Exotic hadrons and doubly heavy baryons at LHCb

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Dec. 21st, 2018

Outline

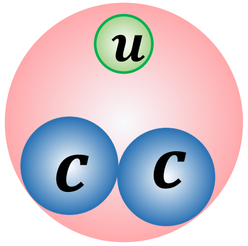
- Introduction

- Recent LHCb results on exotic hadrons and Doubly heavy baryons:
  - Results from Exotic hadrons
  - Results from Doubly heavy baryons

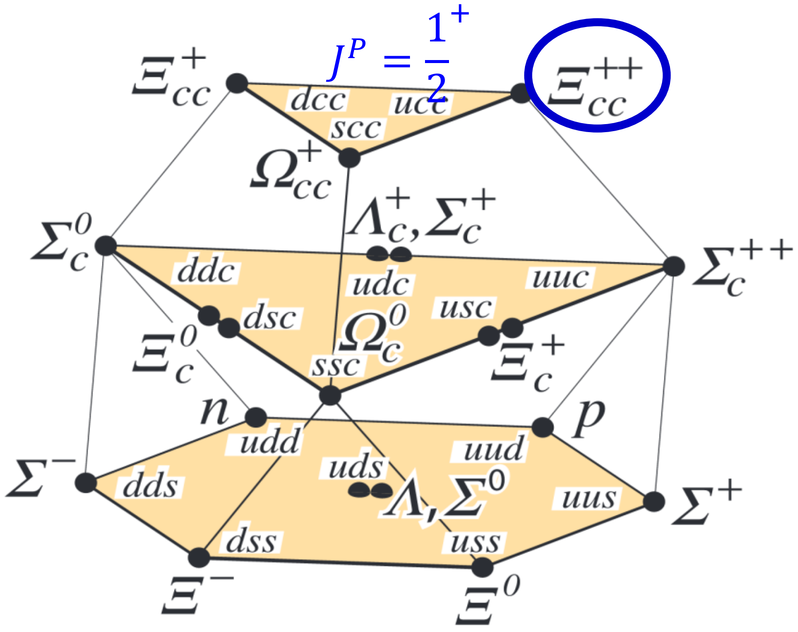
- Summary

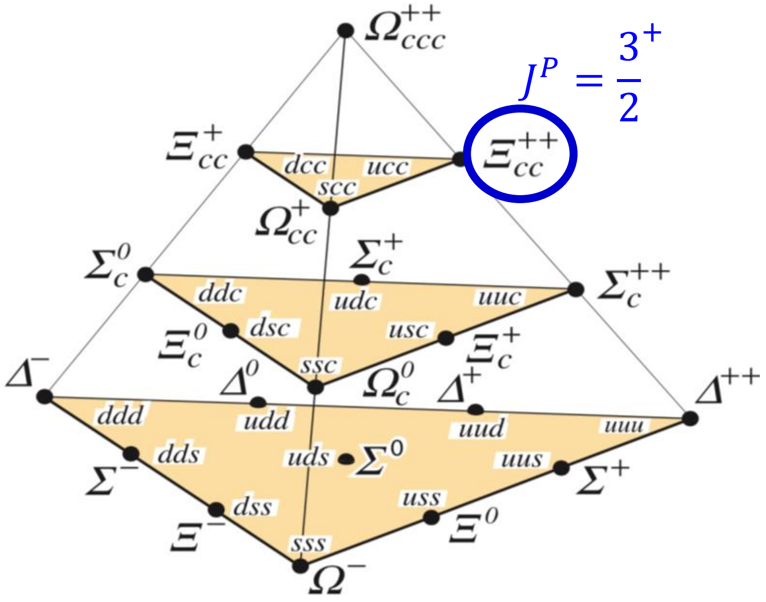
Success of the constituent quark model

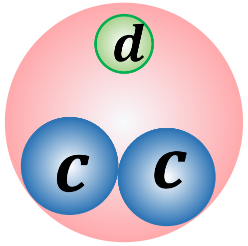
- Quark model, introduced by Gell-Mann and Zweig, in 1964
  - Construct numerous hadrons using quarks
  - SU(4) and SU(5) to include new quarks: charm (c), and bottom (b)



Ξ_{cc}^{++}







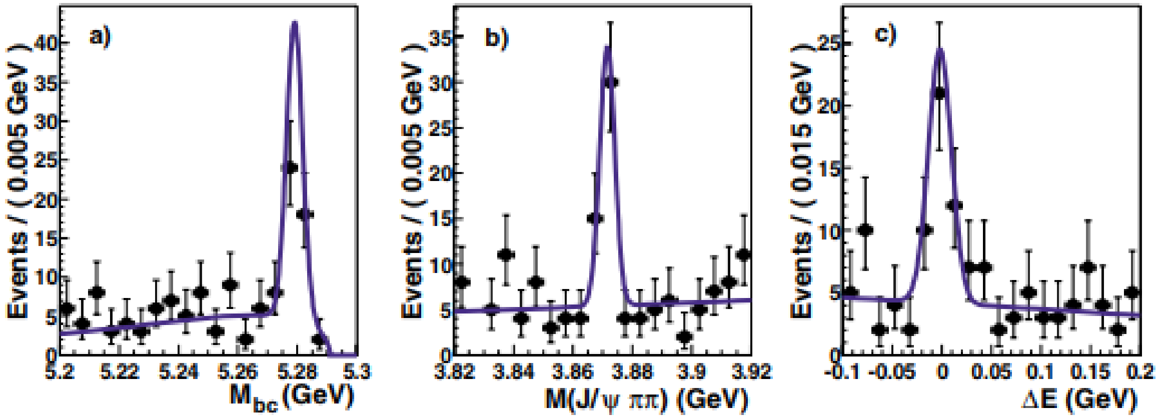
Ξ_{cc}^+

Exotic hadrons

- **Exotic hadrons**: anything beyond meson ($q\bar{q}$) and baryon (qqq) scheme
- Could be various multiquark states, hadron molecules, glueballs, hybirds …
- First seen by Belle in 2003 Phys. Rev. Lett. 91, 262001 (2003)

VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

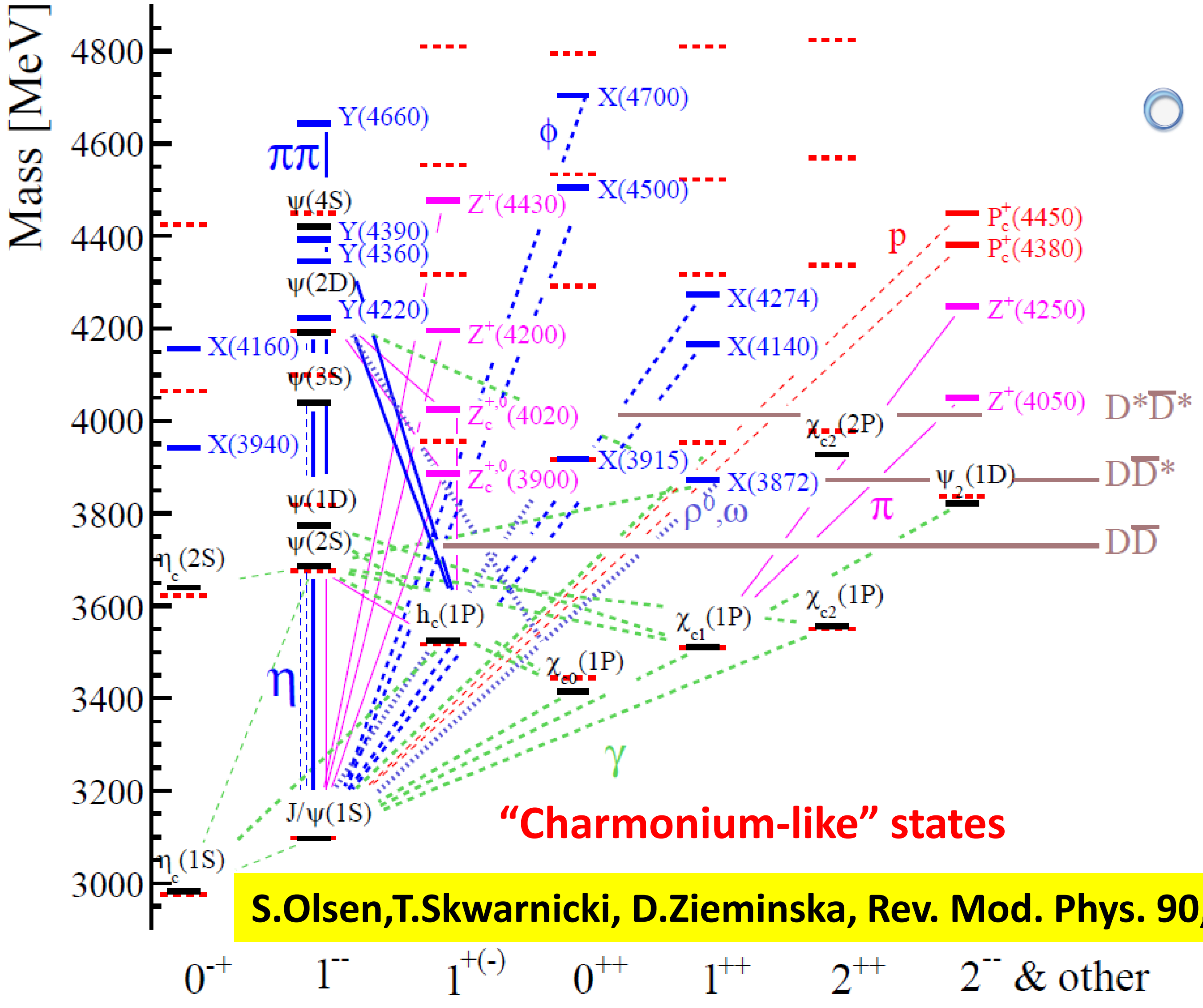
Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays



$$B^{+} \to X(3872)K^{+}$$
$$X(3872) \to J/\Psi\pi^{+}\pi^{-}$$

Expected quark content $[c\bar{c}u\bar{u}]$
Internal structure is still under discussion

Exotic zoo



"Charmonium-like" states

S.Olsen,T.Skwarnicki, D.Zieminska, Rev. Mod. Phys. 90, 15003 (2018)

- Not a very strict naming scheme
  - X : neutral, first seen in B-meson decays, positive parity
  - Y : neutral, first seen in ee annihilation with initial state radiation, negative parity
  - Z : charged (and their isospin partners)
  - P : pentaquarks

No clear pattern seen yet

Theoretical models

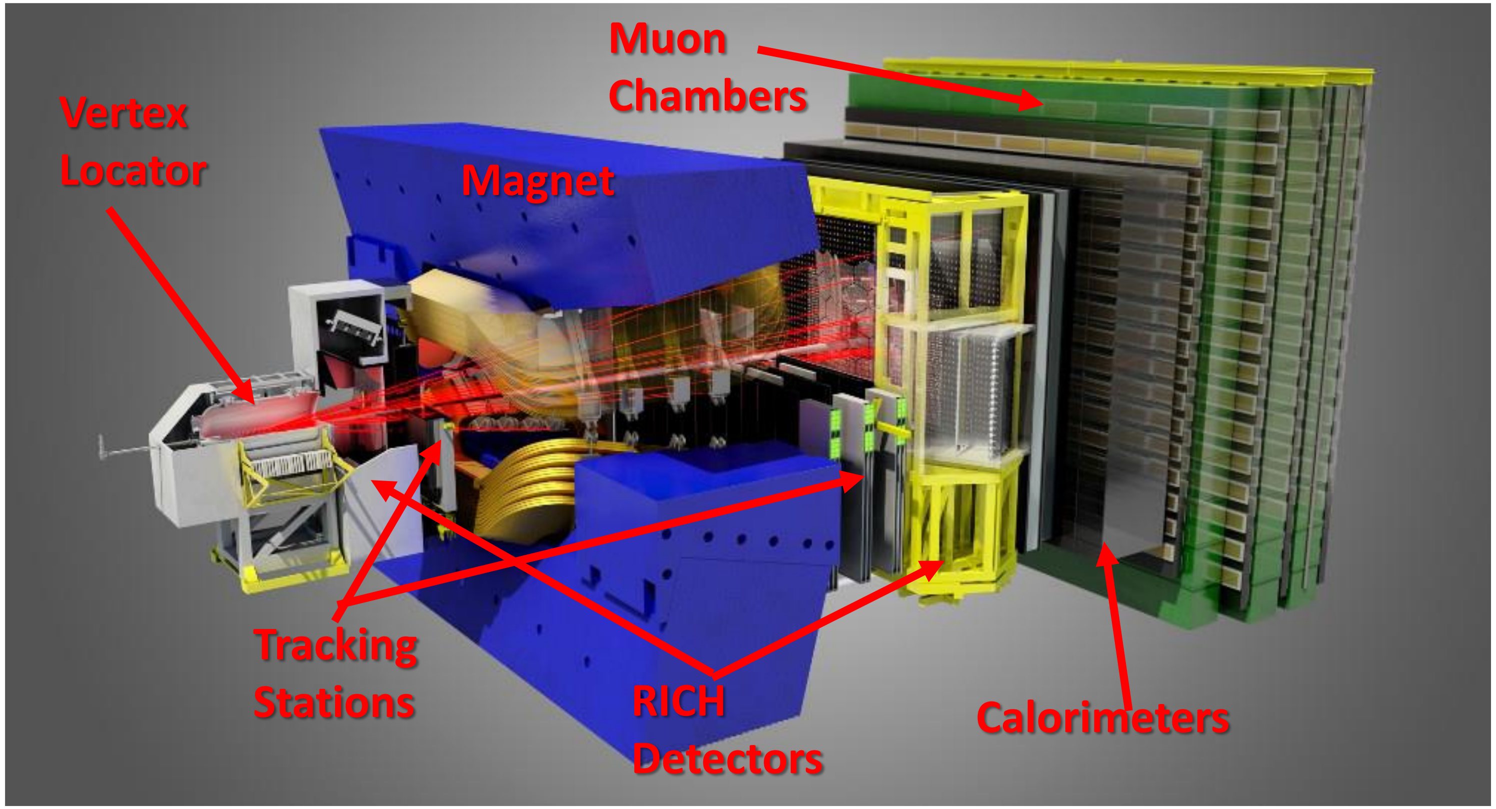
- Lots of predictions within different theoretical models

Tightly bound tetraquarks | Diquark-onium | Meson molecules | Hadro-quarkonium

- Not only to find new exotic hadrons, but also to determine their quantum numbers

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

LHCb detector



- LHCb is a forward spectrometer suited for b, c hadrons: $2 < \eta < 5$
- Momentum resolution:
  - 0.5% at 5 GeV, 1.0% at 200 GeV
- Excellent track and vertex reconstruction
- Good particle-ID separation

Exotic hadrons

$Z_c(4100)^-$ in $B^0 \to \eta_c(1S)K^+\pi^-$

arXiv:1809.07416
Submitted to EPJC

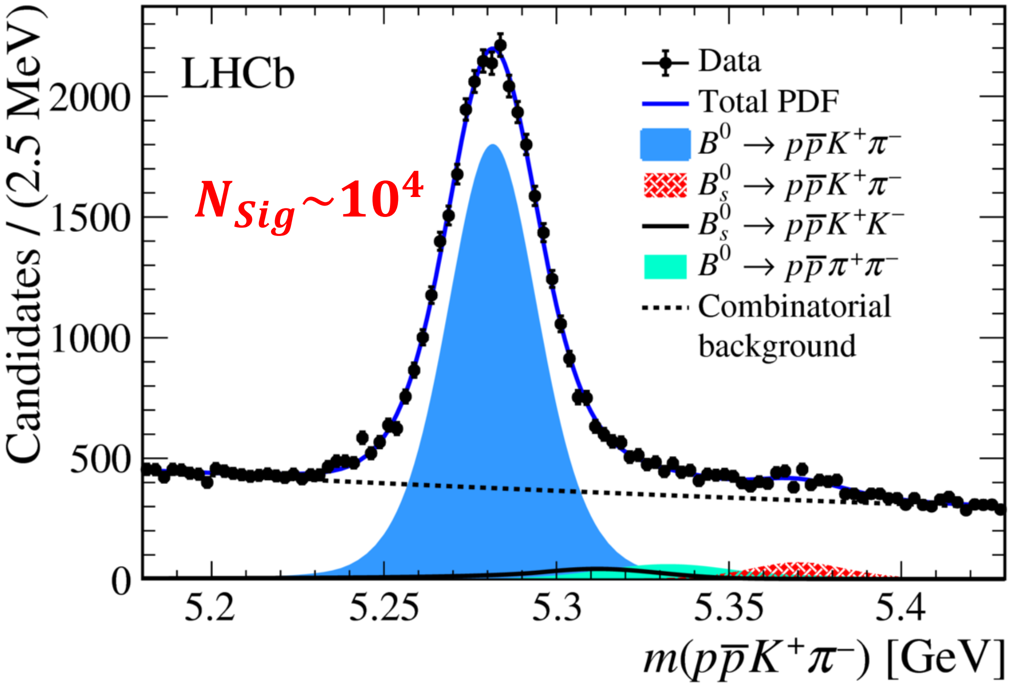
- Understand pattern of Z_c^- states
  - $Z_c(3900)^-$ seen by BES III, and Belle in $Y(4260) \to Z_c^-(\to J/\Psi\pi^-)\pi^+$
- Charmonium-like charged stats: exotic
- $\eta_c\pi^-$ accesses J^P other than 1^+, that several Z_c^- confirmed to be

