Strong-phase measurement of quantum correlated $D^0\bar{D}^0$ samples at BESIII

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BESIII 粲强子物理研讨会
郑州大学　河南工业大学, 郑州

11th May 2024

Outline

$D^0\bar{D}^0$ quantum correlate samples

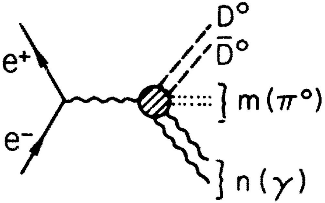
$K^0_{S/L}h^+h^-$ strong phase difference parameters

CP even fraction for $K^0_S\pi^+\pi^-\pi^0$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$

Strong phase parameters for $K^\pm\pi^\mp/K^\pm\pi^\mp\pi^0/K^\pm\pi^\mp\pi^\mp\pi^-$

Summary

Quantum coherent $D^0\bar{D}^0$ in e^+e^- collisions



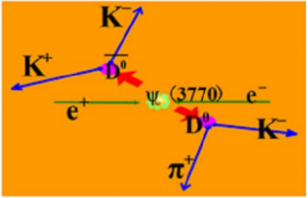
- $e^+e^- \to D^0\bar{D}^0 + m(\pi^0) + n(\gamma)$
- $C(D^0\bar{D}^0) = (-1)^{n+1}$
- [PRD 15, 1254 (1977)]

Quantum $D^0\bar{D}^0$ samples at BESIII:

- 3773 MeV : C-odd: $e^+e^- \to D^0\bar{D}^0$ (m=0, n=0)
- 4180 MeV: C-even: $e^+e^- \to \gamma D^0\bar{D}^0 (m = 0, n = 1)$
- 4180 MeV: C-odd: $e^+e^- \to \pi^0 D^0\bar{D}^0 (m = 1, n = 0)$

Strong phase parameters measurement

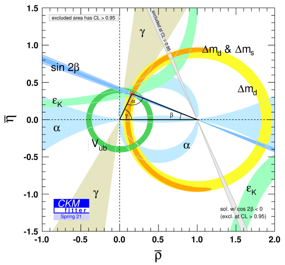
For process: $e^+e^- \to \psi(3770) \to D^0\bar{D}^0 \to$ S+T

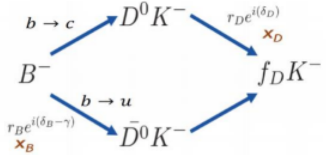


- Measure the strong-phase difference $\Delta\delta_D = \delta_D^T - \delta_D^S$
- Best laboratory to measure strong phase parameters
- Provide inputs for CPV studies and γ measurement

$$\begin{aligned}
\Gamma(S|T) &= \int\int |\mathcal{A}_S(\mathbf{x})\mathcal{A}_{\bar{T}}(\mathbf{y}) - \mathcal{A}_{\bar{S}}(\mathbf{x})\mathcal{A}_T(\mathbf{y})|^2 \mathrm{d}\mathbf{x}\mathrm{d}\mathbf{y} \\
&= [A_S^2 A_{\bar{T}}^2 + A_{\bar{S}}^2 A_T^2 - 2R_S R_T A_S A_{\bar{S}} A_T A_{\bar{T}} \cos(\delta_D^T - \delta_D^S)] \\
&= A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos(\delta_D^T - \delta_D^S)]
\end{aligned}$$

Strong phase parameters used in γ measurement





CKM 2023 WorkShop

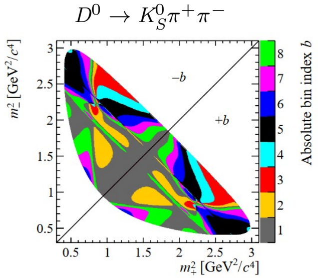
- γ is important to check the unitary of CKM matrix
- D^0 decay strong phase parameters is required in many channels of γ measurement:
  - GLW: strong phase difference between CP even and CP odd
  - ADS: CF and DCS process strong phase parameters
  - BPGGSZ: binned $K^0_{S/L}h^+h^-$ tag strong phase parameters c_i/s_i

Strong phase parameters in CPV and charm mixing

- D decay is an important method to measure charm mixing and CPV
  - from the time-dependent decay rate (mainly B factory)
  - $D^0 \to K_S^0\pi^+\pi^-$ (PRL 127, 111801(2021));
  - $D^0 \to h^+h^-$(PRD 105, 092013(2022))
- Strong phase parameters is the input of mixed CPV measurement and charm mixing studies

Table 3: Uncertainties in units of 10^{-3}. The total systematic uncertainty is the sum in quadrature of the individual components. The uncertainties due to the external inputs and detection asymmetry calibration samples are included in the statistical uncertainty. These are also reported separately, along with the contributions due to the limited sample size, to ease comparison with other sources.

Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36



Methodology

- $\psi(3770)$ integrated luminosity:
  - $2.93(2011\text{-}2012) + 4.97(2021) + 12.16(2022\text{-}2024) \approx 20\text{fb}^{-1}$
- Fully reconstructed tags: all particles can be reconstructed.
  - $m_{\mathrm{BC}} = \sqrt{\mathrm{E}^2_{\mathrm{beam}}/c^4 - |\mathbf{p}^2_{\bar{D}}|/c^2}$
  - $\Delta\mathrm{E} = \mathrm{E}_D - \mathrm{E}_{\mathrm{beam}}$
- Partially reconstructed tags: include a neutral particle like K^0_L that can not be reconstructed
  - $M^2_{\mathrm{miss}} = E^2_{\mathrm{miss}} - |\vec{P}_{\mathrm{miss}}|^2$
  - E_{miss} and $\vec{P}_{\mathrm{miss}}$ are calculated from the reconstructed particles and beam energy.

Flavour tags	$K^\pm\pi^\mp\pi^\mp\pi^-$, $K^\pm\pi^\mp\pi^0$, $K^\pm\pi^\mp$, ...
CP-even tags	K^+K^-, $\pi^+\pi^-$, $\pi^0\pi^0$, $K^0_S\pi^0\pi^0$, $K^0_L\pi^0$, $K^0_L\omega$, $\pi^+\pi^-\pi^{0\dagger}$
CP-odd tags	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$, $K^0_S\eta'$, $K^0_S\phi$, $K^0_L\pi^0\pi^0$
Self-conjugate tags	$K_S\pi^+\pi^-$, $K^0_SK^+K^-$, ...

† $F_{CP+} = 0.973 \pm 0.017$ [PLB 747, 9 (2015); PLB 740, 1 (2015)]

Amplitude model

- Amplitude analysis can provide useful information for strong phase parameters measurement
  - optimize bin schedule, DCS correction ...

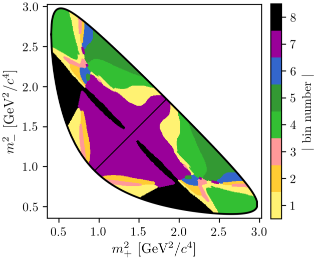
channels	model
$K_S^0\pi\pi$	Belle published
$K_L^0\pi\pi$	corrected $K_S^0\pi\pi$ model (published)
$K^\pm\pi^\mp\pi^\mp\pi^-$	LHCb published
$K^+K^-\pi^+\pi^-$	LHCb published
$\pi^+\pi^-\pi^+\pi^-$	BESIII published
$K^\pm\pi^\mp\pi^0$	CF BESIII ongoing , DCS no model
$K_S^0K^\pm\pi^\pm$	no model
$K^+K^-\pi^0$	BESIII ongoing
$\pi^+\pi^-\pi^0$	BESIII ongoing

Status

Signal decay	Quantities	Status
$K^0_{S/L}h^+h^-$	c_i/s_i unbinnned	c_i/s_i Finished 2.93 fb^{-1} $c_i/s_i/$unbinned ongoing 7.9 fb^{-1}
$K^\pm\pi^\mp\pi^\mp\pi^-$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}
$K^+K^-\pi^+\pi^-$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1}, c_i/s_i ongoing 16 fb^{-1}
$\pi^+\pi^-\pi^+\pi^-$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1},c_i/s_i ongoing 2.93 fb^{-1}
$K^\pm\pi^\mp\pi^0$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}
$K^0_SK^\pm\pi^\pm$	R,δ	ongoing 7.9 fb^{-1}
$\pi^+\pi^-\pi^0$	F_+	ongoing 7.9 fb^{-1}
$K^0_S\pi^+\pi^-\pi^0$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1}
$K^+K^-\pi^0$	F_+	ongoing 7.9 fb^{-1}
$K^\pm\pi^\mp$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}

