Analysis update on γ measurement in $B^{\pm} \to (K^+K^-\pi^+\pi^-)_D h^{\pm}$ decays

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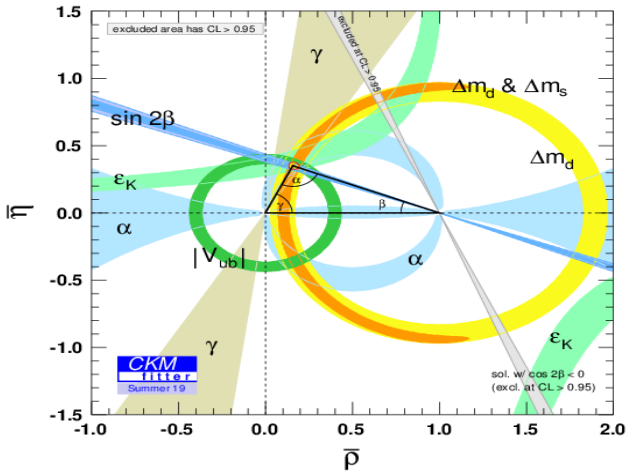
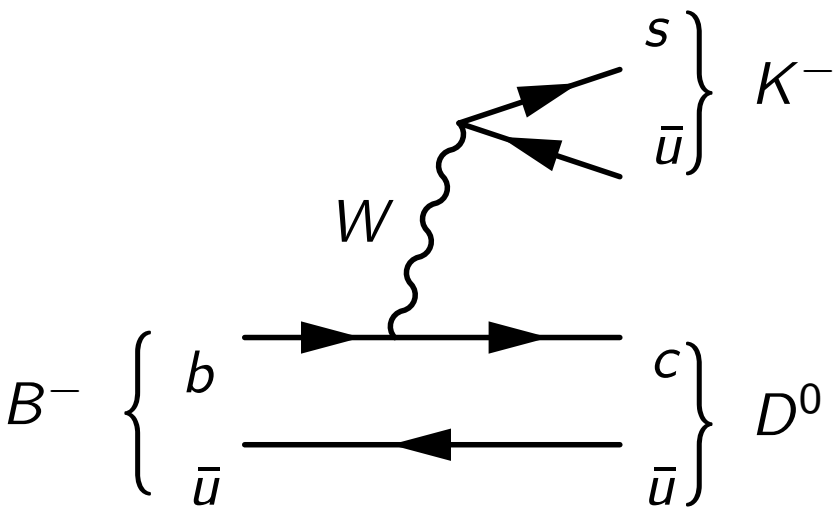
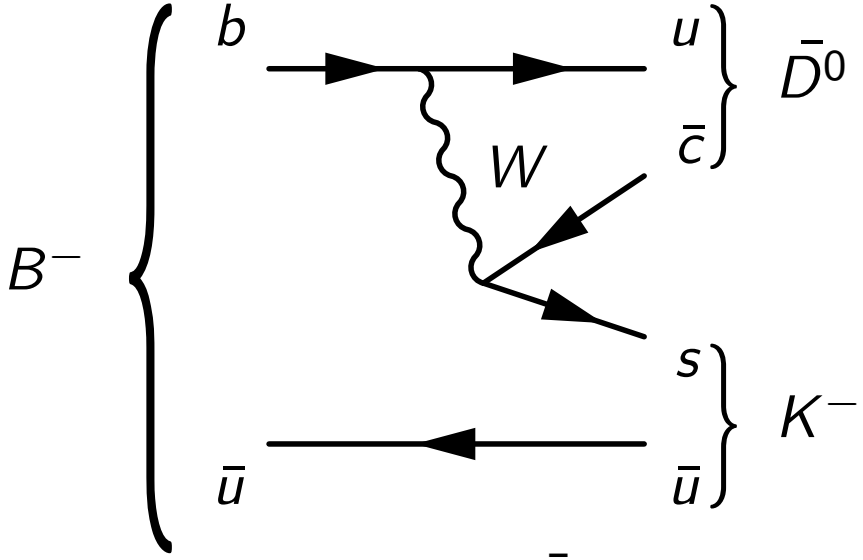


Outline

Introduction



(a) $B^- \to D^0 K^-$



(b) $B^- \to \bar{D}^0 K^-$

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

$b \to u\bar{c}s$ and $b \to u\bar{u}s$ interference when D^0 and $\bar{D}^0$ decay into a common final state

In this analysis, consider $D \to K^+K^-\pi^+\pi^-$

Introduction

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

Event yield in bin i

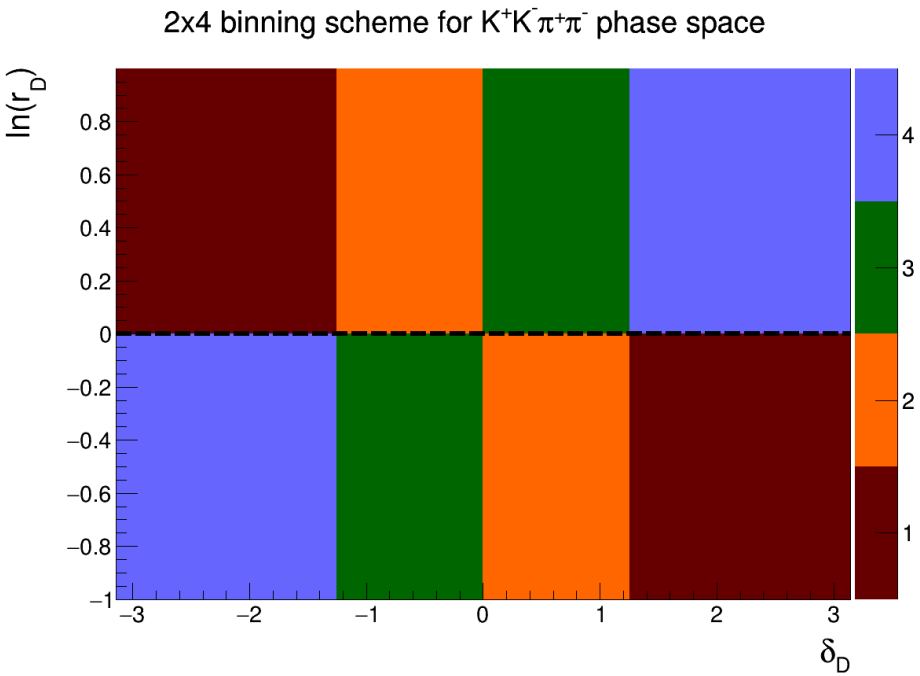
$$N_i^- = h_{B^-}\left(K_i + \left(x_-^2 + y_-^2\right)\bar{K}_i + 2\sqrt{K_i \bar{K}_i}\left(x_- c_i + y_- s_i\right)\right)$$
$$N_{-i}^+ = h_{B^+}\left(K_i + \left(x_+^2 + y_+^2\right)\bar{K}_i + 2\sqrt{K_i \bar{K}_i}\left(x_+ c_i + y_+ s_i\right)\right)$$

Amplitude averaged strong phases and fractional yield

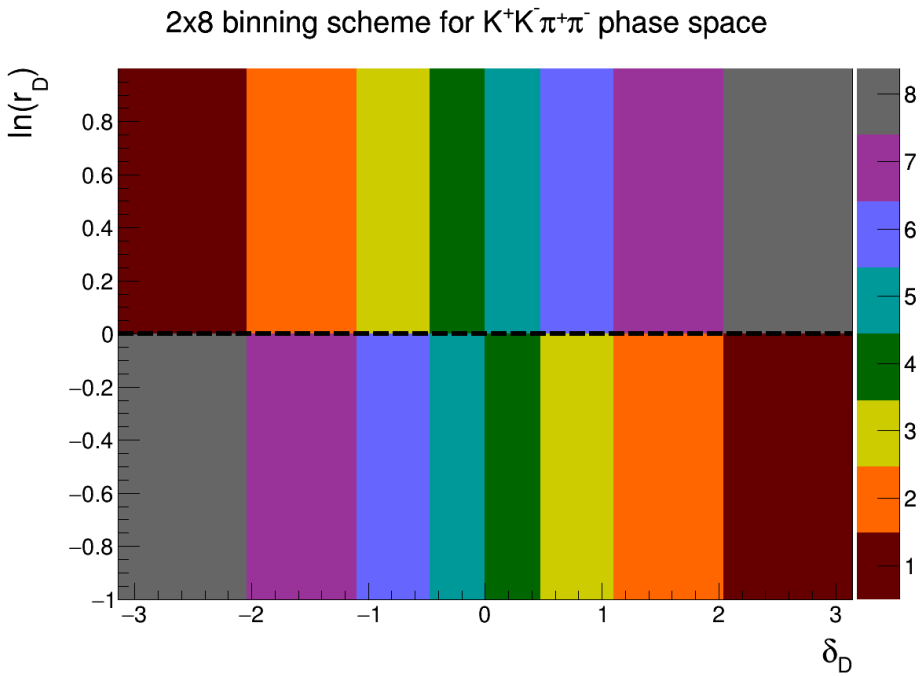
$$c_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)||\mathcal{A}(\bar{D}^0)| \cos(\delta_D)}{\sqrt{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2 \int_i \mathrm{d}\Phi \left|\mathcal{A}(\bar{D}^0)\right|^2}}, \qquad K_i = \frac{\int_i \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}{\sum_j \int_j \mathrm{d}\Phi |\mathcal{A}(D^0)|^2}$$

