# Spectroscopy of heavy baryons

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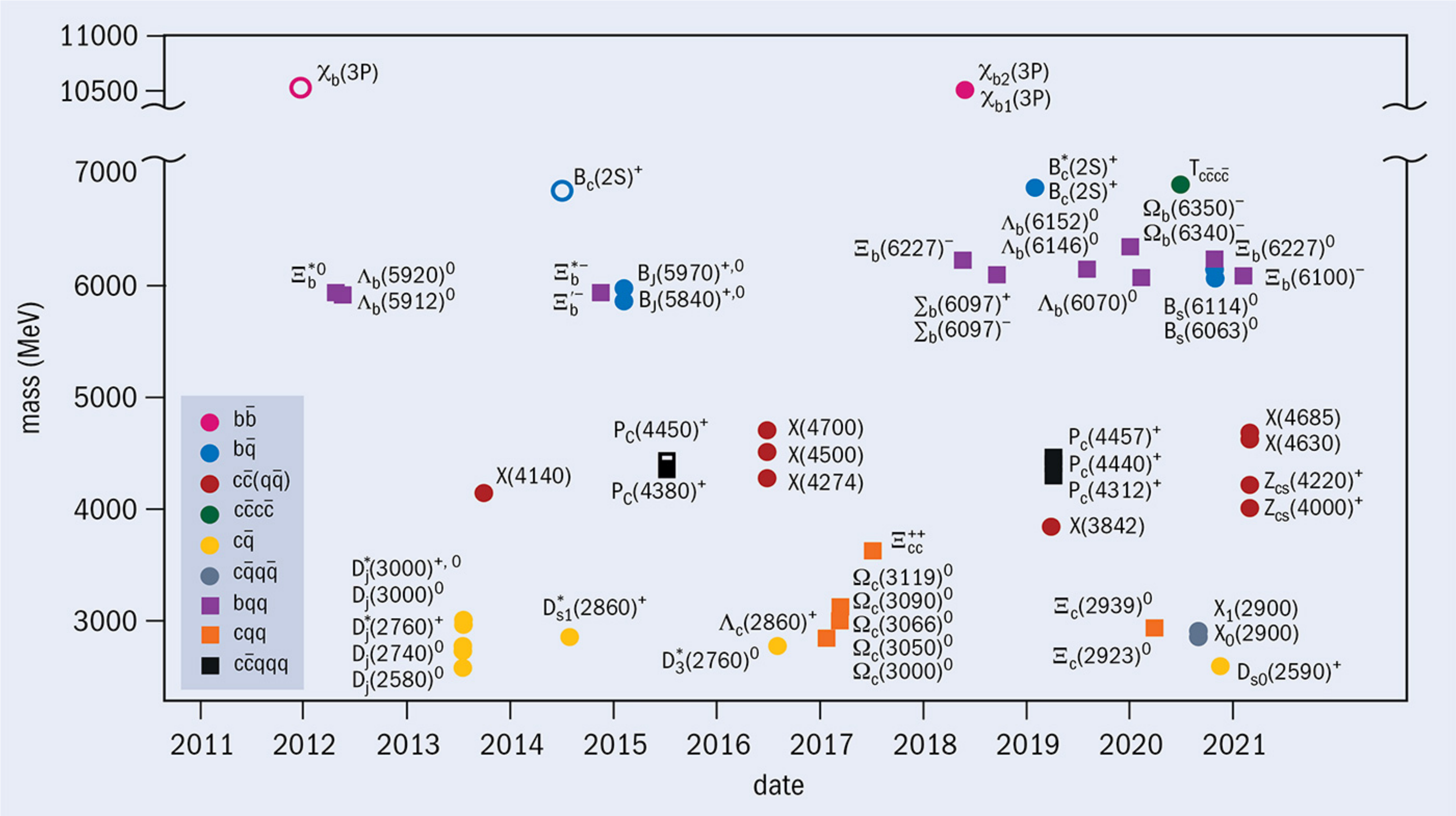
# Outline

- Overview of experimental status
- Theoretical approaches for studying the spectroscopy of single heavy baryons
- Recent progresses on heavy baryons
- Summary

# New hadronic states from LHC

## More and more heavy baryons were reported

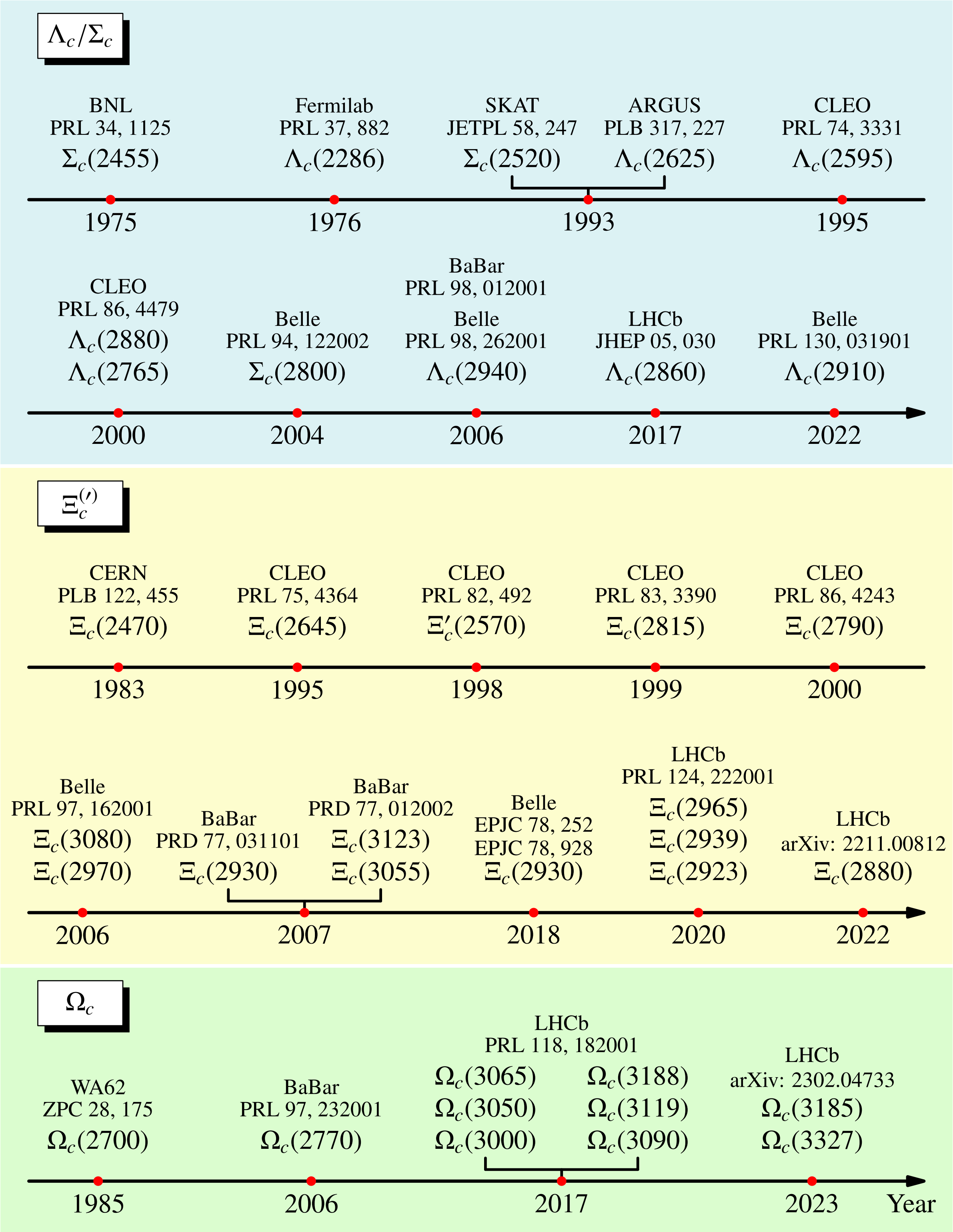


LHCb

CMS

ATLAS EXPERIMENT

# Overview of experimental status



$\Lambda_c/\Sigma_c$

BNL
PRL 34, 1125
$\Sigma_c(2455)$
1975

Fermilab
PRL 37, 882
$\Lambda_c(2286)$
1976

SKAT
JETPL 58, 247
$\Sigma_c(2520)$

ARGUS
PLB 317, 227
$\Lambda_c(2625)$
1993

CLEO
PRL 74, 3331
$\Lambda_c(2595)$
1995

CLEO
PRL 86, 4479
$\Lambda_c(2880)$
$\Lambda_c(2765)$
2000

Belle
PRL 94, 122002
$\Sigma_c(2800)$
2004

BaBar
PRL 98, 012001
Belle
PRL 98, 262001
$\Lambda_c(2940)$
2006

LHCb
JHEP 05, 030
$\Lambda_c(2860)$
2017

Belle
PRL 130, 031901
$\Lambda_c(2910)$
2022

$\Xi_c^{(\prime)}$

CERN
PLB 122, 455
$\Xi_c(2470)$
1983

CLEO
PRL 75, 4364
$\Xi_c(2645)$
1995

CLEO
PRL 82, 492
$\Xi_c'(2570)$
1998

CLEO
PRL 83, 3390
$\Xi_c(2815)$
1999

CLEO
PRL 86, 4243
$\Xi_c(2790)$
2000

Belle
PRL 97, 162001
$\Xi_c(3080)$
$\Xi_c(2970)$
2006

BaBar
PRD 77, 031101
$\Xi_c(2930)$

BaBar
PRD 77, 012002
$\Xi_c(3123)$
$\Xi_c(3055)$
2007

Belle
EPJC 78, 252
EPJC 78, 928
$\Xi_c(2930)$
2018

LHCb
PRL 124, 222001
$\Xi_c(2965)$
$\Xi_c(2939)$
$\Xi_c(2923)$
2020

LHCb
arXiv: 2211.00812
$\Xi_c(2880)$
2022

$\Omega_c$

WA62
ZPC 28, 175
$\Omega_c(2700)$
1985

BaBar
PRL 97, 232001
$\Omega_c(2770)$
2006

LHCb
PRL 118, 182001
$\Omega_c(3065)$ $\Omega_c(3188)$
$\Omega_c(3050)$ $\Omega_c(3119)$
$\Omega_c(3000)$ $\Omega_c(3090)$
2017

LHCb
arXiv: 2302.04733
$\Omega_c(3185)$
$\Omega_c(3327)$
2023

Year

## Charm baryon

- More than 30 charm baryons have been discovered experimentally in the last 40 years
- More than half of them have been discovered in this century
- This experimental data may provide crucial information to construct charmed baryon family

**See reviews:**

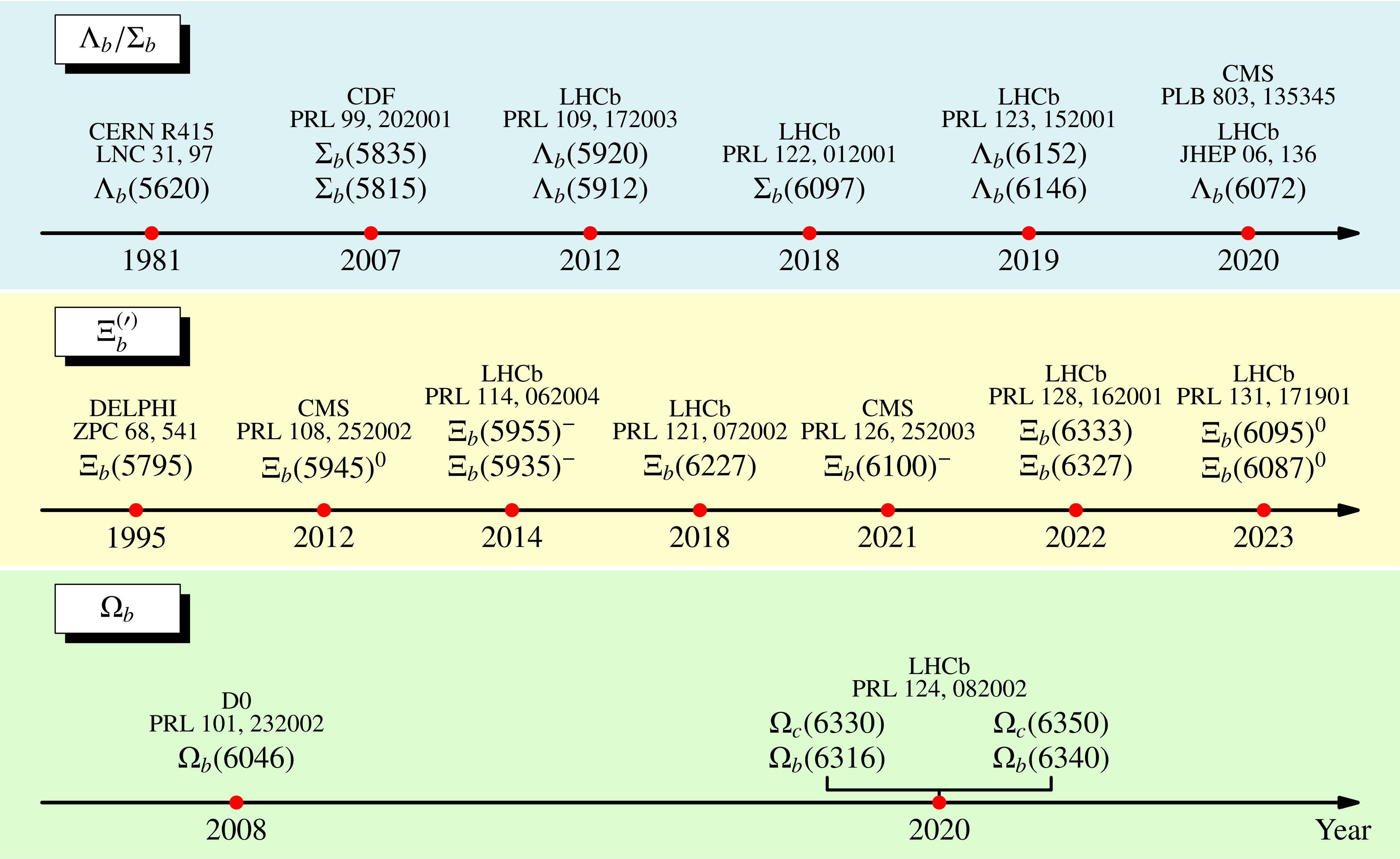
*Rep.Prog.Phys. 86 (2023) 026201*
*Rep.Prog.Phys. 80 (2017) 076201*
*Chin.J.Phys. 78 (2022) 324-362*

1

# Overview of experimental status

## Bottom baryon

**More than 20 states have been announced**



$\Lambda_b/\Sigma_b$

CERN R415
LNC 31, 97
$\Lambda_b(5620)$
1981

CDF
PRL 99, 202001
$\Sigma_b(5835)$
$\Sigma_b(5815)$
2007

LHCb
PRL 109, 172003
$\Lambda_b(5920)$
$\Lambda_b(5912)$
2012

LHCb
PRL 122, 012001
$\Sigma_b(6097)$
2018

LHCb
PRL 123, 152001
$\Lambda_b(6152)$
$\Lambda_b(6146)$
2019

CMS
PLB 803, 135345
LHCb
JHEP 06, 136
$\Lambda_b(6072)$
2020

$\Xi_b^{(\prime)}$

DELPHI
ZPC 68, 541
$\Xi_b(5795)$
1995

CMS
PRL 108, 252002
$\Xi_b(5945)^0$
2012

LHCb
PRL 114, 062004
$\Xi_b(5955)^-$
$\Xi_b(5935)^-$
2014

LHCb
PRL 121, 072002
$\Xi_b(6227)$
2018

CMS
PRL 126, 252003
$\Xi_b(6100)^-$
2021

LHCb
PRL 128, 162001
$\Xi_b(6333)$
$\Xi_b(6327)$
2022

LHCb
PRL 131, 171901
$\Xi_b(6095)^0$
$\Xi_b(6087)^0$
2023

$\Omega_b$

D0
PRL 101, 232002
$\Omega_b(6046)$
2008

LHCb
PRL 124, 082002
$\Omega_c(6330)$
$\Omega_b(6316)$
$\Omega_c(6350)$
$\Omega_b(6340)$
2020

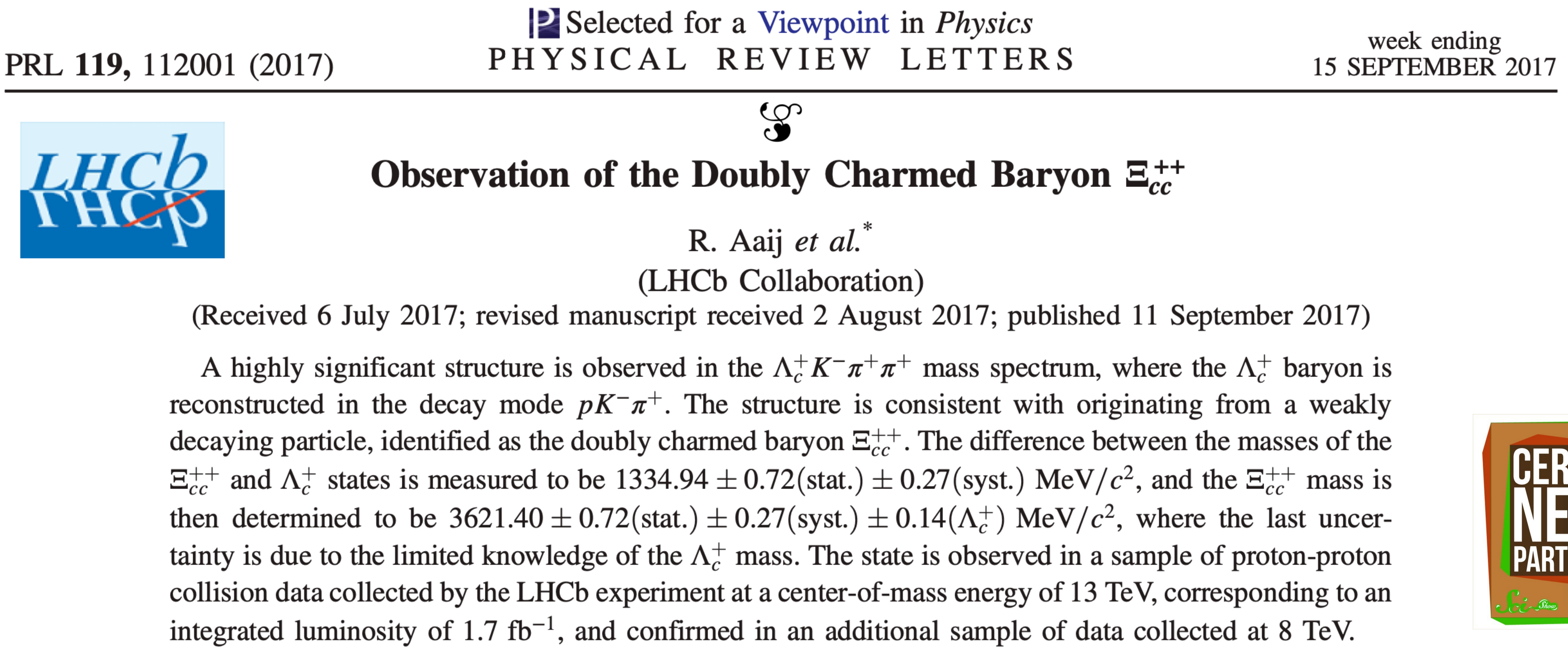
Year

*Rep.Prog.Phys. 86 (2023) 026201, Rep.Prog.Phys. 80 (2017) 076201, Chin.J.Phys. 78 (2022) 324-362*

# 1

# Overview of experimental status

**Doubly charmed baryon**



Selected for a Viewpoint in *Physics*
PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017

