Amplitude Analysis of $B^+ \to D^- K^+ \pi^+$ decays at LHCb

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Outline

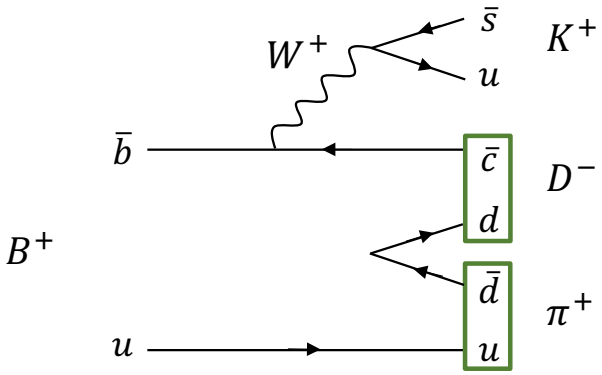
- **Motivation: Hadron spectroscopy**
  - Excited states
  - Exotic states
- **Current amplitude analysis of $B^+ \to D^- K^+ \pi^+$ decays**
  - Selection
  - Backgrounds
  - Mass fit
- **Next steps**
  - Dalitz plot analysis

Motivation

- Hadron spectroscopy

Excited states

- Charm meson spectroscopy provides powerful test of the lattice QCD calculations of hadron mass spectra



Signal

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

$\hookrightarrow K^+ \pi^- \pi^-$

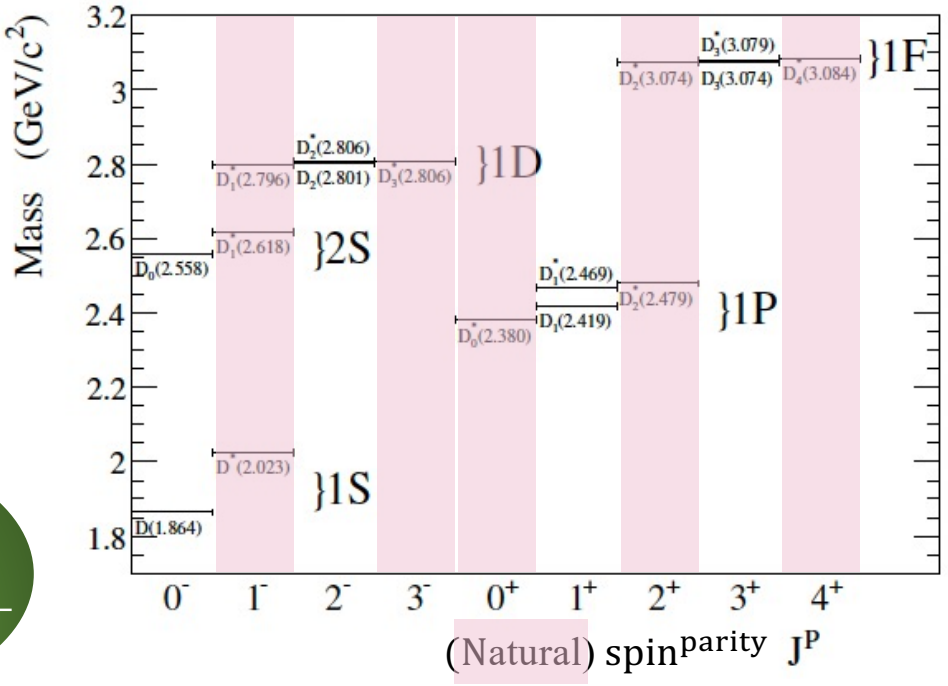


Fig.1: Mass spectrum of the $c\bar{u}$ system. [PhysRevD.32.189]

- Expect to see excited states of neutral D mesons with natural spin - parity in the $D^-\pi^+$ system

Experimental status

- Same decay mode was studied before with data collected with the LHCb detector in Run 1 (2011, 2012) [PhysRevD.91.092002]

- The study reported the first observation of the decay mode, branching fraction calculation and observation of 3 excited states in the $D^-\pi^+$ system:
  - $D_0^*(2400)^0$ - has been changed to $D_0^*(2300)^0$
  - $D_2^*(2460)^0$
  - $D_1^*(2760)^0$

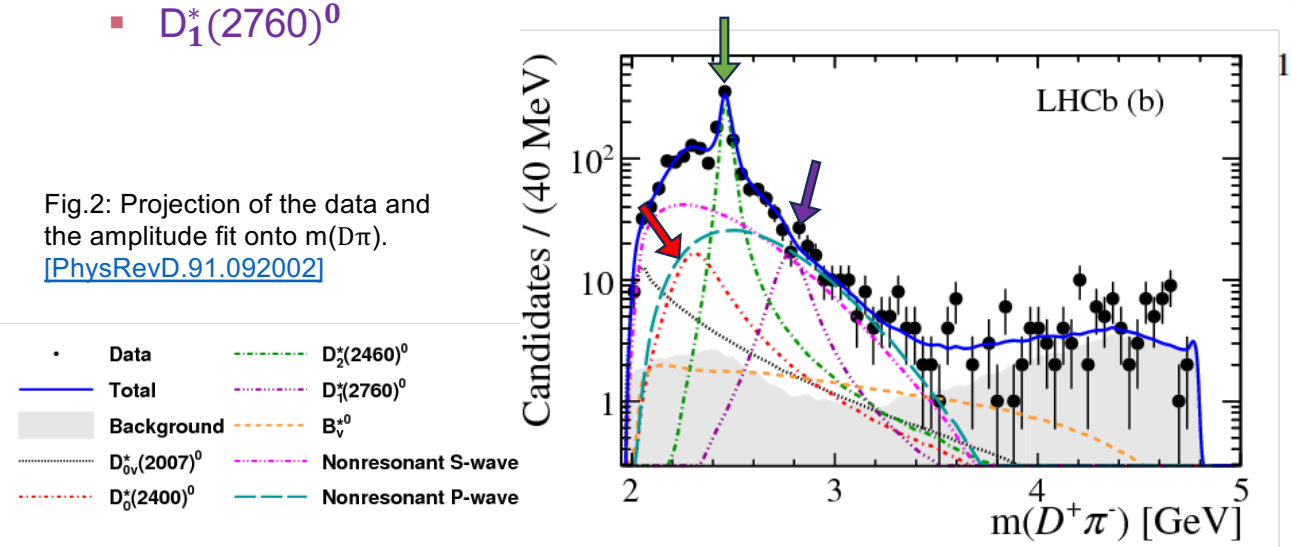


Fig.2: Projection of the data and the amplitude fit onto m(Dπ). [PhysRevD.91.092002]

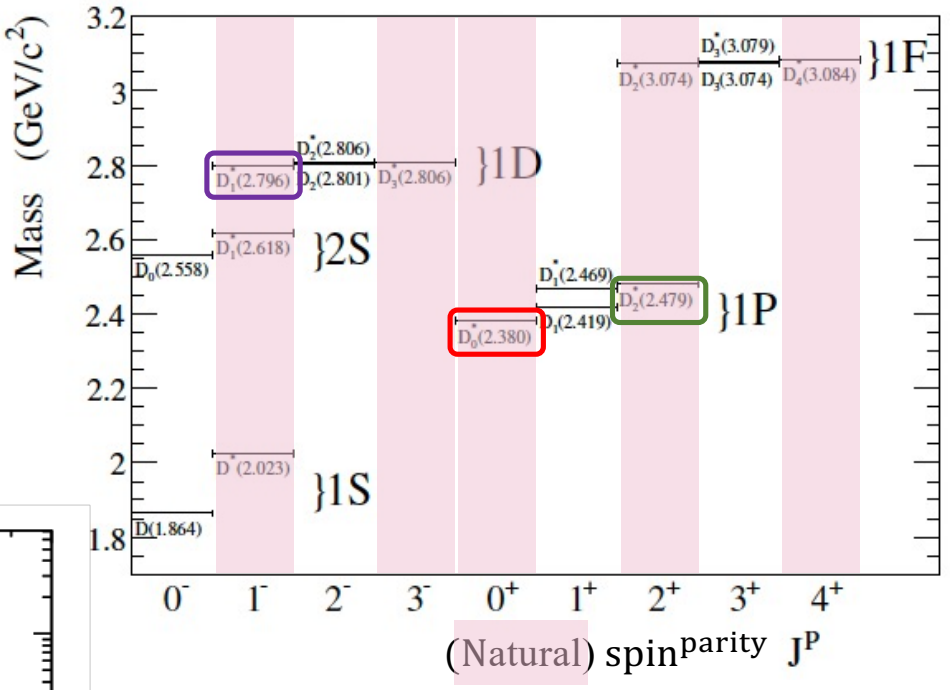
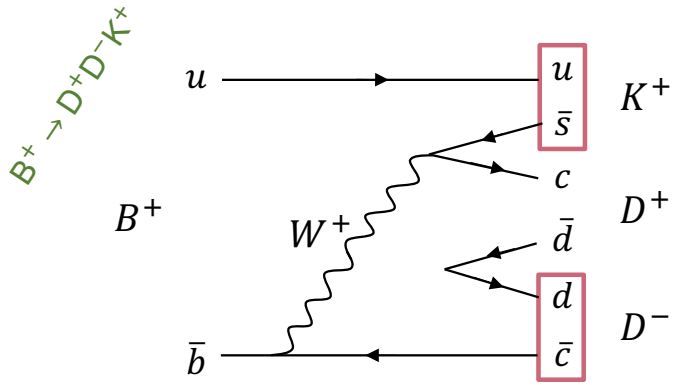


