

# Model-independent determination of the CKM angle $\gamma$ in $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ decays

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# Outline

- 1 Introduction to the CKM angle  $\gamma$
- 2 Binned  $\gamma$  analysis of the  $D \rightarrow K^+ K^- \pi^+ \pi^-$  mode
- 3 Binning scheme
- 4 Fit to data
- 5 Summary of  $KK\pi\pi$  analysis
- 6 Quasi-GLW observables with  $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow \pi^+ \pi^- \pi^+ \pi^-$
- 7 Conclusion

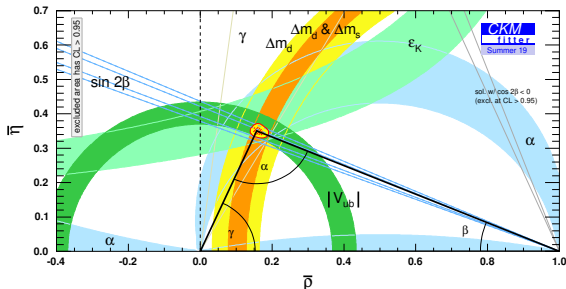
## Introduction to the CKM angle $\gamma$

# $\gamma$ and the unitary triangle

- CP violation in SM is described by the Unitary Triangle

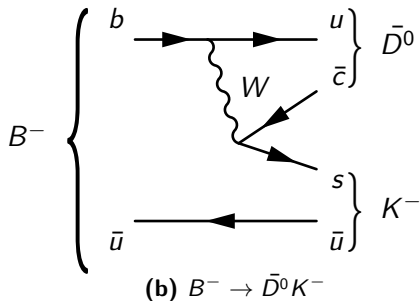
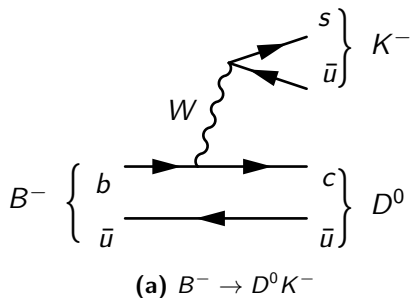
$$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- Only CKM angle accessible at tree level  $\Rightarrow$ 
  - Negligible theoretical uncertainties
  - Ideal Standard Model benchmark
  - Compare with indirect measurements



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

# Sensitivity through interference



- Superposition of  $D^0$  and  $\bar{D}^0$
- $b \rightarrow u\bar{c}s$  and  $b \rightarrow c\bar{u}s$  interference  $\rightarrow$  Sensitivity to  $\gamma$

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

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

# Measurement of $\gamma$ from $B^\pm \rightarrow DK^\pm, D \rightarrow K^+K^-\pi^+\pi^-$

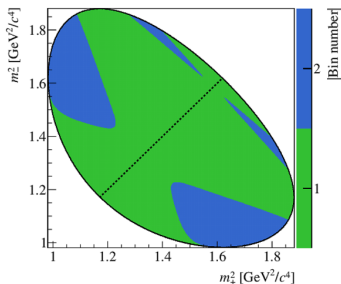
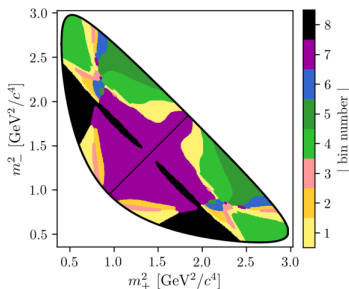
- First proposed by J. Rademacker and G. Wilkinson
  - [arXiv:hep-ph/0611272](#)
  - Amplitude model by FOCUS
  - Expected  $\gamma$  precision from amplitude fit with 1000 candidates:  $14^\circ$
- CLEO amplitude analysis
  - [arXiv:1201.5716](#)
  - Expected  $\gamma$  precision from amplitude fit with 2000 candidates:  $11^\circ$
- State of the art amplitude analysis by LHCb:
  - [LHCb-PAPER-2018-041](#)
  - Use to develop efficient binning scheme

# The $D \rightarrow K^+ K^- \pi^+ \pi^-$ decay

Binned  $\gamma$  analysis of the  
 $D \rightarrow K^+ K^- \pi^+ \pi^-$  mode

# Binned measurement of $\gamma$

- Final measurement will be model-independent
  - Poor binning reduces statistical sensitivity  $\rightarrow$  No bias!
- Need strong phases of  $D$  decay  $\rightarrow$  Measure at BESIII
- LHCb-PAPER-2020-019:  $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow K_S^0 h^+ h^-$ 
  - Single most precise measurement:  $\gamma = (68.7^{+5.2}_{-5.1})^\circ$





# The BPGGSZ method

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

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

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

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

# The BPGGSZ method

## Event yield in bin $i$

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

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

- CP observables:

- $x_{\pm}^{DK} = r_B^{DK} \cos(\delta_B^{DK} \pm \gamma), \quad y_{\pm}^{DK} = r_B^{DK} \sin(\delta_B^{DK} \pm \gamma)$
- $x_{\xi}^{D\pi} = \text{Re}(\xi^{D\pi}), \quad y_{\xi}^{D\pi} = \text{Im}(\xi^{D\pi}) \quad \left( \xi^{D\pi} = \frac{r_B^{D\pi}}{r_B^{DK}} e^{i(\delta_B^{D\pi} - \delta_B^{DK})} \right)$

- Fractional bin yield:

- $F_i = \frac{\int_i d\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j d\Phi |\mathcal{A}(D^0)|^2}$
- Floated in the fit, mostly constrained by  $B^{\pm} \rightarrow D\pi^{\pm}$

- Amplitude averaged strong phases can be obtained from BESIII:

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

## Binning scheme

A binning scheme must satisfy the following:

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

How to bin a 5-dimensional phase space?

