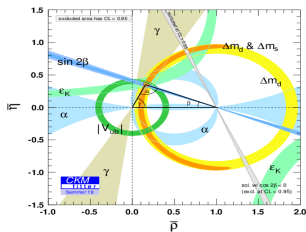


CKM angle γ determination in $B^\pm \rightarrow DK^\pm$, $D \rightarrow K^+K^-\pi^+\pi^-$ decays

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22nd June 2021



Outline

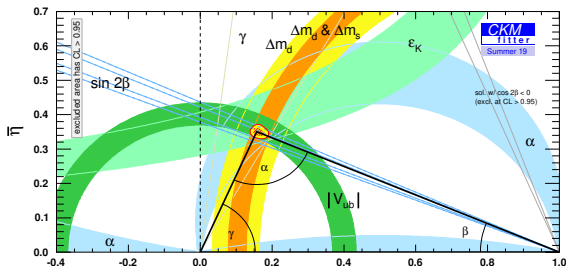
- 1 γ and the unitary triangle
- 2 Motivation for the $D \rightarrow K^+ K^- \pi^+ \pi^-$ decay mode
- 3 Binning scheme and binned fit of $D \rightarrow K^+ K^- \pi^+ \pi^-$
- 4 Global mass fit
- 5 Binned CP fit
- 6 Strong-phase inputs from quantum-correlated $D^0 \bar{D}^0$ pairs
- 7 Summary and next steps

γ and the unitary triangle

How to measure γ ?

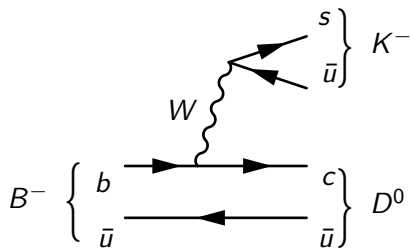
γ and the unitary triangle

- Unitarity of CKM matrix: $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$
- Define $\gamma = \arg\left(-\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)$
- Only CKM angle accessible at tree level \Rightarrow
 - Ideal Standard Model benchmark

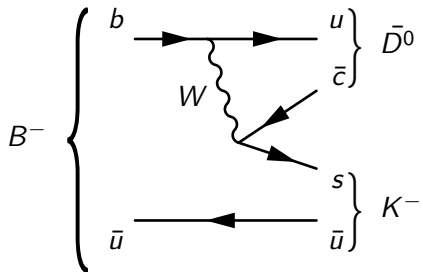


CKMfitter Group (J. Charles et al.), *Eur. Phys. J. C* **41**, 1-131 (2005)

How to measure γ ?



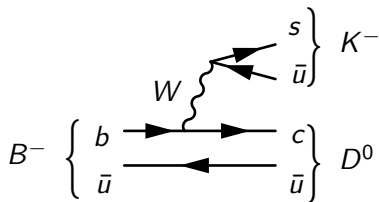
(a) $B^- \rightarrow D^0 K^-$



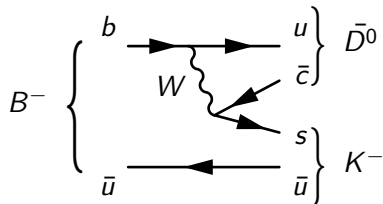
(b) $B^- \rightarrow \bar{D}^0 K^-$ (colour suppressed)

- Need $b \rightarrow c\bar{u}s$ and $b \rightarrow u\bar{c}s$ interference, such as $B^\pm \rightarrow DK^\pm$
 - D : Superposition of D^0 and \bar{D}^0
- Interference when D^0 and \bar{D}^0 decay into a common final state
- Single most precise measurement ($D \rightarrow K_S^0 h^+ h^-$): $\gamma = (68.7^{+5.2}_{-5.1})^\circ$
[JHEP 02 \(2021\) 169](#)

Simplified γ measurement



(a) $B^- \rightarrow D^0 K^-$



(b) $B^- \rightarrow \bar{D}^0 K^-$ (colour suppressed)

- Decay amplitudes:

- $\mathcal{A}(B^- \rightarrow DK^-) = \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$
- $\mathcal{A}(B^+ \rightarrow DK^+) = \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B + \gamma)} \mathcal{A}(D^0)$

