Charm physics at BESIII

Martin Tat, on behalf of the BESIII Collaboration

University of Oxford

FPCP Conference

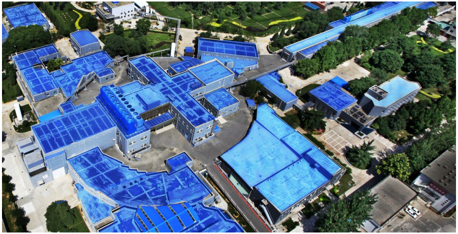
30th May 2023

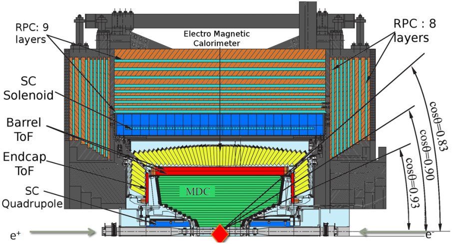
Outline

1. Charm physics at the BESIII experiment
2. $D \to K^-\pi^+$
3. $D \to K^-\pi^+\pi^-\pi^+$
4. $D \to K^+K^-\pi^+\pi^-$
5. Summary and conclusion

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)

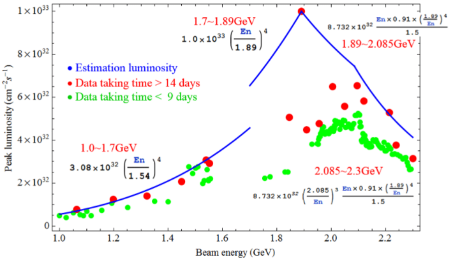




Overview of (left) BEPCII and (right) BESIII.

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 $\psi(3770)$

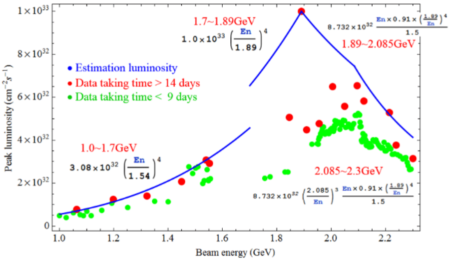


BEPCII peak luminosity.

The BESIII experiment

Key datasets for charm physics:

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



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 γ 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

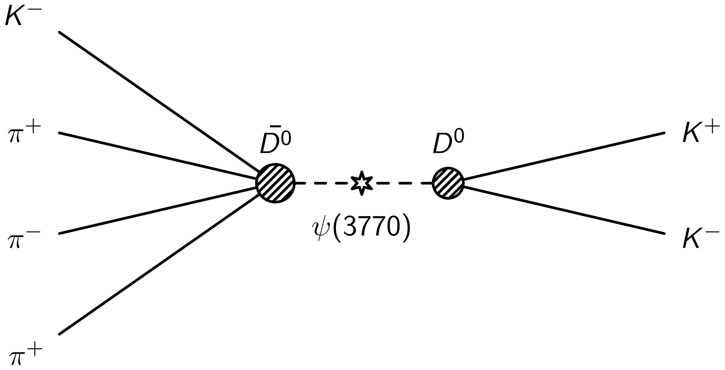
No time to cover all topics in this talk!
I will mainly focus on strong-phase measurements in charm decays...

Recent charm results from BESIII

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

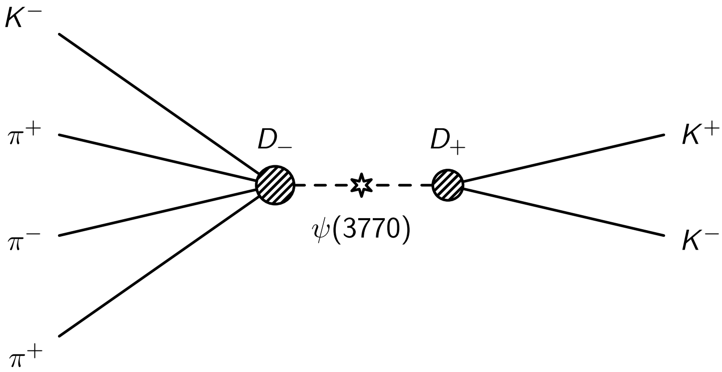


Double-tag method

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

Analysis strategy:

- Large boost in statistics by including $D \to K_L^0 X$ tags
- Independent determinations of $D \to K_L^0 X$ branching fractions