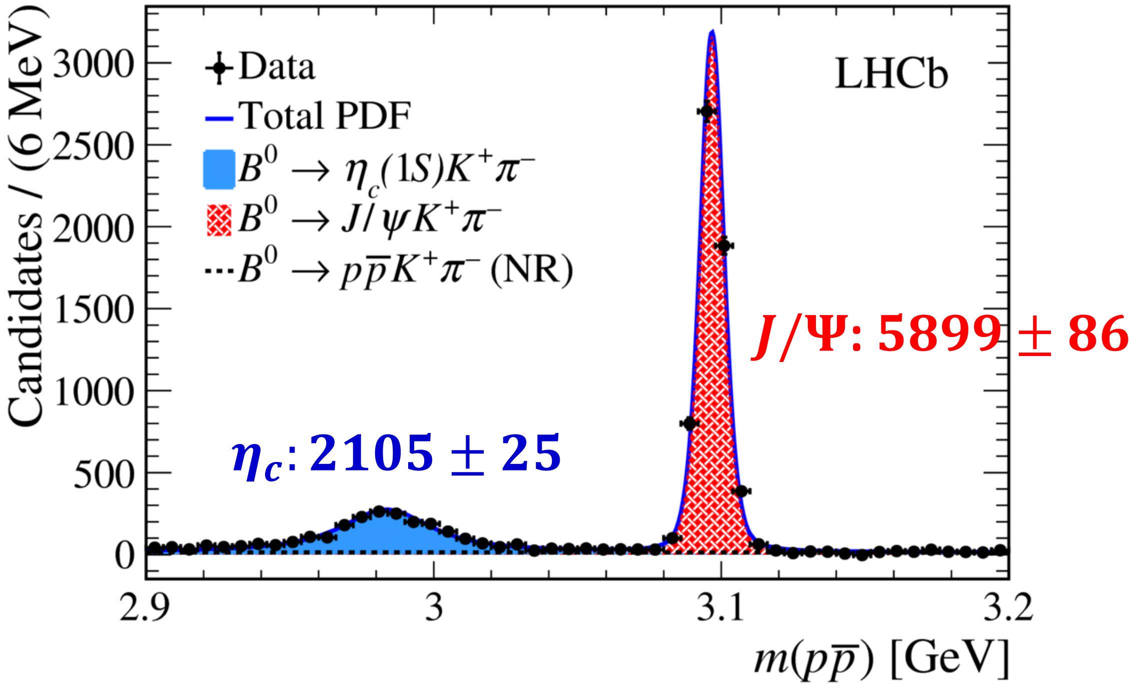
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0} + (J/\psi\,\pi^{+,0})$	BESIII (92; 101), Belle (88)
				$e^+e^- \to \pi^{-,0} + (D\bar{D}^*)^{+,0}$	BESIII (102; 103)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0} + (h_c\,\pi^{+,0})$	BESIII (93; 104)
				$e^+e^- \to \pi^{-,0} + (D^*\bar{D}^*)^{+,0}$	BESIII (105; 106)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle (107), BaBar (108)
$Z^+(4200)$	4196^{+35}_{-32}	$370^{+\ 99}_{-149}$	1^+	$B \to K + (J/\psi\,\pi^+)$	Belle (51)
				$B \to K + (\psi'\pi^+)$	LHCb (46)
$Z^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle (107), BaBar (108)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K + (\psi'\,\pi^+)$	Belle (45; 109; 110), LHCb (46; 111)
				$B \to K + (J\psi\,\pi^+)$	Belle (51)

$B^0 \to \eta_c(1S)K^+\pi^-$ signal

arXiv:1809.07416
Submitted to EPJC

- L = 4.7 fb^{-1}, including Run-1 + Run-2 (2011-2016) data
- Multi-stage signal/bkg separation fits in $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$

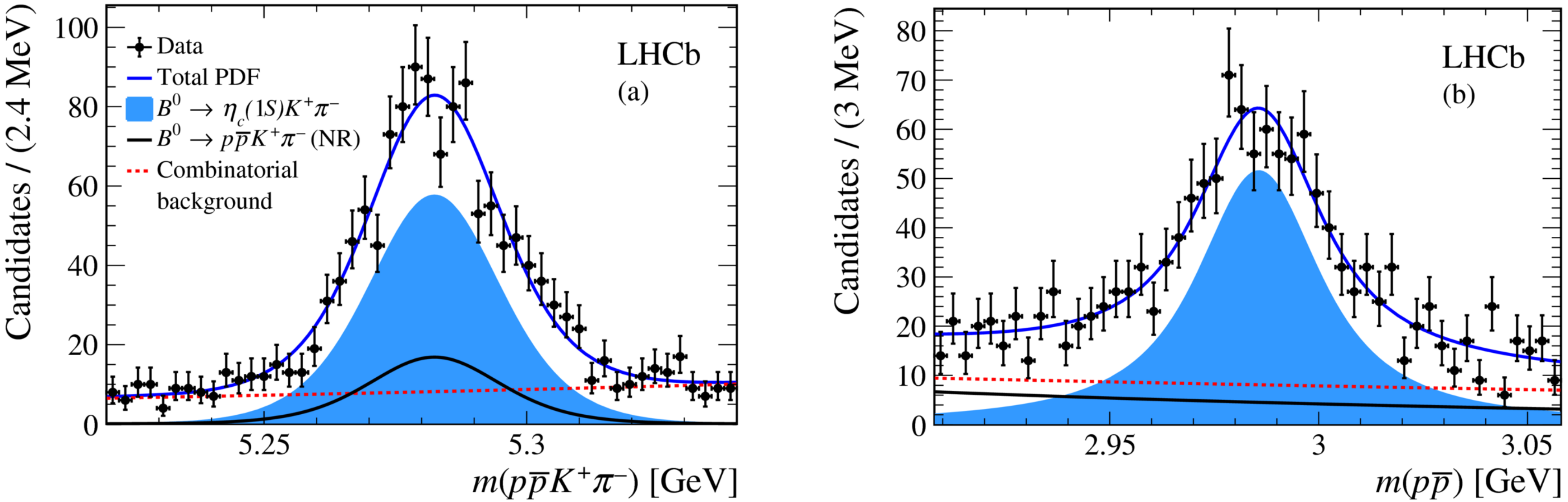




$B^0 \to \eta_c(1S)K^+\pi^-$ 2D mass fit

arXiv:1809.07416
Submitted to EPJC

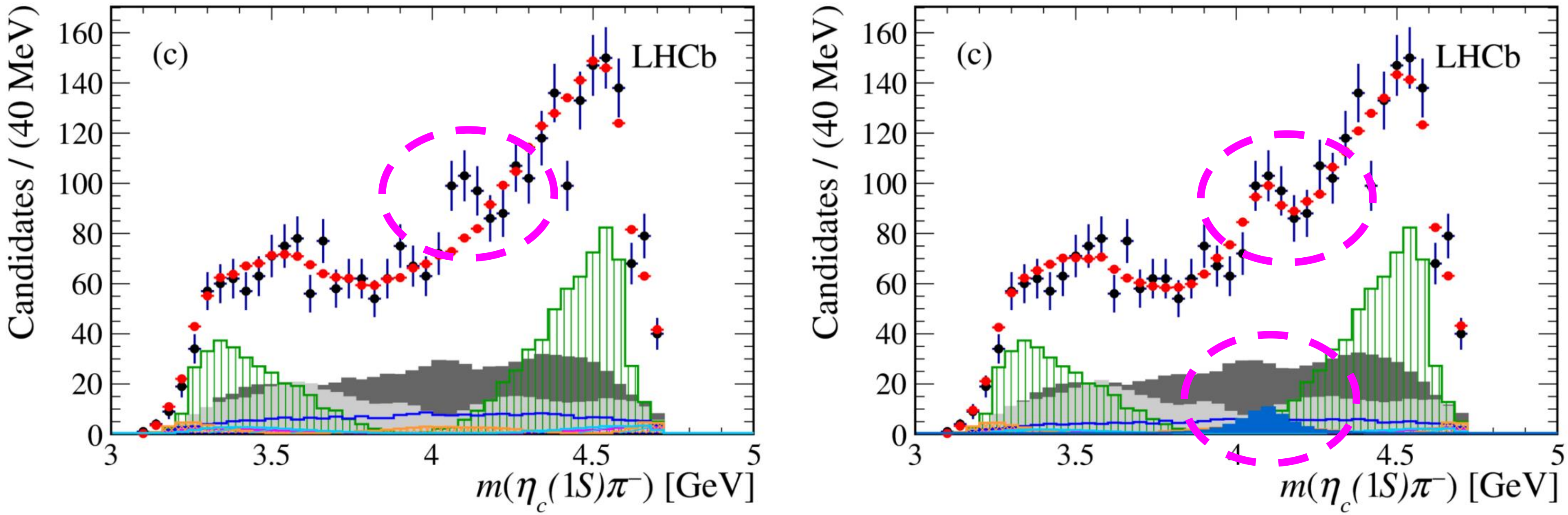
- Unlike narrow J/Ψ , $\Psi(2S)$, η_c has $\Gamma_0 \sim$ 32 MeV
- 2D fit in $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$
- Dalitz analysis: K^* resonances + "non-resonant" $K\pi$ and $p\bar{p}$ S-waves



Evidence for an exotic $Z_c(4100)^-$

arXiv:1809.07416
Submitted to EPJC

- Good description in all variables after adding an exotic Z_c component



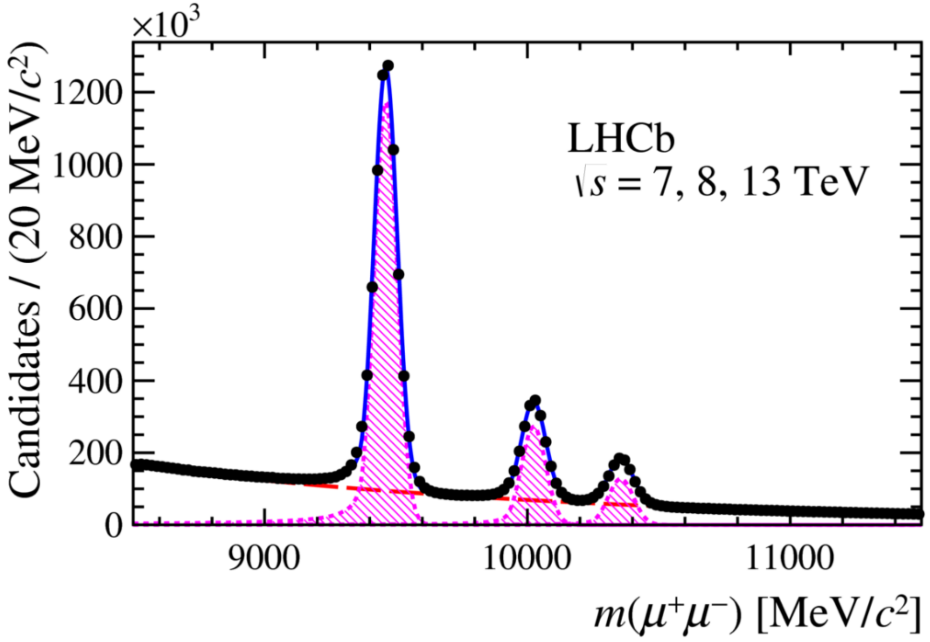
- $Z_c(4100)^-$: $J^P = 1^-$ significance is 3.4σ after considering systematics
- Only 1.2σ difference with alternative $J^P = 0^+$ assignment
- Mass $m_0 = 4096 \pm 20^{+18}_{-22}$ MeV, $\Gamma = 152 \pm 58^{+80}_{-35}$ MeV

Search for beauty teraquarks: $X_{b\bar{b}b\bar{b}}$

JHEP 10 (2018) 086

- No hadron containing > 2 heavy quarks has been observed so far
- Theoretical prediction:
  - Mass within [18.4, 18.8] GeV, $\sigma \times B(\Upsilon l^+ l^-) \sim 1$ fb
  - Typically below $\eta_b \eta_b$ threshold: could decay to $\Upsilon l^+ l^-$ $(l = e, \mu)$
  - Lattice QCD calculation do not find evidence for this state

Phys. Rev. D97 (2018) 054505



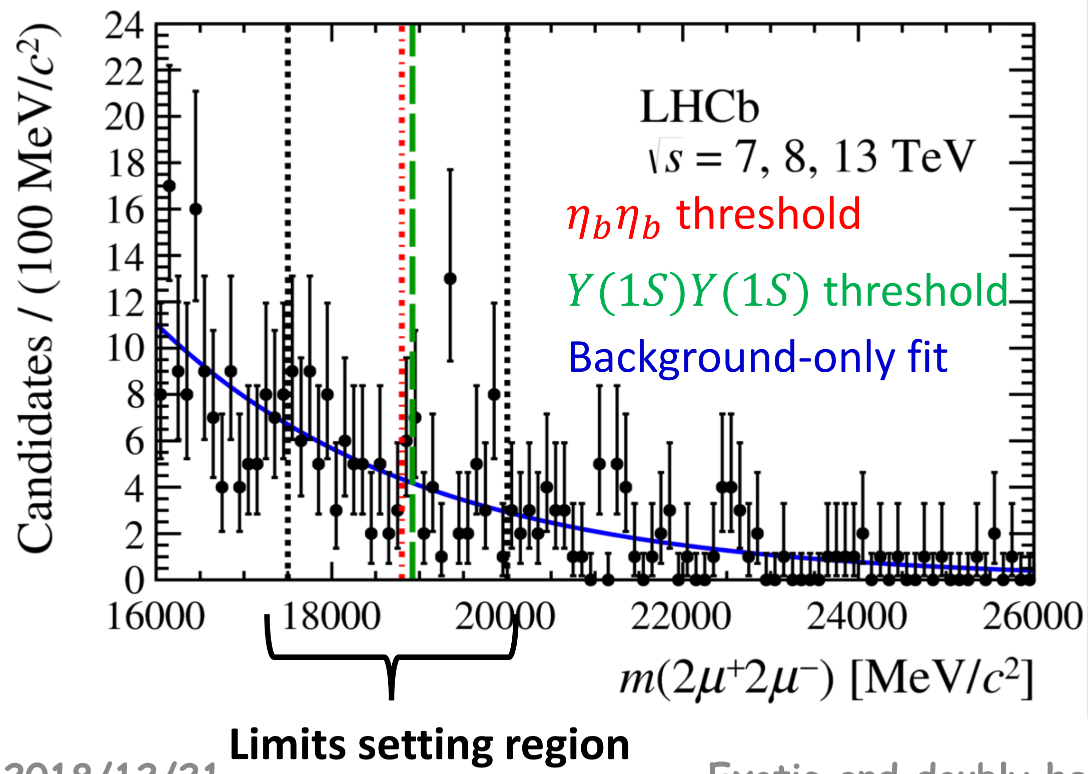
LHCb search:

