Study of $D_s^+ \to K^{(\star)0} e^+ \nu_e$ at BESIII

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Abstract

Based on 3.19 fb^{-1} data taken at $\sqrt{s}$ = 4.18 GeV with the BESIII detector at the BEPCII collider, branching fractions of $D_s^+ \to K^0 e^+ \nu_e$ and $D_s^+ \to K^{\star 0} e^+ \nu_e$ are measured to be $\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = 3.25 \pm 0.38 \pm 0.14$ and $\mathcal{B}(D_s^+ \to K^{\star 0} e^+ \nu_e) = 2.38 \pm 0.26 \pm 0.12$. The form factors in these two decays are also analysed for the first time. The hadronic form factor $f_+(0)$ is determined to be $f_+(0) = 0.720 \pm 0.084 \pm 0.013$ for $D_s^+ \to K^0 e^+ \nu_e$ by fitting the partial decay rates. The form factor ratios r_V and r_2 for the decay $D_s^+ \to K^{\star 0} e^+ \nu_e$ are measured to be $r_V = 1.67 \pm 0.34 \pm 0.16$ and $r_2 = 0.77 \pm 0.28 \pm 0.07$. respectively. Here, the first errors are statistical and the second systematic.

Introduction

- $D_s^+ \to K^{(\star)0} e^+ \nu_e$ are Cabibbo-suppressed processes.
- Current branching fractions (BFs) of these decays are limited to the statistics. Significant improvement is expected with the dataset collected with BESIII.
- First study of the form factors in the decays helps to calibrate the Lattice QCD calculations, and provide additional data to determine the CKM matrix element $|V_{\rm cd}|$.

BESIII and BEPCII

Figure 1: Overview of BEPCII and BESIII.

- The Beijing Spectrometer (BESIII) detects e^+e^- collisions in the double-ring collider Beijing Electron Positron Collider (BEPCII).
- D_s^+ dataset is accumulated in 2016, based on $D_s D_s^*(\to \gamma(\pi^0) D_s)$ production at $\sqrt{s} = 4.180$ GeV. The luminosity is about $\mathcal{L} = 3.19\ \text{fb}^{-1}$, so about 6M D_s^+ events are produced.

Analysis Method

A double tag (DT) analysis method is exploited, where a single tag (ST) D_s^- is reconstructed with the hadronic decays, as the tag side, while the SL candidates could be reconstructed in the signal side. Hence, the BFs of $D_s^+ \to K^{(\star)0} e^+ \nu_e$ could be estimated using: $\mathcal{B}(D_s^+ \to K^{(\star)0} e^+ \nu_e) = \frac{N_{\rm sig}^{\rm obs}}{N_{D_s^-} \times \varepsilon_{\rm sig} \times \mathcal{B}(K^{(\star)\,0} \to \pi^+(K^+)\pi^-)}$. Here, $N_{\rm sig}^{\rm obs}$ is the number of the signal events, $N_{D_s^-}$ is the number of ST D_s^- mesons, $\varepsilon_{\rm sig}$ is the DT efficiencies and $K^{(\star)\,0}$ is reconstructed via their decay to $\pi^+(K^+)\pi^-$. Through out this document, all charge conjugate modes are implied.

ST D_s^- events

13 modes are included in the ST D_s^- reconstruction, as shown in Fig. 2. Charged and neutral particles are selected out to form the D_s^- candidates, then it's recoil mass $\rm M_{rec}$ is calculated with $\rm M_{rec}$ $= \sqrt{(\sqrt{s} - \sqrt{|\vec{P}_{D_s^-}|^2 + m_{D_s^-}^2})^2 - |-\vec{P}_{D_s^-}|^2}$, where $\vec{P}_{D_s^-}$ and $\rm m_{D_s^-}$ are the momentum and nominal mass of D_s^-, respectively. The difference between the recoil mass and the nominal mass of $\rm m_{D_s^{*+}}$ is determined as $\Delta \rm M = M_{rec} - m_{D_s^{*+}}$. Cut on this variable is used for further background suppression, as shown in Fig. 3.

