



Strong-phase measurements of neutral D decays at BESIII

Yu Zhang *for the BESIII Collaboration*

2022000117@usc.edu.cn



Outline

Why strong-phase parameters?

How to measure strong-phase parameters?

Recent progress at BESIII

$D \rightarrow K\pi\pi\pi/K\pi\pi^0$ [JHEP 05 (2021) 164]

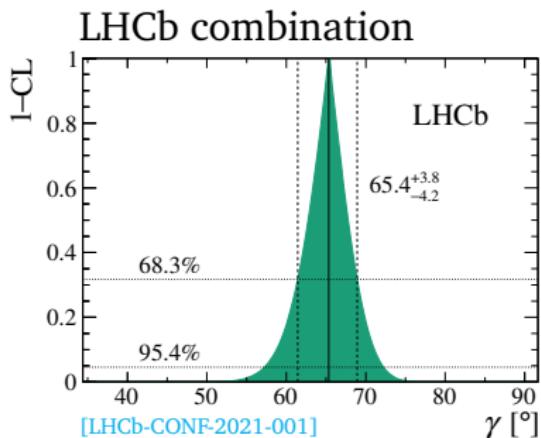
$D \rightarrow K\pi$ [EPJC 82 (2022) 1009]

$D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ [PRD 106 (2022) 092004]

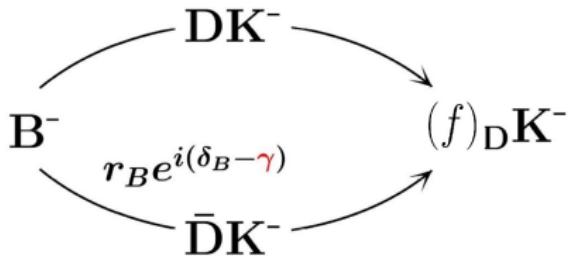
Summary and future prospects

Why strong-phase parameters?

- ▶ CKM angles are large ($\mathcal{O}(1)$) in the b sector to probe the direct CP violation
 - ▶ γ angle receives no NP effects and has negligible theoretical uncertainties
-
- ▶ Determined in tree-level B decays, eg. $B \rightarrow DK$
 - ▶ No interference from NP effects
 - ▶ Large experimental uncertainties
 - ▶ Goal is 1° to be comparable with indirect determination
 - ▶ Statistics, systematics
 - ▶ External inputs



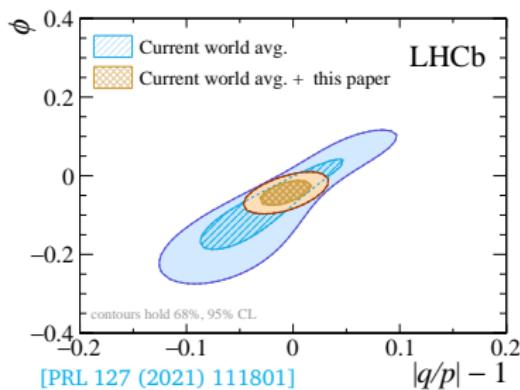
Inputs for γ determination



- ▶ Measure the interference between the two paths depends on the B and D decay parameters
- ▶ Require external inputs of strong phase and associated parameters in D decays:
 - ▶ DCS decays (eg. $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$): "ADS" [PRL 78 (1997) 3257; PRD 63 (2001) 036005] $\Rightarrow \delta_D, R_f$
 - ▶ Self-conjugate decays (eg. $K_S^0 h^+ h^-$, $2(\pi^+ \pi^-)$): "BPGGSZ" [PRD 68 (2003) 054018; PRD 67 (2003) 071301; A. Bondar] $\Rightarrow c_i, s_i$
 - ▶ (Quasi-) CP eigenstates (eg. $h^+ h^-$): "GLW" [PLB 265 (1991) 172; PLB 253 (1991) 483] $\Rightarrow CP$ fraction F^+ ; Others...

