Measuring γ in $B^\pm \to (K^+K^-\pi^+\pi^-)_D K^\pm$ decays

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Outline

1. Background
2. γ and the unitary triangle
3. The $D \to K^+K^-\pi^+\pi^-$ decay
4. Unbinned fit with amplitude model
5. Binned fit of $D \to K^+K^-\pi^+\pi^-$

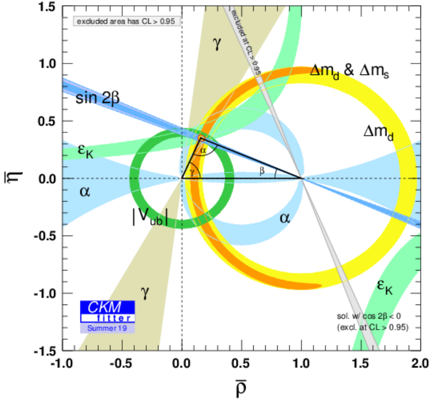
Background

- Supervisors:
  - Prof Guy Wilkinson (γ measurement)
  - Prof Neville Harnew (TORCH)
- 4-year MPhys in Oxford
  - Performance of monolithic CMOS sensors
  - Prof Daniela Bortoletto
- CERN Summer Student 2019
  - Beam loss reduction in TT20 transfer line
  - Dr Yann Dutheil, Dr Matthew Fraser
- Oxford Summer Student 2018
  - Study of PDF uncertainties in W-boson mass measurement
  - Prof Chris Hays
- RAL Summer Student 2018
  - Bending magnets in accelerator simulations
  - Dr Chris Rogers

γ and the unitary triangle

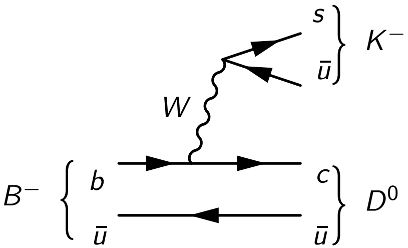
Unitarity of CKM matrix: $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$\text{Define } \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

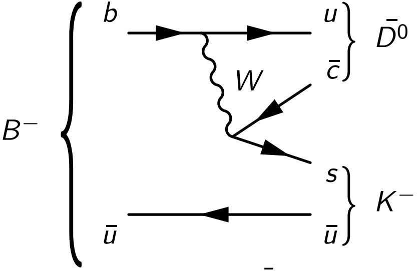


CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005)

b → u and b → c interference



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



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

Similar diagrams for $B^+ \to DK^+$, with $\gamma \to -\gamma \implies$

Inteference when D^0 and $\bar{D}^0$ decay into a common final state

Single most precise measurement: $\gamma = (68.7^{+5.2}_{-5.1})^\circ$ arXiv:2010.08483
$B^\pm \to DK^\pm$, $B^\pm \to D\pi^\pm$, $D \to K^0_S h^+ h^-$

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

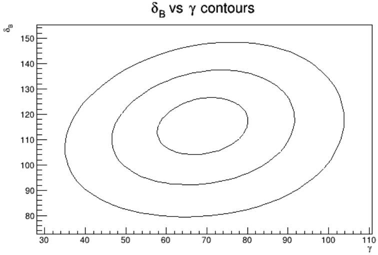
- Estimated 2000 events from LHCb Run 1 and 2
- First proposed by G. Wilkinson and J. Rademacker arXiv:hep-ph/0611272
  - Amplitude analysis: Isobar model
  - Estimated γ precision: 14° with 1000 events
- CLEO amplitude analysis arXiv:1201.5716
  - Estimated γ precision: 11° with 2000 events
- LHCb amplitude analysis arXiv:1811.08304
  - AmpGen for generating events and unbinned fit
- Other 4-body decay studies:
  - Binned analysis of $K_S^0\pi^+\pi^-\pi^0$ by Belle arXiv:1908.09499
  - Inclusive analysis of $h^\pm\pi^\mp\pi^+\pi^-$ arXiv:1906.08297, arXiv:1709.05855, arXiv:1603.08993 by LHCb

