

# Model-independent measurement of $\gamma$ using $B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h^\pm$ decays

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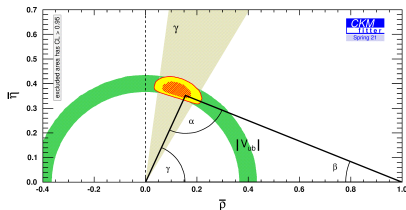
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# Outline

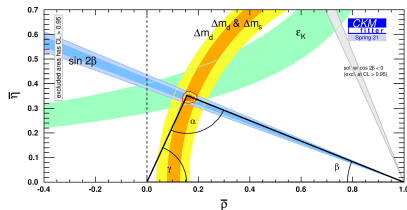
- 1 Introduction to  $\gamma$  and  $CP$  violation
- 2 Model-dependent  $\gamma$  with  $D \rightarrow K^+ K^- \pi^+ \pi^-$
- 3 Strong-phase inputs from BESIII
- 4 Global fit
- 5 CP fit
- 6 Systematic uncertainties
- 7 Interpretation
- 8 Conclusion

# Introduction to $\gamma$ and $CP$ violation

- CPV in SM is described by the Unitary Triangle, with angles  $\alpha, \beta, \gamma$
- The angle  $\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$  is very important:
  - ① Negligible theoretical uncertainties: Ideal SM benchmark
  - ② Accessible at tree level: Indirectly probe New Physics that enter loops
  - ③ Compare with a global CKM fit: Is the Unitary Triangle a triangle?



(a) Tree level:  $\gamma = (72.1^{+5.4}_{-5.7})^\circ$

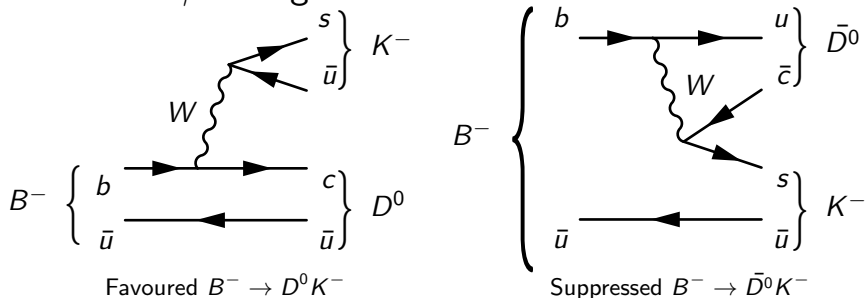


(b) Loop level:  $\gamma = (65.5^{+1.1}_{-2.7})^\circ$

CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005), updated results and plots available at:  
<http://ckmfitter.in2p3.fr>

# Sensitivity through interference

Measure  $\gamma$  through interference effects in  $B^\pm \rightarrow DK^\pm$



- Superposition of  $D^0$  and  $\bar{D}^0$ 
  - Consider  $D^0/\bar{D}^0$  decays to the same final state, such as  $D \rightarrow K^+ K^-$
- $b \rightarrow u\bar{c}s$  and  $b \rightarrow c\bar{u}s$  interference  $\rightarrow$  Sensitivity to  $\gamma$

$$\mathcal{A}(B^-) = \mathcal{A}_B \left( \mathcal{A}_{D^0} + r_B e^{i(\delta_B - \gamma)} \mathcal{A}_{\bar{D}^0} \right)$$

$$\mathcal{A}(B^+) = \mathcal{A}_B \left( \mathcal{A}_{\bar{D}^0} + r_B e^{i(\delta_B + \gamma)} \mathcal{A}_{D^0} \right)$$

# Multi-body charm decays

In this presentation, four-body charm decays are considered:

$$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$$

$$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$$

Note: Such decays have a five-dimensional phase space!

## Degrees of freedom for an $N$ -body decay

$4N$  (momentum components)

–  $N$  ( $E_i^2 - p_i^2 = m_i^2$ )

– 4 (energy-momentum conservation)

– 3 (choice of frame)

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=  $3N - 7$  degrees of freedom

# Previous studies of $\gamma$ with $B^\pm \rightarrow DK^\pm$ , $D \rightarrow K^+K^-\pi^+\pi^-$

- ① First proposed by J. Rademacker and G. Wilkinson
  - [Physics Letters B 647 \(2007\) 400](#)
  - Amplitude model by FOCUS
  - Expected  $\gamma$  precision from amplitude fit with 1000 candidates:  $14^\circ$
- ② CLEO amplitude analysis
  - [Phys. Rev. D 85 \(2012\) 122002](#)
  - Expected  $\gamma$  precision from amplitude fit with 2000 candidates:  $11^\circ$
- ③ State of the art amplitude analysis by LHCb:
  - [JHEP 02 \(2019\) 126](#)
- ④ Model-dependent measurement by LHCb:
  - [Eur. Phys. J. C 83 547 \(2023\)](#)
  - Optimised binning scheme using LHCb amplitude model

# Previous studies of $\gamma$ with $B^\pm \rightarrow DK^\pm$ , $D \rightarrow \pi^+\pi^-\pi^+\pi^-$

## 1 CLEO amplitude analysis

- [JHEP 05 \(2017\) 143](#)

## 2 CLEO-c strong-phase measurement

- [JHEP 01 \(2018\) 144](#)
- Expected  $\gamma$  statistical (systematic) precision with  $2 \times 5$  bins is  $9.7^\circ$  ( $7.4^\circ$ )

## 3 Recent work by Bristol group:

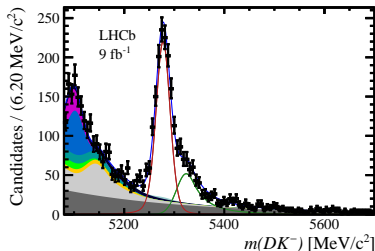
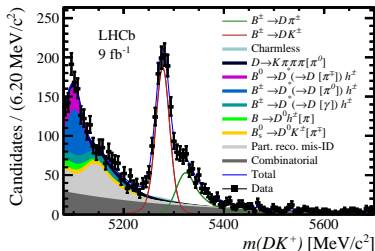
- [B2OC meeting, 18th April 2024](#)

## 4 New BESIII amplitude model:

- [arXiv:2312.02524](#)
- Joint effort between Oxford and Bristol group using a new, optimal binning scheme

# Phase-space integrated CP observables

Phase-space integrated study of  $\gamma$ :  
Charged asymmetries measured for  $D \rightarrow K^+ K^- \pi^+ \pi^-$  and  
 $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  in Eur. Phys. J. C **83** 547 (2023)



