

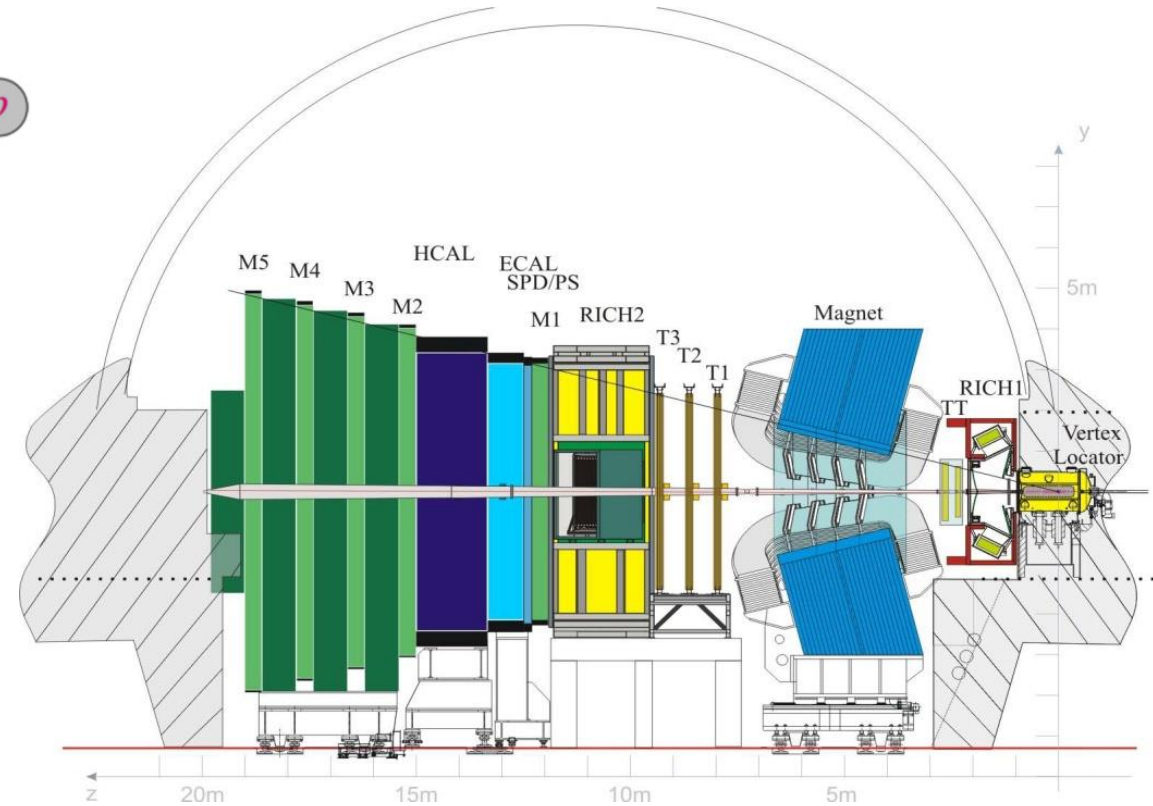
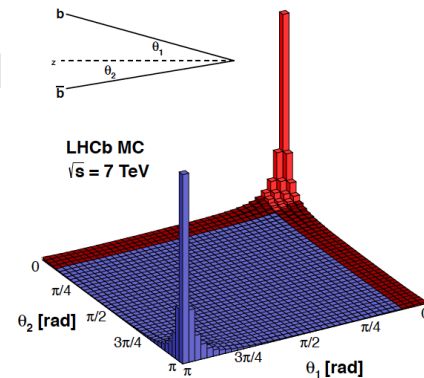
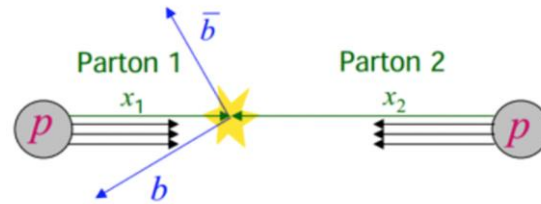
Search for the doubly charmed baryon Ξ_{cc}^+ at LHCb

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The LHCb experiment

- The most important experiment at the LHC on beauty and charmed hadrons
- Dedicated detector
 - Forward spectrometer
 - Large boost
 - $b\bar{b}$ and $c\bar{c}$ in forward/backward cones predominantly
- Two Cherenkov detectors
 - PID in various p-ranges



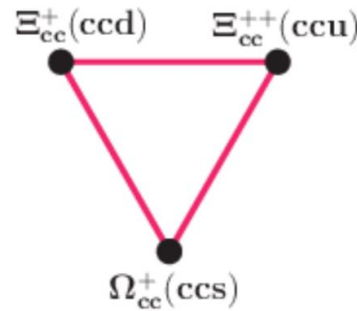
Doubly Charmed Baryon

- Quark model:
 - Six type of quarks: u, d, c, s, t, b
 - Common hadrons
 - Proton (uud)
 - Neutron (udd)