- Generate C++ code for LHCb amplitude model using AmpGen<sup>1</sup>
- For each  $B^\pm$  candidate, calculate

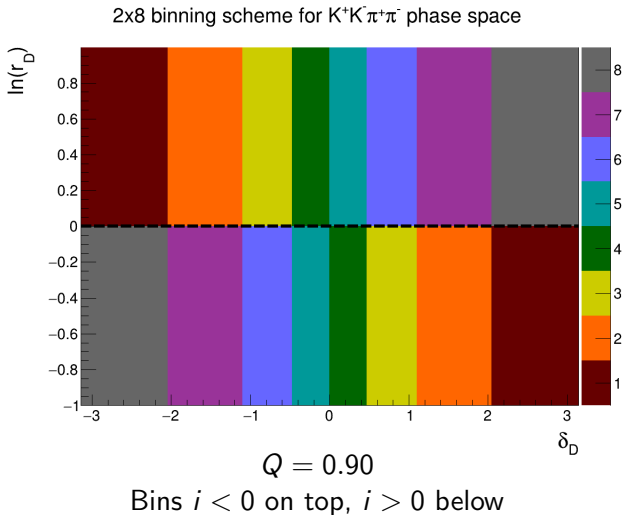
$$\frac{\mathcal{A}(D^0)}{\mathcal{A}(\bar{D}^0)} = r_D e^{i\delta_D}$$

- Bin along  $\delta_D$  and  $r_D$ , maximize  $Q$ -value to optimize

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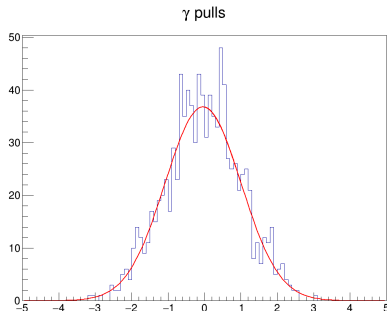
<sup>1</sup>AmpGen by Tim Evans

# Binning scheme

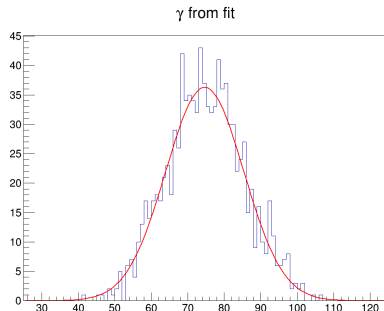


# $\gamma$ precision benchmark

- Generate 2000  $B^\pm \rightarrow DK^\pm$  candidates using LHCb model in AmpGen
- Fit back with same model using AmpGen



(a) Pull of  $\gamma$

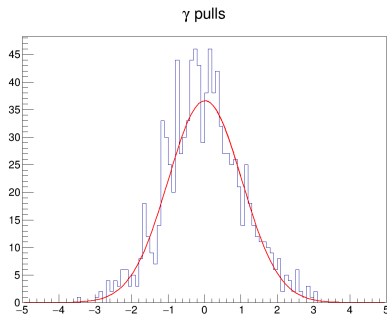


(b) Fitted  $\gamma$  values

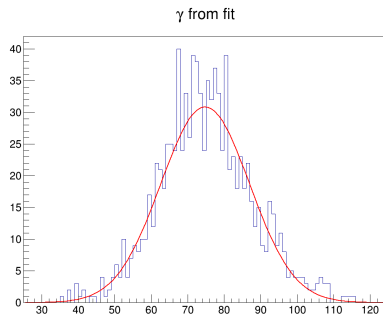
Precision of  $\gamma$  in unbinned fit:  $11^\circ$

# Study of $\gamma$ precision

- Binned fit setup: Optimized  $2 \times 8$  bins
- Fit same AmpGen samples, using  $c_i$ ,  $s_i$  and  $F_i$  from LHCb model



(a) Pull of  $\gamma$



(b) Fitted  $\gamma$  values

Precision of  $\gamma$  in binned fit:  $12^\circ$   
Consistent with unbinned fit and  $Q$ -value

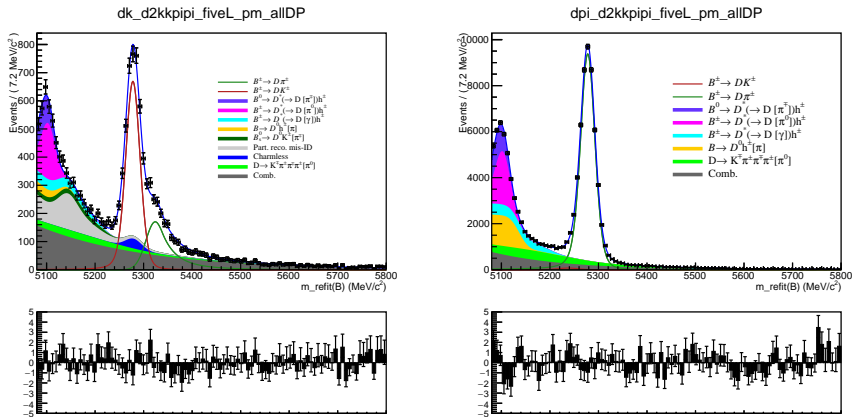
## Global fit



# Signal parameterisation

- PDF shape parameterization identical to LHCb-ANA-2020-001
- Signal: Gaussian + Modified Cruijff
- Shape fixed from MC, yield and width floated
- Combinatorial background (exponential)
- Partially reconstructed background (dini shapes)

$$f_{\text{MG}}(m|m_B, \sigma, \alpha_L, \alpha_R, \beta) \propto \begin{cases} \exp\left(\frac{-\Delta m^2(1+\beta\Delta m^2)}{2\sigma^2+\alpha_L\Delta m^2}\right), & \Delta m = m - m_B < 0 \\ \exp\left(\frac{-\Delta m^2(1+\beta\Delta m^2)}{2\sigma^2+\alpha_R\Delta m^2}\right), & \Delta m = m - m_B > 0 \end{cases}$$



