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Determination of spin and parity of $D^*_{(s)}$ mesons

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ABSTRACT

The spin and parity of the charmed mesons D_s^{*+}, D^{*0} and D^{*+} are determined for the first time to be $J^P = 1^-$ with significances greater than 10σ over other hypotheses of 2^+ and 3^-, using an e^+e^- collision data sample with an integrated luminosity of 3.19 fb^{-1} collected by the BESIII detector at a center-of-mass energy of 4.178 GeV. Different spin-parity hypotheses are tested via a helicity amplitude analysis of the processes $e^+e^- \to D_s^{*+}D_s^-$, $D^{*0}D^0$ and $D^{*+}D^-$, with $D_s^{*+} \to D_s^+\gamma$, $D^{*0} \to D^0\pi^0$, and $D^{*+} \to D^+\pi^0$. The results confirm the quark model predictions.

1. Introduction

Charmed-meson spectroscopy provides a powerful tool to achieve a better understanding of the strong interaction. Following the experimental discovery of the D^+ meson [1], first predictions of the charmed meson spectrum from the quark model emerged in the 1980s [2]. Although the quark model has successfully predicted masses and spin-parity assignments, experimental confirmations are in many places still missing. Notably, the supposed assignment of D_s^{*+}, D^{*0} and D^{*+} as states with quantum numbers $J^P = 1^-$ [3–7] has not yet been confirmed by any experiment. The Particle Data Group (PDG) labels J^P of the D_s^{*+} meson as 'unknown' [3], the only experimental measurement [8] found a spin of 1 for the D^{*0}, ruling out spin 0. The observed decay modes $D_{(s)}^* \to D_{(s)}\pi$ rule out unnatural spin-parity assignments, *i.e.* 1^+, 2^-, or 3^+. The hypotheses 1^-, 2^+, and 3^- remain to be tested.

Over the past decade, charmed-meson spectroscopy has undergone a resurgence due to the discovery of numerous excited charm and charm-strange meson states by the BaBar [9–13], Belle [9,14], CLEO [15] and LHCb [16] collaborations. The observation of these new resonances has provided essential knowledge about the radial excitations ($2S$) and orbital excitations with angular momenta $L = 1$ and 2. The knowledge of spin and parity of the $D_{(s)}^*$ is vital to determine the quantum numbers of higher excited $D_{(s)}^{**}$ states that are reconstructed via $D_{(s)}^*$ mesons. Recently, the first candidates for a hidden-charm tetraquark with strangeness, $Z_{cs}(3985)^+$ [17] and $Z_{cs}(3985)^0$ [18] were observed by BESIII in their decays to the final states $(D_s^-D^{*0} + D_s^{*-}D^0)$ and $(D_s^+D^{*-} + D_s^{*+}D^-)$. Hence, the spin and parity of the D^{*0} and D_s^{*+} are essential to determine the quantum numbers of $Z_{cs}(3985)^+$.

In this Letter, the spin-parity quantum numbers of D_s^{*+}, D^{*0}, and D^{*+} mesons are determined using a data set with an integrated luminosity of 3.19 fb^{-1} collected with the BESIII detector at the center-of-mass (CM) energy of 4.178 GeV. The spin-parity hypotheses 1^-, 2^+, and 3^- are tested by means of the helicity amplitude analysis of $e^+e^- \to D_s^{*+}D_s^-$, $D^{*0}\bar{D}^0$, $D^{*+}D^-$ processes, with $D_s^{*+} \to D_s^+\gamma$, $D^{*0} \to D^0\pi^0$, and $D^{*+} \to D^+\pi^0$ final states. Throughout this letter, charge conjugation is implied, unless explicitly stated otherwise. A partial reconstruction technique is adopted, namely, one $D_{(s)}$ and $\pi^0(\gamma)$ particles are detected to identify the $D_{(s)}^*$ decay, while the other $D_{(s)}$ in the event is undetected. The $D_{(s)}$ candidates are reconstructed in the hadronic decay modes $D_s^+ \to K_S^0K^+$, $D^0 \to K^-\pi^+$, and $D^+ \to K^-\pi^+\pi^+$ processes. The intermediate states K_S^0 and π^0 are reconstructed via their decays to $\pi^+\pi^-$ and $\gamma\gamma$ final states, respectively.

