LHCb experiment on hadron spectroscopy

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On Behalf of the LHCb Collaboration

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Hadron spectroscopy studies at LHCb

- Benefit from excellent tracking, particle identification and efficient trigger system, LHCb is a unique laboratory for hadron spectroscopy studies.

- In this talk, only focus on most recent results on

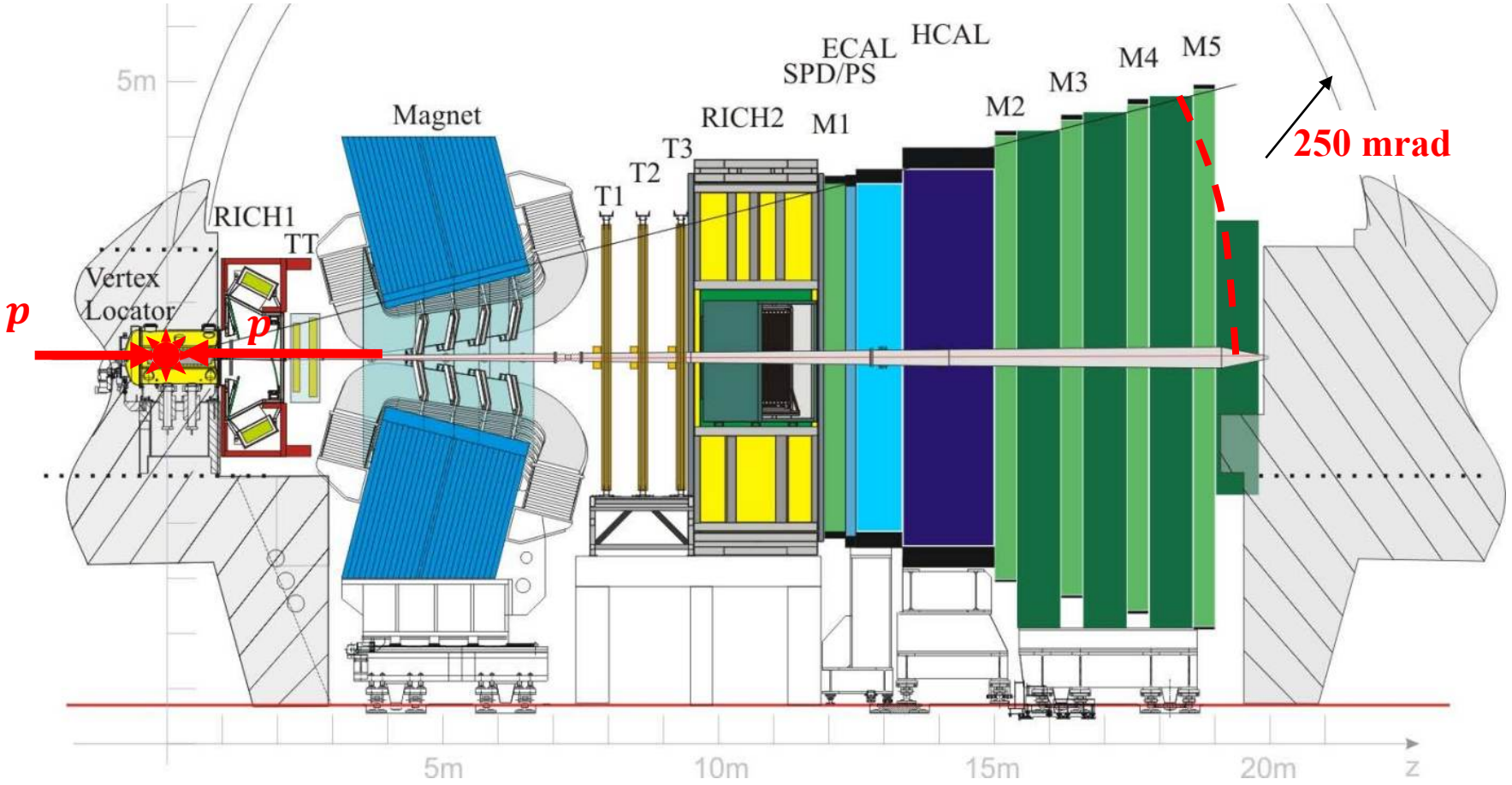
 - Pentaquark studies

 - Observation of excited $\boldsymbol{\Omega_c}$ states

 - Discovery of doubly charmed baryon $\boldsymbol{\Xi_{cc}^{++}}$

LHCb Detector

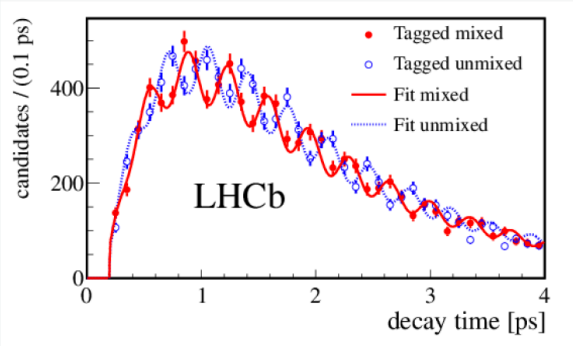
LHCb, Int. J. Mod. Phys. A30 (2015) 1530022; IJMPA 30 (2015) 1530022



Detector performance

Vertexing

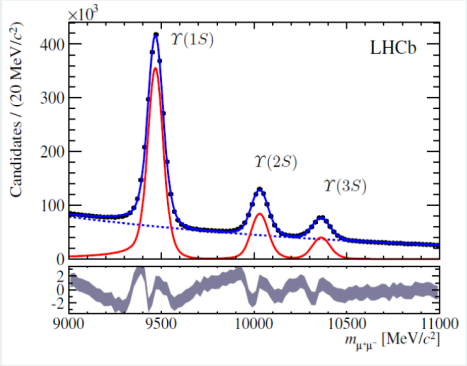
B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

Tracking

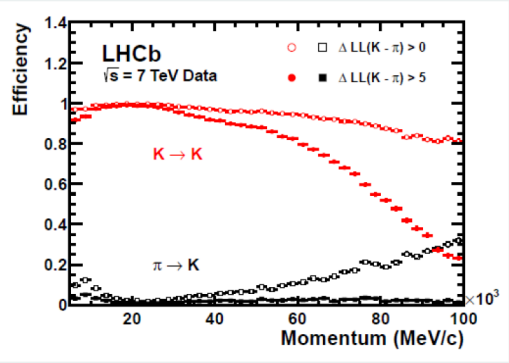
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

PID

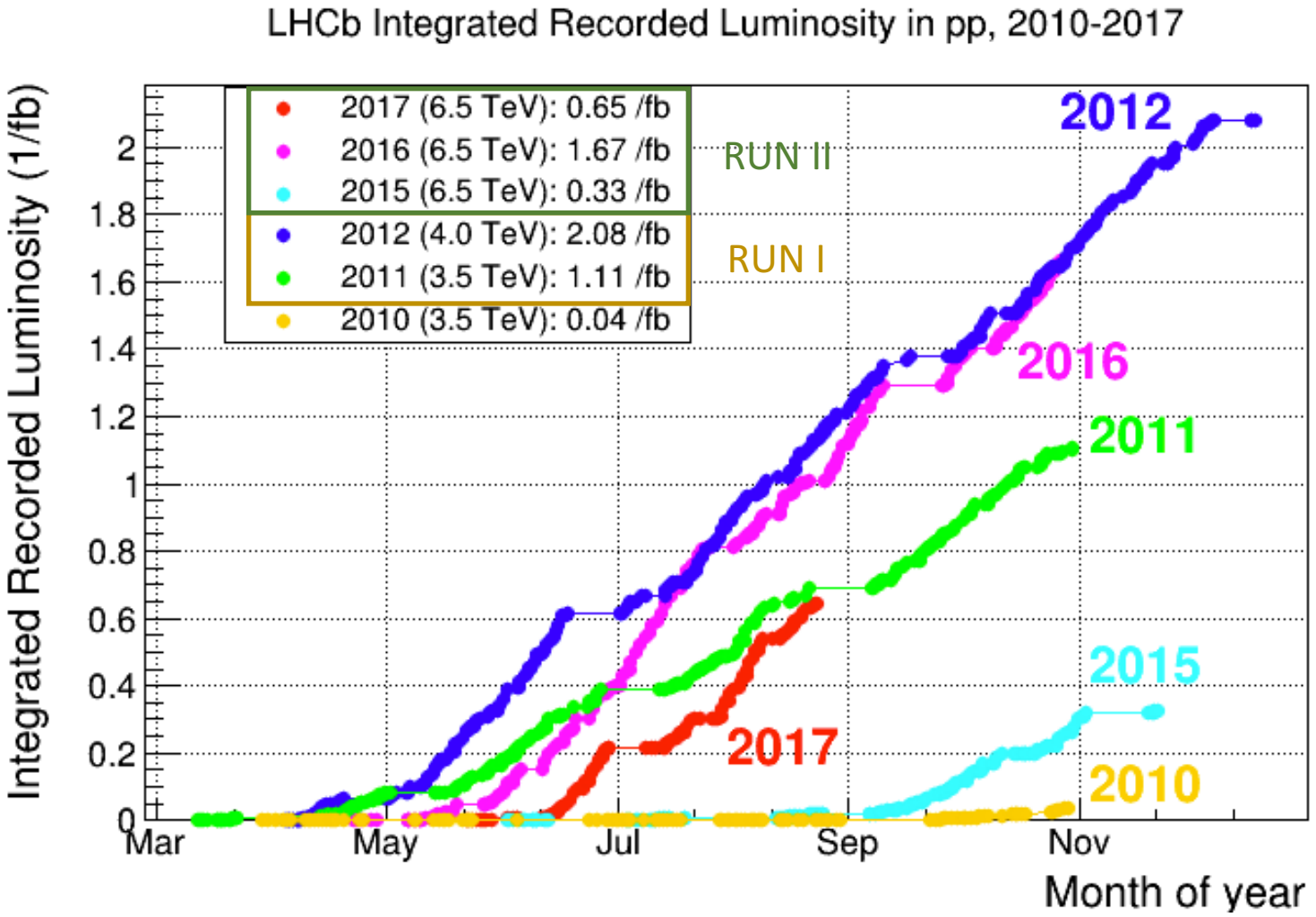
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

Impact parameter:	$\sigma_{IP} = 20\ \mu\text{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%\ (5 - 100\ \text{GeV}/c)$
Mass :	$\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $\text{m}_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

Data Samples

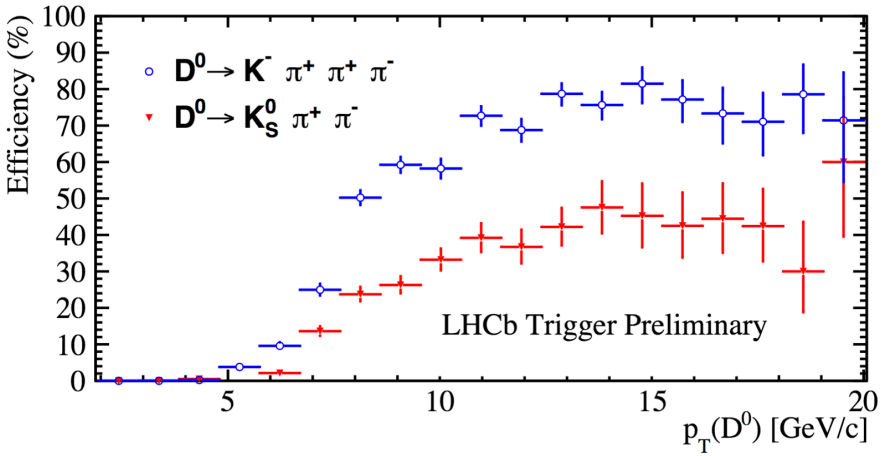


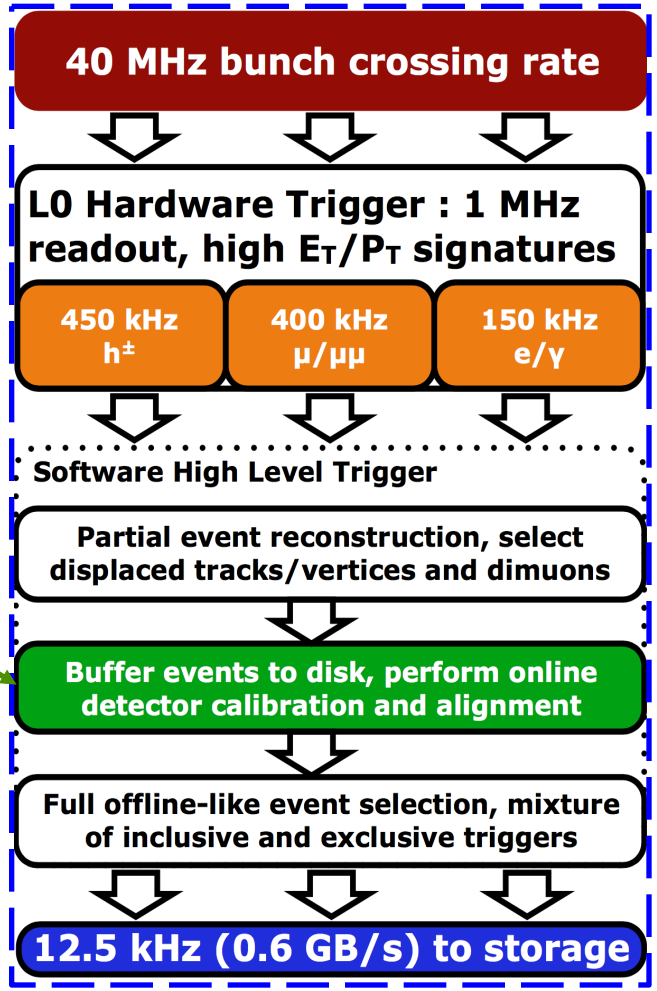
Comput. Phys. Commun. 208 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb Trigger