$D \rightarrow K^+ K^- \pi^+ \pi^-$

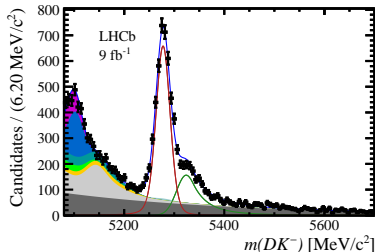
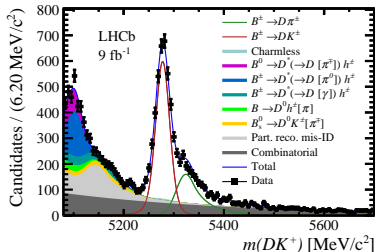
•  $B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h^\pm$  asymmetries:

- $D \rightarrow K^+ K^- \pi^+ \pi^-$ :  $\mathcal{A} = 0.095 \pm 0.023 \pm 0.002$
- $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ :  $\mathcal{A} = 0.061 \pm 0.013 \pm 0.002$



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$$D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$$

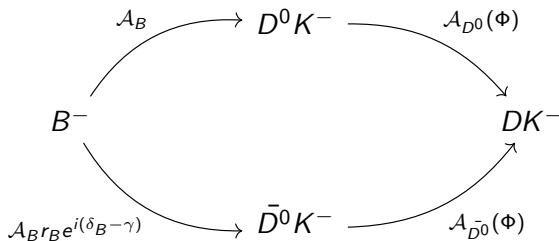
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# Multi-body $D$ decays

This talk: Discuss  $D \rightarrow h^+ h^- \pi^+ \pi^-$ , where interference effects vary across phase space

- Strong-phase difference  $\delta_D$  is a function of phase space
- Compare yields of  $B^+$  and  $B^-$  and determine the asymmetry in local phase space regions, known as phase-space bins



$$|\mathcal{A}(B^-)|^2 \propto |\mathcal{A}_{D^0}(\Phi)|^2 + r_B^2 |\mathcal{A}_{\bar{D}^0}(\Phi)|^2 + 2r_B |\mathcal{A}_{D^0}(\Phi)| |\mathcal{A}_{\bar{D}^0}(\Phi)| \cos(\delta_B - \gamma + \delta_D)$$

# The BPGGSZ method

## Event yield in bin $i$

$$N_i^- = h_{B^-} (F_i + (x_-^2 + y_-^2) \bar{F}_i + 2\sqrt{F_i \bar{F}_i} (x_- c_i + y_- s_i))$$
$$N_{-i}^+ = h_{B^+} (F_i + (x_+^2 + y_+^2) \bar{F}_i + 2\sqrt{F_i \bar{F}_i} (x_+ c_i + y_+ s_i))$$

- CP observables:

- $x_{\pm}^{DK} = r_B^{DK} \cos(\delta_B^{DK} \pm \gamma), \quad y_{\pm}^{DK} = r_B^{DK} \sin(\delta_B^{DK} \pm \gamma)$
- $x_{\xi}^{D\pi} = \text{Re}(\xi^{D\pi}), \quad y_{\xi}^{D\pi} = \text{Im}(\xi^{D\pi}) \quad \left( \xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi} - \delta_B^{DK})} \right)$

- Fractional bin yield:

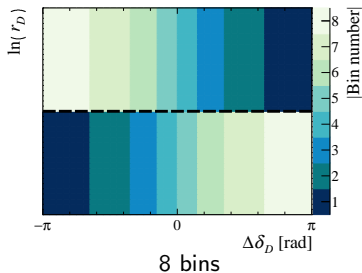
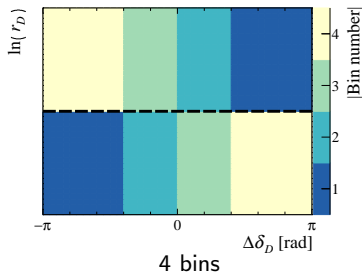
- $F_i = \frac{\int_i d\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j d\Phi |\mathcal{A}(D^0)|^2}$
- Floated in the fit, mostly constrained by  $B^{\pm} \rightarrow D\pi^{\pm}$

- Amplitude averaged strong phases:

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

# $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ binning scheme

- Interpretation of  $\gamma$  from the multi-body charm decays require external inputs of the charm strong-phase differences
- Measure model-independent strong-phases at a charm factory, such as BESIII, using an optimised binning scheme

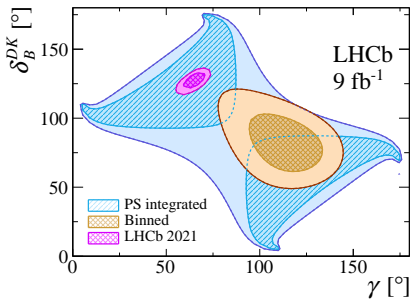
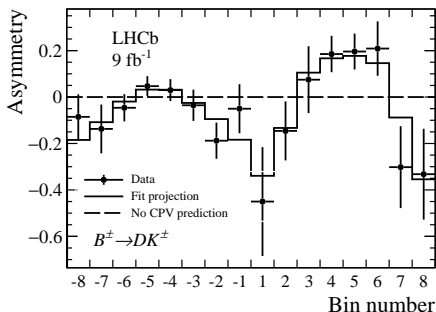


$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$  binning scheme

# Model-dependent measurement with $D \rightarrow K^+ K^- \pi^+ \pi^-$

From the phase-space binned asymmetries, we obtain:

$$\gamma = (116^{+12}_{-14})^\circ$$



[Eur. Phys. J. C 83, 547 \(2023\)](#)

How will this evolve with model-independent BESIII inputs? Will the  $3\sigma$  tension reduce?

## What is new in this presentation?

- I will only discuss the binned analysis of these modes today
- Binned strong-phase analyses of  $D \rightarrow K^+ K^- \pi^+ \pi^-$  (Oxford) and  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  (Oxford-USTC) are emerging from BESIII
  - For  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ , these improve in precision on earlier binned study made with CLEO-c data [JHEP 01 \(2018\) 144](#)
- Make first binned model-independent measurement with  $D \rightarrow K^+ K^- \pi^+ \pi^-$ , updating earlier LHCb model-dependent analysis
- Clone analysis for  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  with same 4-body selection
- After checking for compatibility, perform joint analysis

# Motivation for this analysis

The results shown in this presentation make use of strong-phase results from the BESIII collaboration. They derive from mature analyses led by Oxford and USTC, but are not yet public, and remain preliminary in nature. They are not to be shown outside LHCb. We thank the BESIII management for the privilege of being allowed to use them during the review of this measurement.

