Fermi National Accelerator Laboratory

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Measurement of the Polarization in the Decays $B^0 \rightarrow J/\psi\ K^{*0}$ and $B_s^0 \rightarrow J/\psi\phi$

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ABSTRACT

We report on a measurement of the longitudinal polarization fraction in the decay $B^0 \to J/\psi K^{*0}$ using data collected with the Collider Detector at Fermilab. B^0 mesons are reconstructed through the decay chain $B^0 \to J/\psi K^{*0}, J/\psi \to \mu^+\mu^-, K^{*0} \to K^+\pi^-$. A sample of 65 ± 10 events is used to obtain the result $\Gamma_L/\Gamma = 0.65 \pm 0.10$ (stat) ± 0.04 (sys). The first measurement of Γ_L/Γ in the decay $B_s^0 \to J/\psi\phi$ is also presented.

1 Introduction

We report a measurement of the longitudinal polarization fraction Γ_L/Γ in the decay $B^0 \to J/\psi K^{*0}$ performed by the Collider Detector at Fermilab (CDF) collaboration. Interest in the decay $B^0 \to J/\psi K^{*0}$ was originally stimulated by its potential use in CP violation studies [1]. In addition a measurement of Γ_L/Γ can be used to test theoretical predictions which depend on the factorization hypothesis [2]. In particular, use of the standard factorization methods are unable to simultaneously reproduce the large measured value[3, 4] of Γ_L/Γ in $B^0 \to J/\psi K^{*0}$ and the small value of the ratio of branching ratios, R= $\Gamma(B \to J/\psi K^*)/\Gamma(B \to J/\psi K)$ [5]. Recent theoretical efforts to reproduce the experimental results have included several schemes of modifying the form factors, and some have even relaxed the factorization assumption [6]. They have met with varying degrees of success, but all call for more precise measurements of Γ_L/Γ and related quantities.

2 Data Selection

Using data collected in 1992–93 at the Fermilab Tevatron, B^0 mesons are reconstructed through the decay chain $B^0 \to J/\psi K^{*0}$, $J/\psi \to \mu^+\mu^-$, $K^{*0} \to$

$K^+\pi^-$. The data set consists of approximately 19 pb^{-1} of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The CDF detector has been described in detail elsewhere [7]. Components relevant to this analysis are briefly described here. Proceeding outward from the interaction point the elements of the detector include the Silicon Vertex Detector (SVX) [8], Vertex Time Projection Chamber (VTX), Central Tracking Chamber (CTC), a superconducting solenoidal magnet, electromagnetic and hadronic calorimeters, and muon chambers. The SVX consists of four layers of silicon strip detectors with r-ϕ readout [9]. The pitch between readout strips is 60 μm, resulting in a spatial resolution of 13 μm. The VTX provides the r-z tracking information used to determine the primary vertex. The CTC is an 84 layer drift chamber covering $|\eta| < 1.1$ and located inside a 1.4 T axial magnetic field. The CTC provides a three dimensional measurement of the momenta of charged particles. The combined CTC/SVX momentum resolution is $\delta p_T/p_T = [(0.0009 p_T)^2 + (0.0066)^2]^{\frac{1}{2}}$ where p_T (in GeV/c) is the momentum transverse to the beam. The calorimeters serve as absorbers for this analysis. The central muon system consists of three detector elements. The Central Muon Chambers are located behind ~ 5 absorption lengths of material and cover 85% of the azimuthal region for $|\eta| < 0.6$. This η region is further instrumented by the Central Muon Upgrade behind a total of ~ 8 absorption lengths. The Central Muon Extension chambers are located behind ~ 6 absorption lengths and cover 67% of the azimuthal region for $0.6 < |\eta| < 1.0$.

The data sample used in this analysis was collected using dimuon triggers in the CDF three level trigger system. Two tracks are required in the muon chambers at Level 1. The trigger efficiency for a muon at Level 1 rises from 50% at $p_T = 1.6$ GeV/c to 90% at $p_T = 3.1$ GeV/c with a plateau of 94%. The tracks must be separated by at least 0.09 radians in ϕ. The Level 2 trigger requires that at least one of the muon tracks is matched in ϕ to a CTC track found by the Central Fast Tracker (CFT). The efficiency for finding a track with the CFT rises from 50% at $p_T = 2.65$ GeV/c to 90% at $p_T = 3.1$ GeV/c and reaches a plateau of 93%. The Level 3 trigger requires a pair of oppositely charged muons with an invariant mass between 2.8 and 3.4 GeV/c^2 using online track reconstruction software.

