Conventional spectroscopy at LHCb

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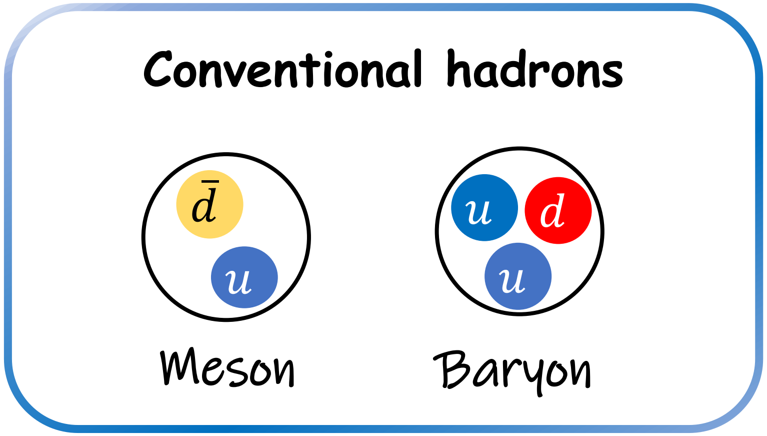
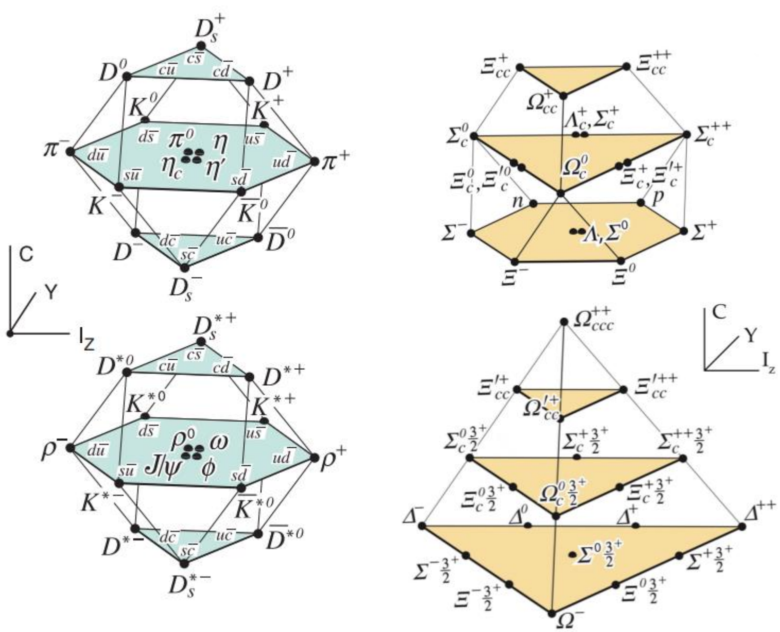
(On behalf of the LHCb collaboration)

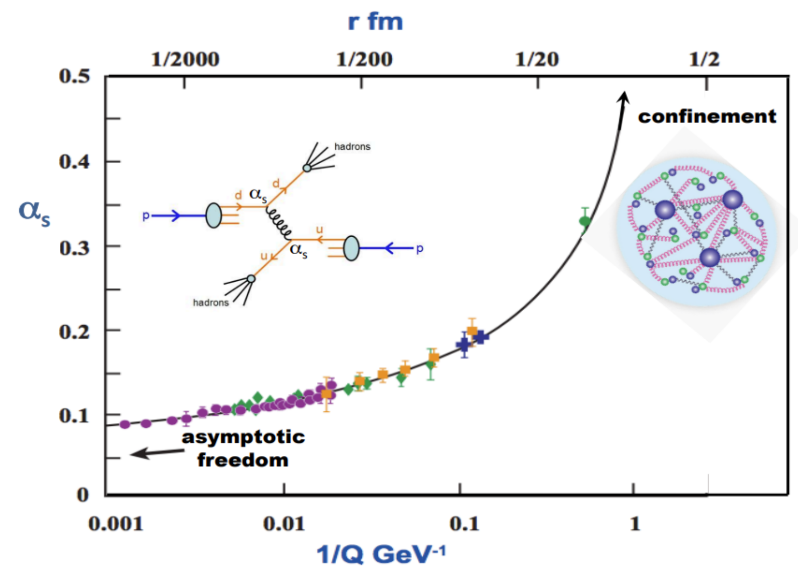
LHCb Implication Workshop

Quark model and Strong Interaction

- **Hadron: Colorless**
  - ✓ Meson: $Q\bar{q}$
  - ✓ Baryon: $Qqq^{(\prime)}$
  - ✓ SU(4) weight diagram:
    Charmed Meson/Baryon formed by u, d, s, c quarks
- **Measurement in hadron spectroscopy**
  - ✓ Important input to theoretical calculation (especially for non-factorizable part)
  - ✓ Extend the knowledge to understand QCD