Strong-phase inputs for CPV in charm decays

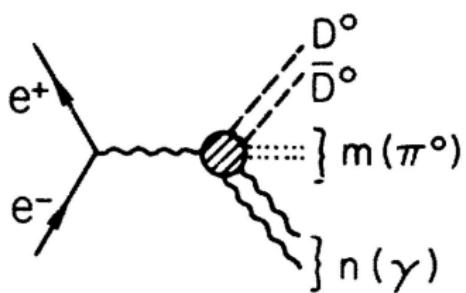
- ▶ Indirect CP violation due to charm mixing and interference of the mixing and decay
- ▶ Non-vanishing ϕ and $|q/p| - 1$ leads to observation
 - ▶ $D \rightarrow K_S^0 \pi^+ \pi^-$
 - ▶ Not observed yet but significantly constrained
 - ▶ c_i, s_i input from BESIII contributes to non-negligible systematics
 - ▶ Other strong-phase measurements could contribute as inputs to charm mixing and CPV studies



[PRD 99 (2019) 012007; PRD 91 (2015) 094032]

[PLB 701 (2011) 353]

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

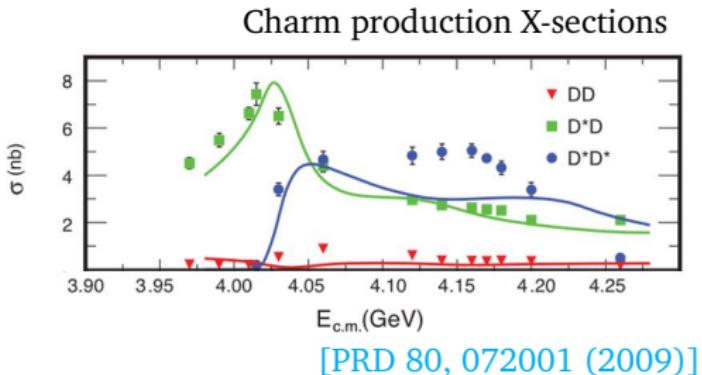


[PRD 15, 1254 (1977)]

- ▶ $e^+e^- \rightarrow \gamma^* \rightarrow D^0\bar{D}^0 + m(\pi^0) + n(\gamma)$
- ▶ $C = (-1)^{n+1}$

	Final state	C
	$D^0\bar{D}^0$	odd
$D^0\bar{D}^{*0}$	$\pi^0 D^0\bar{D}^0$	odd
	$\gamma D^0\bar{D}^0$	even
$D^{*0}\bar{D}^{*0}$	$\pi^0\pi^0/\gamma\gamma D^0\bar{D}^0$	odd
	$\gamma\pi^0 D^0\bar{D}^0$	even

Quantum correlated $D^0\bar{D}^0$ at BESIII



- ▶ 2.93 fb^{-1} @ 3773 MeV $\rightarrow C\text{-odd: } e^+e^- \rightarrow D^0\bar{D}^0$
- ▶ 6.32 fb^{-1} @ 4180-4230 MeV: $D^0\bar{D}^{*0}$, $D^{*0}\bar{D}^{*0}$
- ▶ XYZ datasets at other energy points: $D^0\bar{D}^{*0}$, $D^{*0}\bar{D}^{*0}$

C -odd QC double decay rates

► $\frac{1}{\sqrt{2}} [|D^0(p_1, t_1)\rangle |\bar{D}^0(p_2, t_2)\rangle - |\bar{D}^0(p_1, t_1)\rangle |D^0(p_2, t_2)\rangle]$

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

- $A_{\bar{S}}/A_S = r_D^S \exp(-i\delta_D^S)$
- The coherence factor $R \leq 1$ for all neutral D decays due to intermediate resonances
- CP violation and mixing effects (to the order (x^2, y^2)) are neglected
- Provide constraints on strong-phase parameters

Strong-phase measurements using various tags

Quasi-flavour	$K^\pm\pi^\mp\pi^\mp\pi^-$, $K^\pm\pi^\mp\pi^0$, $K^\pm\pi^\mp$
CP -even	K^+K^- , $\pi^+\pi^-$, $\pi^0\pi^0$, $K_S^0\pi^0\pi^0$, $K_L^0\pi^0$, $K_L^0\omega$, $\pi^+\pi^-\pi^0$ [†]
CP -odd	$K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$, $K_S^0\eta'$, $K_S^0\phi$, $K_L^0\pi^0\pi^0$
Self-conjugate	$K_{S,L}^0\pi^+\pi^-$, $K_S^0K^+K^-$, $\pi^+\pi^-\pi^+\pi^-$, ...

