$D \to K^+K^-\pi^+\pi^-$ strong phase analysis at BESIII

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Recap of BESIII analysis

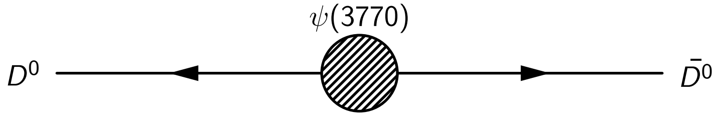
Recap of BESIII analysis

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

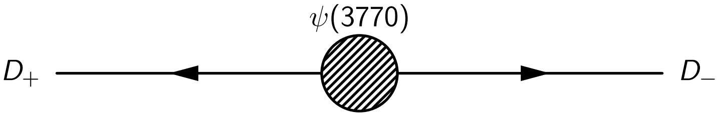
- Study D^0-$\bar{D}^0$ strong phase difference in bins of the 5D phase space
- Measurement of amplitude averaged strong phases c_i and s_i
- c_i and s_i are important inputs to the γ measurement at LHCb
  - LHCb result: $\gamma = (116^{+12}_{-14})^\circ$ with model dependent inputs
  - γ may change when updated with model independent c_i and s_i
- Measurement technique unique to charm factories: Study decays of quantum correlated $D\bar{D}$ pairs using a double tag method

Recap of BESIII analysis

- $\psi(3770) \to D^0 \bar{D}^0$ decay conserves $\mathcal{C} = -1$



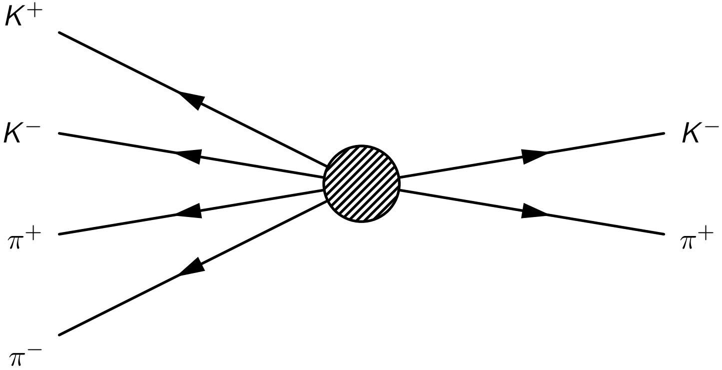
- But since they are quantum correlated, we must consider their CP eigenstates $D_\pm = (|D^0\rangle \pm |\bar{D}^0\rangle)/\sqrt{2}$
- Total wavefunction is $|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle = |D_+\rangle|D_-\rangle + |D_-\rangle|D_+\rangle$



The two D mesons do <u>not</u> communicate, but the $D \to KK\pi\pi$ decay is perfectly correlated with the tagged D

Recap of BESIII analysis

- Tag mode can be a flavour tag
  - $K\pi$, $K\pi\pi^0$, $K\pi\pi\pi$, $Ke\nu$

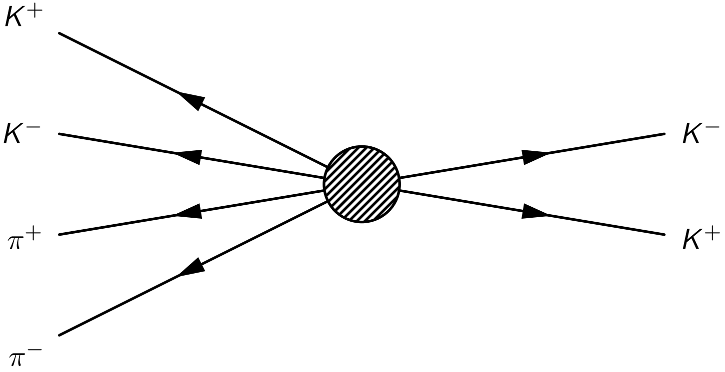


Use flavour tags to measure fraction of $D^0 \to KK\pi\pi$ decays in bin i:

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(KK\pi\pi) \times K_i$$

Recap of BESIII analysis

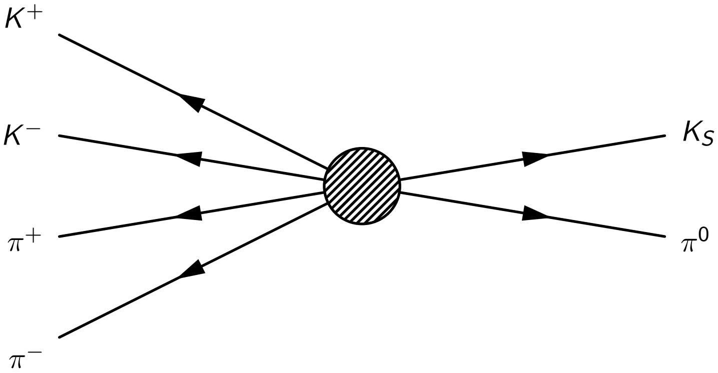
- Tag mode can be a CP even tag
  - KK, $\pi\pi$, $\pi\pi\pi^0$, $K_S\pi^0\pi^0$, $K_L\pi^0$, $K_L\omega$



$D \to K^+K^-$, which is CP even, forces $D \to K^+K^-\pi^+\pi^-$ to be CP odd

Recap of BESIII analysis

- Tag mode can be a CP odd tag
  - $K_S\pi^0$, $K_S\omega$, $K_S\eta$, $K_S\eta'$, $K_L\pi^0\pi^0$



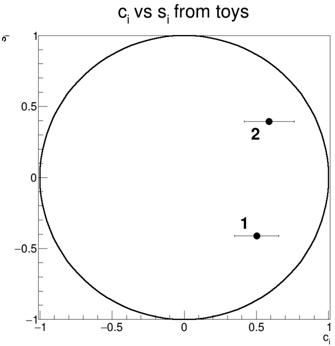
$D \to K_S^0\pi^0$, which is CP odd, forces $D \to K^+K^-\pi^+\pi^-$ to be CP even

Recap of BESIII analysis

The asymmetry between CP even and CP odd double tag yields is sensitive to c_i:

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(KK\pi\pi) \times (K_i + \bar{K}_i \pm 2\sqrt{K_i \bar{K}_i} c_i)$$

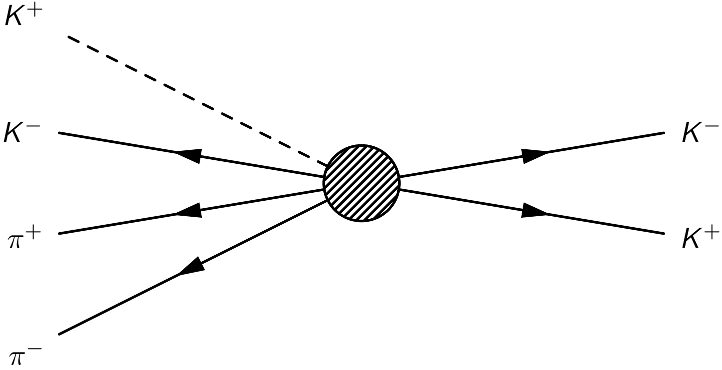
1. K_i: Fraction of D^0 decays in bin i
2. $\bar{K}_i$: Fraction of $\bar{D}^0$ decays in bin i
3. $2\sqrt{K_i \bar{K}_i} c_i$: Interference term, which depend on the cosine of the phase difference between D^0 and $\bar{D}^0$ decays



Double tag yields of partially reconstructed events

Double tag yields of partially reconstructed events

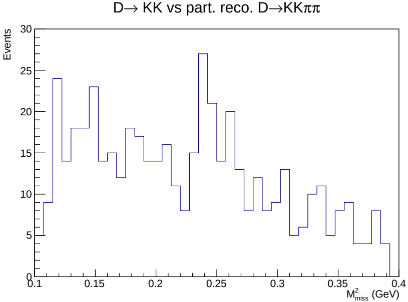
- Reconstruction efficiency of $D \to KK\pi\pi$ is very low (18%), compared to other four body modes such as $D \to \pi\pi\pi\pi$ (49%)
  - Soft kaons get stuck in magnetic field...
- Try out partially reconstructed $D \to KK\pi\pi$ technique
  - No overlap with the fully reconstructed sample



