



Strong-phase measurements at BESIII

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Outline

Quantum correlations in $D^0 \bar{D}^0$

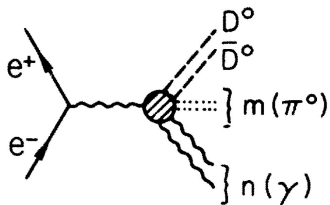
$K_{S,L}^0 h^+ h^-$ ('BPGGSZ' modes)

$K^- \pi^+ / K^- \pi^+ \pi^0 / K^- \pi^+ \pi^+ \pi^-$ (ADS modes)

$\pi^+ \pi^- \pi^+ \pi^-$, $K^+ K^- \pi^+ \pi^-$ (GLW modes)

Summary

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

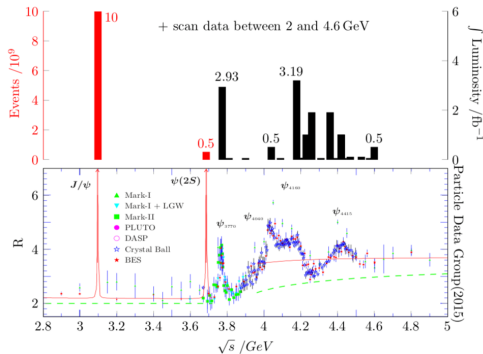


- ▶ $e^+e^- \rightarrow D^0\bar{D}^0 + m(\pi^0) + n(\gamma)$
- ▶ $C(D^0\bar{D}^0) = (-1)^{n+1}$
- ▶ [PRD 15, 1254 (1977)]

Quantum Correlated $D^0\bar{D}^0$:

- ▶ $\frac{1}{\sqrt{2}} [|D^0(p_1, t_1)\rangle |\bar{D}^0(p_2, t_2)\rangle + C | \bar{D}^0(p_1, t_1)\rangle |D^0(p_2, t_2)\rangle]$
- ▶ C -odd: $e^+e^- \rightarrow D^0\bar{D}^0$
- ▶ C -even: $e^+e^- \rightarrow D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$, $D^{*0} \rightarrow \gamma D^0$
- ▶ C -odd: $e^+e^- \rightarrow D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$, $D^{*0} \rightarrow \pi^0 D^0$

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



- ▶ 3773 MeV $\rightarrow$ C -odd: $e^+e^- \rightarrow D^0\bar{D}^0$
- ▶ 4180 MeV $\rightarrow$ C -odd: $e^+e^- \rightarrow D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$, $D^{*0} \rightarrow \gamma D^0$
- ▶ 4180 MeV $\rightarrow$ C -even: $e^+e^- \rightarrow D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$, $D^{*0} \rightarrow \pi^0 D^0$
- ▶ ...

QC double decay rates at $\psi(3770)$

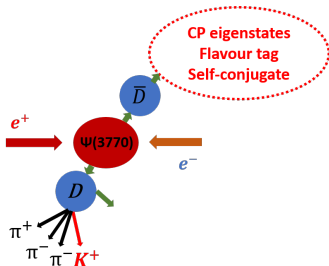
$$\begin{aligned}\Gamma(S|T) &= \int \int |\mathcal{A}_S(\mathbf{x})\mathcal{A}_{\bar{T}}(\mathbf{y}) - \mathcal{A}_{\bar{S}}(\mathbf{x})\mathcal{A}_T(\mathbf{y})|^2 d\mathbf{x}d\mathbf{y} \\ &= [A_S^2 A_{\bar{T}}^2 + A_{\bar{S}}^2 A_T^2 - 2R_S R_T A_S A_{\bar{S}} A_T A_{\bar{T}} \cos(\delta_D^T - \delta_D^S)]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

- ▶ Difference of CP -conserving phases in $D/\bar{D}$ decays
- ▶ CP violation and mixing effects (to the order (x^2, y^2)) can be neglected
- ▶ Best laboratory to measure strong-phase parameters
- ▶ Inputs for CPV studies (in the charm sector and b sector) at B experiments [See Haiping's and Xiaokang's talks]
- ▶ Precision test of perturbative QCD calculations in charm decays, mixing and CPV [Phys. Rev. D 99 (2019) 11300]

