

# 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

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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  $0.113 \pm 0.001$  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

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

Inclusive MC sample: corresponding to the luminosity (shown in the table, cite from the MC sample page of Charm Group of BESIII).

Signal MC sample: 0.6 M for each signal mode.

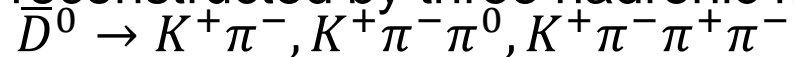
| Physics        | $N_{event}$ | Lum Scale |
|----------------|-------------|-----------|
| $D^0\bar{D}^0$ | 232M        | 21.7x     |
| $D^+D^-$       | 91M         | 10.8x     |
| $qq(lundlw)$   | 366M        | 7.4x      |
| $qq(KKMC)$     | 366M        | 7.4x      |
| $RR2S$         | 102M        | 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 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:

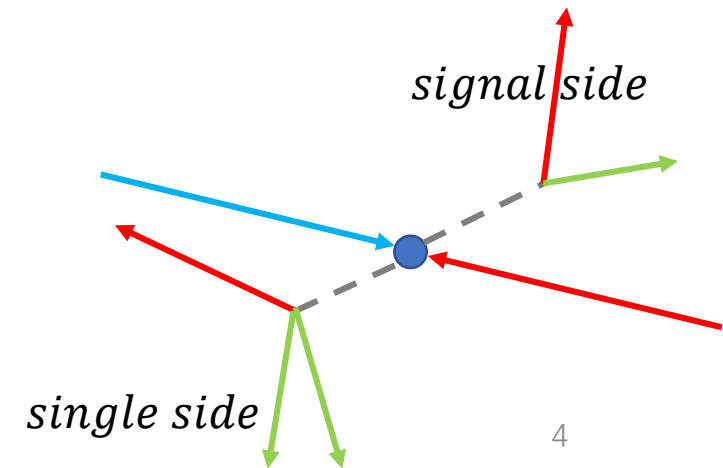


For a special ST mode  $i$ , the ST and DT yields observed in data are given by:

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

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

The effect of quantum-correlation (QC) in  $D^0\bar{D}^0$  pairs:

**For ST:**

The CF and DCS amplitudes:  $r_i^2$  is the ratio of the DCS and CF amplitudes,  $\delta_f^i$  is the strong-phase difference. (e.g.  $D^0 \rightarrow K^+\pi^-$  (DCS),  $\bar{D}^0 \rightarrow K^+\pi^-$  (CF))

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).

**For DT:**

quantum-correlation (QC) factor  $f_{QC}^i = \frac{1}{1-C_f^i(2F_{sig}^+-1)}$

the absolute BF are determined by:

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

$$f_{QC} \equiv \sum_i \frac{N_{ST}^i}{N_{ST}^{tot}} \times f_{QC}^i = 0.937 \pm 0.007$$

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

# Fitting method

$$\Delta E \equiv E_{\bar{D}^0} - E_{beam}$$

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

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

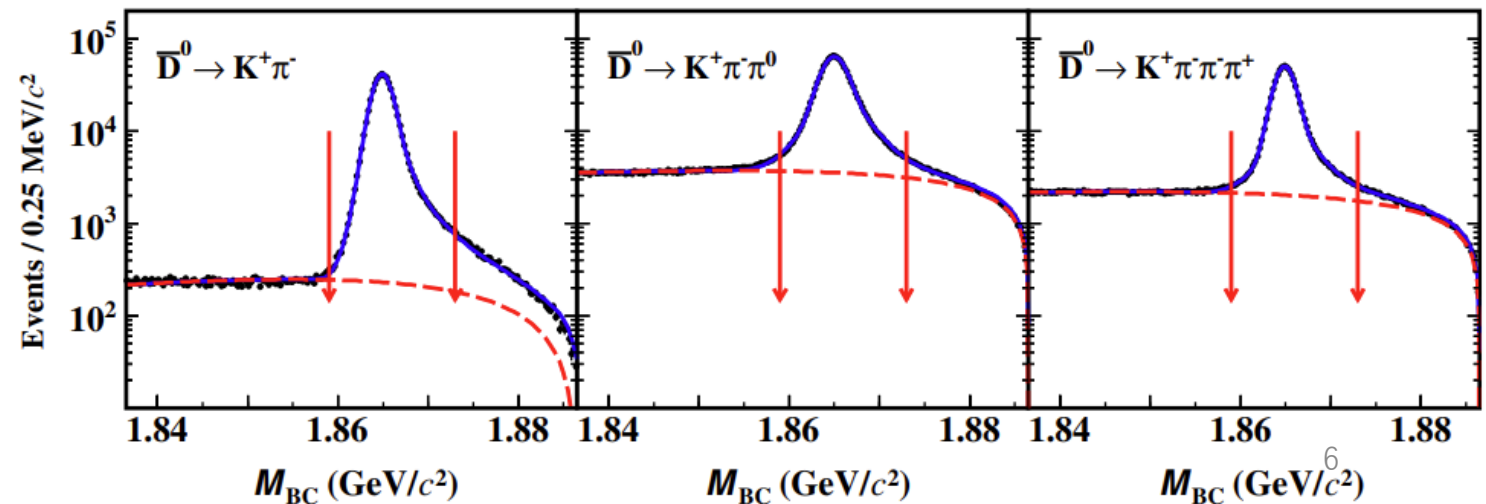
Signal: MC shape  $\otimes$  double-Gaussian.

