Charmed baryon spectrum
and their decay patterns

Hua-Xing Chen

Southeast University

Collaborators: Er-Liang Cui, Hui-Min Yang, Wei Chen, Atsushi Hosaka, Xiang Liu, Shi-Lin Zhu.

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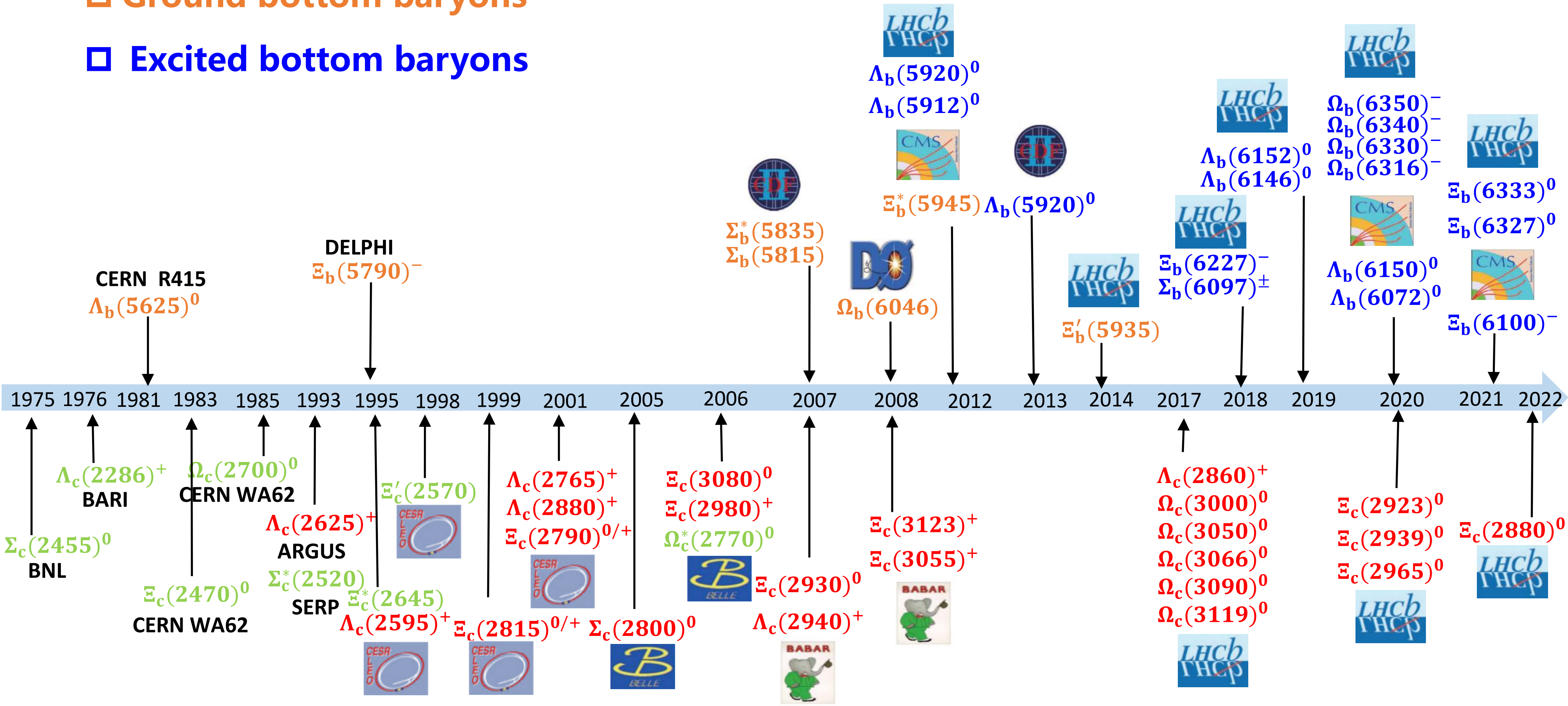
☐ Ground bottom baryons

☐ Excited bottom baryons



$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$

$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$

$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Omega_b(6330)^-$
$\Omega_b(6316)^-$

$\Xi_b(6333)^0$
$\Xi_b(6327)^0$

$\Xi_b^*(5945)$ $\Lambda_b(5920)^0$

$\Sigma_b^*(5835)$
$\Sigma_b(5815)$

DELPHI
$\Xi_b(5790)^-$

CERN R415
$\Lambda_b(5625)^0$

$\Omega_b(6046)$

$\Xi_b(6227)^-$
$\Sigma_b(6097)^\pm$

$\Lambda_b(6150)^0$
$\Lambda_b(6072)^0$

$\Xi_b'(5935)$

$\Xi_b(6100)^-$

1975 1976 1981 1983 1985 1993 1995 1998 1999 2001 2005 2006 2007 2008 2012 2013 2014 2017 2018 2019 2020 2021 2022

$\Lambda_c(2286)^+$
BARI

$\Omega_c(2700)^0$
CERN WA62

$\Xi_c'(2570)$

$\Lambda_c(2765)^+$
$\Lambda_c(2880)^+$
$\Xi_c(2790)^{0/+}$

$\Xi_c(3080)^0$
$\Xi_c(2980)^+$
$\Omega_c^*(2770)^0$

$\Lambda_c(2860)^+$
$\Omega_c(3000)^0$
$\Omega_c(3050)^0$
$\Omega_c(3066)^0$
$\Omega_c(3090)^0$
$\Omega_c(3119)^0$

$\Xi_c(2923)^0$
$\Xi_c(2939)^0$
$\Xi_c(2965)^0$

$\Xi_c(2880)^0$

$\Sigma_c(2455)^0$
BNL

$\Lambda_c(2625)^+$
ARGUS

$\Xi_c(3123)^+$
$\Xi_c(3055)^+$

$\Sigma_c^*(2520)$
SERP

$\Xi_c(2470)^0$
CERN WA62

$\Xi_c^*(2645)$

$\Xi_c(2930)^0$

$\Lambda_c(2595)^+$ $\Xi_c(2815)^{0/+}$ $\Sigma_c(2800)^0$

$\Lambda_c(2940)^+$

☐ Ground charmed baryons

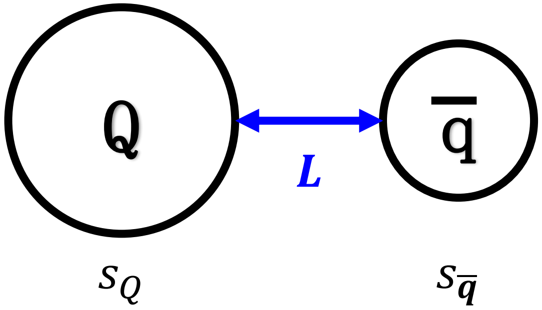
☐ Excited charmed baryons

Contents

- **Internal structure of heavy mesons**
- Internal structure of heavy baryons
- QCD sum rule analyses

