Latest results in hadron spectroscopy from LHCb

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On Behalf of the LHCb Collaboration

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LEPTON PHOTON 2017

10 years ago

Future programs: LHCb, BESIII, Belle2…

Future programs for flavor physics
at
hadron and lepton colliders

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Thanks to: F. Bossi, S. Eydelman, F.Harris, N. Katayama, S.E.Mueller, Y.F.Wang, M. Yamauchi …

Why future programs (1)

(A far from complete list)

- Search for hits of new physics.
  - Further (over) constrain the CKM matrix from tree levels (less sensitive to NP) and from loop levels (sensitive to NP)
  - Rare decays of charm, bottom and tau; charm EDM, kaon interferometer, FCNC decays …

- Understanding the perturbative/non-perturbative nature of QCD. Improve theoretical predictions
  - Hadron spectroscopy (quark+gluon), form factors …
  - R measurements

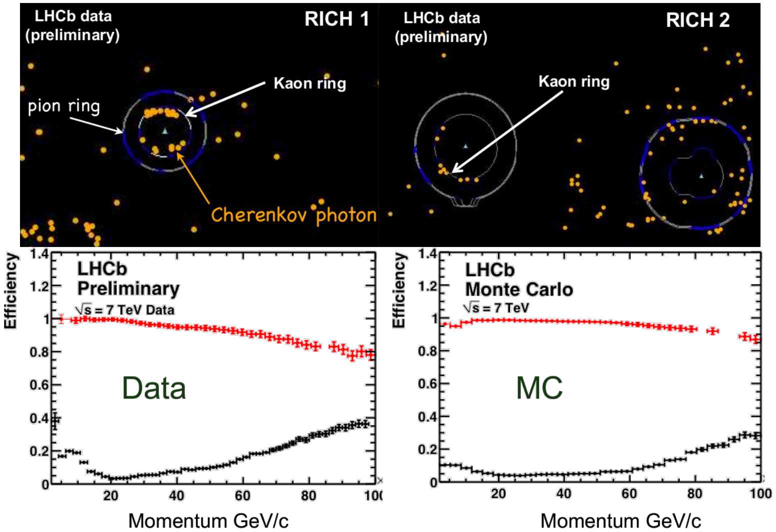
August 17, 2007 Y.Gao / LP07 9

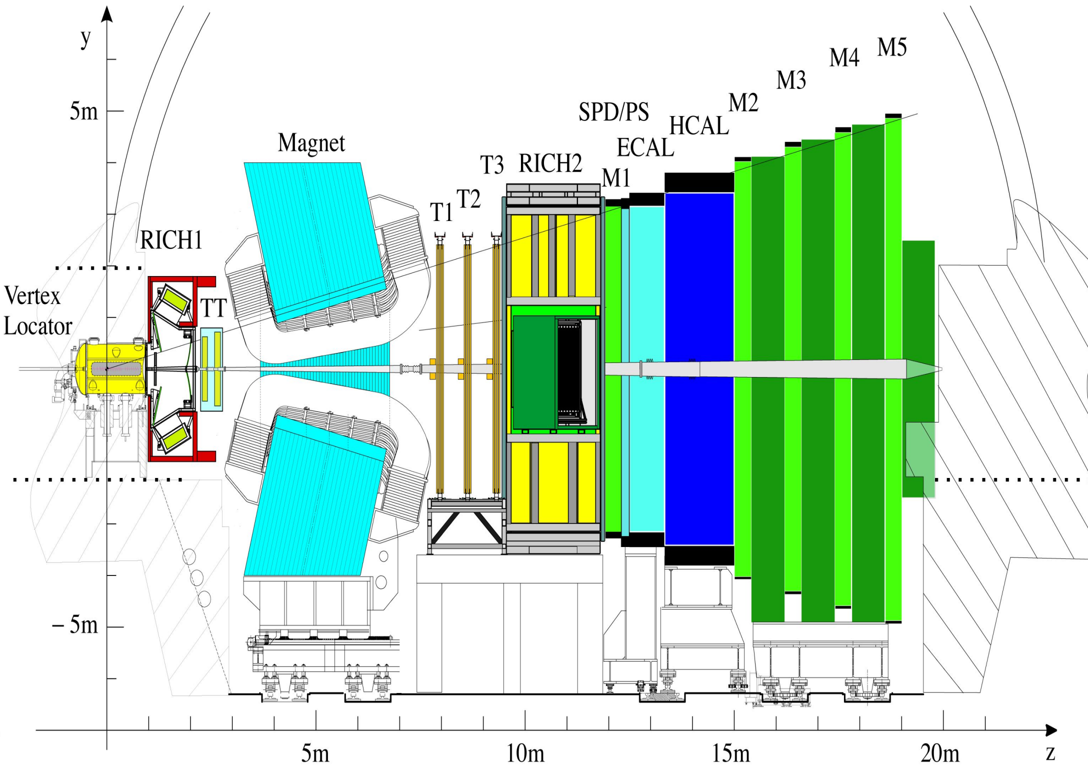
LHCb Detector

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

Forward spectrometer running in pp collider

- Excellent tracking and vertexing
- Excellent Particle ID
- Efficient trigger with μ's
- …

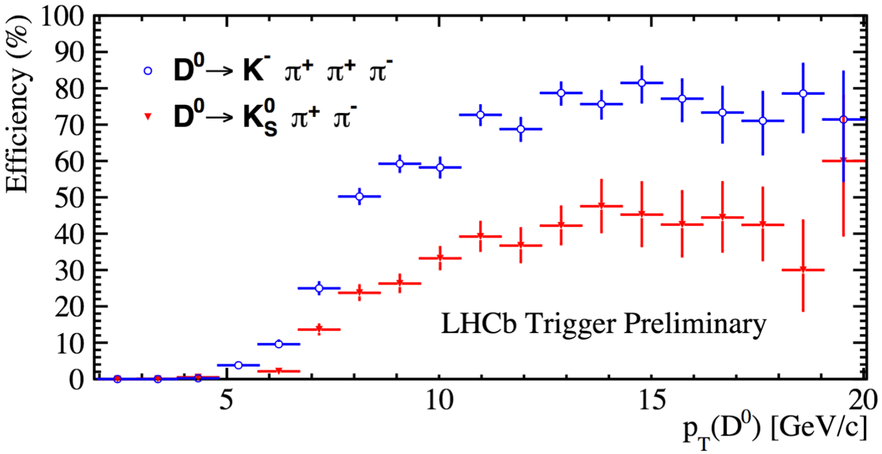


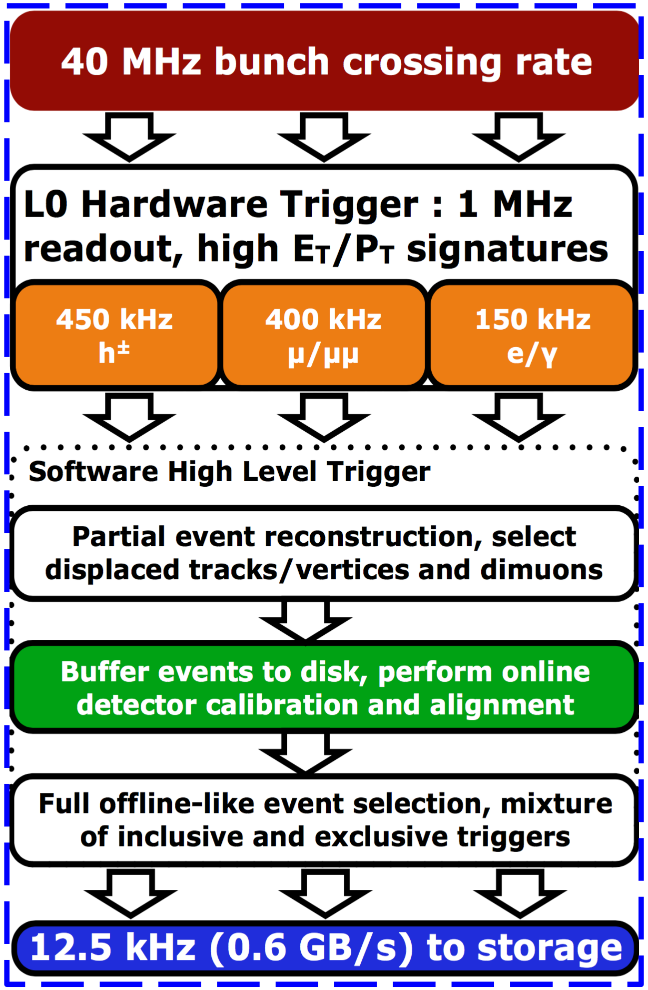


Comput. Phys. Commun. 208 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)

LHCb Trigger

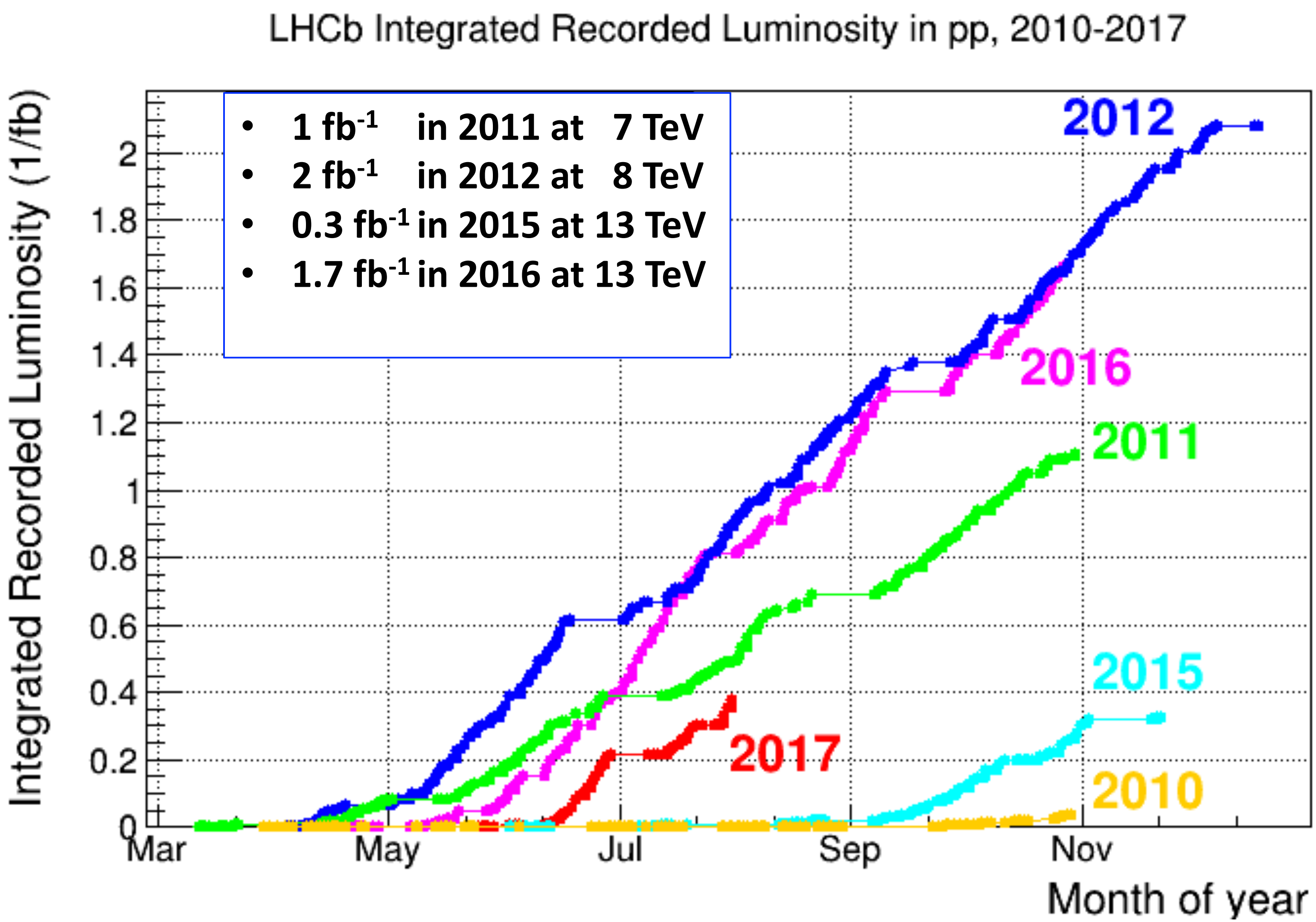
- Versatile two stage trigger
- RUNII Turbo stream: Candidates reconstructed at trigger level saved for offline analyses directly
- Efficient trigger for hadronic channels