Binning scheme

Binning scheme

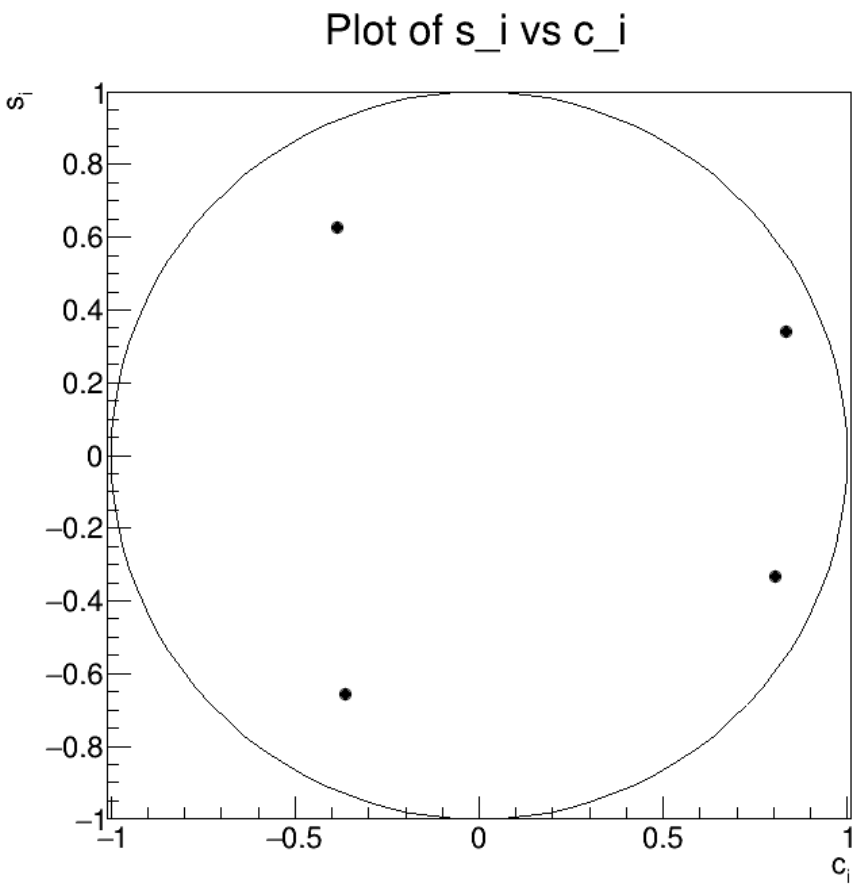


(a) 2×4 binning scheme
$Q = 0.85$

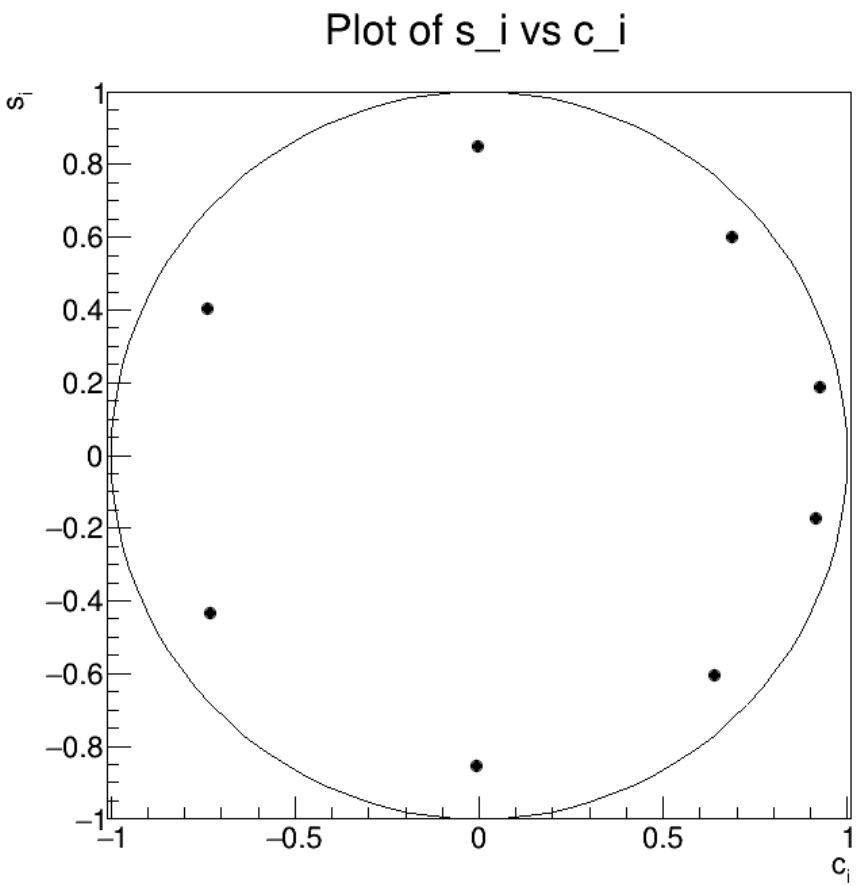


(b) 2×8 binning scheme
$Q = 0.90$

Strong phases

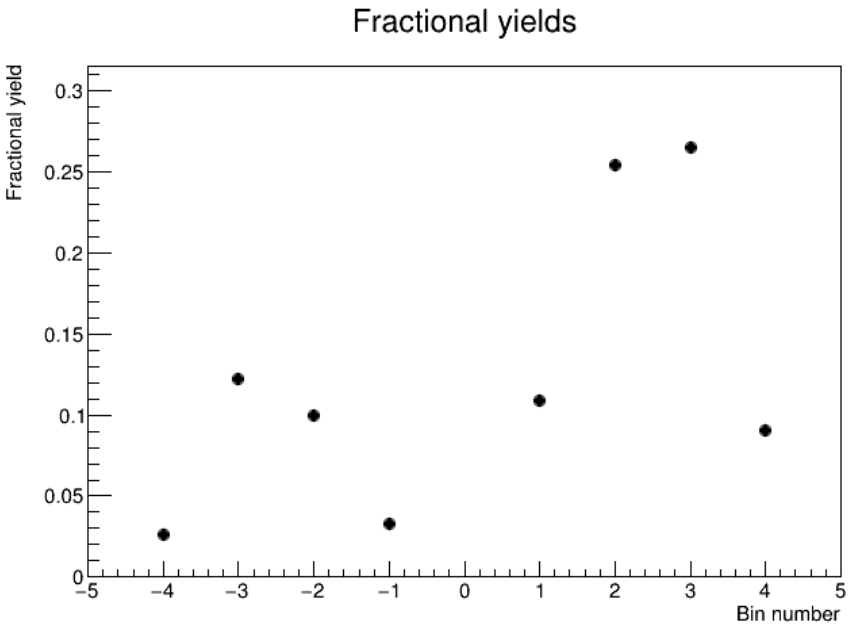


(a) c_i and s_i for the 2×4 binning scheme

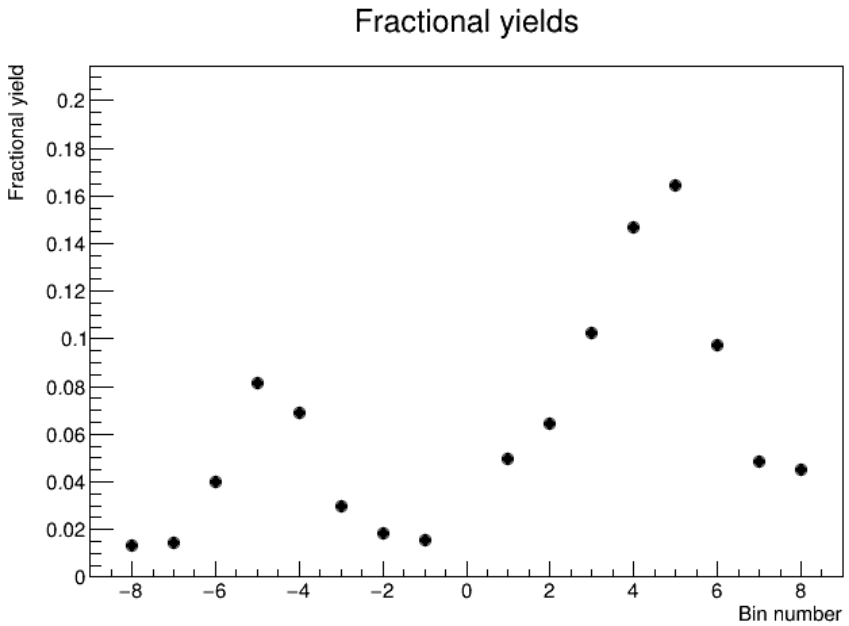


(b) c_i and s_i for the 2×8 binning scheme

Fractional yields



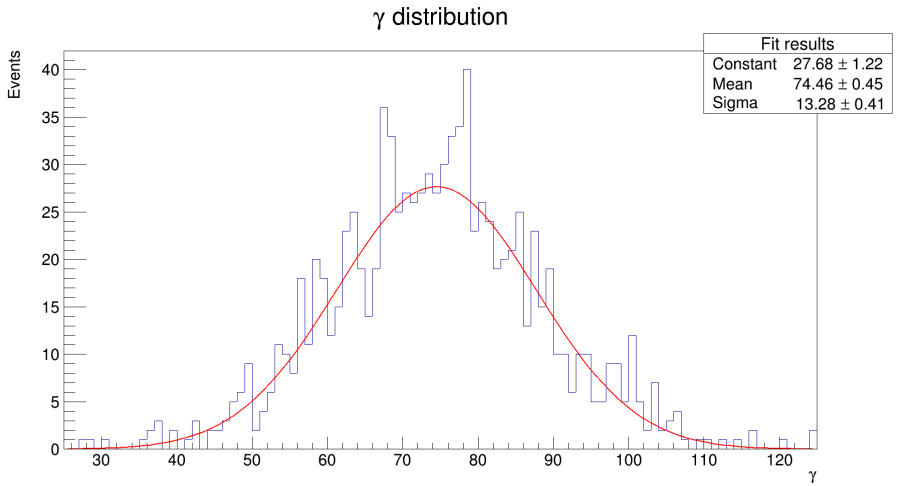
(a) K_i for the 2×4 binning scheme



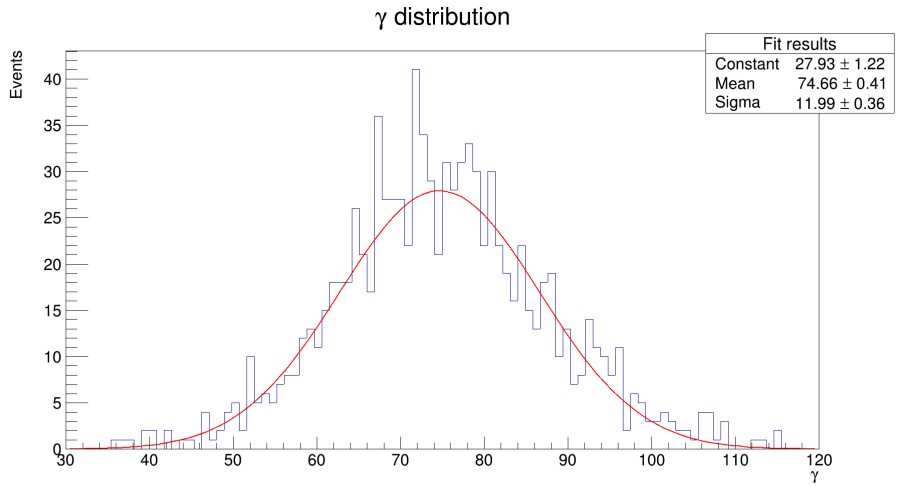
(b) K_i for the 2×8 binning scheme

Study of γ precision

- Generate 2000 $B^{\pm}$ candidates in AmpGen
- Unbinned fit benchmark: $\Delta\gamma = 11^{\circ}$
- Both 2×4 and 2×8 binning schemes are consistent with their Q values



