BESIII Charm Meeting
Measurement of CP even fraction F_+ in $D^0 \to K^+K^-\pi^+\pi^-$

Martin Tat

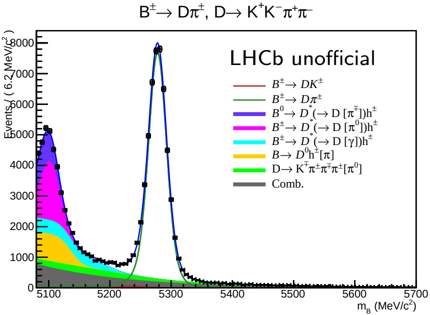
University of Oxford

15th March 2022

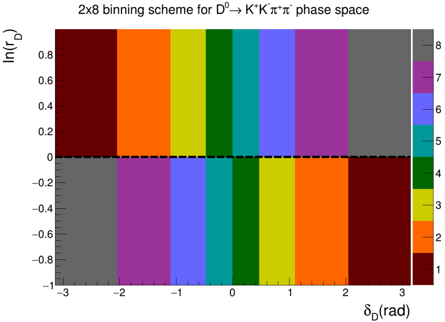
Outline

Introduction

- Original plan (for my PhD):
  - c_i/s_i analysis with new $20\,\text{fb}^{-1}$ BESIII $\psi(3770)$ dataset
  - Develop binning scheme using LHCb model JHEP 02 (2019) 126
  - Perform model independent γ measurement at LHCb simultaneously
    - Expected precision $\Delta\gamma \approx 12^\circ$ with LHCb Run 1+2



(a) Fit of $B^\pm \to [K^+K^-\pi^+\pi^-]_D\pi^\pm$



(b) Binning scheme for $D^0 \to K^+K^-\pi^+\pi^-$

Motivation

- F_+ describes the CP content of a self-conjugate multi-body decay
  - $F_+ = 1$ (0) for CP even (odd) final states
- F_+ can be measured with current $3\,\text{fb}^{-1}$ dataset
  - First model independent measurement of $F_+^{KK\pi\pi}$!
  - Useful to test agreement with LHCb model prediction: $F_+ = 0.73$
- Important input to quasi-GLW analysis of the CKM angle γ
  - Current GLW modes: KK, $\pi\pi$, $\pi\pi\pi\pi$
  - Minimal effort to include $KK\pi\pi$ in GLW analyses $\implies$ More statistics
- Other F_+ measurements:
  - $D^0 \to \pi^+\pi^-\pi^+\pi^-$ JHEP 01 (2018) 144
  - $D^0 \to K_S\pi^+\pi^-\pi^0$ JHEP 01 (2018) 82
  - Both measurements are from CLEO-c, BESIII analyses ongoing

Strategy for strong-phase analysis

1. Select double tags of $KK\pi\pi$ vs flavour, CP and self-conjugate tags
2. Measure flavour tag yields K_i
3. Measure c_i with CP tags:
4. Measure $c_i + s_i$ with self-conjugate tags

c_i/s_i analysis

CP: $M_i \propto \left(K_i + K_{-i} - 2c_i\sqrt{K_i K_{-i}}(2F_+^{\mathrm{tag}} - 1)\right)$

Self-conjugate: $M_{ij} \propto \left(K_i K'_{-j} + K_{-i}K'_j - 2\sqrt{K_i K_{-i} K'_j K'_{-j}}(c_i c'_j + s_i s'_{-j}\right)$

- Sum over all $KK\pi\pi$ bins to measure $F_+^{KK\pi\pi}$:

F_+ analysis

CP: $M \propto \left(1 - 2(2F_+^{KK\pi\pi} - 1)(2F_+^{\mathrm{tag}} - 1)\right)$

Self-conjugate: $M_j \propto \left(K'_j + K'_{-j} - 2c'_j\sqrt{K'_j K'_{-j}}(2F_+^{KK\pi\pi} - 1)\right)$

