Charm physics at BESIII

Peter Weidenkaff for the BESIII collaboration

Institut für Kernphysik, Johann-Joachim-Becher-Weg 45, 55128 Mainz, Germany

E-mail: `weidenka@uni-mainz.de`

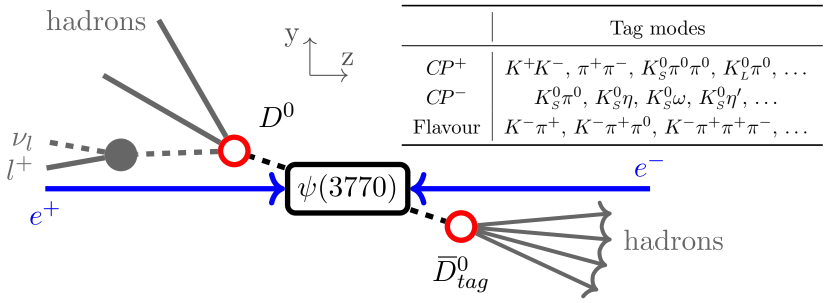
Abstract. The study of mesons and baryons which contain at least on charm quark is referred to as open charm physics. It offers the possibility to study up-type quark transitions. Since the c quark can not be treated in any mass limit, theoretical predictions are difficult and experimental input is crucial. BESIII collected large data samples of e^+e^- collisions at several charm thresholds. The at-threshold decay topology offers special opportunities to study open charm decays.

We present a selection of recent BESIII results. The D_s^+ decay constant is measured using the leptonic decays to $\mu^+\nu$ and $\tau^+\nu$. Using the semi-leptonic decays of D^0 and $D^\pm$ to $Ke^+\nu_e$ and $\pi e^+\nu_e$, a measurement of the form factors $f_+^K(q^2)$ and $f_+^\pi(q^2)$ is performed and furthermore, we show preliminary results of a model independent measurement of the strong phase difference between D^0 and $\overline{D}^0$ in the channel $D^0 \to K_S^0\pi^+\pi^-$ which is an experimental input to the measurement of the CKM angle γ/ϕ_3.

1. Introduction

The BESIII experiment is located at the Beijing Electron-Positron Collider. The accelerator is a e^+e^- storage ring located at the Institute of High Energy Physics in Beijing. It provides symmetric collisions in the energy range between 2.0 GeV and 4.6 GeV. The maximum luminosity of BEPCII is achieved at $\sqrt{s}$ =3.773 GeV. In April 2016 a luminosity of $1 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ was surpassed. The detector measures charged track momenta with a relative precision of 0.5 % (@1.0 GeV) using a multi-wire drift chamber in a 1 T magnetic field. Electromagnetic showers are measured in a caesium iodide calorimeter with a relative precision of 2.5 % (@1.0 GeV) and a good particle identification is achieved by combining information from energy loss in the drift chamber, from the time-of-flight system and from the calorimeter. Muons can be identified using 9 layers of resistive plate chambers integrated in the magnet return yoke. The BESIII experiment is described in detail elsewhere (*1*). BESIII has collected large data samples in the tau-charm region. The interesting samples for the study of charmed hadrons are usually at a center-of-mass energy close to a threshold. The largest such sample was recorded at $\sqrt{s} = 3.773$ GeV with an integrated luminosity of $2.81\,\mathrm{fb}^{-1}$. The corresponding threshold is the $D^0\overline{D}^0/D^+D^-$ threshold. At $\sqrt{s} = 4.009$ GeV, close to the $D_s^+\overline{D}_s^+$ threshold, a sample of $0.482\,\mathrm{fb}^{-1}$ was recorded. Λ_c decays can be studied using a sample of $0.5669\,\mathrm{fb}^{-1}$ at the $\Lambda_c\overline{\Lambda_c}$ threshold ($\sqrt{s} = 4.5995$ GeV).

The implications of those at-threshold decay topologies are discussed in section 2. In the following we present the measurements of the D_s^+ decay constant (section 3), form factor measurements of neutral and charged D decays to $Ke^+\nu$ and $\pi e^+\nu$ (section 4) as well as a model independent measurement of the strong phase difference between D^0 and $\overline{D}^0 \to K_S^0\pi^+\pi^-$ (section 5). Recent results on Λ_c decays are presented in (*2*).