# BESIII preliminary $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ strong-phase results

First binned strong-phase analysis of  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ , which uses the  $2 \times 4$  binning scheme with  $16 \text{ fb}^{-1}$   $\psi(3770)$  data

$$c_1 = -0.28 \pm 0.09 \pm 0.01$$

$$s_1 = -0.68 \pm 0.24 \pm 0.04$$

$$c_2 = +0.83 \pm 0.04 \pm 0.01$$

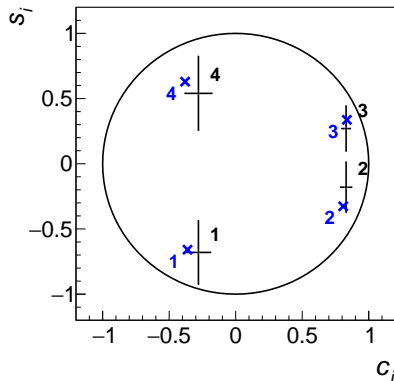
$$s_2 = -0.18 \pm 0.19 \pm 0.03$$

$$c_3 = +0.83 \pm 0.03 \pm 0.01$$

$$s_3 = +0.27 \pm 0.17 \pm 0.03$$

$$c_4 = -0.28 \pm 0.10 \pm 0.01$$

$$s_4 = +0.54 \pm 0.28 \pm 0.04$$



Measured values (black) are consistent and close to LHCb model predictions (blue), so central values are not expected to change much



# BESIII preliminary $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ strong-phase results

- Binned strong-phase analysis of  $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$  uses the  $2 \times 5$  “optimal” binning scheme with  $3 \text{ fb}^{-1}$   $\psi(3770)$
- Earlier CLEO-c analysis with  $0.8 \text{ fb}^{-1}$  [JHEP 01 \(2018\) 144](#)
- New BESIII analysis uses a new binning scheme optimised with a BESIII amplitude model [arXiv:2312.02524](#)
  - Amplitude model constructed from a larger data set
  - In principle more sensitive
- Two binning schemes are available:
  - We use the more sensitive “optimal” binning with  $Q = 0.85$
  - The other “equal  $\delta$ ” binning has  $Q = 0.80$

# BESIII preliminary $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ strong-phase results

Small differences between model prediction and measurement, but data points are generally close to the unit circle

$$c_1 = +0.12 \pm 0.09 \pm 0.02$$

$$s_1 = -0.42 \pm 0.21 \pm 0.04$$

$$c_2 = +0.74 \pm 0.04 \pm 0.02$$

$$s_2 = -0.39 \pm 0.16 \pm 0.06$$

$$s_3 = -0.25 \pm 0.12 \pm 0.03$$

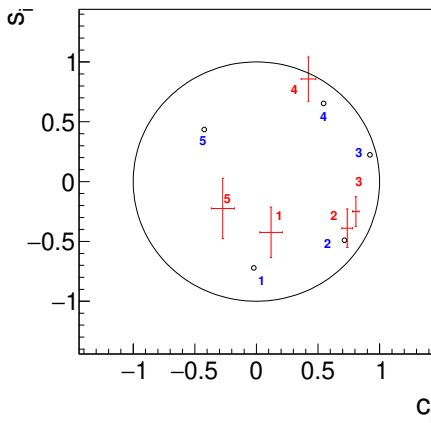
$$c_3 = +0.81 \pm 0.03 \pm 0.01$$

$$c_4 = +0.42 \pm 0.06 \pm 0.02$$

$$s_4 = +0.86 \pm 0.19 \pm 0.07$$

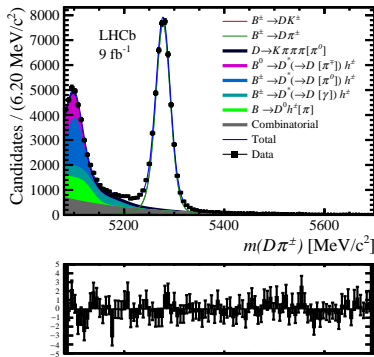
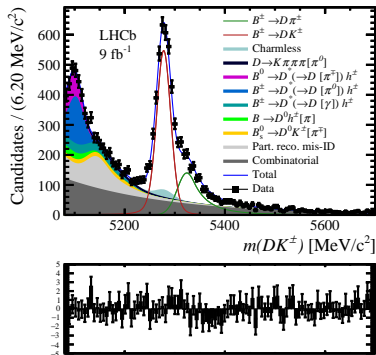
$$c_5 = -0.27 \pm 0.09 \pm 0.03$$

$$s_5 = -0.22 \pm 0.25 \pm 0.08$$



The HyperPlot software is used (binary lookup tree in 5D phase space)

Global fit of  $K^+K^-\pi^+\pi^-$  remains as in model-dependent publication:



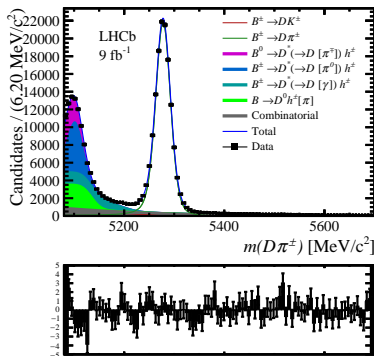
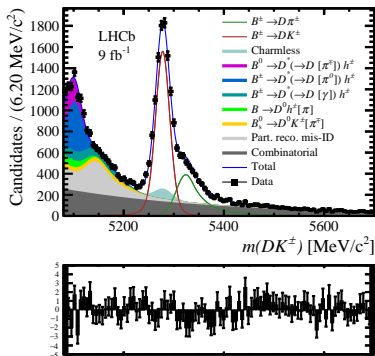
•  $B^\pm \rightarrow [K^+K^-\pi^+\pi^-]_D h^\pm$  signal yield:

- $B^\pm \rightarrow DK^\pm$ :  $3051 \pm 38$
- $B^\pm \rightarrow D\pi^\pm$ :  $44356 \pm 218$

How do we include the  $\pi^+\pi^-\pi^+\pi^-$  mode?