**Figure 4:**  $B^\pm \rightarrow DK^\pm$  channel (left) and  $B^\pm \rightarrow D\pi^\pm$  channel (right)

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

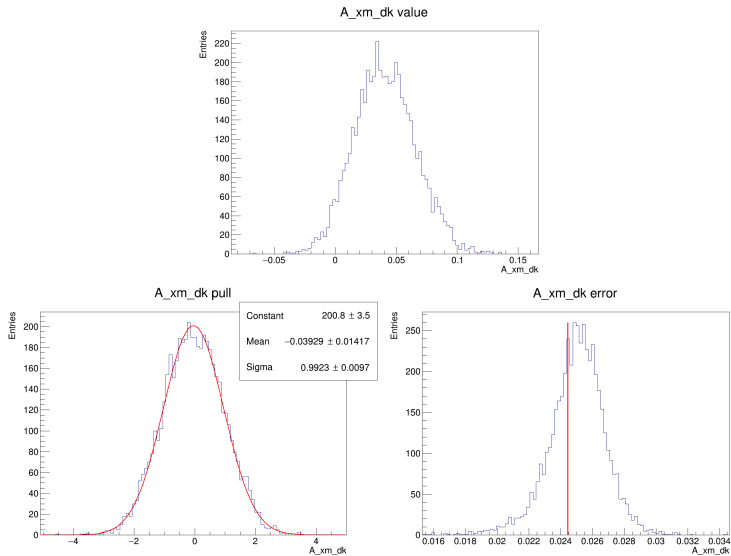
## Binned CP fit

# Binned CP fit

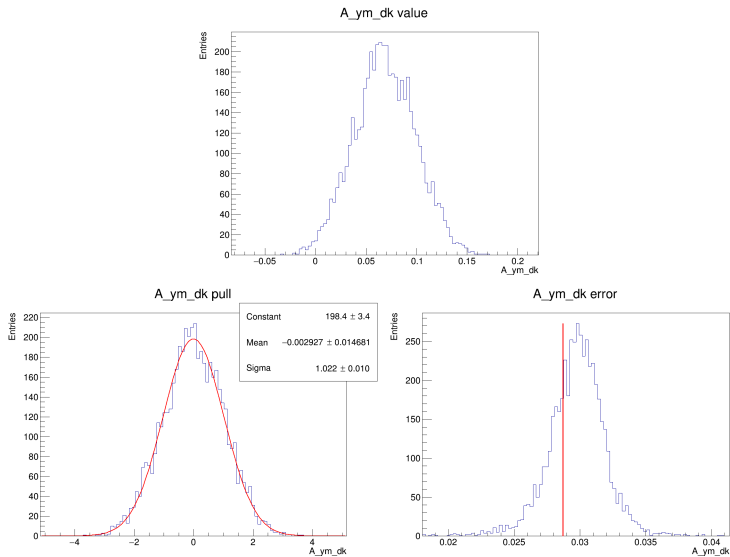
- Use  $2 \times 8$  bins
- $c_i$  and  $s_i$  not available yet  $\implies$ 
  - Calculate using MC integration of LHCb amplitude model for now
- Fit for CP observables
- PDF shape parameters fixed from global fit
- Yield of signal, low mass partially reconstructed background and combinatorial background floated
- Fractional yields  $F_i$  floated

$$\mathcal{R}_i = \begin{cases} F_i, & i = -8 \\ F_i / \sum_{j \geq i} F_j, & -8 < i \leq +8 \end{cases}$$

