Search for the doubly charmed baryon Ω_{cc}^{+}

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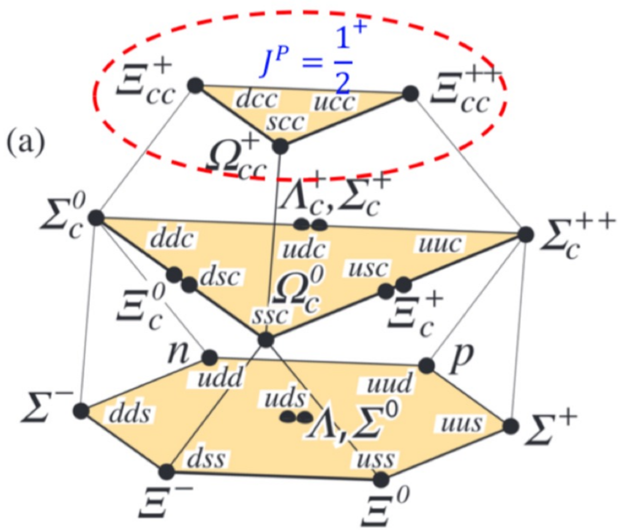
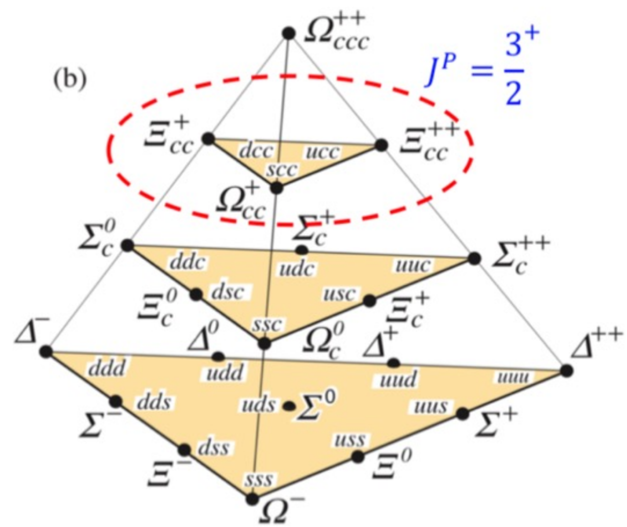
Douby charmed baryons

- Predicted by SU(4) 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$
- Double charm quarks with a SU(3) triplet light quarks:
  Ξ_{cc}^{++}(ccu), Ξ_{cc}^{+}(ccd), $\boldsymbol{\Omega_{cc}^{+}}$**(ccs)**
- $\mathrm{J}^{\boldsymbol{P}} = \frac{\mathbf{3}}{\mathbf{2}}^+$ expected to decay to $\frac{\mathbf{1}}{\mathbf{2}}^+$ states via strong/electromagnetic interaction
- $\mathrm{J}^{\boldsymbol{P}} = \frac{\mathbf{1}}{\mathbf{2}}^+$ decay weakly via a charm quark transformed to lighter quarks



