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

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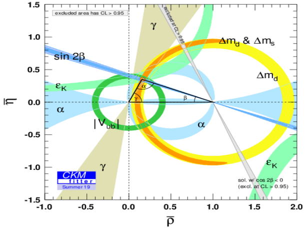


Outline

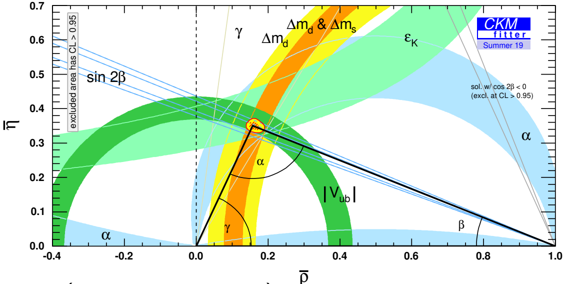
1. γ and the unitary triangle
2. Motivation for the $D \to K^+K^-\pi^+\pi^-$ decay mode
3. Binning scheme and binned fit of $D \to K^+K^-\pi^+\pi^-$
4. Global mass fit
5. Binned CP fit
6. Strong-phase inputs from quantum-correlated $D^0\bar{D}^0$ pairs
7. Summary and next steps

γ and the unitary triangle

How to measure γ?

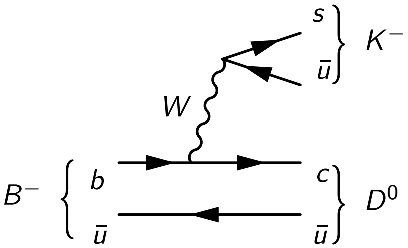
γ and the unitary triangle

- 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 $\implies$
  - Ideal Standard Model benchmark

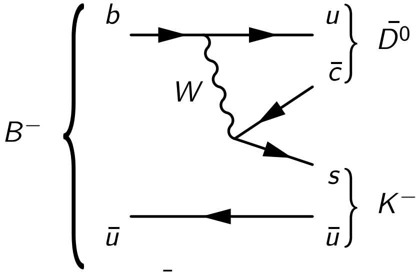


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

How to measure γ?



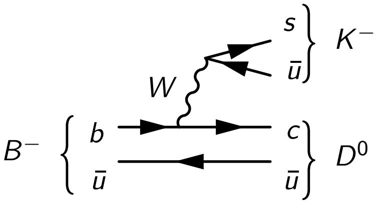
(a) $B^- \to D^0 K^-$



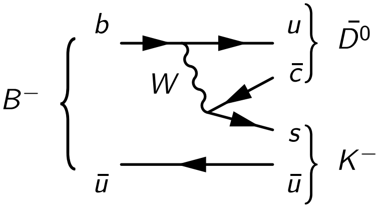
(b) $B^- \to \bar{D}^0 K^-$ (colour suppressed)

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

Simplified γ measurement



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



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

- Decay amplitudes:
  - $\mathcal{A}(B^- \to DK^-) = \mathcal{A}(D^0) + r_B e^{i(\delta_B - \gamma)} \mathcal{A}(\bar{D}^0)$
  - $\mathcal{A}(B^+ \to DK^+) = \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B + \gamma)} \mathcal{A}(D^0)$
- $\mathcal{A}(D^0)$-$\mathcal{A}(\bar{D}^0)$ 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 $D \to K^+K^-\pi^+\pi^-$ decay mode

The need for an efficient binning scheme

Motivation for the $D \to K^+K^-\pi^+\pi^-$ 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. Estimate 2000 candidates from LHCb Run 1+2
  5. New LHCb amplitude model JHEP 02 (2019) 126
  6. New era of 4-body γ measurements
     - $D \to K_S^0\pi^+\pi^-\pi^0$ by Belle JHEP 10 (2019) 178
     - Ongoing analysis of $D \to K^+\pi^-\pi^+\pi^-$ at LHCb

