Search for the Doubly Charmed Baryon Ξ_{cc}^{+} in $\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$

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Summary

A preliminary search for the doubly charmed baryon Ξ_{cc}^{+} is performed via the decay channel $\Xi_{cc}^{+} \rightarrow pD^{+}K^{-}$, where the long lifetime of D^{+} can be helpful to improve the sensitivity in search of Ξ_{cc}^{+}. A detailed study on trigger cuts efficiency in Turbo has been carried out and a dedicated Particle identification (PID) correction has been implemented in calibration of Monte-Carlo samples to match the data. The removal of cloned and duplicated candidate events is also applied in the reconstruction procedure to reduce the background. In this study, the lifetime of Ξ_{cc}^{+} is reweighed to 45 fs according to latest theoretical prediction. To better separate signal events from background, the MVA technique is also used in the event-selection, where the best performance is given by BDTF classifier at 0.52 working point optimised by Punzi FoM. All selections and the optimal BDT cut have been applied in the blinded distribution of Ξ_{cc}^{+}, and no fake signal peak has been observed.

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Contents

1 Introduction

The constituent quark model [1–3] has predicted the existence three isospin states of weakly decaying doubly charmed baryons from SU(4) multiples namely $\Xi_{cc}^{++}(ccu)$, $\Xi_{cc}^{+}(ccd)$, and $\Omega_{cc}^{+}(ccs)$, the masses of the two Ξ_{cc} states will not vary much, as stated in the range of 3500 3700 MeV/c^2 [4]. The lifetime of Ξ_{cc}^{+} is predicted to be 3-4 times smaller than that of Ξ_{cc}^{++}, in the range of 50-250 fs and this is because of the Pauli inteference and contribution from W-exchange in the decay of Ξ_{cc}^{++} [4–10].

To find the triplet of the doubly charmed baryon is essential in understanding three-body bound system and hadron interaction in quantum chromodynamics. According to the studies and searches for the doubly charmed baryon over past few decades, the SELEX experiment from Fermilab has reported the detection of Ξ_{cc}^{+} baryon by $\Xi_{cc}^{+} \to pD^{+}K^{-}$ and $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ channels by using a fixed-target experiment with 600GeV charged Hyperon beam $(\Sigma^{-}, \pi^{-}/p, \pi^{+})$. The averaged mass value over the two decay channels was reported to be (3518.7 ± 1.7)MeV/c^2 [11,12]. The lifetime span was reported to be less than 33fs at a 90% confidence level. SELEX also estimated that around 20% of Λ_c^{+} in the experiment was originated from Ξ_{cc}^{+} decays [11].

However, experiments at FOCUS [13], BABAR [14], LHCb [15] and Belle [16] did not confirm results of SELEX. But recent LHCb experiments has detected the Ξ_{cc}^{++} baryon through the $\Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$ final state [4] with significance to be larger than 12σ and it was further confirmed in the $\Xi_c^{+}\pi^{+}$ final state [17]. The data is recorded with the LHCb detector at centre-of-mass energies $\sqrt{s} = 13$TeV and integrated luminosity of 1.7 fb^{-1}. There is 313±13 signal in the signal yield. The averaged mass of Ξ_{cc}^{++} by two decay channels (see Figure 1) was measured as (3621.24 ± 0.65(stat) ± 0.31(syst)) MeV/c^2 [17], 100 MeV/c^2 larger than the mass reported by SELEX. The lifetime span of Ξ_{cc}^{++} measured in LHCb experiment was $(256^{24}_{-22}$(stat) ± 14(syst))fs [18]. The $\Xi_{cc}^{++} \to D^{+}pK^{-}\pi^{+}$ has also been searched by the LHCb collaboration with a data sample corresponding to an integrated luminosity of 1.7 fb^{-1}, but no signal was observed [19].

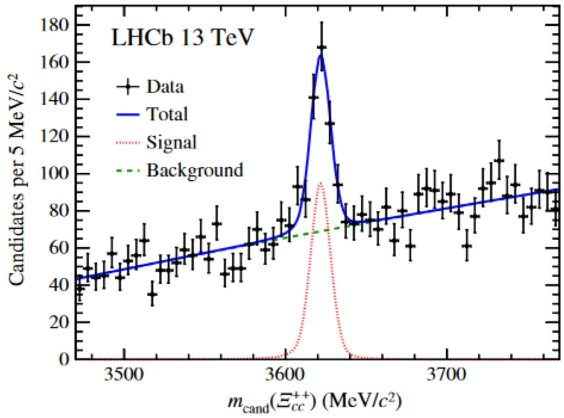

Figure 1: Signal was yielded in the Ξ_{cc}^{++} invariant mass spectrum at LHCb, CERN

The search for Ξ_{cc}^{+} has been performed through $\Xi_{cc}^{+} \to \Lambda_c^{+}(\to pK^-\pi^+)K^-\pi^+$ [20] and $\Xi_{cc}^{+} \to \Xi_c^{+}(\to pK^-\pi^+)\pi^+\pi^-$. In the first decay modes, blind analysis was proceeded within 3.4-3.8GeV signal region with the data corresponding to a total integrated luminosity of 9 fb^{-1}. No significant signal is observed in the region. In the second decay modes, blind analysis was proceeded within 3.3-3.8GeV signal region with the data corresponding to a total integrated luminosity of 5.4 fb^{-1}.

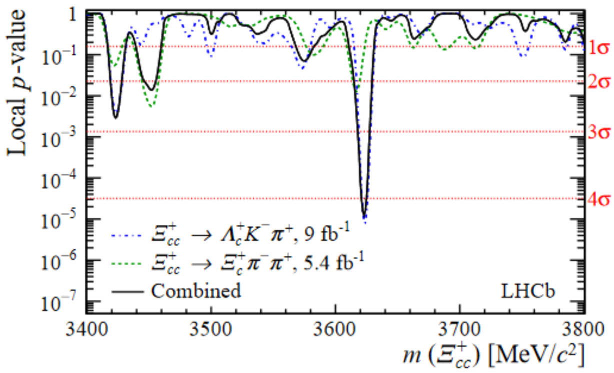

Figure 2: Combined fit improved local significance to 4.2 σ

The best fit of invariant mass was found around 3623.0MeV. But no significant signal was observed. However, the combined fit of $\Lambda_c^{+}K^-\pi^+$ and $\Xi_c^{+}\pi^+\pi^-$ final states could improve the local signiface to 4.2σ.

