

A study of CP violation in $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ and $B^\pm \rightarrow (\pi^+ \pi^- \pi^+ \pi^-)_D h^\pm$ decays

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Approval presentation

2nd September 2022

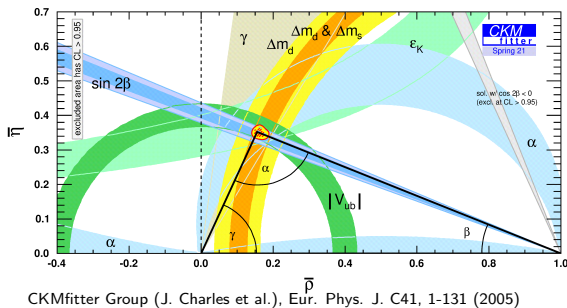


Thank you

- Big thank you to all reviewers!
- B2OC WG reviewers/convenors:
 - Anton Poluektov
 - Nathan Philip Jurik
 - Paras Naik
- RC reviewers:
 - Lucia Grillo
 - Francesco Dettori

Introduction and motivation

- Aim of this analysis: Measure CP observables in $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$, $h = K, \pi$ decays
 - First study of CP violation in this channel
 - Enhance sensitivity through sophisticated binning of 5D phase space
 - Provide input for future model-independent measurement of γ
- Also measure phase space inclusive CP observables for $B^\pm \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D h^\pm$, $h = K, \pi$ decays



Introduction and motivation

- $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D K^\pm$ was first proposed by J. Rademacker and G. Wilkinson
 - [Phys. Lett. B647 \(2007\) 400](#)
 - Expected γ precision from FOCUS amplitude model with 1000 $B^\pm \rightarrow DK^\pm$ candidates: 14°
- Recent state of the art amplitude analysis by LHCb:
 - [JHEP 02 \(2019\) 126](#)
 - Develop a suitable binning scheme
- No measurement of strong phases c_i and s_i exists today
 - Current BESIII dataset is 8 fb^{-1}
 - Allows for a direct measurement of $D \rightarrow K^+ K^- \pi^+ \pi^-$ strong phases
 - Final γ measurement will be model independent

Theory of BPGGSZ method

- $B^\pm \rightarrow Dh^\pm$ amplitude:

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

- $\mathcal{A}(D^0)$ and $\mathcal{A}(\bar{D}^0)$ depend on D phase space
- Strong-phase difference of D^0 and \bar{D}^0 decays inaccessible at LHCb
- Model-independent measurement: Integrate over bins of phase space

Event yield in bin i

$$\begin{aligned}N_{-i}^- &= h_{B^-} \left(F_i + (x_-^2 + y_-^2) \bar{F}_i + 2\sqrt{F_i \bar{F}_i} (x_- c_i + y_- s_i) \right) \\ N_{-i}^+ &= h_{B^+} \left(F_i + (x_+^2 + y_+^2) \bar{F}_i + 2\sqrt{F_i \bar{F}_i} (x_+ c_i + y_+ s_i) \right)\end{aligned}$$

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:

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

A binning scheme must satisfy the following:

- Minimal dilution of strong phases when integrating over bins
- Enhance interference between $B^\pm \rightarrow D^0 h^\pm$ and $B^\pm \rightarrow \bar{D}^0 h^\pm$

How to bin a 5-dimensional phase space?

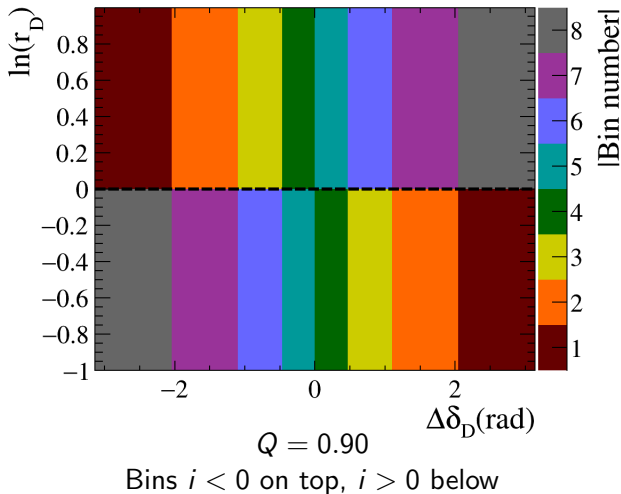
- Generate C++ code for LHCb amplitude model using AmpGen¹
- For each B^\pm candidate, calculate