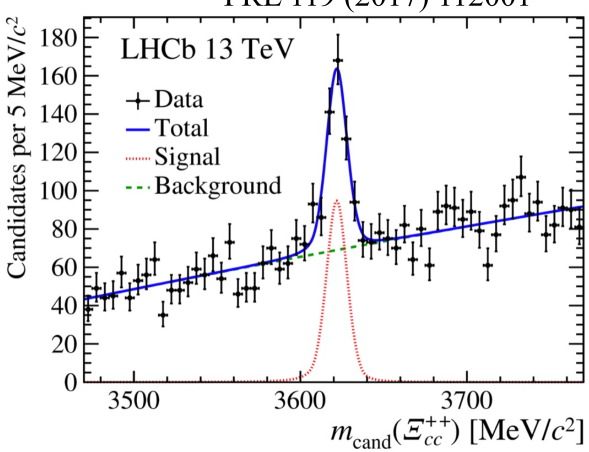


Achievements

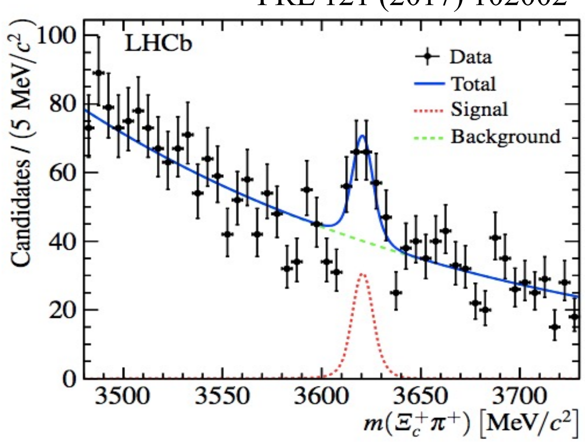
- Many studies done at LHCb

First observation Ξ_{cc}^{++} ($\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$)	PRL 119 (2017) 112001
Confirmation Ξ_{cc}^{++} ($\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$)	PRL 121 (2018) 162002
Lifetime measurement of Ξ_{cc}^{++}	PRL 121 (2018) 052002
Search for $\Xi_{cc}^{++} \to D^+ p K^- \pi^+$ decays	JHEP 10 (2019) 124
Production measurement of Ξ_{cc}^{++}	CPC44 (2020) 022001
Precise mass measurement of Ξ_{cc}^{++}	JHEP 02 (2020) 049
Search for $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ decays	SCPMA 63 (2020) 221062
Search for $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^+$ decays	arXiv:2109.07292
Search for $\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+$ decays	SCPMA 64 (2021) 101062

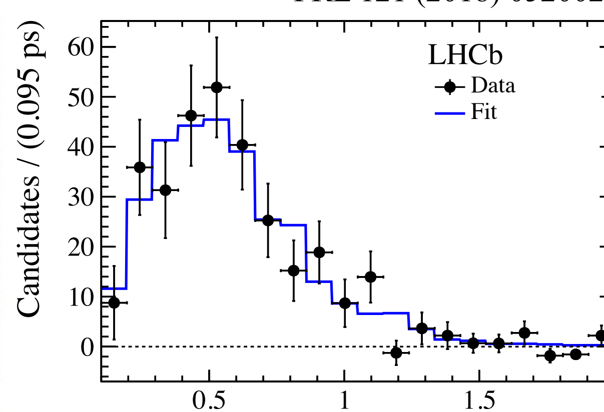
PRL 119 (2017) 112001



PRL 121 (2017) 102002



PRL 121 (2018) 052002



Predictions

- Measurements and predictions
- $M(\Xi_{cc}^{++}) = 3621.55\pm0.23(stat)\pm0.30(syst)\ \mathrm{MeV}$[1]
  $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$, $\mathbf{M(\Omega_{cc}^{+})\sim 3.6\text{–}3.9\ GeV}$[2]
- $\tau(\Xi_{cc}^{++}) = 0.256_{-0.022}^{+0.024}\ (stat)\pm0.014(syst)\ ps$[3]
- $\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^{+}) > \tau(\Xi_{cc}^{+})$, $\boldsymbol{\tau(\Omega_{cc}^{+})\sim[75, 180]fs}$[4]
- $\sigma(\Xi_{cc}^{++})/\sigma(\Lambda_{c}^{+}) = (2.22\pm0.27(stat)\pm0.29(syst))\times10^{-4}$[5]
  $\boldsymbol{\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+}) = 3\sigma(\Omega_{cc}^{+})}$[6]
- $\boldsymbol{\Omega_{cc}^{+} \to \Xi_{c}^{+}K^{-}\pi^{+}}$ expected to have large BR
  $B(\Omega_{cc}^{+} \to \Xi_{c}^{+}\overline{K}^{*0}(K^{-}\pi^{+})) \sim [0.5\%, 3.3\%]$[7]
  $B(\Xi_{c}^{+} \to p^{+}K^{-}\pi^{+}) \sim 0.45\pm0.21(stat)\pm0.07(syst\ )$[8]