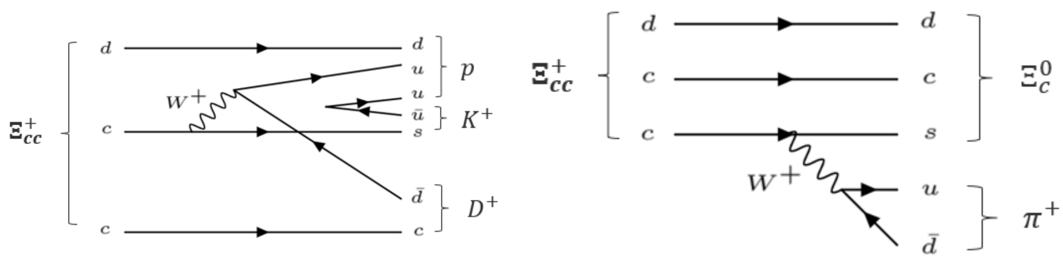

Figure 3: Example of Feynman Diagram of the combination of two decay modes

This paper is motivated by the significance of combined fit and it aims to improve the signal significance in the search for Ξ_{cc}^{+} in a combination of $pD^{+}K^{-}$ and $\Xi_c^0\pi^+$ final states (see Figure 3). Such two featured channels have the advantage that D^+ mesons has long lifetime and the decay mode $\Xi_{cc}^{+} \to \Xi_c^0\pi^+$ is Cabibbo favored.

2 LHCb Detector

The LHCb detector (see Figure 4) is a single-arm forward spectrometer, designed for study of charmed and bottom quarks [21]. The detector has a feature of a high-precision tracking system. It includes a silicon-strip vertex detector surrounding the pp interaction region [22], another silicon-strip detector at the upstream of dipole magnet and three stations of silicon-strip detectors [23] at the downstream of the dipole magnet. The LHCb detector tracking system is able to measure momentum value of charged particles with high precision. The minimum distance between a track to a primary vertex (PV) and the impact parameter (IP), are measured with a resolution of $(15 + 29/p_T)\mu$m, where p_T is the transverse momentum of the beam in GeV/c. The two ring-imaging Cherenkov detectors (RICH1 and RICH2) are capable of particle identification (PID) of particles from various momentum range [24] in order to distinguish different types of charged hadrons. To proceed reconstruction, the online event selection is performed by the trigger [25] composed of a hardware stage first which uses the information from muon systems and calorimeter. Afterthat, the software stage is proceeded which applies the full event reconstruction.

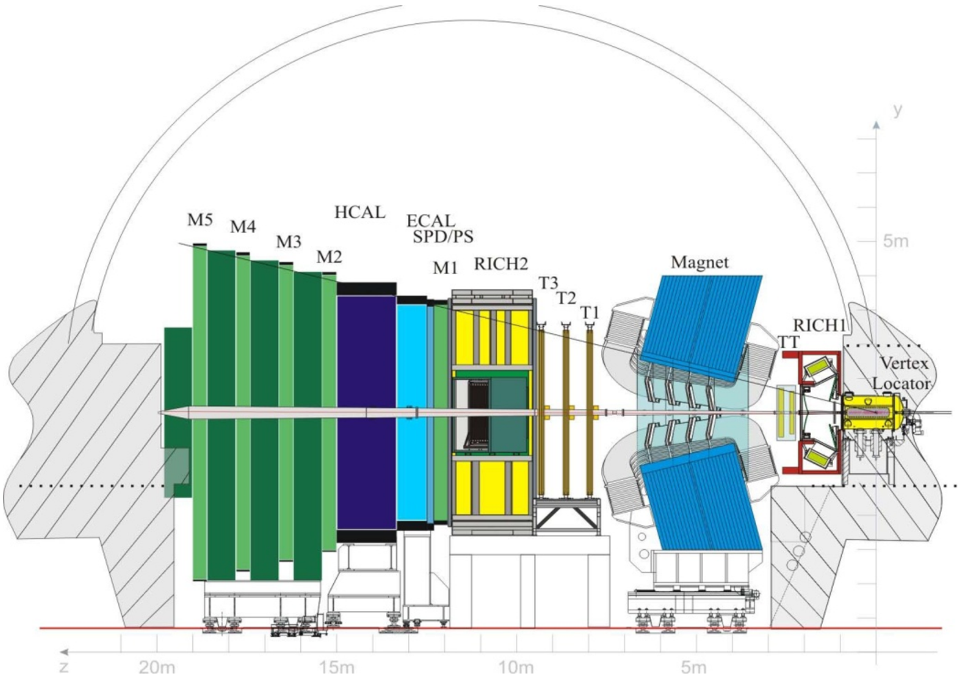

Figure 4: The LHCb detector

3 Triggering and Reconstruction

For the Ξ_{cc}^{+} signal, D^{+} candidates are reconstructed in the $\pi^{+}K^{-}\pi^{+}$ final state. At least one of the three D^{+} child particles is asked to pass the software stage of the trigger which requires the inconsistency between originating from PV and a track with large transverse momentum. The data used in $\Xi_{cc}^{+} \to pD^{+}K^{-}$ has the invariant mass of Ξ_{cc}^{+} after reconstruction to be 3.8-4.0 GeV. The χ^2_{IP} is defined as difference in χ^2 of the PV fit with and without the certain particle and the primary vertex of a single particle is defined as the PV relative to which the particle has the smallest χ^2_{IP}.Particle identification (PID) is required to be imposed upon signal track to suppress combinatorial background and misidentified charm-meson decays.

Before PID correction on PID variable, cuts are removed from MC signal samples. To do the calibration between MC sample and data, 1D correction with PIDGen is performed in order to give better match between signal and data (see Figure 5).

