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Search for the weak decay $\eta' \to K^{\pm}\pi^{\mp}$ and precise measurement of the branching fraction $\mathcal{B}(J/\psi \to \phi\eta')$

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We present the first search for the rare decay of η' into $K^{\pm}\pi^{\mp}$ in $J/\psi \to \phi\eta'$, using a sample of 1.3×10^9 J/ψ events collected with the BESIII detector. No significant signal is observed, and the upper limit at the 90% confidence level for the ratio $\frac{\mathcal{B}(\eta' \to K^{\pm}\pi^{\mp})}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$ is determined to be 1.3×10^{-4}. In addition, we report the measurement of the branching fraction of $J/\psi \to \phi\eta'$ to be $[5.10 \pm 0.03(\mathrm{stat}) \pm 0.32(\mathrm{syst})] \times 10^{-4}$, which agrees with previous results from BESII.

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I. INTRODUCTION

Nonleptonic weak decays are valuable tools for testing the Standard Model (SM), the Kobayashi-Maskawa (KM) mechanism, and the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix; and for exploring physics beyond the SM. Among nonleptonic decays, the decay of the light pseudoscalar meson $\eta' \to K^{\pm}\pi^{\mp}$ is interesting because it is fundamental to understanding the longstanding problem of the $\Delta I = 1/2$ rule in weak nonleptonic interactions.

The experimental $\Delta I = 1/2$ rule was first established in the decay $K \to \pi\pi$. A neutral kaon may decay into a two-pion final state with isospin $I = 0$ or $I = 2$ with amplitude A_0 or A_2, respectively. As the real parts of the amplitudes, $\mathrm{Re}A_0$ is dominated by $\Delta I = 1/2$ transitions and $\mathrm{Re}A_2$ receives contributions from $\Delta I = 3/2$ transitions. $\mathrm{Re}A_0$ is much larger than $\mathrm{Re}A_2$, which expresses the so-called $\Delta I = 1/2$ rule [1,2]

$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} = 22.35. \tag{1}$$

Despite nearly fifty years of efforts, the microscopic dynamical mechanism responsible for such a striking phenomenon is still elusive. The decay $\eta' \to K^{\pm}\pi^{\mp}$ receives contributions from both the $\Delta I = 1/2$ and $\Delta I = 3/2$ parts of the weak Hamiltonian [3]. It is possible to see whether the $\Delta I = 1/2$ rule is functional in this type of decay, and this could shed light on the origin of this rule. The branching fraction of $\eta' \to K^{\pm}\pi^{\mp}$ decay is predicted to be of the order of 10^{-10} or higher [3], with a large long-range hadronic contribution expected, which should become observable in high-luminosity electron-positron collisions.

At present, there is no experimental information on the decay $\eta' \to K^{\pm}\pi^{\mp}$. The world's largest sample of 1.3×10^9 J/ψ events produced at rest and collected with the BESIII detector therefore offers a good opportunity to search for this rare decay. In this paper, the measurement of the ratio $\frac{\mathcal{B}(\eta' \to K^{\pm}\pi^{\mp})}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$ is presented, where the η' is produced in the decay $J/\psi \to \phi\eta'$. The advantage of comparing these two η' decay channels is that parts of the systematic uncertainties due to the tracking, the particle identification (PID), the branching fractions $\mathcal{B}(J/\psi \to \phi\eta')$ and $\mathcal{B}(\phi \to K^+K^-)$, and the number of J/ψ events cancel in the ratio. A measurement of the branching fraction $J/\psi \to \phi\eta'$ is also presented in which ϕ is reconstructed in its K^+K^- decay mode and η' is detected in the $\gamma\pi^+\pi^-$ decay mode. This can be compared with the results reported by the BESII [4], MarkIII [5], and DM2 [6] collaborations.

II. DETECTOR AND MONTE CARLO SIMULATION

BEPCII is a double-ring e^+e^- collider designed to provide a peak luminosity of $10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at the center-of-mass (c.m.) energy of 3.770 GeV. The BESIII [7] detector, with a geometrical acceptance of 93% of the 4π stereo angle, is operating in a magnetic field of 1.0 T provided by a superconducting solenoid magnet. It is composed of a helium-based drift chamber (MDC), a plastic scintillator time-of-flight (TOF) system, a CsI(Tl) electromagnetic calorimeter (EMC) and a multilayer resistive plate chamber (RPC) muon counter system (MUC).