Internal structure of heavy mesons

heavy meson ($Q - \overline{q}$)



$$J = s_Q + s_{\overline{q}} + L$$

Internal structure of heavy mesons

Based on the **heavy quark effective theory**, the leading order Lagrangian does not depend on m_Q. Hence, the two heavy hadrons with the same light degree of freedom form a degenerate doublet:

heavy meson $(\boldsymbol{Q-\bar{q}})$ **:** $\boldsymbol{J = s_Q + \left(L + s_{\bar{q}}\right)_{j_l}}$

spin of the light degree of freedom

Internal structure of heavy mesons

Based on the **heavy quark effective theory**, the leading order Lagrangian does not depend on m_Q. Hence, the two heavy hadrons with the same light degree of freedom form a degenerate doublet:

heavy meson $(\boldsymbol{Q} - \bar{\boldsymbol{q}})$: $$\boldsymbol{J} = \underset{\boxed{= 1/2}}{\boldsymbol{s}_{\boldsymbol{Q}}} + \left(\boldsymbol{L} + \underset{\boxed{= 1/2}}{\boldsymbol{s}_{\bar{\boldsymbol{q}}}}\right)_{j_l}$$

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$$L = 0 : j_l = 1/2, J^P = (0^-, 1^-)$$

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$$L = 0 : j_l = 1/2, J^P = (0^-, 1^-)$$

$$L = 1 : \begin{cases} j_l = 1/2, J^P = (0^+, 1^+) \\ j_l = 3/2, J^P = (1^+, 2^+) \end{cases}$$

Internal structure of heavy mesons

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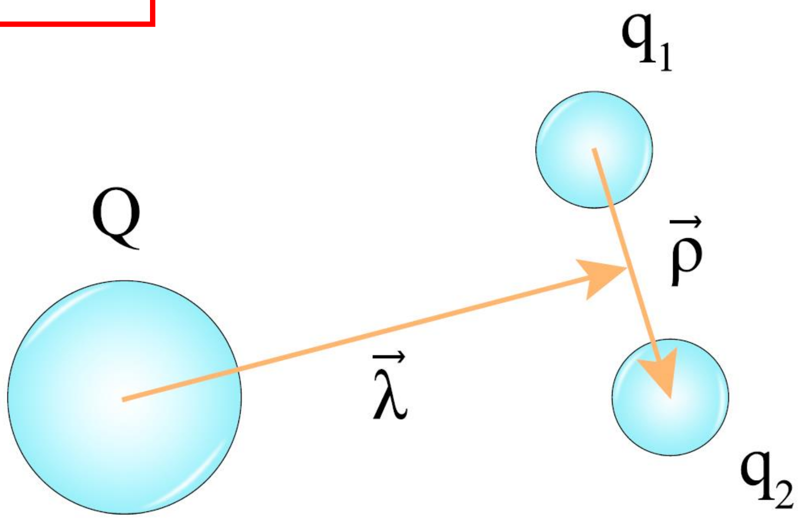
$$L = 2 : \begin{cases} j_l = 3/2, J^P = (1^-, 2^-) \\ j_l = 5/2, J^P = (2^-, 3^-) \end{cases}$$

Contents

- Internal structure of heavy mesons
- **Internal structure of heavy baryons**
- QCD sum rule analyses

Internal structure of heavy baryons

heavy baryon ($\mathbf{Q - q_1 - q_2}$):



λ-excitation and ρ-excitation

$$J = s_Q + s_{q1} + s_{q2} + l_\rho + l_\lambda$$
$$= s_Q + \left(s_{q1} + s_{q2} + l_\rho + l_\lambda\right)_{\boldsymbol{j_l}}$$

spin of the light degree of freedom

Internal structure of heavy baryons

The Pauli principle can be directly applied to the two light quarks:

- color$\longrightarrow\bar{\mathbf{3}}_C$ **antisymmetric**
- orbital$\longrightarrow \boldsymbol{l_\rho} \begin{cases} \textbf{symmetric} \\ \textbf{antisymmetric} \end{cases}$
- spin$\longrightarrow \boldsymbol{s_{qq}} = \begin{cases} \mathbf{1}\ \textbf{symmetric} \\ \mathbf{0}\ \textbf{antisymmetric} \end{cases}$
- SU(3) flavor$\longrightarrow \begin{cases} \mathbf{6}_F\ \textbf{symmetric} \\ \bar{\mathbf{3}}_F\ \textbf{antisymmetric} \end{cases}$

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Totally Antisymmetric

Internal structure of heavy baryons

S-wave heavy baryons:

- color$\longrightarrow\bar{\mathbf{3}}_C$ **antisymmetric**
- orbital$\longrightarrow \boldsymbol{l_\rho = 0}$ **symmetric**
- spin$\longrightarrow \boldsymbol{s_{qq}} = \begin{cases} \mathbf{1}\ \textbf{symmetric} \\ \mathbf{0}\ \textbf{antisymmetric} \end{cases}$
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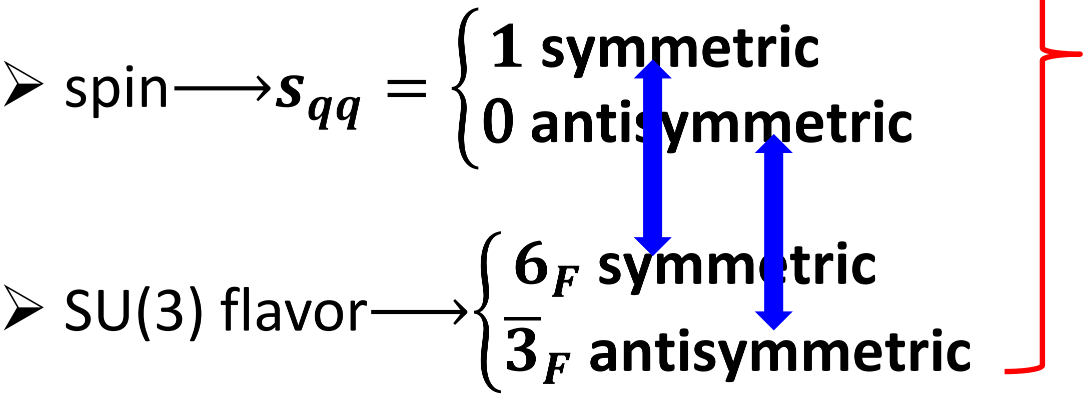

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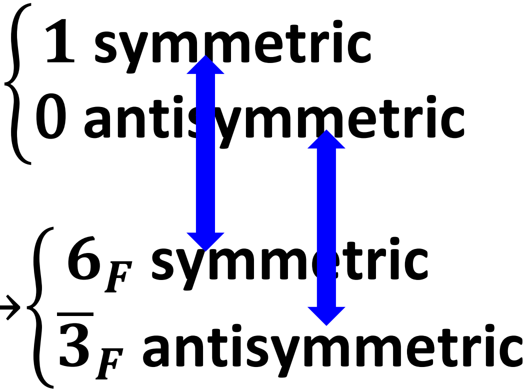

- spin$\longrightarrow \boldsymbol{s_{qq}} = \begin{cases} \mathbf{1} \text{ symmetric} \\ 0 \text{ antisymmetric} \end{cases}$
- SU(3) flavor$\longrightarrow \begin{cases} \mathbf{6}_F \text{ symmetric} \\ \bar{\mathbf{3}}_F \text{ antisymmetric} \end{cases}$

$$L = 0 \begin{cases} \boldsymbol{j_l = s_{qq} = 0}, J^P = 1/2^+ \quad \longleftrightarrow \quad \bar{3}_F \\ \boldsymbol{j_l = s_{qq} = 1}, J^P = (1/2^+, 3/2^+) \quad \longleftrightarrow \quad 6_F \end{cases}$$

