EPS-HEP 2025

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Europe/Paris timezone

Measurement of the strong-phase differences between D^0 and $\bar{D}^0$ decays with quantum-correlated $D\bar{D}$ at BESIII

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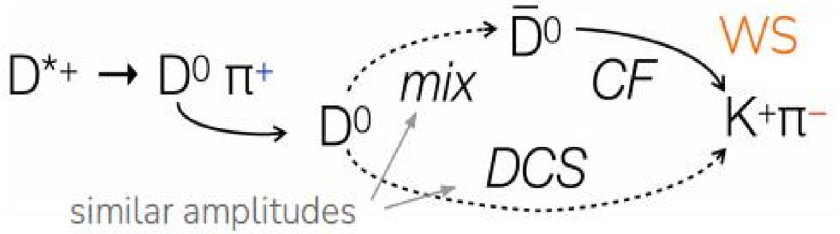
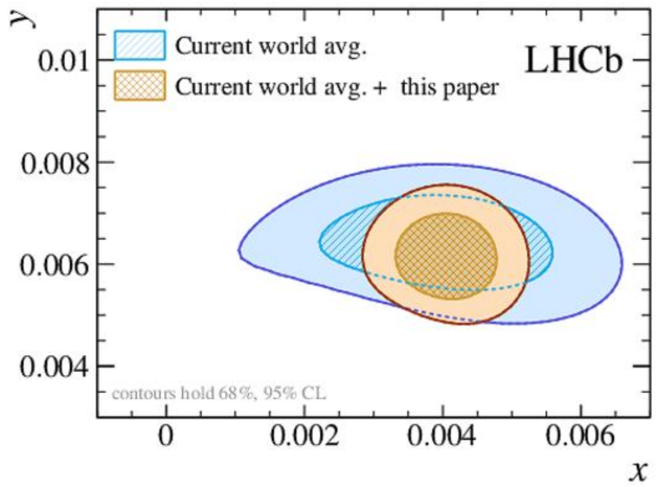
Outline

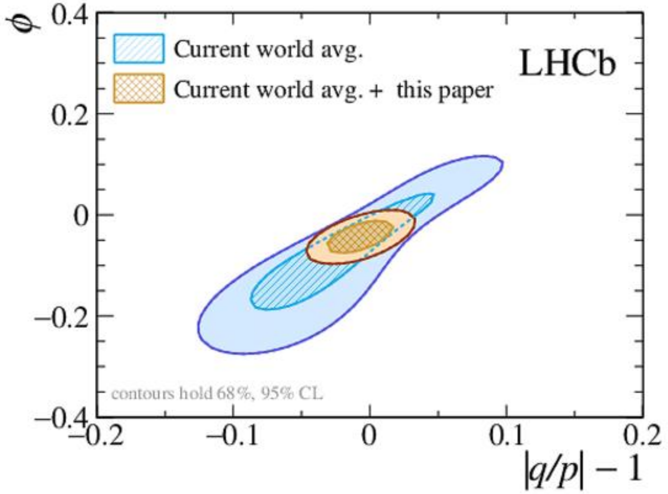
- Strong-phase inputs to charm and bottom CPV studies
- Measurement of the strong-phase differences in $D^0/\overline{D}^0 \rightarrow f$ decays
  - Analysis Method
  - Self-conjugate decays $f = K^0_{S,L}\pi^+\pi^-, h^+h^-\pi^+\pi^-$
  - Quasi flavour eigenstates $f = K^-n\pi$
  - Quasi CP eigenstates $f = h^+h^-\pi^0$
- Prospects and Summary

Input to CPV studies in the charm sector

Strong-phase parameters provide essential inputs to charm mixing and indirect CPV studies in all the three kinds of decays: self-conjugate decays, quasi-flavour eigenstates, and quasi-CP eigenstates



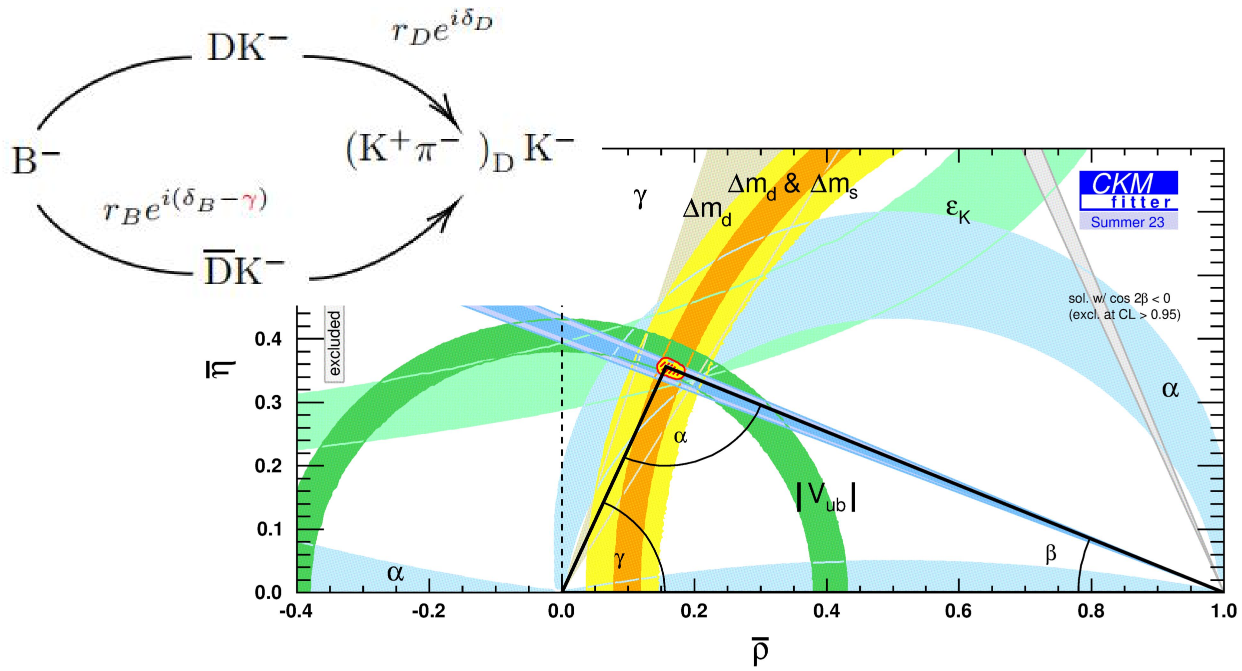




Phys. Rev. Lett. 127, (2021) 111801
Observation of non-zero x with $D^0 \to K_S^0\pi^+\pi^-$

Input to CPV studies in the bottom sector

- Strong-phase parameters provide essential inputs to precision measurement of CKM angle γ with tree-level $B \to DK$ decays
- D decays to the three categories of self-conjugate decays, quasi-flavour eigenstates and (quasi-)CP eigenstates, referred as *BPGGSZ, ADS* and *GLW* methods

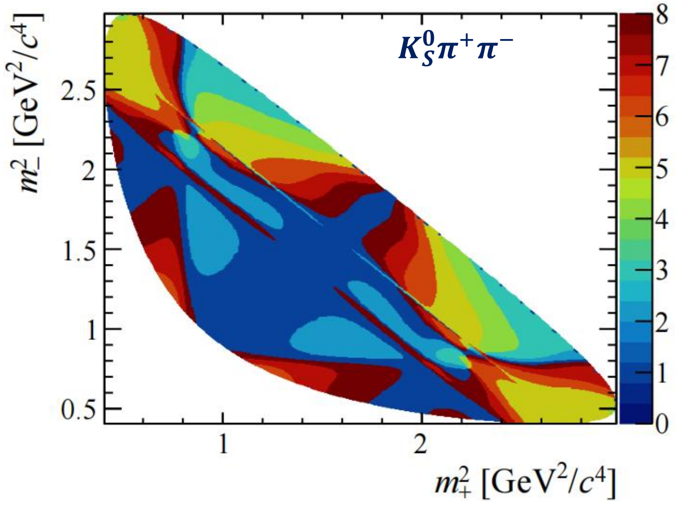


- Direct measurement: $(64.6 \pm 2.8)^o$
- Over-constrained: $(66.23^{+1.86}_{-0.72})^o$
- The uncertainty contributed by the strong-phase inputs should be further reduced to test the CKM unitarity triangle and search for new physics.