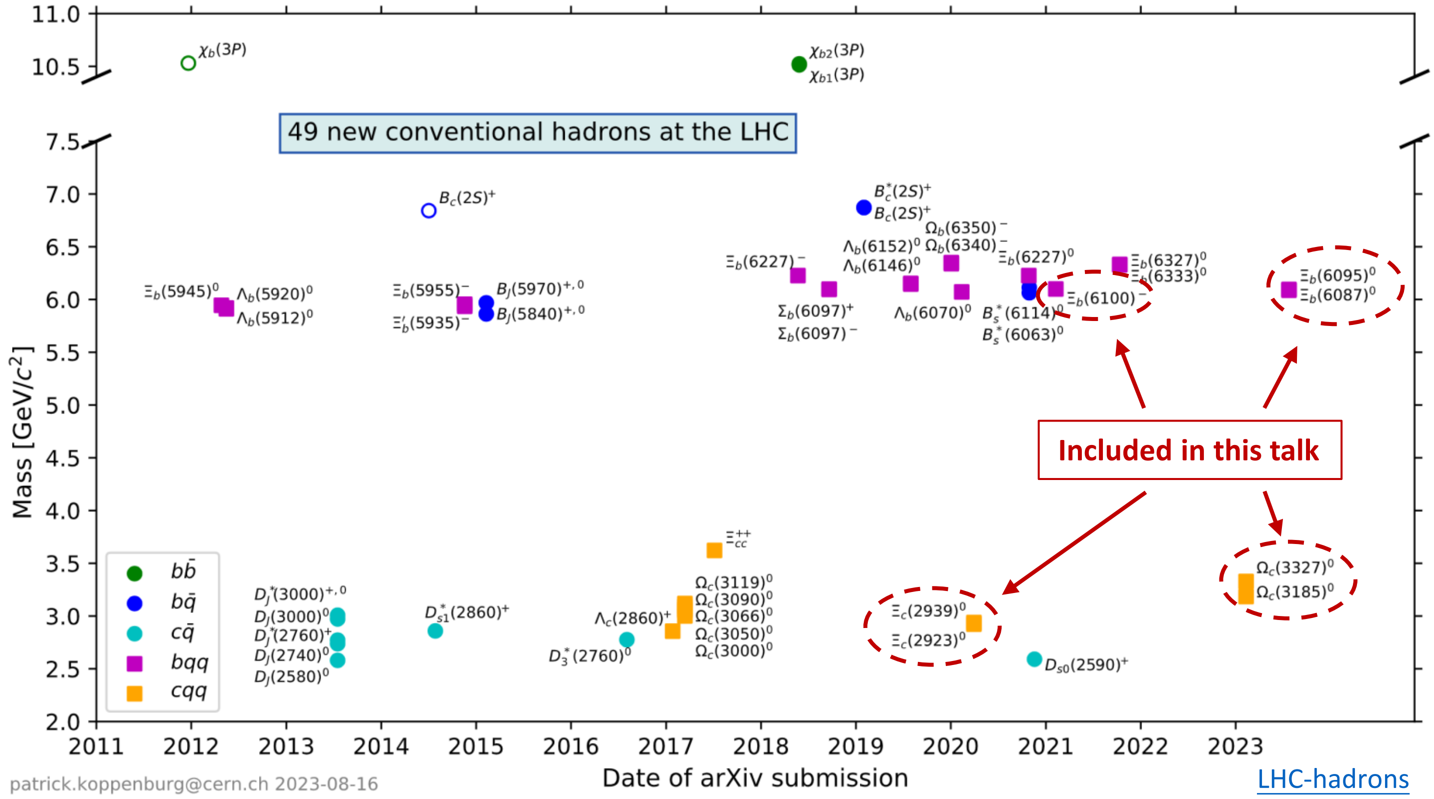






Conventional Hadron Spectroscopy at LHCb

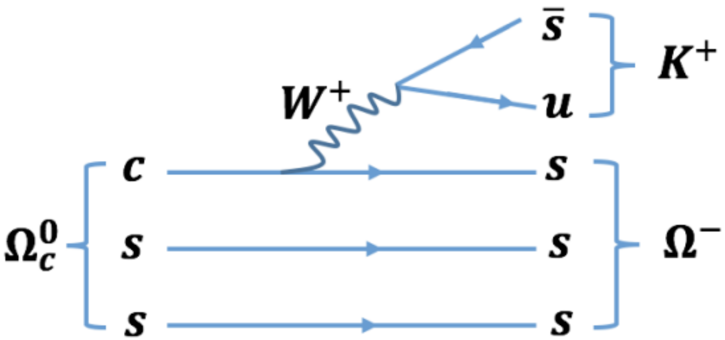
- **The world's largest samples of reconstructed conventional heavy flavour hadrons are collected with LHCb during LHC Run1 and Run2**

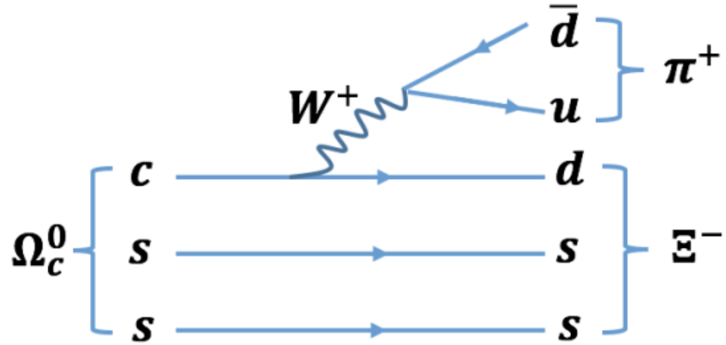


- **This report will focus on the recent observation of new hadron states and decay modes at LHCb**

Overview of selected results

- **Baryons**
  - ✓ **Observation of CS two-body decays of Ω_c^0 & Precise mass measurement of Ω_c^0,** arXiv:2308.08512
  - ✓ **Observation of new baryons in $\Xi_b^{-(0)}\pi^+\pi^-$,** PRL 131, 171901 (2023)
- **Mesons**
  - ✓ **Observation of the decays $B_{(s)}^0 \to D_{s1}(2536)^{\mp}K^{\pm}$,** JHEP 10, 106 (2023)
  - ✓ **Observation of the decay $B^+ \to J/\psi\eta' K^+$,** JHEP 08, 174 (2023)
- **Brief through slightly older analysis**
  - ✓ **Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state,** PRL 131. 131902 (2023)
  - ✓ **Study of the $B^- \to \Lambda_c^+\overline{\Lambda}_c^- K^-$ decay,** PRD 108. 012020 (2023)





Ω_c^0 $I(J^P) = 0(1/2^+)$

The quantum numbers have not been measured, but are simply assigned in accord with the quark model, in which the Ω_c^0 is the $s\,s\,c$ ground state. No absolute branching fractions have been measured.

Ω_c^0 two-body decay & mass measurement

Observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$

arXiv:2308.08512

- **The uncertainty of Ω_c^0 mass is significantly larger than other charmed baryons**

Mass	PDG
Ω_c^0	2695.2 ± 1.7 MeV
Λ_c^+	2286.46 ± 0.14 MeV
Ξ_c^0	2470.44 ± 0.28 MeV
Ξ_c^+	2467.71 ± 0.23 MeV

- **Measurement of hadronic decays is limited, especially for the two-body decays**
- **Can inspire the theoretical calculations**
- **In this work**
  - ✓ First observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$
  - ✓ Report the relative BFs to $\Omega_c^0 \to \Omega^- \pi^+$

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = \frac{r_N}{r_\epsilon}, \quad \frac{\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = \frac{r'_N}{r'_\epsilon} \cdot \frac{\mathcal{B}(\Omega^- \to \Lambda K^-)}{\mathcal{B}(\Xi^- \to \Lambda \pi^-)}.$$

  - ✓ Precise mass measurement of Ω_c^0

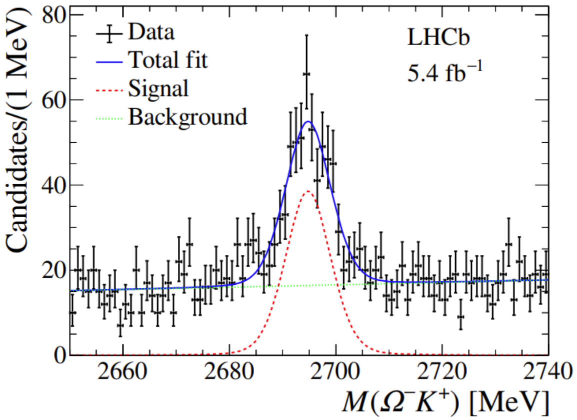
Model (10^{-3})	$\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$	$\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)$
Cheng [1]	36.6	...
Xu et al. [2]	56.6	...
Gutsche et al. [3]	2	...
Hu et al. [4]	...	9.34
Hsiao et al. [5]	5.1 ± 0.7	...
Zhao [6]	...	0.174

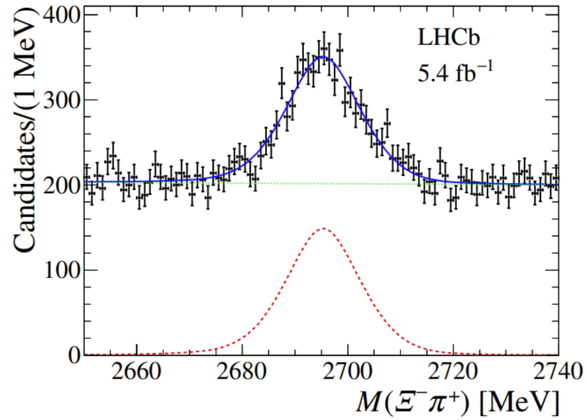
[1] PRD 56, 2799 (2019) [3] PRD 98, 074011 (2018) [5] EPJC 80, 11 (2020)
[2] PRD 46, 3836 (1992) [4] PRD 101, 094033 (2020) [6] CPC 42, 093101 (2018)