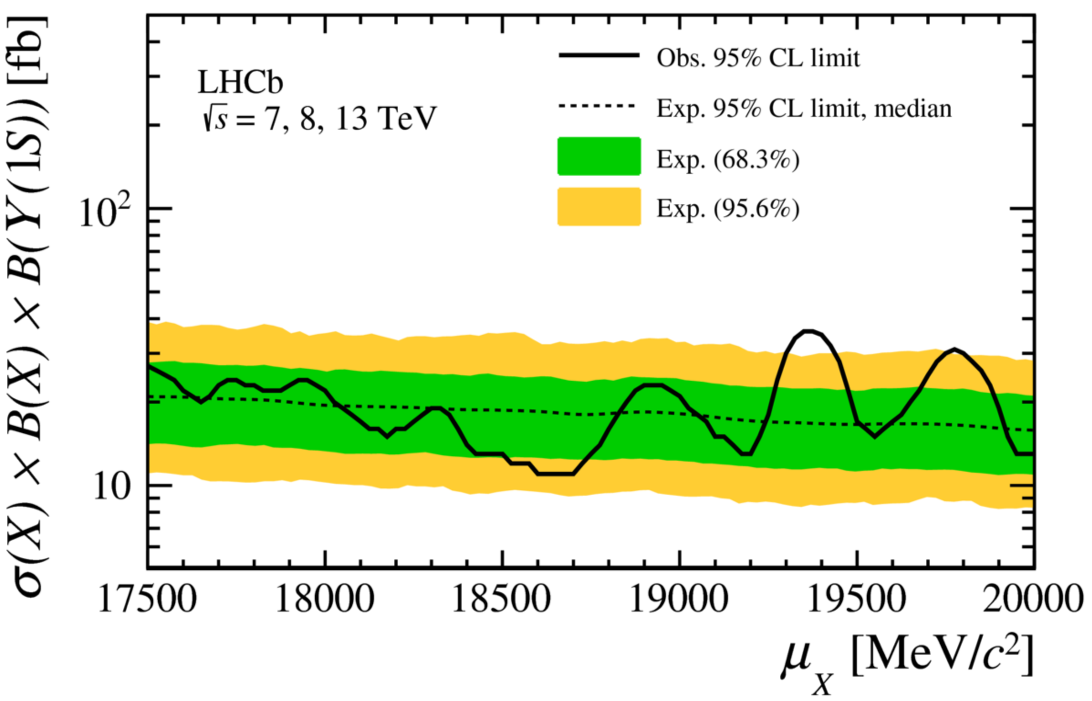
- $X_{b\bar{b}b\bar{b}} \rightarrow \Upsilon(1S)\mu^+\mu^-$, where $\Upsilon(1S) \rightarrow \mu^+\mu^-$
- Mass range : 17.5 – 20.0 GeV
- Run-1 + Run-2 data

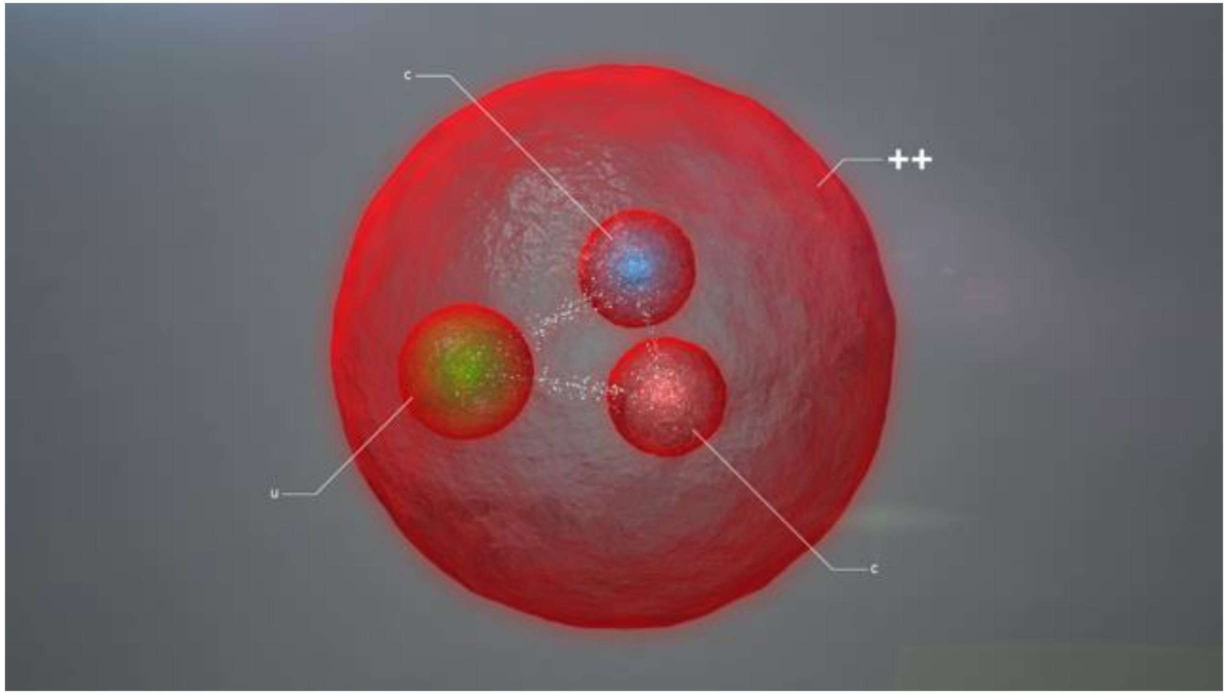
Search for beauty teraquarks: $X_{b\bar{b}b\bar{b}}$

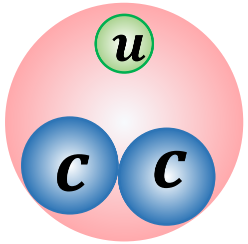
JHEP 10 (2018) 086

- Cut-based selection, with J/Ψ mass veto
- $\Upsilon(1S)$ yields after selection ($\pm 2.5\sigma$ region): ~6×10^6
- No significant excess is seen in data, upper limit are set







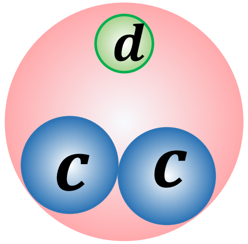


Ξ_{cc}^{++}

Ξ_{cc}^{++} measurements

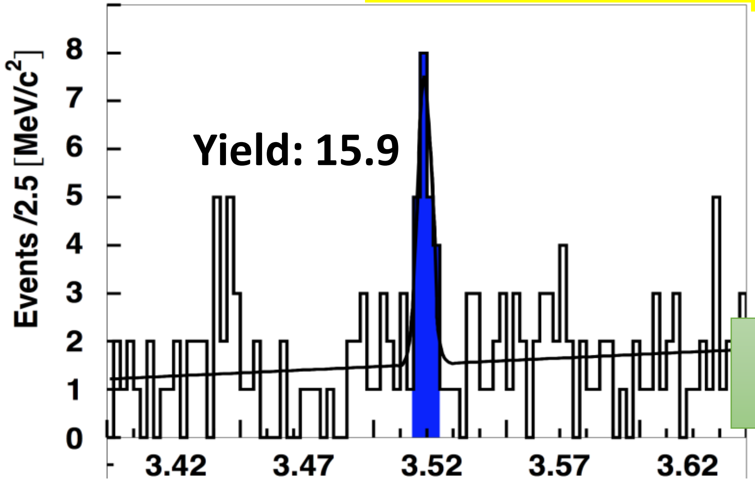
Studies of Ξ_{cc} by SELEX experiment

- SELEX (Fermilab E781) claimed observation of $\Xi_{cc}^{+}(ccd)$ 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

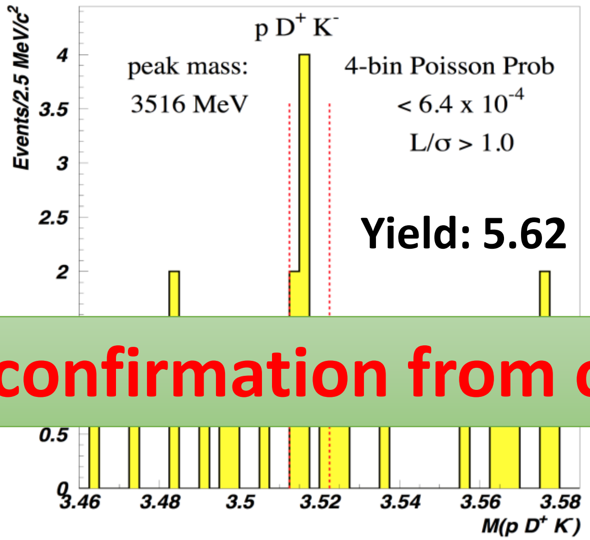


Ξ_{cc}^{+}

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



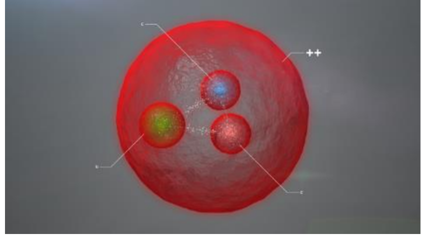
$\Xi_{cc}^{+} \to p D^{+} K^{-}$ PLB 628 (2005) 18



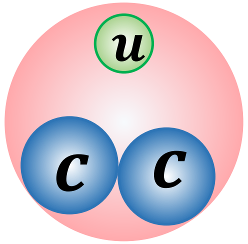
No confirmation from other experiments

Observation of Ξ_{cc}^{++}

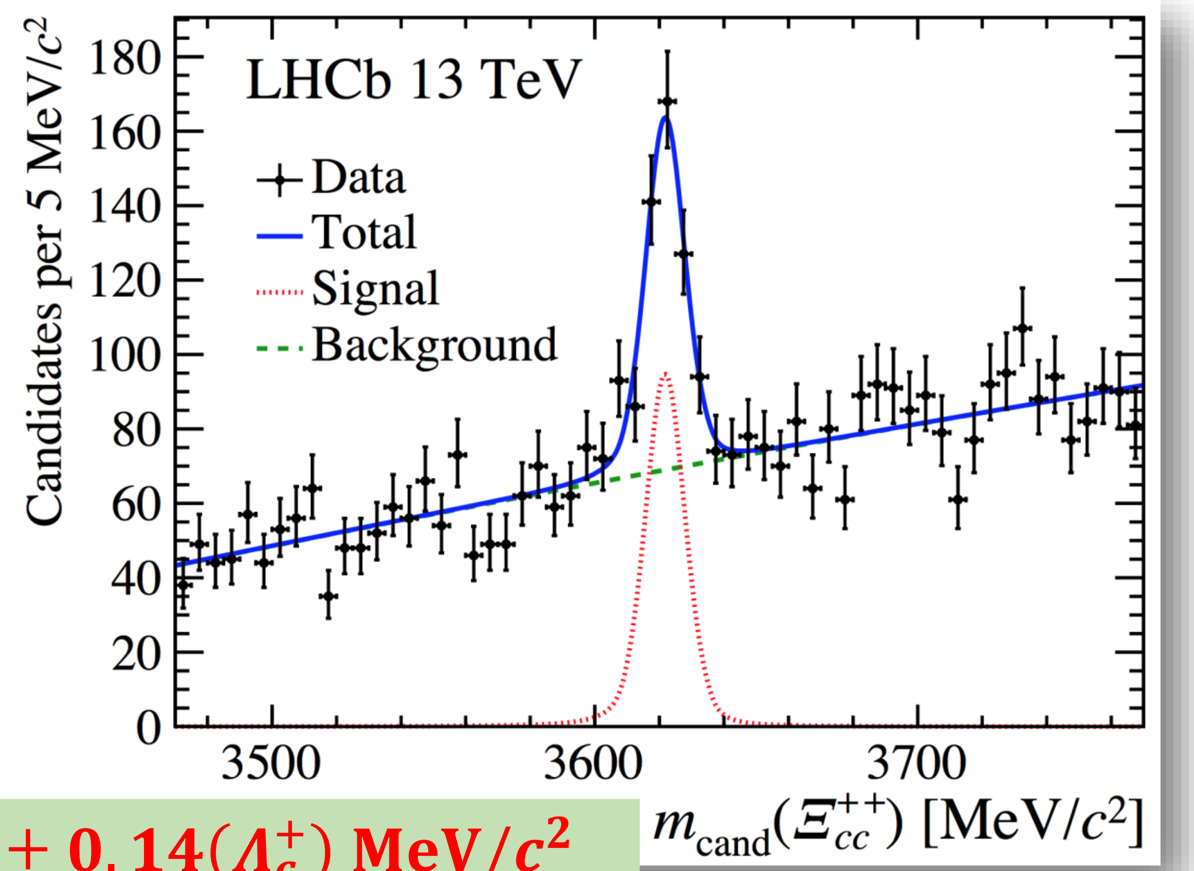
Phys. Rev. Lett. 119, 112001 (2017)



- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ observed by **LHCb** using 2016 data
  - Signal yield: 313 ± 33
  - **Local significance > 12σ**
  - Decaying only via weak interaction



Ξ_{cc}^{++}



$$3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

Ξ_{cc}^{++} lifetime

Phys. Rev. Lett. 121, 052002 (2018)

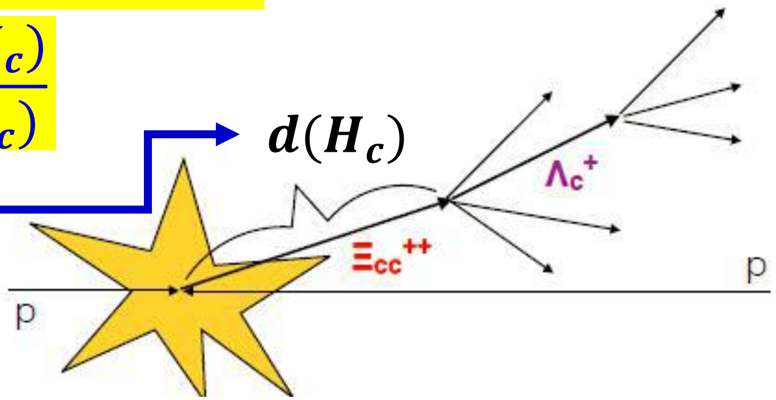
- Inconsistent with zero in the observation paper
- A lifetime measurement is critical:
  - To confirm it is a weak decay
  - Necessary ingredient for theoretical prediction of BR
  - Important information for experimental exploration of Ξ_{cc}^{++}
  - To test various predictions from QCD model

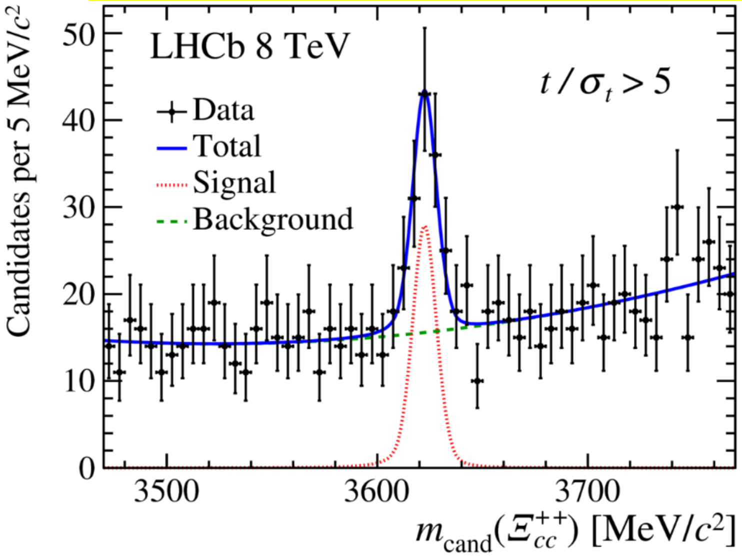
Phys. Rev. Lett. 119, 112001 (2017)