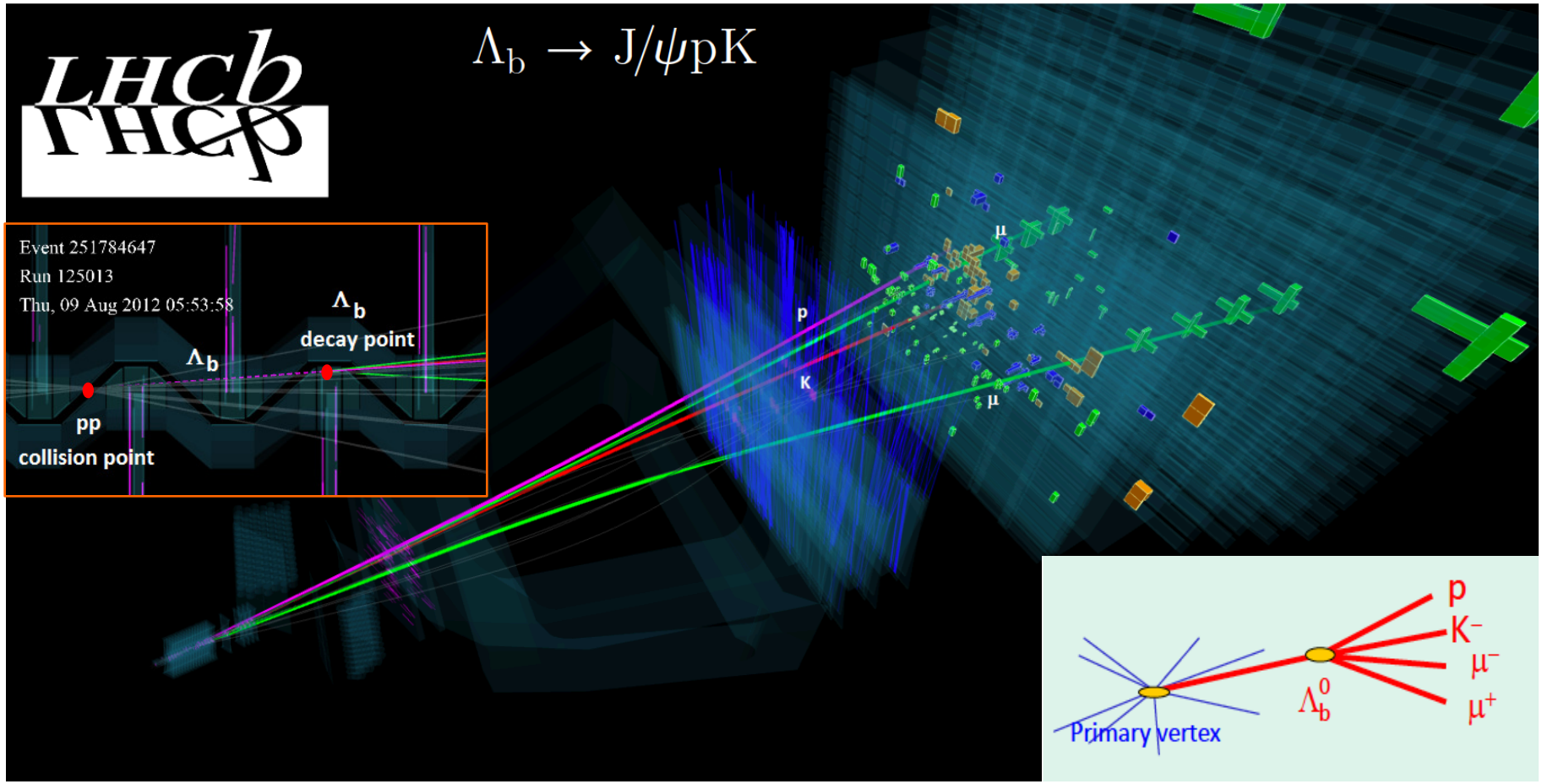
- Versatile two stage trigger
- RUN II Turbo stream: Candidates reconstructed at trigger level saved for offline analyses directly
- Efficient trigger for hadronic channels

New in RUN II





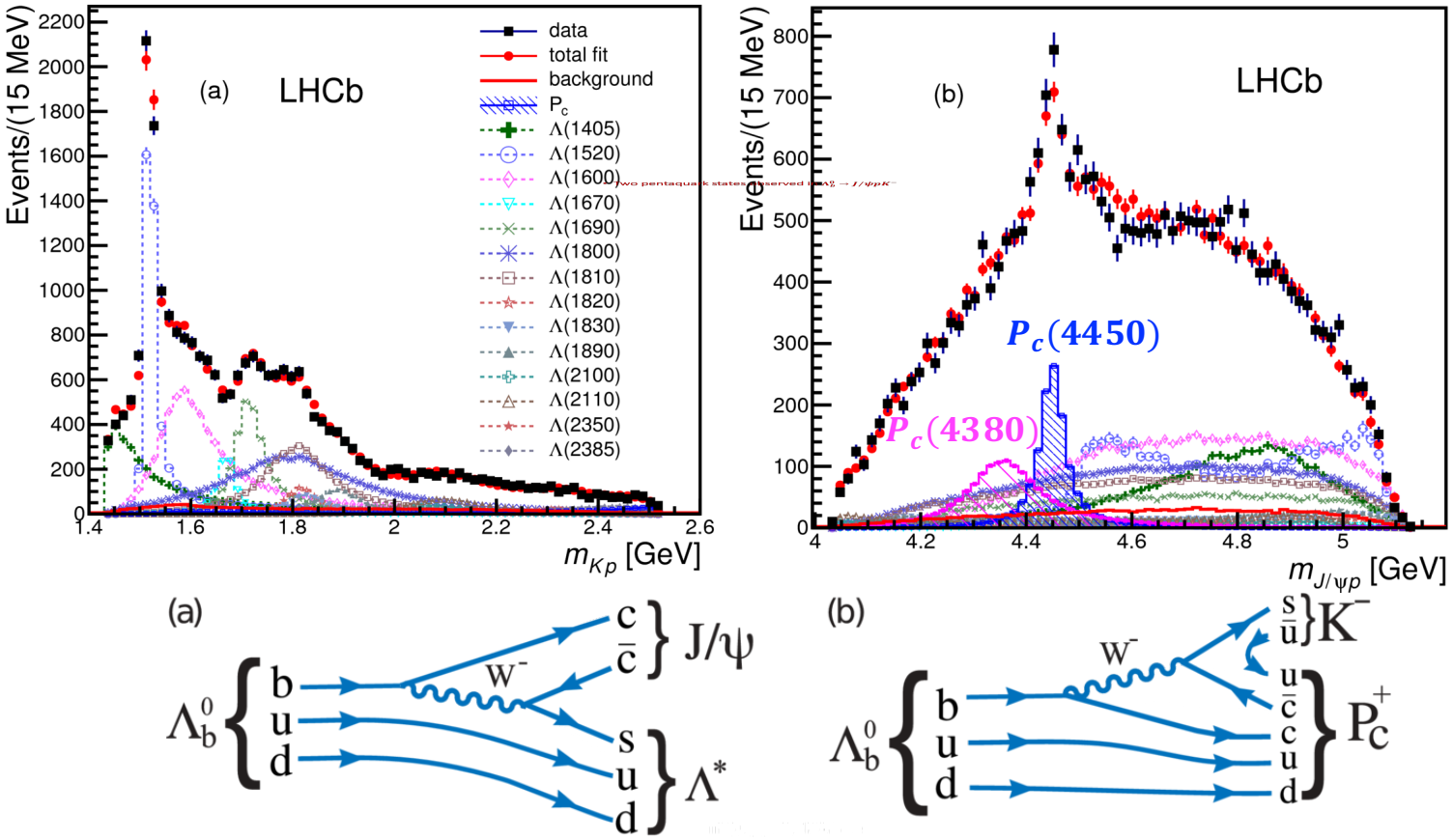
Pentaquark studies



Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

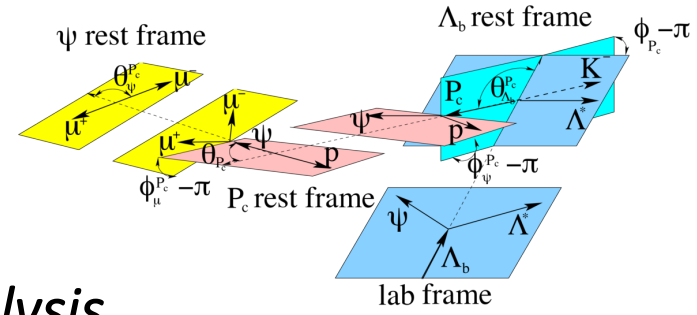
- Two pentaquark states observed in $\Lambda_b^0 \to J/\psi p K^-$



Discovery of pentaquark states

- Amplitude analysis reveals the properties **LHCb, PRL 115(2015) 072001**

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ



- Confirmed by *a model independent analysis*

LHCb, PRL 117 (2016) 082002

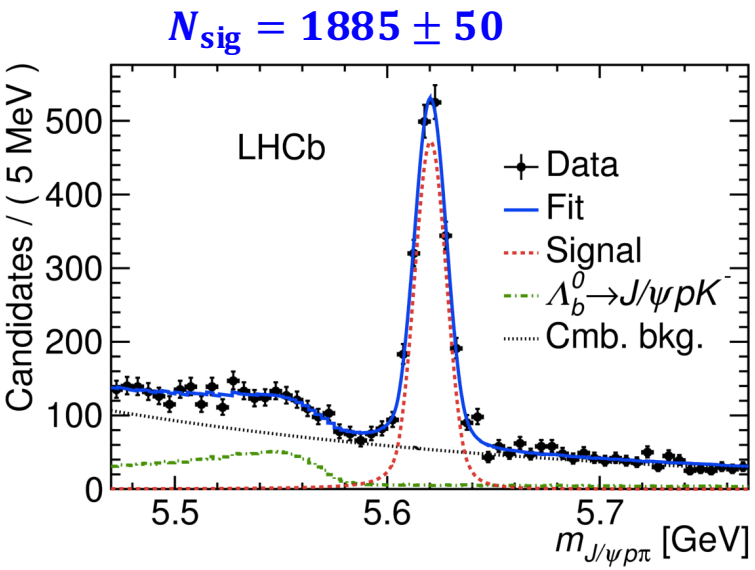
- Production & decay **LHCb, Chin. Phys. C 40 (2016) 011001**

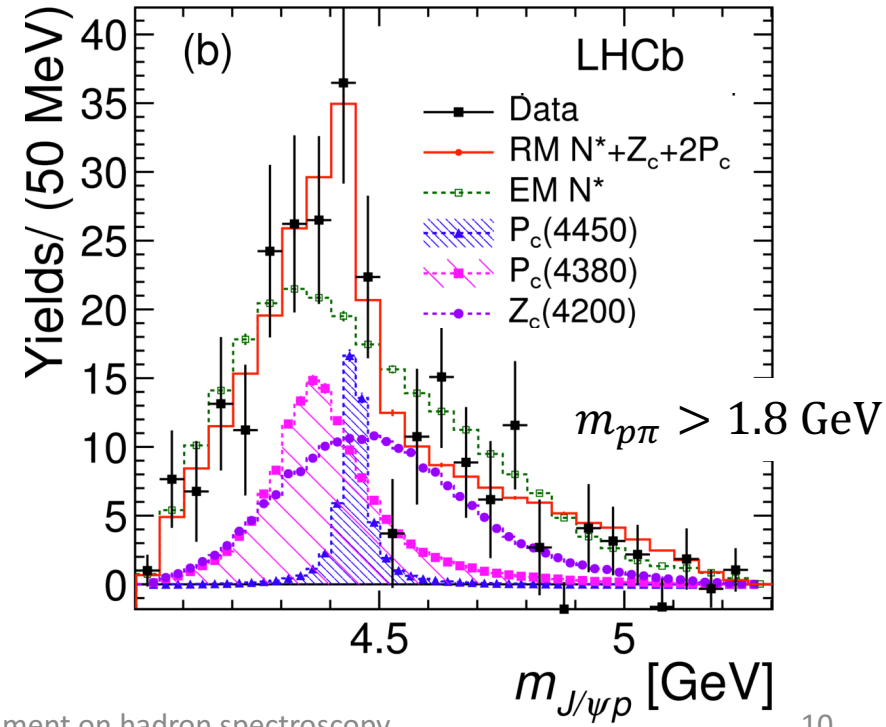
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+\,0.46}_{-\,0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+\,0.22}_{-\,0.18}\right) \times 10^{-5}$$

Study of $\Lambda_b^0 \to J/\psi p\pi^-$

LHCb, PRL 117(2016) 082003

- Cabbibo suppressed mode with less statistics
- Exotic Z contributions in $J/\psi\pi$
- Fit with 2 pentaquarks + $Z_c(4200)$ favored by 3σ compared to no exotic contributions





Observation of $\Lambda_b^0 \to \chi_{c1,2} p K^-$

LHCb, PRL 119 (2017) 062001

- $Pc(4450)$ close to $\chi_{c1} p$ threshold, triangle singularity ?