$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

- Bin along δ_D and r_D , maximize Q -value to optimize
 - $Q = 1$ corresponds to unbinned limit

¹AmpGen by Tim Evans

Binning scheme



Phase-space inclusive CP observables

- Statistically independent analysis without phase space binning
 - BPGGSZ looks at relative bin yields
 - Quasi-GLW observables depend on absolute yields

- Charge asymmetry:

$$A_h = \frac{\Gamma(B^- \rightarrow Dh^-) - \Gamma(B^+ \rightarrow Dh^+)}{\Gamma(B^- \rightarrow Dh^-) + \Gamma(B^+ \rightarrow Dh^+)}$$

- $B \rightarrow DK$ vs $B \rightarrow D\pi$ double ratio:

$$R_{CP} = \frac{R_{hh\pi\pi}}{R_{K\pi\pi\pi}}, \quad R = \frac{\Gamma(B^- \rightarrow DK^-) + \Gamma(B^+ \rightarrow DK^+)}{\Gamma(B^- \rightarrow D\pi^-) + \Gamma(B^+ \rightarrow D\pi^+)}$$

- Measure A_h and R_{CP} for $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$ and $B^\pm \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D h^\pm$

CP observables and physics parameters

$$A_h = \frac{2r_B^{Dh}(2F_+ - 1) \sin(\delta_B^{Dh}) \sin(\gamma)}{1 + (r_B^{Dh})^2 + 2r_B^{Dh}(2F_+ - 1) \cos(\delta_B^{Dh}) \cos(\gamma)},$$

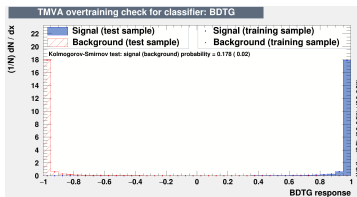
$$R_{\text{CP}} = 1 + (r_B^{Dh})^2 + 2r_B^{Dh}(2F_+ - 1) \cos(\delta_B^{Dh}) \cos(\gamma)$$

- Need CP-even fraction F_+ to interpret in terms of physics parameters
- For $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$:
 - $F_+ = 0.736$
 - Calculated from the model
- For $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$:
 - $F_+ = 0.735 \pm 0.016$
 - Recent measurement by BESIII [arXiv:2208.10098](https://arxiv.org/abs/2208.10098)

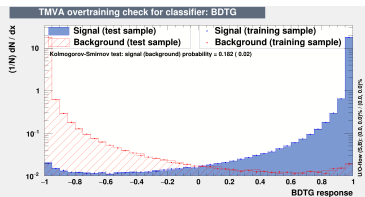
- Strong phases c_i and s_i have not been published by BESIII yet
- We would like to publish a model dependent result initially
 - Focus of the paper should be on CP violation, not γ
 - Bin yields and correlation matrices will be provided in the appendix
- When c_i and s_i become available, the result can be updated to yield a model independent measurement of γ , which can be included in the next combination

Selection

- 1 Initial cuts: Trigger requirements, mass cuts, bachelor p , etc
 - D mass window: 25 MeV
 - B^\pm mass fit range: [5080, 5700] MeV
- 2 BDT: Efficient combinatorial background rejection
 - Signal sample: MC with AmpGen model
 - Background sample: Data from $m_B \in [5800, 7000]$ MeV
 - Pick BDT cut that minimises statistical sensitivity of γ
- 3 Final cuts: PID cuts, flight significance cuts, K_S veto, etc
 - PIDK cut at 4 to separate $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$
 - Flight significance at 2 to reduce charmless backgrounds