**BKG**: ARGUS function.

Signal region: (1.859, 1.873).

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.

The mass window for  $X$  particles are listed in the table.

Signal yields:

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

$E_{miss}$  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 <sup>2</sup> ) |
|-----------------------|-----------------------------------|
| $M_{K^+K^-}$          | (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

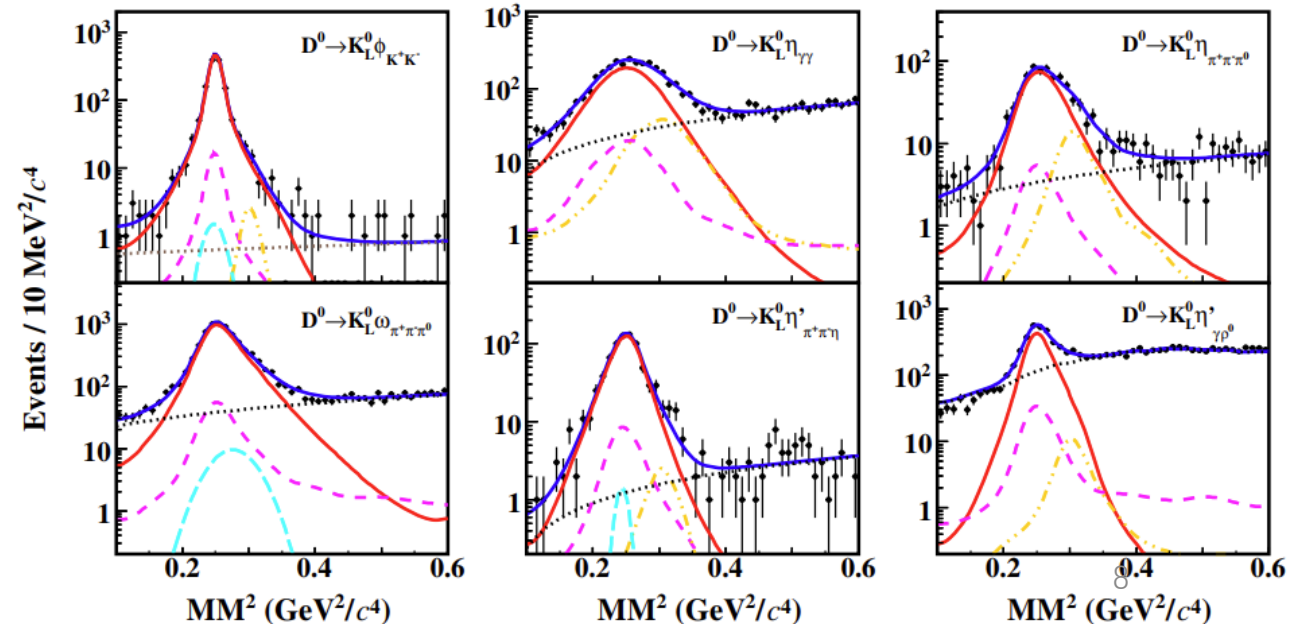
The background candidates into four categories:

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

**BKGIII(light blue)** : remaining peaking background channels (fixed to shape and size obtained from the inclusive MC sample)

**BKG IV(black dot)** : combinatorial background components(MC shape for  $K_L^0 \eta'_{\gamma\rho^0}$ , linear function for the other )