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

$$\begin{aligned}\Gamma(S|CP) &= A_S^2 A_{CP}^2 (1 + (r_D^S)^2 - 2\lambda R_S r_D^S \cos \delta_D^S) \\ \Gamma(S|S) &= A_S^2 A_{\bar{S}}^2 [1 - R_S^2] \\ \Gamma(S|T) &= A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos (\delta_D^T - \delta_D^S)] \\ Y_i^S &= H \left(K_i + (r_D^S)^2 K_{-i} - 2r_D^S R_S \sqrt{K_i K_{-i}} [c_i \cos \delta_D^S - s_i \sin \delta_D^S] \right)\end{aligned}$$

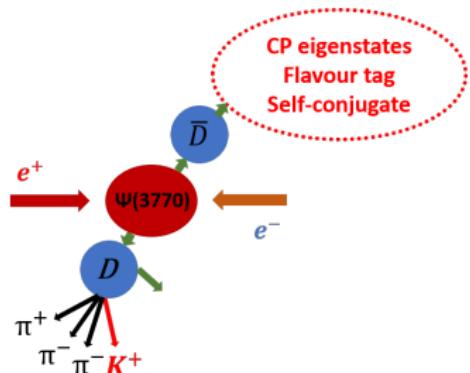
- ▶ Provide comprehensive constraints on strong-phase parameters

Strong-phase measurement with QC $D\bar{D}$

- ▶ Quantum correlated C -odd $D\bar{D}$ produced at BESIII

$$e^+ e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$$

- ▶ $\int dt \mathcal{L} = 2.93 \text{ fb}^{-1}$
- ▶ 10597,000 neutral $D\bar{D}$
[CPC 42 (2018) 083001]
- ▶ "Double-tag" method:
reconstruct both D & \bar{D}
- ▶ $m_{BC} = \sqrt{E_{\text{beam}}^2/c^4 - |\mathbf{p}_{\bar{D}}^2|/c^2}$
- ▶ $\Delta E = E_D - E_{\text{beam}}$



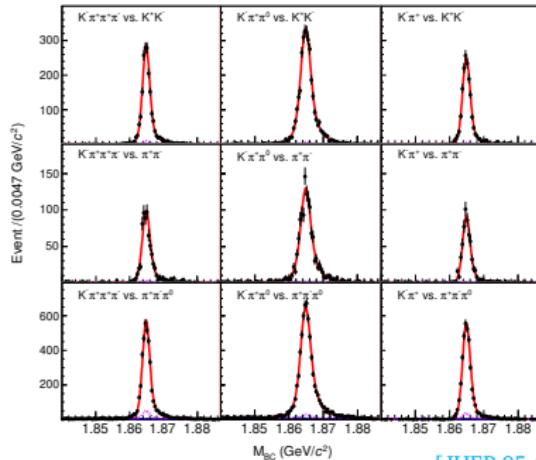
- ▶ Compare the double tag yields w/w.o. quantum correlation

$$\Gamma_{\text{QC}}(S|T) = \Gamma_0 A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos(\delta_D^T - \delta_D^S)]$$

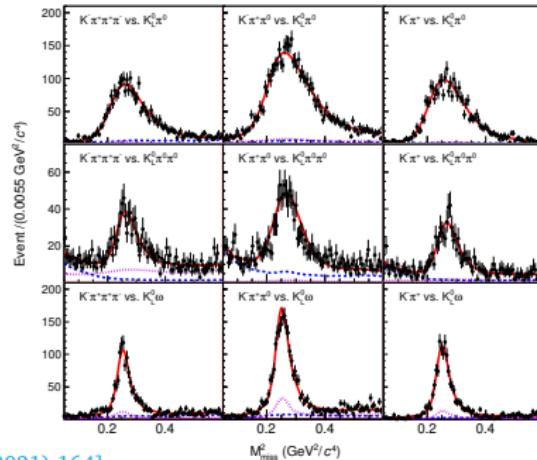
$$\Gamma(ST) = \Gamma_0 A_S^2 A_T^2 [(r_D^S)^2 + (r_D^T)^2]$$

