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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Outline

1. Summary of γ analysis in $B^{\pm} \to Dh^{\pm}$, $D \to h^{+}h^{-}\pi^{+}\pi^{-}$
2. Updates and improvements to analysis
   - $D \to K\pi\pi\pi\pi^{0}$ mis-ID background
   - Some minor changes and improvements
   - Systematic uncertainties
3. CP fit results, including central values (analysis not blind)
4. Summary of $KK\pi\pi$ analysis
5. Conclusion and next steps

Summary of γ analysis in $B^\pm \to Dh^\pm$, $D \to h^+h^-\pi^+\pi^-$

Summary of γ analysis in $B^{\pm} \to Dh^{\pm}$, $D \to h^+h^-\pi^+\pi^-$

- First presented to B2OC WG on 4th November 2022
  - Slides here
  - TWiki page with ANA note here
- GGSZ: Analysis in phase space bins of $D^0 \to K^+K^-\pi^+\pi^-$
  - This publication: c_i/s_i from LHCb model JHEP 02 (2019) 126
  - Long term plan: Strong-phase analysis at BESIII currently ongoing where c_i/s_i are measured directly $\implies$ Model independent analysis
- Quasi-GLW: Phase space integrated analysis of $D^0 \to h^+h^-\pi^+\pi^-$
  - $F_+^{4\pi} = 0.769 \pm 0.023$ from CLEO-c data JHEP 01 (2018) 144
  - $F_+^{KK\pi\pi} = 0.736$ from LHCb model
    - Preliminary BESIII analysis of F_+ shows good agreement with model

The BPGGSZ method

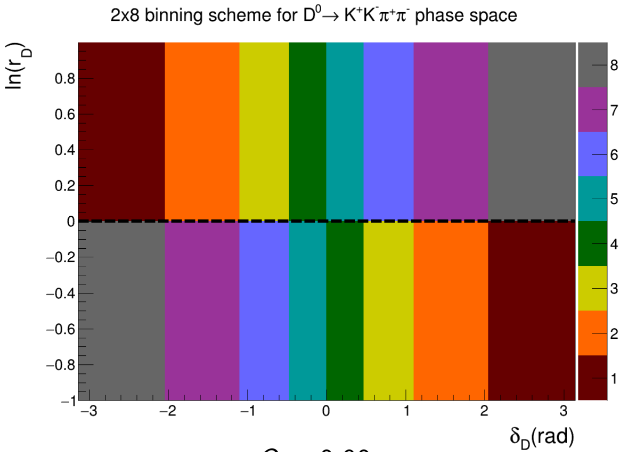
Event yield in bin i

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

- 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



$$Q = 0.90$$

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:

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

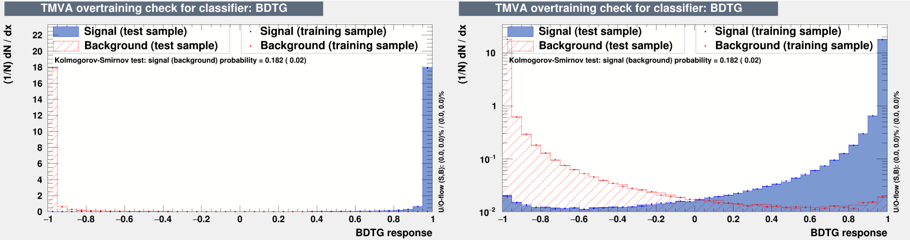
CP observables and physics parameters

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

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

Selection

1. Initial cuts: Trigger requirements, mass cuts, bachelor p, etc
2. BDT: Efficient combinatorial background rejection
3. Final cuts: PID cuts, flight significance cuts, K_S veto, etc