Internal structure of heavy baryons

S-wave heavy baryons:

- color$\longrightarrow\bar{\mathbf{3}}_C$ **antisymmetric**
- orbital$\longrightarrow$$\boldsymbol{l_\rho = 0}$ **symmetric**
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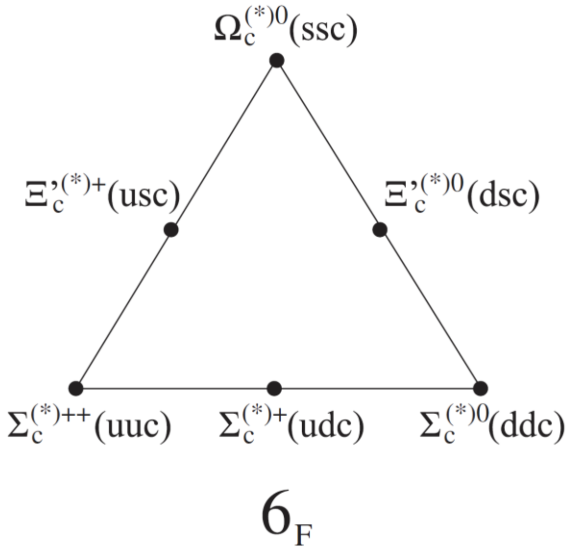
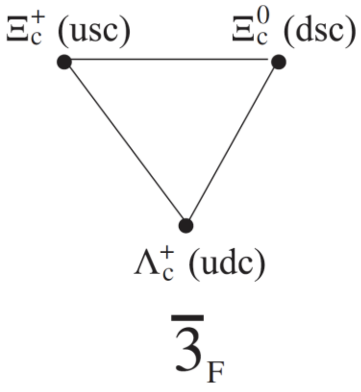




$$L = 0 \begin{cases} \boldsymbol{j_l = s_{qq} = 0}, J^P = 1/2^+ \longleftrightarrow \bar{3}_F \\ \boldsymbol{j_l = s_{qq} = 1}, J^P = (1/2^+, 3/2^+) \longleftrightarrow 6_F \end{cases}$$

Internal structure of heavy baryons

S-wave charmed baryons

$$L = 0 \begin{cases} \boldsymbol{j_l = 0}, J^P = 1/2^+ \\ \boldsymbol{j_l = 1}, J^P = (1/2^+, 3/2^+) \end{cases}$$

$\bar{3}_F\colon\ \Lambda_c, \Xi_c$

$6_F\colon (\Sigma_c, \Sigma_c^*), (\Xi_c', \Xi_c^*), (\Omega_c, \Omega_c^*)$

$\uparrow \quad \uparrow$

$1/2^+ \quad 3/2^+$

S-wave bottom baryons

$$L = 0 \begin{cases} \boldsymbol{j_l = 0}, J^P = 1/2^+ \\ \boldsymbol{j_l = 1}, J^P = (1/2^+, 3/2^+) \end{cases}$$

$\bar{3}_F\colon\ \Lambda_b, \Xi_b$

$6_F\colon (\Sigma_b, \Sigma_b^*), (\Xi_b', \Xi_b^*), (\Omega_b, \Omega_b^*)$

$\uparrow \quad \uparrow$

$1/2^+ \quad 3/2^+$

Internal structure of heavy baryons

S-wave charmed baryons

$$L = 0 \begin{cases} \boldsymbol{j_l = 0}, J^P = 1/2^+ \\ \boldsymbol{j_l = 1}, J^P = (1/2^+, 3/2^+) \end{cases} \quad \begin{array}{l} \bar{3}_F\text{: } \Lambda_c, \Xi_c \\ 6_F\text{: } (\Sigma_c, \Sigma_c^*), (\Xi_c', \Xi_c^*), (\Omega_c, \Omega_c^*) \end{array}$$

$1/2^+$ $3/2^+$

S-wave bottom baryons

$$L = 0 \begin{cases} \boldsymbol{j_l = 0}, J^P = 1/2^+ \\ \boldsymbol{j_l = 1}, J^P = (1/2^+, 3/2^+) \end{cases} \quad \begin{array}{l} \bar{3}_F\text{: } \Lambda_b, \Xi_b \\ 6_F\text{: } (\Sigma_b, \Sigma_b^*), (\Xi_b', \Xi_b^*), (\Omega_b, \Omega_b^*) \end{array}$$

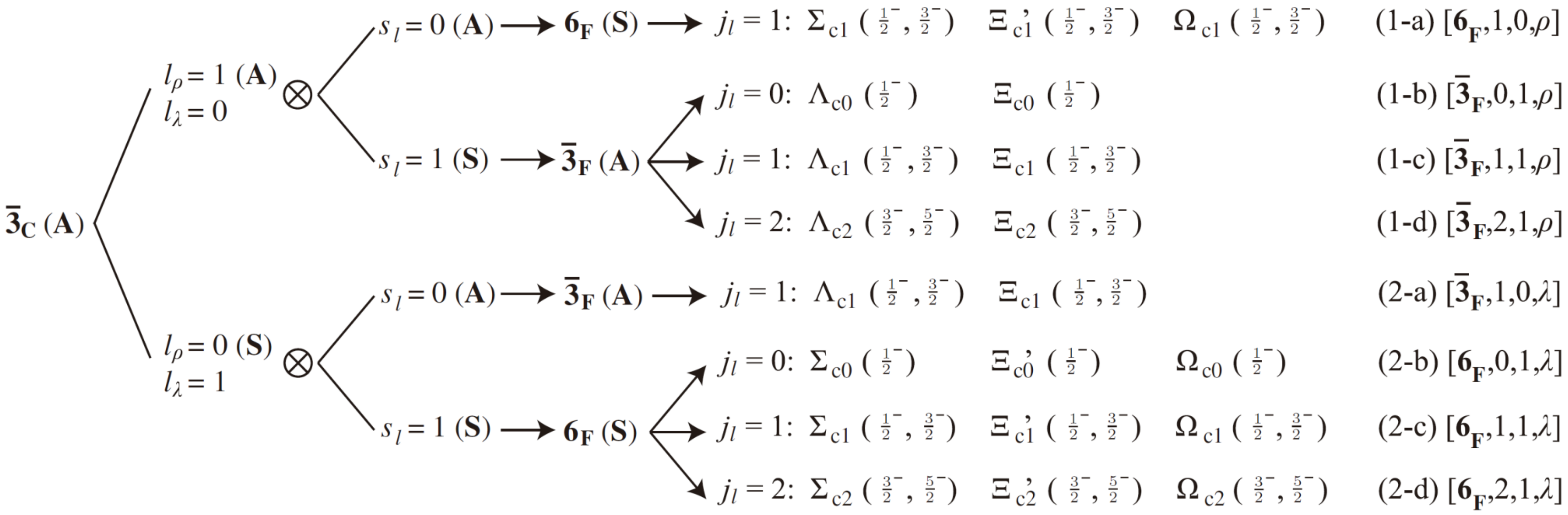
$1/2^+$ $3/2^+$

missing

Internal structure of heavy baryons

P-wave charmed baryons

8 multiplets, 35 baryons, *e.g.*, 7 Ω_c baryons



$\bar{\mathbf{3}}_C$ (**A**)

