

# Measuring $\gamma$ in $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D K^\pm$ decays

Martin Tat

Oxford LHCb

22nd November 2020



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

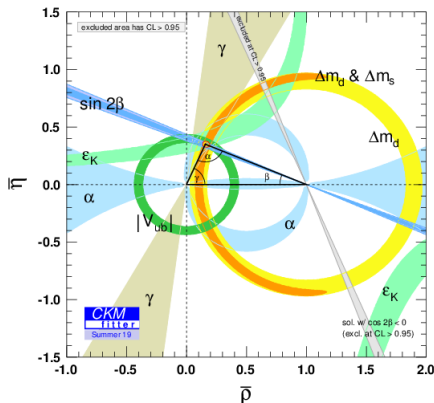
# Background

- Supervisors:
  - Prof Guy Wilkinson ( $\gamma$  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

## $\gamma$ and the unitary triangle

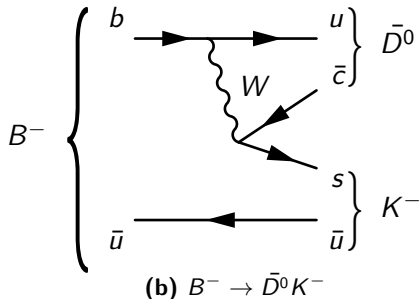
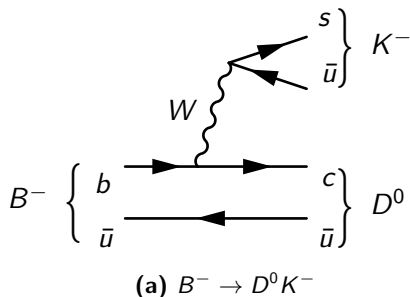
Unitarity of CKM matrix:  $V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

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



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

# $b \rightarrow u$ and $b \rightarrow c$ interference



Similar diagrams for  $B^+ \rightarrow DK^+$ , with  $\gamma \rightarrow -\gamma \Rightarrow$

Interference 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](https://arxiv.org/abs/2010.08483)

$B^\pm \rightarrow DK^\pm$ ,  $B^\pm \rightarrow D\pi^\pm$ ,  $D \rightarrow K_S^0 h^+ h^-$

# The $D \rightarrow K^+ K^- \pi^+ \pi^-$ decay

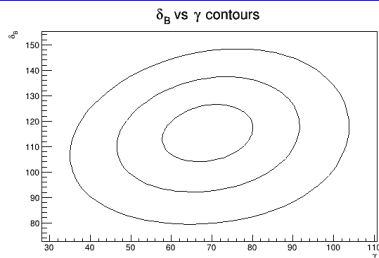
- Estimated 2000 events from LHCb Run 1 and 2
- First proposed by G. Wilkinson and J. Rademacker  
[arXiv:hep-ph/0611272](#)
  - Amplitude analysis: Isobar model
  - Estimated  $\gamma$  precision:  $14^\circ$  with 1000 events
- CLEO amplitude analysis [arXiv:1201.5716](#)
  - Estimated  $\gamma$  precision:  $11^\circ$  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

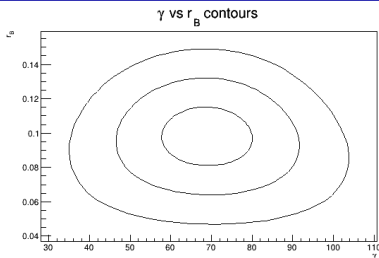
$$\mathcal{A}(B^- \rightarrow (K^+ K^- \pi^+ \pi^-)_D K^-) = \mathcal{A}_B \mathcal{A}(D^0 \rightarrow K^+ K^- \pi^+ \pi^-) \\ + \mathcal{A}_B \mathcal{A}(\bar{D}^0 \rightarrow K^+ K^- \pi^+ \pi^-) r_B e^{i(\delta_B - \gamma)}$$

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

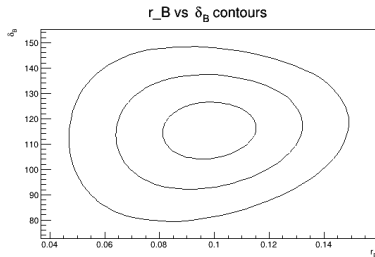
# Unbinned fit of $2 \times 10^3$ events with amplitude model