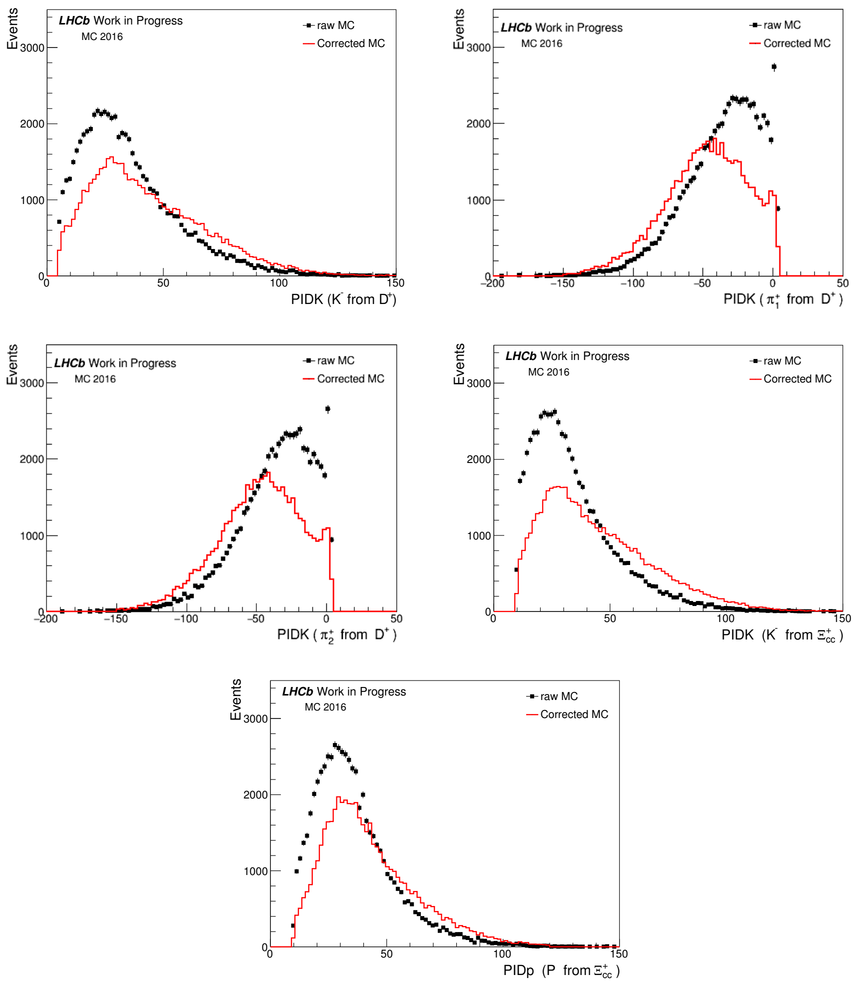

Figure 5: PID variables in signal after correction via PIDGEN

The MC cut should be reimposed after PID correction before training and the turbo line used in this analysis for trigger cut is `Hlt2CharmHadXiccp2DpPpKm_Dp2KmPipPipTurbo` for 2016 data. Only events triggered by the `Hlt2CharmHadXiccp2DpPpKm_Dp2KmPipPipTurbo` are considered in order to evaluate the efficiencies required for those measurements. The requirements for the event to pass the `Hlt2CharmHadXiccp2DpPpKm_Dp2KmPipPipTurbo` selection and their corresponding efficiencies are summarized in Table 1 below, the red color marks the relatively tight cut which will give room for any improvement in Run 3.

The lifetime of Ξ_{cc}^{+} is reweighed from 333 fs to be 45 fs (See Fig.6), according to the theoretical review [26] followed by measurement of lifetime of Ξ_{cc}^{+} and LHCb internal result of $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ [LHCb-PAPER-2021-019, in preparation]. The further optimization on reconstruction will be the removal of cloned and duplicate events in decay tree to remove the multiple candidates that have exactly the same final state tracks, but using them differently. In this analysis, the K^{-} coming from D^{+} decay could be interchangeable with the K^{-} directly pro-

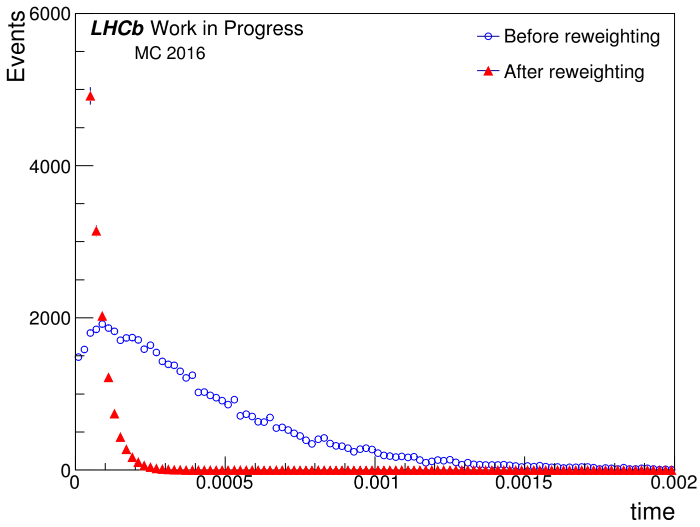

Figure 6: Lifetime of Ξ_{cc}^{+} is reweighed from $\tau_0 = 333$ fs to $\tau = 45$ fs.