- We have already studied  $B^\pm \rightarrow [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$  for phase-space integrated measurement
  - 1 Different  $D$  daughter PID cuts in stripping
  - 2 No  $D \rightarrow K\pi\pi\pi\pi^0$  background
  - 3 Charmless background recalculated using the sideband
  - 4 Use same BDT
  - 5 No additional peaking backgrounds
- Sort candidates into phase-space bins using BESIII binning scheme
- Can fit separately or simultaneously with  $K^+K^-\pi^+\pi^-$

Global fit of  $\pi^+\pi^-\pi^+\pi^-$  has a good fit quality:



- $B^\pm \rightarrow [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$  signal yield:
  - $B^\pm \rightarrow DK^\pm$ :  $8745 \pm 105$
  - $B^\pm \rightarrow D\pi^\pm$ :  $126314 \pm 385$

After global fit, perform a “CP fit” to study CP violation:

- Split candidates by:
  - ①  $B^+$  and  $B^-$  charges
  - ②  $B^\pm \rightarrow DK^\pm$  and  $B^\pm \rightarrow D\pi^\pm$  decays
  - ③  $D$  phase-space bins
- Combinatorial and low-mass backgrounds are floating in each category
- Parameterise signal yields in terms of  $x_\pm^{DK}$ ,  $y_\pm^{DK}$ ,  $x_\xi^{D\pi}$ ,  $y_\xi^{D\pi}$
- $2N - 1$  floating  $F_i$  parameters
- $c_i$  and  $s_i$  are Gaussian constrained

## Summary of free parameters in the CP fit:

$$K^+ K^- \pi^+ \pi^-$$

$$2 \times 2 \times 2 \times 4 = 32 \text{ categories}$$

- 6 CP observables
- 7  $F_i$  parameters
- 8  $c_i$  and  $s_i$  parameters
- 32 combinatorial yields
- 32 low mass yields
- 4 global normalisations
- Total: 89 parameters

$$\pi^+ \pi^- \pi^+ \pi^-$$

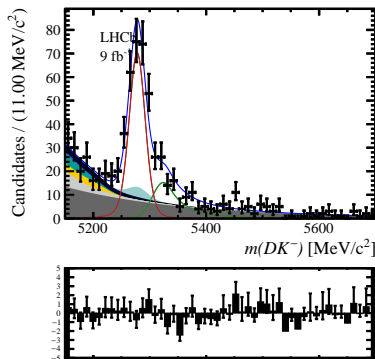
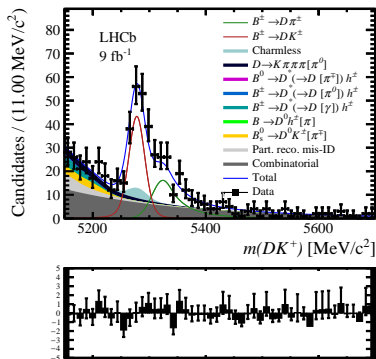
$$2 \times 2 \times 2 \times 5 = 40 \text{ categories}$$

- 6 CP observables
- 9  $F_i$  parameters
- 10  $c_i$  and  $s_i$  parameters
- 40 combinatorial yields
- 40 low mass yields
- 4 global normalisations
- Total: 109 parameters

In a combined fit where CP observables are shared, there are  
 $89 + 109 - 6 = 192$  parameters

## CP fit bin asymmetry

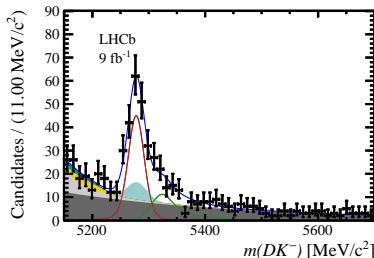
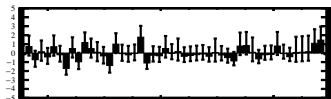
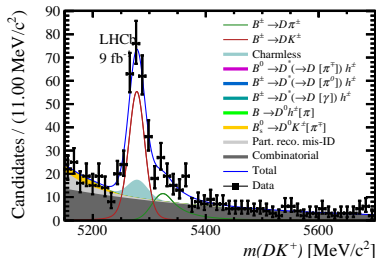
Example of bin asymmetry in  $D \rightarrow K^+ K^- \pi^+ \pi^-$  bin -3:





# CP fit bin asymmetry

Example of bin asymmetry in  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  bin +5:



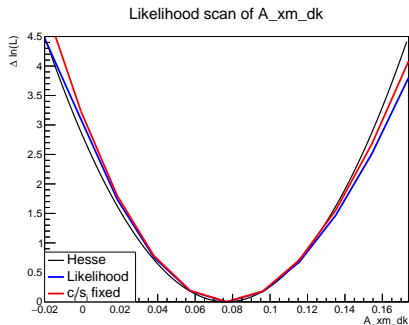
# Strong-phase parameters in CP fit

Why are  $c_i$  and  $s_i$  Gaussian constrained?

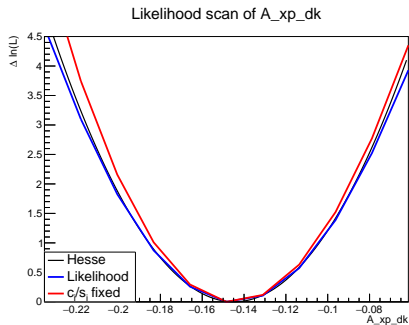
- Previous BPGGSZ analyses have kept  $c_i$  and  $s_i$  fixed
  - ①  $c_i$  and  $s_i$  uncertainties are added as a systematic through smearing
  - ② Convenient for calculating correlations between different analyses
  - ③ Appropriate when  $c_i$  and  $s_i$  uncertainties are small
- In four-body analyses, uncertainties on  $\gamma$  from  $c_i$  and  $s_i$  are almost the same size as the statistical uncertainty
- Large  $s_i$  uncertainties introduces non-Gaussian uncertainties on  $y_{\pm}$
- $\gamma$  moves significantly when fixing  $s_i$  instead of constraining them
- These effects are largest for  $K^+K^-\pi^+\pi^-$ , but are also seen in  $\pi^+\pi^-\pi^+\pi^-$  and in the combined fit