(a) BDT output



(b) BDT output on a log scale

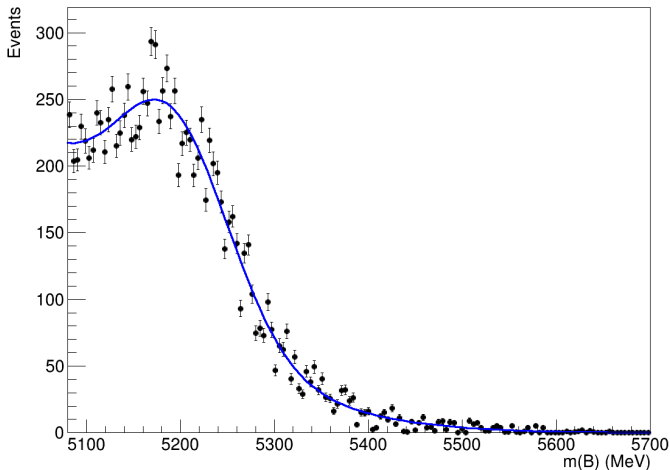
Summary of backgrounds

- Partially reconstructed B decays
 - Modelled in the fit with HILL/HORNSdini shapes
- Combinatorial
 - Floating exponential
- CF $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ and semi-leptonic $D^0 \rightarrow K^- (X) l^+ \nu_l$ background
 - Small, assign systematic
- Charmless
 - Fix from sideband
- CF $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ background
 - Not negligible!

$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+ \pi^0$ partially reconstructed mis-ID

- Missing π^0 and $\pi \rightarrow K$ mis-ID
- Float yield relative to $B \rightarrow D^* h$ background

B mass of $K\pi\pi\pi^0 \rightarrow KK\pi\pi$



Global fit

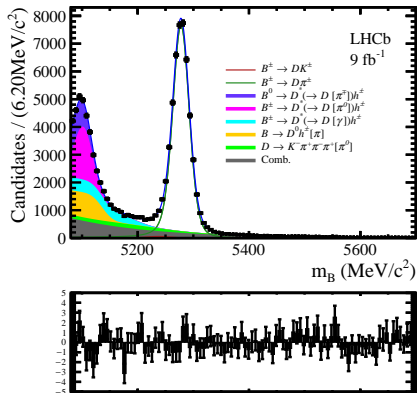
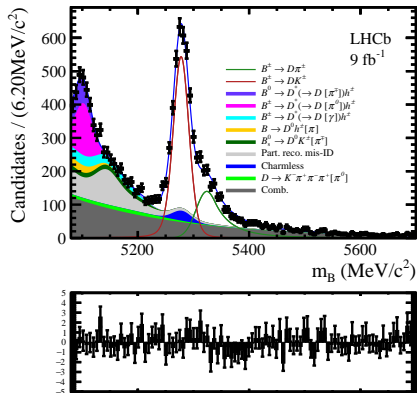


Figure 2: $B^\pm \rightarrow DK^\pm$ channel (left) and $B^\pm \rightarrow D\pi^\pm$ channel (right)

- $B^\pm \rightarrow DK^\pm$ yield: 3026 ± 38
- $B^\pm \rightarrow D\pi^\pm$ yield: $44\,349 \pm 218$