Category	Trigger Cut	N$_{events}$	Efficiencies
Daughters of D^+	$DL0GlobalDec == 1$	133925	$(26.15 \pm 0.06)\%$
	$DHlt1PhysDec == 1$	133925	$(100.00 \pm 0.00)\%$
	$K\ p_T > 200.0$ MeV/c	46845	$(99.99 \pm 0.00)\%$
	$\pi_1\ p_T > 200.0$ MeV/c	46187	$(98.60 \pm 0.05)\%$
	$\pi_2\ p_T > 200.0$ MeV/c	45564	$(98.65 \pm 0.05)\%$
	$K\ \chi^2_{\rm IP}$ to PV > 4.0	44675	$(98.05 \pm 0.06)\%$
	$\pi_1\ \chi^2_{\rm IP}$ to PV > 4.0	43406	$(97.16 \pm 0.08)\%$
	$\pi_2\ \chi^2_{\rm IP}$ to PV > 4.0	42243	$(97.32 \pm 0.08)\%$
	K DLL$_{K\pi} > 5$	38353	$(90.79 \pm 0.14)\%$
	π_1 DLL$_{K\pi} < 5$	36669	$(95.61 \pm 0.10)\%$
	π_2 DLL$_{K\pi} < 5$	35041	$(95.56 \pm 0.11)\%$
D^+	$D^+\ \chi^2_{\rm vtx}/ndf < 6.0$	32961	$(94.06 \pm 0.13)\%$
	$DIRA > cos(0.01)$	32955	$(99.98 \pm 0.01)\%$
	Invariant mass $\in$ (1779.0, 1959.0) MeV/c^2	32622	$(98.99 \pm 0.06)\%$
	Sum of D^+ daughters p_T ¿ 3000.0 MeV/c	25746	$(78.92 \pm 0.23)\%$
	At least one of daughter particles p_T ¿ 1000.0 MeV/c	25746	$(100.00 \pm 0.00)\%$
	At least two of daughter particles p_T ¿ 400.0 MeV/c	25718	$(99.89 \pm 0.02)\%$
	At least one of daughter particles $\chi^2_{\rm IP}$ to PV > 50.0	24326	$(94.59 \pm 0.14)\%$
	At least two of daughter particles $\chi^2_{\rm IP}$ to PV > 10.0	24212	$(99.53 \pm 0.04)\%$
Daughters of Ξ_{cc}^{+}	K DLL$_{K\pi} > 10$	20273	$(83.73 \pm 0.24)\%$
	P DLL$_{p\pi} > 10$	18802	$(92.74 \pm 0.18)\%$
Ξ_{cc}^{+}	$\Xi_{cc}^{+}\ \chi^2_{\rm vtx}/ndf < 30.0$	18595	$(98.90 \pm 0.08)\%$
	$DIRA > cos(1.57079632679)$	16390	$(88.14 \pm 0.24)\%$
	Invariant mass $\in$ (3100.0, 4000.0) MeV/c^2	16388	$(99.99 \pm 0.01)\%$
	Sum of D^+, p, K $p_T > 2000.0$ MeV/c	16388	$(100.00 \pm 0.00)\%$

Table 1: HLT2 trigger requirements for the `Hlt2CharmHadXiccp2DpPpKm_Dp2KmPipPipTurbo` line used in this analysis

duced from Ξ_{cc}^{+}, and therefore they are referred as track-exchange candidates. By removing cloned and duplicate events in our blinded region where signal is removed in the range of 3.5-3.7 GeV and the invariant mass of Ξ_{cc}^{+} is to be reconstructed within this region. With the principle of keeping as many signals as possible, the mass window of D^{+} candidates ranges from 1845 to 1890 GeV/c^2. The mis-ID background is expected to be small for signal events due to small for signal events due to tight PID cuts and D^{+} mass window (only relevant for the case of misID involving D decay tracks) and the misID background is not peaking around signals in this case. Since candidates have different probability to be selected by selections, the implementation of cloned and multiple removal is proceeded at the end selection process. The number of entries and removal of clone and duplicate candidates in Run 2 data is shown in Table 2

Entries before removal	Clone removal	Duplicate removal	Portion after removal
1949420	(-293052) 1656368	(-1218) 1655150	84.9%

Table 2: Number of entries and removal of clone and duplicate candidates in Run 2 data

4 MVA Based Selection

To further suppress combinatorial background and to get a higher signal purity essential for a signal observation, an MVA based selection procedure is developed using the TMVA package. In this analysis, the lifetime-reweighed and PID corrected MC samples were used as a signal proxy. The background used was represented by sideband in which wrong sign minus combinations ($pD^{+}K^{-}$) within the mass region of [3800,4000] MeV/c^2. Only candidates from the exclusive HLT2 trigger which fulfil the trigger requirements for the line mentioned in Section.3 were used for the MVA training. The input variables according to their categories, name and number is shown in the Table 3 Both signal and background samples are randomly divided into two subsamples to use one of them as a training sample (1/2 of the sample) and the second one as a testing one (1/2 of the sample) in the MVA selection. The number of signal events used in the MVA training and testing is 62k and the number of WSM background events $1.5M$. The combination of the input variable sets for the MVA training were tested and ranked according to their discriminating power. Table 4 shows a list of the top 10 variables among 26 input variables which have the variable importance ranked from high to low. The distribution of the variables used in the MVA training for the signal and background are shown in Fig.7

Category	Variable	Number
Fit Quality	$\chi^2_{\rm vtx}$/ndf of the Ξ_{cc}^+ vertex fit	1
	$\chi^2_{\rm vtx}$/ndf of the D^+ vertex fit	1
Topology	$\cos^{-1}$ (DIRA) of Ξ_{cc}^+ to PV	1
	Square root sized flight distance χ^2 of D^+ to PV	1
	Square root sized flight distance χ^2 of Ξ_{cc}^+ to PV	1
	Square root sized $\chi^2_{\rm IP}$ of Ξ_{cc}^+ to PV	1
	Square root sized $\chi^2_{\rm IP}$ of D^+ to PV	1
	Square root sized $\chi^2_{\rm IP}$ of daughters of D^+ to PV	3
	Square root sized $\chi^2_{\rm IP}$ of daughters of Ξ_{cc}^+ to PV	2
	Square root sized sum of $\chi^2_{\rm IP}$ of daughters of Ξ_{cc}^+ and D^+ to PV	1
Kinematics	Log sized p_T of Ξ_{cc}^+, D^+ and daughters of them	7
	Log sized sum of p_T of daughters of Ξ_{cc}^+ and D^+	1
Particle Identification	Kaon particle ID Delta-LL$_{K\pi}$	2
	Pion particle ID Delta-LL$_{K\pi}$	2
	Proton particle ID Delta-LL$_{p\pi}$	1
Total		26

Table 3: 26 input variables used in the MVA selection for $\Xi_{cc}^+ \to pD^+K^-$ channel in the o.

