# Charm physics at BESIII

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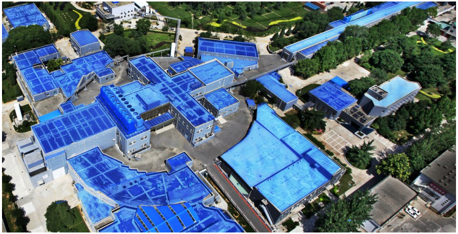
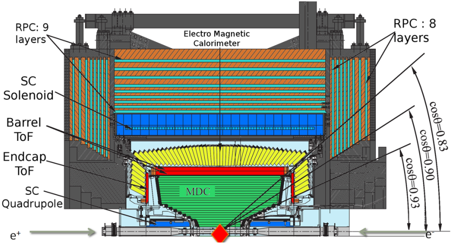
# Outline

# The BESIII experiment

- BEPCII is a symmetric $e^+e^-$ collider with a peak luminosity of $1 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at $\sqrt{s} = 3.773\,\mathrm{GeV}$
- Tracking: Helium-based multilayer drift chamber (MDC)
- PID: Plastic scintillator TOF system and $\frac{\mathrm{d}E}{\mathrm{d}x}$
- Magnet: 1.0 T superconducting solenoid
- Neutral particle tracking: CsI(TI) electromagnetic calorimeter (EMC)



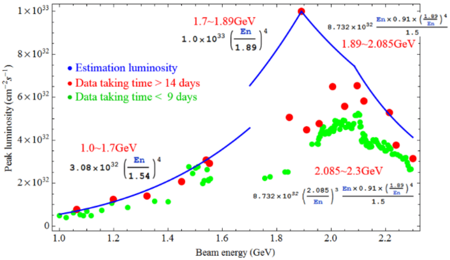



Overview of (left) BEPCII and (right) BESIII.

# The BESIII experiment

Key datasets for charm physics:

- 2010-2011: $2.9\,\text{fb}^{-1}$ at $\psi(3770)$
- 2013-2019: $7.3\,\text{fb}^{-1}$ of $D_s \bar{D}_s^*$
- 2020: $4.5\,\text{fb}^{-1}$ of $\Lambda_c^+ \bar{\Lambda}_c^-$
- 2021-2022: $5.0\,\text{fb}^{-1}$ at $\psi(3770)$
- 2022-: $\sim 8\,\text{fb}^{-1}$ at $\psi(3770)$




BEPCII peak luminosity.

# The BESIII experiment

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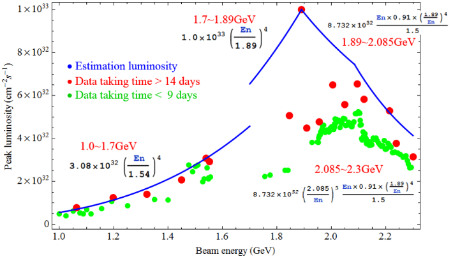



BEPCII peak luminosity.

Charm threshold data at $\psi(3770) \to D\bar{D}$ provide a unique access to strong-phase information that is essential for charm mixing and $\gamma$ measurements at $B$ factories

# Recent charm results from BESIII

BESIII has a rich programme of charm physics:

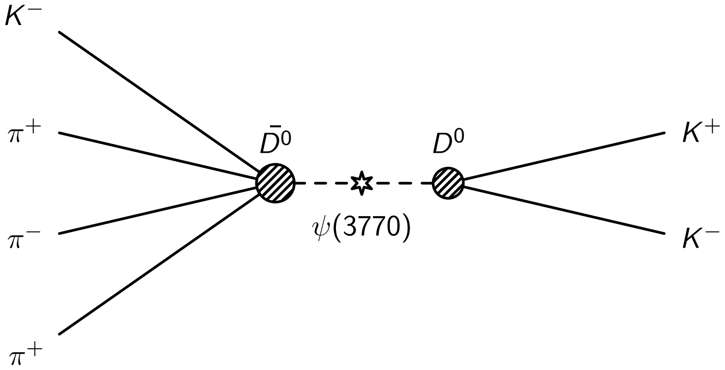
1. Strong-phase measurements
   - Measurement of $\delta_{K\pi}$ EPJC **82** 1009 (2022)
   - $D \to K^-\pi^+\pi^-\pi^+$ strong-phase measurement JHEP **5** (2021) 164
   - $D \to K^+K^-\pi^+\pi^-$ $F_+$ measurement Phys. Rev. D **107** 032009
2. Amplitude analysis
3. Semileptonic charm decays
4. Searches for rare decays
5. Branching fraction measurements

No time to cover all topics in this talk!
I will mainly focus on strong-phase measurements in charm decays...

