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A Search for the Decay $B^0 \to \pi^0\pi^0$

The *BABAR* Collaboration

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Abstract

We present a search for the decay $B^0 \to \pi^0\pi^0$ by the *BABAR* experiment at the PEP-II asymmetric-energy B-factory at SLAC. Using approximately 88 million $B\overline{B}$ pairs collected between 1999 and 2002, we place a 90% confidence level upper limit on the branching fraction of

$$\mathcal{B}(B^0 \to \pi^0\pi^0) < 3.6 \times 10^{-6}\,.$$

This result is preliminary.

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1 Introduction

The study of B meson decays into charmless hadronic final states plays an important role in the understanding of *CP* violation in the B system. Measurements of the *CP*-violating asymmetry in the $B^0 \to \pi^+\pi^-$ decay mode can provide information on the angle α of the Unitarity Triangle. However, in contrast to the theoretically clean determination of the angle β in B decays to charmonium final states [1, 2], the extraction of α in $B^0 \to \pi^+\pi^-$ is complicated by the interference of tree and penguin amplitudes with different weak phases. The time dependent *CP*-violating asymmetry in $B^0 \to \pi^+\pi^-$ is proportional to $\sin 2\alpha_{\text{eff}}$. Assuming an isospin relation [3], $|\alpha_{\text{eff}} - \alpha|$ may be determined from the branching fractions $\mathcal{B}(B^\pm \to \pi^\pm\pi^0)$, $\mathcal{B}(B^0 \to \pi^+\pi^-)$, $\mathcal{B}(\overline{B}^0 \to \pi^+\pi^-)$, $\mathcal{B}(B^0 \to \pi^0\pi^0)$, and $\mathcal{B}(\overline{B}^0 \to \pi^0\pi^0)$. Alternatively, a bound on $\alpha_{\text{eff}} - \alpha$ may be found from the ratio $\mathcal{B}(B^0 \to \pi^0\pi^0)/\mathcal{B}(B^\pm \to \pi^\pm\pi^0)$, using the average of B^0 and $\overline{B}^0$ branching fractions [4]. In this paper, we report on a search for the decay $B^0 \to \pi^0\pi^0$. Here and throughout this paper $B^0 \to \pi^0\pi^0$ is meant to include both B^0 and $\overline{B}^0$ decays.

2 The *BABAR* Detector and Dataset

BABAR is a solenoidal detector optimized for the asymmetric beams at PEP-II and is described in detail in Ref. [5]. Charged particle (track) momentum and direction are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) embedded in a 1.5 T superconducting solenoidal magnet. Neutral cluster position and energy are measured by an electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals. The photon energy resolution is $\sigma_E/E = (2.32/E(\text{ GeV})^{1/4} \oplus 1.85)\%$, and the angular resolution is $\sigma_\theta = 3.87^{\text{o}}/\sqrt{E(\text{ GeV})}$. Charged hadrons are identified with a detector of internally reflected Cherenkov light (DIRC) and specific ionization in the tracking detectors. The instrumented magnetic flux return (IFR) detects neutral hadrons and identifies muons.

This search uses $(87.9 \pm 1.0) \times 10^6$ $B\overline{B}$ pairs from approximately $81\,\text{fb}^{-1}$ of data at the $\Upsilon(4S)$ resonance (on-resonance), and approximately $9\,\text{fb}^{-1}$ of data at $40\,\text{MeV}$ below the $\Upsilon(4S)$ resonance (off-resonance), collected with the *BABAR* detector from 1999 through 2002. The PEP-II collider is operated with asymmetric beam energies, corresponding to a boost for the $\Upsilon(4S)$ of $\beta\gamma = 0.55$.

3 Event Selection

$B\overline{B}$ events are selected using track and neutral cluster content and event topology. Events are required to have either three or more well measured tracks from the interaction point with transverse momentum $p_T > 0.1$ GeV/c and polar angle in the lab frame $0.41 < \theta_{\text{lab}} < 2.54$ rad, or two or fewer such tracks combined with two or more neutral clusters with center-of-mass (CM) energy $E_{CM} > 0.5\,\text{GeV}$ and one or more additional neutral clusters with laboratory energy $E_{\text{lab}} > 0.1\,\text{GeV}$. Backgrounds from lepton pair events are removed by requiring that the ratio of the second to zeroth Fox-Wolfram moment be less than 0.95 and the event sphericity be greater than 0.01. The principal background is from the $e^+e^- \to q\overline{q}$ process ($q = u, d, s, c$), when both quark jets contain a π^0 which combine to mimic a B decay. This background is suppressed by requiring that the cosine of the angle between the sphericity axis of the B candidate and the sphericity axis of the remaining tracks and neutral clusters in the event satisfy $|\cos\theta_S| < 0.7$.