**Signal(red solid curves)**: MC shape  $\otimes$  double-Gaussian.



# Fitting method

Sideband to estimate  $D^0 \rightarrow K_L^0 K^+ K^-$ ,  $K_L^0 \pi^+ \pi^- \pi^0$ ,  $K_L^0 \pi^+ \pi^- \eta$

signal yield:  $N_{net} = N_{sig} - N_{side} \cdot S_{co}$

| Decay  | $N_{sig}$      | $N_{sid}$    | $S_{co}$        | $N_{net}$      | $\epsilon_{sig}(\%)$ | Side-band region        |                                 |
|--|----------------|--------------|-----------------|----------------|----------------------|-------------------------|---------------------------------|
|  |                |              |                 |                |                      | $M$                     | Region                          |
| $D^0 \rightarrow K_L^0 \phi_{K^+ K^-}$             | $1271 \pm 39$  | $276 \pm 19$ | $1.33 \pm 0.17$ | $904 \pm 46$   | $9.02 \pm 0.10$      | $M_{K^+ K^-}$           | (0.985,1.000)U(1.045,1.060) GeV |
| $D^0 \rightarrow K_L^0 \eta_{\gamma\gamma}$        | $2132 \pm 71$  | ...          | ...             | $2132 \pm 71$  | $20.46 \pm 0.15$     | $M_{\pi^+ \pi^- \pi^0}$ | (0.495,0.515)U(0.580,0.600) GeV |
| $D^0 \rightarrow K_L^0 \eta_{\pi^+ \pi^- \pi^0}$   | $565 \pm 29$   | $36 \pm 10$  | $0.61 \pm 0.10$ | $543 \pm 30$   | $5.11 \pm 0.07$      |                         |                                 |
| $D^0 \rightarrow K_L^0 \omega_{\pi^+ \pi^- \pi^0}$ | $6692 \pm 100$ | $368 \pm 39$ | $1.58 \pm 0.07$ | $6110 \pm 118$ | $21.70 \pm 0.18$     | $M_{\pi^+ \pi^- \pi^0}$ | (0.712,0.732)U(0.832,0.852) GeV |
| $D^0 \rightarrow K_L^0 \eta'_{\pi^+ \pi^- \eta}$   | $688 \pm 29$   | $8 \pm 6$    | $0.47 \pm 0.08$ | $684 \pm 29$   | $3.30 \pm 0.10$      |                         |                                 |
| $D^0 \rightarrow K_L^0 \eta'_{\rho^0 \gamma}$      | $2002 \pm 61$  | ...          | ...             | $2002 \pm 61$  | $10.55 \pm 0.15$     | $M_{\pi^+ \pi^- \eta}$  | (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 $N_{\text{tag}}$                     | 0.5                    | 0.5                         | 0.5                              | 0.5                                | 0.5                              | 0.5                           |
| $K^\pm / \pi^\pm$ tracking                     | 0.4                    | -                           | 0.3                              | 0.2                                | 0.6                              | 0.2                           |
| $K^\pm / \pi^\pm$ PID                          | 0.3                    | -                           | 0.2                              | 0.2                                | 0.2                              | 0.2                           |
| $\pi^0 / \eta$ reconstruction                  | -                      | 0.5                         | 0.7                              | 0.7                                | 0.7                              | -                             |
| $\gamma$ 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

1. ST yields uncertainties come from the  $M_{BC}^{tag}$  fits to the ST  $\bar{D}$  candidates .
2.  $K^\pm/\pi^\pm$  tracking/PID: determined by analyzing DT  $D\bar{D}$  events of  $\psi(3770)$ .
3.  $\pi^0$  reconstruction: studied by using the events  $\bar{D}^0 \rightarrow K^+\pi^-, K^+\pi^-\pi^+\pi^-$  vs.  $D^0 \rightarrow K^-\pi^+\pi^0, K_S^0\pi^0$ . That of  $\eta$  reconstruction assigned by referring to the  $\pi^0$  reconstruction.
4. Photon detection in  $D^0 \rightarrow K_L^0\eta'_{\rho^0\gamma} : J/\psi \rightarrow \rho^0\pi^0$  control sample.
5. Mass window: use the control sample of  $D^0 \rightarrow K_S^0X$ , the relative difference in efficiency between data and MC is considered as the systematic uncertainty.
6.  $N_{charged/\pi^0/\eta}^{extra}$ : 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.
7. 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.
8. MM fitting: valuated by varying the signal shape, the background shape, and the size of peaking backgrounds within their uncertainties.
9. Quoted BFs: assigned as individual systematic uncertainties. ( $\phi \rightarrow K^+K^-, \omega \rightarrow \pi^+\pi^-\pi^0, \eta \rightarrow \gamma\gamma/\pi^+\pi^-\pi^0, \eta' \rightarrow \pi^+\pi^-\eta_{\gamma\gamma}/\rho^0\gamma$ )
10. 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  $\mathcal{B}_{sig}^-$ .

$$\mathcal{A}_{CP}^{sig} \equiv \frac{\mathcal{B}_{sig}^+ - \mathcal{B}_{sig}^-}{\mathcal{B}_{sig}^+ + \mathcal{B}_{sig}^-}$$

No significant CP violation is observed.

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

# Summary

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

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