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:

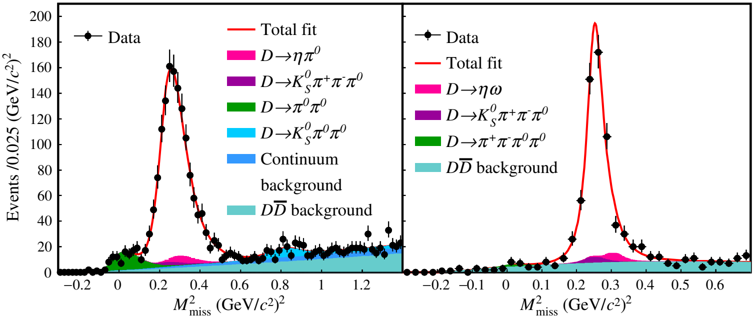
$$r_D^{K\pi} \exp\left(-i\delta_D^{K\pi}\right) = \frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle}$$

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

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

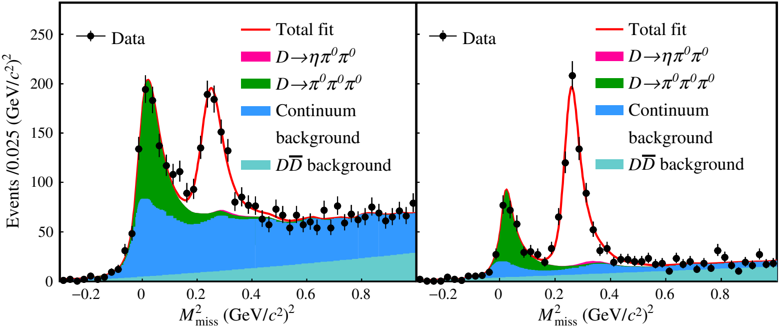
- Branching fractions must be determined independently of $D \to K^-\pi^+ \implies$ Measure using pure CP tags
- $K_L^0\pi^0$ and $K_L^0\omega$ are CP-even decays, and must therefore be tagged by CP-odd decays
  - $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\eta'(\pi^+\pi^-\eta, \pi^+\pi^-\gamma)$, $K_S^0\omega$



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



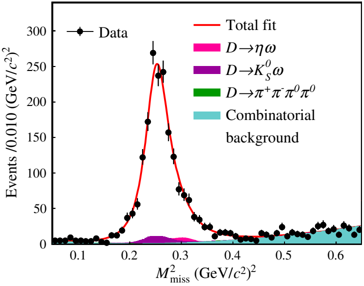
Missing mass squared in (left) $\pi^+\pi^-\pi^0$ tags and all other tags (left).

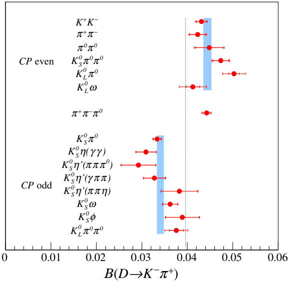
$D \to K^-\pi^+$

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 $\mathcal{A}_{K\pi}$





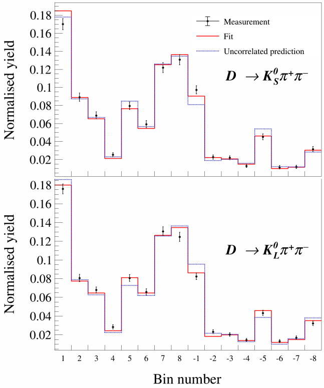
Left: Fit of the $K^-\pi^+$ vs $K_L^0\omega$ double-tag yield. Right: Branching fraction of $D \to K^-\pi^+$ measured using CP tags.