Guo et al., PR D92(2015) 071502

- Study with radiative $\chi_{cJ} \to J/\psi\gamma$ decays

  Mass constraint on χ_{c1} to improve resolution, forces χ_{c2} to lower mass

- First observation of this mode,

  full amplitude analysis foreseen

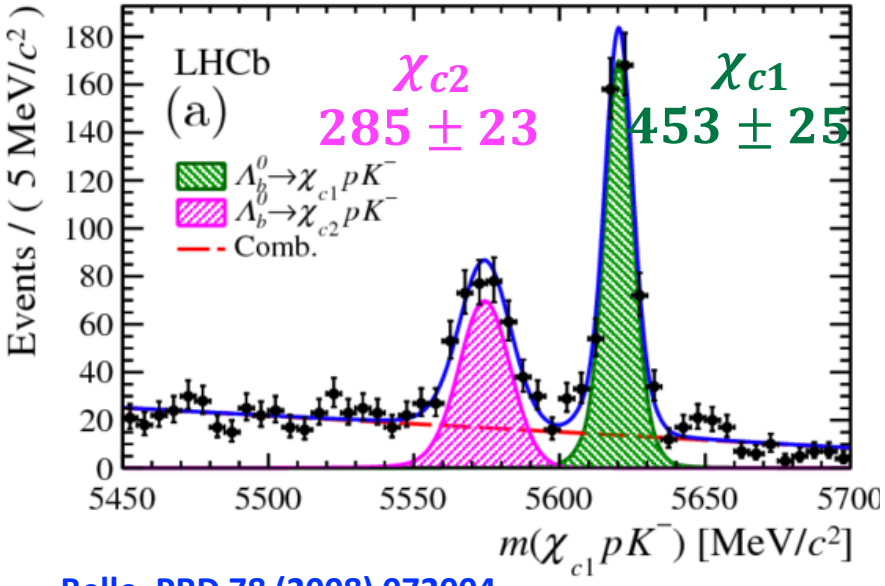
  with RUN II data added in

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)} = 1.02 \pm 0.10 \pm 0.02 \pm 0.05$$

Suppressed in $B \to \chi_{cJ} K$ decays



Belle, PRD 78 (2008) 072004
BaBar, PRL 102 (2009) 132001
LHCb, NPB 874 (2013) 663

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

LHCb, PLB772 (2017) 265

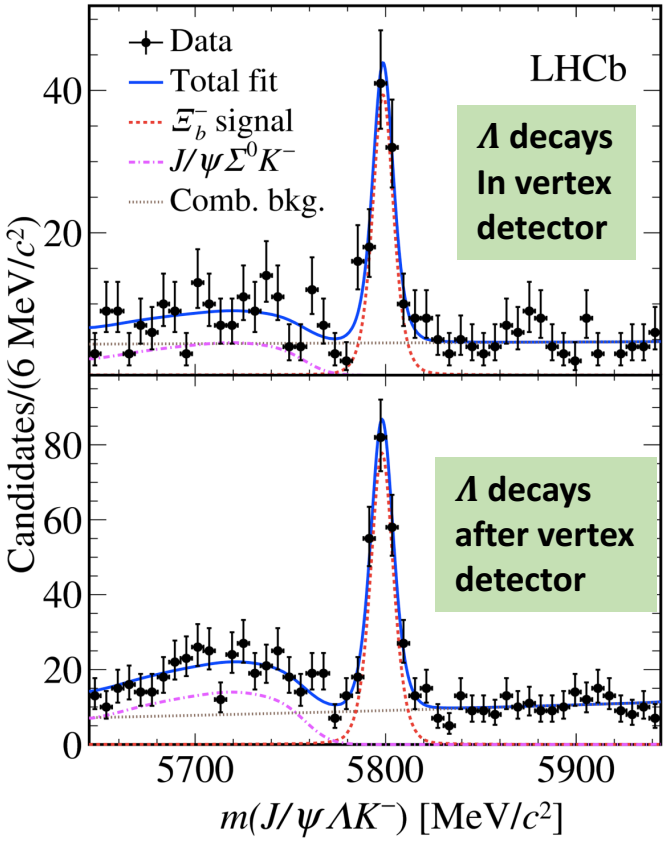
- Look for $udsc\bar{c}c$ pentaquark in this mode
- First observation with RUN I data
- ~300 candidates seen

Wu et al., PRL 105 (2010) 232001
Chen et al., PRC 93 (2016) 065203

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}$$

$$m(\Xi_b^-) - m(\Lambda_b) = 177.08 \pm 0.47 \pm 0.16\,\mathrm{MeV}/c^2$$

(one of the two world best measurements)

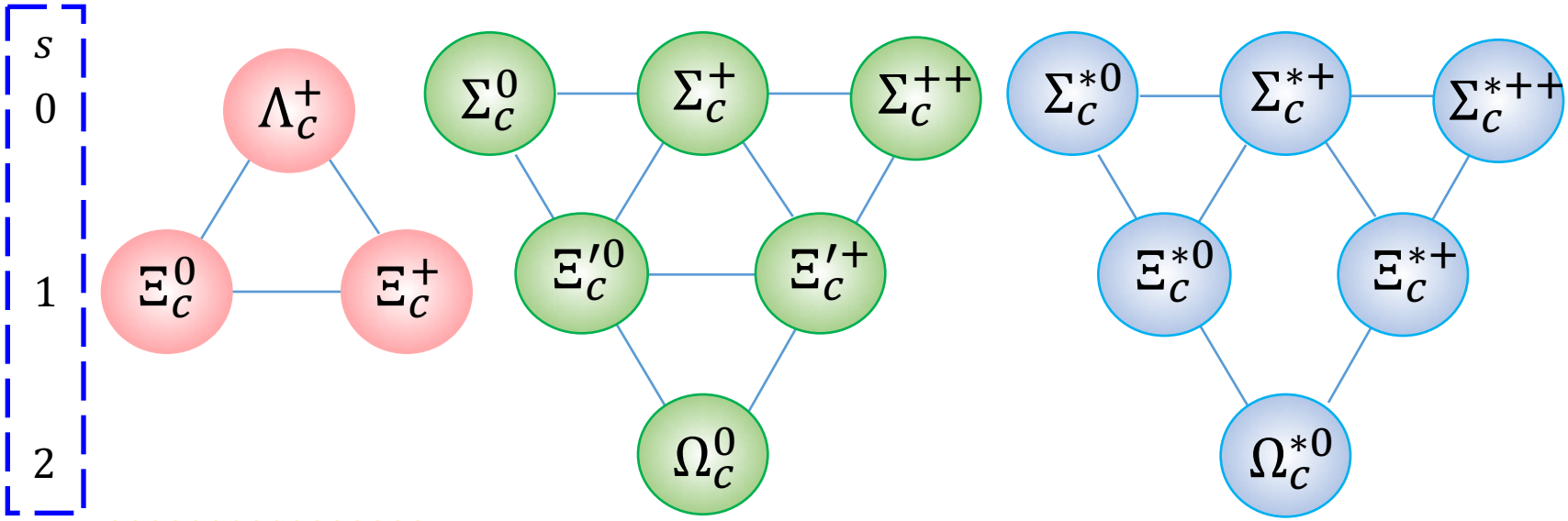


- Full amplitude analysis foreseen with RUN II data added in

Observation of exited Ω_c states

Jaffe, Phys. Rep. 409 (2005) 1

- Single charmed baryons predicted to form SU(3) multiplets: $3 \otimes 3 = \bar{3} \oplus 6$



$j = 0, J^P = \frac{1}{2}^+$ $j = 1, J^P = \frac{1}{2}^+$ $j = 1, J^P = \frac{3}{2}^+$

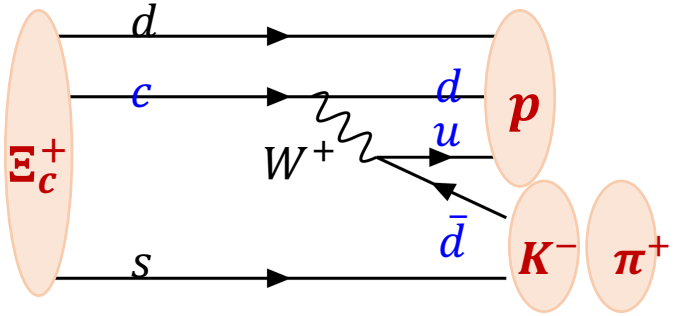
$|\{qq\}\bar{\mathbf{3}}_c(A)\bar{\mathbf{3}}_f(A)0^+(A)\rangle$ $|\{qq\}\bar{\mathbf{3}}_c(A)\mathbf{6}_f(S)1^+(S)\rangle$ $|\{qq\}\bar{\mathbf{3}}_c(A)\mathbf{6}_f(S)1^+(S)\rangle$

- All ground states are observed; Excited $\Lambda_c^+, \Sigma_c, \Xi_c$ states have been reported but no excited Ω_c^0 states were observed before LHCb

Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

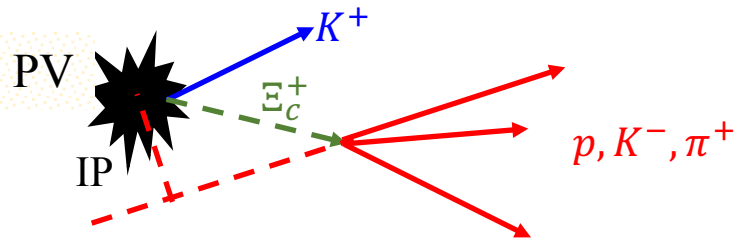
- 3 fb^{-1} Run I + 0.3 fb^{-1} Run II pp collisions data
- Decay: $\Omega_c^{**0} \to \Xi_c^+ K^-,\ \Xi_c^+ \to pK^-\pi^+$



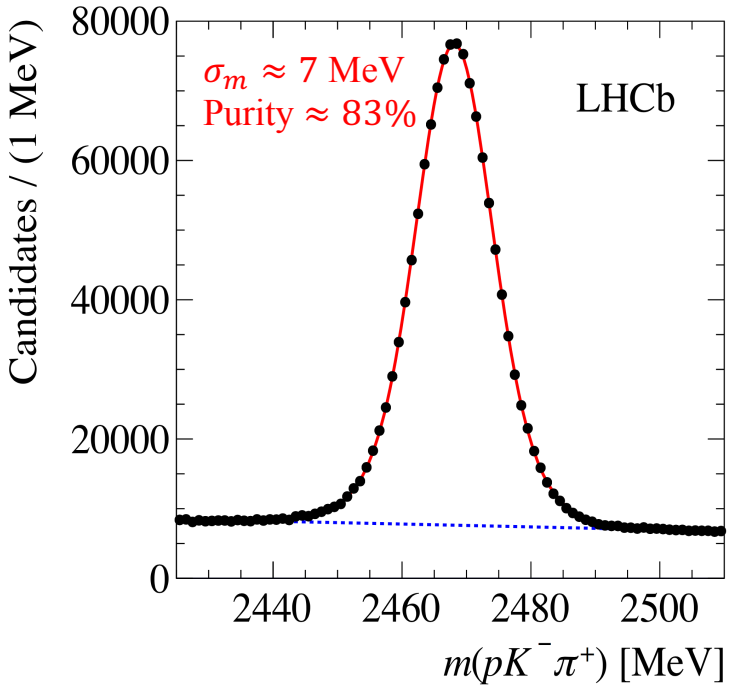
Selections: particle ID, displaced vertex

