

## Measurement of Polarization and Search for $CP$ Violation in $B_s^0 \rightarrow \phi\phi$ Decays

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We present the first measurement of polarization and  $CP$ -violating asymmetries in a  $B_s^0$  decay into two light vector mesons,  $B_s^0 \rightarrow \phi\phi$ , and an improved determination of its branching ratio using 295 decays reconstructed in a data sample corresponding to  $2.9 \text{ fb}^{-1}$  of integrated luminosity collected by the CDF experiment at the Fermilab Tevatron collider. The fraction of longitudinal polarization is determined to be  $f_L = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst})$ , and the branching ratio  $\mathcal{B}(B_s^0 \rightarrow \phi\phi) = [2.32 \pm 0.18(\text{stat}) \pm 0.82(\text{syst})] \times 10^{-5}$ . Asymmetries of decay angle distributions sensitive to  $CP$  violation are measured to be  $A_u = -0.007 \pm 0.064(\text{stat}) \pm 0.018(\text{syst})$  and  $A_v = -0.120 \pm 0.064(\text{stat}) \pm 0.016(\text{syst})$ .

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Several charmless  $B_s^0$  decays were observed at the Tevatron in Run II [1,2], but a detailed investigation of decay properties and of  $CP$  violation in these decays is still lacking. The  $B_s^0 \rightarrow \phi\phi$  process is mediated by a one-loop flavor-changing neutral current, the  $b \rightarrow s$  penguin, and belongs to the class of decays where the final state consists of a pair of light spin-1 mesons ( $V$ ). Three independent amplitudes govern  $B \rightarrow VV$  decays, corresponding to the polarizations of the final-state vector mesons: longitudinal polarization, and transverse polarization with spins parallel or perpendicular to each other. The first two states are  $CP$  even, while the last one is  $CP$  odd. Polarization amplitudes can be measured analyzing angular distributions of final-state particles. Interference between the  $CP$ -even

and  $CP$ -odd amplitudes can generate asymmetries in angular distributions, the triple product (TP) asymmetries, which may signal unexpected  $CP$  violation due to physics beyond the standard model (SM).

The  $V$ - $A$  structure of charged weak currents leads to the expectation of a dominant longitudinal polarization [3,4]. Approximately equal longitudinal and transverse polarizations have been measured instead in  $b \rightarrow s$  penguin-dominated  $B^0$  and  $B^+$  decay modes [5]. This is explained in the SM by including either nonfactorizable penguin-annihilation effects [6] or final-state interactions [7]. Recent theoretical predictions [3,4] indicate a longitudinal fraction  $f_L$  in the 40%–70% range, when phenomenological parameters are adjusted to accommodate present



experimental data. Explanations involving new physics (NP) in the  $b \rightarrow s$  penguin process have also been proposed [8]. Additional experimental information in  $B_s^0$  penguin-dominated decays, such as  $B_s^0 \rightarrow \phi\phi$ , may help distinguishing the various solutions [9], and can be used to derive upper limits for the mixing-induced  $CP$  asymmetries [10].

Triple product asymmetries are odd under time reversal ( $T$ ), and can be generated either by final-state interactions or  $CP$  violation. In flavor-untagged samples, where the initial  $B$  flavor is not identified, TP asymmetries can be shown to signify genuine  $CP$  violation [11]. In this respect they are very sensitive to the presence of NP in the decay since they do not require a strong-phase difference between NP and SM amplitudes, as opposed to direct  $CP$  asymmetries [12]. The TP asymmetry is defined as  $\mathcal{A}_{TP} = \frac{\Gamma(\text{TP}>0) - \Gamma(\text{TP}<0)}{\Gamma(\text{TP}>0) + \Gamma(\text{TP}<0)}$ , where  $\Gamma$  is the decay width for the given process. In  $B_s^0 \rightarrow \phi\phi$  decays two TP asymmetries can be studied, corresponding to the two interference terms between amplitudes with different  $CP$ . These asymmetries are predicted to vanish in the SM, and an observation of a nonzero asymmetry would be an unambiguous sign of NP [12].

In this Letter we present the first measurement of polarization amplitudes and of TP asymmetries in the  $B_s^0 \rightarrow \phi\phi$  decay and an updated measurement of its branching ratio using  $B_s^0 \rightarrow J/\psi\phi$  decays reconstructed in the same data set as a normalization. Data from an integrated luminosity of  $2.9 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$  are analyzed.