	Tag modes
CP^+	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, ...
CP^-	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, ...
Flavour	$K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, ...

Figure 1: $\psi(3770)$ decay topology in the $\psi(3770)$ rest frame. An undetected particle track can be reconstructed using the constrained kinematics of the decay. Typical tag modes for *CP* and flavour eigenstates are listed.

2. Open charm decays at threshold

The at-threshold decay topology at a center-of-mass energy of 3.773 GeV is illustrated in fig. 1. A pair of particles is produced and it is possible to conclude from the decay of one meson (so-called tag meson) properties of the second decay. For instance in case of neutral D decays the flavour or the *CP* quantum numbers of the signal decay can be measured, even if the signal final state does not provide this information. In case of charged D decays the reconstruction of both decays is used to reduce the background and furthermore if undetected particles are involved in the signal decay the four momenta of those can be calculated. In particular the study of leptonic and semi-leptonic decays benefits from this. The reconstruction of both decays in each event is referred to as double tag technique.

3. D_s^+ decay constant

The simplest and cleanest modes of D_s^+ decays are pure leptonic modes. We analyse the final state $\tau^+\nu_\tau$ and $\mu^+\nu_\mu$ and measure their branching fractions. Detailed information can be found in (*3*).

The leptonic decay of D_s^+ proceeds via the annihilation of c and $\overline{s}$ to a virtual $W^\pm$ boson and its decay to $l^+\nu_l$. The decay rate can be parametrized as:

$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi} f^2_{D_s^+} m_l^2 m_{D_s^+} \left(1 - \frac{m_l^2}{m^2_{D_s^+}}\right)^2 |V_{cs}|^2, \tag{1}$$

with the Fermi constant G_F, the lepton mass m_l, the CKM matrix element $|V_{cs}|^2$ and the decay constant $f^2_{D_s^+}$. The decay constant parametrizes the QCD effect on the decay. From the measurement of the decay width $\Gamma(D_s^+ \to l^+\nu_l)$ the decay constant $f^2_{D_s^+}$ can be extracted. The CKM matrix element $|V_{cs}|^2$ is an external input (*4*).

The branching fraction can be measured via the previously described double tag technique. In each event the tag decay is reconstructed via numerous decay channels. The number of events that contain a tag candidate is denoted by N_{tag}. Among those events the signal decay is reconstructed and the number of events that contain a tag decay and a signal decay is denoted by N_{sig}. The branching fraction is then given by:

$$\mathcal{B}(D_s^+ \to l^+\nu_l) = \frac{N_{\text{sig}}}{N_{\text{tag}} \times \epsilon}. \tag{2}$$

The efficiency for reconstruction and selection ϵ is obtained from simulation.

Since the final state contains a neutrino which is not detected the signal yield is determined using the missing mass:

$$MM^2 = \frac{(E_{\text{beam}} - E_\mu)^2}{c^4} - \frac{\left(-\vec{p}_{D_s^+} - \vec{p}_{\mu^+}\right)^2}{c^2}. \tag{3}$$

The beam energy is denoted by E_{beam} and the reconstructed momentum of the tag D_s^+ decay candidate by $\vec{p}_{D_s^+}$.

The distribution is shown in fig. 2. The yield is determined via a simultaneous fit to signal and sideband regions. The $\mu^+\nu_\mu$ signal is shown as red dotted curve and the $\tau^+\nu_\tau$ signal as black dot-dashed curve. Background from misreconstructed tag D_s^+ decays and background from non-$D_s^+\overline{D}_s^+$ events is shown in green and purple, respectively. Within a sample of $15\,127 \pm 312$ event which contain a tag candidate we find 69.3 ± 9.3 $D_s^+ \to \mu^+\nu_\mu$ decays and 32.5 ± 4.3 $D_s^+ \to \tau^+\nu_\tau$ decays. In the fitting procedure the ratio of $D_s^+ \to \mu^+\nu_\mu$ to $D_s^+ \to \tau^+\nu_\tau$ was constraint to its Standard model prediction. Those yields are corrected for radiative effects and we obtain:

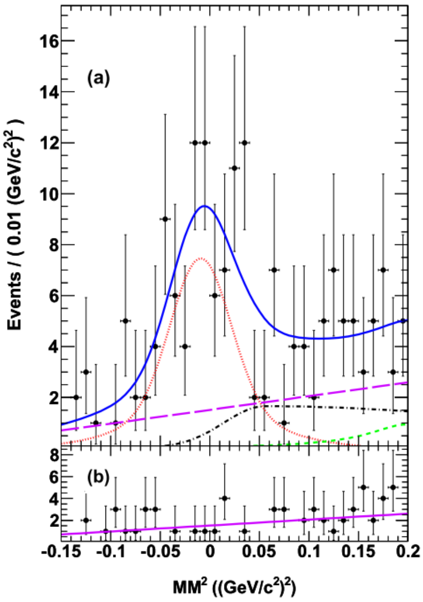


Figure 2: MM^2 distribution of the signal are (a) and the sideband region (b).

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (0.495 \pm 0.067\ (\text{stat.}) \pm 0.026\ (\text{sys.}))\,\% \tag{4}$$

$$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (4.83 \pm 0.65\ (\text{stat.}) \pm 0.26\ (\text{sys.}))\,\%. \tag{5}$$

The branching fractions $\mathcal{B}$ $(D_s^+ \to \mu^+\nu_\mu)$ and $\mathcal{B}$ $(D_s^+ \to \tau^+\nu_\tau)$ is consistent with the world average within 1 and 1.5 standard deviations, respectively. The branching fractions are additionally determined using a fitting method which does not rely on the ratio of $D_s^+ \to \mu^+\nu_\mu$ to $D_s^+ \to \tau^+\nu_\tau$. For further details we refer to (3).

Using $\mathcal{B}$ $(D_s^+ \to \mu^+\nu_\mu)$ the decay constant $f_{D_s^+}$ is determined using eq. (1):

$$f_{D_s^+} = (241.0 \pm 16.3\ (\text{stat.}) \pm 6.6\ (\text{sys.}))\,\text{MeV}. \tag{6}$$

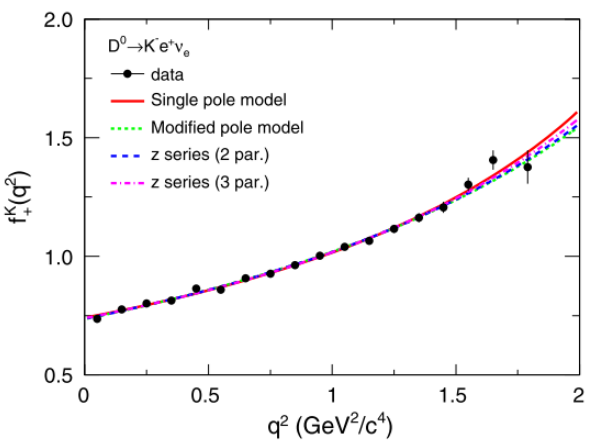
The result is consistent with LQCD calculations.

4. Form factor measurement

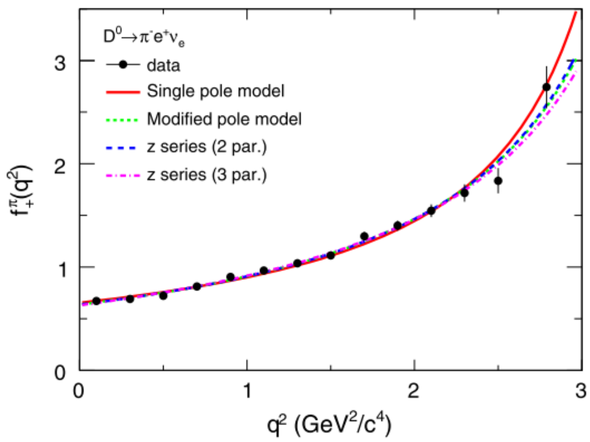
In pure leptonic decays, as described previously, the coupling strength is parametrized using a constant. In case of semi-leptonic decays the coupling strength depends on the momentum of the leptonic system and therefore, has a q^2 dependence. The coupling strength is then referred to as form factor. We analyse the decays of charged and neutral D mesons to the semi-leptonic final states $Ke^+\nu_e$ and $\pi e^+\nu_e$. The decay rate can be parameterized as:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3}\left|V_{cs(d)}\right|^2\left|\vec{p}_{K^-(\pi^-)}\right|^3\left|f_+^{K(\pi)}(q^2)\right|^2, \tag{7}$$