Observation of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$

arXiv:2308.08512

- **Using LHCb 2016-2018 data at 13 TeV ($5.4\ \mathrm{fb}^{-1}$)**





✓ Signal shape: Johnson + Gaussian

✓ Background shape: Exponential

$$\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = 0.0608 \pm 0.0051(\mathrm{stat}) \pm 0.0040(\mathrm{syst})$$

$$\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = 0.1581 \pm 0.0087(\mathrm{stat}) \pm 0.0043(\mathrm{syst}) \pm 0.0016(\mathrm{ext})$$

- **Consistent with the previous measurement from Belle** [JHEP 01, 055 (2023)] **in 2σ:**

$$\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = 0.253 \pm 0.053(\mathrm{stat}) \pm 0.030(\mathrm{syst})$$

- **Significant discrepancy with various theoretical model (algebra, light-front quark mode…)**

Model (10^{-3})	$\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$	$\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)$
Hu *et al.* [1]	(~9%)	9.34
Hsiao *et al.* [2]	5.1 ± 0.7	…
Zhao [3]	…	0.174

→ $\mathcal{B}(\Xi^- \pi^+)/\mathcal{B}(\Omega^- \pi^+) = 0.1038$ (Hu *et al.*)

} $\mathcal{B}(\Xi^- \pi^+)/\mathcal{B}(\Omega^- \pi^+) = 0.0345$ (Hsiao *et al.*, Zhao)

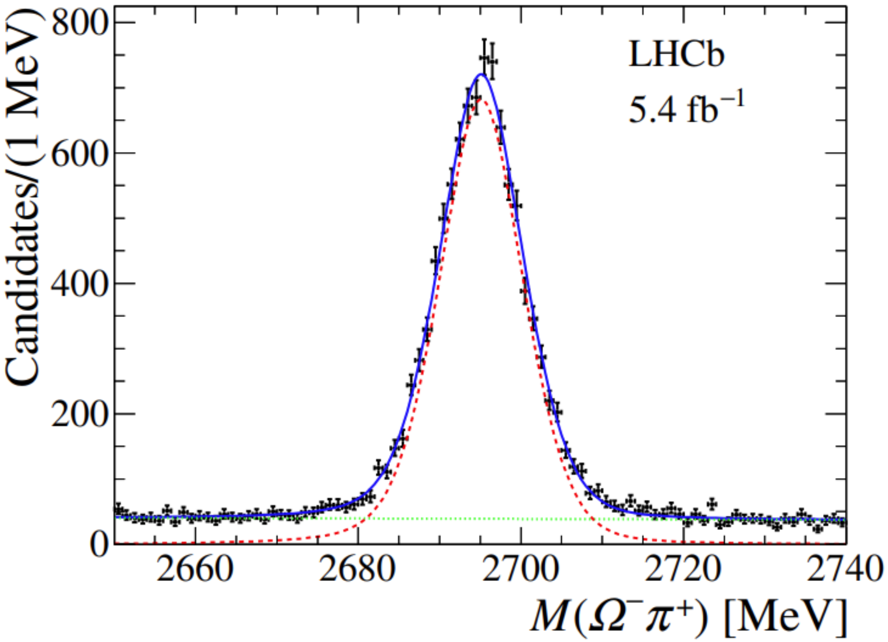
Contributions from non-factorizable are crucial!

[1] PRD 101, 094033 (2020)
[2] EPJC 80, 11 (2020)
[3] CPC 42, 093101 (2018)

Precise mass measurement of Ω_c^0

arXiv:2308.08512

- **Using LHCb 2016-2018 data at 13 TeV** $(5.4\ \mathrm{fb}^{-1})$
  - ✓ Fit to $\Omega_c^0 \to \Omega^-\pi^+$ process with signal yield ~9.3k



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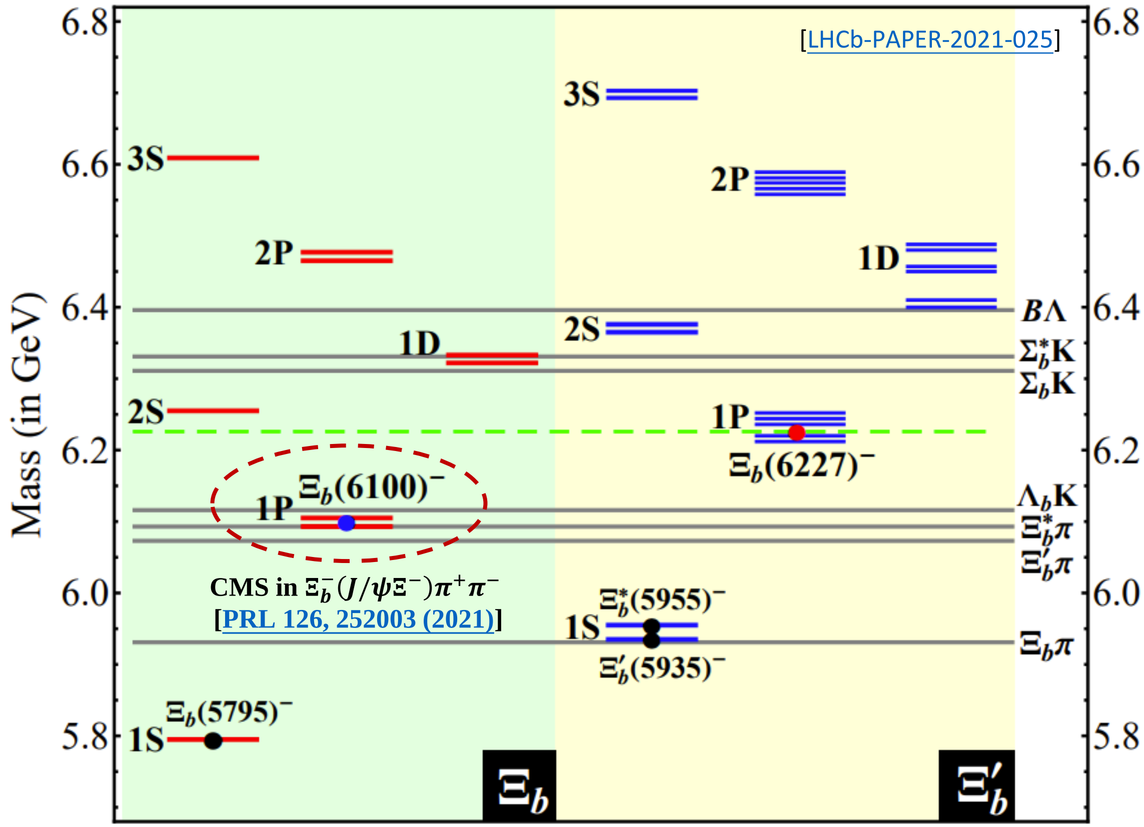
Ξ_c^+	2467.71 $\pm$ 0.23 MeV

- **Systematic uncertainties**

Source	δM [MeV]
Momentum scale calib.	0.27
Energy loss correction	0.03
Fit model	0.01
Total	0.27
External input mass	0.30

$$\boldsymbol{M(\Omega_c^0) = 2695.28 \pm 0.07(\mathrm{stat}) \pm 0.27(\mathrm{syst}) \pm 0.30(\mathrm{ext})\ \mathrm{MeV}}$$

Improve the precision of the previous world-average value by a factor of four



Observation of new baryons in $\Xi_b^{-(0)}\pi^+\pi^-$

Observation of new baryons in $\Xi_b^{-(0)}\pi^+\pi^-$

PRL 131, 171901 (2023)