The components of the CDF II detector relevant for this analysis are briefly described below; a more complete description can be found elsewhere [13]. We reconstruct charged-particle trajectories (tracks) in the pseudorapidity range  $|\eta| \lesssim 1$  [14] using a silicon microstrip vertex detector [15] and a central drift chamber [16], both immersed in a 1.4 T solenoidal magnetic field. The detection of muons in the pseudorapidity range  $|\eta| \lesssim 0.6$  is provided by two sets of drift chambers located behind the calorimeters (CMU) and behind additional steel absorbers (CMP), while the CMX detector covers the range  $0.6 \lesssim |\eta| \lesssim 1.0$  [17]. A sample enriched with heavy-flavor particles is selected by the displaced-track trigger [18], based on the silicon vertex trigger (SVT) [19]. It provides a precise measurement of the track impact parameter ( $d_0$ ), defined as the distance of closest approach to the beam axis in the transverse plane. Decays of heavy-flavor particles are identified by requiring two tracks with  $120 \mu\text{m} \leq d_0 \leq 1.0 \text{ mm}$  and applying a requirement on the two-dimensional decay length,  $L_{xy} > 200 \mu\text{m}$  [20].

We reconstruct  $B_s^0$  mesons by first forming  $\phi \rightarrow K^+K^-$  and  $J/\psi \rightarrow \mu^+\mu^-$  candidate decays from opposite-sign track pairs with mass within 15 and 100  $\text{MeV}/c^2$  of the known [21]  $\phi$  and  $J/\psi$  mass, respectively. At least one  $J/\psi$  track is required to match a segment reconstructed in

the muon detectors. We form  $B_s^0 \rightarrow \phi\phi$  ( $B_s^0 \rightarrow J/\psi\phi$ ) candidates by fitting to a single vertex the  $\phi\phi$  ( $J/\psi\phi$ ) candidate pairs. In the  $B_s^0 \rightarrow J/\psi\phi$  case the fit constrains the mass of the two muons to the  $J/\psi$  mass [21]. At least one pair of tracks in the  $B_s^0$  candidate must satisfy the trigger requirements. Combinatorial background and partially reconstructed decays are reduced by exploiting the long lifetime and relatively hard  $p_T$  spectrum of  $B_s^0$  mesons. We follow closely the selection adopted in [1], using the vertex fit  $\chi^2$ , the  $L_{xy}$ , the reconstructed  $B_s^0$  and  $\phi$  meson impact parameters, and the minimum kaon transverse momentum as discriminating variables. The selection requirements are set by maximizing the quantity  $S/\sqrt{S+B}$ , where the accepted number of signal events  $S$  is derived from a Monte Carlo (MC) simulation [22] of the CDF II detector and trigger, while the number of background events  $B$  is modeled using data in mass sideband regions: (5.02, 5.22) and (5.52, 5.72)  $\text{GeV}/c^2$ . The resulting mass distributions are shown in Fig. 1.

A binned maximum likelihood (ML) fit to the  $m_B$  distribution is performed to determine the  $B_s^0$  yield for both decay modes. The signal is parametrized by two Gaussian functions with the same mean value, but different widths. The ratios between the two widths and between the integrals of the two components are fixed based on MC simulations. The combinatorial background has a smooth mass distribution near the signal and is modeled with an exponential function. A reflection from  $B^0 \rightarrow \phi K^*(892)^0$  ( $B^0 \rightarrow J/\psi K^*(892)^0$ ) with misassigned kaon mass to final-state pions contaminates the  $B_s^0 \rightarrow \phi\phi$  ( $B_s^0 \rightarrow J/\psi\phi$ ) signal region. Parametrizations and efficiencies determined from simulation are used for these backgrounds. Their normalizations are derived from the known [21] branching ratios, fragmentation fraction ratio  $f_s/f_d$ , and the ratio of the detection efficiencies relative to signal ones. We estimate  $(4.19 \pm 0.93)\%$  and  $(2.7 \pm 1.0)\%$  reflection background under the  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow \phi\phi$  signals, respectively. Free parameters of the fit are the