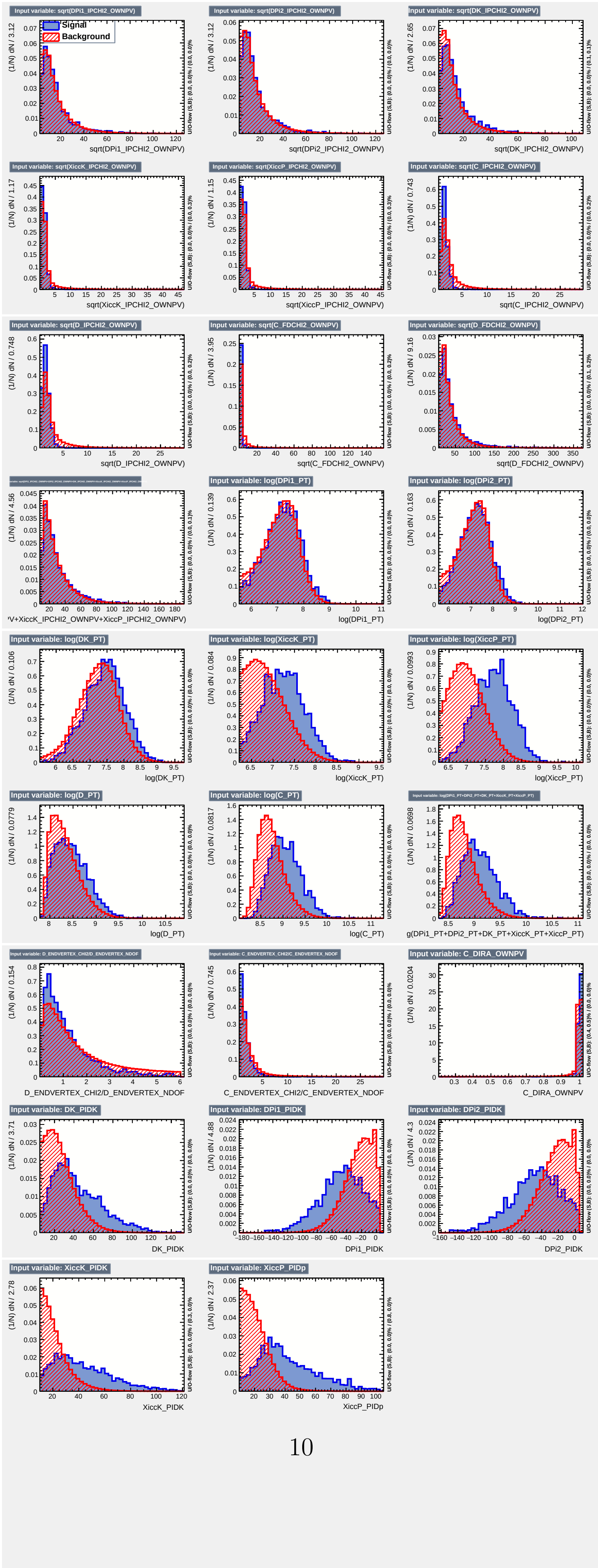

Figure 7: Distributions of the final set of 26 variable used in the MVA for signal (blue area)

Varible	Variable Importance
$\log(\Xi_{cc}^{+}$ daughters $p_T)$	0.212
$\log(\Xi_{cc}^{+}\ p_T)$	0.209
π_2 DLL$_{K\pi}$	0.0719
proton DLL$_{p\pi}$	0.0656
$\log(D^{+}\ p_T)$	0.0610
K(Ξ_{cc}^{+}) DLL$_{K\pi}$	0.0562
K(D^{+}) DLL$_{K\pi}$	0.0445
π_1 DLL$_{K\pi}$	0.0440
log(proton p_T)	0.0361
$\log(\pi_1\ p_T)$	0.0341

Table 4: List of first 10 variables used in the MVA selection for $\Xi_{cc}^{+} \to pD^{+}K^{-}$ channel in the order of their variable importance.

MVA method	ROC area
BDTF	0.994
BDTD	0.991
BDTG	0.991
BDT	0.991
BDTB	0.909

Table 5: Area under the ROC curve for different MVA classifiers.