Parameterize the strong-phase parameters

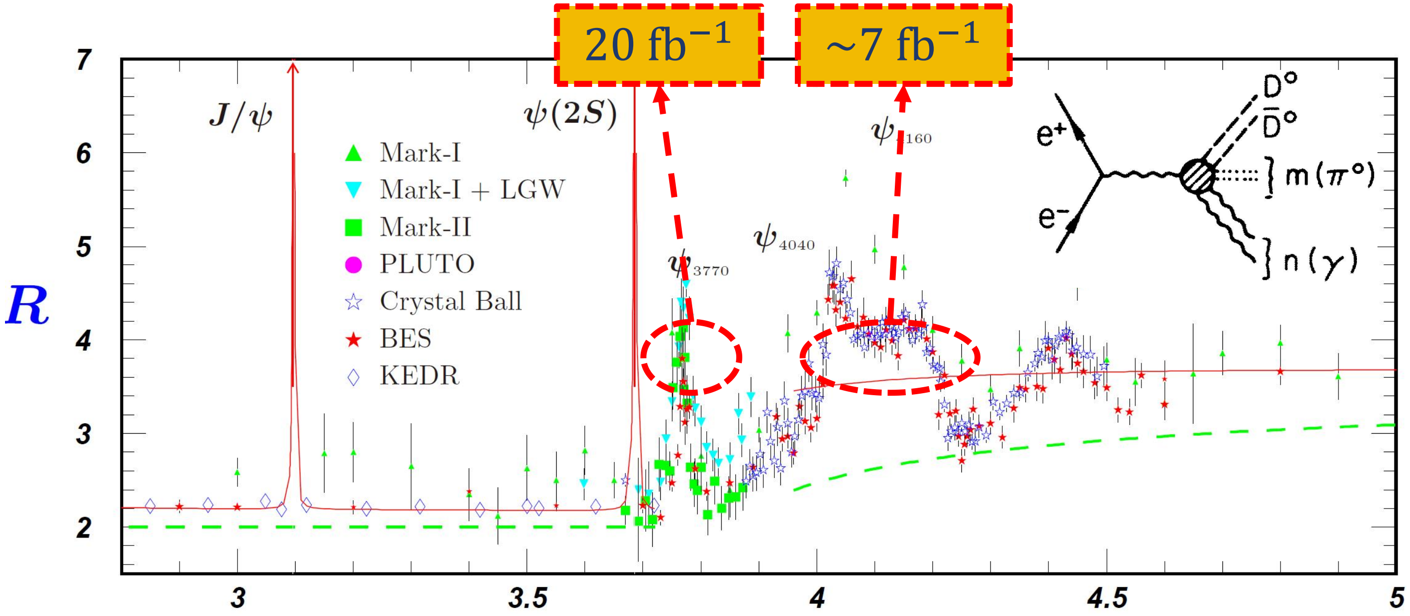
Strong-phase differences can be obtained with amplitudes however with model assumptions. It is more desirable to perform model-independent measurements

- Quasi flavour eigenstates $D \to K^- n\pi$
  - $r_D^F \exp(-i\delta_D^F) = \left(\frac{\bar{A}_F}{A_F}\right)$, $R_F \exp(-i\delta_D^F) = \frac{\int \mathrm{d}X\, A_F^*(X) A_F(X)}{A_F \bar{A}_F}$
- Quasi CP eigenstates $D \to h^+ h^- \pi^0$
  - $F_+ = \frac{\Gamma_+}{\Gamma_+ + \Gamma_-} = \frac{\int \mathrm{d}X\, (|A_F|^2 + |\bar{A}_F|^2 + 2|A_F||\bar{A}_F| \cos\delta_D^F(X))}{\int \mathrm{d}X\, 2(|A_F|^2 + |\bar{A}_F|^2)} = \frac{1 + \int \mathrm{d}X \cos\delta_D^F(X)}{2}$
- Self-conjugate decays $D \to K^0_{S,L} h^+ h^-, h^+ h^- \pi^+ \pi^-$
  - $c_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i \mathrm{d}X |A(X)||\bar{A}(X)| \cos[\delta_D(X)]$
  - $s_i = \frac{1}{\sqrt{F_i F_{-i}}} \int_i \mathrm{d}X |A(X)||\bar{A}(X)| \sin[\delta_D(X)]$
  - $F_i = \frac{\int_i \mathrm{d}X\, |A_F|^2}{\int \mathrm{d}X\, |A_F|^2}$



- Exploit the variation of strong-phase differences across the phase-space of multiple-body decays help to optimize the sensitivity to charm CPV and γ measurements
- The binning scheme can be developed with the amplitude model, the strong-phase measurements are still model-independent

Analysis method



At $\psi(3770)$

C-odd for $e^+e^- \to D^0\overline{D}^0$

$$\Gamma[(e^+e^-)_{\psi(3770)} \to [S]_D[T]_{\overline{D}}]$$
$$\propto A_S^2 A_T^2[(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos(\delta_D^S - \delta_D^T)]$$

Charm mixing can be neglected to $O(x^4,\ y^4)$

At higher energy points

C-odd for $e^+e^- \to D^{(*)0}\overline{D}^{*0} + c.c. \ \to \pi^0(\pi^0)D^0\overline{D}^0$

C-even for $e^+e^- \to D^0\overline{D}^{*0} + c.c. \ \to \gamma D^0\overline{D}^0$

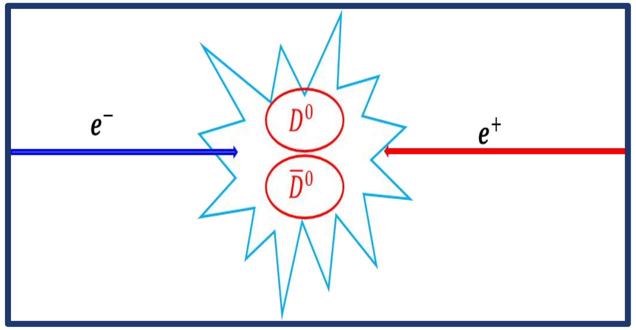
C-even for $e^+e^- \to D^{*0}\overline{D}^{*0} + c.c \to \gamma\pi^0 D^0\overline{D}^0$

$$\Gamma[(e^+e^-)_{4009-4230} \to \gamma(\pi^0)[S]_D[T]_{\overline{D}}]$$
$$\propto A_T^2[(r_D^S)^2 + (r_D^T)^2 + 2R_S R_T r_D^S r_D^T \cos(\delta_D^S - \delta_D^T)$$
$$- 2y(R_S r_D^S \cos\delta_D^S + R_T r_D^T \cos\delta_D^T) + 4x(R_S r_D^S \sin\delta_D^S + R_T r_D^T \sin\delta_D^T)]$$

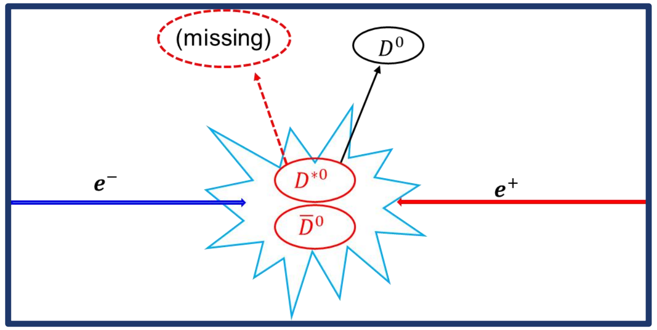
Sensitivity to charm mixing could be acheived

Double-tag method

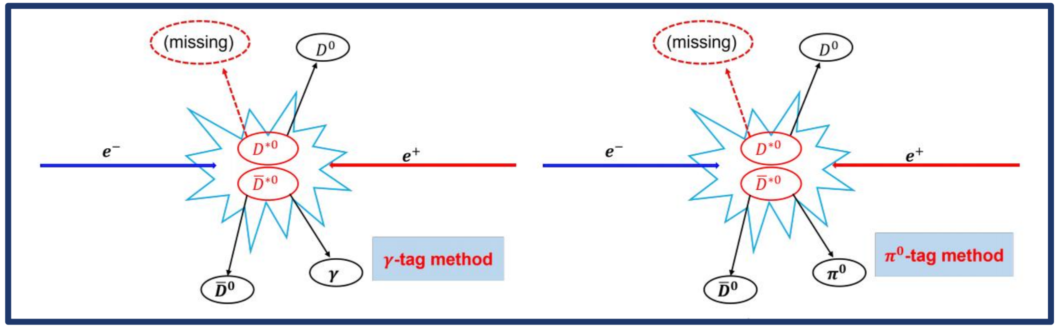
$D\overline{D}$



$\{\gamma, \pi^0\}D\overline{D}$



$\{\gamma\pi^0, \gamma\gamma, \pi^0\pi^0\}D\overline{D}$



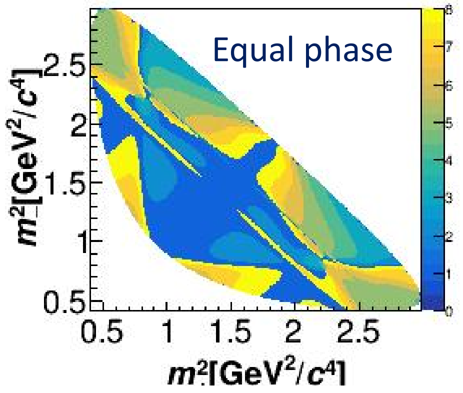
- Study the joint decay of D and $\overline{D}$, referred as the *double tag* method
- Reconstruct one D in the signal decay and the other in the tag decay
- Constrain the tag-side strong-phase differences to extract the parameters in the signal side

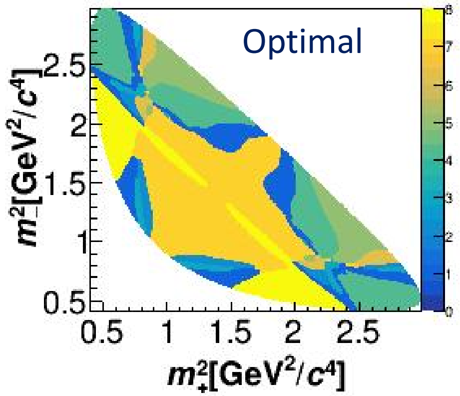
		Tag side	Branching fraction level
Flavour		$K^-e^+\nu_e$、$K^-\pi^+$、$K^-\pi^+\pi^0$、$K^-\pi^+\pi^+\pi^-$	$10^{-1}-10^{-2}$
CP	Even	K^+K^-、$\pi^+\pi^-$、$K_S^0\pi^0\pi^0$、$\pi^+\pi^-\pi^0$、$K_L^0\pi^0$、$K_L^0\omega$	10^{-3}~10^{-2}
	Odd	$K_S^0\pi^0$、$K_S^0\omega$、$K_S^0\eta$、$K_S^0\eta'$、$K_L^0\pi^0\pi^0$	10^{-2}
Self-conjugate		$K_S^0\pi^+\pi^-$、$K_L^0\pi^+\pi^-$	10^{-2}