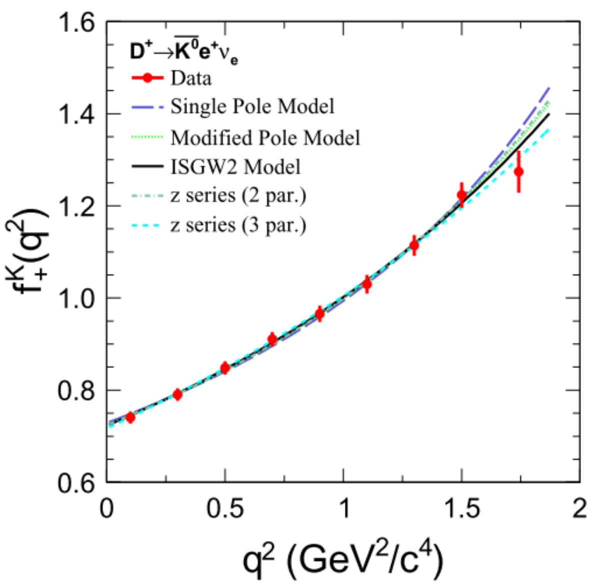
with the Fermi constant G_F^2, the three momentum of the hadronic system $\left|\vec{p}_{K^-(\pi^-)}\right|$, the corresponding CKM matrix element $\left|V_{cs(d)}\right|^2$ and the form factor $\left|f_+^{K(\pi)}(q^2)\right|$. From the measurement of the branching fractions in bins of q^2, the product of matrix elements and form



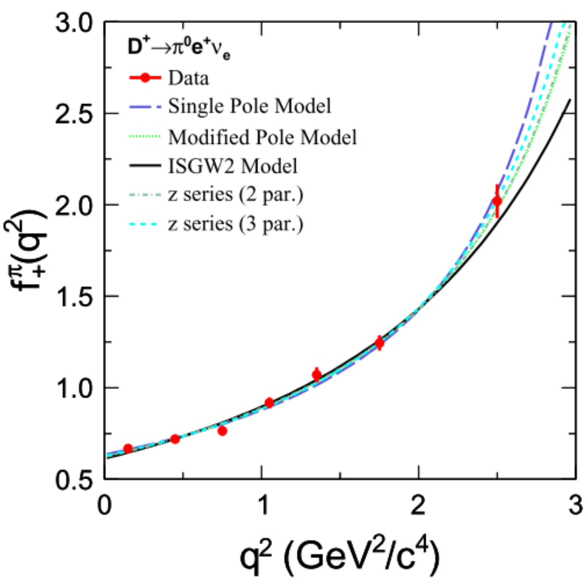
(a) $D^0 \to K^- e^+ \nu_e$



(b) $D^0 \to \pi^- e^+ \nu_e$



(c) $D^+ \to K^0 e^+ \nu_e$



(d) $D^+ \to \pi^0 e^+ \nu_e$

Figure 3: Dependence of the form factor $f_+^{K(\pi)}$ on the momentum transfer q^2 to the leptonic system.

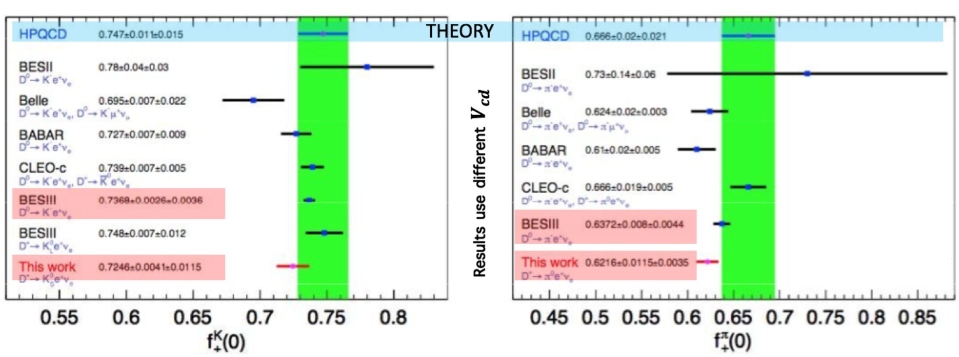


Figure 4: Comparison of form factor measurements with previous results and theory.