Methodology

- ▶ 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 & $\bar{D}$
- ▶ $m_{\text{BC}} = \sqrt{E_{\text{beam}}^2/c^4 - |\mathbf{p}_D^2|/c^2}$
- ▶ $\Delta E = E_D - E_{\text{beam}}$

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

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

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

Methodology

Decay mode	Quantities	Status (2.93 fb ⁻¹)
$K_S^0 \pi^+ \pi^-$	c_i, s_i	Finished (2020)
$K_S^0 K^+ K^-$	c_i, s_i	Finished (2021)
$K^- \pi^+ \pi^+ \pi^-$	R, δ	Finished (2020)
$K^+ K^- \pi^+ \pi^-$	F_+ or c_i, s_i	F_+ Finished (2022), c_i, s_i on going
$\pi^+ \pi^- \pi^+ \pi^-$	F_+ or c_i, s_i	F_+ Finished (2022), c_i, s_i on going
$K^- \pi^+ \pi^0$	R, δ	Finished (2021)
$K_S^0 K^\pm \pi^\mp$	R, δ	On going
$\pi^+ \pi^- \pi^0$	F_+	On going
$K_S^0 \pi^+ \pi^- \pi^0$	F_+ or c_i, s_i	On going
$K^+ K^- \pi^0$	F_+	On going
$K^- \pi^+$	δ	Updated Finished (2022)

From Haiping's talk

Flavour

$K^\pm \pi^\mp \pi^\mp \pi^\mp, K^\pm \pi^\mp \pi^0, K^\pm \pi^\mp, \dots$

CP-even

$K^+ K^-, \pi^+ \pi^-, \pi^0 \pi^0, K_S^0 \pi^0 \pi^0, K_L^0 \pi^0, K_L^0 \omega, \pi^+ \pi^- \pi^0^\dagger$

CP-odd

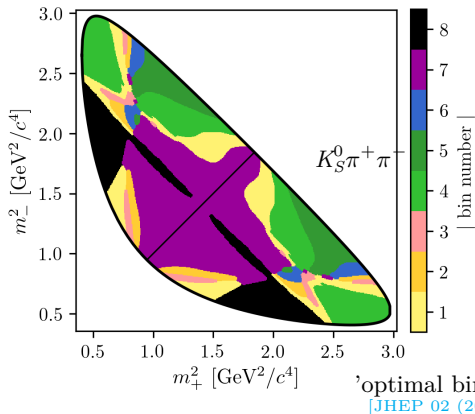
$K_S^0 \pi^0, K_S^0 \eta, K_S^0 \omega, K_S^0 \eta', K_S^0 \phi, K_L^0 \pi^0 \pi^0$

Self-conjugate

$K_S^0 \pi^+ \pi^-, K_S^0 K^+ K^-, \dots$

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

Phase-difference parameters in $D \rightarrow K_S^0 h^+ h^-$

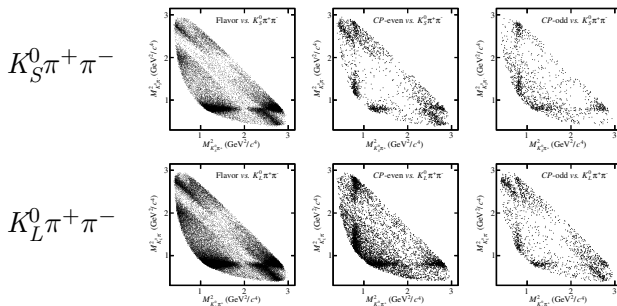


- ▶ $\Delta\delta_D$ between symmetric points
- ▶ $c_i = \cos(\Delta\delta_D)$
- ▶ $s_i = \sin(\Delta\delta_D)$

- ▶ Divide $D \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz plot into bins
- ▶ Full potential to exploit γ angle ['BPGGSZ' method, PRD 68 (2003) 054018; PRD 67 (2003) 071301; A. Bondar]