4 Candidate Selection

Candidate π^0 mesons are formed from two neutral clusters with $E > 0.03\,\mathrm{GeV}$ whose transverse energy profile in the EMC is consistent with that of a single photon. The centroid of the two clusters must be separated by at least one EMC crystal. To reduce the background from false π^0 candidates, the cosine of the angle between the γ momentum vector in the π^0 rest frame and the π^0 momentum vector in the lab frame is required to satisfy $|\cos\theta_\gamma| < 0.95$. The invariant mass of the two photons is required to be within $\pm 3\sigma$ of the π^0 mass.

$B^0 \to \pi^0\pi^0$ candidates are formed from pairs of π^0 candidates. The remaining background is from $q\bar{q}$ events that have a spherical topology and pass the $|\cos\theta_S|$ requirement, and $B^\pm \to \rho^\pm\pi^0$ decays in which the $\pi^\pm$ is emitted nearly at rest in the B frame. No other B decay produces a significant background for $B^0 \to \pi^0\pi^0$. The $B^\pm \to \rho^\pm\pi^0$ decay mode has not been observed; the limit on its branching fraction is $\mathcal{B}(B^\pm \to \rho^\pm\pi^0) < 4.3 \times 10^{-5}$ at 90% CL [6]. Both backgrounds are separated from signal by using the kinematic constraints of B mesons produced at the $\Upsilon(4S)$. The first kinematic parameter is a beam-energy substituted mass $m_{\mathrm{ES}} = \sqrt{E_b^2 - \mathbf{p}_B^2}$, where $E_b = (s/2 + \mathbf{p}_i \cdot \mathbf{p}_B)/E_i$; $\sqrt{s}$ and E_i are the total energy of the e^+e^- system in the CM and laboratory frames, respectively, and $\mathbf{p}_i$ and $\mathbf{p}_B$ are the momentum vectors in the lab frame of the e^+e^- system and the B candidate, respectively. The second kinematic parameter is $\Delta E = E_B - \sqrt{s}/2$, where E_B is the B candidate energy calculated in the CM frame. In $B^0 \to \pi^0\pi^0$ events the m_{ES} and ΔE resolution are predicted to be approximately $3.8\,\mathrm{MeV}/c^2$ and $80\,\mathrm{MeV}$, respectively, based on simulation.

There are 3020 candidates with $m_{\mathrm{ES}} > 5.2\,\mathrm{GeV}/c^2$ and $|\Delta E| < 0.2\,\mathrm{GeV}$ which are used in this search. The $B^0 \to \pi^0\pi^0$ signal efficiency is evaluated with a GEANT4 based detector simulation [7]. The efficiency to separate closely spaced photons in the EMC is measured using $\tau^\pm \to \pi^\pm\pi^0\nu_\tau$ and $\tau^\pm \to \pi^\pm\pi^0\pi^0\nu_\tau$ decays, and uncertainty in this efficiency dominates the error in the signal efficiency. The $B^0 \to \pi^0\pi^0$ efficiency is $(16.5 \pm 1.7)\%$.

The $B^\pm \to \rho^\pm\pi^0$ background is reduced by removing candidates in which the omitted $\pi^\pm$ is identified. Tracks that are not identified as leptons or kaons, and that are not part of a reconstructed $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi$, or $\gamma \to e^+e^-$ candidate, are used. The track that has a $\pi^\pm\pi^0$ invariant mass and m_{ES} of the $\pi^\pm\pi^0\pi^0$ combination most consistent with the ρ mass and $B^\pm \to \rho^\pm\pi^0$ hypothesis is selected. A cut is applied on a linear combination of the $\pi^\pm\pi^0$ invariant mass and the ΔE of the $\pi^\pm\pi^0\pi^0$ combination which removes roughly 50% of $B^\pm \to \rho^\pm\pi^0$, with 93% efficiency for $B^0 \to \pi^0\pi^0$. Only $(0.40 \pm 0.04)\%$ of $B^\pm \to \rho^\pm\pi^0$ decays remain after all cuts.