(a) 2×4 binning scheme
$\Delta\gamma = 13^{\circ}$



(b) 2×8 binning scheme
$\Delta\gamma = 12^{\circ}$

$B^{\pm} \to (K^+K^-\pi^+\pi^-)_D h^{\pm}$ selection

Samples

- Stripping lines:
  - StrippingB2D0PiD2HHHHBeauty2CharmLineDecision
  - StrippingB2D0KD2HHHHBeauty2CharmLineDecision
- Data samples: 2015-2018 (2011-2012 not processed yet)
- MC samples: 2016-2018, filtered, AmpGen

Initial cuts

Trigger requirements identical to that of LHCb-ANA-2020-001

Run 1 trigger requirements	(Bu_L0Global_TIS or Bu_L0HadronDecision_TOS) and (Bu_Hlt1TrackAllL0Decision_TOS) and (Bu_Hlt2Topo2BodyBBDTDecision_TOS or Bu_Hlt2Topo3BodyBBDTDecision_TOS or Bu_Hlt2Topo4BodyBBDTDecision_TOS)
Run 2 trigger requirements	(Bu_L0Global_TIS or Bu_L0HadronDecision_TOS) and (Bu_Hlt1TrackMVADecision_TOS or Bu_Hlt1TwoTrackMVADecision_TOS) and (Bu_Hlt2Topo2BodyDecision_TOS or Bu_Hlt2Topo3BodyDecision_TOS or Bu_Hlt2Topo4BodyDecision_TOS)

Initial cuts

Rectangular cuts before BDT

Standard cuts	Value
Bachelor has RICH	True
$K^{\pm}$ has RICH	True
Bachelor momentum p	$< 100\,\text{GeV}$
$K^{\pm}$ from D momentum p	$< 100\,\text{GeV}$
D invariant mass	Within $\pm 25\,\text{MeV}$ of $m_{D^0}^{\text{PDG}}$
DecayTreeFitter (DTF) convergence	True
$B^{\pm}$ DTF mass range	$[5080, 5800]\text{MeV}$

Boosted Decision Tree

- BDTG from TMVA Toolkit
- Signal sample: $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ MC samples
- Background sample: $B^{\pm} \to D\pi^{\pm}$ using $m^{\mathrm{DTF}}_{B^{\pm}} \in [5800, 7000]\mathrm{MeV}$
- Random, equal sized test and training samples

BDT training particles

BDT training variables part 1

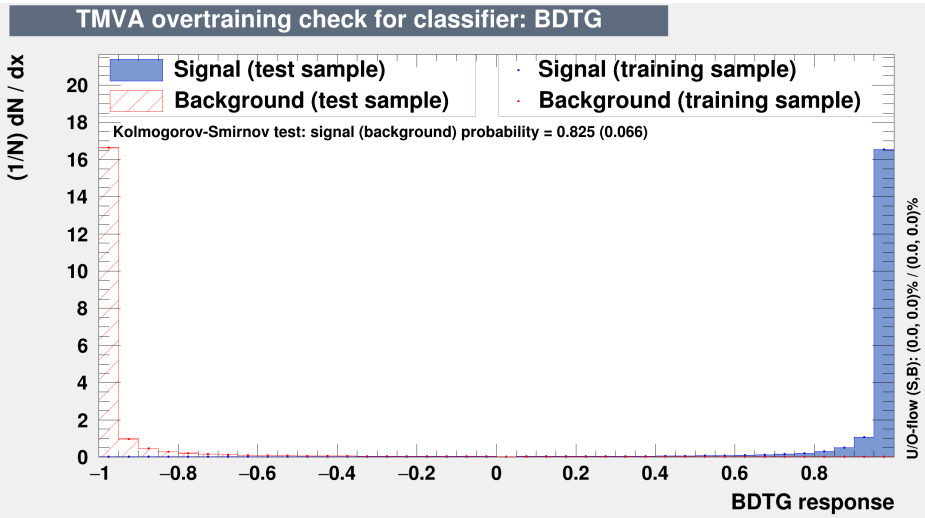
Name	Rank (%)	Description
log(D0_RHO_BPV)	7.7	D radial distance to beamline
log(Bu_FDCHI2_OWNPV)	6.3	$B^{\pm}$ flight distance χ^2
log(Bu_RHO_BPV)	6.1	$B^{\pm}$ radial distance to beamline
log(Bach_PT)	6.1	Bachelor transverse momentum
Bu_PTASY_1.5	5.3	$B^{\pm}$ asymmetry parameter
log(1-D0_DIRA_BPV)	5.0	Angle between PV and D
log(Bu_IPCHI2_OWNPV)	4.8	$B^{\pm}$ impact parameter χ^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 χ^2

BDT training particles

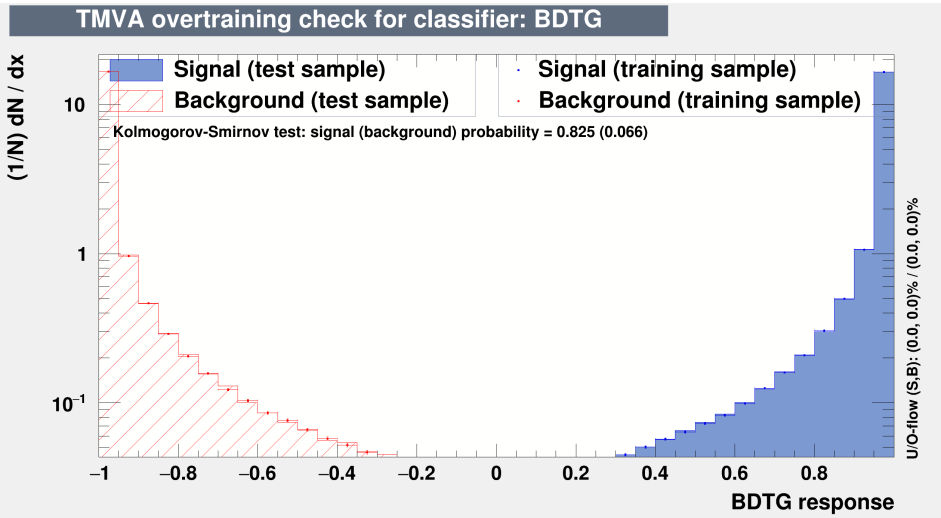
BDT training variables part 2

Name	Rank (%)	Description
log(Bu_constD0PV_D0_P)	3.7	D momentum from DTF
log(D0_VTXCHI2DOF)	3.3	$D0$ vertex fit χ^2
log(h[3,4]_IPCHI2_OWNPV)	3.3	$\pi^{\pm}$ impact parameter χ^2
log(D0_IPCHI2_OWNPV)	3.2	D impact parameter χ^2
log(h[3,4]_PT)	3.2	$\pi^{\pm}$ transverse momentum
log(Bu_PT)	2.8	$B^{\pm}$ transverse momentum
log(h[1,2]_P)	2.8	$K^{\pm}$ momentum
log(Bach_P)	2.7	Bachelor momentum
log(Bu_constD0PV_P)	2.6	$B^{\pm}$ momentum from DTF
log(h[1,2]_IPCHI2_OWNPV)	2.5	$K^{\pm}$ impact parameter χ^2
D0_MAXDOCA	2.5	D distance of closest approach
log(Bu_VTXCHI2DOF)	2.0	$B^{\pm}$ vertex fit χ^2
log(h[3,4]_P)	1.9	$\pi^{\pm}$ momentum