- **Using LHCb data collected at center-of-mass energies of 7, 8, 13 TeV (9 fb^{-1})**

$\Xi_b^-(\Xi_b^0) \rightarrow \Xi_b^{*0}(\Xi_b'^-/\Xi_b^{*-})\ \pi^-(\pi^+)$

$\Xi_b^{*0}(\Xi_b'^-/\Xi_b^{*-}) \rightarrow \Xi_b^-(\Xi_b^0)\ \pi^+(\pi^-)$ — $\Xi_b^-(\Xi_b^0)$: ground state

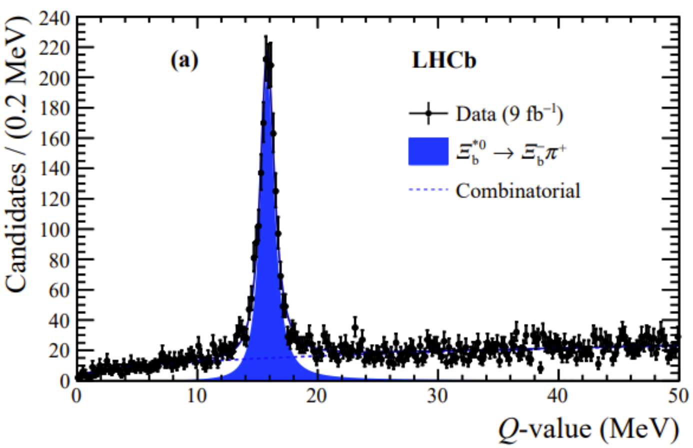
$\Xi_b^-(\Xi_b^0) \rightarrow \Xi_c^0(\Xi_c^+)\ \pi^-$ or $\pi^-\pi^+\pi^-$

(Final states with up to nine track! Excellent performance of LHCb tracking/reconstruction/PID systems!)

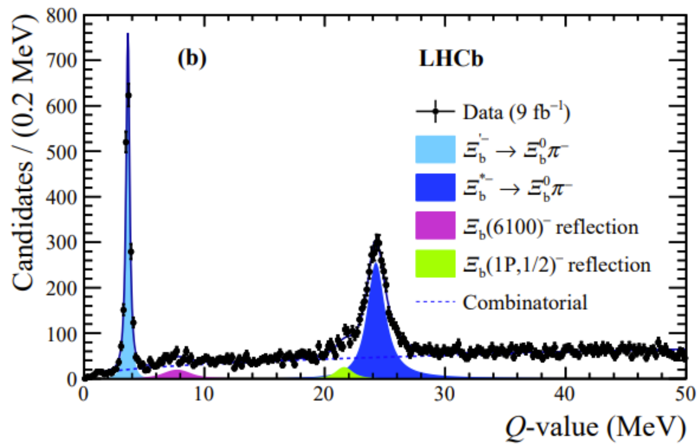
✓ The ground state $\Xi_b^-(\Xi_b^0)$ was firstly reconstructed by combining $\Xi_c^0(\Xi_c^+)$ with π^- or $\pi^-\pi^+\pi^-$

✓ Then combined with another $\pi \Longrightarrow \Xi_b^{*0}$ or Ξ_b'/Ξ_b^{*-}

$$Q = m_{\Xi_b\pi} - m_{\Xi_b} - m_\pi$$



$\Xi_b^{*0} \rightarrow \Xi_b^-\pi^+$



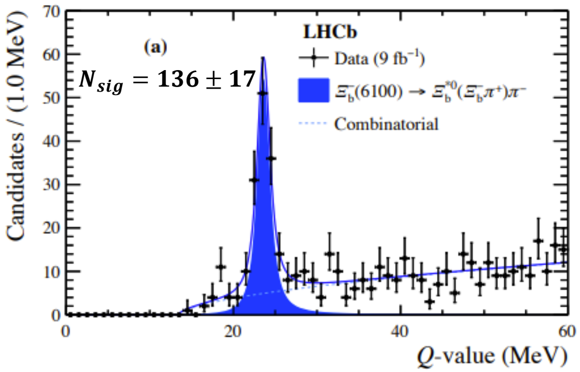
$\Xi_b'^-(\Xi_b^{*-}) \rightarrow \Xi_b^0\pi^-$

State	Yields
Ξ_b^{*0}	2019 ± 58
$\Xi_b'^-$	1750 ± 50
Ξ_b^{*-}	3380 ± 110

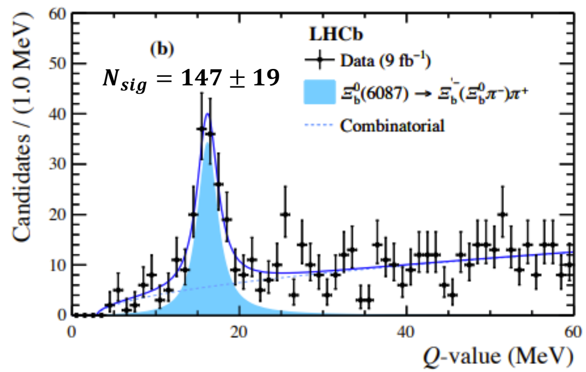
Observation of new baryons in $\Xi_b^{-(0)}\pi^+\pi^-$

PRL 131, 171901 (2023)

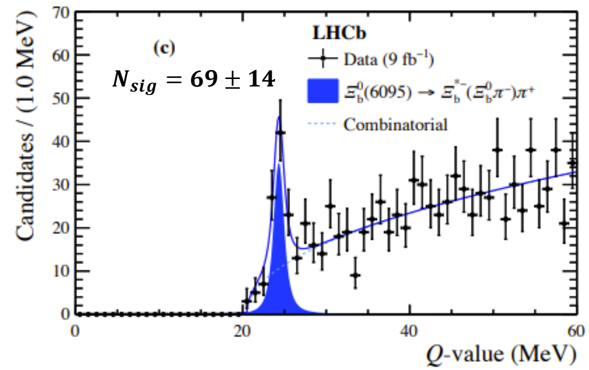
$Q = m_{\Xi_b\pi\pi} - m_{\Xi_b} - 2m_\pi$



$\Xi_b^-(6100) \to \Xi_b^{*0}\pi^-$



$\Xi_b^0(6087) \to \Xi_b'^-\pi^+$



$\Xi_b^0(6095) \to \Xi_b^{*-}\pi^+$

- **Confirm the $\Xi_b(6100)^-$ charged state**
  - ✓ Reported by CMS before [PRL 126, 252003 (2021)]:

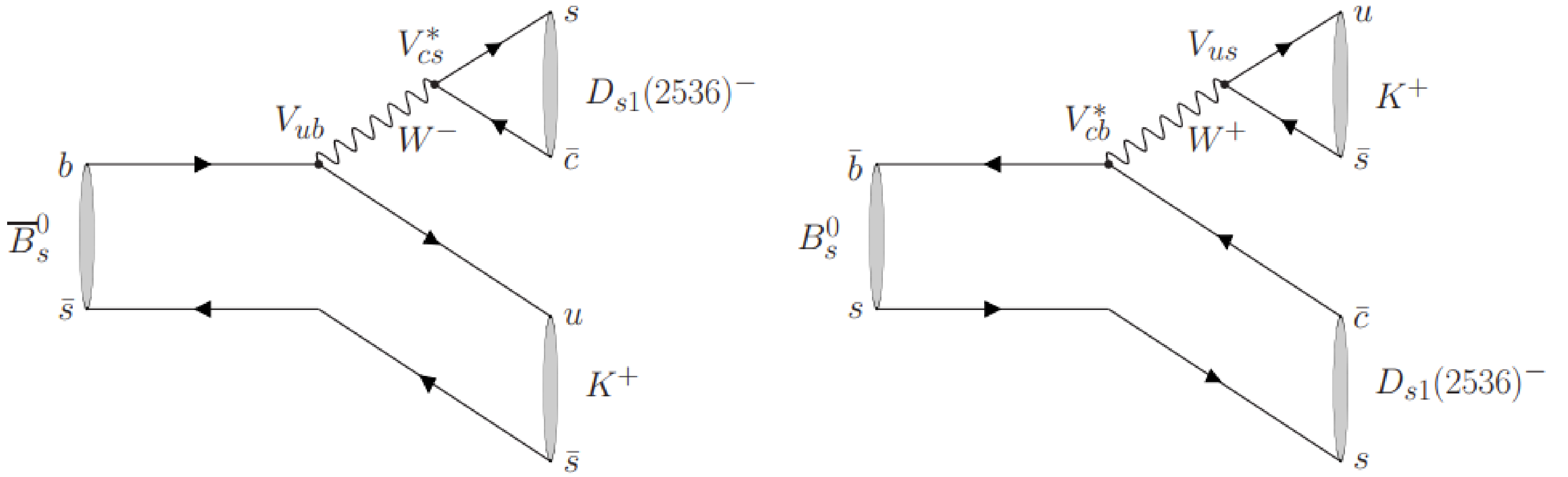
    $M[\Xi_b(6100)^-] = 6100.3 \pm 0.2(\text{stat}) \pm 0.1(\text{syst}) \pm 0.6(\Xi_b^-)$
  - ✓ $\Xi_b(6100)^-$ decays mainly through the $\Xi_b^{*0}\pi^-$
- **First observation of two baryons $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$**
  - ✓ With quark content bsu, reported in $\Xi_b^0\pi^+\pi^-$ final state
  - ✓ Hard to extract the spin-parity due to low statistics
  - ✓ Main decay process

    $\Xi_b(6087)^0 \to \Xi_b^{*0}\pi^-$ and $\Xi_b(6095)^0 \to \Xi_b'\pi^+$
- **Properties of Ξ_b^{*0}, $\Xi_b'^-$ and Ξ_b^{*-} are measured with high precision**

State	Observ.	Value (MeV)
$\Xi_b(6100)^-$	Q_0	$23.6 \pm 0.11 \pm 0.02$
confirm	Γ	$0.94 \pm 0.30 \pm 0.08$
	m_0	$6099.74 \pm 0.11 \pm 0.02 \pm 0.6\ (\Xi_b^-)$
$\Xi_b(6087)^0$	Q_0	$16.20 \pm 0.20 \pm 0.06$
new	Γ	$2.43 \pm 0.51 \pm 0.10$
	m_0	$6087.24 \pm 0.20 \pm 0.06 \pm 0.5\ (\Xi_b^0)$
$\Xi_b(6095)^0$	Q_0	$24.32 \pm 0.15 \pm 0.03$
new	Γ	$0.50 \pm 0.33 \pm 0.11$
	m_0	$6095.36 \pm 0.15 \pm 0.03 \pm 0.5\ (\Xi_b^0)$

- **Theoretical predictions** [PRD **84**, 014025 (2011)]

$nL(J^P)$	Mass (MeV)
$1P(1/2^-)$	6084
$1P(3/2^-)$	6097



Observation of $B_{(s)}^0 \rightarrow D_{s1}(2536)^{\mp} K^{\pm}$

Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

JHEP 10, 106 (2023)

- **Motivation**
  - ✓ CKM angle $\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$, which is sensitive in $B_s^0 - \bar{B}_s^0$ mixing and decay process
  - ✓ The measured BFs of $B^0 \to D^{(*)-}K^+$ and $B_s^0 \to D_s^{(*)-}\pi^+$ are smaller than the predictions with QCD factorization

    [PRD 83, 014017 (2011)] [JHEP 10, 235 (2021)]
    [EPJC 80, 951 (2020)] [JHEP 01, 147 (2022)]

Similar decay dynamics
Provide additional information

$B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

- **Start from the branching fraction measurement**
  - ✓ Using LHCb data collected at center-of-mass energies of 7, 8, 13 TeV (9 fb^{-1})
  - ✓ Partially reconstructed (γ/π^0 missing)

$$B^0_{(s)} \to D_{s1}^{\mp}K^{\pm},\ D_{s1}^{\mp} \to D^{*0}K^{\mp},\ D^{*0} \to D^0\gamma/\pi^0$$

  - ✓ Control channel: $B^0 \to \bar{D}^0K^+K^-$
  - ✓ Relative branching fraction:

$$\mathcal{R}(B^0_{(s)} \to D_{s1}^{\mp}K^{\pm}) \equiv \frac{\mathcal{B}(B^0_{(s)} \to D_{s1}^{\mp}K^{\pm}) \times \mathcal{B}(D_{s1}^{-} \to \bar{D}^{*0}K^{-})}{\mathcal{B}(B^0 \to \bar{D}^0K^+K^-)}$$

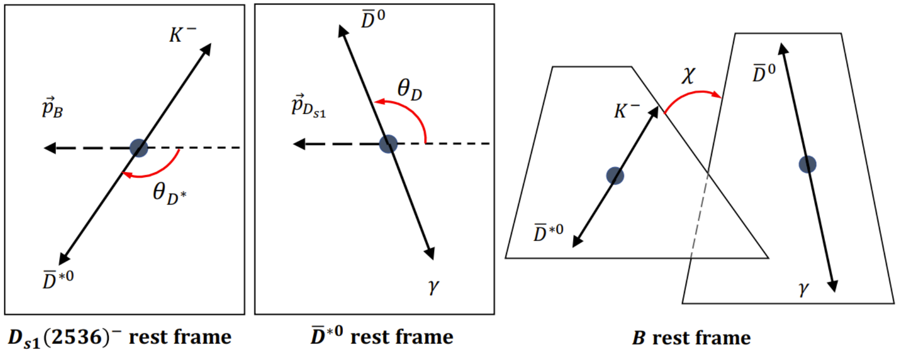
$$= \frac{N(B^0_{(s)} \to D_{s1}^{\mp}K^{\pm})}{N(B^0 \to \bar{D}^0K^+K^-)} \times \frac{\epsilon(B^0 \to \bar{D}^0K^+K^-)}{\epsilon(B^0_{(s)} \to D_{s1}^{\mp}K^{\pm})} \times \left(\frac{1}{f_s/f_d}\right) \times \frac{1}{\mathcal{B}_{\text{inter}}}$$

Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp} K^{\pm}$

JHEP 10, 106 (2023)