The $q\bar{q}$ background that remains after all cuts is further distinguished from signal using a Fisher discriminant $\mathcal{F}_T$ that combines energy flow and B flavor tagging variables. The energy flow variables are $L_0 = \sum_i p_i$, and $L_2 = \sum_i p_i \times \frac{1}{2}(3\cos^2(\theta_i) - 1)$, where the sum is over all tracks and neutral clusters in the event except the daughters of the $B^0 \to \pi^0\pi^0$ candidate. Here θ_i is the angle with respect to the thrust axis of the B candidate and p_i is the momentum magnitude, both in the CM frame. The B flavor tagging variable is a quality index which classifies the lepton, charged kaon, and slow pion $\pi^\pm_{\mathrm{slow}}$ (from the decay $D^{*\pm} \to D^0\pi^\pm_{\mathrm{slow}}$) content of the event. The quality index is ordered by the degree of background rejection. The leptons, charged kaons, and slow pions are selected and the events are classified with the B flavor tagging algorithm described in Ref. [1]. The coefficients of $\mathcal{F}_T$ are optimized using Monte Carlo simulation of signal and $q\bar{q}$ background.

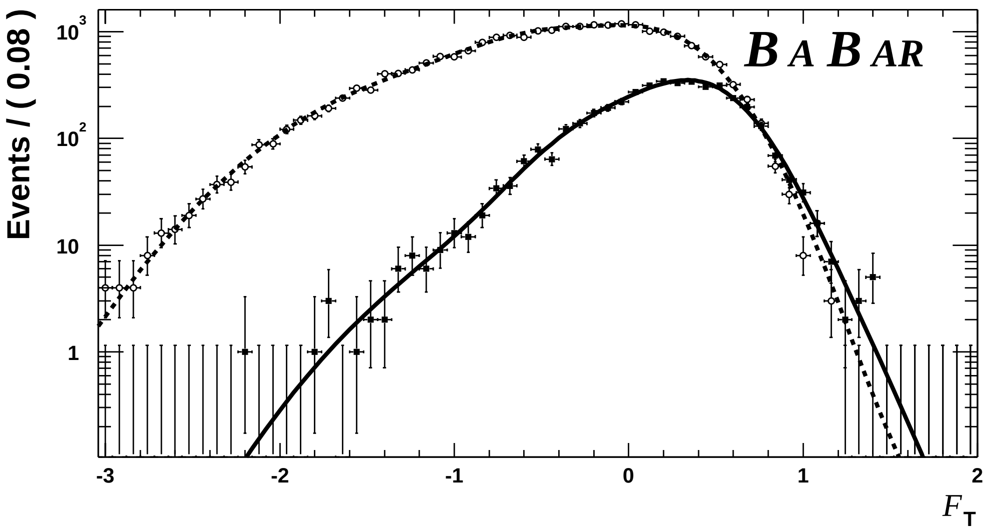

Figure 1: The distribution of the Fisher discriminant $\mathcal{F}_T$ from a fully reconstructed $B \to D^{(*)}n\pi$ data sample (open circles), and from off-resonance data and on-resonance $m_{\rm ES}$ sidebands (filled squares). The triple Gaussian parameterizations used in the likelihood fit for $B^0 \to \pi^0\pi^0$ signal (dotted line) and $q\overline{q}$ background (solid line) are also shown.