Binned strong phase difference parameters

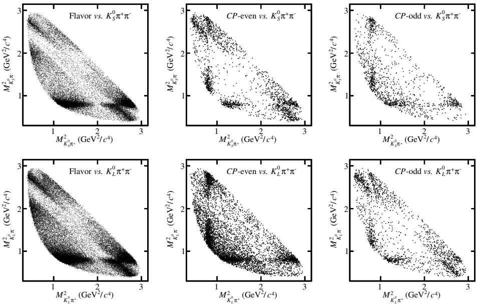
- Divided dalitz plane into bins $\rightarrow$ improve sensitivity in γ measurement
- $K^0_S h^+ h^-$ is the golden channel for γ measurement
- Parameterized strong phase difference:
  - $c_i \propto \int_i A^2_{D^0} A^2_{\bar{D}^0} \cos(\delta_D) dm^2_+ dm^2_-$
  - $s_i \propto \int_i A^2_{D^0} A^2_{\bar{D}^0} \sin(\delta_D) dm^2_+ dm^2_-$



optimal binning scheme in JHEP 02, 169(2021)

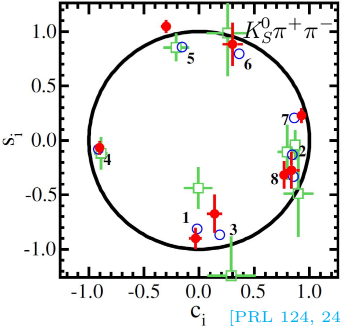
Measurement of c_i/s_i in BESIII

Dalitz plots for different tags:

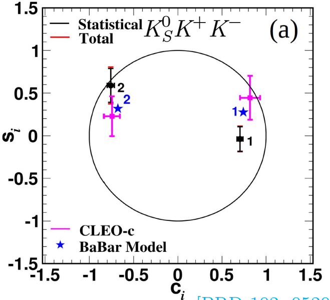


- Flavour tags + CP tags $\rightarrow c_i$
- Flavour tags + self-conjugated tags $\rightarrow c_i/s_i$
- c_i/s_i can be measured through flavour tags, CP tags and self-conjugate tags yields by Double-Tag method

c_i/s_i measurement result



[PRL 124, 241802 (2020)]
[PRD 101, 112002 (2020)]

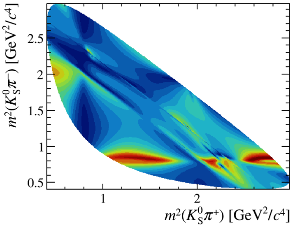


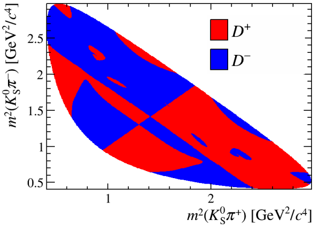
[PRD 102, 052008 (2020)]

- Contribute to a systematic uncertainty of 1° to γ measurement
- Lead to the best single γ measurement. [JHEP 02 (2021) 169]
- c_i/s_i result with 7.9 fb^{-1} data set is under review

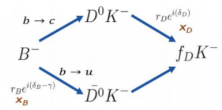
Unbinned strong phase parameters

- Fourier expansion for each point at $\delta_D = \arg(\mathrm{A}^{\mathrm{model}}_{\mathrm{D^0}}) - \arg(\mathrm{A}^{\mathrm{model}}_{\overline{\mathrm{D}}^0})$ in phase space
- Optimize a weight function w_z for dalitz plots to maximise the sensitivity of γ
- Divide the Dalitz plane into two parts from the comparison of points' sensitivity on D^0 and $\bar{D}^0$





γ measurement with unbinned method



$\rightarrow$

$x_\pm + iy_\pm = r_B e^{i(\delta_B \pm \gamma)}$

$$p_B(\mathbf{z}) \propto p_D(\mathbf{z}) + (x_-^2 + y_-^2)\bar{p}_D(\mathbf{z}) + 2[x_- C(\mathbf{z}) + y_- S(\mathbf{z})]$$

input from charm factories

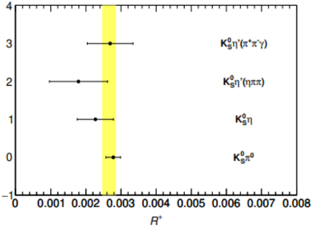
Eur. Phys. J. C **78**, 121 (2018)