# Likelihood scan of CP observables

$x_{\pm}^{DK}$  agree well between likelihood scan and Hesse approximation



$x_{-}^{DK}$

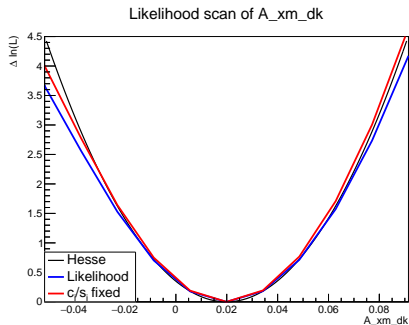


$x_{+}^{DK}$

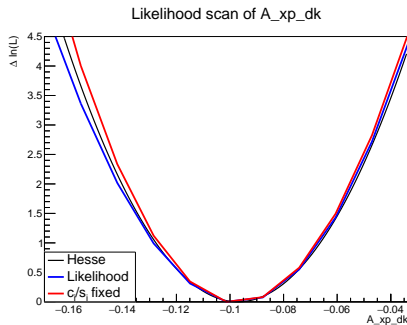
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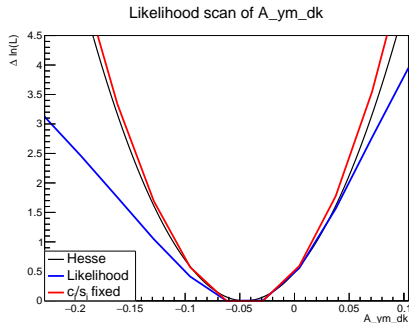


$x_{+}^{DK}$

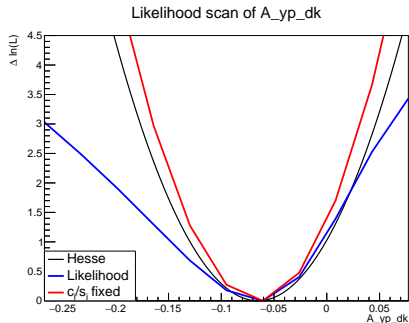
$$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$$

# Likelihood scan of CP observables

$y_{\pm}^{DK}$  diverges from Hesse approximation outside  $1\sigma$



$y_{-}^{DK}$

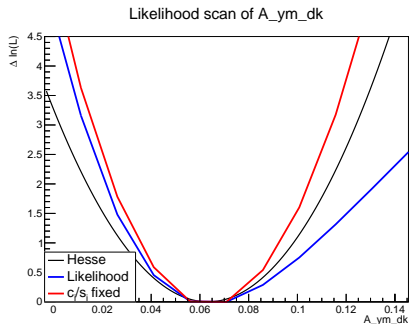


$y_{+}^{DK}$

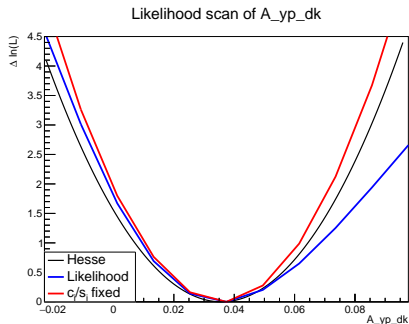
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# Likelihood scan of CP observables

$y_{\pm}^{DK}$  diverges from Hesse approximation outside  $1\sigma$



$y_{-}^{DK}$



$y_{+}^{DK}$

$$D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$$

## What do the likelihood scans tell us?

- Uncertainties from  $c_i$  and  $s_i$  are significant, which justifies Gaussian constraining  $c_i$  and  $s_i$
- Non-Gaussian uncertainties means GammaCombo cannot be used
- New strategy:
  - 1 Produce a likelihood function from CP fit
  - 2 Interpret CP observables in terms of  $\gamma$ , etc
  - 3 Must profile all nuisance parameters ( $F_i$ ,  $c_i$ ,  $s_i$ , backgrounds yields, normalisation constants)
  - 4 Provide direct measurements of  $\gamma$ ,  $\delta_B$  and  $r_B$  without GammaCombo

# Summary of LHCb internal systematic uncertainties

Internal LHCb systematic uncertainties from model-dependent analysis of  $K^+ K^- \pi^+ \pi^-$ :

Source	$x_-^{DK}$	$y_-^{DK}$	$x_+^{DK}$	$y_+^{DK}$	$x_\xi^{D\pi}$	$y_\xi^{D\pi}$
Statistical	2.87	3.40	2.51	3.05	4.24	5.17
Mass shape	0.02	0.02	0.03	0.06	0.02	0.04
Bin-dependent mass shape	0.11	0.05	0.10	0.19	0.68	0.16
PID efficiency	0.02	0.02	0.03	0.06	0.02	0.04
Low-mass background model	0.02	0.02	0.03	0.04	0.02	0.02
Charmless background	0.14	0.15	0.12	0.14	0.01	0.02
$CP$ violation in low-mass background	0.01	0.10	0.08	0.12	0.07	0.26
Semi-leptonic $b$ -hadron decays	0.05	0.27	0.06	0.01	0.07	0.19
Semi-leptonic charm decays	0.02	0.07	0.03	0.15	0.06	0.24
$D \rightarrow K^- \pi^+ \pi^- \pi^+$ background	0.11	0.05	0.07	0.04	0.09	0.05
$\Lambda_b \rightarrow p D \pi^-$ background	0.01	0.25	0.14	0.04	0.06	0.34
$D \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ background	0.30	0.05	0.19	0.07	0.05	0.01
Fit bias	0.06	0.05	0.13	0.02	0.06	0.13
Total LHCb systematic	0.37	0.43	0.34	0.32	0.70	0.57

Give systematic uncertainties in terms of CP observables (not  $\gamma$ ) since these are more Gaussian and better behaved



# Summary of LHCb internal systematic uncertainties

Internal LHCb systematics for  $\pi^+\pi^-\pi^+\pi^-$  have not been calculated yet, but the plan is to run the same procedure from  $K^+K^-\pi^+\pi^-$  on this mode during review, with minor simplifications:

- 1 No  $K\pi\pi\pi$  background
- 2 No  $K\pi\pi\pi\pi^0$  background
- 3 No  $D$  semileptonic background

Reminder: LHCb internal systematic uncertainties are expected to be an order of magnitude smaller than statistical uncertainties!

From CP fit, we have a (negative log) likelihood function with nuisance parameters  $n_k$ :

$$\mathcal{L}(x_-^{DK}, y_-^{DK}, x_+^{DK}, y_+^{DK}, x_\xi^{D\pi}, y_\xi^{D\pi}, \{n_k\})$$

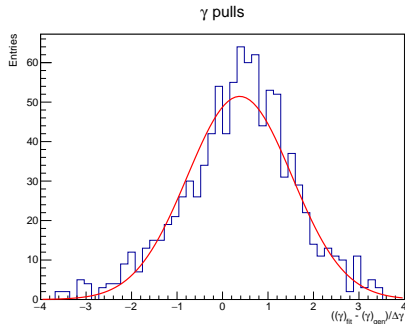
Express in terms of physics parameters:

$$\mathcal{L}(\gamma, \delta_B^{DK}, r_B^{DK}, \delta_B^{D\pi}, r_B^{D\pi}, \{n_k\})$$

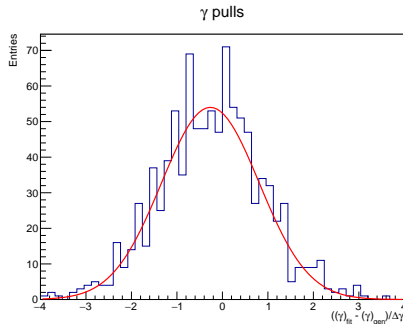
In this step, also add a Gaussian smearing term on CP observables to account for internal LHCb systematics

# Interpretation toys

We can perform toy studies on the interpretation fit, but we do not expect these to behave very Gaussian...