(a) BDT output **(b)** BDT output on a logarithmic scale

Global fit

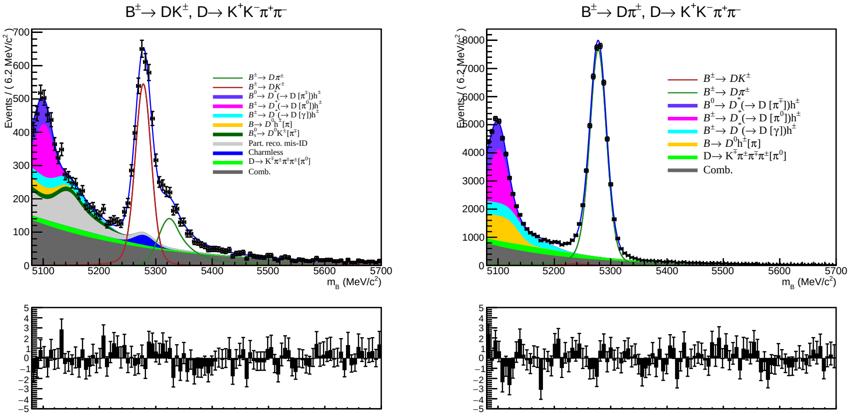


Figure 2: $B^\pm \to DK^\pm$ channel (left) and $B^\pm \to D\pi^\pm$ channel (right)

- $B^\pm \to DK^\pm$ yield: 3306 ± 75
- $B^\pm \to D\pi^\pm$ yield: $46\,695 \pm 256$

Fit split by charge

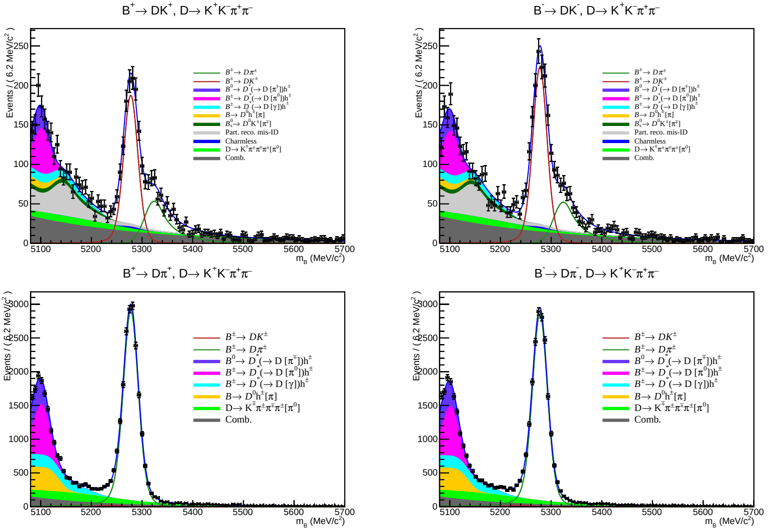


Figure 3: $B^\pm \to (K^+K^-\pi^+\pi^-)Dh^\pm$

Fit split by charge

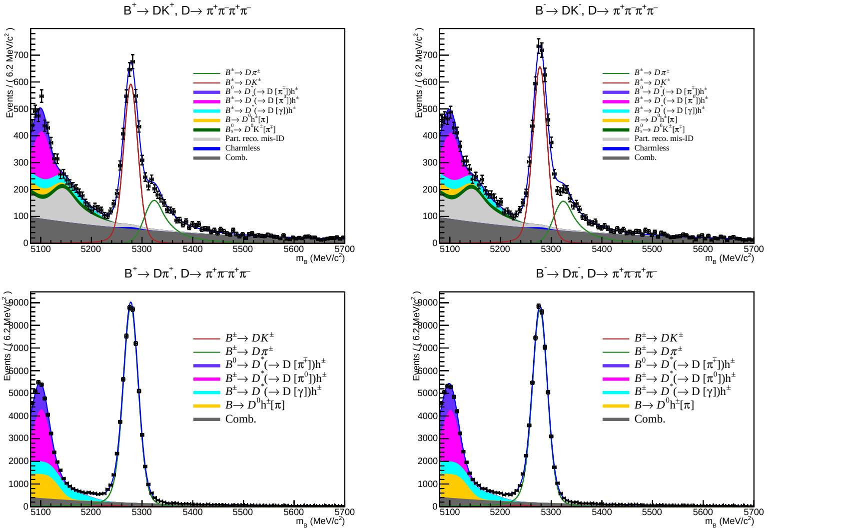


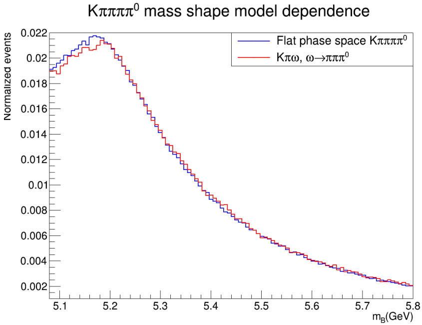
Figure 4: $B^{\pm} \to (\pi^+\pi^-\pi^+\pi^-)Dh^{\pm}$