[1] JHEP 02 (2020) 049

[2] PRD 66 (2002) 014008

[3] PRL 121 (2018) 052002

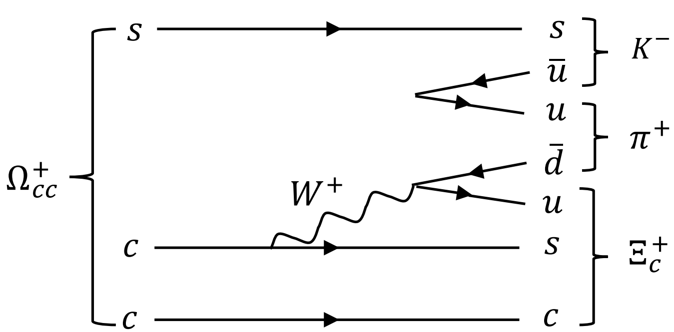
[4] PRD 98 (2018) 113005

[5] CPC44 (2020) 022001

[6] PRD 98 (2018) 113004

[7] EPJC 78 (2018)961

[8] PRD 100 (2019)031101

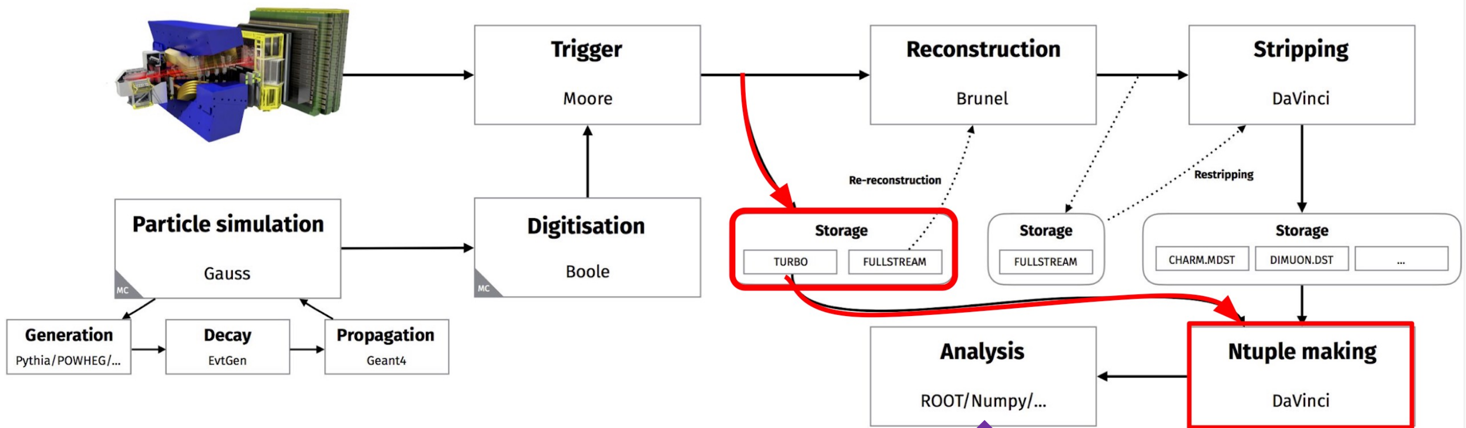


Strategy

- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, normalisation mode
- Data sample: LHCb runII at $\sqrt{s} = 13\text{TeV}$, $\sim 5.4\text{fb}^{-1}$
- Blinded analysis: 3.5 GeV to 4.0 GeV blinded
- Two cases:
  - Case 1: Global significance > 3σ, measure the mass and relative cross-section, report observation (> 5σ)
  - Case 2: Global significance < 3σ, upper limits set

$$R = \frac{\sigma(\Omega_{cc}^{+}) \times \mathcal{B}(\Omega_{cc}^{+} \to \Xi_c^+ K^- \pi^+) \times \mathcal{B}(\Xi_c^+ \to p K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \times \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)} = \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{N_{sig}}{N_{\text{norm}}} \equiv \alpha N_{sig}$$

Selection

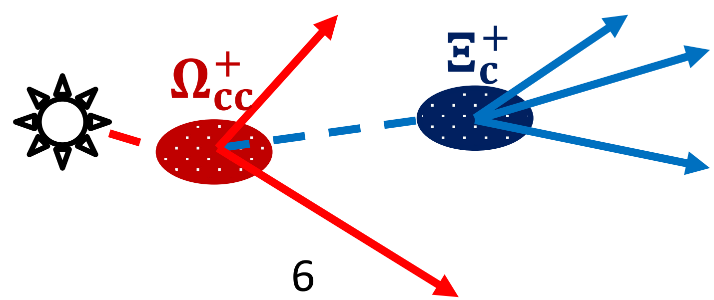


Cut-based selection & MVA

- The topologic and kinematic features are set as selection

- $\boldsymbol{\Xi_c^+ \to p^+ K^- \pi^+}$:
  $p^+K^-\pi^+$: PID, good track quality, large PT, not from PV
  Ξ_c^+: good vertex quality, decay time, separated from PV