Selection

- Selection of charged and neutral particles follow standard track and shower requirements
- Require flight significance > 2 for K_S
- K_S veto for $KK\pi\pi$ and $\pi\pi\pi^0$ tags
- ΔE cut of 3σ
- ΔE fit for 4-body modes allow a non-smooth background at $\Delta E = 0$

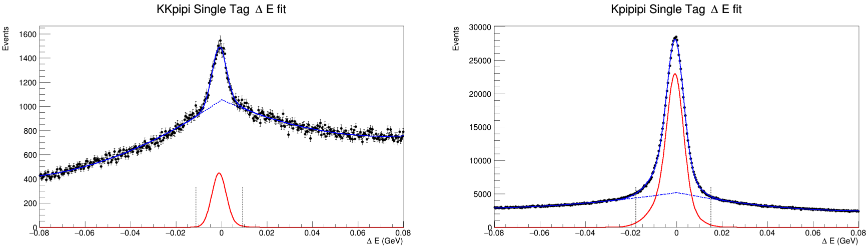


Figure 2: Double Gaussian signal and Chebychev polynomial background

Tag modes

- Flavour tags:
  - $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $\underline{Ke\nu}$
- CP even tags:
  - KK, $\pi\pi$, $\pi\pi\pi^{0*}$, $K_S\pi^0\pi^0$, $K_L\pi^0$, $\underline{K_L\omega}$
- CP odd tags:
  - $K_S\pi^0$, $K_S\eta$, $K_S\omega$, $K_S\eta'_{\pi\pi\eta}$, $K_S\eta'_{\rho\gamma}$, $\underline{K_L\pi^0\pi^0}$
- Self-conjugate tags:
  - $K_S\pi\pi$, $K_L\pi\pi$

Underlined tags have not been finalized yet

*Mostly CP even

Single tag fits

- Fit model:
  - Signal: PDF from signal MC, convoluted with double Gaussian
  - Combinatorial background: Argus PDF

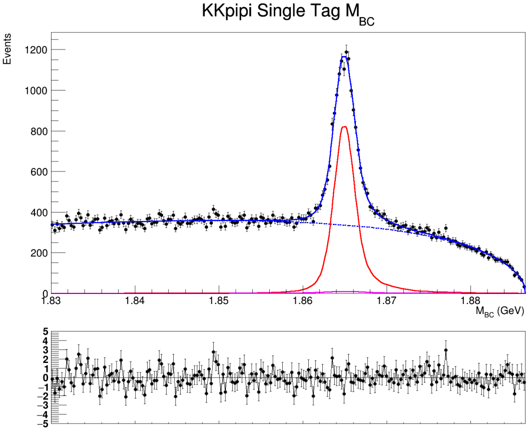


Figure 3: $KK\pi\pi$ single tag fit

Peaking backgrounds

- Strategy for fixing peaking backgrounds:
  1. Generate dedicated MC sample
  2. Obtain retention rate of peaking background
  3. Fit background with appropriate shape (Gaussian, Crystal Ball, ...)
  4. Use BFs from PDG to fix background-to-signal ratio

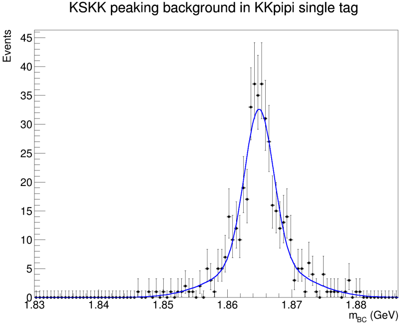
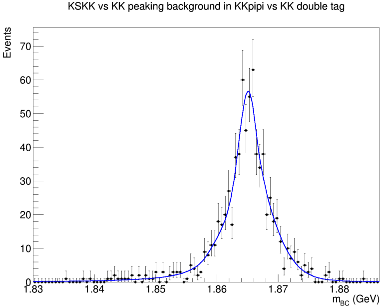