$\tau(\Xi_c^+) \approx 0.45$ ps, Ξ_c^+ decay vertex well separated from primary pp collisions (PV)

Note: decay time resolution ~ 45 fs



Cabibbo suppressed $c \to dW^+$ decay, but much higher reconstruction efficiency



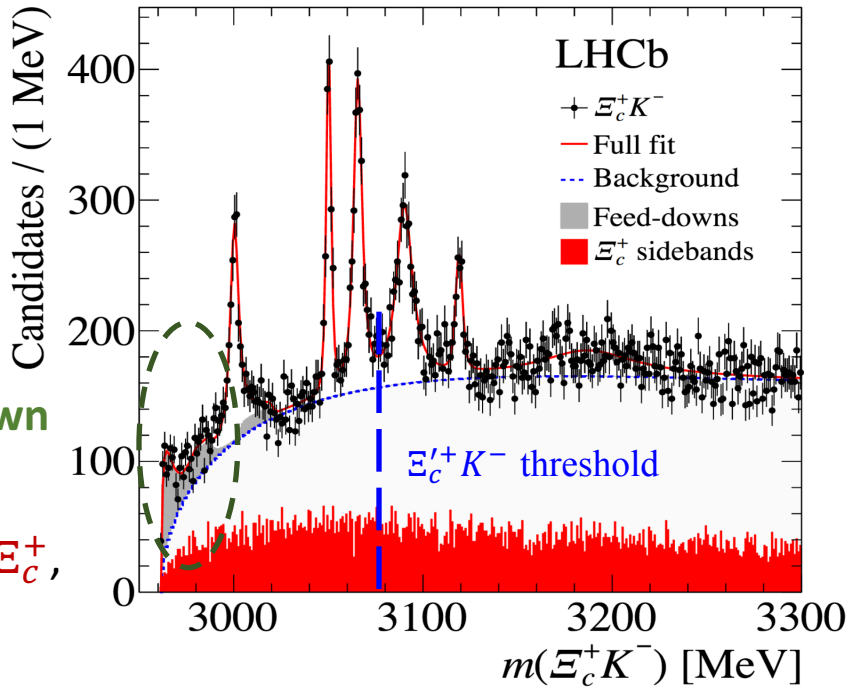
Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

- 5 narrow states & evidence for 6th broader state at high mass

Resonance	Mass (MeV)	Γ (MeV)	$N_\sigma = \sqrt{\Delta\chi^2}$
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	20.4
		< 1.2 MeV, 95% CL	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	10.4
		< 2.6 MeV, 95% CL	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4

Fit quality improves when including a broad structure or multiple states around 3200 MeV



Feed-down

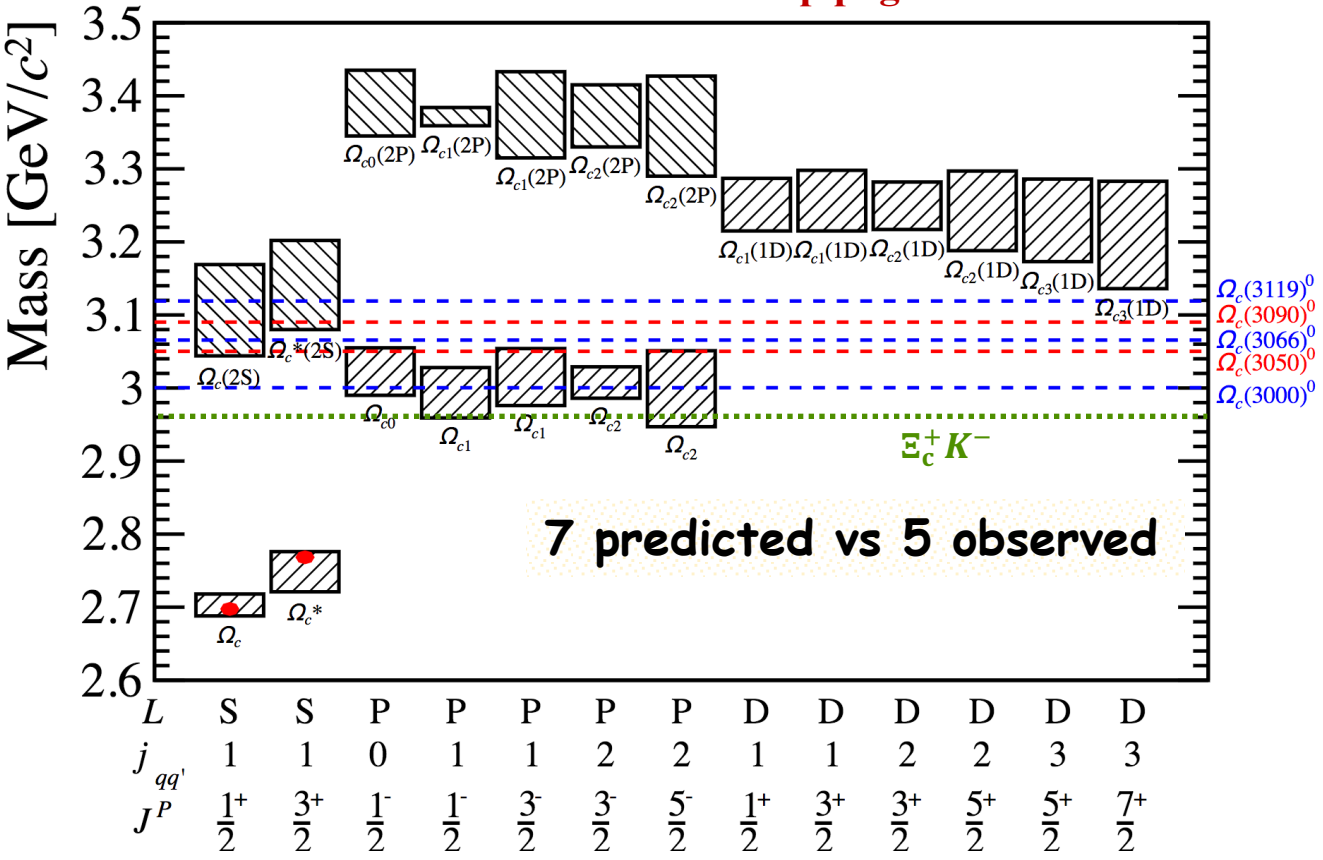
Feed-down: $\Omega_c^{**0} \to K^- \Xi_c'^+, \Xi_c'^+ \to \gamma \Xi_c^+$, $m(\Xi_c^+ K^-)$ mass peaks shifted

Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

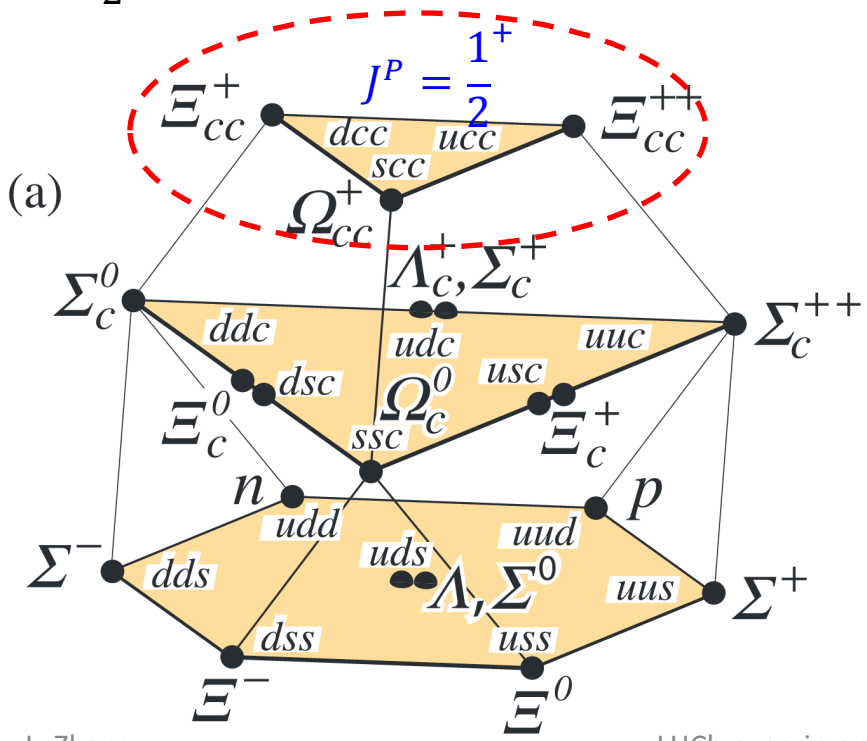
- Matching between observed peaks and predictions requires spin-parity information: studied with three-body decays or in decays of heavier baryons

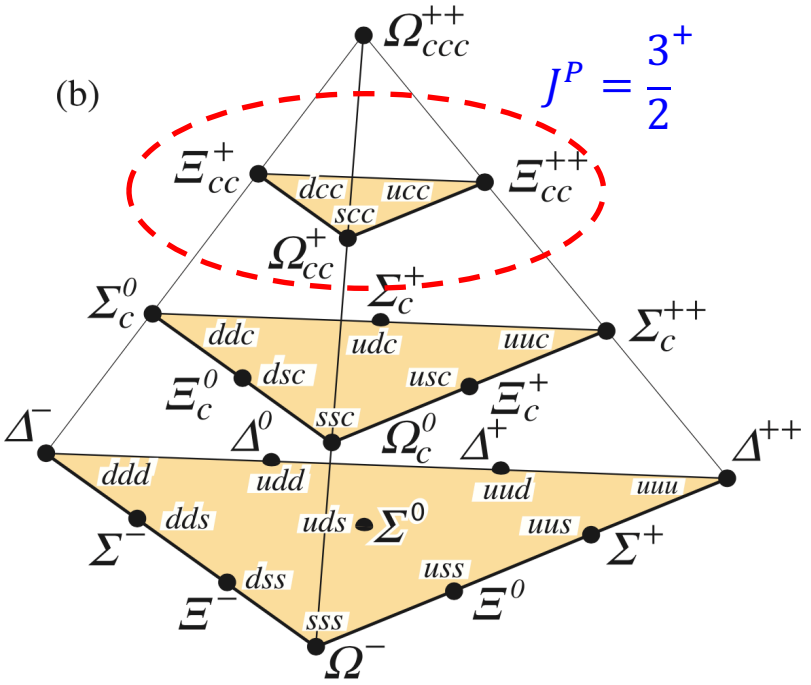
See backup pages for the references



Doubly charmed baryons

- Predicted to form two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^+(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Omega_{cc}^+(ccs)$
- $J^P = \frac{3}{2}^+$ expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic interaction
- $J^P = \frac{1}{2}^+$ states decay weakly with a c quark transformed to lighter quarks