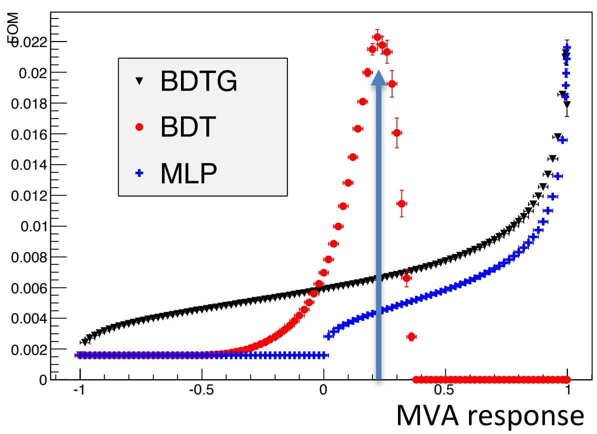
- $\boldsymbol{\Omega_{cc}^+ \to \Xi_c^+ K^- \pi^+}$:
  $K^-\pi^+$: PID, large PT
  Ω_{cc}^+: good vertex quality, from PV

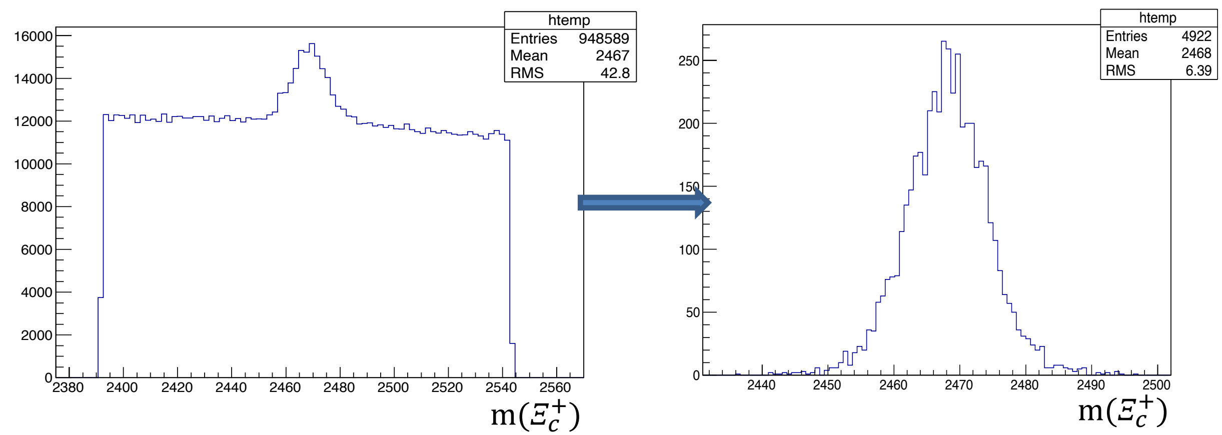


MVA selection

- Variables: features to separate the signal and background
- Samples: MC as signal and WS($\Xi_c^+ K^- \pi^-$) data as background
- Methods: BDT, BDTG and MLP
- Optimization: $F(t) = \frac{\epsilon(t)}{\frac{a}{2}+\sqrt{B(t)}}$, a=5 significance, working point BDT>0.22

Ξ_c^+ seleted from 2016 (20%)