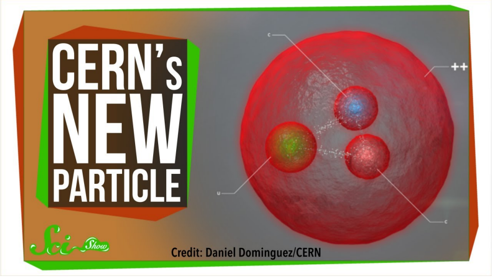
## Observation of the Doubly Charmed Baryon $\Xi_{cc}^{++}$

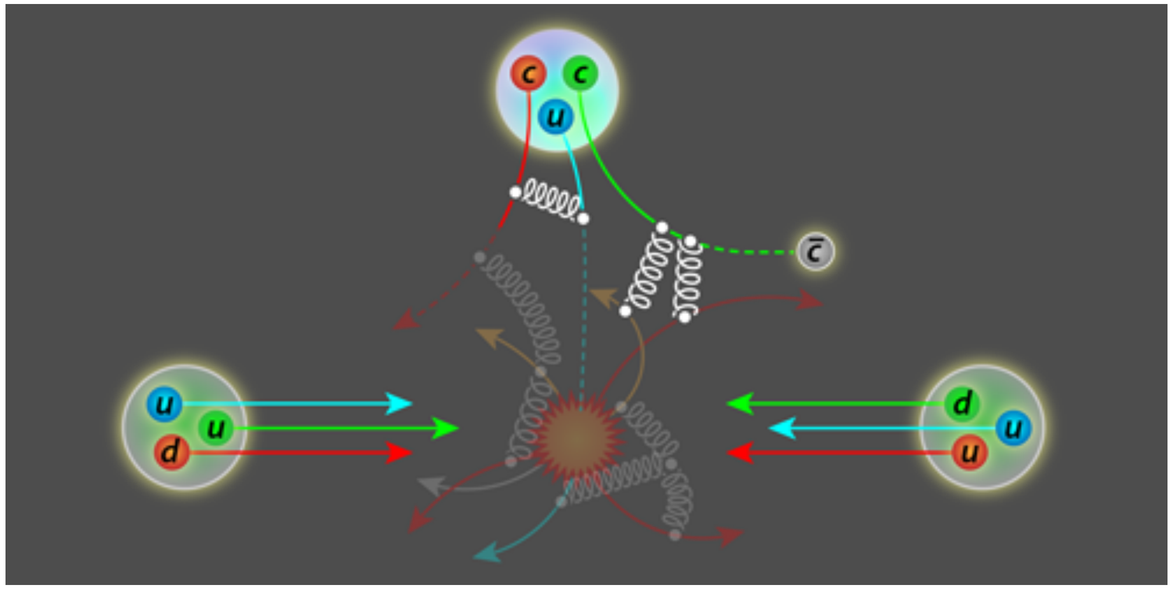
R. Aaij *et al.*[*]
(LHCb Collaboration)

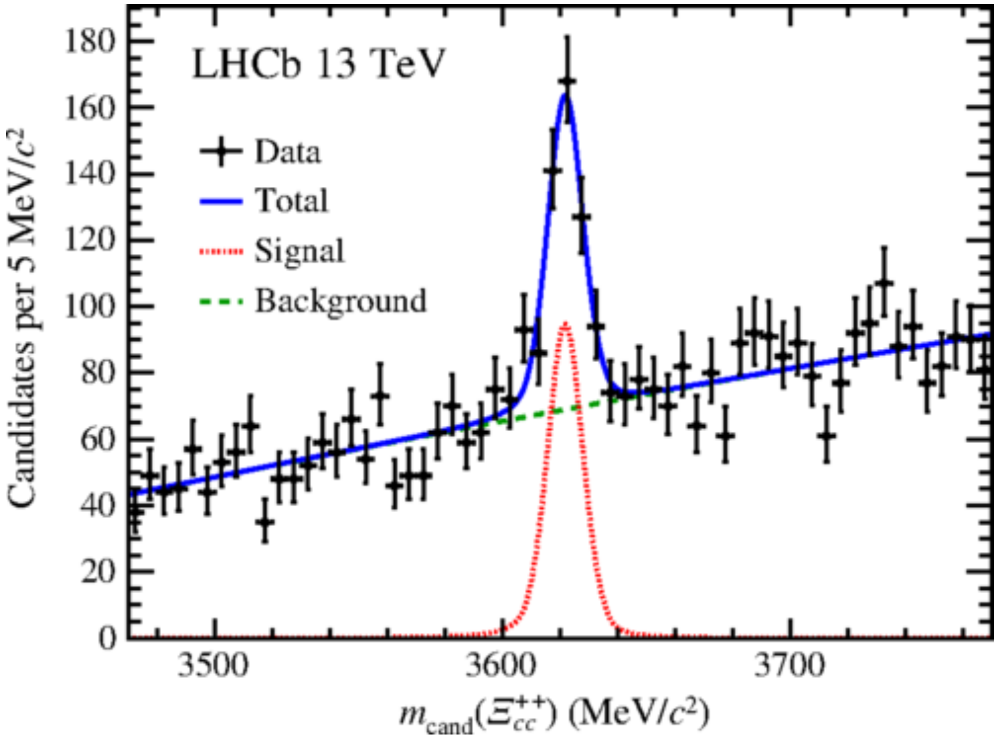
(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the $\Lambda_c^+$ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon $\Xi_{cc}^{++}$. The difference between the masses of the $\Xi_{cc}^{++}$ and $\Lambda_c^+$ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\ \text{MeV}/c^2$, and the $\Xi_{cc}^{++}$ mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the $\Lambda_c^+$ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $1.7\ \text{fb}^{-1}$, and confirmed in an additional sample of data collected at 8 TeV.

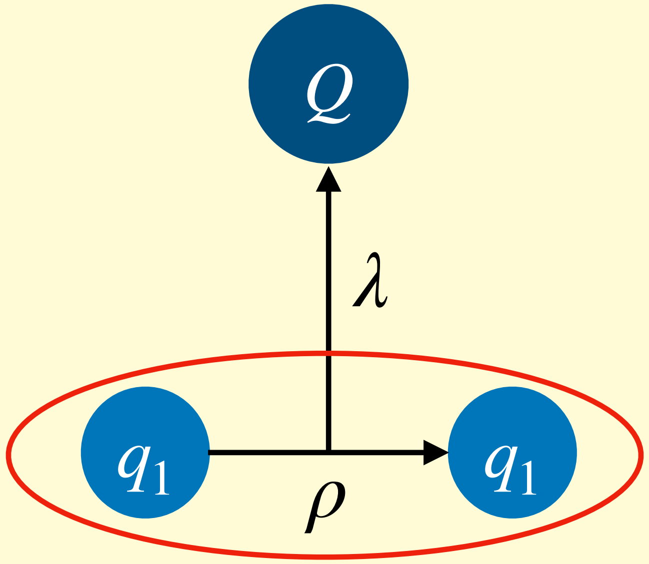
DOI: 10.1103/PhysRevLett.119.112001







## Typical few-body system



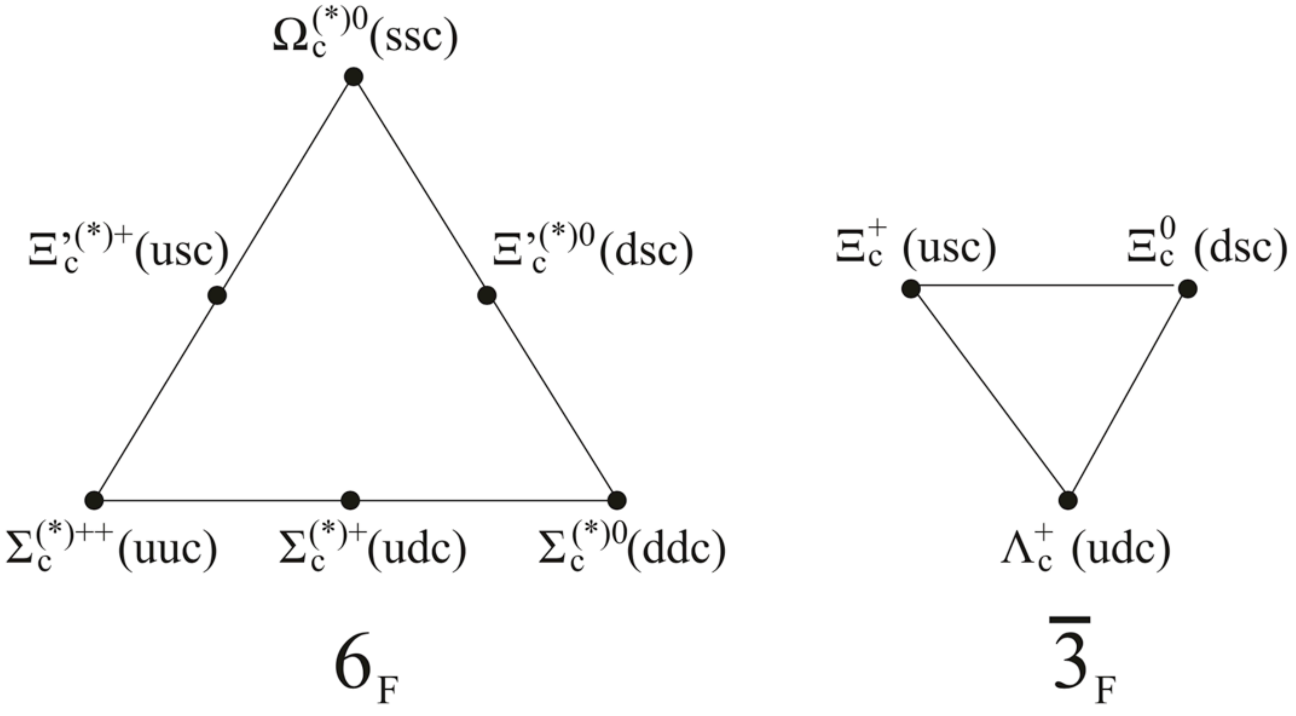
Jacobi coordinates for the three-body system

## SU(3) symmetry

$$3_f \otimes_f = \bar{3}_f \oplus 6_f$$

*Rep.Prog.Phys. 80 (2017) 076201*

## SU(3) flavor multiplets of charm baryons



$$\phi^{\text{flavor}}_{\Lambda_Q} = \frac{1}{\sqrt{2}}(ud - du)Q$$

$$\phi^{\text{flavor}}_{\Xi_Q} = \begin{cases} \frac{1}{\sqrt{2}}(us - su)Q \\ \frac{1}{\sqrt{2}}(ds - sd)Q \end{cases}$$

$$\phi^{\text{flavor}}_{\Sigma_Q} = \begin{cases} uuQ \\ \frac{1}{\sqrt{2}}(ud + du)Q \\ ddQ \end{cases}$$

$$\phi^{\text{flavor}}_{\Xi'_Q} = \begin{cases} \frac{1}{\sqrt{2}}(us + su)Q \\ \frac{1}{\sqrt{2}}(ds + sd)Q \end{cases},$$

$$\phi^{\text{flavor}}_{\Omega_Q} = ssQ.$$

# 2 Theoretical approaches for studying the spectroscopy of singly heavy baryons

**Mass spectrum** **Potential model** **Diquark**

$$\hat{H} = m_{\rm di} + m_Q + \frac{p_{\rm di}^2}{2m_{\rm di}} + \frac{p_Q^2}{2m_Q} + V_{{\rm di}-Q},$$

$$V_{{\rm di}-Q} = H^{\rm conf} + H^{\rm hyp} + H^{\rm so(cm)} + H^{\rm so(tp)}.$$

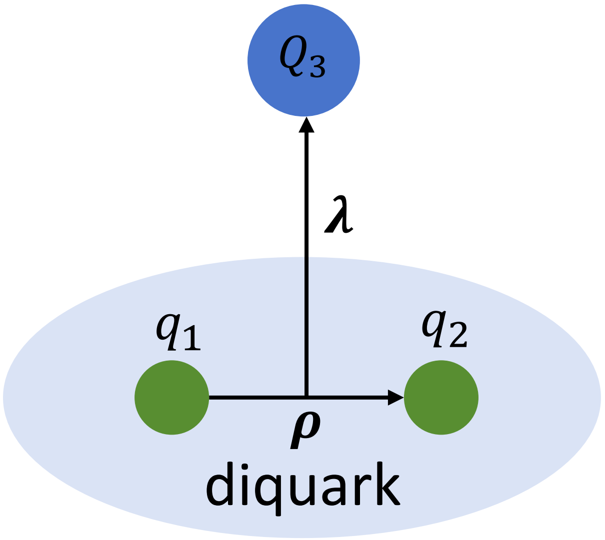
$$H^{\rm conf} = -\frac{4\alpha_s}{3r} + br + C,$$

$$H^{\rm hyp} = \frac{4\alpha_s}{3m_{\rm di}m_Q}\left(\frac{8\pi}{3}\mathbf{s}_{\rm di}\cdot\mathbf{s}_Q\tilde{\delta}(r) + \frac{1}{r^3}S\left(\mathbf{r},\mathbf{s}_{\rm di},\mathbf{s}_Q\right)\right),$$

$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}}e^{-\sigma^2 r^2}, \quad S\left(\mathbf{r},\mathbf{s}_{\rm di},\mathbf{s}_Q\right) = \frac{3\mathbf{s}_{\rm di}\cdot\mathbf{r}\mathbf{s}_Q\cdot\mathbf{r}}{r^2} - \mathbf{s}_{\rm di}\cdot\mathbf{s}_Q,$$

$$H^{\rm so(cm)} = \frac{4\alpha_s}{3r^3}\left(\frac{1}{m_{\rm di}} + \frac{1}{m_Q}\right)\left(\frac{\mathbf{s}_{\rm di}}{m_{\rm di}} + \frac{\mathbf{s}_Q}{m_Q}\right)\cdot\mathbf{L},$$

$$H^{\rm so(tp)} = -\frac{1}{2r}\frac{\partial H^{\rm conf}}{\partial r}\left(\frac{\mathbf{s}_{\rm di}}{m_{\rm di}^2} + \frac{\mathbf{s}_Q}{m_Q^2}\right)\cdot\mathbf{L}.$$



D. Ebert, K. G. Klimenko and V. L. Yudichev, Eur. Phys. J. C 53, 65-76 (2008)

D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D 84, 014025 (2011)

B. Chen, K. W. Wei and A. Zhang, Eur. Phys. J. A 51, 82 (2015)

B. Chen, K. W. Wei, X. Liu and T. Matsuki, Eur. Phys. J. C 77, no.3, 154 (2017)

Q. F. Lu, K. L. Wang, L. Y. Xiao and X. H. Zhong, Phys. Rev. D 96, no.11, 114006 (2017)

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# 2 Theoretical approaches for studying the spectroscopy of singly heavy baryons

**Mass spectrum** **Potential model** **Three-body potential**

$$\hat{H} = \sum_i \left( m_i + \frac{p_i^2}{2m_i} \right) + \sum_{i<j} \left( V_{ij}^{\text{conf}} + V_{ij}^{\text{hyp}} + V_{ij}^{\text{so(cm)}} + V_{ij}^{\text{so(tp)}} \right).$$

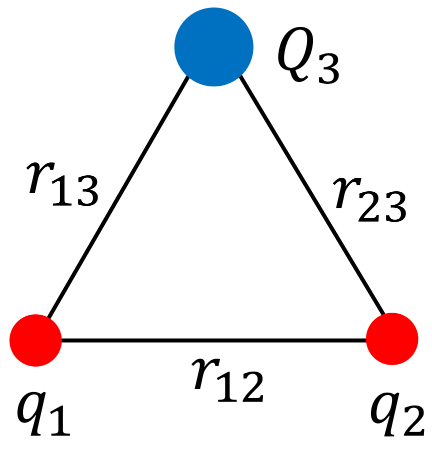
$$V_{ij}^{\text{conf}} = -\frac{2}{3}\frac{\alpha_s}{r_{ij}} + \frac{b}{2} r_{ij} + \frac{1}{2} C,$$

$$V_{ij}^{\text{hyp}} = \frac{2\alpha_s}{3m_i m_j} \left[ \frac{8\pi}{3} \tilde{\delta}(r_{ij}) \mathbf{s}_i \cdot \mathbf{s}_j + \frac{1}{r_{ij}^3} S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) \right],$$

$$\tilde{\delta}(r) = \frac{\sigma^3}{\pi^{3/2}} \mathrm{e}^{-\sigma^2 r^2}, \quad S(\mathbf{r}, \mathbf{s}_i, \mathbf{s}_j) = \frac{3\mathbf{s}_i \cdot \mathbf{r}_{ij} \mathbf{s}_j \cdot \mathbf{r}_{ij}}{r_{ij}^2} - \mathbf{s}_i \cdot \mathbf{s}_j,$$

$$V_{ij}^{\text{so(cm)}} = \frac{2\alpha_s}{3r_{ij}^3} \left( \frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_i - \mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_j}{m_i m_j} \right),$$

$$V_{ij}^{\text{so(tp)}} = -\frac{1}{2r_{ij}} \frac{\partial H_{ij}^{\text{conf}}}{\partial r_{ij}} \left( \frac{\mathbf{r}_{ij} \times \mathbf{p}_i \cdot \mathbf{s}_i}{m_i^2} - \frac{\mathbf{r}_{ij} \times \mathbf{p}_j \cdot \mathbf{s}_j}{m_j^2} \right).$$



S. Capstick and N. Isgur, Phys. Rev. D 34, 2809-2835 (1986)

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T. Yoshida, E. Hiyama, A. Hosaka, M. Oka and K. Sadato, Phys. Rev. D 92, 114029 (2015)

G. Yang, J. Ping and J. Segovia, Few Body Syst. 59, 113 (2018)

S. Q. Luo, B. Chen, Z. W. Liu and X. Liu, Eur. Phys. J. C 80, no.4, 301 (2020)

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Q. F. Song, Q. F. Lu and A. Hosaka, arXiv:2308.03261 [hep-ph].