$K^+ K^- \pi^+ \pi^-$



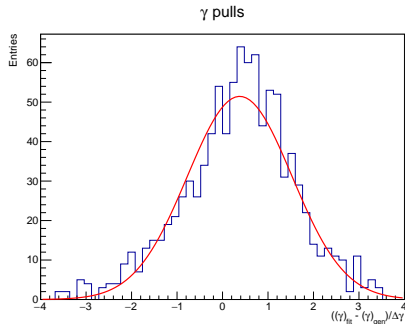
$\pi^+ \pi^- \pi^+ \pi^-$

$\gamma$  pull distributions

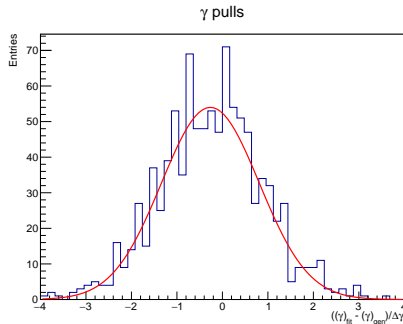
Indeed, small but significant biases are observed!

# Interpretation toys

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$K^+K^-\pi^+\pi^-$



$\pi^+\pi^-\pi^+\pi^-$

$\gamma$  pull distributions

The absolute bias corrections are:

# Interpretation results

Results from interpretation of  $K^+K^-\pi^+\pi^-$ , after correcting for biases in central values (not uncertainties):

Model independent

$$\gamma = (117 \pm 15)^\circ$$

$$\delta_B^{DK} = (83 \pm 12)^\circ$$

$$r_B^{DK} = (12.1 \pm 2.6) \times 10^{-2}$$

$$\delta_B^{D\pi} = (295 \pm 74)^\circ$$

$$r_B^{D\pi} = (0 \pm 5) \times 10^{-3}$$

Model dependent

$$\gamma = (116_{-14}^{+12})^\circ$$

$$\delta_B^{DK} = (81_{-13}^{+14})^\circ$$

$$r_B^{DK} = (11.0 \pm 2.0) \times 10^{-2}$$

$$\delta_B^{D\pi} = (298_{-118}^{+62})^\circ$$

$$r_B^{D\pi} = (4_{-4}^{+5}) \times 10^{-3}$$

LHCb systematics not included yet, but central value of  $\gamma$  remains high...

... it seems that the large tension with the LHCb global result

$$\gamma = (63.8_{-3.7}^{+3.5})^\circ \text{ remains}$$

# Interpretation results

Results from interpretation of  $h^+h^-\pi^+\pi^-$ , after correcting for biases in central values (not uncertainties):

$$K^+K^-\pi^+\pi^-$$

$$\pi^+\pi^-\pi^+\pi^-$$

$$\gamma = (117 \pm 15)^\circ$$

$$\gamma = (45 \pm 11)^\circ$$

$$\delta_B^{DK} = (83 \pm 12)^\circ$$

$$\delta_B^{DK} = (115 \pm 11)^\circ$$

$$r_B^{DK} = (12.1 \pm 2.6) \times 10^{-2}$$

$$r_B^{DK} = (8.2 \pm 1.9) \times 10^{-2}$$

$$\delta_B^{D\pi} = (295 \pm 74)^\circ$$

$$\delta_B^{D\pi} = (204 \pm 42)^\circ$$

$$r_B^{D\pi} = (0 \pm 5) \times 10^{-3}$$

$$r_B^{D\pi} = (4 \pm 5) \times 10^{-3}$$

$\pi^+\pi^-\pi^+\pi^-$  is in much better agreement with LHCb global result, but there is a tension with  $K^+K^-\pi^+\pi^-$ ...

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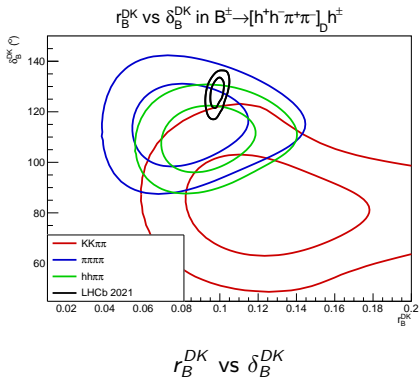
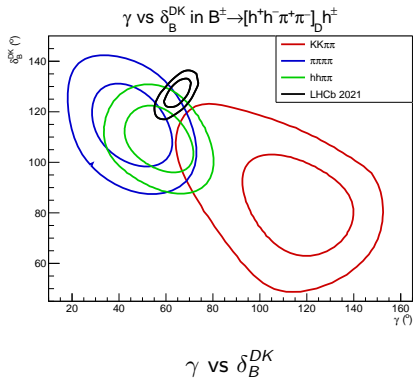
$$\delta_B^{D\pi} = (204 \pm 42)^\circ$$

$$r_B^{D\pi} = (4 \pm 5) \times 10^{-3}$$

$\pi^+\pi^-\pi^+\pi^-$  is in much better agreement with LHCb global result, but there is a tension with  $K^+K^-\pi^+\pi^-$  ...  
...but how Gaussian are these uncertainties?

# Likelihood scan of interpretation fit

In fact, a likelihood scan shows that  $D \rightarrow K^+ K^- \pi^+ \pi^-$  and  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  agree within  $2\sigma$  (no LHCb systematics yet)

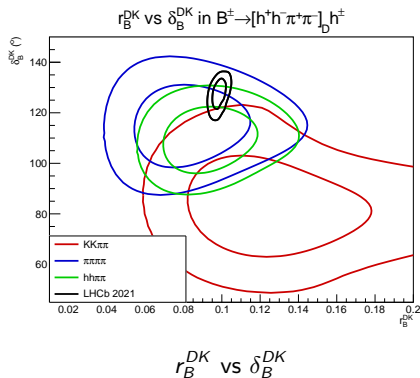
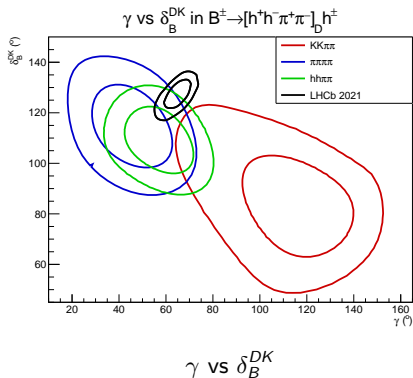


When all biases, correlations and non-Gaussian uncertainties are accounted for, the tension with the LHCb average has reduced significantly



# Likelihood scan of interpretation fit

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However, with all the non-Gaussian behaviour, are we sure these contours cover 68% and 95% ?