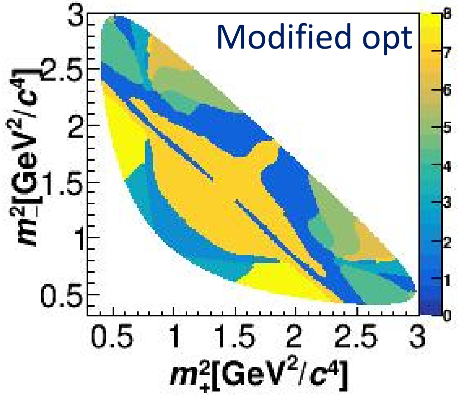
Study of the $D \to K^0_{S,L}\pi^+\pi^-$ decay

- CP tags
  - $M_i \propto K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}$
  - $M'_i \propto K'_i + K'_{-i} + 2c'_i\sqrt{K'_iK'_{-i}}$
- Self-conjugate tags
  - $M_{ij} \propto K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-i}K_jK_{-j}}(c_ic_j + s_is_j)$
  - $M_{ij} \propto K_iK'_{-j} + K_{-i}K'_j + 2\sqrt{K_iK_{-i}K'_jK'_{-j}}(c_ic'_j + s_is'_j)$
- Flavour tags
  - $M_i \propto K_i + (r_D^F)^2K_{-i} - 2R_Dr_D^F\sqrt{K_iK_{-i}}(\cos\delta_D^F c_i - \sin\delta_D^F\, s_i)$
  - $M'_i \propto K'_i + (r_D^F)^2K'_{-i} + 2R_Dr_D^F\sqrt{K'_iK'_{-i}}(\cos\delta_D^F c'_i - \sin\delta_D^F\, s'_i)$
  - K_i are the fractional flavour-specific signal decay events in each bin

Binning schemes for D $\to K^0_{S,L}\pi^+\pi^-$
Equal phase for charm mixing study
Optimal for γ measurement







$D \to K^0_L\pi^+\pi^-$ can be studied with the same binning scheme and can help to improve the measurement of $D \to K^0_S\pi^+\pi^-$

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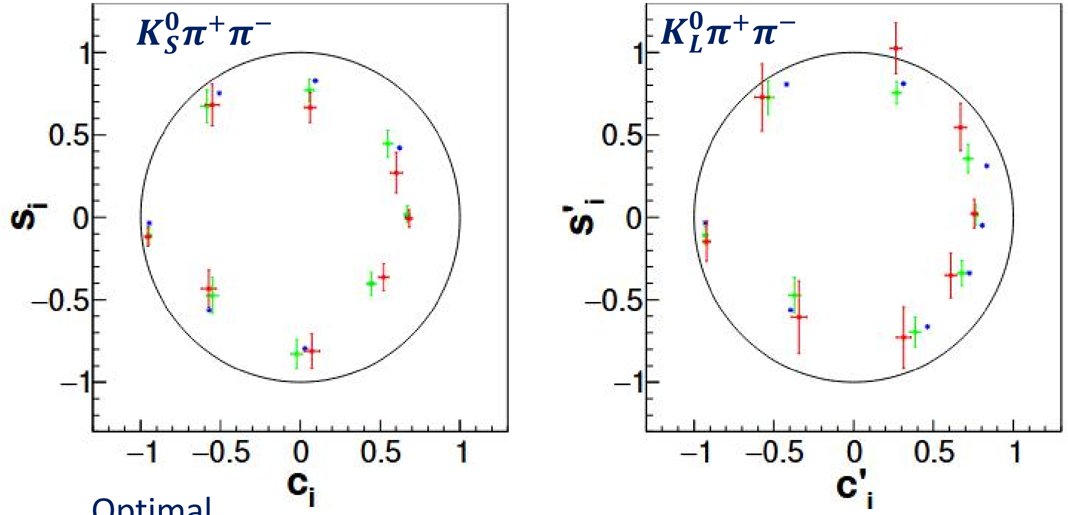
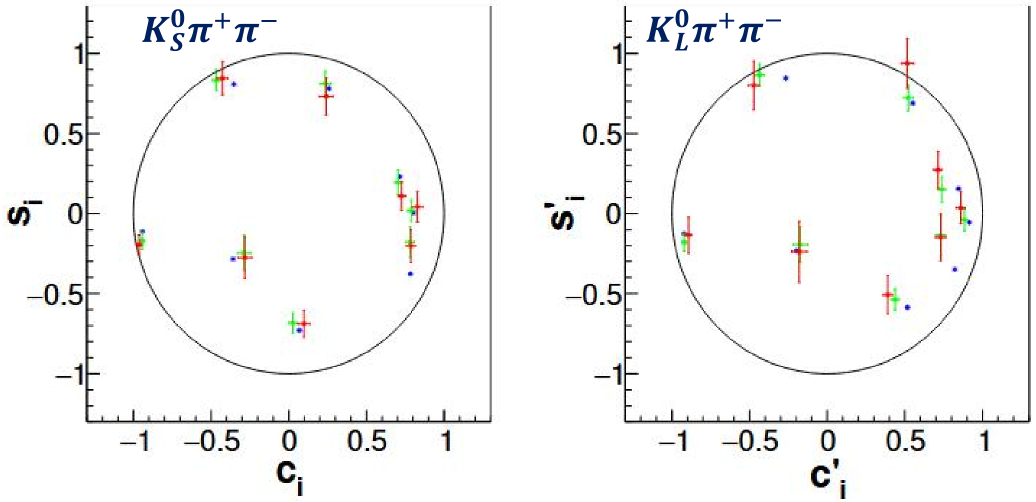
Results of $c_i^{(\prime)}$, $s_i^{(\prime)}$ in $D \to K^0_{S(L)}\pi^+\pi^-$

