Search for the doubly heavy baryons Ω_{bc}^0 and Ξ_{bc}^0 decaying to $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$

Shiyang Li

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Central China Normal University

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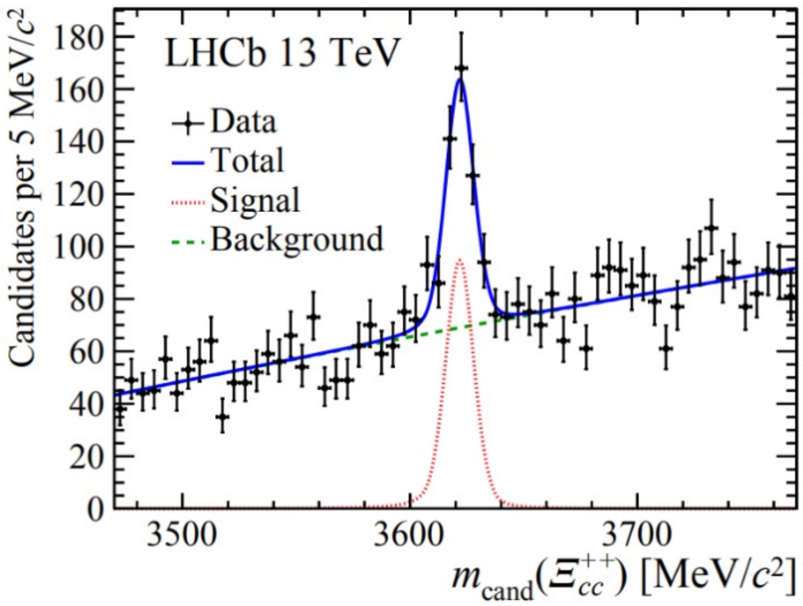
Motivation

- Ξ_{cc}^{++}(ccu): Observed by the LHCb experiment in 2017 using $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$



- To date, no baryons containing one b and one c quark, or two b quarks, have been observed experimentally. An observation would enrich our knowledge of baryon spectroscopy and improve our understanding of the quark structure inside baryons.

LHCb detector

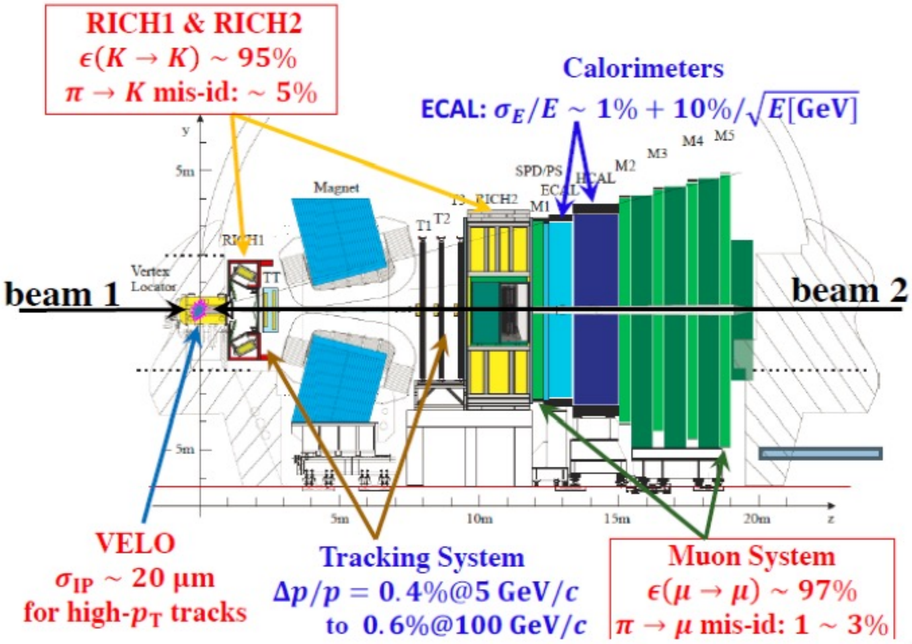
[JINST 3 (2008) S08005]
[Int. J. Mod. Phys. A30(2015) 1530022]

☐ Advantages

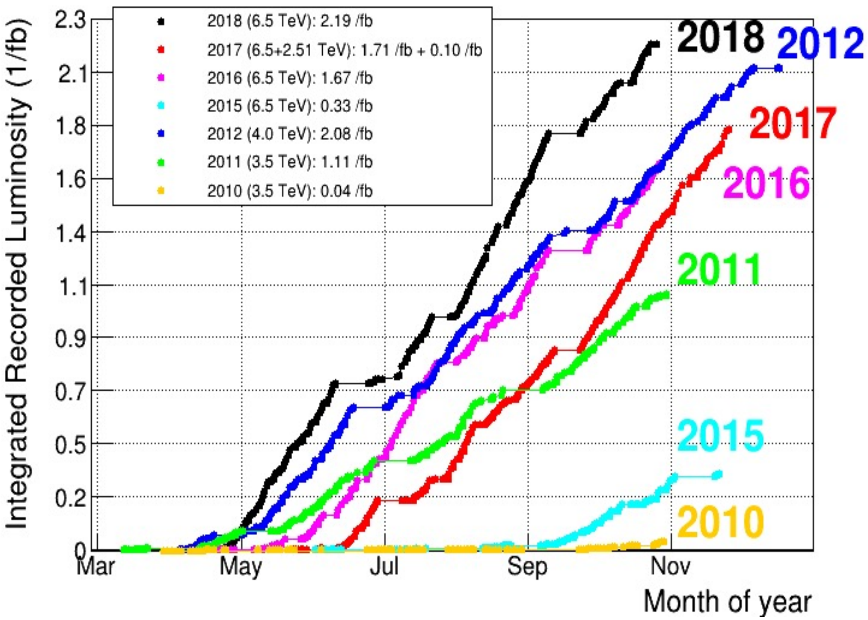
Good particle identification (Muon station & RICHes)