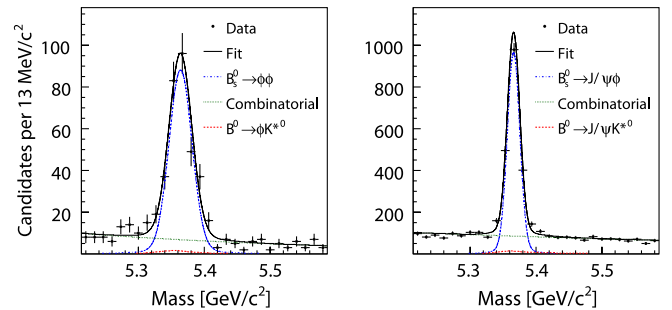


FIG. 1 (color online). The invariant mass of the four kaons (left) and of the  $J/\psi$  and two kaons (right) for  $B_s^0 \rightarrow \phi\phi$  and  $B_s^0 \rightarrow J/\psi\phi$  candidates, overlaid with fit projections and separate signal and background components. The narrower signal peak for the  $B_s^0 \rightarrow J/\psi\phi$  is due to the  $J/\psi$  mass constraint applied in the reconstruction.

signal fraction, the  $B_s^0$  mass  $M$ , and width  $\sigma$ , together with the exponential slope  $b_0$  defining the combinatorial background mass shape. We estimate the total number of signal decays as  $N_{\phi\phi} = 295 \pm 20(\text{stat}) \pm 12(\text{syst})$  and  $N_{\psi\phi} = 1766 \pm 48(\text{stat}) \pm 41(\text{syst})$ , where the systematic uncertainty is estimated by varying signal and background models.

The  $B_s^0 \rightarrow \phi\phi$  decay rate is derived from the relation

$$\frac{\mathcal{B}(B_s^0 \rightarrow \phi\phi)}{\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)} = \frac{N_{\phi\phi}}{N_{\psi\phi}} \frac{\mathcal{B}(J/\psi \rightarrow \mu\mu)}{\mathcal{B}(\phi \rightarrow KK)} \frac{\epsilon_{\psi\phi}}{\epsilon_{\phi\phi}} \epsilon_{\psi\phi}^{\mu}$$

where  $\epsilon_{\psi\phi}/\epsilon_{\phi\phi}$  is the acceptance times efficiency ratio for the two decays and  $\epsilon_{\psi\phi}^{\mu}$  is the efficiency for identifying at least one of the two muons. The efficiency ratio is determined using a MC simulation of the CDF II detector and trigger, whose reliability in determining relative trigger and reconstruction efficiencies has been verified for several different decay modes also using data-driven approaches [23]. We estimate  $\epsilon_{\psi\phi}/\epsilon_{\phi\phi} = 0.939 \pm 0.099$ , where the uncertainty includes systematic effects from polarization uncertainties in the two decay modes (9%), from the different trigger efficiencies for kaons and muons (4%), and from the  $B_s^0 p_T$  spectra (1%). We use inclusive  $J/\psi$  data to derive the single-muon identification efficiency as a function of muon  $p_T$ . It is determined separately in two pseudorapidity regions corresponding, respectively, to the CMU/CMP and CMX detectors, and is described by a turn-on function that depends on a plateau, a slope, and a threshold parameter. We use simulated  $B_s^0 \rightarrow J/\psi\phi$  decays to calculate  $\epsilon_{\psi\phi}^{\mu}$  treating the efficiencies for the two muons as uncorrelated:  $\epsilon_{\psi\phi}^{\mu} = [86.95 \pm 0.44(\text{stat}) \pm 0.75(\text{syst})]\%$ . The systematic uncertainty includes the uncertainty on the background subtraction and effects of residual correlation between the two muon efficiencies.

We measure  $\mathcal{B}(B_s^0 \rightarrow \phi\phi)/\mathcal{B}(B_s^0 \rightarrow J/\psi\phi) = [1.78 \pm 0.14(\text{stat}) \pm 0.20(\text{syst})] \times 10^{-2}$  and derive  $\mathcal{B}(B_s^0 \rightarrow \phi\phi) = [2.32 \pm 0.18(\text{stat}) \pm 0.26(\text{syst}) \pm 0.78(\text{BR})] \times 10^{-5}$ , using the known [21]  $\mathcal{B}(B_s^0 \rightarrow J/\psi\phi)$ , which contributes the dominant uncertainty, labeled (BR). This result is in agreement and supersedes our previous measurement [1] with a substantial reduction of its statistical uncertainty; it is also consistent with recent theoretical calculations [3,4].