BDT training results



(a) BDT output

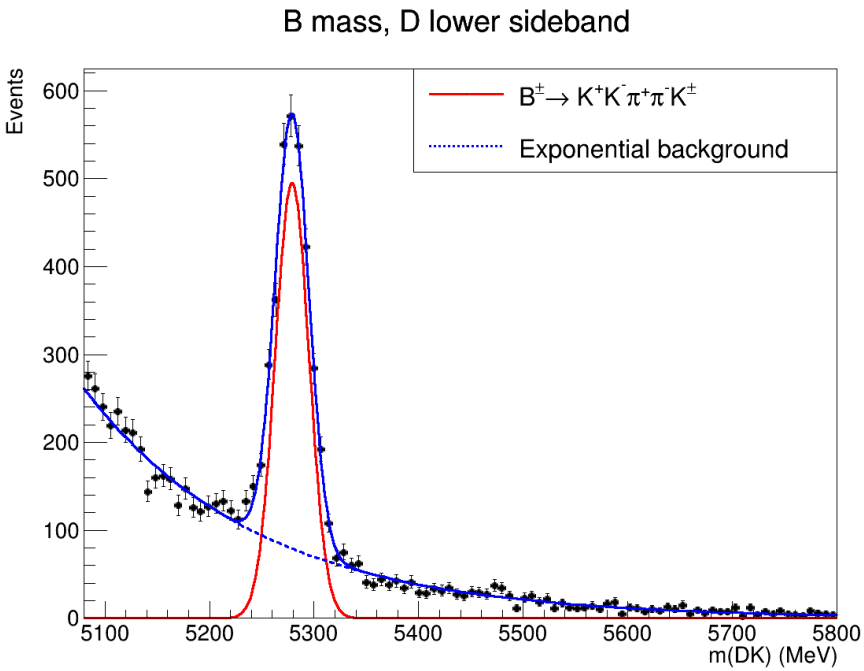


(b) BDT output on a logarithmic scale

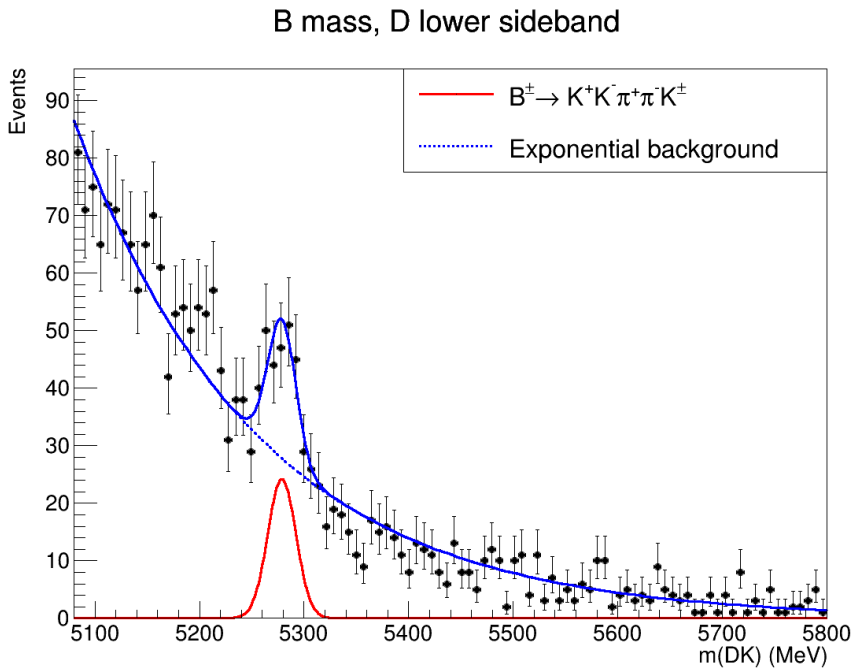
- Choose working point at 0.75

Charmless backgrounds from $B^{\pm} \to K^{+}K^{-}\pi^{+}\pi^{-}K^{\pm}$

- Remove cut on DTF χ^2
- Look in the D mass sideband $[1770, 1820]$MeV



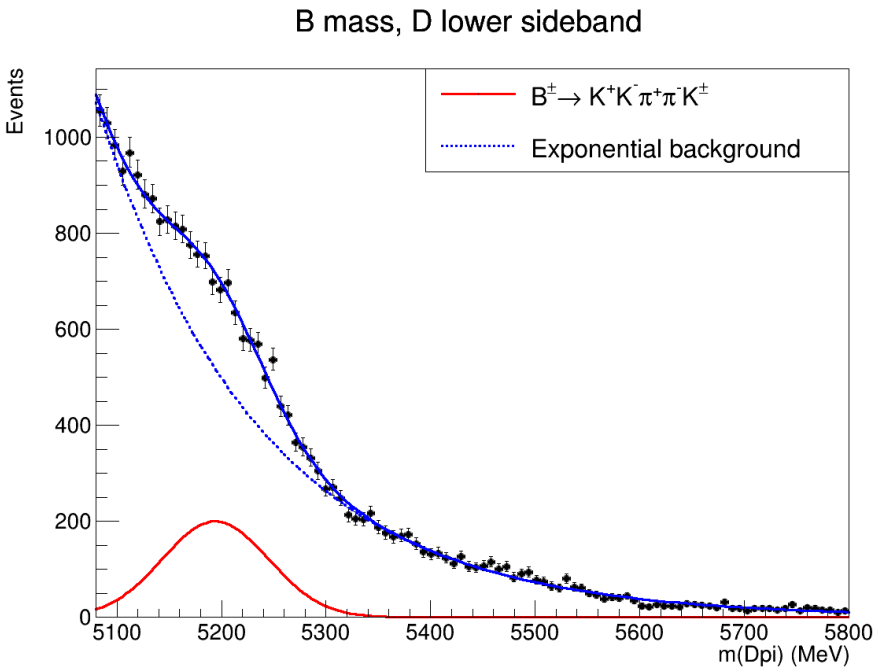
(a) No flight significance cut
Yield: 2605 ± 57



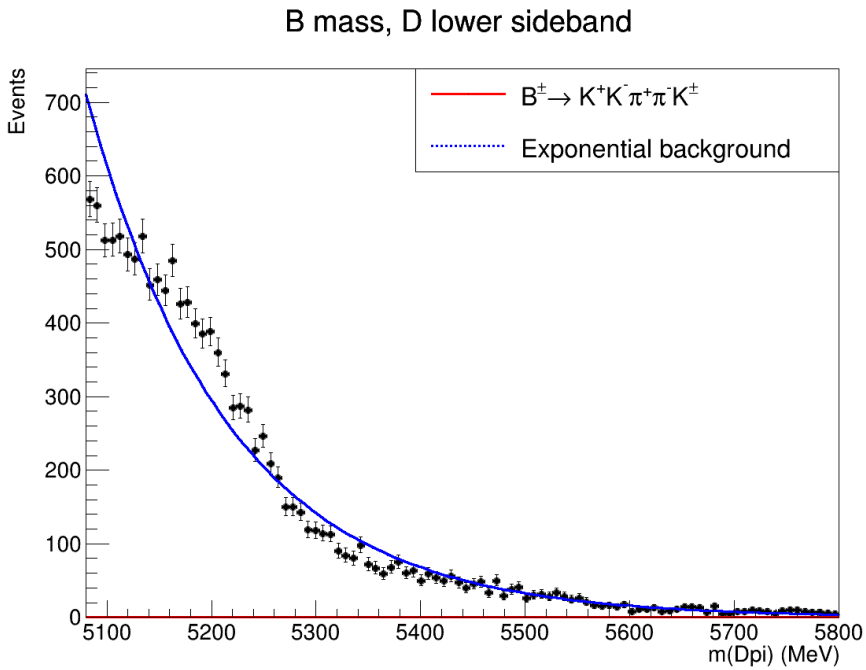
(b) Flight significance cut at 2
Yield: 110 ± 19

- Choose flight significance cut at 2
- A cut larger than ≈ 3 gives a charmless yield consistent with 0

Charmless backgrounds from $B^{\pm} \to K^{+}K^{-}\pi^{+}\pi^{-}\pi^{\pm}$



(a) No flight significance cut

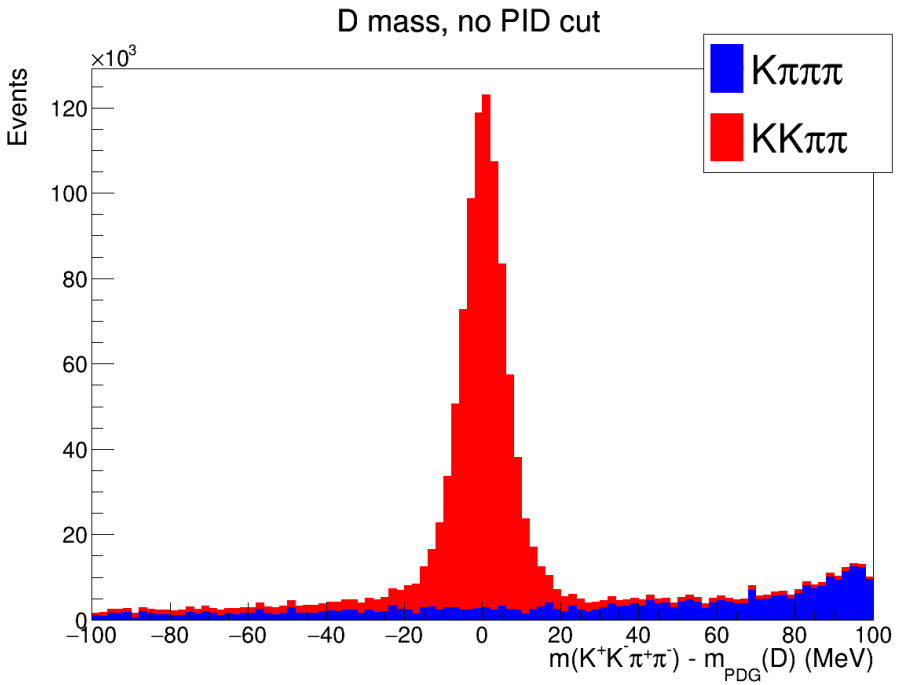


(b) Flight significance cut at 2

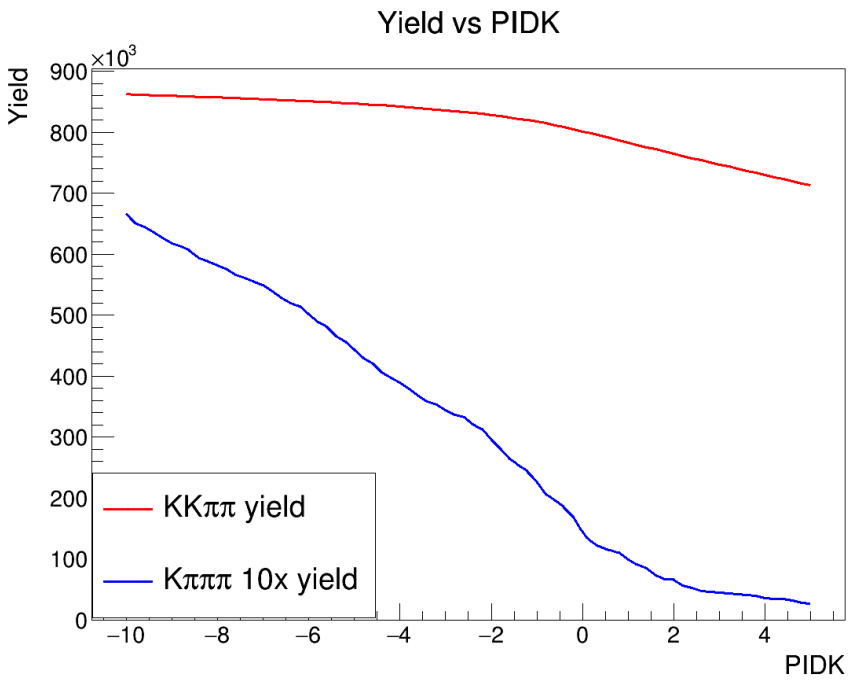
- No charmless background observed in the $B^{\pm} \to D\pi^{\pm}$ channel!