Excellent vertex resolution

Dedicated to precision study of b/c-hadrons



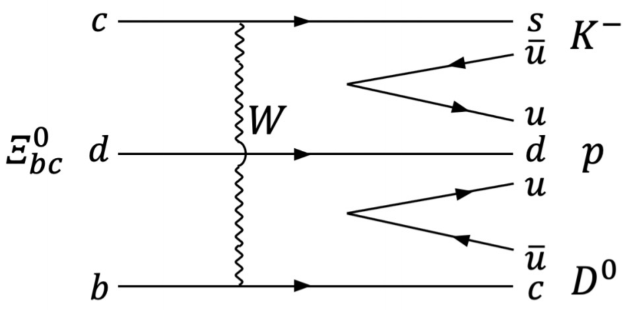
LHCb detector

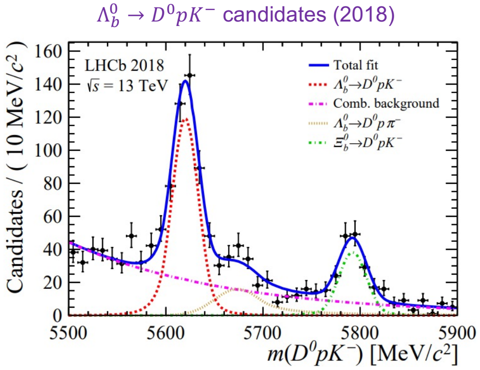


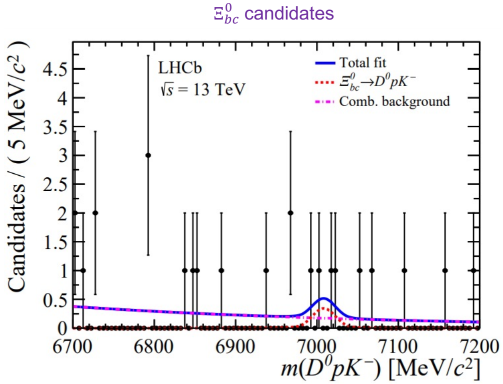
LHCb integrated luminosity

Previous result from LHCb

- First search for $\Xi_{bc}^0 \to D^0 p K^-$ in run2 (2016+2017+2018) data







- Control channel: $\Lambda_b^0 \to D^0 p K^-$ (top-middle)

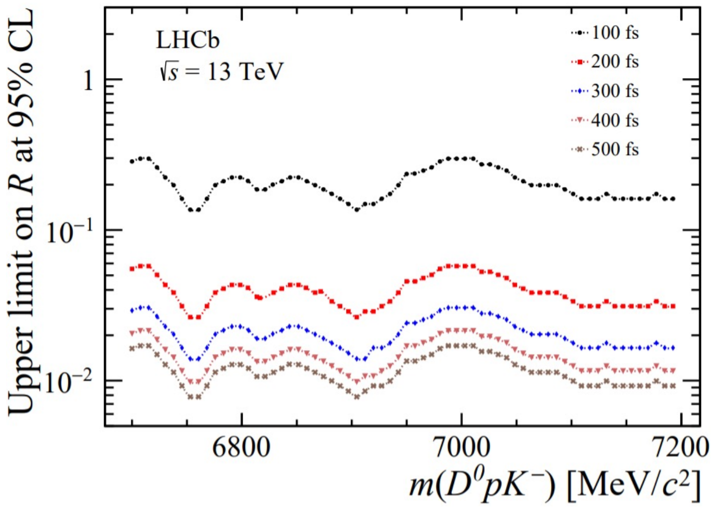
- No $\Xi_{bc}^0 \to D^0 p K^-$ signal (top-right)

- Using CLs method to set upper limits on:

$$\mathcal{R} = \frac{\sigma(\Xi_{bc}^0)\mathcal{B}(\Xi_{bc}^0 \to D^0 p K^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to D^0 p K^-)}$$

Upper limit range: $1.7\times10^{-2} - 3.0\times10^{-1}$ @95% C.L.

