University of Chinese Academy of Sciences

Quantum correlation of neutral charmed mesons at BESIII

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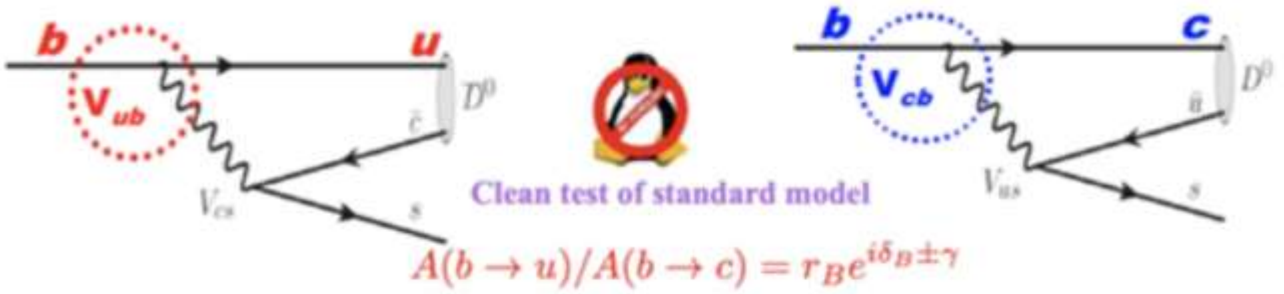
γ measurement

- Direct measurement: CP asymmetry in B decay

$$\gamma = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$



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

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

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

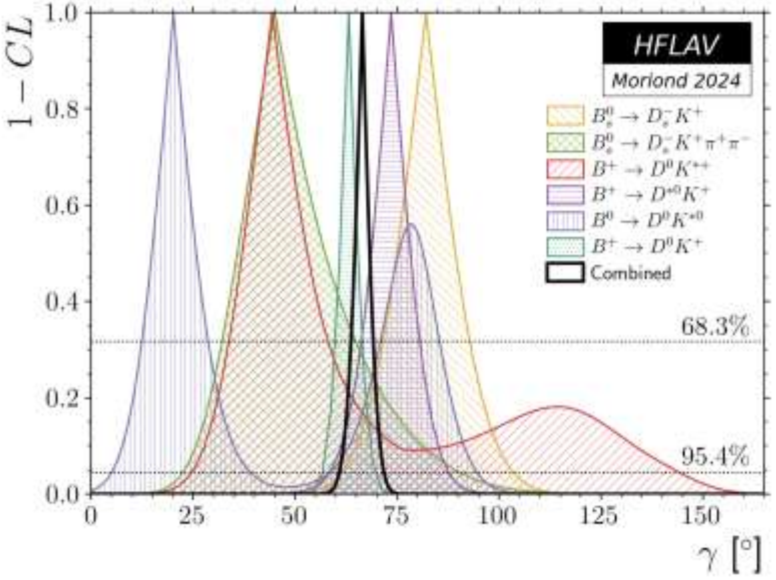
D decay density

$$\{\mathcal{C}, \mathcal{S}\} = \sqrt{p_D \bar{p}_D}\{cos, sin\}(\phi)$$

- Indirect measurement: CKM matrix unitary

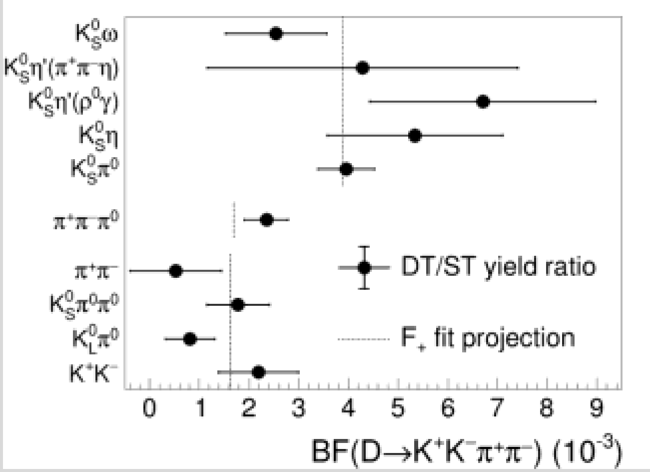
CKMfitter: $\gamma_{ind} = (66.3^{+0.7}_{-1.9})^\circ$

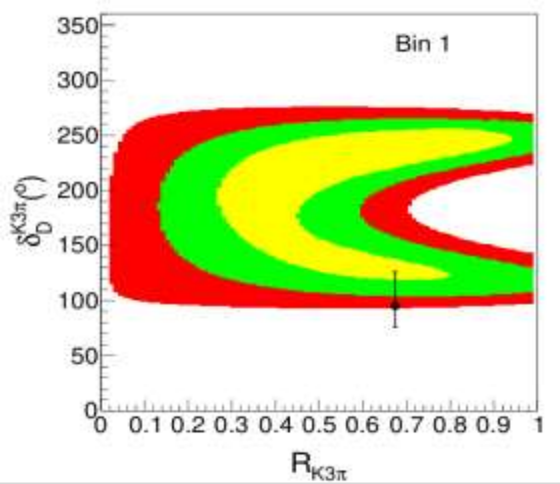
LHCb: $\gamma_{dir} = (66.4^{+2.8}_{-3.0})^\circ$

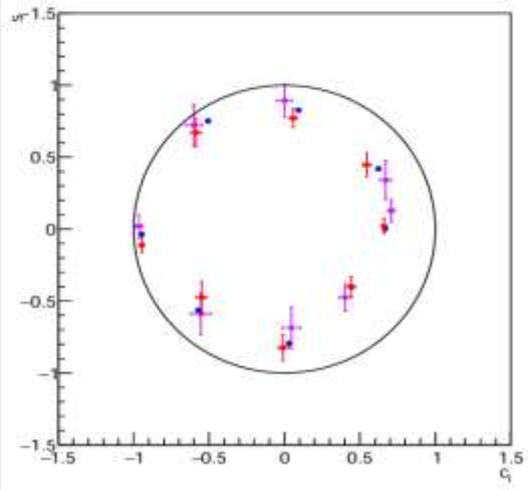


Quantum correlation measurement at BESIII

- Quantum correlated $D\bar{D}$ samples are the best laboratory for strong phase difference parameters measurement.
- γ measurement needs various strong phase difference parameters as inputs:
  - GLW method : CP eigenstate (CP even fraction F_+)
  - ADS method: CF/DCS process in flavor decays (strong phase difference δ_D, coherent factor R_D, amplitude ratio r_D)
  - BPGGSZ method: multi-body decays (bin − averaged $\mathcal{C}(\boldsymbol{z})/\mathcal{S}(\boldsymbol{z})$ c_i/s_i)
- Provide precision test of perturbative QCD calculation in charm mixing and CPV studies.



