Model-independent (sort of) determination of the CKM angle γ in $B^\pm \to (K^+K^-\pi^+\pi^-)_D h^\pm$ decays

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Thank you

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- B2OC WG reviewers/convenors:
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    - Paras Naik
- RC reviewers:
    - Lucia Grillo
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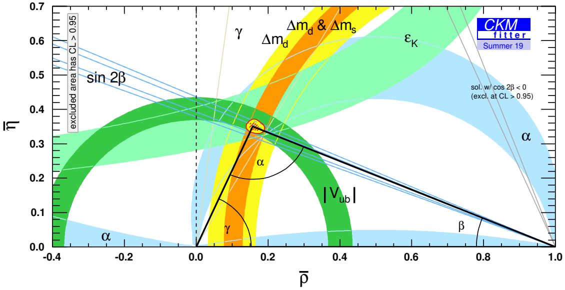
Introduction and motivation

- Aim of this analysis: Model independent measurement of γ with $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$, $h = K, \pi$
  - First study of CP violation in this channel
  - Enhance CP asymmetries through sophisticated binning of 5D phase space



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
- Anticipate 20 fb^{-1} of $\psi(3770)$ data from BESIII by end of 2023
  - Allows for a direct strong phase measurements of $D^0 \to K^+K^-\pi^+\pi^-$
  - 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

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

- 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?

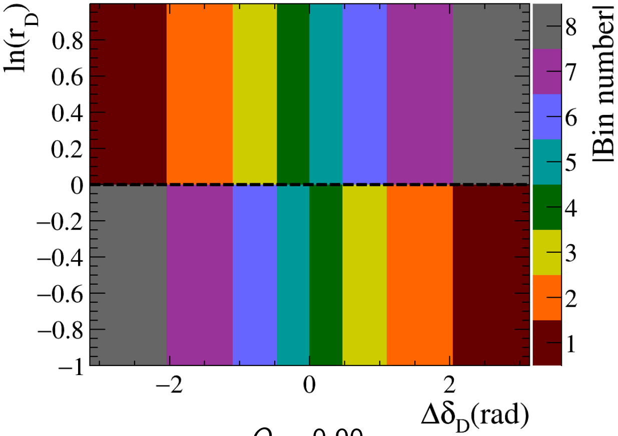
- Generate C++ code for LHCb amplitude model using AmpGen[1]
- For each $B^\pm$ candidate, calculate

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

- Bin along δ_D and r_D, maximize Q-value to optimize

[1] AmpGen by Tim Evans

Binning scheme



$Q = 0.90$

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

The quasi-GLW method

- 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:

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

CP observables and physics parameters

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

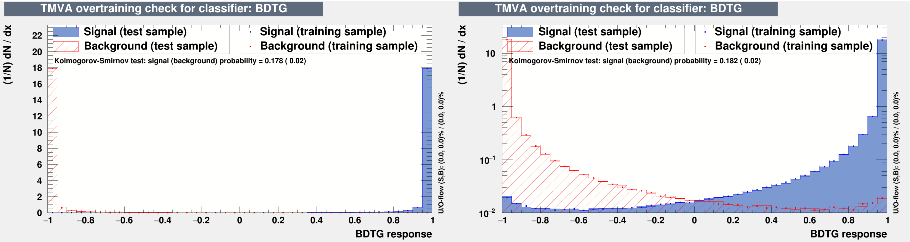
$$R_{\mathrm{CP}} = 1 + (r_B^{Dh})^2 + 2r_B^{Dh}(2F_+ - 1)\cos\left(\delta_B^{Dh}\right)\cos(\gamma)$$

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

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
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
   - Pick BDT cut that minimised statistical sensitity of γ