5 Unbinned Maximum Likelihood Fit

The number of $B^0 \to \pi^0\pi^0$ events is determined by an unbinned extended maximum likelihood fit to $m_{\rm ES}$, ΔE, and $\mathcal{F}_T$. The probability $\mathcal{P}_i\left(\vec{x}_j;\vec{\alpha}_i\right)$ for a given hypothesis is the product of probability density functions (PDFs) for each of the variables $\vec{x}_j = (m_{\rm ES}, \Delta E, \mathcal{F}_T)$ given the set of parameters $\vec{\alpha}_i$. The likelihood function is given by a product over all events N and three signal and background components:

$$\mathcal{L} = \exp\left(-\sum_{i=1}^{3} n_i\right) \prod_{j=1}^{N} \left[\sum_{i=1}^{3} n_i \mathcal{P}_i\left(\vec{x}_j;\vec{\alpha}_i\right)\right] .$$

The n_i are the number of events in each of the three components: $B^0 \to \pi^0\pi^0$ ($n_{\pi^0\pi^0}$), $B^\pm \to \rho^\pm\pi^0$ ($n_{\rho\pi^0}$), and $q\overline{q}$ ($n_{q\overline{q}}$). Monte Carlo simulations are used to verify that the fit is unbiased.

The $m_{\rm ES}$ PDF for $q\overline{q}$ is parameterized by a threshold function [8]

$$f(m_{\rm ES}) = m_{\rm ES}\sqrt{1-(m_{\rm ES}/m_0)^2}\exp\left\{-\xi(1-(m_{\rm ES}/m_0)^2)\right\},$$

where m_0 is the average CM beam energy, and ξ is found from a fit to on-resonance data with $|\cos\theta_S| > 0.9$. The ΔE PDF for $q\overline{q}$ is parameterized by a quadratic function with coefficients found from a fit to both on-resonance data in the $m_{\rm ES}$ sidebands and off-resonance data. The $\mathcal{F}_T$ PDF for $q\overline{q}$ is the sum of three Gaussians and is also found using both $m_{\rm ES}$ sideband and off-resonance data, as shown in Fig. 1. The $m_{\rm ES}$ and ΔE PDFs for signal and $B^\pm \to \rho^\pm\pi^0$ background are found from Monte Carlo simulation. The $B^0 \to \pi^0\pi^0$ and $B^\pm \to \rho^\pm\pi^0$ $m_{\rm ES}$ and ΔE variables are correlated, so a two dimensional PDF derived from a smoothed Monte Carlo distribution is used. The $\mathcal{F}_T$ PDFs, shown in Fig. 1, for both $B^0 \to \pi^0\pi^0$ and $B^\pm \to \rho^\pm\pi^0$ are parameterized as the sum of three Gaussians and are found from a sample of fully reconstructed $B^0 \to D^{(*)} n\pi$ events, with $n = 1$, 2, or 3.

The result of the fit is $n_{\pi^0\pi^0} = 23^{+10}_{-9}$ and $n_{q\overline{q}} = 2990 \pm 55$ events. These statistical errors correspond to the point at which $\log \mathcal{L}$ changes by one half. The number of $B^\pm \to \rho^\pm\pi^0$ events is fixed in the fit to $n_{\rho\pi^0} = 8.4$, based on the central value from Ref. [6] of $\mathcal{B}(B^\pm \to \rho^\pm\pi^0) = 2.4 \times 10^{-5}$ and our estimated efficiency. The distributions of $m_{\rm ES}$, ΔE, and $\mathcal{F}_T$ are shown in Fig. 2 after a cut on the probability ratio

$$\mathcal{R} = \frac{n_{\pi^0\pi^0}\mathcal{P}_{\pi^0\pi^0}}{n_{\pi^0\pi^0}\mathcal{P}_{\pi^0\pi^0} + n_{\rho\pi^0}\mathcal{P}_{\rho\pi^0} + n_{q\overline{q}}\mathcal{P}_{q\overline{q}}}.$$

Here the $\mathcal{P}_i$ are products of the PDFs for the two other variables, and the n_i are the central values from the fit. The cut is optimized by maximizing the ratio

$$\mathcal{S} = \frac{n_{\pi^0\pi^0}\epsilon_{\pi^0\pi^0}}{\sqrt{n_{\pi^0\pi^0}\epsilon_{\pi^0\pi^0} + n_{\rho\pi^0}\epsilon_{\rho\pi^0} + n_{q\overline{q}}\epsilon_{q\overline{q}}}},$$

where ϵ_i is the efficiency of the cut. The efficiencies for the $m_{\rm ES}$ distribution are 20%, 12%, and 0.8% for the $B^0 \to \pi^0\pi^0$, $B^\pm \to \rho^\pm\pi^0$, and $q\overline{q}$ components, respectively. The PDF projections for each of the fit components, scaled by the appropriate ϵ_i, are also shown in Fig. 2.