Monte Carlo (MC) simulations are used to determine the mass resolutions and detection efficiencies. The GEANT4-based simulation software BOOST [8] includes the geometric and material description of the BESIII detector, the

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detector response, and the digitization models, as well as the detector running conditions and performance. The production of the J/ψ resonance is simulated with the MC event generator KKMC [9,10], while the decays are generated by EVTGEN [11] for known decay modes with branching fractions set to the Particle Data Group (PDG) [12] world average values, and by LUNDCHARM [13] for the remaining unknown decays. The analysis is performed in the framework of the BESIII offline software system (BOSS) [14].

III. DATA ANALYSIS

A. $J/\psi \to \phi\eta'$, $\eta' \to \gamma\pi^+\pi^-$

For the decay $J/\psi \to \phi\eta'$, $\phi \to K^+K^-$, $\eta' \to \gamma\pi^+\pi^-$, candidate events are selected by requiring four well reconstructed charged tracks and at least one isolated photon in the EMC. The four charged tracks are required to have zero net charge. Each charged track, reconstructed using hits in the MDC, is required to be in the polar angle range $|\cos\theta| < 0.93$ and pass within ± 10 cm of the interaction point along the beam direction, and within ± 1 cm in the plane perpendicular to the beam, with respect to the interaction point. For each charged track, information from the TOF and the specific ionization measured in the MDC (dE/dx) is combined to form PID confidence levels (C.L.) for the K, π and p hypotheses, and the particle type with the highest C.L. is assigned to each track. Two of the tracks are required to be identified as kaons and the remaining two tracks as pions.

Photon candidates are reconstructed by clusters of energy deposited in the EMC. The energy deposited in the TOF counter in front of the EMC is included to improve the reconstruction efficiency and the energy resolution. Photon candidates are required to have a deposited energy larger than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) and 50 MeV in the end-cap region ($0.86 < |\cos\theta| < 0.92$). EMC cluster timing requirements are used to suppress electronic noise and energy deposits that are unrelated to the event. To eliminate showers associated with charged particles, the angle between the cluster and the nearest track must be larger than 15°.

A four-constraint (4C) kinematic fit is performed to the $\gamma K^+K^-\pi^+\pi^-$ hypothesis. For events with more than one photon candidate, the candidate combination with the smallest χ^2_{4C} is selected, and it is required that $\chi^2_{4C} < 50$.

The scatter plot of $M(\gamma\pi^+\pi^-)$ versus $M(K^+K^-)$ is shown in Fig. 1, where the $J/\psi \to \phi\eta'$ decay is clearly visible. To extract the number of $\phi\eta'$ events, an unbinned extended maximum likelihood fit is performed to the $M(\gamma\pi^+\pi^-)$ versus $M(K^+K^-)$ distribution with the requirements of $0.988\ \mathrm{GeV}/c^2 < M(K^+K^-) < 1.090\ \mathrm{GeV}/c^2$ and $0.880\ \mathrm{GeV}/c^2 < M(\gamma\pi^+\pi^-) < 1.040\ \mathrm{GeV}/c^2$. Assuming zero correlation between the two discriminating variables $M(K^+K^-)$ and $M(\gamma\pi^+\pi^-)$, the composite probability density function (PDF) in the two-dimensional fit is constructed as follows:

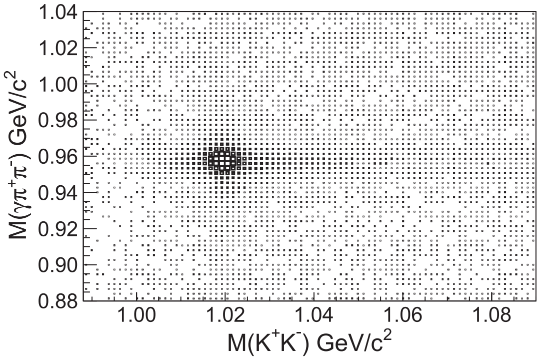

FIG. 1. Scatter plot of $M(\gamma\pi^+\pi^-)$ versus $M(K^+K^-)$.

$$\begin{aligned} F = {} & N_{\mathrm{sig}} \times (F^{\phi}_{\mathrm{sig}} \cdot F^{\eta'}_{\mathrm{sig}}) \\ & + N^{\text{non-}\eta'}_{\mathrm{bkg}} \times (F^{\phi}_{\mathrm{sig}} \cdot F^{\text{non-}\eta'}_{\mathrm{bkg}}) \\ & + N^{\text{non-}\phi}_{\mathrm{bkg}} \times (F^{\text{non-}\phi}_{\mathrm{bkg}} \cdot F^{\eta'}_{\mathrm{sig}}) \\ & + N^{\text{non-}\phi\eta'}_{\mathrm{bkg}} \times (F^{\text{non-}\phi}_{\mathrm{bkg}} \cdot F^{\text{non-}\eta'}_{\mathrm{bkg}}). \end{aligned} \tag{2}$$