Unbinned fit with amplitude model

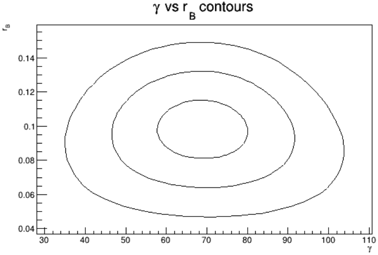
$$\mathcal{A}(B^- \to (K^+K^-\pi^+\pi^-)_D K^-) = \mathcal{A}_B \mathcal{A}(D^0 \to K^+K^-\pi^+\pi^-) + \mathcal{A}_B \mathcal{A}(\bar{D}^0 \to K^+K^-\pi^+\pi^-) r_B e^{i(\delta_B - \gamma)}$$

- $\mathcal{A}(D \to K^+K^-\pi^+\pi^-)$ obtained from amplitude model
- Fit with γ, δ_B and r_B as free parameters
- Initial values:
  - $\gamma = 75^\circ$
  - $\delta_B = 130^\circ$
  - $r_B = 0.1$
- Results from unbinned fit of 2×10^3 events:
  - $\gamma = (69 \pm 11)^\circ$
  - $\delta_B = (115 \pm 11)^\circ$
  - $r_B = 0.098 \pm 0.017$
- Results from unbinned fit of 2×10^4 events:
  - $\gamma = (77.1 \pm 3.5)^\circ$
  - $\delta_B = (129 \pm 4)^\circ$
  - $r_B = 0.093 \pm 0.006$

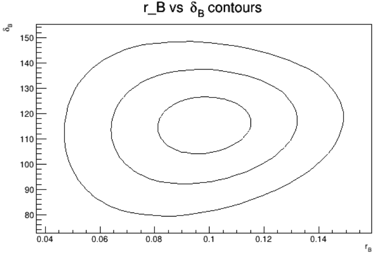
Unbinned fit of 2×10^3 events with amplitude model



(a) γ vs δ_B

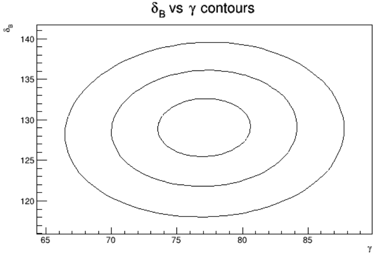


(b) γ vs r_B

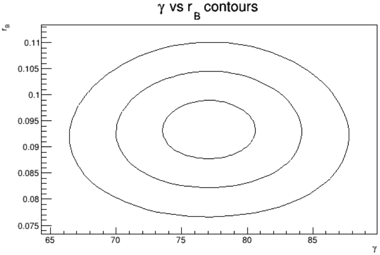


(c) r_B vs δ_B

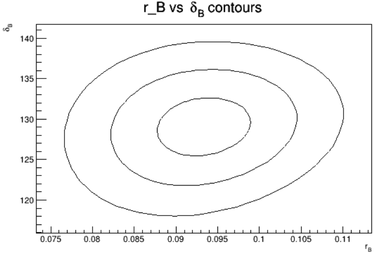
Unbinned fit of 2×10^4 events with amplitude model



(a) γ vs δ_B



(b) γ vs r_B



(c) r_B vs δ_B

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

$$\mathcal{A}(B^- \to (K^+K^-\pi^+\pi^-)_D K^-) = \mathcal{A}_B \mathcal{A}(D^0 \to K^+K^-\pi^+\pi^-) + \mathcal{A}_B \mathcal{A}(\bar{D}^0 \to K^+K^-\pi^+\pi^-) r_B e^{i(\delta_B - \gamma)}$$

Event yield in bin i

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

CP-violating observables

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

- c_i, s_i: Amplitude-averaged strong phase difference of D decay
- Measure c_i and s_i at BES III detector
- Can measure K_i and $\bar{K}_i$ at both LHCb and BES III
- Need to divide phase space into bins