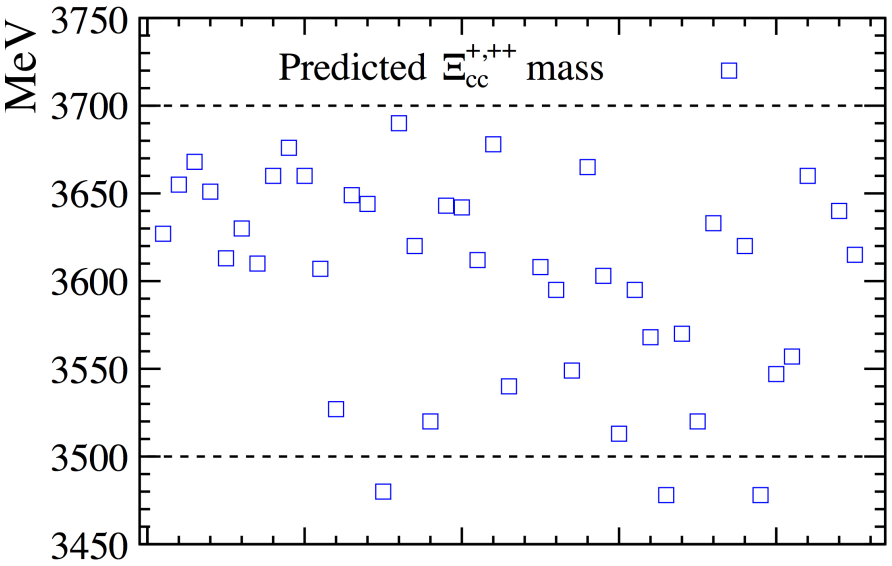


Doubly charmed baryons

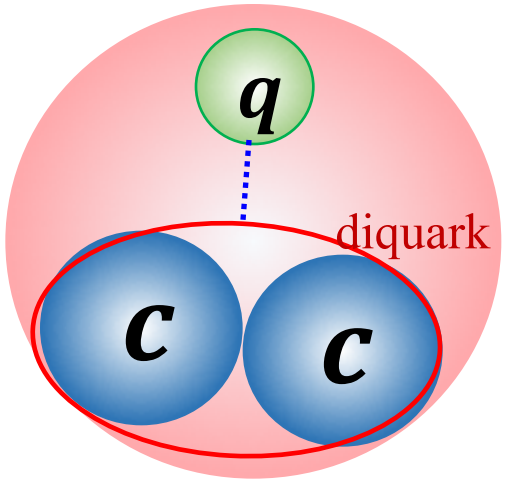
- Masses of ground state and excitations by many theoretical models
  - Predicted $\Xi_{cc}^{+,++}$ masses in range $3.5 - 3.7$ GeV, $M(\Omega_{cc}^{+}) \approx M(\Xi_{cc}) + 0.1$ GeV
  - Mass splitting between Ξ_{cc}^{+} and Ξ_{cc}^{++} only a few MeV due to u, d symmetry

- Lattice QCD computations:

$M(\Xi_{cc}) \approx 3.6$ GeV, $\quad M(\Omega_{cc}^{+}) \approx 3.7$ GeV



HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson Qq

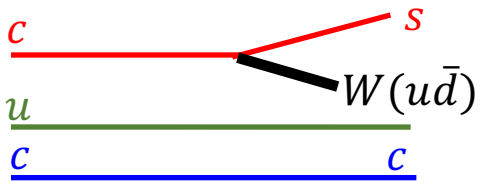


See backup pages for the references

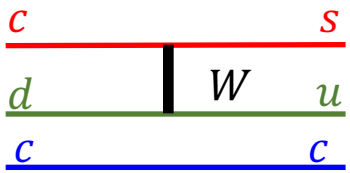
Doubly charmed baryons

- Lifetimes known to be affected by spectator decays + non-spectator decays and Pauli interference, qualitatively

Spectator (Γ_s)



W-exchange (W)



Ξ_{cc}^{++} Negative Pauli interference maks $\Gamma\downarrow;\tau\uparrow$

Ξ_{cc}^{+} Additional W-exchange process makes $\Gamma\uparrow;\tau\downarrow$

- Expectation: $\tau(\Xi_{cc}^{++}(ccu)) \gg \tau(\Xi_{cc}^{+}(ccd))$

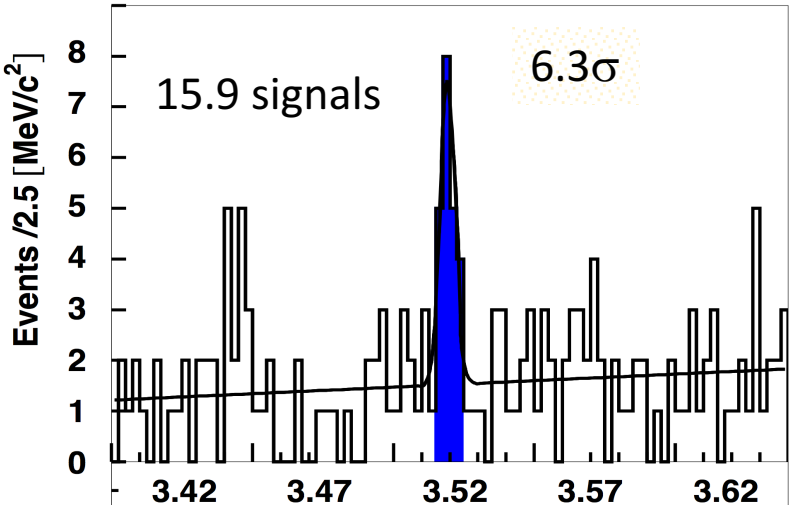
- Calculations give $\tau(\Xi_{cc}^{++}) \in [\,200-700]$ fs

See backup pages for references

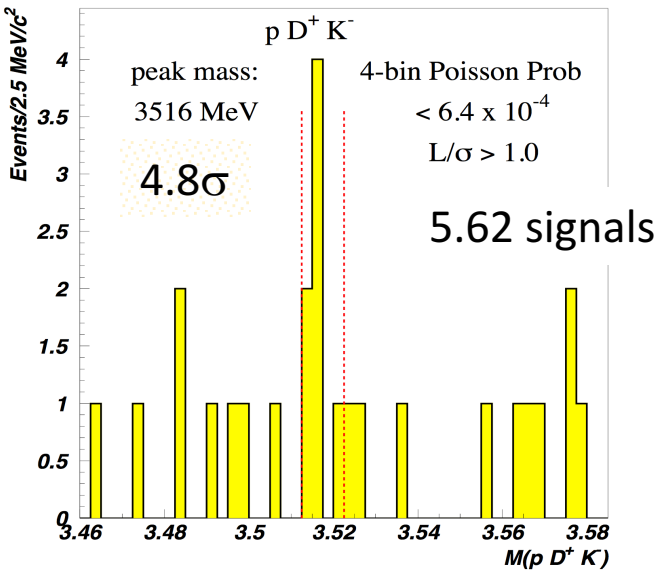
Results from SELEX

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ decays
  - **Short lifetime**: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
  - **Large production**: $R = \frac{\sigma(\Xi_{cc}^+) \times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - **Mass (combined)**: 3518.7 ± 1.7 MeV

$\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ **PRL 89 (2002) 112001**



$\Xi_{cc}^+ \to p D^+ K^-$ **PLB 628 (2005) 18**



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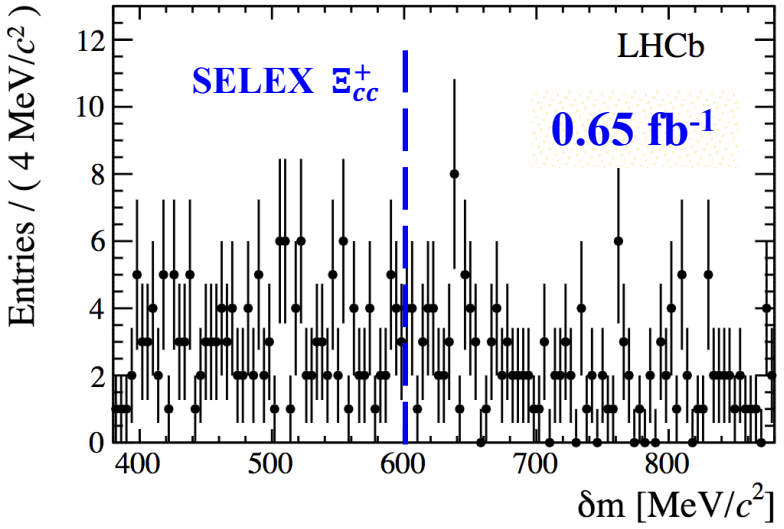
  - **Mass (combined):** 3518.7 ± 1.7 MeV

Very puzzling

- **Not confirmed by FOCUS, Belle, Babar, neither by LHCb with 0.65 fb^{-1} data**
- **These experiments have very different production environment than the SELEX**



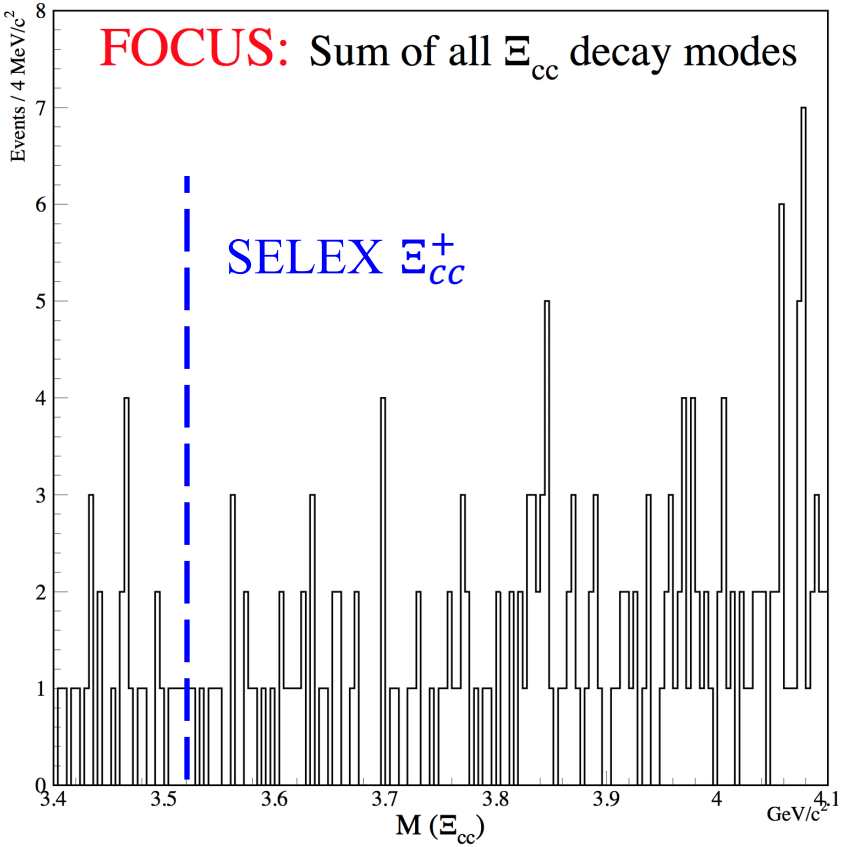
Results from FOCUS

- FOCUS (Fermilab E831) studies charm hadrons produced in photon-nuclear fixed target collisions
- FOCUS didn't confirm Ξ_{cc}^{+} observed by SELEX in $\Lambda_c^+ K^- \pi^+$ decay

Decay Mode	$\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$	
Experiment	FOCUS	SELEX
Ξ_{cc} Events	<2.21 @ 90%	15.8
Reconstructed Λ_c	$19,444 \pm 262$	1650
Relative Efficiency	5%	10%
Ξ_{cc}/Λ_c^+	$<0.23\%$ @ 90%	9.6%
$\frac{\text{SELEX}}{\text{FOCUS}}$ Rel $\frac{\Xi_{cc}}{\Lambda_c}$ Prod	>42 @ 90%	

- Other modes also studied: $\Xi_{cc}^{+} \to \Lambda_c^+ X$, $D^0 X$ $D^+ X$, no SELEX-like signal peak observed

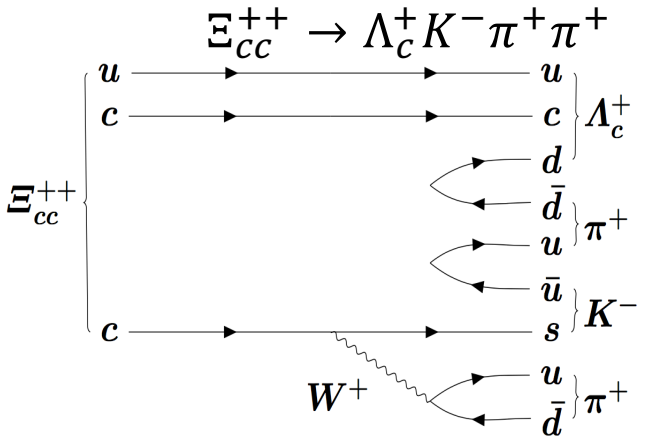
Nucl. Phys. Proc. Suppl. 115 (2003) 33

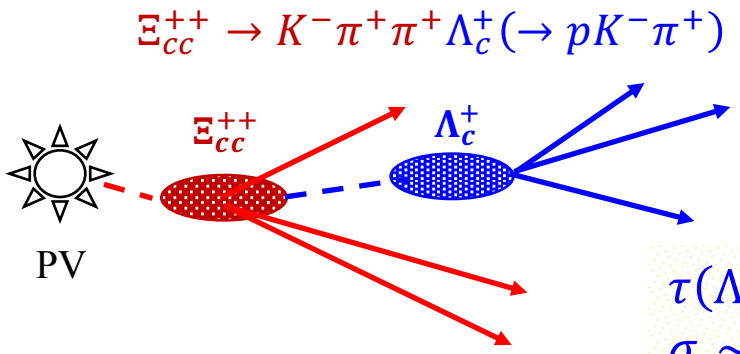


Search for $\Xi_{cc}^{++}(ccu)$ at LHCb PRL 111 (2017) 180001

- Expected to have longer lifetime than Ξ_{cc}^{+}, higher efficiency at LHCb
- Decay: $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$, branching fraction up to 10%