Data Samples

- 1 fb^{-1} in 2011 at 7 TeV
- 2 fb^{-1} in 2012 at 8 TeV
- 0.3 fb^{-1} in 2015 at 13 TeV
- 1.7 fb^{-1} in 2016 at 13 TeV



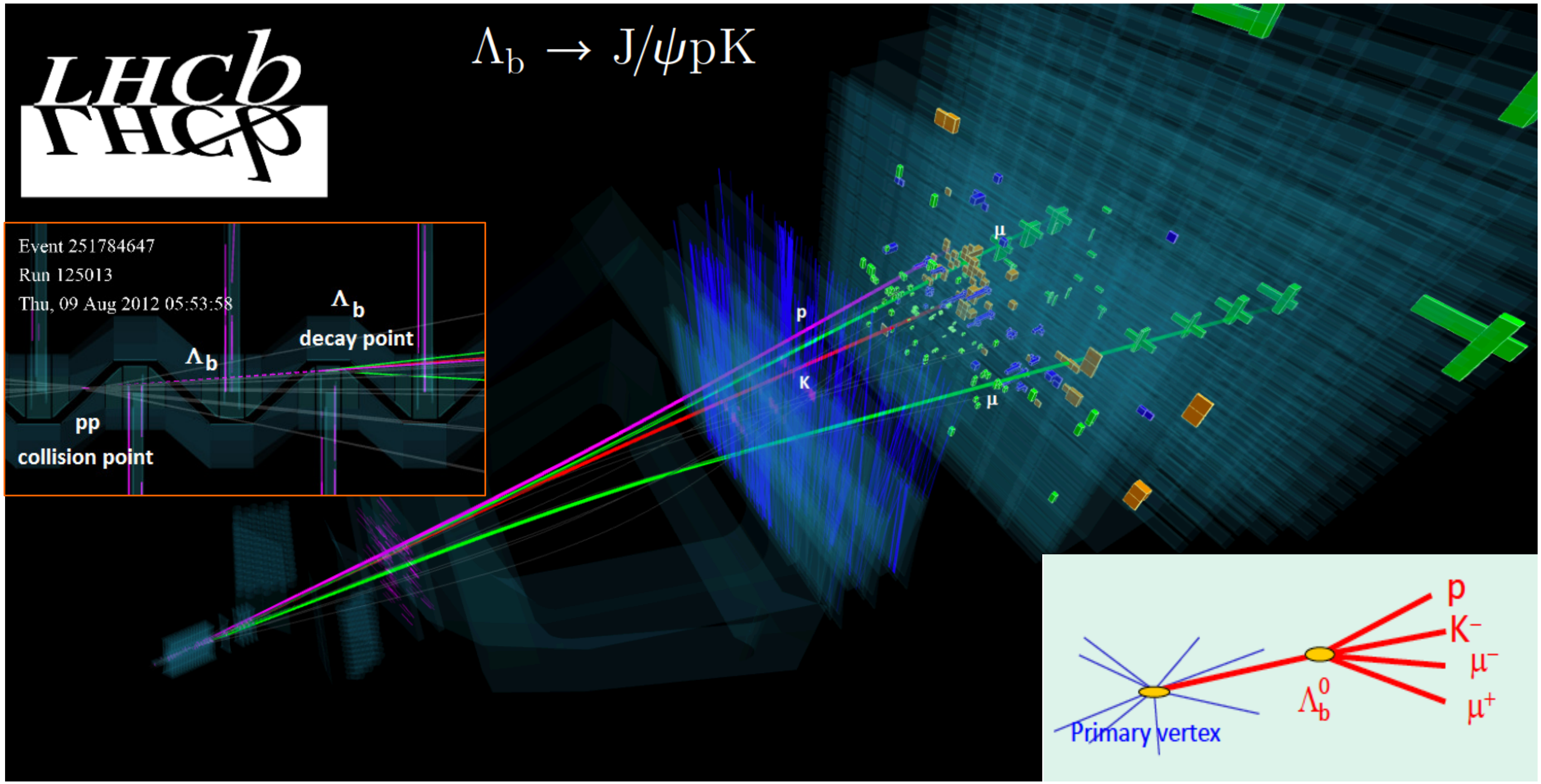
Hadron spectroscopy studies at LHCb

- 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 Ω_c states
- Discovery of doubly charmed baryon Ξ_{cc}^{++}

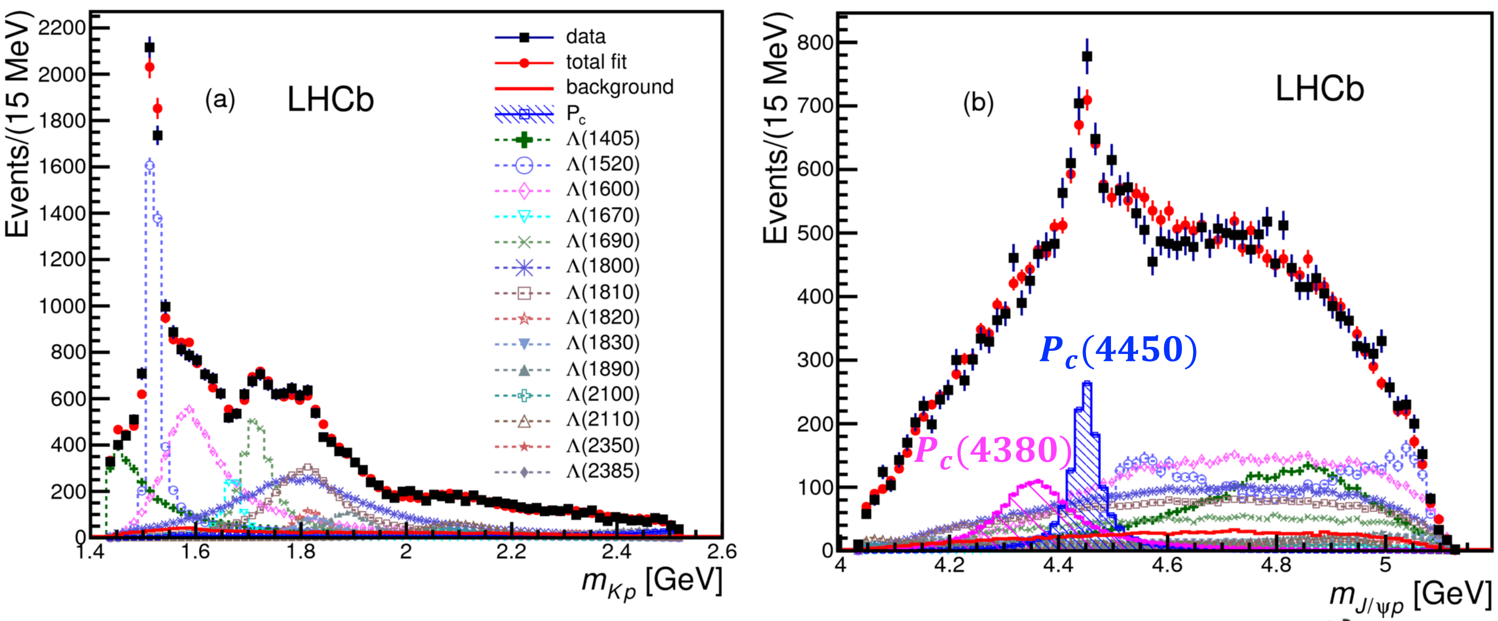
Pentaquark studies

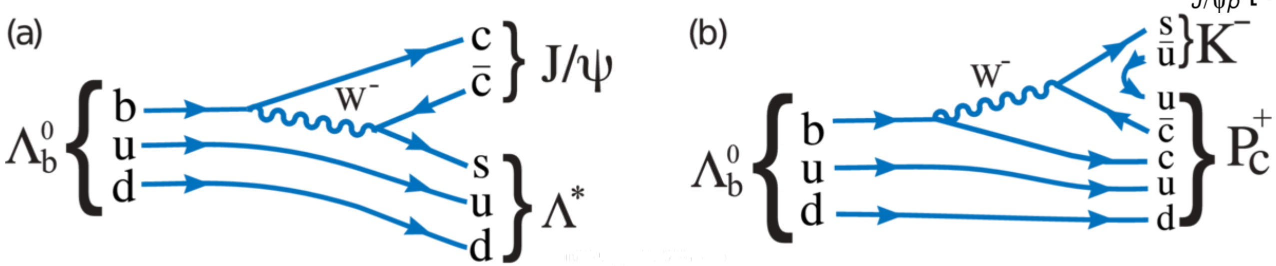


Discovery of pentaquark states

LHCb, PRL 115(2015) 072001

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

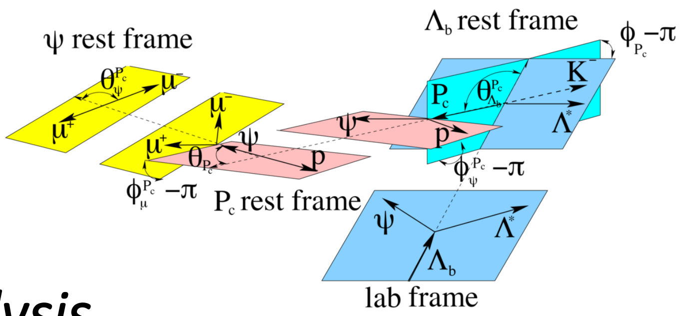




Discovery of pentaquark states

- 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 $[\mathrm{MeV}/c^2]$	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width $[\mathrm{MeV}]$	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Significance	9σ	12σ



- Confirmed by *a model independent analysis*

LHCb, PRL 117 (2016) 082002

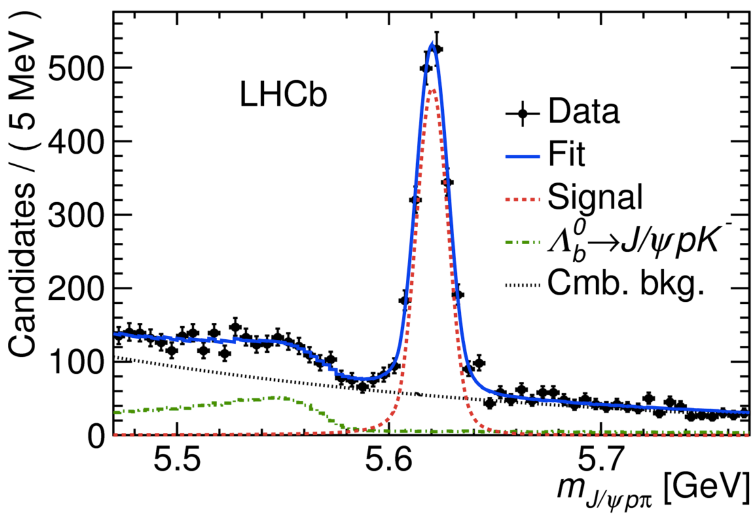
- Production & decay **LHCb, Chin. Phys. C 40 (2016) 011001**