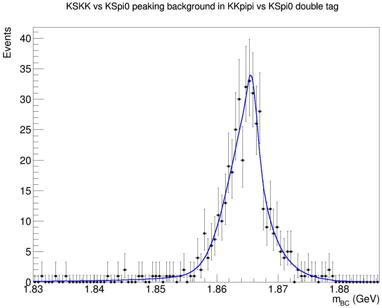
Figure 4: $K_S KK$ background in $KK\pi\pi$ single tag fit, fitted with Double Gaussian

Quantum correlation in peaking backgrounds

- Strategy for peaking backgrounds with different CP:
  - Correct using $F_+^{KK\pi\pi}$ from LHCb model
- Strategy for $K_S KK$ background in $KK\pi\pi$
  - $F_+^{K_S KK} = 0.524 \pm 0.018$ from Phys. Rev. D **102**, 052008
  - Use dedicated MC to find retention in each $K_S KK$ bin
  - K_S veto removes more $K_S\phi$ than $K_S a(980)^0 \implies$ Calculate effective F_+ for $K_S KK$ to $KK\pi\pi$ background



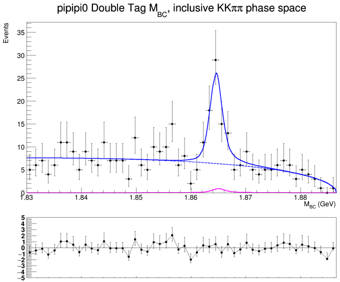
(a) $F_+^{K_S KK} = 0.726 \pm 0.030$



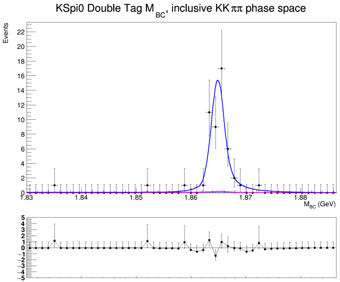
(b) $F_+^{K_S KK} = 0.840 \pm 0.034$

Double tag fits

- Fit strategy: Only fit signal side m_{BC} because of low statistics
- Fit model:
  - Signal: PDF from signal MC, convoluted with single Gaussian
  - Background: Argus PDF
  - Simple sideband subtraction for correct signal but wrong tag event
- For tags with multiple bins, perform a simultaneous fit of all bins
  - Shape is floated and shared across all bins
  - Yield of signal and combinatorial background is floated in each bin



(a) $KK\pi\pi$ vs $\pi\pi\pi^0$



(b) $KK\pi\pi$ vs $K_S\pi^0$

Double tag fits

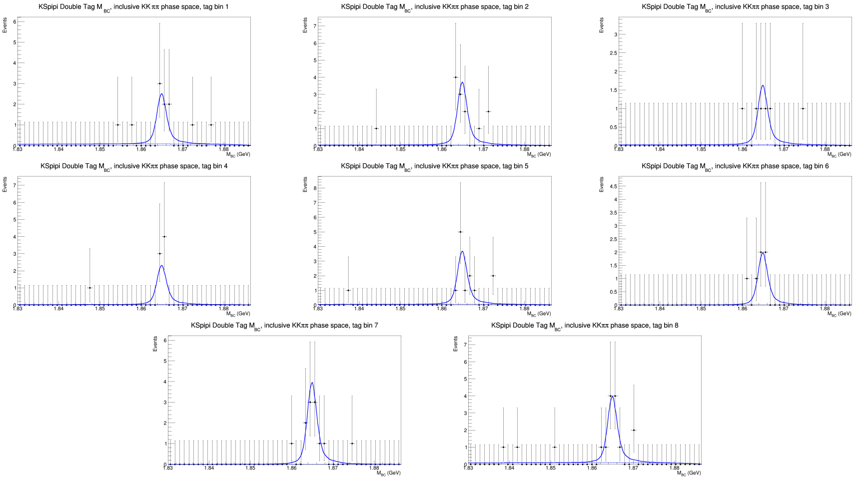


Figure 7: $KK\pi\pi$ vs $K_S\pi\pi$ simultaneous fit

Initial look at K_i for $D^0 \to KK\pi\pi$

- Expect fractional bin yields K_i to be well described by LHCb model
- K_i are accessible at LHCb in $B \to D\mu X$ processes with large statistics
- Excellent agreement between model and data!

