Strong-phase inputs for *CP*V measurements at LHCb

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Outline

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

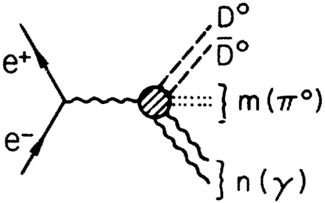
$K^0_{S,L} h^+ h^-$ ('BPGGSZ' modes)

$K^-\pi^+/K^-\pi^+\pi^0/K^-\pi^+\pi^+\pi^-$ ('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

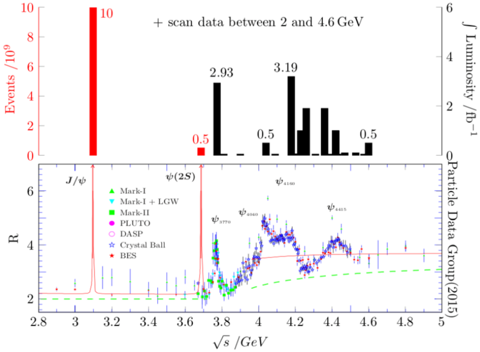


- $e^+e^- \to D^0\bar{D}^0 + m(\pi^0) + n(\gamma)$
- $C(D^0\bar{D}^0) = (-1)^{n+1}$
- [PRD 15, 1254 (1977)]

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

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

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 $\psi(3770)$

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

- Difference of *CP*-conserving phases in $D/\bar{D}$ decays
- Mixing effects (to the order $(x^2,\ y^2)$) and *CP*V can be neglected
- Best laboratory to measure strong-phase parameters
- Inputs for *CP*V studies (in the charm sector and b sector) at B experiments
- Theoretical interpretation of the large charm mixing and *CP*V effects [Phys. Rev. D 99 (2019) 113001]

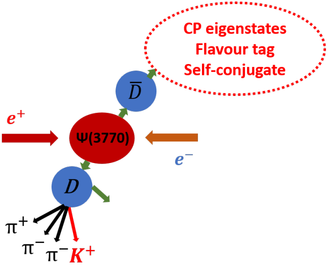
Strong-phase parameters

Decay mode	Parameters	Status (2.93fb^{-1})
$K_S^0\pi^+\pi^-$	$c_i,\ s_i$	PRL 124, 241802 (2020) PRD 101, 112002 (2020)
$K_S^0K^+K^-$	$c_i,\ s_i$	PRD 102, 052008 (2020)
$K^-\pi^+\pi^+\pi^-$	$\delta_D,\ R_D$	JHEP 05, 164 (2021)
$K^-\pi^+\pi^0$	$\delta_D,\ R_D$	
$K^-\pi^+$	δ_D	EPJC 82, 1009 (2022)
$\pi^+\pi^-\pi^+\pi^-$	F_+	PRD 106, 092004 (2022)
	$c_i,\ s_i$	ongoing
$K^+K^-\pi^+\pi^-$	F_+	PRD 107, 032009 (2023)
	$c_i,\ s_i$	ongoing
$K_S^0\pi^+\pi^-\pi^0$	F_+ and $c_i,\ s_i$	ongoing
$\pi^+\pi^-\pi^0$	F_+	ongoing
$K^+K^-\pi^0$	F_+	ongoing
$K_S^0K^\pm\pi^\mp$	$\delta_D,\ R_D$	ongoing

