

Measurements of absolute branching fractions

$$D^0 \rightarrow K_L^0 X \quad (X = \phi \eta \omega \eta')$$

Author: Sanqiang Qu

Presenter: Haoran Zhang(张浩然)

Introduction

Studies of CP violation of the weak decays of D mesons are important for exploring physics within and beyond the Standard Model.

theoretical research based on factorization-assisted topological-amplitude (FAT) approach, predicted the $K_S^0 - K_L^0$ asymmetry to be 0.113 ± 0.001 for all possible processes of two-body nonleptonic D^0 decays.

This paper reports the first measurements of the BFs of $D^0 \rightarrow K_L^0 X$ ($X = \phi\eta\omega\eta'$), as well as the BF asymmetries between $K_L^0 X$ and $K_S^0 X$, the CP asymmetries in these decays are also determined.

Data and MC sets

Data sample: 2.93 fb^{-1} sample of e^+e^- annihilation data at $\sqrt{s} = 3.773 \text{ GeV}$ with BESIII detector.

Inclusive MC sample: corresponding to the luminosity, containing the production of DD pairs, the non DD decays of the $\psi(3770)$, the ISR production of the J/ψ and $\psi(3686)$ states, and the continuum processes, is used in this analysis (shown in the table, cite from the MC sample page of Charm Group of BESIII).

Signal MC sample: additionally generate signal MC sample (0.6 M for each signal mode), to obtain their signal line shapes and to determine double tag (DT) efficiencies.

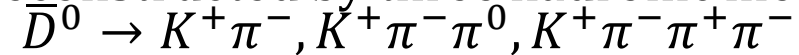
Physics	N_{event}	Lum Scale
$D^0\bar{D}^0$	232M	21.7x
D^+D^-	91M	10.8x
$qq(lundlw)$	366M	7.4x
$qq(KKMC)$	366M	7.4x
$RR2S$	102M	10.2x
$RR2S$	33M	10.2x
$\tau\tau$	90M	10.2x
ee	400M	0.26x
$nonDD$	15M	10.2x
$\mu\mu$	92M	5.0x

Analysis method

Double-tag (DT) method:

In $\psi(3770) \rightarrow D^0 \bar{D}^0$, \bar{D}^0 meson is found as a “single side” or “single tag” (ST), the partner D^0 meson is reconstructed by the rest of the event and called “signal side” or “double tag (DT)” (charge conjugate channels are implied, unless noted otherwise).

In this analysis the \bar{D}^0 meson is reconstructed by three hadronic modes:

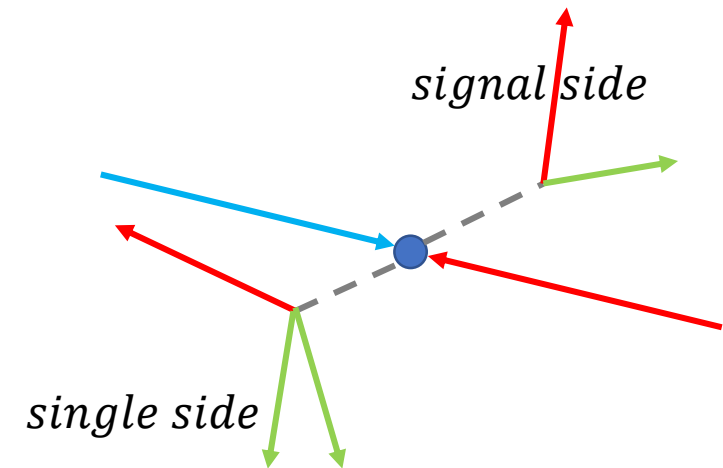


For a special ST mode i , the ST and DT yields observed in data are given by:

$$N_{ST}^i = 2N_{DD} \cdot \mathcal{B}_{tag}^i \cdot \epsilon_{tag}^i$$
$$N_{DT}^i = 2N_{DD} \cdot \mathcal{B}_{tag}^i \cdot \mathcal{B}_{sig} \cdot \epsilon_{tag,sig}^i$$