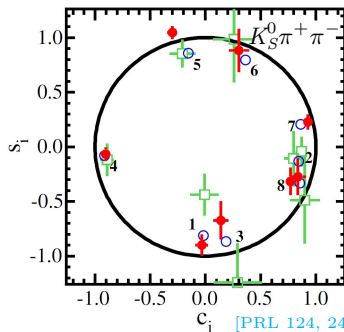
Measurement of c_i and s_i

- ▶ CP tags (eg. $\pi\pi\pi^0$, $K_S^0\pi^0$): different behaviour in Dalitz plot for CP -even/odd events $\Rightarrow c_i$
- ▶ Self tags (tagged by itself) $\Rightarrow c_i, s_i$
- ▶ $K_S^0 h' + h'^- / K_L^0 h^{(\prime)} + h^{(\prime)-}$ tags $\Rightarrow c_i, s_i$ and c'_i, s'_i

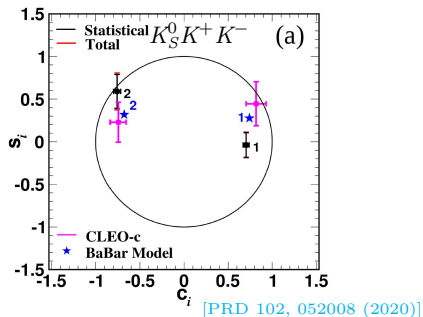


[PRD 101, 112002 (2020)]

Results of c_i and s_i at BESIII



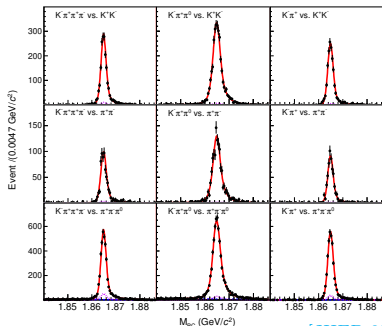
[PRL 124, 241802 (2020)]
[PRD 101, 112002 (2020)]



- ▶ Contribute to a systematic uncertainty of 1° to γ measurement
- ▶ Lead to the best single γ measurement and indirect charm CPV study [JHEP 02 (2021) 169, PRL 127 (2021) 111801]

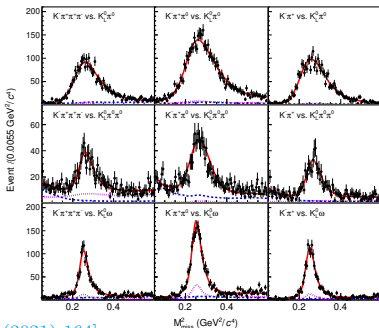
Double tagged $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$

Fully reconstructed CP tags



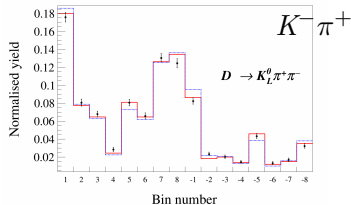
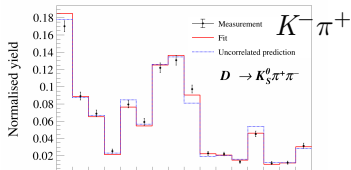
[JHEP 05 (2021) 164]

K_L^0 tags

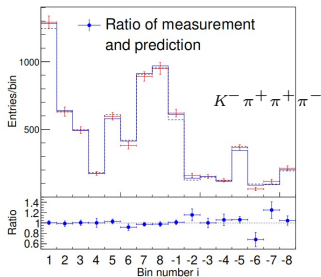
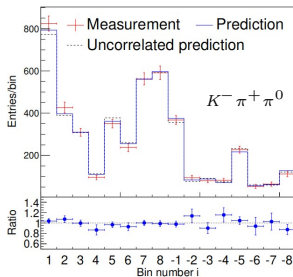


- Clean background in fully reconstructed events
- K_L^0 momentum inferred from tagged D and particles in the signal side