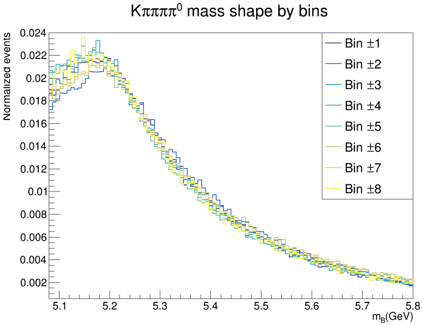
Updates and improvements to analysis

Thanks to Anton, Nathan, Paras
for reading the ANA note!

$D \to K\pi\pi\pi\pi^0$ mis-ID background

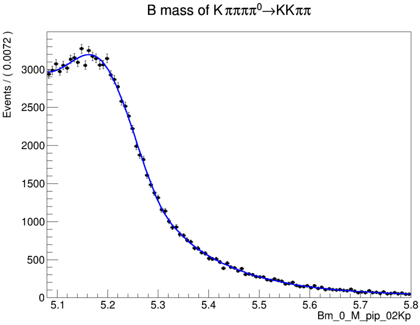
- Missing π^0 and $\pi \to K$ mis-ID
- Two changes:
  1. Unclear how DTF affects mass shape $\implies$ Requested LHCb MC
  2. Float yield relative to $B \to D^* h$ background instead of all partially reconstructed background
- Cross checks: Model dependence and bin dependence



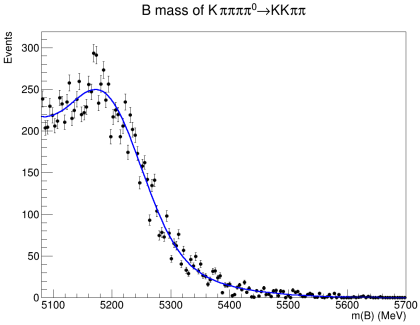


$D \to K\pi\pi\pi\pi^0$ mis-ID background

- Reweighting procedure:
  1. Run through same reconstruction as $KK\pi\pi$
  2. Use $KK\pi\pi$ MC to calculate PID efficiency of $\mathrm{PIDK} > -10$ as a function of p and η
  3. Reweight each event to "undo" the PID cut from stripping
  4. Reweight with PIDCalib2 to account for $\mathrm{PIDK} > 0$ cut in selection



(a) RapidSim



(b) Full LHCb simulation

Some minor changes and improvements

1. K_S veto for $D \to \pi\pi\pi\pi$ added to match the CLEO-c F_+ analysis
2. Fit bias is corrected for
3. Fit range reduced from 5800 MeV to 5700 MeV
4. BPGGSZ and quasi-GLW correlations accounted for

Systematic uncertainties

1. c_i/s_i systematic uncertainty from modelling
   - Strategy: Generate toys with c_i/s_i from older CLEO model, fit with c_i/s_i from LHCb model
   - Largest systematic uncertainty
   - Will be replaced when BESIII results become available
2. Charmless background: Vary the total yield and fractional bin yields
3. $K\pi\pi\pi\pi^0$: Vary bin distribution from D^0-like to $D^0+\bar{D}^0$-like
4. D mixing: Bias from toy fit
   - More or less negligible when F_i are floated
   - Relatively large if F_i are fixed
5. All quasi-GLW systematic studies finished

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

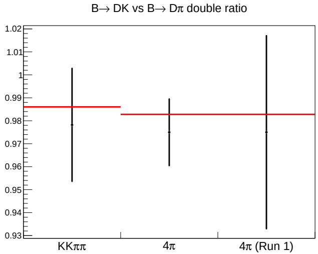
Summary of all quasi-GLW systematic uncertainties

