

$D \rightarrow K^+ K^- \pi^+ \pi^-$ analysis at LHCb and BESIII

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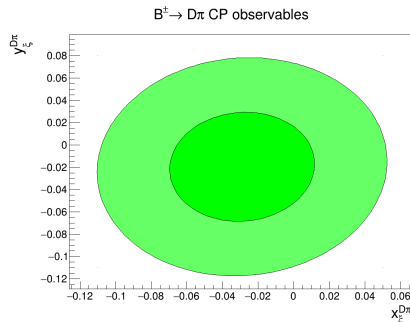
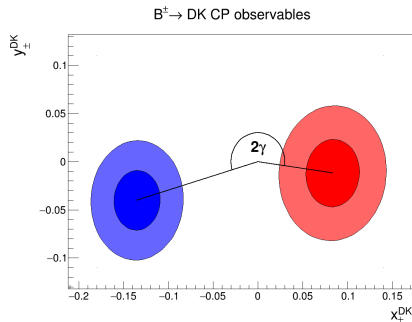
$B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ GGSZ+GLW analysis at LHCb

$$B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$$

GGSZ+GLW analysis at LHCb

Summary of LHCb analysis status

- Previously on γ measurement in $B^\pm \rightarrow Dh^\pm$, $D \rightarrow K^+K^-\pi^+\pi^-$:
 - Model-independent binned GGSZ and inclusive GLW analysis
 - WG approval on 10th March
 - Received 1st comments from RC reviewers, replies sent back



Results for γ

$$\gamma = (103 \pm 14)^\circ$$

$$\delta_B^{DK} = (92 \pm 14)^\circ$$

$$r_B^{DK} = 0.117 \pm 0.020$$

$$\delta_B^{D\pi} = (296 \pm 84)^\circ$$

$$r_B^{D\pi} = 0.004 \pm 0.005$$

- Sign error in the strong phase? $\gamma \rightarrow 180^\circ - \gamma$
- Unfortunately, sign error looks unlikely...
 - Interference fractions agree between LHCb and CLEO models
 - BESIII data seems to support the sign from the model

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

$D \rightarrow K^+ K^- \pi^+ \pi^-$ strong-phase analysis as BESIII

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

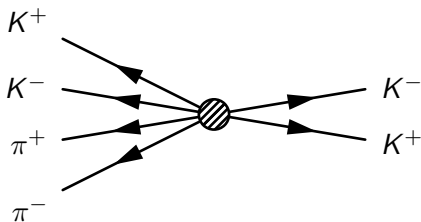
strong-phase analysis as BESIII

Measurement of CP even fraction F_+

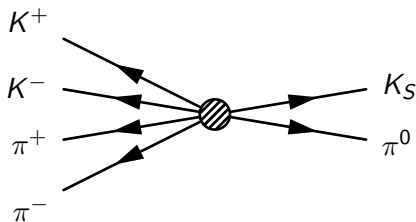
- BESIII: e^+e^- collider at $\psi(3770) \rightarrow D^0\bar{D}^0$ threshold
- Reconstruct signal mode $D \rightarrow KK\pi\pi$ and a tag mode $D \rightarrow f$
- Signal mode is quantum correlated with tag mode
- Measure BF with CP even/odd tags to determine F_+

$$\text{BF}(KK\pi\pi|f) = \text{BF}(KK\pi\pi) \times (1 - \lambda_{\text{CP}}(2F_+ - 1))$$

$$\text{BF}(KK\pi\pi|f) = \text{BF}(KK\pi\pi) \times (K_i + K_{-i} \mp 2\sqrt{K_i K_{-i}} c_i (2F_+ - 1))$$