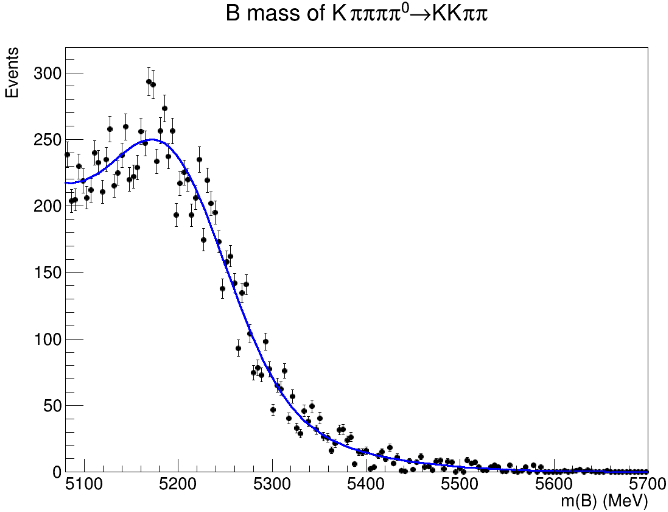


Summary of backgrounds

- 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

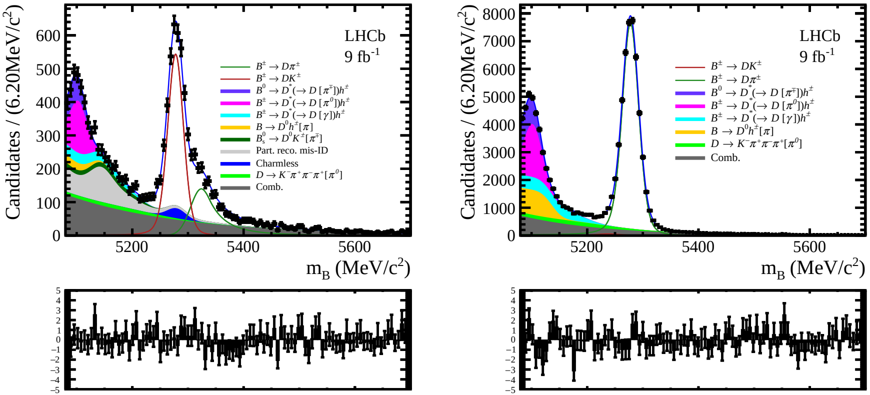


Figure 2: $B^{\pm} \to DK^{\pm}$ channel (left) and $B^{\pm} \to D\pi^{\pm}$ channel (right)