1. Strong-phase measurements
   - $D \to K_S^0\pi^+\pi^-\pi^0$ $F_+$ measurement arXiv:2305.03975
2. Amplitude analysis
   - Amplitude analysis of $D^0 \to K_L^0\pi^+\pi^-$ arXiv:2212.0904
   - Observation of an $a_0(980)$-like state Phys. Rev. Lett. **129**, 182001
3. Semileptonic charm decays
   - First study of $D_s^{*+} \to e^+\nu_e$ arXiv:2304.12159
   - $D_s^+ \to \tau^+\nu_\tau$ arXiv:2303.12600, arXiv:2303.12600, arXiv:2303.12468
   - Study of $D_s^+ \to \pi^+\pi^-e^+\nu_e$ arXiv:2303.12927
4. Searches for rare decays
   - See Liang's talk

... but here I provide references to some recent interesting charm results

# Double-tag analysis

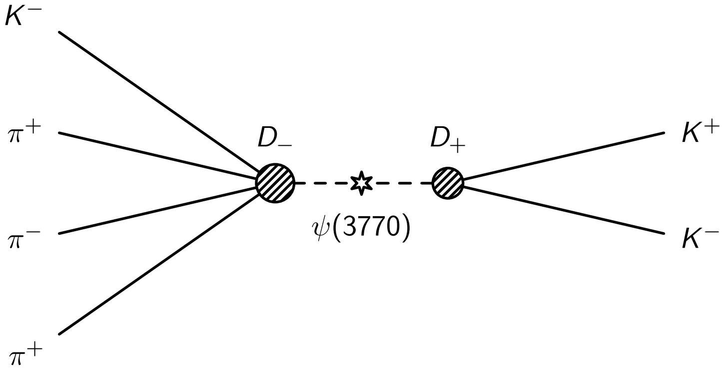



Double-tag method

The $D$ mesons are produced in a quantum correlated state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle\right)$$

# Double-tag analysis




Double-tag method

Equivalently, we can consider the CP even (odd) eigenstates $D_+$ ($D_-$):

$$|\psi\rangle = \frac{1}{\sqrt{2}}\big(|D_+\rangle|D_-\rangle - |D_-\rangle|D_+\rangle\big)$$

# Double-tag analysis

Double-tag analysis has many advantages:

1. $D\bar{D}$ pairs are quantum correlated, which provide direct access to the $D^0$-$\bar{D}^0$ strong-phase difference
2. Measurements are, to first order, free from systematic uncertainties due to efficiencies and branching fractions
3. Full reconstruction ensures that the environment is extremely clean

Only one minor drawback:

1. Lower statistics

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

EPJC **82** 1009 (2022)

Improved measurement of the strong-phase difference $\delta_D^{K\pi}$ in quantum-correlated $D\bar{D}$ decays

What is measured:

- Strong-phase difference between CF and DCS $D \to K^\mp \pi^\pm$ decays

Significance:

- Most precise measurement of $\delta_D^{K\pi}$ in quantum-correlated $D\bar{D}$ decays

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

The strong-phase difference $\delta_D^{K\pi}$ between CF and DCS $D \to K^-\pi^+$ is a key parameter in charm physics:

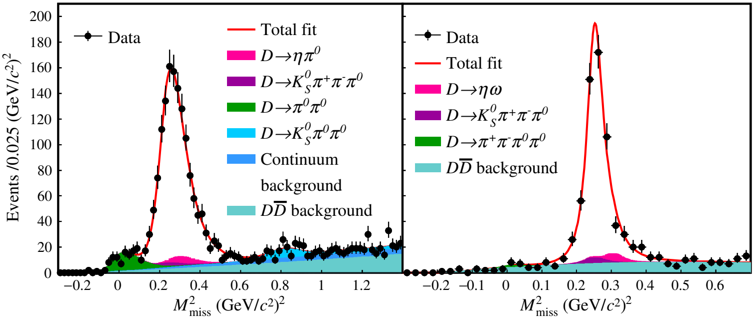
$$r_D^{K\pi} \exp\left(-i\delta_D^{K\pi}\right) = \frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle}$$

Analysis is split into three main sections:

1. Determination of $D \to K_L^0 X$ branching fractions
2. Measurement of the asymmetry $\mathcal{A}_{K\pi}$ using $CP$ tags
3. Measurement of $r_D^{K\pi}\cos\left(\delta_D^{K\pi}\right)$ and $r_D^{K\pi}\sin\left(\delta_D^{K\pi}\right)$ with $K_{S,L}^0\pi^+\pi^-$ tags

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

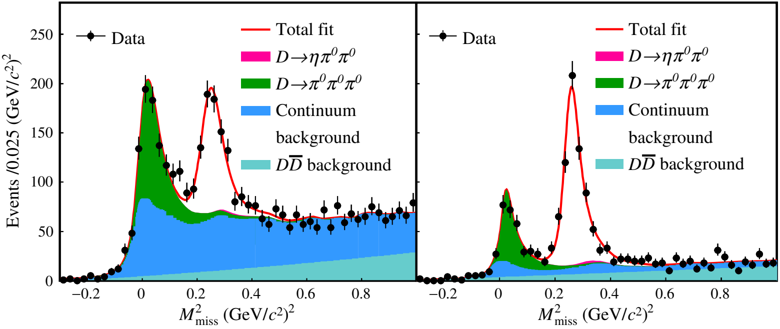
- Branching fractions must be determined independently of $D \to K^-\pi^+ \implies$ Measure using pure $CP$ tags
- $K_L^0\pi^0$ and $K_L^0\omega$ are $CP$-even decays, and must therefore be tagged by $CP$-odd decays
  - $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\eta'(\pi^+\pi^-\eta, \pi^+\pi^-\gamma)$, $K_S^0\omega$




Missing mass squared in $CP$-tagged (left) $D \to K_L^0\pi^0$ and (right) $D \to K_L^0\omega$.

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

- Branching fractions must be determined independently of $D \to K^-\pi^+ \implies$ Measure using pure $CP$ tags
- Similarly, $K_L^0\pi^0\pi^0$ is a $CP$-odd decay and is tagged by $CP$-even decays
  - $K^+K^-$, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$



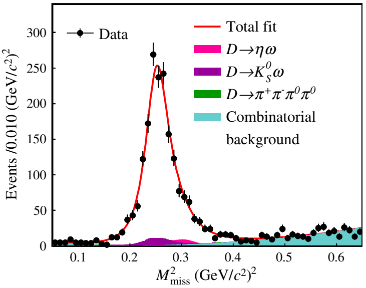

Missing mass squared in (left) $\pi^+\pi^-\pi^0$ tags and all other tags (left).

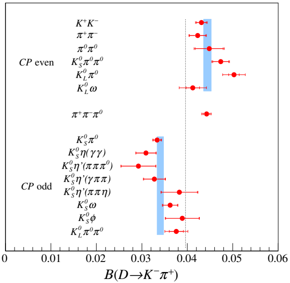
# $D \to K^- \pi^+$

Asymmetry $\mathcal{A}_{K\pi}$ of the branching fraction, tagged with $CP$-even and $CP$-odd decays, is sensitive to $\delta_D^{K\pi}$:

$$\mathcal{A}_{K\pi} = \frac{-2r_D^{K\pi}\cos(\delta_{K\pi})+y}{1+(r_D^{K\pi})^2}$$

Using external inputs for $y$ and $r_D^{K\pi}$, $r_D^{K\pi}\cos\left(\delta_D^{K\pi}\right)$ is calculated from $\mathcal{A}_{K\pi}$



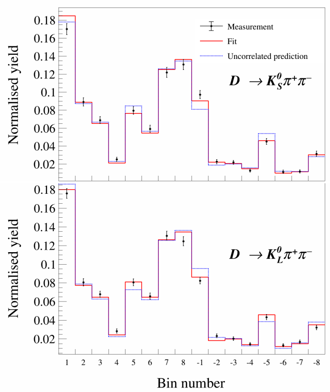

Left: Fit of the $K^-\pi^+$ vs $K_L^0\omega$ double-tag yield. Right: Branching fraction of $D \to K^-\pi^+$ measured using $CP$ tags.