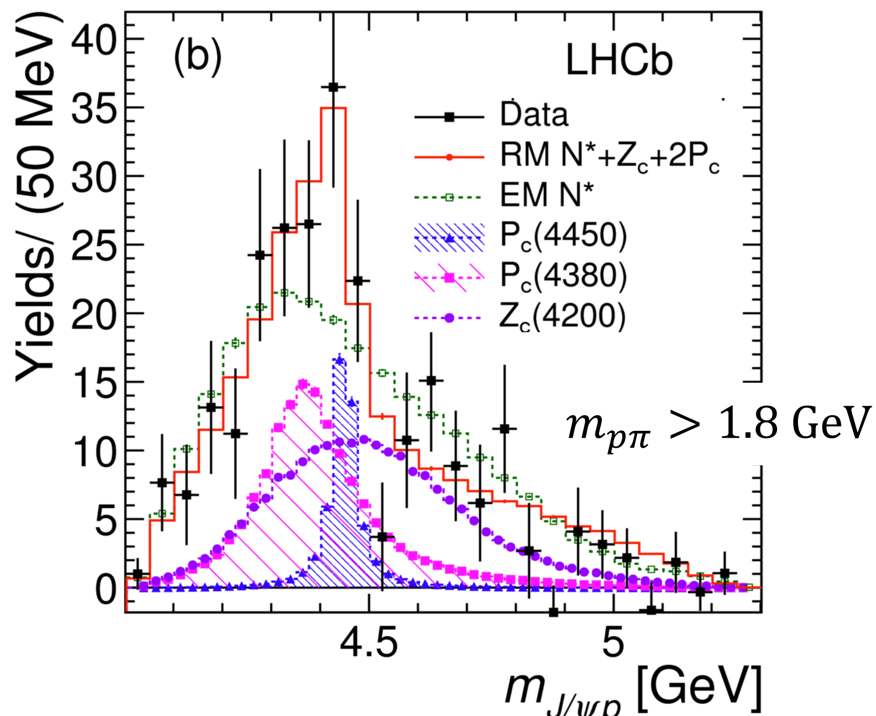
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(2.56 \pm 0.22 \pm 1.28\,^{+0.46}_{-0.36}\right) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi\, p) = \left(1.25 \pm 0.15 \pm 0.33\,^{+0.22}_{-0.18}\right) \times 10^{-5}$$

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

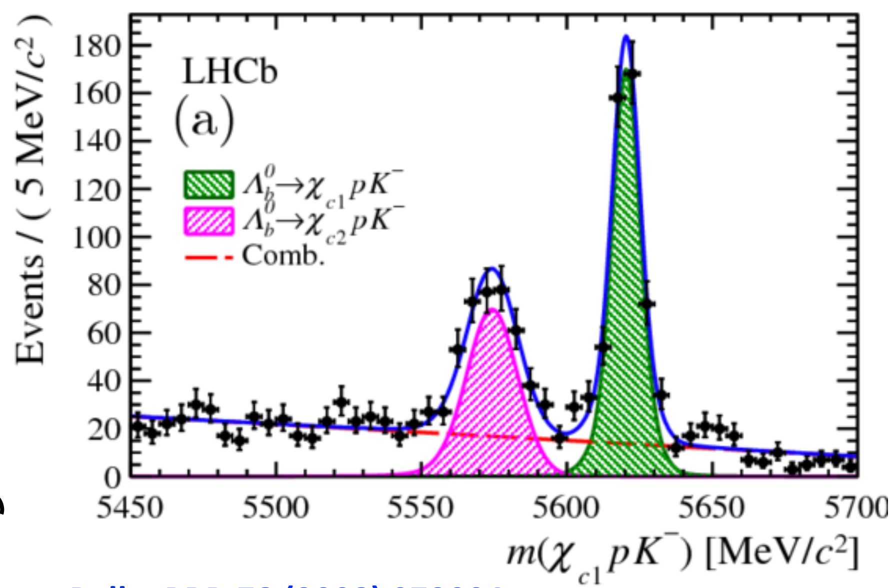
  with RUNII data added in

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

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

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

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 $uds\bar{c}c$ pentaquark in this mode

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

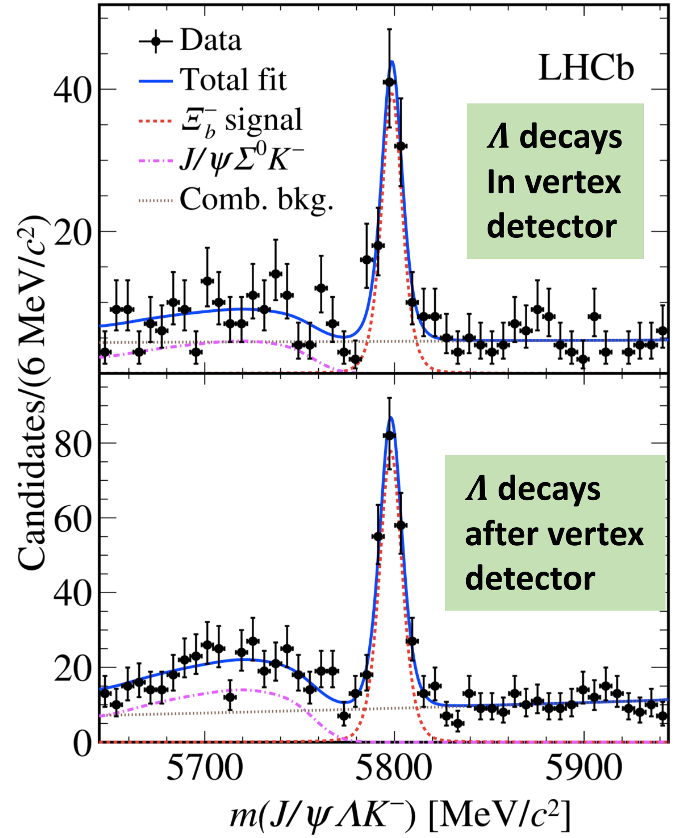
- First observation with RUNI data
- ~300 candidates seen

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

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

(one of the two world best measurements)

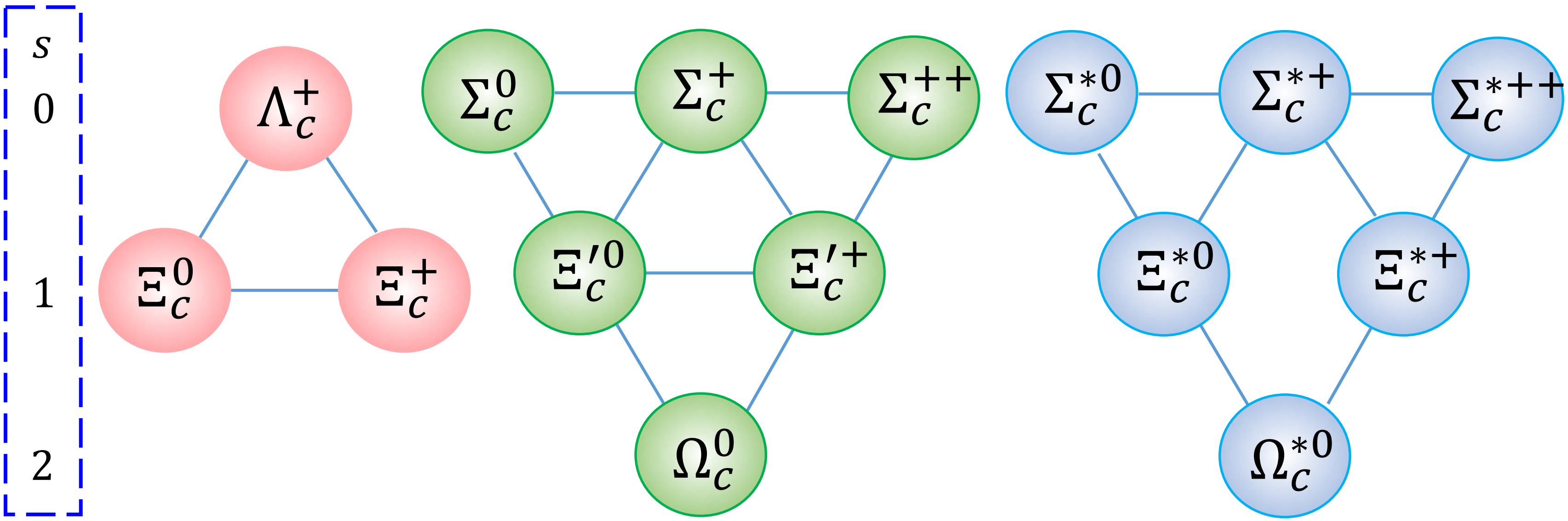
- Full amplitude analysis foreseen with RUNII data added in



Observation of exited Ω_c states

Jaffe, Phys. Rep. 409 (2005) 1

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



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

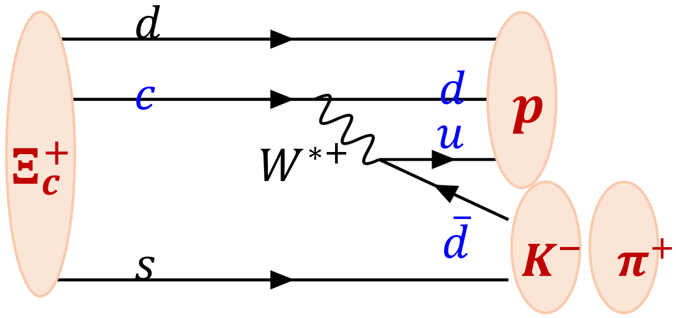
$|\{qq\}\bar{\mathbf{3}}_c(A)\bar{\mathbf{3}}_f(A)0^+(A)\rangle$ $\quad$ $|\{qq\}\bar{\mathbf{3}}_c(A)\mathbf{6}_f(S)1^+(S)\rangle$ $\quad$ $|\{qq\}\bar{\mathbf{3}}_c(A)\mathbf{6}_f(S)1^+(S)\rangle$

- 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

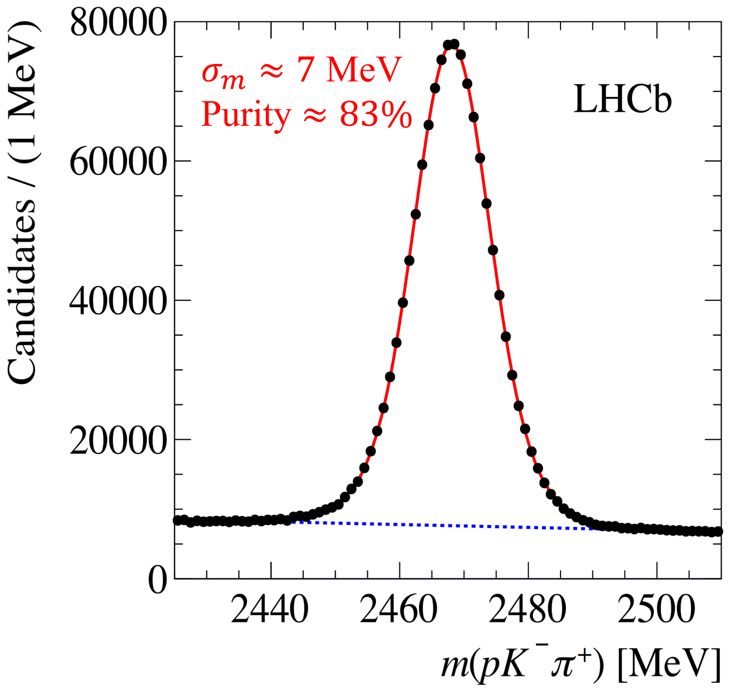
Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