$l_\rho = 1$ (**A**), $l_\lambda = 0$ $\otimes$

$s_l = 0$ (**A**) $\longrightarrow$ $\mathbf{6}_\mathbf{F}$ (**S**) $\longrightarrow$ $j_l = 1$: $\Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ (1-a) $[\mathbf{6}_\mathbf{F},1,0,\rho]$

$s_l = 1$ (**S**) $\longrightarrow$ $\bar{\mathbf{3}}_\mathbf{F}$ (**A**) $\longrightarrow$

$j_l = 0$: $\Lambda_{c0}(\frac{1}{2}^-)$ $\Xi_{c0}(\frac{1}{2}^-)$ (1-b) $[\bar{\mathbf{3}}_\mathbf{F},0,1,\rho]$

$j_l = 1$: $\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ (1-c) $[\bar{\mathbf{3}}_\mathbf{F},1,1,\rho]$

$j_l = 2$: $\Lambda_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Xi_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ (1-d) $[\bar{\mathbf{3}}_\mathbf{F},2,1,\rho]$

$l_\rho = 0$ (**S**), $l_\lambda = 1$ $\otimes$

$s_l = 0$ (**A**) $\longrightarrow$ $\bar{\mathbf{3}}_\mathbf{F}$ (**A**) $\longrightarrow$ $j_l = 1$: $\Lambda_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ (2-a) $[\bar{\mathbf{3}}_\mathbf{F},1,0,\lambda]$

$s_l = 1$ (**S**) $\longrightarrow$ $\mathbf{6}_\mathbf{F}$ (**S**) $\longrightarrow$

$j_l = 0$: $\Sigma_{c0}(\frac{1}{2}^-)$ $\Xi'_{c0}(\frac{1}{2}^-)$ $\Omega_{c0}(\frac{1}{2}^-)$ (2-b) $[\mathbf{6}_\mathbf{F},0,1,\lambda]$

$j_l = 1$: $\Sigma_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Xi'_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ $\Omega_{c1}(\frac{1}{2}^-, \frac{3}{2}^-)$ (2-c) $[\mathbf{6}_\mathbf{F},1,1,\lambda]$

$j_l = 2$: $\Sigma_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Xi'_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ $\Omega_{c2}(\frac{3}{2}^-, \frac{5}{2}^-)$ (2-d) $[\mathbf{6}_\mathbf{F},2,1,\lambda]$

λ-excitation and ρ-excitation ($\boldsymbol{l_\rho + l_\lambda = 1}$)

Currents for P-wave charmed baryons of the flavor 6_F

$$[6_F, 1, 0, \rho] \left\{ \begin{aligned} J_{1/2,-,\mathbf{6}_F,1,0,\rho} &= i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma_5 q^b - q^{aT}C\gamma_5[\mathcal{D}^{\mu}_t q^b])\gamma^{\mu}_t\gamma_5 h^c_v, \\ J^{\alpha}_{3/2,-,\mathbf{6}_F,1,0,\rho} &= i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma_5 q^b - q^{aT}C\gamma_5[\mathcal{D}^{\mu}_t q^b])\left(g^{\alpha\mu}_t - \frac{1}{3}\gamma^{\alpha}_t\gamma^{\mu}_t\right)h^c_v, \end{aligned} \right.$$

$$[6_F, 0, 1, \lambda] \quad \boxed{J_{1/2,-,\mathbf{6}_F,0,1,\lambda} = i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma^{\mu}_t q^b + q^{aT}C\gamma^{\mu}_t[\mathcal{D}^{\mu}_t q^b])h^c_v.}$$

$$[6_F, 1, 1, \lambda] \left\{ \begin{aligned} J_{1/2,-,\mathbf{6}_F,1,1,\lambda} &= i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma^{\nu}_t q^b + q^{aT}C\gamma^{\nu}_t[\mathcal{D}^{\mu}_t q^b])\sigma^{\mu\nu}_t h^c_v, \\ J^{\alpha}_{3/2,-,\mathbf{6}_F,1,1,\lambda} &= i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma^{\nu}_t q^b + q^{aT}C\gamma^{\nu}_t[\mathcal{D}^{\mu}_t q^b])\left(g^{\alpha\mu}_t\gamma^{\nu}_t\gamma_5 - g^{\alpha\nu}_t\gamma^{\mu}_t\gamma_5 - \frac{1}{3}\gamma^{\alpha}_t\gamma^{\mu}_t\gamma^{\nu}_t\gamma_5 + \frac{1}{3}\gamma^{\alpha}_t\gamma^{\nu}_t\gamma^{\mu}_t\gamma_5\right)h^c_v. \end{aligned} \right.$$

$$[6_F, 2, 1, \lambda] \left\{ \begin{aligned} J^{\alpha}_{3/2,-,\mathbf{6}_F,2,1,\lambda} &= i\epsilon_{abc}([\mathcal{D}^{\mu}_t q^{aT}]C\gamma^{\nu}_t q^b + q^{aT}C\gamma^{\nu}_t[\mathcal{D}^{\mu}_t q^b]) \times \left(g^{\alpha\mu}_t\gamma^{\nu}_t\gamma_5 + g^{\alpha\nu}_t\gamma^{\mu}_t\gamma_5 - \frac{2}{3}g^{\mu\nu}_t\gamma^{\alpha}_t\gamma_5\right)h^c_v, \\ J^{\alpha_1\alpha_2}_{5/2,-,\mathbf{6}_F,2,1,\lambda} &= i\epsilon_{abc}\Big([\mathcal{D}^{\alpha_1}_t q^{aT}]C\gamma^{\alpha_2}_t q^b + q^{aT}C\gamma^{\alpha_2}_t[\mathcal{D}^{\alpha_1}_t q^b] + [\mathcal{D}^{\alpha_2}_t q^{aT}]C\gamma^{\alpha_1}_t q^b + q^{aT}C\gamma^{\alpha_1}_t[\mathcal{D}^{\alpha_2}_t q^b] \\ &\quad - \frac{2}{3}g^{\alpha_1\alpha_2}_t g^{\mu\nu}_t \times ([\mathcal{D}^{\mu}_t q^{aT}]C\gamma^{\nu}_t q^b + q^{aT}C\gamma^{\nu}_t[\mathcal{D}^{\mu}_t q^b])\Big)h^c_v. \end{aligned} \right.$$

General discussions on hadronic currents

- Hadronic currents well describe **the internal color, flavor, spin, and orbital quantum numbers**.

- Hadronic currents well describe **the internal symmetries of hadrons**, e.g,

  the Pauli principle is automatically satisfied.