Additional offline requirements are placed on the muons in order to isolate the J/ψ signal and minimize biases due to trigger thresholds. The match between the extrapolated CTC track and the track in the muon chamber is required to be less than 3σ, where σ is the expected multiple scattering error combined in quadrature with the measurement errors. SVX information is added to the CTC tracks when it is available. Both muons are required to have a transverse momentum greater than 1.8 GeV/c, and at least one must have a transverse momentum greater than 2.5 GeV/c. The invariant mass of the muon pair is formed while constraining the muons to come from a common vertex. After all of the above requirements are applied there are approximately 54000 J/ψ candidate events, with a signal width of about 16 MeV/c^2.

Muon pairs within 80 MeV/c^2 of the J/ψ mass are combined with other charged particles to search for B^0 mesons. Pairs of oppositely charged particles with transverse momentum greater than 500 MeV/c are considered. For each such pair the K-π particle assignment with invariant mass closest to the K^{*0} mass is used. K^{*0} candidates within 80 MeV/c^2 of the mass of the K^{*0} are retained. All of the particles are constrained to come from a common vertex, the muon pair is mass constrained to the J/ψ mass, and the momentum of the B^0 candidate is constrained to point from the primary vertex to the secondary vertex in the r-ϕ plane. The combined confidence level from the constrained fit is required to be greater than 1%.

Additional requirements are made to reduce combinatoric backgrounds. The proper decay distance of the B^0 candidate must be greater than 100 μm, the transverse momentum of the B^0 candidate must be greater than 8.0 GeV/c, and the transverse momentum of the K^{*0} candidate must be greater than 2.0 GeV/c. The momentum of the B^0 candidate is also required to be greater than half of the sum of its momentum and the momenta of all other charged particles within an η-ϕ cone of radius 1.0 around the direction of the B^0 candidate. Reflections from B_s decay are removed by reconstructing the events as $J/\psi\phi$, $\phi \to K^+K^-$ and removing events that satisfy cuts for the B_s. The resulting mass distribution is shown in Figure 1. A binned maximum likelihood fit to a Gaussian plus a flat background yields 65 ± 10 events.

3 The Helicity Analysis

The decay distribution for $B^0 \to J/\psi K^{*0}$, $J/\psi \to \mu^+\mu^-$, $K^{*0} \to K^+\pi^-$ can be written[10] as:

$$\frac{d^2\Gamma}{d\cos\theta_{K^*}\, d\cos\theta_\psi} \propto \frac{1}{4}\sin^2\theta_{K^*}(1+\cos^2\theta_\psi)\frac{\Gamma_T}{\Gamma} + \cos^2\theta_{K^*}\sin^2\theta_\psi\frac{\Gamma_L}{\Gamma}$$

where the helicity angle θ_{K^*} is the decay angle of the kaon in the K^{*0} rest frame with respect to the K^{*0} direction in the B rest frame. Similarly, θ_ψ is