fiducial region: 2.0<y<4.5 & 5<p_T<25GeV/c



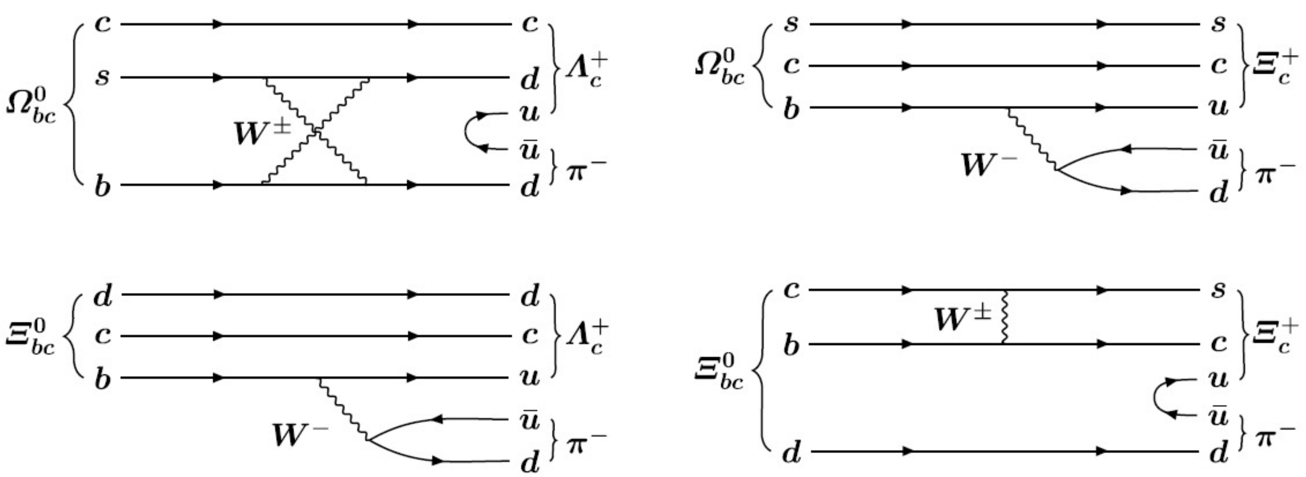
JHEP 11 (2020) 095

Searching for Ω_{bc}^{0} and Ξ_{bc}^{0} in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

- Theory predicts for Ξ_{bc}^{0} and Ω_{bc}^{0}

	Mass	Lifetime	Production cross-section	Branching fractions
Ξ_{bc}^{0}	$[6700,7200]\mathrm{MeV/c^2}$	$0.09-0.28\mathrm{ps}$	$19-39\mathrm{nb}$	$\sim10^{-7}$
Ω_{bc}^{0}	about 100 MeV heavier than Ξ_{bc}^{0}	$0.22\mathrm{ps}$	$\sim40\mathrm{nb}$	$\sim10^{-7}$

- Examples Feynman diagram



Searching for Ω_{bc}^{0} and Ξ_{bc}^{0} in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

□ Analysis strategy (Blinded analysis)

- Event selection of $\Xi_{bc}^{0} \to \Lambda_c^+\pi^-$,$\Xi_{bc}^{0} \to \Xi_c^+\pi^-$candidates in run2 (2016+2017+2018) data
- Multivariate selector to suppress combinatorial background

  Simulation as signal, data upper sideband as background

- Open signal window
  - ✓ $> 3\sigma$ signal: mass measurement
  - ✓ Otherwise: set upper limit on the BR

Searching for Ω_{bc}^0 and Ξ_{bc}^0 in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

☐ Event selection

- Pre-selection
  - Tracks:
    - good quality, inconsistent with originating from any PV in the event
  - Vertex:
    - The tracks must also form a common vertex of good fit quality
  - $\Lambda_c^+(\Xi_c^+)$ mass windows:
    - The $\Lambda_c^+(\Xi_c^+)$ candidate is required to have an invariant mass in the range 2271–2301 $\mathrm{MeV/c^2}$ (2450 –2488 $\mathrm{MeV/c^2}$),
    - corresponding to approximately six times the $\Lambda_c^+(\Xi_c^+)$ mass resolution, and to be inconsistent with originating from any PV

- Particle misidentification background

Physics background		Veto mass window
ϕ	K^-K^+	$[1014,1024]\mathrm{MeV/c^2}$
$D^+(D_s^+)$	$K^-\pi^+\pi^+$	$[1869,1875]\mathrm{MeV/c^2}$
	$K^-K^+\pi^+$	$[1860,1874]\mathrm{MeV/c^2}$ and $[1962,1976]\mathrm{MeV/c^2}$

Searching for Ω_{bc}^0 and Ξ_{bc}^0 in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

☐ Multivariate selection(MVA)

- 23 input variables: similar to $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$ analysis, but we add four PID variables(after PID resamping)

23 training variables:

$\sqrt{\chi^2_{IP}}$ of Λ_c^+/Ξ_c^+ daughters (P,K,π) to its PV

log(PT) of Λ_c^+/Ξ_c^+ dauters (P,K,π)

$\sqrt{\chi^2_{IP}}$ of Λ_c^+/Ξ_c^+ to its PV

log(PT) of Λ_c^+/Ξ_c^+

$\sqrt{\chi^2_{FD}}$ of Λ_c^+/Ξ_c^+ from its PV

χ^2_{vtx}/ndf of the Λ_c^+/Ξ_c^+ vertex fit

$\sqrt{\chi^2_{IP}}$ of Ξ_{bc}^0 daughters π to its PV

$\sqrt{\chi^2_{IP}}$ of Ξ_{bc}^0 to its PV $\sqrt{\sum\chi^2_{IP}}$ among the daughters $(P,K,\pi,\ \Lambda_c^+/\Xi_c^+-\pi)$ of Ξ_{bc}^0

log(PT) of Ξ_{bc}^0 daughters

$\cos^{-1}(DIRA)$ of the Ξ_{bc}^0 to its PVπ

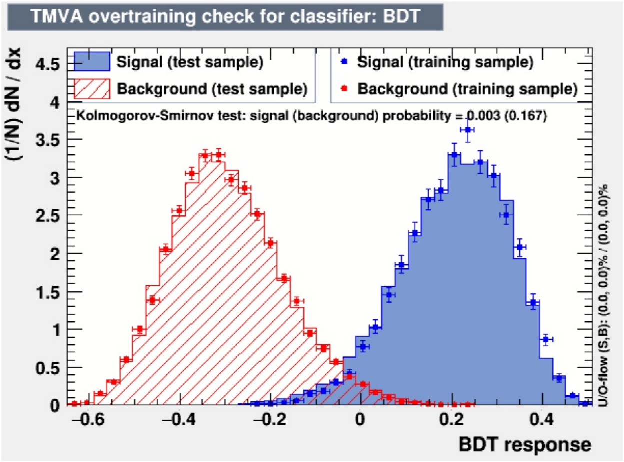
χ^2_{vtx}/ndf of the Ξ_{bc}^0 vertex fit (non-DTF)