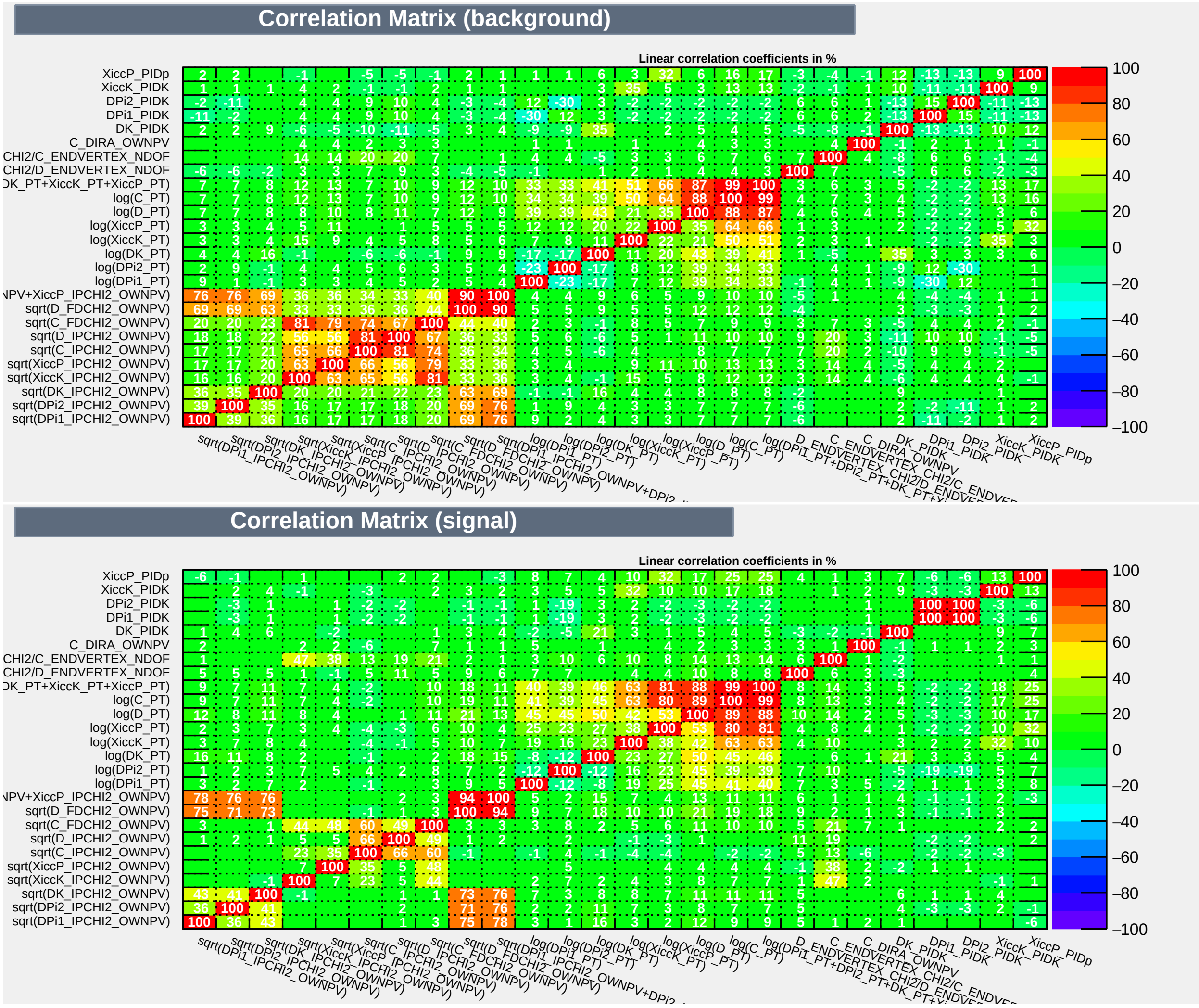

Figure 8: Correlation matrix for the MVA variables for the background and the signal used in this analysis.

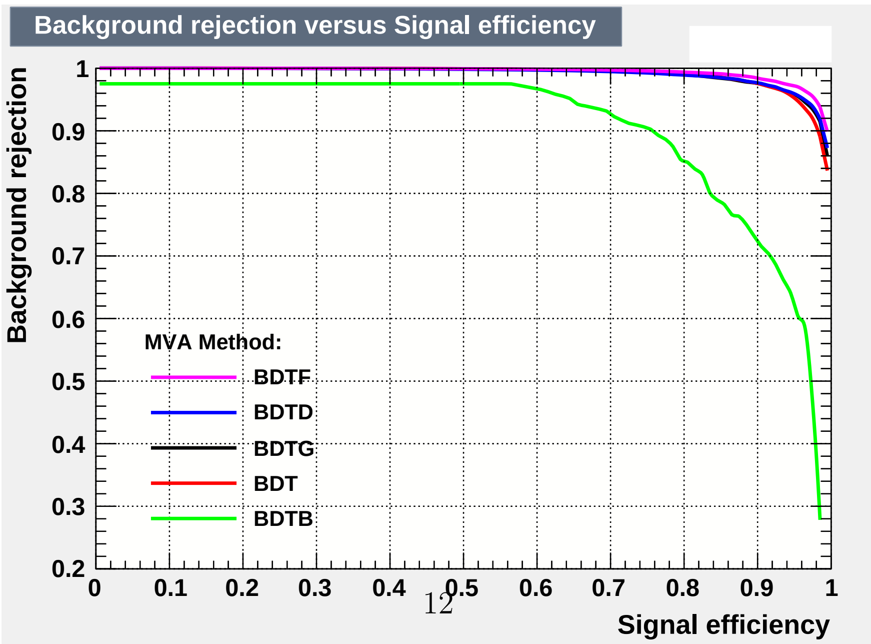

Figure 9: ROC curve for tested MVA classifiers.