Here, the signal shape for ϕ (i.e. F^{ϕ}_{sig}) is modeled with a relativistic Breit-Wigner function convoluted with a Gaussian function taking into account the detector resolution; the signal shape for η' (i.e. $F^{\eta'}_{\mathrm{sig}}$) is described by a normal Breit-Wigner function convoluted with a Gaussian function. The widths and masses of ϕ and η' are free parameters in the fit. The background shape of ϕ ($F^{\text{non-}\phi}_{\mathrm{bkg}}$) is described by a second-order Chebychev polynomial function, and the background shape of η' ($F^{\text{non-}\eta'}_{\mathrm{bkg}}$) is described by a first-order Chebychev polynomial function. All parameters related to the background shapes are free in the fit. N_{sig} is the number of $J/\psi \to \phi\eta'$, $\phi \to K^+K^-$, $\eta' \to \gamma\pi^+\pi^-$ signal events. The backgrounds are divided into three categories: non-$\phi\eta'$ background (i.e. $J/\psi \to \gamma K^+K^-\pi^+\pi^-$); non-$\phi$-peaking background (i.e. $J/\psi \to K^+K^-\eta'$); and non-η'-peaking background (i.e. $J/\psi \to \phi\gamma\pi^+\pi^-$). The parameters $N^{\text{non-}\phi\eta'}_{\mathrm{bkg}}$, $N^{\text{non-}\phi}_{\mathrm{bkg}}$ and $N^{\text{non-}\eta'}_{\mathrm{bkg}}$ are the corresponding three background yields.

The resulting fitted number of signal events is $N_{\mathrm{sig}} = (31321 \pm 201)$; the projections of the fit on the $M(K^+K^-)$ and $M(\gamma\pi^+\pi^-)$ distributions are shown in Figs. 2(a) and 2(b), respectively. The detection efficiency, $32.96 \pm 0.04\%$, is obtained from the MC simulation in which the angular distribution and the shape of $M(\pi^+\pi^-)$ are taken into account according to a previous BESIII measurement for $\eta' \to \pi^+\pi^-e^+e^-$ [15], where the nonresonant contribution (known as the "box anomaly") is included in the simulation of $\eta' \to \gamma\pi^+\pi^-$.

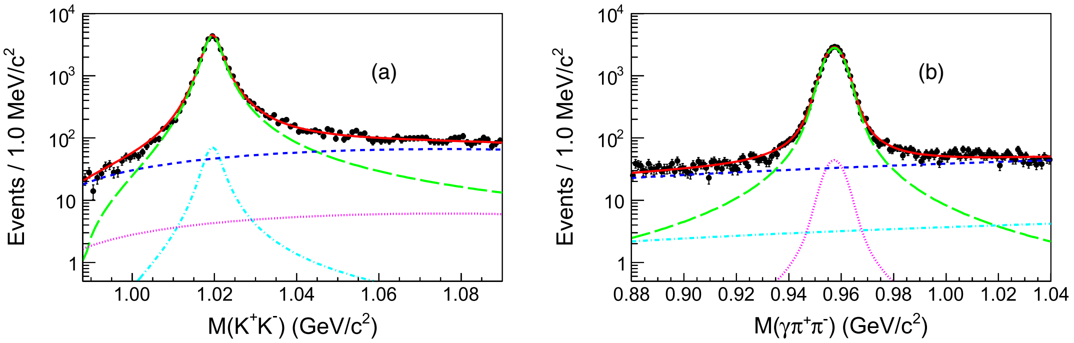

FIG. 2. Distributions of (a) $M(K^+K^-)$ and (b) $M(\gamma\pi^+\pi^-)$ with projections of the fit result superimposed for $J/\psi \to \phi\eta'$, $\phi \to K^+K^-$, $\eta' \to \gamma\pi^+\pi^-$. The dots with errors are for data, the solid curve shows the result of the fit to signal plus background distributions, the long-dashed curve is for the $\phi\eta'$ signal, the dot-dashed curve shows the non-η'-peaking background, the dotted curve shows the non-ϕ-peaking background, and the short-dashed curve is for the non-$\phi\eta'$ background.