Double tagged $K\pi\pi\pi$ events

Fully reconstructed CP modes



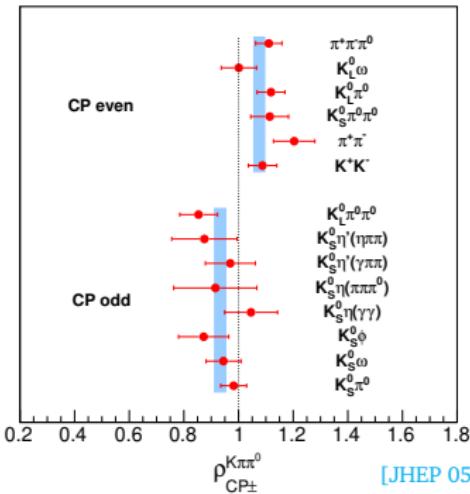
K_L^0 modes



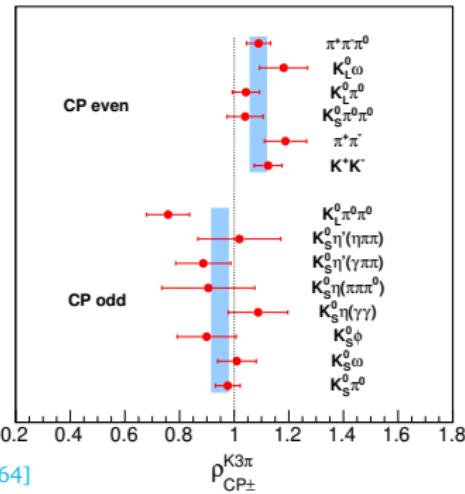
[JHEP 05 (2021) 164]

- ▶ Clean background in fully reconstructed events
- ▶ K_L^0 can be reconstructed with the missing mass M_{miss}^2 recoiled against the tagged D and particles in the signal side

CP observables

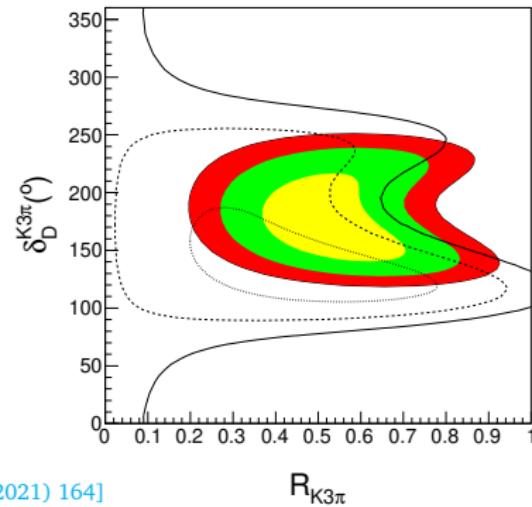
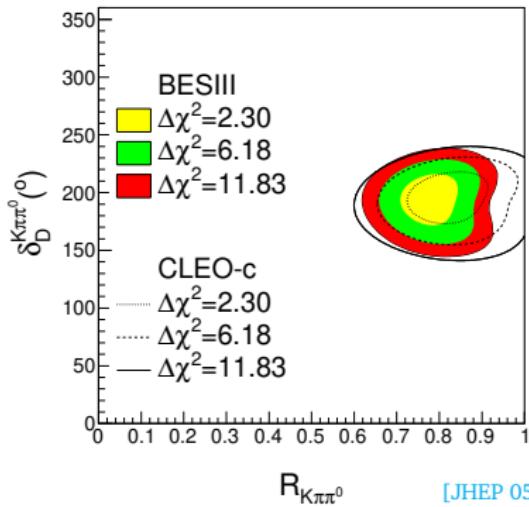


[JHEP 05 (2021) 164]