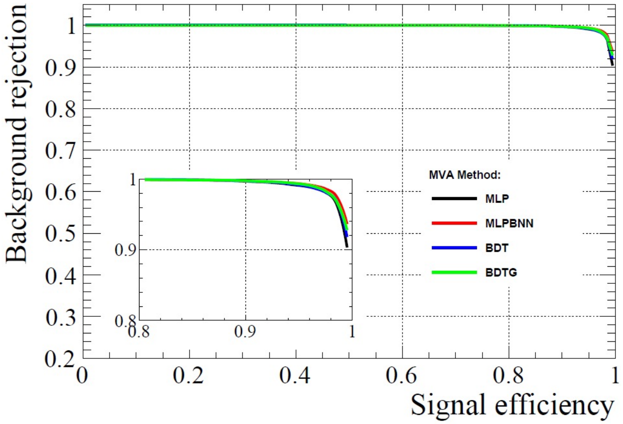
χ^2 of the Ξ_{bc}^0 vertex fit (DTF,with PV constraint)

PID of each final track

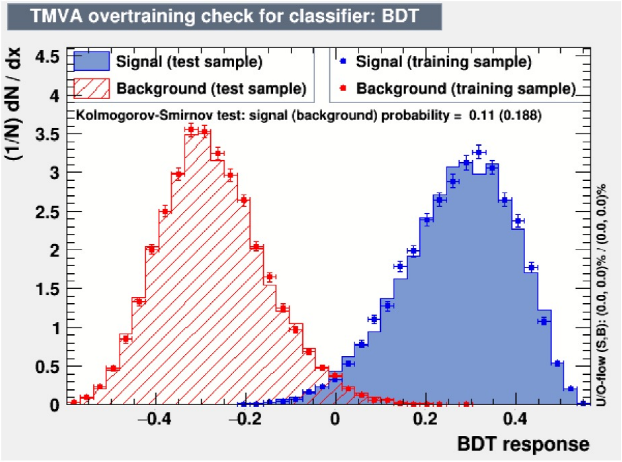
☐ MVA performance

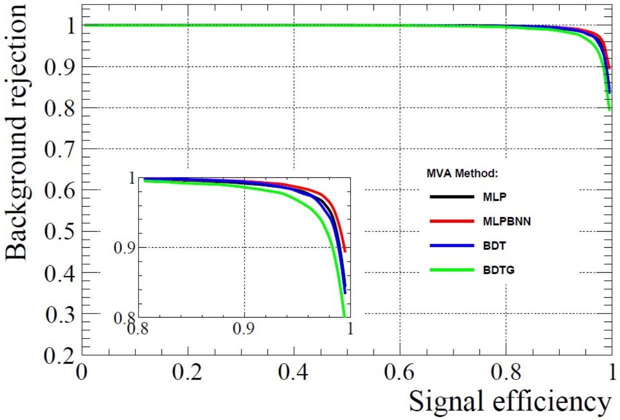
$\Lambda_c^+\pi^-$





$\Xi_c^+\pi^-$





Searching for Ω_{bc}^{0} and Ξ_{bc}^{0} in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

☐ Punzi figure of merit (FoM)

- The FOM is used to quantify the performance of the selectors and to choose a working point
- The FOM is defined as :

$$F(t) \equiv \frac{\varepsilon(t)}{\frac{a}{2} + \sqrt{B(t)}}$$

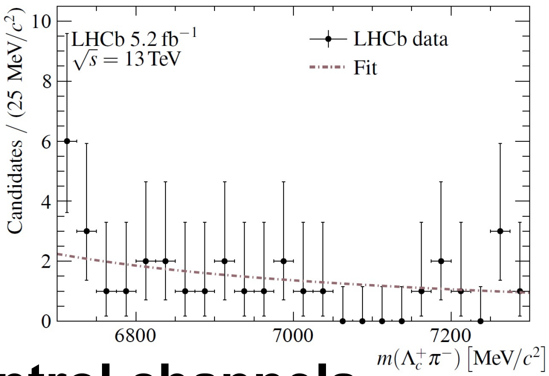
  - ✓ $a = 5$
  - ✓ $\varepsilon(t)$ from signal MC
  - ✓ $\mathrm{B}(t)$ extrapolated from sideband

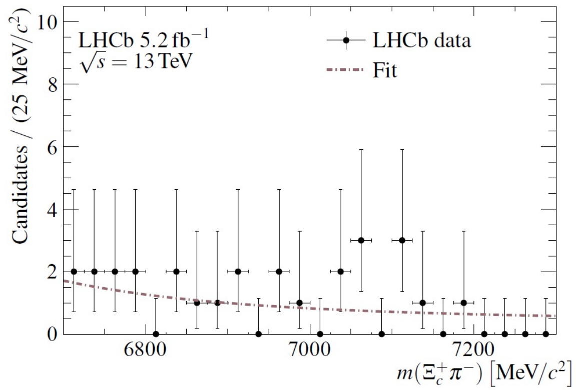
- Optimization results: BDT is the best

	Optimal cut	$\boldsymbol{\varepsilon(t)}$	$\boldsymbol{F(t)}$
$\Lambda_c^+\pi^-$	**0.2370**	**0.46$\pm$0.01**	**0.97$\pm$0.01**
$\Xi_c^+\pi^-$	**0.2760**	**0.52$\pm$0.02**	**0.51$\pm$0.01**