2. BESIII detector and Monte Carlo simulation

The BESIII detector [19] records symmetric e^+e^- collisions provided by the BEPCII storage ring [20], which operates in the CM energy range from 2.0 GeV to 4.946 GeV, where BESIII has collected large data samples [21]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a time-of-flight system (TOF) using plastic scintillators in the central region (barrel) and multi-gap RPCs in the end caps, and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported

by an octagonal flux-return yoke instrumented with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution at 1 GeV/c is 0.5%, and the specific ionization energy loss (dE/dx) resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end cap region is 60 ps [22].

Simulated data samples are produced with a GEANT-4 [23] based Monte Carlo (MC) package, which includes the geometric description [24] of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation includes the beam energy spread and initial state radiation in the e^+e^- annihilations modeled with the event generator KKMC [25]. An MC sample of inclusive decays, forty times larger than the data set, includes the production of open charm processes, the initial state radiation production of vector charmonium(-like) states, and the continuum processes. The known decay modes are modeled with EVTGEN [26] using branching fractions taken from the PDG [3], and the remaining unknown charmonium decays are modeled with LUNDCHARM [27]. Final state radiation (FSR) from charged final state particles is incorporated using PHOTOS [28]. MC samples of $e^+e^- \to \pi^0(\gamma)D_{(s)}D_{(s)}$, simulated following a three-body phase space (PHSP) distribution, are used to determine the selection efficiency. In these simulations, one of the $D_{(s)}$ mesons decays inclusively, based on the branching fractions listed in PDG, and the second one decays to the signal final states.

3. Event selection

To select the signal candidates of the analyzed processes $e^+e^- \to D_s^{*+}D_s^- \to \gamma D_s^+ D_s^-$, $e^+e^- \to D^{*0}\bar{D}^0 \to \pi^0 D^0 \bar{D}^0$, and $e^+e^- \to D^{*+}D^- \to \pi^0 D^+ D^-$, the selection criteria described below are implemented. The decay modes of $D_{(s)}$ used for reconstruction are $D_s^+ \to K_S^0 K^+$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$.

The distance of closest approach of each charged track to the e^+e^- interaction point (IP) is required to be within 10 cm along the beam direction and within 1 cm in the plane perpendicular to the beam direction, except for the tracks from K_S^0 decays. The polar angle θ between the direction of a charged track and the positron beam must satisfy $|\cos\theta| < 0.93$ for an effective measurement in the active volume of the MDC. The dE/dx information recorded by the MDC and the time-of-flight information measured by the TOF are used to identify particles by calculating the probabilities $\mathcal{P}$ for various particle hypotheses. Charged kaons and pions are identified requiring $\mathcal{P}(K) > \mathcal{P}(\pi)$ and $\mathcal{P}(\pi) > \mathcal{P}(K)$, respectively.

Shower clusters in the EMC without associated charged tracks are identified as photon candidates if the deposited energy is greater than 25 MeV in the barrel region ($|\cos\theta| < 0.80$) or greater than 50 MeV in the endcap region ($0.86 < |\cos\theta| < 0.92$). To suppress background from electronic noise and coincidental EMC showers, the difference between the event start time and the EMC signal is required to be smaller than 700 ns. The π^0 candidates are reconstructed from photon pairs with an invariant mass $M(\gamma\gamma)$ within [0.115, 0.150] GeV/c^2.

The K_S^0 candidates are reconstructed from two oppositely charged tracks, without a particle identification (PID) requirement. These tracks are required to originate at a common decay vertex (with a vertex χ^2 less than 100) lying within a distance of 20 cm from the interaction point along the beam direction, accounting for the long lifetime of the K_S^0 meson. Furthermore, the decay vertex is required to be separated from the IP by a distance of at least twice the fitted vertex resolution. The invariant mass of $\pi^+\pi^-$ pairs, $M(\pi^+\pi^-)$, is required to be in the range [0.487, 0.511] GeV/c^2.