The absolute BF are determined by:

$$\mathcal{B}_{sig} = \frac{N_{DT}^i \cdot \epsilon_{tag}^i}{N_{ST}^i \cdot \epsilon_{tag,sig}^i}$$



Analysis method

At $\sqrt{s} = 3.773$ GeV, $D^0\bar{D}^0$ pairs are produced coherently, the effect of quantum-correlation (QC) in $D^0\bar{D}^0$ pairs:

The Cabibbo-favored (CF) and doubly Cabibbo-suppressed (DCS) amplitudes: r_i^2 the ratio of the DCS and CF amplitudes for $D^0\bar{D}^0$ decays to same final state, δ_f^i is the strong-phase difference between these two amplitudes.

strong-phase factor: $C_f^i = \frac{2r_i R_i \cos \delta_f^i}{1+r_i^2}$, R_i is the coherence factor, $0 < R_i < 1$ (quantifies the dilution due to integrating over the phase space).

The amplitude of the neutral D decays can be decomposed as mixture of the CP+ and CP- components. quantum-correlation (QC) factor $f_{QC}^i = \frac{1}{1-C_f^i(2F_{sig}^+-1)}$, all signal decay final states studied are CP+ eigenstates.

the absolute BF are determined by:

$$\mathcal{B}_{sig} = f_{QC} \cdot \frac{N_{DT}^i \cdot \epsilon_{tag}^i}{\sum_i N_{ST}^i \cdot \epsilon_{tag,sig}^i}$$

Tag Mode	f_{QC}
$\bar{D}^0 \rightarrow K^+ \pi^-$	0.898 ± 0.007
$\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$	0.935 ± 0.007
$\bar{D}^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	0.972 ± 0.019

Fitting method

Two kinematic variables: energy difference $\Delta E \equiv E_{\bar{D}^0} - E_{beam}$, to suppress combinatorial backgrounds: $(-0.055, 0.040)$ GeV for channels with π^0 , and $(-0.025; 0.025)$ GeV for channels without π^0 .

beam-constrained mass $M_{BC} \equiv \sqrt{(E_{beam}^2/c^4 - \vec{p}_{\bar{D}^0}^2/c^2)}$

A binned maximum-likelihood fit is performed on the corresponding M_{BC} distribution.

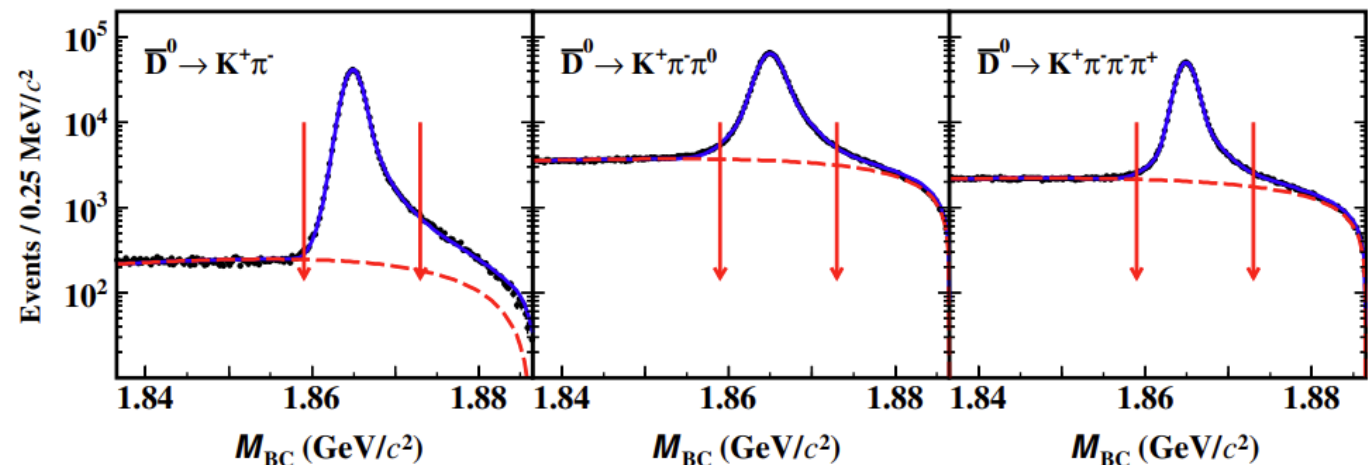
The signal is modeled by the MC shape convolved with a double-Gaussian function.