- ▶ ρ_{CP} , the ratio of the observed yields and expected yields w.o. QC, differ from 1
- ▶ Other tags also contribute: Like-sign flavour tags (eg. $K^+3\pi$ vs $K^+3\pi$); $K_S^0\pi^+\pi^-$ tag (phase variations over Dalitz plane)

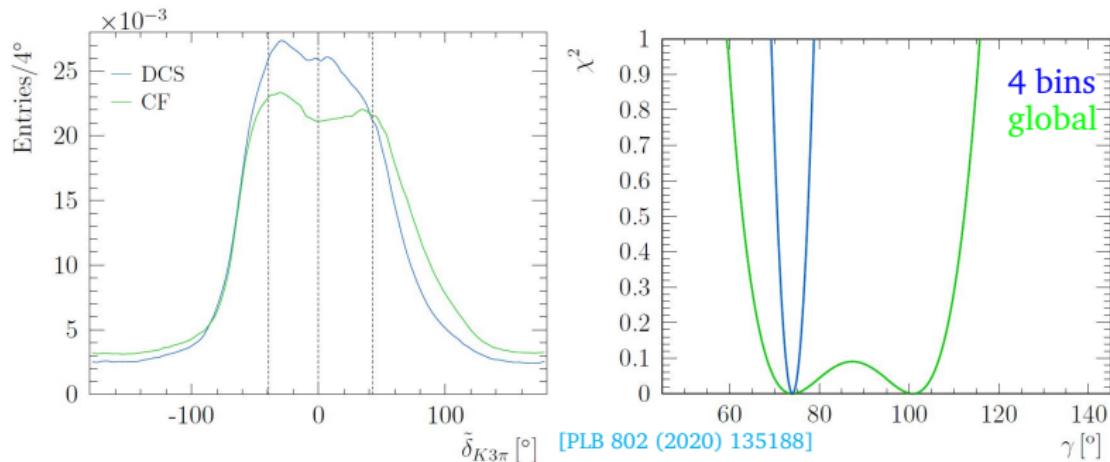
Global strong-phase differences



- ▶ Significant improvement compared to CLEO-c results [JHEP 05 (2021) 164] (2016) 520]

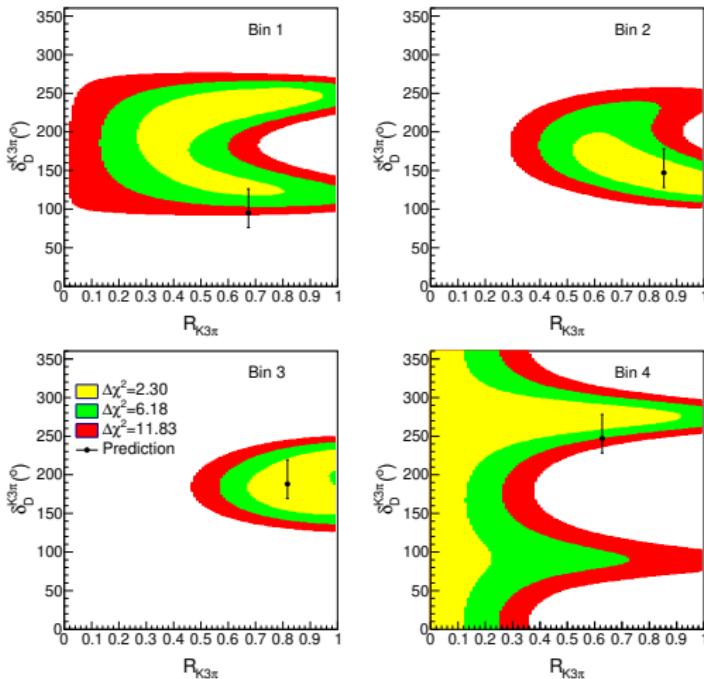
Binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$

- Sensitivity on γ can be much improved by exploiting $\delta_D^{K3\pi}$ in different phase space regions