The purity of the selected sample is improved by various constraints listed in Table 1, involving the invariant mass $M(D_{(s)})$ of the reconstructed $D_{(s)}$ meson and the energy difference ΔE between the total energy of the $\pi^0(\gamma)D_{(s)}D_{(s)}$ system in the CM frame and the CM energy E_0. The applied constraints correspond to three times the resolution of the respective observables,

$$\Delta E = E_{D_{(s)}} + E_{\pi^0(\gamma)} + E_{\rm rec} - E_0, \tag{1}$$

where $E_{D_{(s)}}$ and $E_{\pi^0(\gamma)}$ are the energies of reconstructed $D_{(s)}$ and $\pi^0(\gamma)$ from $D_{(s)}^*$ candidates, respectively, and $E_{\rm rec}$ is the energy of the recoil side, defined as

$$E_{\rm rec} = \sqrt{\left|\vec{p}_{D_{(s)}} + \vec{p}_{\pi^0(\gamma)}\right|^2 c^2 + m_{D_{(s)}}^2 c^4}, \tag{2}$$

where $\vec{p}_{D_{(s)}}$ is the total momentum of the reconstructed $D_{(s)}$ meson, $\vec{p}_{\pi^0(\gamma)}$ is the momentum of the $\pi^0(\gamma)$ from $D_{(s)}^*$, and $m_{D_{(s)}}$ is the known mass of the $D_{(s)}$ meson [3]. For each decay mode with multiple $D_{(s)}\pi^0(\gamma)$ candidates in an event, the one with the minimal $|\Delta E|$ is selected.

In order to suppress background contributions and to improve the momentum resolution, a kinematic fit is performed for the three processes. In the case of the $\gamma D_s^+ D_s^-$ decay mode, the invariant mass of $K_S^0 K^+$ system is constrained to the known D_s^+ mass, and the recoil $D_s^+\gamma$ mass is constrained to the known D_s^- mass. After the kinematic fit, the four-momenta of all final state particles are updated for further analyses.

Fig. 1 shows two-dimensional distribution of the $D_{(s)}^*$ invariant mass, $M(D_{(s)}\pi^0(\gamma))$, and the $D_{(s)}$ recoil mass, $M_R(D_{(s)})$, where two structures are evident. Taking Fig. 1(a) as an example, the horizontal band represents the $e^+e^- \to D_s^{*+}D_s^-$ process, while the vertical band represents the $e^+e^- \to D_s^{*-}D_s^+$ process. For the subsequent analysis, only events located in regions of the horizontal or vertical bands defined in Table 1, also illustrated in Fig. 1, are retained. In addition, events in the region common to the horizontal and vertical bands are rejected, since it is impossible to determine whether they stem from the $e^+e^- \to D_s^{*+}D_s^-$ or the $e^+e^- \to D_s^+ D_s^{*-}$ process. Here, the horizontal band is defined as D_s^{*+}-tag sample and the vertical band is defined as D_s^+-recoil sample. The background events are studied with the inclusive MC, and the background contamination is determined to be less than 8%. These two data samples are used to perform the helicity amplitude analysis. Similar selection procedures are also applied to D^{*0} and D^{*+}.

4. Formalism

To examine the implications of the spin and parity of the D_s^{*+}, D^{*0}, and D^{*+}, the helicity formalism [29,30] is applied to the analysis of the joint angular distribution for charmed mesons and their daughter particles. Fig. 2 shows the helicity frame for the $e^+e^- \to D_s^{*+}D_s^-$ process. The helicity angle θ_0 is defined as the angle between the D_s^{*+} momentum and the e^+ beam axis in the CM system. The helicity angles θ_1 and ϕ_1 are related to the decay $D_s^{*+} \to D_s^+\gamma$. The former is defined as the angle between the D_s^+ momentum in the D_s^{*+} rest frame and the D_s^{*+} momentum in the CM frame, and the latter as the angle between the D_s^{*+} production and decay planes.