# CP observables result: $x_{-}^{DK}$

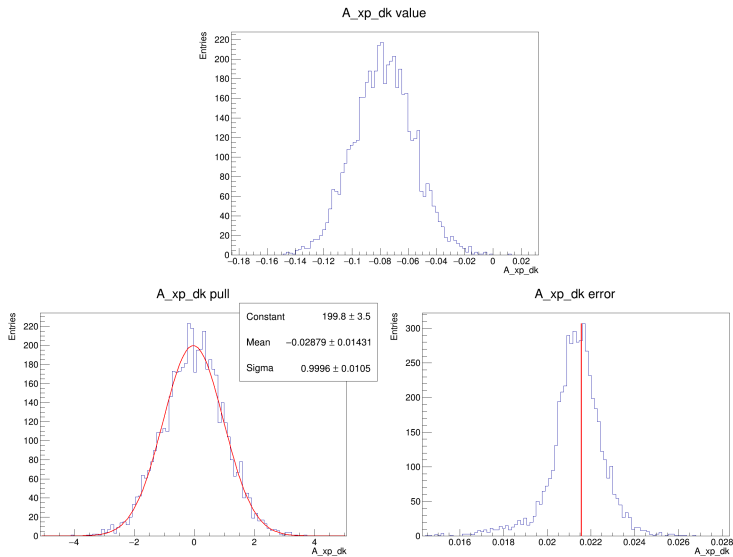


# CP observables result: $y_-^{DK}$



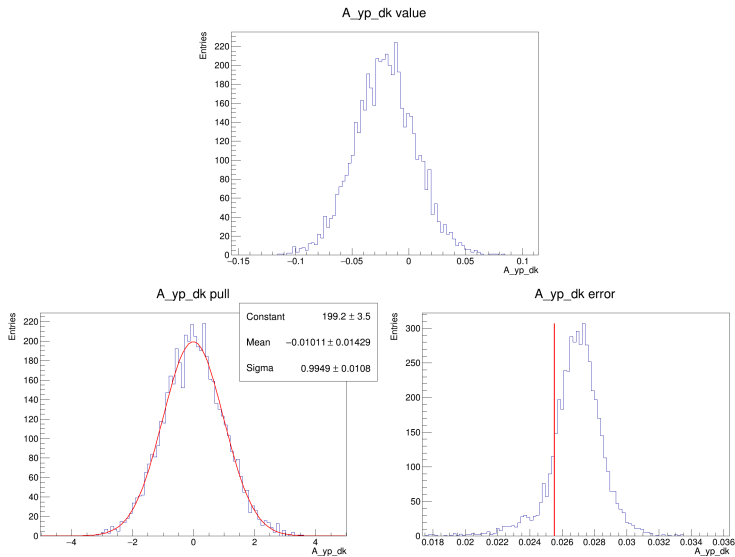
Red line: Uncertainty in fit to data

# CP observables result: $x_+^{DK}$



Red line: Uncertainty in fit to data

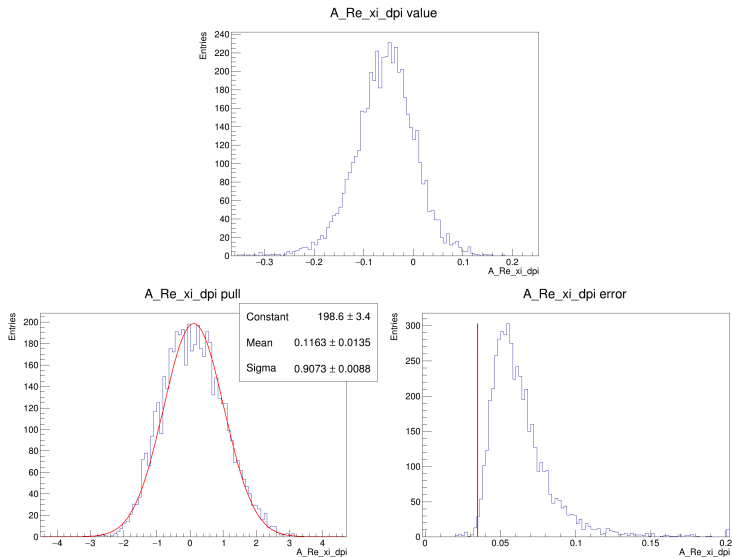
# CP observables result: $y_+^{DK}$



Red line: Uncertainty in fit to data

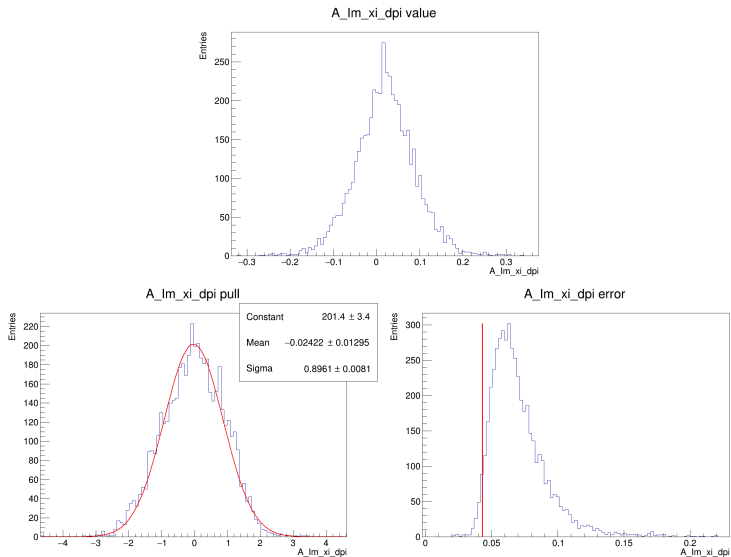


# CP observables result: $x_{\xi}^{D\pi}$



Red line: Uncertainty in fit to data

# CP observables result: $y_{\xi}^{D\pi}$



Red line: Uncertainty in fit to data

## Summary of $KK\pi\pi$ analysis

# Summary of CP observables

- Measured CP observables:

$$x_-^{DK} = (x.x \pm 2.4 \pm 0.4 \pm 0.7) \times 10^{-2},$$

$$y_-^{DK} = (x.x \pm 2.9 \pm 0.2 \pm 1.6) \times 10^{-2},$$

$$x_+^{DK} = (x.x \pm 2.2 \pm 0.3 \pm 0.3) \times 10^{-2},$$

$$y_+^{DK} = (x.x \pm 2.9 \pm 0.3 \pm 1.3) \times 10^{-2},$$

$$x_\xi^{D\pi} = (x.x \pm 3.5 \pm 0.9 \pm 1.7) \times 10^{-2},$$

$$y_\xi^{D\pi} = (x.x \pm 4.3 \pm 0.6 \pm 1.0) \times 10^{-2},$$

- Note: Currently using  $c_i$  and  $s_i$  from the LHCb model
- Publication strategy: Publish current results together with binned yields  $\rightarrow$  Redo fit to obtain model-independent CP observables once  $c_i$  and  $s_i$  from BESIII are available
- Will update  $c_i$  and  $s_i$  with model-dependent uncertainties

Bonus measurement:

Quasi-GLW observables with  
 $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow \pi^+\pi^-\pi^+\pi^-$

# Bonus measurement

- The mode  $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow \pi^+\pi^-\pi^+\pi^-$  very similar
- Run this through same selection (including BDT)
- Can measure quasi-GLW observables of  $\pi^+\pi^-\pi^+\pi^-$  and  $K^+K^-\pi^+\pi^-$  as additional constraints on  $\gamma$ :

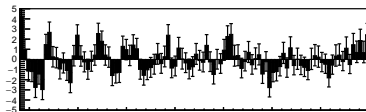
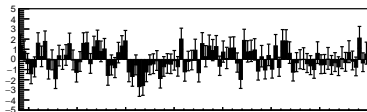
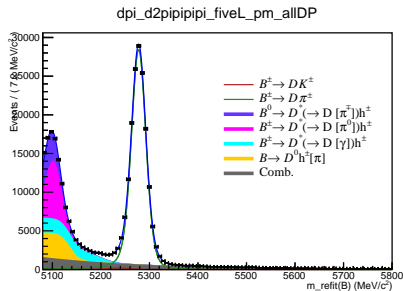
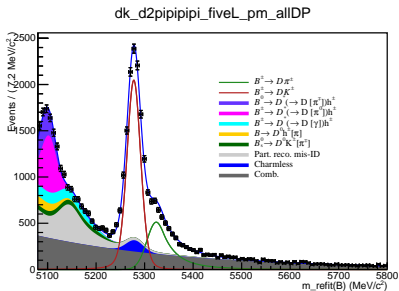
$$A_h = \frac{\Gamma(B^- \rightarrow Dh^-) - \Gamma(B^+ \rightarrow Dh^+)}{\Gamma(B^- \rightarrow Dh^-) + \Gamma(B^+ \rightarrow Dh^+)},$$

$$R_{\text{CP}} = \frac{R(4\pi)}{R(K3\pi)},$$

$$R = \frac{\Gamma(B \rightarrow DK)}{\Gamma(B \rightarrow D\pi)}.$$

- $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow K\pi\pi\pi$  yields provided by Tim Evans

# Global fit of $B^\pm \rightarrow Dh^\pm$ , $D \rightarrow \pi^+\pi^-\pi^+\pi^-$



$$\frac{\text{Yield}(\pi\pi\pi\pi)}{\text{Yield}(KK\pi\pi)} = \frac{161\,900 \pm 455}{54\,039 \pm 256} = 2.996 \pm 0.017$$

Compare with PDG:  $3.06 \pm 0.16$

## Conclusion



# Conclusion

- Binned  $\gamma$  analysis of  $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$  is mostly complete, with promising results
- Add quasi-GLW observables of  $K^+ K^- \pi^+ \pi^-$  and  $\pi^+ \pi^- \pi^+ \pi^-$  to further constrain  $\gamma$
- ANA note is ready!
- Will publish model-dependent measurement for now, update with model-independent results when  $c_i$  and  $s_i$  from BESIII are available

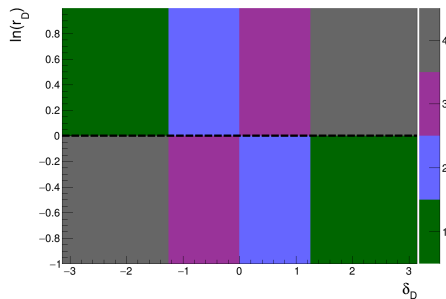
Thank you!