(a)  $\gamma$  vs  $\delta_B$



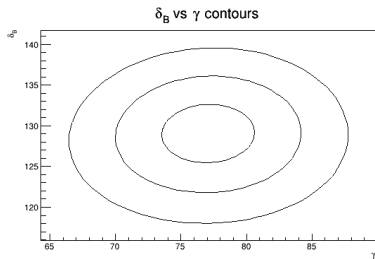
(b)  $\gamma$  vs  $r_B$



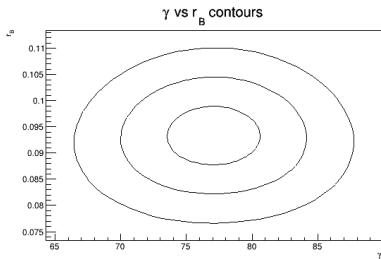
(c)  $r_B$  vs  $\delta_B$



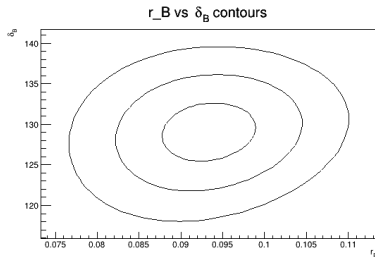
# Unbinned fit of $2 \times 10^4$ events with amplitude model



(a)  $\gamma$  vs  $\delta_B$



(b)  $\gamma$  vs  $r_B$



(c)  $r_B$  vs  $\delta_B$

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

$$\begin{aligned}\mathcal{A}(B^- \rightarrow (K^+ K^- \pi^+ \pi^-)_D K^-) &= \mathcal{A}_B \mathcal{A}(D^0 \rightarrow K^+ K^- \pi^+ \pi^-) \\ &\quad + \mathcal{A}_B \mathcal{A}(\bar{D}^0 \rightarrow K^+ K^- \pi^+ \pi^-) r_B e^{i(\delta_B - \gamma)}\end{aligned}$$

### Event yield in bin $i$

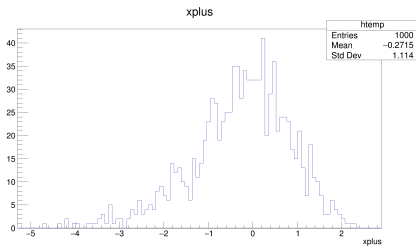
$$\begin{aligned}N_i^- &= h_{B^-} \left( K_i + (x_-^2 + y_-^2) \bar{K}_i + 2\sqrt{K_i \bar{K}_i} (x_- c_i + y_- s_i) \right) \\ N_i^+ &= h_{B^+} \left( \bar{K}_i + (x_+^2 + y_+^2) K_i + 2\sqrt{K_i \bar{K}_i} (x_+ c_i - y_+ s_i) \right)\end{aligned}$$

### CP-violating observables

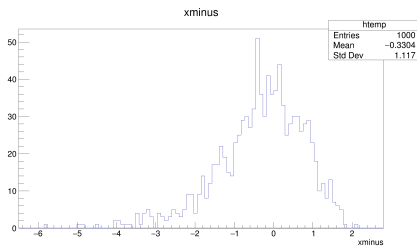
$$x_{\pm} = r_B \cos(\delta_B \pm \gamma), \quad y_{\pm} = r_B \sin(\delta_B \pm \gamma)$$

- $c_i, s_i$ : 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

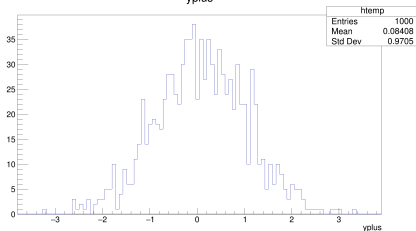
# Pull study with $2 \times 10^3$ events



