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Evidence for $B^0 \to \phi \phi$ Decay and Measurements of Branching Ratio and $A_{CP}$ for $B^+ \to \phi K^+$


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We present the first evidence of charmless decays of the $B_s^0$ meson, the decay $B_s^0 \rightarrow \phi \phi$, and a measurement of the branching ratio $BR(B_s^0 \rightarrow \phi \phi)$ using 180 pb$^{-1}$ of data collected by the CDF II experiment at the Fermilab Tevatron collider. In addition, the BR and direct $CP$ asymmetry for the $B^+ \rightarrow \phi K^+$ decay are measured. We obtain $BR(B_s^0 \rightarrow \phi \phi) = [14^{+4}_{-4}(\text{stat}) \pm 6(\text{syst})] \times 10^{-6}$, $BR(B^+ \rightarrow \phi K^+) = [7.6 \pm 1.3(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}$, and $A_{CP}(B^+ \rightarrow \phi K^+) = -0.07 \pm 0.17(\text{stat})^{+0.03}_{-0.02} (\text{syst})$. Both decays are governed in the standard model by second order (penguin) $b \rightarrow s\bar{s}s$ amplitudes.

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the observed $b \rightarrow s\bar{s}s$ asymmetries. The measurement of
the branching ratio $BR(B^0 \rightarrow \phi \phi)$ gives insight into the
size of penguin amplitudes as well as tightens the con-
straints on poorly known form factors. Recent calculations predict
$BR(B^0 \rightarrow \phi \phi) \ll 10^{-6}$ $\times 10^{-6}$ [5] and $37 \times$
$10^{-6}$ [6]. Within the SM the $B^+ \rightarrow \phi K^+$ direct CP asym-
metry ($A_{CP}$) is predicted not to exceed a few percent [7].
No single experiment [8] has yet reached the sensitivity to
detect this asymmetry. Further measurements of decay rates and
$A_{CP}$ may help identifying the origin of the observed deviations from SM predictions in $b \rightarrow s\bar{s}s$ peng-

The first example of $B^0 \rightarrow \phi \phi$ decays, and
present the first measurements of the CP-averaged BR and
$A_{CP}$ for $B^+ \rightarrow \phi K^+$ [9] at hadron colliders. To cancel the
uncertainty in the $B$ hadron production cross section and to
reduce systematic uncertainties on detector efficiencies,
the branching fractions are extracted from ratios of the
decay rates of interest normalized to the established
$B^0 \rightarrow J/\psi \phi$ and $B^+ \rightarrow J/\psi K^+$ decay modes, which are charac-
terized by the same number of decay vertices and charged
tracks in the final state as in the signal modes.

In this analysis, we use 180 pb$^{-1}$ of $p\bar{p}$ collision data at
$\sqrt{s} = 1.96$ TeV collected by the upgraded collider detec-
tor (CDF II) at the Fermilab Tevatron. The components of
the CDF II detector pertinent to this analysis are briefly
described. A more complete description can be found else-
where [10]. We use tracks in the pseudorapidity range
$|\eta| \leq 1$ [11] reconstructed by a silicon microstrip vertex
detector (SVX II) [12] and the central outer tracker (COT)
[13], which are immersed in a 1.4 T solenoidal magnetic
field. The SVX II detector consists of double-sided sensors
arranged in five cylindrical layers. Surrounding the SVX II
is the COT, an open cell drift chamber with 96 sense wires.
The integrated charge collected by each wire provides a measure-
ment of the specific ionization $(dE/dx)$ for charged particles, allowing a separation equivalent to
$1.4 G \sigma$ between $\pi$ and $K$ for $p_T > 2$ GeV/c. A set of planar drift chambers, located outside the calorimeters and
additional steel absorbers, is used to detect muons within
$|\eta| \leq 1$ with high purity.