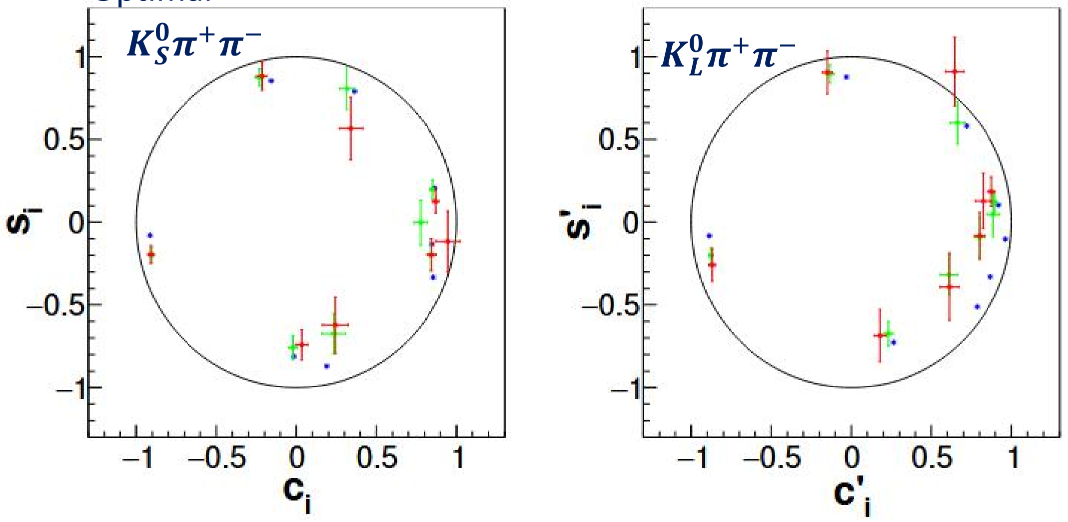
Equal phase



Modified optimal

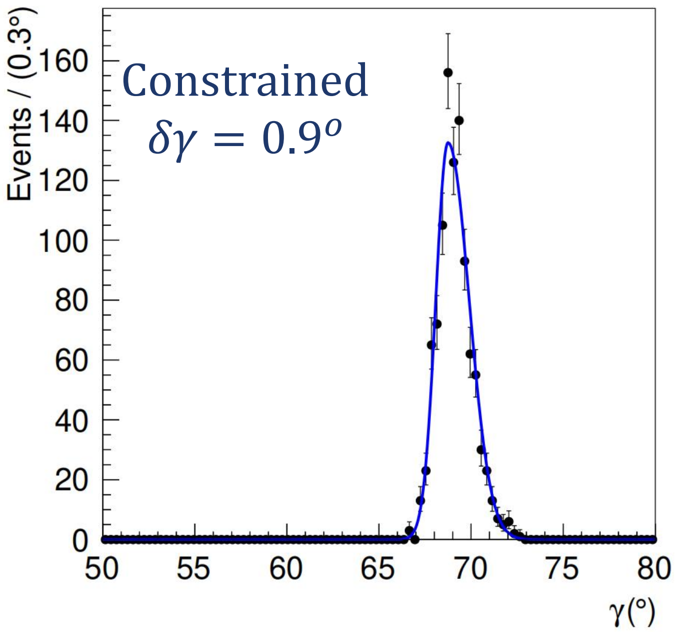


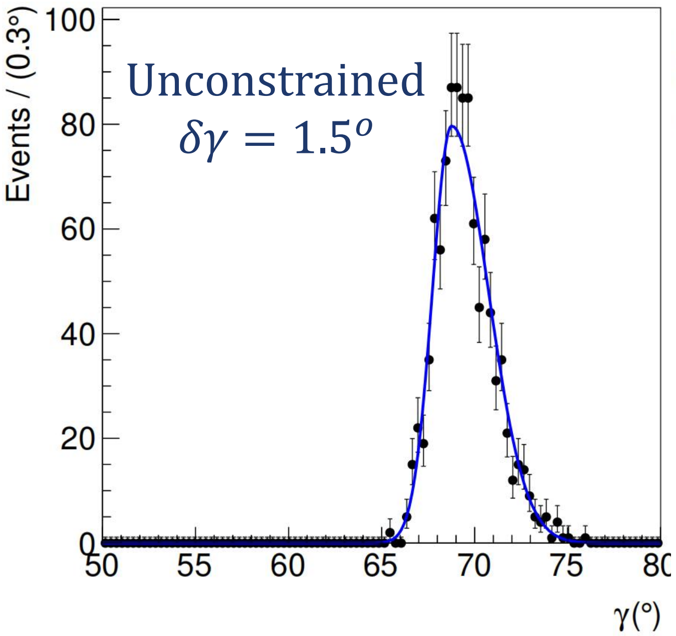
Optimal



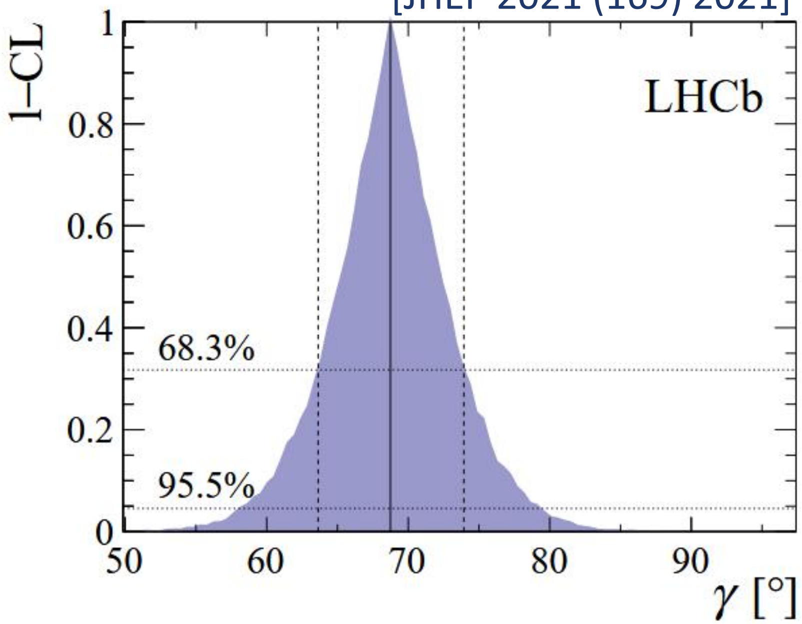
- Based on 7.93 fb^{-1} $\psi(3770)$ data
- The model constraints of $\Delta c_i = c_i - c'_i$ and $\Delta s_i = s_i - s'_i$ have been adopted to improve the sensitivity
- Model predictions are consistent within 2σ
- First measurement relies no constraints of amplitude models
- $D \to K^0_L\pi^+\pi^-$ can be used for γ measurement at Belle II

Results of $c_i^{(\prime)}$, $s_i^{(\prime)}$ in $D \to K^0_{S(L)}\pi^+\pi^-$





[JHEP 2021 (169) 2021]

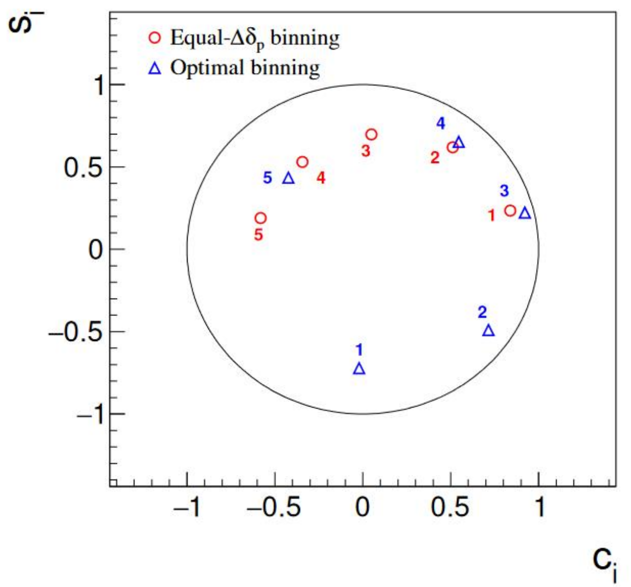


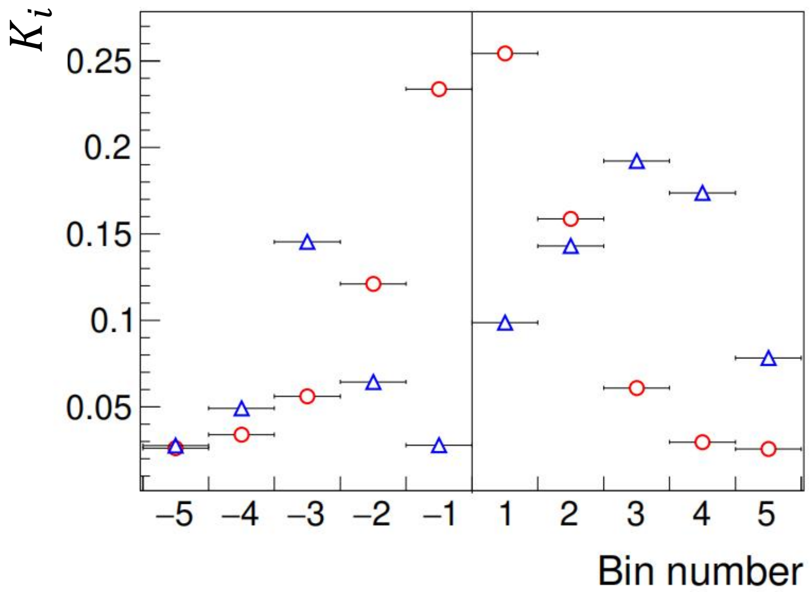
- The uncertainty contribution to γ is improved by ~1.4 compared to the previous BESIII measurement
- The constrained strong-phase parameters would contribute an uncertainty to γ sub-leading to the experimental systematic uncertainty
- Mean value of γ shift about 0.5^o taking the unconstrained parameters as inputs

$$x_-^{DK} = (5.68 \pm 0.96 \pm 0.20 \pm 0.23) \times 10^{-2}$$
$$y_-^{DK} = (6.55 \pm 1.14 \pm 0.25 \pm 0.35) \times 10^{-2}$$
$$x_+^{DK} = (-9.30 \pm 0.98 \pm 0.24 \pm 0.18) \times 10^{-2}$$
$$y_+^{DK} = (-1.25 \pm 1.23 \pm 0.26 \pm 0.28) \times 10^{-2}$$
$$\gamma = \left(68.7^{+5.2}_{-5.1}\right)^o$$

Study of the decay $D \to \pi^+\pi^-\pi^+\pi^-$

- Binning schemes are developed in the 5D phase space ($m_{\pi^+\pi^+}$, $m_{\pi^-\pi^-}$, $\cos\theta_{\pi^+\pi^+}$, $\cos\theta_{\pi^-\pi^-}$, $\phi_{+/-}$) based on the amplitude model [Chin. Phys. C 48, 083001 (2024)]
- Phase space fold under CP transformation and exchange of identical particles, where the strong-phase differences are invariant
- The optimal binning scheme is constructed where negative (positive) bins are chosen to have $|A/\bar{A}| < (>) 1$ to optimize the sensitivity to γ angle
- The binning method is optimized by maximizing the sensitivity compared to an unbinned analysis, which is 85%