For a two-body decay, $A(J,m) \to B(s,\lambda)C(\sigma,\nu)$, the helicity amplitude $F^J_{\lambda,\nu}$ is related to the covariant amplitude via [31–33]

$$F^J_{\lambda,\nu} = \sum_{LS} \sqrt{\frac{2L+1}{2J+1}} \langle L0, S\delta | J, \delta\rangle \langle s\sigma, \lambda - \nu | S, \delta\rangle g_{LS} r^L \frac{B_L(r)}{B_L(r_0)}, \tag{3}$$

where $\delta = \lambda - \nu$, $\langle \ldots \rangle$ are the Clebsch-Gordan Coefficients, g_{LS} is the LS-coupling constant, S the total spin, L the orbital angular

Table 1
Requirements on ΔE, $M(D_{(s)})$, $M(D_{(s)}\pi^0(\gamma)$ and $M_R(D_{(s)})$ for each data sample.

Data sample	ΔE (MeV)	$M(D_{(s)})$ (MeV/c^2)	$M(D_{(s)}\pi^0(\gamma))$ (MeV/c^2)	$M_R(D_{(s)})$ (MeV/c^2)
D_s^{*+}-tag D_s^+-recoil	$(-20, 30)$	(1950, 1990)	(2105, 2120) $\notin$(2095, 2135)	$\notin$(2095, 2135) (2105, 2120)
D^{*0}-tag D^0-recoil	$(-30, 30)$	(1840, 1890)	(2005, 2009) (2010, 2090)	(2010, 2090) (2005, 2009)
D^{*+}-tag D^+-recoil	$(-20, 20)$	(1850, 1890)	(2008.5, 2012.5) (2010, 2090)	(2010, 2090) (2008.5, 2012.5)

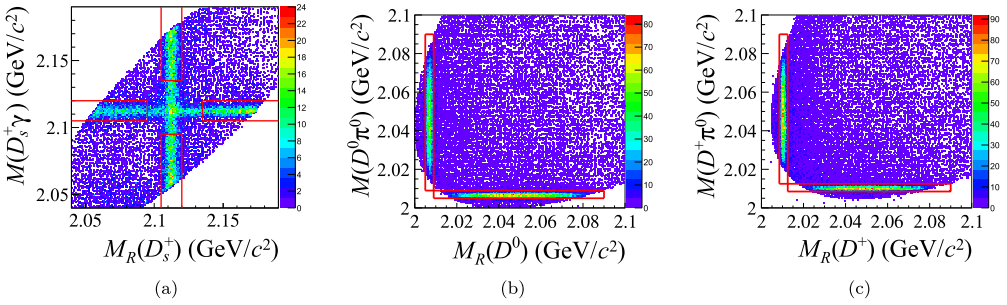

Fig. 1. Two-dimensional distributions of $M(D_{(s)}\pi^0(\gamma))$ and $M_R(D_{(s)})$, where the red rectangle denotes the signal region.

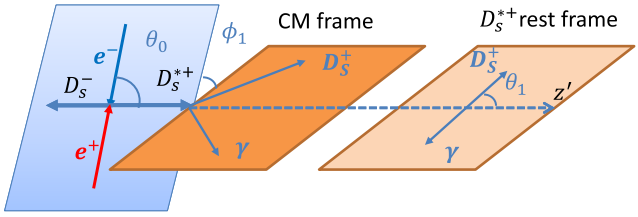

Fig. 2. Definition of the helicity frame for $e^+e^- \to \gamma^* \to D_s^{*+}D_s^-$, $D_s^{*+} \to \gamma D_s^+$ sequential decay.

momentum. The Blatt-Weisskopf factor [34] is represented by B_L, and $r = |\vec{p}_B - \vec{p}_C|$ is the modulus of 3-vector momentum difference between the two final state particles, and r_0 corresponds to choice by setting resonant invariant mass equal to its nominal mass.