☐ Signal channels

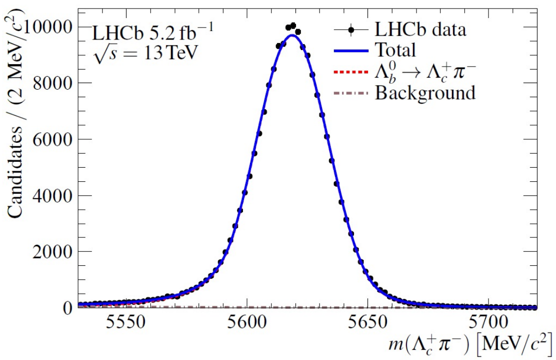
Invariant mass distributions of selected (left) $\Omega_{bc}^0(\Xi_{bc}^0) \to \Lambda_c^+\pi^-$ and (right) $\Omega_{bc}^0(\Xi_{bc}^0) \to \Xi_c^+\pi^-$ candidates with results of the background only fit (blue solid line)



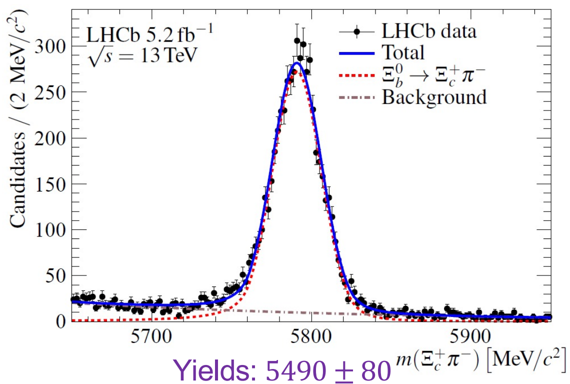


☐ Control channels

Invariant mass distributions of (left) $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$ and (right) $\Xi_b^0 \to \Xi_c^+(\to pK^-\pi^+)\pi^-$ candidates with the fit results overlaid (blue solid line)



Yields: 191000 ± 500



Yields: 5490 ± 80

☐Systematic uncertainty

Fit model: signal: double-sided CB -> Ipatia function
background: double exponential -> first-order polynomial function

Size of simulated samples: track detection efficiency largely cancel, the uncertainty due to limited size of simulation samples

Particle identification efficiency: bins of particle momentum, pseudorapidity, and track multiplicity using control channels in the data

Mass resolution: Ξ_c^+ mass resolution difference between data and simulation.

Simulation model: BDT response correction and the kinematic modeling of the simulated control samples

$\chi^2_{\rm IP}$ simulation: mismatch between the data and simulation, studied in the previous $\Xi_{bc}^0 \to D^0 pK^-$ analysis to be 5%.

	$H_{bc}^0 \to \Lambda_c^+\pi^-$	$H_{bc}^0 \to \Xi_c^+\pi^-$
Fit model	0.1%	0.9%
Size of simulated samples	1.6%	0.7%
Particle identification efficiency	1.7%	2.1%
Mass resolution	<0.1%	0.2%
Simulation model	1.6%	3.0%
$\chi^2_{\rm IP}$ simulation	5.0%	5.0%
Total	5.7%	6.3%

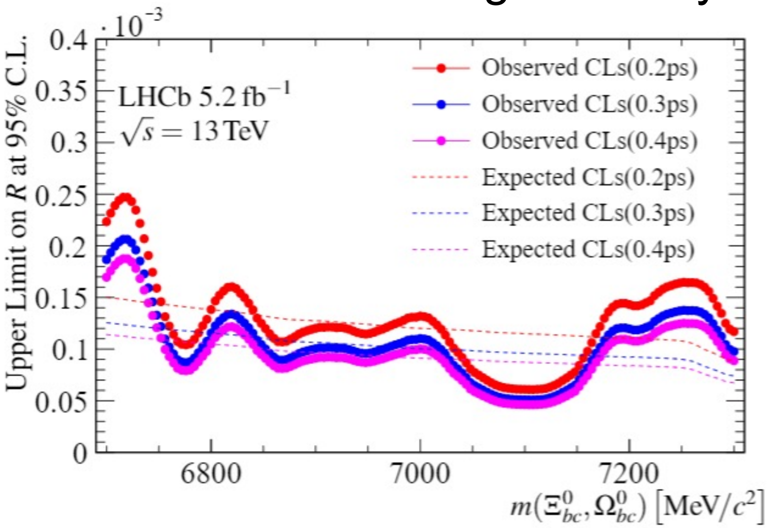
Searching for Ω_{bc}^0 and Ξ_{bc}^0 in $\Lambda_c^+\pi^-$ and $\Xi_c^+\pi^-$ decays