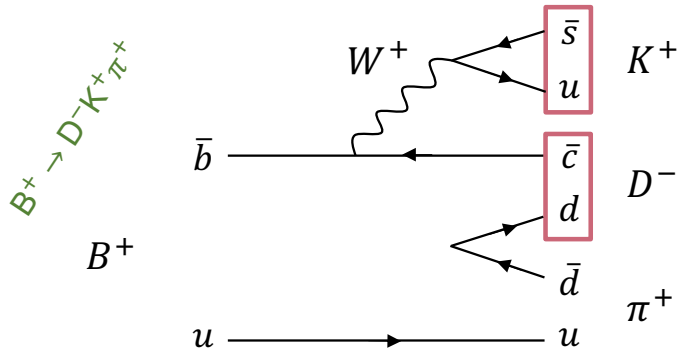
Fig.1: Mass spectrum of the $c\bar{u}$ system. [PhysRevD.32.189]

Exotic states

- Neutral tetraquarks T^*_{cs0} (2870)^0 and T^*_{cs1} (2900)^0 observed in $B^+ \to D^+D^-K^+$ decays [PhysRevD.102.112003]



D^-K^+ channel:
$\mathbf{T^*_{cs}}$ $[\bar{c}d\bar{s}u]$



D^-K^+ channel:

?

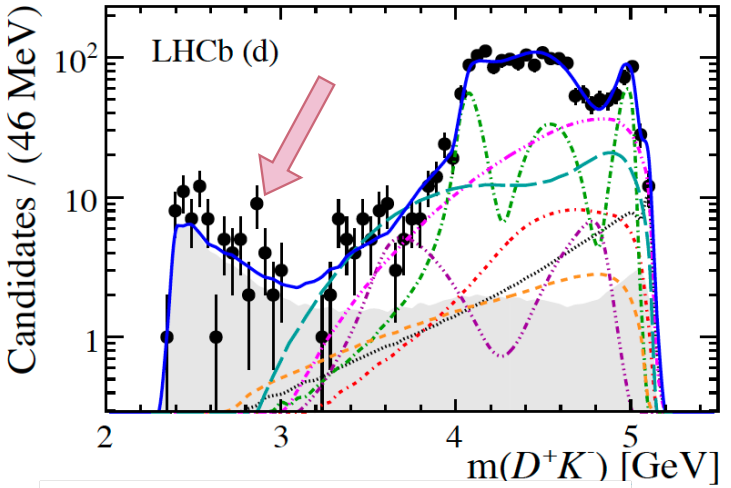


Fig.3: Projection of the data and the amplitude fit onto m(DK). [PhysRevD.91.092002]

- Two more states added to the family of T^*_{cs} tetraquarks: $T^*_{c\bar{s}0}$ (2900)^0 and $T^*_{c\bar{s}0}$ (2900)$^{++}$ observed in $B^0 \to D^0D^+_s\pi^-$ and $B^+ \to D^-D^+_s\pi^+$ decays [PhysRevLett.131.041902]

Current analysis

- Data collected with the LHCb experiment in Run 1 (2011 and 2012) and Run 2 (2015 – 2018)

Selection: Multivariate analysis

Initial selection: Loose cuts on kinematic and PID variables

Multivariate analysis (MVA): Used to suppress combinatorial backgrounds

combinatorial background
D meson + random tracks
$B^0 \to D^- K^+$ + random pion
$B^0 \to D^- \pi^+$ + random kaon

- Choice of MVA method to use: XGBoost
- Samples used to train the classifier :
  Signal – Monte Carlo generated $B^+ \to D^- K^+ \pi^+$ sample
  Background – from data; B-candidate mass sidebands with B mass > 5400 MeV/c^2
- Classifier applied separately to Run 1 and Run 2

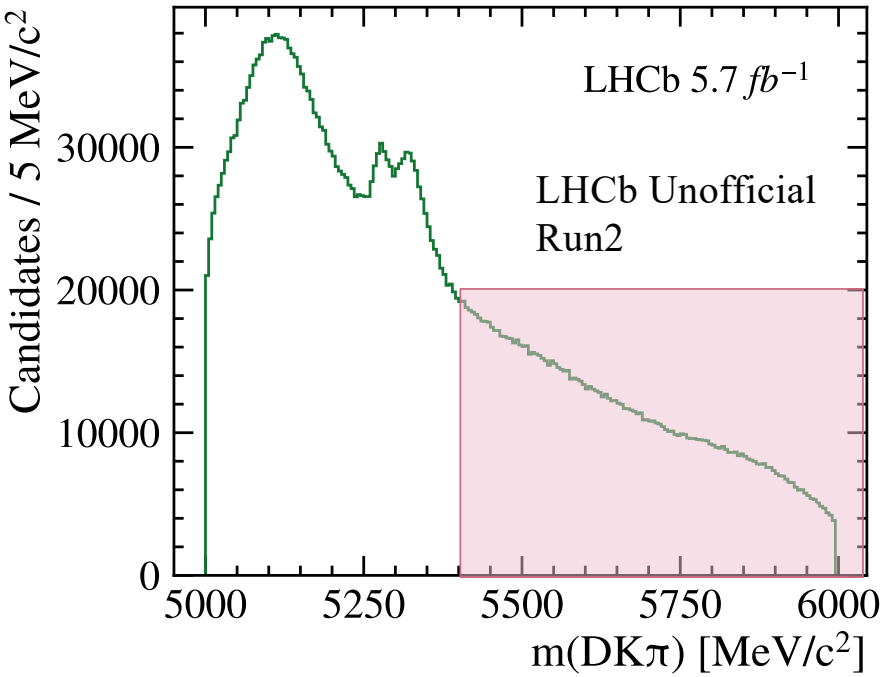


Fig.4: B reconstructed mass after initial selection.

Selection: Particle Identification

peaking backgrounds
Real D meson + misidentified particles
$B^0 \to D^- \pi^+ \pi^+ \pi^-$

- **Particle identification (PID) requirements:**
  - To minimise the number of $B^+ \to D^- \pi^+ \pi^+$ and other peaking backgrounds
  - For the kaon from B^+ cut on $p(K) \times (1 - p(\pi))$ - PID cut
  - The PID variables in the MC are corrected to match these in data [further info]

- The XGBoost and PID cuts are optimised simultaneously

  Figure of merit : $\frac{S}{\sqrt{S+B}} \times \frac{S}{S+B}$

  (significance × purity)

- S (signal) and B (background) entries determined by fitting the B mass distribution for each XGBoost output and PID cut combination
  - Signal and $B^+ \to D^- \pi^+ \pi^+$ background - Double Crystal Ball
  - Other background – exponential

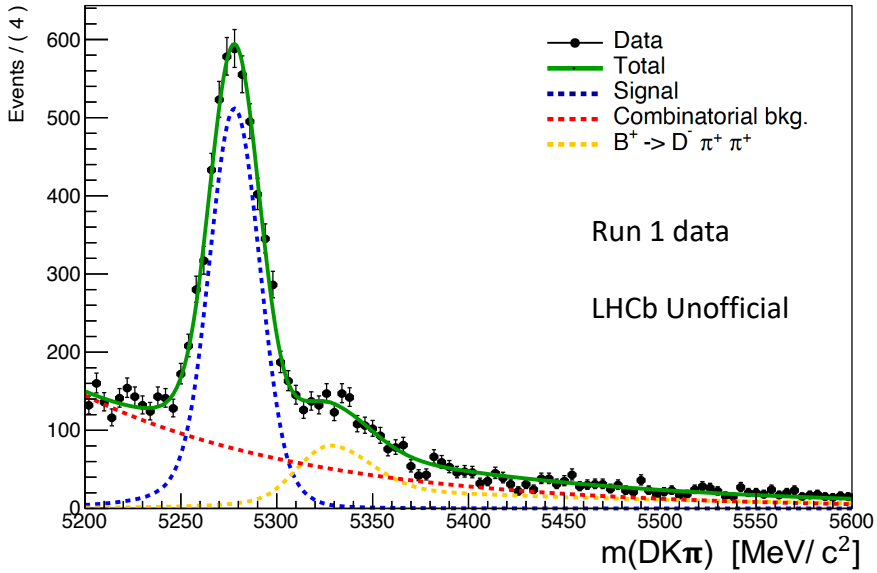


Fig.5: Simple mass fit for estimating the number of signal and background candidates