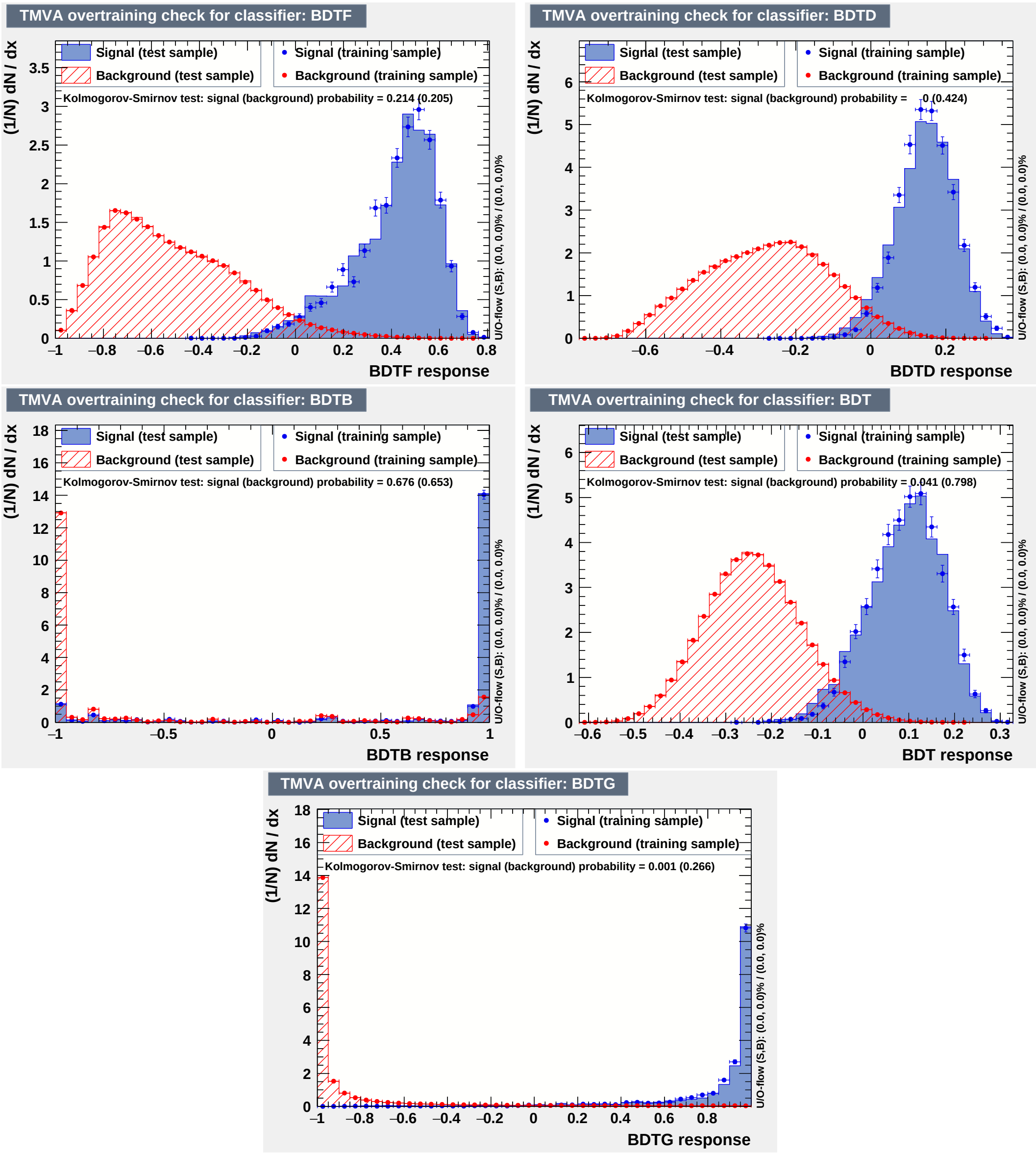

Figure 10: Overtraining plots for five BDT algorithms.

Several different MVA classification algorithms of Boosted Decision Tree (BDT) including BDT, BDTG, BDTD, BDTB and BDTF were compared for the purpose of this analysis. The Correlation matrices for the combination of input variables are shown in Fig.8. Overtraining checks for all used classifiers are shown in Fig.10.Cut efficiencies and optimal cut value of different BDT methods are showed in Fig.**??**. Performance of different BDT model can be compared based on a receiver operating characteristic (ROC) curve, which tells the classifier background rejection against signal efficiency at response thresholds. Table 5 shows the area under the ROC curve for five tested BDT classifiers. Figure 9 shows the ROC curve for different BDT methods. Among all the used methods, BDTF has the best performance.

The weights used in BDTF is used in the evaluation of the Punzi figure of merit (FoM) which is particularly useful for the optimization of processes in which the expected number of signal events is a priori unknown. The Punzi FoM in this analysis is used to determine the optimal working point for classification algorithms based on the equation

$$FoM = \frac{\epsilon(t)}{a/2 + \sqrt{B(t)}}, \tag{1}$$

where $\epsilon(t)$ is the signal efficiency, $B(t)$ is the expected number of background events under the Ξ_{cc}^{+} mass peak for a given cut t and $a = 5$ indicates a target significance level (5σ in this analysis). The optimal working point is found to be 0.52 and the peak of FoM is shown in Fig.11.

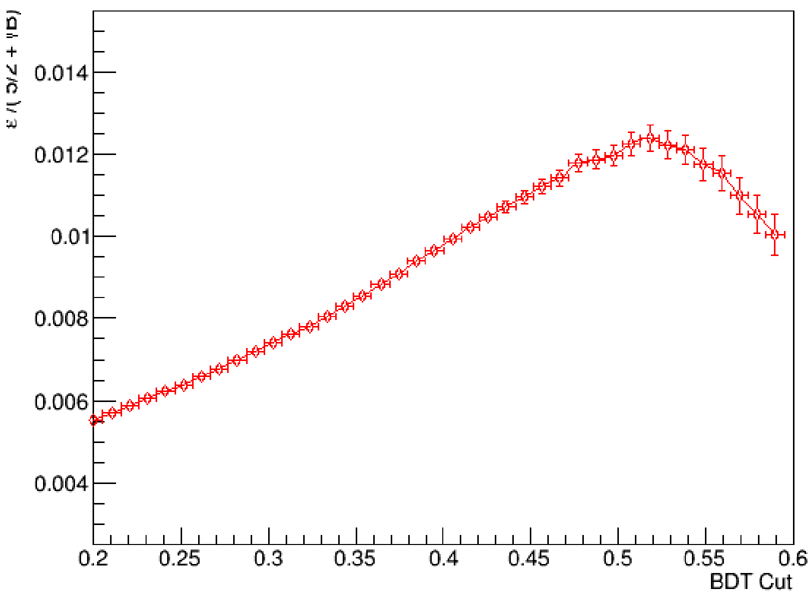

Figure 11: The optimal working point for classification method (BDTF in this analysis).

To study the background distributions in a blinded manner, Right-sign data from 2016-2018 is used. The clone and duplicate candidates are removed and the optimal BDTF cut is imposed and a clean D^{+} signal could be seen in Fig. 12. Moreover, after applying all the selection and optimal BDT cut, the wrong-sign data is drawn together within [3200, 4000] MeV/c^2 region in comparison with the right-sign data (See Fig. 13). According to the ratio of number of events of RS to WS within [3800, 4000] MeV/c^2 region, the scaling factor of WS to RS is determined to be 1.32. The consistency in the graph indicates that the event selection does not actually cause fake signal peak