The process $e^+e^- \to \gamma^* \to D_s^{*+}(\lambda_R)D_s^-$, $D_s^{*+} \to \gamma(\lambda_1)D_s^+$ is discussed for illustration. The D_s^{*+} meson is assigned spin J and helicity λ_R, the decay photon and the virtual photon γ^* have helicities λ_1 and m, respectively. Then the joint amplitude is

$$A(m, \lambda_1, \vec{\omega}) = \sum_{\lambda_R} F_{\lambda_R,0} D^{1*}_{m,\lambda_R}(\phi_0, \theta_0, 0) \\ BW(m_{12}) F^J_{0,\lambda_1} D^{J*}_{\lambda_R,-\lambda_1}(\phi_1, \theta_1, 0), \tag{4}$$

where $\vec{\omega} = (\theta_0, \phi_0, \theta_1, \phi_1, m_{12})$, $D^J_{m,\lambda}(\phi, \theta, 0)$ is the Wigner-D function, BW denotes the Breit-Wigner function, m_{12} is the γD_s^+ invariant mass, and $F_{\lambda_R,0}$ and F^J_{0,λ_1} are the helicity amplitudes of the two sequential decays. The decay amplitude for the D^{*0} and D^{*+} mesons can be constructed analogously. Then the differential cross section of the sequential decay via D_s^* is

$$\mathcal{W}^{J^P}(\theta_0, \theta_1, \phi_1, m_{12}) = \sum_{m,\lambda_1} |A(m, \lambda_1, \vec{\omega})|^2, \tag{5}$$

with summation over $m = \pm 1$ for the virtral photon, corresponding to the diagonal γ^* spin density matrix diag$\{1, 0, 1\}$ and $\lambda_1 = \pm 1$ for the radiative photon.

5. Significance estimation

The spin-parity hypotheses are tested using the likelihood function,

$$\mathcal{L}^{J^P}(N) = \prod_{i=1}^{N} \frac{1}{\mathcal{C}} \mathcal{W}^{J^P}(\theta_0^i, \theta_1^i, \phi_1^i, m_{12}^i), \tag{6}$$

where N is the number of selected events, $(\theta_0^i, \theta_1^i, \phi_1^i)$ are the helicity angles for the i-th event describing the $D^*_{(s)}$ decay, and $\mathcal{W}^{J^P}$ is the differential cross section of the sequential decay. The normalization factor $\mathcal{C} = \int \mathcal{W}^{J^P}(\theta_0^i, \theta_1^i, \phi_1^i, m_{12})\, \mathrm{d}\cos\theta_0\, \mathrm{d}\cos\theta_1\, \mathrm{d}\phi_1\, \mathrm{d}m_{12}$ is numerically evaluated using a phase-space MC sample, but only including the events passing the detector acceptance and final event selection stage in order to also include efficiency effects.

We perform an unbinned maximum likelihood fit to the angular distribution of the selected events in the signal region. The background contributions are subtracted from the log-likelihood values based on selected events in the inclusive MC falling inside the signal region. The MINUIT package [35] is used to minimize the negative net log-likelihood defined by

$$S = -\ln \mathcal{L}^{J^P} = -\alpha[\ln \mathcal{L}^{J^P} - \omega_{\rm bkg} \ln \mathcal{L}^{J^P}], \tag{7}$$

where N_s (N_b) is the number of events in data and MC samples. The background weight, $\omega_{\rm bkg} = 0.025$, is the ratio of the integrated luminosities of the data and the MC sample. To achieve an unbiased uncertainty estimation, the normalization factor derived in Ref. [36–38] is taken into account, expressed as

$$\alpha = \frac{N_s - \omega_{\rm bkg} N_b}{N_s + \omega^2_{\rm bkg} N_b}. \tag{8}$$

Fit results for the mass and angular distributions of the $D^*_{(s)}$-tag sample for the hypotheses J^P=1^- are shown in Fig. 3. Mass and angular distributions of the hypotheses $J^P = 2^+$ and 3^- can be found in the supplemental material [39]. The moment $\langle \sin^2\theta_1 \rangle$, which represents an average observed in each ϕ_1 bin, is a useful observable illustrating the different behaviors expected for different hypotheses (J^P = 1^-, 2^+ and 3^-). Fig. 4 shows the $\langle \sin^2\theta_1 \rangle$