We describe the angular distribution of the  $B_s^0 \rightarrow \phi\phi$  decay products using the helicity variables  $\vec{\omega} = (\cos\vartheta_1, \cos\vartheta_2, \Phi)$ , where  $\vartheta_i$  is the angle between the direction of the  $K^+$  from each  $\phi$  and the direction opposite the  $B_s^0$  in the vector meson rest frame, and  $\Phi$  is the angle between the two resonance decay planes in the  $B_s^0$  rest frame. The three independent complex amplitudes are  $A_0$  for the longitudinal polarization and  $A_{\parallel}$  ( $A_{\perp}$ ) for transverse polarization with spins parallel (perpendicular) to each other. They are related by  $|A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2 = 1$ . The differential decay rate is expressed as

$d^4\Gamma/(dt d\vec{\omega}) \propto \sum_{i=1}^6 K_i(t) f_i(\vec{\omega})$ , where the functions  $K_i(t)$  encode the  $B_s^0$  time evolution including mixing and depend on the polarization amplitudes, and the  $f_i(\vec{\omega})$  are functions of the helicity angles only [12]. To extract the polarization amplitudes we measure the time-integrated angular distribution assuming no direct  $CP$  violation and a negligible weak phase difference between  $B_s^0$  mixing and  $B_s^0 \rightarrow \phi\phi$  decay as predicted in the SM. The time-integrated differential decay rate depends on the polarization amplitudes at  $t = 0$  and on the light and heavy  $B_s^0$  mass-eigenstate lifetimes,  $\tau_L$  and  $\tau_H$ , as follows:

$$\frac{d^3\Gamma}{d\vec{\omega}} \propto \tau_L[|A_0|^2 f_1(\vec{\omega}) + |A_{\parallel}|^2 f_2(\vec{\omega}) + |A_0||A_{\parallel}| \cos\delta_{\parallel} f_5(\vec{\omega})] + \tau_H|A_{\perp}|^2 f_3(\vec{\omega}), \quad (1)$$

where  $\delta_{\parallel} = \arg(A_0^* A_{\parallel})$  and

$$\begin{aligned} f_1(\vec{\omega}) &= 4\cos^2\vartheta_1 \cos^2\vartheta_2, \\ f_2(\vec{\omega}) &= \sin^2\vartheta_1 \sin^2\vartheta_2 (1 + \cos 2\Phi), \\ f_3(\vec{\omega}) &= \sin^2\vartheta_1 \sin^2\vartheta_2 (1 - \cos 2\Phi), \\ f_5(\vec{\omega}) &= \sqrt{2} \sin 2\vartheta_1 \sin 2\vartheta_2 \cos\Phi. \end{aligned}$$

Two triple products are present in  $B \rightarrow VV$  decays:  $\text{TP}_2 \equiv \text{Im}(A_{\parallel}^* A_{\perp})$ , and  $\text{TP}_1 \equiv \text{Im}(A_0^* A_{\perp})$ . These factors appear, respectively, in the decay rate terms  $K_4(t)$  and  $K_6(t)$  multiplied by the functions

$$\begin{aligned} f_4(\vec{\omega}) &= -2\sin^2\vartheta_1 \sin^2\vartheta_2 \sin 2\Phi, \\ f_6(\vec{\omega}) &= -\sqrt{2} \sin 2\vartheta_1 \sin 2\vartheta_2 \sin\Phi. \end{aligned}$$

In flavor-untagged samples the TP terms, that vanish in the absence of NP, are proportional to the so-called *true* triple products, and provide two  $CP$ -violating observables,  $\mathcal{A}_{\text{TP}}^1$  and  $\mathcal{A}_{\text{TP}}^2$  [11]. We access  $\mathcal{A}_{\text{TP}}^2$  through the observable  $u = \sin 2\Phi$ . We measure the  $u$  asymmetry,  $A_u$ , by integrating over  $\cos\vartheta_{1,2}$  the untagged decay rate and counting events with  $u > 0$  ( $N_u^+$ ) and  $u < 0$  ( $N_u^-$ ). Similarly,  $\mathcal{A}_{\text{TP}}^1$  is accessed through an asymmetry in  $\sin\Phi$ . We define the observable  $v$  as  $v = \sin\Phi$  ( $v = -\sin\Phi$ ) if  $\cos\vartheta_1 \cos\vartheta_2 \geq 0$  ( $\cos\vartheta_1 \cos\vartheta_2 < 0$ ) and measure its asymmetry  $A_v$  by counting events with  $v > 0$  ( $N_v^+$ ) and  $v < 0$  ( $N_v^-$ ). The asymmetries are defined as