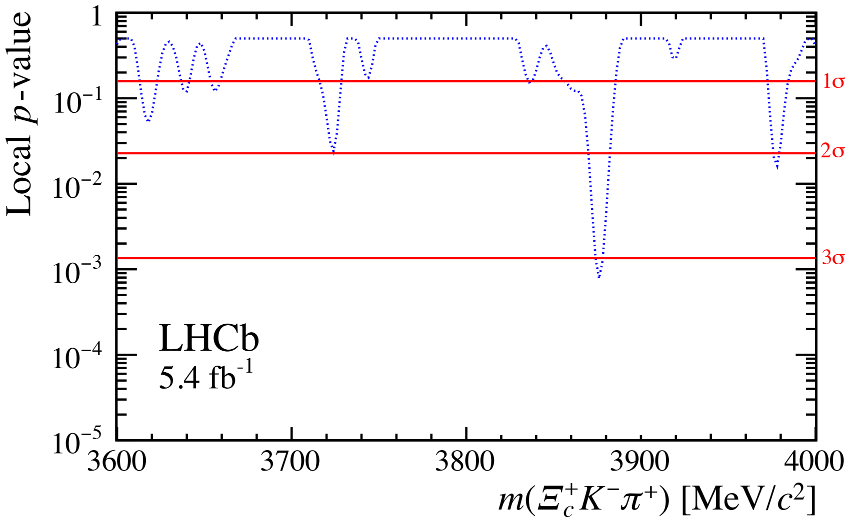


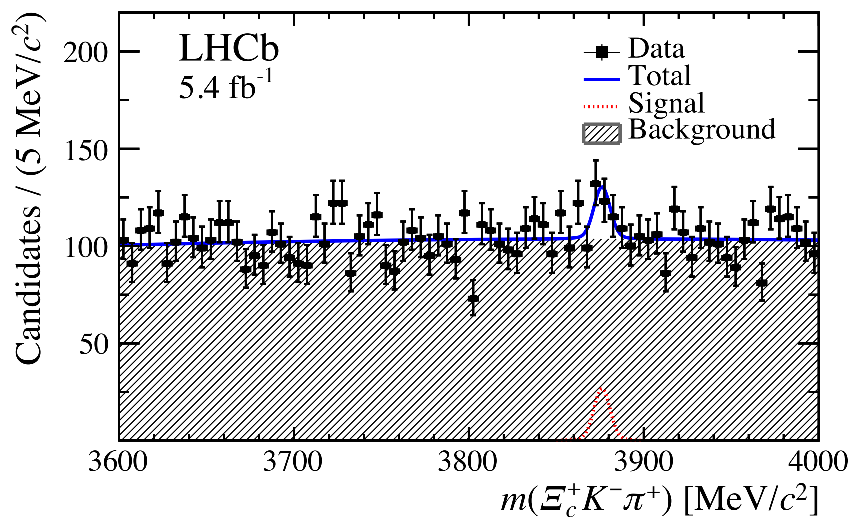
- PID show very good ability on separation
  - PID of **all** daughters to improve the sensitivity for Case1 (observation)
  - PID of just Ξ_c^+ daughters for Case2 (upperlimit)

Signal yields

[SCPMA. 64, 101062 (2021)](#)

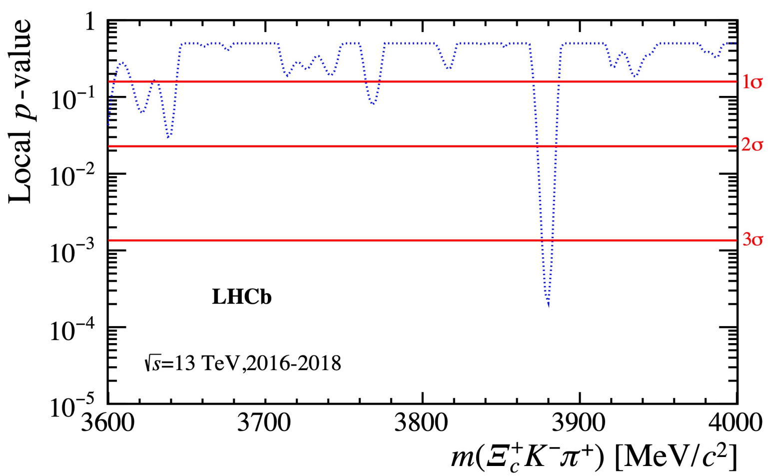
- $M_{cand}(\Omega_{cc}^{+}) = M(\Xi_c^{+}K^{-}\pi^{+}) - M(\Xi_c^{+}) + M_{PDG}(\Xi_c^{+})$
- 3.2 σ (1.8 σ) for local (global) significance, the largest local significance found around 3876.1 MeV (larger than common mass predictions)