Yu et al., arXiv:1703.09086





$\tau(\Lambda_c^+) \approx 200$ fs
$\sigma_\tau \sim 45$ fs

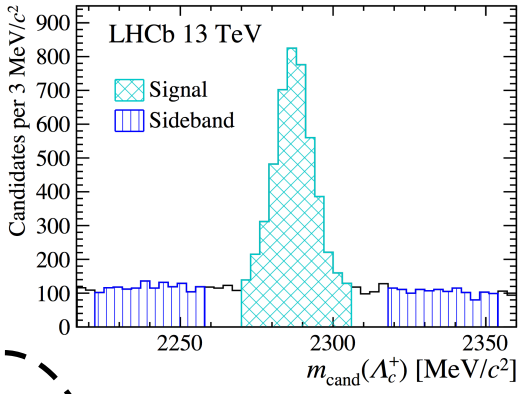
- Data sample: LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - Dedicated exclusive trigger ensuring high efficiency, full event reconstruction at trigger level
  - Run I data (2012) also analyzed for cross-check

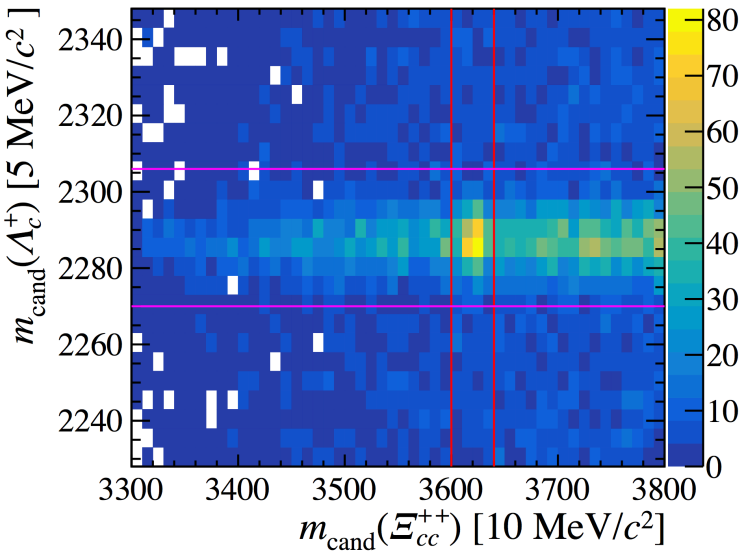
Mass spectrum

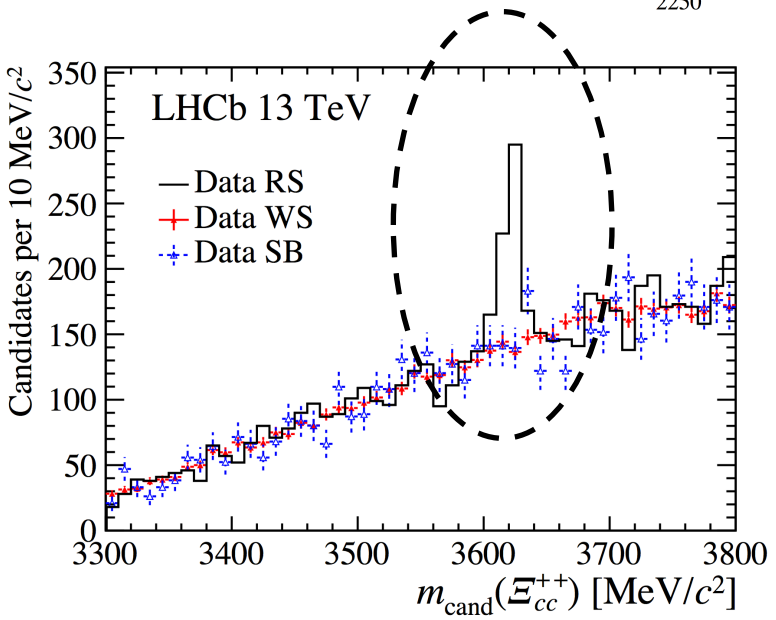
PRL 111 (2017) 180001

- A significant structure in right sign (RS) combinations: $\Lambda_c^+ K^- \pi^+ \pi^+$
- Not present in wrong sign (WS) combinations: $\Lambda_c^+ K^- \pi^+ \pi^-$
- Not observed for Λ_c^+ background candidates
- Distributions similar except the peak in RS
- Signal candidates only present in Λ_c^+ signal region

A significant peak!





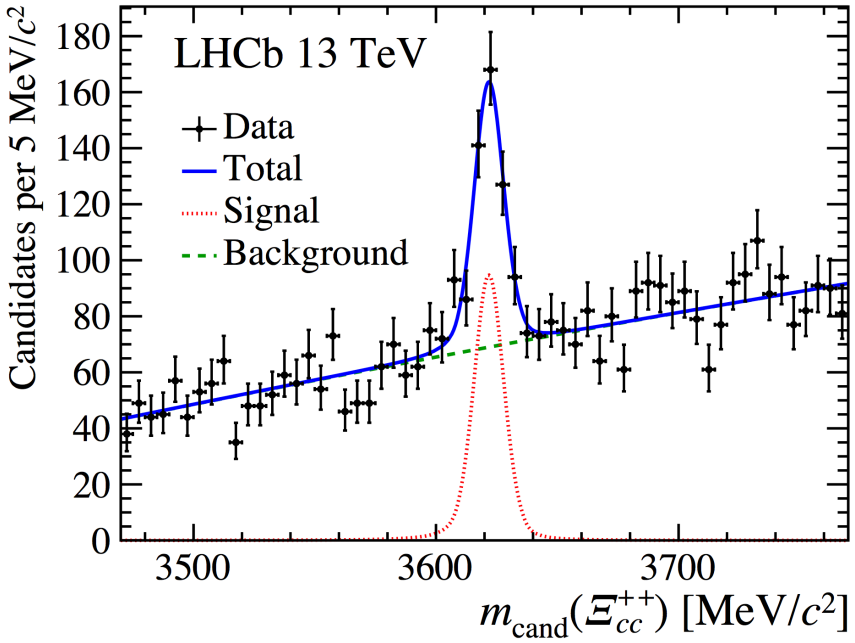


Fitting the mass peak

PRL 111 (2017) 180001

- Studying Λ_c^+-mass corrected mass: $m_{\rm cand}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\rm PDG}(\Lambda_c^+)$
  - Signal yield: 313 ± 33
  - Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - Local significance $> 12\sigma$

$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$



Systematic uncertainties

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

Fitting the mass peak

PRL 111 (2017) 180001

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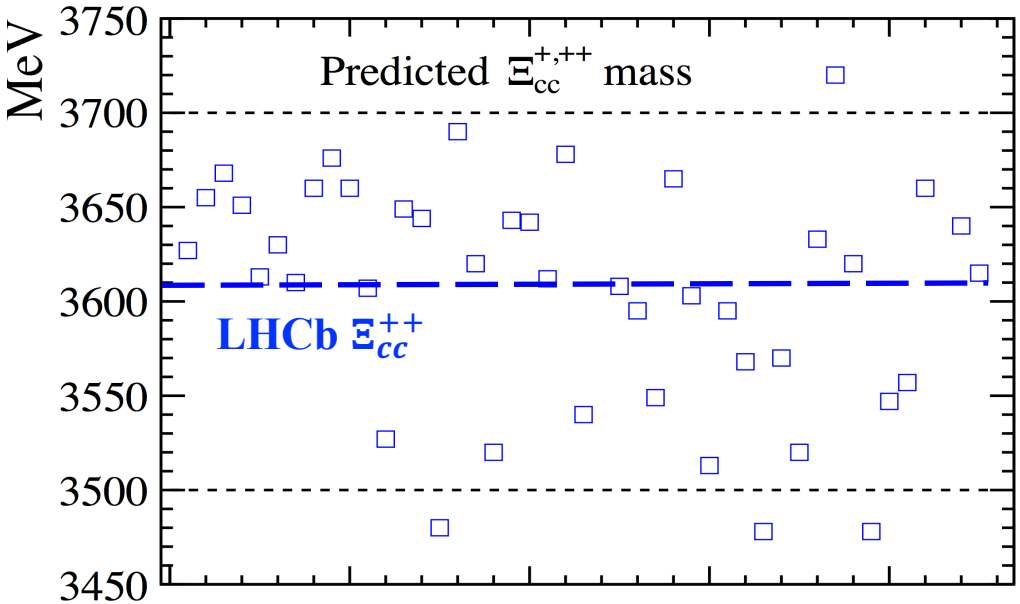
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$

Value consistent with many theoretical calculations, especially LQCD

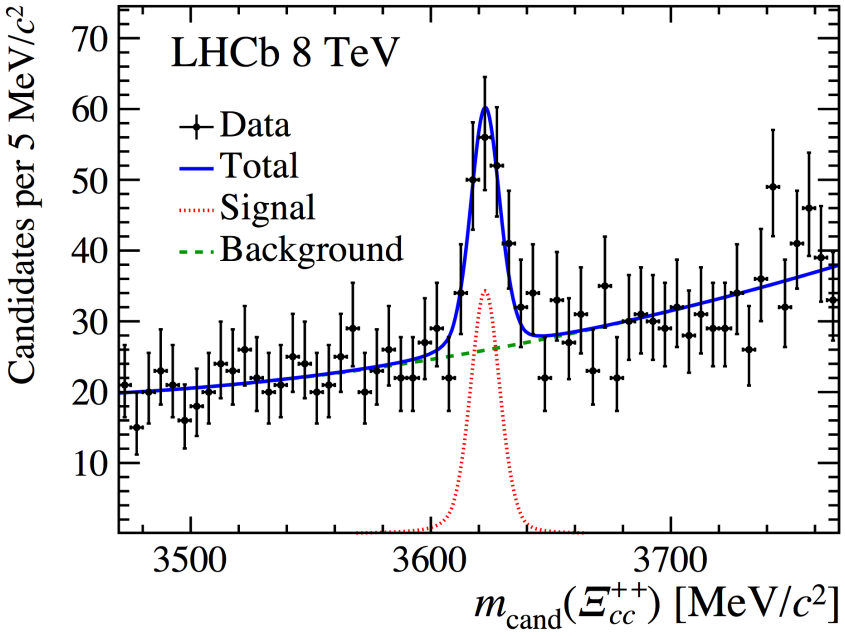


See backup pages for references

Test with RUN I data

PRL 111 (2017) 180001

- Signal peak presents in RUN I data sample with significance $> 7\sigma$



$N(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) = 113 \pm 21$

Resolution: 6.6 ± 1.4 MeV

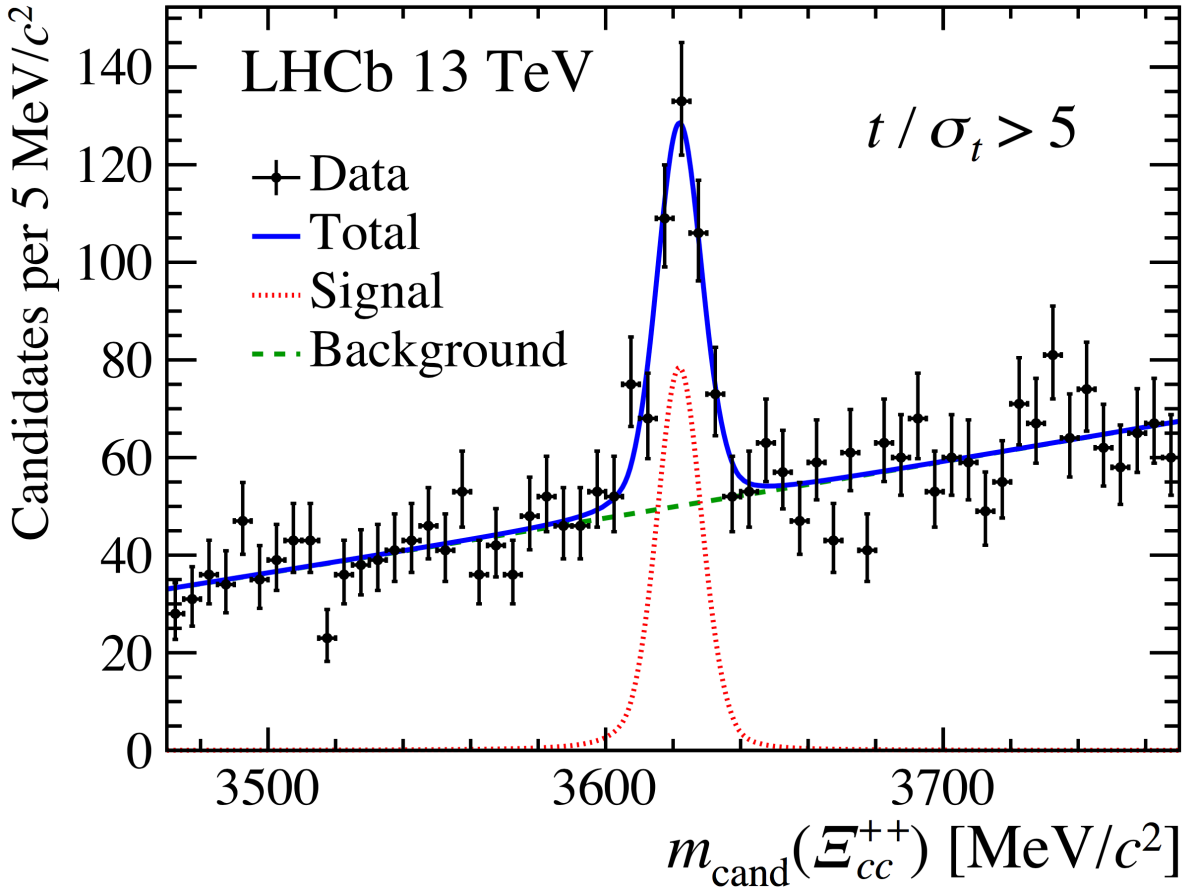
$\delta M(\text{run I, run II}) = 0.8 \pm 1.4$ MeV

Consistent between two samples

Signal properties

PRL 111 (2017) 180001

- Peaking structure remains significant ($> 12\sigma$) after requiring minimum decay time, $t > 5\sigma_t$. It is indeed a weak decay.