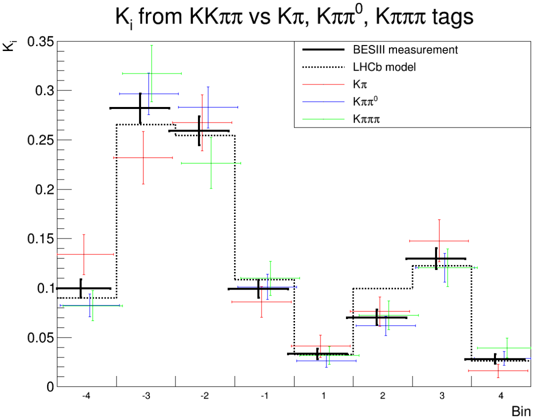


Figure 8: K_i measurement for $KK\pi\pi$ using 2×4 bins

F_+ measurement with CP tags

- Normalize double tag yields with single tag yields:

$$\frac{N_{\mathrm{DT}}(KK\pi\pi|\text{tag})}{N_{\mathrm{ST}}(\text{tag})}\frac{\epsilon(\text{tag})}{\epsilon(KK\pi\pi|\text{tag})} = \text{BF}(KK\pi\pi)(1-2(2F_+^{KK\pi\pi}-1)(2F_+^{\text{tag}}-1))$$

- Fit all CP tags simultaneously with BF$(KK\pi\pi)$ and $F_+^{KK\pi\pi}$ floated

Mode	Single tag yield	Double tag yield
KK	$56\,303 \pm 262$	26 ± 6
$\pi\pi$	$19\,771 \pm 130$	4 ± 4
$\pi\pi\pi^0$	$113\,780 \pm 644$	56 ± 10
$K_S\pi^0\pi^0$	$25\,122 \pm 331$	8.5 ± 2.9
$K_L\pi^0$	$48\,148 \pm 463$	6 ± 4
$K_S\pi^0$	$68\,230 \pm 280$	48 ± 7
$K_S\eta$	9296 ± 33	8.8 ± 2.9
$K_S\eta'_{\pi\pi\eta}$	3220 ± 6	2.2 ± 1.6
$K_S\eta'_{\rho\gamma}$	8740 ± 196	8.9 ± 3.0
$K_S\omega$	$21\,636 \pm 170$	10 ± 4

F_+ measurement with CP tags

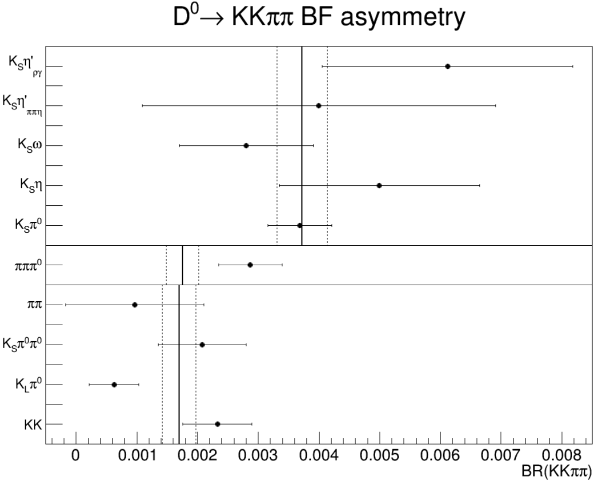


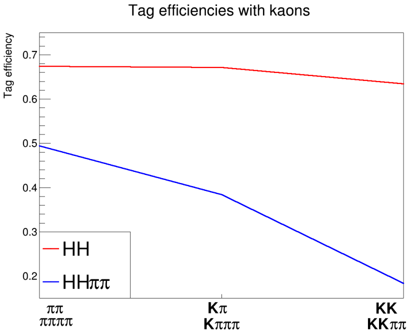
Figure 9: F_+ combination of CP tags
Fit result: $F_+ = 0.69 \pm 0.04$

F_+ measurement with $K_S\pi\pi$ tag

- With $K_S\pi\pi$, increase sensitivity through binning of $K_S\pi\pi$ phase space

$$M_j \propto \left(K'_j + K'_{-j} - 2\sqrt{K'_j K'_{-j}}c'_j(2F_+^{KK\pi\pi-1})\right)$$

- Problem: $KK\pi\pi$ reconstruction efficiency is too low $\rightarrow$ Low yields!



