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

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Approval presentation

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Thank you

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  - Nathan Philip Jurik
  - Paras Naik

- RC reviewers:
  - Lucia Grillo
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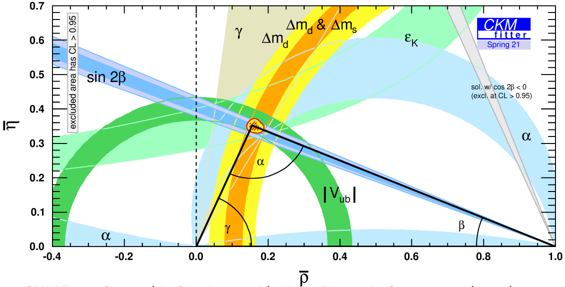
Introduction and motivation

- Aim of this analysis: Measure CP observables in $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ decays using full Run 1 and 2 (9 fb^{-1})
  - 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 $D \to K^+K^-\pi^+\pi^-$, as well as $D \to \pi^+\pi^-\pi^+\pi^-$



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

Introduction and motivation

- $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D K^{\pm}$ was first proposed by J. Rademacker and G. Wilkinson
  - Phys. Lett. B647 (2007) 400
  - Expected γ precision from FOCUS amplitude model with 1000 $B^{\pm} \to DK^{\pm}$ 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 $D \to K^+K^-\pi^+\pi^-$ strong phases
  - Final γ measurement will be model independent

Theory of BPGGSZ method

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

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

- $\mathcal{A}(D^0)$ 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

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

Theory of BPGGSZ method

Event yield in bin i

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

- CP observables:
  - $x_\pm^{DK} = r_B^{DK}\cos\left(\delta_B^{DK} \pm \gamma\right), \quad y_\pm^{DK} = r_B^{DK}\sin\left(\delta_B^{DK} \pm \gamma\right)$
  - $x_\xi^{D\pi} = \mathrm{Re}(\xi^{D\pi}),\ y_\xi^{D\pi} = \mathrm{Im}(\xi^{D\pi}) \qquad \left(\xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi} - \delta_B^{DK})}\right)$
- Fractional bin yield:
  - $F_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}$
  - Floated in the fit, mostly constrained by $B^\pm \to D\pi^\pm$
- Amplitude averaged strong phases:

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

Binning scheme

A binning scheme must satisfy the following:

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

How to bin a 5-dimensional phase space?

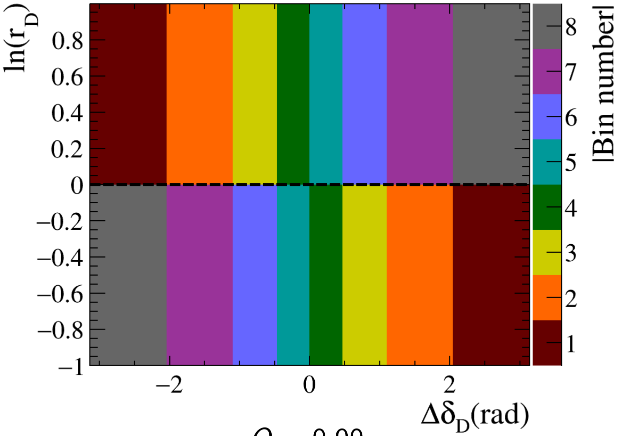
- Generate C++ code for LHCb amplitude model using AmpGen[1]
- For each $B^{\pm}$ candidate, calculate

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

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

[1] AmpGen by Tim Evans

Binning scheme



$Q = 0.90$

Bins $i < 0$ on top, $i > 0$ below

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:

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

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

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

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

Phase-space inclusive CP observables

CP observables and physics parameters

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

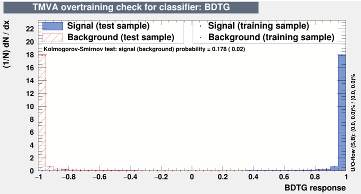
$$R_{\mathrm{CP}} = 1 + (r_B^{Dh})^2 + 2r_B^{Dh}(2F_+ - 1)\cos\left(\delta_B^{Dh}\right)\cos(\gamma)$$