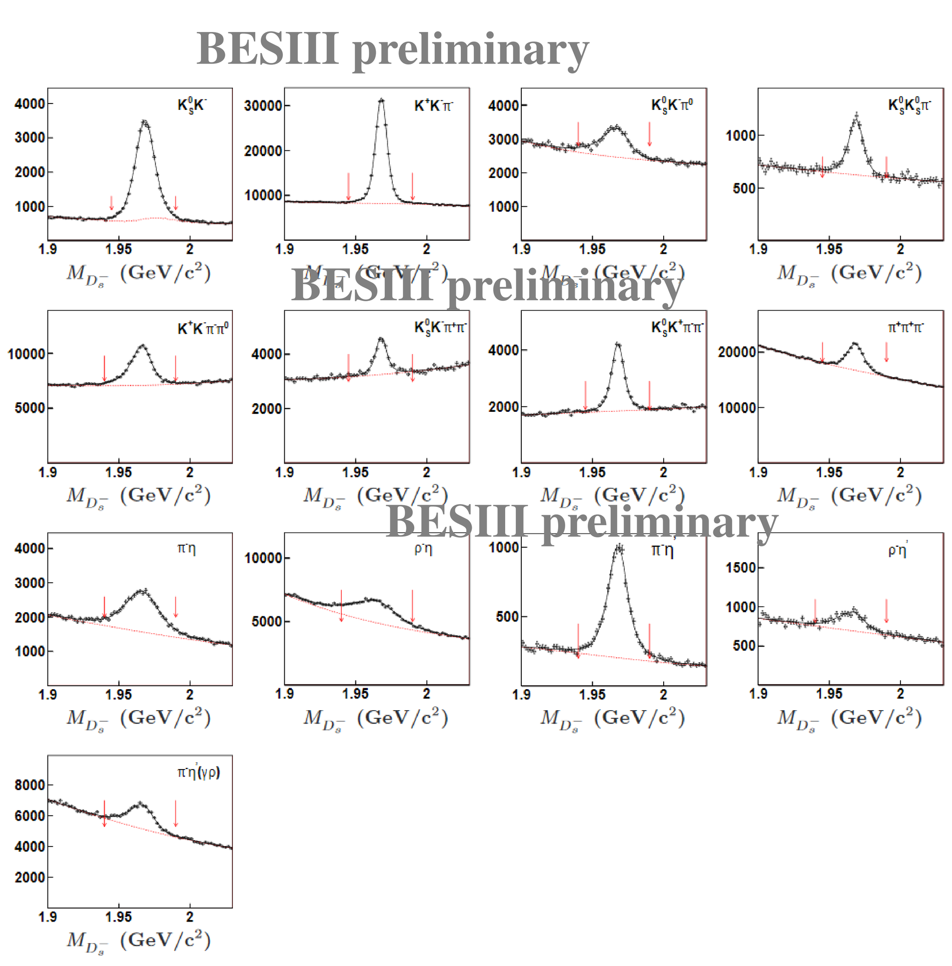

Figure 2: Fit to $M_{D_s^-}$ in data.

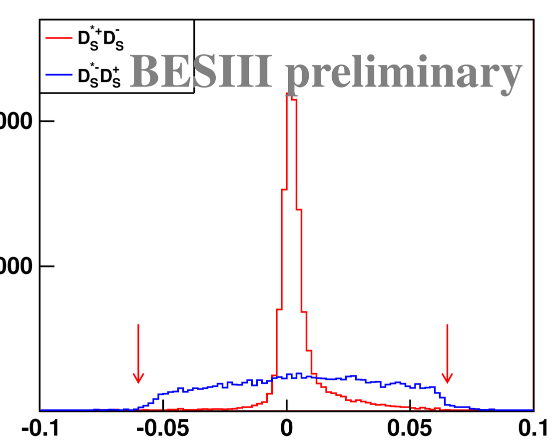

Figure 3: Simulated ΔM distribution.

ST modes	$N_{\rm tag}^{\rm obs}$	$\varepsilon_{\rm tag}$
BESIII preliminary		
$K_S^0 K^-$	25858±217	40.46±0.07
$K^+K^-\pi^-$	130666±575	40.02±0.03
$K_S^0 K^- \pi^0$	10807±398	15.91±0.05
$K_S^0 K_S^0 \pi^-$	3810±131	19.56±0.09
$K^+K^-\pi^-\pi^0$	35091±702	9.50±0.03
$K_S^0 K^- \pi^+\pi^-$	7722±235	17.67±0.07
$K_S^0 K^+ \pi^-\pi^-$	14802±259	20.51±0.06
$\pi^+\pi^-\pi^-$	36258±832	52.51±0.07
$\pi^-\eta$	17535±400	43.86±0.13
$\rho^-\eta$	30114±886	16.58±0.04
$\pi^-\eta'(\to pi^+\pi^-\eta)$	7704±152	18.70±0.07
$\rho^-\eta'(\to pi^+\pi^-\eta)$	3039±226	4.88±0.03
$\pi^-\eta'(\to \gamma\rho)$	17919±481	21.01±0.06
Total	341325±1764	

Table 1: ST yields in data.