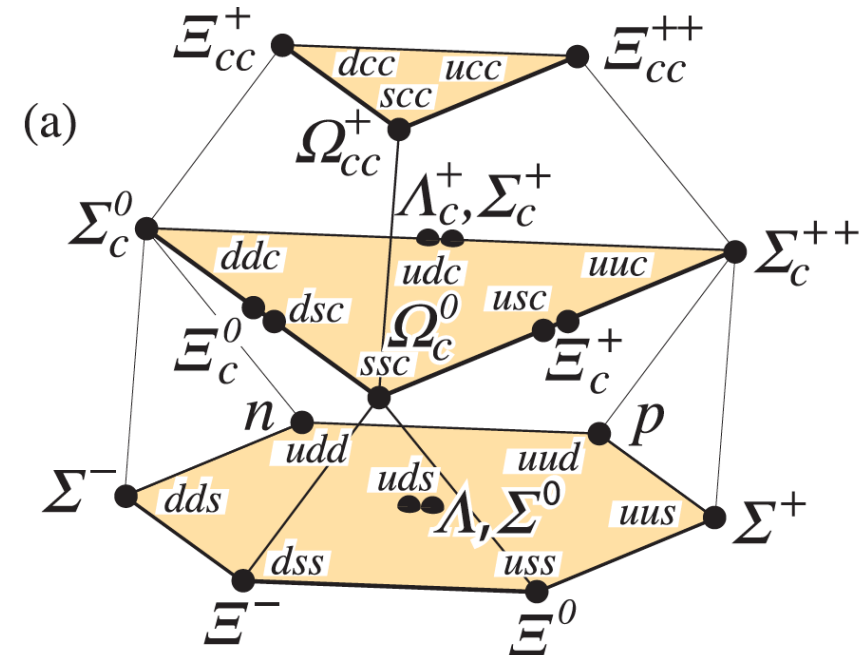
	I	II	III
mass	2.4 MeV	1.27 GeV	171.2 GeV
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name	u up	c charm	t top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d down	s strange	b bottom

- Doubly charmed baryons from SU(4) multiples:

- $\Xi_{cc}^{++}(ccu)$
- $\Xi_{cc}^{+}(ccd)$
- $\Omega_{cc}^{+}(ccs)$



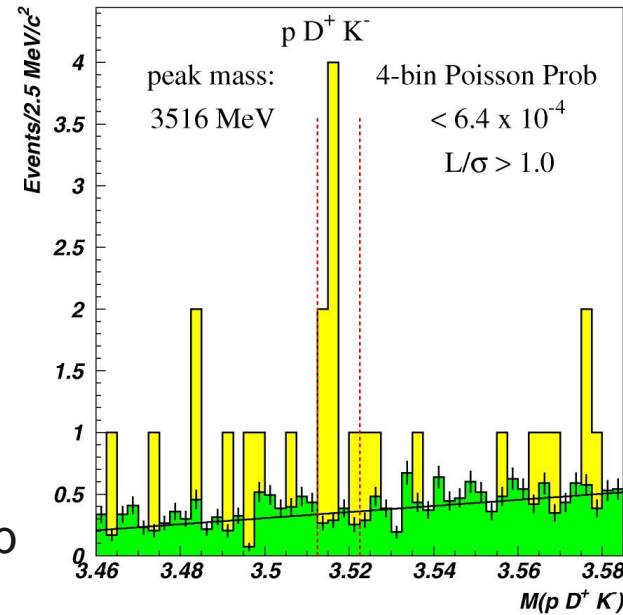
- Understanding
 - Three-body bound system
 - Hadron Interaction-QCD