A sample enriched with heavy flavor particles is selected
by the three-level displaced track trigger. At level 1,
charged tracks are reconstructed in the COT by the ex-
remely fast tracker (XFT) [14]. The trigger requires two
oppositely charged tracks with transverse momenta $p_T \geq$
2 GeV/c and the scalar sum $p_{T1} + p_{T2} \geq 5.5$ GeV/c. At
level 2, the silicon vertex tracker [15] associates SVX II
$r$-$\phi$ position measurements with XFT tracks, providing a
precise measurement of the track impact parameter ($d_0$),
the distance of closest approach of the track trajectory to
the beam axis in the transverse plane. Decays of heavy
flavor particles are identified by requiring two tracks with
$120 \mu m \leq d_0 \leq 1.0 mm$ and an opening angle $2^\circ \leq$
$|\Delta \phi| \leq 90^\circ$. A requirement $L_{xy} > 200 \mu m$ is also ap-
plied, where the two-dimensional decay length $L_{xy}$ is
calculated as the transverse distance from the beam axis
to the two track intersection projected onto the total trans-
verse momentum of the track pair. A complete event
reconstruction is performed at level 3, where the level 1
and level 2 trigger requirements are confirmed.

$B$ candidates are reconstructed by detecting $\phi \rightarrow K^+ K^-$
and $J/\psi \rightarrow \mu^+ \mu^-$ decays. In the latter case, at least one of
the muons has to be identified in the muon detectors to
suppress contamination from other two-body $J/\psi$ decays.
At least one pair of tracks ("trigger tracks") has to satisfy the
trigger requirements. $B^+ (B^0)$ candidates are formed by
fitting three (four) tracks with $p_T > 0.4$ GeV/c to a com-
mon vertex. Requiring a good vertex fit $\chi^2$ reduces back-
ground from mismeasured tracks. Combinatoric
background is reduced by exploiting several variables
sensitive to the long lifetime and relatively hard $p_T$
spectrum of $B$ mesons and the isolation of $B$ hadrons inside
$b$-quark jets. For this purpose we define the quantity $I_R$
as the ratio of the $B^+$ candidate $p_T$ over the total transverse
momenta of all tracks within a cone of radius $R =$
$\sqrt{\Delta \eta^2 + \Delta \phi^2} = 1$ around the $B$ flight direction.
Requiring the $B$ flight direction to extrapolate back to the
beam axis decreases background from partially recon-
structed decays. The cut values on the discriminating vari-
ables are optimized by maximizing $S/\sqrt{S + B}$ for
the already observed $B^+ \rightarrow \phi K^+$ signal and $S/(1.5 + \sqrt{B})$
for $B^0 \rightarrow \phi \phi$ whose branching ratio is unknown.

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for $B^0 \rightarrow \phi \phi$ whose branching ratio is unknown.

The latter choice is equivalent to maximizing the potential to
reach a $3 \sigma$ observation of a new signal [16]. The signal ($S$)
is derived from a Monte Carlo (MC) simulation [17] of the
CDF II detector and trigger that uses the $B$ meson moment-
and rapidity distributions from Ref. [18], which were
matched to CDF data. The background ($B$) is represented
by appropriately normalized data selected with the same
requirements as the signal except for the two-kaon invar-
iant mass lying in the $\phi$ sideband region: $1.04 < m_{KK}$ <
1.06 GeV/c$^2$.

We discuss first the $B^+ \rightarrow \phi K^+$ analysis. The optimi-
Zation results in the following requirements: vertex $\chi^2 < 8$, $B^+$ decay length $L_{xy} > 350 \mu m$. $B^+$ reconstructed impact
parameter $d_0^\phi < 100 \mu m$, isolation $I_R > 0.5$, nontrigger
track transverse momentum $p_T^{\text{soft}} > 1.3$ GeV/c, and
impact parameter $d_0^{\text{soft}} > 120 \mu m$.