Decay time measurement:

$$\tau(H_c) = d(H_c)\frac{m(H_c)}{p(H_c)}$$

$d(H_c)$



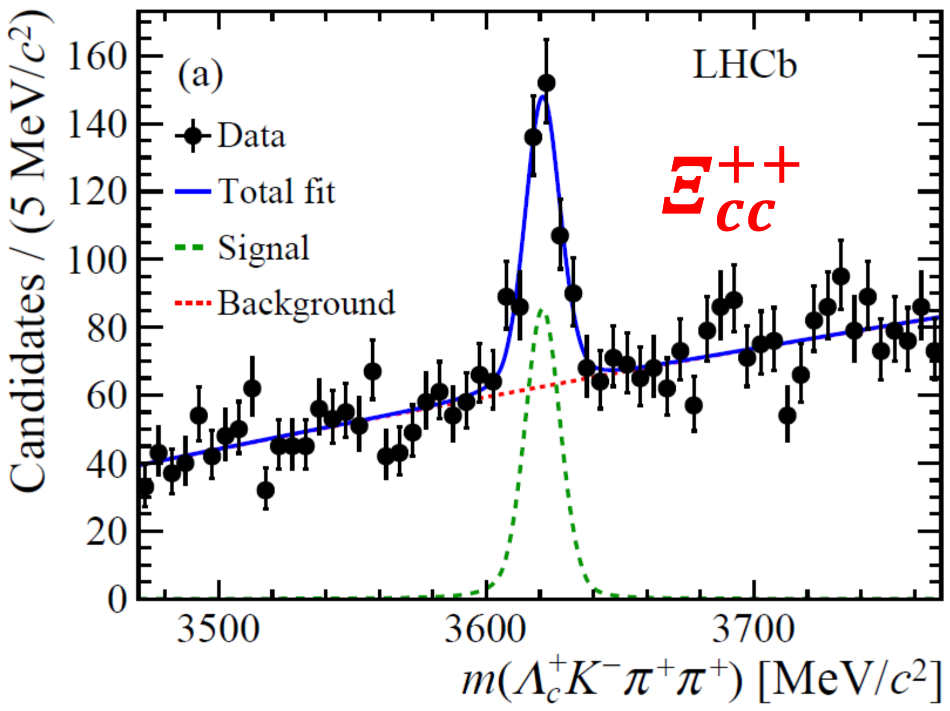


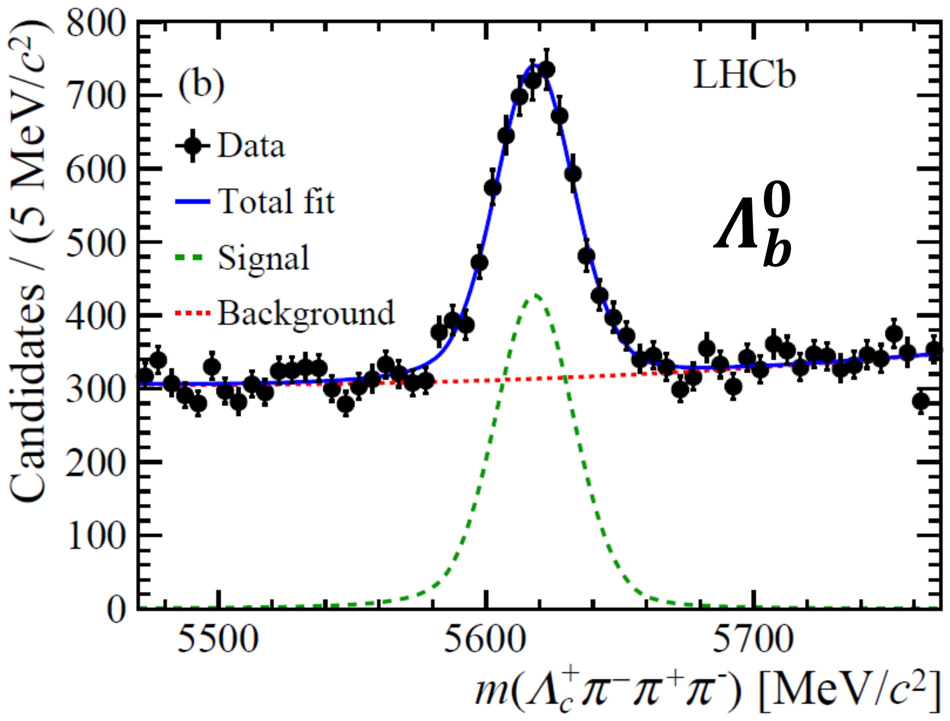
Mass fit

Phys. Rev. Lett. 121, 052002 (2018)

Yields: (2016)
Ξ_{cc}^{++}: 304±35
Λ_b^0: 3379 ± 119

- **Signal**: Double-sided Crystal-Ball + Gaussian
- **Background**: 2nd order Chebychev





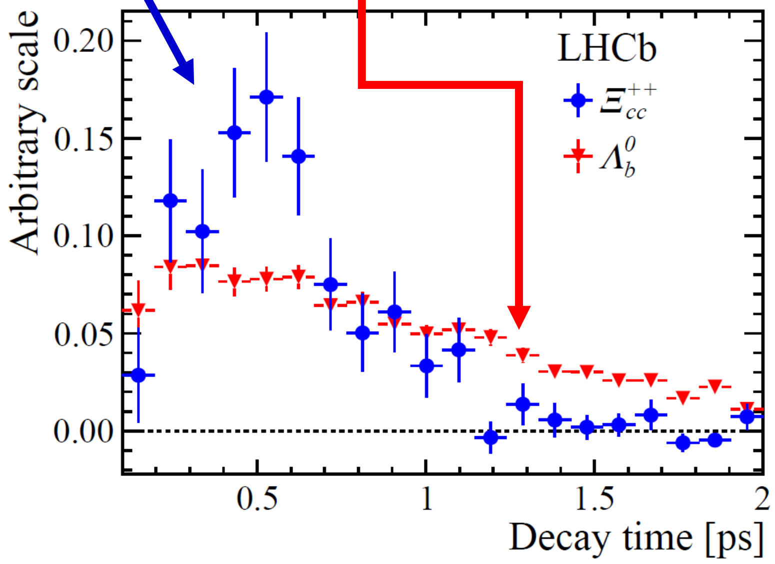
Lifetime fit

Phys. Rev. Lett. 121, 052002 (2018)

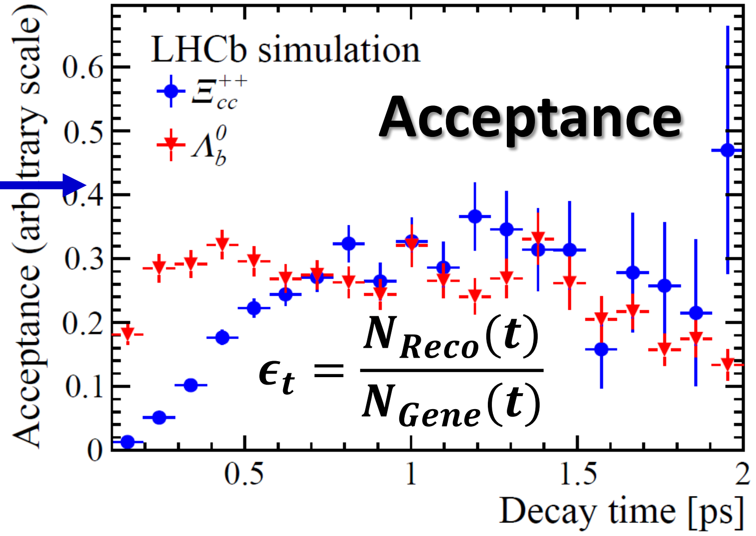
$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

$\tau_{\Lambda_b^0} = 1.470 \pm 0.010$ ps (PDG)

Free parameter



Background subtracted decay time distributions

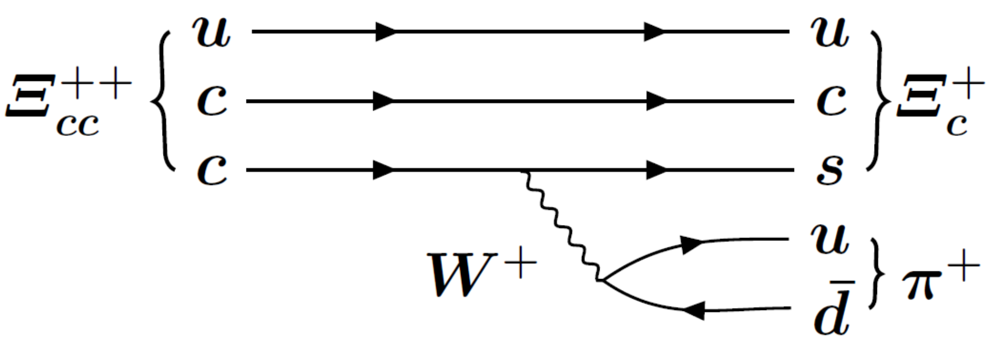


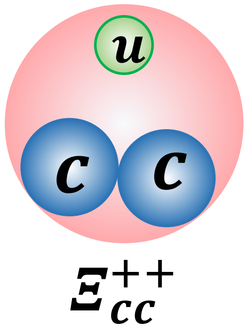
$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014\ (\text{syst})\ \text{ps}$$

F.-S. Yu et al., Chin. Phys. C 42, 051001 (2018)

Search for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$

- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: one of the best channels to confirm Ξ_{cc}^{++}
  - $BR(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \sim \mathcal{O}(1\%)$ **Prediction**
  - $BR(\Lambda_c^+ \to p^+ K^- \pi^+)$~(6.35%), **Measurement**
    $BR(\Xi_c^+ \to p^+ K^- \pi^+)$~(2%) **Prediction**
  - Fewer tracks (4 tracks) → higher efficiency





Mass fit

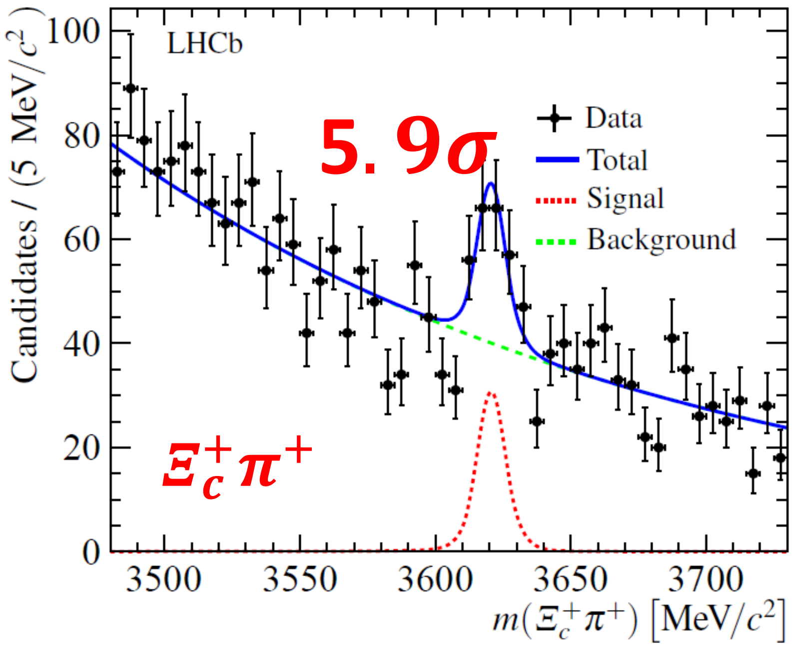
Phys. Rev. Lett. 121, 162002 (2018)

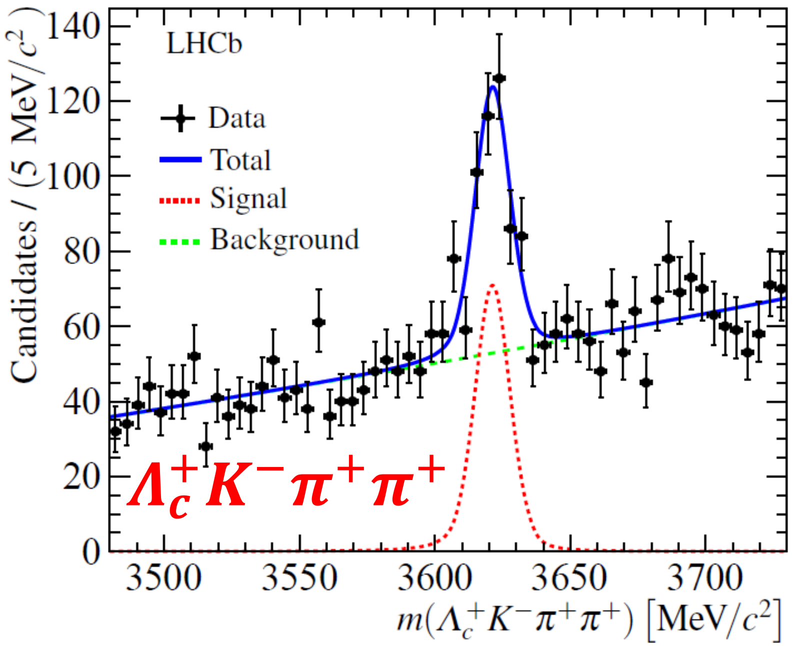
Yields: (2016)

$\Xi_c^+\pi^+: 91 \pm 20$

$\Lambda_c^+K^-\pi^+\pi^+: 289 \pm 35$

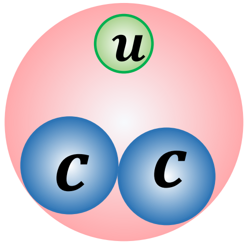
- **Signal**: Double-Sided Crystal-Ball + Gaussian
- **Background**: Exponential function
- $M(\Xi_{cc}^{++}) = M(\Xi_c^+\pi^+) - M(\Xi_c^+) + M_{PDG}(\Xi_c^+)$





Measured results

Phys. Rev. Lett. 121, 162002 (2018)



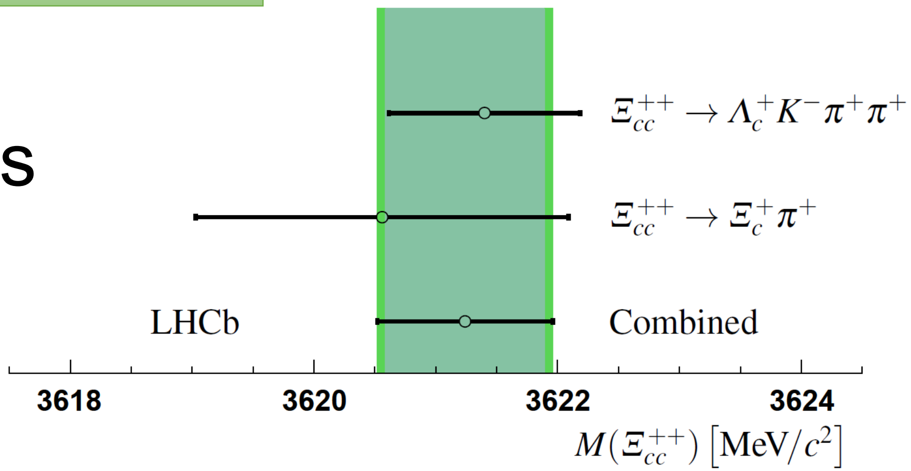
Ξ_{cc}^{++}

- The measured Ξ_{cc}^{++} mass is (with $\Xi_c^+\pi^+$ channel):
  - $3620.56 \pm 1.5\,(stat) \pm 0.4\,(syst) \pm 0.3\,(\Xi_c^+)\ \mathrm{MeV}/c^2$

Confirm previous LHCb observation of Ξ_{cc}^{++}

- Ratio of branching fraction is defined as

$$= \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= \frac{N(\Xi_c^+\pi^+)}{N(\Lambda_c^+K^-\pi^+\pi^+)} \cdot \frac{\varepsilon(\Lambda_c^+K^-\pi^+\pi^+)}{\varepsilon(\Xi_c^+\pi^+)}$$



  - $\mathcal{R} = 0.035 \pm 0.009\,(stat) \pm 0.003\,(syst)$
  - consistent with prediction