Selection

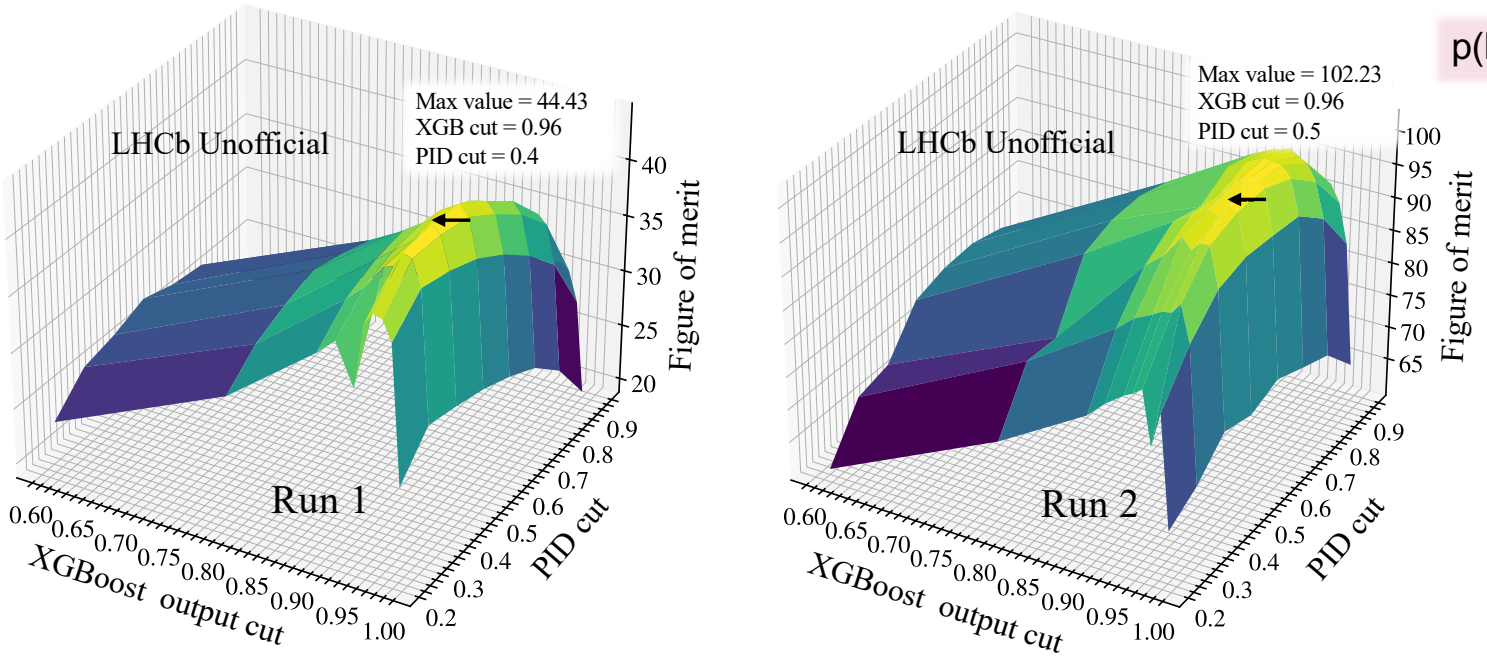


Fig.5: Optimising the XGBoost output and PID cuts simultaneously

p(K) * (1 – p(π)) - PID cut on K from B^+

Figure of merit = $\frac{S}{\sqrt{S+B}} \cdot \frac{S}{S+B}$

XGBoost output cut
Signal efficiency = 65%
Background rejection = 98%

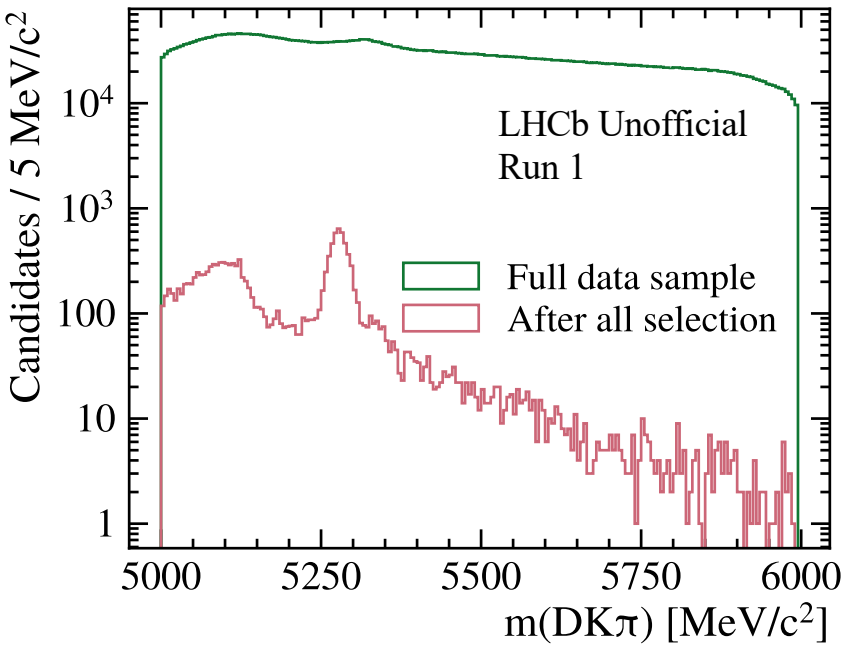
PID cut
$B^+ \to D^-\pi^+\pi^+$ rejection = 95%

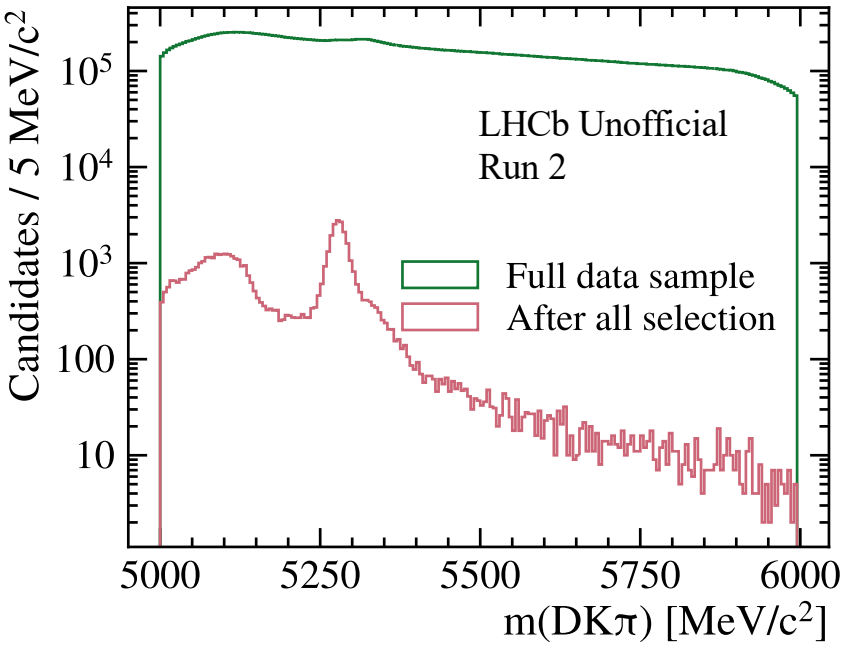
Invariant mass vetoes: Stricter PID cuts applied in certain mass regions to discard peaking backgrounds

peaking backgrounds
Real D meson + misidentified particles
$B^+ \to \Lambda_c^- K^+ \pi^+$
$B^+ \to D_s^- K^+ \pi^+$