Analysis strategy

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

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



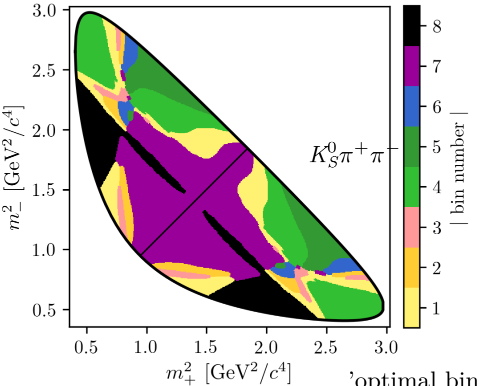
- $\int dt\mathcal{L} = 2.93\ \text{fb}^{-1}$
- 10597,000 neutral $D\bar{D}$
  [CPC 42 (2018) 083001]
- ”Double-tag” method: reconstruct both $D\&\bar{D}$
- $m_{\text{BC}} = \sqrt{\text{E}^2_{\text{beam}}/c^4 - |\mathbf{p}^2_{\bar{D}}|/c^2}$
- $\Delta\text{E} = \text{E}_D - \text{E}_{\text{beam}}$

Tag modes

1. (Quasi-)flavour modes: $K^{\pm}\pi^{\mp}\pi^{\mp}\pi^{-}$, $K^{\pm}\pi^{\mp}\pi^{0}$, $K^{\pm}\pi^{\mp}$, ...
2. CP-even eigenstates: $K^{+}K^{-}$, $\pi^{+}\pi^{-}$, $\pi^{0}\pi^{0}$, $K^{0}_{S}\pi^{0}\pi^{0}$, $K^{0}_{L}\pi^{0}$, $K^{0}_{L}\omega$, $\pi^{+}\pi^{-}\pi^{0}$
3. CP-odd eigenstates: $K^{0}_{S}\pi^{0}$, $K^{0}_{S}\eta$, $K^{0}_{S}\omega$, $K^{0}_{S}\eta'$, $K^{0}_{S}\phi$, $K^{0}_{L}\pi^{0}\pi^{0}$
4. Self-conjugate modes: $K^{0}_{S,L}\pi^{+}\pi^{-}$, $K^{0}_{S,L}K^{+}K^{-}$, ...

$$\begin{aligned}\Gamma(S|T) &= A_S^2 A_T^2 \left[(r_D^S)^2 + (r_D^T)^2 - 2R_S R_T r_D^S r_D^T \cos\left(\delta_D^T - \delta_D^S\right)\right] \\ \Gamma(S) &= A_S^2 \left[(r_D^S)^2 - R_S r_D^S (y\cos\delta_D^S - x\sin\delta_D^S) + (x^2+y^2)/2\right]\end{aligned}$$

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

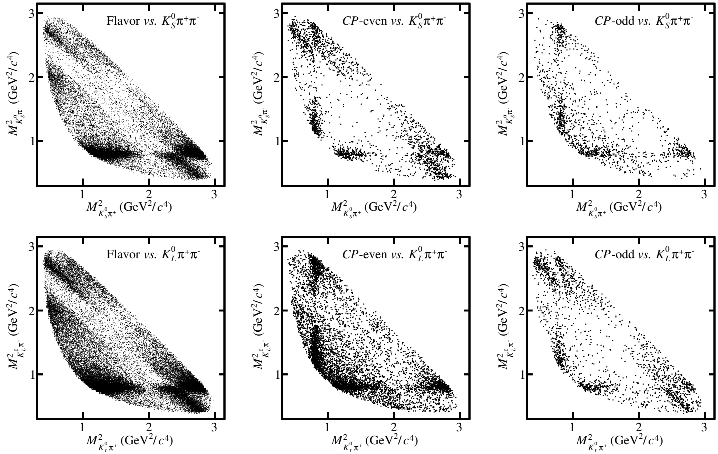


'optimal binning'
[JHEP 02 (2021) 169]

- $\Delta\delta_D$ between symmetric points
- c_i: bin-averaged $\cos(\Delta\delta_D)$
- s_i: bin-averaged $\sin(\Delta\delta_D)$

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

Quantum correlation effects



[PRD 101, 112002 (2020)]