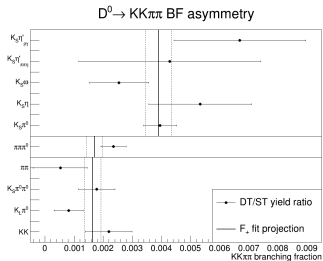


(a) CP even tag

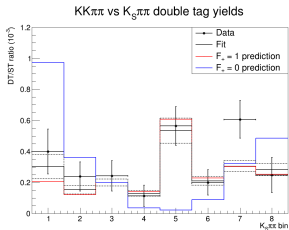


(b) CP odd tag

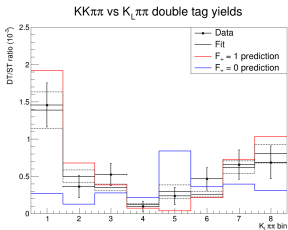
F_+ measurement with CP, $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags



(a) CP tags



(b) $K_S^0\pi^+\pi^-$ tag



(c) $K_L^0\pi^+\pi^-$ tag

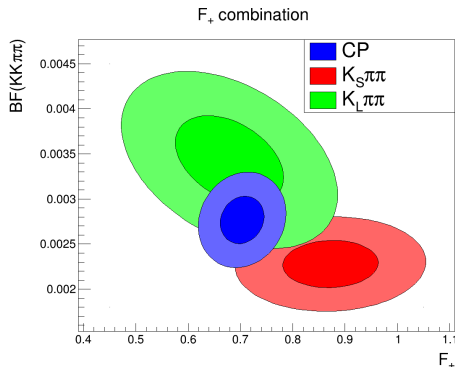


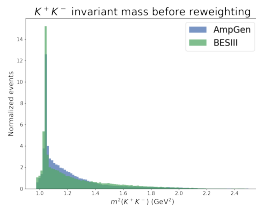
Figure 3: F_+ combination

- Observe large anti-correlation in $K_L\pi\pi$ because $F_+^{K_L\pi\pi} \approx 0.354$
 - Yield of $K_L\pi\pi$ is twice as large as that of $K_S\pi\pi$
 - Fractional bin yields and total yield contains information about F_+
 - When $K_L\pi\pi$ BF is available, combine all tags!

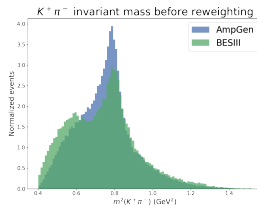
Efficiency corrections

- All yields must be corrected for efficiency
- Problem: BESIII simulation uses a very old $KK\pi\pi$ model in EvtGen
- Solution: Reweight BESIII simulation to look like the LHCb model
 - Use Python hep_ml Gradient Boosted Reweighter
 - Variables:
 - 1 $m^2(K^+K^-)$
 - 2 $m^2(K^+\pi^-)$
 - 3 $m^2(K^-\pi^+)$
 - 4 $m^2(\pi^+\pi^-)$
 - 5 $m^2(K^+K^-\pi^+)$