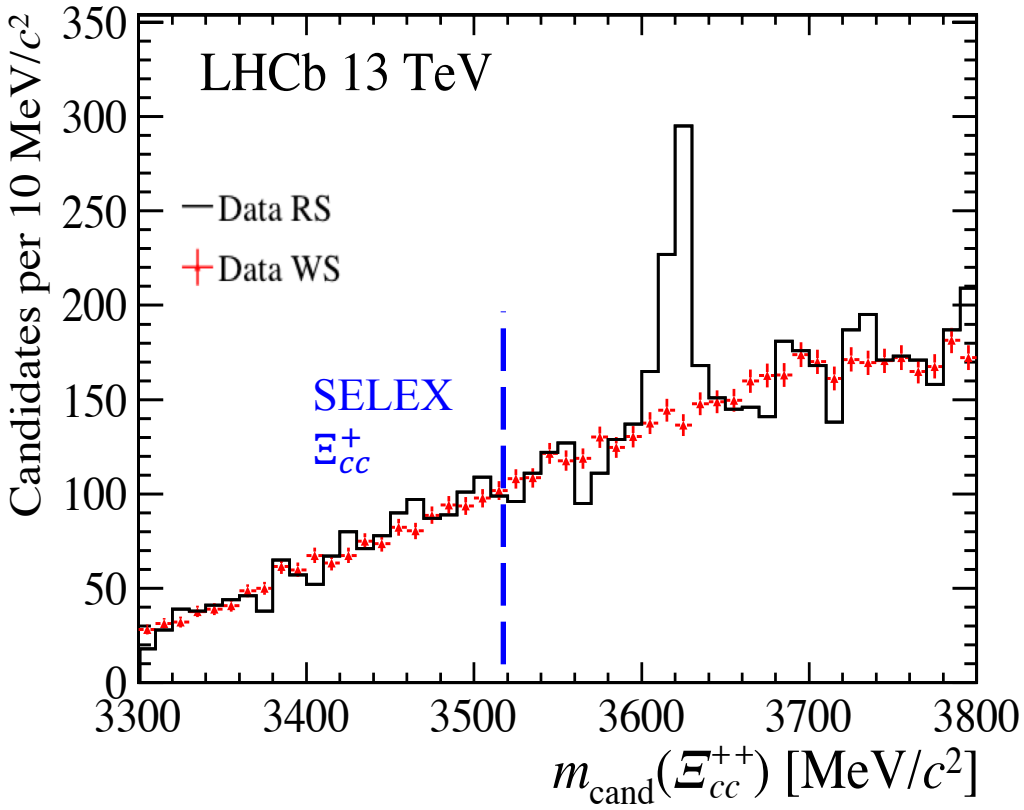
Comparison with SELEX

PRL 111 (2017) 180001

- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV
  - ➢ Inconsistent with being isospin partners

Hwang and Chung, PRD 78(2008) 073013;
Brodsky et al., PLB 698 (2011) 251;
Karliner and Rosener, arXiv: 1706.06961

- Production: $N(\Xi_{cc})/N(\Lambda_c^+)$ much smaller in LHCb result



Summary

- LHCb has made important contributions to the understanding of hadron spectroscopy

  — Observation/study of excited $B(D)$mesons & $b(c)$ baryons

  $B_1(5721), B_2^*(5747), B_J(5840), B_J(5960), \Xi_b', \Xi_b^*, \Omega_c^{**}$,...

  — Observation/study of exotic states

  $Z(4430), X(4140), X(4274), X(4500), X(4700), P_c(4380), P_c(4450)$, ...

  — Discovery of doubly charmed baryon

  — ……

- Stay tuned with RUN II data + LHCb upgrade.

Backup slides

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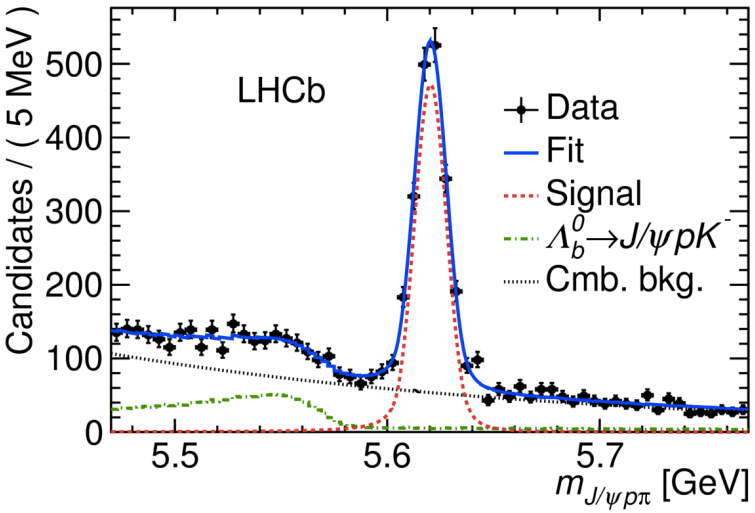
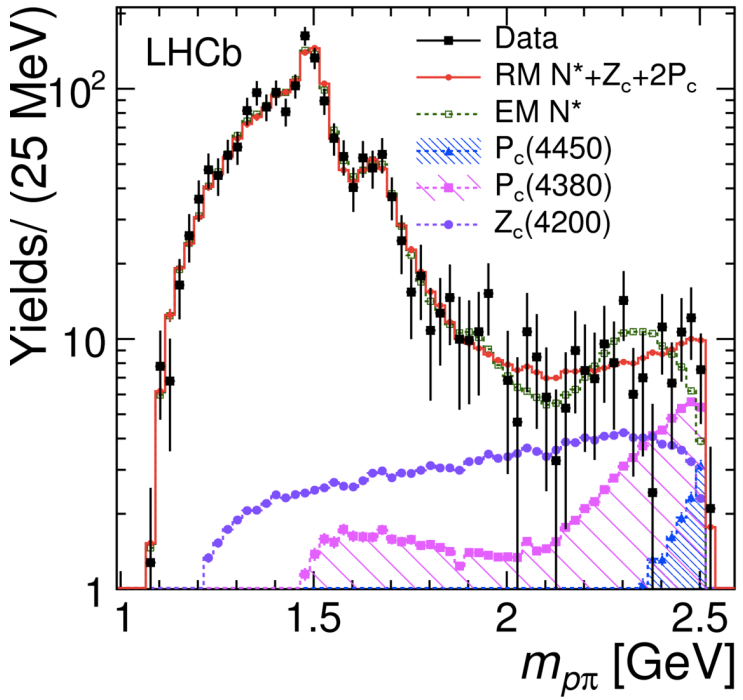
Study of $\Lambda_b^0 \to J/\psi p\pi^-$

LHCb, PRL 117(2016) 082003

- Cabbibo suppressed mode with less statistics
- Exotic Z contributions in $J/\psi\pi$
- Fit with 2 pentaquarks + $Z_c(4200)$ favored by 3σ compared to no exotic contributions

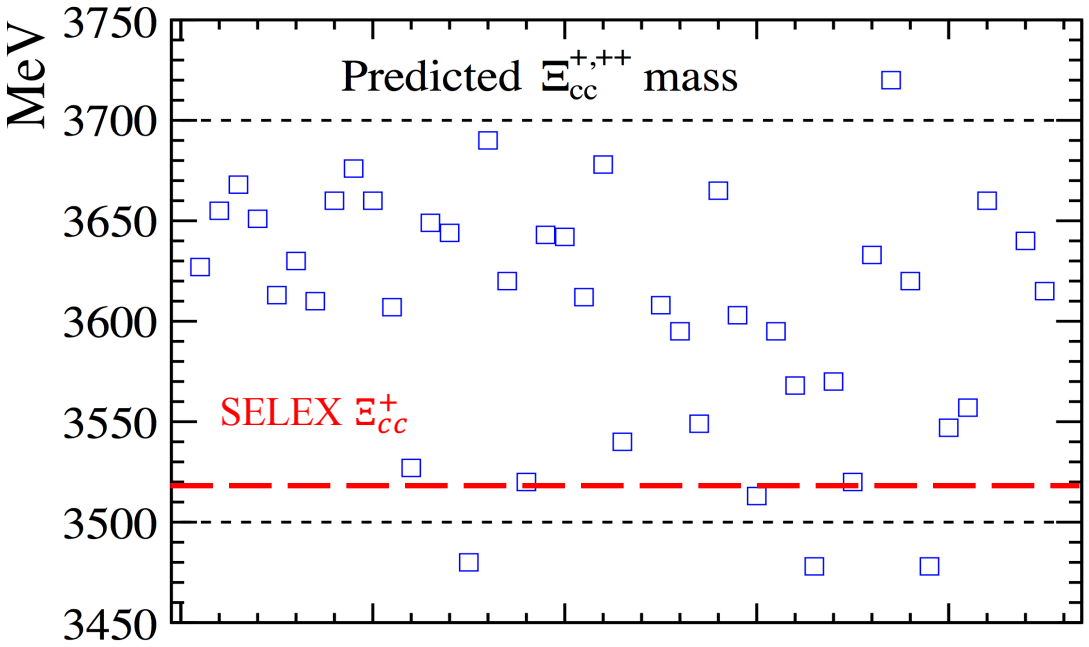




Results from SELEX

- SELEX (Fermilab E781) collides high energy hyperon beams (Σ^-, p) with nuclear targets, dedicated to study charm baryons
- Observed $\Xi_{cc}^+(ccd)$ in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^+ \to p D^+ K^-$ decays
  - **Signal yields**: 15.9 ($\Lambda_c^+ K^- \pi^+$) and 5.62 ($p D^+ K^-$)
  - **Short lifetime**: $\tau(\Xi_{cc}^+) < 33$ fs @90% CL, but not zero
  - **Large production:** $R = \frac{\sigma(\Xi_{cc}^+) \times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \sim 20\%$
  - **Mass (combined):** 3518.7 ± 1.7 MeV