Thank you!

Backup

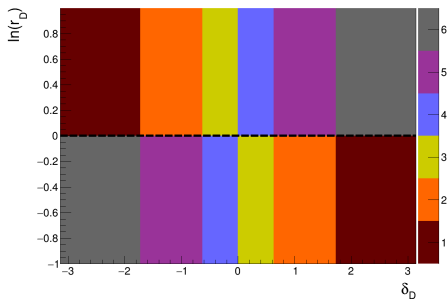
# Binning scheme

2x4 binning scheme for  $K^+K^-\pi^+\pi^-$  phase space



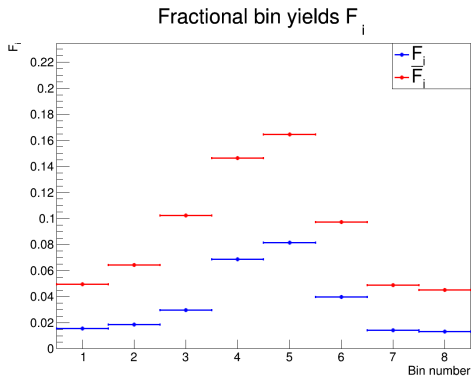
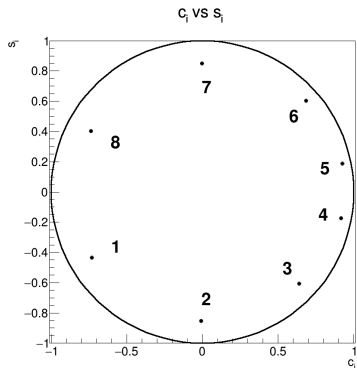
(a)  $Q = 0.85$

2x6 binning scheme for  $K^+K^-\pi^+\pi^-$  phase space



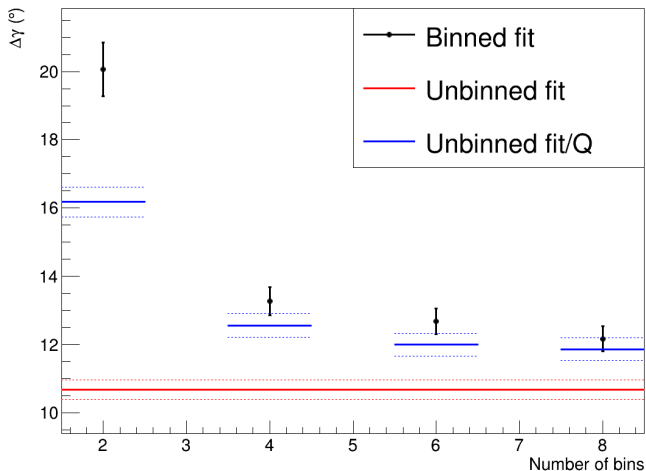
(b)  $Q = 0.89$

$c_i$ ,  $s_i$  and  $F_i$



# Comparison of binned fit precision with unbinned fit

$\gamma$  precision vs number of bins



# Trigger requirements

Run 1 trigger requirements	(Bu_LOGlobal_TIS or Bu_LOHadronDecision_TOS) and (Bu_Hlt1TrackAllL0Decision_TOS) and (Bu_Hlt2Topo2BodyBBDTDecision_TOS or Bu_Hlt2Topo3BodyBBDTDecision_TOS or Bu_Hlt2Topo4BodyBBDTDecision_TOS or Bu_Hlt2IncPhiDecision_TOS)
Run 2 trigger requirements	(Bu_LOGlobal_TIS or Bu_LOHadronDecision_TOS) and (Bu_Hlt1TrackMVADecision_TOS or Bu_Hlt1TwoTrackMVADecision_TOS) and (Bu_Hlt2Topo2BodyDecision_TOS or Bu_Hlt2Topo3BodyDecision_TOS or Bu_Hlt2Topo4BodyDecision_TOS or Bu_Hlt2IncPhiDecision_TOS)

## Rectangular cuts before BDT

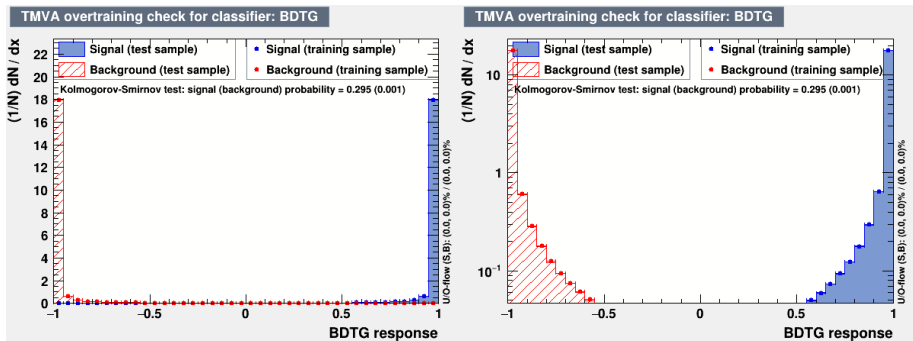
Number	Variable description	Cut
1	DTF converged	True
2	Bachelor momentum	$< 100\text{GeV}$
3	Bachelor has RICH	True
4	$D$ invariant mass	$[1839.84, 1889.84]\text{MeV}$
5	$B^\pm$ invariant mass	$[5080, 5800]\text{MeV}$
6	$K^\pm$ daughter PID	$> -10$
7	$\pi^\pm$ daughter PID	$< 20$