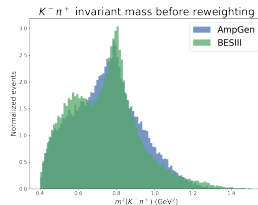
Naive efficiency correction



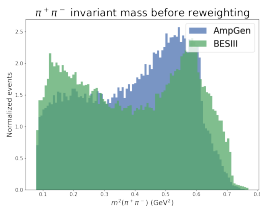
(a) $m^2(K^+ K^-)$



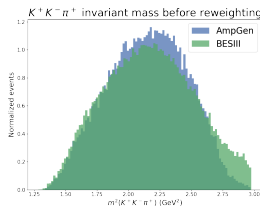
(b) $m^2(K^+ \pi^-)$



(c) $m^2(K^- \pi^+)$



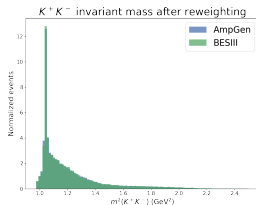
(d) $m^2(\pi^+ \pi^-)$



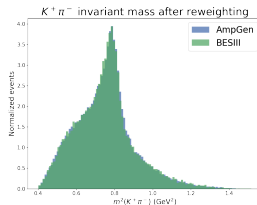
(e) $m^2(K^+ K^- \pi^+ \pi^-)$

Figure 4: Before reweighting

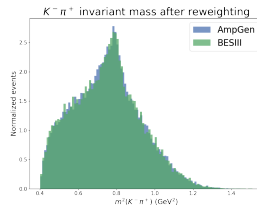
Naive efficiency correction



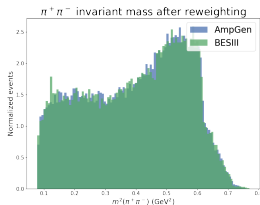
(a) $m^2(K^+ K^-)$



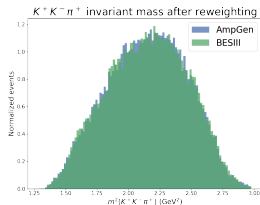
(b) $m^2(K^+ \pi^-)$



(c) $m^2(K^- \pi^+)$



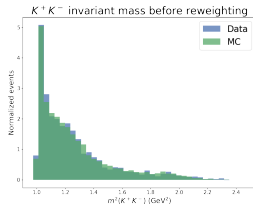
(d) $m^2(\pi^+ \pi^-)$



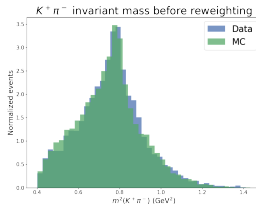
(e) $m^2(K^+ K^- \pi^+ \pi^-)$

Figure 5: After reweighting

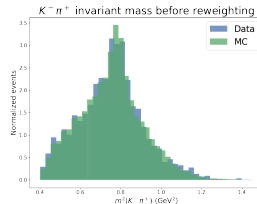
Does the naive reweighting work?



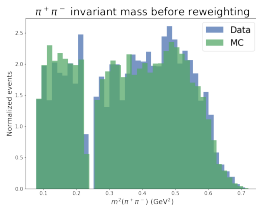
(a) $m^2(K^+K^-)$



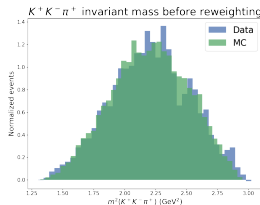
(b) $m^2(K^+\pi^-)$



(c) $m^2(K^-\pi^+)$



(d) $m^2(\pi^+\pi^-)$



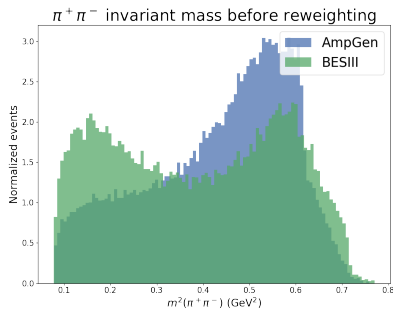
(e) $m^2(K^+K^-\pi^+)$

Figure 6: Single tag $D \rightarrow KK\pi\pi$ in data and MC after reweighting

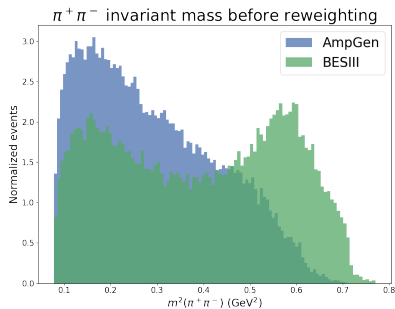
Quantum correlated LHCb model

- Problem with naive reweighting:
 - LHCb model assumes a pure $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decay
 - No quantum correlations
 - Example: If tag is $D \rightarrow KK$, the $D \rightarrow KK\pi\pi$ decay will be CP odd!
 - Quantum correlations will affect phase space distribution \implies Efficiencies could change
- Solution: Separate reweighters for CP even/odd $D \rightarrow K^+ K^- \pi^+ \pi^-$
 - CP even tags: Use efficiencies after reweighting to CP odd model
 - CP odd tags: Use efficiencies after reweighting to CP even model
 - $K_{S,L}\pi\pi$ tags: Do a weighted average of the two efficiencies