Fit split by charge

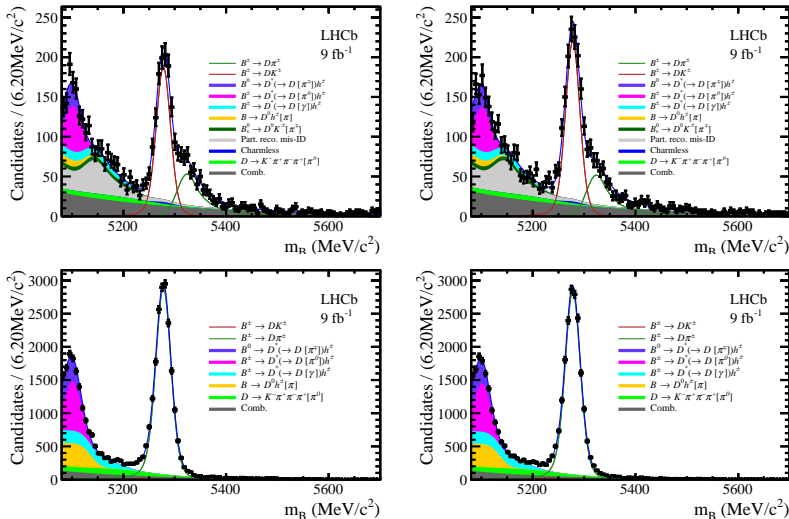


Figure 3: $B^\pm \rightarrow (K^+K^-\pi^+\pi^-)Dh^\pm$

Fit split by charge

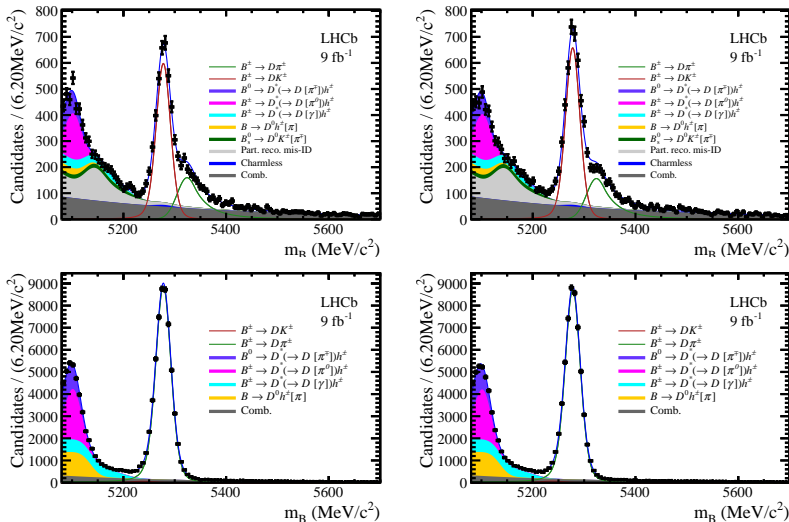
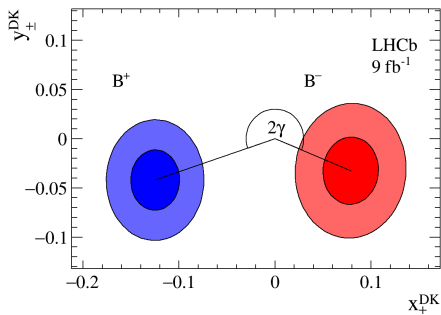


Figure 4: $B^\pm \rightarrow (\pi^+\pi^-\pi^+\pi^-)Dh^\pm$

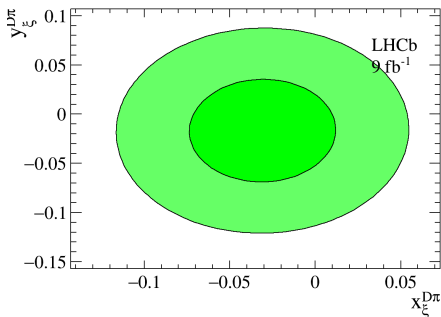
CP fit setup

- Fix mass shape from global fit
- Split by B^\pm charge and D phase space bins
 - Simultaneous fit with 64 categories
- Signal yields parameterised in terms of CP observables x_\pm^{DK}, y_\pm^{DK}
 $x_\xi^{D\pi}, y_\xi^{D\pi}$ (6 parameters)
- Fractional bin yields F_i are floating (15 parameters)
- Combinatorial background yield floated in each bin (64 parameters)
- Total partially reconstructed background yield is floated in each bin (64 parameters)
- Normalisation of each charge and B^\pm decay is floated (4 parameters)
- In total: 153 free parameters