The results from the likelihood fit are compared to an analysis that simply uses the number of candidates satisfying the requirements $5.260 < m_{\rm ES} < 5.289\,{\rm GeV}/c^2$, $-0.16 < \Delta E < 0.10\,{\rm GeV}$, and $\mathcal{F}_T < -0.20$. These cuts were chosen in advance by maximizing the ratio

$$\frac{N_{\pi^0\pi^0}}{\sqrt{N_{\pi^0\pi^0} + N_{\rho\pi^0} + N_{q\overline{q}}}},$$

where N is the number of events from each source that satisfy the cuts. There are 89 events satisfying these requirements. The number of background $q\overline{q}$ events was determined by scaling the number of events with $5.20 < m_{\rm ES} < 5.26\,{\rm GeV}/c^2$, $-0.16 < \Delta E < 0.10\,{\rm GeV}$, and $\mathcal{F}_T < -0.20$ by the appropriate factor given the threshold function describing the $m_{\rm ES}$ distribution. The number of background $B^\pm \to \rho^\pm\pi^0$ events was estimated using the efficiency from the simulation. We find $N_{\pi^0\pi^0} = -6 \pm 11$ (stat.). Using simulations based on our PDFs, and assuming a flat prior distribution for $\mathcal{B}(B^0 \to \pi^0\pi^0)$, we estimate that there is a 2.5% probability to observe 89 or fewer events given the central value of our likelihood fit.

6 Systematic Uncertainties

We have estimated the systematic uncertainty in the likelihood fit by varying the PDF parameters by their statistical errors, by using different parametrizations, and by varying the $B^\pm \to \rho^\pm\pi^0$ branching fraction. In each case the likelihood fit to the data is repeated and the change in $n_{\pi^0\pi^0}$ is used as the systematic uncertainty. The systematic errors are listed in Table 1. The dominant systematic uncertainty is due to the statistically limited sample of data used to parameterize the $\mathcal{F}_T$ PDF for $q\overline{q}$. Since the parameters in the triple Gaussian are highly correlated we transform to the uncorrelated parameter space and vary the uncorrelated parameters by $\pm 1\sigma$. The fit is repeated for each 1σ variation of the uncorrelated parameters, and the positive and negative changes in $n_{\pi^0\pi^0}$ are separately summed in quadrature. The fit is also repeated using an interpolated histogram as the $q\overline{q}$ $\mathcal{F}_T$ PDF, with a change of $\Delta(n_{\pi^0\pi^0}) = -1.1$ events. The fit is repeated for values for