Before weighting to CP even/odd models



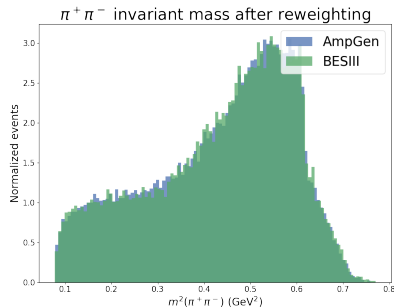
(a) CP even



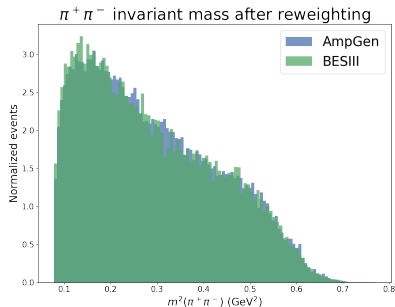
(b) CP odd

Figure 7: $m^2(\pi^+\pi^-)$ before reweighting

After weighting to CP even/odd models



(a) CP even



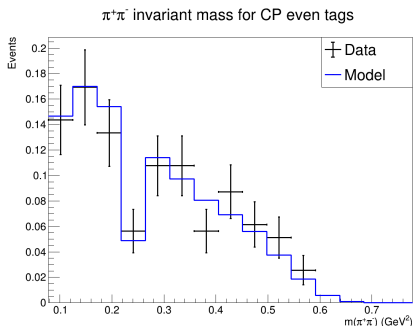
(b) CP odd

Figure 8: $m^2(\pi^+ \pi^-)$ after reweighting

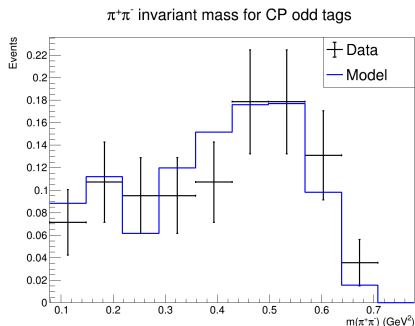
No reweighting	Naive reweighting	CP even model	CP odd model
18.0%	19.0%	18.1%	21.9%

Agreement between quantum correlated data and model

- Note: LHCb model knows nothing about quantum correlations
- D^0/\bar{D}^0 amplitudes simply combined to obtain CP even/odd models
- Important question: Can the model describe quantum correlated double tag data at all? Answer: Yes!



(a) Double tags of $KK\pi\pi$ vs CP even



(b) Double tags of $KK\pi\pi$ vs CP odd

Figure 9: $m^2(\pi^+\pi^-)$ in double tags, compared with CP even/odd LHCb models

- Final fit result: $F_+ = 0.73 \pm 0.04$
 - First model-independent measurement
 - Compare with model prediction: $F_+ = 0.736$
 - Good news for GLW analyses: Can include $D \rightarrow KK\pi\pi$
- Systematics studies finished
 - Very small, completely statistics dominated
- Analysis note (MEMO) written up and reviewed by charm conveners
 - All three conveners approved last week
 - Next step: Present to BESIII on Friday before entering RC

- LHCb $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ GGSZ+GLW analysis:
 - Final result of GGSZ part: $\gamma = 103 \pm 14$
 - In RC, currently waiting for further comments
 - $\gamma(\delta_B^{DK})$ too large(small), still looking for bugs
- BESIII $D \rightarrow K^+ K^- \pi^+ \pi^-$ strong-phase analysis:
 - First model-independent measurement: $F_+ = 0.73 \pm 0.04$
 - Analysis required model-dependent efficiency corrections
 - Will present to BESIII on Friday 3rd June 10th June before entering RC
- What now?
 - Currently studying PID performance with TORCH
 - Start at CERN next Monday!

Thank you!