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

- Decay amplitudes:
  - $\mathcal{A}(B^- \to DK^-) = \mathcal{A}(D^0) + r_B e^{i(\delta_B-\gamma)}\mathcal{A}(\bar{D}^0)$
  - $\mathcal{A}(B^+ \to DK^+) = \mathcal{A}(\bar{D}^0) + r_B e^{i(\delta_B+\gamma)}\mathcal{A}(D^0)$
- Split into bins $-i, ..., -1, +1, ..., +i$ and integrate over phase space:
  - $N_i^- = h_{B^-}\left(K_i + \left(x_-^2 + y_-^2\right)\bar{K}_i + 2\sqrt{K_i\bar{K}_i}\left(x_-c_i + y_-s_i\right)\right)$
  - $N_{-i}^+ = h_{B^+}\left(K_i + \left(x_+^2 + y_+^2\right)\bar{K}_i + 2\sqrt{K_i\bar{K}_i}\left(x_+c_i + y_+s_i\right)\right)$
- Fit to extract $x_\pm$ and $y_\pm$ $\implies$ Interpret in terms of γ, r_B, δ_B

CP-violating observables

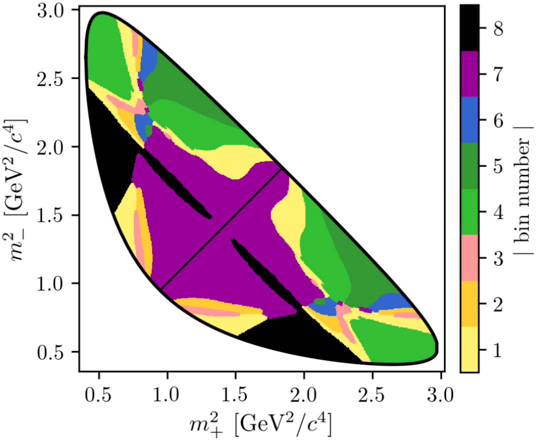
$x_\pm = r_B\cos(\delta_B \pm \gamma), \quad y_\pm = r_B\sin(\delta_B \pm \gamma)$

External strong-phase input

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

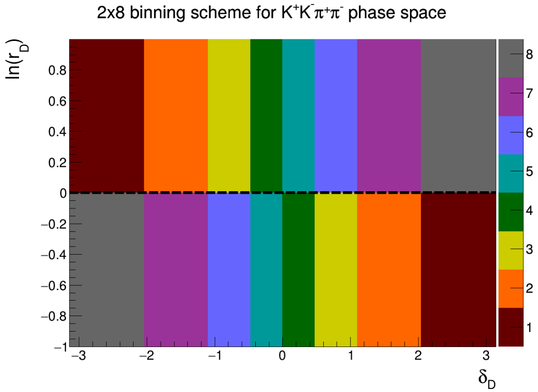
Binning scheme

- 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

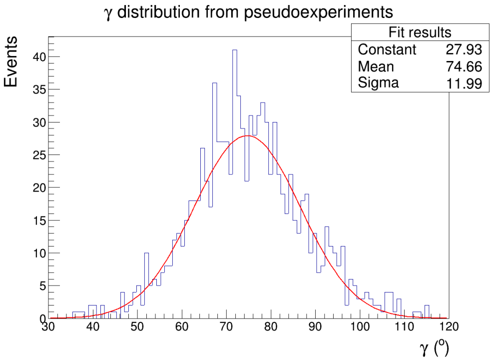


Figure 3: γ distribution

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

Global mass fit

Global mass fit

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

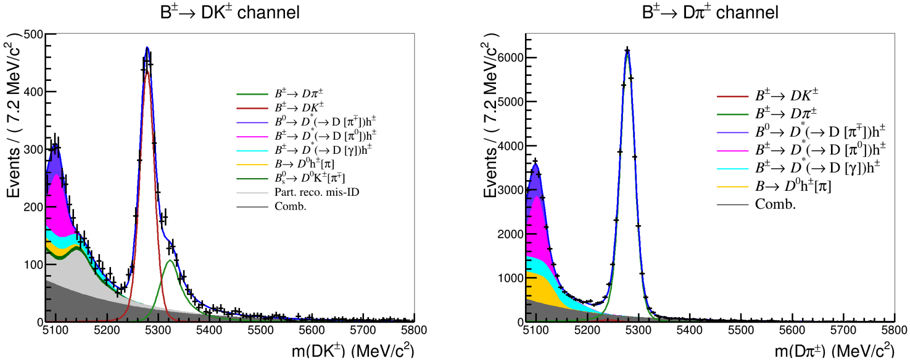


Figure 4: Signal yields are 2290 ± 59 (left) and $33\,113 \pm 211$ (right)

Binned CP fit

Global mass fit

- Strong-phase inputs are taken from LHCb amplitude model for now
- Generated 1000 toy datasets $\implies$ No biases in CP observables!