Contents

- Internal structure of heavy mesons
- Internal structure of heavy baryons
- **QCD sum rule analyses**

QCD Sum Rules

- In sum rule analyses, we consider two-point correlation functions:

$$\Pi\left(q^2\right) \overset{\text{def}}{=} i\int d^4x e^{iqx}\langle 0|\mathrm{T}\eta(x)\eta^+(0)\;|0\rangle$$

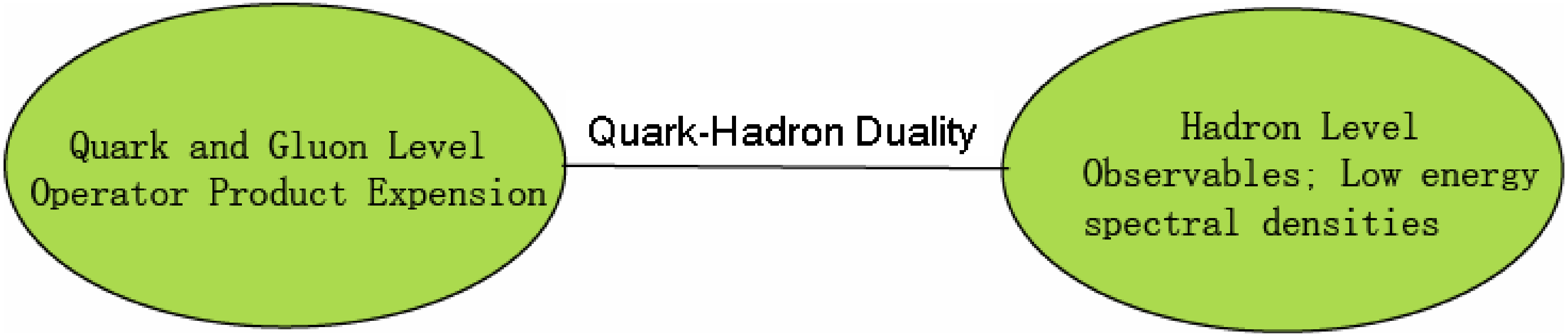
$$\approx \sum_{\mathrm{n}}\langle 0|\eta|\mathrm{n}\rangle\langle \mathrm{n}|\eta^+|0\rangle$$

  where η is the current which can couple to hadronic states.

- By using the dispersion relation, we can obtain the spectral density

$$\Pi\left(q^2\right) = \int_{s_<}^{\infty} \frac{\rho(s)}{s - q^2 - i\varepsilon} ds$$

- In QCD sum rule, we can calculate these matrix elements from QCD (OPE) and relate them to observables by using dispersion relation.



Quark and Gluon Level
Operator Product Expension

Quark-Hadron Duality

Hadron Level
Observables; Low energy
spectral densities

Nielsen et al, Phys. Rept. 497, 41 (2010); Albuquerque et al, JPG46, 093002 (2019).

SVZ sum rule

Quark and Gluon Level

(Convergence of OPE)

$$\Pi_{OPE}(q^2) \xrightarrow[s\,=\,-q^2]{\text{dispersion relation}} \rho_{OPE}(s) = a_n\, s^n + a_{n-1}\, s^{n-1}$$

$$\Updownarrow$$

Quark-Hadron Duality

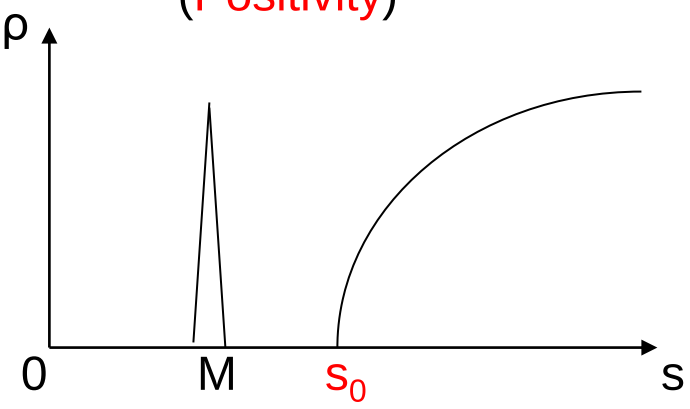
Hadron Level

$$\Pi_{phys}(q^2) = f_x^2 \frac{1}{q^2 - M^2} \longleftrightarrow \rho_{phys}(s) = \lambda_x^2 \delta(s - M_x^2) + \cdots$$

(for boson case)

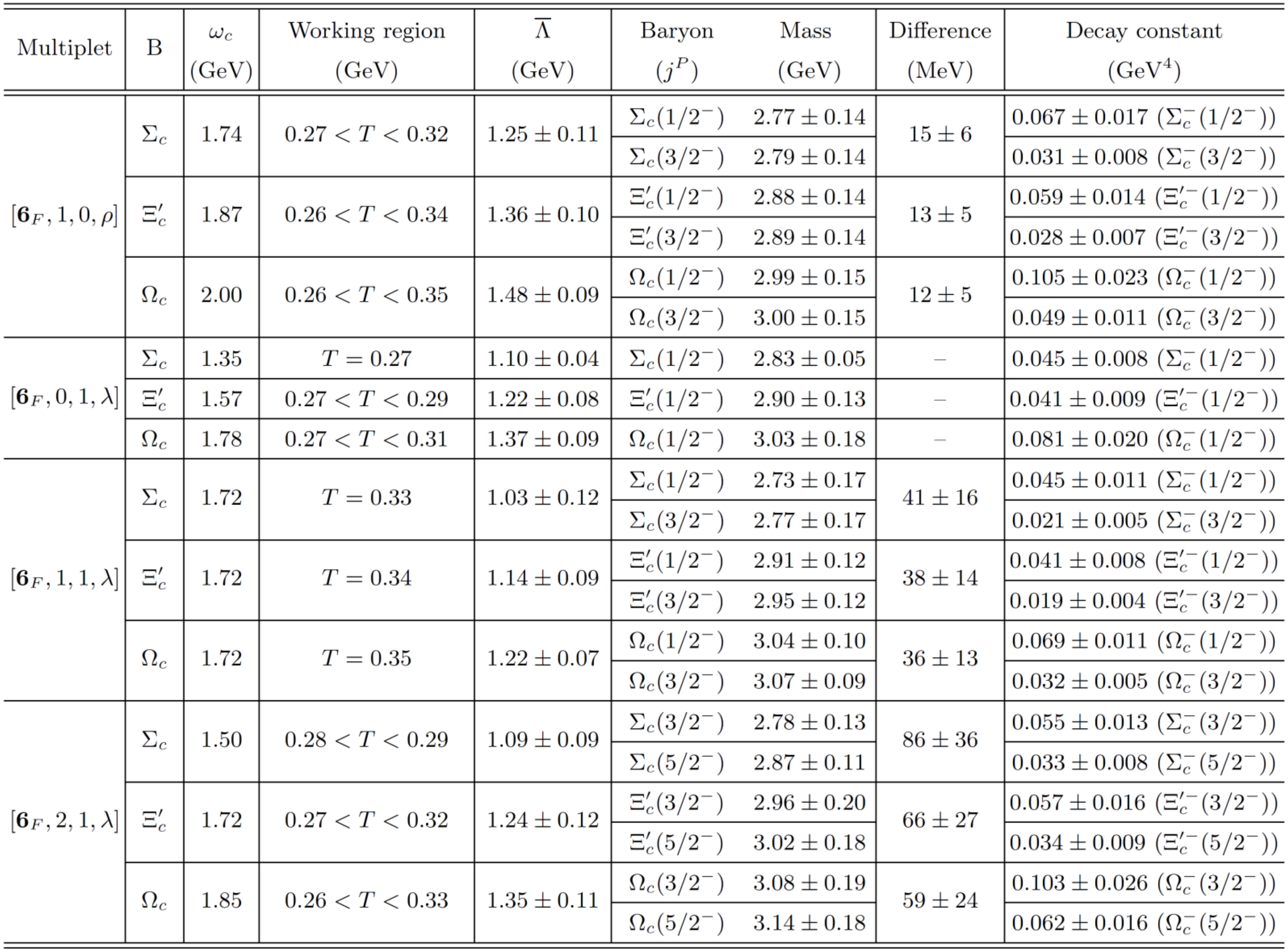
(Positivity)