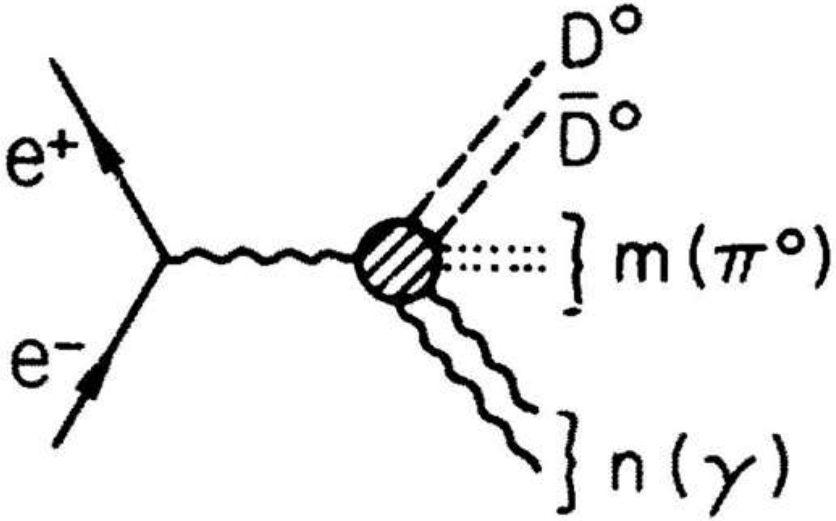




CP even fraction

Strong phase difference parameters

Quantum coherent $D\bar{D}$ samples at BESIII

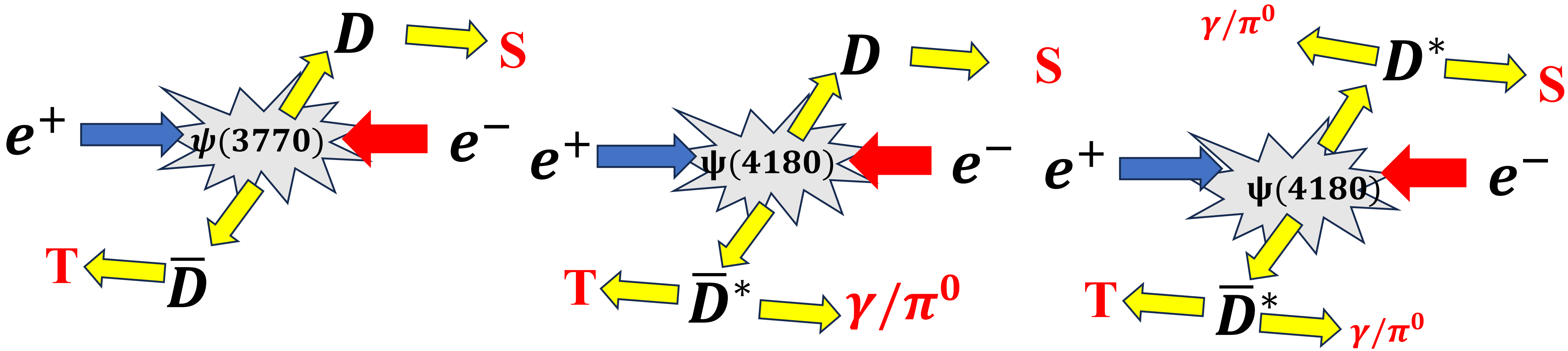


- $e^+e^- \rightarrow D\bar{D} + m(\pi^0) + n(\gamma)$
  - $C(D\bar{D}) = (-1)^{n+1}$
- **$D\bar{D}$ samples at BESIII:**
  - 3770 MeV: C-odd $D\bar{D}$
  - 4130-4230 MeV: C-even: $\gamma D\bar{D}, \gamma\pi^0 D\bar{D}$
  - 4130-4230 MeV: C-odd: $\pi^0 D\bar{D}, \gamma\gamma D\bar{D}, \pi^0\pi^0 D\bar{D}$

- $D\bar{D}$ samples decay to a signal mode (S) and a tagged mode (T), the decay rate:
  - $\Gamma(S|T) \propto A_S^2 A_T^2[(r_D^S)^2 + (r_D^T)^2 - 2C(D\bar{D})R_S R_T\, r_D^S r_D^T \cos(\delta_D^T - \delta_D^S)]$
  - strong phase difference δ_D^T can be determined by double tag (DT) yields

Production & Methodology

- **Data Sets**:
  - 2.93 fb^{-1}(2012)+4.99 fb^{-1}(2022)+12.35 fb^{-1}(2024)≈20 fb^{-1} @3.773 GeV $D\bar{D}$
  - 7.13 fb^{-1} @4.13-4.23 GeV $D^*\bar{D}^*$ / $D^*\bar{D}$
- **Double tag (DT) Methods:**



Publication

- In the past two years, BESIII has many results in quantum coherent measurement.