$$\begin{aligned} A_{u(v)} &= \frac{N_{u(v)}^+ - N_{u(v)}^-}{N_{u(v)}^+ + N_{u(v)}^-} = \mathcal{N}_{u(v)} \times [\text{Im}(A_{\parallel(0)}^* A_{\perp}) \\ &\quad + \text{Im}(\bar{A}_{\parallel(0)}^* \bar{A}_{\perp})] = \mathcal{N}_{u(v)} \mathcal{A}_{\text{TP}}^{2(1)}, \end{aligned}$$

where the two normalization factors are  $\mathcal{N}_u = -2/\pi$  and  $\mathcal{N}_v = -\sqrt{2}/\pi$ . Both  $A_u$  and  $A_v$  are proportional to  $CP$ -violating TP asymmetries, and are also sensitive to mixing-induced TP when considering the decay-width difference of the  $B_s^0$  system.

We perform an unbinned ML fit to the reconstructed mass of the  $B_s^0$  candidates and the helicity angles in order to measure the polarization amplitudes. The contribution of each candidate to the likelihood is  $\mathcal{L}_i = f_s \mathcal{P}_s(m_{B_i}, \vec{\omega}_i | \vec{\xi}_s) + (1 - f_s) \mathcal{P}_b(m_{B_i}, \vec{\omega}_i | \vec{\xi}_b)$ , where  $f_s$  is the signal fraction and  $\mathcal{P}_j$  are the probability density functions (PDFs) for the  $B_s^0 \rightarrow \phi\phi$  signal ( $j = s$ ) and background ( $j = b$ ) components, which depend on the fit parameters  $\vec{\xi}_s$  and  $\vec{\xi}_b$ , respectively. The effects of neglecting the reflection background are included in the systematic uncertainties. Both the signal and the background PDFs are the products of a mass component, described earlier, and an angular one. The signal angular component is given by Eq. (1) multiplied by an acceptance factor. The acceptance is computed in bins of the helicity angles from simulated  $B_s^0 \rightarrow \phi\phi$  decays averaged over all possible spin states of the decay products and passed through detector simulation, full reconstruction, and analysis cuts. We use an empirical parametrization derived from the observed angular distributions in the mass sidebands to model the background angular PDF: the product of a flat distribution for the  $\Phi$  angle and a parabolic function for the other two, whose single parameter  $b_1$  is a fit parameter. We fix  $\tau_L$  and  $\tau_H$  to the world average values [21]. There are eight free parameters in the fit:  $f_s$ ,  $\vec{\xi}_s = (M, \sigma, |A_0|^2, |A_{\parallel}|^2, \cos\delta_{\parallel})$  and  $\vec{\xi}_b = (b_0, b_1)$ . The fit has been extensively tested using simulated samples with a variety of input parameters and shows unbiased estimates of parameters and their uncertainties. We also perform the polarization measurement using the sample of  $\approx 1700$   $B_s^0 \rightarrow J/\psi\phi$  candidates described earlier. We find  $|A_0|^2 = 0.534 \pm 0.019(\text{stat})$  and  $|A_{\parallel}|^2 = 0.220 \pm 0.025(\text{stat})$ , in good agreement with current measurements [24]. The results of the polarization analysis for the  $B_s^0 \rightarrow \phi\phi$  sample are summarized in Table I. In Fig. 2 we show the fit projections onto the helicity angles. The dominant correlation of the fit parameters is between  $|A_0|^2$  and  $|A_{\parallel}|^2$  ( $-0.447$ ), the others being much smaller. Several sources of systematic uncertainty have been studied. We account for the neglected physics backgrounds considering the  $B^0 \rightarrow \phi K^*(892)^0$  decay and two other possible contaminations:  $B_s^0 \rightarrow \phi f_0(980)$ , with  $f_0 \rightarrow K^+ K^-$ , and  $B_s^0 \rightarrow \phi K^+ K^-$  (nonresonant). The latter