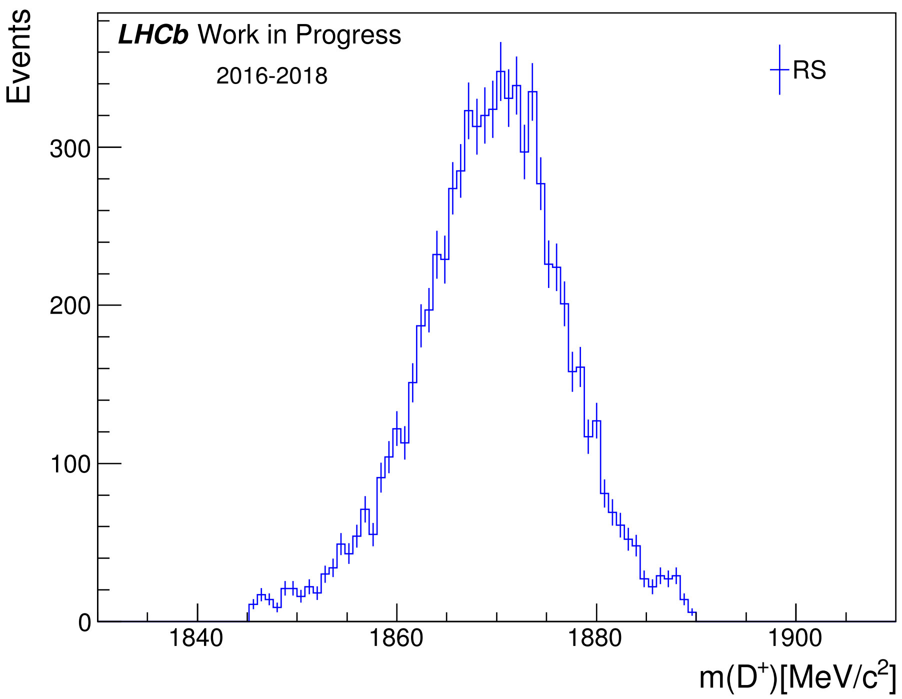

Figure 12: The signal of D^+ in 2016-2018 Right-sign sample.

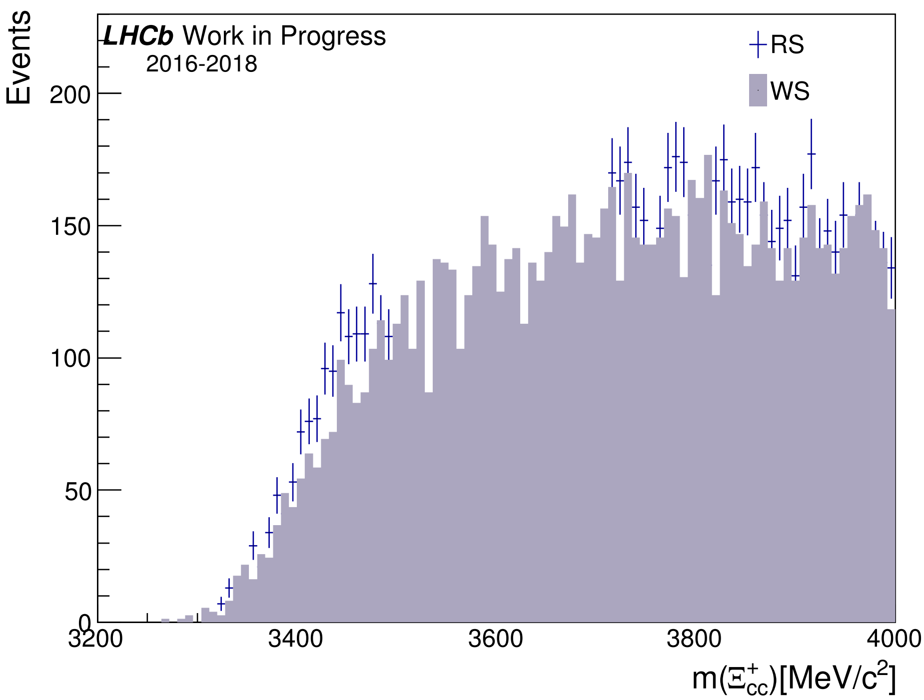

Figure 13: Blinded Ξ_{cc}^{+} after applying all selection and optimal BDT cut (both WS and RS).

5 Conclusion

In this project a preliminary study on search for $\Xi_{cc}^{+} \to D^{+}pK^{-}$ is performed. we have studied on the optimization of decay channel with respect of reconstruction and selection. The efficiency of Turbo cuts are also studied. We have done PID correction by PIDGen on the Monte Carlo signal sample in order to calibrate the signal to better fit with the data. When applying the calibration on PID variables, cuts are removed and we will add the cuts according to trigger requirements before proceeding to TMVA training. The lifetime of Ξ_{cc}^{+} is reweighed to 45 fs with the reference of theoretical revision.

The PID-corrected MC signal samples with lifetime reweighing are trained and tested by 1:1 ratio in TMVA package. We have used five classifiers (BDT, BDTB, BDTD, BDTF, BDTG). Among five TMVA-based classifiers, BDTF has the best performance and we add its weights to events in signal and data in order to determine optimal BDT working point and the Punzi figure of merit which could essentially contribute to effectively suppress the background and improve the significance.

On the completion of TMVA, we proceeded to a further optimization of the reconstruction of invariant mass of Ξ_{cc}^{+}. We have done the blinded analysis on the background with the blinded region from 3.5-3.7 GeV. By removal of cloned trees and multiple events, the data could be further purified when applied to fitting between signal and events and statistical analysis later. Also, we have studied the background distributions in a blinded manner by imposing all the selection and optimal BDT cut. In future, we will continue to study efficiencies and systematic uncertainties, followed by unblinding the distribution. As aforementioned in the introduction part, the combined search of two new channels with $pD^{+}K^{-}$ and $\Xi_{c}^{0}\pi^{+}$ final states and published $\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}, \Xi_{c}^{+}\pi^{+}\pi^{-}$ will be the main focus on the future search for the doubly charmed baryon Ξ_{cc}^{+}. In the upcoming Run 3 of the LHCb experiments, the instantaneous luminosity increased by a factor of 5 with a fully software trigger. It is very hopefully to find Ξ_{cc}^{+} by the improved detector performance together with larger data samples which constructively help people to understand strong interaction and quark model.

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