CP fit results



(a) x_\pm^{DK} vs y_\pm^{DK}



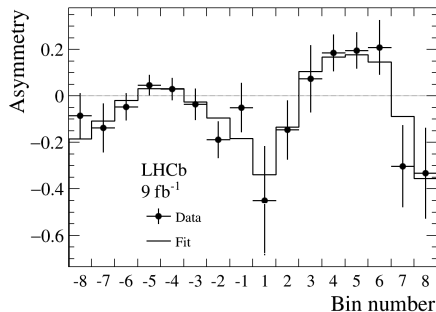
(b) $x_\xi^{D\pi}$ vs $y_\xi^{D\pi}$

$$x_\pm^{DK} = r_B \cos(\delta_B \pm \gamma)$$

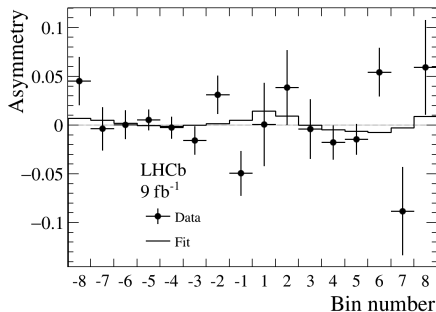
$$y_\pm^{DK} = r_B \sin(\delta_B \pm \gamma)$$

- Shown are the 2σ contours of fitted CP observables
- The distinct $B^\pm \rightarrow DK^\pm$ contours indicate CP violation, while the $B^\pm \rightarrow D\pi^\pm$ mode has very low sensitivity to CP violation

Fractional bin asymmetries



(a) $B^\pm \rightarrow DK^\pm$



(b) $B^\pm \rightarrow D\pi^\pm$

- Useful cross check to compare measured bin asymmetries against bin asymmetries predicted by the fitted CP observables
- The $B^\pm \rightarrow DK^\pm$ mode show non-zero bin asymmetries, and the non-trivial distribution is driven by the change in strong phases across phase space

- Dominant c_i/s_i systematic uncertainty due to model dependence
 - Strategy: Generate toys with c_i/s_i from older CLEO model, fit with c_i/s_i from LHCb model
 - Will be replaced when BESIII results become available
- All internal systematic uncertainties are much smaller than the statistical uncertainties

Summary of all BPGGSZ systematic uncertainties

Uncertainties of BPGGSZ CP observables in units of 10^{-2}

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
c_i, s_i	0.35	3.64	1.74	1.29	0.14	1.10
Total systematic	0.51	3.67	1.78	1.33	0.72	1.24

Summary of all quasi-GLW systematic uncertainties

Uncertainties of quasi-GLW CP observables in units of 10^{-2}

Source	$A_K^{KK\pi\pi}$	$A_\pi^{KK\pi\pi}$	$A_K^{\pi\pi\pi\pi}$	$A_\pi^{\pi\pi\pi\pi}$	$R_{CP}^{KK\pi\pi}$	$R_{CP}^{\pi\pi\pi\pi}$
Statistical	23.5	5.5	13.3	3.1	24.2	14.3
Charmless background	1.2	< 0.1	0.4	< 0.1	13.9	8.5
External parameters	1.0	0.7	1.0	0.7	4.0	4.0
Fixed yield fractions	0.1	< 0.1	0.1	< 0.1	1.3	1.4
Mass shape	0.3	< 0.1	0.2	< 0.1	3.1	3.1
PID efficiency	0.1	< 0.1	0.1	< 0.1	2.5	1.6
Total systematic	1.6	0.7	1.1	0.7	15.1	10.1