B. $J/\psi \to \phi\eta'$, $\eta' \to K^\pm\pi^\mp$

To search for $\eta' \to K^\pm\pi^\mp$, the two-body decay $J/\psi \to \phi\eta'$ is chosen because of its simple event topology, $K^+K^-K^\pm\pi^\mp$, and because the narrow ϕ meson is easy to detect through $\phi \to K^+K^-$ decay. The selection criteria for the charged tracks are the same as those for the $J/\psi \to \phi\eta'$, $\eta' \to \gamma\pi^+\pi^-$ decay. Three tracks are required to be identified as kaons with the combination of TOF and dE/dx information, and the remaining one is required to be identified as a pion.

A $4C$ kinematic fit imposing energy-momentum conservation is performed under the $K^+K^-K^\pm\pi^\mp$ hypothesis, and a requirement of $\chi^2_{4C} < 50$ is imposed. To suppress the dominant background contamination from $J/\psi \to \phi\pi^+\pi^-$, the χ^2_{4C} of the $K^+K^-K^\pm\pi^\mp$ hypothesis is required to be less than that for the $K^+K^-\pi^+\pi^-$ hypothesis. Candidates for $\phi \to K^+K^-$ are reconstructed from the K^+K^- combination with invariant mass closest to the nominal mass value. The remaining kaon together with the pion forms the η' candidate.

Figure 3(a) shows the scatter plot to the invariant mass $M(K^+K^-)$ versus $M(K^\pm\pi^\mp)$. The process $\phi\eta'(\eta' \to K^\pm\pi^\mp)$ would result in an enhancement of events around the nominal masses of the ϕ and η' mesons, while no evident cluster is seen. Within 3 standard deviations of the ϕ mass, $|M(K^+K^-) - M(\phi)| < 15\ \mathrm{MeV}/c^2$, the $K^\pm\pi^\mp$ invariant mass distribution is displayed in Fig. 3(b); a few events are retained around the η' mass region, shown as the dots with error bars. To estimate the number of signal events passing the selection criteria, a region of $\pm3\sigma$ around the η' nominal mass is selected—that is, $|M(K^\pm\pi^\mp) - M(\eta')| < 7\ \mathrm{MeV}/c^2$, where $\sigma = 2.2$ MeV is the mass resolution determined from MC simulation. Only one event survives in the signal region for further analysis.

To investigate the potential background contributions, a study with an inclusive MC sample of 1.2×10^9 generic J/ψ decays is performed. It is found that the remaining background events mainly come from $J/\psi \to \phi\pi^+\pi^-$. Therefore, an exclusive MC sample of $1.3 \times 10^6 J/\psi \to \phi\pi^+\pi^-$ events is generated in accordance with the partial wave analysis results of Ref. [16]. This sample corresponds to twice the expected $J/\psi \to \phi\pi^+\pi^-$ events in data. After normalizing to the world average value for

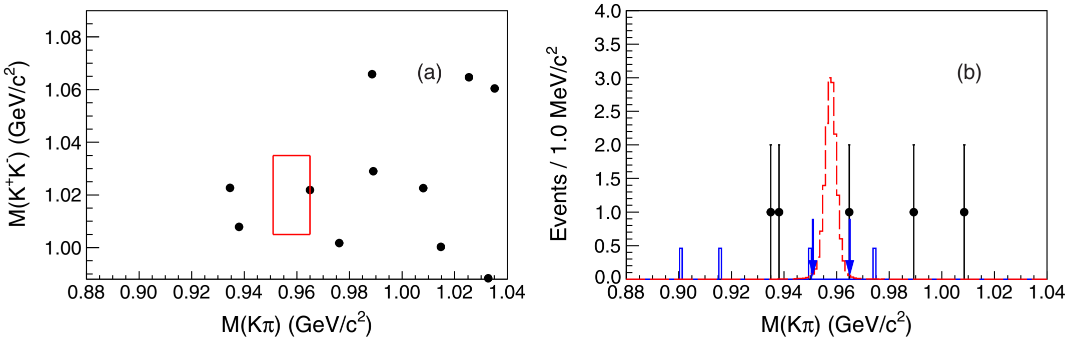

FIG. 3. (a) Scatter plot of $M(K^+K^-)$ versus $M(K^\pm\pi^\mp)$, where the box indicates the signal region with $|M(K^+K^-) - M(\phi)| < 15\ \mathrm{MeV}/c^2$ and $|M(K^\pm\pi^\mp) - M(\eta')| < 7\ \mathrm{MeV}/c^2$. (b) The $K^\pm\pi^\mp$ invariant mass distribution, where the arrows show the signal region. The dots with error bars are for data, the dashed histogram is for the signal MC with arbitrary normalization, and the solid histogram is the background contamination from a MC simulation of $J/\psi \to \phi\pi^+\pi^-$.