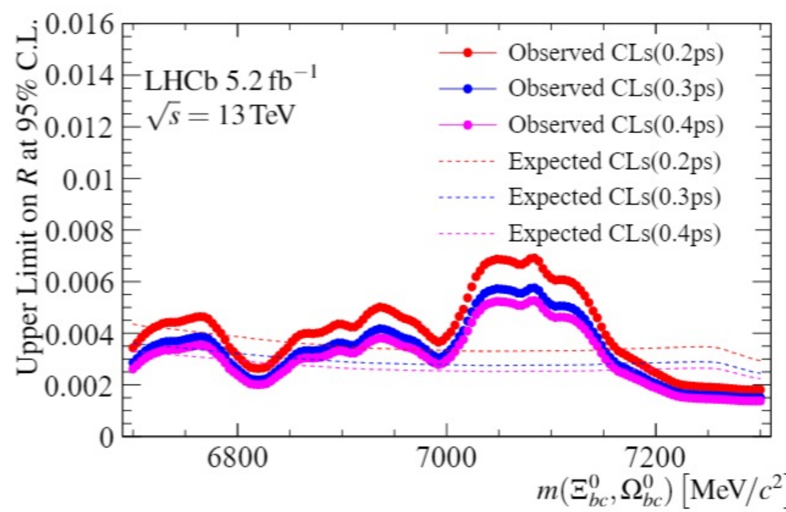
□Result

- The first search for the doubly heavy Ω_{bc}^0 baryon
- No Ω_{bc}^0 and Ξ_{bc}^0 signal in run2(2016+2017+2018) data
- Using CLs method to set upper limits on:

$$\mathcal{R}(\Lambda_c^+\pi^-) = \frac{\sigma(pp \to H_{bc}^0 X)\mathcal{B}(H_{bc}^0 \to \Lambda_c^+\pi^-)}{\sigma(pp \to \Lambda_b^0 X)\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \qquad \mathcal{R}(\Xi_c^+\pi^-) = \frac{\sigma(pp \to H_{bc}^0 X)\mathcal{B}(H_{bc}^0 \to \Xi_c^+\pi^-)}{\sigma(pp \to \Xi_b^0 X)\mathcal{B}(\Xi_b^0 \to \Xi_c^+\pi^-)}$$

fiducial region: 2.0<y<4.5 & 2<p_T<20 GeV/c





Upper limit range: $0.5\times10^{-4} - 2.5\times10^{-4}$ [$\mathcal{R}(\Lambda_c^+\pi^-)$]
$1.4\times10^{-3} - 6.9\times10^{-3}$ [$\mathcal{R}(\Xi_c^+\pi^-)$] @95% C.L.

[CHIN. PHYS. C 45 093002]

Summary

- The first search for the doubly heavy baryon Ω_{bc}^{0} and a search for the baryon Ξ_{bc}^{0} decaying to $\Lambda_{c}^{+}\pi^{-}$ and $\Xi_{c}^{+}\pi^{-}$ in run2 (2016+2017+2018) data
  - No signal
  - Using CLs method to set upper limits:

$$0.5\times10^{-4} - 2.4\times10^{-4} \ (\Xi_{bc}^{0}(\Omega_{bc}^{0})\rightarrow \Lambda_{c}^{+}\pi^{-})$$

$$1.4\times10^{-3} - 6.9\times10^{-3} \ (\Xi_{bc}^{0}(\Omega_{bc}^{0}) \rightarrow \Xi_{c}^{+}\pi^{-})$$

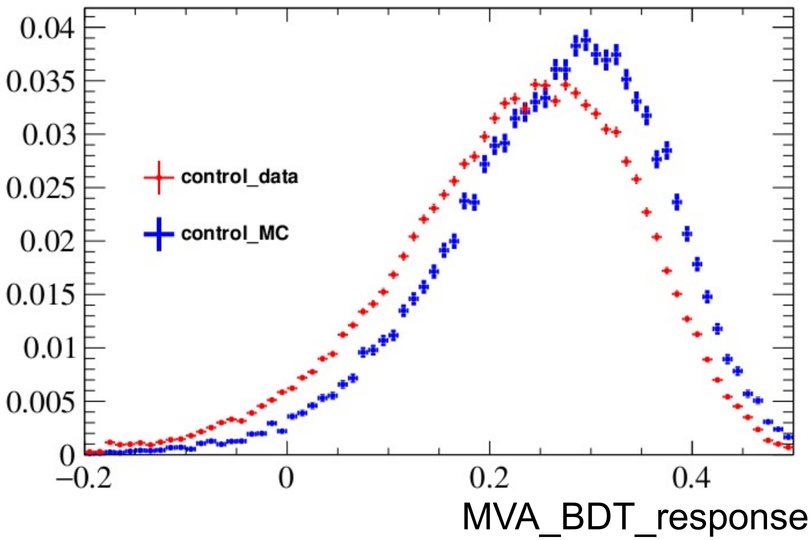
- With LHCb upgrade (50 fb^{-1}) & upgrade-II (300 fb^{-1}), more exciting results are coming.
  - $\Xi_{bc}^{+} \rightarrow J/\psi\Xi^{+}$?
  - $\Xi_{bc}^{+} \rightarrow \Xi_{cc}^{++}X$?

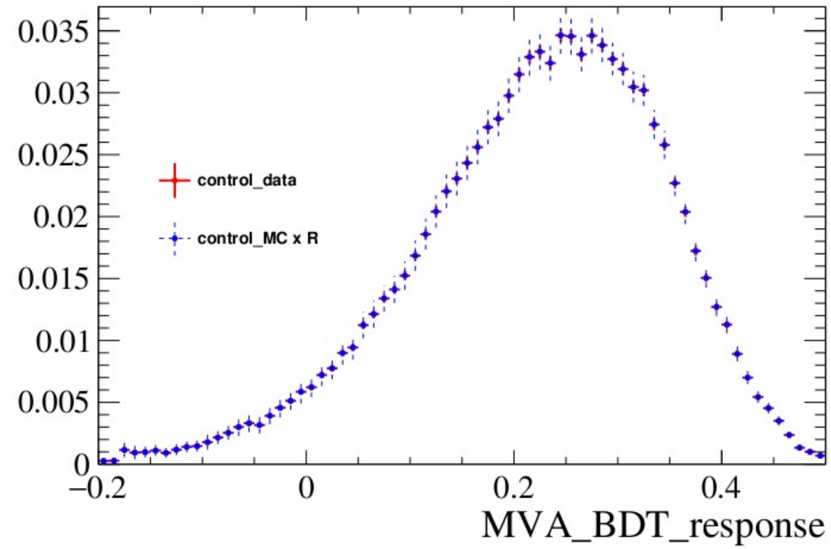
Thanks for your attention!