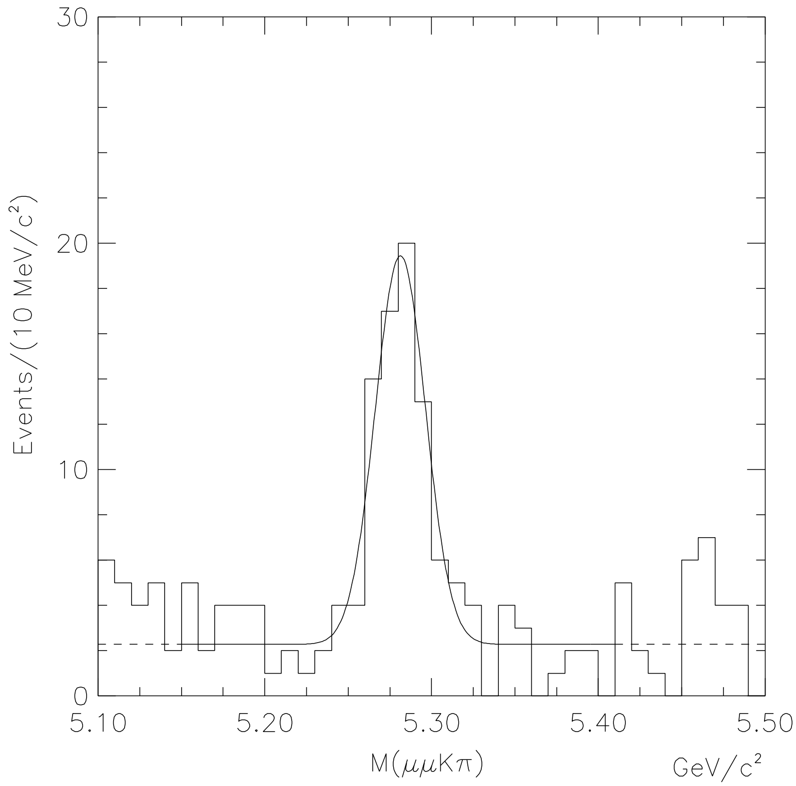

Figure 1: Invariant mass distribution for $B^0 \to J/\psi K^{*0}$. The curve is a binned likelihood fit to a Gaussian plus a flat background. The regions with mass below 5.15 GeV/c^2 or above 5.40 GeV/c^2, where B decays with either a missing or an extra pion can contribute (dashed line), are excluded from the fit. There are 65 ± 10 events under the peak and the peak has a width of 15 ± 3 MeV/c^2.

the decay angle of the muon in the J/ψ rest frame with respect to the J/ψ direction in the B rest frame. The above expression has been integrated over the angle ϕ between the J/ψ and K^{*0} decay planes. The first and second terms represent the transverse and longitudinal helicity states respectively.

The polarization is determined using an unbinned likelihood fit to the two dimensional decay distribution. The likelihood computed for each event includes both signal and background probability distribution functions appropriately weighted by a mass dependent ratio of signal to background obtained from Figure 1. The signal probability distribution function is the normalized sum of the two helicity states. The normalization factor is the sum of each polarization fraction multiplied by the integrated angular acceptance of the associated helicity state. The background amplitude is taken to be unpolarized as determined from a fit to the B^0 mass sideband events. The integrated angular acceptances are derived from Monte Carlo. The differential B meson cross section measured at CDF[11] is used as the default input B meson p_T spectrum. The Monte Carlo events are passed through a simulation of the CDF detector and reconstructed in the same way as the data events.

4 Result for $B^0 \rightarrow J/\psi K^{*0}$

The signal region for the helicity angle analysis is defined as $\mid m_{\mu\mu K\pi} - m_B \mid < 0.03$ GeV/c^2. The result of the unbinned likelihood fit to the data is $\Gamma_L/\Gamma = 0.65 \pm 0.10$ (statistical error only). The result, projected onto background subtracted, acceptance corrected plots of the data, is shown in Figure 2. No particle identification information is used and therefore the chosen K-π assignment can be incorrect. The percentage of misassigned K and π masses runs from $4.3 \pm 0.3\%$ for longitudinally polarized events up to $6.6 \pm 0.4\%$ for transversely polarized events, as determined from Monte Carlo. The events with incorrect K-π assignments produce a small downward shift in the fit value determined to be independent of the value of the polarization and equal to 0.041 ± 0.010. The result given above has been corrected for this shift.

One of the largest sources of systematic uncertainty is associated with the misassignment of the K and π masses. An estimate of the fraction of events with misassigned particles is obtained from the data by plotting the B mass distribution using the opposite particle assignment to the normal one. The number of observed events is consistent with the prediction from Monte Carlo, but the 1 σ upper limit on the number of observed events indicates that as much as 9% of the events could have incorrect K-π particle assignments.