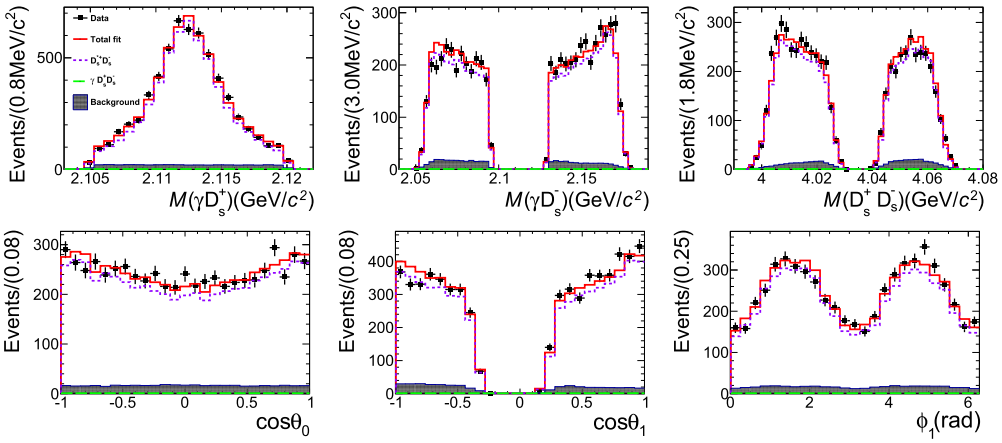

Fig. 3. Mass and angular distributions of D_s^{*+} tag sample for $J^P = 1^-$ hypothesis. Points with error bars are data. The solid red line, dotted purple line, and long dashed green line are the total fit results, $D_s^{*+}D_s^-$, and $\gamma D_s^+ D_s^-$ processes, respectively. The shaded black histograms indicate the scaled backgrounds derived from the inclusive MC samples.

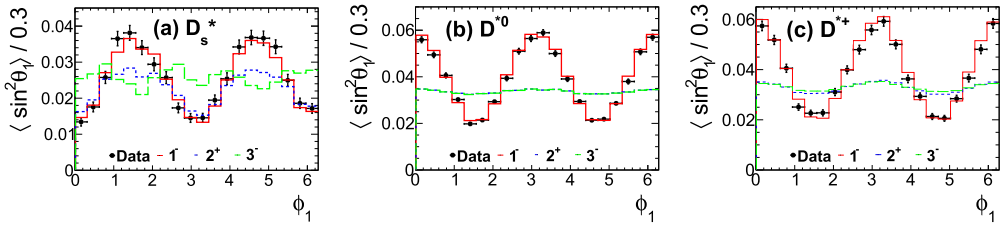

Fig. 4. Distributions of the normalized moment $\left\langle \sin^2\theta_\gamma \right\rangle$ versus ϕ_1 for the processes $e^+e^- \to$ (a) $D_s^{*+}D_s^-$, (b) $D^{*0}\bar{D}^0$ and (c) $D^{*+}D^-$. Points with error bars are data summing over D^*-tag sample and D-recoil sample with background events subtracted. The solid red line, dotted blue line, and the long-dashed green line are the fit results for the $J^P = 1^-$, 2^+, and 3^- hypothesis, respectively. For the (b) and (c) processes, the blue line is hidden below green line.

Table 2
The significance of $J^P = 1^-$ over other quantum number hypotheses. The significance is obtained considering changes in the difference of NDF. In each case that change is $\Delta(\text{NDF}) = 4$, accounting for the mass and width of the D^* and the magnitude and phase for each component. The significance in all cases exceeds 10 σ.

Process	Hypothesis	$\Delta(-2\ln\mathcal{L})$
$D_s^{*+}D_s^-$	1^- over 2^+	1102
	1^- over 3^-	2104
$D^{*0}\bar{D}^0$	1^- over 2^+	12134
	1^- over 3^-	12096
$D^{*+}D^-$	1^- over 2^+	11308
	1^- over 3^-	11222

distributions for the three spin-parity hypotheses, which combine the $D_{(s)}^*$-tag sample and the $D_{(s)}$-recoil sample.