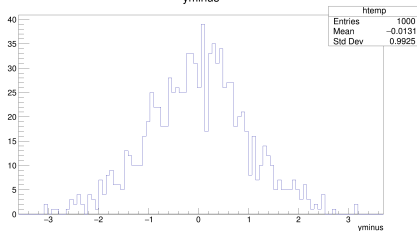
(a)  $x_+$  pull



(b)  $x_-$  pull

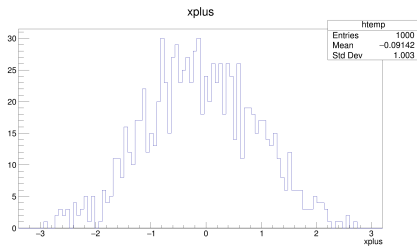


(c)  $y_+$  pull

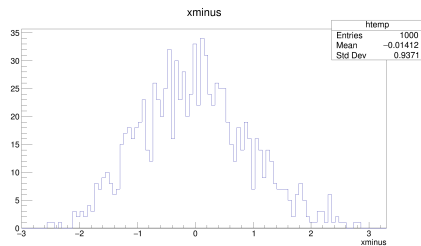


(d)  $y_-$  pull

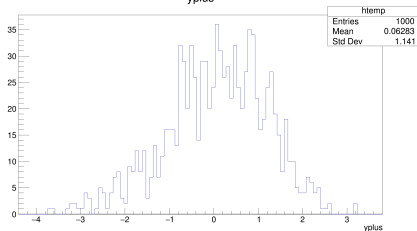
# Pull study with $2 \times 10^4$ events



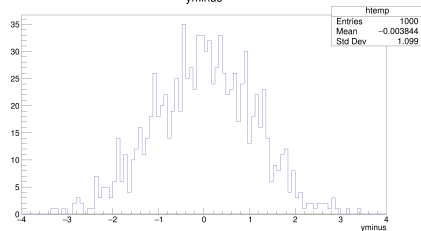
(a)  $x_+$  pull



(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

$$x_1 = m(K^+\pi^+) + \alpha$$

$$x_2 = m(K^-\pi^-) + \alpha, \quad \alpha = \min(m(K^+\pi^+), m(K^-\pi^-))$$

$$x_3 = \cos(\theta_+), \quad (\text{Helicity angles})$$

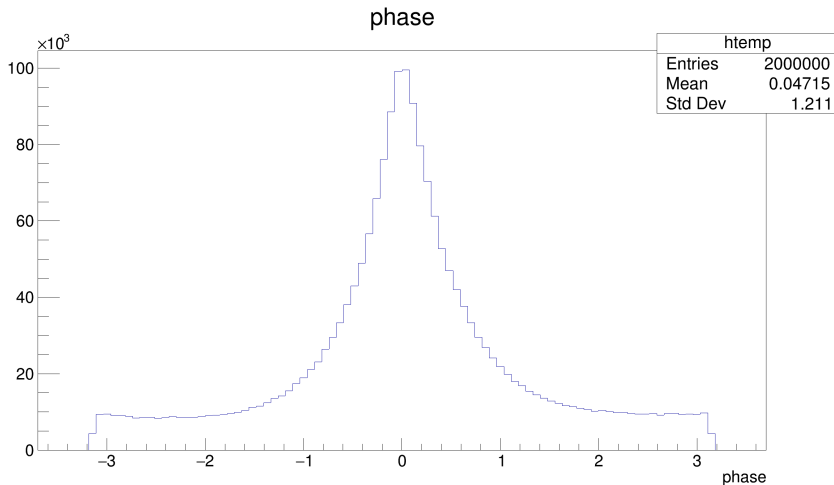
$$x_4 = \cos(\theta_-)$$

$$x_5 = \phi$$

- 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

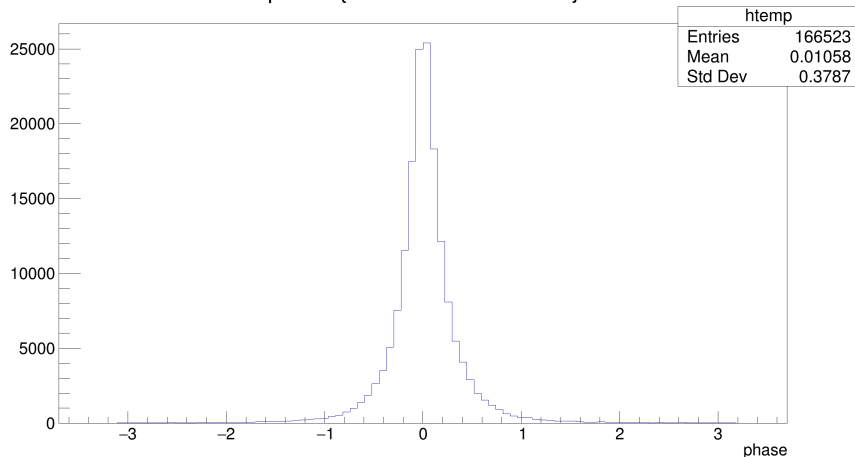
Strong phase difference from amplitude model:



# Histogram of strong phase difference

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

phase {X3 > 0.8 && X4 > 0.8}



# Summary and next steps

## Summary:

- Model independent determination of  $\gamma$  from  $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D K^\pm$  decay
- External input from BES III
- Precision from unbinned fit with  $2 \times 10^3$  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