Mis-ID background from $B^{\pm} \to (K\pi\pi\pi)_D h^{\pm}$

- Study using MC samples from 2018
- Yields have been scaled to account for differences in sample size and branching fractions
- $\pi\pi\pi\pi$ background is negligible



(a) D invariant mass distribution



(b) Signal and $K\pi\pi\pi$ background yield

- A cut at PIDK > 0 reduces the contamination from 7.2% to 1.8%

Final cuts

Cuts after BDT training

Background suppression cuts	Value
BDTG	< 0.75
Bachelor PID	PIDK > 4 (< 4) for DK ($D\pi$)
$K^{\pm}$ from D PID	PIDK > 0
Flight significance	> 2
DTF χ^2	$\ln(\chi^2) < 3$

Global fit

Signal parameterisation

- PDF shape parameterization identical to LHCb-ANA-2020-001
- Signal: Gaussian + Modified Gaussian
- Shape fixed from MC, yield and width floated
- Exponential background

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

Partially reconstructed background

- $B^{\pm} \to D\pi^{\pm}$:
  1. $B^{\pm} \to (D^{*0} \to D^0[\pi^0])\pi^{\pm}$
  2. $B^0 \to (D^{*\mp} \to D^0[\pi^{\mp}])\pi^{\pm}$
  3. $B^{\pm(0)} \to D^0[\pi^{0(\mp)}]\pi^{\pm}$
  4. $B^{\pm} \to (D^{*0} \to D^0[\gamma])\pi^{\pm}$
- $B^{\pm} \to DK^{\pm}$:
  1. $B^{\pm} \to (D^{*0} \to D^0[\pi^0])K^{\pm}$
  2. $B^0 \to (D^{*\mp} \to D^0[\pi^{\mp}])K^{\pm}$
  3. $B^{\pm(0)} \to D^0[\pi^{0(\mp)}]K^{\pm}$
  4. $B^{\pm} \to (D^{*0} \to D^0[\gamma])K^{\pm}$
  5. $B_s^0 \to \bar{D}^0[\pi^+]K^-$
  6. Mis-ID from partially reconstructed $B^{\pm} \to D\pi^{\pm}$ channel

Global fit

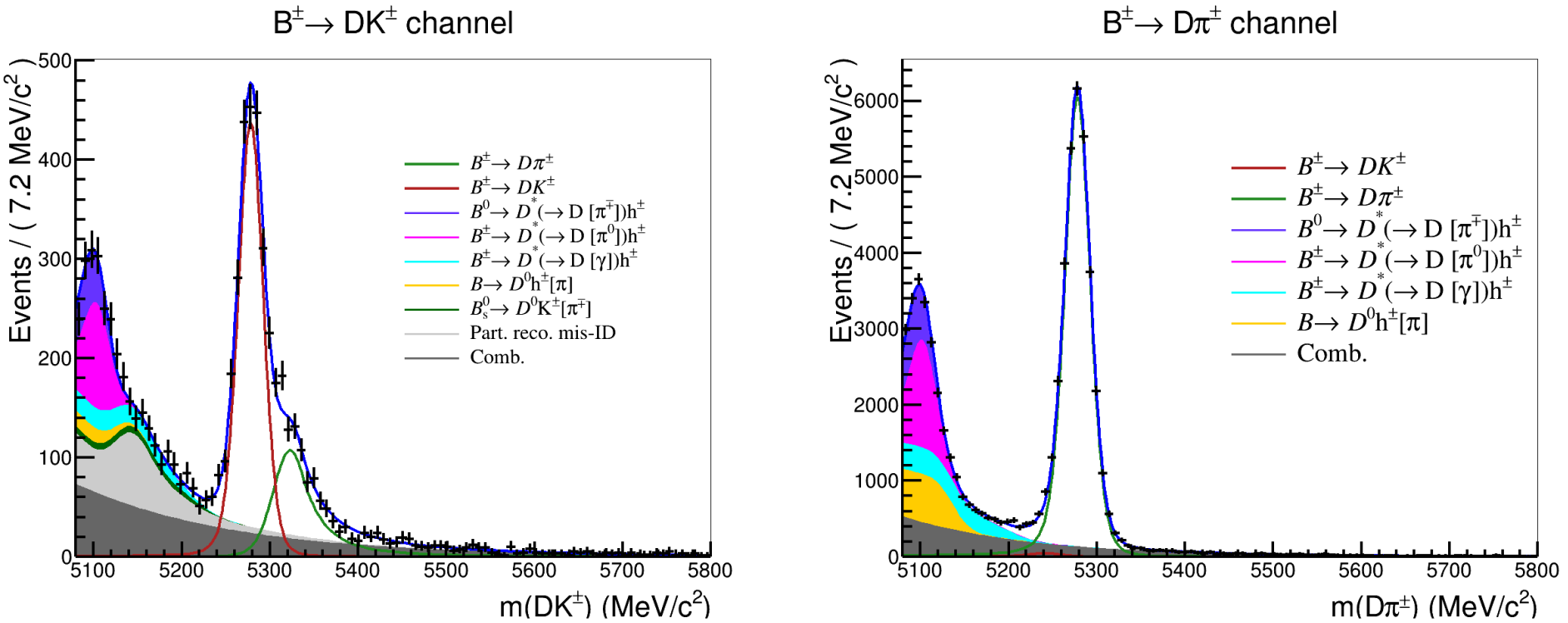


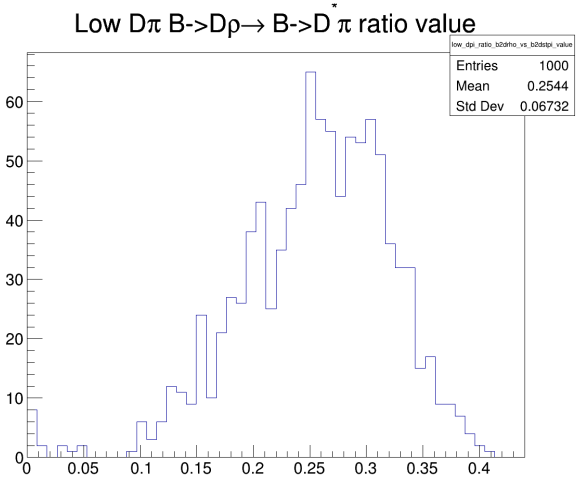
Figure 10: Global fit of $B^{\pm}$ mass distribution for the $DK^{\pm}$ channel (left) and $D\pi^{\pm}$ channel (right)

- $B^{\pm} \to DK^{\pm}$ yield: 2290 ± 59
- $B^{\pm} \to D\pi^{\pm}$ yield: $33\,113 \pm 211$

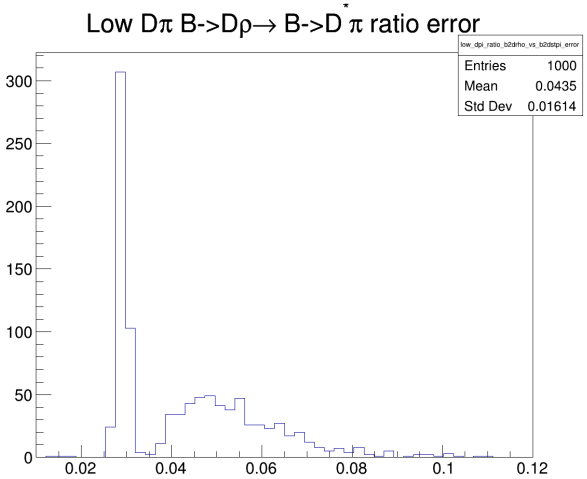
Global fit toy studies

- Generated 1000 toy datasets using the fitted parameters
- Almost all free parameters have pull distributions with zero mean and standard deviation 1
- Consistent with LHCb-ANA-2020-001