In MC, the yields were found to be similar to fully reconstructed DTs

Double tag yields of partially reconstructed events

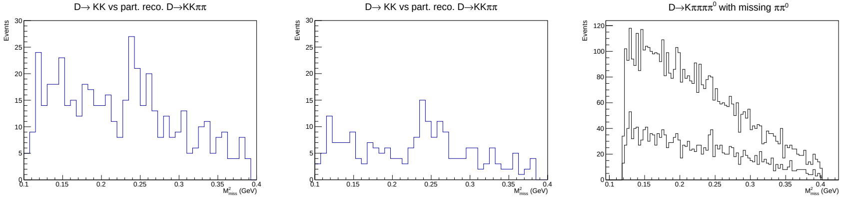
First look at partially reconstructed $D \to KK\pi\pi$ vs $D \to KK$:



- Large background from $D \to K\pi\pi\pi^0$, $\pi\pi^0$ not reconstructed
- Background is non-peaking since two particles are missing
- No reliable MC because no model for this decay exists!

Double tag yields of partially reconstructed events

Method for removing π^0 backgrounds: Veto events with π^0 candidates
Signal efficiency is reduced by 30%, but 65% of $K\pi\pi\pi\pi^0$ is rejected



(a) Data, without veto **(b)** Data, with π^0 veto **(c)** MC, with/without veto

Figure 1: Study of π^0 veto

Double tag yields of partially reconstructed events

Using the method of trial and error, I also discovered that a cut on the kaon energy is highly efficient at removing the $K\pi\pi\pi\pi^0$ background:

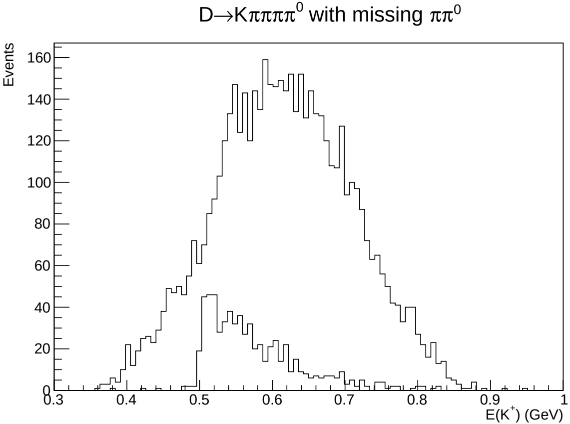


Figure 2: The energy spectrum of the kaon from the background $D \to K\pi\pi\pi\pi^0$ and the signal $D \to KK\pi\pi$

Double tag yields of partially reconstructed events

Unfortunately a cut of $E > m_K$ affects the mass shape...

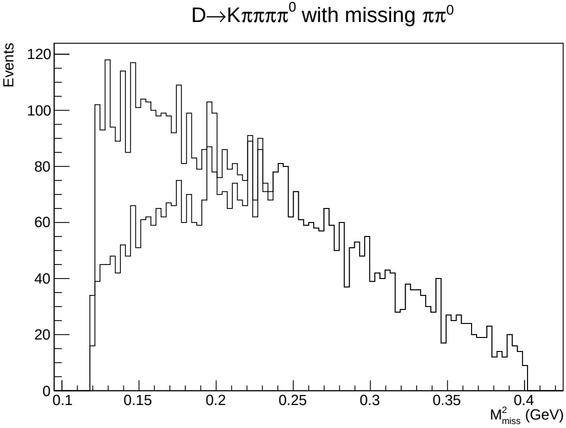


Figure 3: Mass shape before and after a $E > m_K$ cut

Double tag yields of partially reconstructed events

… but luckily a $E < 0.7\,\text{GeV}$ cut does not change the mass shape!