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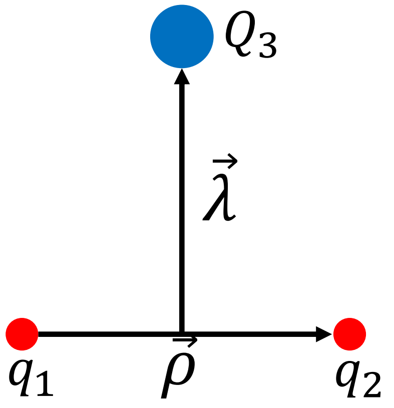
# 2 Theoretical approaches for studying the spectroscopy of singly heavy baryons

**Mass spectrum** **Potential model** **Gaussian expansion method**



Jacobi coordinate

$$\vec{\rho} = \vec{r}_2 - \vec{r}_1$$

$$\vec{\lambda} = \vec{r}_3 - \frac{m_1\vec{r}_1 + m_2\vec{r}_2}{m_1 + m_2}$$

**Gaussian base**

$$\phi_{nlm}(\mathbf{r}) = \phi_{nl}(r)Y_{lm}(\hat{\mathbf{r}})$$

$$\phi_{nl}(r) = N_{nl}r^l e^{-\nu_n r^2}$$

$$N_{nl} = \sqrt{\frac{2^{l+2}(2\nu_n)^{l+\frac{3}{2}}}{\sqrt{\pi}(2l+1)!!}}$$

$$\nu_n = \frac{1}{r_n^2} \qquad r_n = r_1 a^{n-1} \quad (n = 1 - n_{\max})$$

$$\Psi^{\text{total}} = \phi^{\text{color}} \times \phi^{\text{flavor}} \times \phi^{\text{spin}} \times \phi^{\text{orbit}}$$

$$\phi^{\text{orbit}} = \sum_{n_\rho n_\lambda} C_{n_\rho n_\lambda} \sum_{m_\rho m_\lambda} \langle l_\rho m_\rho; l_\lambda m_\lambda | LM \rangle \phi_{n_\rho l_\rho m_\rho}(\boldsymbol{\rho}) \phi_{n_\lambda l_\lambda m_\lambda}(\boldsymbol{\lambda})$$

Rayleigh-Ritz variational method

E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. 51, 223-307 (2003)

# 2

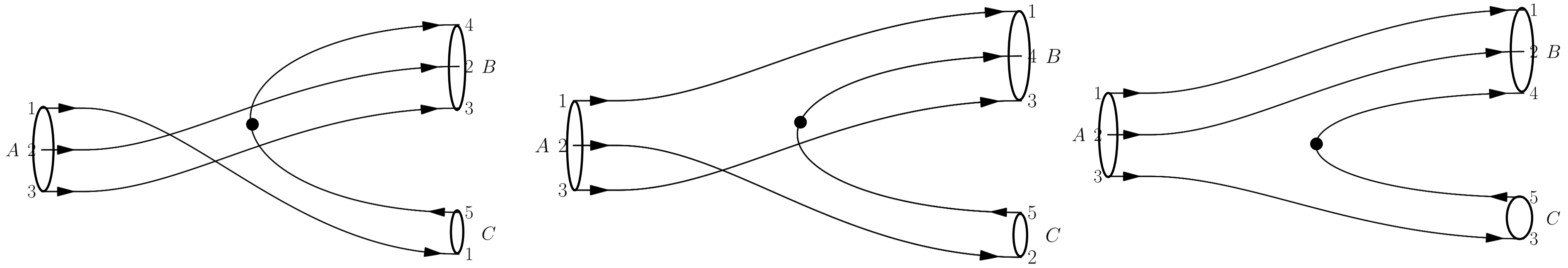
# Theoretical approaches for studying the spectroscopy of singly heavy baryons

**Mass spectrum** **QCD sum rules** **Lattice QCD** **Regge trajectory**

| QCD sum rules | Regge trajectories | Lattice QCD | |
|---|---|---|---|
| X. Liu, H. X. Chen, Y. R. Liu, A. Hosaka and S. L. Zhu, Phys. Rev. D **77**, 014031 (2008)<br>H. X. Chen, Q. Mao, A. Hosaka, X. Liu and S. L. Zhu, Phys. Rev. D **94**, 114016 (2016)<br>H. X. Chen, Q. Mao, W. Chen, A. Hosaka, X. Liu and S. L. Zhu, Phys. Rev. D **95**, 094008 (2017)<br>Z. G. Wang, F. Lu and Y. Liu, Eur. Phys. J. C **83**, 689 (2023)<br>… | D. Ebert, R. N. Faustov and V. O. Galkin, Phys. Rev. D **84**, 014025 (2011)<br>K. Chen, Y. Dong, X. Liu, Q. F. Lu and T. Matsuki, Eur. Phys. J. C **78**, 20 (2018)<br>H. Y. Cheng and C. W. Chiang, Phys. Rev. D **95**, 094018 (2017)<br>Z. Shah, K. Thakkar, A. K. Rai and P. C. Vinodkumar, Chin. Phys. C **40**, 123102 (2016)<br>… | M. Padmanath and N. Mathur, Phys. Rev. Lett. **119**, 042001 (2017)<br>M. Padmanath, R. G. Edwards, N. Mathur and M. Peardon, Phys. Rev. D **91**, 094502 (2015)<br>N. Mathur, R. Lewis and R. M. Woloshyn, Phys. Rev. D **66**, 014502 (2002)<br>… | … |

# 2 Theoretical approaches for studying the spectroscopy of singly heavy baryons

## Decay Strong decay Quark pair creation model



Decay modes

$$\hat{\mathcal{T}} = -3\gamma \sum_{m} \langle 1, m; 1, -m|0, 0\rangle \int \mathrm{d}^3\mathbf{p}_i \mathrm{d}^3\mathbf{p}_j \delta(\mathbf{p}_i + \mathbf{p}_j) \times \mathcal{Y}_1^m\left(\frac{\mathbf{p}_i - \mathbf{p}_j}{2}\right)\omega_0^{(i,j)}\phi_0^{(i,j)}\chi_{-m}^{(i,j)} b_i^\dagger(\mathbf{p}_i) d_j^\dagger(\mathbf{p}_j)$$

$0^{++}$: match the quantum number of amplitude

L. Micu, Nucl. Phys. B10, 521 (1969)

**Amplitude:**

$$\mathcal{M}_{A\to BC}^{J_{BC}L}(p) = \langle BC, J_{BC}L, p|\hat{\mathcal{T}}|A\rangle$$

**Partial width:**

$$\Gamma_{A\to BC}^{J_{BC}L} = 2\pi \frac{E_B(p)E_C(p)p}{M_A}\left|M_{A\to BC}^{J_{BC}L}(p)\right|^2$$

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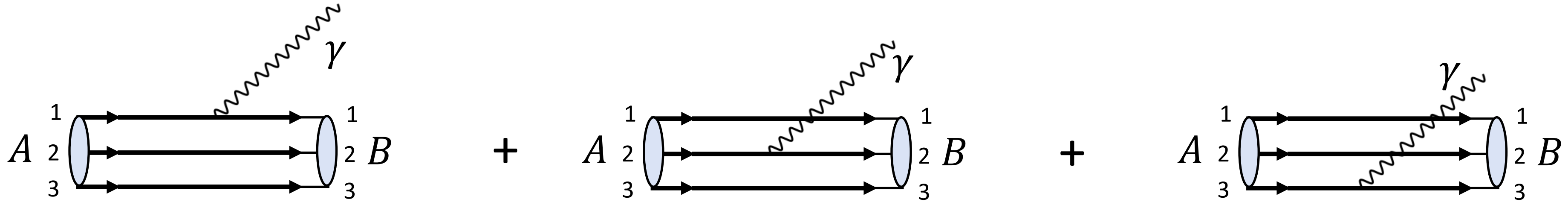
# Theoretical approaches for studying the spectroscopy of singly heavy baryons

**Decay** **Radiative decay**



Radiative decay at quark level

$$H_e = -\sum_j e_j \bar{\psi}_j \gamma_\mu^j A^\mu(\mathbf{k}, \mathbf{r}_j)\psi_j,$$

$$H_e^{nr} = \sum_j \left[ e_j \mathbf{r}_j \cdot \boldsymbol{\epsilon} - \frac{e_j}{2m_j} \boldsymbol{\sigma}_j \cdot (\boldsymbol{\epsilon} \times \hat{\mathbf{k}}) \right] \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{r}_j},$$

$$\begin{aligned}\mathcal{A}_{M_{J_f}M_{J_i}} &= -i\sqrt{\frac{k}{2}}\langle f|H_e^{nr}|i\rangle \\ &= \mathcal{A}^E_{M_{J_f}M_{J_i}} + \mathcal{A}^M_{M_{J_f}M_{J_i}},\end{aligned}$$

$$\mathcal{A}^E_{M_{J_f}M_{J_i}} = -i\sqrt{\frac{k}{2}}\langle f \sum_j \left[ e_j \mathbf{r}_j \cdot \boldsymbol{\epsilon} \right] \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{r}_j}|i\rangle,$$

(E-transition)

$$\mathcal{A}^M_{M_{J_f}M_{J_i}} = -i\sqrt{\frac{k}{2}}\langle f \sum_j \left[ -\frac{e_j}{2m_j} \boldsymbol{\sigma}_j \cdot (\boldsymbol{\epsilon} \times \hat{\mathbf{k}}) \right] \mathrm{e}^{-i\mathbf{k}\cdot\mathbf{r}_j}|i\rangle,$$

(M-transition)

$$\Gamma_\gamma = \frac{k^2}{\pi} \frac{2}{2J_i + 1} \frac{M_f}{M_i} \sum_{M_{J_f} M_{J_i}} |\mathcal{A}_{M_{J_f}M_{J_i}}|^2$$

L. Y. Xiao, K. L. Wang, Q. f. Lu, X. H. Zhong and S. L. Zhu, Phys. Rev. D 96, 094005 (2017)

Q. F. Lu, K. L. Wang, L. Y. Xiao and X. H. Zhong, Phys. Rev. D 96, 114006 (2017)

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K. L. Wang, Y. X. Yao, X. H. Zhong and Q. Zhao, Phys. Rev. D 96, 116016 (2017)

Y. X. Yao, K. L. Wang and X. H. Zhong, Phys. Rev. D 98, 076015 (2018)

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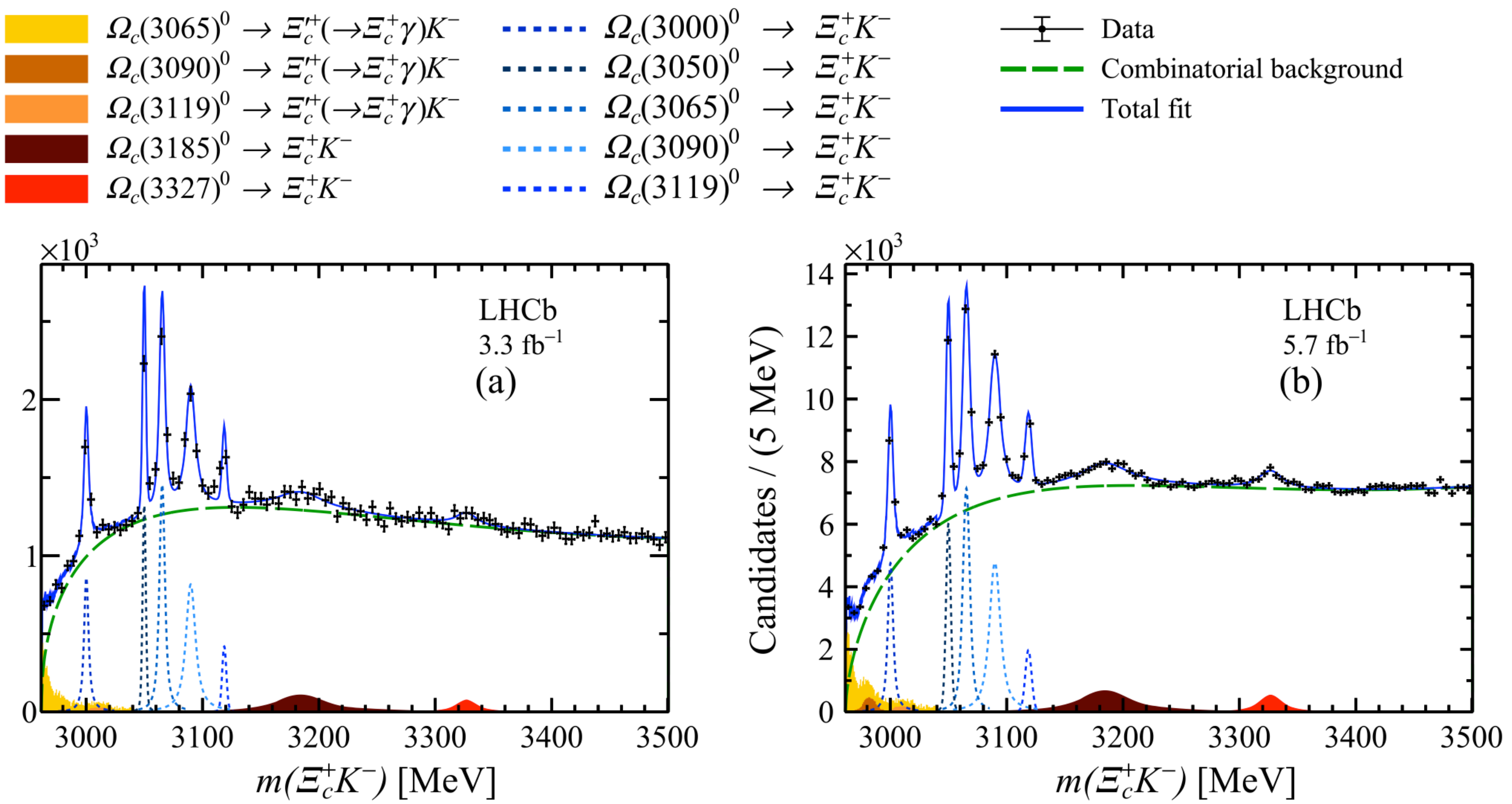
# Recent progresses on single heavy baryons

PHYSICAL REVIEW LETTERS **131,** 131902 (2023)

**Editors' Suggestion**

## Observation of New $\Omega_c^0$ States Decaying to the $\Xi_c^+ K^-$ Final State

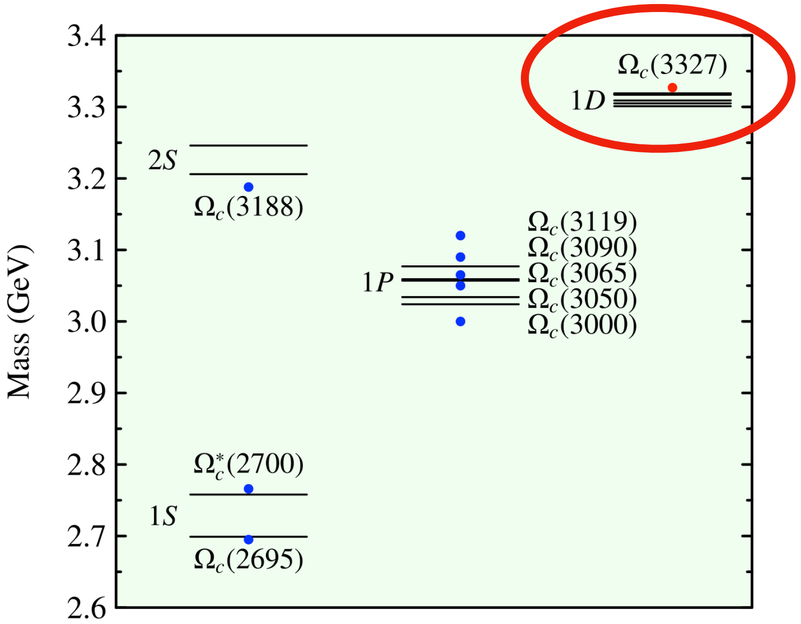
R. Aaij *et al.*[*]
(LHCb Collaboration)



| Resonance | $m$ (MeV) | $\Gamma$ (MeV) |
|---|---|---|
| $\Omega_c(3000)^0$ | $3000.44 \pm 0.07$ | $3.83 \pm 0.23$ |
| $\Omega_c(3050)^0$ | $3050.18 \pm 0.04$ | $0.67 \pm 0.17$ |
| $\Omega_c(3065)^0$ | $3065.63 \pm 0.06$ | $3.79 \pm 0.20$ |
| $\Omega_c(3090)^0$ | $3090.16 \pm 0.11$ | $8.48 \pm 0.44$ |
| $\Omega_c(3119)^0$ | $3118.98 \pm 0.12$ | $0.60 \pm 0.63$ |
| $\Omega_c(3185)^0$ | $3185.1 \pm 1.7$ | $50 \pm 7$ |
| $\Omega_c(3327)^0$ | $3327.1 \pm 1.2$ | $20 \pm 5$ |

$\Omega_c(3327)$

# Decoding the properties of $\Omega_c(3327)$: Mass+Strong decay



**$\Omega_c(3327)$ is a good candidate for 1D state of charm baryon family**

**S.Q. Luo and X. Liu, Phys. Rev. D 107, 074041 (2023)**

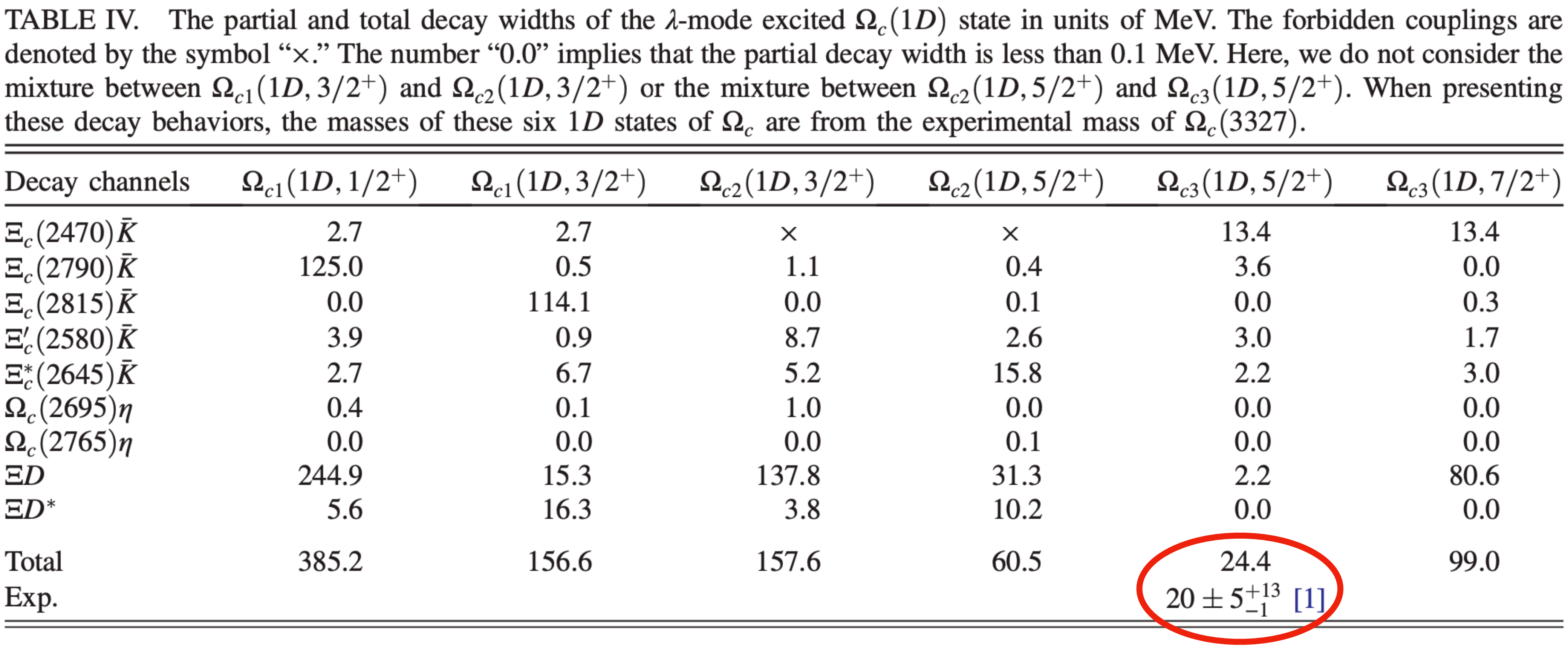


TABLE IV. The partial and total decay widths of the $\lambda$-mode excited $\Omega_c(1D)$ state in units of MeV. The forbidden couplings are denoted by the symbol "×." The number "0.0" implies that the partial decay width is less than 0.1 MeV. Here, we do not consider the mixture between $\Omega_{c1}(1D, 3/2^+)$ and $\Omega_{c2}(1D, 3/2^+)$ or the mixture between $\Omega_{c2}(1D, 5/2^+)$ and $\Omega_{c3}(1D, 5/2^+)$. When presenting these decay behaviors, the masses of these six $1D$ states of $\Omega_c$ are from the experimental mass of $\Omega_c(3327)$.