- $\mathcal{A}(D^0)$ - $\mathcal{A}(\bar{D}^0)$ strong phase difference varies throughout phase space

- Two approaches:

- 1 Predict $\mathcal{A}(D)$ using an amplitude model
- 2 Split phase space into bins and use external strong-phase inputs

Motivation for the $D \rightarrow K^+ K^- \pi^+ \pi^-$ decay mode

Motivation for the $D \rightarrow K^+ K^- \pi^+ \pi^-$
decay mode

The need for an efficient binning scheme

Motivation for the $D \rightarrow K^+ K^- \pi^+ \pi^-$ decay mode

- Proposed by G. Wilkinson, J. Rademacker [Phys. Lett. B, 647\(2007\)](#)
 - Estimated γ precision: 14° with 1000 events
- Why this mode, and why now?
 - ① Estimate 2000 candidates from LHCb Run 1+2
 - ② Model-independent analysis reduces systematic uncertainties
 - ③ Much more data from BESIII during 2022-2023 for strong-phase inputs
 - ④ New LHCb amplitude model [JHEP 02 \(2019\) 126](#)
 - ⑤ New era of 4-body γ measurements
 - $D \rightarrow K_S^0 \pi^+ \pi^- \pi^0$ by Belle [JHEP 10 \(2019\) 178](#)
 - Ongoing analysis of $D \rightarrow K^+ \pi^- \pi^+ \pi^-$ at LHCb

Binned fit of $D \rightarrow K^+ K^- \pi^+ \pi^-$

- Decay amplitudes:

- $\mathcal{A}(B^- \rightarrow DK^-) = \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$

- $\mathcal{A}(B^+ \rightarrow DK^+) = \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B + \gamma)} \mathcal{A}(D^0)$

- Split into bins $-8, \dots, -1, +1, \dots, +8$ and integrate over phase space:

- $N_i^- = h_{B^-} \left(K_i + (x_-^2 + y_-^2) \bar{K}_i + 2\sqrt{K_i \bar{K}_i} (x_- c_i + y_- s_i) \right)$

- $N_{-i}^+ = h_{B^+} \left(K_i + (x_+^2 + y_+^2) \bar{K}_i + 2\sqrt{K_i \bar{K}_i} (x_+ c_i + y_+ s_i) \right)$

- Fit to extract x_{\pm} and $y_{\pm} \implies$ Interpret in terms of γ , r_B , δ_B

CP-violating observables

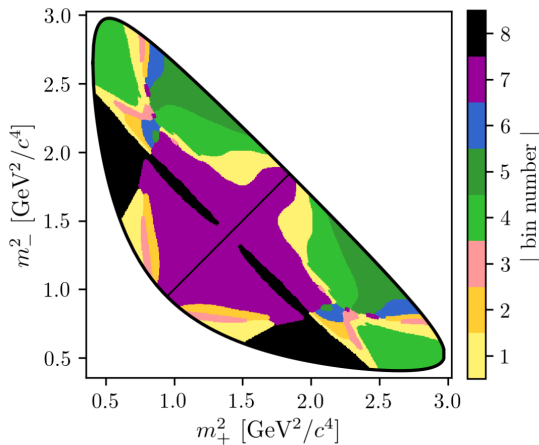
$$x_{\pm} = r_B \cos(\delta_B \pm \gamma), \quad y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

External strong-phase input

c_i, s_i : Amplitude-averaged strong phase difference of D decay

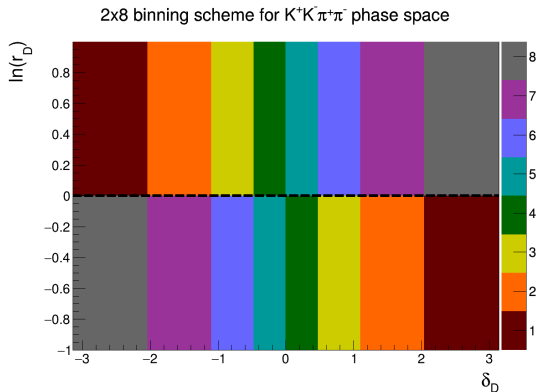
Binning scheme

- Aim: Maximize interference \implies Enhance x_{\pm} and y_{\pm} sensitivity
- Analogy: $K_S\pi^+\pi^-$ Dalitz analysis



