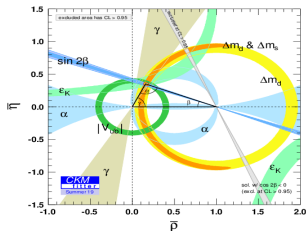


Analysis update on γ measurement in $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ decays

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Oxford LHCb

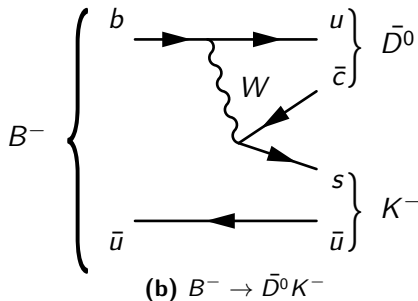
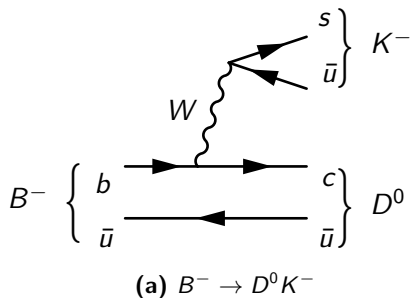
21st May 2021



Outline

- 1 Introduction
- 2 Binning scheme
- 3 $B^\pm \rightarrow (K^+ K^- \pi^+ \pi^-)_D h^\pm$ selection
- 4 Global fit
- 5 Global fit
- 6 Summary

Introduction



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

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

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

Introduction

- CP observables:

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

Event yield in bin i

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

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

Amplitude averaged strong phases and fractional yield

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

Binning scheme

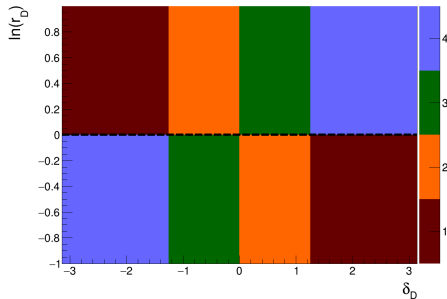
Binning scheme

- Use LHCb model ([arXiv:1811.08304](https://arxiv.org/abs/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 $\delta_D = 0$:

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

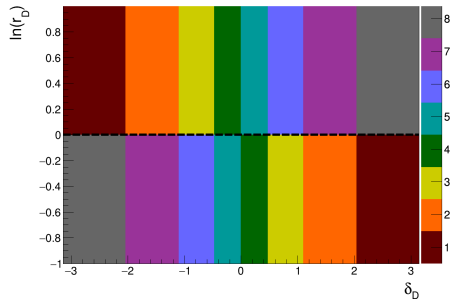
Binning scheme

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



(a) 2×4 binning scheme
 $Q = 0.85$

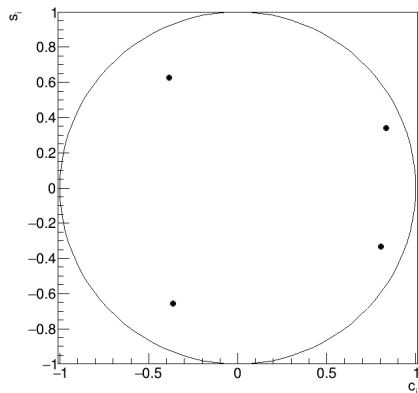
2x8 binning scheme for $K^+K^-\pi^+\pi^-$ phase space