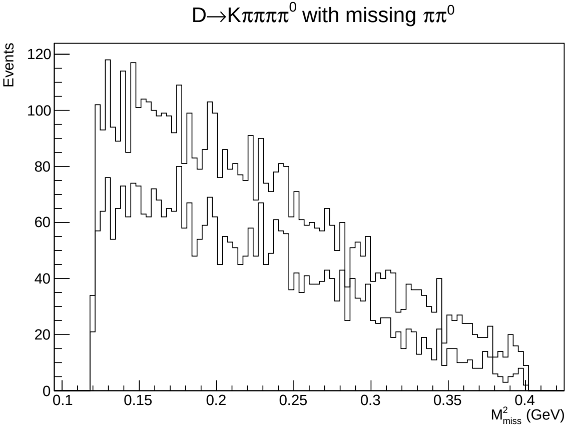
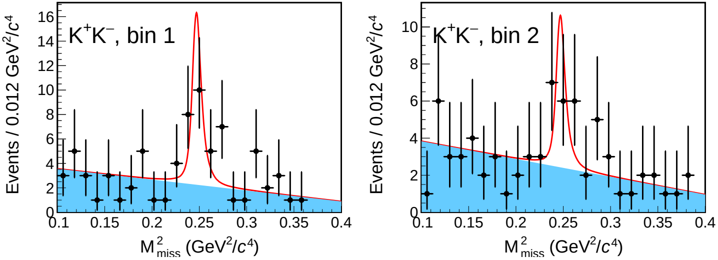


Figure 4: Mass shape before and after a $E < 0.7\,\text{GeV}$ cut

Finally, I can run the fit and the yields were found to be similar to the fully reconstructed samples

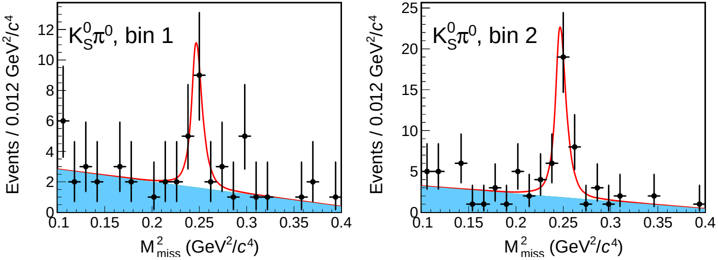


(a) Bin 1, $N^{\mathrm{DT}} = 17.3^{+5.9}_{-5.0}$ **(b)** Bin 2, $N^{\mathrm{DT}} = 10.1^{+5.1}_{-4.2}$

Figure 5: Double tag fit of partially reconstructed $KK\pi\pi$ vs KK

Double tag yields of partially reconstructed events

Finally, I can run the fit and the yields were found to be similar to the fully reconstructed samples



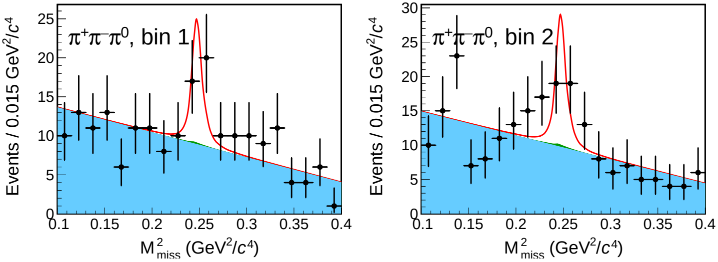
(a) Bin 1, $N^{\mathrm{DT}} = 13.8^{+5.0}_{-4.2}$ **(b)** Bin 2, $N^{\mathrm{DT}} = 30.2^{+6.9}_{-6.2}$