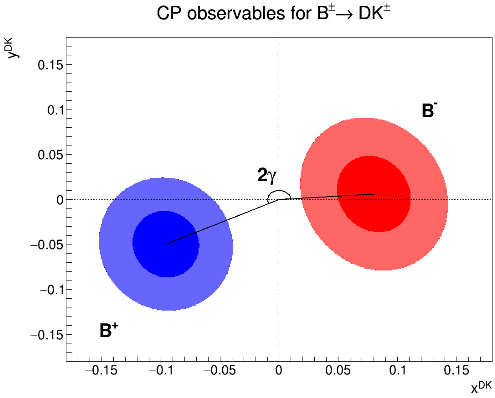
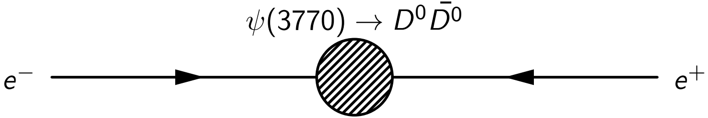


Figure 5: Confidence intervals for fitted CP observables $x_{\pm}$ and $y_{\pm}$

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

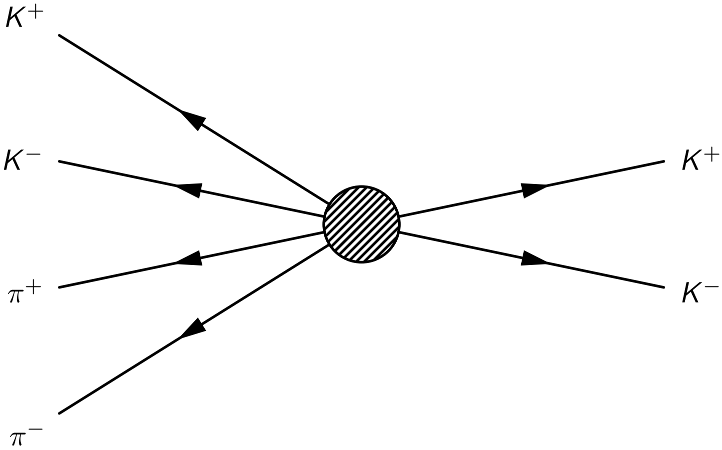
BESIII double tag analysis

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



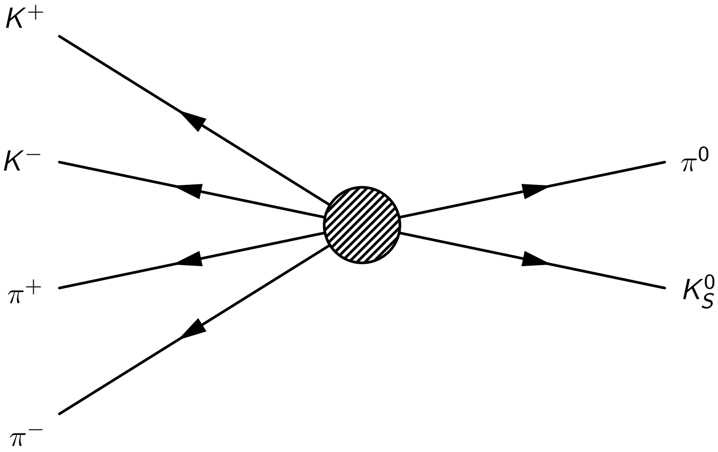
BESIII double tag analysis

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 ($K_S^0\pi^0$)