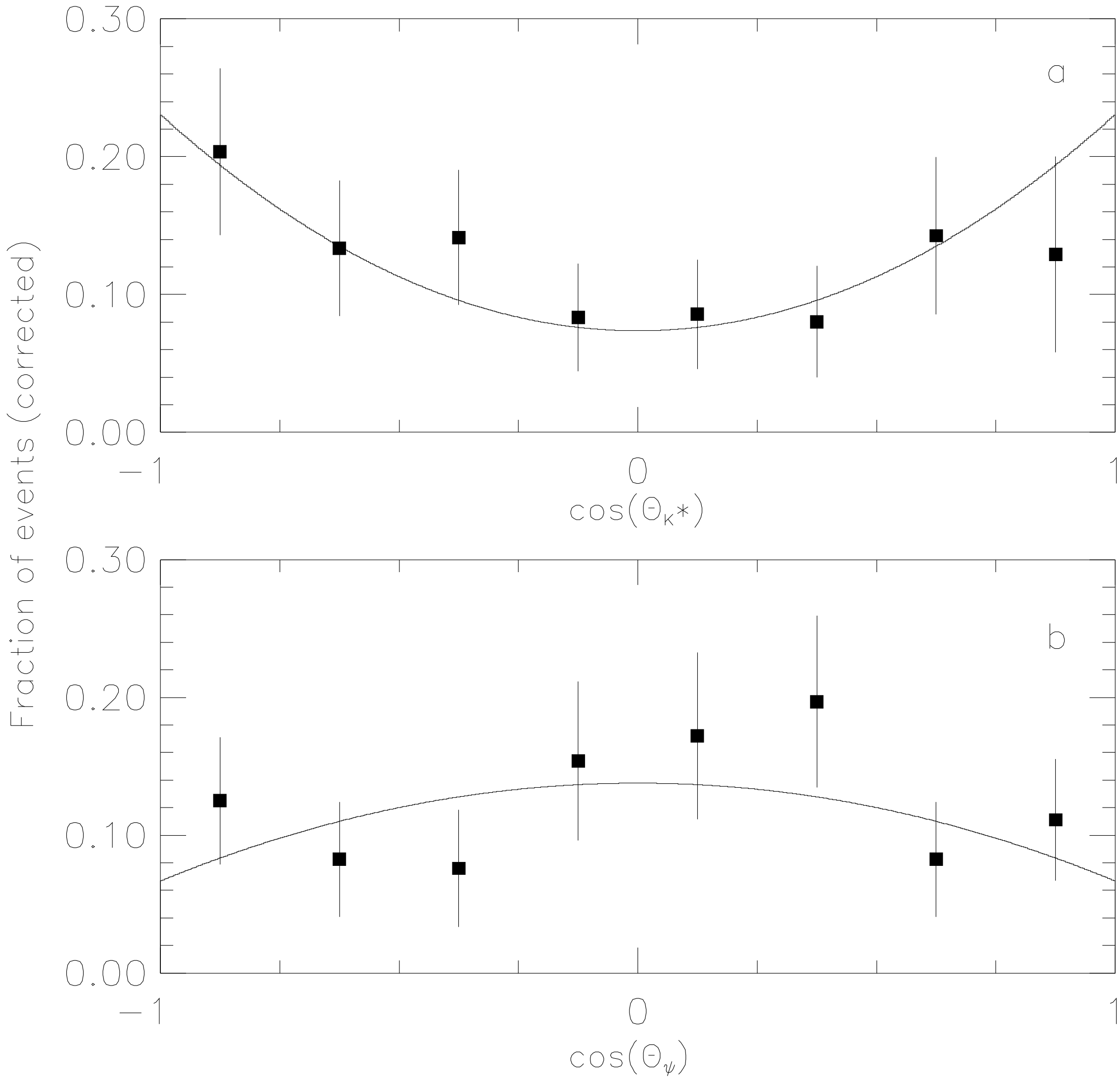

Figure 2: K^{*0} (a) and J/ψ (b) helicity angle distributions for the decay $B^0 \to J/\psi K^{*0}$, background subtracted and corrected for acceptance. The fitted value of the longitudinal polarization fraction, $\Gamma_L/\Gamma = 0.65$, is indicated by the solid curves.

This amount of reversed events corresponds to an additional correction to the polarization and a systematic uncertainty of 4.2% is assigned.

The polarization of the background is also a large source of systematic uncertainty. Data from the B^0 mass sidebands are used to determine the polarization of the background. The helicity amplitude used for the background in the likelihood function is varied by the uncertainty on the sideband fit to obtain a systematic uncertainty of 3.9%. The signal to background ratio used in the fit is varied to obtain a systematic uncertainty of 2.3%. Nonresonant decays of the type $B^0 \to J/\psi K^+\pi^-$ can contribute to the signal region. Fitting data from the mass sidebands of the K^{*0}, $0.4^{+2.8}_{-0.4}$ events are expected in the K^{*0} region, while no more than $0.7^{+2.6}_{-0.7}$ events are expected from known branching fractions and phase space. Three nonresonant events are included in the fit, using both a longitudinal and a transverse amplitude. A systematic uncertainty of 1.9% is assigned. Systematic uncertainties from the trigger model are small. All of the systematic uncertainties are summed in quadrature to obtain the result $\Gamma_L/\Gamma = 0.65 \pm 0.10$ (stat) ± 0.04 (sys).