(Sufficient amount of Pole contribution)



Mass spectrum

P-wave charmed baryons of the flavor 6_F



Multiplet	B	ω_c (GeV)	Working region (GeV)	$\overline{\Lambda}$ (GeV)	Baryon (j^P)	Mass (GeV)	Difference (MeV)	Decay constant (GeV^4)
$[\mathbf{6}_F, 1, 0, \rho]$	Σ_c	1.74	$0.27 < T < 0.32$	1.25 ± 0.11	$\Sigma_c(1/2^-)$	2.77 ± 0.14	15 ± 6	0.067 ± 0.017 $(\Sigma_c^-(1/2^-))$
					$\Sigma_c(3/2^-)$	2.79 ± 0.14		0.031 ± 0.008 $(\Sigma_c^-(3/2^-))$
	$\Xi_c^\prime$	1.87	$0.26 < T < 0.34$	1.36 ± 0.10	$\Xi_c^\prime(1/2^-)$	2.88 ± 0.14	13 ± 5	0.059 ± 0.014 $(\Xi_c^{\prime-}(1/2^-))$
					$\Xi_c^\prime(3/2^-)$	2.89 ± 0.14		0.028 ± 0.007 $(\Xi_c^{\prime-}(3/2^-))$
	Ω_c	2.00	$0.26 < T < 0.35$	1.48 ± 0.09	$\Omega_c(1/2^-)$	2.99 ± 0.15	12 ± 5	0.105 ± 0.023 $(\Omega_c^-(1/2^-))$
					$\Omega_c(3/2^-)$	3.00 ± 0.15		0.049 ± 0.011 $(\Omega_c^-(3/2^-))$
$[\mathbf{6}_F, 0, 1, \lambda]$	Σ_c	1.35	$T = 0.27$	1.10 ± 0.04	$\Sigma_c(1/2^-)$	2.83 ± 0.05	–	0.045 ± 0.008 $(\Sigma_c^-(1/2^-))$
	$\Xi_c^\prime$	1.57	$0.27 < T < 0.29$	1.22 ± 0.08	$\Xi_c^\prime(1/2^-)$	2.90 ± 0.13	–	0.041 ± 0.009 $(\Xi_c^{\prime-}(1/2^-))$
	Ω_c	1.78	$0.27 < T < 0.31$	1.37 ± 0.09	$\Omega_c(1/2^-)$	3.03 ± 0.18	–	0.081 ± 0.020 $(\Omega_c^-(1/2^-))$
$[\mathbf{6}_F, 1, 1, \lambda]$	Σ_c	1.72	$T = 0.33$	1.03 ± 0.12	$\Sigma_c(1/2^-)$	2.73 ± 0.17	41 ± 16	0.045 ± 0.011 $(\Sigma_c^-(1/2^-))$
					$\Sigma_c(3/2^-)$	2.77 ± 0.17		0.021 ± 0.005 $(\Sigma_c^-(3/2^-))$
	$\Xi_c^\prime$	1.72	$T = 0.34$	1.14 ± 0.09	$\Xi_c^\prime(1/2^-)$	2.91 ± 0.12	38 ± 14	0.041 ± 0.008 $(\Xi_c^{\prime-}(1/2^-))$
					$\Xi_c^\prime(3/2^-)$	2.95 ± 0.12		0.019 ± 0.004 $(\Xi_c^{\prime-}(3/2^-))$
	Ω_c	1.72	$T = 0.35$	1.22 ± 0.07	$\Omega_c(1/2^-)$	3.04 ± 0.10	36 ± 13	0.069 ± 0.011 $(\Omega_c^-(1/2^-))$
					$\Omega_c(3/2^-)$	3.07 ± 0.09		0.032 ± 0.005 $(\Omega_c^-(3/2^-))$
$[\mathbf{6}_F, 2, 1, \lambda]$	Σ_c	1.50	$0.28 < T < 0.29$	1.09 ± 0.09	$\Sigma_c(3/2^-)$	2.78 ± 0.13	86 ± 36	0.055 ± 0.013 $(\Sigma_c^-(3/2^-))$
					$\Sigma_c(5/2^-)$	2.87 ± 0.11		0.033 ± 0.008 $(\Sigma_c^-(5/2^-))$
	$\Xi_c^\prime$	1.72	$0.27 < T < 0.32$	1.24 ± 0.12	$\Xi_c^\prime(3/2^-)$	2.96 ± 0.20	66 ± 27	0.057 ± 0.016 $(\Xi_c^{\prime-}(3/2^-))$
					$\Xi_c^\prime(5/2^-)$	3.02 ± 0.18		0.034 ± 0.009 $(\Xi_c^{\prime-}(5/2^-))$
	Ω_c	1.85	$0.26 < T < 0.33$	1.35 ± 0.11	$\Omega_c(3/2^-)$	3.08 ± 0.19	59 ± 24	0.103 ± 0.026 $(\Omega_c^-(3/2^-))$
					$\Omega_c(5/2^-)$	3.14 ± 0.18		0.062 ± 0.016 $(\Omega_c^-(5/2^-))$