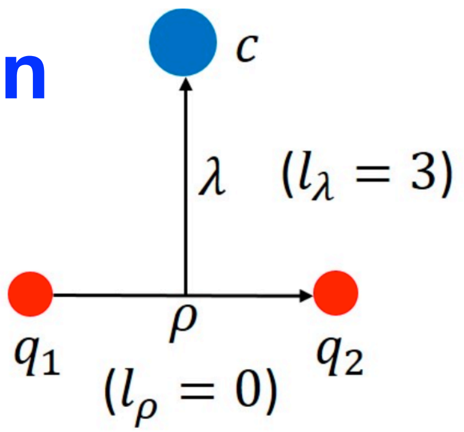
| Decay channels | $\Omega_{c1}(1D, 1/2^+)$ | $\Omega_{c1}(1D, 3/2^+)$ | $\Omega_{c2}(1D, 3/2^+)$ | $\Omega_{c2}(1D, 5/2^+)$ | $\Omega_{c3}(1D, 5/2^+)$ | $\Omega_{c3}(1D, 7/2^+)$ |
|---|---|---|---|---|---|---|
| $\Xi_c(2470)\bar{K}$ | 2.7 | 2.7 | × | × | 13.4 | 13.4 |
| $\Xi_c(2790)\bar{K}$ | 125.0 | 0.5 | 1.1 | 0.4 | 3.6 | 0.0 |
| $\Xi_c(2815)\bar{K}$ | 0.0 | 114.1 | 0.0 | 0.1 | 0.0 | 0.3 |
| $\Xi_c'(2580)\bar{K}$ | 3.9 | 0.9 | 8.7 | 2.6 | 3.0 | 1.7 |
| $\Xi_c^*(2645)\bar{K}$ | 2.7 | 6.7 | 5.2 | 15.8 | 2.2 | 3.0 |
| $\Omega_c(2695)\eta$ | 0.4 | 0.1 | 1.0 | 0.0 | 0.0 | 0.0 |
| $\Omega_c(2765)\eta$ | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 |
| $\Xi D$ | 244.9 | 15.3 | 137.8 | 31.3 | 2.2 | 80.6 |
| $\Xi D^*$ | 5.6 | 16.3 | 3.8 | 10.2 | 0.0 | 0.0 |
| Total | 385.2 | 156.6 | 157.6 | 60.5 | 24.4 | 99.0 |
| Exp. | | | | | $20 \pm 5^{+13}_{-1}$ [1] | |

# Recent progresses on single heavy baryons

## Why are we interested in the 1F state of the singly heavy baryon?

- Well established 1S states
- More and more candidates for 1P states
- Some candidates for 1D, 2S, 2P states
- **1F states are still missing**
- **Test phenomenological mode applied to depict low-lying states**

**$\lambda$-mode excitation**



S.Q. Luo and X. Liu, Phys. Rev. D 108, 034002 (2023)

| Symmetry | States | $J$ | $s_\ell$ | $l_\rho$ | $l_\lambda$ | $L$ | $j_\ell$ |
|---|---|---|---|---|---|---|---|
| $\bar{3}_f$ | $\Lambda_c/\Xi_c(nF, 5/2^-)$ | $\frac{5}{2}$ | 0 | 0 | 3 | 3 | 3 |
| | $\Lambda_c/\Xi_c(nF, 7/2^-)$ | $\frac{7}{2}$ | 0 | 0 | 3 | 3 | 3 |
| $6_f$ | $\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(nF, 3/2^-)$ | $\frac{3}{2}$ | 1 | 0 | 3 | 3 | 2 |
| | $\Sigma_{c2}/\Xi'_{c2}/\Omega_{c2}(nF, 5/2^-)$ | $\frac{5}{2}$ | 1 | 0 | 3 | 3 | 2 |
| | $\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(nF, 5/2^-)$ | $\frac{5}{2}$ | 1 | 0 | 3 | 3 | 3 |
| | $\Sigma_{c3}/\Xi'_{c3}/\Omega_{c3}(nF, 7/2^-)$ | $\frac{7}{2}$ | 1 | 0 | 3 | 3 | 3 |
| | $\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(nF, 7/2^-)$ | $\frac{7}{2}$ | 1 | 0 | 3 | 3 | 4 |
| | $\Sigma_{c4}/\Xi'_{c4}/\Omega_{c4}(nF, 9/2^-)$ | $\frac{9}{2}$ | 1 | 0 | 3 | 3 | 4 |

# Recent progresses on single heavy baryons

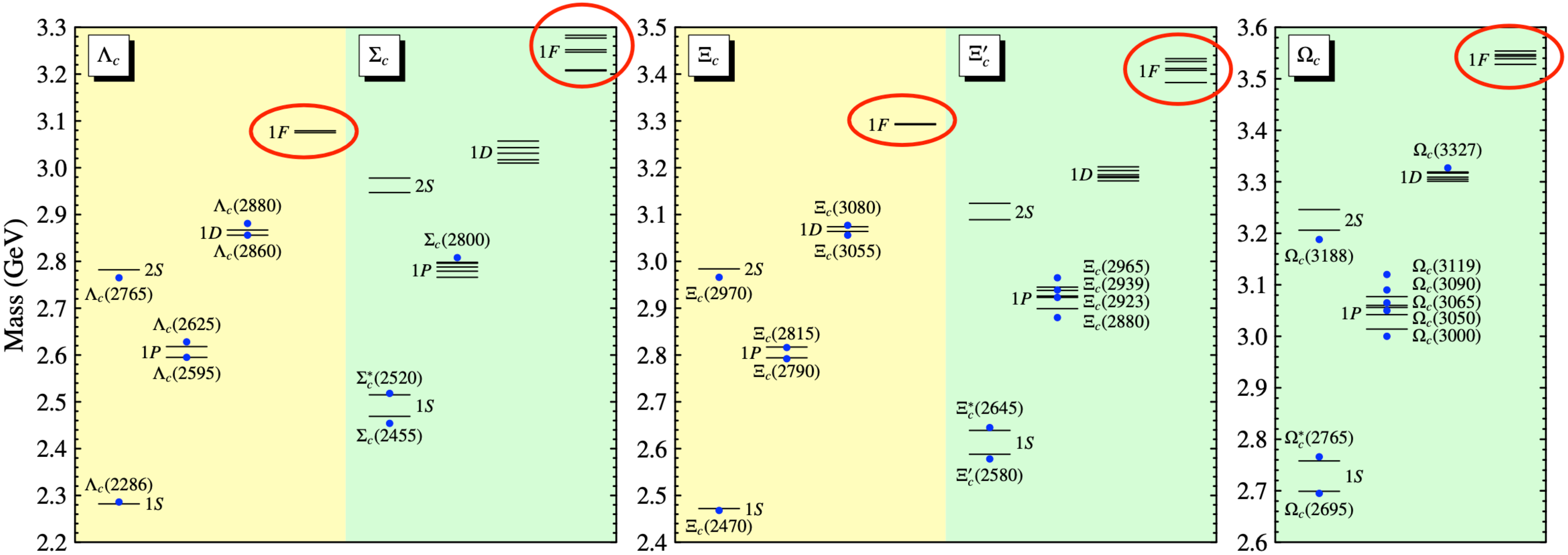
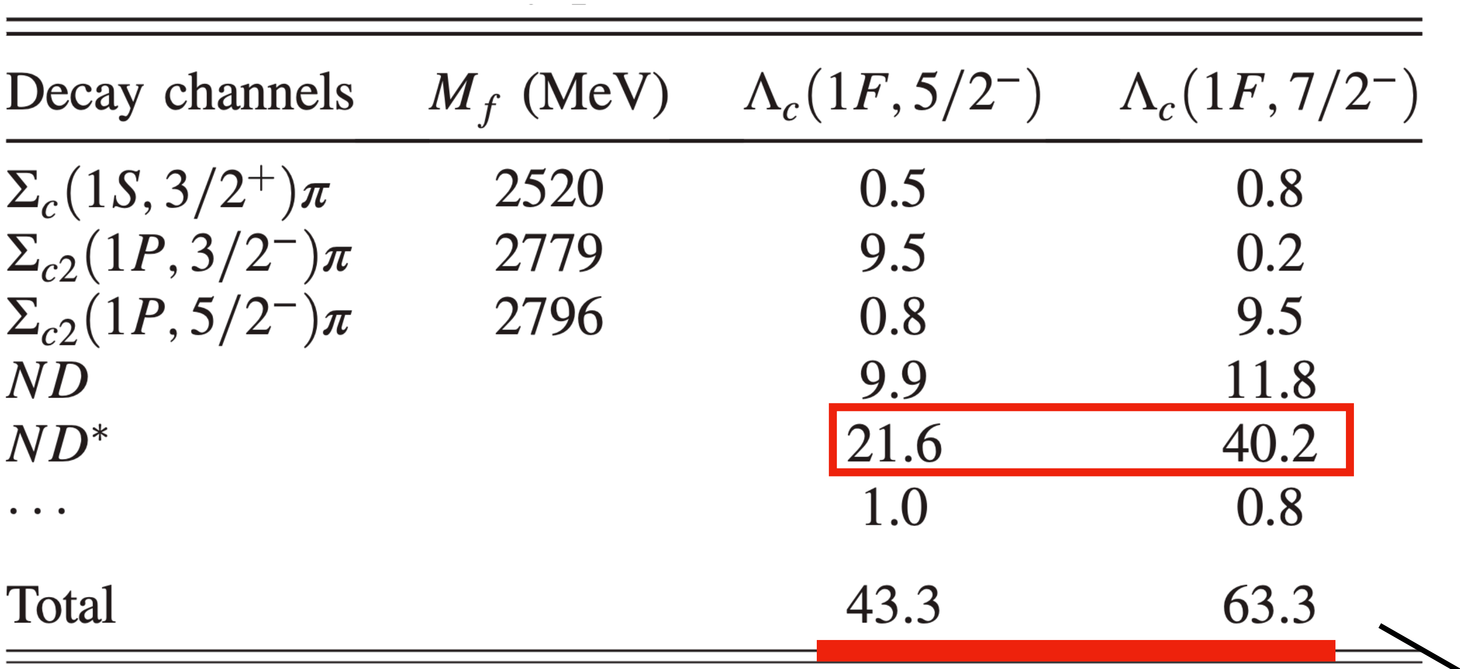


TABLE III. A comparison of predicted masses for $F$-wave singly charmed baryons from various studies. Here, the listed masses are in units of MeV.

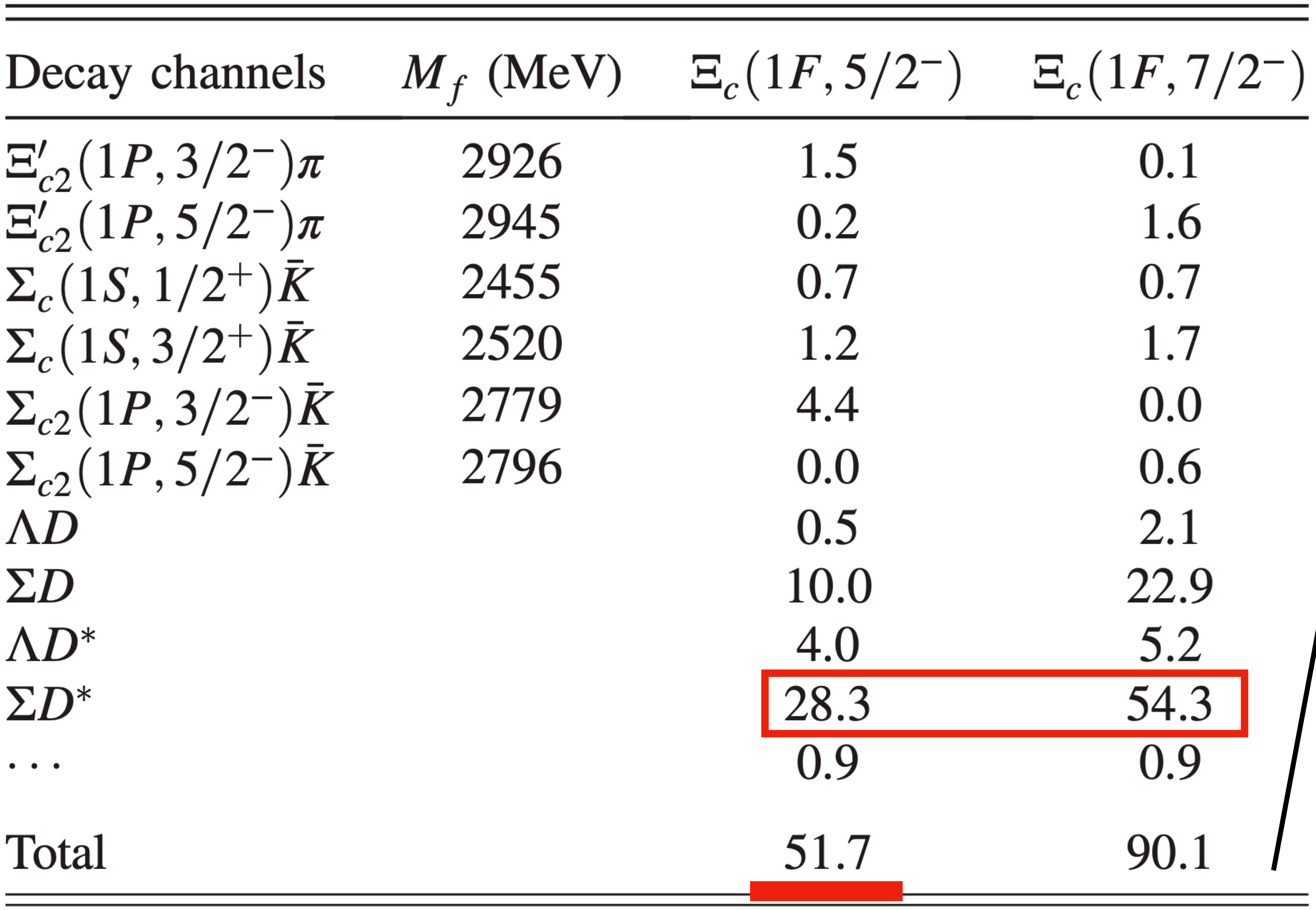
| States | Our | Ref. [81] | Ref. [80] | States | Our | Ref. [81] | Ref. [82] | States | Our | Ref. [81] | Ref. [80] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\Lambda_c(1F,5/2^-)$ | 3075 | 3097 | 3104 | $\Xi_c(1F,5/2^-)$ | 3292 | 3278 | 3289 | | | | |
| $\Lambda_c(1F,7/2^-)$ | 3079 | 3078 | 3111 | $\Xi_c(1F,7/2^-)$ | 3295 | 3292 | 3294 | | | | |
| $\Sigma_{c2}(1F,3/2^-)$ | 3276 | 3288 | 3299 | $\Xi'_{c2}(1F,3/2^-)$ | 3427 | 3418 | 3424 | $\Omega_{c2}(1F,3/2^-)$ | 3540 | 3533 | 3525 |
| $\Sigma_{c2}(1F,5/2^-)$ | 3283 | 3254 | 3304 | $\Xi'_{c2}(1F,3/2^-)$ | 3433 | 3394 | 3428 | $\Omega_{c2}(1F,5/2^-)$ | 3547 | 3515 | 3528 |
| $\Sigma_{c3}(1F,5/2^-)$ | 3247 | 3283 | 3299 | $\Xi'_{c3}(1F,3/2^-)$ | 3408 | 3408 | 3424 | $\Omega_{c3}(1F,5/2^-)$ | 3532 | 3522 | 3525 |
| $\Sigma_{c3}(1F,7/2^-)$ | 3252 | 3227 | 3305 | $\Xi'_{c3}(1F,3/2^-)$ | 3412 | 3373 | 3428 | $\Omega_{c3}(1F,7/2^-)$ | 3537 | 3498 | 3529 |
| $\Sigma_{c4}(1F,7/2^-)$ | 3207 | 3253 | 3299 | $\Xi'_{c4}(1F,3/2^-)$ | 3382 | 3393 | 3423 | $\Omega_{c4}(1F,7/2^-)$ | 3521 | 3514 | 3524 |
| $\Sigma_{c4}(1F,9/2^-)$ | 3209 | 3209 | 3305 | $\Xi'_{c4}(1F,3/2^-)$ | 3383 | 3357 | 3428 | $\Omega_{c4}(1F,9/2^-)$ | 3520 | 3485 | 3529 |

**S.Q. Luo and X. Liu, Phys. Rev. D 108, 034002 (2023)**

# 3 Recent progresses on single heavy baryons



| Decay channels | $M_f$ (MeV) | $\Lambda_c(1F,5/2^-)$ | $\Lambda_c(1F,7/2^-)$ |
|---|---|---|---|
| $\Sigma_c(1S,3/2^+)\pi$ | 2520 | 0.5 | 0.8 |
| $\Sigma_{c2}(1P,3/2^-)\pi$ | 2779 | 9.5 | 0.2 |
| $\Sigma_{c2}(1P,5/2^-)\pi$ | 2796 | 0.8 | 9.5 |
| $ND$ | | 9.9 | 11.8 |
| $ND^*$ | | 21.6 | 40.2 |
| $\cdots$ | | 1.0 | 0.8 |
| Total | | 43.3 | 63.3 |



| Decay channels | $M_f$ (MeV) | $\Xi_c(1F,5/2^-)$ | $\Xi_c(1F,7/2^-)$ |
|---|---|---|---|
| $\Xi'_{c2}(1P,3/2^-)\pi$ | 2926 | 1.5 | 0.1 |
| $\Xi'_{c2}(1P,5/2^-)\pi$ | 2945 | 0.2 | 1.6 |
| $\Sigma_c(1S,1/2^+)\bar{K}$ | 2455 | 0.7 | 0.7 |
| $\Sigma_c(1S,3/2^+)\bar{K}$ | 2520 | 1.2 | 1.7 |
| $\Sigma_{c2}(1P,3/2^-)\bar{K}$ | 2779 | 4.4 | 0.0 |
| $\Sigma_{c2}(1P,5/2^-)\bar{K}$ | 2796 | 0.0 | 0.6 |
| $\Lambda D$ | | 0.5 | 2.1 |
| $\Sigma D$ | | 10.0 | 22.9 |
| $\Lambda D^*$ | | 4.0 | 5.2 |
| $\Sigma D^*$ | | 28.3 | 54.3 |
| $\cdots$ | | 0.9 | 0.9 |
| Total | | 51.7 | 90.1 |

**Some typical OZI-allowed strong decays of $\bar{3}_f$ states**

$$BR[\Lambda_c(1F,5/2^-) \to ND^*] = 49.9\,\%$$

$$BR[\Lambda_c(1F,7/2^-) \to ND^*] = 63.5.9\,\%$$

**Width is not so broad**

$$BR[\Xi_c(1F,5/2^-) \to \Sigma D^*] = 54.7\,\%$$

$$BR[\Xi_c(1F,7/2^-) \to \Sigma D^*] = 60.2\,\%$$

Searching for these states can be accessible at experiment

**S.Q. Luo and X. Liu, Phys. Rev. D 108, 034002 (2023)**

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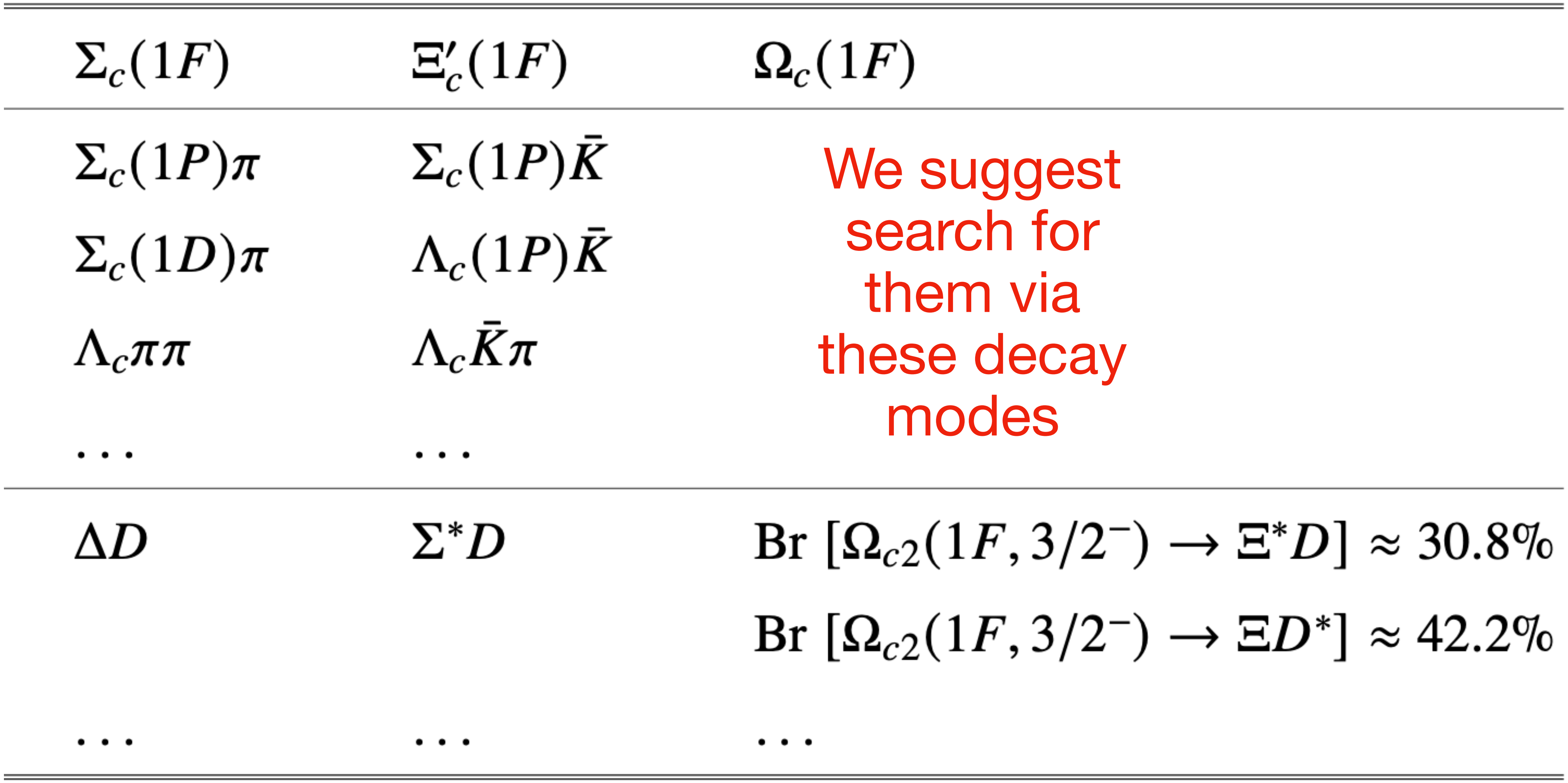
# Recent progresses on single heavy baryons