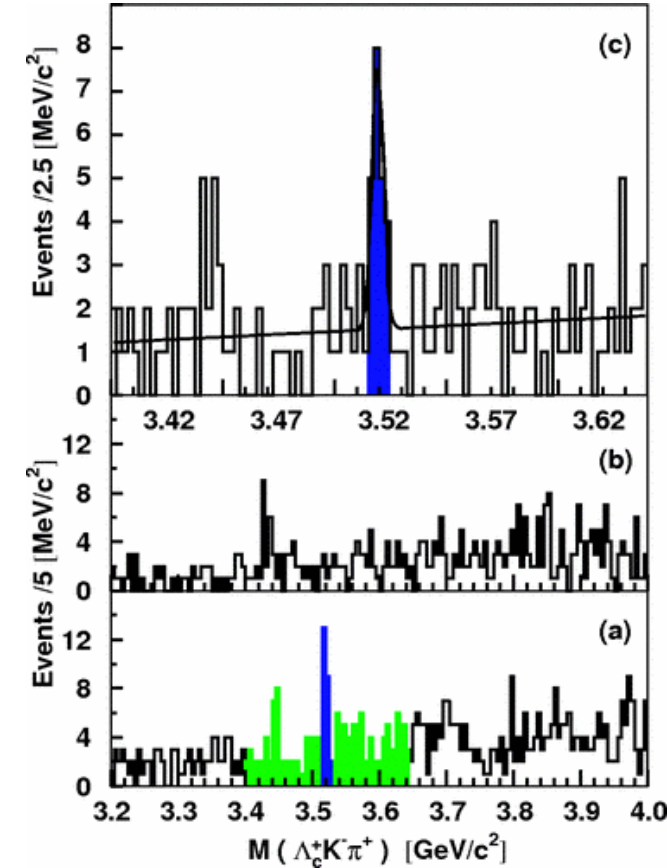
Ξ_{cc} @SELEX



- Fixed-target experiment at Fermilab (1996-1997)
 - 600GeV charged Hyperon beam (Σ^- , π^- / p , π^+)
 - Cu or diamond + 3 spectrometers
- $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ (6.3σ)
 - Mass: 3519 ± 1 MeV
 - Lifetime $\tau < 33$ fs @ 90%CL
 - σ_{prod} : 20% Λ_c^+ from Ξ_{cc}^+
- $\Xi_{cc}^+ \rightarrow p D^+ K^-$ (4.8σ)
 - Mass: 3518 ± 3 MeV
 - Lifetime consistent with 0 fs
- Results not confirmed by FOCUS, Babar, Belle & LHCb
- Ξ_{cc}^{++} reported by SELEX
 - $M(\Xi_{cc}^{++}) = 3460$ MeV (4.4σ)
 - Isospin symmetry breaking?

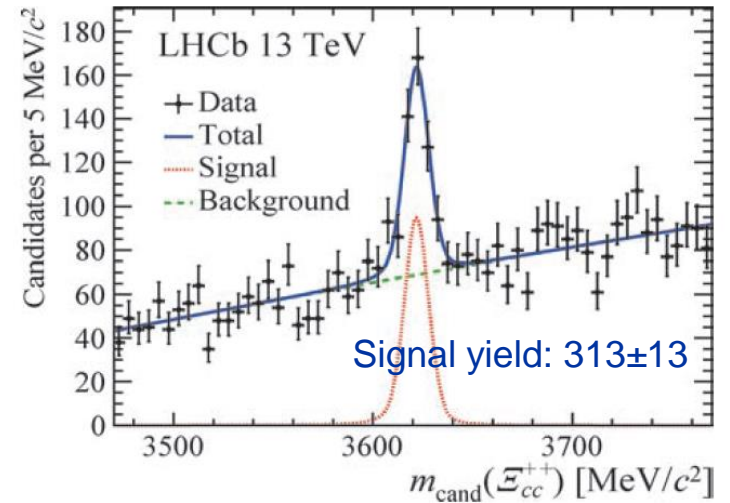
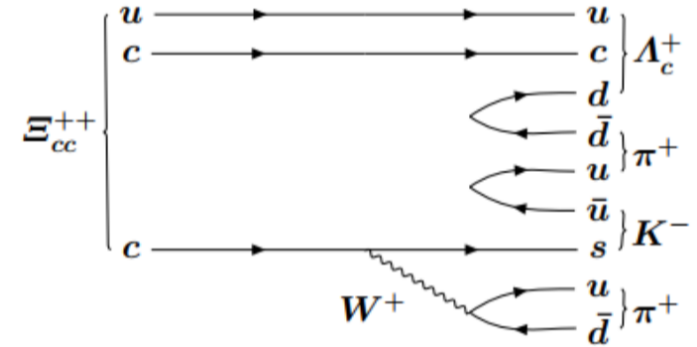


[Phys.Lett.B628:18-24,2005](#)

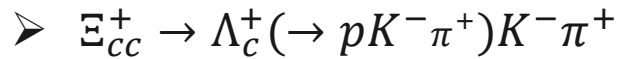
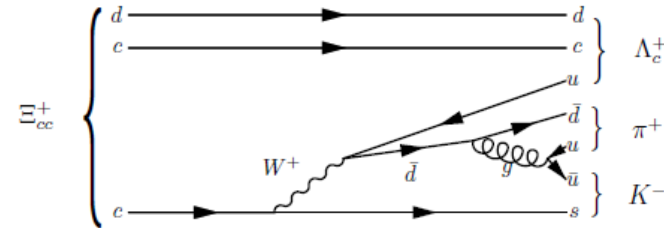


[Phys.Rev.Lett.89,112001,2002](#)

- Observation of Ξ_{cc}^{++} (ccu state)
 - $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ ($>12 \sigma$)
 - Data: $\sqrt{s} = 13 \text{ TeV}$, $\int L = 1.7 \text{ fb}^{-1}$
 - Mass: $3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)$ MeV
 >100 MeV higher than the SELEX mass
 - Lifetime: 256_{-22}^{+24} (stat) ± 14 (syst) fs
 - $R \equiv \frac{\sigma(\Xi_{cc}^{++}) \times B(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+)}{\sigma(\Lambda_c^+)} = (2.22 \pm 0.27 \pm 0.29) \times 10^{-4}$
 - Confirmed in a second decay channel: $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$
- Discovery of Ξ_{cc}^{++} opens up other important possibilities :
 - Ξ_{cc}^+
 - Ω_{cc}^+