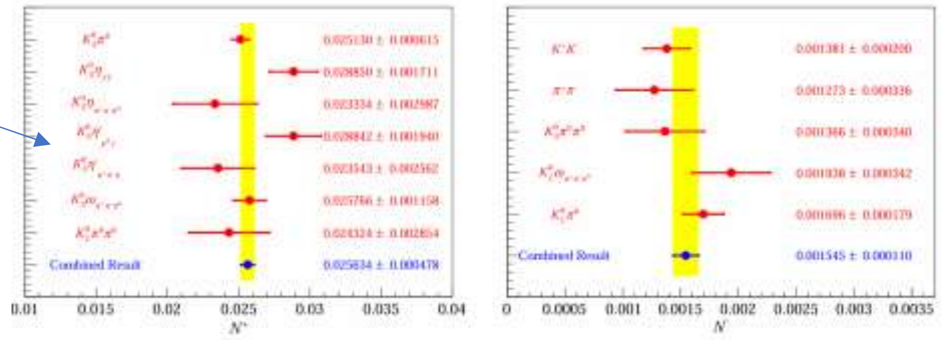
Signal decay	Quantities	Status
$K^0_{S/L}\pi^+\pi^-$	c_i/s_i, unbinned	c_i/s_i Finished 7.9 fb^{-1}(2025), unbinned on going 7.9 fb^{-1}, c_i/s_i on going 20 fb^{-1}
$K^0_{S/L}K^+K^-$	c_i/s_i, unbinned	c_i/s_i Finished 2.93 fb^{-1}(2021), unbinned on going 7.9 fb^{-1}, c_i/s_i on going 20 fb^{-1}
$K^\pm\pi^\mp\pi^\mp\pi^-$	R,δ	Finished 2.93 fb^{-1}(2020), on going 20 fb^{-1}
$K^+K^-\pi^+\pi^-$	F_+, c_i/s_i	$F_+/c_i/s_i$ Finished 20fb^{-1}(2025)
$\pi^+\pi^-\pi^+\pi^-$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1}(2022), c_i/s_i Finished 2.93 fb^{-1}(2024)
$K^\pm\pi^\mp\pi^0$	R,δ	Finished 2.93fb^{-1}(2021), on going 20 fb^{-1}
$K^0_S K^\pm\pi^\pm$	R,δ	on going 20 fb^{-1}
$\pi^+\pi^-\pi^0$	F_+	Finished 7.9 fb^{-1}(2024)
$K^0_S\pi^+\pi^-\pi^0$	F_+, c_i/s_i	F_+ Finished 2.93fb^{-1}(2023)
$K^+K^-\pi^0$	F_+	Finished 7.9 fb^{-1}(2024)
$K^\pm\pi^\mp$	δ	Finished 2.93fb^{-1} $D^0\bar{D}^0$(2022) on going 20 fb^{-1} Finished 7.13fb^{-1}@4.13-4.23 GeV(2025)

CP even fraction measurements

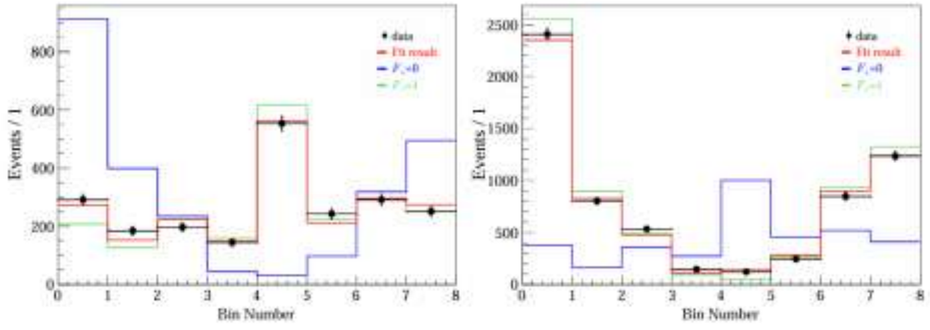
- **Tagged by CP tags:**
  - CP even (N^+) and CP odd (N^-) components can be determined by C-odd and C-even tags.
  - CP even fraction $F_+ = \frac{N^+}{N^+ + N^-}$

- **Tagged by binned muti-body tags ($K^0_{S/L}\pi^+\pi^-$)**
  - $M_i = h[K_i + K_{-i} \mp 2c_i\sqrt{K_i K_{-i}}(2F_+ - 1)]$
  - Binned strong phase difference parameters as inputs

Phys. Rev. D 111, 012007 (2025)



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



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

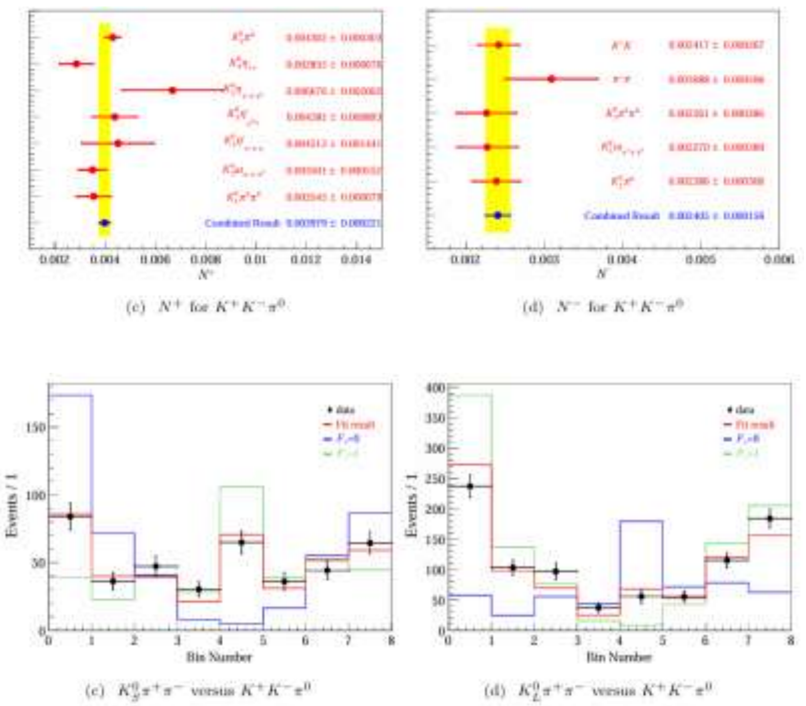
$D \to \pi^+\pi^-\pi^0$ 7.9 fb^{-1} @3.773GeV

$F_+ = 0.941 \pm 0.006_{\text{stat}} \pm 0.003_{\text{syst}}$

2.6 times more precise than CLEO

CP even fraction results

Phys. Rev. D 111, 012007 (2025), Phys. Rev. D 108, 032003 (2023) ,Phys. Rev. D 107, 032009 (2023)