The combinatorial background is described by the ARGUS function.

The candidates with M_{BC} within $(1.859, 1.873)$ are kept for further analyses.

The total yield of ST \bar{D}^0 mesons is

$$N_{ST}^{tot} = 2266311 \pm 1842$$



Fitting method

To obtain the DT yields. X ($X = \phi\eta\omega\eta'$) particles are reconstructed with:

$$\phi \rightarrow K^+K^-, \omega \rightarrow \pi^+\pi^-\pi^0, \eta \rightarrow \gamma\gamma/\pi^+\pi^-\pi^0, \eta' \rightarrow \pi^+\pi^-\eta\gamma\gamma/\rho^0\gamma$$

For $\eta \rightarrow \gamma\gamma$, 1-C kinematic fit are performed and required $M_{\gamma\gamma} \in (0.51, 0.57)$ GeV.

The mass window for X particle are listed in the table.

Then the signal yields are extracted by fitting to missing mass square M_{miss}^2 (MM²) distributions for each signal channel.

$$MM^2 \equiv E_{miss}^2/c^4 - \vec{p}_{miss}^2/c^2$$

E_{miss} and \vec{p}_{miss} are the missing energy and momentum of the DT event in the e^+e^- center-of-mass frame, respectively.

$$E_{miss} = E_{D^0} - E_X, \vec{p}_{miss} = \vec{p}_{D^0} - \vec{p}_X$$

Requirement	Mass window (GeV/c ²)
$M_{K^+K^-}$	(1.005, 1.035)
$M_{\pi^+\pi^-\pi^0}$	(0.535, 0.560)
$M_{\pi^+\pi^-\pi^0}$	(0.752, 0.812)
$M_{\pi^+\pi^-\eta}$	(0.945, 0.970)
$M_{\rho^0\gamma}$	(0.938, 0.978)

Fitting method

The background candidates into four categories:

BKGI(pink) : $D^0 \rightarrow K_S^0 X$, $K_S^0 \rightarrow \pi^0 \pi^0$, **BKGI**(yellow) : $D^0 \rightarrow \eta \eta$, $D^0 \rightarrow \eta \phi$, $D^0 \rightarrow \eta \eta'$

BKGI(light blue) : remaining peaking background channels, like $D^0 \rightarrow K_L^0 K^+ K^-$, $K_L^0 \pi^+ \pi^- \pi^0$

BKG IV(black dot) : combinatorial background components

In this fit:

Signal(red solid curves) is modeled by the MC shape convolved with a double-Gaussian function.

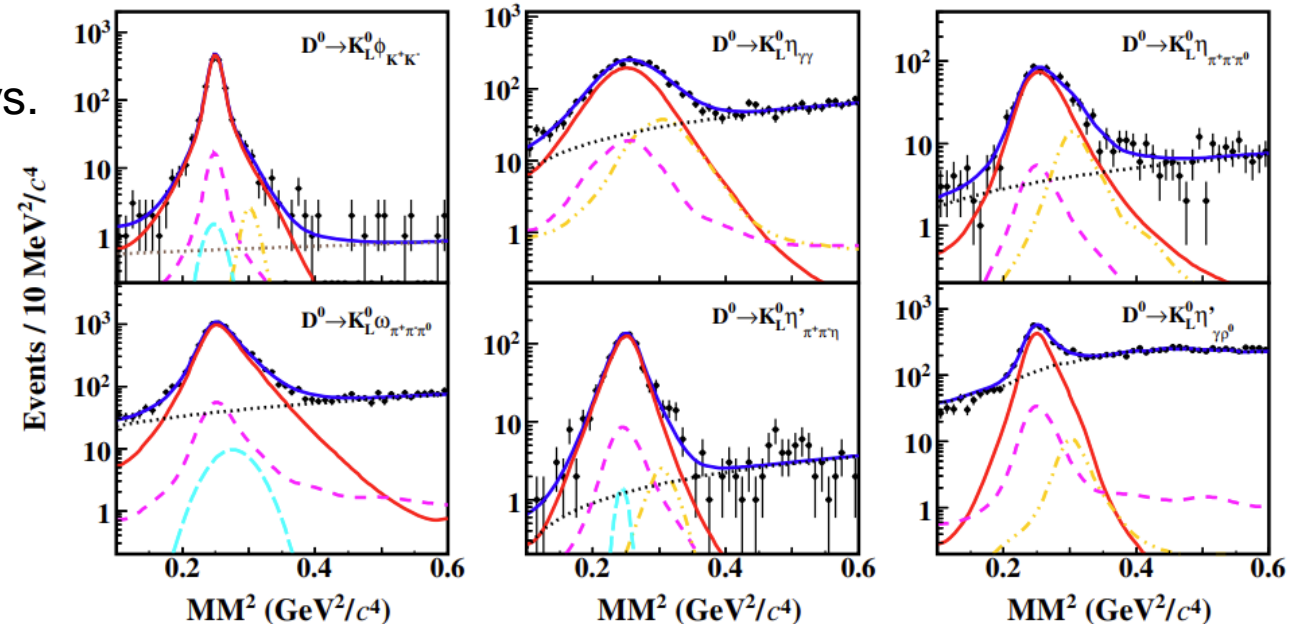
BKGI and **BKGI** are described by the corresponding MC shapes.