Summary of measured CP observables

- Measured binned CP observables:

$$x_-^{DK} = (7.9 \pm 2.9 \pm 0.4 \pm 0.4) \times 10^{-2}$$

$$y_-^{DK} = (-3.3 \pm 3.4 \pm 0.4 \pm 3.6) \times 10^{-2}$$

$$x_+^{DK} = (-12.5 \pm 2.5 \pm 0.3 \pm 1.3) \times 10^{-2}$$

$$y_+^{DK} = (-4.2 \pm 3.1 \pm 0.3 \pm 1.3) \times 10^{-2}$$

$$x_\xi^{D\pi} = (-3.1 \pm 4.3 \pm 0.7 \pm 0.1) \times 10^{-2}$$

$$y_\xi^{D\pi} = (-1.7 \pm 5.2 \pm 0.6 \pm 1.1) \times 10^{-2}$$

- Measured inclusive CP observables:

$$A_K^{KK\pi\pi} = 0.093 \pm 0.023 \pm 0.002$$

$$A_\pi^{KK\pi\pi} = -0.009 \pm 0.006 \pm 0.001$$

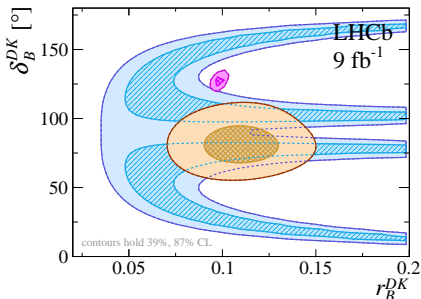
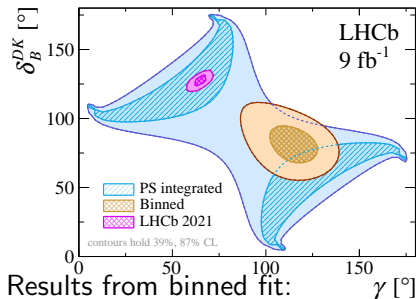
$$A_K^{\pi\pi\pi\pi} = 0.060 \pm 0.013 \pm 0.001$$

$$A_\pi^{\pi\pi\pi\pi} = -0.0082 \pm 0.0031 \pm 0.0007$$

$$R_{CP}^{KK\pi\pi} = 0.974 \pm 0.024 \pm 0.015$$

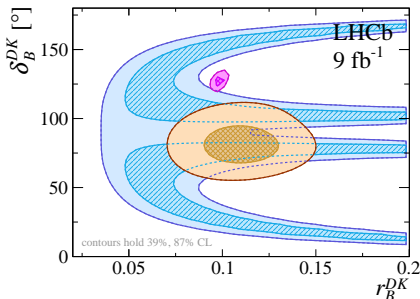
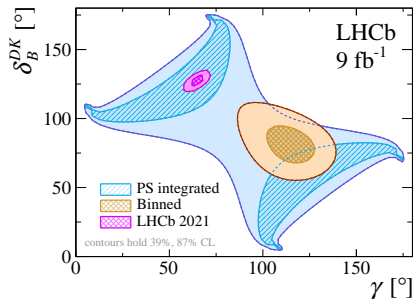
$$R_{CP}^{\pi\pi\pi\pi} = 0.978 \pm 0.014 \pm 0.010$$

Interpretation



$$\begin{aligned}\gamma &= (116_{-14}^{+12})^\circ \\ \delta_B^{DK} &= (81_{-13}^{+14})^\circ \\ r_B^{DK} &= 0.110_{-0.020}^{+0.020} \\ \delta_B^{D\pi} &= (298_{-118}^{+62})^\circ \\ r_B^{D\pi} &= 0.0041_{-0.0041}^{+0.0055}\end{aligned}$$

Interpretation



- Value of γ from binned analysis is somewhat high, but falls within the 3σ contours
- Phase space inclusive measurement are compatible with our expectations
- Interpretation may evolve when full model independent inputs are available

Conclusion

- First study of CP violation has been performed in $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$ in bins of phase space
- Phase space inclusive measurement for $B^\pm \rightarrow [K^+ K^- \pi^+ \pi^-]_D h^\pm$ and $B^\pm \rightarrow [\pi^+ \pi^- \pi^+ \pi^-]_D h^\pm$
- This publication is model dependent, but strong phases will become available from BESIII soon
 - Sufficient information will be provided in the paper to allow a model independent update when c_i and s_i become available
- Complete paper draft is available
- Link to:
 - [TWiki](#)
 - [ANA note](#)
 - [Paper draft](#) (also uploaded to Indico)

Thanks for listening!