Summary

- LHCb detector is designed for the heavy flavour physics

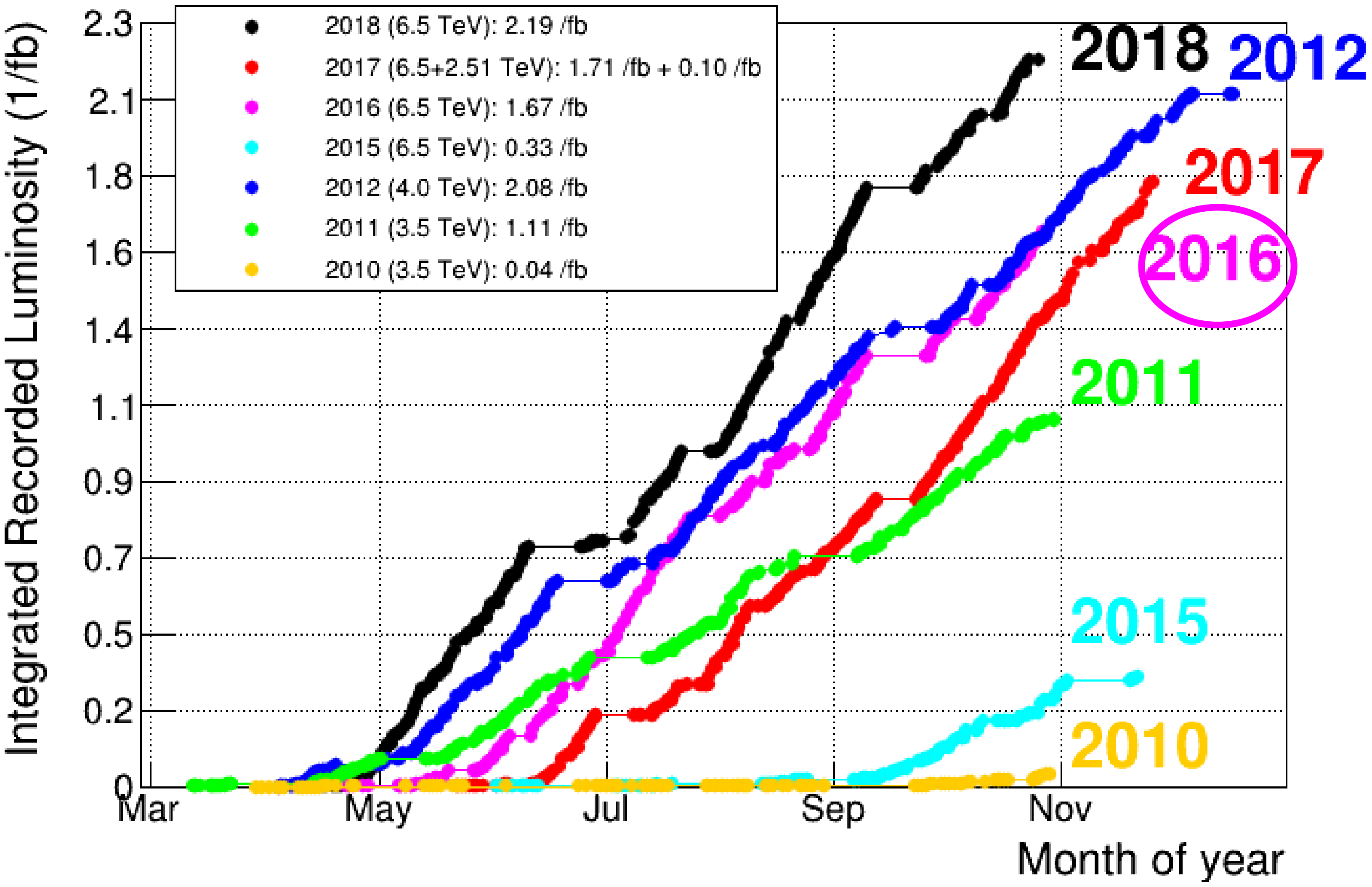
- The exotic studies sector is rapidly developing
  - Many new states confirmed, or waiting for confirmation
  - Still a large area for studies: both experimental and theoretical sides

- LHCb has made significant progresses in the study of: Ξ_{cc}^{++}
  - [PRL 119, 112001 (2007)]: Discovery of Ξ_{cc}^{++}
  - [PRL 121, 162002 (2018)]: Confirmation of the discovery of Ξ_{cc}^{++} using $\Xi_c^{+}\pi^{+}$ channel
  - [PRL 121, 052002 (2018)]: Measurement of Ξ_{cc}^{++} lifetime: long lifetime as expected

Stay tuned for new results !

Backup

LHCb integrated luminosity

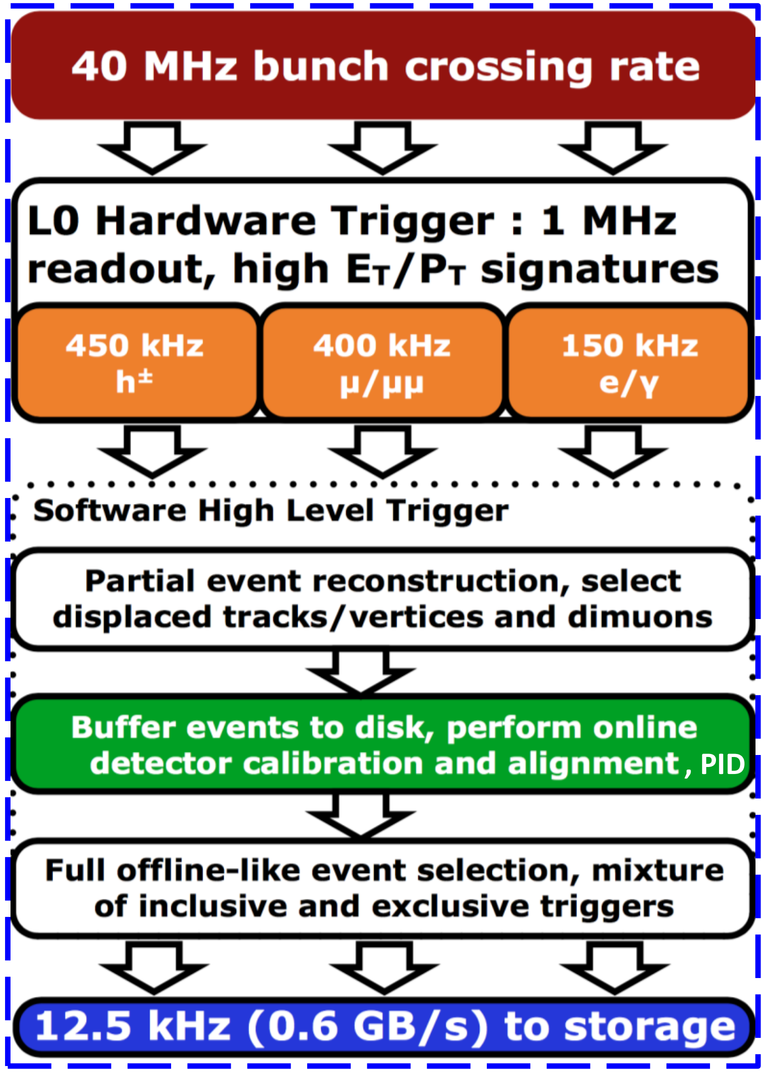


Today's talk with
2016 ($1.7\ \mathrm{fb}^{-1}$)
data

Thanks to the LHC team!

LHCb trigger

Comput. Phys. Commun. 208 (2016) 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)



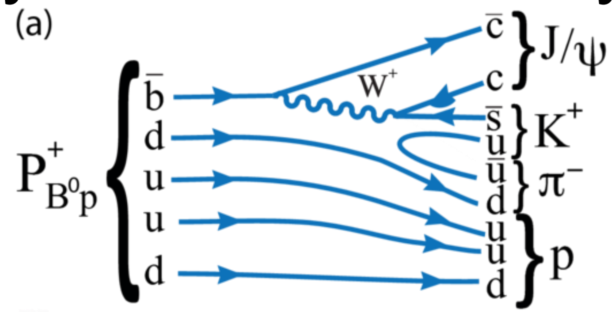
- Run real-time alignment and calibration of the detector
- Data buffered out of first software trigger stage
- Second software trigger runs asynchronously
- Permits Turbo real-time analysis strategy
  - Candidates reconstructed at the trigger level saved directly for offline analysis + (online alignment and calibration)

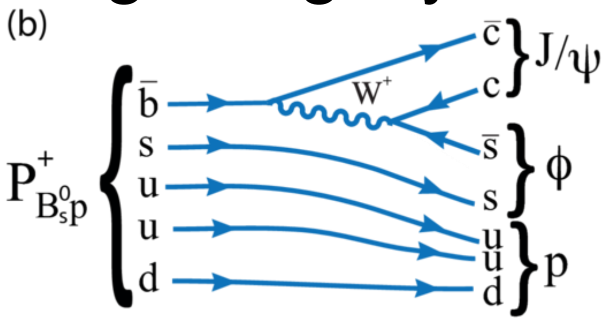
The first two analyses of today's talk benefit from the Turbo stream.

Weakly decaying b-flavoured pentaquarks

PRD 97 (2018) 032010

- Skyrme model: heavy quarks give tightly bound pentaquarks





PLB 590(2004) 185;
PLB 586(2004)337;
PLB 331(1994)362

- Search for mass peaks below strong decay threshold

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

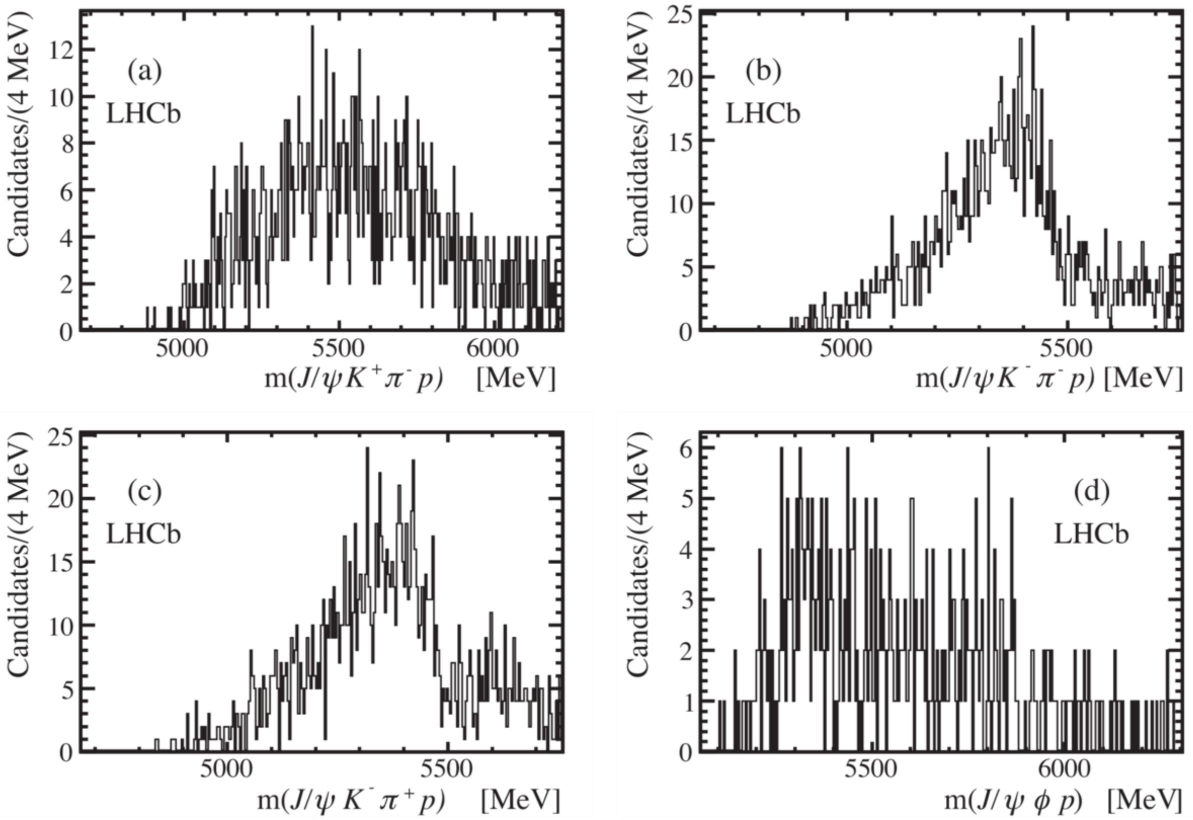
- Upper limit on production ratio $\sigma \cdot B$ wrt $\Lambda^0_b \to J/\Psi K^- p$

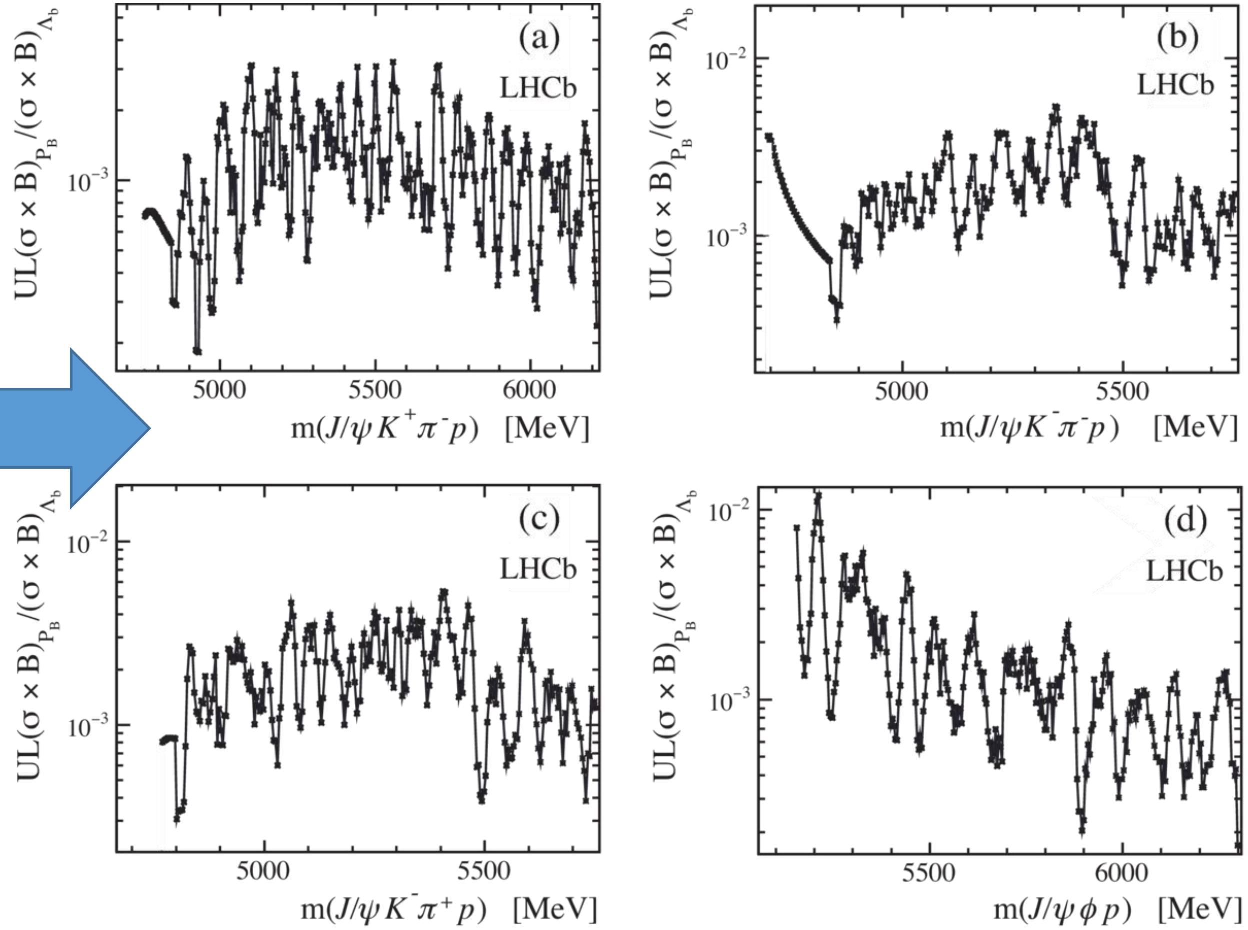
$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda^0_b X) \cdot \mathcal{B}(\Lambda^0_b \to J/\psi K^- p)}$$