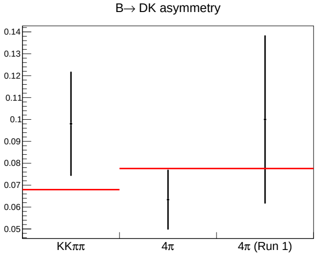
Uncertainties of quasi-GLW CP observables in units of 10^{-2}

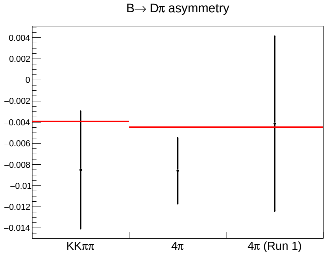
Source	$A_K^{KK\pi\pi}$	$A_\pi^{KK\pi\pi}$	$A_K^{\pi\pi\pi\pi}$	$A_\pi^{\pi\pi\pi\pi}$	$R_{\mathrm{CP}}^{KK\pi\pi}$	$R_{\mathrm{CP}}^{\pi\pi\pi\pi}$
Statistical	23.49	13.36	5.56	3.12	24.54	14.46
Charmless background	1.20	0.44	0.01	0.00	13.72	8.43
External parameters	0.98	0.99	0.74	0.74	3.98	3.96
Fixed 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

CP fit results

GLW CP observables



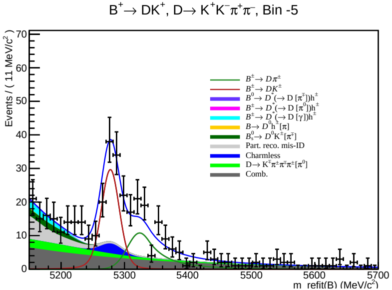


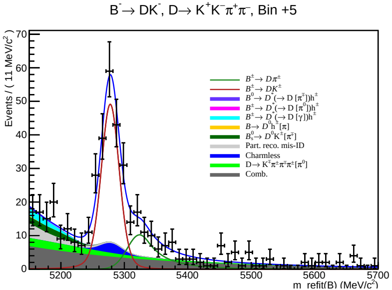


Red line: Prediction for CP observables using γ+charm combination

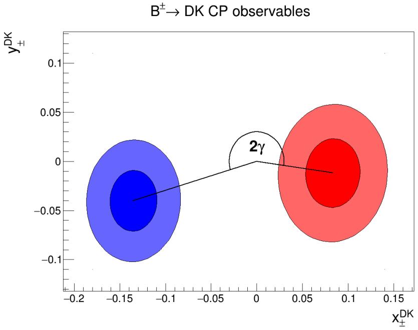
Binned CP fit

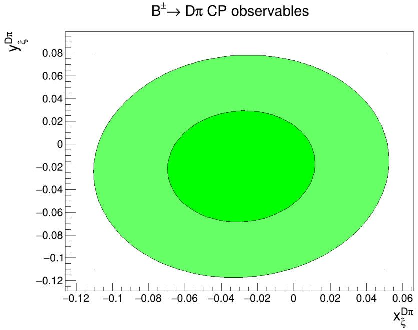
- PDF shape parameters fixed from global fit
- 2 charges, 2 B decays, 2×8 bins $\Longrightarrow$ 64 categories
- Nuisance parameters:
  - Combinatorial and low mass background (2×64 parameters)
  - F_i (15 parameters)
  - Yield normalization for each charge and B decay (4 parameters)
- 6 CP observables $\Longrightarrow$ 153 free parameters in total