Binning schemes available at https://zenodo.org/records/14029568

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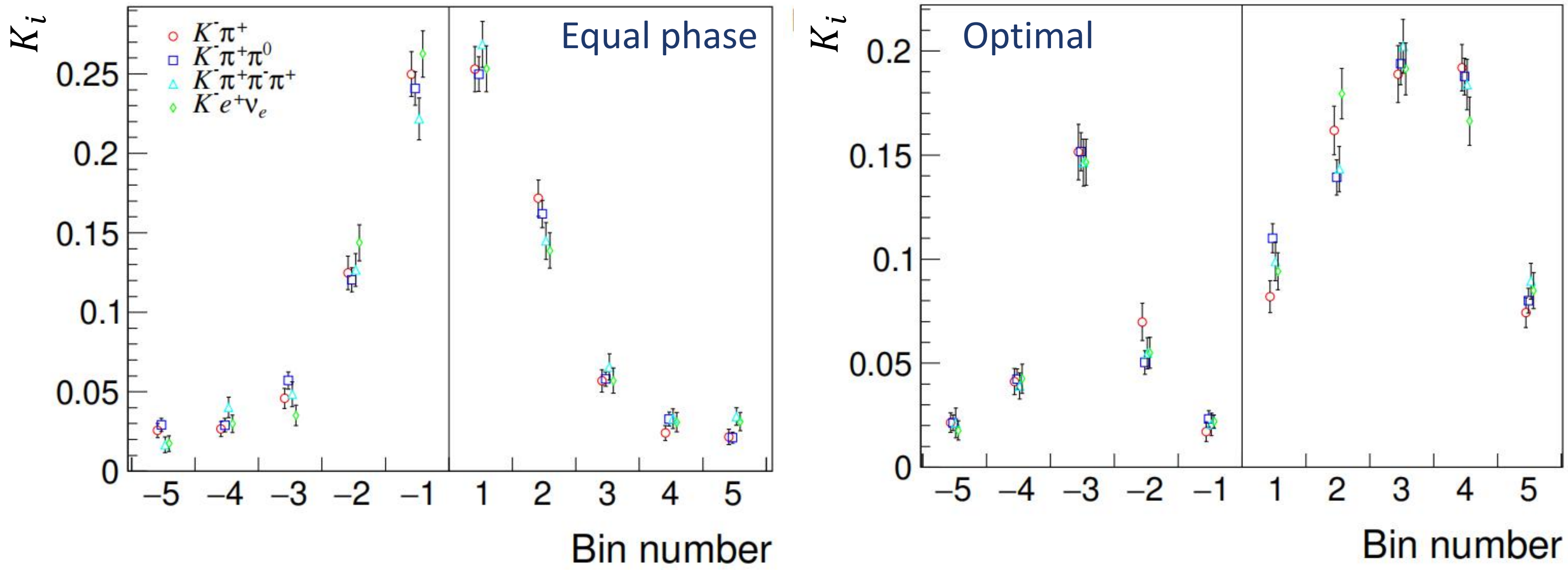
Study of the decay $D \to \pi^+\pi^-\pi^+\pi^-$

- Flavour tags are used to measure the fractional binned signal events
  - $M_i \propto K_i + (r_D^F)^2 K_{-i} - 2R_D r_D^F \sqrt{K_i K_{-i}}(\cos\delta_D^F c_i - \sin\delta_D^F s_i)$
  - $M_i' \propto K_i' + (r_D^F)^2 K_{-i}' + 2R_D r_D^F \sqrt{K_i' K_{-i}'}(\cos\delta_D^F c_i' - \sin\delta_D^F s_i')$



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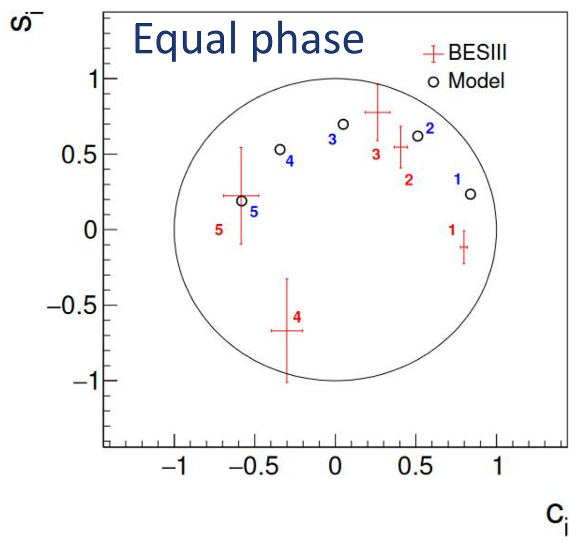
Results of c_i, s_i in $D \to \pi^+\pi^-\pi^+\pi^-$

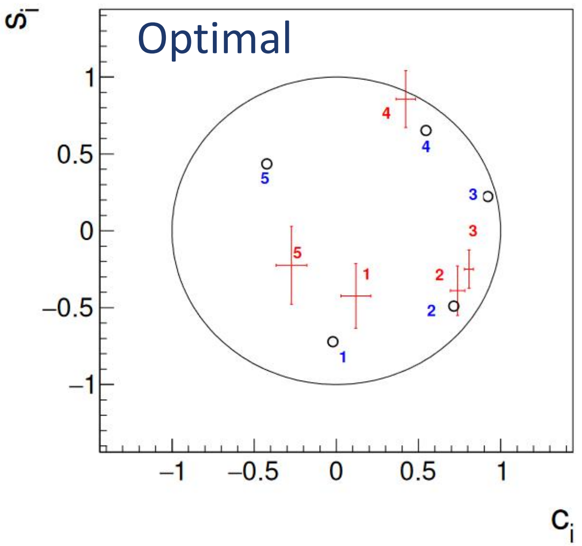
CP tags

$$M_i \propto K_i + K_{-i} - 2c_i\sqrt{K_iK_{-i}}$$
$$M'_i \propto K'_i + K'_{-i} + 2c'_i\sqrt{K'_iK'_{-i}}$$

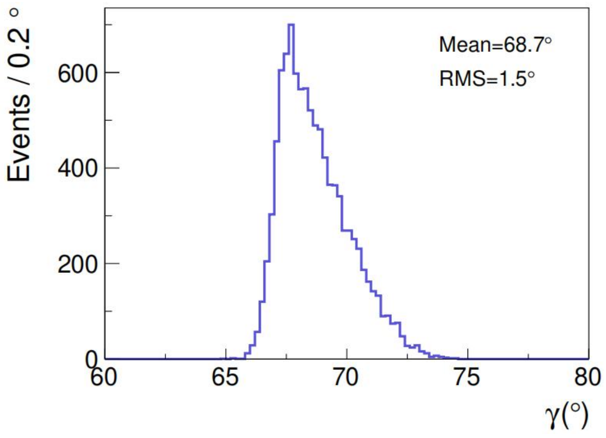
Self-conjugate tags

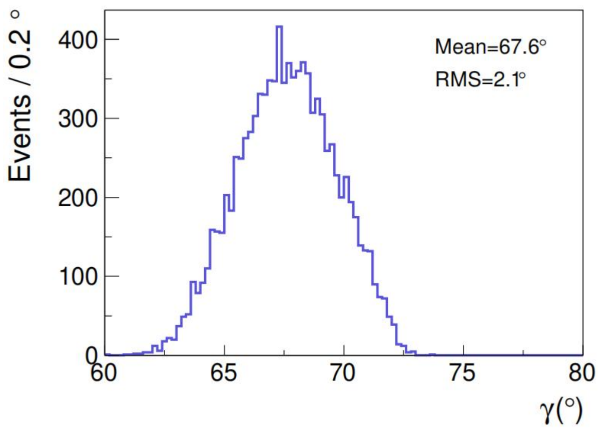
$$M_{ij} \propto K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-i}K_jK_{-j}}(c_ic_j + s_is_j)$$
$$M_{ij} \propto K_iK'_{-j} + K_{-i}K'_j + 2\sqrt{K_iK_{-i}K'_jK'_{-j}}(c_ic'_j + s_is'_j)$$





- The statistical uncertainty of γ measured with binned $D \to \pi^+\pi^-\pi^+\pi^-$ is found to be around 6^o, only next to the $D \to K^0_S\pi^+\pi^-$ decay
- The uncertainty contributed by BESIII inputs is around 2.1^o with around 3 fb^{-1} $\psi(3370)$ data
- It can be further improved with the total BESIII $\psi(3770)$ dataset

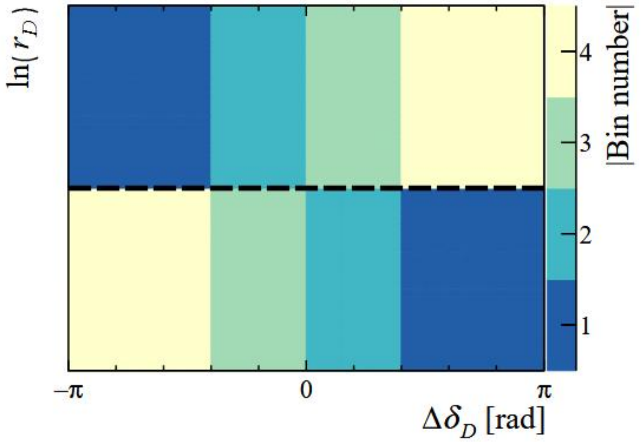




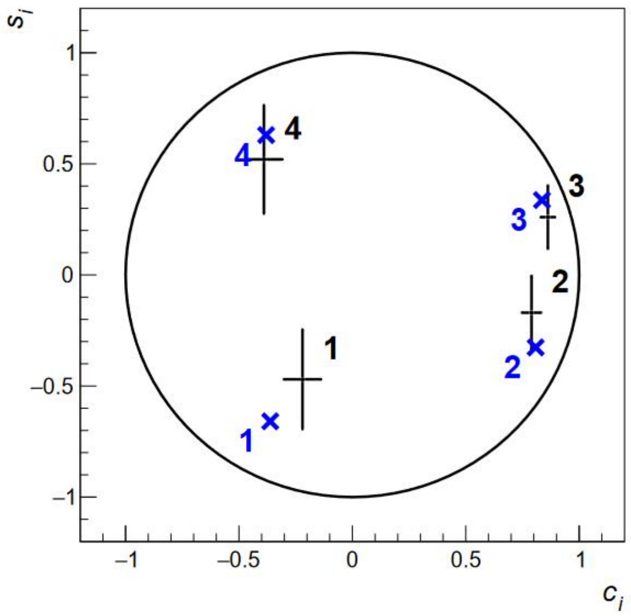
arXiv: 2502.12873

Study of the decay $D \to K^+K^-\pi^+\pi^-$

- Binning scheme is developed with the decay amplitude model in the 5D phase space EPJC 83 (2023) 547
- The binning method is found to have a sensitivity about 85% that of the model-dependent measurement
- Three categories of tags have been used