- Likely explanation: Softer kaons $\rightarrow$ Kaons get stuck inside tracker

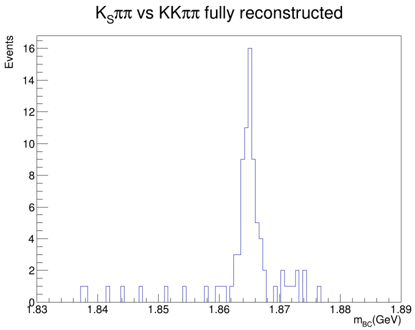
F_+ measurement with $K_S\pi\pi$ tag

- Solution: Partially reconstructed $KK\pi\pi$
- Strategy:
  1. Reconstruct $D \to K_S\pi\pi$
  2. Require 3 remaining good tracks consistent with $K\pi\pi$
  3. Use missing mass to reconstruct missing kaon

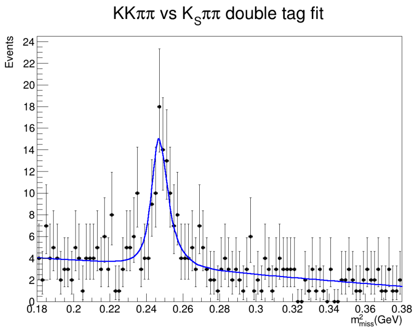
Mode	Inclusive yield	Double tag efficiency
$K_S\pi\pi$ (fully reconstructed)	67.2	6.63 ± 0.04
$K_S\pi\pi$ (partially reconstructed)	85.9	6.50 ± 0.03
$K_L\pi\pi$ (partially reconstructed)	176.9	7.29 ± 0.04

Partially reconstructed $KK\pi\pi$ vs $K_S\pi\pi$

- Main challenge with partially reconstructed $KK\pi\pi$: $K\pi\pi\pi\pi^0$
- Require no π^0 candidates