Weakly decaying *b*-flavoured pentaquarks

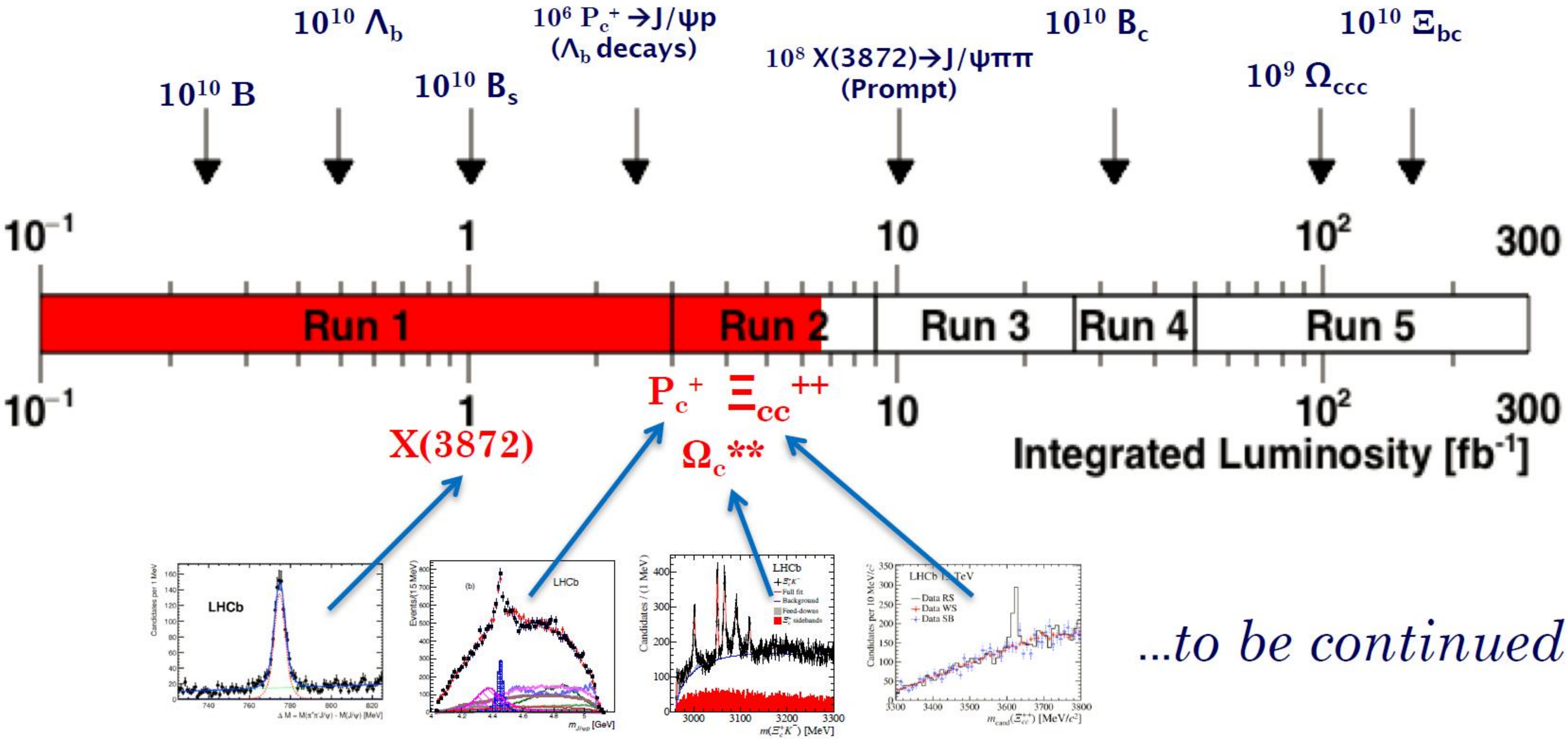
PRD 97 (2018) 032010

- No evidence for signal, 90% CL upper limits are set for the ratio





Hadron spectroscopy @ LHCb



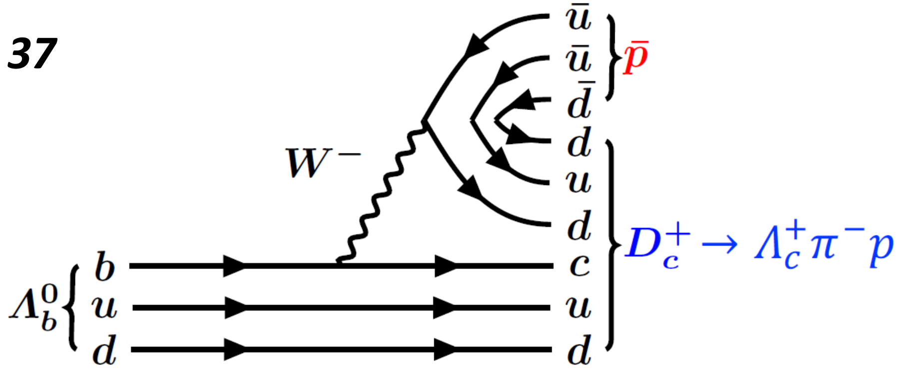
...to be continued

Get from M. Pappagallo

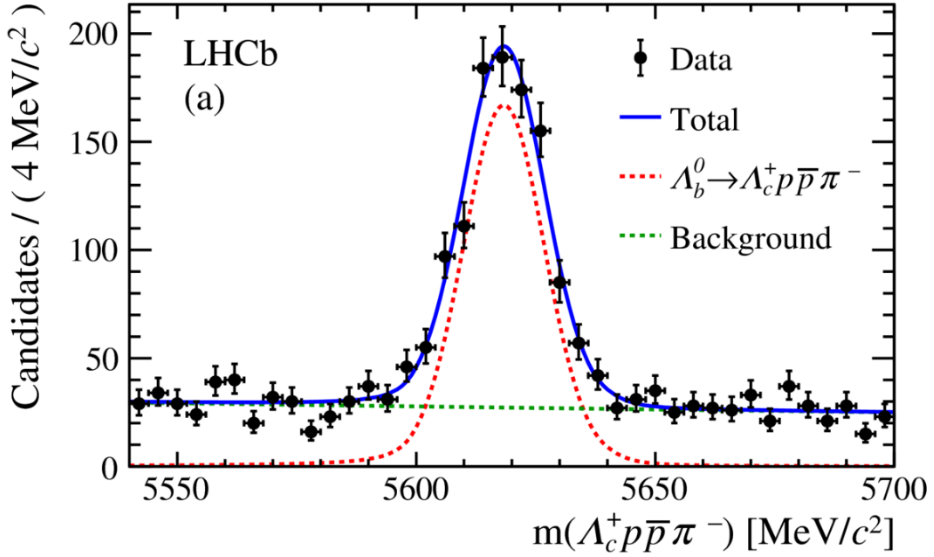
Search for dibaryon state

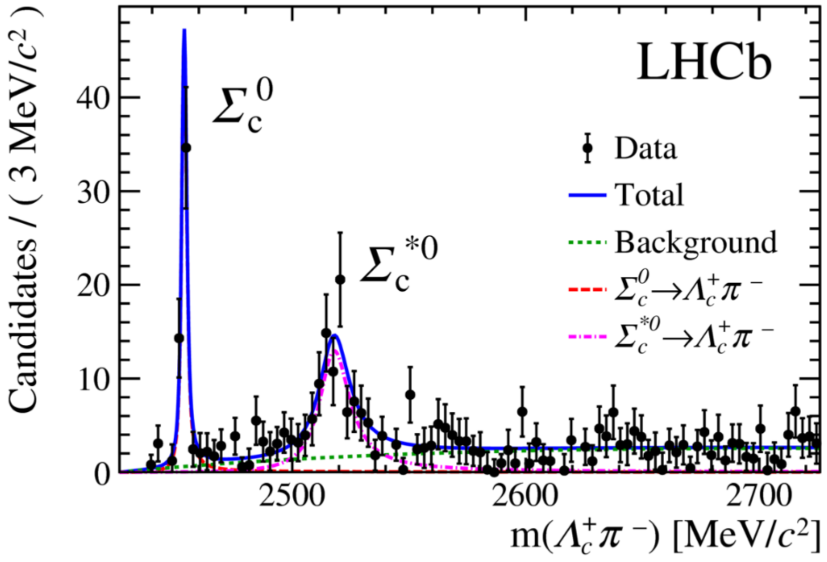
PHYS. LETT. B784 (2018) 101

- A dibaryon state $[cd][ud][ud]$ could be produced in Λ_b^0 decays to final state $\Lambda_c^+\pi^+p\bar{p}$ L. Maiani, et al. PLB 750 (2015) 37



- LHCb has discovered the decay $\Lambda_b^0 \to \Lambda_c^+\pi^+p\bar{p}$





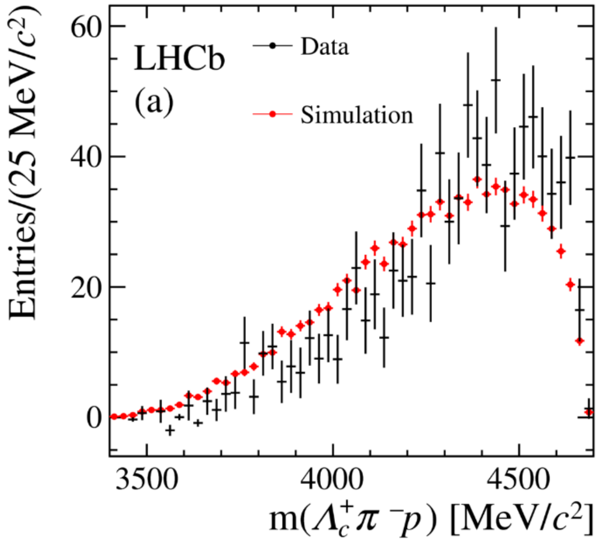
Search for dibaryon state

PHYS. LETT. B784 (2018) 101

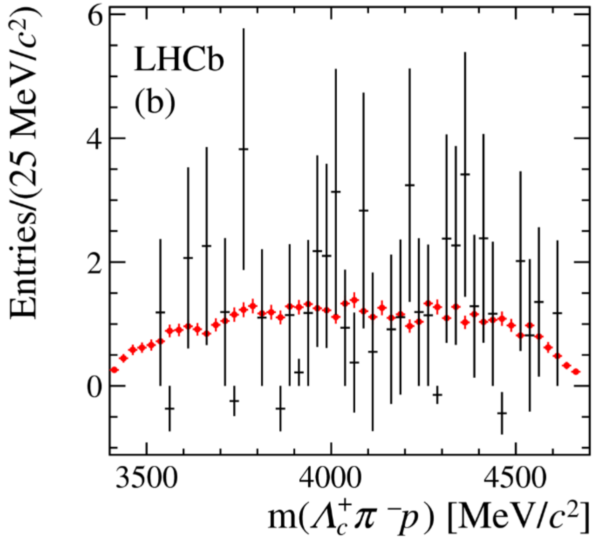
- Ratio of branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

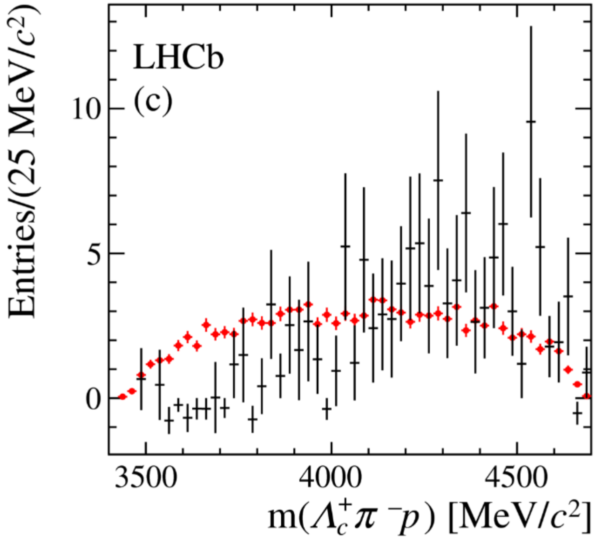
- No obvious dibaryon peak in $m(\Lambda_c^+\pi^- p)$ spectra



All signals



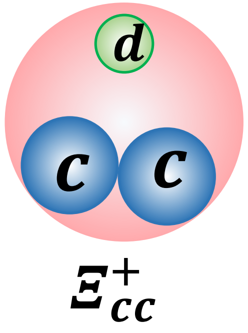
Σ_c^0 region signals

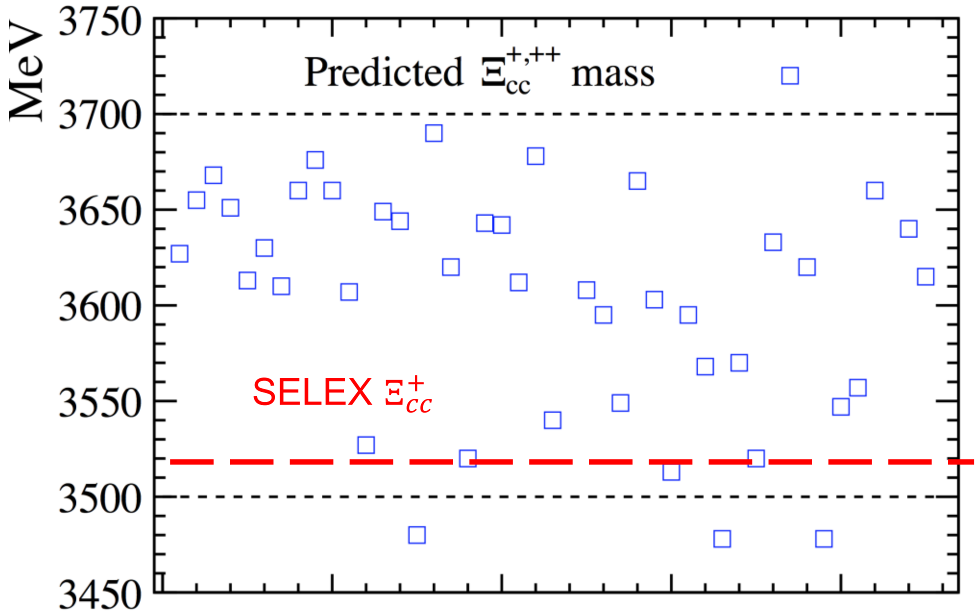


Σ_c^{*0} region signals

SELEX result in tension with predictions

- Models to determine masses of ground state and excitations:
  - (non-) relativistic QCD potential models, triple harmonic-oscillator potential model, QCD sum rules, bag model or quark model …
  - Predicted $\Xi_{cc}^{+,++}$ masses in range $\mathbf{3.5-3.7}$ GeV,
  - Masses of Ξ_{cc}^{+} and Ξ_{cc}^{++} only differ by a few MeV due to u, d symmetry





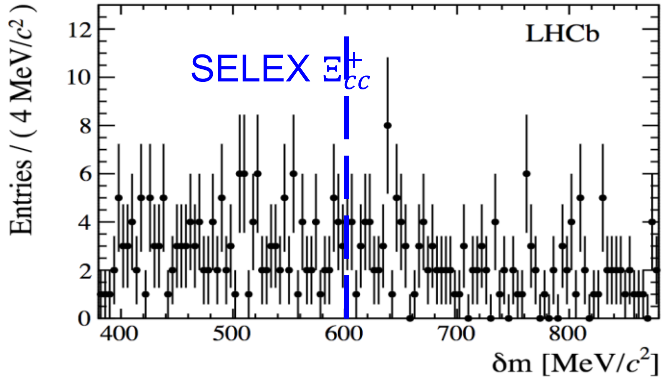
No confirmation from other experiments

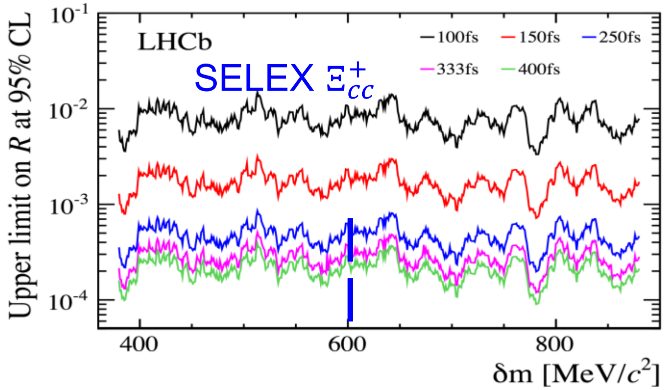
- Fixed target: **FOCUS** (Fermilab E831) **Nucl. Phys. Proc. Suppl. 115 (2003) 33**
  - Studies charm hadrons produced in photon-nuclear fixed target collisions