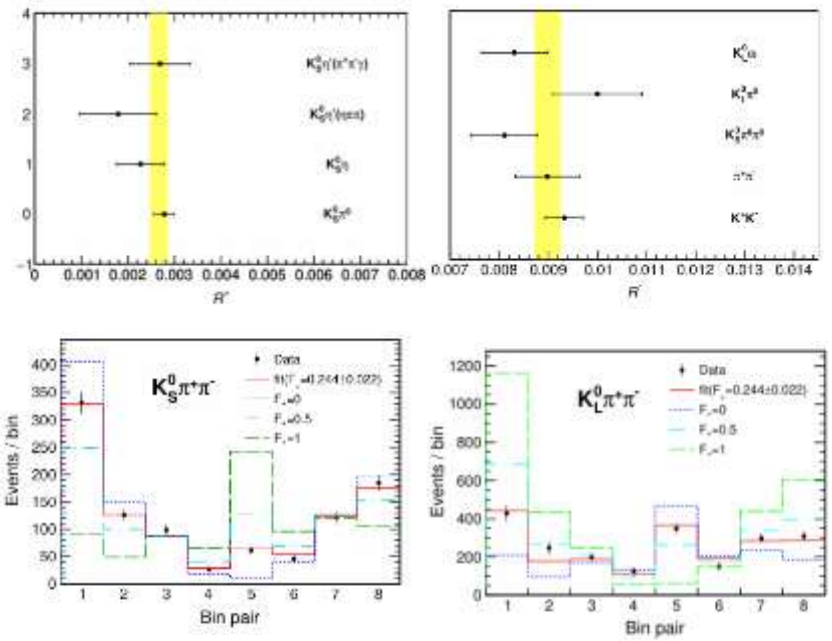


$D \to K^+K^-\pi^0$

7.9 fb^{-1} @3.773GeV

$F_+ = 0.631 \pm 0.014_{\text{stat}} \pm 0.011_{\text{syst}}$

2.6 times more precise than CLEO

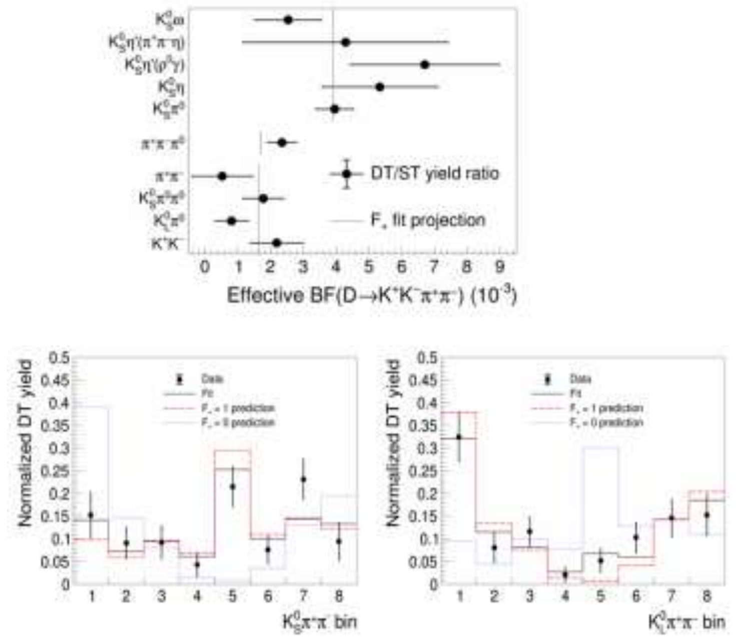


$D \to K_S^0\pi^+\pi^-\pi^0$

2.93 fb^{-1} @3.773GeV

$F_+ = 0.235 \pm 0.010_{\text{stat}} \pm 0.002_{\text{syst}}$

1.7 times more precise than CLEO



$D \to K^+K^-\pi^+\pi^-$

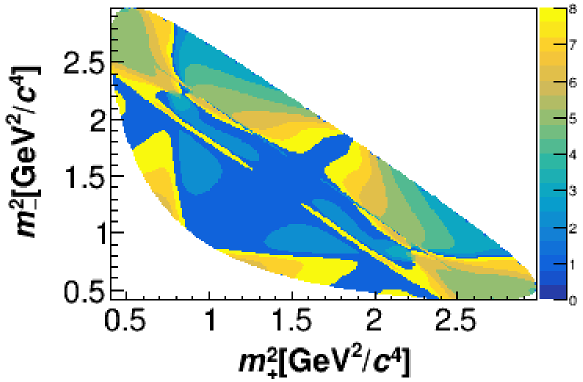
2.93 fb^{-1} @3.773GeV

$F_+ = 0.730 \pm 0.037_{\text{stat}} \pm 0.021_{\text{syst}}$

first model-independent measurement

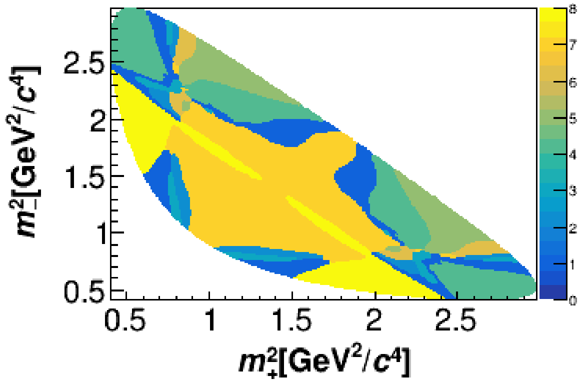
Binned strong phase difference parameters

- Divide dalitz plots into bins → improve sensitivity in γ measurements/CPV studies
- Different binning schemes for different physics goals: ($K_S^0\pi^+\pi^-$ as example)