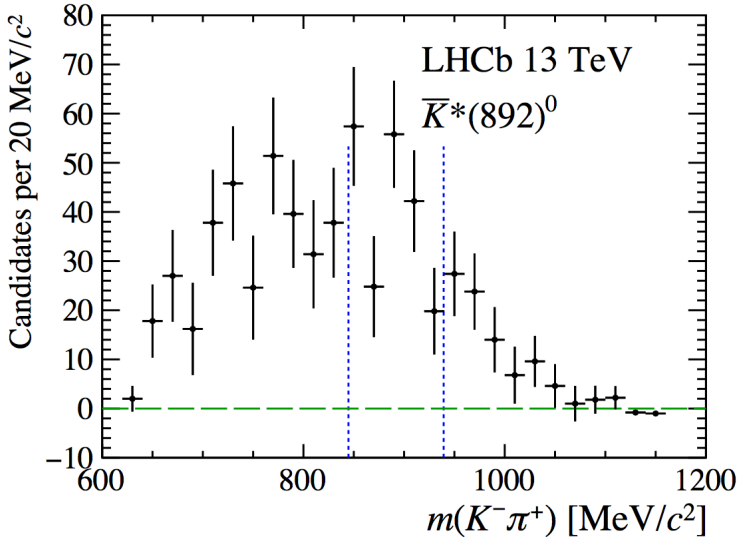
Very puzzling

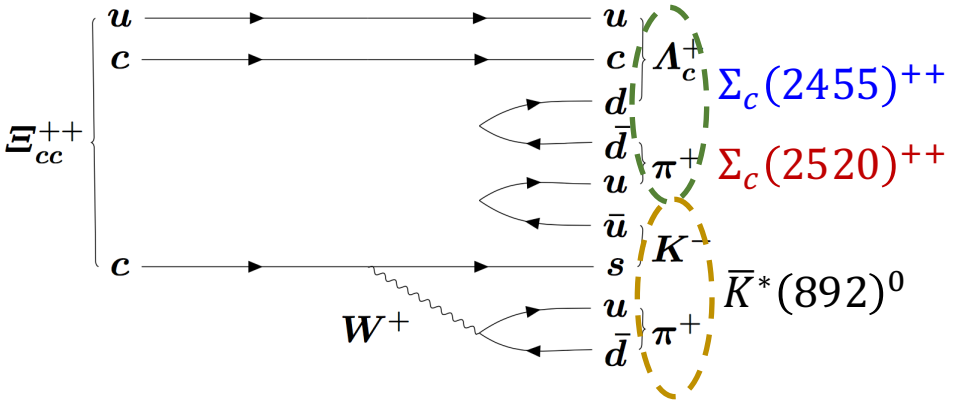


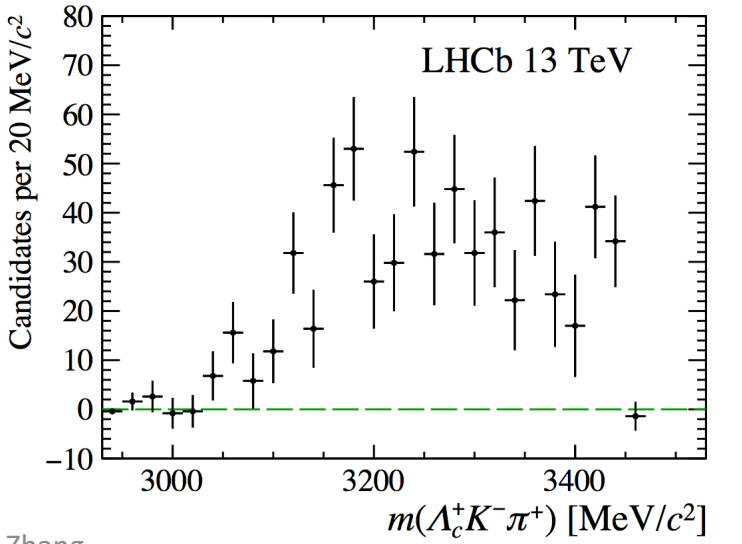
Signal properties

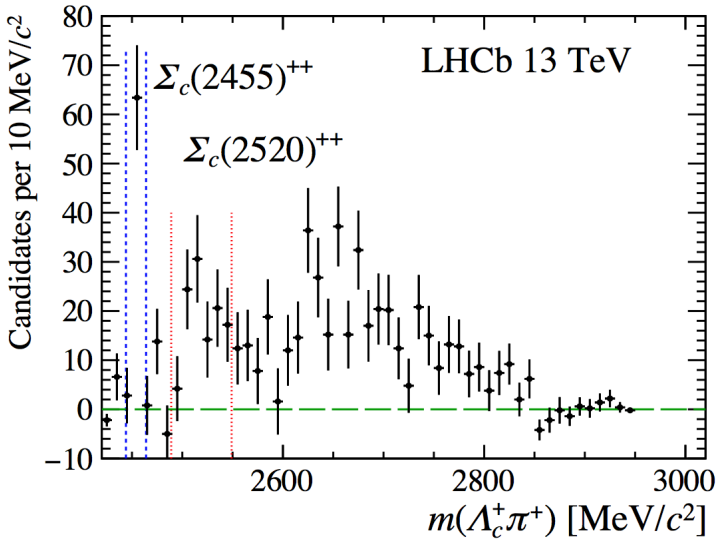
LHCb-PAPER-2017-018

- Intermediate resonances: $\overline{K}^*(892)^0, \Sigma_c(2455)^{++}, \Sigma_c(2520)^{++}$







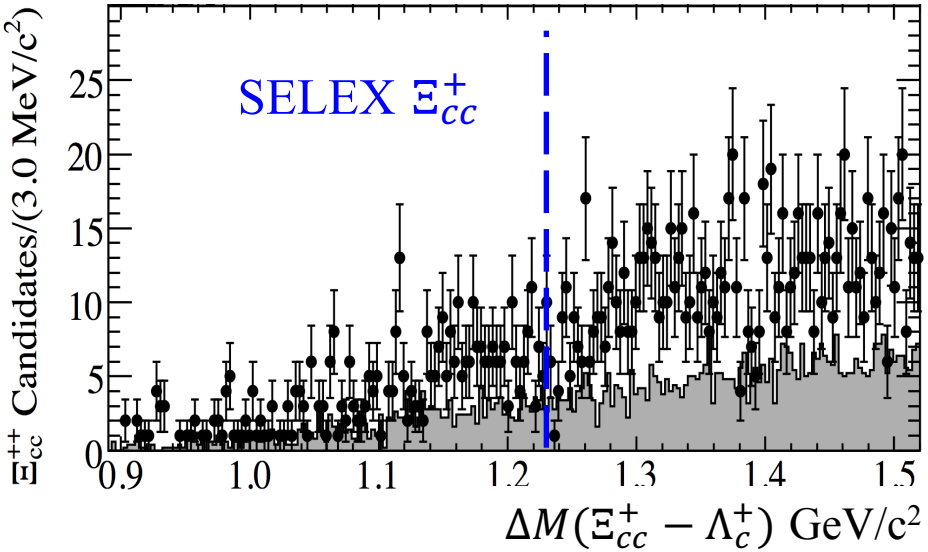


Results from Babar & Belle

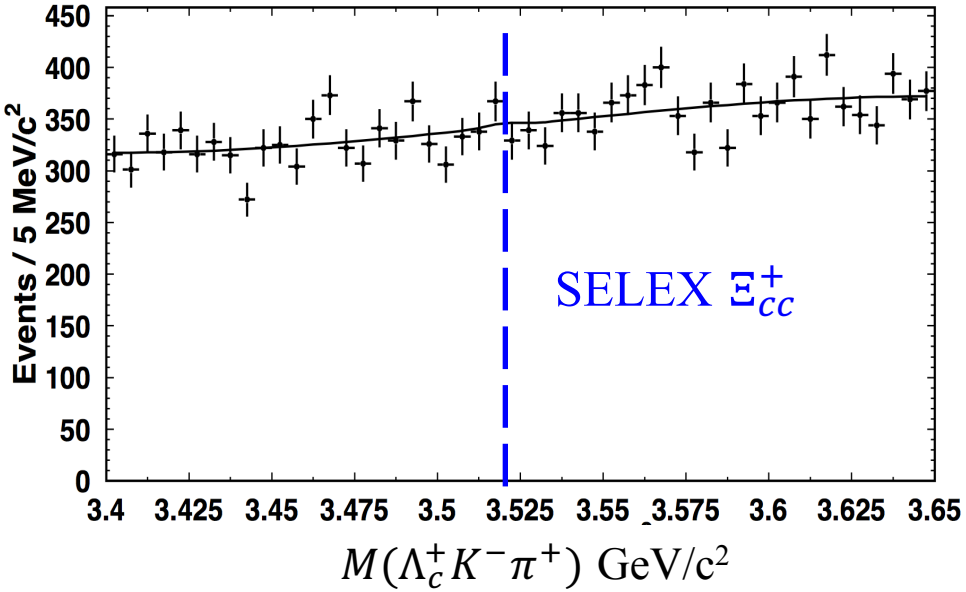
- e^+e^- colliders working at $\Upsilon(4S)$ mass $\sqrt{s} = 10.58$ GeV
- Large Λ_c^+ yields: ≈ 0.6 M at BaBar, ≈ 0.8 M at Belle
- SELEX-like Ξ_{cc}^+ signal not confirmed in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays

$$R = \frac{\sigma(\Xi_{cc}^+) \times \mathrm{BF}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 2.7\times10^{-4}\ \text{(BaBar)} \quad 1.5\times10^{-4}\ \text{(Belle)}\ @\ 95\%\ \text{CL}$$

BaBar: PRD 74 (2006) 011103



Belle: PRL 97 (2006) 162001



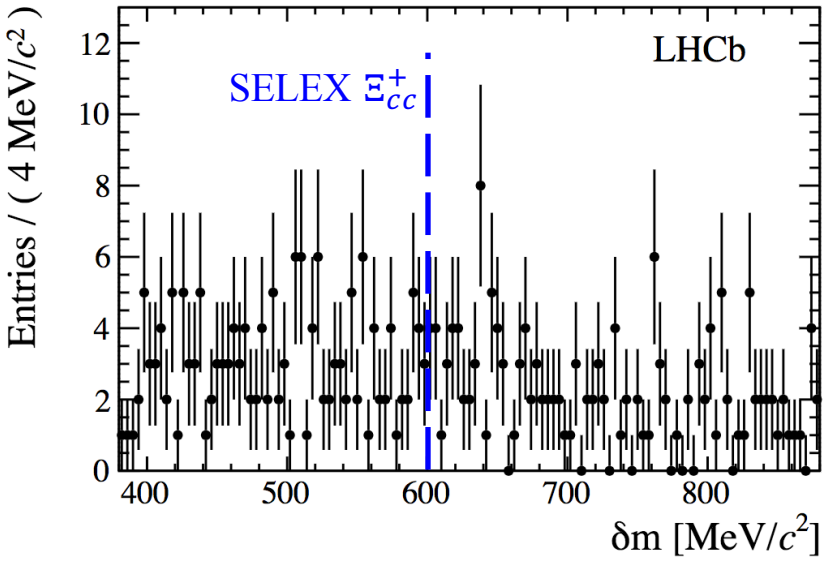
Previous studies from LHCb

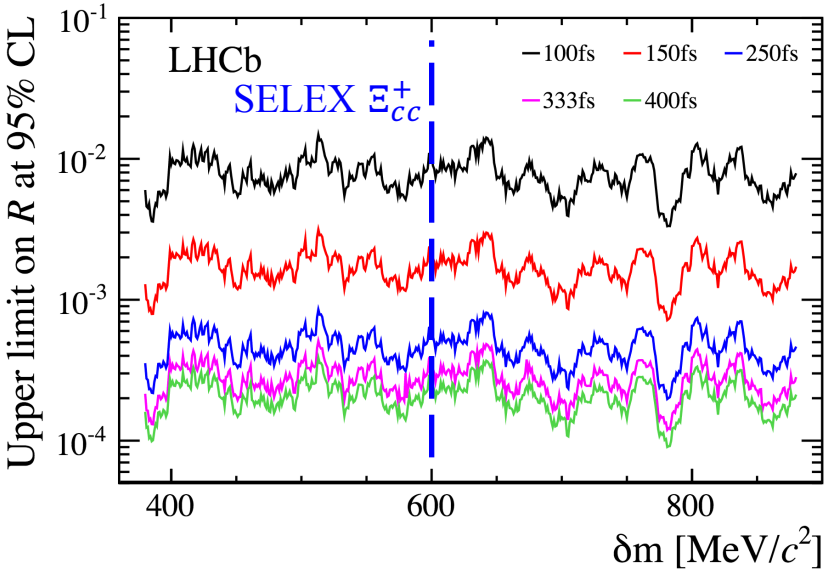
LHCb, JHEP 12 (2013) 090

- LHCb searched for $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ decay with 0.65 fb^{-1} of 7 TeV data
  - $N(\Lambda_c^{+}) \approx 0.8$ M, requiring high-p_T
  - No significant peaking structure observed with $m \in [3.3, 3.8]$ GeV
  - Experiment sensitivity strongly depends on Ξ_{cc}^{+} lifetime

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} < 0.013 \text{ for } \tau = 100 \text{ fs},$$

$$< 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \quad @ \ 95\% \text{ CL}$$





$$\delta m = m\left([pK^{-}\pi^{+}]_{\Lambda_c^{+}} K^{-} \pi^{+}\right) - m\left([pK^{-}\pi^{+}]_{\Lambda_c^{+}}\right) - m(K^{-}) - m(\pi^{+})$$