Observables

1 CP-tagged $K_S^0 h^+ h^-$ yields:

$$M_i^{\pm} = h_{CP\pm}(K_i \pm 2c_i\sqrt{K_i K_{-i}} + K_{-i})$$

K_i are the fractional flavour-tagged $K_S^0 h^+ h^-$ events; $h_{CP\pm} = S^{\pm}/2S_{flav.}$, ratio of single-tagged yields of CP modes and flavour-tagged $K_S^0 h^+ h^-$ yields

2 Self-tagged $K_S^0 h^+ h^-$ yields:

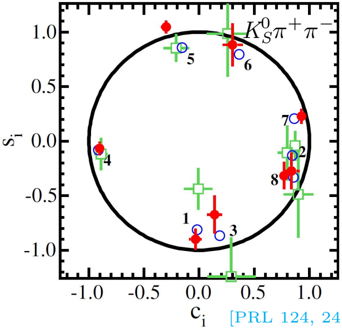
$$M_{ij} = h_{corr.}\left[K_i K_{-j} + K_{-i}K_j - 2\sqrt{K_i K_{-i}} K_j K_{-j}(c_i c_j + s_i s_j)\right]$$

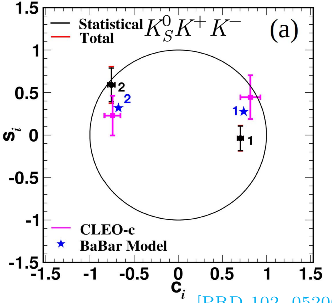
$h_{corr.} = N_{D^0 \bar{D}^0}/2S^2_{flav.}$

3 $K_S^0 h^+ h^-$ yields tagged with $K_L^0 h^+ h^-$:

$$M_{ij} = h'_{corr.}\left[K_i K'_{-j} + K_{-i}K'_j - 2\sqrt{K_i K_{-i}} K'_j K'_{-j}(c_i c'_j + s_i s'_j)\right]$$

Results of c_i and s_i at BESIII





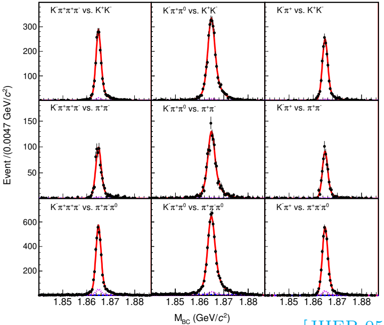
[PRL 124, 241802 (2020)]
[PRD 101, 112002 (2020)]

[PRD 102, 052008 (2020)]

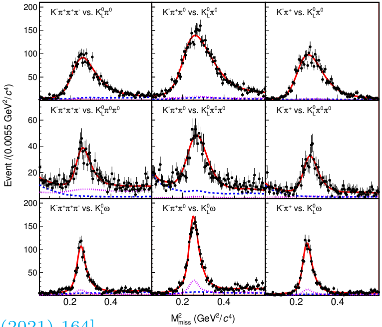
- Contribute to a systematic uncertainty of 1° to γ measurement
- Lead to the best single γ measurement and indirect charm CPV study [JHEP 02 (2021) 169, PRL 127 (2021) 111801]

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

Fully reconstructed CP tags



K_L^0 tags



[JHEP 05 (2021) 164]

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

Observables

- The quantum correlated LS (*e.g.* $K^+3\pi$ vs. $K^+\pi\pi^0$) and CP tagged yields are different with those uncorrelated
- Their ratios are parametrized with D decay parameters:

$$\rho^S_{LS} = \frac{(1-R_S)^2}{1-R_S\left((y/r^S_D)\cos\delta^S_D-(x/r^S_D)\sin\delta^S_D\right)+(x^2+y^2)/(2[r^S_D]^2)}$$

$$\begin{aligned}\rho^S_{T,LS} = &\Big(1+(r^S_D/r^T_D)^2-2(r^S_D/r^T_D)R_SR_T\cos(\delta^T_D-\delta^S_D)\Big)\,/\\ &\Big(1+(r^S_D/r^T_D)^2-R_T([y/r^T_D]\cos\delta^T_D-x/r^T_D]\sin\delta^T_D)-\\ &R_S([yr^S_D/(r^T_D)^2]\cos\delta^S_D-[xr^S_D/(r^T_D)^2]\sin\delta^S_D)+(x^2+y^2)/(r^T_D)^2\Big)\end{aligned}$$

$$\rho^S_{CP\pm} = \frac{\left(1+(r^S_D)^2\mp 2r^S_DR_S\cos\delta^S_D\right)}{\left(1\mp y+(r^S_D)^2(1\mp y)-2r^S_DR_Sy\cos\delta^S_D+2y^2\right)}$$