# Boosted Decision Tree

- BDTG from TMVA Toolkit
- Signal sample:  $B^\pm \rightarrow DK^\pm$  and  $B^\pm \rightarrow D\pi^\pm$  MC samples
- Background sample: Data sample with  $m_{B^\pm}^{\text{DTF}} \in [5800, 7000]\text{MeV}$
- Random, equal sized test and training samples

# BDT training results



(a) BDT output

(b) BDT output on a logarithmic scale

## Rectangular cuts after BDT

Number	Variable description	Cut
8	$K^\pm$ bachelor PID	$> 4$
9	$\pi^\pm$ bachelor PID	$< 4$
10	Bachelor is muon	False
11	$z$ flight significance	$> 2$
12	$K^\pm$ PID	$> 0$
13	$K_S^0$ mass veto	$[477, 507]\text{MeV}$

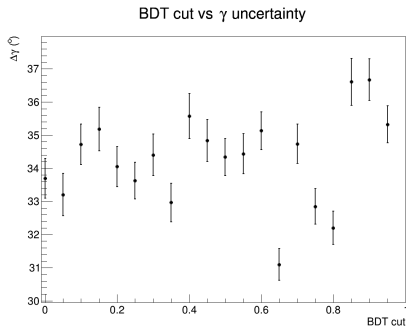
# BDT training variables

Name	Rank (%)	Description
$\log(D0\_RHO\_BPV)$	7.7	$D$ radial distance to beamline
$\log(Bu\_FDCHI2\_OWNPV)$	6.3	$B^\pm$ flight distance $\chi^2$
$\log(Bu\_RHO\_BPV)$	6.1	$B^\pm$ radial distance to beamline
$\log(Bach\_PT)$	6.1	Bachelor transverse momentum
$Bu\_PTASY\_1.5$	5.3	$B^\pm$ asymmetry parameter
$\log(1-D0\_DIRA\_BPV)$	5.0	Angle between PV and $D$
$\log(Bu\_IPCHI2\_OWNPV)$	4.8	$B^\pm$ impact parameter $\chi^2$
$\log(1-Bu\_DIRA\_BPV)$	4.7	Angle between PV and $B^\pm$
$\log(h[1,2]\_PT)$	4.4	$K^\pm$ transverse momentum
$Bu\_MAXDOCA$	4.4	$B^\pm$ distance of closest approach
$\log(Bach\_IPCHI2\_OWNPV)$	4.1	Bachelor impact parameter $\chi^2$

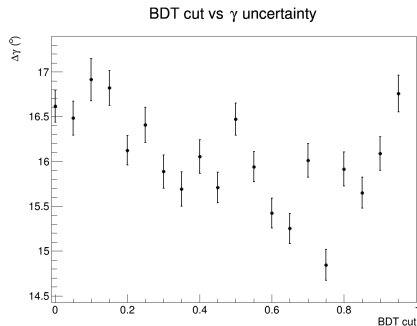
# BDT training particles

Name	Rank (%)	Description
$\log(\text{Bu\_constD0PV\_D0\_P})$	3.7	$D$ momentum from DTF
$\log(\text{D0\_VTXCHI2D0F})$	3.3	$D0$ vertex fit $\chi^2$
$\log(\text{h}[3,4]_{\text{IPCHI2\_OWNPV}})$	3.3	$\pi^\pm$ impact parameter $\chi^2$
$\log(\text{D0\_IPCHI2\_OWNPV})$	3.2	$D$ impact parameter $\chi^2$
$\log(\text{h}[3,4]_{\text{PT}})$	3.2	$\pi^\pm$ transverse momentum
$\log(\text{Bu\_PT})$	2.8	$B^\pm$ transverse momentum
$\log(\text{h}[1,2]_{\text{P}})$	2.8	$K^\pm$ momentum
$\log(\text{Bach\_P})$	2.7	Bachelor momentum
$\log(\text{Bu\_constD0PV\_P})$	2.6	$B^\pm$ momentum from DTF
$\log(\text{h}[1,2]_{\text{IPCHI2\_OWNPV}})$	2.5	$K^\pm$ impact parameter $\chi^2$
$\text{D0\_MAXDOCA}$	2.5	$D$ distance of closest approach
$\log(\text{Bu\_VTXCHI2D0F})$	2.0	$B^\pm$ vertex fit $\chi^2$
$\log(\text{h}[3,4]_{\text{P}})$	1.9	$\pi^\pm$ momentum

# BDT optimization study



(a) Run 1



(b) Run 2

- Run 1: Pick BDT working point at 0.65
- Run 2: Pick BDT working point at 0.75

# Partially reconstructed background

- $B^\pm \rightarrow D\pi^\pm$ :

- ①  $B^\pm \rightarrow (D^{*0} \rightarrow D^0[\pi^0])\pi^\pm$

- ②  $B^0 \rightarrow (D^{*\mp} \rightarrow D^0[\pi^\mp])\pi^\pm$

- ③  $B^{\pm(0)} \rightarrow D^0[\pi^{0(\mp)}]\pi^\pm$

- ④  $B^\pm \rightarrow (D^{*0} \rightarrow D^0[\gamma])\pi^\pm$

- $B^\pm \rightarrow DK^\pm$ :

- ①  $B^\pm \rightarrow (D^{*0} \rightarrow D^0[\pi^0])K^\pm$

- ②  $B^0 \rightarrow (D^{*\mp} \rightarrow D^0[\pi^\mp])K^\pm$

- ③  $B^{\pm(0)} \rightarrow D^0[\pi^{0(\mp)}]K^\pm$

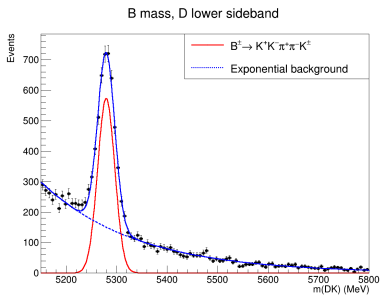
- ④  $B^\pm \rightarrow (D^{*0} \rightarrow D^0[\gamma])K^\pm$

- ⑤  $B_s^0 \rightarrow \bar{D}^0[\pi^+]K^-$

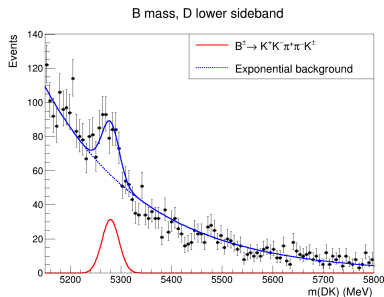
- ⑥ Mis-ID from partially reconstructed  $B^\pm \rightarrow D\pi^\pm$  channel