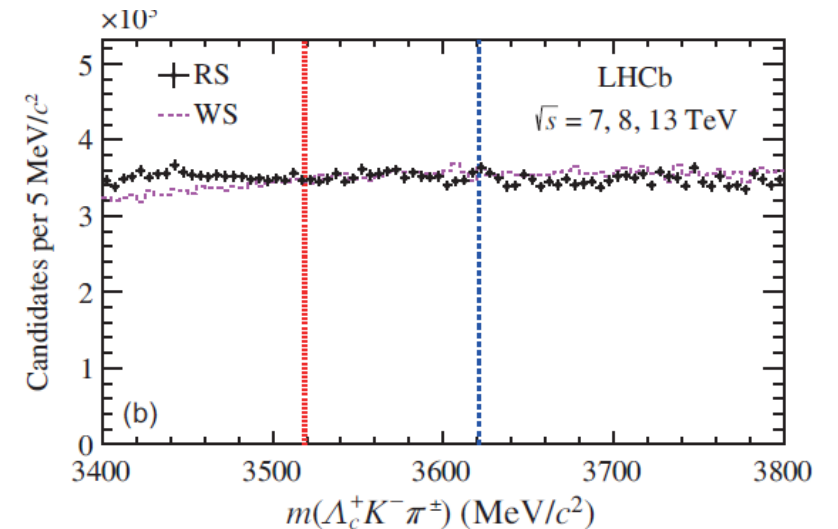
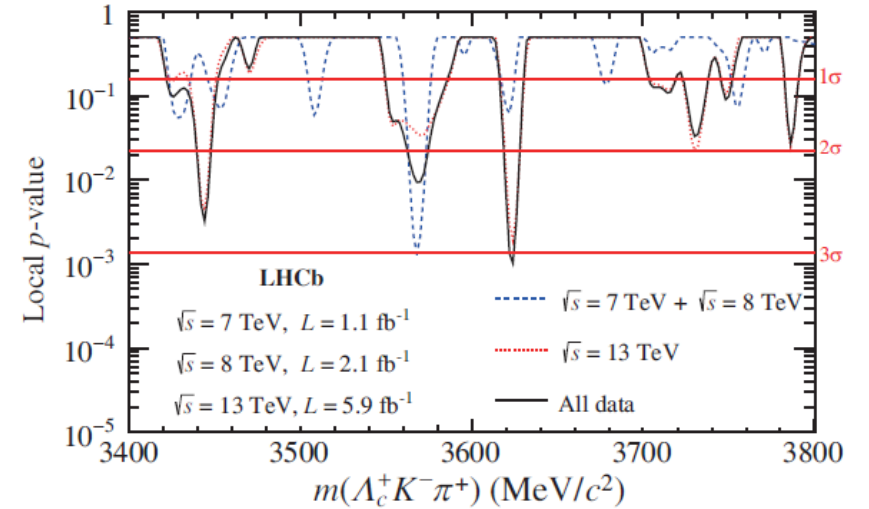


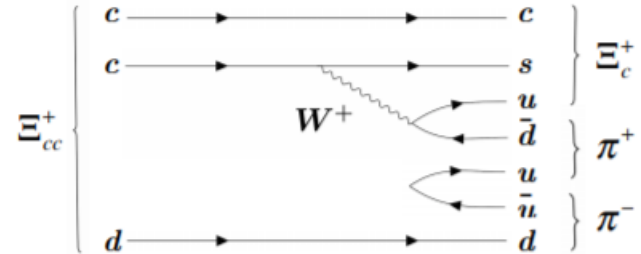
Phys. Rev. Lett. **119**, 112001



- Blind analysis, signal region 3.4-3.8 GeV
- Data: Run 1 & Run 2, $\int L = 9 \text{ fb}^{-1}$
- Hypothesis: $\tau(\Xi_{cc}^+)$: (0 fs, 80 fs) \times (non)observation
- Local significance reached 3.1σ around LHCb Ξ_{cc}^{++} mass
- No significant signal is observed

[Sci. China Phys. Mech. Astron. 63, 221062 \(2020\).](#)