The shape and size of **BKGI** are fixed to those obtained from the inclusive MC sample

BKGI is modeled by the MC shape for $K_L^0 \eta' \gamma \rho^0$ and

modeled by a linear function for the other signal decays.

Blue solid curves are the fit result, data are shown as points with error bars.



Fitting method

There are combinatorial backgrounds which can form a peak in the MM^2 distributions, is estimated by the corresponding sideband regions.

the normalization factors of background events in the signal and sideband regions (S_{co}), the net signal yield ($N_{net} = N_{sig} - N_{side} \cdot S_{co}$)

Decay	N_{sig}	N_{sid}	S_{co}	N_{net}	$\epsilon_{sig}(\%)$
$D^0 \rightarrow K_L^0 \phi_{K^+K^-}$	1271 ± 39	276 ± 19	1.33 ± 0.17	904 ± 46	9.02 ± 0.10
$D^0 \rightarrow K_L^0 \eta_{\gamma\gamma}$	2132 ± 71	2132 ± 71	20.46 ± 0.15
$D^0 \rightarrow K_L^0 \eta_{\pi^+\pi^-\pi^0}$	565 ± 29	36 ± 10	0.61 ± 0.10	543 ± 30	5.11 ± 0.07
$D^0 \rightarrow K_L^0 \omega_{\pi^+\pi^-\pi^0}$	6692 ± 100	368 ± 39	1.58 ± 0.07	6110 ± 118	21.70 ± 0.18
$D^0 \rightarrow K_L^0 \eta'_{\pi^+\pi^-\eta}$	688 ± 29	8 ± 6	0.47 ± 0.08	684 ± 29	3.30 ± 0.10
$D^0 \rightarrow K_L^0 \eta'_{\rho^0\gamma}$	2002 ± 61	2002 ± 61	10.55 ± 0.15

Side-band region	
$M_{K^+K^-}$	(0.985,1.000)U(1.045,1.060) GeV
$M_{\pi^+\pi^-\pi^0}$	(0.495,0.515)U(0.580,0.600) GeV
$M_{\pi^+\pi^-\pi^0}$	(0.712,0.732)U(0.832,0.852) GeV
$M_{\pi^+\pi^-\eta}$	(0.913,0.938)U(0.978,1.003) GeV

Systematic uncertainty

By using the DT method, the systematic uncertainties associated with the ST selection are canceled. Systematic uncertainties are estimated as follow.

Tab. 22: Systematic uncertainties (%) in the measurements of the BFs.