Binning scheme

- What to do with 5D phase space?
 - Evaluate amplitudes of each event using the LHCb model
 - Calculate $\mathcal{A}(D^0)/\mathcal{A}(\bar{D}^0) = r_D \exp(i\delta_D)$
 - Effectively reduces 5D \rightarrow 2D



Pull study

- Generate 1000 toy datasets using LHCb amplitude model
- Fit for γ on each dataset

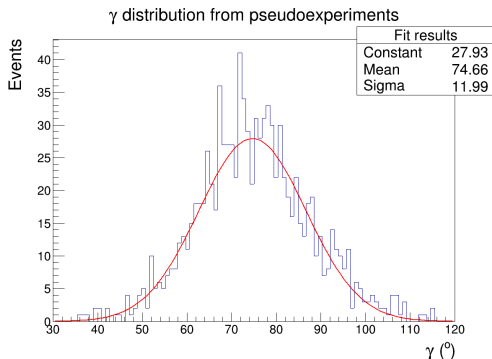


Figure 3: γ distribution

Achieved γ precision of $\sigma(\gamma) = 12^{\circ}$

Global mass fit

Global mass fit

- Fit all $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ candidates
- Fix overall signal yield and PDF shape parameters for binned CP fit

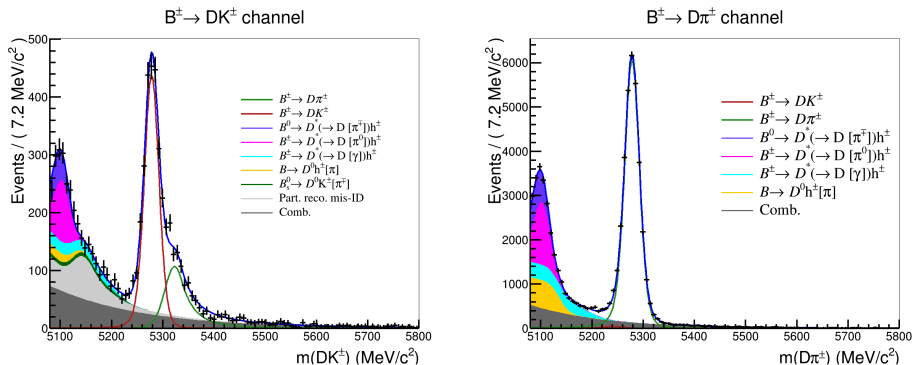


Figure 4: Signal yields are 2290 ± 59 (left) and $33\,113 \pm 211$ (right)

Binned CP fit

- Strong-phase inputs are taken from LHCb amplitude model for now

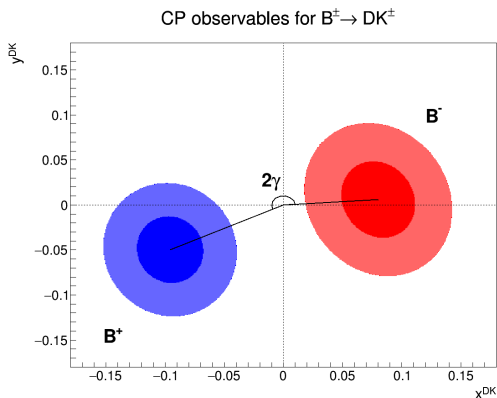
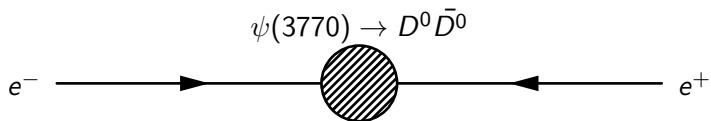