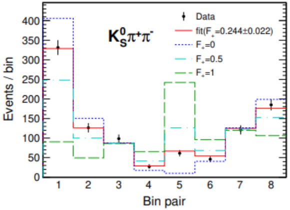
- Decay rate p_D and parameters $C(z)/S(z)$ associated with strong phase difference
  - $p_{D^0} = \frac{a_0^D}{2} + \Sigma_{n=1}^M (a_n^D \cos(n\delta_D) + b_n^D \sin(n\delta_D))$
  - $C(z) = \mathrm{Re}[A_D^* \overline{A}_D] = \frac{a_0^C}{2} + \Sigma_{n=1}^M (a_n^C \cos(n\delta_D) + b_n^C \sin(n\delta_D))$
  - $S(z) = \mathrm{Im}[A_D^* \overline{A}_D] = \frac{a_0^S}{2} + \Sigma_{n=1}^M (a_n^S \sin(n\delta_D) + b_n^S \sin(n\delta_D))$
- Inputs of Fourier coefficients to γ measurement
  - $a_n^{B+} = h_B[a_n^{D+} + (x_-^2 + y_-^2) a_n^{D-} + 2(x_- a_n^C + y_- a_n^S)]$

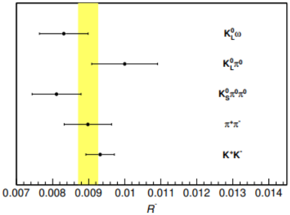
Joint fit between BESIII and LHCb data

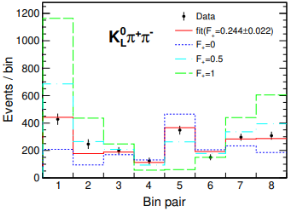
- BESIII data:
  - Flavour tag: $a_n^{\text{flav}} = h_{\text{flav}}[a_n^{D+} + (x_D^2 + y_D^2)a_n^{D-} - 2R_D(x_D a_n^C - y_D a_n^S)]$
  - CP tag: $a_n^{\pm} = h_{\pm}[a_n^{D+} + a_n^{D-} \mp 2a_n^C]$
  - Self-conjugated tag: $a_{mn}^{DD} = h_{DD}[a_m^{D+}a_n^{D-} + a_m^{D-}a_n^{D+} - 2(a_m^C a_n^C + a_m^S a_n^S)]$
- LHCb data
  - $a_n^{B+} = h_B[a_n^{D+} + (x_-^2 + y_-^2)a_n^{D-} + 2(x_- a_n^C + y_- a_n^S)]$
- The order of coefficients need the cooperation between LHCb and BESIII
- LHCb data could improve the determination of a_n^C and a_n^S
- Measurement result with unbinned method will be available soon.

CP even fraction for $K_S^0\pi^+\pi^-\pi^0$





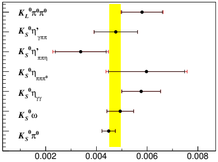


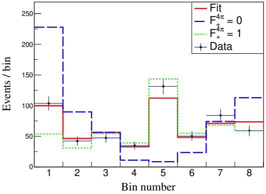


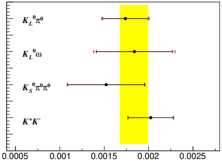
[PRD 108, 032003 (2023)]

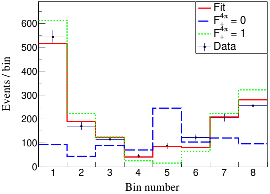
- CP tag: $F_+ = \frac{N^+}{N^+ + N^-} = 0.229 \pm 0.013 \pm 0.002$
- Combined $F_+ = 0.235 \pm 0.010 \pm 0.002$

CP even fraction for $\pi^+\pi^-\pi^+\pi^-$





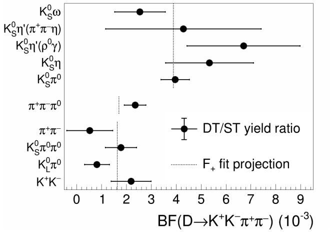




[PRD 106, 092004 (2022)]

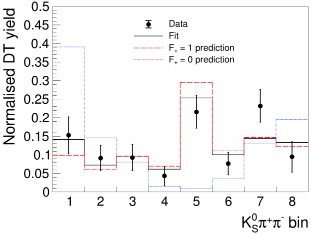
- Combined $F_+ = 0.735 \pm 0.015 \pm 0.005$
- c_i/s_i measurement is under review

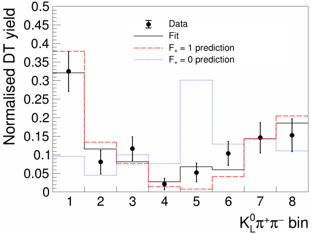
CP even fraction for $K^+K^-\pi^+\pi^-$



[PRD 106, 092004 (2022)]