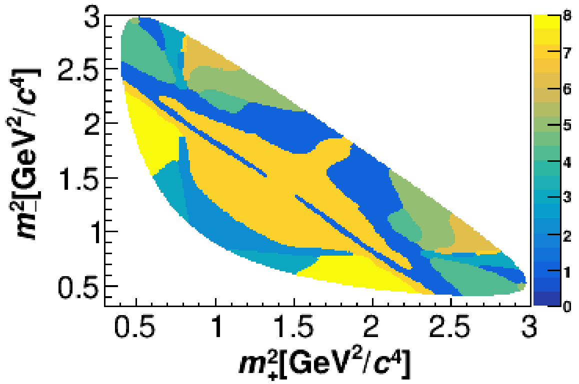
equal binning schemes

charm mixing and CPV studies



optimal binning schemes

γ measurements



modified optimal binning schemes

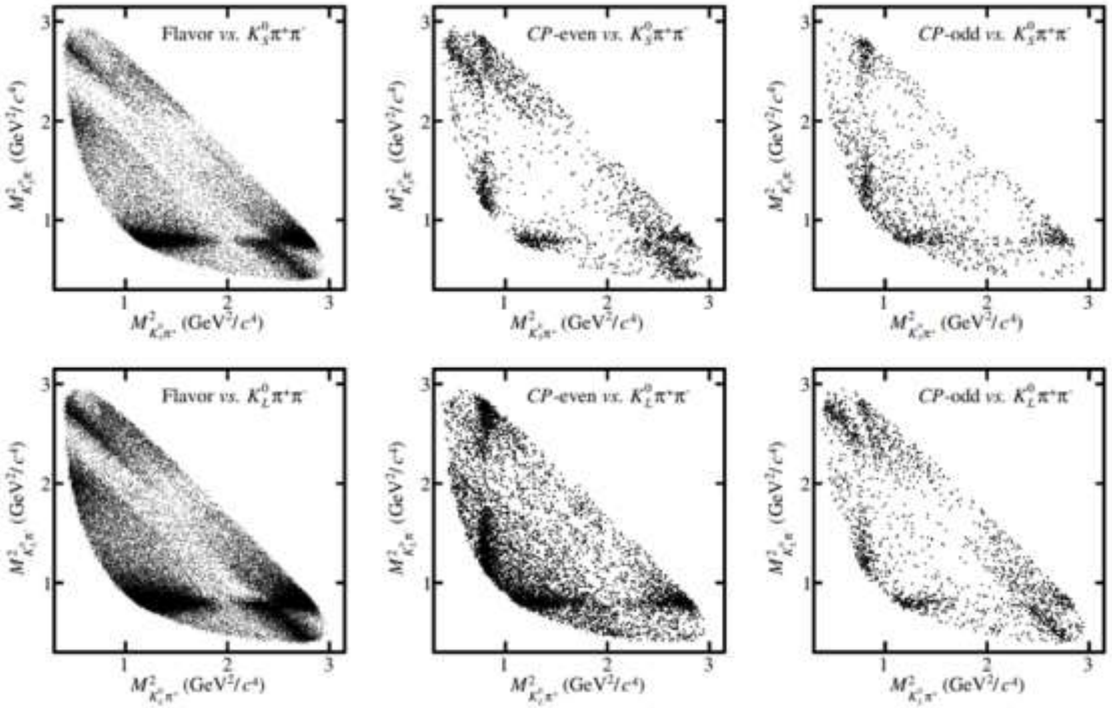
γ measurements with low B statistics

- Binned strong-phase difference parameters:
  - $T_i\,/F_i \propto \int_i \; A_D^2 d\boldsymbol{z}$, $c_i \propto \int_i \; A_D^2 A_{\bar{D}}^2 \cos\delta \, d\boldsymbol{z}$, $s_i \propto \int_i \; A_D^2 A_{\bar{D}}^2 \sin\delta \, d\boldsymbol{z}$;

Methodology of determining c_i/s_i

- Difference in Dalitz plots of DT samples tagging with different kinds of channels show the quantum coherent effect.

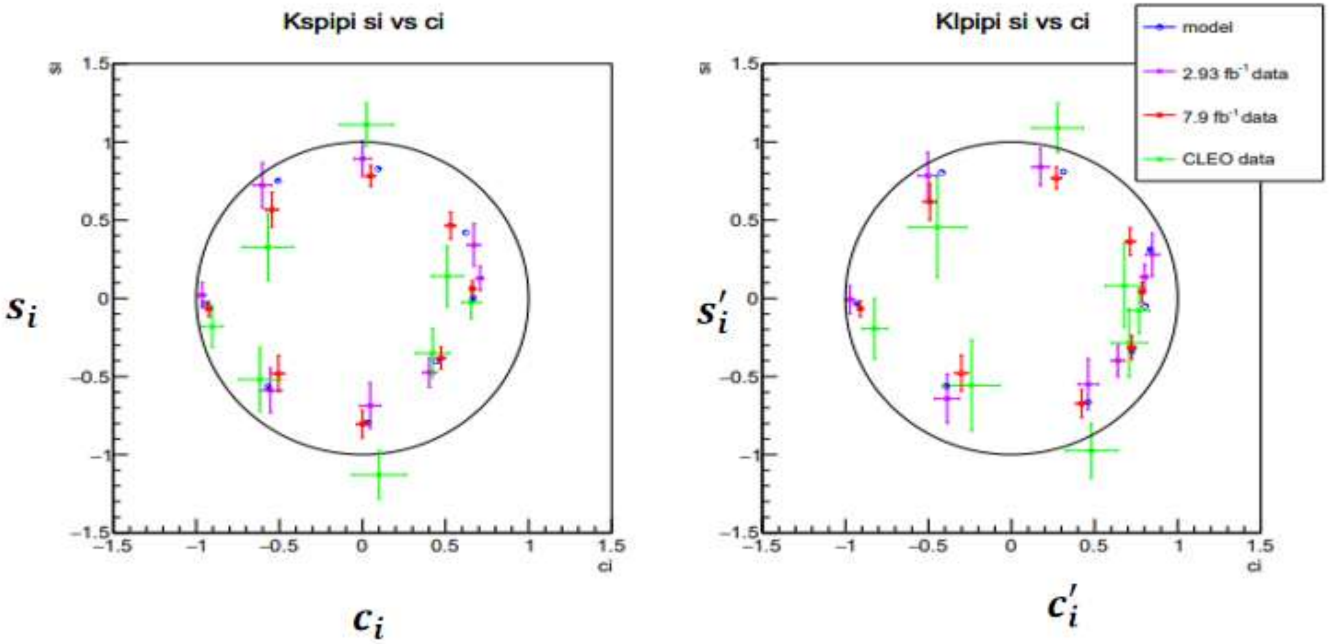
- Different tagging channels provide constraints on the decay parameters of D mesons
  - flavor specific tags → $T_i\ /F_i$
  - CP tags and $T_i\ /F_i$ → c_i
  - $K^0_{S/L}\pi^+\pi^-$ tags → s_i



$K^0_{S/L}\pi^+\pi^-$ c_i/s_i measurements

JHEP06(2025)086

- Equal, optimal and modified optimal binning scheme are applied.