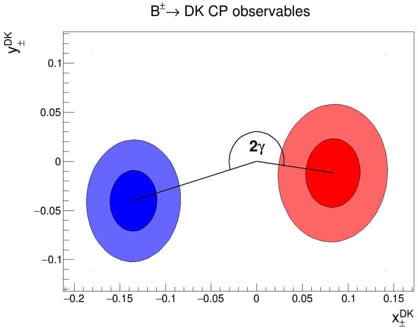


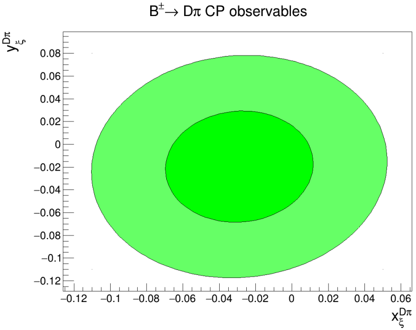
CP observables result





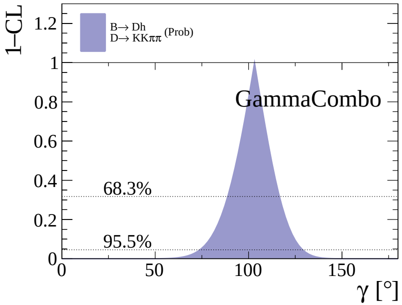
CP observables result

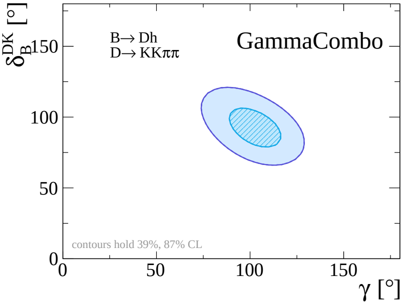




Could there be a sign error in s_i?

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 of $KK\pi\pi$ analysis

Summary of $KK\pi\pi$ analysis

- 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 and next steps

Conclusion and next steps

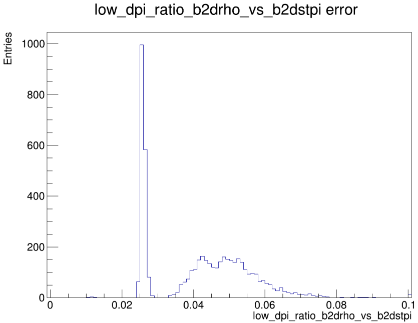
- Binned γ analysis of $B^{\pm} \to (K^+K^-\pi^+\pi^-)_D h^{\pm}$ is ready for RC
- Quasi-GLW observables of $h^+h^-\pi^+\pi^-$ further constrains γ
- All systematics have been evaluated
- Next steps:
  1. Understand double peak error distribution in global fit toys
  2. Make sure s_i has the correct sign

Thank you!

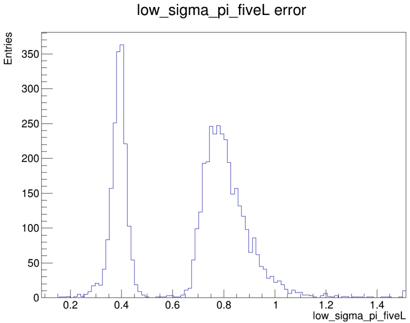
Thank you!

Backup

Double-peaked error distributions



(a) $f_{D\pi\pi}^{D\pi}$



(b) $\sigma_{\pi}^{\mathrm{low}}$

s_i sign problem

- Amplitude model gives us: $A(\Phi) = \sum_k a_k S_k(\Phi)$
- Flavour-tagged LHCb data measures: $|A(\Phi)|^2$
- a_k phase is fixed from phase convention of $S_k(\Phi)$ lineshapes
- Physical observable: Interference fractions
  - Toy fit shows that LHCb and CLEO models are consistent
  - Thanks to Tim Evans for checking!

Resonance	LHCb model phase (rad)	CLEO model (rad)
$D^0 \to [\phi(1020)\rho^0]_{L=0}$	0 (fixed)	0 (fixed)
$D^0 \to K_1(1400)^+ K^-$	1.05	-1.79
$D^0 \to K_1(1270)^+ K^-$	2.02	-2.56

s_i sign problem

- BESIII data can determine sign uniquely!
- Reconstruct $KK\pi\pi$ vs $K_{S,L}\pi\pi$ double tags:

$$M_{i,j} \propto \left(K_i K'_{-j} + K_{-i} K'_j \mp 2\sqrt{K_i K_{-i} K'_j K'_{-j}}(c_i c'_j + s_i s'_j)\right)$$

s_i sign problem

Cross checks:

1. Can use BESIII data with $KK\pi\pi$ vs $K_{S,L}\pi\pi$ tags to check s_i sign
2. Same fit code was used in $B \to Dh$, $D \to K_S\pi\pi$ analysis
3. Same code used to bin events in data and in calculation of c_i/s_i
4. Independent binned fit toys are consistent with AmpGen unbinned fit