Source	$K_L^0 \phi_{K^+K^-}$	$K_L^0 \eta_{\gamma\gamma}$	$K_L^0 \eta_{\pi^+\pi^-\pi^0}$	$K_L^0 \omega_{\pi^+\pi^-\pi^0}$	$K_L^0 \eta'_{\pi^+\pi^-\eta}$	$K_L^0 \eta'_{\rho^0\gamma}$
ST yields N_{tag}	0.5	0.5	0.5	0.5	0.5	0.5
K^\pm/π^\pm tracking	0.4	-	0.3	0.2	0.6	0.2
K^\pm/π^\pm PID	0.3	-	0.2	0.2	0.2	0.2
π^0/η reconstruction	-	0.5	0.7	0.7	0.7	-
γ reconstruction	-	-	-	-	-	1.0
Mass window requirement	0.2	-	0.2	0.1	0.5	0.1
$N_{\text{charged}/\pi^0/\eta}^{\text{extra}}$	0.8	0.8	0.8	0.8	0.8	0.8
MM2 fitting	0.9	2.3	2.4	1.1	1.4	1.2
open angle	1.4	1.4	1.4	1.3	0.9	1.6
Quoted BFs	1.0	0.5	1.2	0.7	1.2	1.3
MC statistics	0.6	0.3	0.5	0.5	0.6	0.4
Strong phase	0.7	0.7	0.7	0.7	0.7	0.7
Total	2.4	3.0	3.4	2.4	2.6	2.9

Systematic uncertainty

Tab. 22: Systematic uncertainties (%) in the measurements of the BFs.

Source	$K_L^0 \phi_{K^+ K^-}$	$K_L^0 \eta_{\gamma\gamma}$	$K_L^0 \eta_{\pi^+ \pi^- \pi^0}$	$K_L^0 \omega_{\pi^+ \pi^- \pi^0}$	$K_L^0 \eta'_{\pi^+ \pi^- \eta}$	$K_L^0 \eta'_{\rho^0 \gamma}$
ST yields N_{tag}	0.5	0.5	0.5	0.5	0.5	0.5
K^\pm/π^\pm tracking	0.4	-	0.3	0.2	0.6	0.2
K^\pm/π^\pm PID	0.3	-	0.2	0.2	0.2	0.2
π^0/η reconstruction	-	0.5	0.7	0.7	0.7	-
γ reconstruction	-	-	-	-	-	1.0
Mass window requirement	0.2	-	0.2	0.1	0.5	0.1
$N_{\text{charged}/\pi^0/\eta}^{\text{extra}}$	0.8	0.8	0.8	0.8	0.8	0.8
MM2 fitting	0.9	2.3	2.4	1.1	1.4	1.2
open angle	1.4	1.4	1.4	1.3	0.9	1.6
Quoted BFs	1.0	0.5	1.2	0.7	1.2	1.3
MC statistics	0.6	0.3	0.5	0.5	0.6	0.4
Strong phase	0.7	0.7	0.7	0.7	0.7	0.7
Total	2.4	3.0	3.4	2.4	2.6	2.9

ST yields uncertainties come from the M_{BC}^{tag} fits to the ST \bar{D} candidates .

K^\pm/π^\pm tracking/PID: determined by analyzing DT $D\bar{D}$ events of $\psi(3770)$.

π^0 reconstruction: studied by using the events $\bar{D}^0 \rightarrow K^+ \pi^-$, $K^+ \pi^- \pi^+ \pi^-$ vs. $D^0 \rightarrow K^- \pi^+ \pi^0$, $K_S^0 \pi^0$, after correcting the MC efficiency to data, the residual uncertainties as the uncertainty. That of η reconstruction assigned by referring to the π^0 reconstruction.

Photon detection in $D^0 \rightarrow K_L^0 \eta'_{\rho^0 \gamma}$: 1.0% per photon, estimated from a $J/\psi \rightarrow \rho^0 \pi^0$ control sample.

Mass window: use the control sample of $D^0 \rightarrow K_S^0 X$, the relative difference in efficiency between data and MC is considered as the systematic uncertainty.

$N_{\text{charged}/\pi^0/\eta}^{\text{extra}}$: Based on double-hadronic-tag events ($\bar{D}^0 \rightarrow \text{tag}$ vs. $D^0 \rightarrow K_S^0 \pi^0$), the difference between data and MC simulation for these requirements were studied.