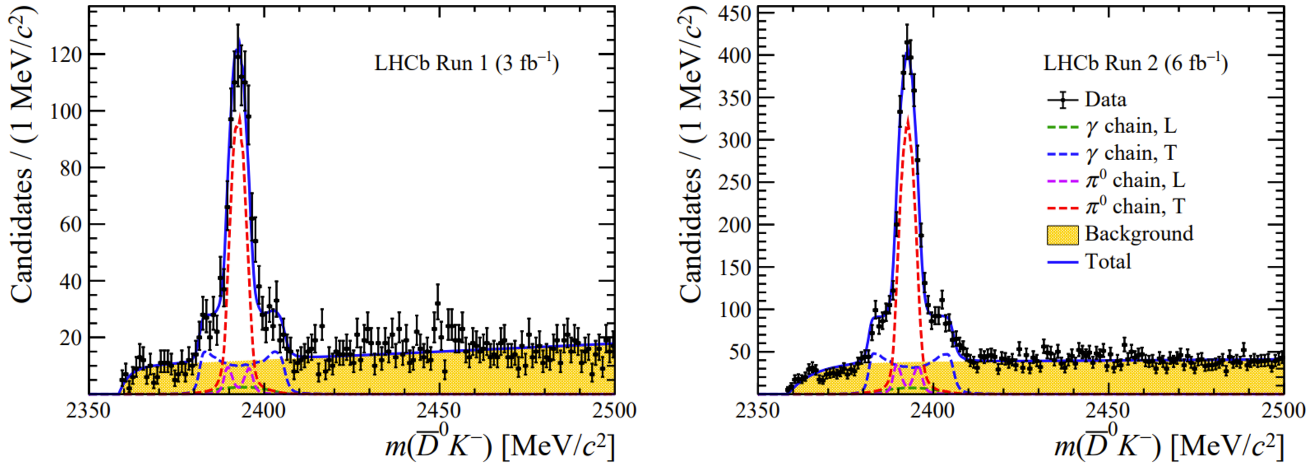
- **Angular distribution of signal process**

$$\frac{d^2\Gamma}{d\cos\theta_{D^*} d\cos\theta_D d\chi} \propto \omega_{\text{long}}(\theta_{D^*},\theta_D)|H_0|^2 + \omega_{\text{tran}}(\chi,\theta_{D^*},\theta_D)|H_+|^2 + \omega_{\text{int}}(\chi,\theta_{D^*},\theta_D)\Re(H_0^* H_+)^2$$



  - ✓ H_0: longitudinal, H_+: transverse, $H_+/H_0 \equiv ke^{i\phi}$
  - ✓ Contributions are proportional as $\omega_{\text{long}}:\omega_{\text{tran}}:\omega_{\text{int}} = 1:k^2:k\cos\phi$

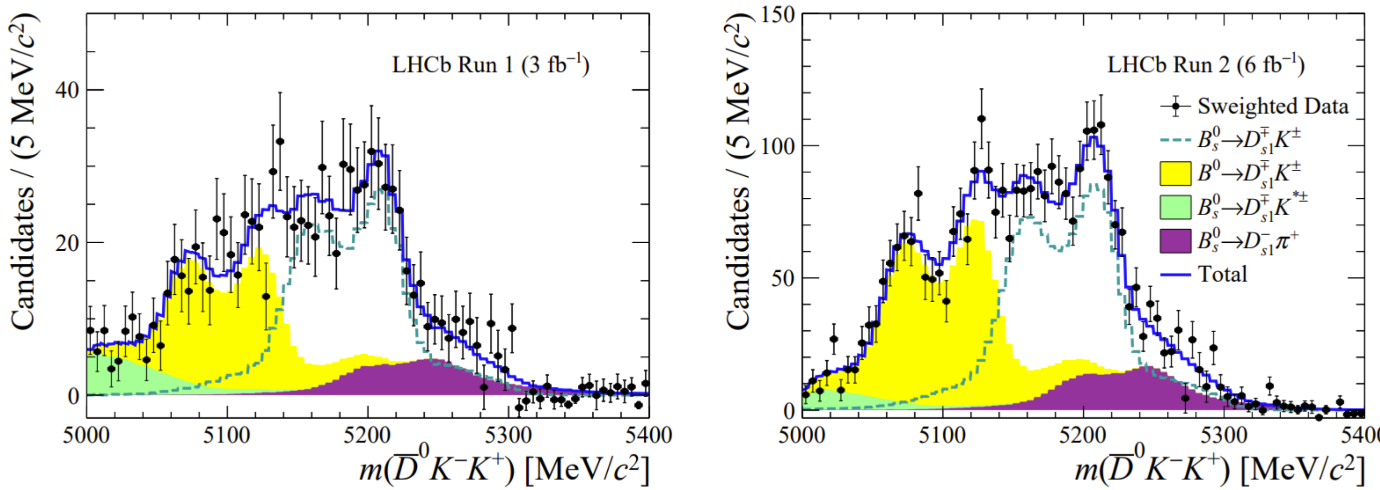
- **Fit to $m(\bar{D}^0 K^-)$**
  - ✓ No interference contribution
  - ✓ Extract D_{s1} signal with *sPlot*



Observation of $B^0_{(s)} \to D_{s1}(2536)^{\mp}K^{\pm}$

JHEP 10, 106 (2023)

- **Fit to $m(\overline{D}^0K^-K^+)$**
  - ✓ Derive sWeight from fit to $m(\overline{D}^0K^-)$
  - ✓ Fit to sWeighted $m(\overline{D}^0K^-K^+)$ distribution to determine B_s^0 yields



- **Branching fractions**

$$\mathcal{B}(B_s^0 \to D_{s1}(2536)^{\mp}K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^*(2007)^0K^-) = (2.49 \pm 0.11 \pm 0.12 \pm 0.25 \pm 0.06) \times 10^{-5}$$

$$\mathcal{B}(B^0 \to D_{s1}(2536)^{\mp}K^{\pm}) \times \mathcal{B}(D_{s1}(2536)^- \to \overline{D}^*(2007)^0K^-) = (0.510 \pm 0.021 \pm 0.036 \pm 0.050) \times 10^{-5}$$

- **Decay of $D_{s1}(2536)^- \to \overline{D}^*(2007)^0K^-$**
  - ✓ Ratio of S-wave / D-wave = $1.11 \pm 0.15 \pm 0.06$ $\Longrightarrow$ Fraction of S-wave: $(55 \pm 7 \pm 3)\%$
  - ✓ Agree with the result in isospin partner $D_{s1}(2536)^+ \to D^{*+}K^0$: $(72 \pm 5 \pm 1)\%$

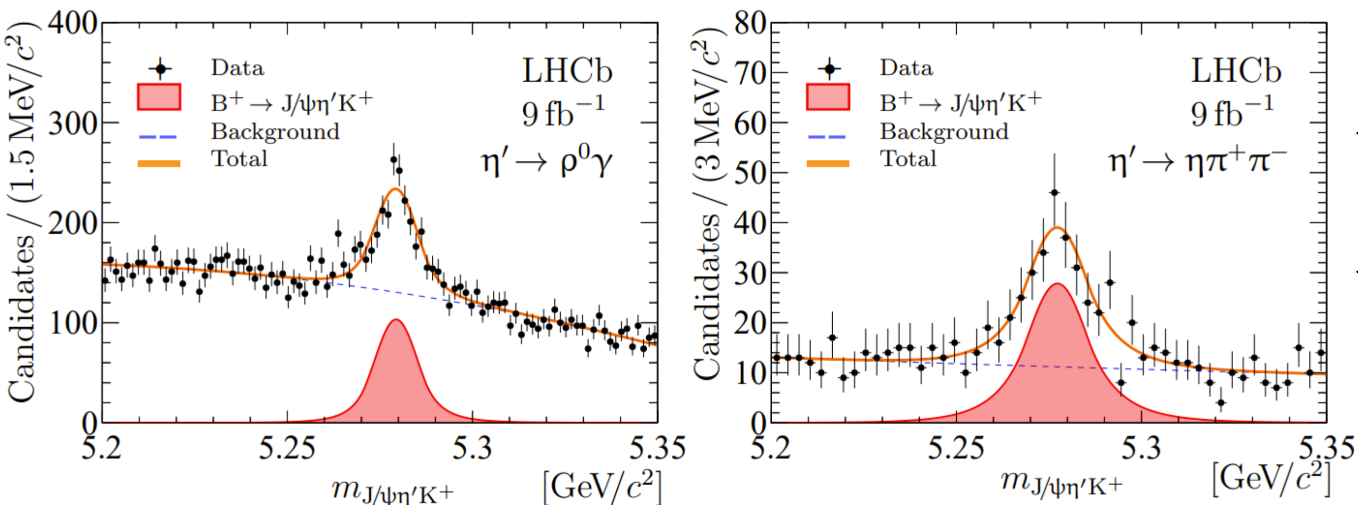
[Phys. Rev. D 77, 032001 (2008)]