## Some typical OZI-allowed strong decays of $6_f$ states

More decay channels are open, making decay more complicated

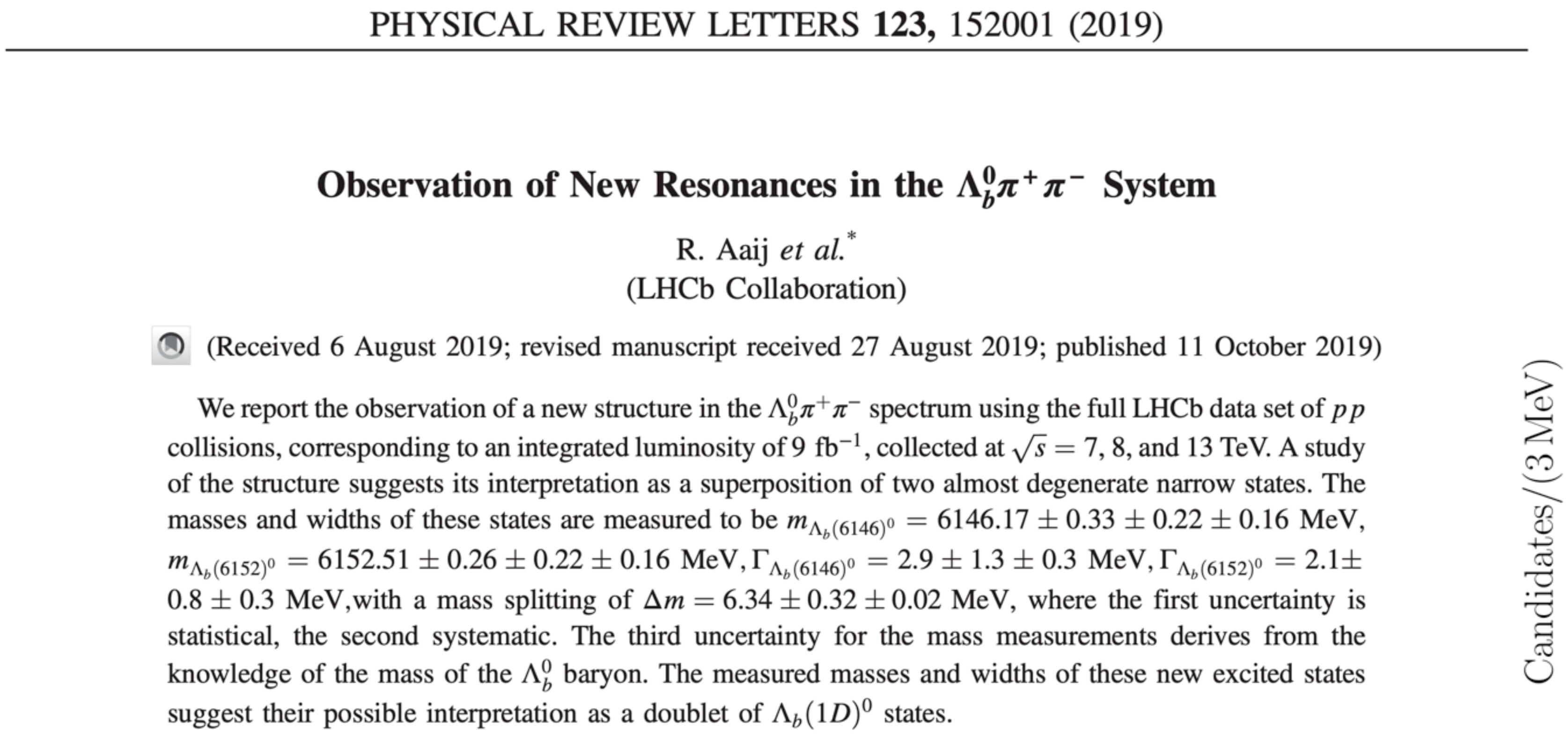


| $\Sigma_c(1F)$ | $\Xi'_c(1F)$ | $\Omega_c(1F)$ |
|---|---|---|
| $\Sigma_c(1P)\pi$ | $\Sigma_c(1P)\bar{K}$ | |
| $\Sigma_c(1D)\pi$ | $\Lambda_c(1P)\bar{K}$ | |
| $\Lambda_c\pi\pi$ | $\Lambda_c\bar{K}\pi$ | |
| $\ldots$ | $\ldots$ | |
| $\Delta D$ | $\Sigma^* D$ | $\mathrm{Br}\,[\Omega_{c2}(1F, 3/2^-) \to \Xi^* D] \approx 30.8\%$ |
| | | $\mathrm{Br}\,[\Omega_{c2}(1F, 3/2^-) \to \Xi D^*] \approx 42.2\%$ |
| $\ldots$ | $\ldots$ | $\ldots$ |

We suggest search for them via these decay modes

S.Q. Luo and X. Liu, Phys. Rev. D 108, 034002 (2023)

# Recent progresses on single heavy baryons



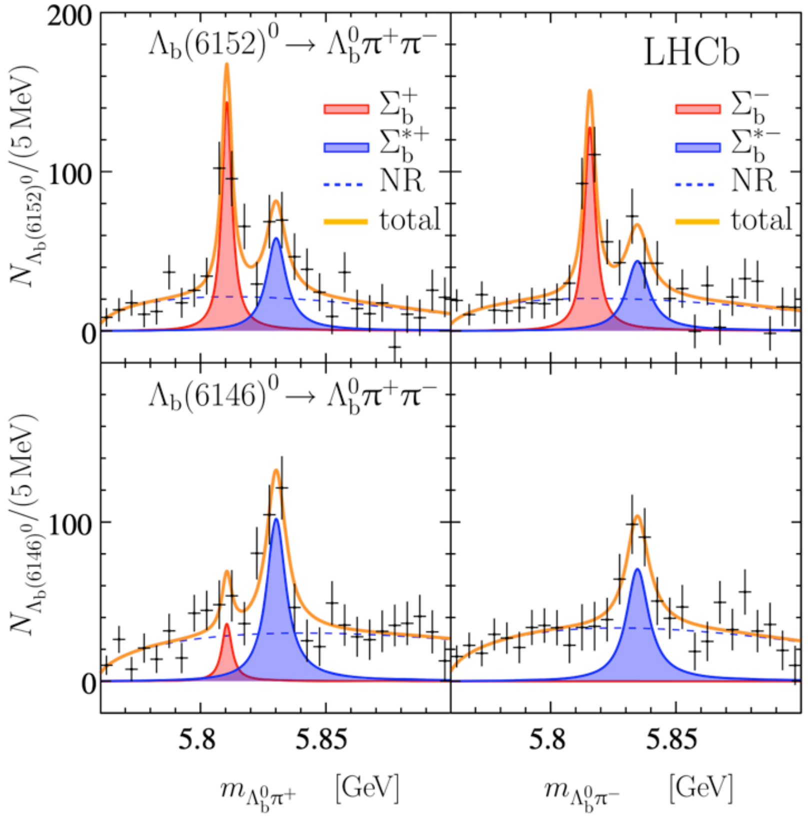
PHYSICAL REVIEW LETTERS **123**, 152001 (2019)

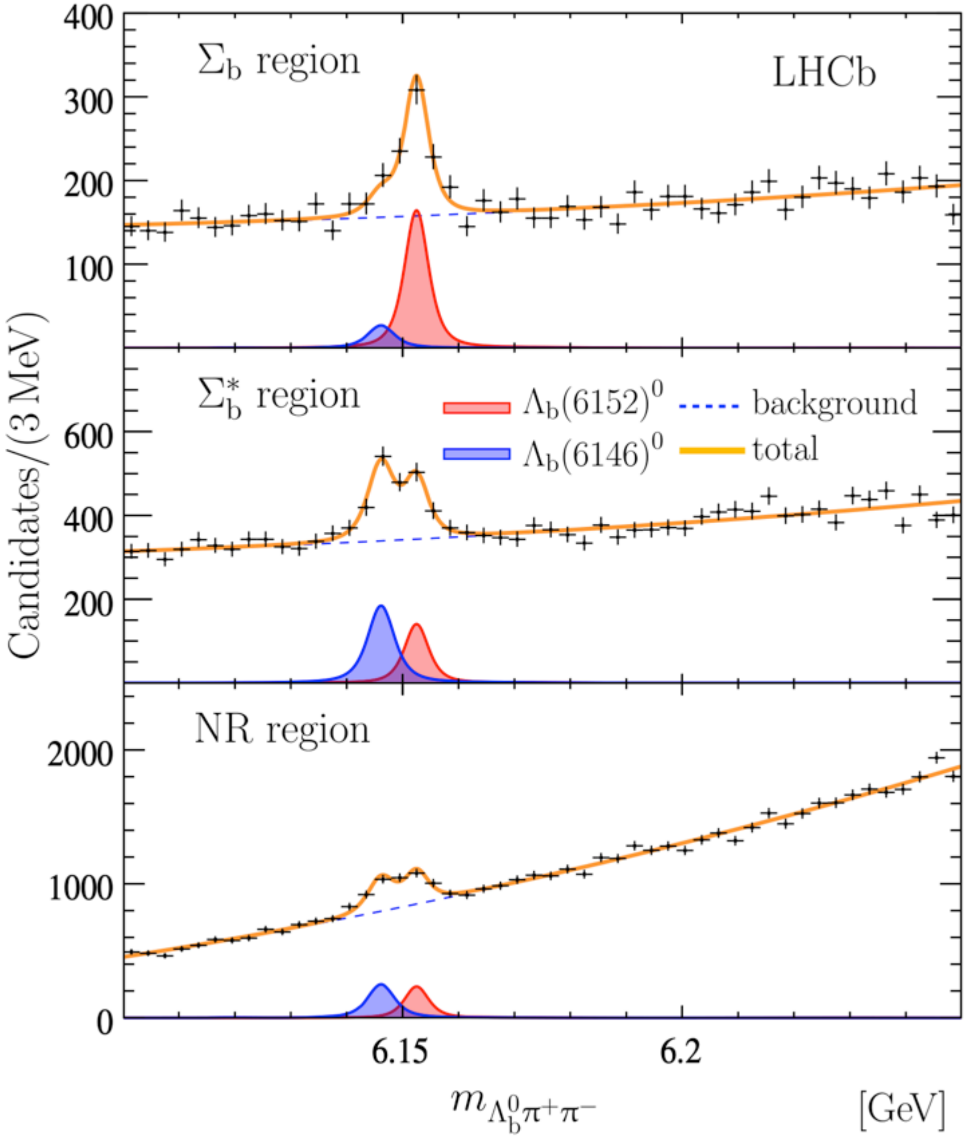
### Observation of New Resonances in the $\Lambda_b^0\pi^+\pi^-$ System

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 August 2019; revised manuscript received 27 August 2019; published 11 October 2019)

We report the observation of a new structure in the $\Lambda_b^0\pi^+\pi^-$ spectrum using the full LHCb data set of $pp$ collisions, corresponding to an integrated luminosity of 9 $\mathrm{fb}^{-1}$, collected at $\sqrt{s} = 7$, 8, and 13 TeV. A study of the structure suggests its interpretation as a superposition of two almost degenerate narrow states. The masses and widths of these states are measured to be $m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16$ MeV, $m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16$ MeV, $\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3$ MeV, $\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3$ MeV,with a mass splitting of $\Delta m = 6.34 \pm 0.32 \pm 0.02$ MeV, where the first uncertainty is statistical, the second systematic. The third uncertainty for the mass measurements derives from the knowledge of the mass of the $\Lambda_b^0$ baryon. The measured masses and widths of these new excited states suggest their possible interpretation as a doublet of $\Lambda_b(1D)^0$ states.





$$m_{\Lambda_b(6146)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16\ \mathrm{MeV},$$
$$m_{\Lambda_b(6152)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16\ \mathrm{MeV},$$
$$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3\ \mathrm{MeV},$$
$$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3\ \mathrm{MeV},$$

$\Lambda_b(6146)$

$\Lambda_b(6152)$

# Recent progresses on single heavy baryons

B. Chen, S.Q. Luo, X. Liu, T. Matsuki, Phys. Rev. D.100, 094032 (2019)

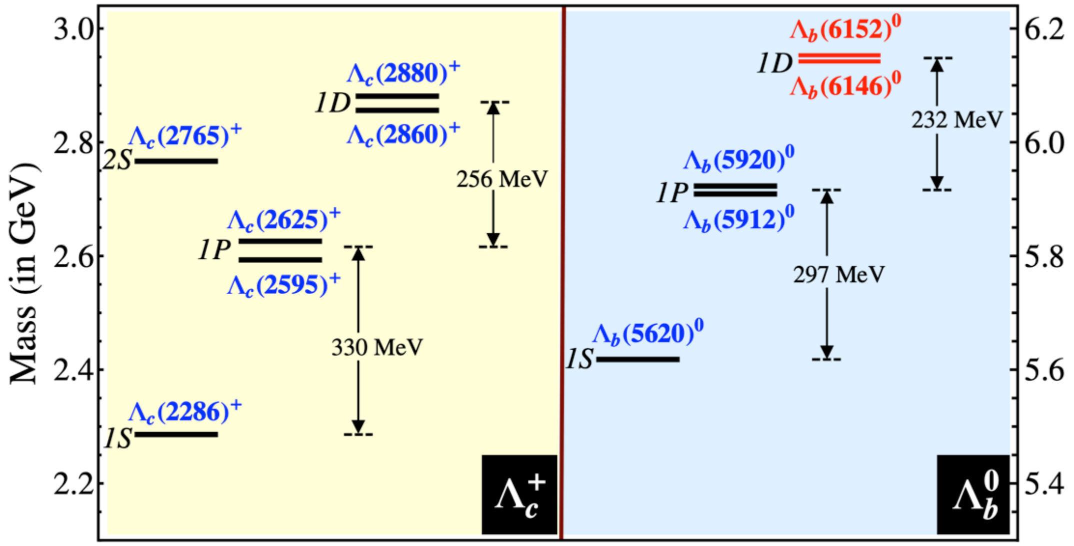


FIG. 2. The established $\Lambda_c^+$ and $\Lambda_b^0$ states and the newly observed $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$.

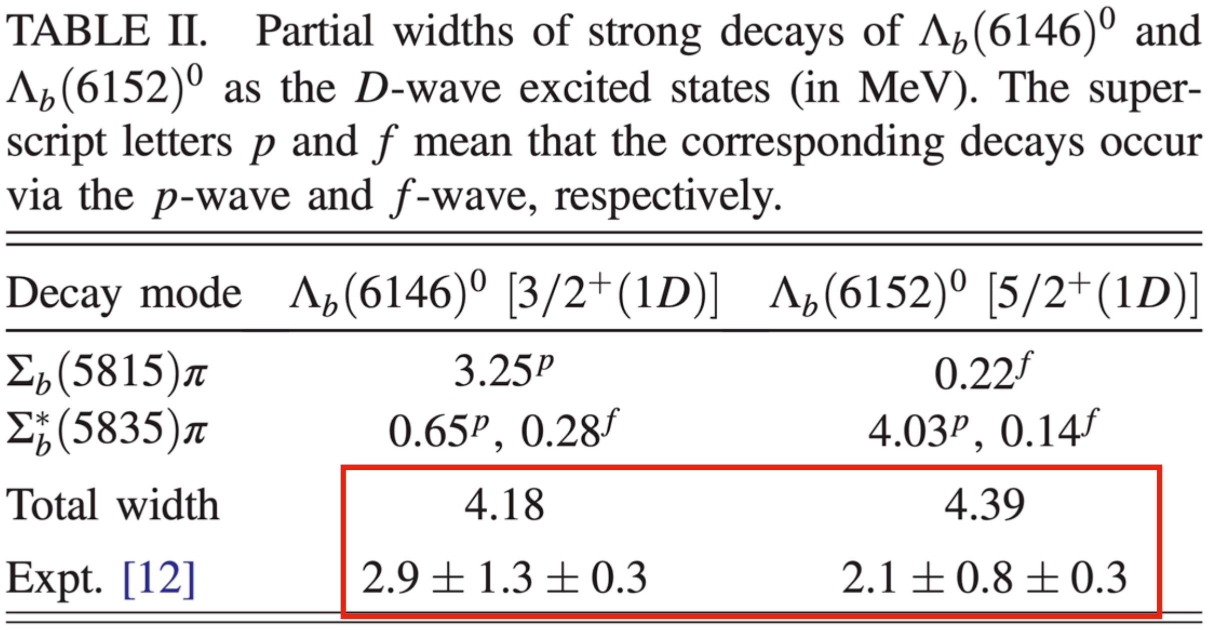


TABLE II. Partial widths of strong decays of $\Lambda_b(6146)^0$ and $\Lambda_b(6152)^0$ as the $D$-wave excited states (in MeV). The superscript letters $p$ and $f$ mean that the corresponding decays occur via the $p$-wave and $f$-wave, respectively.

| Decay mode | $\Lambda_b(6146)^0$ $[3/2^+(1D)]$ | $\Lambda_b(6152)^0$ $[5/2^+(1D)]$ |
|---|---|---|
| $\Sigma_b(5815)\pi$ | $3.25^p$ | $0.22^f$ |
| $\Sigma_b^*(5835)\pi$ | $0.65^p$, $0.28^f$ | $4.03^p$, $0.14^f$ |
| Total width | 4.18 | 4.39 |
| Expt. [12] | $2.9 \pm 1.3 \pm 0.3$ | $2.1 \pm 0.8 \pm 0.3$ |