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

Double-tag yields using the $K^0_{S,L}\pi^+\pi^-$ tags, in bins of phase space, are also sensitive to $\delta_D^{K\pi}$:

$$Y_i \propto \left(K_i + (r_D^{K\pi})^2 K_{-i} - 2r_D^{K\pi}\sqrt{K_i K_{-i}}\left[c_i \cos\left(\delta_D^{K\pi}\right) - s_i \sin\left(\delta_D^{K\pi}\right)\right]\right)$$

- $\delta_D^{K\pi}$ is close to $\pi \implies \sin\left(\delta_D^{K\pi}\right)$ is much more sensitive to $\delta_D^{K\pi}$
- Unique determination of $\delta_D^{K\pi}$ without ambiguity
- External inputs for $K_i$, $c_i$ and $s_i$ are recalculated without inputs from $D \to K^-\pi^+$




Bin yields of $D \to K^0_{S,L}\pi^+\pi^-$

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

Putting this all together:

$$\delta_D^{K\pi} = (187.6^{+8.9+5.4}_{-9.7-6.4})^\circ$$

Furthermore, the following braching fractions will be valuable additions to the PDG:

$$\begin{aligned}\mathcal{B}(D^0 \to K_L^0\pi^0) =&(0.97 \pm 0.03 \pm 0.02) \times 10^{-2}\\ \mathcal{B}(D^0 \to K_L^0\omega) =&(1.09 \pm 0.06 \pm 0.03) \times 10^{-2}\\ \mathcal{B}(D^0 \to K_L^0\pi^0\pi^0) =&(1.26 \pm 0.05 \pm 0.03) \times 10^{-2}\end{aligned}$$

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

JHEP **5** (2021) 164

Measurement of the $D \to K^-\pi^+\pi^-\pi^-$ and $D \to K^-\pi^+\pi^0$ coherence factors and average strong-phase differences in quantum-correlated $D\bar{D}$ decays

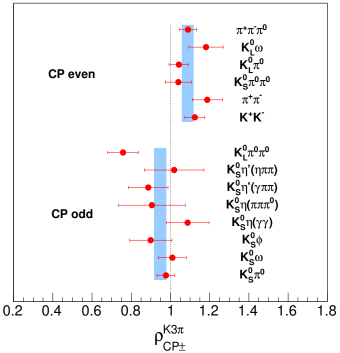
What is measured:

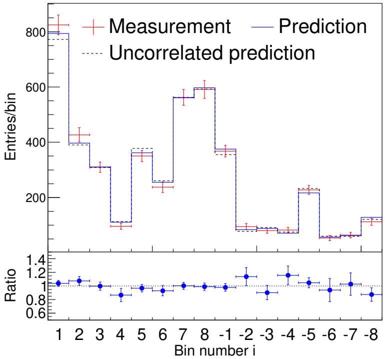
- Strong-phase difference and coherence factors between CF and DCS $D \to K^\mp\pi^\pm\pi^\mp\pi^\pm$ decays in phase space bins

Significance:

- Crucial input to one of the most precise measurements of $\gamma$

The average strong-phase difference of multi-body decays may be determined analogously using *CP* and multi-body tags



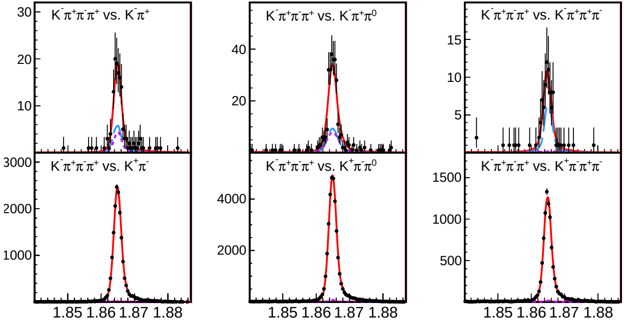




Left: Asymmetry of $D \to K^-\pi^+\pi^-\pi^+$ branching fraction with *CP*-even and *CP*-odd tags. Right: Double-tag yields of $K^0_S\pi^+\pi^-$ vs $K^-\pi^+\pi^-\pi^+$.

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

However, averaging over phase space dilutes interference effects, which is parameterised in terms of the coherence factor:

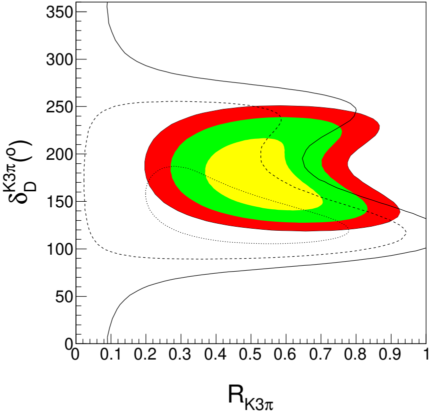
$$R_{K3\pi}\exp(i\delta_{K3\pi}) \equiv \frac{\int \mathrm{d}\vec{x}\,\mathcal{A}_{\bar{D}^0\to K^+\pi^-\pi^+\pi^-}(\vec{x})\mathcal{A}^*_{D^0\to K^+\pi^-\pi^+\pi^-}(\vec{x})}{A_{\bar{D}^0\to K^+\pi^-\pi^+\pi^-}A_{D^0\to K^+\pi^-\pi^+\pi^-}}$$




Like-sign yields are proportional to $(1 - R^2)$ and brings sensitivity to $R_{K3\pi}$.