Feldman-Cousins method, or Plugin, is a “brute-force” approach to assigning a confidence interval

At each scan point of  $\gamma$ , perform these fits to data:

- 1 Fit with all parameters floating, and save the log-likelihood  $\chi^2$
- 2 Fit with  $\gamma$  fixed to scan point, and save  $\chi_{\text{fix}}^2$
- 3 Calculate  $\Delta\chi_{\text{data}}^2 = \chi_{\text{fix}}^2 - \chi^2$

We expect  $\Delta\chi_{\text{data}}^2$  to become large as we move away from best-fit value, but without direct knowledge of underlying PDF, we cannot determine any confidence intervals from this

Feldman-Cousins method, or Plugin, is a “brute-force” approach to assigning a confidence interval

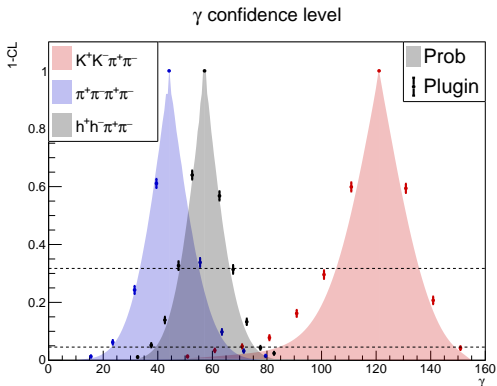
At each scan point of  $\gamma$ , perform these fits to toy:

- 1 Fix  $\gamma$  to scan point and generate 1000 toys
- 2 Perform fits to each toy, with  $\gamma$  both floating and fixed
- 3 Calculate  $\Delta\chi_{\text{toy}}^2$

At each scan point, the fraction of toys with  $\Delta\chi_{\text{toy}}^2 > \Delta\chi_{\text{data}}^2$  is equal to  $1 - \text{CL}$ , and the exact 68% confidence interval can then be obtained using an interpolation between points

# Plugin/Feldman-Cousins method

LHCb average within  $2\sigma$  of  $D \rightarrow K^+ K^- \pi^+ \pi^-$  Plugin result  
Combined fit shows good agreement between Plugin and Prob scans



Combined fit result:  $\gamma = (57 \pm 9)^\circ$

Third most precise single measurement of  $\gamma$  in  $B^\pm$  decays

# Conclusion

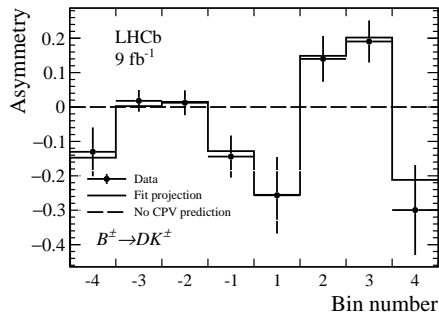
- Binned model-independent measurement of  $\gamma$  with  $B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h^\pm$  has been performed:  $\gamma = (57 \pm 9)^\circ$ 
  - Uses BESIII strong-phase inputs which are not yet public, but are expected to become so on timescale of  $\sim 2$  months
- $3\sigma$  tension in  $D \rightarrow K^+ K^- \pi^+ \pi^-$  has reduced to less than  $2\sigma$  due to:
  - 1 Non-Gaussian uncertainties in  $y_\pm^{DK}$  originating from  $s_i$  uncertainties
  - 2 Large anti-correlation between  $\gamma$  and  $\delta_B^{DK}$
- $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$  measurement benefits from commonalities with  $K^+ K^- \pi^+ \pi^-$  analysis and larger BESIII data set

- Binned model-independent measurement of  $\gamma$  with  $B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h^\pm$  has been performed:  $\gamma = (57 \pm 9)^\circ$ 
  - Uses BESIII strong-phase inputs which are not yet public, but are expected to become so on timescale of  $\sim 2$  months
- Statistically limited measurement, but  $s_i$  uncertainties are large
  - $\pi^+ \pi^- \pi^+ \pi^-$ :  $s_i$  uncertainties will improve with full BESIII data set
  - $K^+ K^- \pi^+ \pi^-$ : Charm mixing studies can improve  $s_i$  precision
- The ANA note is ready and available for B2OC WG review

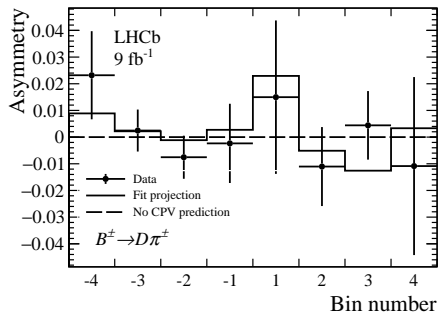
Thanks for your attention!

# Backup: Bin asymmetries

$B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$  bin asymmetries



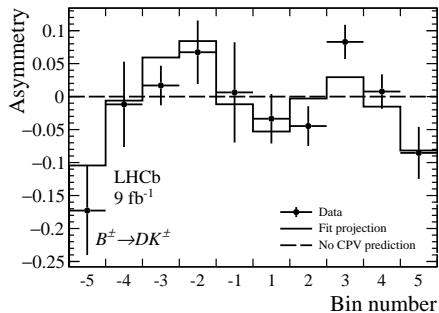
$B^\pm \rightarrow DK^\pm$



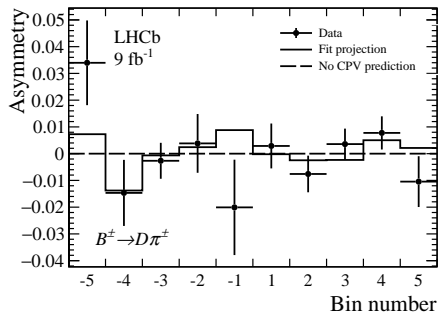
$B^\pm \rightarrow D\pi^\pm$

# Backup: Bin asymmetries

$B^\pm \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D h^\pm$  bin asymmetries