Pull studies

- Pull studies shows that this works
- $x_{\pm}$ pulls show asymmetric tails for 2×10^3 events
- $x_{\pm}$ and $y_{\pm}$ are all satisfactory for 2×10^4 events
- Used an arbitrary and naiive binning scheme with 4 bins

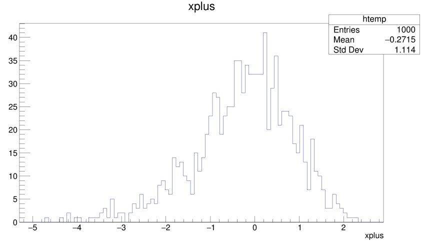
Binning scheme

Split phase space along the boundaries $E_{K^+} = E_{K_-}$ and $E_{\pi^+} = E_{\pi^-}$
Bin 1: $E_{K^+} > E_{K^-}, \quad E_{\pi^+} > E_{\pi^-}, \ldots$

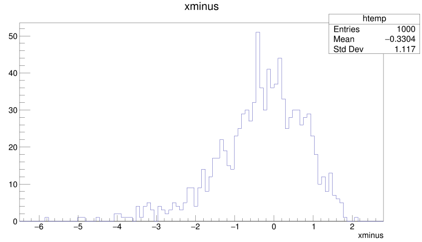
D decay hadronic parameters

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

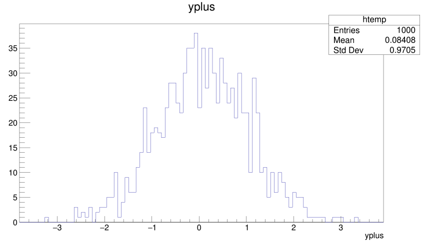
Pull study with 2×10^3 events



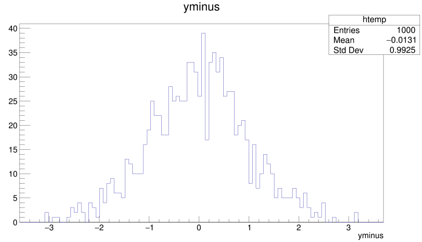
(a) x_+ pull



(b) x_- pull

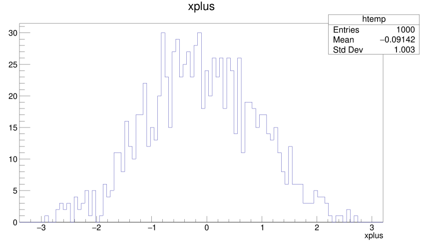


(c) y_+ pull

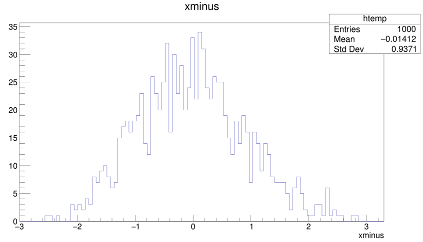


(d) y_- pull

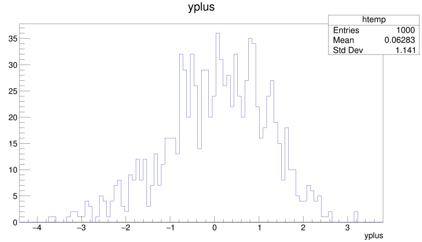
Pull study with 2×10^4 events



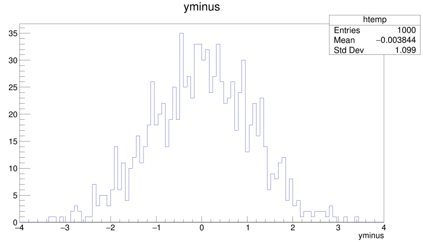
(a) x_+ pull



(b) x_- pull



(c) y_+ pull



(d) y_- pull

Parameterisation of phase space

- 4-body phase space is 5-dimensional
- Convenient to choose rectangular coordinates