$\mathcal{B}(J/\psi \to \phi\pi^+\pi^-)$, 2.0 events are expected in the $K\pi$ mass range of $[0.88, 1.04]$ GeV/c^2, with a total of 0.5 events in the η' signal region, as shown by the solid histogram in Fig. 3(b).

To conservatively estimate the upper limit, it is assumed that the only event in the signal region is a signal event. According to the Feldman-Cousins method [17], the corresponding upper limit of the number of events is $N^{\mathrm{UL}} = 4.36$ at the 90% C.L.

IV. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties in branching fraction measurement originate mainly from the differences of data and MC on tracking efficiency, photon reconstruction, PID efficiency, the 4C kinematic fit, different fitting range and background shape, uncertainties from $\mathcal{B}(\phi \to K^+K^-)$ and $\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$, the total number of J/ψ events and MC statistics. Other uncertainties related to the common selection criteria of the channels $J/\psi \to \phi\eta'$, $\eta' \to K^\pm\pi^\mp$ and $J/\psi \to \phi\eta'$, $\eta' \to \gamma\pi^+\pi^-$ cancel to first order in the ratio between the branching fractions.

The systematic uncertainties associated with the tracking efficiency and PID efficiency have been studied in the analysis of $J/\psi \to p\bar{p}\pi^+\pi^-$ and $J/\psi \to K_S^0K^\pm\pi^\mp$ [18,19]. The results indicate that the kaon/pion tracking and PID efficiencies for data agree with those of MC simulation within 1%.

The photon detection is estimated by the study of $J/\psi \to \rho\pi$ [18]. The difference in the detection efficiency between data and MC is less than 1% per photon, which is taken as the systematic uncertainty because of the only photon in the $J/\psi \to \phi\eta'$, $\eta' \to \gamma\pi^+\pi^-$ channel.

The uncertainty associated with the 4C kinematic fit comes from the difference between data and MC simulation. The method used in this analysis is to correct the tracking parameters of the helix fit to reduce the difference between MC and data, as described in Ref. [20]. This procedure yields systematic uncertainties of 0.3% and 1.0% for the measurement of $\mathcal{B}(J/\psi \to \phi\eta')$ and the search of $\eta' \to K^\pm\pi^\mp$, respectively.

To estimate the systematic contribution due to the fit ranges, several alternative fits in different ranges are performed. The maximum difference in the number of signal events from alternative fits in different mass ranges is 0.1%, and this value is taken as systematic uncertainty. To estimate the systematic contribution due to the background shape, a fit is performed replacing the second-order Chebychev polynomial function with an Argus function [21]; the change of signal yields is found to be 0.04%, which is negligible.

The decay $J/\psi \to \phi\eta'$, $\phi \to K^+K^-$, $\eta' \to \gamma\pi^+\pi^-$ is used as a control sample to estimate the uncertainty from the ϕ mass window criterion in the search of $\eta' \to K^\pm\pi^\mp$. The ϕ mass window criterion is applied to the control sample, and a fit is performed to $M(\gamma\pi^+\pi^-)$. After considering the efficiency difference, the difference of 1.2% in the number of signal events between this fit and the nominal 2D fit is taken as the uncertainty from the ϕ mass window.

TABLE I. Summary of systematic uncertainty sources and their contributions (in %).

Source	$\mathcal{B}(J/\psi \to \phi\eta')$	$\mathcal{B}(\eta' \to K^\pm\pi^\mp)/\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$
Tracking efficiency	4.0	...
PID efficiency	4.0	...
Photon reconstruction	1.0	1.0
4C kinematic fit	0.3	1.0
Fit range	0.1	0.1
Background shape	...	...
ϕ mass window	...	1.2
$\mathcal{B}(\phi \to K^+K^-)$	1.0	...
$\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$	2.0	...
$N_{J/\psi}$	0.8	...
MC statistic of $\eta' \to \gamma\pi^+\pi^-$	0.1	0.1
MC statistic of $\eta' \to K^\pm\pi^\mp$	...	0.1
Total	6.2	1.9

The uncertainties on the intermediate-decay branching fractions of $\phi \to K^+K^-$ and $\eta' \to \gamma\pi^+\pi^-$ are taken from world average values [12].