(b) 2×8 binning scheme
 $Q = 0.90$

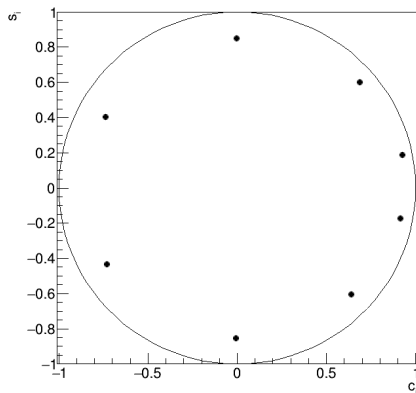
Strong phases

Plot of s_i vs c_i



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

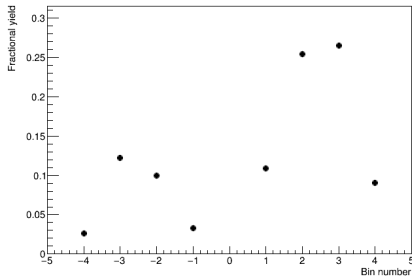
Plot of s_i vs c_i



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

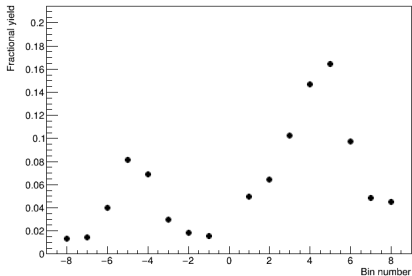
Fractional yields

Fractional yields



(a) K_i for the
 2×4 binning scheme

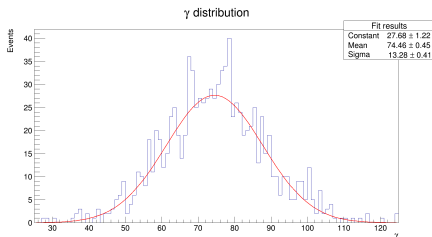
Fractional yields



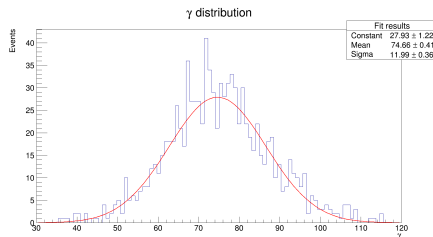
(b) K_i for the
 2×8 binning scheme

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
 $\Delta\gamma = 12^\circ$

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

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

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

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

Run 1 trigger requirements	(Bu_LOGlobal_TIS or Bu_LOHadronDecision_TOS) and (Bu_Hlt1TrackAllLODecision_TOS) and (Bu_Hlt2Topo2BodyBBDTDecision_TOS or Bu_Hlt2Topo3BodyBBDTDecision_TOS or Bu_Hlt2Topo4BodyBBDTDecision_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)

Rectangular cuts before BDT

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

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

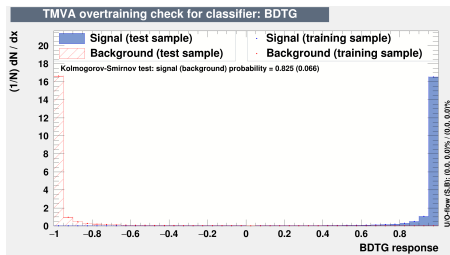
BDT training variables part 1

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

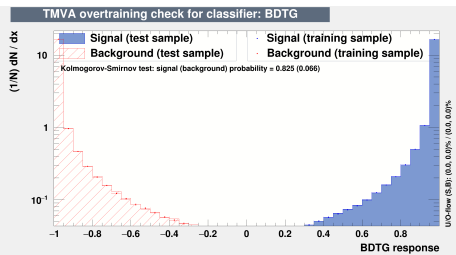
BDT training variables part 2

Name	Rank (%)	Description
<code>log(Bu_constD0PV_D0_P)</code>	3.7	D momentum from DTF
<code>log(D0_VTXCHI2D0F)</code>	3.3	$D0$ vertex fit χ^2
<code>log(h[3,4]_IPCHI2_OWNPV)</code>	3.3	π^\pm impact parameter χ^2
<code>log(D0_IPCHI2_OWNPV)</code>	3.2	D impact parameter χ^2
<code>log(h[3,4]_PT)</code>	3.2	π^\pm transverse momentum
<code>log(Bu_PT)</code>	2.8	B^\pm transverse momentum
<code>log(h[1,2]_P)</code>	2.8	K^\pm momentum
<code>log(Bach_P)</code>	2.7	Bachelor momentum
<code>log(Bu_constD0PV_P)</code>	2.6	B^\pm momentum from DTF
<code>log(h[1,2]_IPCHI2_OWNPV)</code>	2.5	K^\pm impact parameter χ^2
<code>D0_MAXDOCA</code>	2.5	D distance of closest approach
<code>log(Bu_VTXCHI2D0F)</code>	2.0	B^\pm vertex fit χ^2
<code>log(h[3,4]_P)</code>	1.9	π^\pm momentum