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

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

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

- $\delta_D^{K\pi}$ 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
- Phase-space integrated analysis of $D \to K^{\mp}\pi^{\pm}\pi^0$

Analysis strategy:

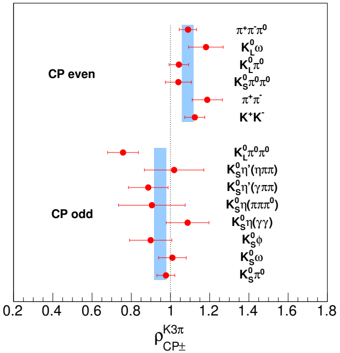
- Binning of 5D phase space enhances the coherence factors

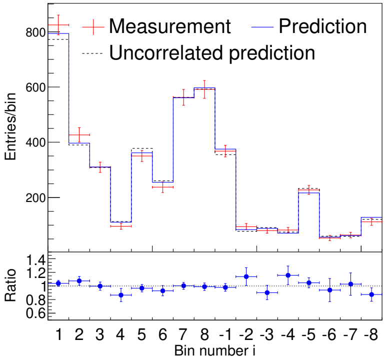
Significance:

- Crucial input to one of the most precise measurements of γ

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

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



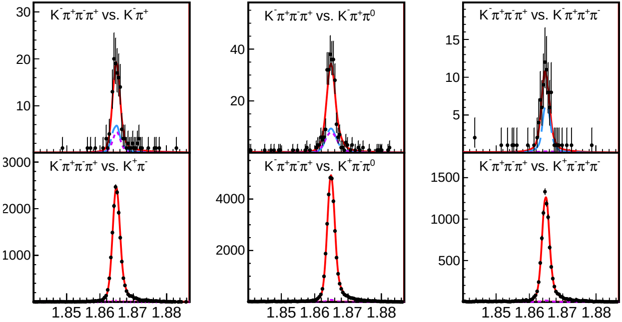


Left: Asymmetry of $D \to K^-\pi^+\pi^-\pi^+$ branching fraction with *CP*-even and *CP*-odd tags. Right: Double-tag yields of $K^0_S\pi^+\pi^-$ vs $K^-\pi^+\pi^-\pi^+$.

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

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

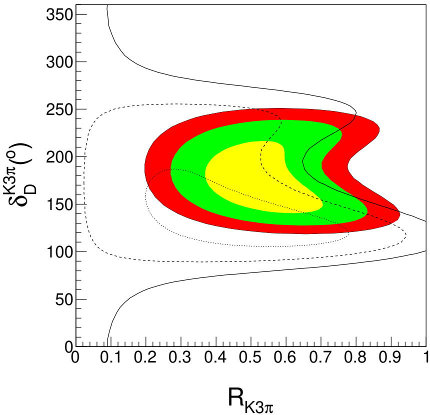
$$R_{K3\pi}\exp(i\delta_{K3\pi}) \equiv \frac{\int \mathrm{d}\vec{x}\,\mathcal{A}_{\bar{D}^0\to K^+\pi^-\pi^+\pi^-}(\vec{x})\mathcal{A}^*_{D^0\to K^+\pi^-\pi^+\pi^-}(\vec{x})}{A_{\bar{D}^0\to K^+\pi^-\pi^+\pi^-}A_{D^0\to K^+\pi^-\pi^+\pi^-}}$$



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

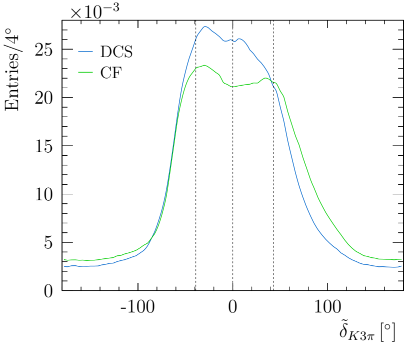


But: $R_{K3\pi} = 0.52^{+0.12}_{-0.10}$, so interference effects are very diluted

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

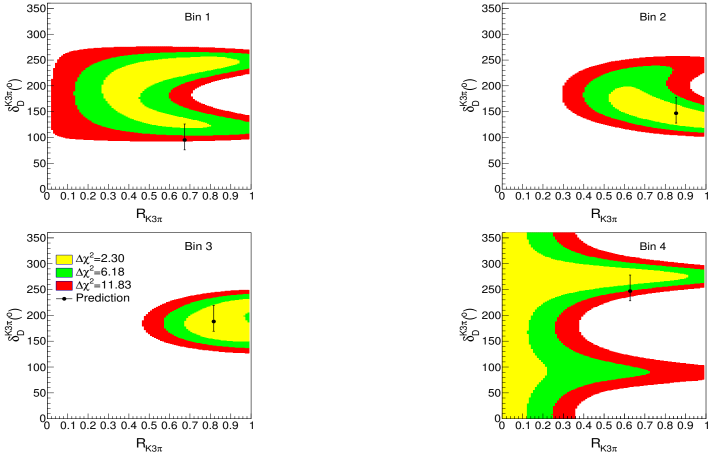
Can improve coherence factors by defining a binning scheme in terms of the normalised phase difference