Figure 5: Confidence intervals for fitted CP observables x_\pm and y_\pm

Strong-phase inputs from quantum-correlated $D^0\bar{D}^0$ pairs

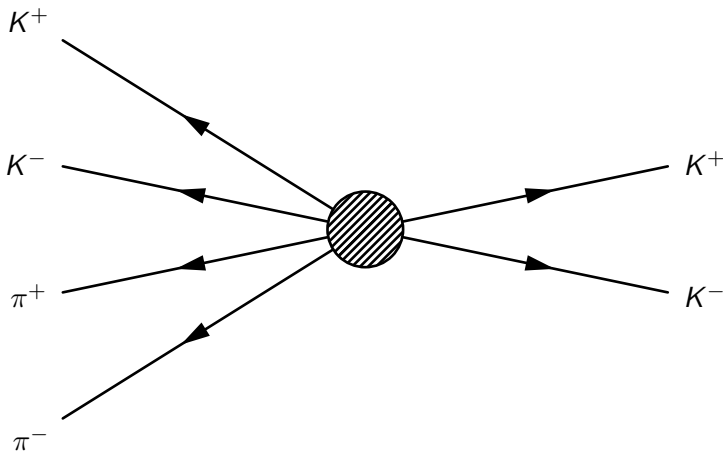
BESIII double tag analysis

BESIII is a charm factory: $e^+e^- \rightarrow \psi(3770) \rightarrow D^0\bar{D}^0$



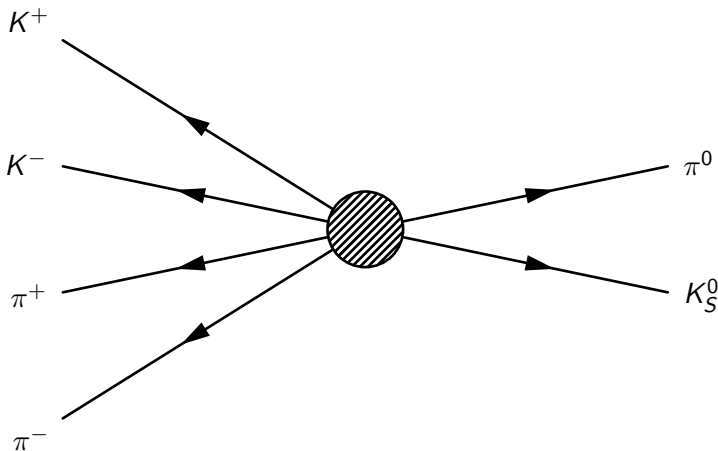
BESIII double tag analysis

Double tagged signal ($K^+K^- \pi^+ \pi^-$) with known CP even tag (K^+K^-)



BESIII double tag analysis

Double tagged signal ($K^+K^-\pi^+\pi^-$) with known CP odd tag ($K_S^0\pi^0$)

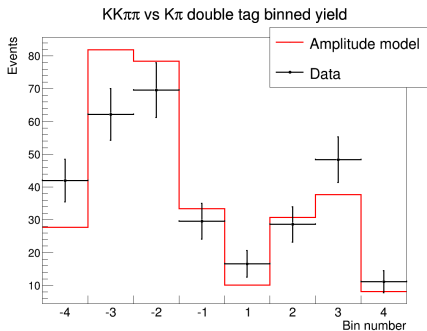


Double tag method

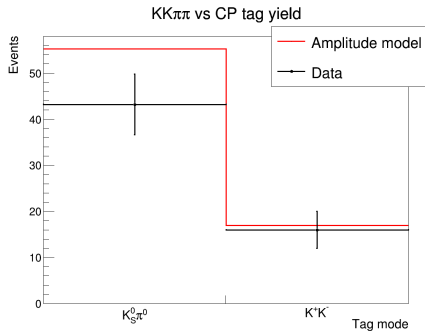
- Signal decay $D \rightarrow K^+ K^- \pi^+ \pi^-$ is correlated with the tag decay mode
- “Spooky action at a distance”!
- Double-tag yield of CP even tag:
 - $N_i = h(K_i - 2c_i \sqrt{K_i \bar{K}_i} + \bar{K}_i)$
- Double-tag yield of CP odd tag:
 - $N_i = h(K_i + 2c_i \sqrt{K_i \bar{K}_i} + \bar{K}_i)$

Double tag yields

- Current 3 fb^{-1} dataset is insufficient, expect 20 fb^{-1} by end of 2023
- For now, simply compare double tag yields with expectation from LHCb model



(a) $KK\pi\pi$ vs $K\pi$ (flavour tag)



(b) $KK\pi\pi$ vs $KK, K_S^0\pi^0$ (CP tags)

Summary and next steps

Summary:

- LHCb: Model-independent binned γ analysis looks promising
- BESIII: Initial double tag yields of BESIII data look consistent

Next steps:

- LHCb: Ensure peaking backgrounds are under control and study systematic uncertainties
- BESIII: Finalize double tag yield for all tag modes

Thank you!