Signal Events of $D_s^+ \to K^{(\star)0} e^+ \nu_e$

- $e^+e^- \to D_s D_s^* \to \gamma D_s^+ D_s^-$ is used to select out the signal candidates
- To find the best photon candidate for the D_s^* candidate, all the residual photons are looped and constrained to the nominal mass of D_s^* under the hypothesis that photon comes from the tag side, i.e. D_s^{*-} or the signal side, i.e. D_s^{*+}. The combination with less χ^2 is kept.
- The missing neutrino is reconstructed with the missing mass square, $\rm MM^2$, which is calculated as: $\rm MM^2 = (E_{cm} - E_{D_s^-} - E_\gamma - E_{K^{(\star)0}, e^+})^2 - (-\vec{P}_{D_s^-} - \vec{P}_\gamma - \vec{P}_{K^{(\star)0}, e^+})^2$. Here, $E_{K^{(\star)0}, e^+} = E_{K^{(\star)0}} + E_{e^+}$ and $\vec{P}_{K^{(\star)0}, e^+} = \vec{P}_{K^{(\star)0}} + \vec{P}_{e^+}$. The $\rm MM^2$ distributions for the two decays are shown in Fig. 4.
- The signal yields are 117.2±13.9 and 155.0±17.2 for $D_s^+ \to K^0 e^+ \nu_e$ and $D_s^+ \to K^{\star 0} e^+ \nu_e$, and the BFs are measured to be $\mathcal{B}(D_s^+ \to K^0 e^+ \nu_e) = (3.25 \pm 0.38 \pm 0.14) \times 10^{-3}$ and $\mathcal{B}(D_s^+ \to K^{\star 0} e^+ \nu_e) = (2.38 \pm 0.26 \pm 0.12) \times 10^{-3}$, respectively. All of these numbers are BESIII preliminary.

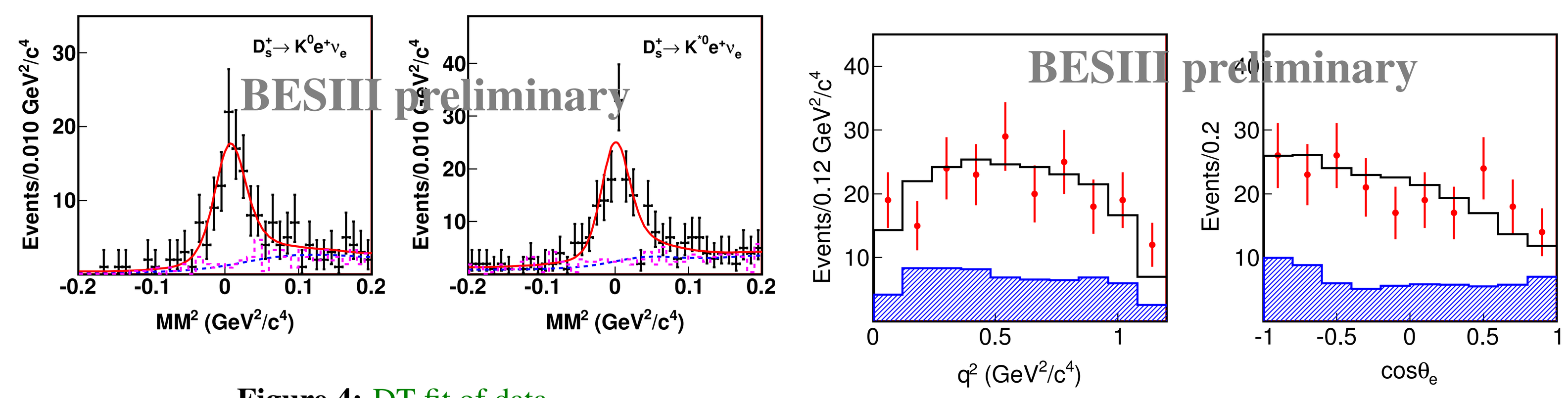

Figure 4: DT fit of data.