Optimal binning scheme

7.9 fb^{-1} @3.773GeV

Consistent with previous result and model in 2σ

1.5 times more precise

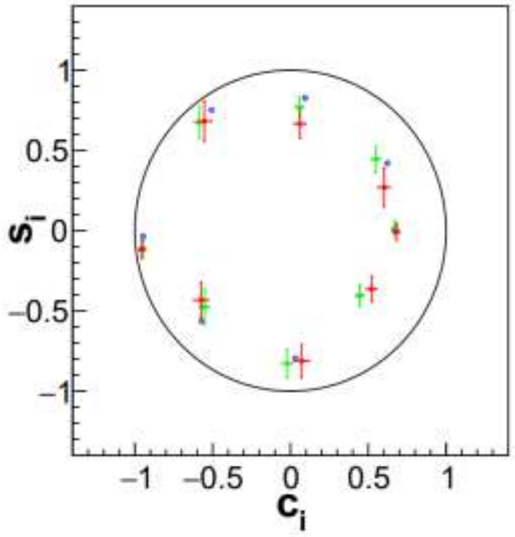
arXiv:1808.08865

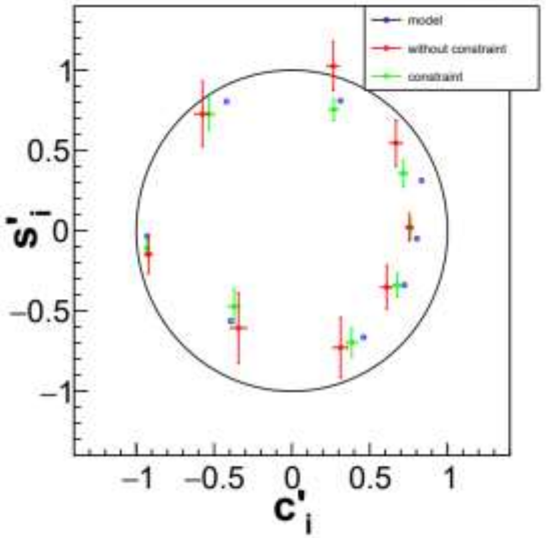
- Impact on γ measurement : 0.7° (equal), 0.9° (optimal), 0.8° (modified)
  - smaller than the predicted γ statistical uncertainty after LHCb Upgrade I (50 fb^{-1} 1.9°)

$K^0_{S/L}\pi^+\pi^-$ c_i/s_i measurements

JHEP06(2025)086

- $\Delta c_i = c_i' - c_i$ and $\Delta s_i = s_i' - s_i$ are constrained by model in nominal method
- .Release the constrain to identify the influence of amplitude model



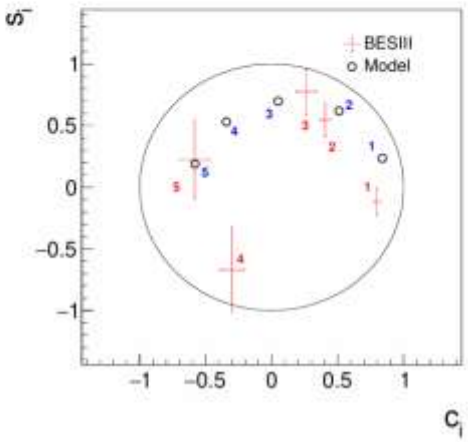


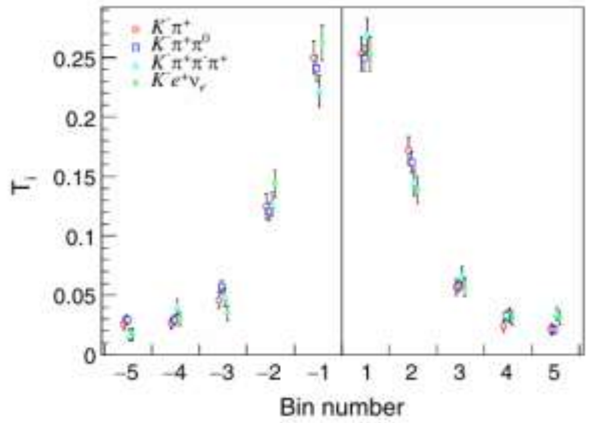
- Closer to the model with smaller uncertainties for constrained result.
- Impact on γ measurement : 1.5° (optimal, unconstrained)
- 0.4° difference on γ value between taking constrained and unconstrained result.

$\pi^+\pi^-\pi^+\pi^-$ c_i/s_i measurements

Phys.Rev.D110, 112008(2024) 2.93 fb^{-1} @3.773GeV

Equal binning scheme





T_i are consistent among different flavor tags

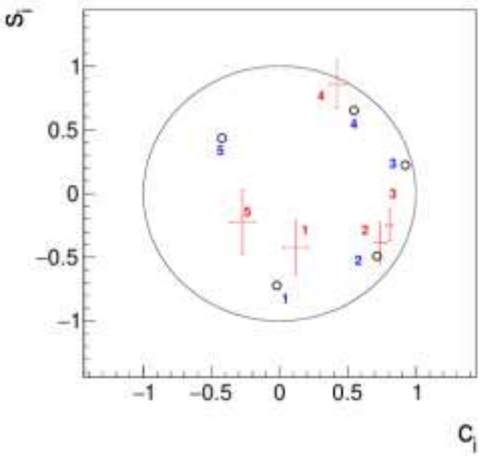
Impact on γ measurement : 1.5°(<stat ~6°)

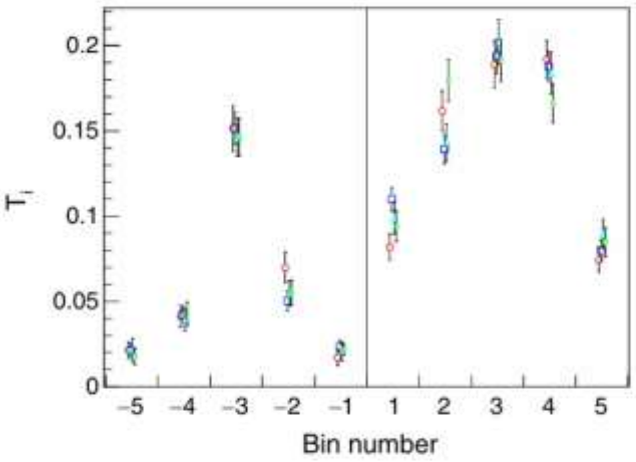
$F_+ = 0.746 \pm 0.010_{stat} \pm 0.004_{syst}$

30% more precise than nominal method with same data set

Optimal binning scheme

Adjust T_i to achieve best sensitivity on γ measurement





Impact on γ measurement :