Table 1: Single and double tag yields for the form factor measurement. The branching fraction is calculated according to eq. (1). Uncertainties are statistical followed by systematical uncertainty.

	D^0	D^+
N_{tag}	$2\,793\,317 \pm 3684$	$1\,703\,054 \pm 3405$
$N_{sig}(Ke^+\nu_e)$	$70\,727 \pm 278$	$26\,008 \pm 168$
$N_{sig}(\pi e^+\nu_e)$	6297 ± 87	3402 ± 70
$\mathcal{B}\ (Ke^+\nu_e)$ [%]	$3.505 \pm 0.014 \pm 0.033$	$8.60 \pm 0.06 \pm 0.15$
$\mathcal{B}\ (\pi e^+\nu_e)$ [%]	$0.295 \pm 0.004 \pm 0.003$	$0.363 \pm 0.008 \pm 0.005$

factor can be extracted. Using external measurements as input for the CKM matrix element, the form factor can be extracted or vice-versa, from a lattice QCD calculation of the form factor, the matrix element can be calculated. Since the final state contains a neutrino which is not detected, we use the constrained kinematics of the at-threshold production of $D^0\overline{D}^0/D^+D^-$ at $\sqrt{s} = 3.773\,\text{GeV}$. Similarly to the previously described measurement the double tag technique is used and the branching fraction is given by eq. (2). Yields and branching fractions are listed in table 1. The q^2 dependence of the form factor is shown in fig. 3. It is then extrapolated to $q^2 = 0$ using various models. A comparison of measurements of $f_+^h(0)$ with theory, given in fig. 4, shows that BESIII is able the reduce the uncertainty significantly.

The analysis of $D^0 \to K^-/\pi^- e^+\nu_e$ is published in (5) and the analysis of $D^+ \to \overline{K}^0/\pi^0 e^+\nu_e$ is a BESIII preliminary result, but is expected to be published soon.

5. Strong phase measurement in $D^0 \to K_{S/L}\pi^+\pi^-$

The CKM angle γ/ϕ_3 can be measured in B^- decays to the final state $D^0K^-/\overline{D}^0K^-$, as illustrated in fig. 5. Since the D^0 final state $f(D)$ needs to be accessible from D^0 as well as from $\overline{D}^0$ it has to be charge conjugate state. 'Golden modes' for such a state are $K_S^0\,\pi^+\pi^-$ and $K_L^0\,\pi^+\pi^-$. The interference term of the decay rate is sensitive to the CKM angle γ/ϕ_3:

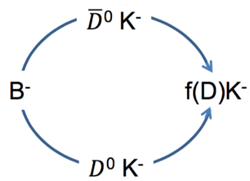


Figure 5: Measurement of the CKM angle γ/ϕ_3 in B decays via the GGSZ method.