- Need CP-even fraction F_+ to interpret in terms of physics parameters
- For $D^0 \to K^+K^-\pi^+\pi^-$:
  - $F_+ = 0.736$
  - Calculated from the model
- For $D^0 \to \pi^+\pi^-\pi^+\pi^-$:
  - $F_+ = 0.735 \pm 0.016$
  - Recent measurement by BESIII arXiv:2208.10098

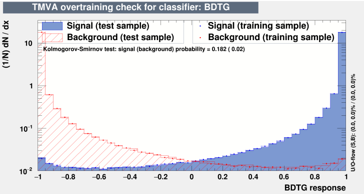
Publication strategy

- 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

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 sensitity of γ
3. Final cuts: PID cuts, flight significance cuts, K_S veto, etc
    - PIDK cut at 4 to separate $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$
    - Flight significance at 2 to reduce charmless backgrounds



(a) BDT output



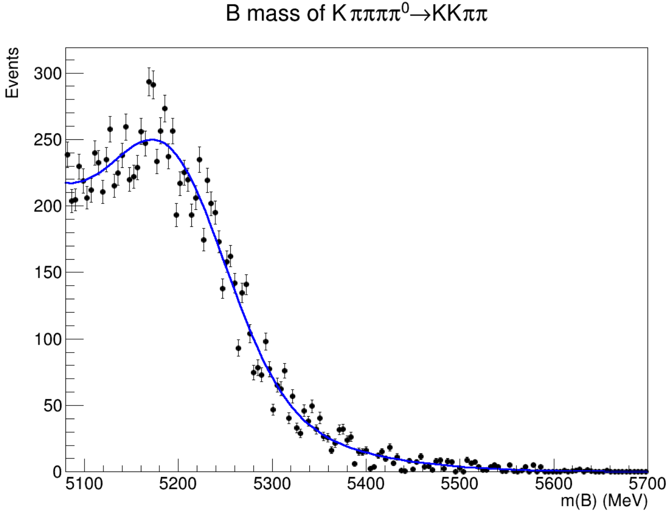
(b) BDT output on a log scale

Summary of backgrounds

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

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

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



Global fit

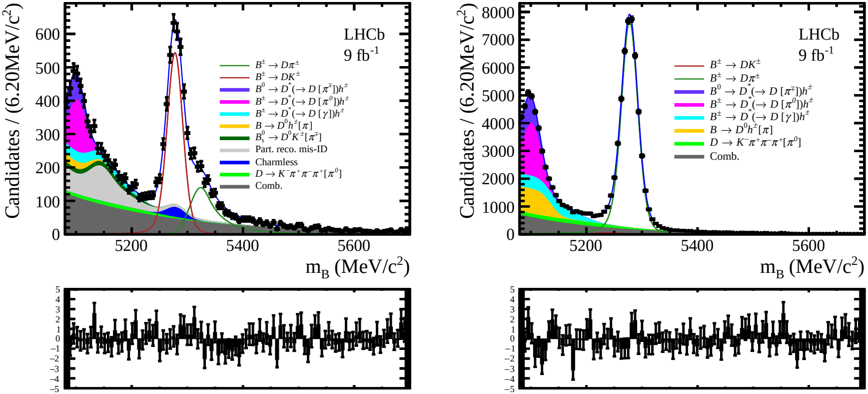


Figure 2: $B^\pm \to DK^\pm$ channel (left) and $B^\pm \to D\pi^\pm$ channel (right)