Decay properties

P-wave charmed baryons of the flavor 6_F

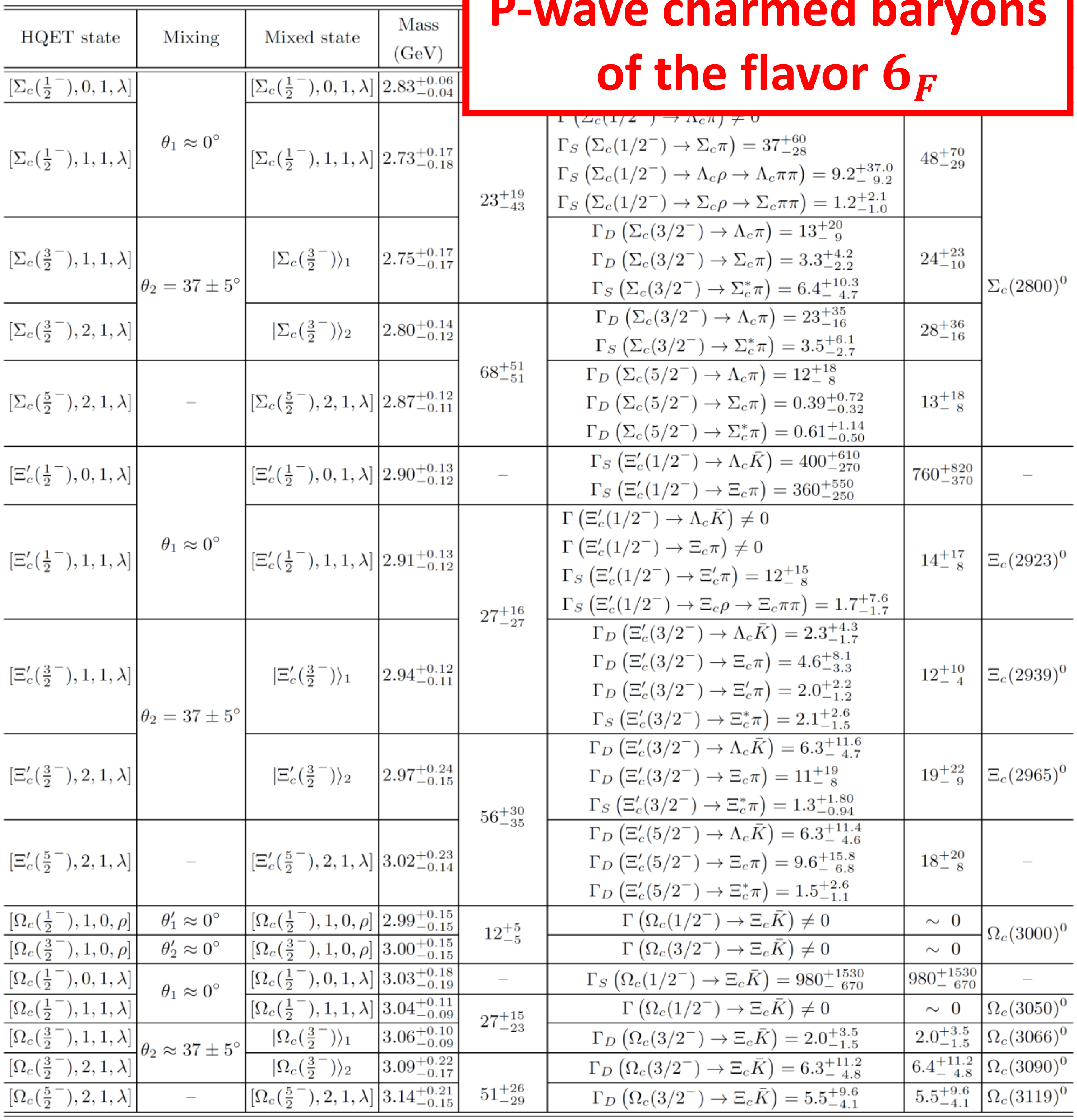
$\Omega_c^0(1/2^-) \rightarrow \Xi_c + \bar{K}$ (S-wave)

$\Omega_c^0(1/2^-) \rightarrow \Xi_c + \bar{K}^* \rightarrow \Xi_c + \bar{K} + \pi$

$\Omega_c^0(1/2^-) \rightarrow \Xi_c^* + \bar{K}$ (D-wave)