The $B^\pm \rightarrow \phi K^\pm$ total yield and $A_{CP}$, defined as

$$A_{CP} = \frac{N(B^- \rightarrow \phi K^-) - N(B^+ \rightarrow \phi K^+)}{N(B^- \rightarrow \phi K^-) + N(B^+ \rightarrow \phi K^+),}$$

are extracted simultaneously from an extended unbinned
maximum likelihood fit on four variables to the combined
$B^+$ and $B^-$ sample: the three-kaon invariant mass ($m_{KKK}$),
the invariant mass of the $\phi$ candidate ($m_{\phi}$), the cosine of
the $\phi$ meson helicity angle (defined as the angle between
the $K^+$ momentum in the parent $\phi$ rest frame and the
momentum of the $\phi$ in the $B$ rest frame), and the measured $dE/dx$ deviation from the expected value for pions for the lowest momentum trigger track. The likelihood function has seven components: signal, partially reconstructed $b \rightarrow X$ decays, combinatoric background, $B^+ \rightarrow K^{0}(892)\pi^+$, with $K^0 \rightarrow K^-\pi^+$, $B^+ \rightarrow f_0(980)K^+$, with $f_0 \rightarrow K^+K^-$, nonresonant $B^+ \rightarrow K^+K^-K^+$, and nonresonant $B^+ \rightarrow K^+\pi^-\pi^+$. The normalizations of the last three components are fixed to the $B^+ \rightarrow K^{0}(892)\pi^+$ yield, determined in the fit, through their relative decay rates and detection efficiencies. For each component the likelihood function is the product of four one-dimensional probability density functions (PDFs) of the fit variables, which are assumed to be uncorrelated. The $m_{KKK}$ and $m_{KK}$ distributions are shown in Fig. 1 with projections for the different components.

A combination of MC simulation and sideband data is used to derive the PDF in each variable for the various fit components. For $m_{KKK}$ the fully reconstructed signals are modeled by Gaussian functions. The mass and width of the $B$ signals are determined from the fit in the case of $KKK$ final states, while for $K\pi\pi$ they are fixed to the values predicted by the simulation. We derive a parametrization from simulation for the partially reconstructed decays that populate the low mass side of the $m_{KKK}$ distribution. An exponential plus a constant describe the combinatoric background. In the PDF for $m_{KK}$, the $\phi$ resonance is described by a Breit-Wigner convoluted with a Gaussian resolution function, while the combinatoric background is modeled by an empirical phase space function. Shapes for other backgrounds are derived from simulation. The $\phi$ helicity PDFs for $B$ decays are derived from simulation, while the combinatoric background PDF is modeled using data from the $\phi$ sideband. The $dE/dx$ PDFs for kaons and pions are derived from a high statistics $D^0 \rightarrow K^-\pi^+$ sample obtained from $D^+\pi^-$ decays. We find $N_{\phi K} = 47.0 \pm 8.4$, $A_{CP} = -0.07 \pm 0.17$, and $N_{\phi K} = 7.8 \pm 0.6$ (statistical errors only) from which we estimate a $B^+ \rightarrow f_0(980)K^+$ contamination of 11% under the signal peak.

Candidates for the normalization mode, $B^+ \rightarrow J/\psi K^+$, are selected with the same requirements as the $B^+ \rightarrow \phi K^+$ candidates except for the invariant mass of the two muons being within 100 MeV/$c^2$ of the $J/\psi$ mass [8]. Using an extended likelihood fit of the $m_{\mu\mu}K$ and $m_{\mu\mu}$ distributions, we obtain a total yield of $N_{\phi K} = 439 \pm 22$ (statistical error only). The asymmetry $A_{CP}(B^+ \rightarrow J/\psi K^+) = 0.046 \pm 0.050$ is consistent with zero, as expected for this mode.