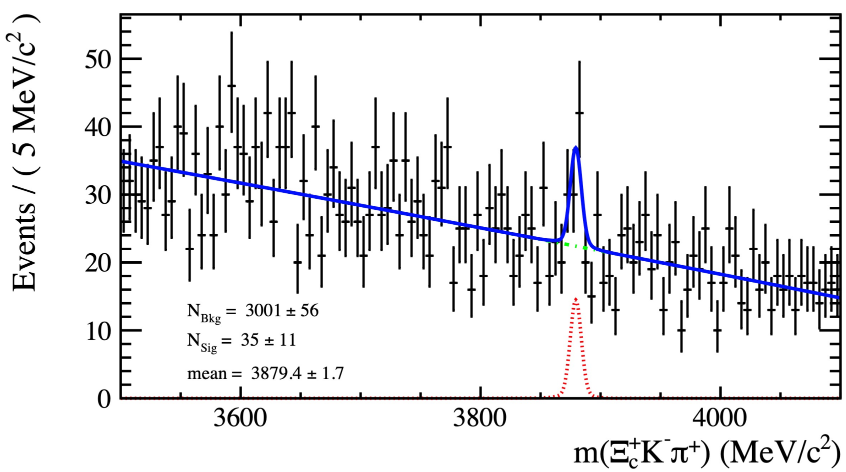


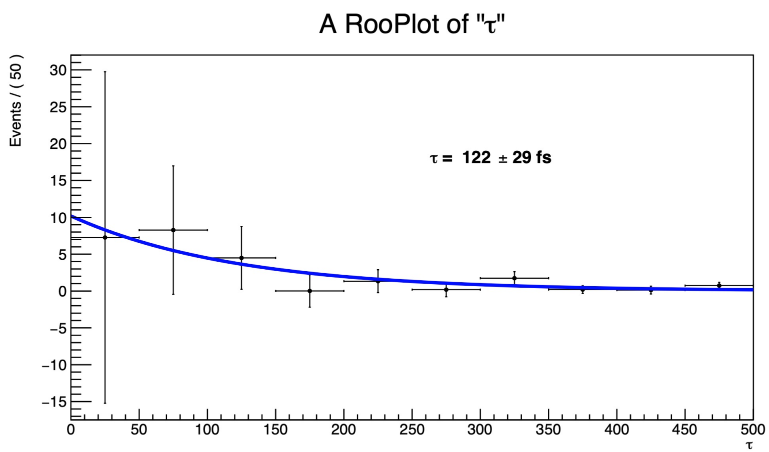


Ω_{cc}^{+} lifetime

- Require lifetime signifiance $(t/\sigma_t)>5\sigma$
- Local significance 3.2 σ → 3.6 σ
- Lifetime fit 122±29 fs

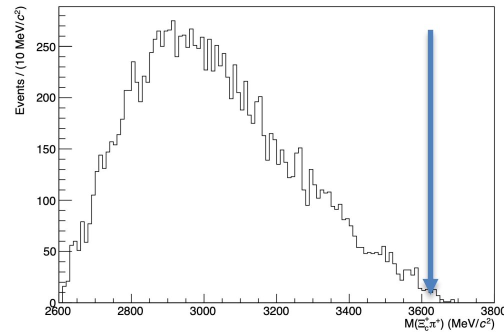






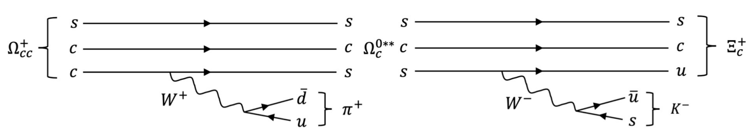
Intermediate states

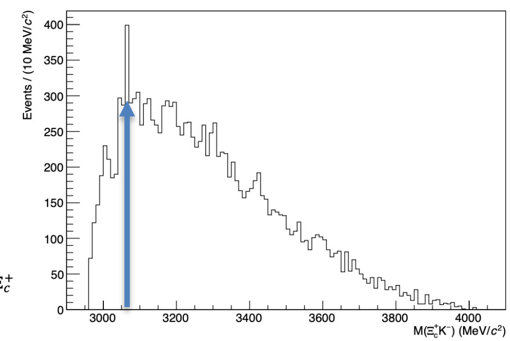
- $\Omega_{cc}^{+*} \rightarrow \Xi_{cc}^{++}(\Xi_c^+\pi^+)K^-$?



Lower than the mass of Ξ_{cc}^{++}

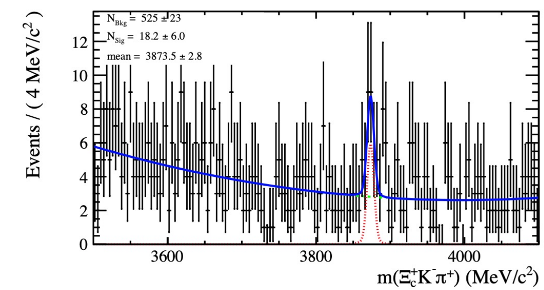
- $\Omega_{cc}^{+} \rightarrow \Omega_c^{0*}(\Xi_c^+K^-)\pi^+$?





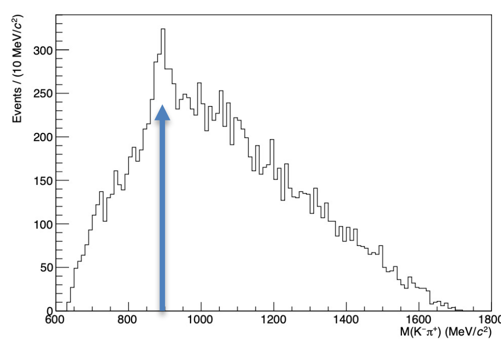
$\Omega_c^{0*}(3050)$, $\Omega_c^{0*}(3067)$

m($\Xi_c^+ K^-$) $\in$ [3049,3067]



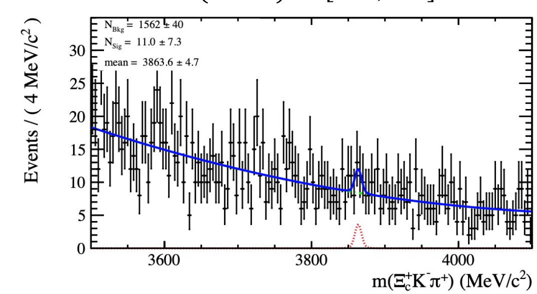
Local significance 3.6 σ

- $\Omega_{cc}^{+} \rightarrow \Xi_c^+ K^{0*}(K^-\pi^+)$?



