

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

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## 1 LHCb

- Summary of LHCb analysis status

## 2 BESIII

- Measurement of CP even fraction  $F_+$
- Efficiency corrections
- Current status

## 3 Summary

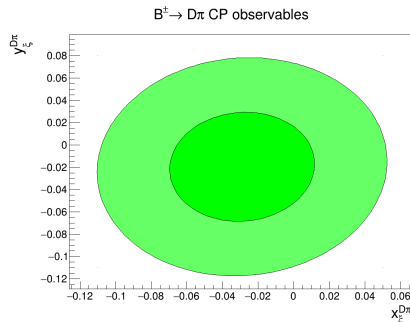
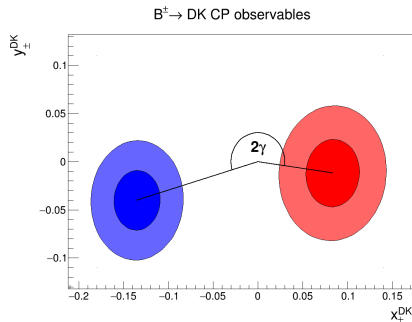
$B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$  GGSZ+GLW analysis at LHCb

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

GGSZ+GLW analysis at LHCb

# Summary of LHCb analysis status

- Previously on  $\gamma$  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 $\gamma$

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

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

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

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

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

- 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

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

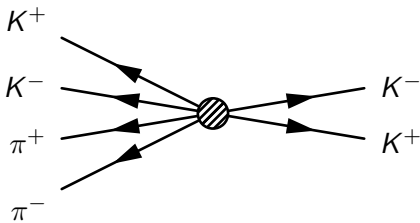
strong-phase analysis as BESIII

# Measurement of CP even fraction $F_+$

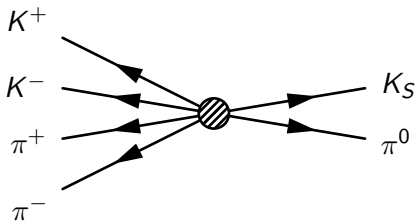
- BESIII:  $e^+e^-$  collider at  $\psi(3770) \rightarrow D^0\bar{D}^0$  threshold
- Reconstruct signal mode  $D \rightarrow KK\pi\pi$  and a tag mode  $D \rightarrow f$
- Signal mode is quantum correlated with tag mode
- Measure BF with CP even/odd tags to determine  $F_+$

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

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

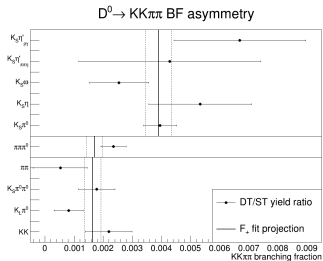


(a) CP even tag

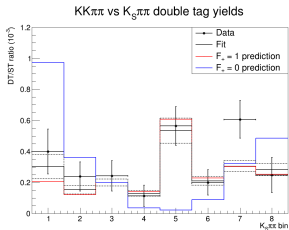


(b) CP odd tag

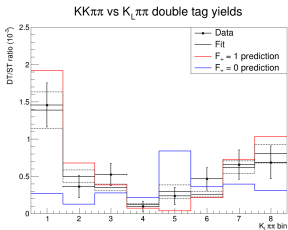
# $F_+$ measurement with CP, $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags



(a) CP tags

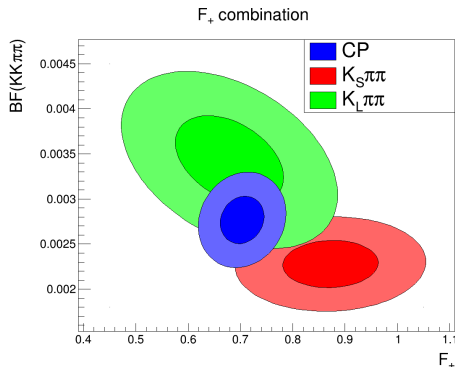


(b)  $K_S^0\pi^+\pi^-$  tag



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





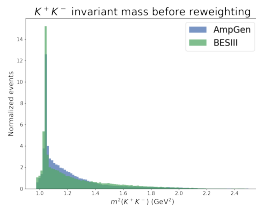
**Figure 3:**  $F_+$  combination

- 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!

