and have separately allowed the C parameter to vary in a fit for the charged inclusive B background. The deviations of the fitted values of the signal S and C from the nominal fit results are assigned as systematic errors. The uncertainty from *CP* violation in $B^0 \to J/\psi K_S^0$ is determined by varying S and C within current experimental limits [14].

The inclusive B background uses an effective lifetime in the nominal fit and we replace this with the world-average B lifetime [12] to evaluate the systematic error due to the *CP* background lifetime. There is also a small asymmetry in the tagging efficiency between B^0 and $\bar{B}^0$ tagged events, for which a systematic uncertainty is evaluated. We study the possible interference between the suppressed $\bar{b} \to \bar{u}c\bar{d}$ amplitude with the favored $b \to c\bar{u}d$ amplitude for some tagside B decays [20]. The difference in the distribution of $\mathcal{F}$ between data and MC is evaluated with a large sample of $B \to D^* \rho$ decays. There are additional systematic uncertainties that contribute only to the branching fraction. These come from uncertainties for charged particle identification (5.2%), π^0 meson reconstruction efficiency (3%), the $J/\psi \to \ell^+ \ell^-$ branching fractions (2.4%), the tracking efficiency (1.2%) and the number of B meson pairs (1.1%). The systematic error contribution from MC statistics is negligible. The 109 ± 12 signal events correspond to a branching fraction of

$$\mathcal{B}(B^0 \to J/\psi \pi^0) = (1.94 \pm 0.22(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-5}.$$

We determine the *CP* asymmetry parameters to be

$$C = -0.21 \pm 0.26(\text{stat}) \pm 0.06(\text{syst}),$$

$$S = -0.68 \pm 0.30(\text{stat}) \pm 0.04(\text{syst}),$$

where the correlation between S and C is 8.3%. The value of S is consistent with SM expectations for a tree-dominated $b \to c\bar{c}d$ transition of $S = -\sin 2\beta$ and $C = 0$. All results presented here are consistent with previous measurements from the B factories [7–10].

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