2.1°(<stat ~5°) , predicted 0.8° for 20 fb^{-1} data

Potential channel for γ measurement (introduce in the next talk)

$K^+K^-\pi^+\pi^-$ c_i/s_i measurements

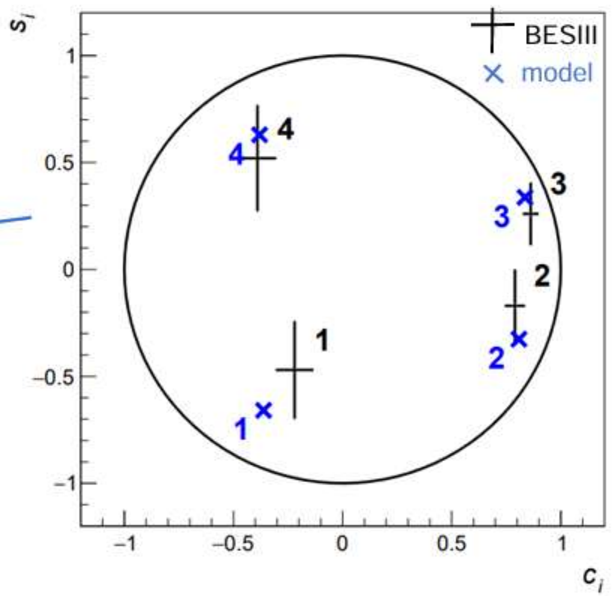
Preliminary

arXiv:2506.07907 20.3 fb^{-1} @3.773GeV

- Only optimal binning scheme are applied
  - Adjust T_i to achieve best sensitivity on γ measurement
- $R_i = T_i/\sum_{j\geq i} T_j$, consistent with $K^+K^-\pi^+\pi^-$ model from
- $\mathcal{B}(D^0 \to K^+K^-\pi^+\pi^-) = (2.863 \pm 0.028_{\text{stat}} \pm 0.045_{\text{syst}}) \times 10^{-3}$
  - 3σ higher than world averaged result $(2.47 \pm 0.11) \times 10^{-3}$
  - twice more precise
- $F_+ = 0.754 \pm 0.010_{\text{stat}} \pm 0.008_{\text{syst}}$
  - three times more precise
- Impact on γ measurement : 10° [introduce in the next talk]

Table IX. Comparison of R_i between fit results and model predictions [50].

Variable	Fit result	Model prediction
R_{-4}	0.0876 ± 0.0027	0.086
R_{-3}	0.294 ± 0.005	0.297
R_{-2}	0.399 ± 0.007	0.398
R_{-1}	0.252 ± 0.007	0.267
R_1	0.119 ± 0.006	0.110
R_2	0.406 ± 0.012	0.401
R_3	0.815 ± 0.010	0.833

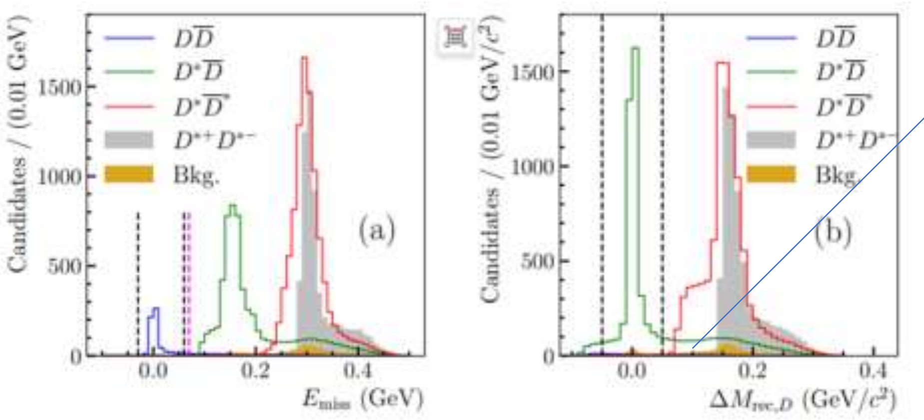


Additional quantum coherent $D\bar{D}$ samples

arXiv:2506.07907 7.13fb^{-1} @4.13-4.23 GeV

- 7.13fb^{-1} @4.13-4.23 GeV $D^*\bar{D}^*$ / $D^*\bar{D}$

Production mechanism	C
$e^+e^- \to D\bar{D}$	-1
$e^+e^- \to D^*\bar{D} \to D\bar{D}\gamma$	$+1$
$e^+e^- \to D^*\bar{D} \to D\bar{D}\pi^0$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\gamma\gamma$	-1
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\pi^0\gamma$	$+1$
$e^+e^- \to D^*\bar{D}^* \to D\bar{D}\pi^0\pi^0$	-1