$K^{0*}(892)$

m($K^-\pi^+$) $\in$ [842,942]



Local significance 1.6 σ

Upper limits

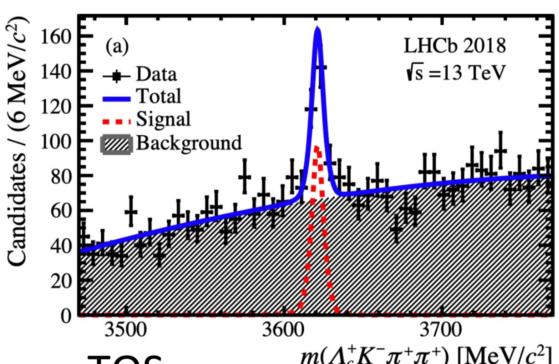
SCPMA. 64, 101062 (2021)

- Efficiency ratio study ($\frac{\varepsilon_{norm}}{\varepsilon_{sig}}$)
- Signal yields for normalization mode (N_{norm})

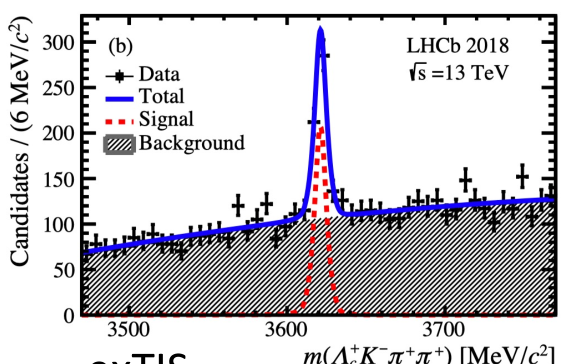
$$R = \frac{\sigma(\Omega_{cc}^{+})\times\mathcal{B}(\Omega_{cc}^{+} \to \Xi_c^{+}K^{-}\pi^{+})\times\mathcal{B}(\Xi_c^{+} \to pK^{-}\pi^{+})}{\sigma(\Xi_{cc}^{++})\times\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^{+}K^{-}\pi^{+}\pi^{+})\times\mathcal{B}(\Lambda_c^{+} \to pK^{-}\pi^{+})} = \frac{\varepsilon_{norm}}{\varepsilon_{sig}}\frac{N_{sig}}{N_{norm}} \equiv \alpha N_{sig}$$

- Fiducial region: 2.0<y<4.5 and 4<p_T<15 GeV/c
- $\frac{\varepsilon_{norm}}{\varepsilon_{sig}}$ and N_{norm} are measured by TOS and exTIS in L0

$\varepsilon\ [\times 10^{-3}]$	2016		2017		2018	
	TOS	exTIS	TOS	exTIS	TOS	exTIS
$r(\Xi_{cc}^{++}) = \varepsilon(\Xi_{cc}^{++})/\varepsilon(\Omega_{cc}^{+})$	0.32 ± 0.03	0.28 ± 0.02	0.55 ± 0.03	0.71 ± 0.02	0.61 ± 0.04	0.69 ± 0.02