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



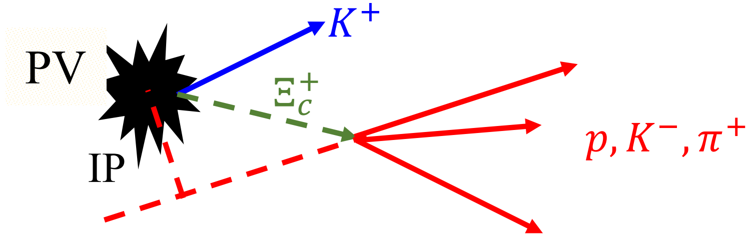
Cabibbo suppressed $c \to dW^{*+}$ decay, but much higher reconstruction efficiency



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



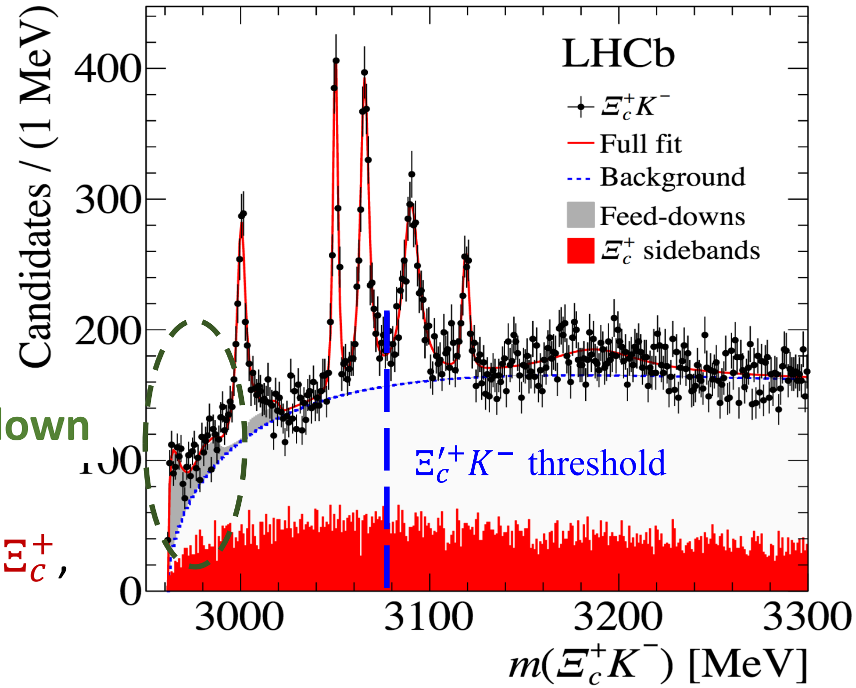
Observation of exited Ω_c states

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
		$< 1.2\,\text{MeV}, 95\%\ \text{CL}$	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	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
		$< 2.6\,\text{MeV}, 95\%\ \text{CL}$	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	6.4

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



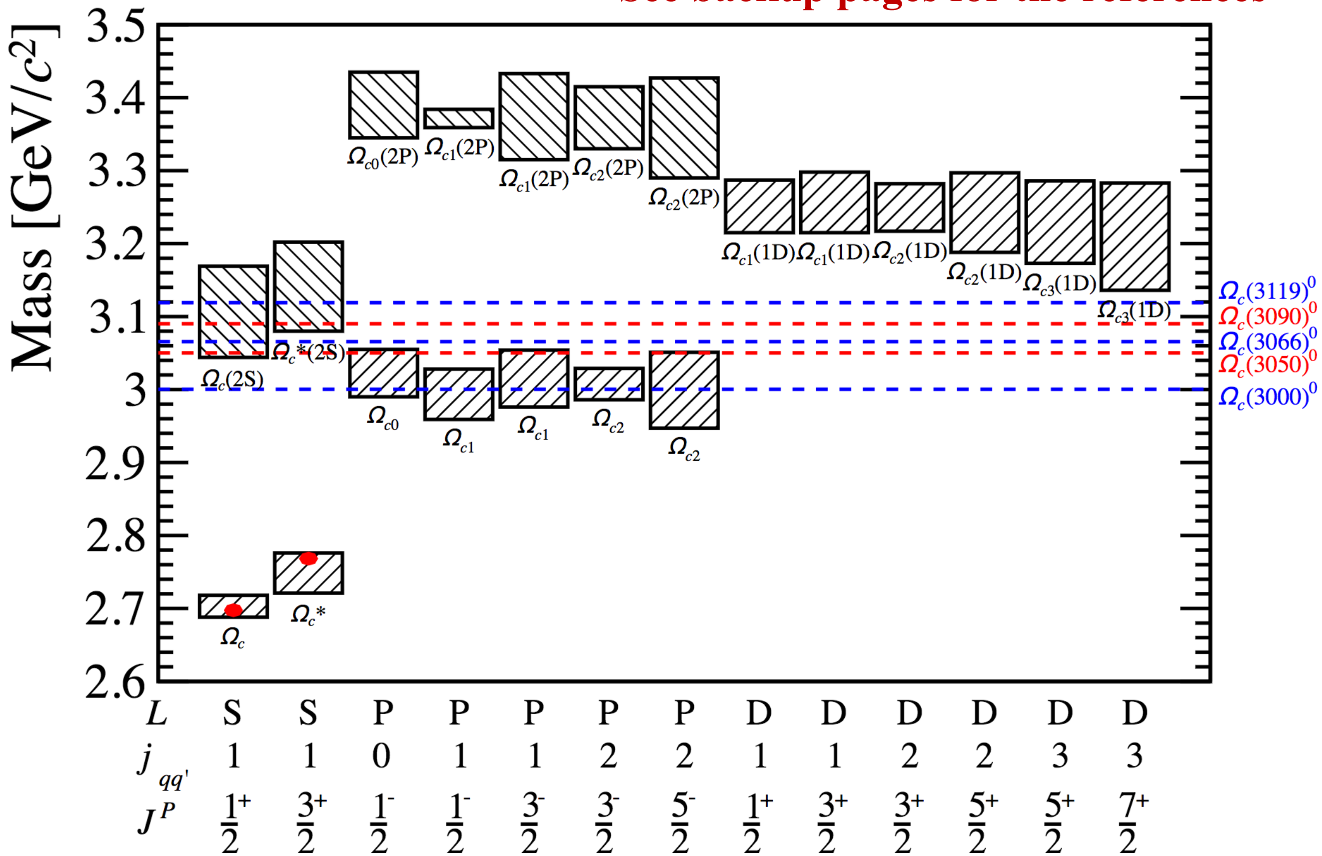
Feed-down: $\Omega_c^{**0} \to K^-\Xi_c'^+, \Xi_c'^+ \to \gamma\Xi_c^+$,
$m(\Xi_c^+K^-)$ mass peaks shifted

Observation of exited Ω_c states

LHCb, PRL 118 (2017) 182001

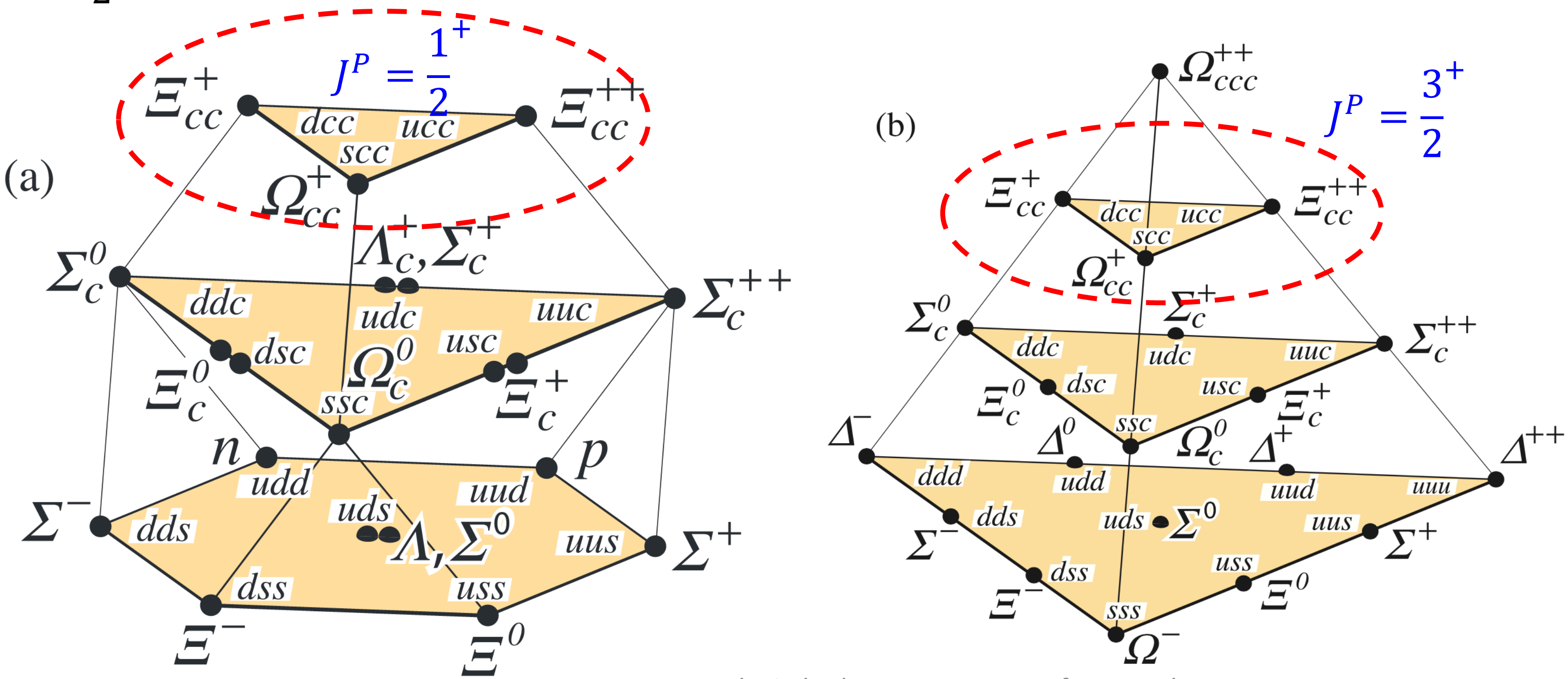
- Matching between observed peaks and predictions requires spin-parity information: studied with three-body decays or in decays of heavier baryons

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

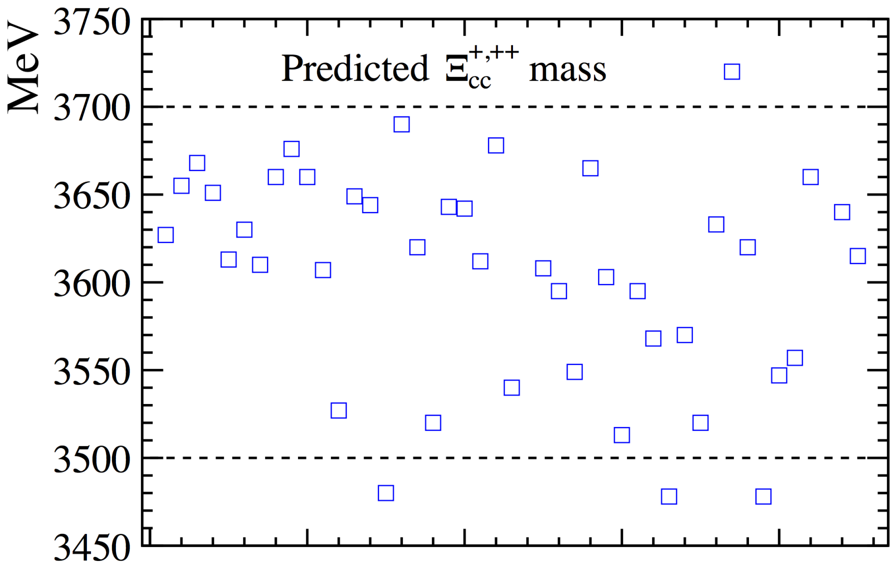


Doubly charmed baryons

- 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

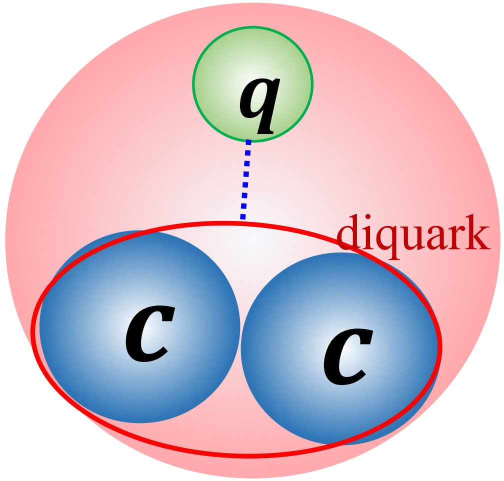
- Lattice QCD computations:

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



See backup pages for the references

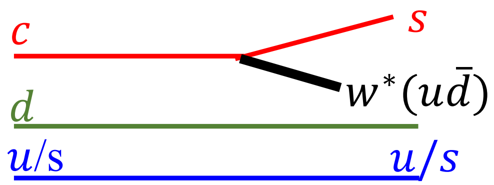
HQET: two charm quarks considered as a heavy diquark, doubly heavy baryon similar to a heavy meson Qq



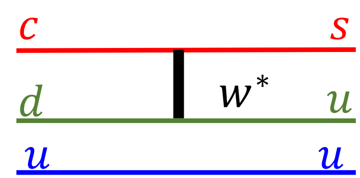
Doubly charmed baryons

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

Spectator (Γ_s)



W-exchange (W)



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

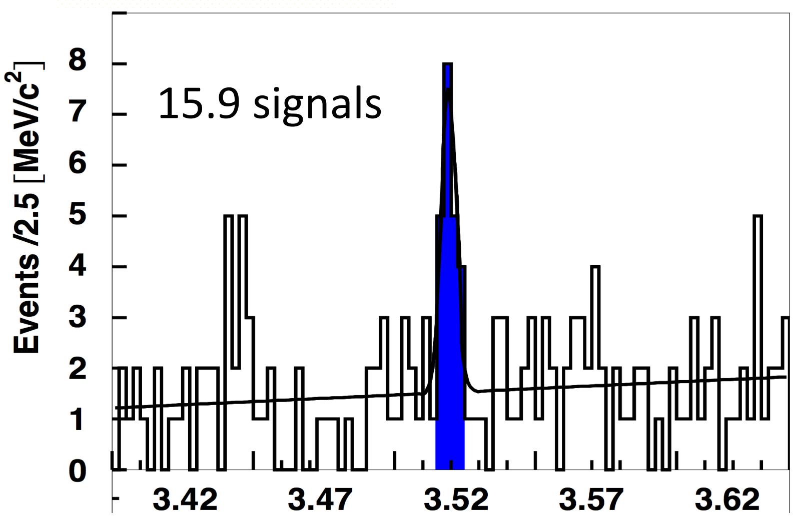
- Calculations give $\tau(\Xi_{cc}^{++}) \in [200 - 700]$ fs

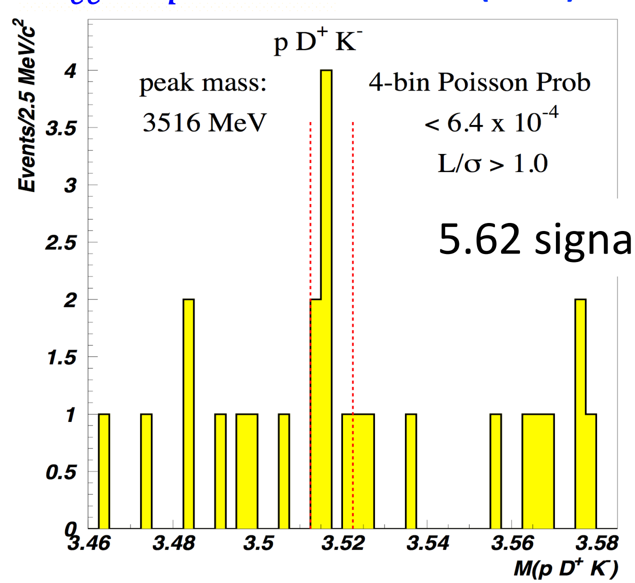
See backup pages for references

Particle	τ (ps)
D^0	0.410 ± 0.002
D_s^+	0.500 ± 0.007
D^+	1.040 ± 0.007
$D_b^+(B_c^+)$	0.507 ± 0.009
$\Lambda_c^+(cud)$	0.200 ± 0.006
$\Xi_c^0\ (csd)$	0.112 ± 0.012
$\Xi_c^+(csu)$	0.442 ± 0.026
$\Omega_c^0\ (css)$	0.069 ± 0.012

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





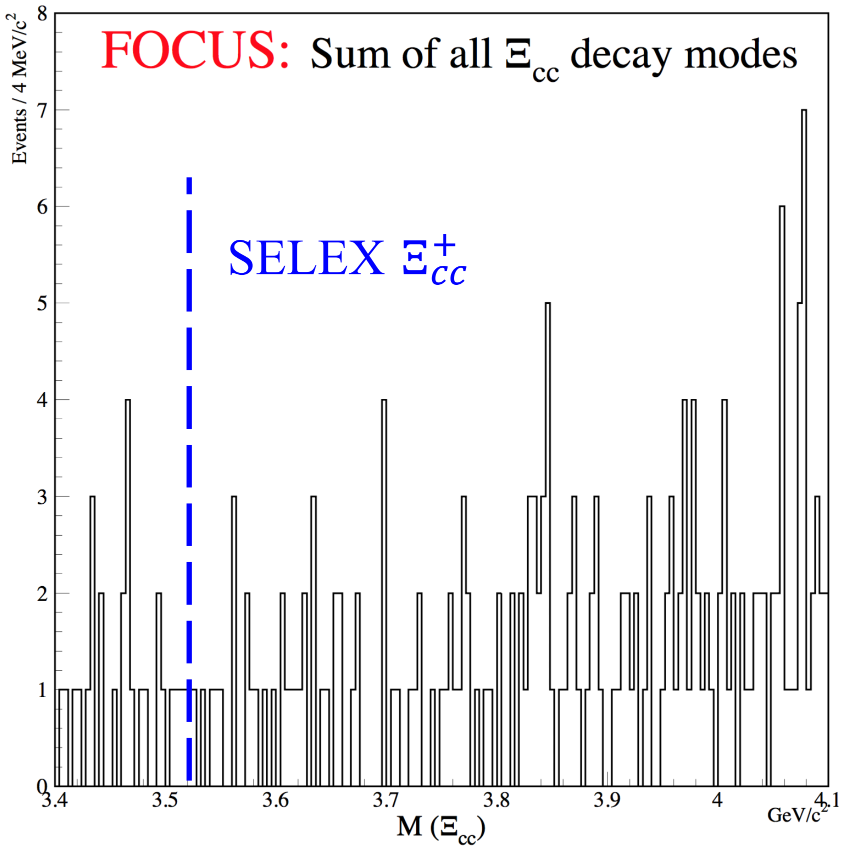
Results from FOCUS

- 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

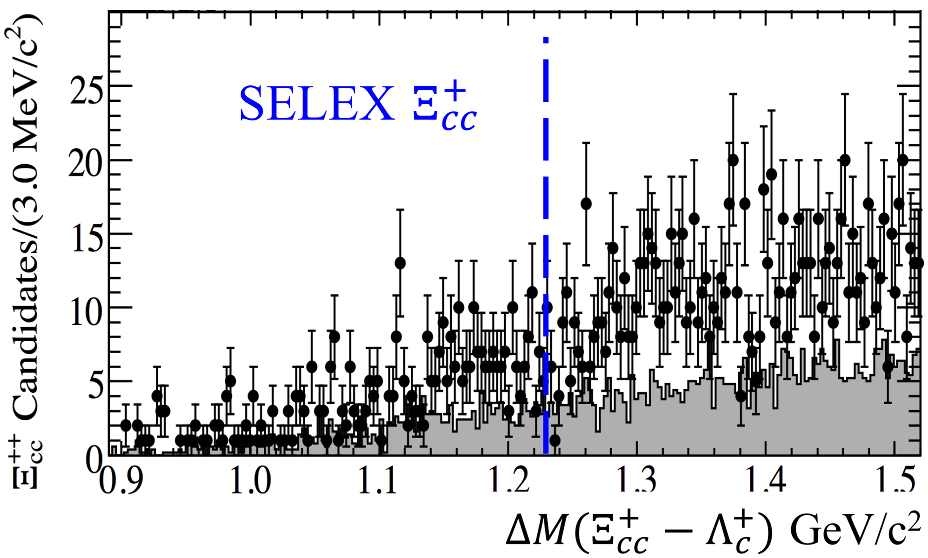


Results from Babar & Belle

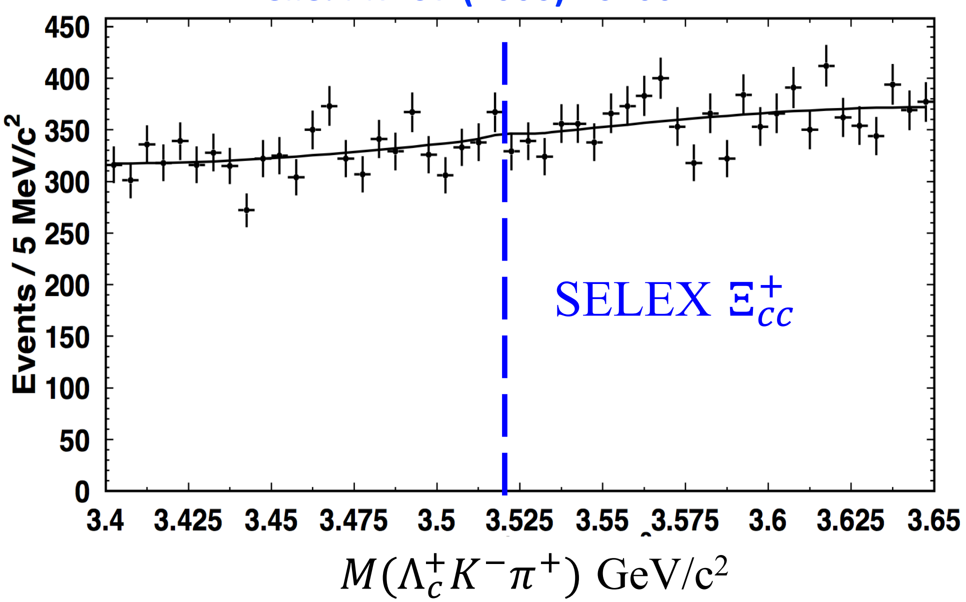
- e^+e^- colliders working at $\Upsilon(4S)$ mass $\sqrt{s} = 10.58$ GeV
- Large Λ_c^+ yields: $\approx$ 0.6 M at BaBar, $\approx$ 0.8 M at Belle
- SELEX-like Ξ_{cc}^+ signal not confirmed in $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$ decays