Selection: Result

- Data after all selections applied

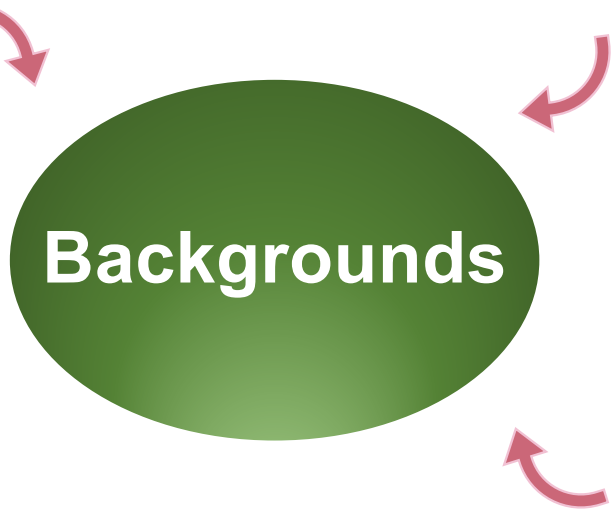




Backgrounds

combinatorial background
D meson + random tracks
MVA classifier

Significantly reduced –
the rest is modelled using an exponential function



charmless peaking background
Same final state, no D meson
MVA classifier

No charmless peaking background observed after all selections

peaking backgrounds
Real D meson +
misidentified particles
PID cut + vetoes

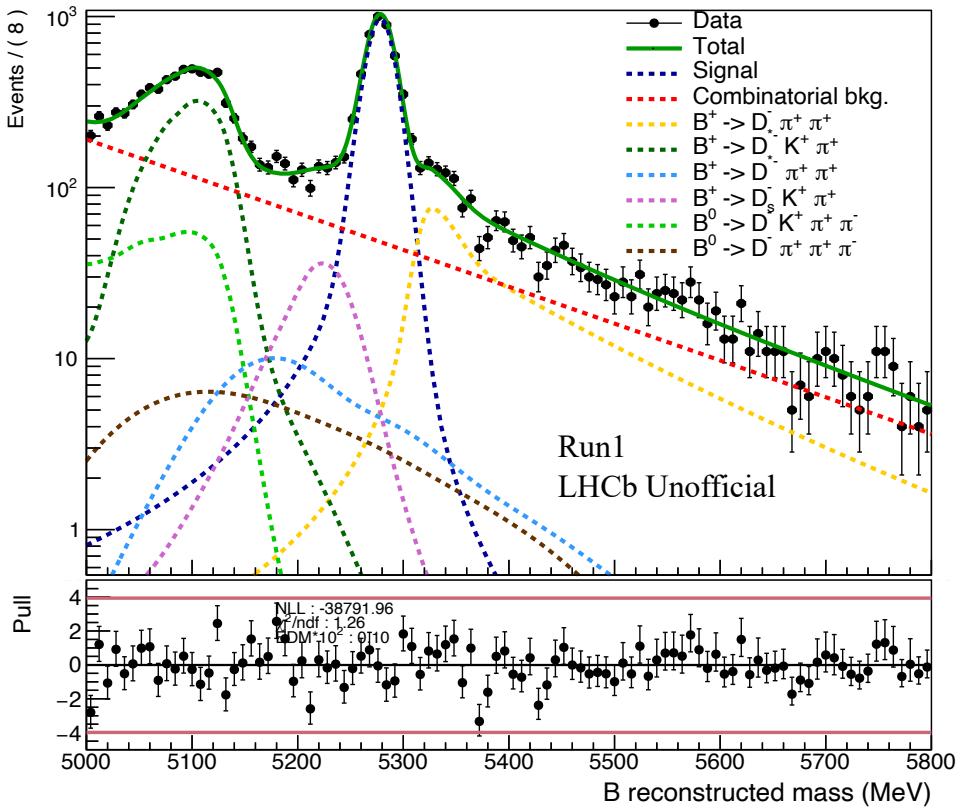
Model using MC samples

partially reconstructed
D meson + two other tracks
+ additional tracks that are not reconstructed

Model using MC samples

Mass fit

Fit to B candidate invariant mass distribution for DKπ



Next steps

Next steps

- **The Dalitz Plot:** A 2D scatter plot for a 3-body decay, where the axes are the invariant mass squares of two of the three particles

  - Shows resonances in pairs of invariant masses squared
  - Can infer the mass and spin of the resonance from the shape in the Dalitz plot

The current ongoing analysis is blind due to the potential of tetraquarks

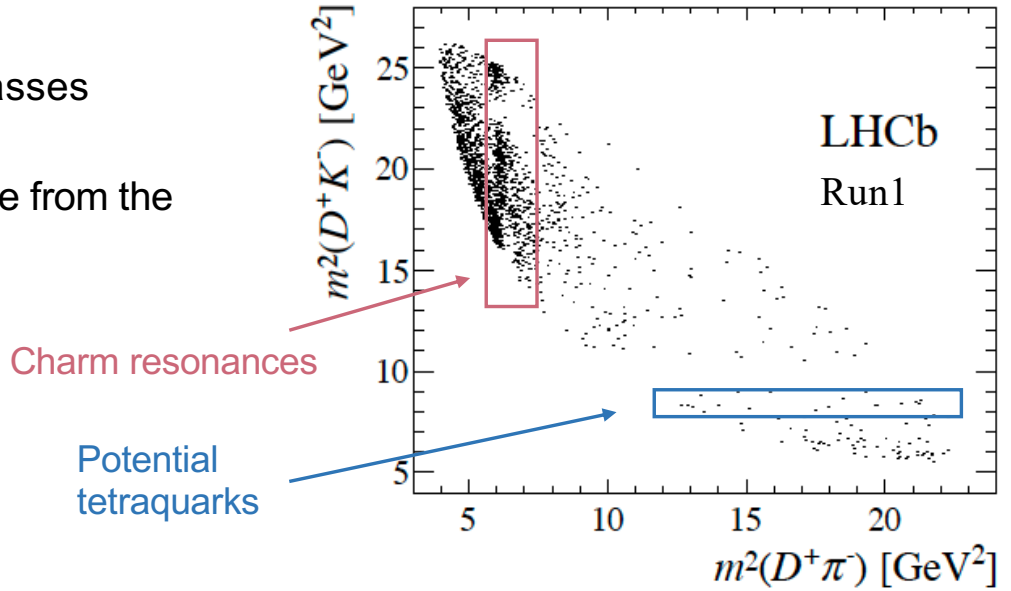


Fig.5: Distribution of $B^- \to D^+K^-\pi^-$ candidates over the Dalitz plot. Plot taken from the previous analysis [PhysRevD.91.092002]

Summary

Hadron spectroscopy

- Previous studies of the $B^+ \to D^- K^+ \pi^+$ channel
- Excited states and exotic states

Status of the current amplitude analysis of $B^+ \to D^- K^+ \pi^+$ decays

- Selection, backgrounds, mass fit

Next steps

- Dalitz plot analysis

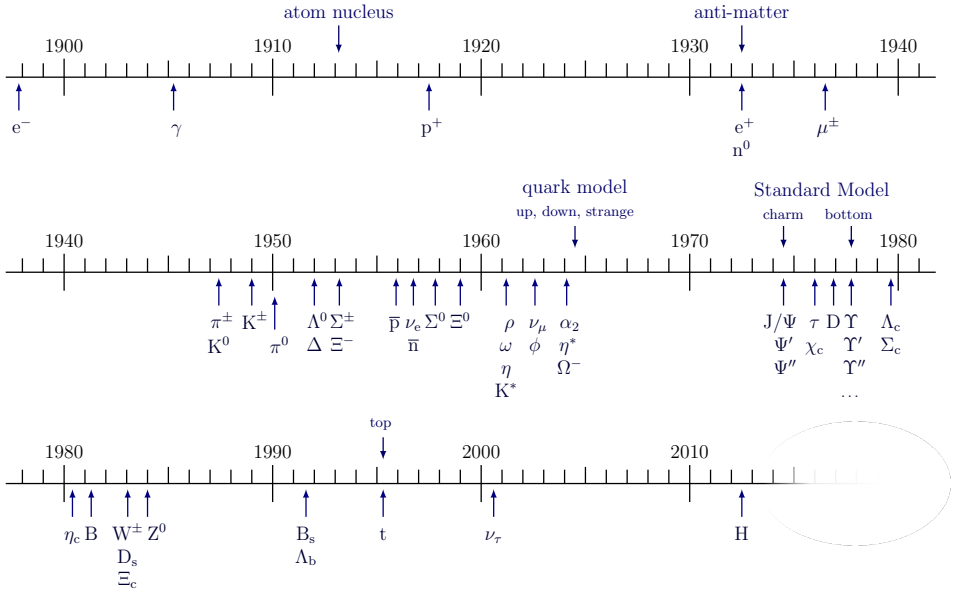
Thank you for the attention!