Binning scheme available at 10.5281/zenodo.6940031



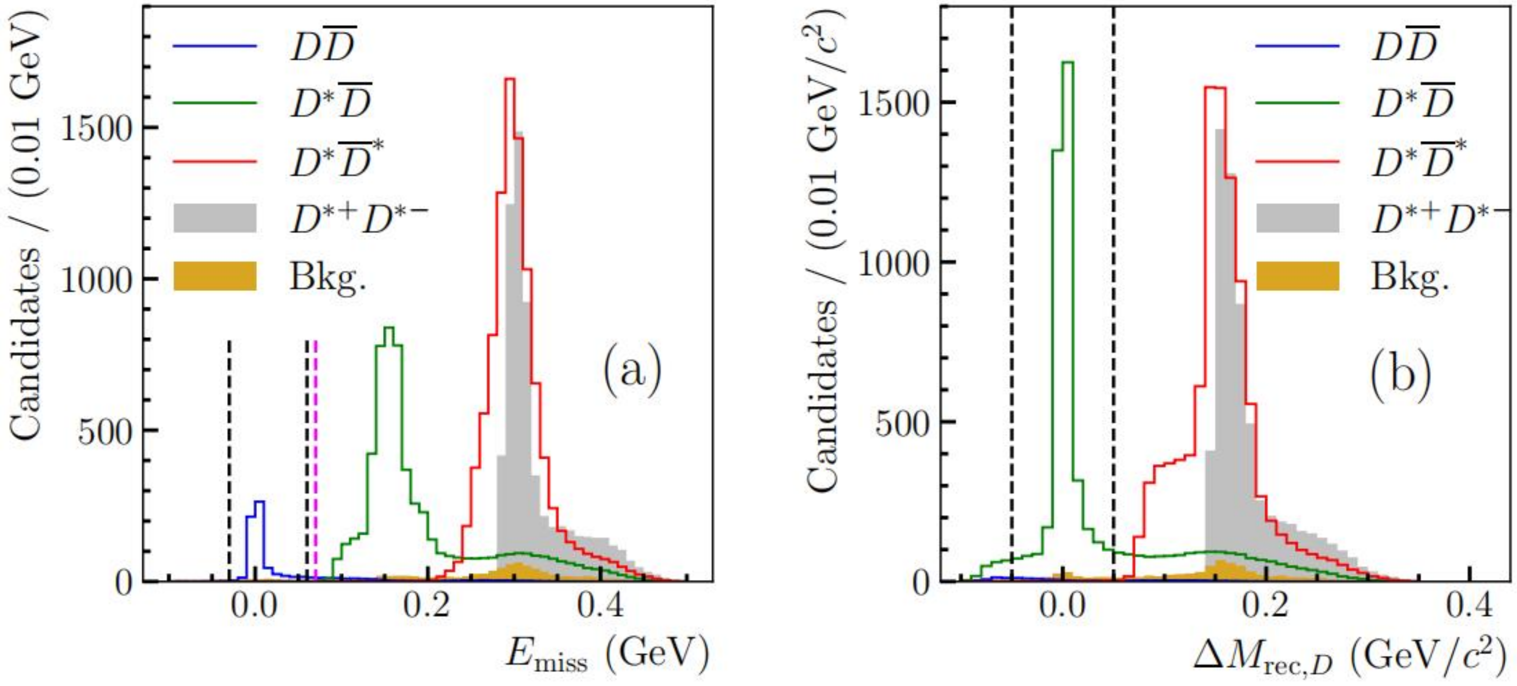
Variable	Results	Model
K_{-4}	0.0871(27)(38)	0.086
K_{-3}	0.294(5)(6)	0.297
K_{-2}	0.400(7)(3)	0.398
K_{-1}	0.252(7)(12)	0.267
K_1	0.119(6)(6)	0.110
K_2	0.405(12)(2)	0.401
K_3	0.818(10)(10)	0.833

- The first strong-phase measurement with the total 20 fb^{-1} dataset
- Model predictions of strong-phase differences and fractional $D^0 \to KK\pi\pi$ signal events are in agreement with the measurements
- The uncertainty contributing to γ is found to be around 10^o, the statistical uncertainty of γ is 12.7^o

arXiv: 2506.07907

First exploration of the C-even correlation

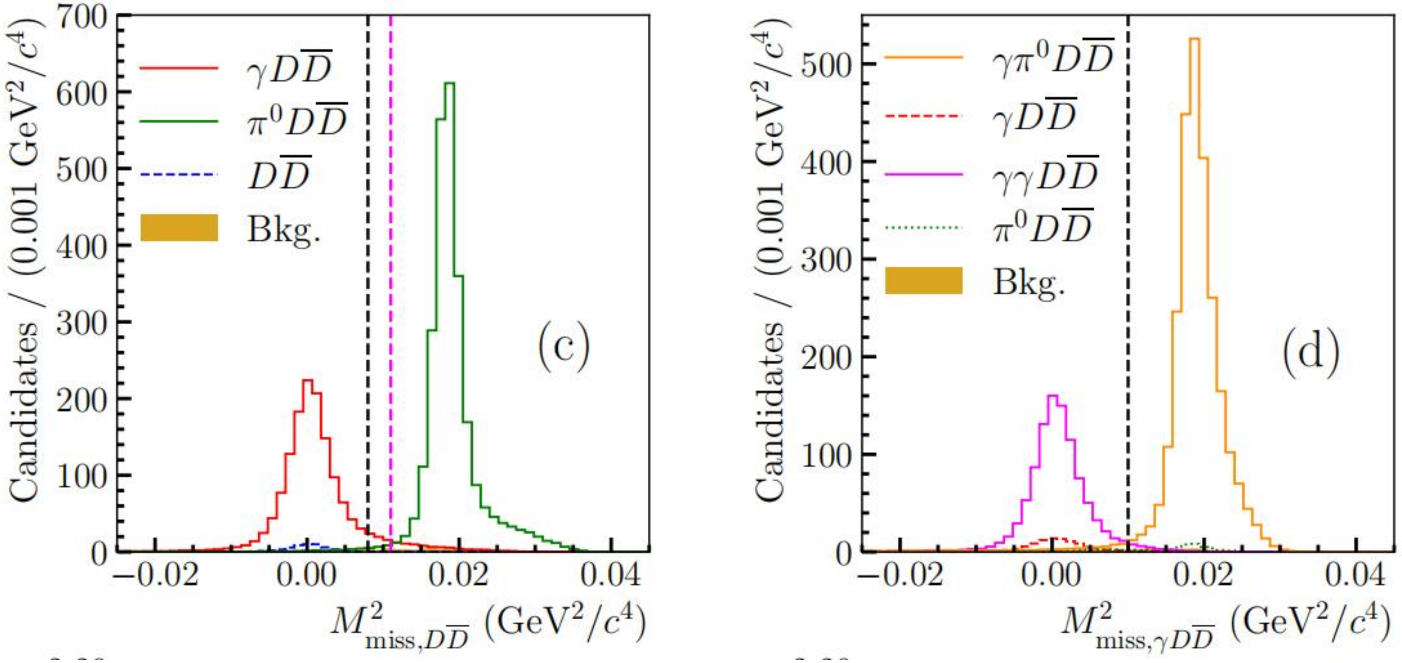
Based on simulation of $(K^-\pi^+)_D(K^+\pi^-)_{\overline{D}}$ decays produced in different mechanism



- The D and $\overline{D}$ decays are jointly reconstructed
- Distinguish between $D\overline{D}$, $D^*\overline{D}$ and D^*D^*
  - "Missing energy" that the transition γ/π^0 particle carries
  - Minimum difference between the recoil mass of each D and the D^* nominal mass