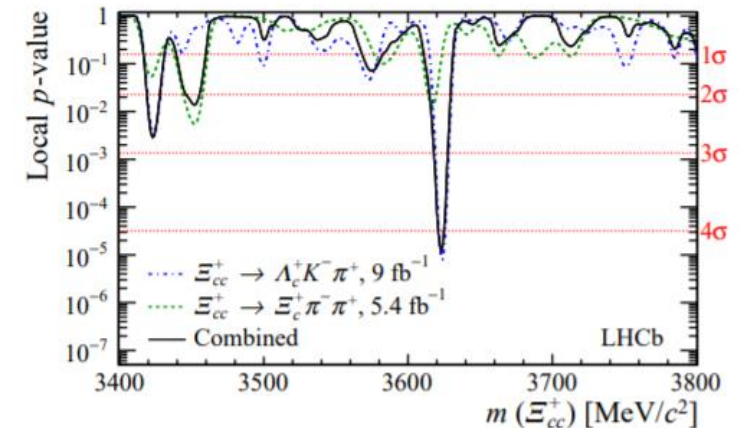
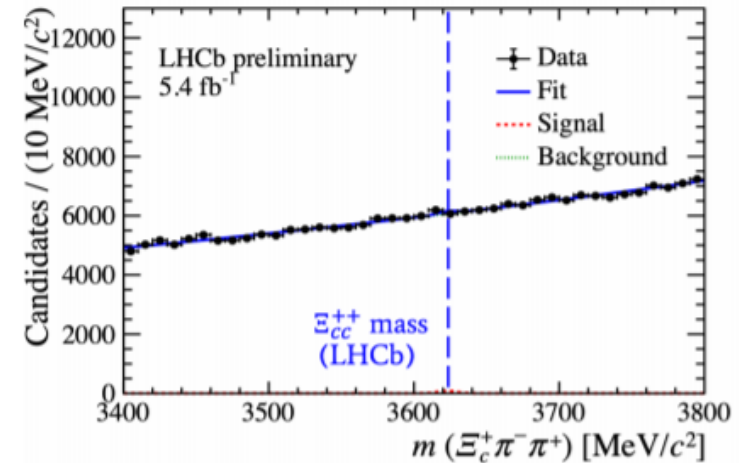




➤ $\Xi_{cc}^+ \rightarrow \Xi_c^+ (\rightarrow p K^- \pi^+) \pi^+ \pi^-$

- Blind analysis, signal region 3.3-3.8 GeV
- Data: Run 2, $\int L = 5.4 \text{ fb}^{-1}$
- Best fit found around 3623.0 MeV
- No significant signal observed
- Combined fit with $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ final state leads to a local significance of 4.0σ

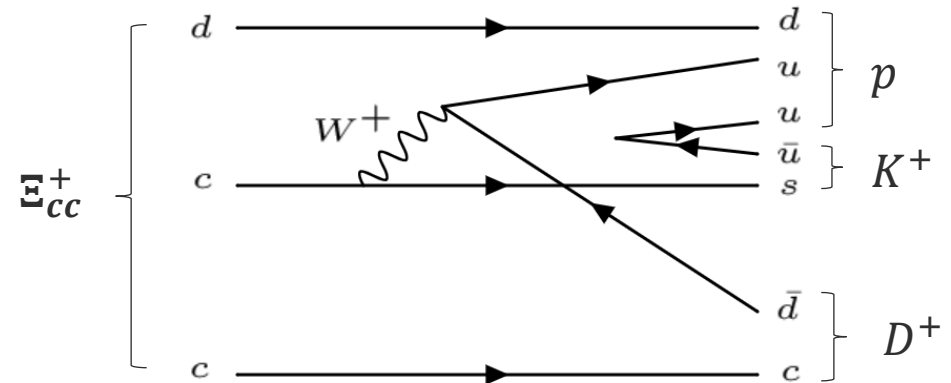
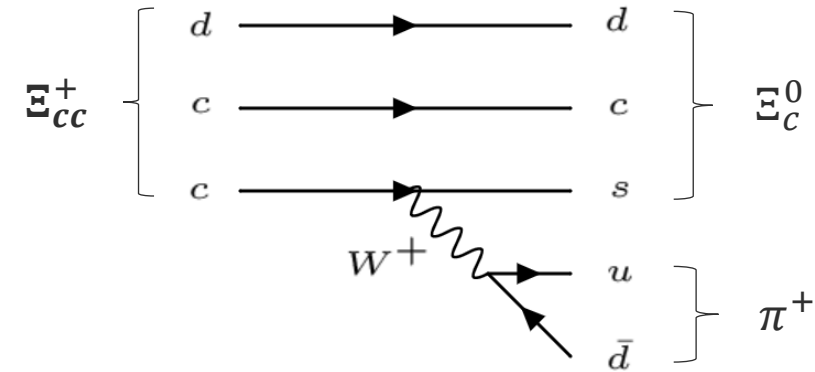
[LHCb-PAPER-2021-019 \(in preparation\)](#)