BDT training results



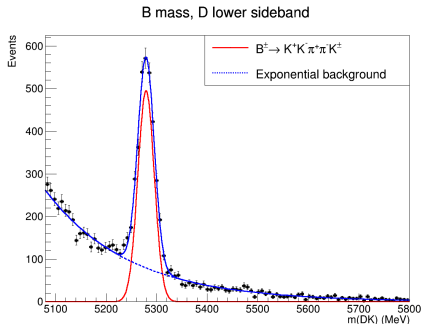
(a) BDT output



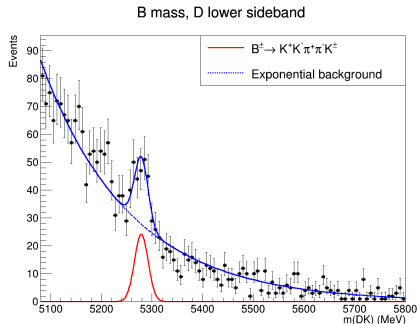
(b) BDT output on a logarithmic scale

Charmless backgrounds from $B^\pm \rightarrow K^+ K^- \pi^+ \pi^- K^\pm$

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



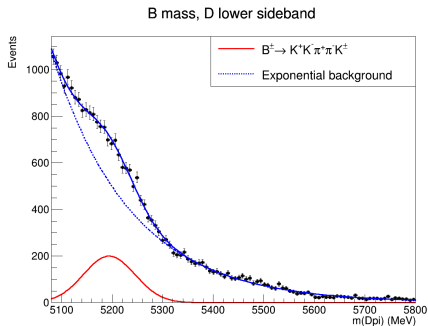
(a) No charmless cuts
Yield: 2605 ± 57



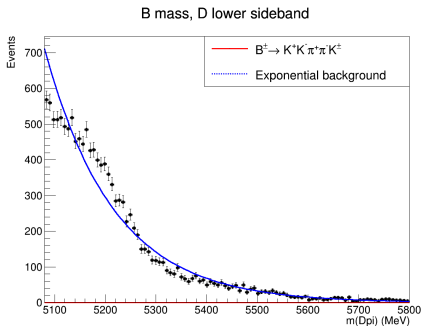
(b) Flight significance cut at 2
Yield: 110 ± 19

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

Charmless backgrounds from $B^\pm \rightarrow K^+ K^- \pi^+ \pi^- \pi^\pm$



(a) No charmless cuts

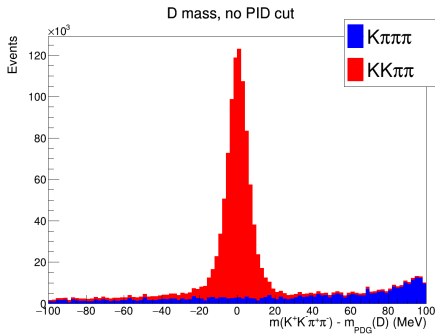


(b) Flight significance cut at 2

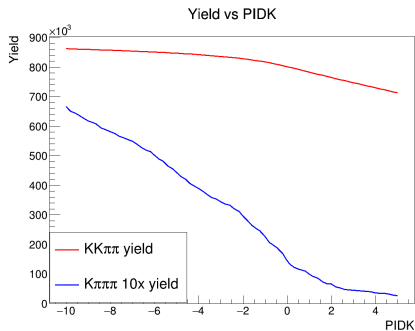
- No charmless background observed in the $B^\pm \rightarrow D\pi^\pm$ channel!

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

- 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 $\text{PIDK} > 0$ reduces the contamination from 7.2% to 1.8%

Cuts after BDT training

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

Global fit

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

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

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

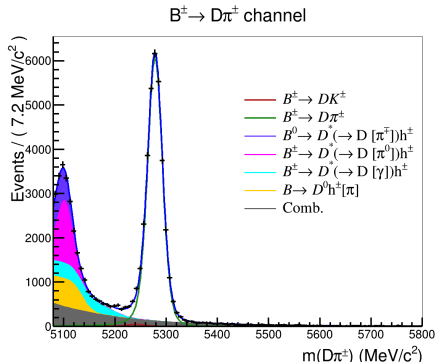
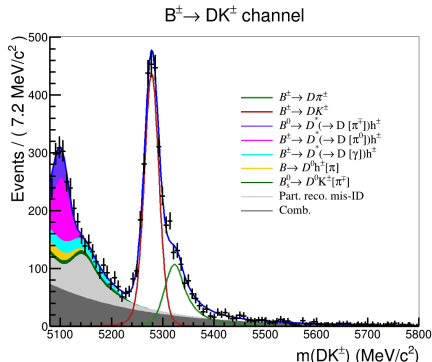