two contributions are normalized to the signal yield in analogy with similar  $B^0 \rightarrow \phi X$  decays. We assume up to 4.6% contamination from  $B_s^0 \rightarrow \phi f_0$  and 0.9% of  $B_s^0 \rightarrow \phi K^+ K^-$ , and determine a 1.5%(0.4%) shift in the central value for  $|A_0|^2(|A_{\parallel}|^2)$  using simulated experiments. Biases introduced by the time integration are examined with MC simulation: they are created by the dependence of the angular acceptance on  $\Delta\Gamma_s$  and by a nonuniform acceptance in the  $B_s^0$  proper decay time introduced by the displaced-track trigger. The assigned systematic uncertainty (1%) is the full shift expected in the central value, assuming a value for  $\Delta\Gamma_s$  equal to the world average plus 1 standard deviation [21]. We also consider the propagation of  $\tau_{L(H)}$  uncertainties to the polarization amplitudes (1%). Other sources of minor systematic uncertainties are the modeling of the combinatorial background (0.4%) and of the angular acceptance (0.5%). The impact of  $CP$ -violating effects on the measured amplitudes is negligible.

The asymmetries  $A_i$  ( $i = u, v$ ) are evaluated through an unbinned ML fit to  $m_B$  only, using the joint likelihood for the  $N_i^+$  and  $N_i^-$  events with positive and negative  $u$  ( $v$ ). The same  $m_B$  PDF parametrization discussed above is used for samples with both  $u$  ( $v$ ) signs. We multiply the total likelihood by the binomial  $f(N_i^+, N_i^- | p)$ , where the probability  $p$  of obtaining  $N_i^+$  and  $N_i^-$  events depends on the overall signal fraction  $f_s$ , the signal asymmetry  $A_i$ , and the background asymmetry  $A_b^i$ :  $p = \frac{1}{2}[1 + A_i f_s + (1 - f_s) A_b^i]$ . Mass and width for the  $B_s^0$  signal, as well as signal fraction, are consistent with those obtained in the polarization analysis, while background asymmetries are consistent with zero. The measured  $B_s^0 \rightarrow \phi\phi$  asymmetries are reported in Table I. The systematic uncertainty is evaluated using an alternate background parametrization as in the polarization analysis and by conservatively assigning maximal asymmetry to the neglected physics background peaking in the signal region. Using a large sample of simulated events, we check that the detector acceptance and resolution introduce a bias in the asymmetries smaller than 0.2%.

In summary, we measure for the first time the polarization amplitudes and the triple product asymmetries in the  $B_s^0 \rightarrow \phi\phi$  decay. We find a significantly suppressed longitudinal fraction  $f_L = |A_0|^2 = 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst})$ , smaller than in other  $b \rightarrow s$  penguin  $B \rightarrow VV$

TABLE I. Summary of the  $B_s^0 \rightarrow \phi\phi$  measurements. The first uncertainty quoted is statistical and the second is systematic.

Observable	Result
$\mathcal{B}$	$[2.32 \pm 0.18 \pm 0.82] \times 10^{-5}$
$ A_0 ^2$	$0.348 \pm 0.041 \pm 0.021$
$ A_{\parallel} ^2$	$0.287 \pm 0.043 \pm 0.011$
$ A_{\perp} ^2$	$0.365 \pm 0.044 \pm 0.027$
$\cos\delta_{\parallel}$	$-0.91_{-0.13}^{+0.15} \pm 0.09$
$A_u$	$-0.007 \pm 0.064 \pm 0.018$
$A_v$	$-0.120 \pm 0.064 \pm 0.016$

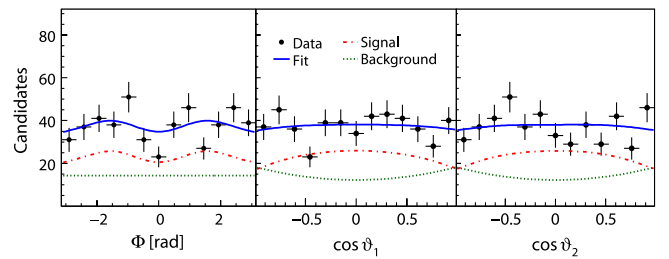


FIG. 2 (color online). Angular distribution for  $B_s^0 \rightarrow \phi\phi$  events with the fit projection, signal, and background component superimposed.



decays [5]. This result agrees well with predictions [3] based on QCD factorization, but only marginally with perturbative QCD ones [4], and hints at a large penguin-annihilation contribution [9]. The two measured asymmetries are statistically consistent with the no  $CP$  violation hypothesis, although  $A_{\nu}$  is  $1.8\sigma$  different from zero.

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