$B^\pm \rightarrow DK^\pm$

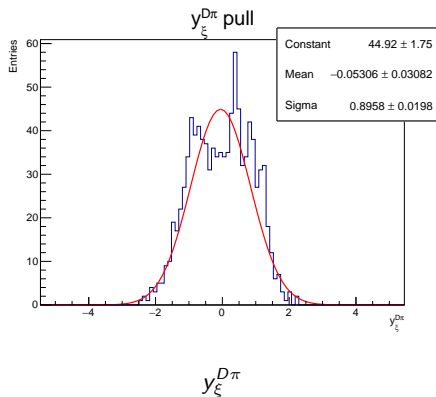
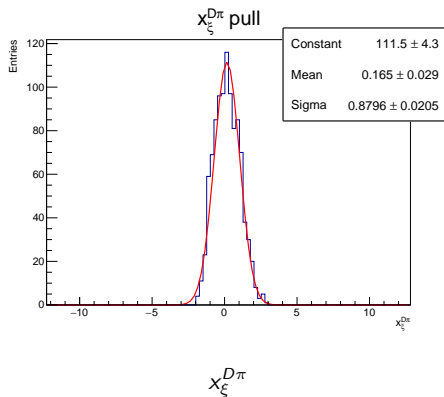


$B^\pm \rightarrow D\pi^\pm$



# Backup: CP fit toy studies

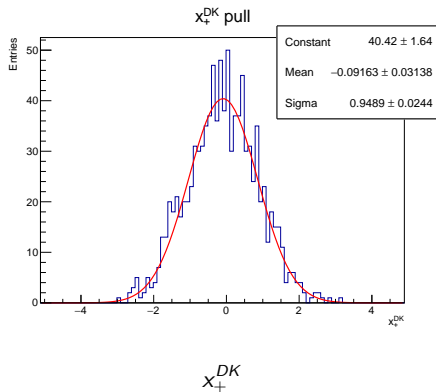
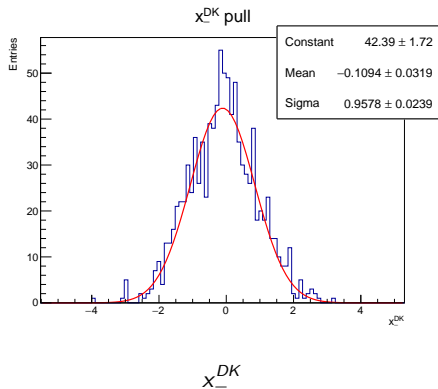
In toy studies biases in  $D\pi$  observables are consistent with model-dependent analysis



$$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$$

# Backup: CP fit toy studies

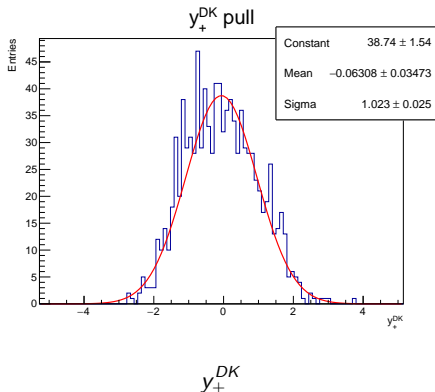
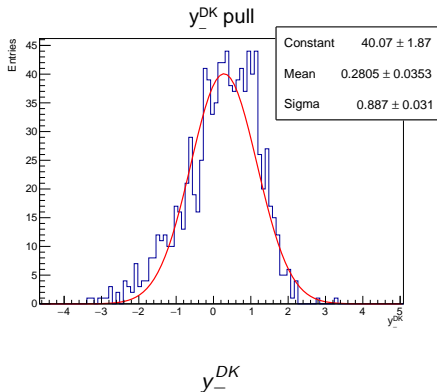
Minor biases in  $x_{\pm}^{DK}$  are seen but can be corrected for...



$$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$$

# Backup: CP fit toy studies

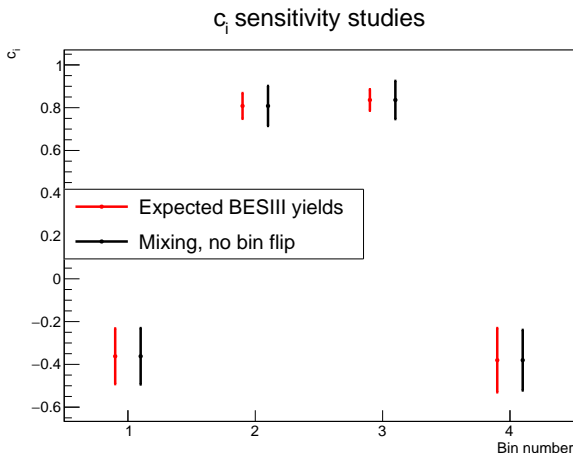
...but  $y_{\pm}^{DK}$  pulls are now slightly asymmetric!



$$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$$

# Backup: Charm mixing studies with multi-body decays

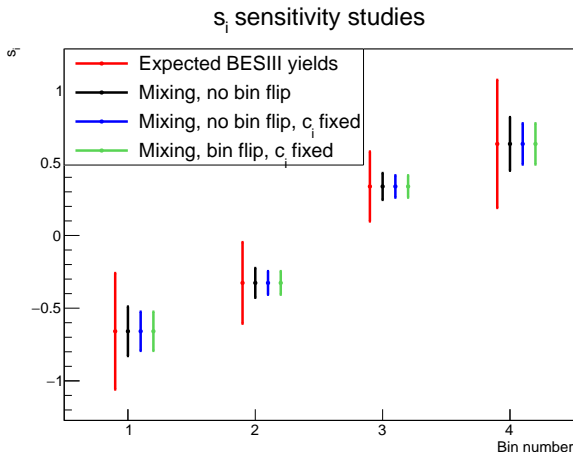
Sensitivity to  $c_i$ : Similar between BESIII and charm mixing at LHCb



- BESIII yields equivalent to  $8 \text{ fb}^{-1}$  of  $\psi(3770)$
- 4 million  $D \rightarrow K^+ K^- \pi^+ \pi^-$  candidates in mixing analysis

# Backup: Charm mixing studies with multi-body decays

Sensitivity to  $s_i$ : Significant improvements expected!



- BESIII yields equivalent to  $8 \text{ fb}^{-1}$  of  $\psi(3770)$
- 4 million  $D \rightarrow K^+ K^- \pi^+ \pi^-$  candidates in mixing analysis