Backup

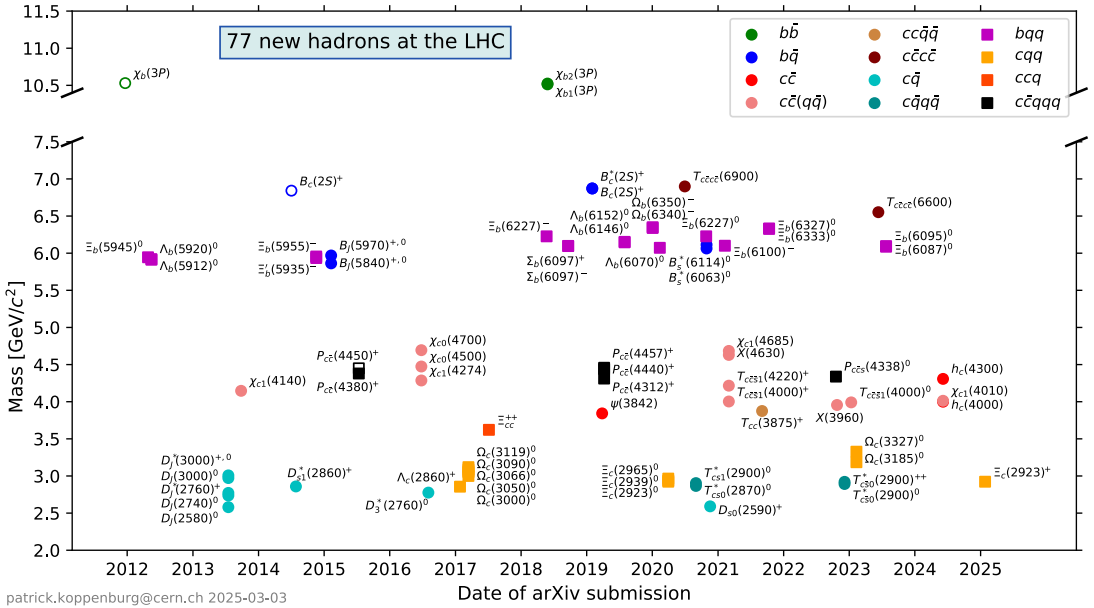
Motivation – Hadron spectroscopy

There are almost 300 particles discovered to date

- Many particles were discovered between the 1950s and 70s – The Particle Zoo



- Since the LHC started operating 77 hadrons have been discovered, of which 69 by LHCb
- 54 conventional and 23 exotic hadrons including excited states



MC sample

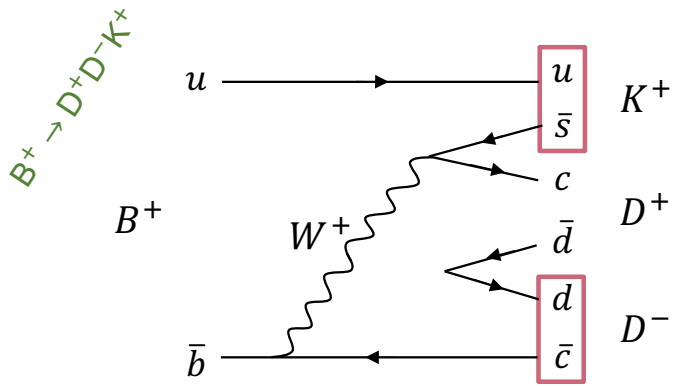
MC Sample:

Sample type	Event number	Decay	Number of events
Signal	12165064	$B^+ \to D^- K^+ \pi^+$	5.0 million
Background	12165063	$B^+ \to D^- \pi^+ \pi^+$	2.5 million
Background	12165611	$B^+ \to D^{*-} K^+ \pi^+$	2.5 million
Background	12165601	$B^+ \to D^{*-} \pi^+ \pi^+$	2.5 million
Background	12165065	$B^+ \to D_s^- K^+ \pi^+$	2.5 million
Background	11266006	$B^0 \to D^- \pi^+ \pi^+ \pi^-$	2.5 million
Background	11266007	$B^0 \to D^- K^+ \pi^+ \pi^-$	2.5 million
Background	11264001	$B^0 \to D^- \pi^+$	2.5 million
Background	11264011	$B^0 \to D^- K^+$	2.5 million

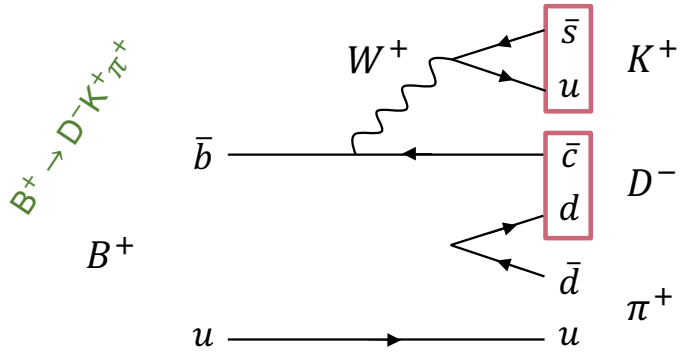
Momentum scaling is applied to data and momentum smearing to MC

Exotic states

- Neutral tetraquarks $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ observed in $B^+ \to D^+D^-K^+$ decays [PhysRevD.102.112003]



D^-K^+ channel:
$\mathbf{T^*_{cs}}$ $[\bar{c}d\bar{s}u]$

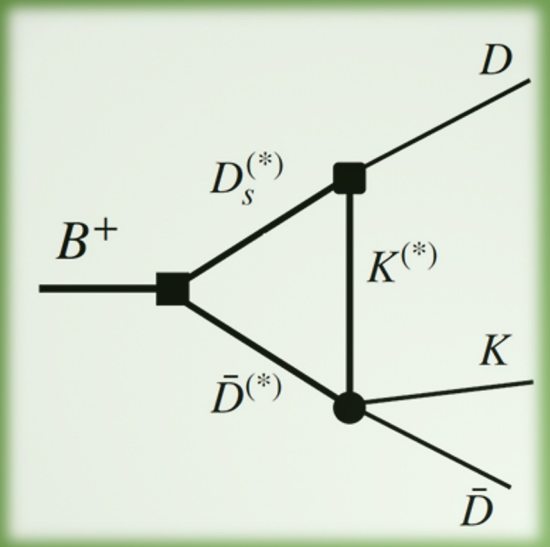


D^-K^+ channel:

?

- $T^*_{cs0,1}$ states – different interpretations:

  Tetraquark or molecule or produced through triangle diagrams with two D mesons in the final state [PhysRevD.103.014004]



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Mode: $B^+ \to D^+T^*_{cs}$, $T^*_{cs} \to D^-K^+$

Initial selection

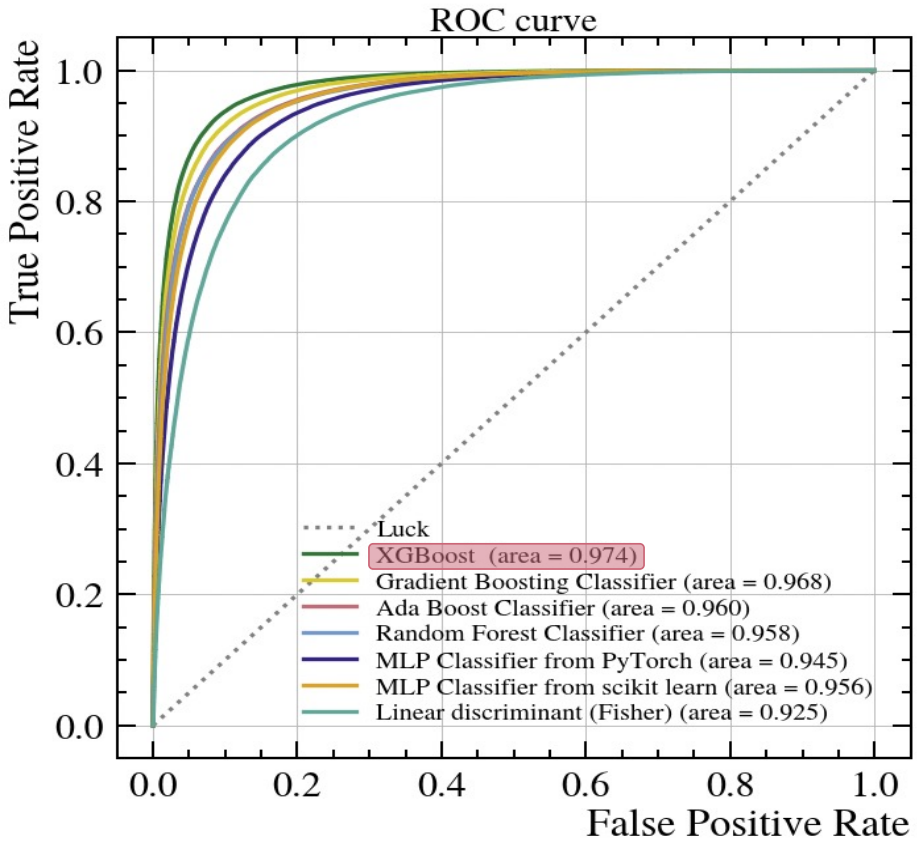
Pre-selection cuts:

+ Truth matching for MC

Particle	Parameter	Cut value
B^+	$\cos\theta_{\text{dir. own PV}}$	> 0.99997
	$\chi^2_{\text{flight w.r.t. own PV}}$	> 260
D^-	M	> 1770 and < 1968 MeV/c^2
	$\chi^2_{\text{flight w.r.t. own PV}}$	> 260
D daughter K^+	p	< 100 GeV/c
D daughter π^-	p	< 100 GeV/c
D daughter π^-	p	< 100 GeV/c
Bachelor K^+	ProbNNk	> 0.15
	p	> 3 GeV/c and < 100 GeV/c
Bachelor π^+	p	< 100 GeV/c

MVA method

- **Choice of an MVA method to use**



MVA Input variables

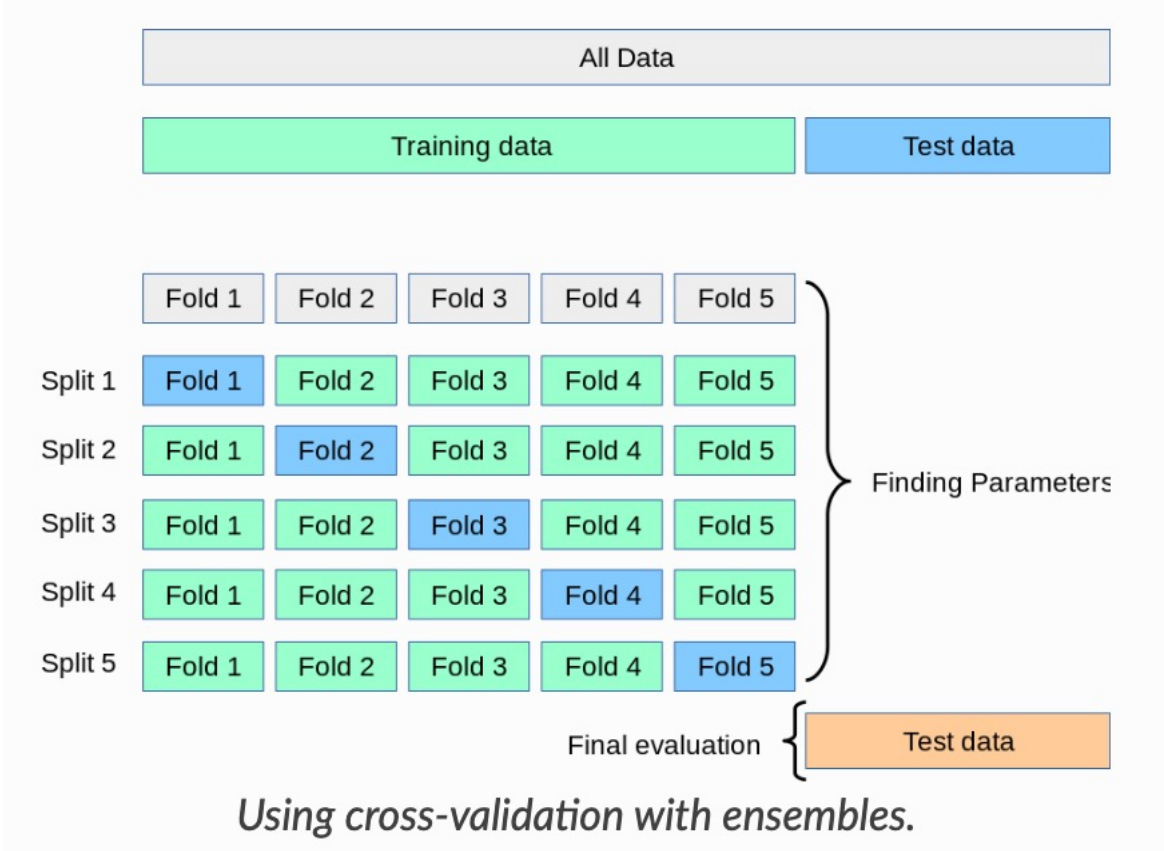
- **Input variables and their ranking for the XGBoost classifier**

Particle	Parameter	XGBoost ranking Run 1	XGBoost ranking Run 2
B^+	p_{T}	11	12
	p_{z}	16	16
	$\cos\theta_{\text{dir. own PV}}$	1	18
	$\chi^2_{\text{flight w.r.t. own PV}}$	14	13
	$(\chi^2/\mathrm{NDF})_{\text{end vertex}}$	9	5
	$\chi^2_{\text{IP w.r.t. own PV}}$	2	1
	DOCA	5	2
D^-	$\cos\theta_{\text{dir. own PV}}$	15	14
	$\chi^2_{\text{flight w.r.t. own PV}}$	3	3
	$(\chi^2/\mathrm{NDF})_{\text{end vertex}}$	13	10
	$\chi^2_{\text{IP w.r.t. own PV}}$	17	17
	$\chi^2_{\text{decay time}}$	18	15
	$(\chi^2/\mathrm{NDF})_{\mathrm{PV}}$	19	19
	$\cos\theta_{\text{dir. orig. PV}}$	8	8
	$\chi^2_{\text{flight w.r.t. orig. PV}}$	4	4
D decay products, $K\pi_{\text{low pT}}$	$m^2(K\pi_{\text{low pT}})$	12	11
D decay products, $\pi\pi$	$m^2(\pi\pi)$	10	9
Bachelor K	$\chi^2_{\text{IP w.r.t. own PV}}$	7	6
Bachelor π	$\chi^2_{\text{IP w.r.t. own PV}}$	6	7

K – folding for the MVA

K – folding with 5 folds

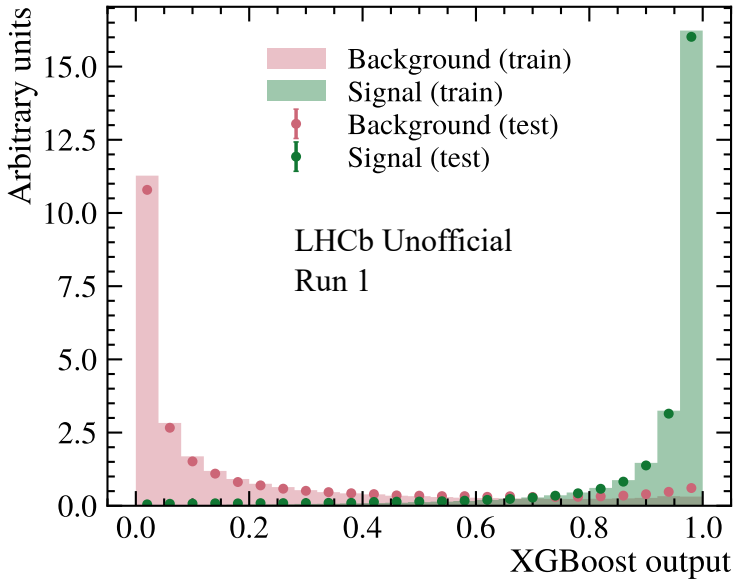
- Data is divided in training set (80 %) and validation set (20 %)
- k – folding is applied on training set (80 %) final BDT response is an average from 5 models => higher accuracy