QC effects observed in $K_{S,L}^0 \pi^+ \pi^-$ tags

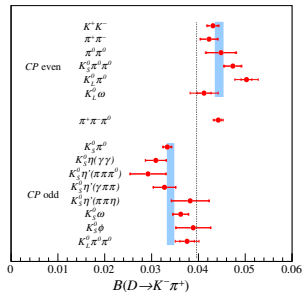
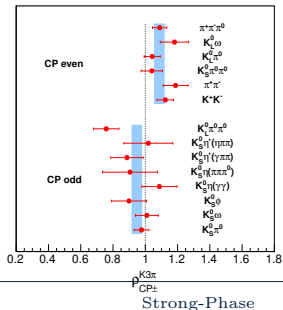
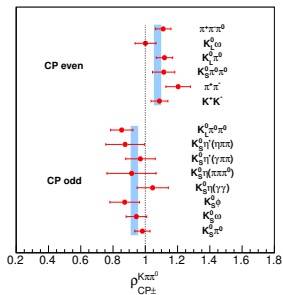


[EPJC 82 (2022) 1009]



[JHEP 05 (2021) 164]

QC effects observed in CP tags

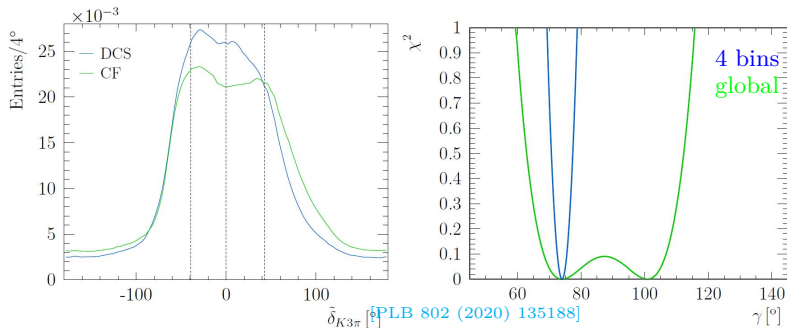


[JHEP 05 (2021) 164]
[EPJC 82 (2022) 1009]

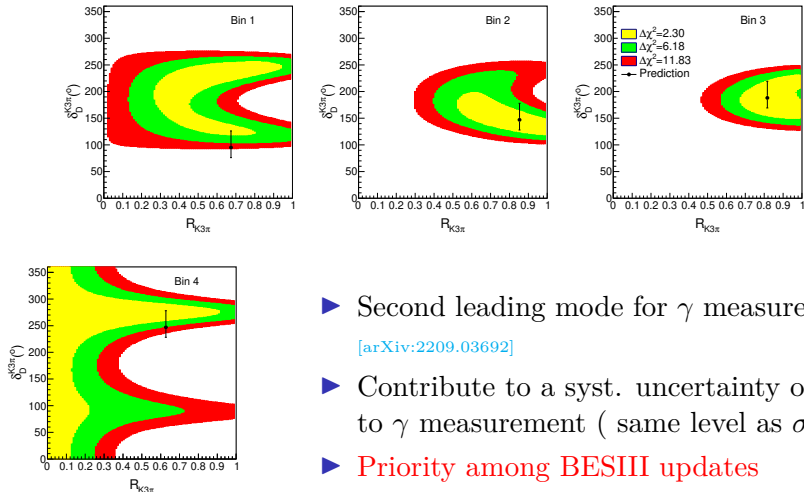
Decay	$\delta_D^f(^{\circ})$	R_f
$K^-\pi^+$	$187.5^{+8.9+5.4}_{-9.7-6.4}$	—
$K^-\pi^+\pi^0$	196^{+14}_{-15}	0.78 ± 0.04
$K^-\pi^+\pi^+\pi^-$	167^{+31}_{-19}	$0.52^{+0.12}_{-0.10}$

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

- ▶ $\delta_D^{K3\pi}$ varies in phase space regions due to rich resonances
- ▶ Sensitivity on γ can be significantly improved

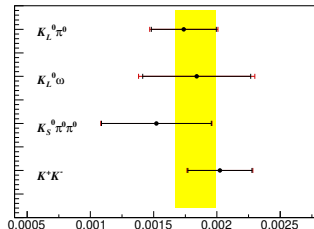
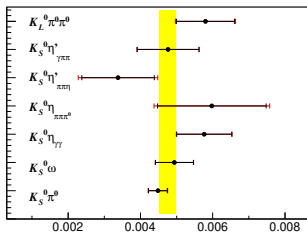


Results of binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$



- ▶ Second leading mode for γ measurement
[arXiv:2209.03692]
- ▶ Contribute to a syst. uncertainty of 6° to γ measurement (same level as $\sigma_{\text{stat.}}$)
- ▶ Priority among BESIII updates