Open angle: the BFs are measured using different angle requirements, maximum deviation of the BFs from 0.9–1.6% is taken as the systematic uncertainty.

MM fitting: valuated by varying the signal shape, the background shape, and the size of peaking backgrounds within their uncertainties.

Quoted BFs: assigned as individual systematic uncertainties. ($\phi \rightarrow K^+ K^-$, $\omega \rightarrow \pi^+ \pi^- \pi^0$, $\eta \rightarrow \gamma\gamma/\pi^+ \pi^- \pi^0$, $\eta' \rightarrow \pi^+ \pi^- \eta_{\gamma\gamma}/\rho^0 \gamma$)

The uncertainties arising from the finite sizes of the signal MC samples are 0.3–0.6%.

Summary

The BFs of D^0 and \bar{D}^0 , \mathcal{B}_{sig}^+ and \mathcal{B}_{sig}^- , are also measured separately.

\mathcal{A}_{CP}^{sig} is determined as $\mathcal{A}_{CP}^{sig} \equiv \frac{\mathcal{B}_{sig}^+ - \mathcal{B}_{sig}^-}{\mathcal{B}_{sig}^+ + \mathcal{B}_{sig}^-}$, the obtained BFs and asymmetries are summarized in Table, No significant CP violation is observed.

Decay	\mathcal{B}_{sig}^+ (%)	\mathcal{B}_{sig}^- (%)	\mathcal{A}_{CP}^{sig} (%)
$D^0 \rightarrow K_L^0 \phi$	0.428 ± 0.029	0.405 ± 0.034	$2.7 \pm 5.4 \pm 0.7$
$D^0 \rightarrow K_L^0 \eta$	0.445 ± 0.018	0.421 ± 0.017	$2.8 \pm 2.9 \pm 0.4$
$D^0 \rightarrow K_L^0 \omega$	1.200 ± 0.030	1.121 ± 0.031	$3.4 \pm 1.9 \pm 0.6$
$D^0 \rightarrow K_L^0 \eta'$	0.789 ± 0.028	0.826 ± 0.028	$-2.2 \pm 2.5 \pm 0.4$

Summary

The first measurements of the absolute BFs of $D^0 \rightarrow K_L^0 X$ ($X = \phi\eta\omega\eta'$), these results are important to test the theoretical prediction for the BFs of $D^0 \rightarrow K_L^0 X$.

The difference of $\mathcal{B}(D^0 \rightarrow K_S^0 X)$ and $\mathcal{B}(D^0 \rightarrow K_L^0 X)$ are obtained.

These results can help to deeper understand the $K_S^0 - K_L^0$ asymmetry.

TABLE IV. Comparison of measured BFs and $K_S^0 - K_L^0$ asymmetries with theoretical calculations of Ref. [6]. \mathcal{B}_{exp} (\mathcal{B}_{FAT}) and $\mathcal{R}(D^0)_{\text{exp}}$ ($\mathcal{R}(D^0)_{\text{FAT}}$) are the BFs and $K_S^0 - K_L^0$ asymmetries of the experimental measurements (theoretical calculations).

Decay	\mathcal{B}_{exp} (%)	\mathcal{B}_{FAT} (%)	Difference	$\mathcal{R}(D^0)_{\text{exp}}$	$\mathcal{B}(D^0)_{\text{FAT}}$	Difference
$D^0 \rightarrow K_L^0 \phi$	$0.414 \pm 0.021 \pm 0.010$	0.33 ± 0.03	2.2σ	-0.001 ± 0.047		2.4σ
$D^0 \rightarrow K_L^0 \eta$	$0.433 \pm 0.012 \pm 0.010$	0.40 ± 0.07	0.5σ	0.080 ± 0.022		1.5σ
$D^0 \rightarrow K_L^0 \omega$	$1.164 \pm 0.022 \pm 0.028$	0.95 ± 0.15	1.4σ	-0.024 ± 0.031	0.113 ± 0.001	4.4σ
$D^0 \rightarrow K_L^0 \eta'$	$0.809 \pm 0.020 \pm 0.016$	0.77 ± 0.07	0.5σ	0.080 ± 0.023		1.6σ