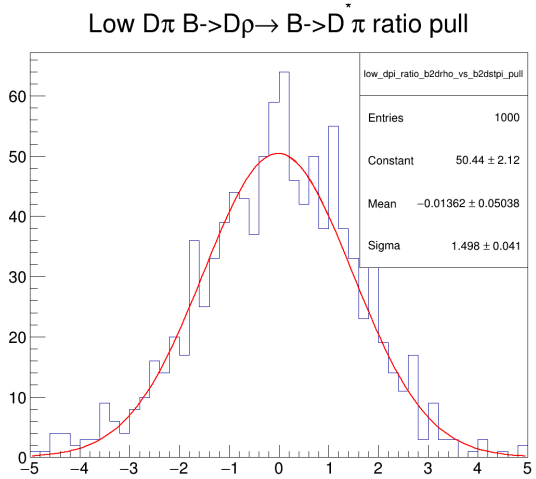
Global fit toy studies



(a) Value



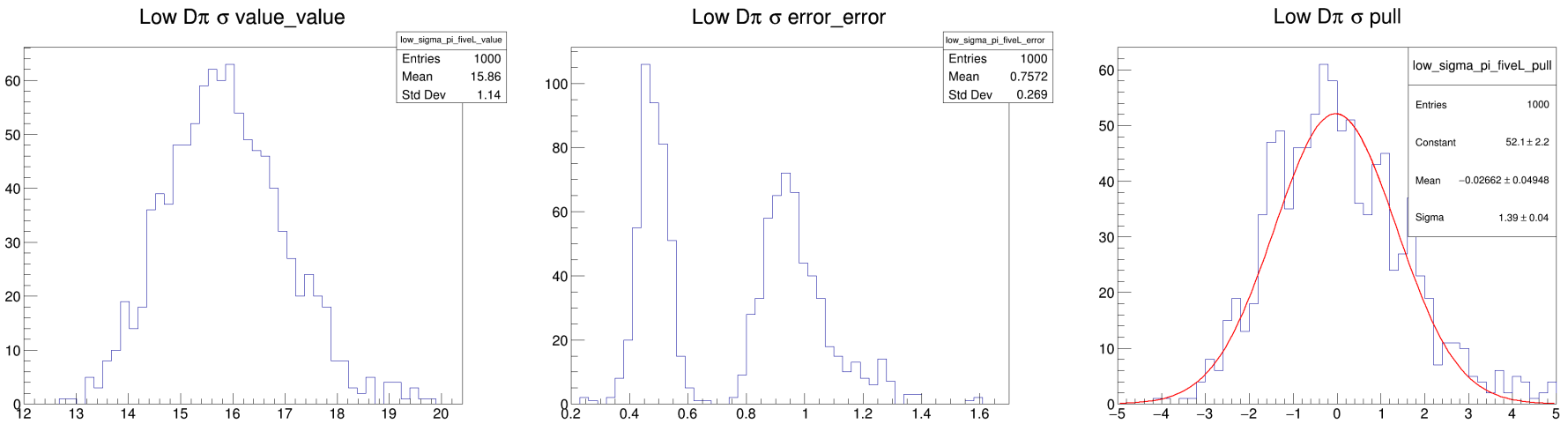
(b) Error



(c) Pull

Figure 11: `low_dpi_ratio_b2drho_vs_b2dstpi`

Global fit toy studies



(a) Value **(b)** Error **(c)** Pull

Figure 12: `low_sigma_pi_fiveL_error.png`

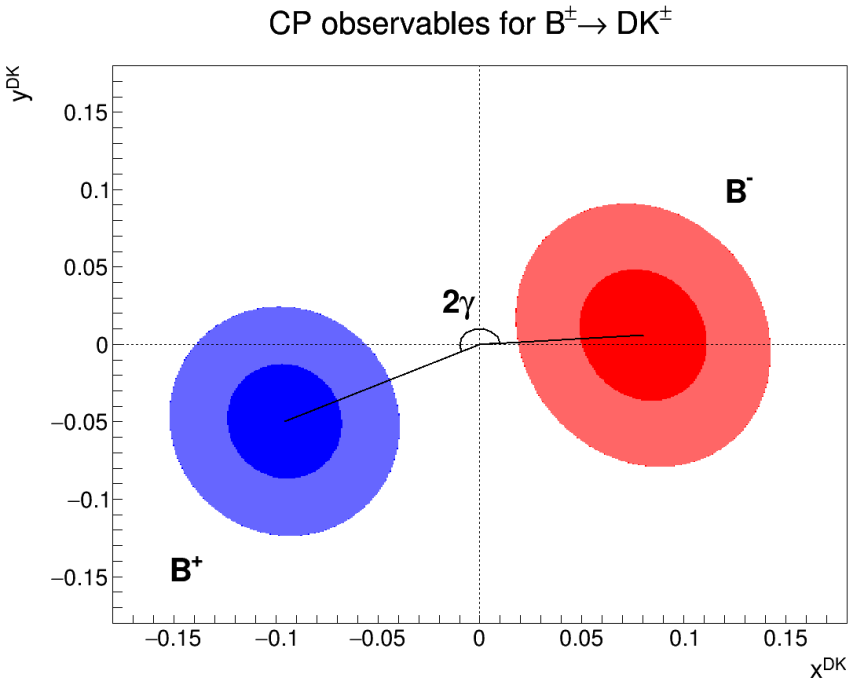
Binned CP fit

Binned CP fit

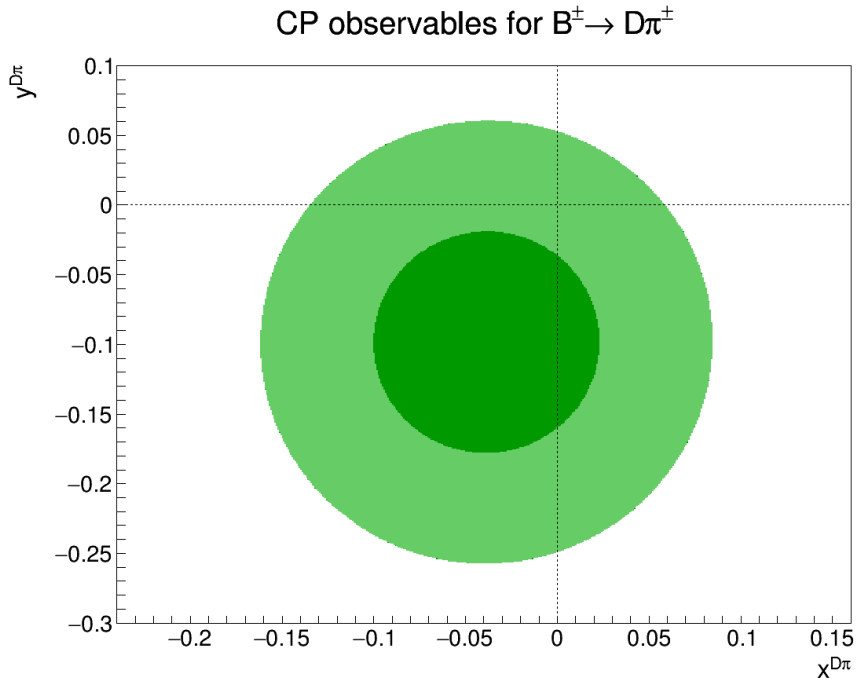
- Use 8 bins for now
- c_i and s_i calculated using MC integration of LHCb amplitude model
- Fit for CP observables
- PDF shape parameters fixed from global fit
- Yield of signal, low mass partially reconstructed background and combinatorial background floated
- Fractional yields K_i (F_i) floated

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

Fitted CP observables



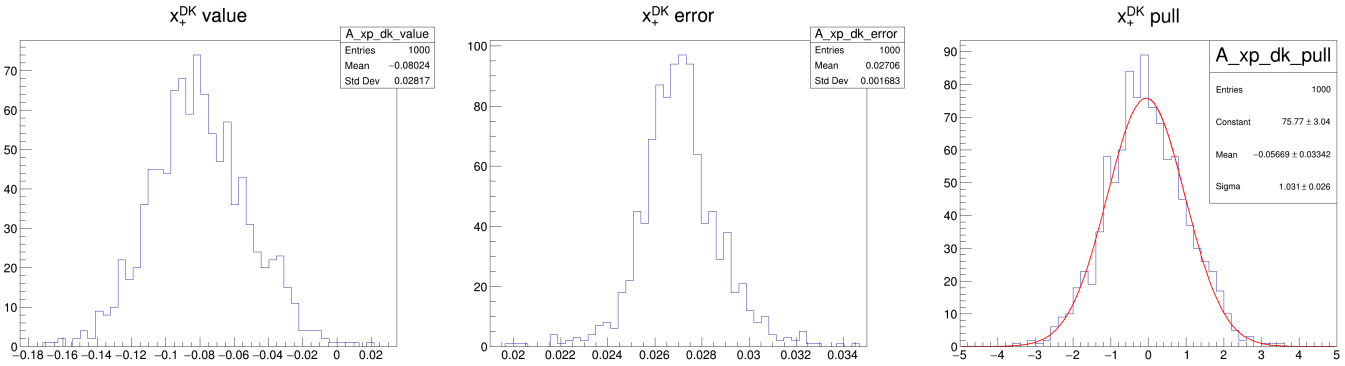
(a) $x_{\pm}^{DK}$ and $y_{\pm}^{DK}$



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

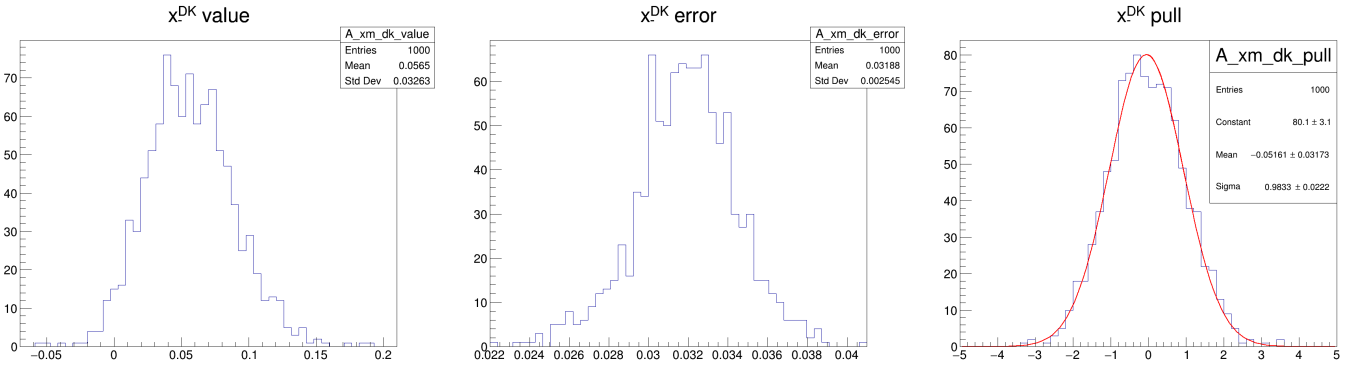
Figure 13: 68.2% and 95.5% confidence intervals of CP observables