# Charmless background

- $B \rightarrow KK\pi\pi K$  background in  $B \rightarrow DK$  channel
- Flight significance cut at 2
- Fix remaining background with Gaussian shape of lower sideband



(a) No FS cut



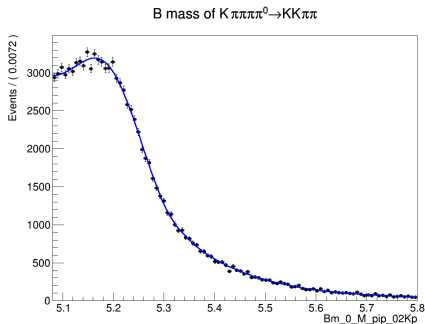
(b) FS cut at 2

**Figure 15:**  $B$  invariant mass in lower  $D$  sideband



# $D \rightarrow K\pi\pi\pi\pi^0$ mis-ID background

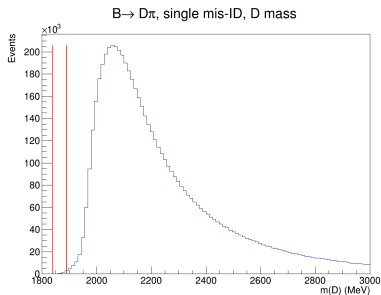
- $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow K\pi\pi\pi[\pi^0]$
- $\pi^0$  not reconstructed  $\rightarrow$  Lower  $D$  mass
- Single mis-ID:  $K\pi\pi\pi \rightarrow KK\pi\pi \rightarrow$  Higher  $D$  mass
- Generate RapidSim samples, reweight with PIDCalib2



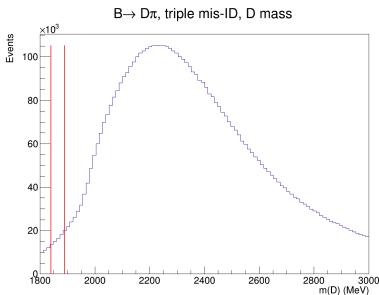
Conclusion: Fix shape from RapidSim, allow yield to float

# $D \rightarrow K\pi\pi\pi$ mis-ID background

- $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow K\pi\pi\pi$
- Single mis-ID:  $K\pi\pi\pi \rightarrow KK\pi\pi$
- Triple mis-ID:  $\pi\pi K\pi \rightarrow KK\pi\pi$
- Use LHCb MC generated with AmpGen, reweight with PIDCalib2



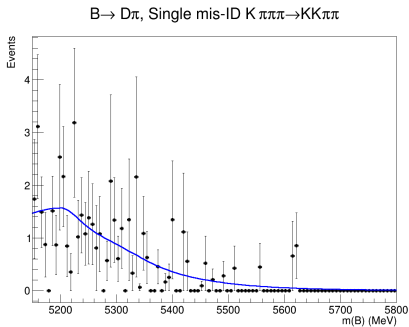
(a) Single mis-ID



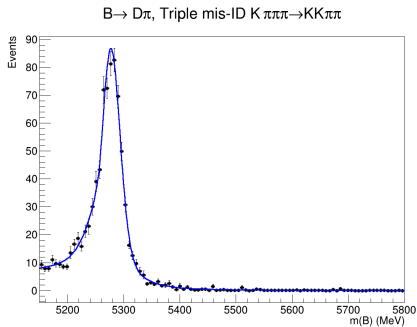
(b) Triple mis-ID

**Figure 16:**  $D$  invariant mass

# $D \rightarrow K\pi\pi\pi$ mis-ID background



(a) Single mis-ID



(b) Triple mis-ID

**Figure 17:**  $B$  invariant mass

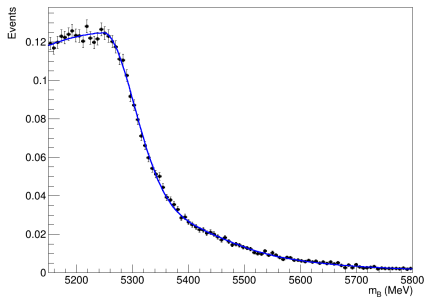
Conclusion: Negligible impact, include in systematics

# $D$ semileptonic backgrounds

- $B^\pm \rightarrow Dh^\pm$ ,  $D \rightarrow K(X)l\nu$ ,  $K(X) \rightarrow K\pi\pi$ 
  - $K_1(1270)$
  - $K_1(1400)$
  - $K^*(1410)$
  - $K^*(1680)$
  - $K_2^*(1430)$
- Single mis-ID:  $K\mu\pi\pi \rightarrow KK\pi\pi$
- Double mis-ID:  $K\pi\pi\mu \rightarrow KK\pi\pi$
- Generate RapidSim samples, reweight with PIDCalib2

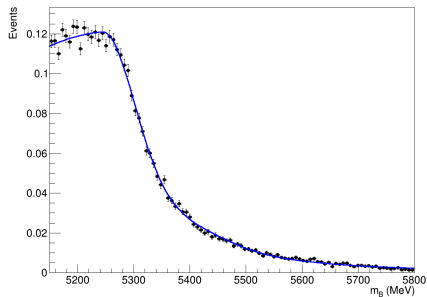
# D semileptonic backgrounds

B mass of SL  $D \rightarrow K(X)\mu\nu$  backgrounds,  $B \rightarrow DK$



(a)  $B \rightarrow DK$

B mass of SL  $D \rightarrow K(X)\mu\nu$  backgrounds,  $B \rightarrow D\pi$



(b)  $B \rightarrow D\pi$

Conclusion: Negligible impact, include in systematics

## $c_i$ and $s_i$ systematic uncertainty

- $c_i$  and  $s_i$  uncertainty will come from BESIII analysis
  - Mostly statistical in origin
- Largest systematic uncertainty
- Use estimated uncertainties corresponding to  $20 \text{ fb}^{-1}$  at  $\psi(3770)$
- Smear  $c_i$  and  $s_i$  and do many fits to data

# Remaining systematic uncertainties

Different strategies for evaluating systematic uncertainties:

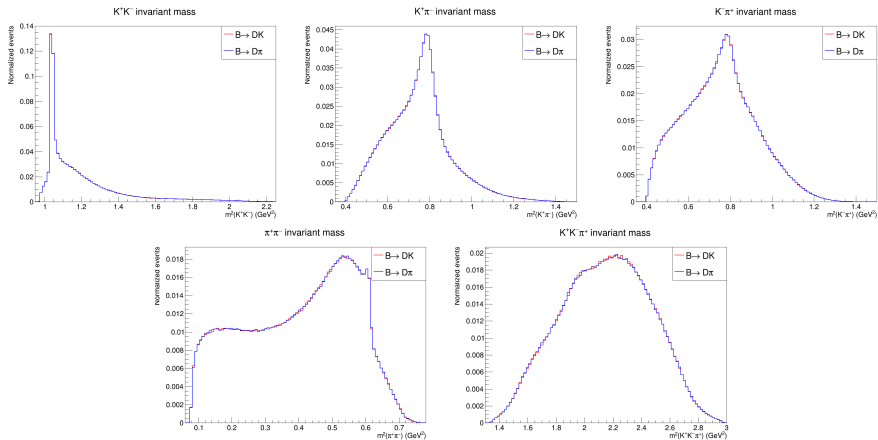
- Generate toy datasets with systematics, fit with default model and take the bias as a systematic:
  - Small backgrounds ( $D \rightarrow K(X)l\nu_l$ ,  $D \rightarrow K\pi\pi\pi$ ,  $B \rightarrow Dl\nu_l$ ,  $\Lambda_b$ )
  - Bin dependent mass shape
  - Low mass physics effects
- Do multiple fits to data while smearing parameters:
  - $c_i$  and  $s_i$
  - Mass shape
  - Fixed yield fractions
  - PID efficiency
- Fit bias: Take bias toys as systematic uncertainty

Efficiency related systematics:

- Difference in  $B^\pm \rightarrow DK^\pm$  and  $B^\pm \rightarrow D\pi^\pm$  phase space acceptance
- Efficiency correction of  $c_i$  and  $s_i$

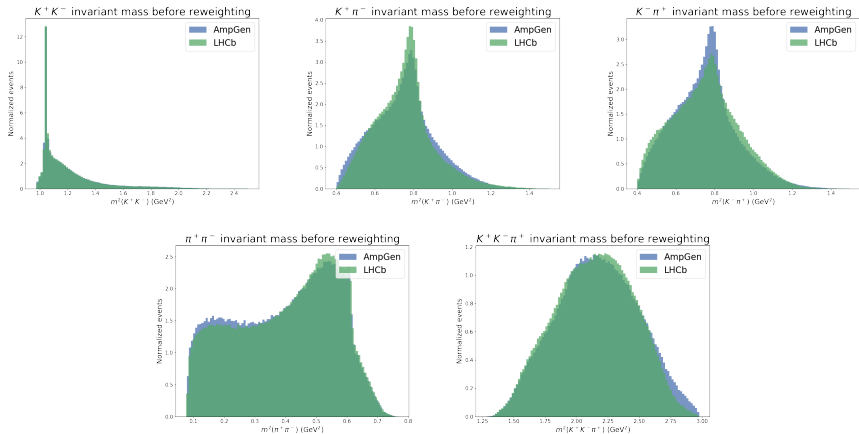


# Efficiency differences between $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$



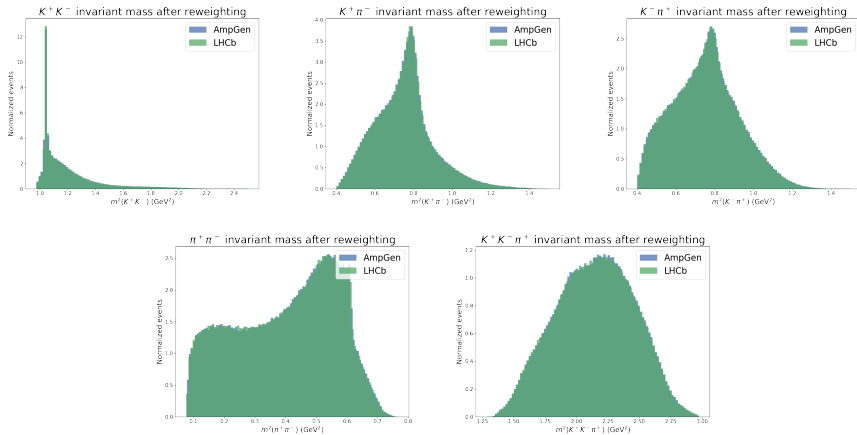
Conclusion: More or less identical phase space acceptance, no systematic uncertainty considered

# Efficiency correction of $c_i$ and $s_i$



Need to reweight events to account for efficiency differences between AmpGen samples and LHCb MC

# Efficiency correction of $c_i$ and $s_i$



After reweighting, use weights to recalculate  $c_i$  and  $s_i$

Conclusion: Efficiency correction of  $c_i$  and  $s_i$  is an order of magnitude smaller than their uncertainties, no systematic uncertainty considered

# Summary of all systematic uncertainties

Uncertainties of 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	2.44	2.87	2.16	2.87	3.47	4.30
$c_i, s_i$	0.66	1.55	0.32	1.31	1.73	1.03
$B^\pm \rightarrow D\mu\nu$ background	0.04	0.03	0.02	0.15	0.30	0.10
$D \rightarrow K(X)l\nu_l$ background	0.15	0.05	0.11	0.03	0.35	0.25
$D \rightarrow K\pi\pi\pi$ background	0.17	0.03	0.04	0.01	0.46	0.18
$\Lambda_b$ background	0.09	0.11	0.00	0.18	0.16	0.21
Bin dependent mass shape	0.21	0.05	0.17	0.01	0.37	0.11
Fit bias	0.19	0.03	0.16	0.04	0.30	0.16
Fixed yield fractions	0.02	0.03	0.02	0.02	0.01	0.01
Low mass physics effects	0.05	0.09	0.05	0.18	0.41	0.48
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
Total LHCb systematic	0.39	0.17	0.27	0.30	0.92	0.65
Total systematic	0.77	1.55	0.41	1.34	1.96	1.22