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

BaBar: PRD 74 (2006) 011103



Belle: PRL 97 (2006) 162001

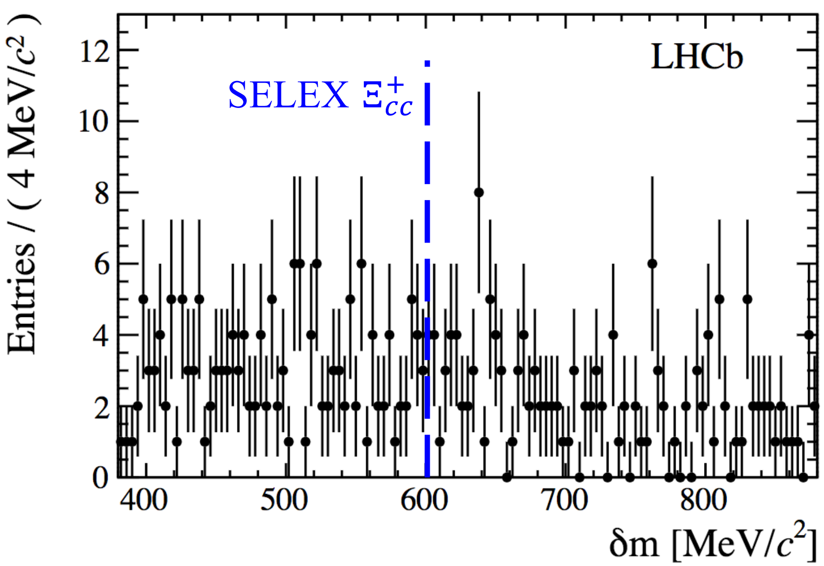


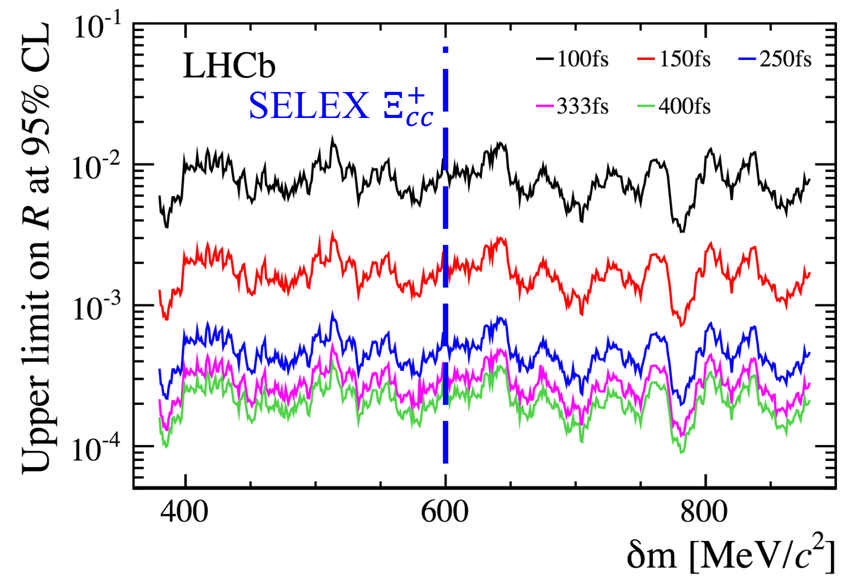
Previous studies from LHCb

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

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 0.013 \text{ for } \tau = 100 \text{ fs},$$
$$< 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \quad @ \; 95\% \text{ CL}$$





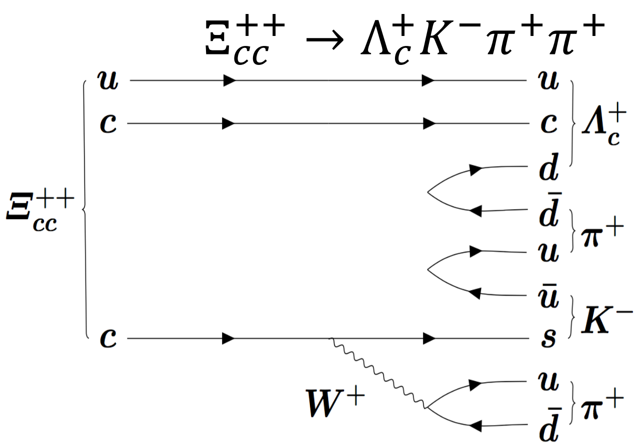
$$\delta m = m([pK^-\pi^+]_{\Lambda_c^+} K^- \pi^+) - m([pK^-\pi^+]_{\Lambda_c^+}) - m(K^-) - m(\pi^+)$$

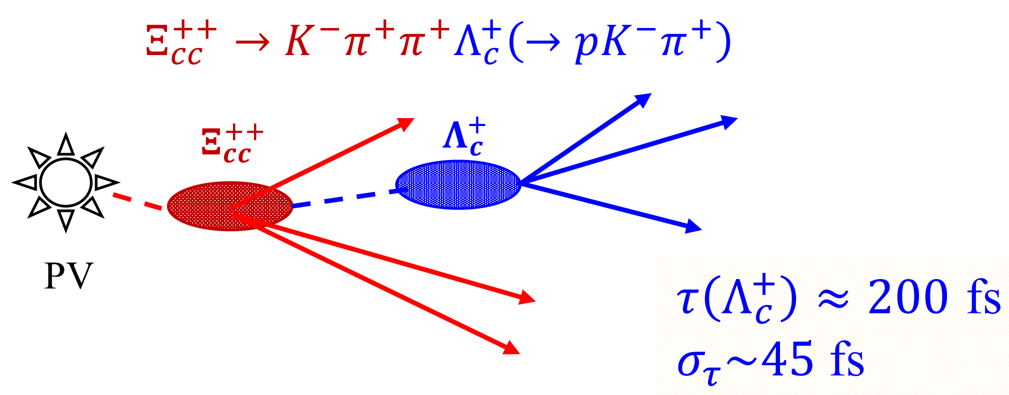
Search for $\Xi_{cc}^{++}(ccu)$ at LHCb

LHCb-PAPER-2017-018 (accepted by PRL)

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

Yu et al., arXiv:1703.09086



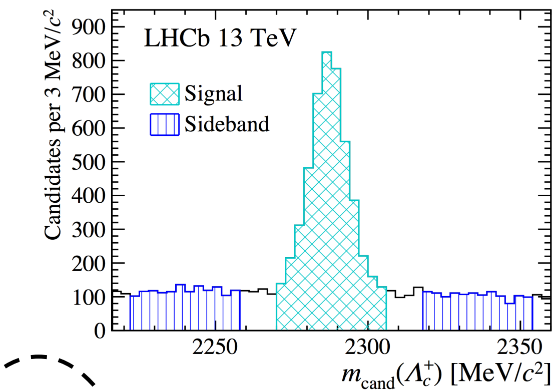


- Data sample: LHCb run II at $\sqrt{s} = 13$ TeV, ~1.7 fb^{-1}
  - Dedicated exclusive trigger ensuring high efficiency, full event reconstruction at trigger level
  - Run I data (2012) also analyzed for cross-check

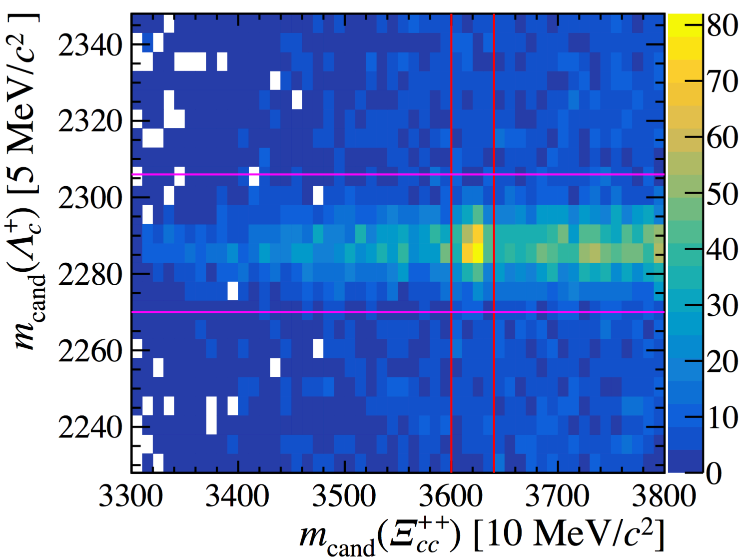
Mass spectrum

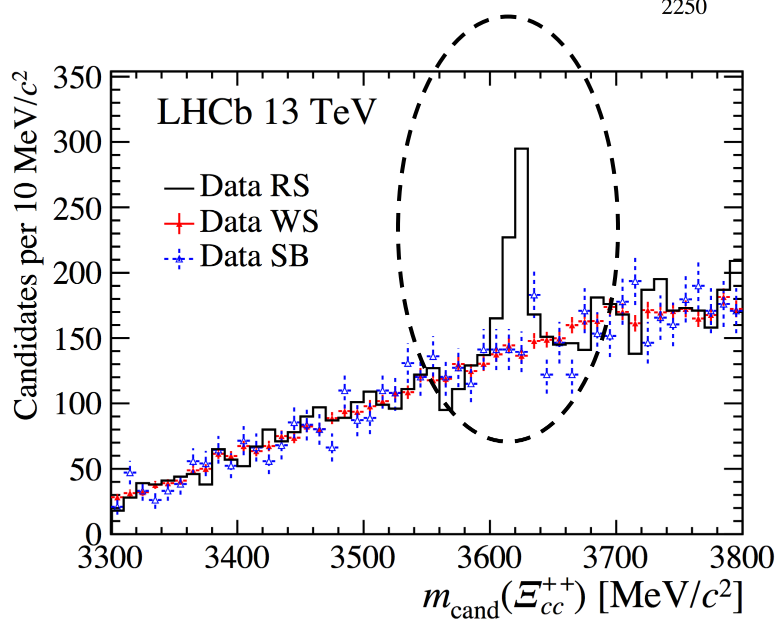
LHCb-PAPER-2017-018

- 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



A significant peak!





Fitting the mass peak

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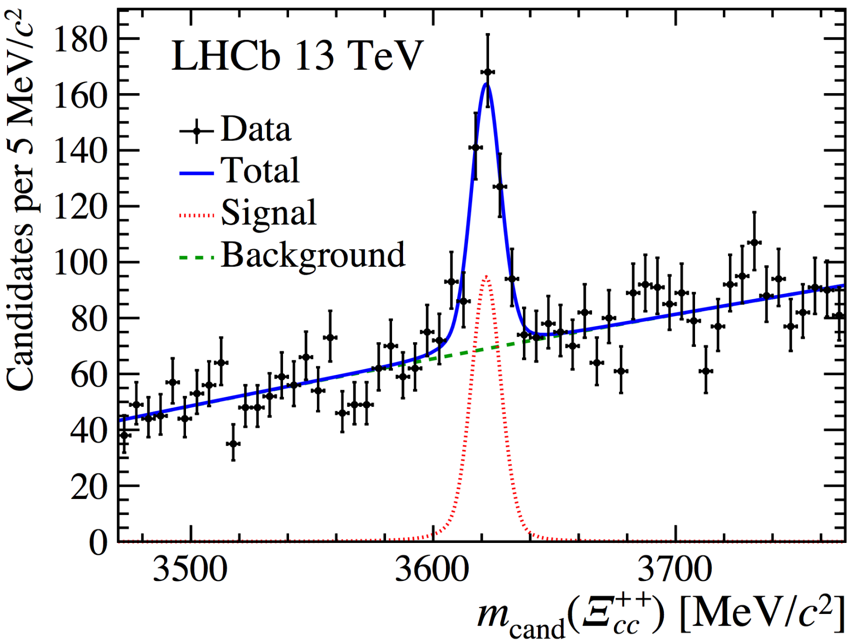
- Studying Λ_c^+-mass corrected mass: $m_{\text{cand}}(\Xi_{cc}^{++}) = m(\Lambda_c^+ K^- \pi^+) - m(\Lambda_c^+) + m_{\text{PDG}}(\Lambda_c^+)$
  - Signal yield: 313 ± 33
  - Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
  - Local significance $> 12\sigma$