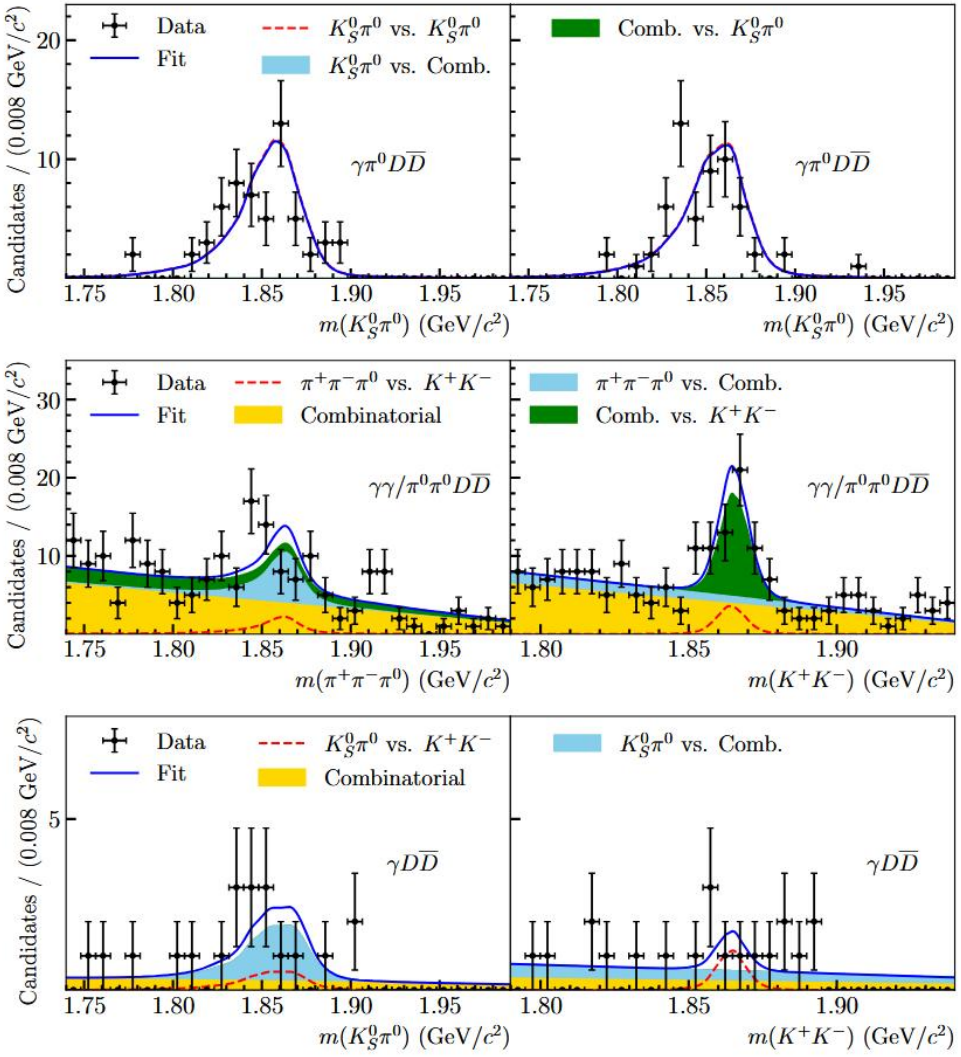
First exploration of the C-even correlation

Based on simulation of $(K^-\pi^+)_D(K^+\pi^-)_{\bar{D}}$ decays produced in different mechanism

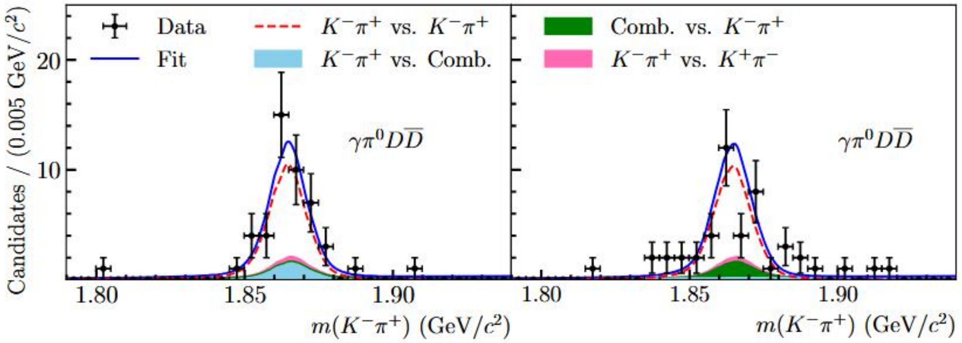


- $D^*\bar{D} \to \gamma/\pi^0 D\bar{D}$
  - Well separated by the "squared missing mass" of the two D mesons
- $D^*\bar{D}^* \to \gamma\gamma/\gamma\pi^0 D\bar{D}$
  - Reconstruct one of the accompanying photon
  - Well separated by the "squared missing mass" of the two D mesons and the reconstructed photon

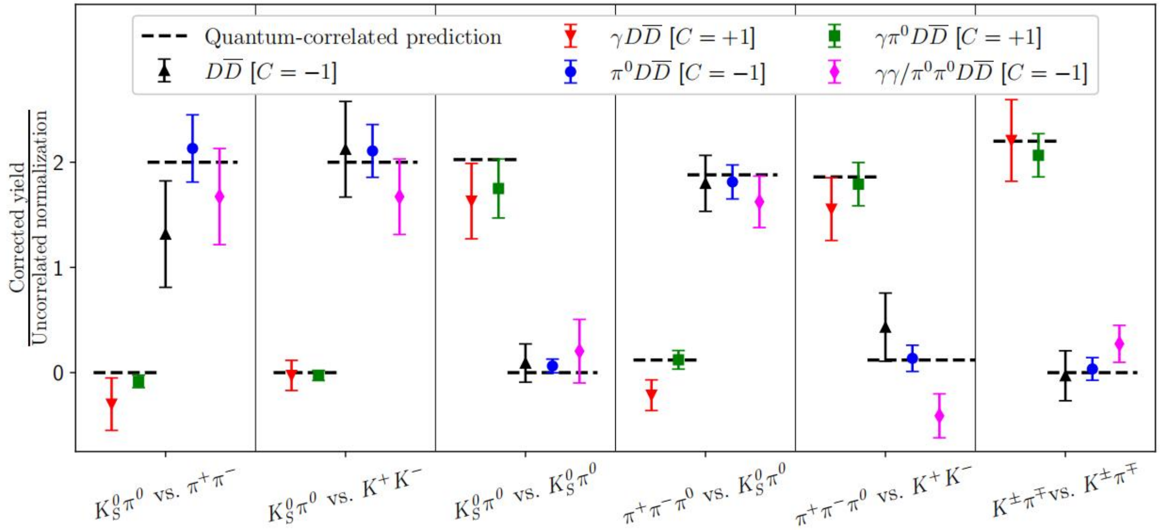
First exploration of the C-even correlation



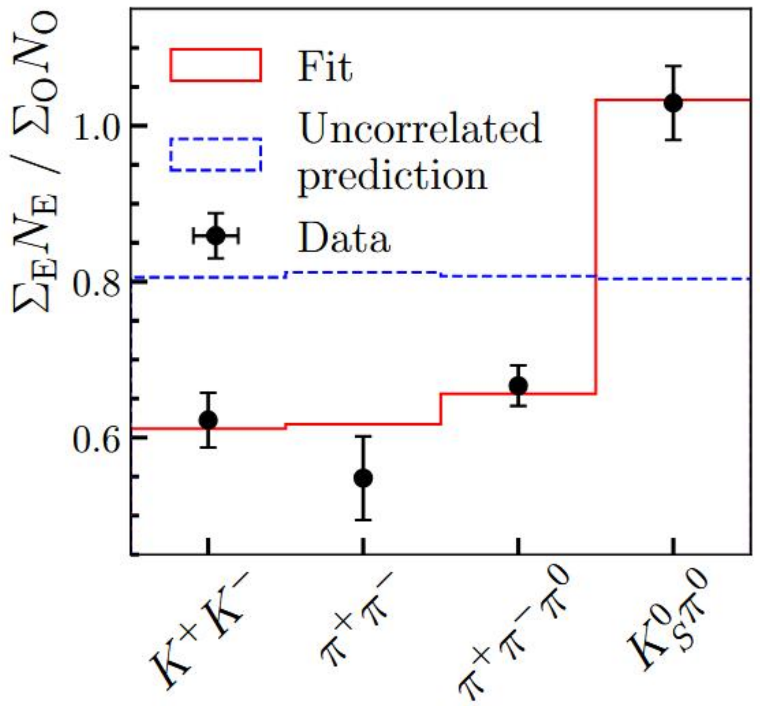
7.13 fb^{-1} from 4.13-4.23 GeV

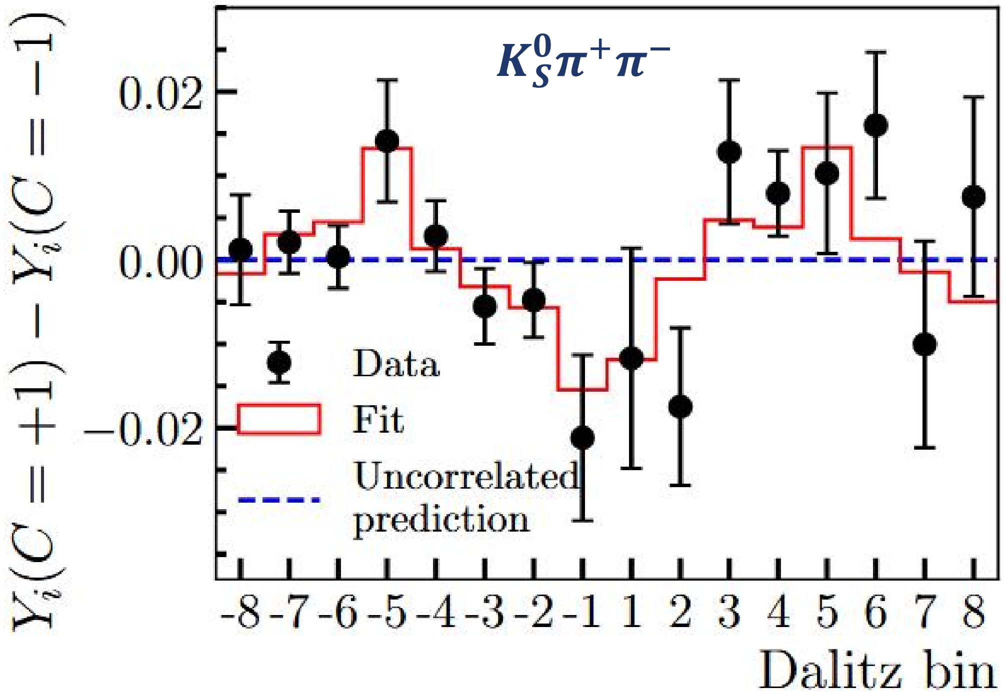


- Clear difference of the observed CP even (odd) vs CP even (odd) signal events in $\gamma\pi^0 D\bar{D}$ and $\gamma\gamma/\pi^0\pi^0 D\bar{D}$ samples
- CP even vs CP odd signal decays are suppressed in $\gamma D\bar{D}$ sample
- Like-sign signal event are observed in C-even sample