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

Fit split by charge

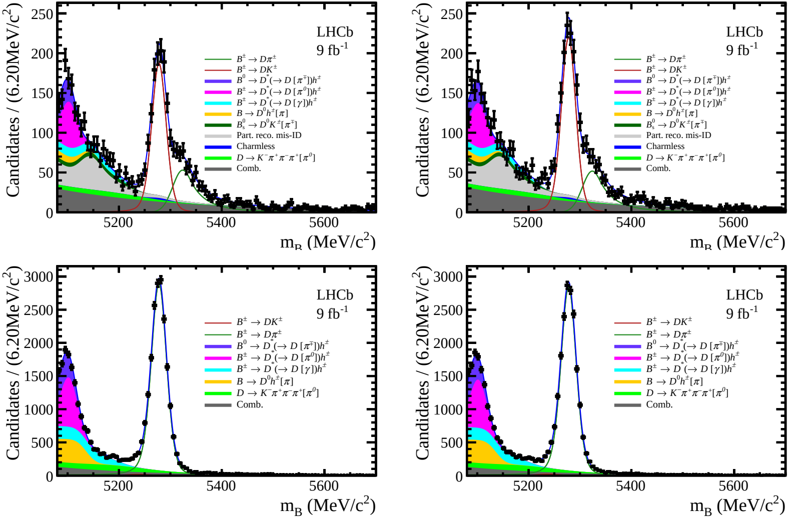


Figure 3: $B^{\pm} \to (K^{+}K^{-}\pi^{+}\pi^{-})Dh^{\pm}$

Fit split by charge

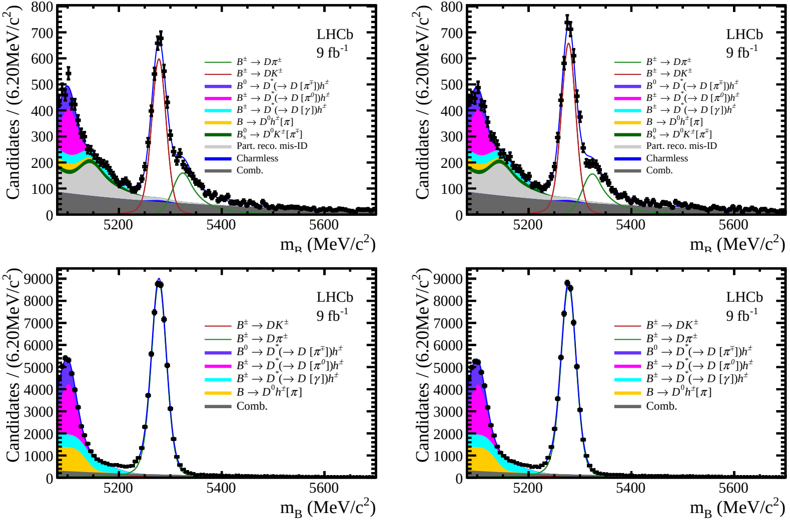
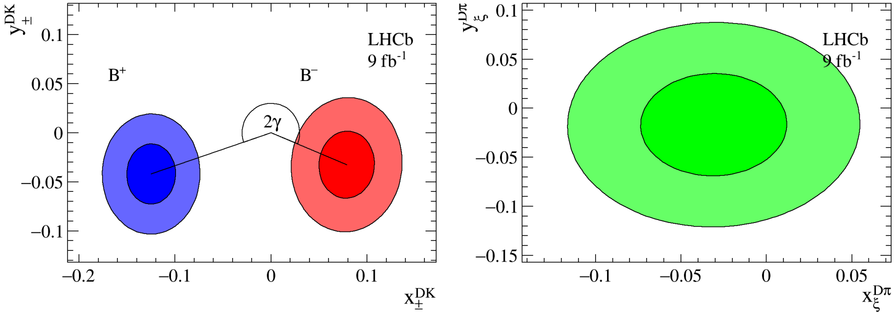


Figure 4: $B^{\pm} \to (\pi^+\pi^-\pi^+\pi^-)Dh^{\pm}$

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

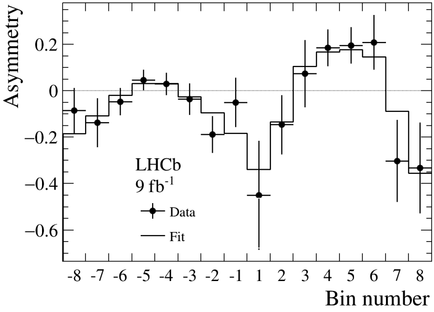
CP fit results



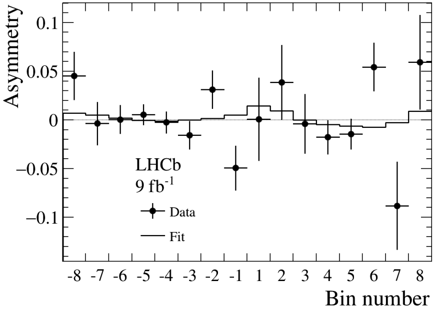
(a) $x_\pm^{DK}$ vs $y_\pm^{DK}$ **(b)** $x_\xi^{D\pi}$ vs $y_\xi^{D\pi}$