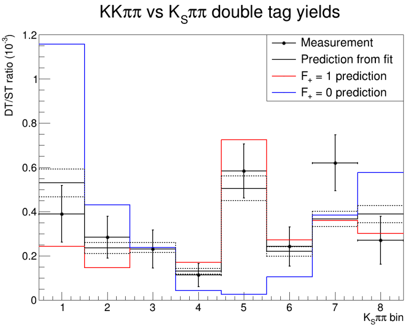
(a) Fully reconstructed



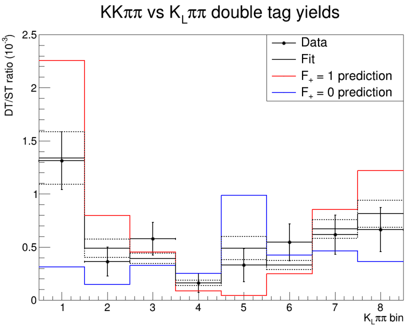
(b) Partially reconstructed

Figure 10: $KK\pi\pi$ vs $K_S\pi\pi$

Binned fit with $K_{S,L}\pi\pi$ tags



(a) $K_S\pi\pi$
Fit result: $F_+ = 0.80 \pm 0.09$



(b) $K_L\pi\pi$
Fit result: $F_+ = 0.54 \pm 0.10$

Figure 11: $KK\pi\pi$ vs $K_{S,L}\pi\pi$ binned F_+ fit

F_+ combination

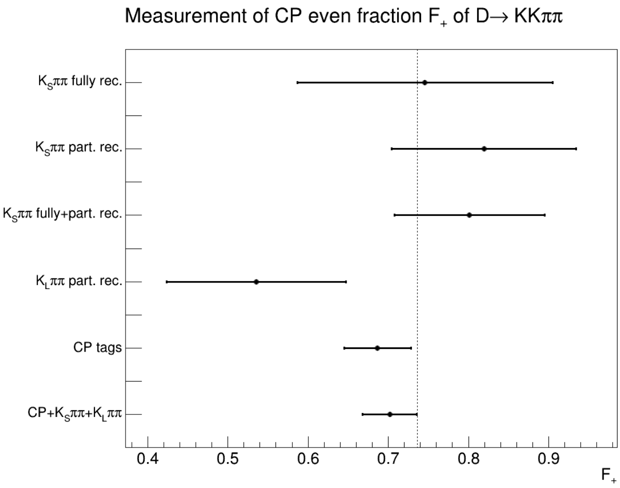


Figure 12: Combination of F_+ measurements
$F_+ = 0.702 \pm 0.034$

Summary

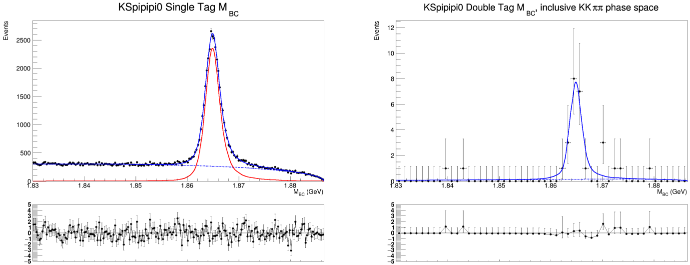
- Good progress has been made on the strong-phase analysis of $D^0 \to KK\pi\pi$
  - K_i is very consistent with LHCb model
  - Expect sufficient statistics with $20\,\text{fb}^{-1}$ of $\psi(3770)$ data for a c_i/s_i measurement with 2×8 bins
- F_+ has been measured using CP tags and $K_{S,L}\pi\pi$ tags
  - Central value agrees with model
  - Will allow all GLW analyses to include $KK\pi\pi$ to increase statistics
- Next steps:
  1. Finalise all peaking backgrounds
  2. Include partially reconstructed $KK\pi\pi$ vs KK, $\pi\pi\pi^0$ and $K_S\pi^0$
  3. Systematics studies
  4. Write up MEMO

Thank you!

Backup

$K_S\omega$ CP even tag using sPlot

- $D \to K_S\omega$ is CP odd
- CP-even contamination from non-resonant $D \to K_S\pi\pi\pi^0$
  - $F_+(K_S\pi\pi\pi^0) = 0.238 \pm 0.012 \pm 0.012$ from CLEO



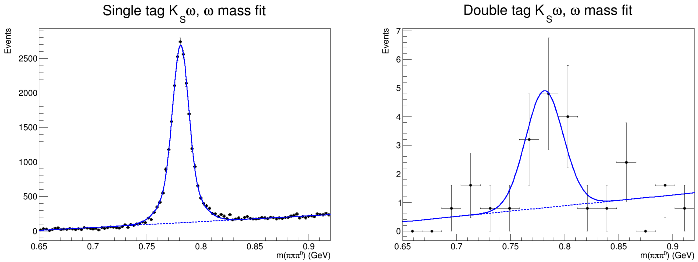
(a) Single tag

(b) Double tag

Figure 13: $D \to K_S\pi\pi\pi^0$ D mass (beam constrained)

$K_S\omega$ CP even tag using sPlot

- Strategy:
  1. From D mass fit, remove non-$K_S\pi\pi\pi^0$ background using sPlot
  2. Fit $\pi\pi\pi^0$ invariant mass to obtain $K_S\omega$ yield



(a) Single tag **(b)** Double tag

Figure 14: $\pi\pi\pi^0$ invariant mass in $D \to K_S\pi\pi\pi^0$