- Electron colliders: **Babar, Belle** **BaBar: PRD 74 (2006) 011103** **Belle: PRL 97 (2006) 162001**
  - Large Λ_c^+ yields, 0.6 (0.8) M at Babar (Belle)

- Hadron Collider: **LHCb**

JHEP 12 (2013) 090

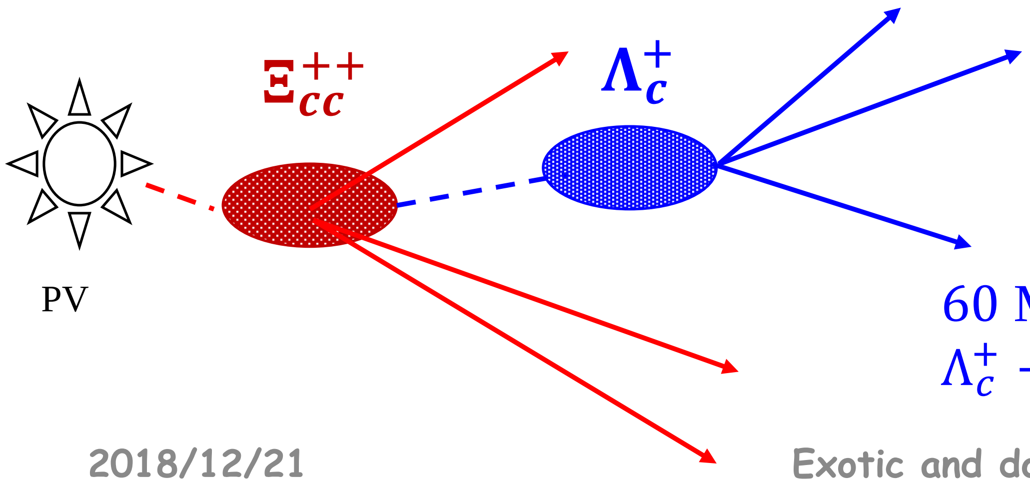




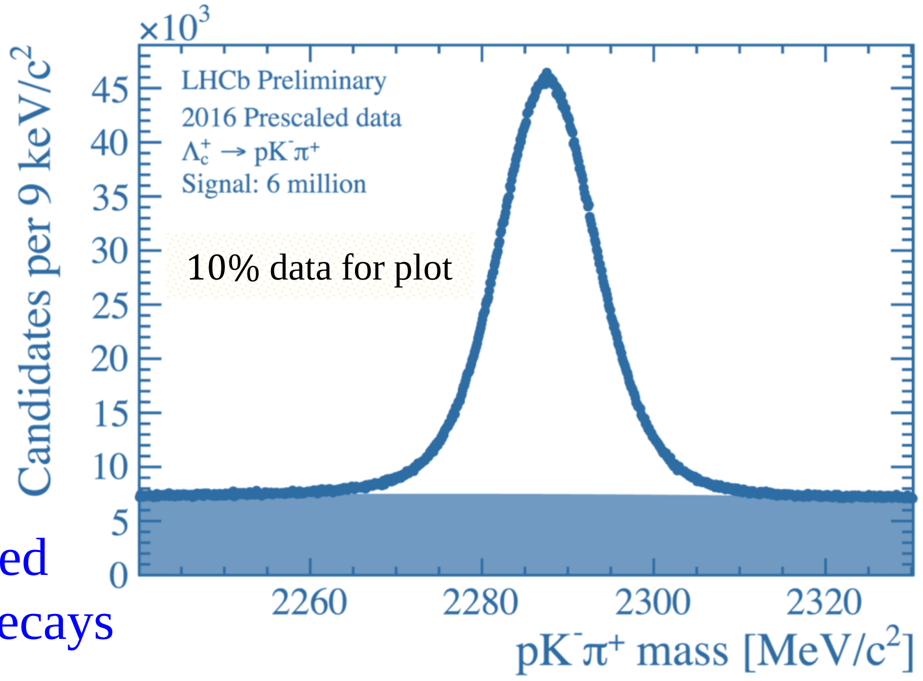
Selections

- $\Lambda_c^+ \to pK^-\pi^+$:
  - p, K^-, π^+ tracks: positive particle ID, not produced from primary vertices
  - Λ_c^+: good vertex quality, separated from primary vertices
  - p, K^-, π^+ tracks and Λ_c^+ have large p_{T}
- Multivariate Selection:

$$\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$$

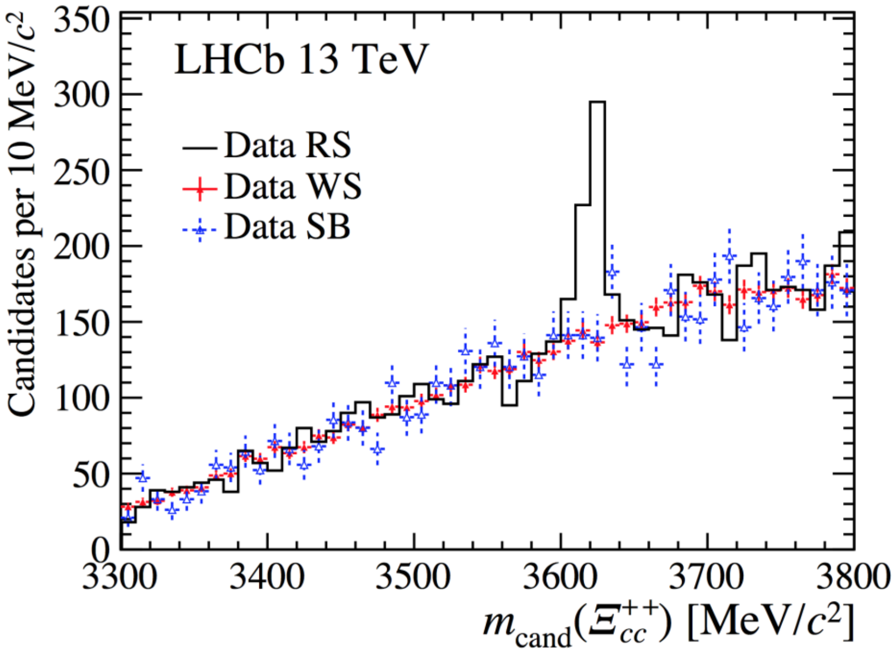


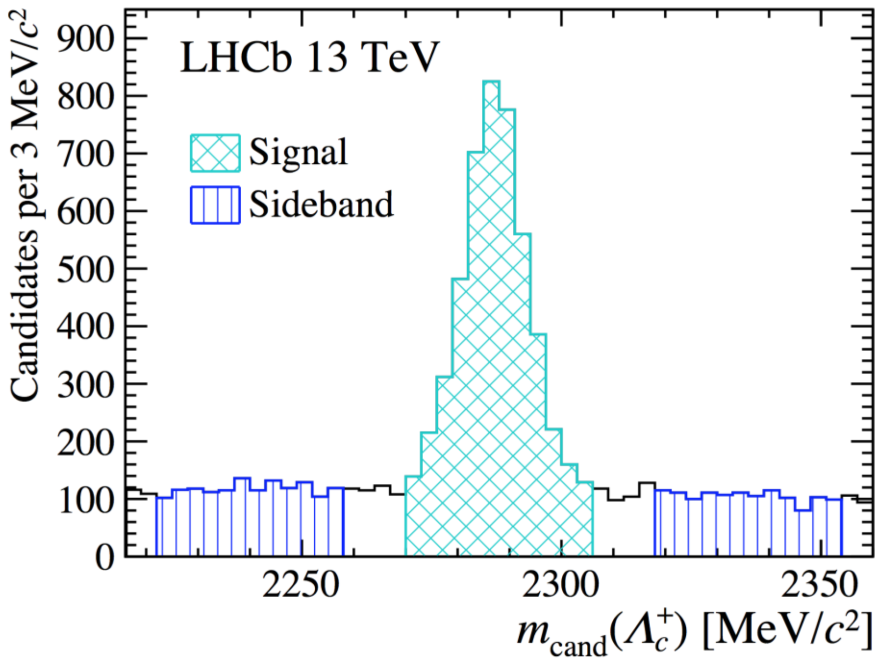
60 M fully reconstructed
$\Lambda_c^+ \to pK^-\pi^+$ signal decays



Mass spectrum

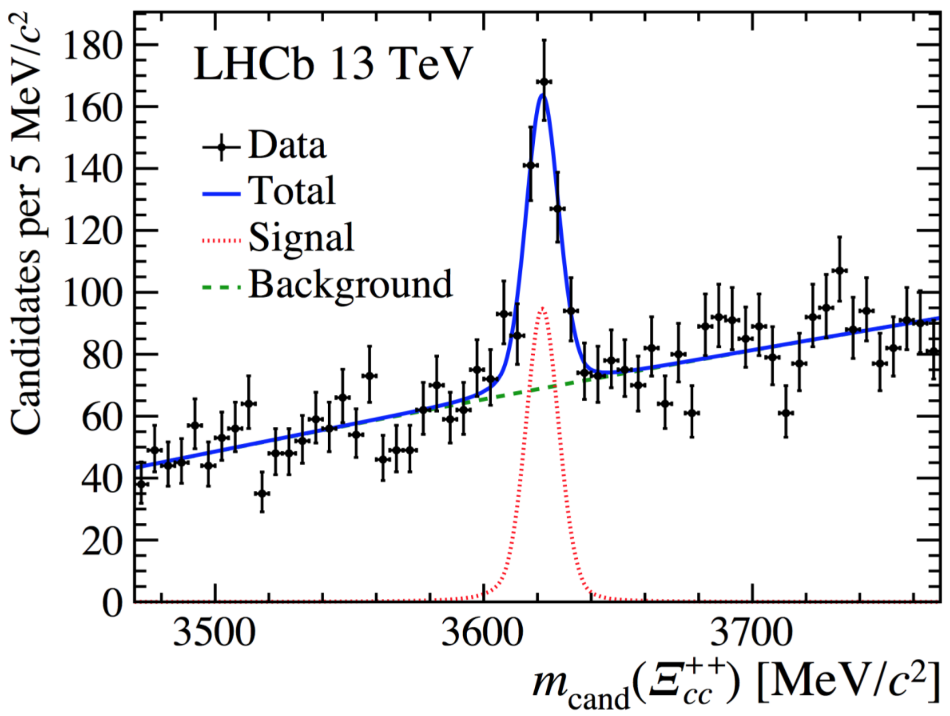
- A significant structure in right sign (RS) combinations
- Not present in wrong sign (WS) combinations
- Not observed for Λ_c^+ background candidates
- Distributions similar except the peak in RS

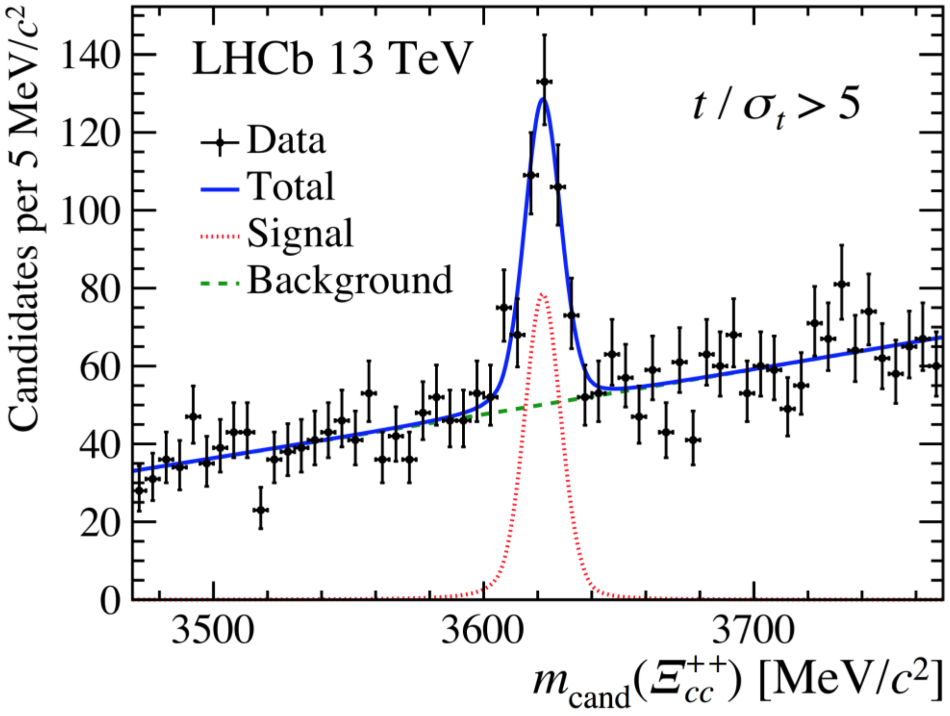




Mass fitting

- Signal yield: 313 ± 33
- Resolution: 6.6 ± 0.8 MeV, consistent with simulated value
- Local significance $> 12\sigma$



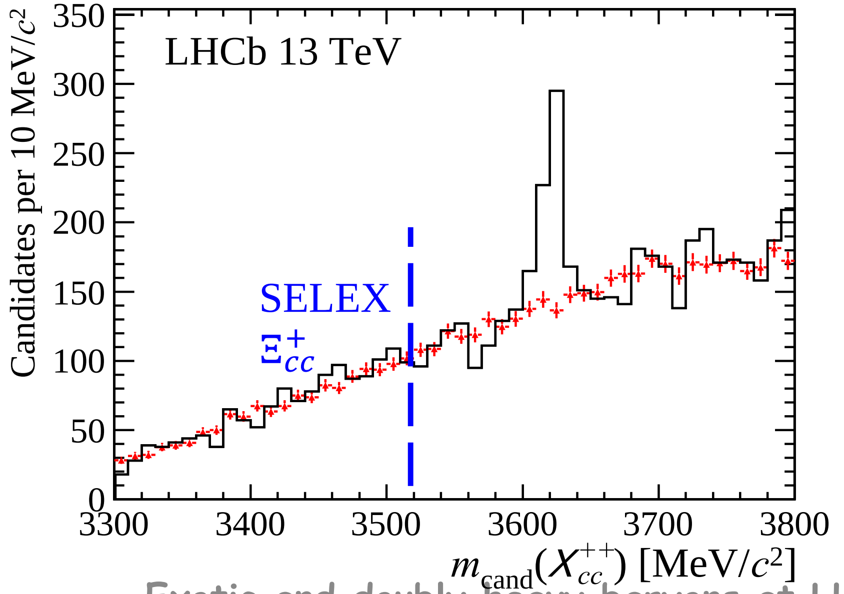


($> 12\sigma$) after requiring $t > 5\sigma_t$.
It is indeed a weak decay.