Backup: Analytical expressions

- $c_i = \frac{\int_i d\Phi |\mathcal{A}(D^0)| |\mathcal{A}(\bar{D}^0)| \cos(\delta_D)}{\sqrt{\int_i d\Phi |\mathcal{A}(D^0)|^2 \int_i d\Phi |\mathcal{A}(\bar{D}^0)|^2}}$
- $s_i = \frac{\int_i d\Phi |\mathcal{A}(D^0)| |\mathcal{A}(\bar{D}^0)| \sin(\delta_D)}{\sqrt{\int_i d\Phi |\mathcal{A}(D^0)|^2 \int_i d\Phi |\mathcal{A}(\bar{D}^0)|^2}}$
- $K_i = \frac{\int_i d\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j d\Phi |\mathcal{A}(D^0)|^2}$

Backup: Optimize bin widths

- Optimize x_{\pm} , y_{\pm} sensitivity
- Vary bin edges, keep symmetric around $\delta_D = 0$

Binning Q value

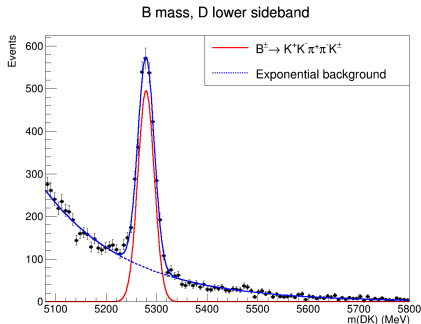
$$Q^2 = 1 - \sum_i \frac{K_i \bar{K}_i (1 - c_i^2 - s_i^2)}{N_i} \bigg/ \sum_i K_i$$

$$Q^2 \approx \sum_i N_i (c_i^2 + s_i^2) \bigg/ \sum_i N_i \text{ if } r_B = 0$$

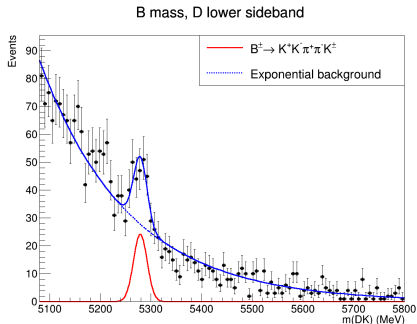
- Can achieve $Q \approx 0.90$ with 8 bins \implies expect $\sigma(\gamma) = 12^\circ$

Backup: Charmless backgrounds

- Study the D mass sideband to estimate yield of charmless background



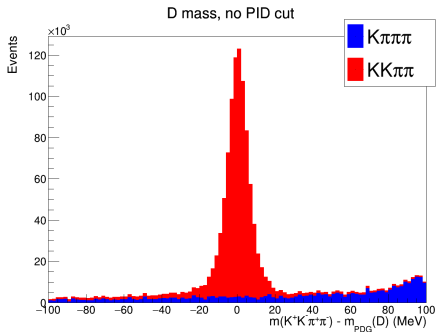
(a) No flight significance cut



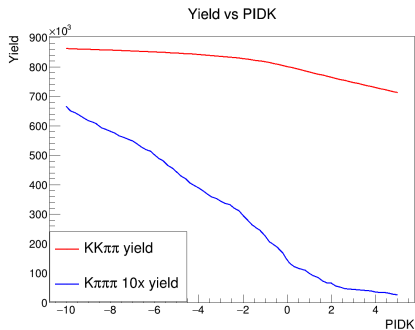
(b) Flight significance cut at 2

Backup: $K\pi\pi\pi$ background

- Use MC samples to study contamination of $D \rightarrow K\pi\pi\pi$ under the signal



(a) D mass spectrum of the signal $KK\pi\pi$ and background $K\pi\pi\pi$.



(b) Yield of signal $KK\pi\pi$ and background $K\pi\pi\pi$ as a function of PID cut.