Back up

BDT check using Ξ_b^0 or Λ_b^0 channel

s-weighted data





	$\Xi_{bc}^0 \to \Lambda_c^+\pi^-$	$\Lambda_b^0 \to \Lambda_c^+\pi^-$	Ratio	$\Xi_{bc}^0 \to \Xi_c^+\pi^-$	$\Xi_b^0 \to \Xi_c^+\pi^-$	Ratio
Before	0.572±0.005	0.683±0.003	1.194±0.012	0.618±0.002	0.779±0.001	1.261±0.004
After	0.431±0.005	0.561±0.003	1.261±0.004	0.442±0.002	0.595±0.001	1.346±0.006

The BDT efficiencies in different channels before and after reweighting

Efficiencies

	$\Xi_{bc}^0 \to \Lambda_c^+ \pi^-$	$\Lambda_b^0 \to \Lambda_c^+ \pi^-$	R
Acc	0.7981±0.0004	0.8372±0.0003	1.0490±0.0006
Reco	0.0181±0.0001	0.0543±0.0002	3.0040±0.0273
PID	0.9358±0.0022	0.9298±0.0010	0.9936±0.0025
Track	0.9621±0.0017	0.9609±0.0008	0.9987±0.0020
L0	0.4312±0.0042	0.4107±0.0019	0.9524±0.0104
HLT1 and HLT2	0.9582±0.0026	0.9751±0.0010	1.0176±0.0029
MC-Match (1./)	0.9800±0.0008	0.9631±0.0010	1.0176±0.0010
Total	$(5.48 \pm 0.07) \times 10^{-3}$	$(1.69 \pm 0.01) \times 10^{-2}$	3.08±0.05

	$\Xi_{bc}^0 \to \Xi_c^+ \pi^-$	$\Xi_b^0 \to \Xi_c^+ \pi^-$	R
Acc	0.7916±0.0002	0.8288±0.0002	1.0470±0.0004
Reco	0.0290±0.0001	0.0810±0.0002	2.7930±0.0105
PID	0.9382±0.0009	0.9313±0.0005	0.9926±0.0010
Track	0.9637±0.0007	0.9620±0.0004	0.9983±0.0008
L0	0.4027±0.0018	0.3865±0.0010	0.9597±0.0048
HLT1 and HLT2	0.8920±0.0018	0.9498±0.0007	1.0649±0.0022
MC-Match (1./)	0.9659±0.0007	0.9475±0.0009	1.0194±0.0009
Total	$(7.72 \pm 0.05) \times 10^{-3}$	$(2.33 \pm 0.08) \times 10^{-3}$	3.02±0.02

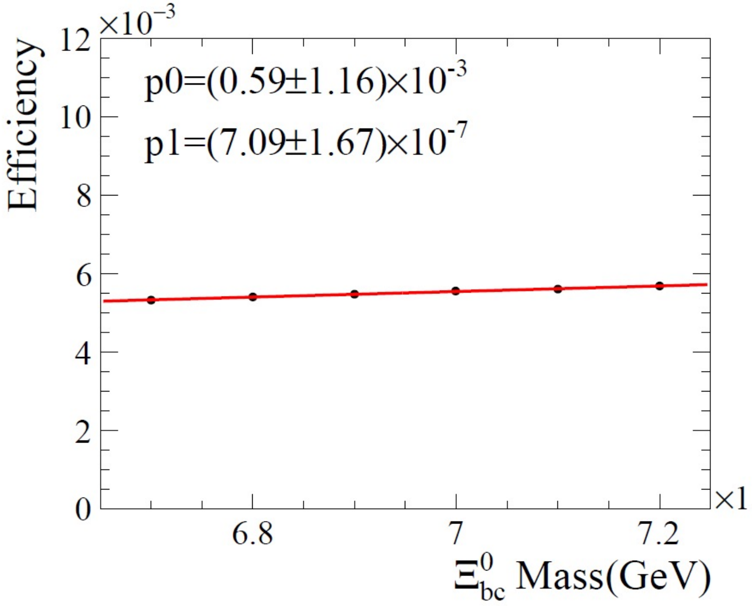
Efficiency dependence on the Ξ_{bc}^{0} mass

- Efficiencies with different Ξ_{bc}^{0} mass hypotheses for $\Xi_{bc}^{0} \to \Lambda_c^{+}\pi^{-}$

Mass(MeV/c^2)	6700	6800	6900
Acc	0.8016±0.0004	0.8001±0.0004	0.7981±0.0004
Reco and Sel	0.0175±0.0001	0.0178±0.0001	0.0181±0.0001
PID	0.9354±0.0022	0.9347±0.0022	0.9358±0.0022
Track	0.9621±0.0017	0.9621±0.0017	0.9621±0.0017
L0	0.4315±0.0042	0.4317±0.0042	0.4312±0.0042
HLT1 and HLT2	0.9593±0.0026	0.9583±0.0026	0.9582±0.0026
MC-Match (1./)		0.9800±0.0008	
Total	$(5.33 \pm 0.07) \times 10^{-3}$	$(5.41 \pm 0.07) \times 10^{-3}$	$(5.48 \pm 0.07) \times 10^{-3}$