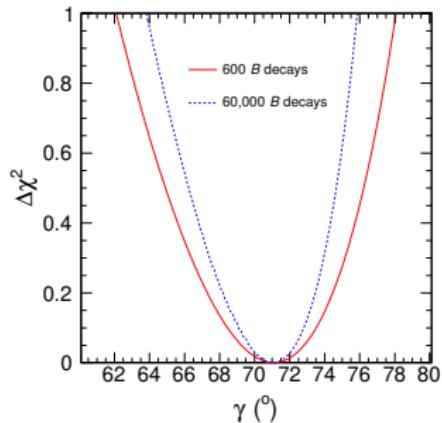


- Model-independent measurement, only binning method depends on the DCS and CF model of $D \rightarrow K3\pi$ [[EPJC 78 \(2018\) 443](#)]

Results of binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$



[JHEP 05 (2021) 164]

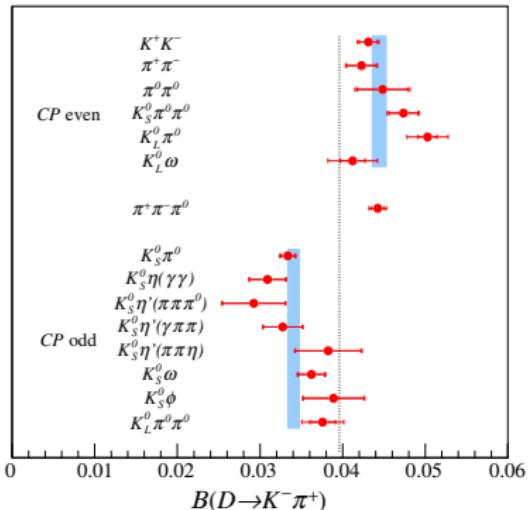


► $\sim 6^\circ$ comes from BESIII

- Second-leading $\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.3})^\circ$ [LHCb; arXiv:2209.03692]
- Better strong-phase measurement is urgent!

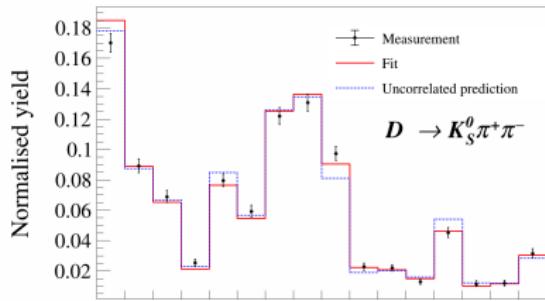
Determination of $\delta_D^{K\pi}$

- ▶ An update of the previous BESIII measurement [PLB 05, 071 (2014)]
- ▶ Proposed at HFCPV2020 by studying more CP tags and using $K_{S,L}^0 \pi^+ \pi^-$ bin-flip method

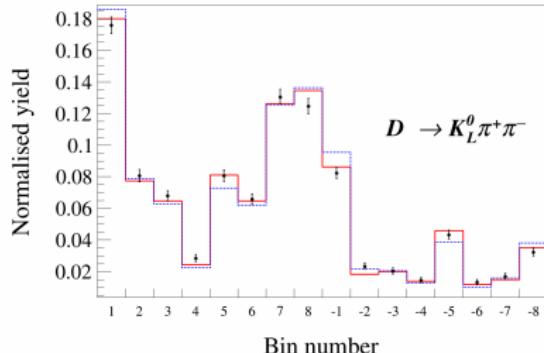


[EPJC 82 (2022) 1009]

Determination of $\delta_D^{K\pi}$

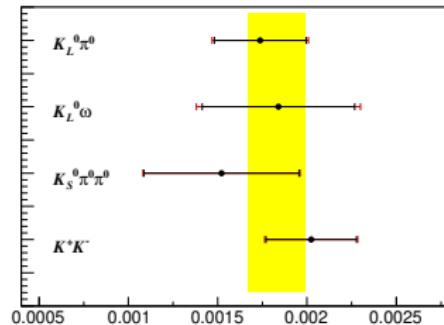
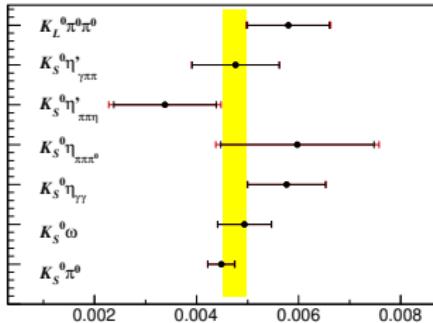