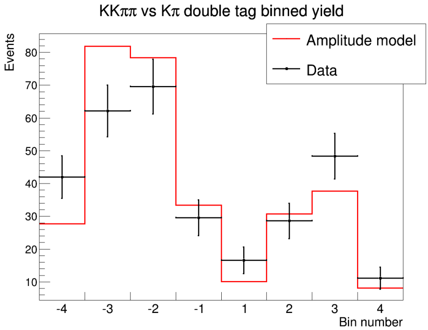


Double tag method

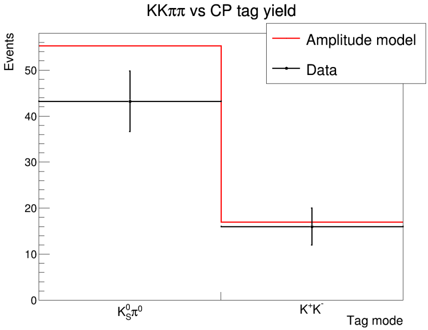
- Signal decay $D \to K^+K^-\pi^+\pi^-$ is correlated with the tag decay mode
- "Spooky action at a distance"!
- Double-tag yield of CP even tag:
  - $N_i = h(K_i - 2c_i\sqrt{K_i\bar{K}_i} + \bar{K}_i)$
- Double-tag yield of CP odd tag:
  - $N_i = h(K_i + 2c_i\sqrt{K_i\bar{K}_i} + \bar{K}_i)$

Double tag yields

- Current $3\,\text{fb}^{-1}$ insufficient, expect $20\,\text{fb}^{-1}$ 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

- $c_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D^0})| \cos(\delta_D)}{\sqrt{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2 \int_i \mathrm{d}\Phi \left|\mathcal{A}(\bar{D^0})\right|^2}}$

- $s_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D^0})| \sin(\delta_D)}{\sqrt{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2 \int_i \mathrm{d}\Phi \left|\mathcal{A}(\bar{D^0})\right|^2}}$

- $K_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}$

Backup: Optimize bin widths

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

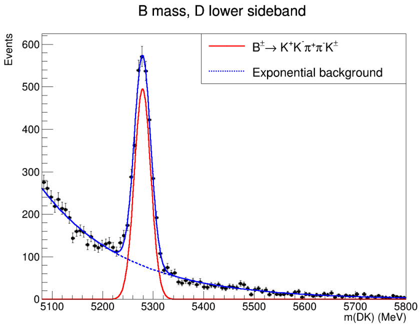
Binning Q value

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

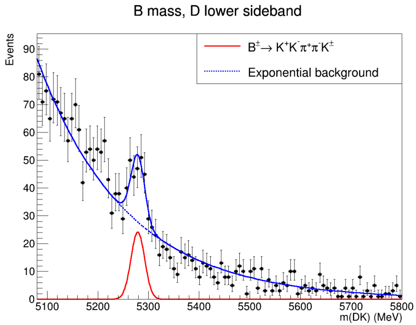
$$Q^2 \approx \sum_i N_i (c_i^2 + s_i^2) \Big/ \sum_i N_i \text{ if } r_B = 0$$

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

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



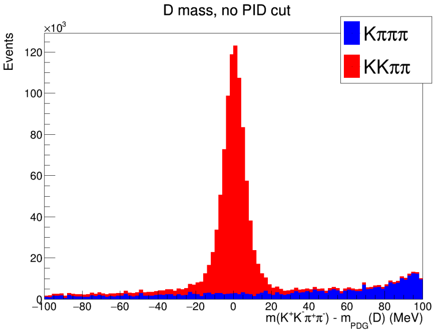
(a) No flight significance cut



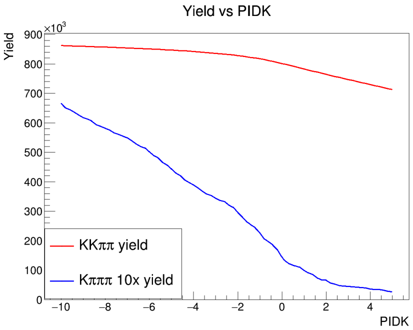
(b) Flight significance cut at 2

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

- Use MC samples to study contamination of $D \to K\pi\pi\pi$ 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.