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

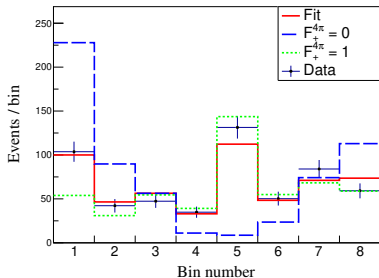


[PRD 106 (2022) 092004]

► $F_+ = \frac{N^+}{N^+ + N^-} = 0.721 \pm 0.019 \pm 0.007$

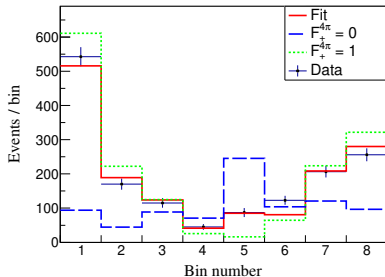
► $F_+ = \frac{N^+ F_+^{\pi\pi\pi^0}}{N^{\pi\pi\pi^0} - N^+ + 2N^+ F_+^{\pi\pi\pi^0}} = 0.753 \pm 0.028 \pm 0.010$

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

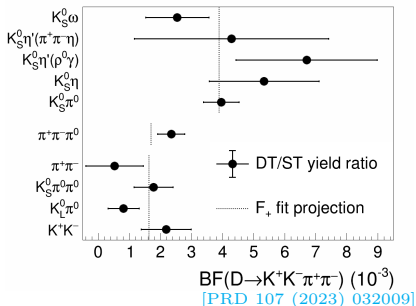


[PRD 106 (2022) 092004]

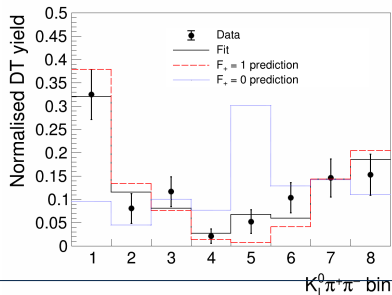
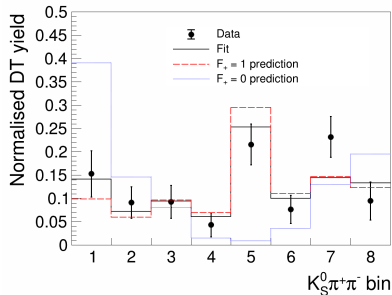
- ▶ $F_{+} = 0.735 \pm 0.015 \pm 0.005$
- ▶ c_i, s_i parameters will be measured



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



- ▶ $F_+ = 0.730 \pm 0.037 \pm 0.021$
- ▶ c_i, s_i parameters will be measured with larger data samples



Summary

Decay mode	Quantities	Status (2.93 fb ⁻¹)
$K_S^0 \pi^+ \pi^-$	c_l, s_l	Finished (2020)
$K_S^0 K^+ K^-$	c_l, s_l	Finished (2021)
$K^- \pi^+ \pi^+ \pi^-$	R, δ	Finished (2020)
$K^+ K^- \pi^+ \pi^-$	F_+ or c_l, s_l	F_+ Finished (2022), c_l, s_l on going
$\pi^+ \pi^- \pi^+ \pi^-$	F_+ or c_l, s_l	F_+ Finished (2022), c_l, s_l on going
$K^- \pi^+ \pi^0$	R, δ	Finished (2021)
$K_S^0 K^\pm \pi^\mp$	R, δ	On going
$\pi^+ \pi^- \pi^0$	F_+	On going
$K_S^0 \pi^+ \pi^- \pi^0$	F_+ or c_l, s_l	On going
$K^+ K^- \pi^0$	F_+	On going
$K^- \pi^+$	δ	Updated Finished (2022)

From Haiping's talk

- ▶ Making progress in past few years
- ▶ Many ongoing projects
 - 1 Updates with 8 and eventually 20 fb⁻¹ $\psi(3770)$ data sample
 - 2 New methods, eg. unbinned $K_{S,L}^0 h^+ h^-$ measurement, $C = +1$ studies

Thanks and stay tuned!