Observation of the $B^+ \to J/\psi\eta' K^+$ decay

Observation of the $B^+ \to J/\psi\eta' K^+$ decay

JHEP 08, 174 (2023)

- **Motivation**
  - ✓ Transitions of charmonium states to $J/\psi\eta$ have been observed [PRD 87, 051101 (2013)], but none to $J/\psi\eta'$
  - ✓ Various theory modes predict the charmonium(-like) states decay into $J/\psi\eta'$ [PRD 57, 5653 (1998)] [PRD 79, 077502 (2009)]
  - ✓ Belle reported the upper limit of $\mathcal{B}(B^+ \to J/\psi\eta' K^+) < 8.8 \times 10^{-5}$(90% CL) [PRD 75, 017101 (2007)]
- **Using LHCb data collected at center-of-mass energies of 7, 8, 13 TeV** (**9 fb**$^{-1}$)
  - ✓ Normalization channel: $B^+ \to \psi(2S)K^+$



✓ Signal shape:

Gaussian + Power-law tails

✓ Background shape:

Second-order polynomial

$$\frac{\mathcal{B}(B^+ \to J/\psi\eta' K^+)}{\mathcal{B}(B^+ \to \psi(2S)K^+)} = (4.91 \pm 0.47 \pm 0.29 \pm 0.07) \times 10^{-2}$$

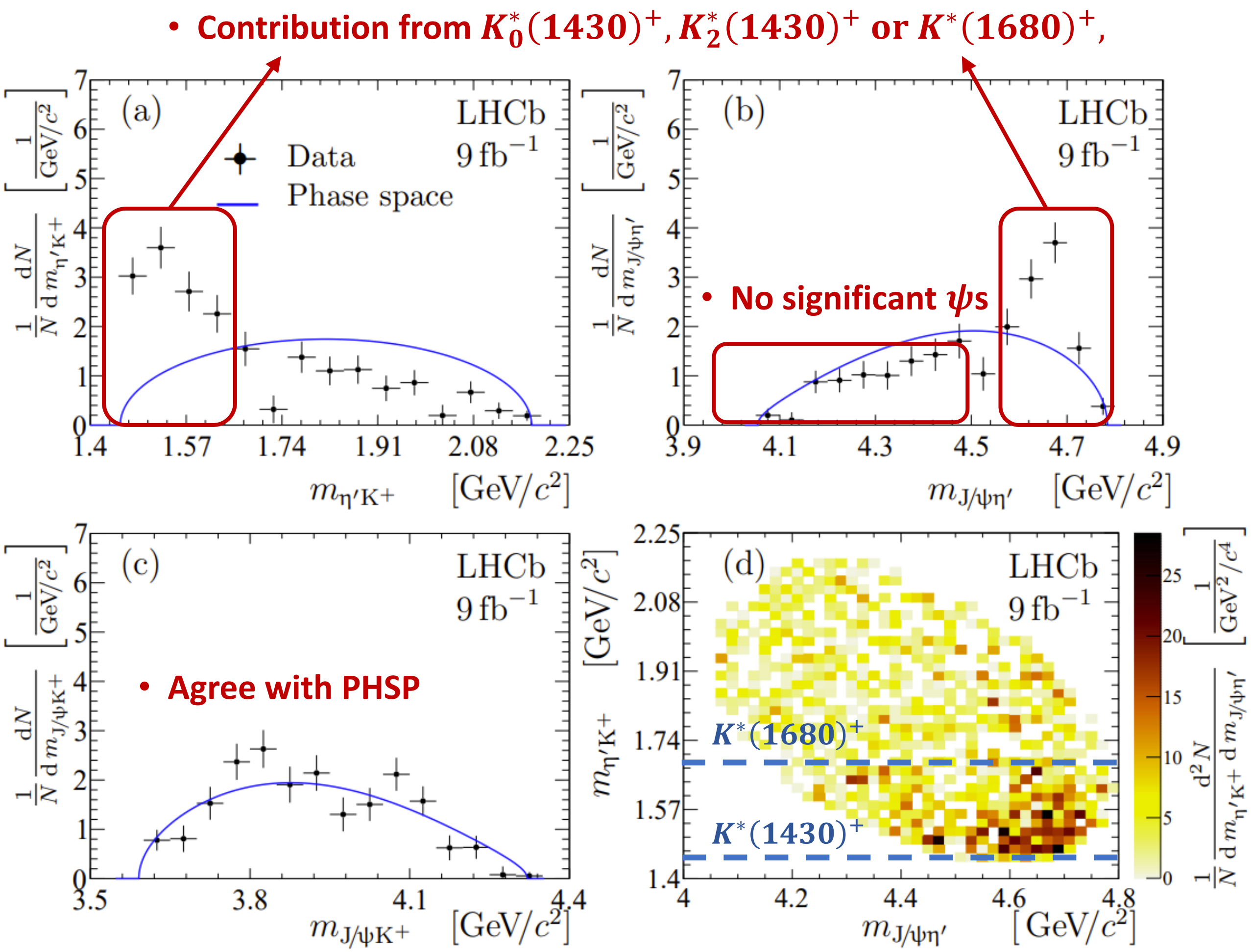
$$\Longrightarrow \mathcal{B}(B^+ \to J/\psi\eta' K^+) = (3.06 \pm 0.29 \pm 0.18 \pm 0.04) \times 10^{-5}$$

*only $\eta' \to \rho\gamma$ process used in the subsequent studies.

Observation of the $B^+ \to J/\psi\eta' K^+$ decay

JHEP 08, 174 (2023)

- **Determination of the resonant structure of the $B^+ \to J/\psi\eta' K^+$ decay**
  - ✓ Background subtracted by *sPlot* technique
  - ✓ PV constraint and Mass constraint of $J/\psi, \eta'$, and B^+ are applied



Quick look at other studies

- **Observation of new Ω_c^0 states decaying to the $\Xi_c^+ K^-$ final state, PRL 131. 131902 (2023)**
- **Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay, PRD 108. 012020 (2023)**