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

Fit $R_{K3\pi}$ and $\delta_{K3\pi}$: Huge improvements from CLEO-c analysis

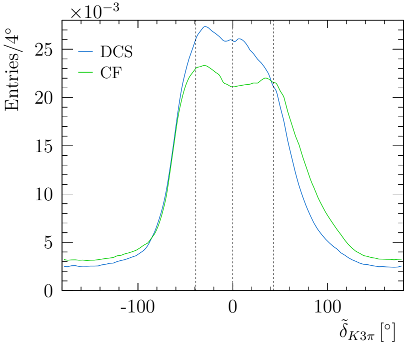



But: $R_{K3\pi} = 0.52^{+0.12}_{-0.10}$, so interference effects are very diluted

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

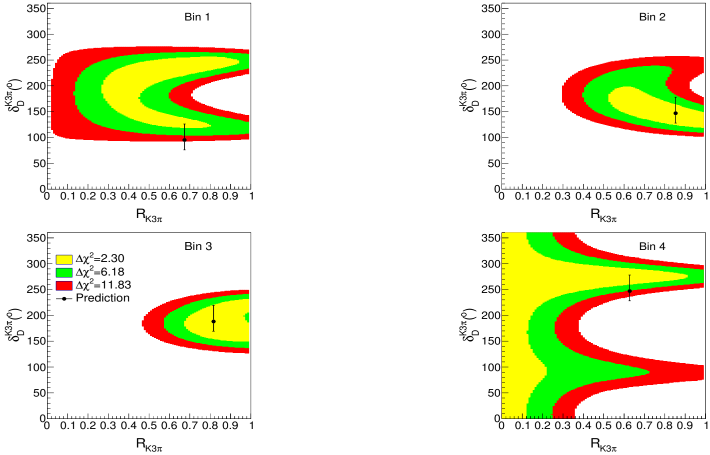
Can improve coherence factors by defining a binning scheme in terms of the normalised phase difference

$$\delta_{K3\pi}(\vec{x}) = \arg\left(\mathcal{A}_{\bar{D}^0}(\vec{x})\mathcal{A}^*_{D^0}(\vec{x})\right) - \arg\left(\int \mathrm{d}\vec{x}'\, \mathcal{A}_{\bar{D}^0}(\vec{x}')\mathcal{A}^*_{D^0}(\vec{x}')\right)$$



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

And indeed, the coherence factor is greatly improved in bin 2 and 3!




Binned fit of $\delta_{K3\pi}$ and $R_{K3\pi}$.

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

Phys. Rev. D **107** 032009

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

What is measured:

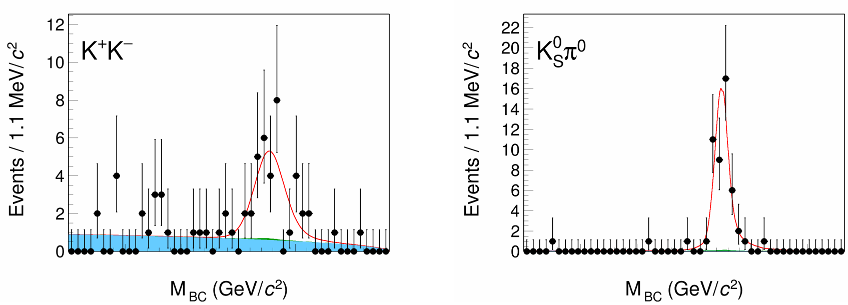
- Phase-space integrated strong-phase analysis of $D \to K^+K^-\pi^+\pi^-$

Significance:

- First model-independent study of the $CP$ content of this decay

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

This decay suffers from both low branching fraction and low efficiency, as seen in the double-tag fits

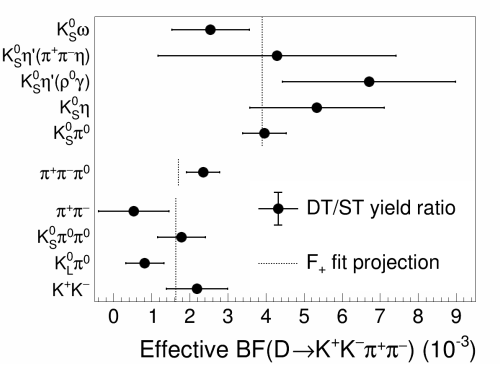



Double-tag fits of $K^+K^-\pi^+\pi^-$ vs (left) $K^+K^-$ and (right) $K_S^0\pi^0$.