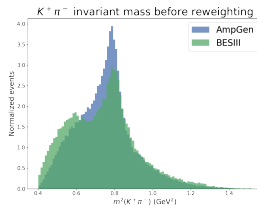
# Efficiency corrections

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

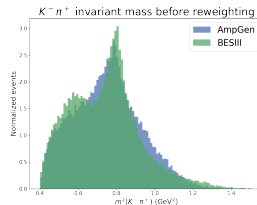
# Naive efficiency correction



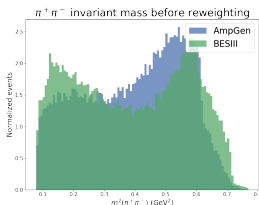
(a)  $m^2(K^+ K^-)$



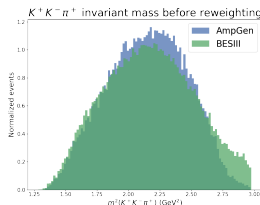
(b)  $m^2(K^+ \pi^-)$



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



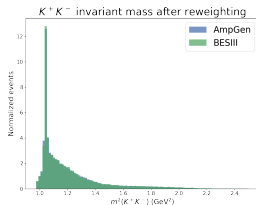
(d)  $m^2(\pi^+ \pi^-)$



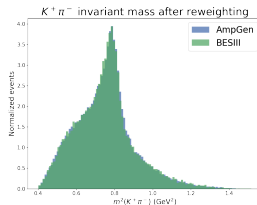
(e)  $m^2(K^+ K^- \pi^+ \pi^-)$

**Figure 4: Before reweighting**

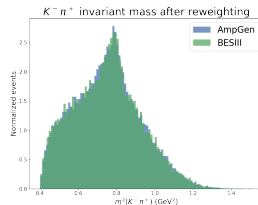
# Naive efficiency correction



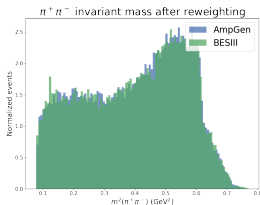
(a)  $m^2(K^+ K^-)$



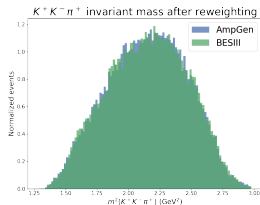
(b)  $m^2(K^+ \pi^-)$



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



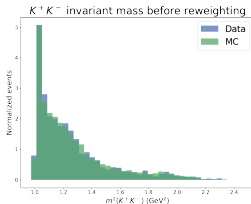
(d)  $m^2(\pi^+ \pi^-)$



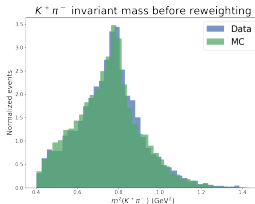
(e)  $m^2(K^+ K^- \pi^+ \pi^-)$

**Figure 5: After reweighting**

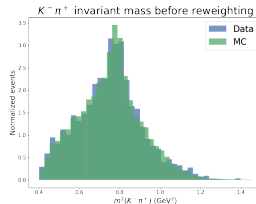
# Does the naive reweighting work?



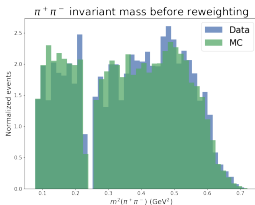
(a)  $m^2(K^+K^-)$



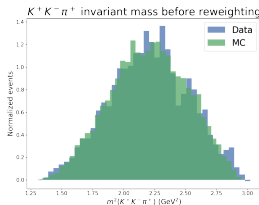
(b)  $m^2(K^+\pi^-)$



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



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



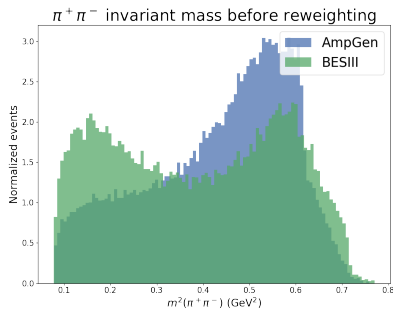
(e)  $m^2(K^+K^-\pi^+)$

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

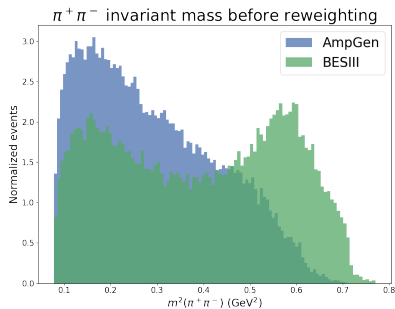
# Quantum correlated LHCb model

- 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



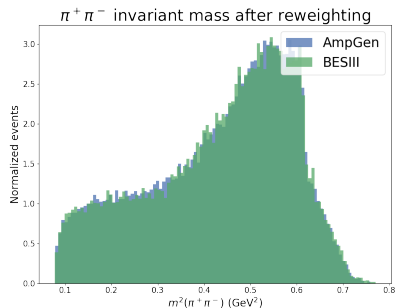
(a) CP even



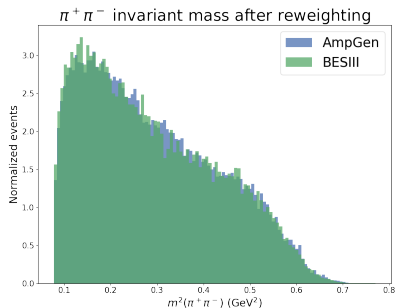
(b) CP odd

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

# After weighting to CP even/odd models



(a) CP even



(b) CP odd

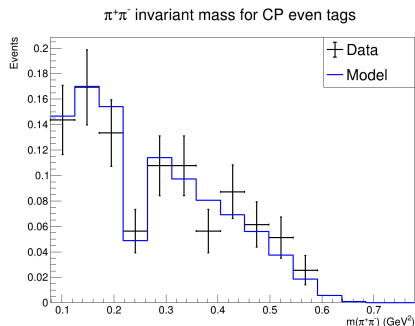
**Figure 8:**  $m^2(\pi^+ \pi^-)$  after reweighting

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

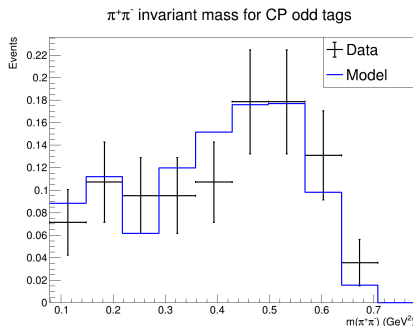


# Agreement between quantum correlated data and model

- 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
  - Sign of  $s_i$  remains uncertain
- 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 26th May before entering RC
- What now?
  - Currently studying PID performance with TORCH
  - Start at CERN next Monday!

## Thank you!