The relative $B^+ \rightarrow \phi K^+$ decay rate is calculated using

$$\frac{BR(B^+ \rightarrow \phi K^+)}{BR(B^+ \rightarrow J/\psi K^+)} = \frac{N_{\phi K}}{N_{\phi K}} \frac{BR(J/\psi \rightarrow \mu\mu)}{BR(\phi \rightarrow KK)} \frac{e_{\phi K}^f}{e_{\phi K}^r},$$

where $e_{\phi K}/e_{\phi K} = 0.721 \pm 0.011$ is the ratio of the combined trigger and selection efficiencies derived from MC simulations with a correction of about 5% due to the different trigger efficiency for muons and kaons as measured in unbiased samples. The efficiency for identifying at least one of the decay muons, $e_{\mu} = 0.81 \pm 0.02$, is obtained by weighting the expected $p_T$ spectra in our signal with the single muon identification efficiency measured as a function of $p_T$ in a sample of inclusive $J/\psi \rightarrow \mu^+\mu^-$ decays. The relative $BR(B^+ \rightarrow \phi K^+)$ and $A_{CP}$ results are reported in Table I. Systematic uncertainties on signal yield ($\pm 1.4\%$ events) and asymmetry ($\pm 0.03$, $-0.02$) are evaluated by varying the PDFs used in the likelihood fit, including a variation of the $f_0(980)$ width from 40 to 100 MeV/$c^2$. The uncertainties on the determination of efficiency and muon identification introduce a 5.6% relative error in the measurement of the branching ratio and have no effect for $A_{CP}$. The uncertainties from $BR(\phi \rightarrow KK)$ and $BR(J/\psi \rightarrow \mu\mu)$ contribute an additional 2% to the total systematic. We determine a $\pm 0.005\%$ uncertainty on the $A_{CP}$ measurement arising from a possible tracking efficiency asymmetry for $K^+$ and $K^-$ as measured in minimum bias data.

A "blind" search for $B^0 \rightarrow \phi \phi$ decays was performed fixing the selection requirements and evaluating the combinatoric background from independent samples before taking data.
examing the signal region in the data. The signal is selected requiring two pairs of kaons having an invariant mass within 15 MeV/c² of the world average φ mass [8]. The optimized selection criteria are the following: vertex χ² < 10, B^0 decay length Lxy > 350 μm, φ reconstructed impact parameter d_0^p < 80 μm, minimum φ meson transverse momentum p_T ^φ > 2.5 GeV/c, and the minimum of the two kaons’ impact parameters from each φ meson candidate d_0^p min > 40 μm, d_0^p min > 110 μm, where φ_1 is the lower momentum φ candidate. The B^0 → φ φ candidate mass distribution is shown in Fig. 2. In a region of ±72 MeV/c² around the world average [8] B^0 mass, corresponding to a window 3 times the expected mass resolution, we observe 8 events.

Two sources of background are expected in the B^0 signal region: combinatoric background and B^0 → φ K^{−0} decays with the pion from the K^{−0} decay treated as a kaon. The combinatoric background generates a smooth distribution in the invariant mass region close to m_φ^0. Its contribution in the signal region is 0.35 ± 0.37 events (combining statistical and systematic uncertainties), estimated using a background enriched sample where both φ meson candidates have invariant mass lying in the φ mass sideband region. The B^0 → φ K^{−0} background results in an approximately Gaussian distribution underneath the B^0 signal. Its contribution, derived from simulation, is 0.37 ± 0.18 events, where the error includes both statistical and systematic uncertainties, resulting in a signal yield of 7.3 ± 2.5 events. The probability of a Poisson fluctuation of the background to the observed or higher number of events is 1.3 × 10^{-6}, corresponding to 4.7σ one-sided Gaussian significance.

For the determination of BR(B^0_s → φ φ), a normalization sample of B^0_s → J/ψ φ decays is selected, requiring one pair of kaons and one pair of muons within 15 and 50 MeV/c² of the world average φ and J/ψ mass, respectively. The other kinematic selection criteria are similar to the B^0_s → φ φ mode. To extract the number of B^0_s → J/ψ φ events, the candidate invariant mass distribution, shown in Fig. 2, is fit with a binned maximum likelihood function using a Gaussian for the signal and an exponential for the background. The fit returns N_{φ φ} = 69 ± 10(stat) ± 5(syst) events, where the systematic error is evaluated using alternative background models for the low mass region where partially reconstructed B decays are expected. We subtract 3.7 ± 1.7 background events from B^0 → J/ψ K^{−0} decays, with the pion treated as a kaon, as estimated from simulation.