5 Result for $B_s^0 \to J/\psi\phi$

The method used to obtain Γ_L/Γ in the decay $B^0 \to J/\psi K^{*0}$ can be applied directly to the decay $B_s^0 \to J/\psi\phi$. The selection of the data sample, the requirements on the J/ψ and on the additional particles, plus the confidence level cut on the B vertex are all unchanged from those used for the $B^0 \to J/\psi K^{*0}$ analysis. The transverse momentum of the ϕ candidate must be greater than 2.0 MeV/c and the reconstructed K^+K^- mass must be within 10 MeV/c^2 of the mass of the ϕ. The transverse momentum of the B_s^0 candidate must be greater than 6.0 GeV/c, and the proper decay length of the B_s^0 candidate must be greater than 50 μm. A binned maximum likelihood fit to a Gaussian plus a flat background for the events passing all of the above requirements yields 19 ± 5 events, and a width of 13 ± 3 MeV/c^2. Only 2 background events are expected under the peak.

The polarization in $B_s^0 \to J/\psi\phi$ is determined with the same likelihood function used for $B^0 \to J/\psi K^{*0}$. The result of the unbinned likelihood fit to the data is $\Gamma_L/\Gamma = 0.56^{+0.20}_{-0.21}$(stat) $^{+0.03}_{-0.04}$(sys). The systematic studies carried out for $B^0 \to J/\psi K^{*0}$ are repeated for $B_s^0 \to J/\psi\phi$, except that nonresonant events are neglected, and the background amplitude is varied over all polarization values. This is the first measurement of Γ_L/Γ in the decay $B_s^0 \to J/\psi\phi$.

6 Conclusion

A measurement of the longitudinal polarization fraction $\Gamma_L/\Gamma = 0.65 \pm 0.10$ (stat) ± 0.04 (sys) in the decay $B^0 \to J/\psi K^{*0}$ from a sample of 65 ± 10 events is presented. Combining this result with those from ARGUS, $\Gamma_L/\Gamma = 0.97 \pm 0.16 \pm 0.15$ [3] and CLEO, $\Gamma_L/\Gamma = 0.80 \pm 0.08 \pm 0.05$ [4] yields a world average of $\Gamma_L/\Gamma = 0.74 \pm 0.07$ [12]. The lower value of Γ_L/Γ presented in this letter, compared to the ARGUS and CLEO results, suggests that the $B^0 \to J/\psi K^{*0}$ decay mode may be more difficult to use for CP violation studies than previously believed. In addition this lower value is easier to accommodate within the factorization assumption. Further measurements are needed to fully understand the limitations of factorization. These results also demonstrate the feasibility of studying the dynamics of B meson decays in a hadron collider environment.

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[1] The final state is a CP eigenstate in the mode $K^{*0} \rightarrow K^0\pi^0$ if the decay is fully polarized, but has opposite CP for the longitudinal and transverse amplitudes. The observed asymmetry is diluted if the decay is partially polarized, but the CP asymmetry can still be extracted. See, for example, I. Dunietz *et al.*, Phys. Rev. D **43**, 2193 (1991).

[2] The factorization hypothesis assumes that the decay amplitude can be described as the product of two independent hadronic currents. See, for example, M. Bauer, B. Stech, and M. Wirbel, Z. Phys. C **34**, 103 (1987); M. Wirbel, B. Stech, and M. Bauer, Z. Phys. C **29**, 637, (1985).

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[9] In CDF the positive z axis lies along the proton direction, r is the radius from this axis, θ is the polar angle and ϕ is the azimuthal angle. The pseudorapidity, η, is defined as $-ln\,[\tan(\theta/2)]$.

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[12] The uncertainty on the polarization obtained from a fixed number of events is a function of the value of the polarization. This dependence must be accounted for when calculating the world average. In the result given here the approximation that the systematic uncertainties are independent of the polarization has been made.