Figure 6: Double tag fit of partially reconstructed $KK\pi\pi$ vs $K_S\pi^0$

Double tag yields of partially reconstructed events

Partially reconstructed $KK\pi\pi$ vs $\pi\pi\pi^0$ mode not understood yet...
Probably background from light hadrons, such as

$$e^+e^- \to K_1\bar{K}^*\rho \to KK\pi\pi\pi\pi\pi^0$$



(a) Bin 1 **(b)** Bin 2

Figure 7: Double tag fit of partially reconstructed $KK\pi\pi$ vs $\pi\pi\pi^0$

c_i and s_i fit

c_i and s_i fit

Equations for c_i and s_i

$$\frac{N_i^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(KK\pi\pi) \times (K_i + \bar{K}_i \pm 2\sqrt{K_i\bar{K}_i}c_i)$$

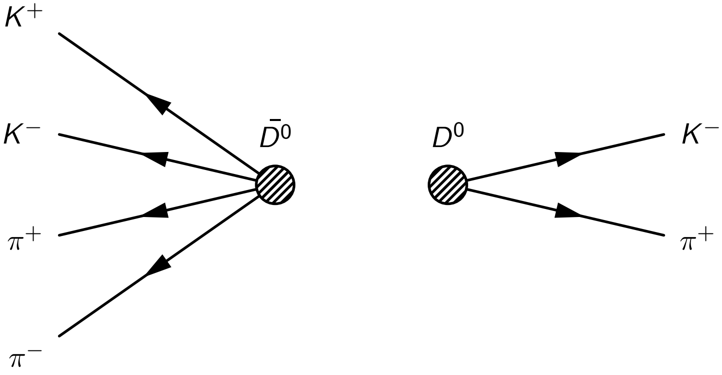
$$\frac{N_{ij}^{\mathrm{DT}}}{N^{\mathrm{ST}}} = \mathcal{B}(KK\pi\pi) \times \left(K_i\bar{K}_j' + \bar{K}_iK_j' - 2\sqrt{K_i\bar{K}_iK_j'\bar{K}_j'}(c_ic_j' + s_is_j')\right)$$

Fit setup:

1. K_i and N^{ST} are fixed, apply systematic or Gaussian constrain
2. $\mathcal{B}(KK\pi\pi)$, c_i and s_i are floating
3. Construct likelihood from DT yields and their (asymmetric) uncertainties, using the equations above
4. Correct K_i for DCS decays directly in the fit

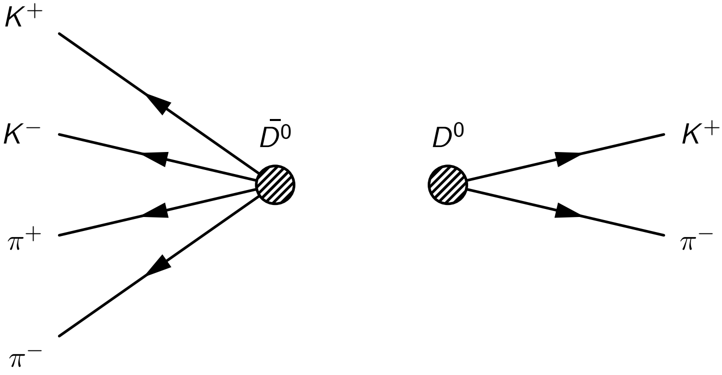
c_i and s_i fit

- What are DCS corrections?
  - Naively, we expect a $K^-\pi^+$ to originate from D^0 (CF mode)
  - Therefore the other decay must be $\bar{D}^0 \to KK\pi\pi$



c_i and s_i fit

- What are DCS corrections?
  - But what if $D^0 \to K^+\pi^-$ (DCS mode)?
  - This leads to a bias in K_i because the flavour of $D \to KK\pi\pi$ is wrong



c_i and s_i fit

- Since $|\mathcal{A}(CF)| = r_D|\mathcal{A}(DCS)|$, where $r_D \approx 5\%$, DCS decays are suppressed by $r_D^2 = \mathcal{O}(10^{-3})$
- However, since $D\bar{D}$ are quantum correlated, there is an interference!
- Interference depends on the CF/DCS ratio r_D, coherence factor R and strong phase δ_D
- It also depends on c_i and s_i, which we are trying to determine...