CP fit toy studies



(a) Value **(b)** Error **(c)** Pull

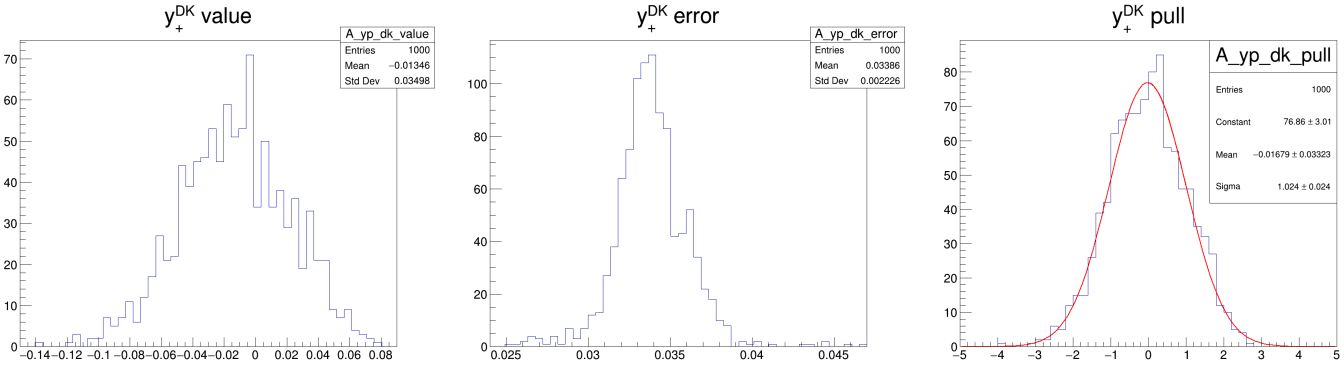
Figure 14: x_+^{DK}



(a) Value **(b)** Error **(c)** Pull

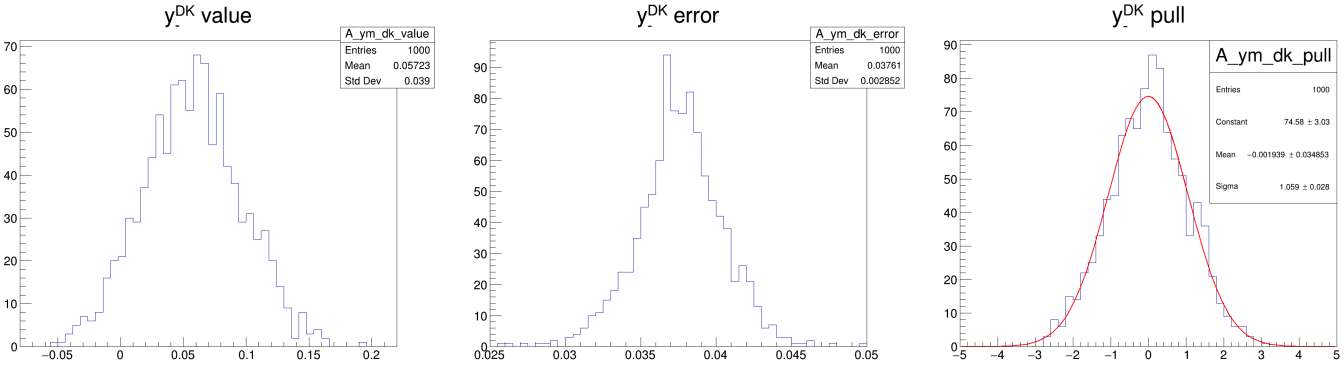
Figure 15: x_-^{DK}

CP fit toy studies



(a) Value **(b)** Error **(c)** Pull

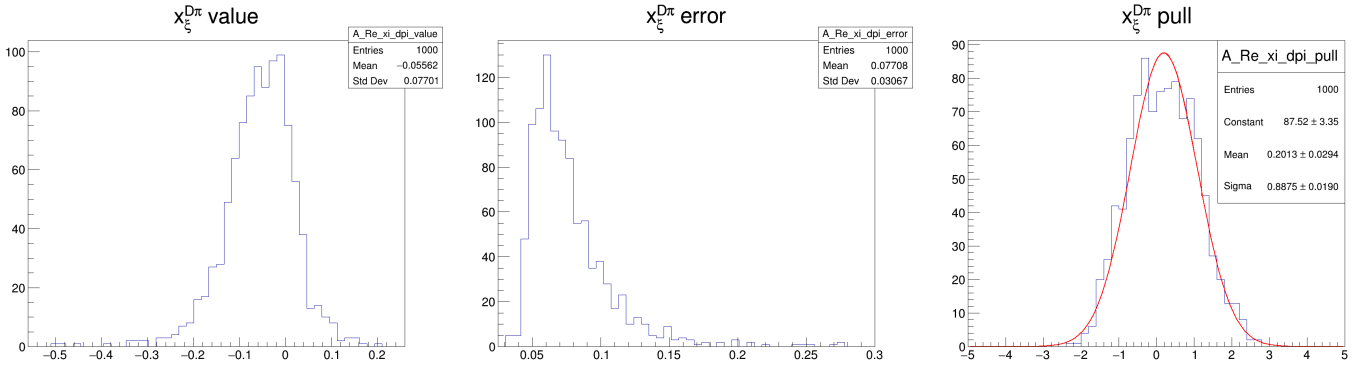
Figure 16: y_+^{DK}



(a) Value **(b)** Error **(c)** Pull

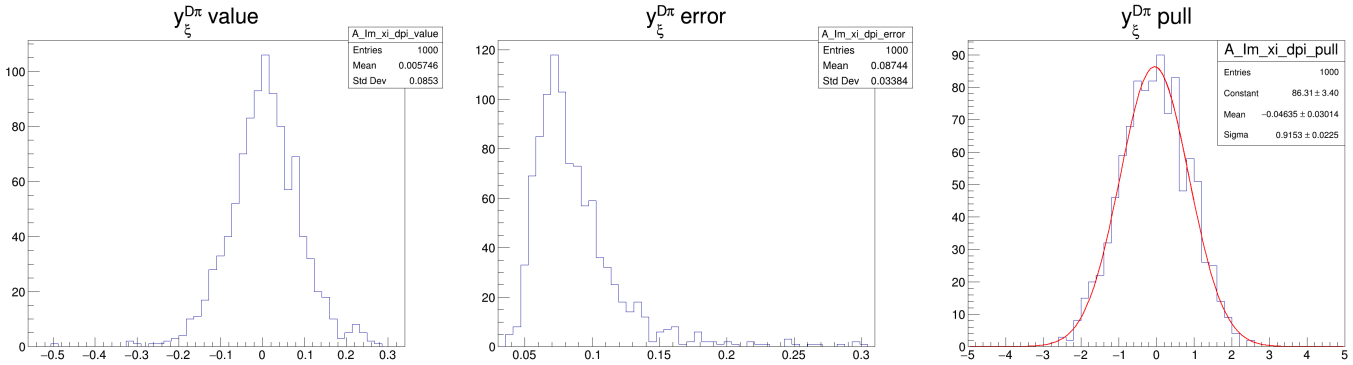
Figure 17: y_-^{DK}

CP fit toy studies



(a) Value **(b)** Error **(c)** Pull

Figure 18: $x_\xi^{D\pi}$

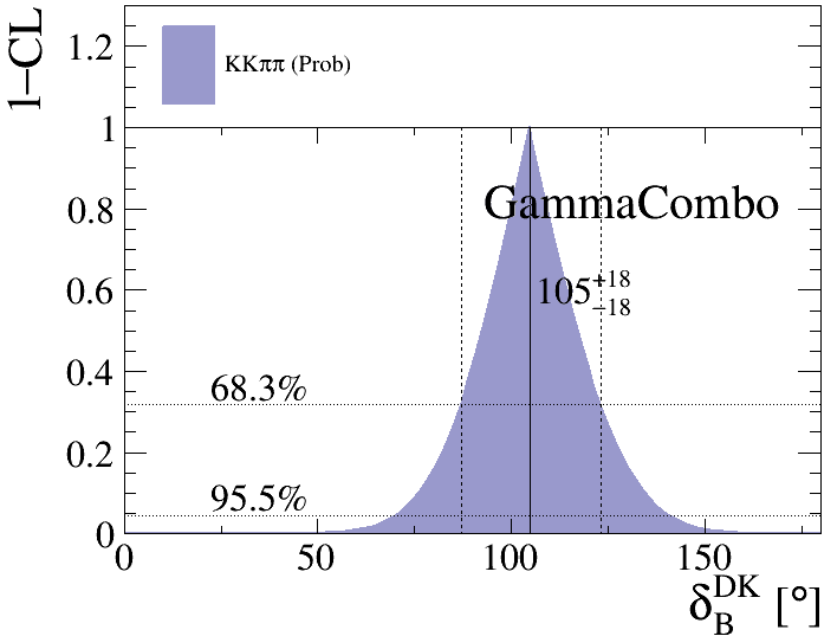


(a) Value **(b)** Error **(c)** Pull

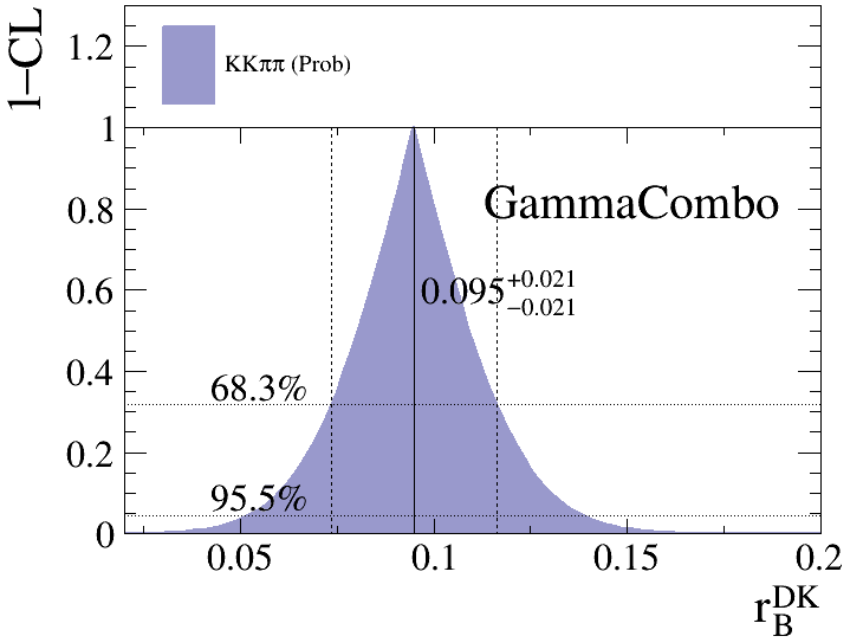
Figure 19: $y_\xi^{D\pi}$

GammaCombo

GammaCombo δ_B^{DK} and r_B^{DK}



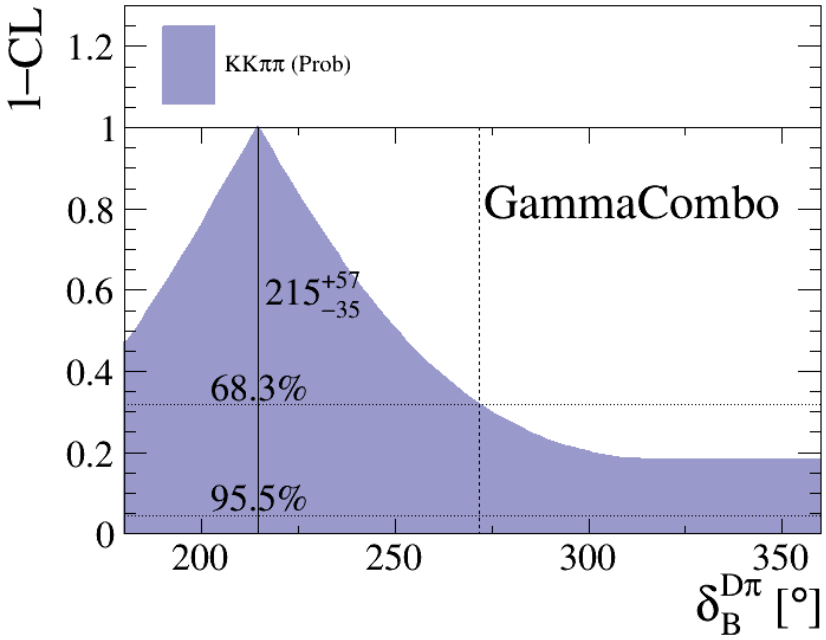
(a) δ_B^{DK}



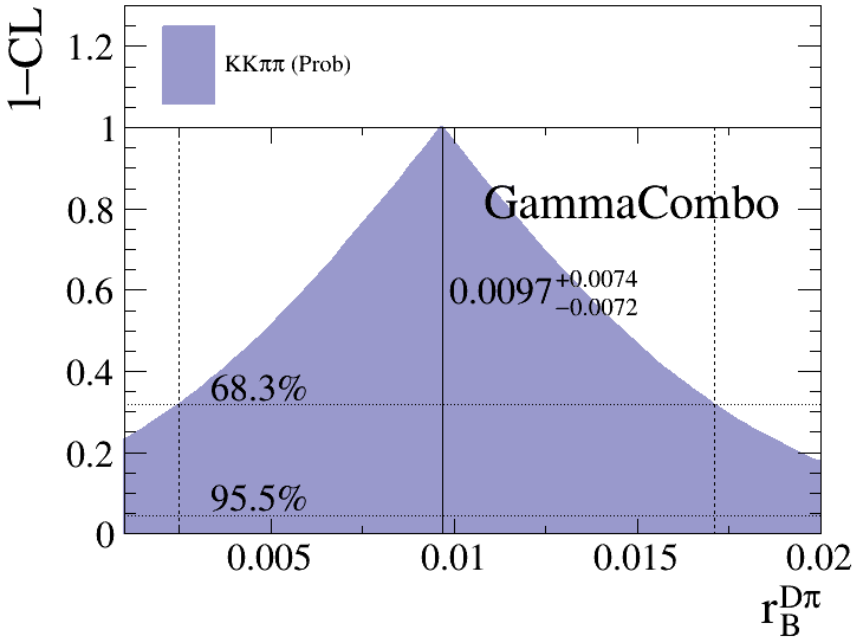
(b) r_B^{DK}

Figure 20

GammaCombo $\delta_B^{D\pi}$ and $r_B^{D\pi}$



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



(b) $r_B^{D\pi}$

Figure 21

GammaCombo γ

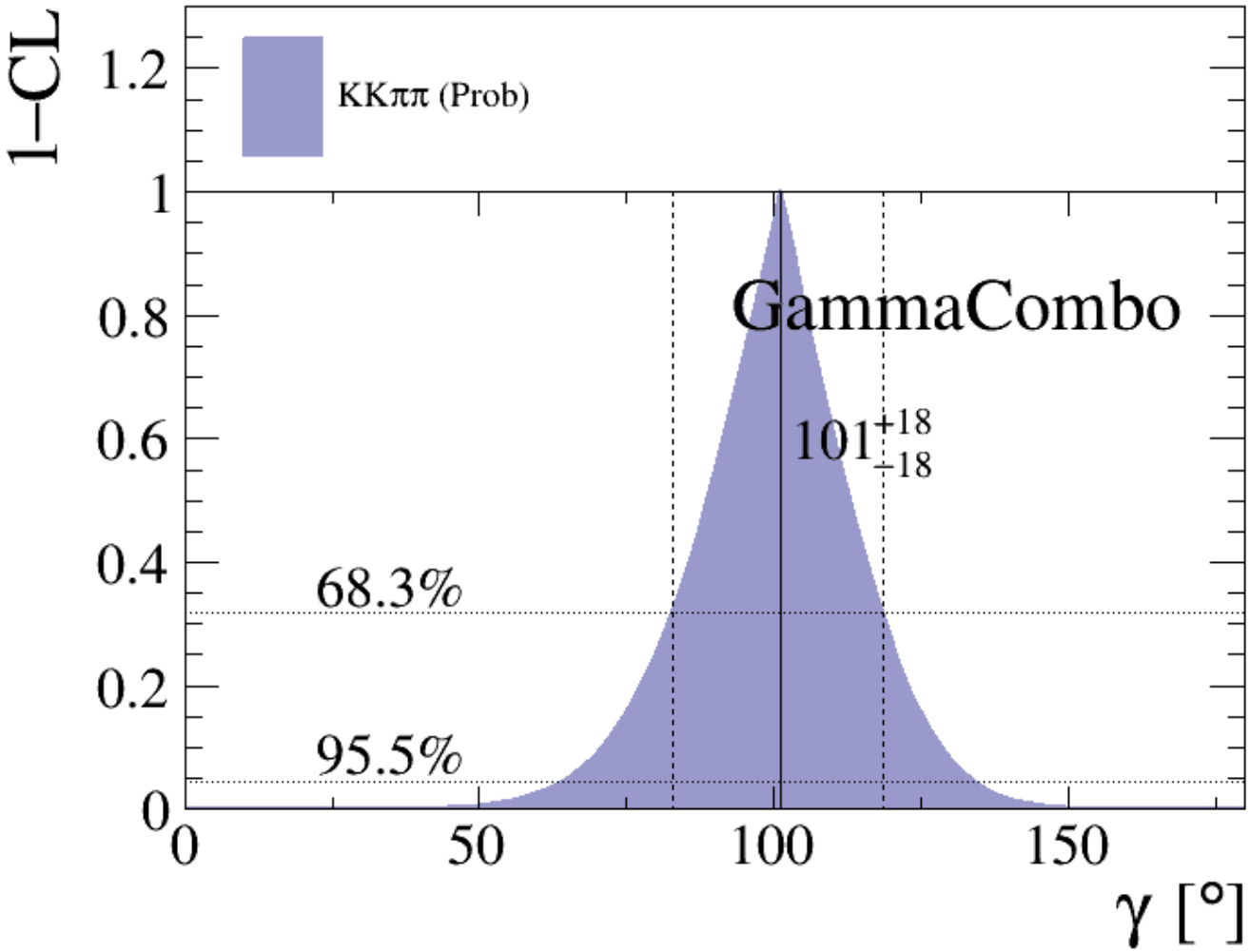


Figure 22: γ

Summary

Summary:

- Global and CP fits are working
- Toy studies show no suspicious behaviour

Next steps:

- Fine tuning the PDF shape parameters and efficiencies?

Backup

Backup: Binning scheme

- Use LHCb model (arXiv:1811.08304) implemented in AmpGen
- Calculate D^0 and $\bar{D}^0$ amplitude from D daughter momenta
- $\mathcal{A}(D^0)/\mathcal{A}(\bar{D}^0) = r_D \exp(i\delta_D)$
- Bin along δ_D to avoid dilution during averaging
- Enhance interference by separating bin $+i$ and $-i$ at $r_D = 1$
- Analogy from $K_S\pi^+\pi^-$: $m_+^2 = m_-^2$ separates CF and DCS resonances