Compared with SELEX results

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

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



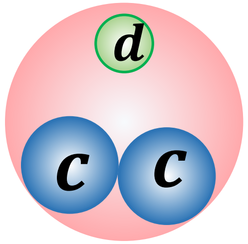
Analysis strategy

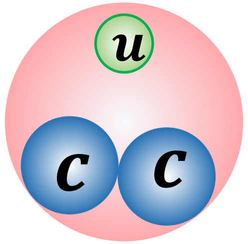
- Same data sample, event selection as previous Ξ_{cc}^{++} observation
  - Specific trigger requirement to simplify trigger efficiency determination
  - Signal yields (2016): 313 → 304
- **Measure decay time distribution relative to $\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$**
  - Acceptance correction based on MC
- Weighted unbinned maximum likelihood fit (sFit)

Y. Xie, arXiv:0905.072

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$

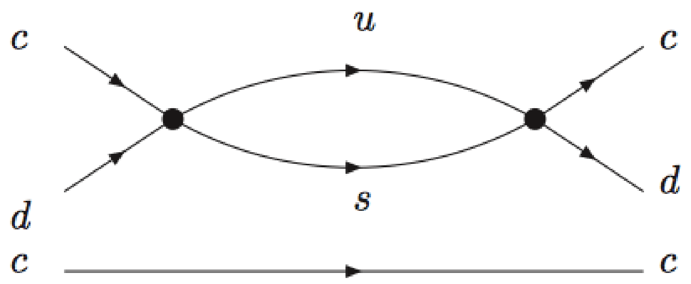
Predictions: long lived Ξ_{cc}^{++}



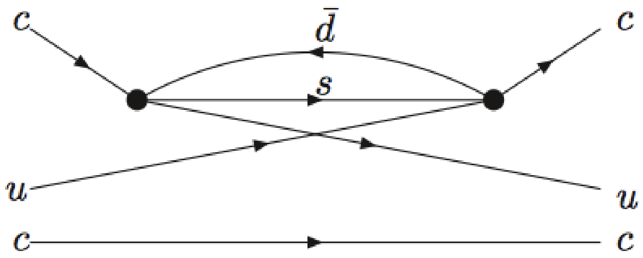


- Predicted $\tau(\Xi_{cc}^{++})$ in range of [0.20, 1.05] ps
  - Diquark model, effective constituent model, NRQCD potential model, harmonic oscillator model …
  - Significant non-spectator contribution from Pauli-Interference diagrams

W-exchange



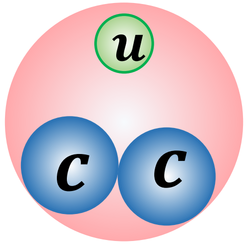
Pauli-interference



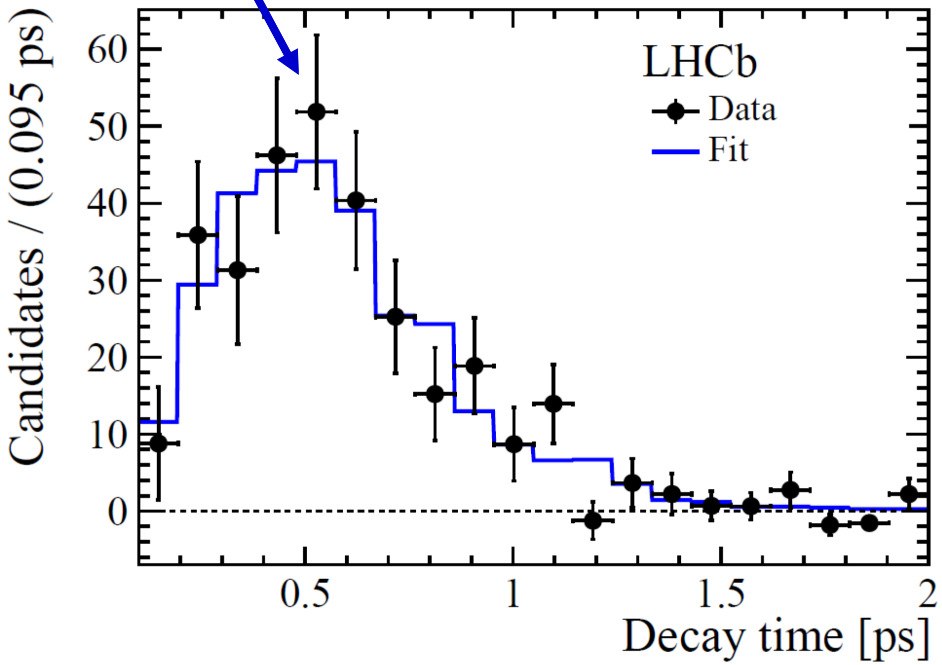
- $\tau(\Xi_{cc}^{++}) \sim 3 - 4\ \tau(\Xi_{cc}^{+})$
  - Destructive Pauli interference in Ξ_{cc}^{++} decays
  - W-exchange between c and d quarks only in Ξ_{cc}^{+} decays

Lifetime fit

$$f_{\Xi_{cc}^{++}}(t) = f_{\Lambda_b^0}(t) \times \frac{\epsilon_{\Xi_{cc}^{++}}}{\epsilon_{\Lambda_b^0}} \times e^{-\left(\frac{t}{\tau_{\Xi_{cc}^{++}}} - \frac{t}{\tau_{\Lambda_b^0}}\right)}$$



Ξ_{cc}^{++}



$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}$ ps

Systematic Uncertainty

Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014

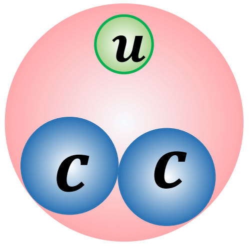
- **Binning**:
  - Systematics due to binned acceptance estimated with pseudo experiments
- **Resonant**:
  - Weight MC to match $M(K^-\pi^+\pi^+)$ (for Ξ_{cc}^{++}), and $M(\pi^-\pi^+\pi^-)$ (for Λ_b^0) distributions in data

Measured results: $\boldsymbol{\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})\ \mathrm{ps}}$

Cross-checks and Results

- Various cross-checks had been done: no evidence of other effects
  - Charge: Ξ_{cc}^{++} vs. $\bar{\Xi}_{cc}^{--}$
  - Magnet polarities: Down vs. Up
  - Number of PV
- Binned χ^2 fit: consistent with nominal result
- Λ_b^0 lifetime using simulation-based acceptance correction, consistent with PDG Value

Confirmation of Ξ_{cc}^{++} with $\Xi_c^+\pi^+$ channel
First measurement of Ξ_{cc}^{++} lifetime: weakly decay



Ξ_{cc}^{++}

$\Xi_c^+\pi^+$ Prediction

$$\mathcal{B}(\Xi_{cc}^{++}\to\Xi_c^+\pi^+)=\left(\frac{\tau_{\Xi_{cc}^{++}}}{300\,\mathrm{fs}}\right)\times 7.2\%.$$

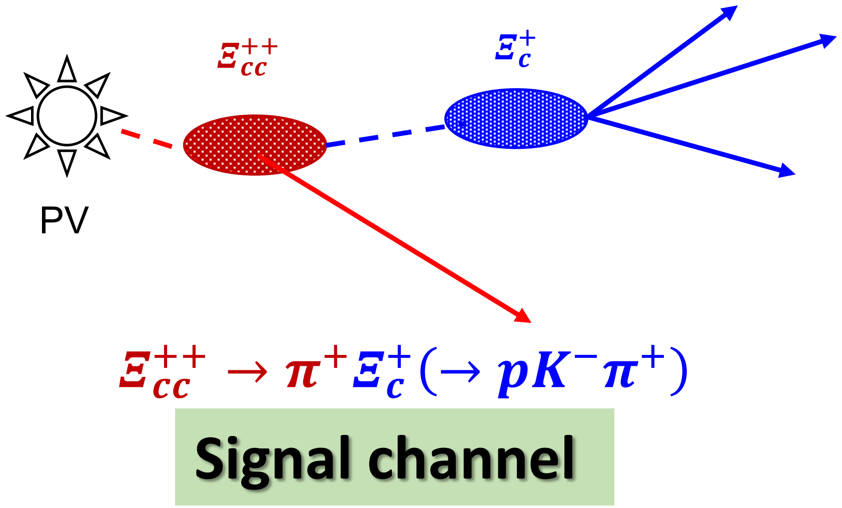
$$\mathcal{B}(\Xi_c^+\to pK^-\pi^+)=(2.2\pm0.8)\%.$$

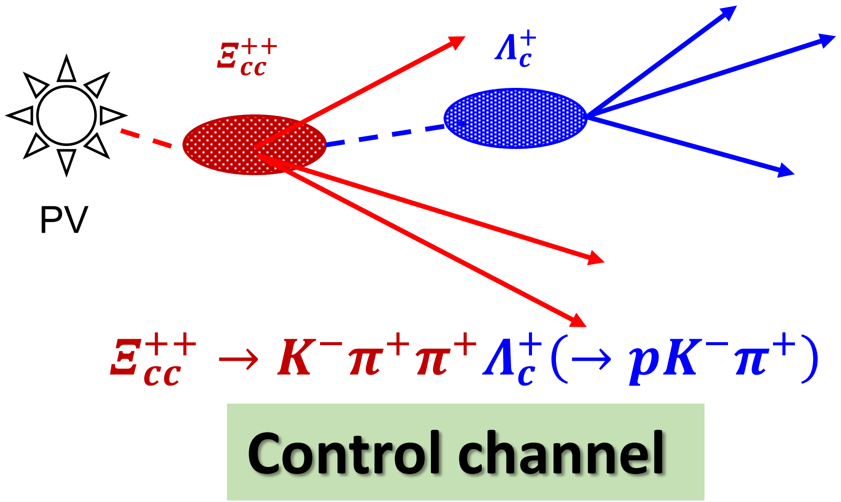
as $\mathcal{B}(\Xi_c^+ \to p\overline{K}^{*0})/\mathcal{B}(\Xi_c^+ \to pK^-\pi^+) = 0.54\pm0.10$ [33]. Besides, the relation $\mathcal{A}(\Xi_c^+ \to p\overline{K}^{*0}) = \mathcal{A}(\Lambda_c^+ \to \Sigma^+K^{*0})$ holds under U-spin symmetry. With the measurement of $\mathcal{B}(\Lambda_c^+ \to \Sigma^+K^{*0}) = (0.36\pm0.10)\%$ [34], the branching

$$\mathcal{B}(\Xi_{cc}^{++}\to\Sigma_c^{++}(2455)\overline{K}^{*0})=\left(\frac{\tau_{\Xi_{cc}^{++}}}{300\,\mathrm{fs}}\right)\times(3.8\sim24.6)\%, \tag{11}$$

Signal and control channels

- Signal channel: $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$, with $\Xi_c^+ \to pK^-\pi^+$
- Control channels:
  - $\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+$, with $\Lambda_c^+ \to pK^-\pi^+$
  - $\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$, $\Lambda_b^0 \to \Lambda_c^+\pi^-$, with $\Lambda_c^+ \to pK^-\pi^+$
  - Λ_b^0 data is used to calibrate trigger efficiency, and life time measurement



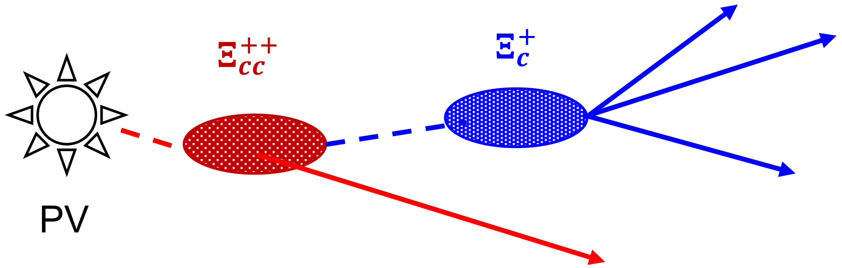


Event selection

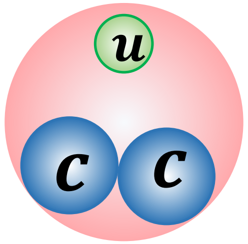
- **Hadron trigger**: hardware trigger (p, K, π), and high level software trigger (Ξ_c^+)
- **Final state hadrons, $\boldsymbol{p, K, \pi}$**: particle ID, not produced from primary vertex (PV)
- $\boldsymbol{\Lambda_c^+}$ **or** $\boldsymbol{\Xi_c^+}$: good vertex quality, separated from PV
- **Multivariate selector** is used to further suppress the backgrounds
  - p_T, decay angle, vertex fitting quality, IP χ^2, flight distance

As a follow-up analysis of $\boldsymbol{\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+}$, $\boldsymbol{\Xi_{cc}^{++} \to \Xi_c^+ \pi^+}$ has similar selection cuts as in previous analysis.

$\boldsymbol{\Xi_{cc}^{++} \to \pi^+ \Xi_c^+ (\to pK^- \pi^+)}$



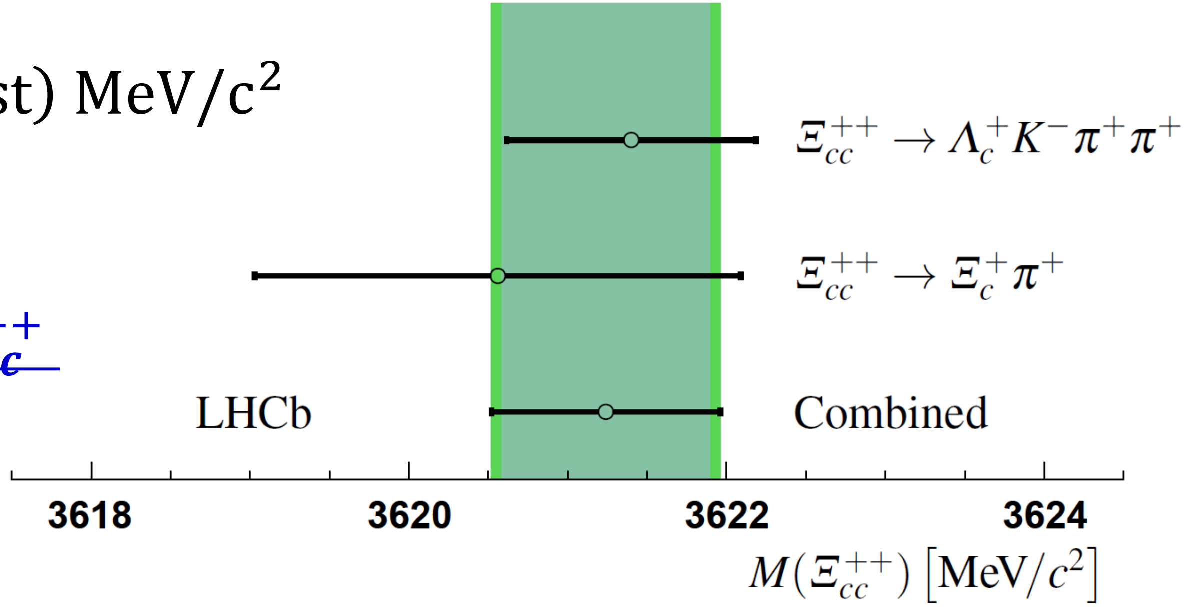
Mass measurement



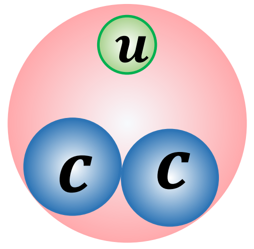
Ξ_{cc}^{++}

- The measured Ξ_{cc}^{++} mass is (with $\Xi_c^+\pi^+$ channel):
  - $\mathbf{3620.56 \pm 1.5\ (\mathit{stat}) \pm 0.4\ (\mathit{syst}) \pm 0.3\ (\Xi_c^+)\ MeV/\mathit{c}^2}$
- Consistent with $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ result:
  - $3621.40 \pm 0.72\ (stat) \pm 0.27\ (\mathrm{syst}) \pm 0.14\ (\Lambda_c^+)\ \mathrm{MeV/c^2}$
- **Combined results**:
  - $3621.24 \pm 0.65\ (stat) \pm 0.31\ (\mathrm{syst})\ \mathrm{MeV/c^2}$

Confirm previous LHCb observation of Ξ_{cc}^{++}



Branching fraction measurement



Ξ_{cc}^{++}

- The ratio of branching fraction is defined as:

$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)} \times \frac{\mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= \frac{N(\Xi_c^+ \pi^+)}{N(\Lambda_c^+ K^- \pi^+ \pi^+)} \cdot \frac{\varepsilon(\Lambda_c^+ K^- \pi^+ \pi^+)}{\varepsilon(\Xi_c^+ \pi^+)}$$

No direct branching fraction measurement of $\Xi_c^+ \to pK^-\pi^+$ from experiments.

- Measure the signal yields and efficiency for each channel
- $\mathcal{R} = 0.035 \pm 0.009\ (stat) \pm 0.003\ (syst)$
  - Consistent with prediction

F.-S. Yu et al., Chin. Phys. C 42051001 (2018)

Uncertainty

$\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}$ channel

Source	Mass $[\mathrm{MeV}/c^2]$	$\mathcal{R}(\mathcal{B})$ [%]
Momentum calibration	0.38	—
Selection bias correction	0.10	—
Fit model	0.05	5.2
Relative efficiency	—	6.5
Simulation modelling	—	1.2
Selection	—	0.7
Sum in quadrature	0.40	8.5

With limited statistics of both signal and control samples, the dominated uncertainty is statistical uncertainty (1.5 MeV, 0.009)