Our work: Search for Ξ_{cc}^+ in pD^+K^- and $\Xi_c^0\pi^+$ final states

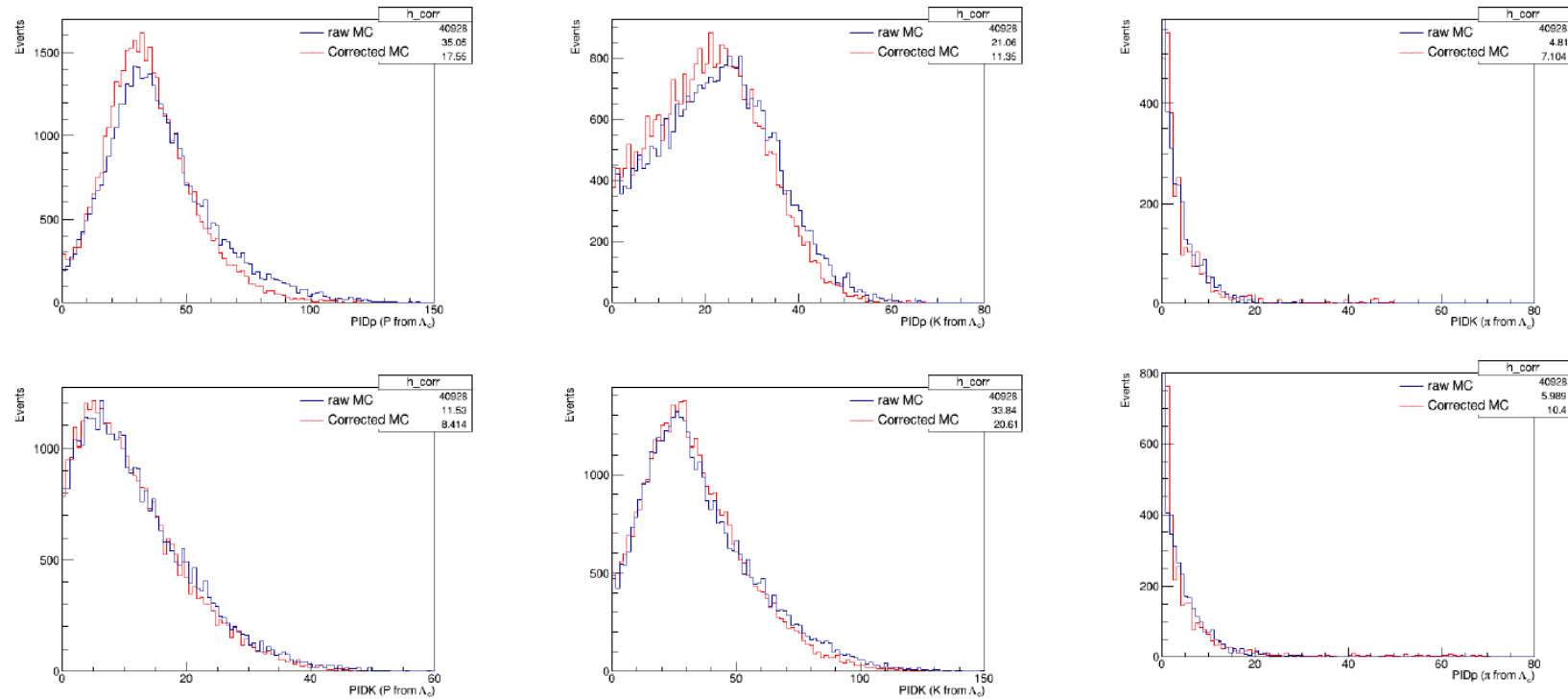
Motivation

- Search for Ξ_{cc}^+ in two **new** decay modes:
 - $\Xi_{cc}^+ \rightarrow pD^+(\rightarrow pK^-\pi^+)K^-$
 - $\Xi_{cc}^+ \rightarrow \Xi_c^0(\rightarrow pK^-K^-\pi^+)\pi^+$
- Advantage:
 - D^+ long lifetime
 - $\Xi_{cc}^+ \rightarrow \Xi_c^0\pi^+$ Cabibbo favored
- Combine with the two previous decay modes:
 - $\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+$
 - $\Xi_{cc}^+ \rightarrow \Xi_c^+\pi^+\pi^-$
- **Aim is to improve the signal significance**



Analysis status – PID correction

- After pre-selection
- Correct MC and data with calibration samples



PID variables before & after PID correction

Analysis status – MVA

✓ Input variables

- Long lifetime of Ξ_{cc}^+ \rightarrow IP chi2, flight distance
- $\Xi_{cc}^+ \rightarrow \Lambda_c^+(\rightarrow pK^-\pi^+)K^-\pi^+$
- Lifetime, p_T , PID