Figure 10: Global fit of B^\pm mass distribution for the DK^\pm channel (left) and $D\pi^\pm$ channel (right)

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

- 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

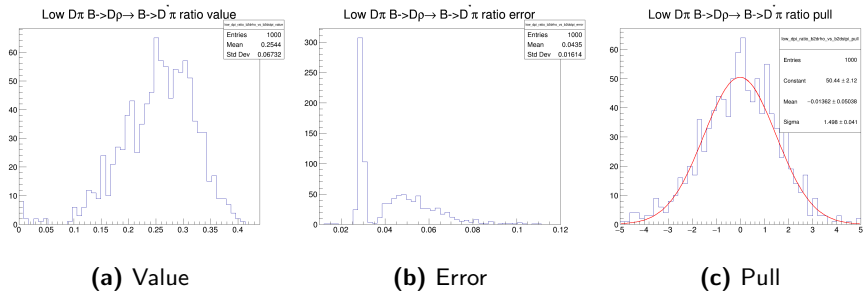


Figure 11: low_dpi_ratio_b2drho_vs_b2dstpi

Global fit toy studies

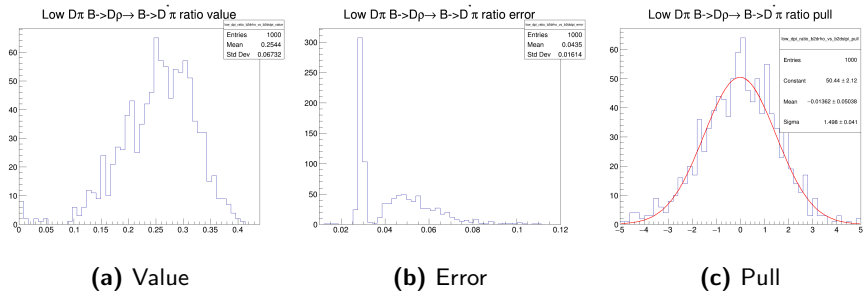


Figure 12: low_dpi_ratio_b2drho_vs_b2dstpi

Summary:

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

Next steps:

- Fine tuning the PDF shape parameters and efficiencies?

Backup slides: DaVinci error

DaVinci error message:

```
B2DPi_D2KKPiPl.... INFO TupleToolDecayTreeFitter:: The INFO message is suppressed : 'Renaming duplicate to Bu_constD0PV_D0_piplus_0'
B2DPi_D2KKPiPl.... INFO TupleToolDecayTreeFitter:: The INFO message is suppressed : 'Renaming duplicate to Bu_constD0PV_D0_Kplus_1'
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_ID != Bu_constD0PV_D0_Kplus_1_ID StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PE != Bu_constD0PV_D0_Kplus_1_PE StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PX != Bu_constD0PV_D0_Kplus_1_PX StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PY != Bu_constD0PV_D0_Kplus_1_PY StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_Kplus_0_PZ != Bu_constD0PV_D0_Kplus_1_PZ StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_ID != Bu_constD0PV_D0_piplus_0_ID StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PE != Bu_constD0PV_D0_piplus_0_PE StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PX != Bu_constD0PV_D0_piplus_0_PX StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PY != Bu_constD0PV_D0_piplus_0_PY StatusCode=FAILURE
B2DPi_D2KKPiPl.... ERROR TupleToolDecayTreeFitter:: Tuple entry error : Bu_constD0PV_D0_piplus_1_PZ != Bu_constD0PV_D0_piplus_0_PZ StatusCode=FAILURE
B2DPi_D2KKPiPl.... FATAL Tool 'TupleToolDecayTreeFitter' acting on particle 'Bu' returned a failure status.
```