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

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



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

LHCb-PAPER-2017-018

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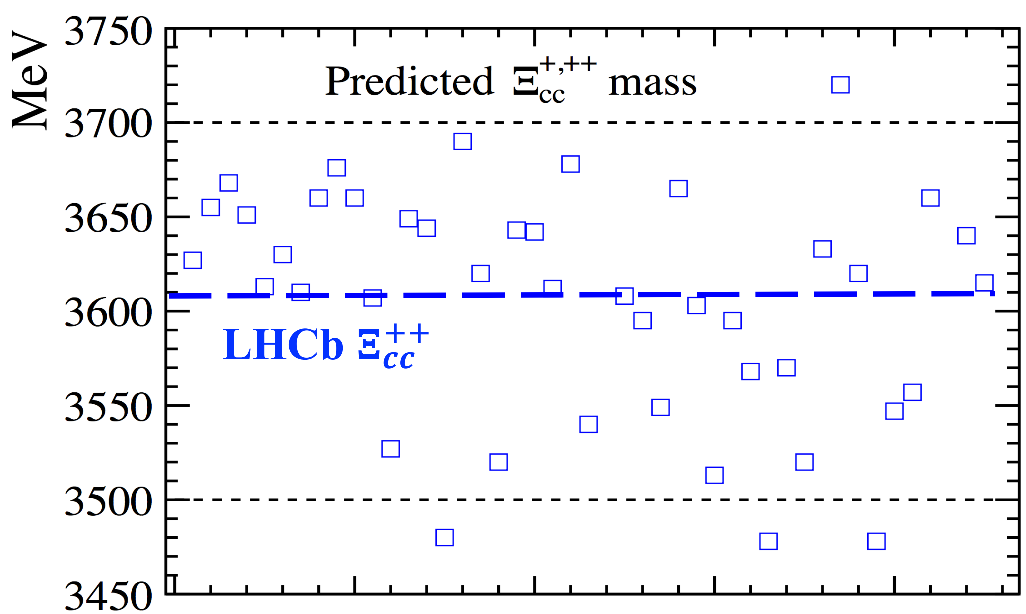
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$

Value consistent with many theoretical calculations, especially LQCD



See backup pages for references

Test with RUNI data

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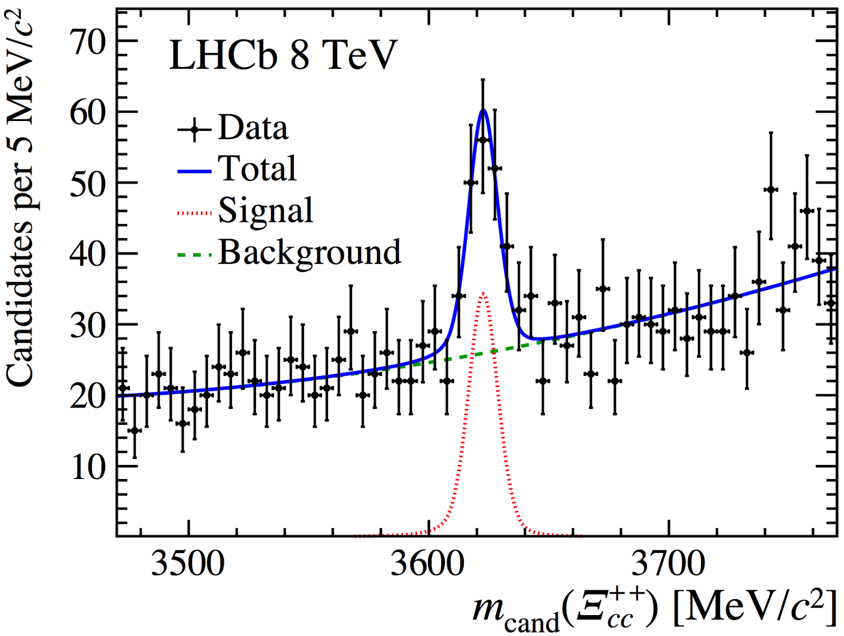
- Signal peak presents in RUNI data sample with significance $> 7\sigma$



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

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

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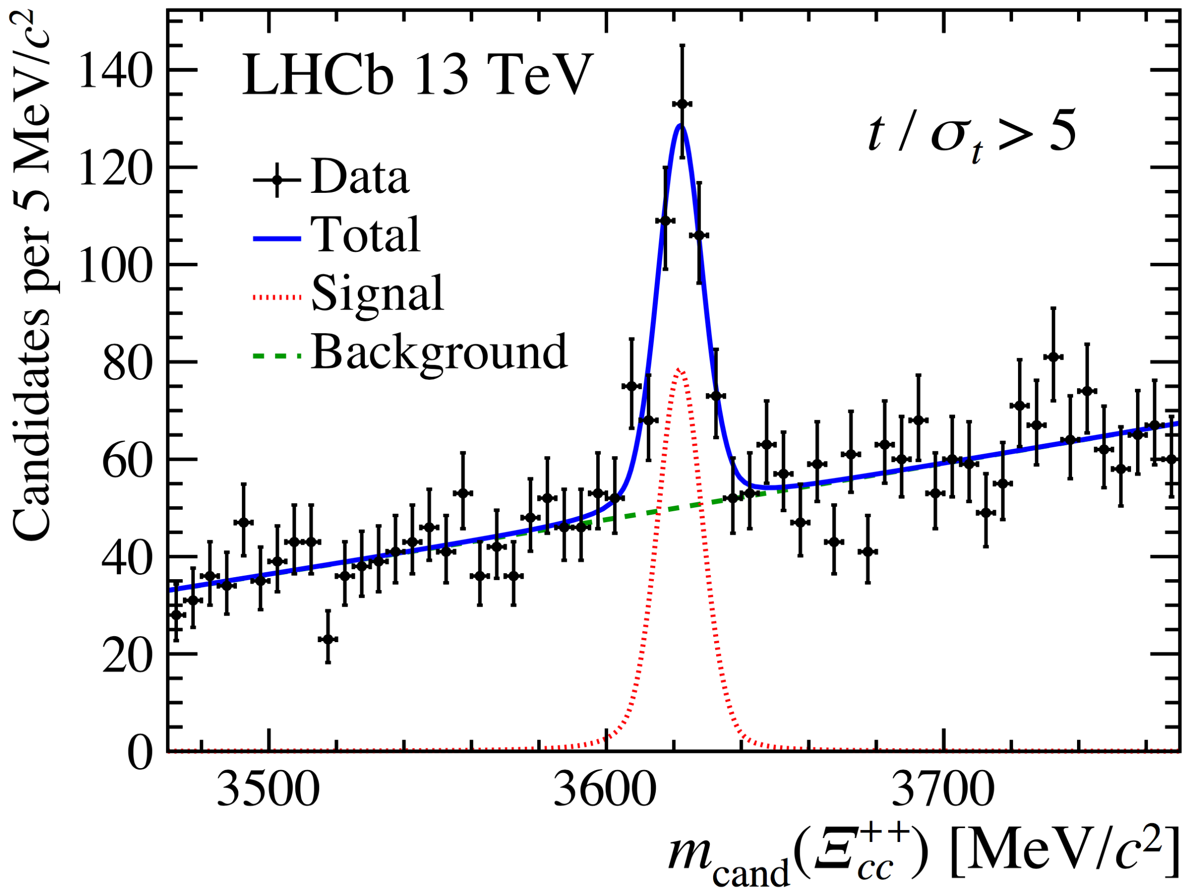
- Peaking structure remains significant ($> 12\sigma$) after requiring minimum decay time, $t > 5\sigma_t$. It is indeed a weak decay.



Comparison with SELEX

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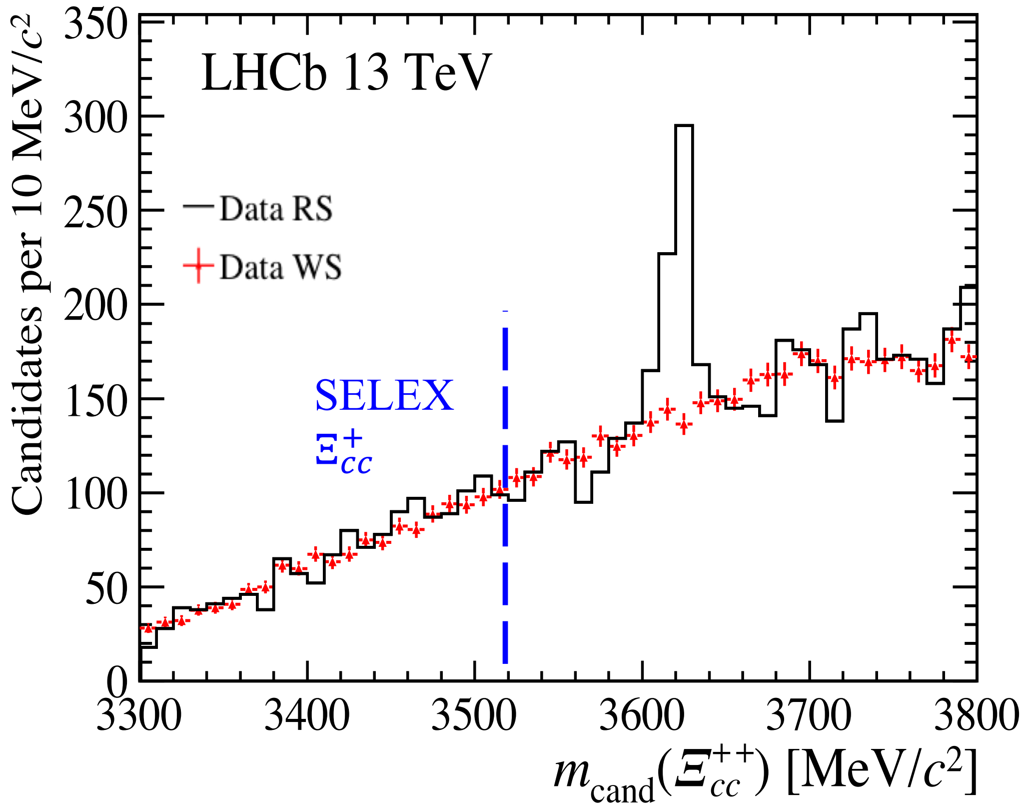
- Large mass difference: $m(\Xi_{cc}^{++})_{\text{LHCb}} - m(\Xi_{cc}^{+})_{\text{SELEX}} = 103 \pm 2$ MeV
  - ➢ Inconsistent with being isospin partners

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 $\boldsymbol{B(D)}$mesons & $\boldsymbol{b(c)}$ baryons

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

  — Observation/study of exotic states

  $\boldsymbol{X(4430), X(4140), X(4274), X(4500), X(4700), P_c(4380), P_c(4450)}$, ...

  — Discovery of doubly charmed baryons

  — ……

- Stay tuned with RUNII data + LHCb upgrade.

Backup slides

References: Ω^{**} mass

D. Ebert, R. N. Faustov, and V. O. Galkin, *Masses of excited heavy baryons in the relativistic quark-diquark picture*, Phys. Lett. **B659** (2008) 612, arXiv:0705.2957.

W. Roberts and M. Pervin, *Heavy baryons in a quark model*, Int. J. Mod. Phys. **A23** (2008) 2817, arXiv:0711.2492.

H. Garcilazo, J. Vijande, and A. Valcarce, *Faddeev study of heavy-baryon spectroscopy*, J. Phys. **G34** (2007) 961, arXiv:hep-ph/0703257.

S. Migura, D. Merten, B. Metsch, and H.-R. Petry, *Charmed baryons in a relativistic quark model*, Eur. Phys. J. **A28** (2006) 41, arXiv:hep-ph/0602153.

D. Ebert, R. N. Faustov, and V. O. Galkin, *Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture*, Phys. Rev. **D84** (2011) 014025, arXiv:1105.0583.

A. Valcarce, H. Garcilazo, and J. Vijande, *Towards an understanding of heavy baryon spectroscopy*, Eur. Phys. J. **A37** (2008) 217, arXiv:0807.2973.

Z. Shah, K. Thakkar, A. K. Rai, and P. C. Vinodkumar, *Mass spectra and Regge trajectories of* Λ_c^+, Σ_c^0, Ξ_c^0 *and* Ω_c^0 *baryons*, Chin. Phys. **C40** (2016) 123102, arXiv:1609.08464.