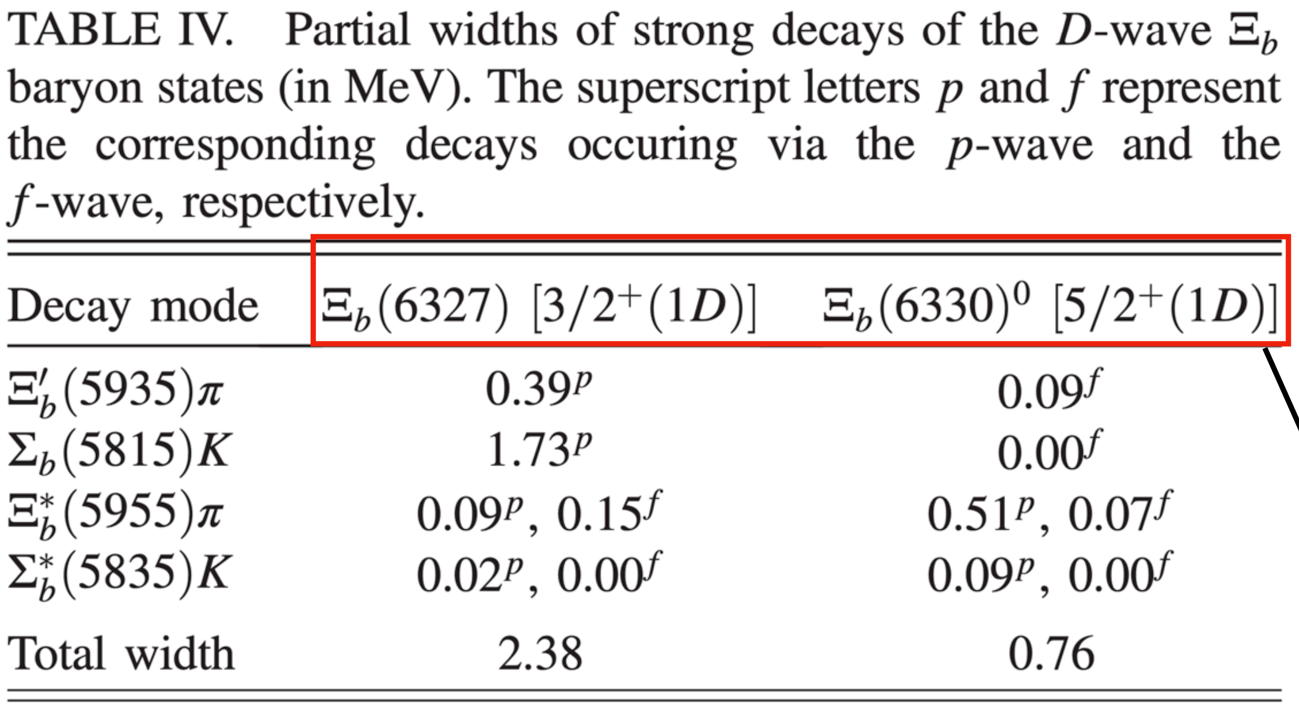
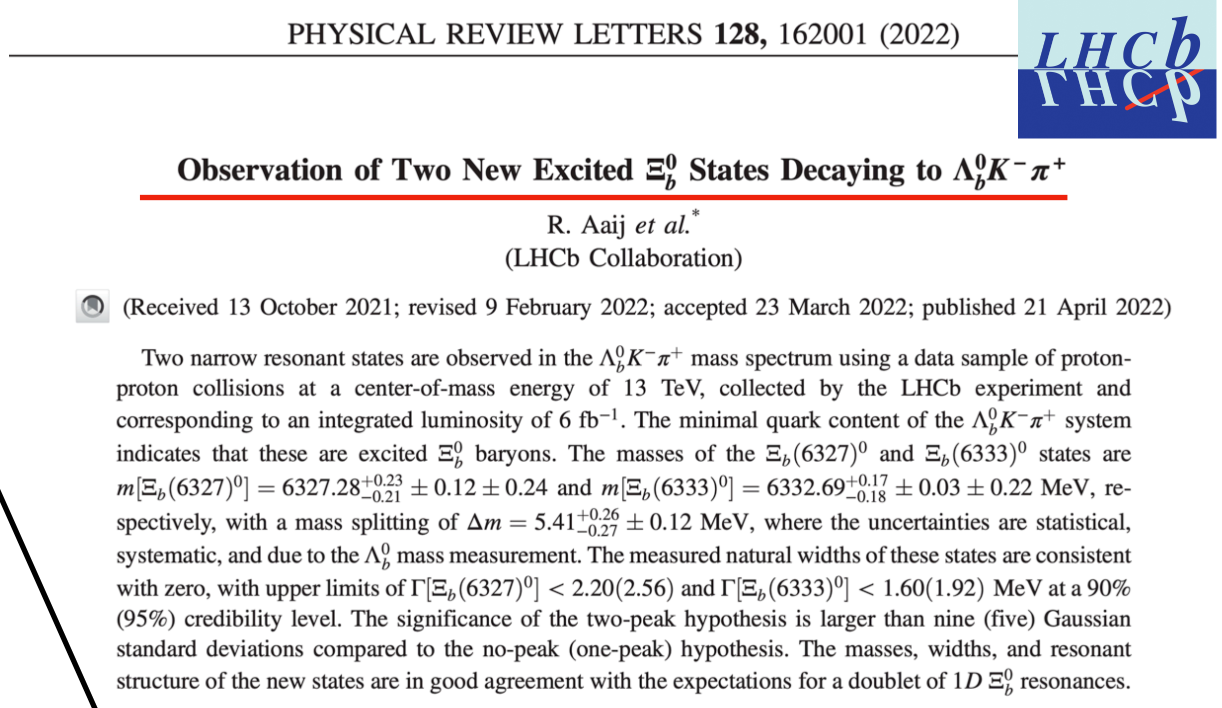


TABLE IV. Partial widths of strong decays of the $D$-wave $\Xi_b$ baryon states (in MeV). The superscript letters $p$ and $f$ represent the corresponding decays occuring via the $p$-wave and the $f$-wave, respectively.

| Decay mode | $\Xi_b(6327)$ $[3/2^+(1D)]$ | $\Xi_b(6330)^0$ $[5/2^+(1D)]$ |
|---|---|---|
| $\Xi_b'(5935)\pi$ | $0.39^p$ | $0.09^f$ |
| $\Sigma_b(5815)K$ | $1.73^p$ | $0.00^f$ |
| $\Xi_b^*(5955)\pi$ | $0.09^p$, $0.15^f$ | $0.51^p$, $0.07^f$ |
| $\Sigma_b^*(5835)K$ | $0.02^p$, $0.00^f$ | $0.09^p$, $0.00^f$ |
| Total width | 2.38 | 0.76 |



PHYSICAL REVIEW LETTERS **128,** 162001 (2022)

LHCb

**Observation of Two New Excited $\Xi_b^0$ States Decaying to $\Lambda_b^0 K^- \pi^+$**

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 13 October 2021; revised 9 February 2022; accepted 23 March 2022; published 21 April 2022)

Two narrow resonant states are observed in the $\Lambda_b^0 K^- \pi^+$ mass spectrum using a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the LHCb experiment and corresponding to an integrated luminosity of 6 fb$^{-1}$. The minimal quark content of the $\Lambda_b^0 K^- \pi^+$ system indicates that these are excited $\Xi_b^0$ baryons. The masses of the $\Xi_b(6327)^0$ and $\Xi_b(6333)^0$ states are $m[\Xi_b(6327)^0] = 6327.28^{+0.23}_{-0.21} \pm 0.12 \pm 0.24$ and $m[\Xi_b(6333)^0] = 6332.69^{+0.17}_{-0.18} \pm 0.03 \pm 0.22$ MeV, respectively, with a mass splitting of $\Delta m = 5.41^{+0.26}_{-0.27} \pm 0.12$ MeV, where the uncertainties are statistical, systematic, and due to the $\Lambda_b^0$ mass measurement. The measured natural widths of these states are consistent with zero, with upper limits of $\Gamma[\Xi_b(6327)^0] < 2.20(2.56)$ and $\Gamma[\Xi_b(6333)^0] < 1.60(1.92)$ MeV at a 90% (95%) credibility level. The significance of the two-peak hypothesis is larger than nine (five) Gaussian standard deviations compared to the no-peak (one-peak) hypothesis. The masses, widths, and resonant structure of the new states are in good agreement with the expectations for a doublet of $1D$ $\Xi_b^0$ resonances.

**Confirmed by LHCb**

# Recent progresses on single heavy baryons

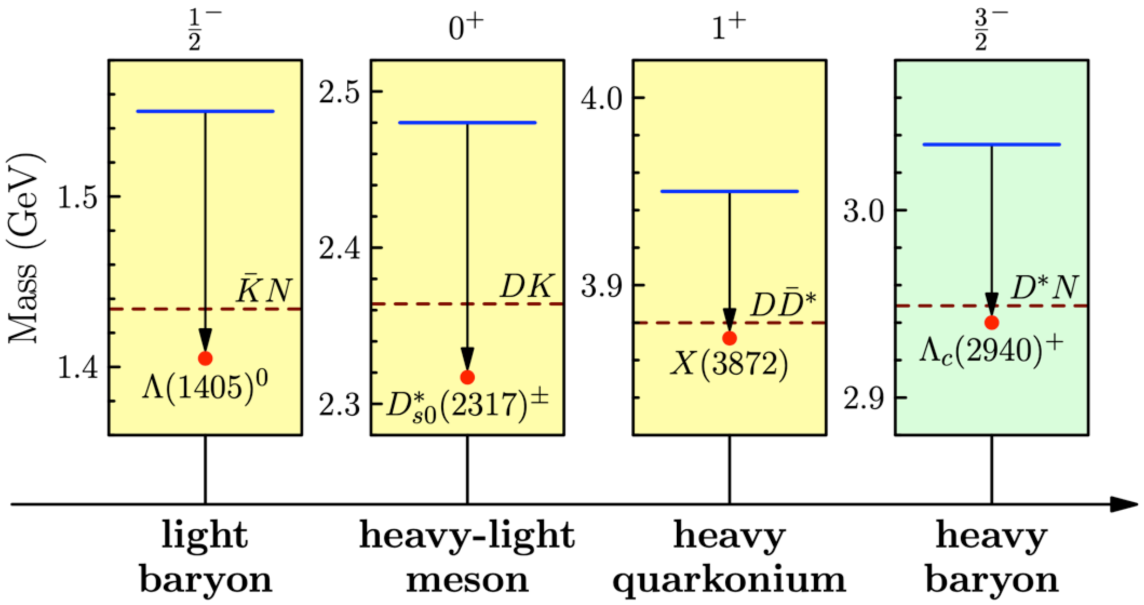
Eur. Phys. J. C (2020) 80:301
https://doi.org/10.1140/epjc/s10052-020-7874-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

## Resolving the low mass puzzle of $\Lambda_c(2940)^+$

Si-Qiang Luo[1,3,a], Bing Chen[2,3,b], Zhan-Wei Liu[1,3,c], Xiang Liu[1,3,d]



**Introducing unquenched effect to solve the mass puzzle**

$$M - M_0 - \Delta M(M) = 0,$$

$$\Delta M(M) = \mathrm{Re}\int_0^\infty dq\, q^2 \frac{\left|\mathcal{M}^{\Lambda_c^{\mathrm{bare}}(2P,3/2^-)\to D^*N}(q)\right|^2}{M - E_{D^*N}(\mathbf{q})}$$

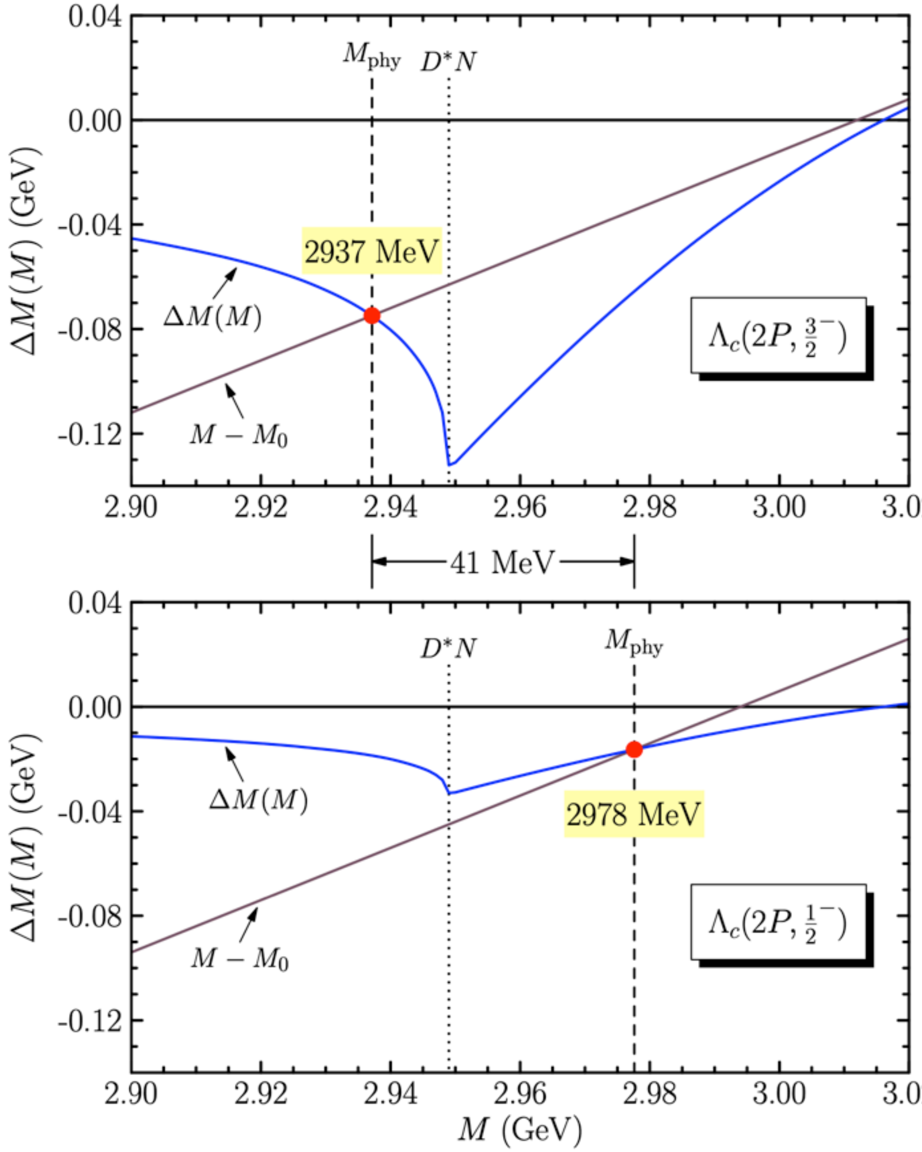


**Fig. 2** The dependence of functions $M - M_0$ and $\Delta M(M)$ on $M$ for $\Lambda_c(2P, 3/2^-)$ (up) and $\Lambda_c(2P, 1/2^-)$ (down). Here, the $M_{\mathrm{phy}}$ values correspond to the red points of the intersections of two lines are physical masses of the $\Lambda_c(3/2^-, 2P)$ (up) and $\Lambda_c(1/2^-, 2P)$ (down) states. The gap between the two subgraphs represents that the physical mass of $\Lambda_c(2P, 1/2^-)$ is 41 MeV higher than that of $\Lambda_c(2P, 3/2^-)$

# 3 Recent progresses on single heavy baryons

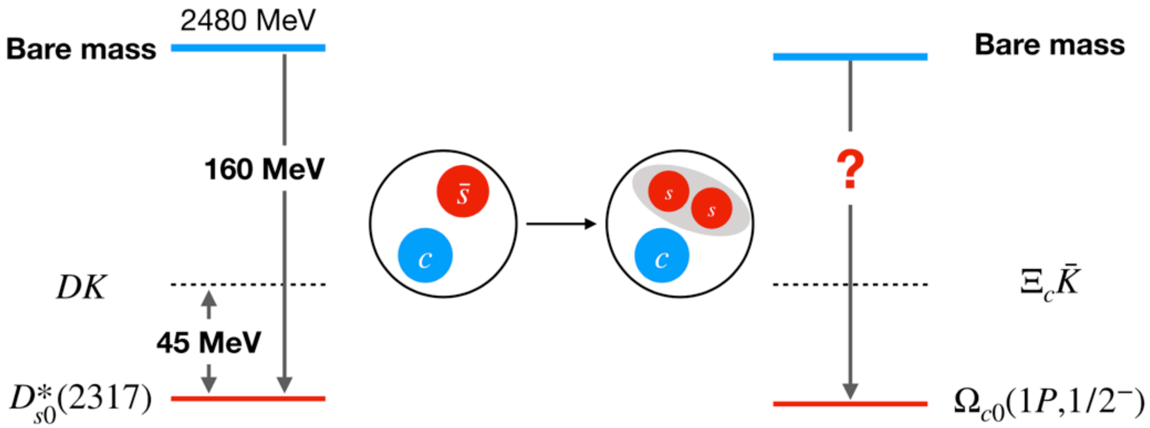
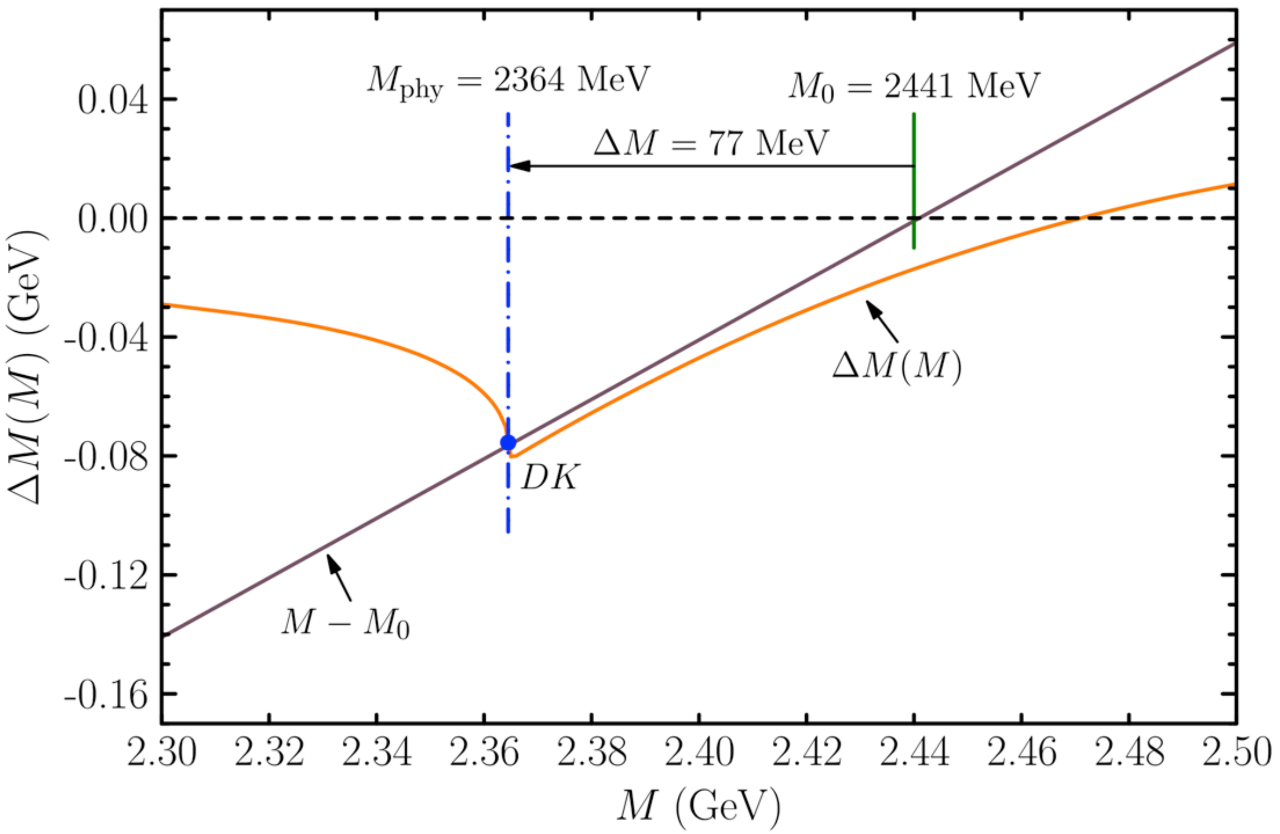
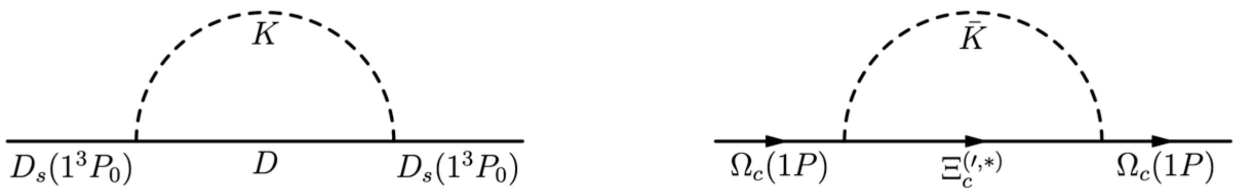


FIG. 1. The similarity between $D_{s0}^*(2317)$ and $\Omega_{c0}(1P,1/2^-)$. The predicted bare mass of $D_s$ meson is taken from the GI model [12,13]. The dashed lines represent $DK$ threshold (left) and $\Xi_c\bar{K}$ threshold (right).





$$\begin{pmatrix} M^{j_\ell=0} & \tilde{V}^{\rm spin} & \int p^2{\rm d}p\langle\Omega_{c0}|\hat{H}_I|\Xi_c\bar{K}\rangle & 0 \\ \tilde{V}^{\rm spin} & M^{j_\ell=1} & 0 & \int p^2{\rm d}p\langle\Omega_{c1}|\hat{H}_I|\Xi_c'\bar{K}\rangle \\ \langle\Xi_c\bar{K}|\hat{H}_I|\Omega_{c0}\rangle & 0 & H_{\Xi_c\bar{K}} & 0 \\ 0 & \langle\Xi_c'\bar{K}|\hat{H}_I|\Omega_{c1}\rangle & 0 & H_{\Xi_c'\bar{K}} \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \\ c_{\Xi_c\bar{K}} \\ c_{\Xi_c'\bar{K}} \end{pmatrix} = M \begin{pmatrix} c_0 \\ c_1 \\ c_{\Xi_c\bar{K}} \\ c_{\Xi_c'\bar{K}} \end{pmatrix}$$

The mass of the $\Omega_{c0}^d(1P1/2^-)$ is predicted to be **2945 MeV**, which is below the $\Xi_c\bar{K}$ threshold due to the nontrivial coupled-channel effect.