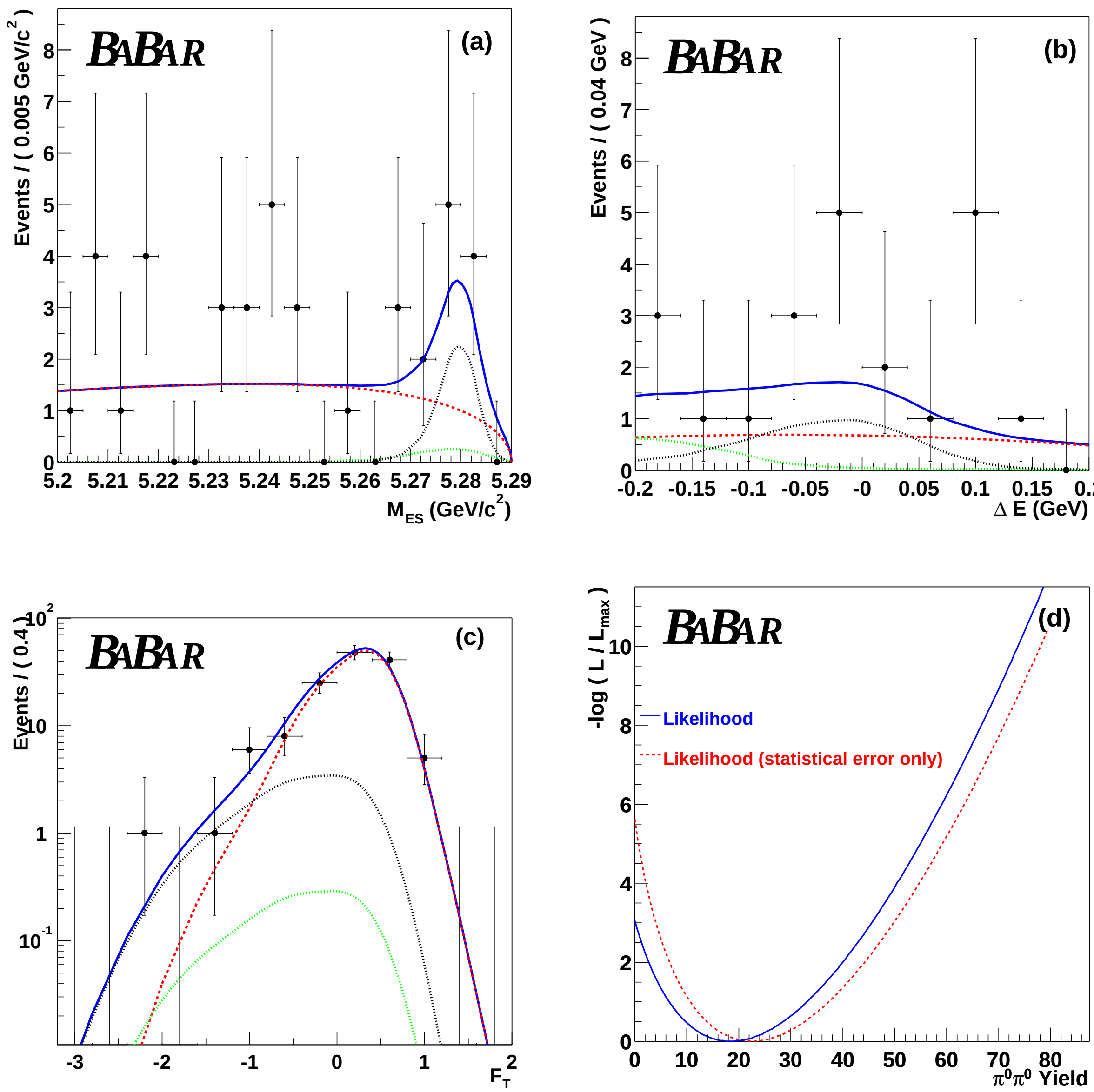

Figure 2: Results from the maximum likelihood fit. The distributions for a) $m_{\rm ES}$, b) ΔE, c) $\mathcal{F}_T$ are shown, for candidates satisfying an optimized cut on the probability ratio $\mathcal{R}$. Also shown are the PDF projections for signal (dotted line), $B^{\pm} \to \rho^{\pm}\pi^0$ (dot-dashed line), $q\overline{q}$ background (dashed line), and the sum (solid line). These plots do not represent the full information used in the maximum likelihood fit, but only a subset of the data. The ratio $-\log\left(\mathcal{L}/\mathcal{L}_{max}\right)$ is shown in d) (solid line) and with statistical errors only (dashed line).

the $q\overline{q}$ $m_{\rm ES}$ shape parameter of $\xi = 24.3 \pm 1.3$, based on the change in ξ as a function of $\cos\theta_S$. The $q\overline{q}$ ΔE parameters are varied by their statistical errors. The EMC energy scale is varied by $\pm 10.4\,\text{MeV}$ based on the statistical error in the mean of ΔE in the $B^{\pm} \to h^{\pm}\pi^0$ analysis [9], and the

$B^0 \to \pi^0\pi^0$ ΔE PDF is changed accordingly. The $B^\pm \to \rho^\pm\pi^0$ veto cut is varied and the changes taken as a systematic error. Lastly, the $B^\pm \to \rho^\pm\pi^0$ branching fraction is varied from 1.2×10^{-5} to 4.3×10^{-5}.

Table 1: Systematic errors on the number of $B^0 \to \pi^0\pi^0$ events in the maximum likelihood fit. $\Delta_\pm(n_{\pi^0\pi^0})$ are the positive and negative change in the number of signal events from the likelihood fit for each systematic source.