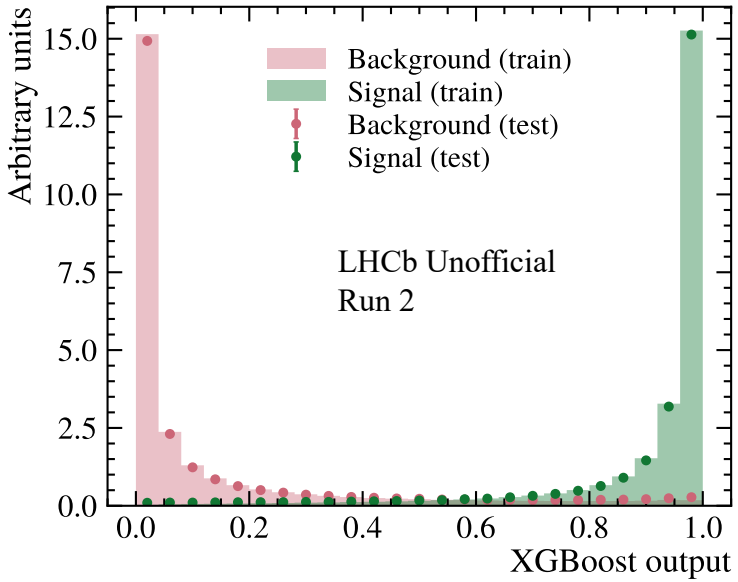


XGBoost performance

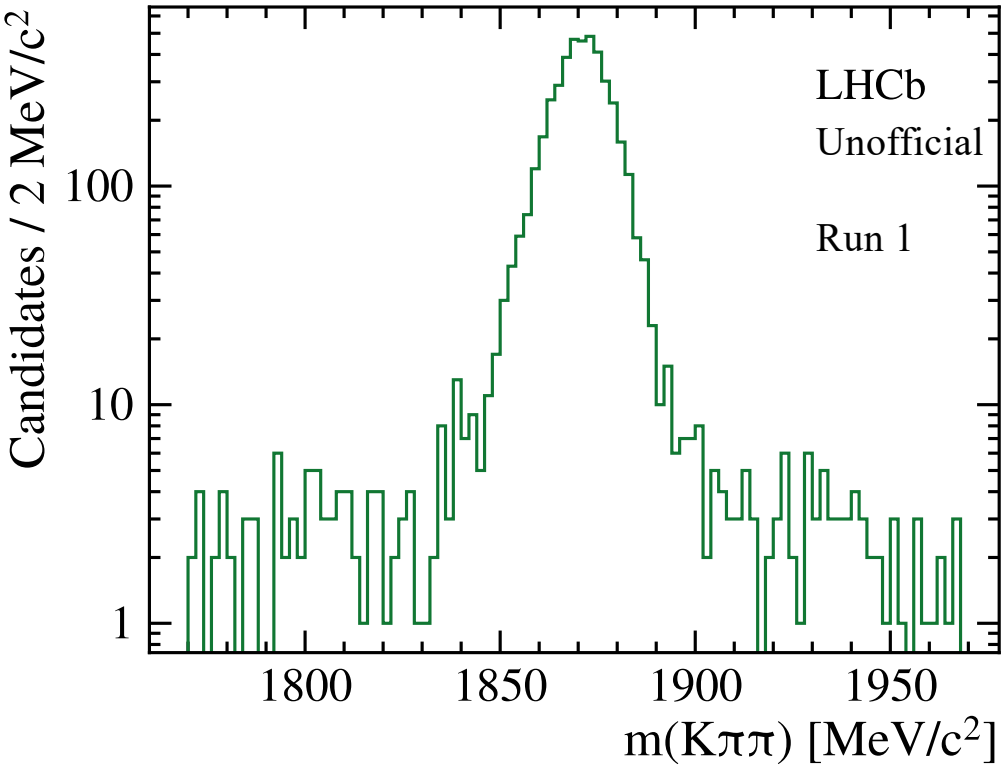
- Accuracy for Run 1 and Run 2 is 94 %
- **No sign of overtraining**

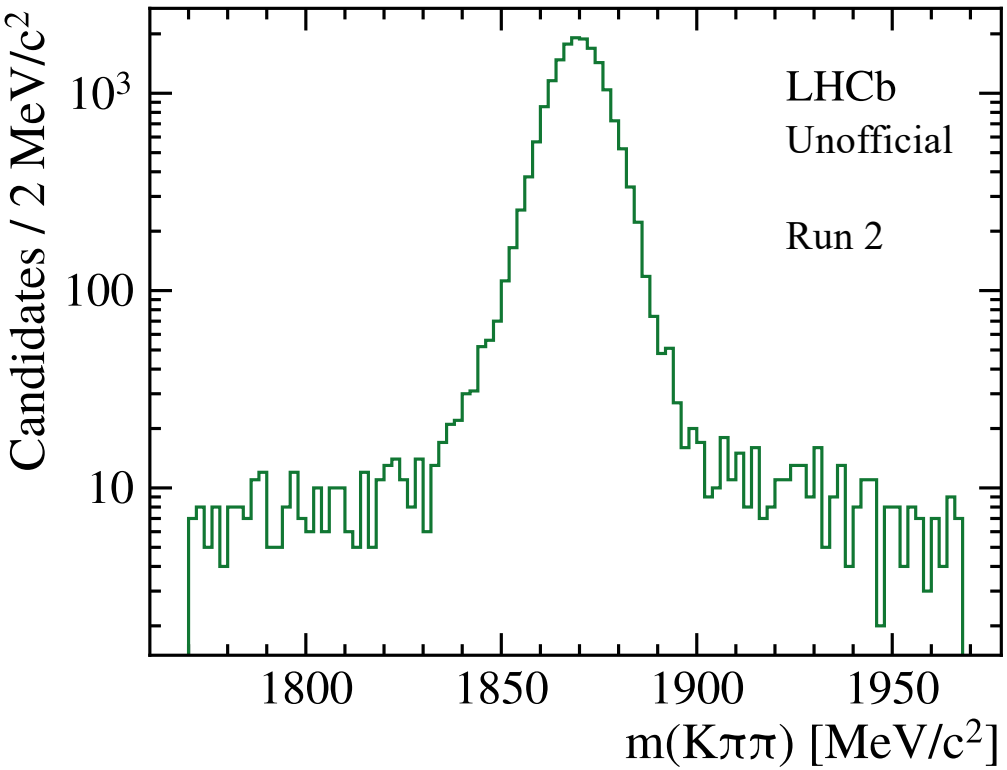
Accuracy: the fraction of number of correctly identified signal entries and total number of signal entries





D meson invariant mass distribution





Signal and Backgrounds

combinatorial background
D meson + random tracks
$B^0 \to D^- K^+$
$B^0 \to D^- \pi^+$

charmless peaking background
Same final state, no D meson
$B^+ \to D^- K^+ \pi^+ K^+ \pi^- \pi^-$

Signal
$B^+ \to D^- K^+ \pi^+$
$\hookrightarrow K^+ \pi^- \pi^-$

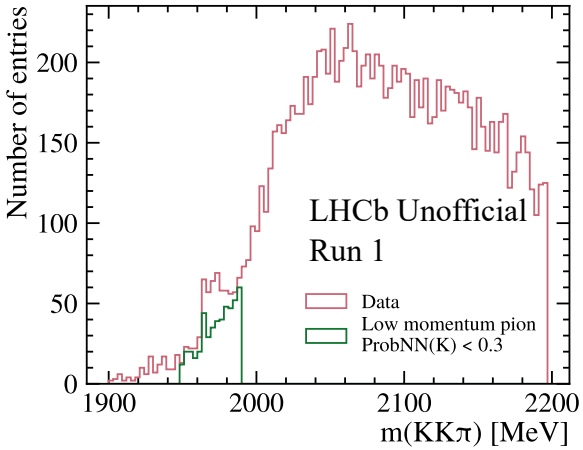
peaking backgrounds
Real D meson +
misidentified particles
$B^+ \to \Lambda_c^- K^+ \pi^+$
$B^+ \to D_s^- K^+ \pi^+$
$B^+ \to D^- \pi^+ \pi^+$
$B^0 \to D^- K^+ \pi^+ \pi^-$
$B^0 \to D^- \pi^+ \pi^+ \pi^-$

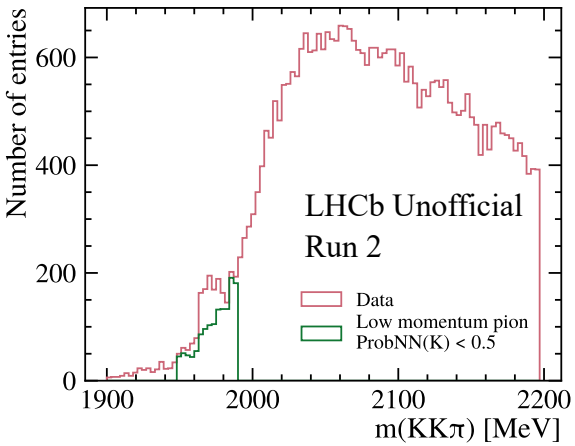
partially reconstructed
D meson + two other tracks
+ additional tracks that are
not reconstructed
$B^+ \to D^{*-} K^+ \pi^+$
$B^+ \to D^{*-} \pi^+ \pi^+$

Vetoes

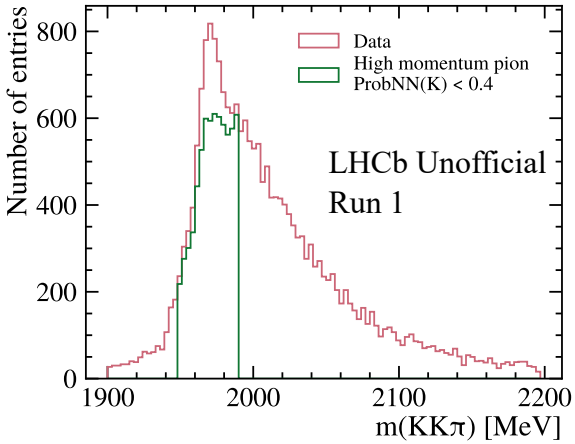
Signal: $B^+ \to D^- K^+ \pi^+$,
where $D^- \to K^+ \pi^- \pi^-$