Observables

- The ratios can be measured as:

$$\rho^S_{LS} = \frac{N(S|S) + N(\bar{S}|\bar{S})}{2N(S|\bar{S})\left(\mathcal{B}(D^0 \to \bar{S})/\mathcal{B}(D^0 \to S)\right)}$$

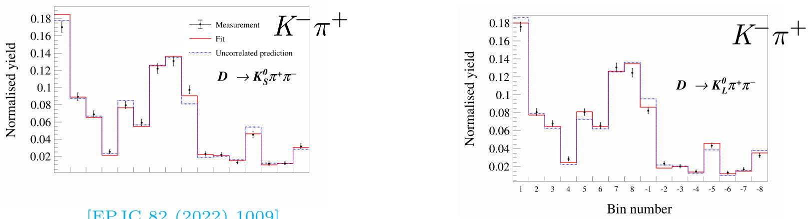
$$\rho^S_{T,LS} = \frac{N(S|T) + N(\bar{S}|\bar{T})}{\left(N(S|\bar{T}) + N(\bar{S}|T)\right)\left(\frac{\mathcal{B}(D^0\to\bar{T})}{\mathcal{B}(D^0\to T)} + \frac{\mathcal{B}(D^0\to\bar{S})}{\mathcal{B}(D^0\to S)}\right)}$$

$$\rho^S_{CP\pm} = \frac{N(S|CP) + N(\bar{S}|CP)}{N(K^-\pi^+|CP) + N(K^+\pi^-|CP)} \cdot \frac{\mathcal{B}(D^0 \to K^-\pi^+) + \mathcal{B}(D^0 \to K^+\pi^-)}{\mathcal{B}(D^0 \to S) + \mathcal{B}(D^0 \to \bar{S})} \cdot \rho^{K\pi}_{CP\pm}$$

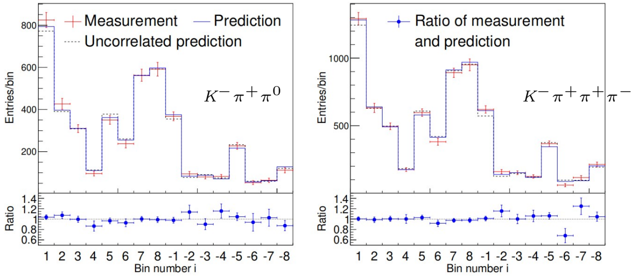
- $K^0_S\pi^+\pi^-$ tag mode can constrain the parameters

$$Y^S_i = H\left(K_i + \left(r^S_D\right)^2 K_{-i} - 2r^S_D R_S \sqrt{K_i K_{-i}}\left[c_i \cos\delta^S_D - s_i \sin\delta^S_D\right]\right)$$

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

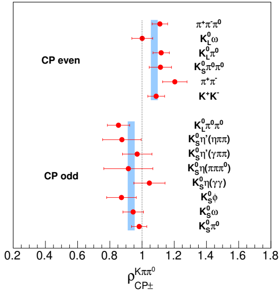


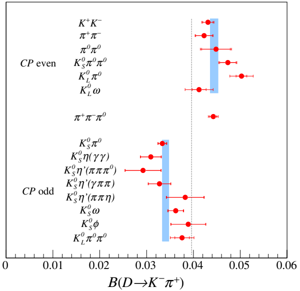
[EPJC 82 (2022) 1009]