S.Q. Luo, B. Chen, X. Liu, T. Matsuki, Phys. Rev. D.103, 074027 (2021)

# Recent progresses on single heavy baryons

## Universal behavior of mass gaps existing in the single heavy baryon family

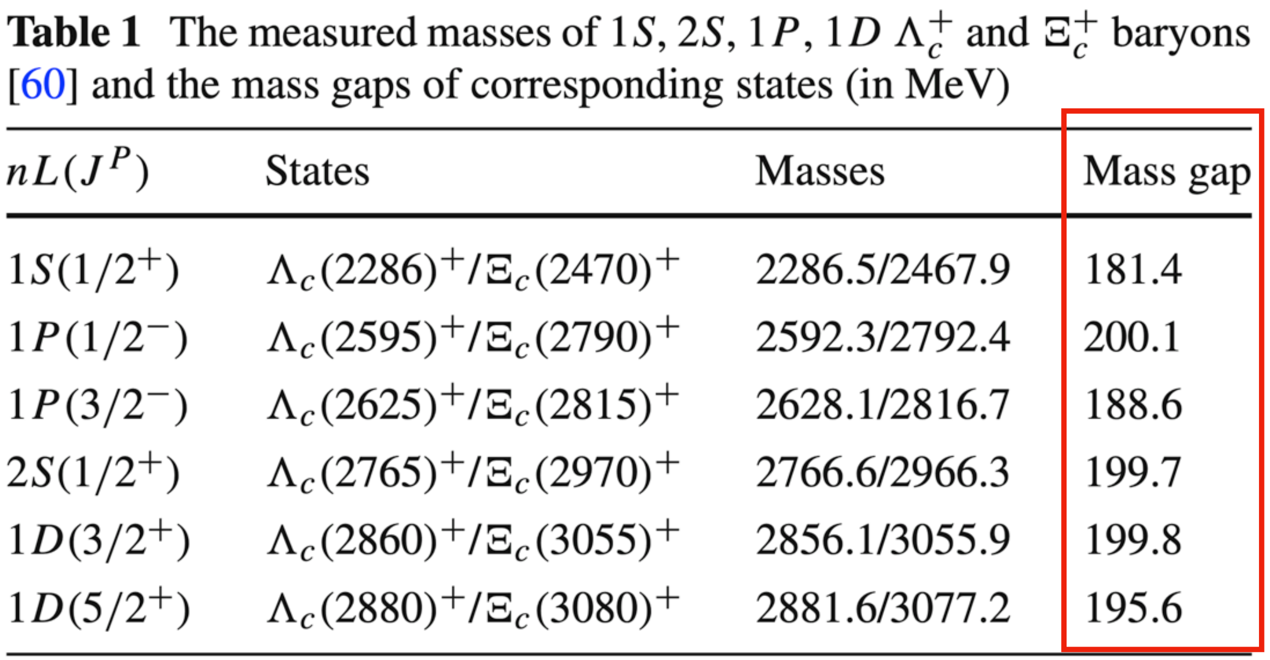


**Table 1** The measured masses of $1S$, $2S$, $1P$, $1D$ $\Lambda_c^+$ and $\Xi_c^+$ baryons [60] and the mass gaps of corresponding states (in MeV)

| $nL(J^P)$ | States | Masses | Mass gap |
|---|---|---|---|
| $1S(1/2^+)$ | $\Lambda_c(2286)^+/\Xi_c(2470)^+$ | 2286.5/2467.9 | 181.4 |
| $1P(1/2^-)$ | $\Lambda_c(2595)^+/\Xi_c(2790)^+$ | 2592.3/2792.4 | 200.1 |
| $1P(3/2^-)$ | $\Lambda_c(2625)^+/\Xi_c(2815)^+$ | 2628.1/2816.7 | 188.6 |
| $2S(1/2^+)$ | $\Lambda_c(2765)^+/\Xi_c(2970)^+$ | 2766.6/2966.3 | 199.7 |
| $1D(3/2^+)$ | $\Lambda_c(2860)^+/\Xi_c(3055)^+$ | 2856.1/3055.9 | 199.8 |
| $1D(5/2^+)$ | $\Lambda_c(2880)^+/\Xi_c(3080)^+$ | 2881.6/3077.2 | 195.6 |

| System | Number of strange quark |
|---|---|
| $\Lambda_c, \Sigma_c$ | 0 |
| $\Xi_c, \Xi_c'$ | 1 |
| $\Omega_c$ | 2 |

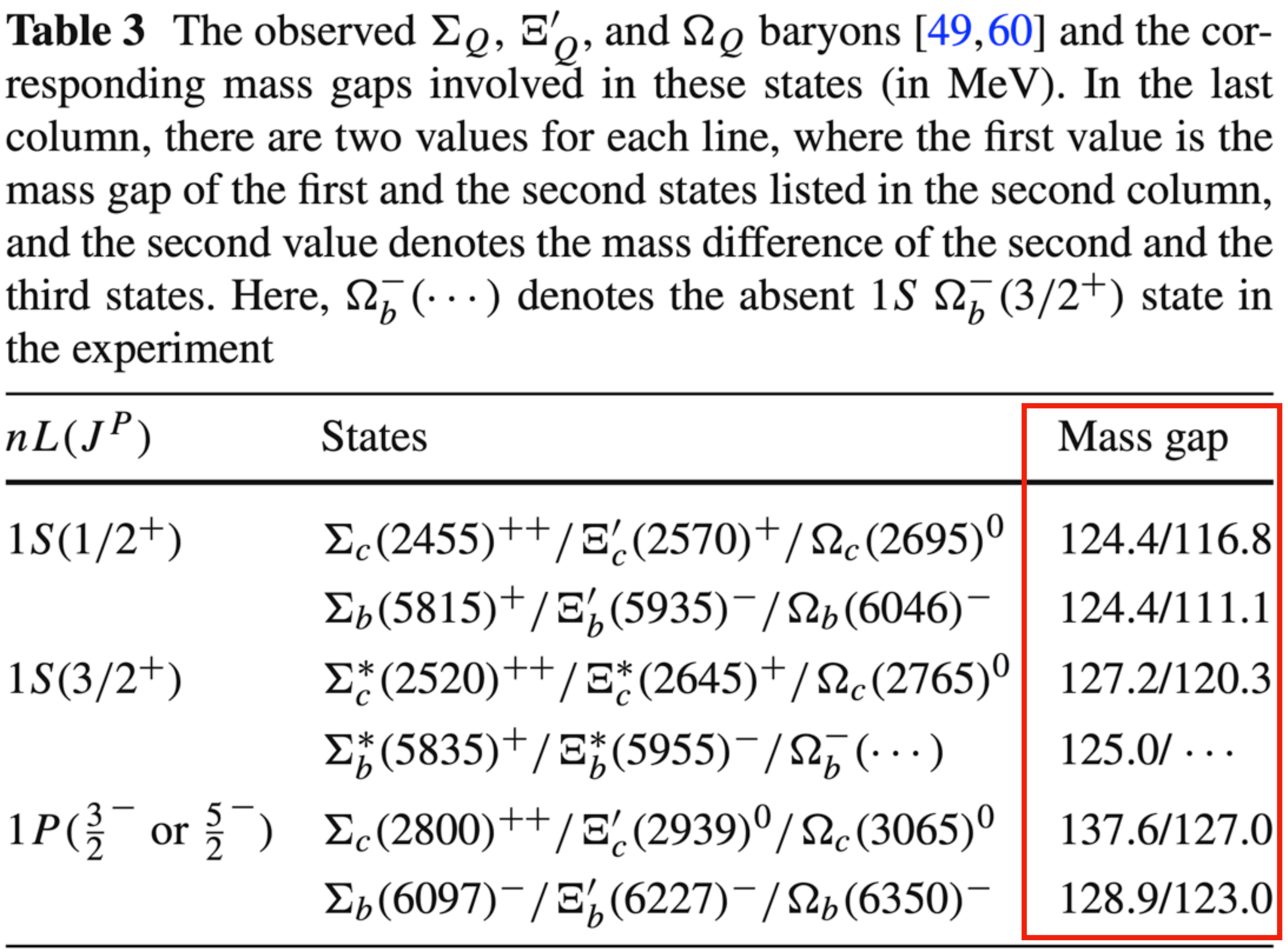


**Table 3** The observed $\Sigma_Q$, $\Xi_Q'$, and $\Omega_Q$ baryons [49,60] and the corresponding mass gaps involved in these states (in MeV). In the last column, there are two values for each line, where the first value is the mass gap of the first and the second states listed in the second column, and the second value denotes the mass difference of the second and the third states. Here, $\Omega_b^-(\cdots)$ denotes the absent $1S$ $\Omega_b^-(3/2^+)$ state in the experiment

| $nL(J^P)$ | States | Mass gap |
|---|---|---|
| $1S(1/2^+)$ | $\Sigma_c(2455)^{++}/\Xi_c'(2570)^+/\Omega_c(2695)^0$ | 124.4/116.8 |
| | $\Sigma_b(5815)^+/\Xi_b'(5935)^-/\Omega_b(6046)^-$ | 124.4/111.1 |
| $1S(3/2^+)$ | $\Sigma_c^*(2520)^{++}/\Xi_c^*(2645)^+/\Omega_c(2765)^0$ | 127.2/120.3 |
| | $\Sigma_b^*(5835)^+/\Xi_b^*(5955)^-/\Omega_b^-(\cdots)$ | 125.0/ $\cdots$ |
| $1P(\frac{3}{2}^- \text{ or } \frac{5}{2}^-)$ | $\Sigma_c(2800)^{++}/\Xi_c'(2939)^0/\Omega_c(3065)^0$ | 137.6/127.0 |
| | $\Sigma_b(6097)^-/\Xi_b'(6227)^-/\Omega_b(6350)^-$ | 128.9/123.0 |

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# 3 Recent progresses on singly heavy baryons

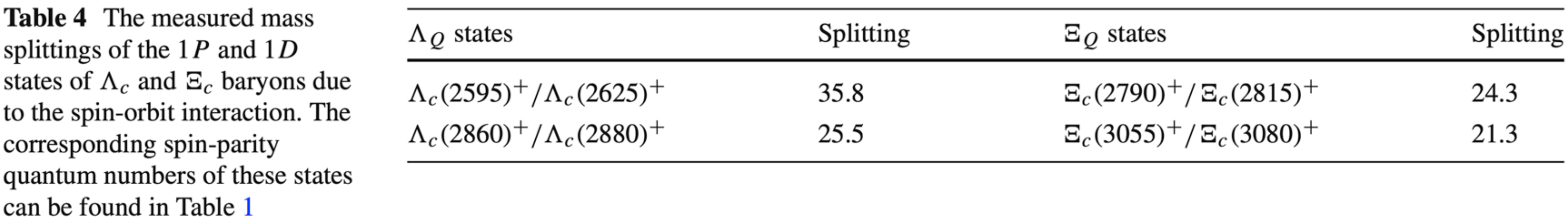

**Table 4** The measured mass splittings of the $1P$ and $1D$ states of $\Lambda_c$ and $\Xi_c$ baryons due to the spin-orbit interaction. The corresponding spin-parity quantum numbers of these states can be found in Table 1

| $\Lambda_Q$ states | Splitting | $\Xi_Q$ states | Splitting |
|---|---|---|---|
| $\Lambda_c(2595)^+/\Lambda_c(2625)^+$ | 35.8 | $\Xi_c(2790)^+/\Xi_c(2815)^+$ | 24.3 |
| $\Lambda_c(2860)^+/\Lambda_c(2880)^+$ | 25.5 | $\Xi_c(3055)^+/\Xi_c(3080)^+$ | 21.3 |

For the $nL$ excited states of $\Lambda_Q$ and $\Xi_Q$, the two states with $J = L - 1$ and $J = L + 1$ are generated

$$m_{\Lambda_c(L+\frac{1}{2})} - m_{\Lambda_c(L-\frac{1}{2})} \approx m_{\Xi_c(L+\frac{1}{2})} - m_{\Xi_c(L-\frac{1}{2})}$$

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# Recent progresses on singly heavy baryons

**Application**

**We may predict the mass of $\Xi_b$ excitation**

$$m_{\Xi_b^{\text{excited}}} = m_{\Xi_b^{\text{ground}}} + \left(m_{\Lambda_b^{\text{excited}}} - m_{\Lambda_b^{\text{ground}}}\right)$$

$$m_{\Xi_b(2S,1/2^+)} = 6257\ \text{MeV}$$

$$m_{\Xi_b(1P,1/2^-)} = 6097\ \text{MeV} \qquad m_{\Xi_b(1P,3/2^-)} = 6105\ \text{MeV}$$

$$m_{\Xi_b(1D,3/2^+)} = 6331\ \text{MeV} \qquad m_{\Xi_b(1D,5/2^+)} = 6337\ \text{MeV}$$

- **CMS [1] and LHCb [2] confirmed our prediction for the mass of $\Xi_b(1P)$**
- **LHCb [3] confirmed our result for the mass of $\Xi_b(1D)$ state**

[1] [CMS] Phys. Rev. Lett. 126, 252003 (2021)
[2] [LHCb] Phys. Rev. Lett. 131, 171901 (2023)
[3] [LHCb] Phys. Rev. Lett. 128, 162001 (2022)

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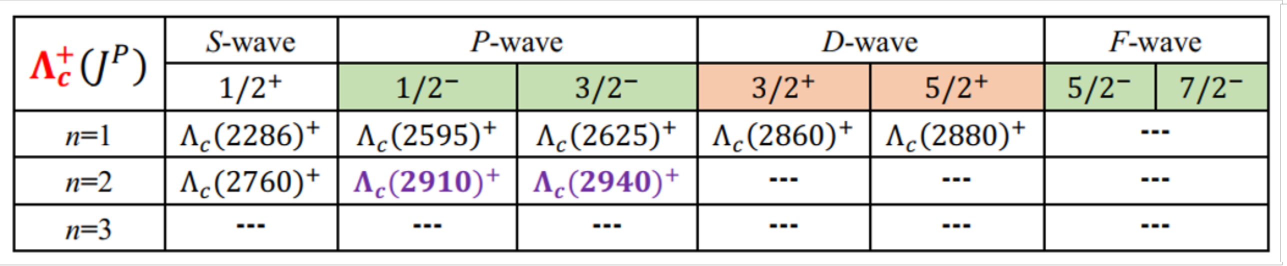
# 4 Summary

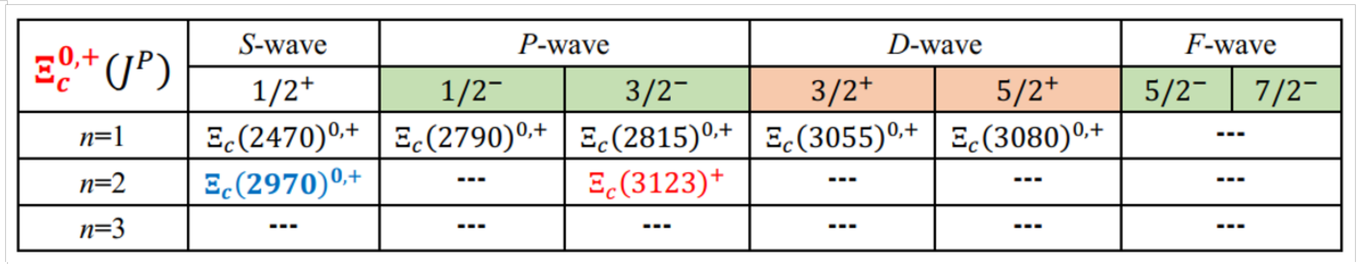
- **So far, there are about 56 single heavy baryon states discovered by experiments.**

$$\Lambda_c^+(8), \Xi_c^{0,+}(7), \Sigma_c(4), \Xi_c'(6), \Omega_c(9) \qquad \Lambda_b^0(6), \Xi_b^{0,-}(5), \Sigma_b(3), \Xi_b'(3), \Omega_b(5)$$

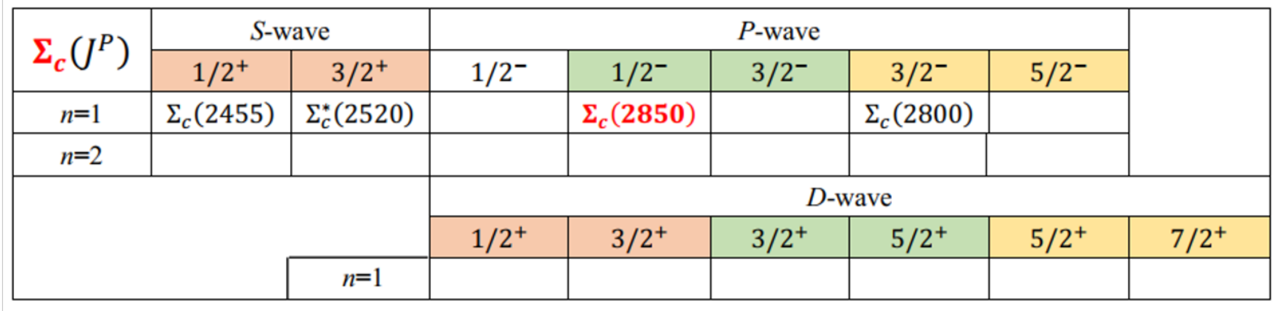
## Charm baryon family



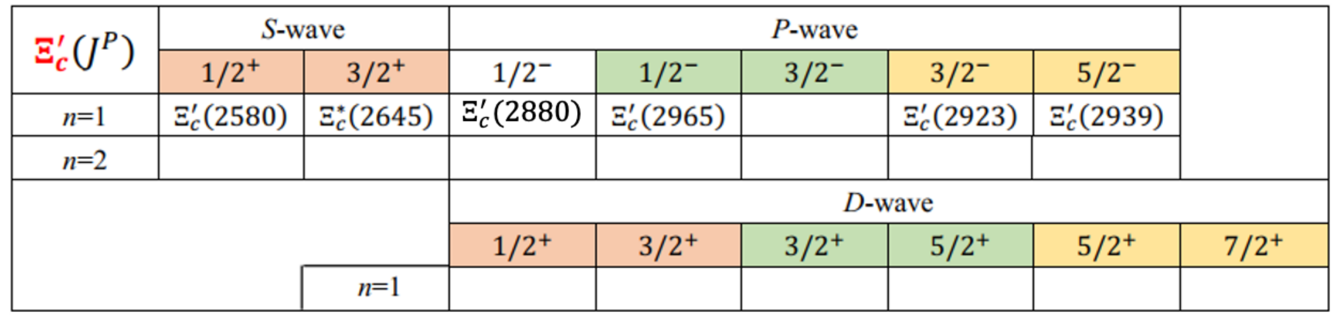
| $\Lambda_c^+(J^P)$ | *S*-wave | *P*-wave | | *D*-wave | | *F*-wave | |
|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $1/2^-$ | $3/2^-$ | $3/2^+$ | $5/2^+$ | $5/2^-$ | $7/2^-$ |
| $n$=1 | $\Lambda_c(2286)^+$ | $\Lambda_c(2595)^+$ | $\Lambda_c(2625)^+$ | $\Lambda_c(2860)^+$ | $\Lambda_c(2880)^+$ | --- | |
| $n$=2 | $\Lambda_c(2760)^+$ | $\Lambda_c(2910)^+$ | $\Lambda_c(2940)^+$ | --- | --- | --- | |
| $n$=3 | --- | --- | --- | --- | --- | --- | |