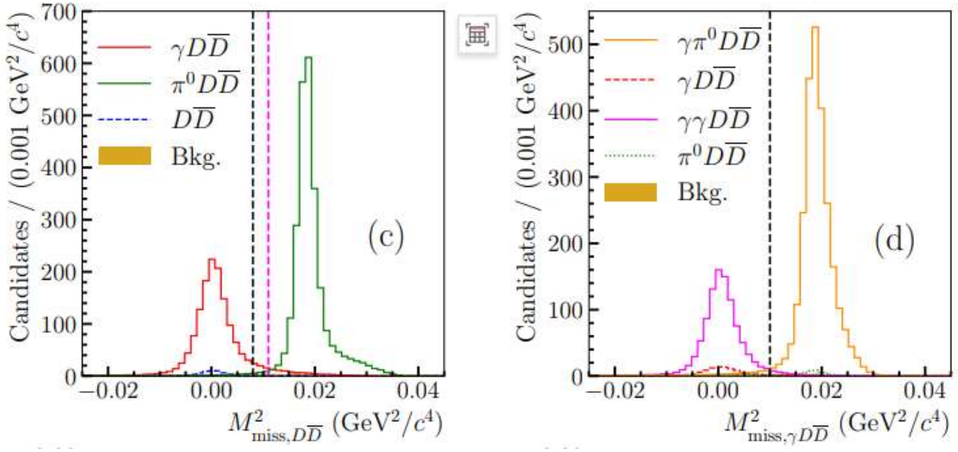
Accepted by PRL

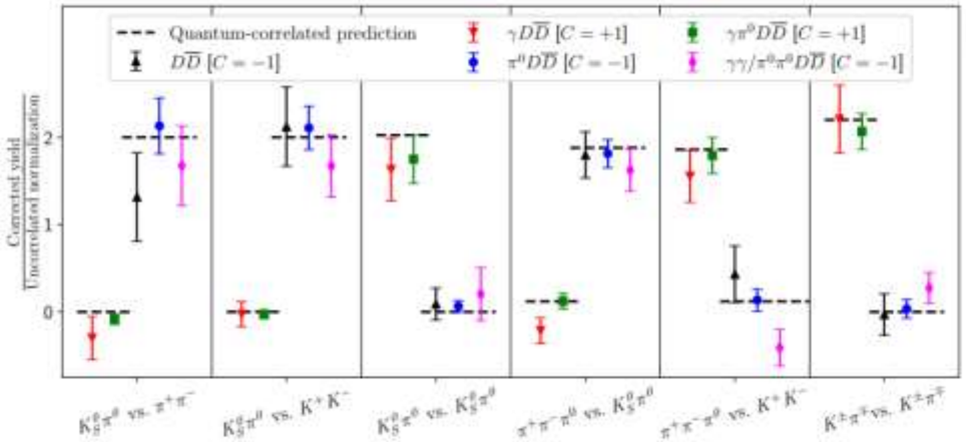
- Separation: $D\bar{D}, D^*\bar{D}^*/D^*\bar{D}$
  - $E_{miss} = E_{cm} - E_{D\bar{D}}$
  - $M_{rec,D} = [(E_{cm}^2 - \sqrt{|\boldsymbol{p_D}|^2 + m_{D^0}^2})^2 - |\boldsymbol{p_D}|^2]$

- The separation is not perfect due to ISR
  - Cross-feed is accounted by a mis-reconstructed matrix

Additional quantum coherent $D\bar{D}$ samples

arXiv:2506.07907



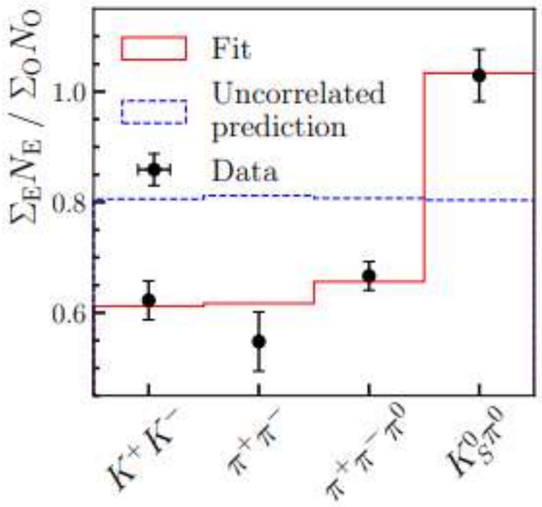


- Separation: $\gamma D\bar{D}/\pi^0 D\bar{D}$; $\gamma\gamma D\bar{D}/\gamma\pi^0 D\bar{D}$
  - $M^2_{miss,D\bar{D}} = (E_{cm} - E_{D\bar{D}})^2 - |\boldsymbol{p}_{D_1} + \boldsymbol{p}_{D_2}|^2$
  - $M^2_{miss,\gamma D\bar{D}} = (E_{cm} - E_{D^*\bar{D}})^2 - |\boldsymbol{p}_{D} + \boldsymbol{p}_{D^*}|^2$
- $\pi^0\pi^0 D\bar{D}$ are considered together with $\gamma\gamma D\bar{D}$
- Yields are consistent with quantum-correlated predicted.

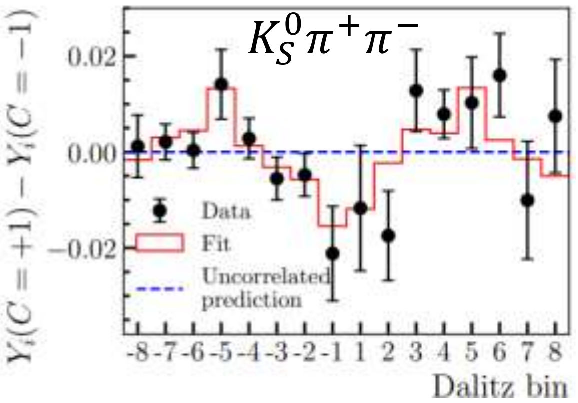
$\delta_{K\pi}$ measurement with $D^*\bar{D}^*$ samples

arXiv:2506.07907

- First measurement using both C-even and C-odd $D\bar{D}$ samples.
- Determine the $r_D \sin\delta_D$ and $r_D \cos\delta_D$
  - $r_D \sin\delta_D$ ($K_S^0\pi^+\pi^-$ tag)
  - $r_D \cos\delta_D$ (CP tags, $K_S^0\pi^+\pi^-$ tag)
  - Fix r_D with previous result with 2.93 fb^{-1} @3.773GeV data



- $\delta_{K\pi} = (192.8^{+11.0+1.9}_{-12.4-2.4})^\circ$
  - The systematic uncertainty reduce significantly by the use of both C-even and C-odd samples.
  - Completive to the results $\delta_{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$ with 2.93 fb^{-1} @3.773GeV data
  - Combined fit result with $\psi(3770)$ data: $\delta_{K\pi} = (189.2^{+6.9+3.4}_{-7.4-3.8})^\circ$



Summary and Prospects

- In the past two years, BESIII has reported a series of important results in quantum correlated $D^0\bar{D}^0$ measurement.
  - Updated CP-even fraction for mix CP tags.
  - $K^0_{S/L}\pi^+\pi^-, \pi^+\pi^-\pi^+\pi^-, K^+K^-\pi^+\pi^-$ binned strong phase difference parameters measurement.
  - $\delta_{K\pi}$ measurement with additional quantum coherent $D\bar{D}$ samples at 4.13-4.23 GeV
- With 20 fb^{-1} of quantum-correlated $D^0\bar{D}^0$ data collected at 3.773 GeV, BESIII will pursue further measurements in the near future.
  - The contribution of binned strong-phase difference parameters to the uncertainty in the γ measurement will reach approximately 0.5°. Eur.Phys.J.C 78 (2018)2,121
  - A novel unbinned model-independent method applied in decays such as $K^0_{S/L}\pi^+\pi^-$.
  - More analyses will be performed using additional quantum-coherent $D\bar{D}$ samples collected in the 4.13–4.23 GeV energy region.