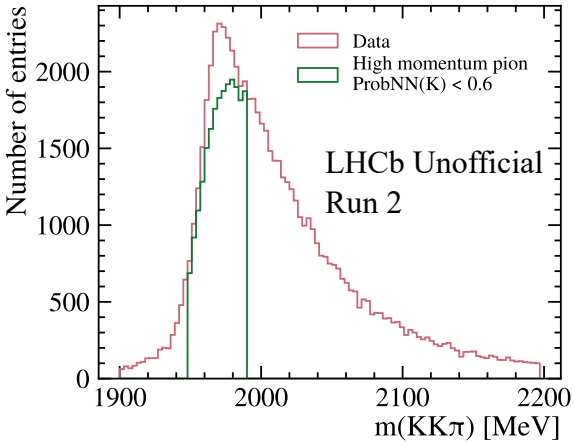
Background: $B^+ \to D_s^- K^+ \pi^+$,
where $D_s^- \to K^+ K^- \pi^-$





The Kaon mass hypothesis is assigned to the low pT pion



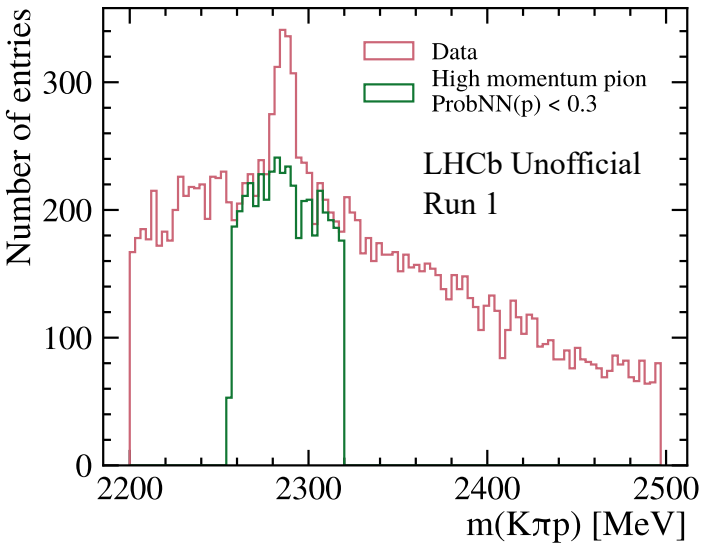


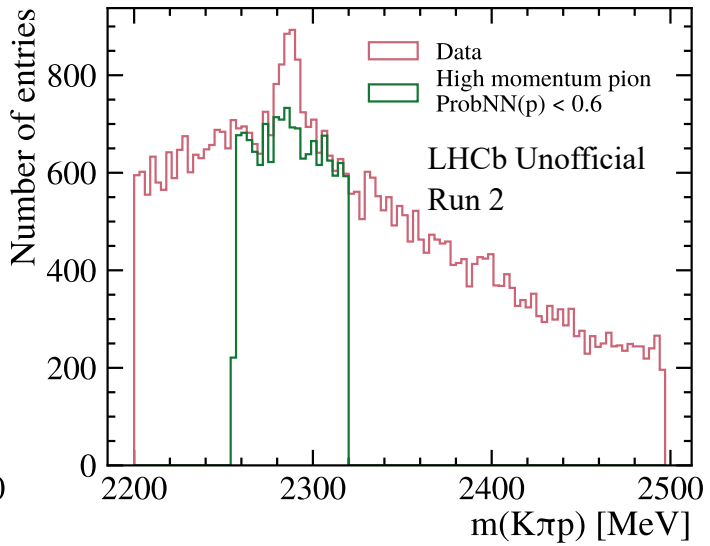
The Kaon mass hypothesis is assigned to the high pT pion

Vetoes

Signal: $B^+ \to D^- K^+ \pi^+$,
where $D^- \to K^+ \pi^- \pi^-$

Background: $B^+ \to \Lambda_c^- K^+ \pi^+$,
where $\Lambda_c^+ \to K^- \pi^+ p$



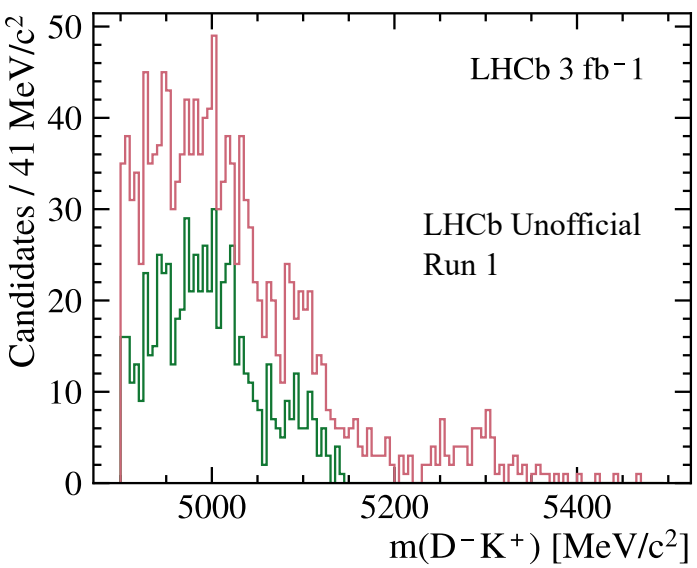


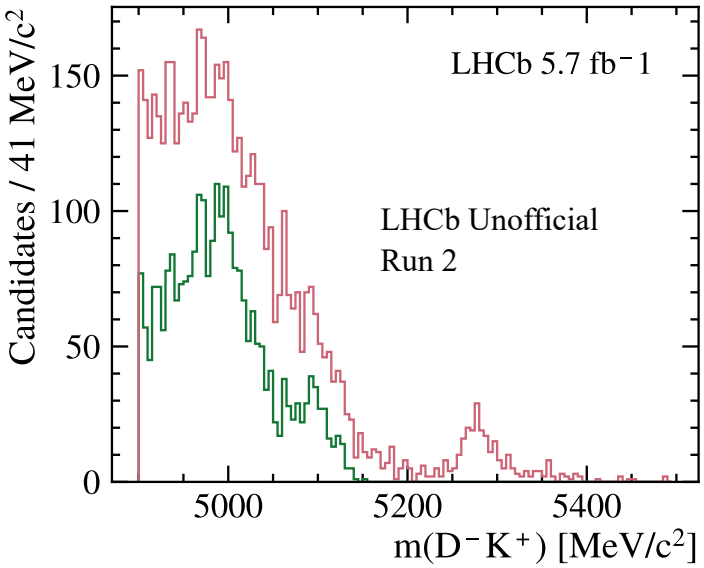
The proton mass hypothesis is assigned to the high pT pion

Vetoes

Signal: $B^+ \to D^- K^+ \pi^+$

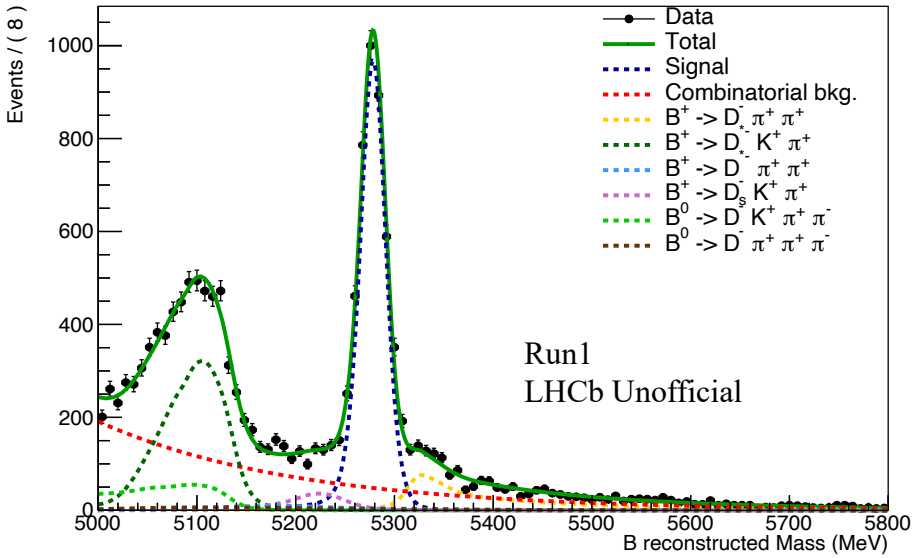
Background:
$B^0 \to D^- K^+$ + a random track





Combination of $D^- K^+$ particles in the $B^+ \to D^- K^+ \pi^+$ full B mass region (pink) and narrow B mass region (green)

Mass fit


Data
Total
Signal
Combinatorial bkg.
B+ -> D- π+ π+
B+ -> D*- K+ π+
B+ -> D- π+ π+
B+ -> Ds- K+ π+
B0 -> D- K+ π+ π-
B0 -> D- π+ π+ π-
Run1
LHCb Unofficial
Events / (8)
B reconstructed Mass (MeV)
0
200
400
600
800
1000
5000
5100
5200
5300
5400
5500
5600
5700
5800