[EPJC 82 (2022) 1009]



- ▶ $\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$
- ▶ HFLAV2022: $\delta_D^{K\pi} = (191.7^{+3.6}_{-3.8})^\circ$
- ▶ Precision test of the theoretical prediction
 $\delta_D^{K\pi} = (183 \pm 5.7)^\circ$ [PRD 99 (2019) 113001] based on SU(3) breaking effects of FSI to accommodate the large observed direct CPV

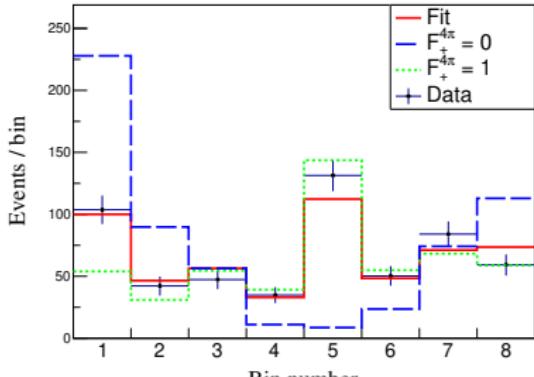
Determination of CP -even fraction in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



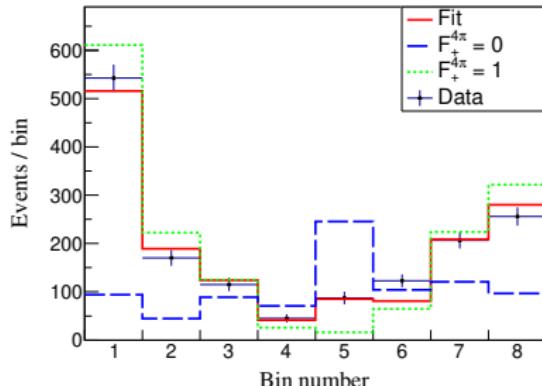
[PRD 106 (2022) 092004]

- ▶ $F_+ = \frac{N^+}{N^+ + N^-} = 0.721 \pm 0.019 \pm 0.007$
- ▶ $F_+ = \frac{N^+ F_{\pi\pi\pi^0}}{N^{\pi\pi\pi^0} - N^+ + 2N^+ F_{\pi\pi\pi^0}} = 0.753 \pm 0.028 \pm 0.010$

Determination of CP -even fraction in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$



[PRD 106 (2022) 092004]



- ▶ $F_+ = 0.735 \pm 0.015 \pm 0.005$
- ▶ c_i, s_i parameters in the $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ phase space can also be further exploited with larger BESIII data samples

Summary and future prospects

Decay mode	Quantity of interest
$\checkmark \quad D \rightarrow K_S^0 \pi^+ \pi^-$	c_i and s_i
	<u>PRD 101 (2020) 112002</u>
$\checkmark \quad D \rightarrow K_S^0 K^+ K^-$	c_i and s_i
	<u>PRD 102 (2020) 052008</u>
$\checkmark \quad D \rightarrow K^\pm \pi^\mp \pi^+ \pi^-$	R, δ
$D \rightarrow K^+ K^- \pi^+ \pi^-$	c_i and s_i
$\checkmark \quad D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$	F_+ or c_i and s_i
$\checkmark \quad D \rightarrow K^\pm \pi^\mp \pi^0$	R, δ
$D \rightarrow K_S^0 K^\pm \pi^\mp$	R, δ
$D \rightarrow \pi^+ \pi^- \pi^0$	F_+
$D \rightarrow K_S^0 \pi^+ \pi^- \pi^0$	F_+ or c_i and s_i
$D \rightarrow K^+ K^- \pi^0$	F_+
$\checkmark \quad D \rightarrow K^\pm \pi^\mp$	δ

- ▶ SCS decays are still limited by statistics
- ▶ Larger data samples at BESIII will be available in the coming years
- ▶ Study the $D\bar{D}$ at higher energy points
- ▶ Super tau-charm factory will also be very helpful

Thanks for attention!