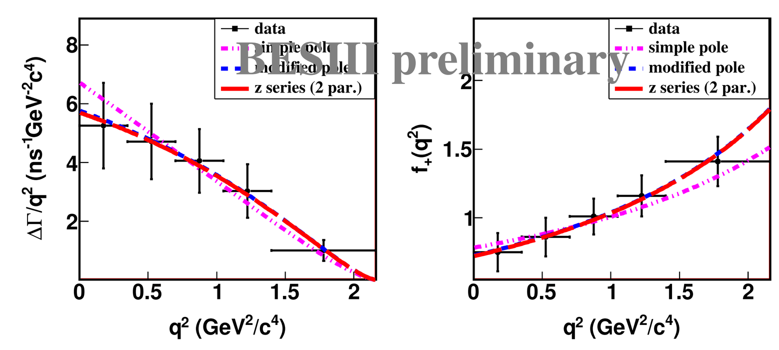

Figure 5: Form factor fit for $D_s^+ \to K^0 e^+ \nu_e$

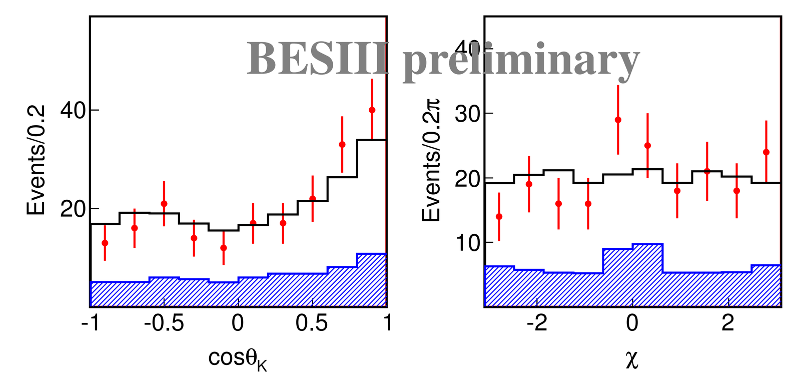

Figure 6: Form factor fit for $D_s^+ \to K^{\star 0} e^+ \nu_e$

Form Factor of $D_s^+ \to K^0 e^+ \nu_e$

The differential decay width for $D_s^+ \to K^0 e^+ \nu_e$ is given by: $\frac{d\Gamma(D_s^+ \to K^0 e^+ \nu_e)}{dq^2} = \frac{G_F^2 |V_{\rm cd}|^2}{24\pi^3} p_{K^0}^3 |f_+(q^2)|$, where p_{K^0} is the momentum of K^0 in the rest frame of the D_s^+ meson, and q^2 is the four momentum transfer, defined as: $q^2 = (E_{cm} - E_{D_s^-} - E_\gamma - E_{K^0})^2 - |-\vec{P}_{D_s^-} - \vec{P}_\gamma - \vec{P}_{K^0}|^2$. Three parametrizations of form factors are used in the fit to partial decay widths to extract the $f_+(0)$:

1. Simple model: $f_+(q^2) = \frac{f_+(0)}{1 - q^2/\rm M_{pole}^2}$, here $\rm M_{pole} = m_{D_s^{*+}} = 2112.4 \pm 0.4\ MeV/c^2$.
2. Modified pole model: $f_+(q^2) = \frac{f_+(0)}{(1 - q^2/\rm M_{pole}^2)(1 - \alpha q^2/M_{pole}^2)}$, here $\rm M_{pole}$ is float in the fit.
3. Series expansion: $f_+(q^2) = \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0)\left(1 + r_1(t_0)[z(t, t_0)]\right)$,

The fit is performed via constructing $\chi^2 = \Sigma(\Delta\Gamma_i^{\rm measured} - \Delta\Gamma_i^{\rm expected}) \mathcal{C}_{ij} \Sigma(\Delta\Gamma_j^{\rm measured} - \Delta\Gamma_j^{\rm expected})$, as shown in Fig. 5.