Mass(MeV/c^2)	7000	7100	7200
Acc	0.7967±0.0004	0.7931±0.0004	0.7920±0.0004
Reco	0.0184±0.0001	0.0187±0.0001	0.0191±0.0001
PID	0.9350±0.0020	0.9358±0.0020	0.9356±0.0020
Track	0.9621±0.0017	0.9621±0.0017	0.9621±0.0017
L0	0.4317±0.0042	0.4294±0.0042	0.4273±0.0042
HLT1 and HLT2	0.9584±0.0026	0.9580±0.0026	0.9583±0.0026
MC-Match (1./)		0.9800±0.0008	
Total	$(5.56 \pm 0.07) \times 10^{-3}$	$(5.61 \pm 0.07) \times 10^{-4}$	$(5.69 \pm 0.07) \times 10^{-4}$

- Fitted result with a polynomial function



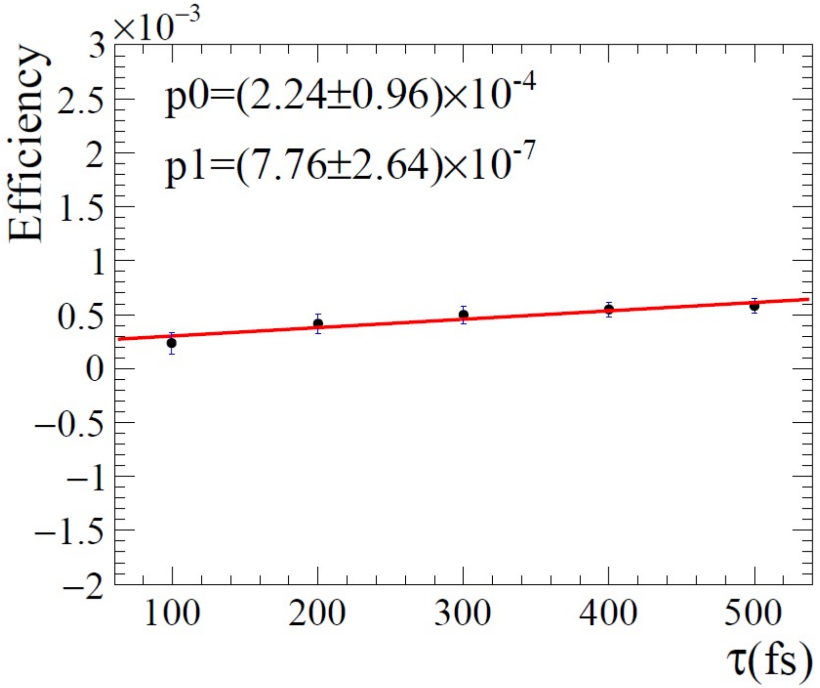
Efficiency dependence on the Ξ_{bc}^{0} lifetimne

- Efficiencies with different Ξ_{bc}^{0} lifetime hypotheses for $\Xi_{bc}^{0} \to \Lambda_c^+ \pi^-$

Mass(MeV/c^2)	100fs	200fs	300fs
Acc	0.7981±0.0004	0.7981±0.0004	0.7981±0.0004
Reco	0.0063±0.0001	0.0126±0.0001	0.0159±0.0001
PID	0.9357±0.0095	0.9371±0.0038	0.9365±0.0026
Track	0.9645±0.0071	0.9632±0.0029	0.9625±0.0020
L0	0.5512±0.0188	0.4801±0.0076	0.4489±0.0052
HLT1 and HLT2	0.8957±0.0016	0.9352±0.0054	0.9503±0.0034
MC-Match (1./)		0.9800±0.0008	
Total	$(2.29 \pm 0.10) \times 10^{-3}$	$(4.16 \pm 0.09) \times 10^{-3}$	$(4.98 \pm 0.08) \times 10^{-3}$

Mass(MeV/c^2)	400fs	500fs
Acc	0.7981±0.0004	0.7981±0.0004
Reco	0.0181±0.0001	0.0196±0.0001
PID	0.9358±0.0022	0.9352±0.0019
Track	0.9621±0.0017	0.9618±0.0015
L0	0.4312±0.0042	0.4203±0.0037
HLT1 and HLT2	0.9582±0.0026	0.9630±0.0022
MC-Match (1./)		0.9800±0.0008
Total	$(5.48 \pm 0.07) \times 10^{-3}$	$(5.81 \pm 0.07) \times 10^{-3}$

- Fitted result with a polynomial function



Upper limit: CLs

- Define signal range [6700,7300] MeV/c^2

- After all cuts, fit lower and upper sideband data to get background shape

- Use true data to calculate CLs

$$R(\Lambda_c^+\pi^-) = \frac{\sigma\left(pp \to \Xi_{bc}^0 X\right) B\left(\Xi_{bc}^0 \to \Lambda_c^+(\to p^+K^-\pi^+)\pi^-\right)}{\sigma\left(pp \to \Lambda_b^0 X\right) B\left(\Lambda_b^0 \to \Lambda_c^+(\to p^+K^-\pi^+)\pi^-\right)} = \frac{N(\Xi_{bc}^0 \to \Lambda_c^+\pi^-)}{N(\Lambda_b^0 \to \Lambda_c^+\pi^-)} \frac{\varepsilon(\Lambda_b^0)}{\varepsilon(\Xi_{bc}^0)}$$