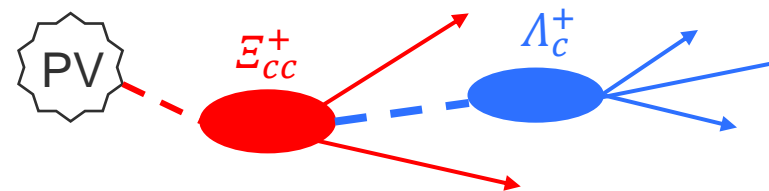


Table 2: Input Variables

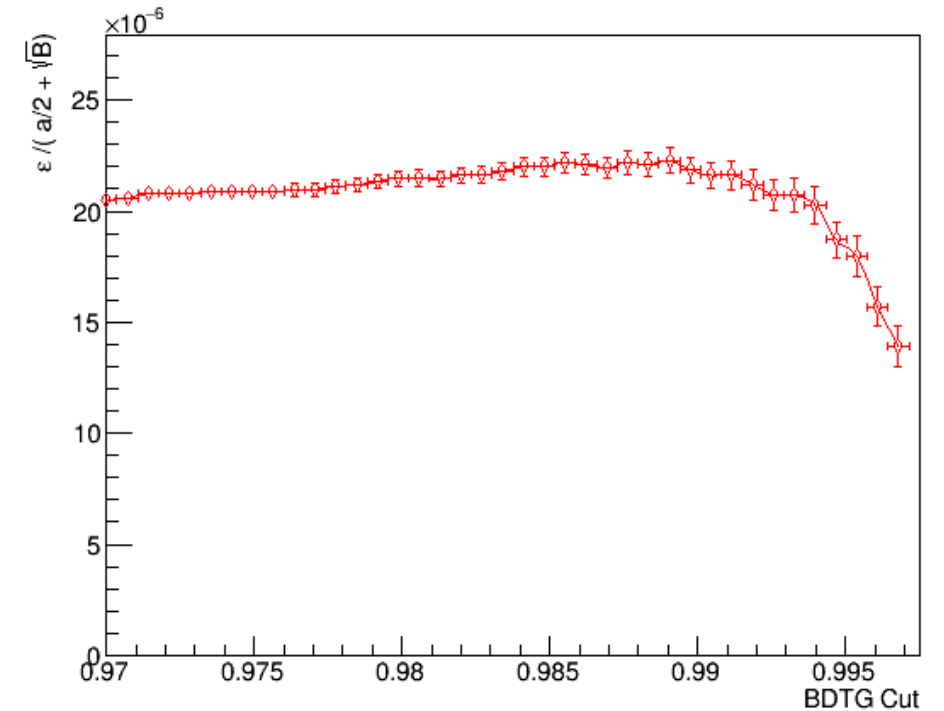
Type	Variable	Number
	χ_{vtx}^2 /ndf of the Λ_c^+ vertex fit	1
	χ_{vtx}^2 /ndf of the Ξ_{cc}^+ vertex fit	1
	χ_{vtx}^2 /ndf of the Ξ_{cc}^+ candidate with PV constraint	1
	Log sized flight distance χ^2 of Λ_c^+ to PV	1
	Log sized flight distance χ^2 of Λ_c^+ to its original vertex	1
	Log sized flight distance χ^2 of Ξ_{cc}^+ to PV	1
	Log sized χ_{IP}^2 of daughters of Ξ_{cc}^+ to PV	3
	Log sized p_T of Ξ_{cc}^+ , Λ_c^+ and of their daughters	7
	Momentum of proton from Λ_c^+ to scalar sum of momenta of daughters of Λ_c^+	1
PID	Kaon particle ID DLL_{KK}	2
	Pion particle ID $DLL_{\pi K}$	2
	Proton particle ID DLL_{pp}	1
	$\cos^{-1}(\text{DIRA})$ of Ξ_{cc}^+ to PV	1
Total		23

Analysis status – optimization

✓ Optimization of the BDT working point :

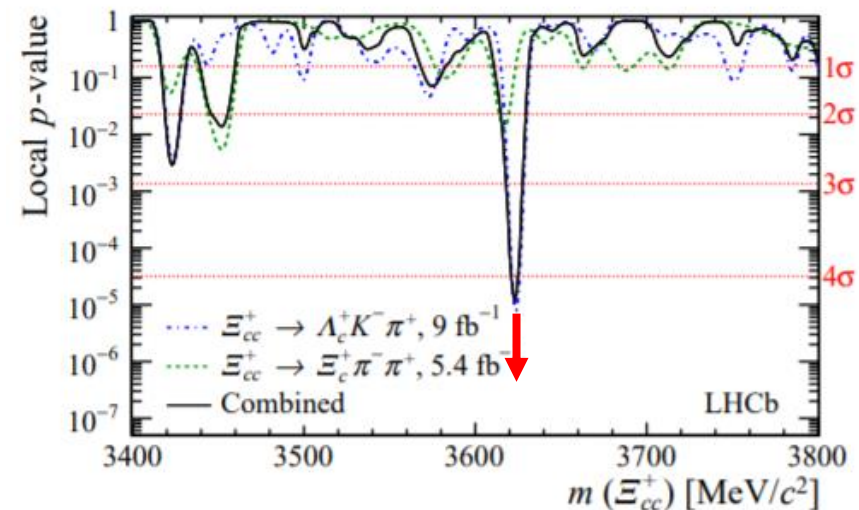
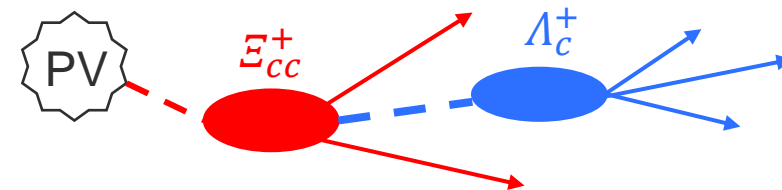
- Scan of Punzi figure of merit (FoM)
- Definition of search sensitivity:
- $\epsilon(t)$: signal efficiency at cut t
- a : number of sigmas corresponding to one-sided Gaussian test at significance α , taken as 5 for discovery
- Determination of the optimal working point