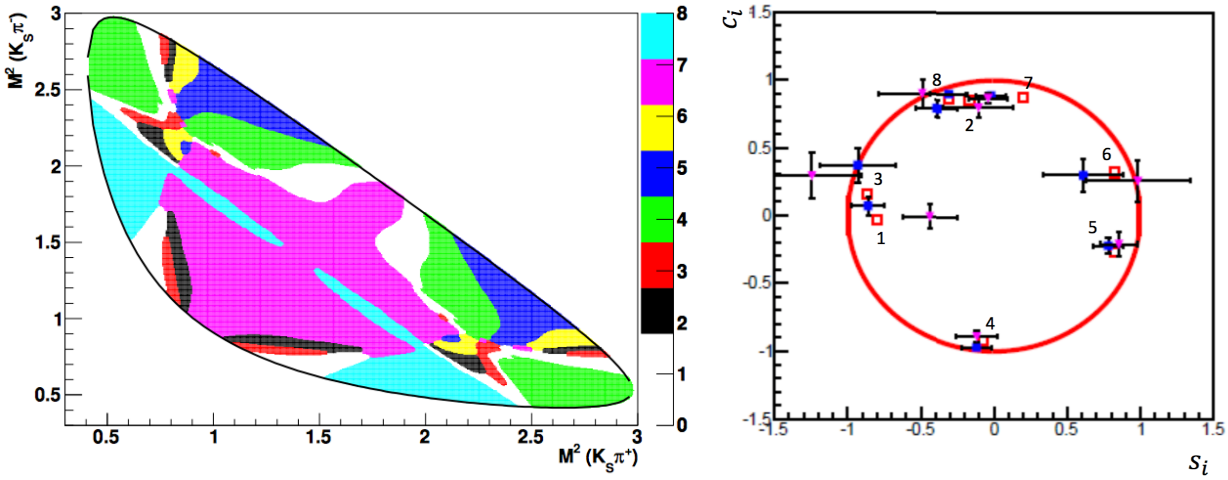
$$\Gamma(B^- \to f(D^0)K^-) = A_B^2 A_f^2 (r_B^2 + r_D^2 + 2 r_D r_B \cos(\delta_B + \delta_D - \phi_3)), \quad (8)$$

where the amplitude for the B^- and D^0 decay are denoted by A_B and A_D, respectively. The phase difference δ_D between D^0 and $\overline{D}^0$ to the same final state is an external input to this type of measurement. It can be extracted from a amplitude analysis of the final state but since those analyses have large uncertainties on the amplitude model, a model independent measurement is of advantage. Using the possibility to tag the CP quantum number of the signal decay, we present the preliminary result of a model independent measurement of the strong phase difference between D^0 and $\overline{D}^0$ to the final state $K_{S/L}\pi^+\pi^-$. For simplicity we only discuss the final state $K_S^0\pi^+\pi^-$ here.

The measurement is performed on a binned phase space. The binning (fig. 6(a)) relies on an amplitude model and is chosen such that the sensitivity on δ_D is maximal. In each event both D^0 mesons are reconstructed. One in the final state $K_S^0\pi^+\pi^-$ and the second decay in either a $CP^\pm$ eigenstate or in a flavour eigenstate. Furthermore, a sample with both D^0 mesons decaying to $K_S^0\pi^+\pi^-$ is used. The number of events in each bin of the phase space of the flavour tagged sample is denoted by K_i. Then, for the CP tagged samples and for the $K_S^0\pi^+\pi^-$ versus $K_S^0\pi^+\pi^-$

Table 2: Expected number of events per bin. K_i is the event rate in bin i measured using the flavour tagged sample. The cosine and sine of δ_D are denoted by c_i and s_i, respectively.

Tag mode	$K_S^0\ \pi^+\pi^-$
Flavour	K_i
$CP\ \pm$	$M_i^{\pm} \propto \left(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i}\right)$
$K_S^0\ \pi^+\pi^-$	$M_{i,j}^{\pm} \propto \left(K_i K_{-j} + K_{-i}K_j - 2\sqrt{K_i K_{-j} K_{-i} K_j}\,(c_i c_j + s_i s_j)\right)$



(a) Phase space binning scheme (*6*).

(b) Cosine versus sine of the strong phase between D^0 and $\bar{D}^0$.

Figure 6: Strong phase between D^0 and $\bar{D}^0$ in phase space bins. The measurement (blue) is compatible with the model dependent prediction (red). BESIII is able to improve the existing result from CLEO-c (pink) significantly.

sample the event rate in each bin i is given in table 2. The cosine and sine of δ_D for each bin are determined in a simultaneous fit. The preliminary result is shown in fig. 6(b). Since the sample with two $K_S^0\pi^+\pi^-$ decays is very limited we also use the channel $K_L^0\pi^+\pi^-$ for this result. We are able to significantly reduce the uncertainty on the measurement compared to CLEO-c (*6*).

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