J. Vijande, A. Valcarce, T. F. Carames, and H. Garcilazo, *Heavy hadron spectroscopy: A quark model perspective*, Int. J. Mod. Phys. **E22** (2013) 1330011, arXiv:1212.4383.

References: Ω_c^* masses (cont'd)

T. Yoshida *et al.*, *Spectrum of heavy baryons in the quark model*, Phys. Rev. **D92** (2015) 114029, `arXiv:1510.01067`.

H.-X. Chen *et al.*, *P-wave charmed baryons from QCD sum rules*, Phys. Rev. **D91** (2015) 054034, `arXiv:1502.01103`.

H.-X. Chen *et al.*, *D-wave charmed and bottomed baryons from QCD sum rules*, Phys. Rev. **D94** (2016) 114016, `arXiv:1611.02677`.

G. Chiladze and A. F. Falk, *Phenomenology of new baryons with charm and strangeness*, Phys. Rev. **D56** (1997) R6738, `arXiv:hep-ph/9707507`.

M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, *Excited-state spectroscopy of singly, doubly and triply-charmed baryons from lattice QCD*, `arXiv:1311.4806`.

References: Ξ_{cc} masses

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys. Atom. Nucl. **63**, 274 (2000), [Yad. Fiz. 63, 334 (2000)], arXiv:hep-ph/9811212 [hep-ph].

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Mod. Phys. Lett. **A14**, 135 (1999), arXiv:hep-ph/9807375 [hep-ph].

C. Itoh, T. Minamikawa, K. Miura, and T. Watanabe, Phys. Rev. **D61**, 057502 (2000).

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys.Rev. **D62**, 054021 (2000).

K. Anikeev *et al.*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999* (2001) arXiv:hep-ph/0201071 [hep-ph].

V. Kiselev and A. Likhoded, Phys.Usp. **45**, 455 (2002), arXiv:hep-ph/0103169 [hep-ph].

D. Ebert, R. Faustov, V. Galkin, and A. Martynenko, Phys.Rev. **D66**, 014008 (2002), arXiv:hep-ph/0201217 [hep-ph].

D.-H. He, K. Qian, Y.-B. Ding, X.-Q. Li, and P.-N. Shen, Phys.Rev. **D70**, 094004 (2004), arXiv:hep-ph/0403301 [hep-ph].

C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, Phys.Rev. **D73**, 094022 (2006), arXiv:hep-ph/0601032 [hep-ph].

W. Roberts and M. Pervin, Int.J.Mod.Phys. **A23**, 2817 (2008), arXiv:0711.2492 [nucl-th].

A. Valcarce, H. Garcilazo, and J. Vijande, Eur.Phys.J. **A37**, 217 (2008), arXiv:0807.2973 [hep-ph].

J.-R. Zhang and M.-Q. Huang, Phys.Rev. **D78**, 094007 (2008), arXiv:0810.5396 [hep-ph].

Z.-G. Wang, Eur.Phys.J. **A45**, 267 (2010), arXiv:1001.4693 [hep-ph].

M. Karliner and J. L. Rosner, Phys. Rev. **D90**, 094007 (2014), arXiv:1408.5877 [hep-ph].

K.-W. Wei, B. Chen, and X.-H. Guo, Phys. Rev. **D92**, 076008 (2015), arXiv:1503.05184 [hep-ph].

Z.-F. Sun and M. J. Vicente Vacas, Phys. Rev. **D93**, 094002 (2016), arXiv:1602.04714 [hep-ph].

C. Alexandrou and C. Kallidonis, (2017), arXiv:1704.02647 [hep-lat].

B. O. Kerbikov, M. I. Polikarpov, and L. V. Shevchenko, Nucl. Phys. **B331**, 19 (1990).

S. Fleck and J.-M. Richard, Prog. Theor. Phys. **82**, 760 (1989).

S. Chernyshev, M. A. Nowak, and I. Zahed, Phys. Rev. **D53**, 5176 (1996), arXiv:hep-ph/9510326 [hep-ph].

T. M. Aliev, K. Azizi, and M. Savcı, Nucl. Phys. **A895**, 59 (2012), arXiv:1205.2873 [hep-ph].

Z.-F. Sun, Z.-W. Liu, X. Liu, and S.-L. Zhu, Phys. Rev. **D91**, 094030 (2015), arXiv:1411.2117 [hep-ph].

N. Mathur, R. Lewis, and R. M. Woloshyn, Phys. Rev. **D66**, 014502 (2002), arXiv:hep-ph/0203253 [hep-ph].

Y. Namekawa *et al.* (PACS-CS collaboration), Phys. Rev. **D87**, 094512 (2013), arXiv:1301.4743 [hep-lat].

Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, Phys. Rev. **D90**, 094507 (2014), arXiv:1409.0497 [hep-lat].

M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, Phys. Rev. **D91**, 094502 (2015), arXiv:1502.01845 [hep-lat].

P. Pérez-Rubio, S. Collins, and G. S. Bali, Phys. Rev. **D92**, 034504 (2015), arXiv:1503.08440 [hep-lat].

Y. Liu and I. Zahed, Phys. Rev. **D95**, 116012 (2017), arXiv:1704.03412 [hep-ph]; (2017), arXiv:1705.01397

References: Ξ_{cc} lifetimes

K. Anikeev *et al.*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999* (2001) arXiv:hep-ph/0201071 [hep-ph].

V. Kiselev and A. Likhoded, Phys.Usp. **45**, 455 (2002), arXiv:hep-ph/0103169 [hep-ph].

M. Karliner and J. L. Rosner, Phys. Rev. **D90**, 094007 (2014), arXiv:1408.5877 [hep-ph].

S. Fleck and J.-M. Richard, Prog. Theor. Phys. **82**, 760 (1989).

B. Guberina, B. Melić, and H. Štefančić, Eur.Phys.J. **C9**, 213 (1999), arXiv:hep-ph/9901323 [hep-ph].

V. Kiselev, A. Likhoded, and A. Onishchenko, Phys.Rev. **D60**, 014007 (1999), arXiv:hep-ph/9807354 [hep-ph].

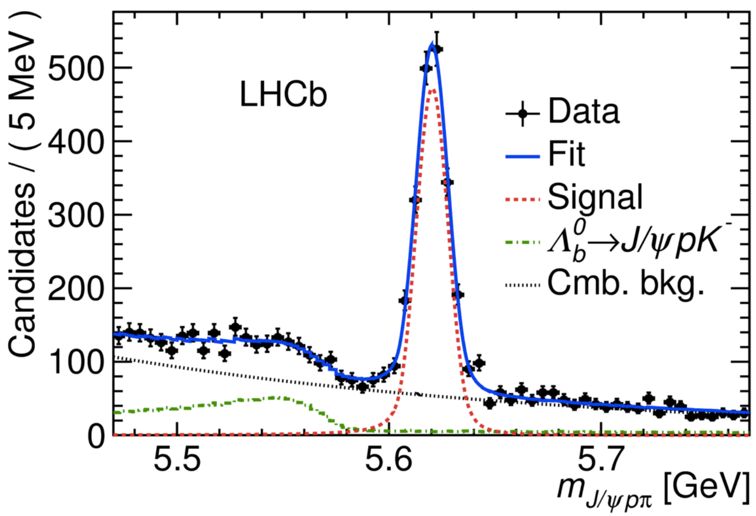
C.-H. Chang, T. Li, X.-Q. Li, and Y.-M. Wang, Commun.Theor.Phys. **49**, 993 (2008), arXiv:0704.0016 [hep-ph].

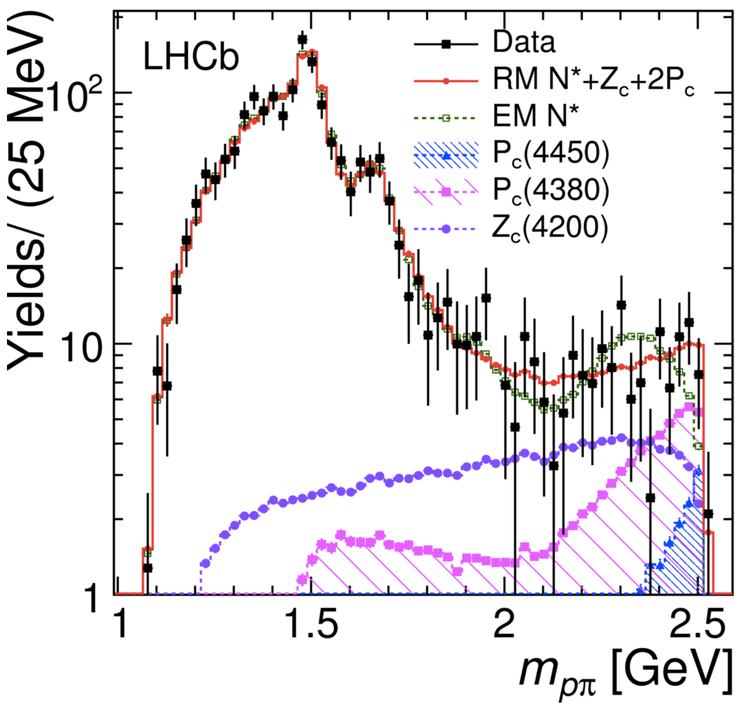
A. V. Berezhnoy and A. K. Likhoded, Phys. Atom. Nucl. **79**, 260 (2016), [Yad. Fiz. 79, 151 (2016)].

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

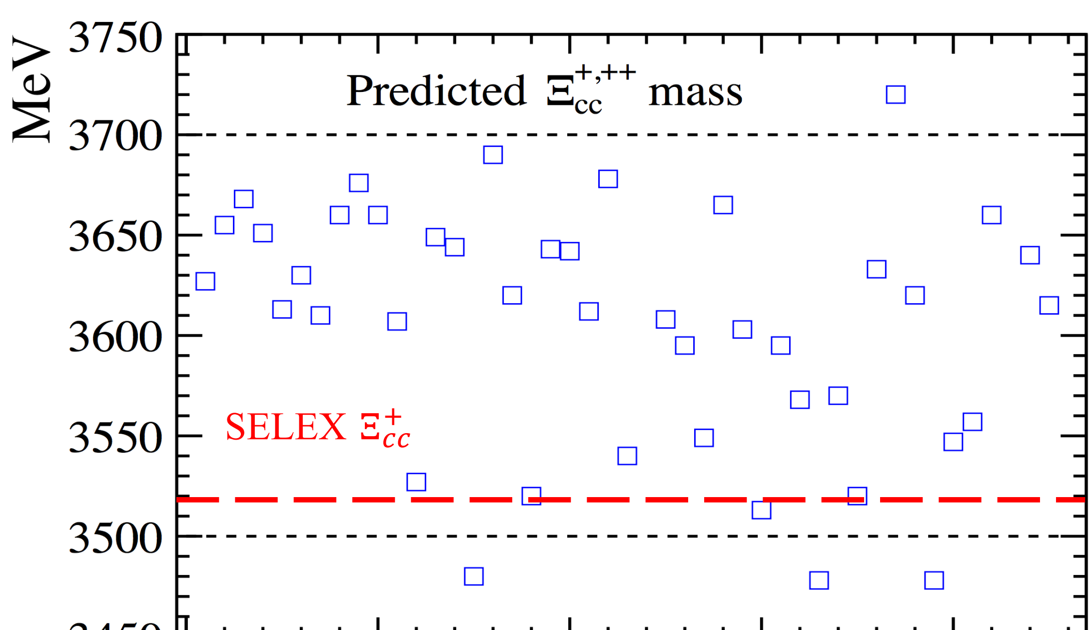




Results from SELEX

- 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 $\Xi_{cc}^+ \to pD^+K^-$ decays
  - **Signal yields**: 15.9 ($\Lambda_c^+ K^- \pi^+$) and 5.62 (pD^+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

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