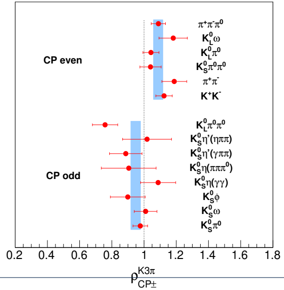
[JHEP 05 (2021) 164]

QC effects observed in *CP* tags



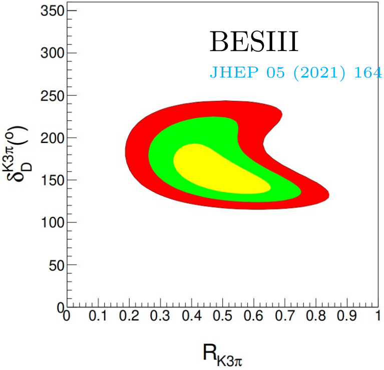


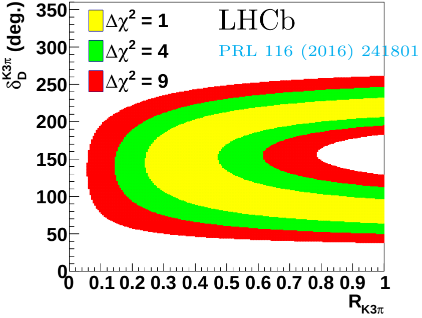
[JHEP 05 (2021) 164]
[EPJC 82 (2022) 1009]



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}	$0.52^{+0.12}_{-0.10}$

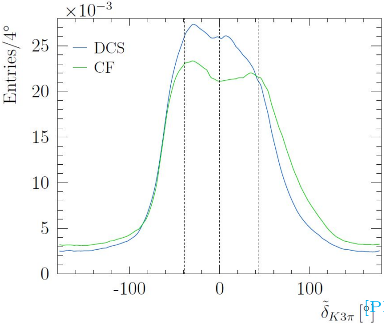
Quantum correlated and uncorrelated measurements

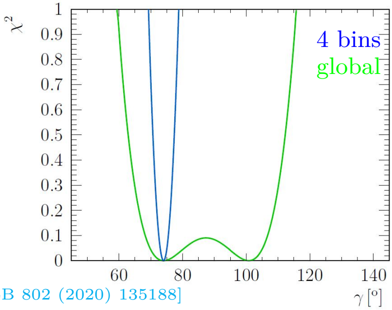




Binned $\delta_D^{K3\pi}$ and $R_{K3\pi}$

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

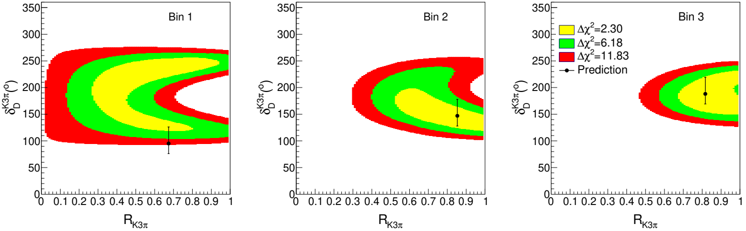


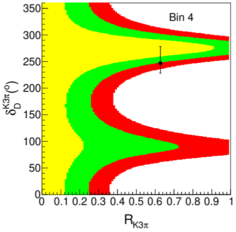


[PLB 802 (2020) 135188]

- Binning scheme depends on the DCS and CF model of $D \to K3\pi$ measured by LHCb [EPJC 78 (2018) 443]