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



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

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

Analysis strategy:

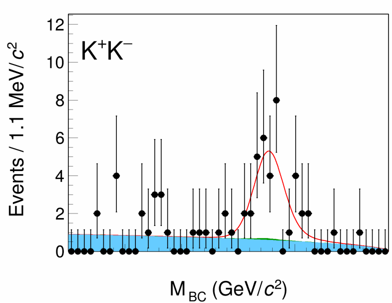
- Uses a combination of CP and multi-body tags
- Novel partially reconstructed technique to mitigate low efficiencies

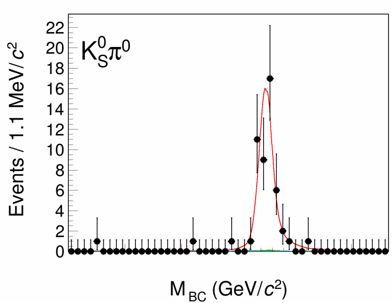
Significance:

- 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





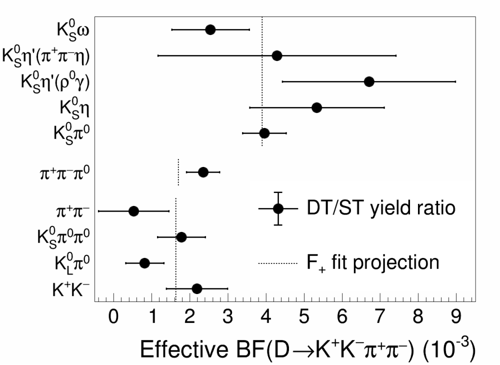
Double-tag fits of $K^+K^-\pi^+\pi^-$ vs (left) K^+K^- and (right) $K_S^0\pi^0$.

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

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

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

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

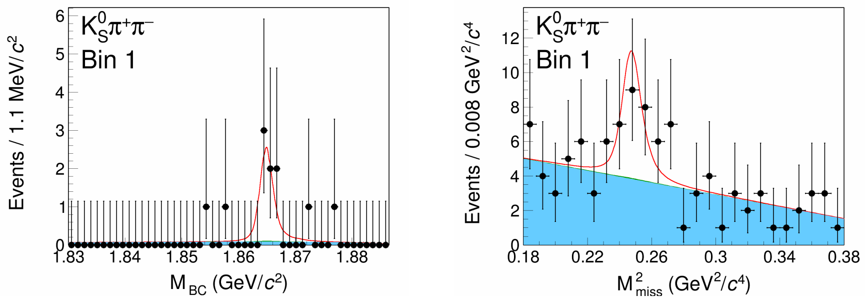


Branching fractions of $D \to K^+K^-\pi^+\pi^-$ measured against CP-even/odd tags.

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

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

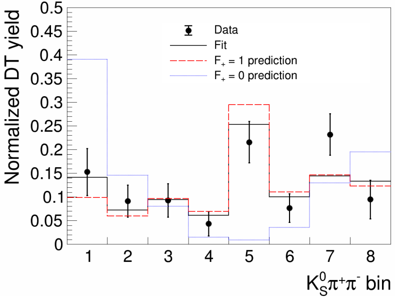
- To mitigate the low reconstruction efficiency, explore a novel partially reconstructed technique
- Poor low momentum kaon tracking efficiency $\implies$ Only reconstruct one kaon

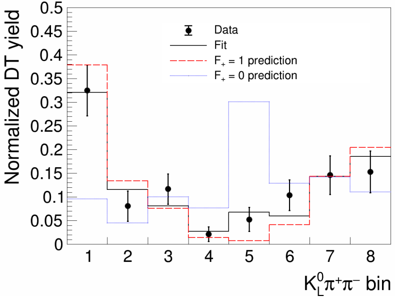


Fits of (left) fully and (right) partially reconstructed $K^+K^-\pi^+\pi^-$ vs $K_S^0\pi^+\pi^-$.

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

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 γ 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 $3\,\mathrm{fb}^{-1}$ 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 $8\,\mathrm{fb}^{-1}$ dataset
4. BESIII is expected to collect $20\,\mathrm{fb}^{-1}$ 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!