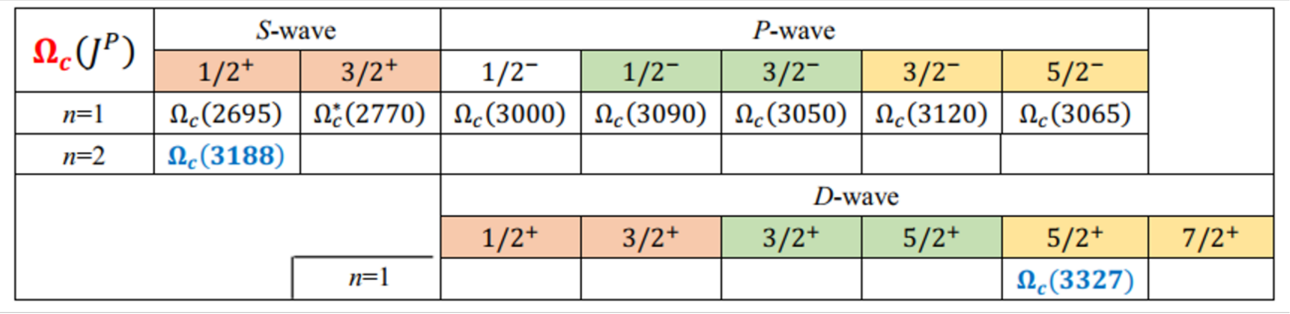
| $\Xi_c^{0,+}(J^P)$ | *S*-wave | *P*-wave | | *D*-wave | | *F*-wave | |
|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $1/2^-$ | $3/2^-$ | $3/2^+$ | $5/2^+$ | $5/2^-$ | $7/2^-$ |
| $n$=1 | $\Xi_c(2470)^{0,+}$ | $\Xi_c(2790)^{0,+}$ | $\Xi_c(2815)^{0,+}$ | $\Xi_c(3055)^{0,+}$ | $\Xi_c(3080)^{0,+}$ | --- | |
| $n$=2 | $\Xi_c(2970)^{0,+}$ | --- | $\Xi_c(3123)^+$ | --- | --- | --- | |
| $n$=3 | --- | --- | --- | --- | --- | --- | |



| $\Sigma_c(J^P)$ | *S*-wave | | *P*-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Sigma_c(2455)$ | $\Sigma_c^*(2520)$ | | $\Sigma_c(2850)$ | | $\Sigma_c(2800)$ | | |
| $n$=2 | | | | | | | | |
| | | | *D*-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | | |



| $\Xi_c'(J^P)$ | *S*-wave | | *P*-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Xi_c'(2580)$ | $\Xi_c^*(2645)$ | $\Xi_c'(2880)$ | $\Xi_c'(2965)$ | | $\Xi_c'(2923)$ | $\Xi_c'(2939)$ | |
| $n$=2 | | | | | | | | |
| | | | *D*-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | | |



| $\Omega_c(J^P)$ | *S*-wave | | *P*-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Omega_c(2695)$ | $\Omega_c^*(2770)$ | $\Omega_c(3000)$ | $\Omega_c(3090)$ | $\Omega_c(3050)$ | $\Omega_c(3120)$ | $\Omega_c(3065)$ | |
| $n$=2 | $\Omega_c(3188)$ | | | | | | | |
| | | | *D*-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | $\Omega_c(3327)$ | |

$\mathbf{\Lambda_c(2910)^+}$: This state was reported by the Belle collaboration in the $\bar{B}^0$ decay process. It could be a $\frac{1}{2}^-$ $(1P)$ state.

$\mathbf{\Xi_c(2970)^{0,+}}$: The $J^P$ quantum number has been measured by Belle.

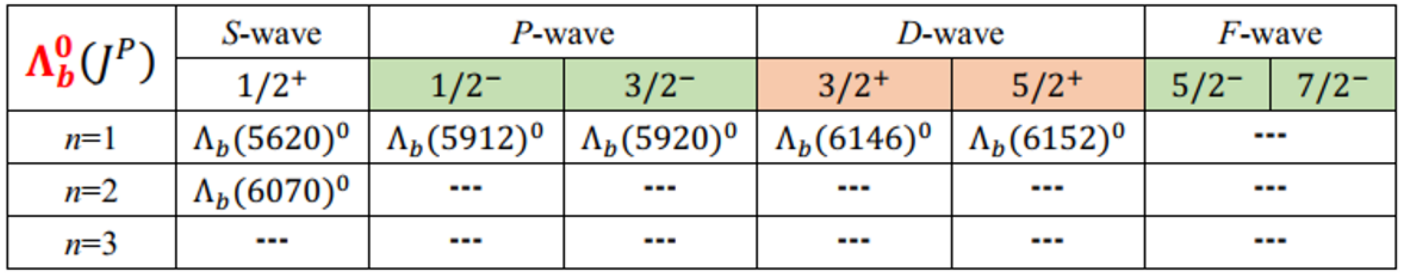
$\mathbf{\Xi_c(3123)^+}$: This state was only seen by BABAR.

$\mathbf{\Sigma_c(2850)^0}$: This state was only reported by BABAR.

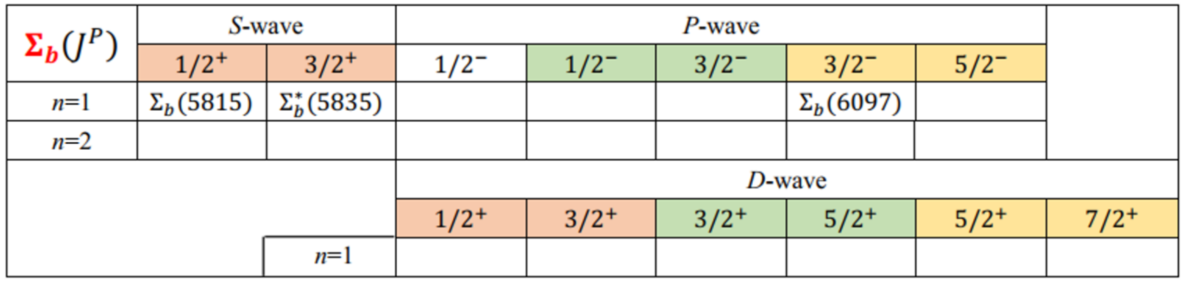
$\mathbf{\Omega_c(3327)^0}$: It might be the first *D*-wave heavy baryon with bad diquark.

# 4 Summary

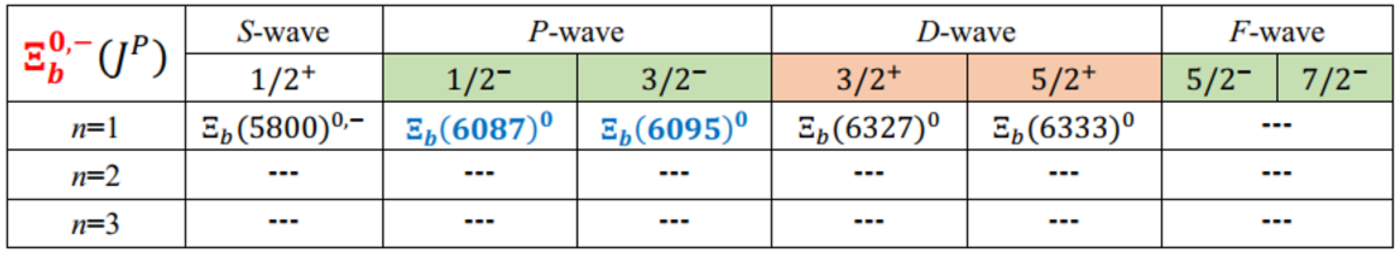
## Bottom baryon family



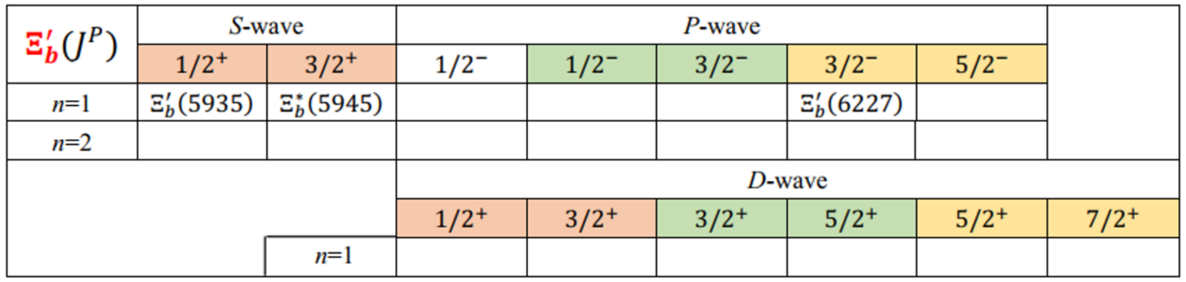
| $\Lambda_b^0(J^P)$ | S-wave | P-wave | | D-wave | | F-wave | |
|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $1/2^-$ | $3/2^-$ | $3/2^+$ | $5/2^+$ | $5/2^-$ | $7/2^-$ |
| $n$=1 | $\Lambda_b(5620)^0$ | $\Lambda_b(5912)^0$ | $\Lambda_b(5920)^0$ | $\Lambda_b(6146)^0$ | $\Lambda_b(6152)^0$ | --- | |
| $n$=2 | $\Lambda_b(6070)^0$ | --- | --- | --- | --- | --- | |
| $n$=3 | --- | --- | --- | --- | --- | --- | |



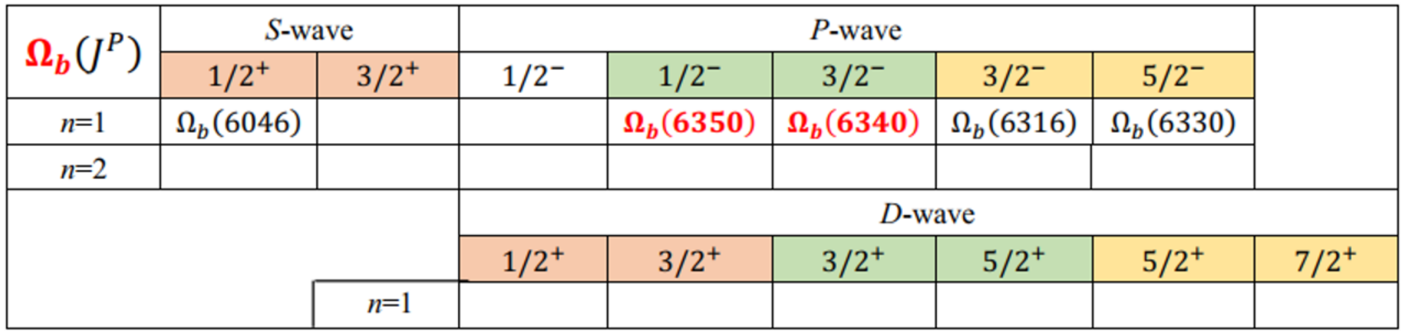
| $\Sigma_b(J^P)$ | S-wave | | P-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Sigma_b(5815)$ | $\Sigma_b^*(5835)$ | | | | $\Sigma_b(6097)$ | | |
| $n$=2 | | | | | | | | |
| | | | D-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | | |



| $\Xi_b^{0,-}(J^P)$ | S-wave | P-wave | | D-wave | | F-wave | |
|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $1/2^-$ | $3/2^-$ | $3/2^+$ | $5/2^+$ | $5/2^-$ | $7/2^-$ |
| $n$=1 | $\Xi_b(5800)^{0,-}$ | $\Xi_b(6087)^0$ | $\Xi_b(6095)^0$ | $\Xi_b(6327)^0$ | $\Xi_b(6333)^0$ | --- | |
| $n$=2 | --- | --- | --- | --- | --- | --- | |
| $n$=3 | --- | --- | --- | --- | --- | --- | |



| $\Xi_b'(J^P)$ | S-wave | | P-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Xi_b'(5935)$ | $\Xi_b^*(5945)$ | | | | $\Xi_b'(6227)$ | | |
| $n$=2 | | | | | | | | |
| | | | D-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | | |



| $\Omega_b(J^P)$ | S-wave | | P-wave | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $1/2^+$ | $3/2^+$ | $1/2^-$ | $1/2^-$ | $3/2^-$ | $3/2^-$ | $5/2^-$ | |
| $n$=1 | $\Omega_b(6046)$ | | | $\Omega_b(6350)$ | $\Omega_b(6340)$ | $\Omega_b(6316)$ | $\Omega_b(6330)$ | |
| $n$=2 | | | | | | | | |
| | | | D-wave | | | | | |
| | | | $1/2^+$ | $3/2^+$ | $3/2^+$ | $5/2^+$ | $5/2^+$ | $7/2^+$ |
| | | $n$=1 | | | | | | |

The 1S, 2S, 1P, and 1D $\Lambda_b^0$ states may have been established by experiments.

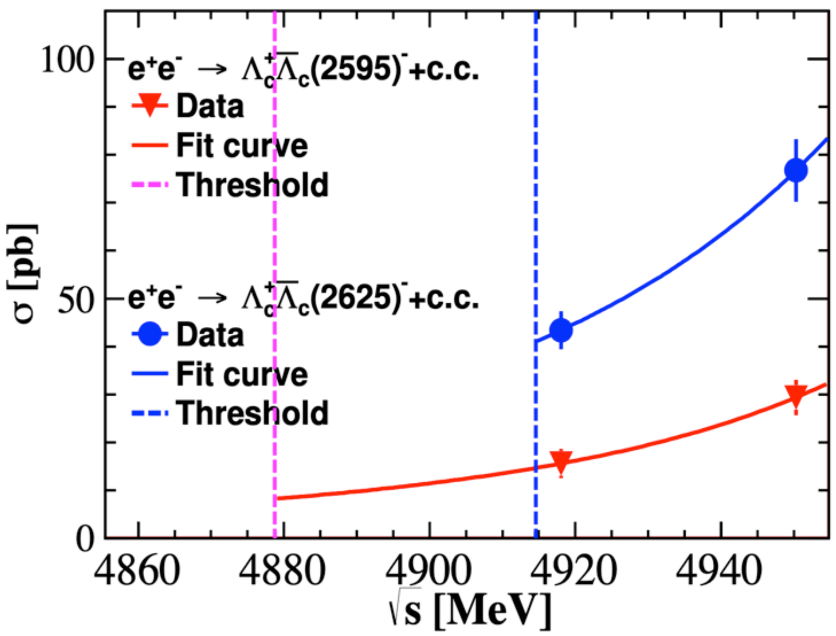
$\Xi_b(6087)^0/\Xi_b(6095)^0$: Two 1P candidates with $J^P = 1/2^-$ and $3/2^-$ were observed by LHCb

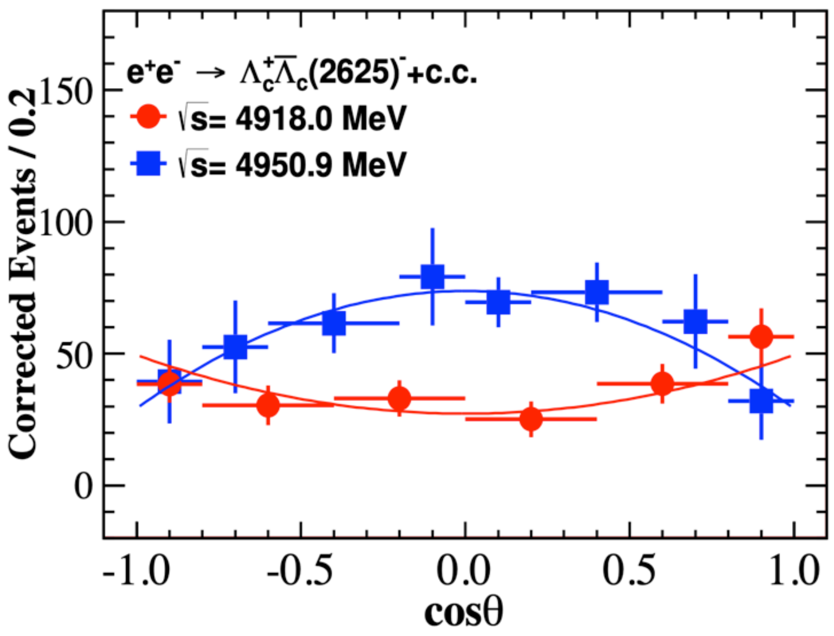
# Summary

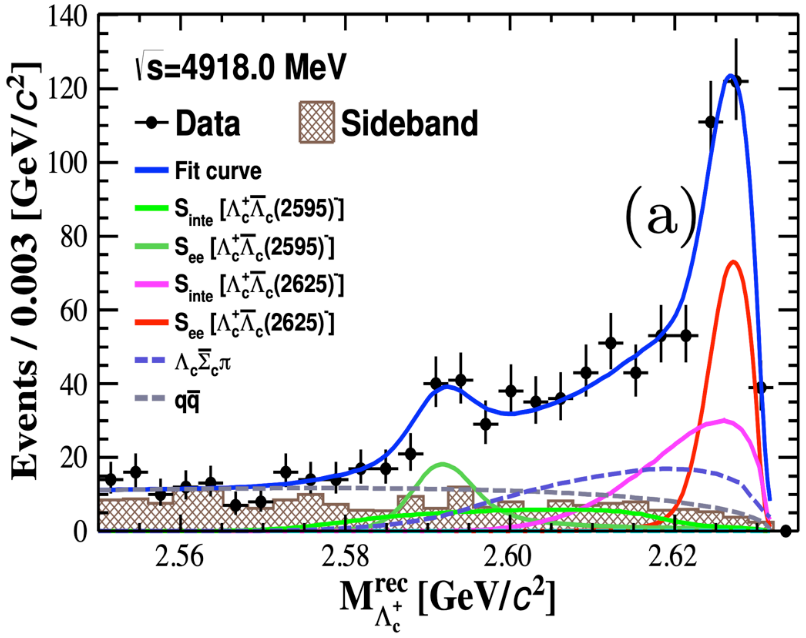
- **The potential at Super Tau Charm Facilities for exploring charm baryons**

**BESIII arXiv:2312.08414**

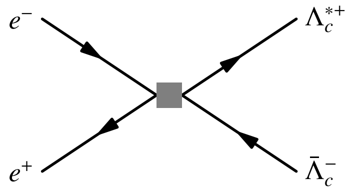
**Measurements of Born Cross Sections for $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^- + \text{c.c.}$ and $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^- + \text{c.c.}$ at $\sqrt{s} = 4918.0$ and $4950.9$ MeV**







**Super Tau Charm Facilities: A good platform for investigating higher states of charm baryon family!**



# Thank you for your attention!