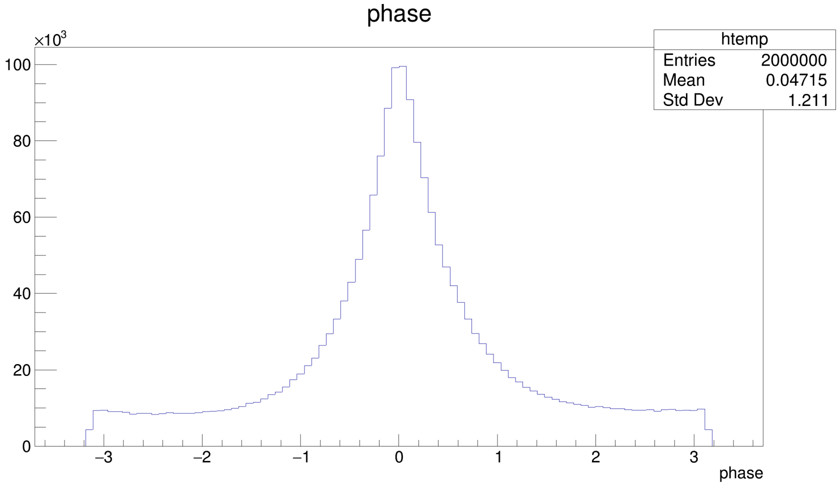
Phase space parameterisation

$$
\begin{aligned}
x_1 &= m(K^+\pi^+) + \alpha \\
x_2 &= m(K^-\pi^-) + \alpha, \quad \alpha = \min\big(m(K^+\pi^+), m(K^-\pi^-)\big) \\
x_3 &= \cos(\theta_+), \quad \text{(Helicity angles)} \\
x_4 &= \cos(\theta_-) \\
x_5 &= \phi
\end{aligned}
$$

- Define binning scheme in terms of these coordinates
- Ideally have a constant strong phase difference in each bin
- Determine binning scheme based on amplitude model, but final fit is model independent

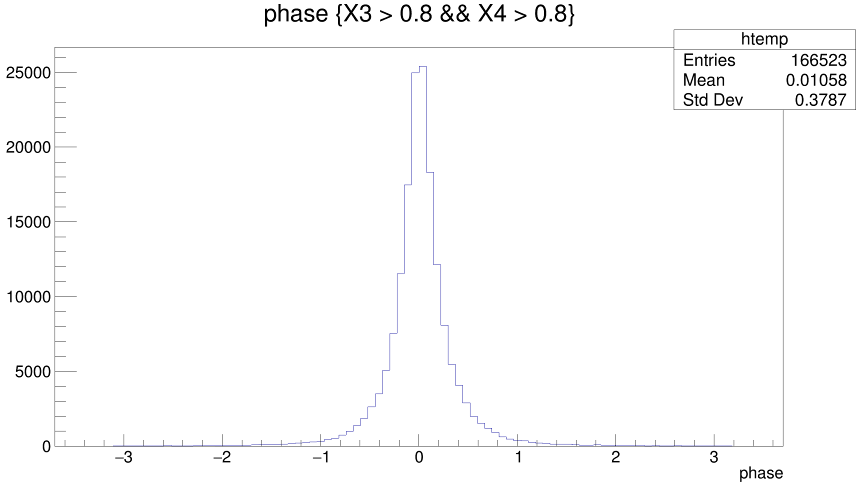
Histogram of strong phase difference

Strong phase difference from amplitude model:



Histogram of strong phase difference

Place cuts $x_3 > 0.8, x_4 > 0.8$:



Summary and next steps

Summary:

- Model independent determination of γ from $B^\pm \to (K^+K^-\pi^+\pi^-)_D K^\pm$ decay
- External input from BES III
- Precision from unbinned fit with 2×10^3 events: $\sigma(\gamma) \approx 11^\circ$
- Binned fit in 5 dimensions, need to understand phase space

Next steps:

- Finish mapping out phase space
- Decide on a suitable binning scheme
- Look at data from BES III
- Look at LHCb data