The significances to accept the 1^- hypothesis for D_s^{*+}, D^{*0}, and D^{*+} are determined by the continuous test following Refs. [40,41], where the null hypothesis (H_0) represents the J^P of $D_{(s)}^*$ taken as 2^+ or 3^- and the alternative hypothesis (H_1) represents J^P of $D_{(s)}^*$ taken as a linear combination of either $[2^+, 1^-]$ or $[3^-, 1^-]$. The angular fits based on the two hypotheses are performed to data and the likelihood function values are denoted as $\ln(\mathcal{L}_{H_0})$ and $\ln(\mathcal{L}_{H_1})$.

The significance of the J^P=1^- hypothesis is found to be larger than 10σ, based on the change in likelihood $(-2\ln\mathcal{L})$ and number of degrees of freedom (NDF) listed in Table 2.

6. Systematic uncertainties

The results of the helicity amplitude analysis can be affected by detector effects and analysis procedures. In order to quantify the impact of such systematic effects on this work, dedicated studies on control samples are performed and corrections for eventual data/MC differences are evaluated.

The sources of systematic uncertainties include the tracking and PID efficiencies for $K^\pm$ and $\pi^\pm$, which are studied with control samples of $e^+e^- \to K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$, $K^+K^-\pi^+\pi^-\pi^0$, $\pi^+\pi^-\pi^+\pi^-$, and $\pi^+\pi^-\pi^+\pi^-\pi^0$ events [42]. The photon reconstruction efficiency is studied using $J/\psi \to \rho^0\pi^0$ events [43]. The K_S^0 reconstruction efficiency is studied with control samples of $J/\psi \to K^*(892)^\pm K^\mp$, $K^*(892)^\pm \to K_S^0\pi^\pm$ and $J/\psi \to \phi K_S^0 K^\mp\pi^\pm$ [44] decays. The π^0 reconstruction efficiency is studied by the double-tag $D\bar{D}$ hadronic decays $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$ versus $\bar{D}^0 \to K^+\pi^-\pi^0$, $K_S^0\pi^0$ [45,46]. According to the efficiency differences determined above, an overall weighting of MC events is performed to match the data events in the fit.

Additionally, inconsistencies between data and MC in the description of the track helix parameters may result in systematic effects. The helix parameters in MC simulations are, therefore, corrected following the procedure described in Ref. [47].

To estimate potential bias due to differences between the data and MC simulation in the selected regions, the distributions of the kinematic variables ΔE and invariant mass $M(D_{(s)})$, $M(D_{(s)}\pi^0(\gamma))$, and $RM(D_{(s)})$ in MC simulations are smeared with Gaussian functions to match the corresponding distributions in the data.

The systematic uncertainty due to the background weight factor (ω_{bkg}) is estimated by setting it to 0. For the non-perfect resolution description, the values of the BW parameters are varied by one standard deviation ($\pm 1\sigma$) from the nominal fit result and the result with the lowest significance is assigned as the systematic uncertainty.

Taking into account all of the systematic uncertainties, the $J^P = 1^-$ hypothesis is always unambiguous and its significance is always greater than 10σ.

7. Summary

The spin and parity of D_s^{*+}, D^{*0}, and D^{*+} mesons are determined in the processes $e^+e^- \to D_s^{*+}D_s^-$, $D^{*0}\bar{D}^0$, and $D^{*+}D^-$, based on 3.19 fb^{-1} of e^+e^- collision data accumulated at $\sqrt{s} = 4.178$ GeV with the BESIII detector. The application of a helicity amplitude analysis results in a preference of the quantum number $J^P = 1^-$ over the 2^+ and 3^- hypotheses with a significance of more than 10σ, thus confirming the quark model predictions. This is the first experimental determination of the spin and parity of the $D_{(s)}^*$ mesons, which are the cornerstone for the exploration of the properties of heavier charm and beauty mesons [48].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.physletb.2023.138245.

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