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

Fit split by charge

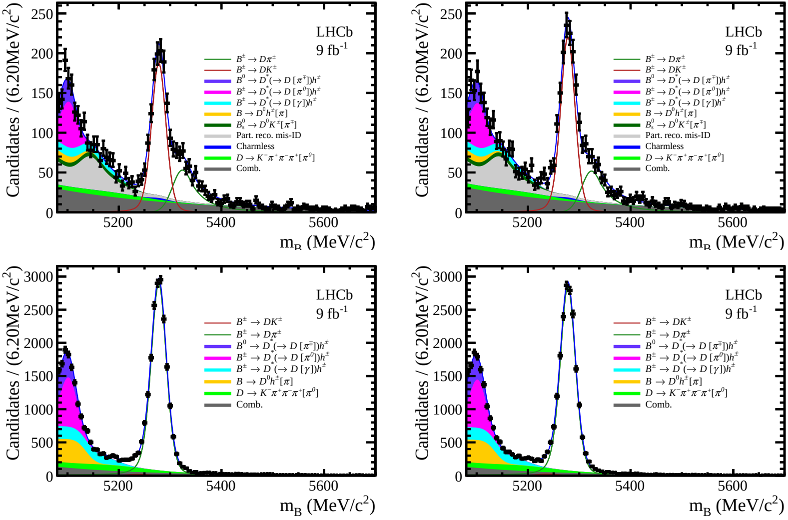


Figure 3: $B^\pm \to (K^+K^-\pi^+\pi^-)Dh^\pm$

Fit split by charge

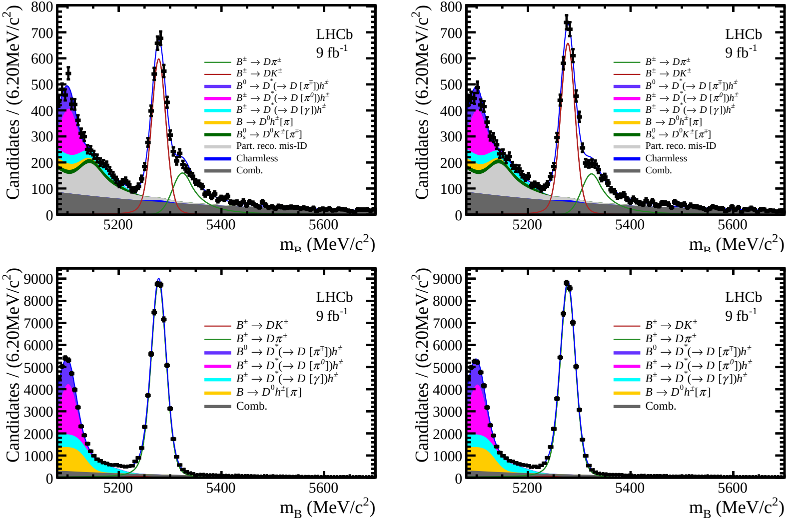
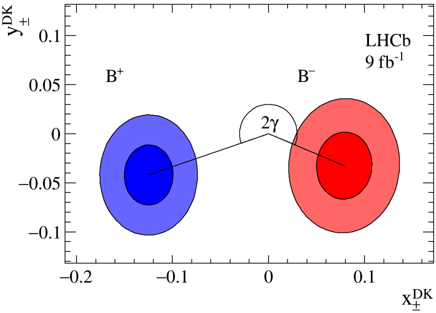


Figure 4: $B^\pm \to (\pi^+\pi^-\pi^+\pi^-)Dh^\pm$

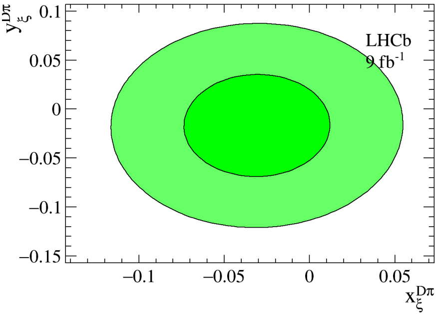
CP fit setup

- 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 $x_\pm^{DK}$, $y_\pm^{DK}$ $x_\xi^{D\pi}$, $y_\xi^{D\pi}$ (6 parameters)
- Fractional bin yields F_i are floating (15 parameter)
- Combinatorial background yield floated in each bin (64 parameters)
- Total partially reconstructed background yield 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