Form Factor of $D_s^+ \to K^{\star 0} e^+ \nu_e$

The differential decay width for $D_s^+ \to K^{\star 0} e^+ \nu_e$ can be expressed in terms of three helicity amplitudes $(H_+(q^2),\ H_-(q^2),\ H_0(q^2))$:

$$\begin{aligned}
\frac{d^5\Gamma}{dm_{K\pi} dq^2 d\cos\theta_K d\cos\theta_e d\chi} &= \frac{3}{8(4\pi)^4} G_F^2 |V_{\rm cd}|^2 \frac{p_{K\pi} q^2}{M_{D_s}^2} \mathcal{B}(K^{\star 0} \to K^+\pi^-) |\mathcal{BW}(m_{K\pi})|^2 \times \\
&[(1 + \cos\theta_e)^2 \sin\theta_K^2 |H_+(q^2, m_{K\pi})|^2 + \\
&(1 - \cos\theta_e)^2 \sin\theta_K^2 |H_-(q^2, m_{K\pi})|^2 + 4\sin\theta_e^2 \cos\theta_K^2 |H_0(q^2, m_{K\pi})|^2 + \\
&4\sin\theta_e (1 + \cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_+(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) - \\
&4\sin\theta_e (1 + \cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_-(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) - \\
&2\sin\theta_e^2 \sin\theta_K^2 \cos 2\chi H_+(q^2, m_{K\pi}) H_-(q^2, m_{K\pi})].
\end{aligned} \tag{1}$$

Here, the helicity amplitudes take the form $H_\pm(q^2) = (M_{D_s} + m_{K\pi}) A_1(q^2) \mp \frac{2m_{D_s} P_{K\pi}}{m_{D_s} + m_{K\pi}}$ and $H_0(q^2) = \frac{1}{2m_{K\pi} q}[(m_{D_s}^2 - m_{K\pi}^2 - q^2)(m_{D_s} + m_{K\pi}) A_1(q^2) - \frac{4m_{D_s}^2 P_{K\pi}^2}{M_{D_s} + m_{K\pi}} A_2(q^2)]$. Hence, two form factor ratios $r_V = \frac{V(0)}{A_1(0)}$ and $r_2 = \frac{A_2(0)}{A_1(0)}$ are defined in the fit. A 4-dimensional unbinned likelihood fit is performed, where likelihood function is defined as: $\ln\mathcal{L} = \ln\mathcal{L}_{\rm data} - \rm f \times \ln\mathcal{L}_{bkg}$.

Results and Summary

1. BFs of the two decays are consistent with PDG, with improved precision, as shown in Table 2. And discrepancies from some theoretical predictions arise according to this work.
2. First study of the form factors in these decays is performed. The fitted parameters of the form factors for the two decays are show in Table 3.
3. Taking $|V_{\rm cd}| = 0.22492 \pm 0.00050$ as input, $f_+(0)$ of $D_s^+ \to K^0 e^+ \nu_e$ is determined to be $0.720 \pm 0.084 \pm 0.013$ under Series Expansion parametrization.

Decay	$\mathcal{B}_{\rm exp.}(\times 10^{-3})$	$\mathcal{B}_{\rm the.}(\times 10^{-3})$
$D_s^+ \to K^0 e^+ \nu_e$	3.25±0.38±0.14	2.0[1]
	(BESIII preliminary)	3.2[2]
	3.9±0.9	$3.90^{+0.74}_{-0.57}$[3]
	(PDG2017)	2.9[4]
$D_s^+ \to K^{\star 0} e^+ \nu_e$	2.38±0.26±0.12	2.2[5]
	(BESIII preliminary)	1.9[2]
	1.8±0.4	$2.33^{+0.29}_{-0.30}$[3]
	(PDG2017)	1.7[4]

Table 2: BFs in experiment and theory.

Decay	model	parameter	value
$D_s^+ \to K^0 e^+ \nu_e$	Simple pole	$f_+(0)\lvert V_{\rm cd}\rvert$	0.175±0.010±0.001
(BESIII preliminary)	Modified pole	$f_+(0)\lvert V_{\rm cd}\rvert$	0.163±0.017±0.003
		α	0.45±0.44±0.02
	Series expansion	$f_+(0)\lvert V_{\rm cd}\rvert$	0.162±0.019±0.003
		r_1	−2.94±2.32±0.14
$D_s^+ \to K^{\star 0} e^+ \nu_e$		r_V	1.67±0.34±0.16
(BESIII preliminary)		r_2	0.77±0.28±0.07

Table 3: Parameters extracted from the form factor fit.

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