Systematic	$\Delta_+(n_{\pi^0\pi^0})$ (events)	$\Delta_-(n_{\pi^0\pi^0})$ (events)
$q\overline{q}$ $\mathcal{F}_T$ PDF parameters	+7.5	−2.4
$q\overline{q}$ $\mathcal{F}_T$ PDF functional form	+1.1	−1.1
$q\overline{q}$ $m_{\rm ES}$ PDF	+1.2	−1.1
$q\overline{q}$ ΔE PDF	+1.0	−0.2
$B^0 \to \pi^0\pi^0$ ΔE	+0.8	−1.1
$B^\pm \to \rho^\pm\pi^0$ cut variation	+1.3	−1.3
$B^\pm \to \rho^\pm\pi^0$ branching fraction	+1.6	−1.9
Total systematic error on $n_{\pi^0\pi^0}$	+8.1	−3.8
Efficiency systematics	10.1%	−10.1%
Total systematic	+8.4	−4.4

We calculate the significance of the result, defined as $s = \sqrt{-2\log\left(\mathcal{L}(n_{\pi^0\pi^0}=0)/\mathcal{L}_{max}\right)}$, and the 90% CL upper limit. The upper limit is evaluated by finding $n^{UL}_{\pi^0\pi^0}$ where

$$\frac{\int_0^{n^{UL}_{\pi^0\pi^0}} \mathcal{L}(n)dn}{\int_0^\infty \mathcal{L}(n)dn} = 0.9.$$

Systematic errors are included in the following way. For the significance, we repeat the fit using the changes in $q\overline{q}$ $\mathcal{F}_T$ parameterization, $q\overline{q}$ $m_{\rm ES}$ parameterization, and $B^\pm \to \rho^\pm\pi^0$ branching fraction which cause $n_{\pi^0\pi^0}$ to decrease. The $-\log\left(\mathcal{L}/\mathcal{L}_{max}\right)$ function is shown in Fig. 2d, along with the same function before systematic errors are included. The significance of the result is $s = 2.5\sigma$. The systematic errors are included by adding the total systematic $\Delta_+(n_{\pi^0\pi^0})$, in Table 1, to $n^{UL}_{\pi^0\pi^0}$. We find $n_{\pi^0\pi^0} < 46$ events at 90% CL.

7 Results

To convert the number of events $n_{\pi^0\pi^0}$ into a branching fraction we use

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = \frac{n_{\pi^0\pi^0}}{\epsilon_{\pi^0\pi^0} \cdot N_{B\overline{B}}}.$$

$N_{B\overline{B}} = (87.9 \pm 1.0) \times 10^6$ is the number of $B\overline{B}$ pairs in our data sample and the efficiency is $\epsilon_{\pi^0\pi^0} = 0.165 \pm 0.017$. The central value of the likelihood fit is $\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.6^{+0.7}_{-0.6}(\text{stat.})\,^{+0.6}_{-0.3}(\text{syst.})) \times 10^{-6}$. To calculate the branching fraction upper limit we decrease $\epsilon_{\pi^0\pi^0}$ and $N_{B\overline{B}}$ by one σ. The upper limit on the branching fraction is

$$\mathcal{B}(B^0 \to \pi^0\pi^0) < 3.6 \times 10^{-6} \ \text{ at 90\% CL.}$$

These results are preliminary. The upper limit may be combined with our measurement of the branching fraction $\mathcal{B}(B^{\pm} \to \pi^{\pm}\pi^{0}) = (5.5 \pm 1.0 \pm 0.6) \times 10^{-6}$ [9] to bound the ratio $\mathcal{B}(B^{0} \to \pi^{0}\pi^{0})/\mathcal{B}(B^{\pm} \to \pi^{\pm}\pi^{0})$. Treating the systematic uncertainties in the same way as for the $\mathcal{B}(B^{0} \to \pi^{0}\pi^{0})$ upper limit, and removing correlated systematic uncertainties, we find $\mathcal{B}(B^{0} \to \pi^{0}\pi^{0})/\mathcal{B}(B^{\pm} \to \pi^{\pm}\pi^{0}) < 0.61$ at 90% CL. Assuming the isospin relations for $B \to \pi\pi$ [4] this corresponds to an upper limit of $|\alpha_{\rm eff} - \alpha| < 51^{\rm o}$ at 90% CL.

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