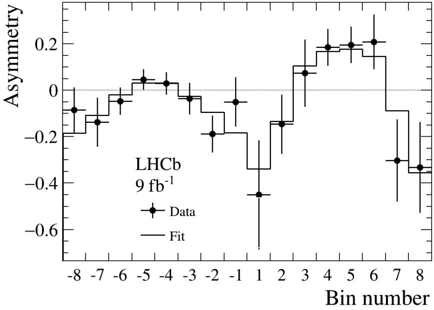


(a) $x_\pm^{DK}$ vs $y_\pm^{DK}$

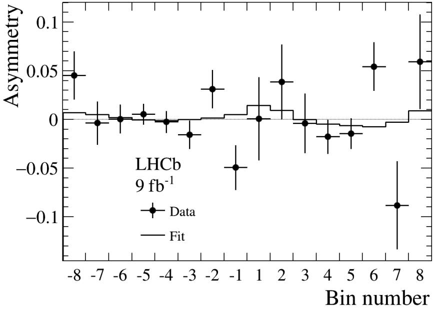


(b) $x_\xi^{D\pi}$ vs $y_\xi^{D\pi}$

Fractional bin asymmetries



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



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

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}

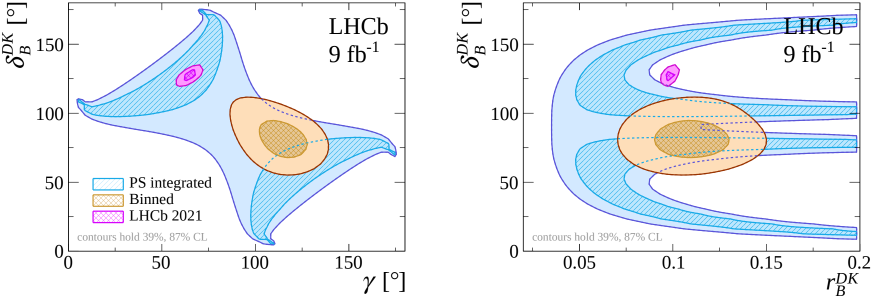
Source	x_-^{DK}	y_-^{DK}	x_+^{DK}	y_+^{DK}	$x_\xi^{D\pi}$	$y_\xi^{D\pi}$
Statistical	2.99	3.50	2.58	3.10	4.07	4.89
c_i, s_i	0.14	3.82	1.78	1.03	0.01	0.71
$B^\pm \to D\mu\nu$ background	0.07	0.06	0.08	0.30	0.17	0.00
$D \to K(X)l\nu_l$ background	0.08	0.00	0.73	0.14	0.27	0.44
$D \to K\pi\pi\pi$ background	0.25	0.00	0.73	0.06	0.07	0.27
$D \to K\pi\pi\pi\pi^0$ background	0.37	0.07	0.20	0.04	0.45	0.19
Λ_b background	0.10	0.06	0.06	0.26	0.15	0.07
Bin dependent mass shape	0.06	0.12	0.13	0.12	0.24	0.12
Charmless background	0.15	0.18	0.14	0.16	0.01	0.01
Fit bias	0.00	0.00	0.00	0.00	0.00	0.00
Fixed yield fractions	0.02	0.03	0.02	0.02	0.01	0.01
Low mass physics effects	0.15	0.21	0.05	0.20	0.03	0.44
Mass shape	0.03	0.03	0.02	0.02	0.04	0.01
PID Efficiency	0.03	0.03	0.02	0.02	0.04	0.01
D mixing	0.00	0.02	0.01	0.02	0.00	0.00
Total LHCb systematic	0.52	0.32	1.08	0.52	0.63	0.72
Total systematic	0.54	3.83	2.08	1.15	0.63	1.01

Summary of all quasi-GLW systematic uncertainties

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

Source	$A_K^{KK\pi\pi}$	$A_\pi^{KK\pi\pi}$	$A_K^{\pi\pi\pi\pi}$	$A_\pi^{\pi\pi\pi\pi}$	$R_{\mathrm{CP}}^{KK\pi\pi}$	$R_{\mathrm{CP}}^{\pi\pi\pi\pi}$
Statistical	23.49	13.36	5.56	3.12	24.54	14.46
Charmless background	1.20	0.44	0.01	0.00	13.72	8.43
External parameters	0.98	0.99	0.74	0.74	3.98	3.96
Fixed yield fractions	0.11	0.08	0.02	0.00	1.32	1.44
Mass shape	0.27	0.20	0.03	0.02	3.11	3.05
PID efficiency	0.18	0.12	0.01	0.00	2.55	1.64
Total systematic	1.59	1.11	0.74	0.74	14.90	10.04

Interpretation



$$\gamma = (103 \pm 14)^\circ$$
$$\delta_B^{DK} = (92 \pm 14)^\circ$$
$$r_B^{DK} = 0.117 \pm 0.020$$
$$\delta_B^{D\pi} = (296 \pm 84)^\circ$$
$$r_B^{D\pi} = 0.004 \pm 0.005$$

Summary

- Measured CP observables:

$$
\begin{aligned}
x_-^{DK} &= (8.3 \pm 3.0 \pm 0.5 \pm 0.1) \times 10^{-2}, \\
y_-^{DK} &= (-1.2 \pm 3.5 \pm 0.3 \pm 3.8) \times 10^{-2}, \\
x_+^{DK} &= (-13.5 \pm 2.6 \pm 1.1 \pm 1.8) \times 10^{-2}, \\
y_+^{DK} &= (-4.0 \pm 3.1 \pm 0.5 \pm 1.0) \times 10^{-2}, \\
x_\xi^{D\pi} &= (-2.9 \pm 4.1 \pm 0.6 \pm 0.0) \times 10^{-2}, \\
y_\xi^{D\pi} &= (-2.0 \pm 4.9 \pm 0.7 \pm 0.7) \times 10^{-2},
\end{aligned}
$$

- Measured physics parameters:

$$
\begin{aligned}
\gamma &= (103 \pm 14)^\circ \\
\delta_B^{DK} &= (92 \pm 14)^\circ \\
r_B^{DK} &= 0.117 \pm 0.020 \\
\delta_B^{D\pi} &= (296 \pm 84)^\circ \\
r_B^{D\pi} &= 0.004 \pm 0.005
\end{aligned}
$$

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 be available from BESIII soon

Thank you!