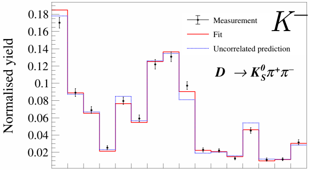
- Combined $F_+ = 0.730 \pm 0.037 \pm 0.021$
- $K_S^0\pi\pi$ c_i/s_i under 7.9 fb^{-1} is under review

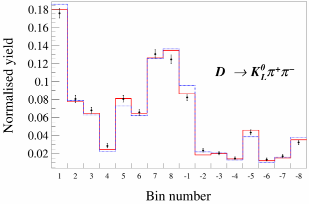


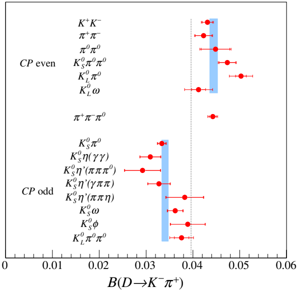


Strong phase parameters measurement of flavour channe

$K^-\pi^+$



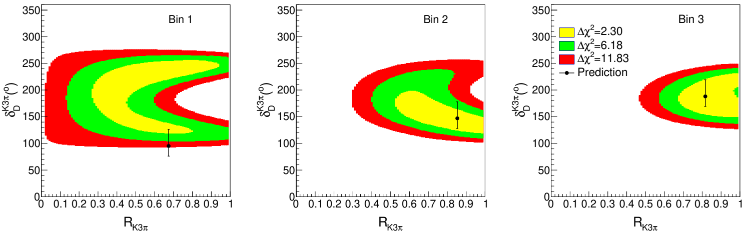


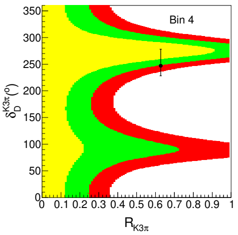


[JHEP 05, 164 (2021)]
[EPJC 82, 1009(2022)]

Decay	$\delta_D^f(^\circ)$	R_f
$K^-\pi^+$	$187.5^{+8.9+5.4}_{-9.7-6.4}$	$-$
$K^-\pi^+\pi^0$	196^{+14}_{-15}	0.78 ± 0.04
$K^-\pi^+\pi^+\pi^-$	167^{+31}_{-19}	$0.52^{+0.12}_{-0.10}$

Binned $R_{K^\pm\pi^\mp\pi^\mp\pi^-}$ and $\delta_{K^\pm\pi^\mp\pi^\mp\pi^-}$ for γ measurement





- Rich resonances of $K^\pm\pi^\mp\pi^\mp\pi^-$ brings the difference of $\delta_{K^\pm\pi^\mp\pi^\mp\pi^-}$ in phase space
- Second leading mode for γ measurement with a syst uncertainty of 6° to γ measurement [arXiv:2209.03692]
- update in 7.9 fb^{-1} $\psi(3770)$ data now

Summary

Signal decay	Quantities	Status
$K^0_{S/L}h^+h^-$	c_i/s_i, unbinned	c_i/s_i Finished 2.93 fb^{-1}, c_i/s_i/unbinned ongoing 7.9 fb^{-1}
$K^\pm\pi^\mp\pi^\mp\pi^-$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}
$K^+K^-\pi^+\pi^-$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1},c_i/s_i ongoing 16 fb^{-1}
$\pi^+\pi^-\pi^+\pi^-$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1},c_i/s_i ongoing 2.93 fb^{-1}
$K^\pm\pi^\mp\pi^0$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}
$K^0_S K^\pm\pi^\pm$	R,δ	ongoing 7.9 fb^{-1}
$\pi^+\pi^-\pi^0$	F_+	ongoing 7.9 fb^{-1}
$K^0_S\pi^+\pi^-\pi^0$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1}
$K^+K^-\pi^0$	F_+	ongoing 7.9 fb^{-1}
$K^\pm\pi^\mp$	R,δ	Finished 2.93fb^{-1},ongoing 7.9 fb^{-1}

- lots of progresses with 2.93 fb^{-1} $\psi(3770)$ data set
- important inputs for CPV, charm mixing and γ
- New methods like unbinned is applied

Future:

- The total 20 fb^{-1} $\psi(3770)$ data set $\rightarrow \gamma$ uncertainty $\approx 0.4^\circ$
- Data Sets at higher energy points as complementary