The B^0_s → φ φ decay rate is derived from the relation

\[
\frac{BR(B^0_s \rightarrow φ φ)}{BR(B^0_s \rightarrow J/ψ φ)} = \frac{N_{φ φ} BR(J/ψ → μ μ)}{N_{φ φ} BR(φ → KK)} \frac{ε_φ}{ε_φ} \frac{ε_μ}{ε_μ},
\]

where ε_φ/ε_φ = 0.821 ± 0.015 is derived from simulation as in the B^+ → φ K^+ case and ε_μ/ε_μ = 0.92 ± 0.05 is obtained using the p_T spectra of the B^0_s → J/ψ φ signal and the muon identification efficiency curve discussed above.

The uncertainty on the B^0_s → J/ψ φ yield and background evaluation contribute 8% to the relative systematic error. The efficiencies significantly depend on both the polarization of the decay vector particles and the assumed value of ΔΓ_s since they affect the impact parameter of the decay products on which the trigger operates. We vary the longitudinal polarization of the B^0_s → φ φ decay from 20% to 80%, the B^0_s → J/ψ φ polarization amplitudes within 1σ of the CDF measurement [19], and ΔΓ_s in the range 0.06 < ΔΓ_s/Γ_s < 0.18 to assign a relative systematic un-
certainty of 4%. Summing in quadrature all contributions, we estimate a total relative systematic uncertainty on the ratio of $\text{BR}(B^+_d \to \phi \phi)$ to $\text{BR}(B^0 \to J/\psi \phi)$ of 11%. To convert the ratio $\text{BR}(B^+_d \to \phi \phi)/\text{BR}(B^0 \to J/\psi \phi)$ reported in Table I in a measurement of $\text{BR}(B^+_d \to \phi \phi)$, we use $\text{BR}(B^0 \to J/\psi \phi) = (1.38 \pm 0.49) \times 10^{-3}$, obtained from correcting the CDF measurement [20] for the current study two fully reconstructed $B$ decays. Using the world average [8] $\text{BR}(B^+ \to J/\psi K^+)$, we measure $\text{BR}(B^+ \to \phi K^+) = [7.6 \pm 1.3(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}$ and $A_{CP}(B^+ \to \phi K^+) = -0.07 \pm 0.17(\text{stat}) \pm 0.03(\text{syst})$, which agree with previous measurements [8]. We find the first evidence of a charmless vector-vector $B^0$ decay and measure $\text{BR}(B^0 \to \phi \phi)$, in agreement with the estimate of Ref. [5] and the recently amended calculation in [6].

In summary, we have used $p\bar{p}$ collision data collected with the displaced track trigger of the CDF II detector to study two fully reconstructed $b \to s \bar{s}s$ penguin dominated $B$ decays. Using the world average [8] $\text{BR}(B^+ \to J/\psi K^+)$, we measure $\text{BR}(B^+ \to \phi K^+) = [7.6 \pm 1.3(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}$ and $A_{CP}(B^+ \to \phi K^+) = -0.07 \pm 0.17(\text{stat}) \pm 0.03(\text{syst})$, which agree with previous measurements [8]. We find the first evidence of a charmless vector-vector $B^0$ decay and measure $\text{BR}(B^0 \to \phi \phi)$, in agreement with the estimate of Ref. [5] and the recently amended calculation in [6].

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[9] Charge conjugate decay modes are implied throughout this Letter unless otherwise stated.
[11] CDF II uses a cylindrical coordinate system in which $\phi$ is the azimuthal angle, $r$ is the radius from the nominal beam axis, $y$ points up, and $z$ points in the proton beam direction with the origin at the center of the detector. The transverse plane is the plane perpendicular to the $z$ axis.