Clear quantum correlation: The yield of $K^+K^-\pi^+\pi^-$ vs $K^+K^-$ ($CP$-even) is suppressed, while that of $K_S^0\pi^0$ ($CP$-odd) is enhanced

The strong-phase information is parameterised in terms of the $CP$-even fraction $F_+$:

$$\frac{N^{\mathrm{DT}}}{N^{\mathrm{ST}}} \propto 1 \mp (2F_+ - 1)$$

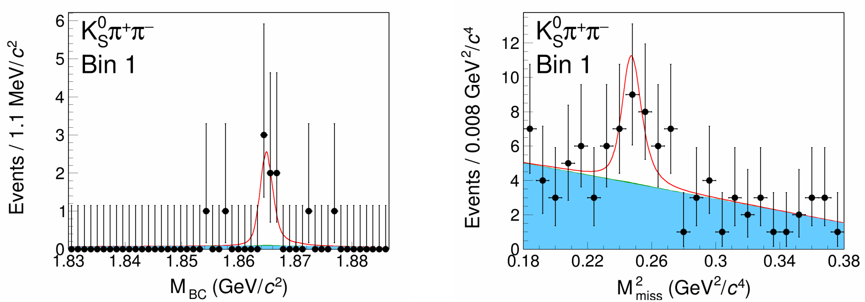



Branching fractions of $D \to K^+K^-\pi^+\pi^-$ measured against $CP$-even/odd tags.

Clearly, $D^0 \to K^+K^-\pi^+\pi^-$ is predominantly $CP$-even

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

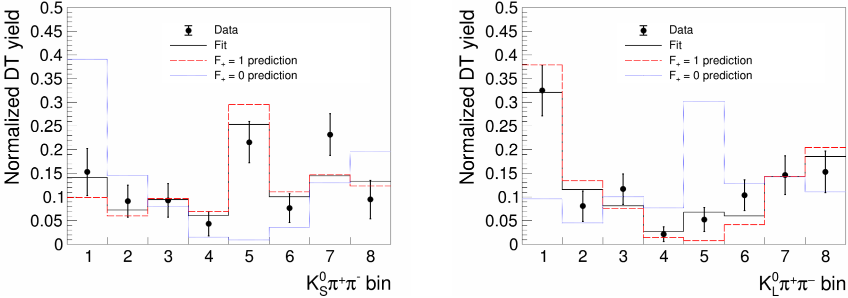
- To mitigate the low reconstruction efficiency, explore a novel partially reconstructed technique
- Poor low momentum kaon tracking efficiency $\implies$ Only reconstruct one kaon




Fits of (left) fully and (right) partially reconstructed $K^+K^-\pi^+\pi^-$ vs $K_S^0\pi^+\pi^-$.

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

The multi-body tags $K^0_{S,L}\pi^+\pi^-$, which are split into phase-space bins, provide sensitivity to $F_+$




Bin yields of $K^+K^-\pi^+\pi^-$ vs $K^0_{S,L}\pi^+\pi^-$.

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

Combining the $CP$ and $K^0_{S,L}\pi^+\pi^-$ tags:

$$F_+ = 0.730 \pm 0.037 \pm 0.021$$

This is not the end of the story:

1. A phase-space binned analysis is ongoing
2. The statistical precision will improve greatly with more data
3. This fully charged mode will provide valuable inputs to $\gamma$ and charm mixing at LHCb and Belle II

# Summary and conclusion

1. Many exciting measurements using quantum-correlated $D\bar{D}$ pairs have been performed, using the $3\,\text{fb}^{-1}$ dataset
2. Previous analyses, such as $\delta_{K\pi}$, have been improved using more tags and more precise inputs
3. BESIII is now exploring four-body decays, and many binned analyses are in the pipeline using the larger $8\,\text{fb}^{-1}$ dataset
4. BESIII is expected to collect $20\,\text{fb}^{-1}$ of $\psi(3770)$ data by 2024
   - Strong-phase measurements, which are currently statistics limited, will improve significantly in the next few years
   - This unique dataset will be essential for providing inputs to the foreseen datasets at LHCb and Belle II

# Thanks for listening!