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

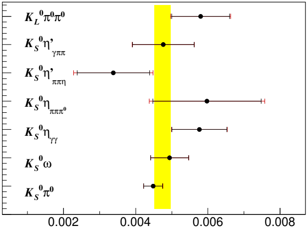


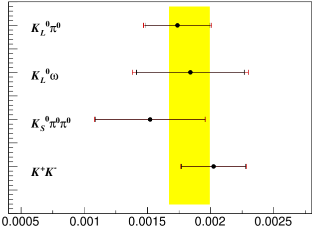


- Second leading mode for γ measurement

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

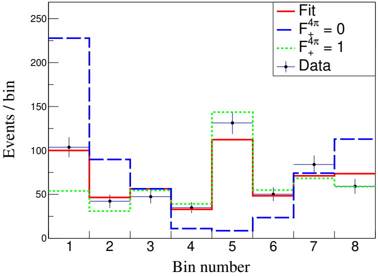




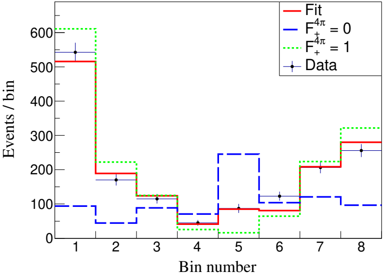
[PRD 106 (2022) 092004]

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

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

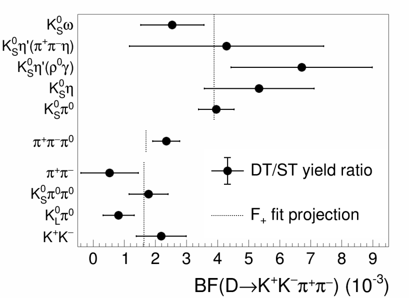


[PRD 106 (2022) 092004]

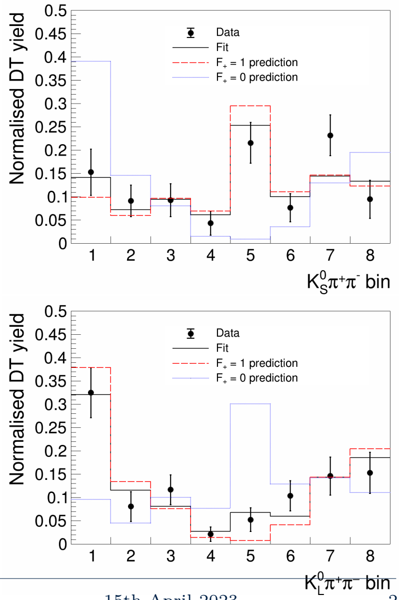


- $F_+ = 0.735 \pm 0.015 \pm 0.005$
- $c_i,\ s_i$ parameters will be measured

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



[PRD 107 (2023) 032009]



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

Summary

Decay mode	Parameters	Status (2.93fb^{-1})
$K_S^0\pi^+\pi^-$	$c_i,\ s_i$	PRL 124, 241802 (2020) PRD 101, 112002 (2020)
$K_S^0K^+K^-$	$c_i,\ s_i$	PRD 102, 052008 (2020)
$K^-\pi^+\pi^+\pi^-$	$\delta_D,\ R_D$	JHEP 05, 164 (2021)
$K^-\pi^+\pi^0$	$\delta_D,\ R_D$	
$K^-\pi^+$	δ_D	EPJC 82, 1009 (2022)
$\pi^+\pi^-\pi^+\pi^-$	F_+ $c_i,\ s_i$	PRD 106, 092004 (2022) ongoing
$K^+K^-\pi^+\pi^-$	F_+ $c_i,\ s_i$	PRD 107, 032009 (2023) ongoing
$K_S^0\pi^+\pi^-\pi^0$	F_+ and $c_i,\ s_i$	ongoing
$\pi^+\pi^-\pi^0$	F_+	ongoing
$K^+K^-\pi^0$	F_+	ongoing
$K_S^0K^\pm\pi^\mp$	$\delta_D,\ R_D$	ongoing

Other ongoing projects

1. Update with 8 and eventually 20 fb^{-1} $\psi(3770)$ data sample
2. New unbinned $K_{S,L}^0h^+h^-$ measurement

Thanks and stay tuned!