The true K_i has contributions from CF and DCS decays, and their interference:

$$K_i^{\mathrm{true}} = K_i^{\mathrm{obs}} + r_D^2 \bar{K}_i^{\mathrm{obs}} - 2r_D R\sqrt{K_i^{\mathrm{obs}} \bar{K}_i^{\mathrm{obs}}}\left(c_i\cos(\delta_D) - s_i\sin(\delta_D)\right)$$

c_i and s_i fit

DCS correction factors:

$$f_i = \frac{1}{1+r_D^2\frac{\bar{K}_i^{\mathrm{obs}}}{K_i^{\mathrm{obs}}}-2r_D R\sqrt{\frac{\bar{K}_i^{\mathrm{obs}}}{K_i^{\mathrm{obs}}}}\left(c_i\cos(\delta_D)-s_i\sin(\delta_D)\right)}$$

- In previous analyses of $D \to K_S\pi\pi$ and K_SKK, f_i were calculated using model predictions of c_i and s_i
- Unfortunately, we don't know if the model prediction of $D \to KK\pi\pi$ strong phases is accurate
- In the $D \to K_S\pi\pi\pi^0$ analysis, only the $D \to Ke\nu$ flavour tag was used, because no amplitude model exists (yet)

Solution: Add DCS corrections directly into the fit
Calculate K_i^{true}, using 3 iterations, with the fitted c_i/s_i

With this strategy, the fit will determine the DCS corrections for us
Here, using $D \to K\pi$ as an example:

Bin	f_i	f_{-i}
1	0.95	0.98
2	0.94	0.97

Bonus measurement: Instead of using the $K\pi$ tag to measure K_i, we can actually float $\delta_D^{K\pi}$ directly in the fit, and hence simultaneously measure the strong phase of the $D \to K\pi$ decay!

c_i and s_i fit

Perform fit of c_i and s_i, using the fully reconstructed KK, $\pi\pi\pi^0$, $K_S\pi^0$ and $K_S\pi\pi$ tags, as well as partially reconstructed $KK\pi\pi$ vs KK and $K_S\pi^0$

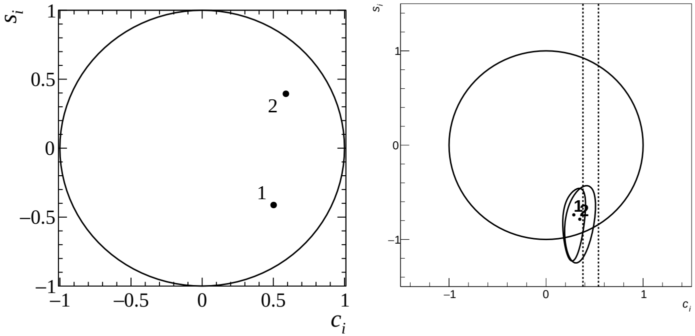


Figure 8: Comparison of fitted values of c_i and s_i (left), and the model predictions (right)

c_i agrees well with F_+ measurement (as it should), but s_i clearly shows a tension with the model!

Summary and next steps

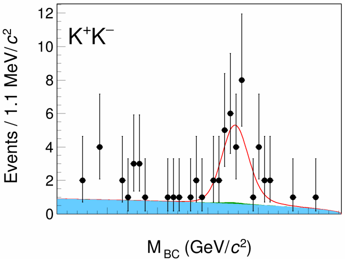
- BESIII measurement of c_i and s_i is progressing well
- A partially reconstructed $D \to KK\pi\pi$ method has been tested, but there were some challenges with large $D \to K\pi\pi\pi\pi^0$ backgrounds
- The preliminary fit of c_i and s_i shows promising results
  - A method for direct DCS decay corrections is working well
  - Results of c_i agree with the F_+ measurement
  - s_i shows tensions with the LHCb model
- Next steps:
  1. Finish calculation of peaking backgrounds in each bin
  2. Reprocess all data and generate new MC once new data is available
  3. Add the rest of the tags
  4. Charm WG review

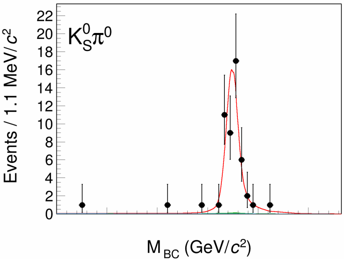
Thank you for listening!