The above systematic uncertainties, together with the uncertainties due to the number of J/ψ events [22,23] and MC statistics, are all summarized in Table I, where the uncertainties associated with MDC tracking, PID, and the branching fraction of $\phi \to K^+K^-$ cancel in the ratio $\frac{\mathcal{B}(\eta' \to K^\pm\pi^\mp)}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$. The total systematic uncertainty is taken to be the sum in quadrature of the individual contributions.

V. RESULTS

At the 90% C.L., the upper limit on the ratio of $\mathcal{B}(\eta' \to K^\pm\pi^\mp)$ to $\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$ is given by

$$\frac{\mathcal{B}(\eta' \to K^\pm\pi^\mp)}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)} < \frac{N^{\mathrm{UL}} \cdot \varepsilon_{\gamma\pi^+\pi^-}}{N_{\mathrm{sig}} \cdot \varepsilon_{K^\pm\pi^\mp}} \frac{1}{(1 - \sigma_{\mathrm{syst}})}, \qquad (3)$$

where N^{UL} is the upper limit of the number of observed events at the 90% C.L. for $\eta' \to K^\pm\pi^\mp$; $\varepsilon_{K^\pm\pi^\mp}$ and $\varepsilon_{\gamma\pi^+\pi^-}$ are the detection efficiencies of $J/\psi \to \phi\eta'$ for the two decays which are obtained from the MC simulations; and σ_{syst} is the total systematic uncertainty in the search of $\eta' \to K^\pm\pi^\mp$. The 90% C.L. upper limit on the ratio $\frac{\mathcal{B}(\eta' \to K^\pm\pi^\mp)}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$ is determined to be 1.3×10^{-4} by using the values of different parameters listed in Table II.

TABLE II. Values used in the calculations of the branching ratios, including the fitted signal yields N (or 90% C.L. upper limit) and the detection efficiency ε.

Decay mode	$\varepsilon\,(\%)$	N
$\eta' \to K^\pm\pi^\mp$	36.75 ± 0.04	< 4.36 (90% C.L.)
$\eta' \to \gamma\pi^+\pi^-$	32.96 ± 0.04	31321 ± 201

The branching fraction of $J/\psi \to \phi\eta'$ decay is calculated with the equation

$$\mathcal{B}(J/\psi \to \phi\eta') = \frac{N_{\mathrm{sig}}/\varepsilon_{\gamma\pi^+\pi^-}}{N_{J/\psi}\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)\mathcal{B}(\phi \to K^+K^-)}, \tag{4}$$

where $N_{J/\psi} = 1310.6 \times 10^6$ is the number of J/ψ events as determined by J/ψ inclusive hadronic decays [22,23]. The obtained value for the branching fraction of $J/\psi \to \phi\eta'$ is $[5.10 \pm 0.03(\mathrm{stat}) \pm 0.32(\mathrm{syst})] \times 10^{-4}$.

VI. SUMMARY

Based on the 1.3×10^9 J/ψ events accumulated with the BESIII detector, a search for the nonleptonic weak decay $\eta' \to K^\pm\pi^\mp$ is performed for the first time through the $J/\psi \to \phi\eta'$ decay. No evidence for $\eta' \to K^\pm\pi^\mp$ is seen, and the 90% C.L. upper limit on the ratio of $\frac{\mathcal{B}(\eta' \to K^\pm\pi^\mp)}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$ is measured to be 1.3×10^{-4}. Using the world average value of $\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)$ [12], the corresponding upper limit on $\mathcal{B}(\eta' \to K^\pm\pi^\mp)$ is calculated to be 3.8×10^{-5}.

For the determination of the ratio of $\frac{\mathcal{B}(\eta' \to K^\pm\pi^\mp)}{\mathcal{B}(\eta' \to \gamma\pi^+\pi^-)}$, the $J/\psi \to \phi\eta'$ decay with $\phi \to K^+K^-$, $\eta' \to \gamma\pi^+\pi^-$ is analyzed and the corresponding branching fraction is $\mathcal{B}(J/\psi \to \phi\eta') = [5.10 \pm 0.03(\mathrm{stat}) \pm 0.32(\mathrm{syst})] \times 10^{-4}$. It is the most precise measurement to date and in agreement with the world average value.

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