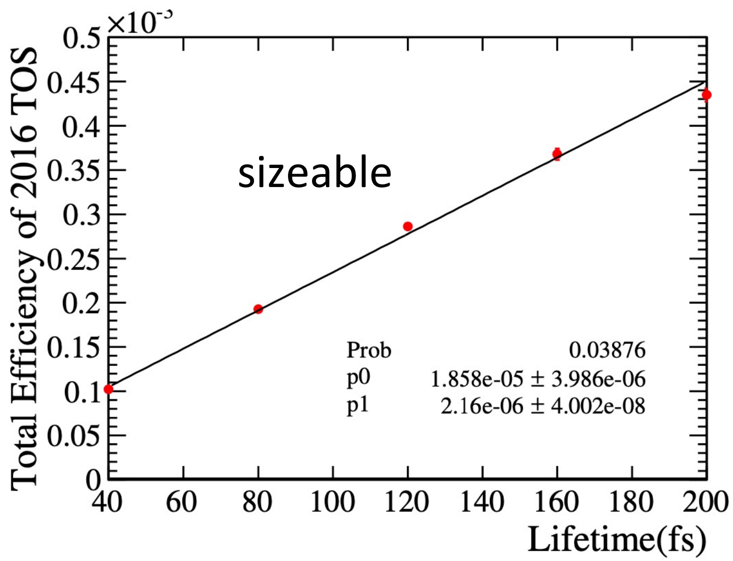
TOS

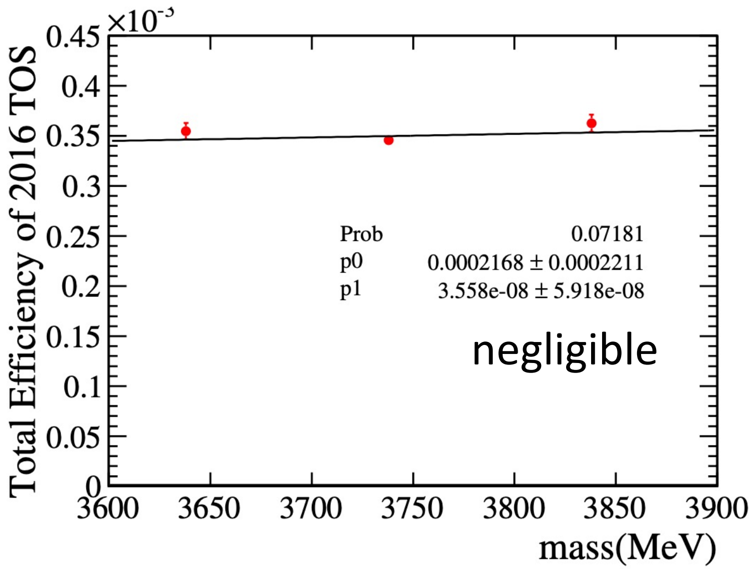


exTIS

Dependence check

- Unknown mass and lifetime would impact the efficiency ratio
- Would set upperlimits on different lifetime hypotheses
- The effect from mass is negligible





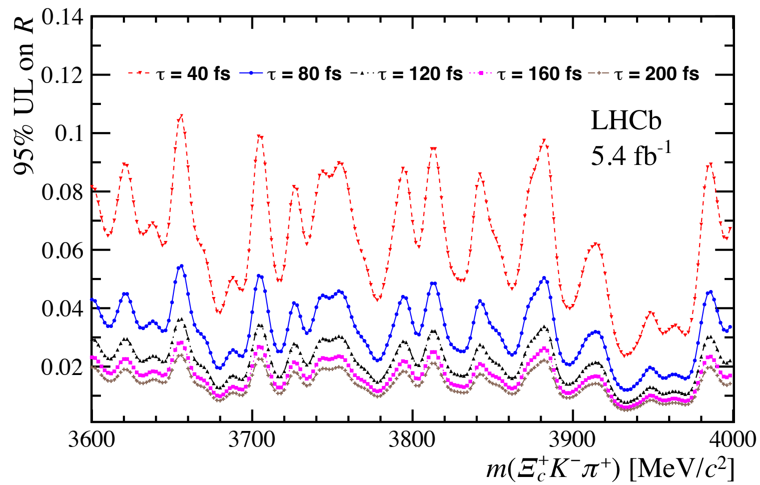
Results

SCPMA. 64, 101062 (2021)

- Systematic uncertainties

Source	R (%)
Fit model	3.5
Hardware trigger	11.2
Tracking	2.7
PID	0.9
Ξ_{cc}^{++} lifetime	12.0
Simulation/data difference	5.0
Total	17.7

- Upper limit scan in mass region on R for different lifetime hypotheses at 95%CL



Summary

- First search for the doubly charmed baryon Ω_{cc}^{+}
- Blinded analysis designed for two forseeable cases
- 3.2 σ (1.8 σ) for local (global) significance, the largest local significance found around 3876.1 MeV
  - Larger than common mass predictions
  - Enhanced by significant lifetime requirement (t/σ_t>5σ)
  - Enhanced by intermediate Ω_c^{0*} contribution $\Omega_{cc}^{+} \rightarrow \Omega_c^{0*}(\Xi_c^{+}K^{-})\pi^{+}$
- Upper limit scan in mass region on R for different lifetime hypotheses at 95%CL
- Upgraded detectors, improved trigger conditions, additional decay modes, and larger data samples will further increase the Ω_{cc}^{+} signal sensitivity.