Backup: Double tag yields of fully reconstructed events

Strategy for measuring DT yields of fully reconstructed events:

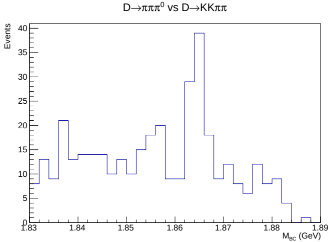
- Fit the beam constrained mass $M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - \sum_i |\vec{p}_i|^2}$
- Signal shape: MC-derived shape, convolved with Gaussian
- Flat background: Argus function
- Peaking background: Fixed from MC



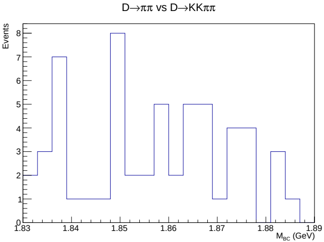


Backup: Double tag yields of fully reconstructed events

Problem: Fully pionic tag modes have very large backgrounds!



(a) $D \to \pi\pi\pi^0$ tag



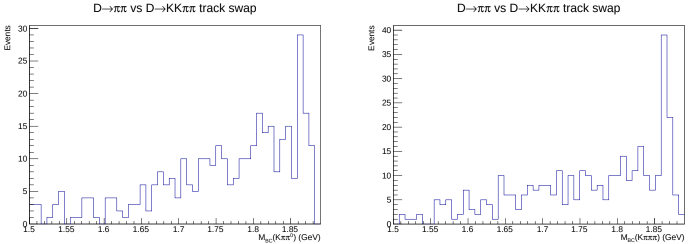
(b) $D \to \pi\pi$ tag

Figure 9: $D \to KK\pi\pi$ with pionic tags

Flat background mainly from light hadrons, such as
$e^+e^- \to K^*\bar{K}^*\rho \to KK\pi\pi\pi\pi$

Backup: Double tag yields of fully reconstructed events

However, in the $\pi\pi\pi^0$ tag there is track swap background we can veto
$K\pi\pi^0$ vs $K\pi\pi\pi \rightarrow \pi\pi\pi^0$ vs $KK\pi\pi$
Consider M_{BC} with a track swap:



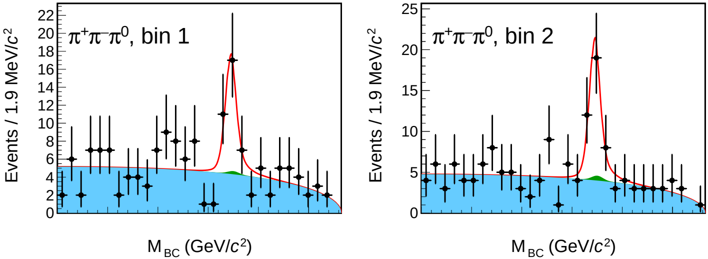
(a) $D \rightarrow K\pi\pi^0$ **(b)** $D \rightarrow K\pi\pi\pi$

Figure 10: Track swapped M_{BC}

A veto in the region $[1.86, 1.87]$GeV removes 20% of the flat background

Backup: Double tag yields of fully reconstructed events

Double tag yield uncertainties improved, but still lots of background



(a) Bin 1, $N^{\mathrm{DT}} = 22.6^{+6.4}_{-5.7}$ **(b)** Bin 2, $N^{\mathrm{DT}} = 28.1^{+6.9}_{-6.2}$

Figure 11: Double tag fit of $\pi\pi\pi^0$ tag