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

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



(a) $B^{\pm} \to DK^{\pm}$



(b) $B^{\pm} \to D\pi^{\pm}$

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

Systematic uncertainties

- 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
$D \to K^-\pi^+\pi^-\pi^+$ background	0.11	0.05	0.07	0.04	0.09	0.05
$\Lambda_b \to pD\pi^-$ background	0.01	0.25	0.14	0.04	0.06	0.34
$D \to K^-\pi^+\pi^-\pi^+\pi^0$ 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

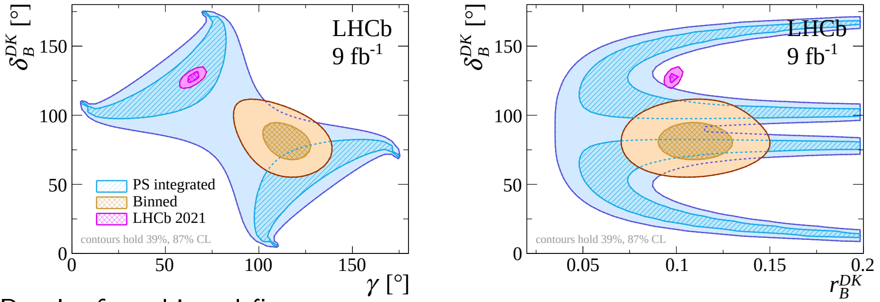
- Measured binned CP observables:

$$x_-^{DK} = (7.9 \pm 2.9 \pm 0.4 \pm 0.4) \times 10^{-2}$$
$$y_-^{DK} = (-3.3 \pm 3.4 \pm 0.4 \pm 3.6) \times 10^{-2}$$
$$x_+^{DK} = (-12.5 \pm 2.5 \pm 0.3 \pm 1.3) \times 10^{-2}$$
$$y_+^{DK} = (-4.2 \pm 3.1 \pm 0.3 \pm 1.3) \times 10^{-2}$$
$$x_\xi^{D\pi} = (-3.1 \pm 4.3 \pm 0.7 \pm 0.1) \times 10^{-2}$$
$$y_\xi^{D\pi} = (-1.7 \pm 5.2 \pm 0.6 \pm 1.1) \times 10^{-2}$$

- Measured inclusive CP observables:

$$A_K^{KK\pi\pi} = 0.093 \pm 0.023 \pm 0.002$$
$$A_\pi^{KK\pi\pi} = -0.009 \pm 0.006 \pm 0.001$$
$$A_K^{\pi\pi\pi\pi} = 0.060 \pm 0.013 \pm 0.001$$
$$A_\pi^{\pi\pi\pi\pi} = -0.0082 \pm 0.0031 \pm 0.0007$$
$$R_{\mathrm{CP}}^{KK\pi\pi} = 0.974 \pm 0.024 \pm 0.015$$
$$R_{\mathrm{CP}}^{\pi\pi\pi\pi} = 0.978 \pm 0.014 \pm 0.010$$

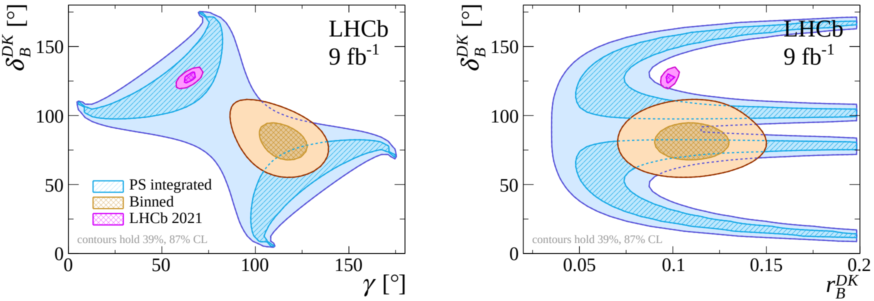
Interpretation



Results from binned fit:

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

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 $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ in bins of phase space
- Phase space inclusive measurement for $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$
- 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!