- Maximize $Q = \frac{1}{2}(Q_+ + Q_-)$ by moving bin boundaries symmetrically around $\delta_D = 0$:

$$Q_\pm^2 = 1 - \sum_i \frac{K_i \bar{K}_i (1 - c_i^2 - s_i^2)}{N_i^\pm} \Big/ \sum_i K_i$$

Backup: DaVinci error

DaVinci error message:

```
B2DPi_D2KKPiPi....    INFO TupleToolDecayTreeFitter:: The INFO message is suppressed : 'Renaming duplicate to Bu_constD0PV_D0_piplus_0'
B2DPi_D2KKPiPi....    INFO TupleToolDecayTreeFitter:: The INFO message is suppressed : 'Renaming duplicate to Bu_constD0PV_D0_Kplus_1'
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_ID != Bu_constD0PV_D0_Kplus_1_ID StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PE != Bu_constD0PV_D0_Kplus_1_PE StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PX != Bu_constD0PV_D0_Kplus_1_PX StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PY != Bu_constD0PV_D0_Kplus_1_PY StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PZ != Bu_constD0PV_D0_Kplus_1_PZ StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_ID != Bu_constD0PV_D0_piplus_0_ID StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PE != Bu_constD0PV_D0_piplus_0_PE StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PX != Bu_constD0PV_D0_piplus_0_PX StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PY != Bu_constD0PV_D0_piplus_0_PY StatusCode=FAILURE
B2DPi_D2KKPiPi....   ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PZ != Bu_constD0PV_D0_piplus_0_PZ StatusCode=FAILURE
B2DPi_D2KKPiPi       FATAL Tool 'TupleToolDecayTreeFitter' acting on particle 'Bu' returned a failure status.
```