$$\frac{\epsilon(t)}{a/2 + \sqrt{B(t)}}$$



Analysis status - Next steps & plans

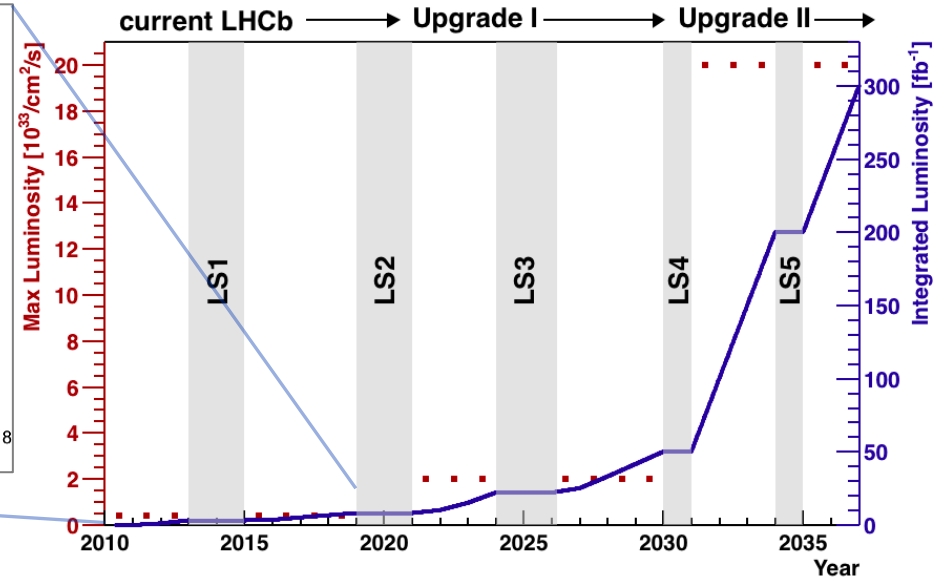
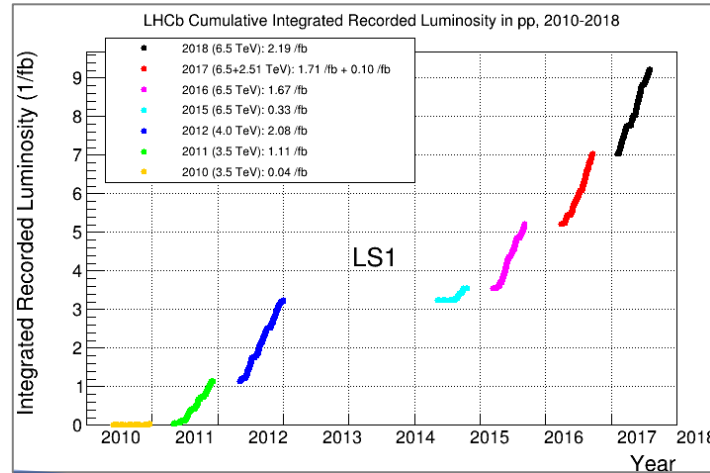
- ❑ Remove cloned and **duplicate**d tracks
- ❑ Fit signal and background
- ❑ Combine decay modes, statistical analysis...
- ❑ Previous work combining $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$ and $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ leads to **4.0 σ** local significance
- ❑ Combination with the two new channels will hopefully lead to improved significance



LHCb upgrade



- Upcoming Run 3
- Instantaneous luminosity increased by a factor of 5
- Fully software trigger
- Improved detector performance
- Larger data samples



LHC era		HL-LHC era		
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb ⁻¹	6 fb ⁻¹	23 fb ⁻¹	46 fb ⁻¹	>300 fb ⁻¹ ??
		Phase-1 Upgrade!!	Phase-1b Upgrade!?	Phase-2 Upgrade??

Summary & outlook

- Quark model considering u, c, d, s quarks predicted the existence of doubly charmed baryon
- Well-established observation of Ξ_{cc}^{++} in decay modes: $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$.
- Search for Ξ_{cc}^+ in $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$, combined fit leads to local significance 4.0σ
- Combined search for Ξ_{cc}^+ in four different channels, adding **two new channels**, will enhance the LHCb discovery capabilities:
 - $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$
 - $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^+ \pi^-$
 - $\Xi_{cc}^+ \rightarrow p D^+ K^-$
 - $\Xi_{cc}^+ \rightarrow \Xi_c^0 \pi^+$
- Upgraded LHCb will provide even better performance
- This analysis will contribute to a deeper understanding of the strong interactions



Thank you for listening!