Novel measurement of $\delta_{K\pi}$





Comparing the DT yields in C-even and C-odd correlated samples yields

$$\delta_D^{K\pi} = (192.8^{+11.0+1.9}_{-12.4-2.4})^o$$

The first measurement with C-even correlated samples

Implying these samples can be used for measurement of other decays

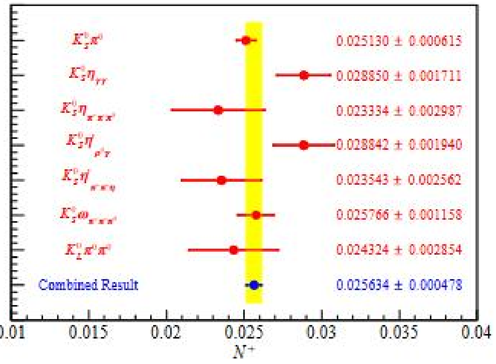
Feasibility of performing charm mixing and indirect CPV studies with larger samples produced at future Super Tau-Charm Facility are also discussed

PRD 111 (2025) 012007

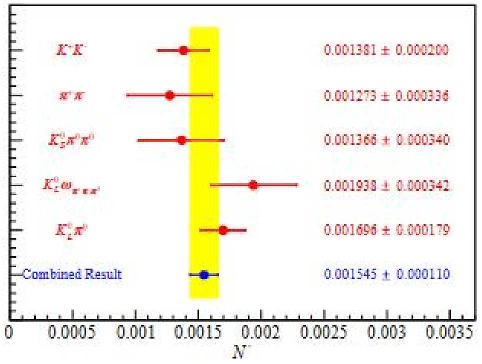
Measurement of CP-even fraction in $D \to \pi^+\pi^-\pi^0,\ K^+K^-\pi^0$

CP tags

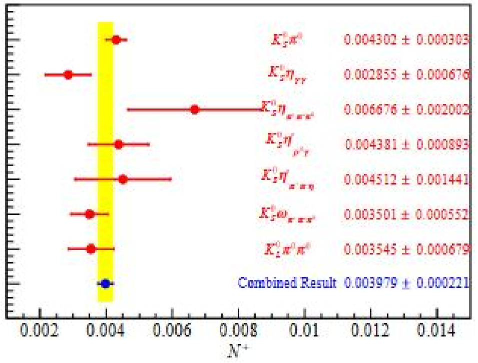
$$\Gamma = A_S^2 A_T^2[1-(2F_+ - 1)\cos\delta_D^{CP\pm}]$$



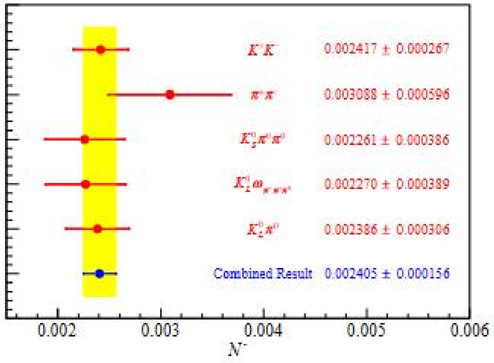
(a) N^+ for $\pi^+\pi^-\pi^0$



(b) N^- for $\pi^+\pi^-\pi^0$



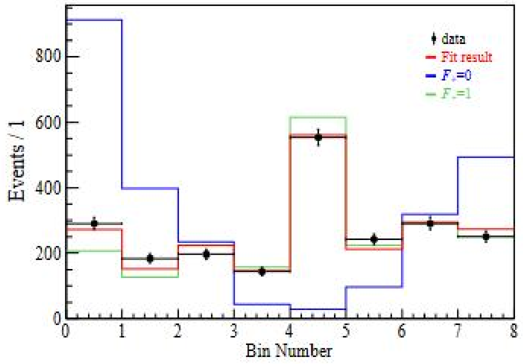
(c) N^+ for $K^+K^-\pi^0$



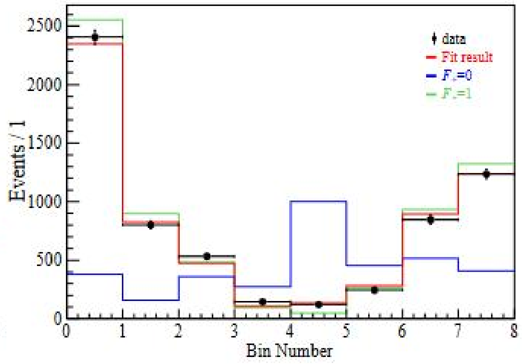
(d) N^- for $K^+K^-\pi^0$

Self-conjugate tags

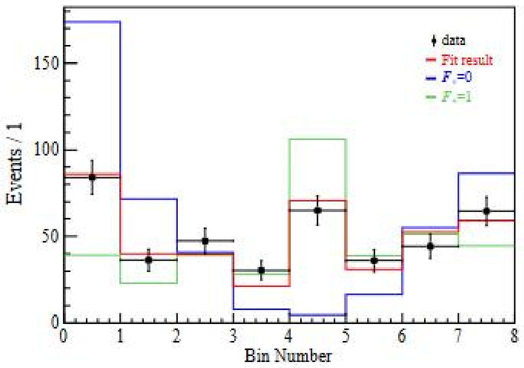
$$\Gamma_i = A_S^2 A_T^2\left[K_i + K_{-i} - 2\sqrt{K_i K_{-i}}\,c_i(2F_+ - 1)\right]$$



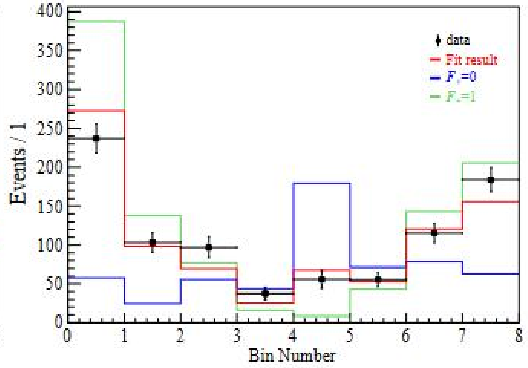
(a) $K_S^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$



(b) $K_L^0\pi^+\pi^-$ versus $\pi^+\pi^-\pi^0$



(c) $K_S^0\pi^+\pi^-$ versus $K^+K^-\pi^0$



(d) $K_L^0\pi^+\pi^-$ versus $K^+K^-\pi^0$

	$F_+^{\pi\pi\pi^0}$	$F_+^{KK\pi^0}$
This analysis	$0.9406 \pm 0.0055 \pm 0.0033$	$0.631 \pm 0.014 \pm 0.011$
CLEO-c	0.973 ± 0.017	0.732 ± 0.055

Summary

BESIII	Decay	Parameters	2.93 fb^{-1} $\psi(3770)$	Prospects
Self-conjugate	$K^0_{S,L}\pi^+\pi^-$	c_i, s_i	PRL 124 (2020) 241802 PRD 101 (2020) 112002	8 fb^{-1} JHEP 06 (2025) 086 20 fb^{-1} ongoing
	$K^0_{S,L}K^+K^-$	c_i, s_i	PRD 102 (2020) 052008	20 fb^{-1} ongoing
	$\pi^+\pi^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 106 (2022) 092004 PRD 110 (2024) 112008	20 fb^{-1} ongoing
	$K^+K^-\pi^+\pi^-$	F^+/c_i, s_i	PRD 107 (2023) 032009	20 fb^{-1} arXiv: 2502.12873
	$K^0_{S,L}\pi^+\pi^-\pi^0$	F^+/c_i, s_i	PRD 108 (2023) 032003	c_i, s_i: ongoing
"Flavour"	$K^-\pi^+\pi^+\pi^-$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$ ongoing
	$K^-\pi^+\pi^0$	δ_D, R_D	JHEP 05 (2021) 164	8 and 20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$ ongoing
	$K^-\pi^+$	δ_D	EPJC 82 (2022) 1009	20 fb^{-1} ongoing $D^*\bar{D}^{(*)}$: 2506.07906
	$K^0_S K^\pm\pi^\mp$	δ_D, R_D	–	20 fb^{-1} ongoing
Quasi CP	$\pi^+\pi^-\pi^0$、$K^+K^-\pi^0$	F^+/c_i, s_i	–	8 fb^{-1} PRD 111 (2025) 012007 20 fb^{-1} ongoing

- Progresses have been made at BESIII to provide strong-phase inputs to charm and bottom CPV studies
- Many analyses are ongoing and novel method have been investigated
- Larger data samples at future Super Tau-Charm Facility [Front.Phys.(Beijing) 19 (2024) 1, 14701]
  - Improved strong-phase differences are of great importance in the era of LHCb upgrade and Belle II
  - Time-integrated charm mixing and CPV studies complementary to LHCb and Belle II [arXiv:2502.08907]