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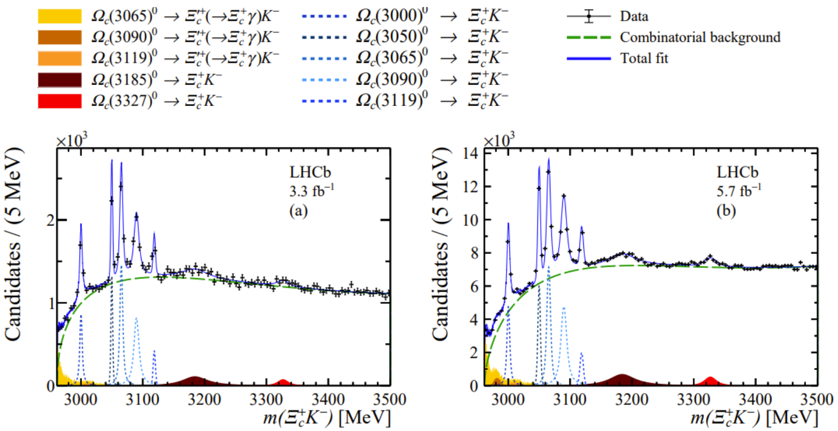
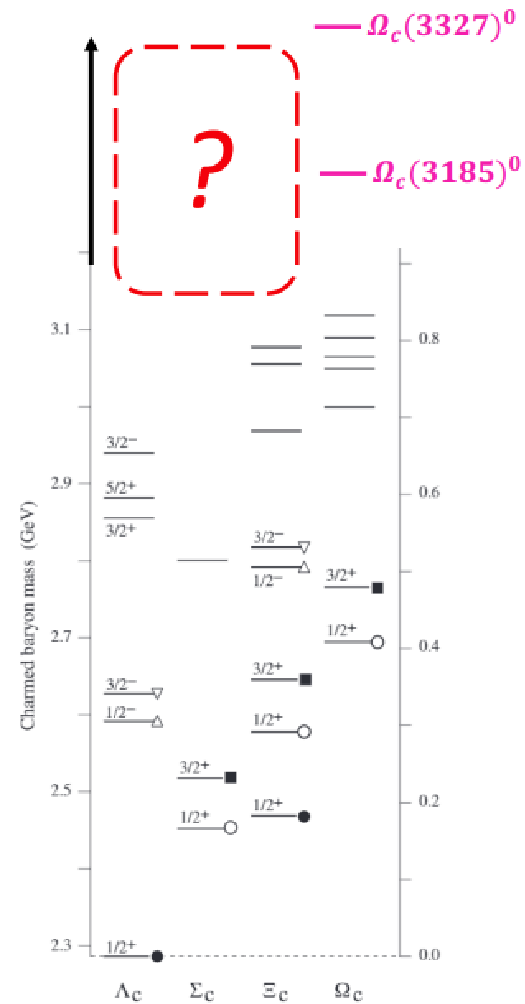
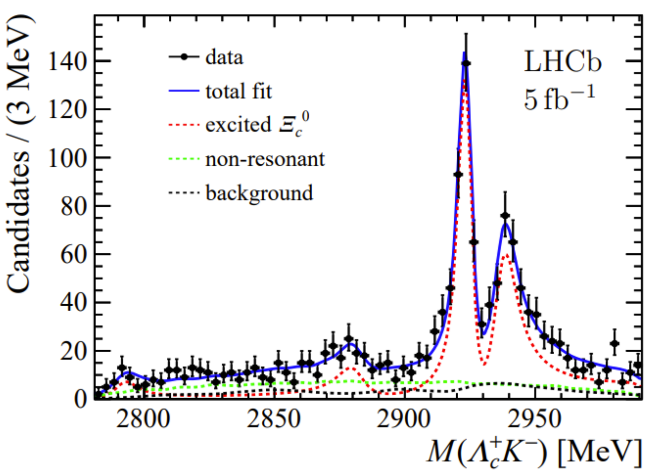


m (MeV)	Γ (MeV)
• $\Omega_c(3185)^0$	
$3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7^{+10}_{-20}$
• $\Omega_c(3327)^0$	
$3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5^{+13}_{-1}$



- **Study of the $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ decay, [PRD 108. 012020 (2023)]**

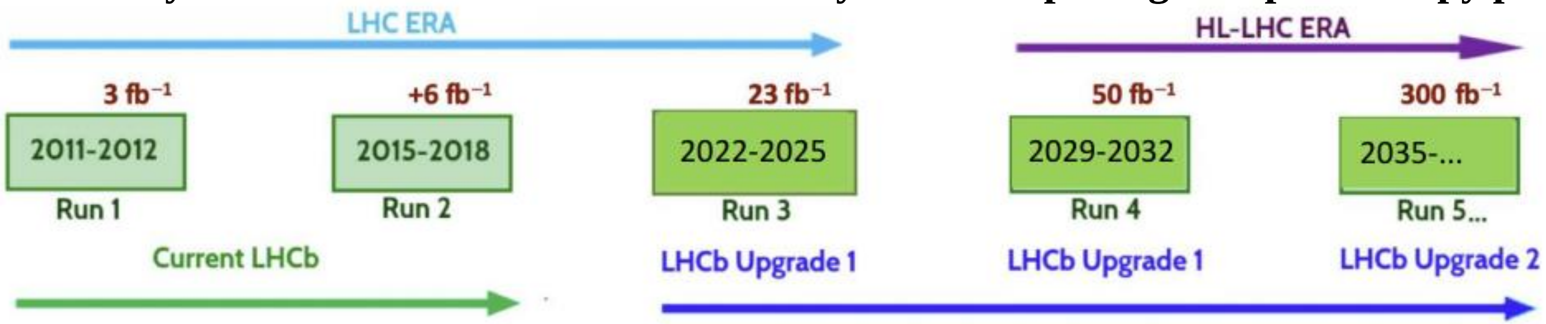


Resonance	m (MeV)	Γ (MeV)
$\Xi_c(2923)^0$	$2924.5 \pm 0.4 \pm 1.1$	$4.8 \pm 0.9 \pm 1.5$
$\Xi_c(2939)^0$	$2938.5 \pm 0.9 \pm 2.3$	$11.0 \pm 1.9 \pm 7.5$
$\Xi_c(2880)^0$ (3.8σ)	$2881.8 \pm 3.1 \pm 8.5$	$12.4 \pm 5.3 \pm 5.8$
$\Xi_c(2790)^0$ (3.7σ)	–	–

- **With more data sets in LHCb Run 3, good opportunities to search for more high excited charmed baryons!**

Summary and prospect

- **Recent interesting results presented**
  - ✓ **First measurement of BFs of $\Omega_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Xi^- \pi^+$ decays,** arXiv:2308.08512
  - ✓ **Precise mass measurement of Ω_c^0,** arXiv:2308.08512
  - ✓ **Confirm $\Xi_b(6100)^-$ & first observation of $\Xi_b(6087)^0$ and $\Xi_b(6095)^0$,** PRL 131, 171901 (2023)
  - ✓ **First observation of $B_{(s)}^0 \to D_{s1}(2536)^{\mp} K^{\pm}$,** JHEP 10, 106 (2023)
  - ✓ **First observation of $B^+ \to J/\psi \eta' K^+$,** JHEP 08, 174 (2023)
- **Higher statistics in Run 3 boosts hadron spectroscopy studies at LHCb**
  - ✓ **Today's discovery, tomorrow's precision tool to test our knowledge of QCD**
  - ✓ **We are only one more conventional hadron away from completing the spectroscopy puzzle**



Thanks for your attention~

Backup

$\mathcal{B}(\Omega_c^0 \to \Xi^- \pi^+)/\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)$

arXiv:2308.08512

- **Negligible non-factorizable contributions**
- **Relevant form factor is similar to $\Omega_c^0 \to \Omega^- \pi^+$**

$$\frac{\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)}{\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \times R_{phsp} \approx 0.0467 \pm 0.0003$$

This work

$\mathcal{B}(\Omega_c^0 \to \Omega^- K^+)/\mathcal{B}(\Omega_c^0 \to \Omega^- \pi^+) = 0.0608 \pm 0.0051(\text{stat}) \pm 0.0040(\text{syst})$