… …

Total: 128 decay channels



HQET state	Mixing	Mixed state	Mass (GeV)				
$[\Sigma_c(\frac{1}{2}^-),0,1,\lambda]$	$\theta_1 \approx 0^\circ$	$[\Sigma_c(\frac{1}{2}^-),0,1,\lambda]$	$2.83^{+0.06}_{-0.04}$				
$[\Sigma_c(\frac{1}{2}^-),1,1,\lambda]$		$[\Sigma_c(\frac{1}{2}^-),1,1,\lambda]$	$2.73^{+0.17}_{-0.18}$	23^{+19}_{-43}	$\Gamma(\Sigma_c(1/2^-) \to \Lambda_c\pi) \neq 0$ $\Gamma_S\left(\Sigma_c(1/2^-) \to \Sigma_c\pi\right) = 37^{+60}_{-28}$ $\Gamma_S\left(\Sigma_c(1/2^-) \to \Lambda_c\rho \to \Lambda_c\pi\pi\right) = 9.2^{+37.0}_{-\ 9.2}$ $\Gamma_S\left(\Sigma_c(1/2^-) \to \Sigma_c\rho \to \Sigma_c\pi\pi\right) = 1.2^{+2.1}_{-1.0}$	48^{+70}_{-29}	$\Sigma_c(2800)^0$
$[\Sigma_c(\frac{3}{2}^-),1,1,\lambda]$	$\theta_2 = 37 \pm 5^\circ$	$\vert\Sigma_c(\frac{3}{2}^-)\rangle_1$	$2.75^{+0.17}_{-0.17}$		$\Gamma_D\left(\Sigma_c(3/2^-) \to \Lambda_c\pi\right) = 13^{+20}_{-\ 9}$ $\Gamma_D\left(\Sigma_c(3/2^-) \to \Sigma_c\pi\right) = 3.3^{+4.2}_{-2.2}$ $\Gamma_S\left(\Sigma_c(3/2^-) \to \Sigma_c^*\pi\right) = 6.4^{+10.3}_{-\ 4.7}$	24^{+23}_{-10}	
$[\Sigma_c(\frac{3}{2}^-),2,1,\lambda]$		$\vert\Sigma_c(\frac{3}{2}^-)\rangle_2$	$2.80^{+0.14}_{-0.12}$	68^{+51}_{-51}	$\Gamma_D\left(\Sigma_c(3/2^-) \to \Lambda_c\pi\right) = 23^{+35}_{-16}$ $\Gamma_S\left(\Sigma_c(3/2^-) \to \Sigma_c^*\pi\right) = 3.5^{+6.1}_{-2.7}$	28^{+36}_{-16}	
$[\Sigma_c(\frac{5}{2}^-),2,1,\lambda]$	–	$[\Sigma_c(\frac{5}{2}^-),2,1,\lambda]$	$2.87^{+0.12}_{-0.11}$		$\Gamma_D\left(\Sigma_c(5/2^-) \to \Lambda_c\pi\right) = 12^{+18}_{-\ 8}$ $\Gamma_D\left(\Sigma_c(5/2^-) \to \Sigma_c\pi\right) = 0.39^{+0.72}_{-0.32}$ $\Gamma_D\left(\Sigma_c(5/2^-) \to \Sigma_c^*\pi\right) = 0.61^{+1.14}_{-0.50}$	$13^{+18}_{-\ 8}$	
$[\Xi_c'(\frac{1}{2}^-),0,1,\lambda]$	$\theta_1 \approx 0^\circ$	$[\Xi_c'(\frac{1}{2}^-),0,1,\lambda]$	$2.90^{+0.13}_{-0.12}$	–	$\Gamma_S\left(\Xi_c'(1/2^-) \to \Lambda_c\bar{K}\right) = 400^{+610}_{-270}$ $\Gamma_S\left(\Xi_c'(1/2^-) \to \Xi_c\pi\right) = 360^{+550}_{-250}$	760^{+820}_{-370}	–
$[\Xi_c'(\frac{1}{2}^-),1,1,\lambda]$		$[\Xi_c'(\frac{1}{2}^-),1,1,\lambda]$	$2.91^{+0.13}_{-0.12}$	27^{+16}_{-27}	$\Gamma\left(\Xi_c'(1/2^-) \to \Lambda_c\bar{K}\right) \neq 0$ $\Gamma\left(\Xi_c'(1/2^-) \to \Xi_c\pi\right) \neq 0$ $\Gamma_S\left(\Xi_c'(1/2^-) \to \Xi_c'\pi\right) = 12^{+15}_{-\ 8}$ $\Gamma_S\left(\Xi_c'(1/2^-) \to \Xi_c\rho \to \Xi_c\pi\pi\right) = 1.7^{+7.6}_{-1.7}$	$14^{+17}_{-\ 8}$	$\Xi_c(2923)^0$
$[\Xi_c'(\frac{3}{2}^-),1,1,\lambda]$	$\theta_2 = 37 \pm 5^\circ$	$\vert\Xi_c'(\frac{3}{2}^-)\rangle_1$	$2.94^{+0.12}_{-0.11}$		$\Gamma_D\left(\Xi_c'(3/2^-) \to \Lambda_c\bar{K}\right) = 2.3^{+4.3}_{-1.7}$ $\Gamma_D\left(\Xi_c'(3/2^-) \to \Xi_c\pi\right) = 4.6^{+8.1}_{-3.3}$ $\Gamma_D\left(\Xi_c'(3/2^-) \to \Xi_c'\pi\right) = 2.0^{+2.2}_{-1.2}$ $\Gamma_S\left(\Xi_c'(3/2^-) \to \Xi_c^*\pi\right) = 2.1^{+2.6}_{-1.5}$	$12^{+10}_{-\ 4}$	$\Xi_c(2939)^0$
$[\Xi_c'(\frac{3}{2}^-),2,1,\lambda]$		$\vert\Xi_c'(\frac{3}{2}^-)\rangle_2$	$2.97^{+0.24}_{-0.15}$	56^{+30}_{-35}	$\Gamma_D\left(\Xi_c'(3/2^-) \to \Lambda_c\bar{K}\right) = 6.3^{+11.6}_{-\ 4.7}$ $\Gamma_D\left(\Xi_c'(3/2^-) \to \Xi_c\pi\right) = 11^{+19}_{-\ 8}$ $\Gamma_S\left(\Xi_c'(3/2^-) \to \Xi_c^*\pi\right) = 1.3^{+1.80}_{-0.94}$	$19^{+22}_{-\ 9}$	$\Xi_c(2965)^0$
$[\Xi_c'(\frac{5}{2}^-),2,1,\lambda]$	–	$[\Xi_c'(\frac{5}{2}^-),2,1,\lambda]$	$3.02^{+0.23}_{-0.14}$		$\Gamma_D\left(\Xi_c'(5/2^-) \to \Lambda_c\bar{K}\right) = 6.3^{+11.4}_{-\ 4.6}$ $\Gamma_D\left(\Xi_c'(5/2^-) \to \Xi_c\pi\right) = 9.6^{+15.8}_{-\ 6.8}$ $\Gamma_D\left(\Xi_c'(5/2^-) \to \Xi_c^*\pi\right) = 1.5^{+2.6}_{-1.1}$	$18^{+20}_{-\ 8}$	–
$[\Omega_c(\frac{1}{2}^-),1,0,\rho]$	$\theta_1' \approx 0^\circ$	$[\Omega_c(\frac{1}{2}^-),1,0,\rho]$	$2.99^{+0.15}_{-0.15}$	12^{+5}_{-5}	$\Gamma\left(\Omega_c(1/2^-) \to \Xi_c\bar{K}\right) \neq 0$	$\sim\ 0$	$\Omega_c(3000)^0$
$[\Omega_c(\frac{3}{2}^-),1,0,\rho]$	$\theta_2' \approx 0^\circ$	$[\Omega_c(\frac{3}{2}^-),1,0,\rho]$	$3.00^{+0.15}_{-0.15}$		$\Gamma\left(\Omega_c(3/2^-) \to \Xi_c\bar{K}\right) \neq 0$	$\sim\ 0$	
$[\Omega_c(\frac{1}{2}^-),0,1,\lambda]$	$\theta_1 \approx 0^\circ$	$[\Omega_c(\frac{1}{2}^-),0,1,\lambda]$	$3.03^{+0.18}_{-0.19}$	–	$\Gamma_S\left(\Omega_c(1/2^-) \to \Xi_c\bar{K}\right) = 980^{+1530}_{-\ 670}$	$980^{+1530}_{-\ 670}$	–
$[\Omega_c(\frac{1}{2}^-),1,1,\lambda]$		$[\Omega_c(\frac{1}{2}^-),1,1,\lambda]$	$3.04^{+0.11}_{-0.09}$	27^{+15}_{-23}	$\Gamma\left(\Omega_c(1/2^-) \to \Xi_c\bar{K}\right) \neq 0$	$\sim\ 0$	$\Omega_c(3050)^0$
$[\Omega_c(\frac{3}{2}^-),1,1,\lambda]$	$\theta_2 \approx 37 \pm 5^\circ$	$\vert\Omega_c(\frac{3}{2}^-)\rangle_1$	$3.06^{+0.10}_{-0.09}$		$\Gamma_D\left(\Omega_c(3/2^-) \to \Xi_c\bar{K}\right) = 2.0^{+3.5}_{-1.5}$	$2.0^{+3.5}_{-1.5}$	$\Omega_c(3066)^0$
$[\Omega_c(\frac{3}{2}^-),2,1,\lambda]$		$\vert\Omega_c(\frac{3}{2}^-)\rangle_2$	$3.09^{+0.22}_{-0.17}$	51^{+26}_{-29}	$\Gamma_D\left(\Omega_c(3/2^-) \to \Xi_c\bar{K}\right) = 6.3^{+11.2}_{-\ 4.8}$	$6.4^{+11.2}_{-\ 4.8}$	$\Omega_c(3090)^0$
$[\Omega_c(\frac{5}{2}^-),2,1,\lambda]$	–	$[\Omega_c(\frac{5}{2}^-),2,1,\lambda]$	$3.14^{+0.21}_{-0.15}$		$\Gamma_D\left(\Omega_c(3/2^-) \to \Xi_c\bar{K}\right) = 5.5^{+9.6}_{-4.1}$	$5.5^{+9.6}_{-4.1}$	$\Omega_c(3119)^0$

Our QCD sum rule studies

- 1502.01103 Masses of P-wave charmed baryons ($\bar{3}_F$ and 6_F)
- 1510.05267 Masses of P-wave bottom baryons ($\bar{3}_F$ and 6_F)
- 1611.02677 Masses of D-wave charmed/bottom baryons ($\bar{3}_F$)
- 1707.03712 Masses of D-wave charmed/bottom baryons (6_F)
- 1703.07703 Decays of P-wave charmed baryons ($\bar{3}_F$ and 6_F, partly)
- 1903.10369 Decays of P-wave bottom baryons (6_F, partly)
- 1909.13575 Decays of P-wave bottom baryons ($\bar{3}_F$ and 6_F, partly)
- 2003.07488 Masses/Decays of P-wave bottom baryons (6_F, fully)
- 2106.15488 Masses/Decays of P-wave charmed baryons (6_F, fully)

Heavy baryons possibly known

P-wave charmed baryons of the flavor $\bar{\mathbf{3}}_F$

$$L = 1, \boldsymbol{j_l = 1}, J^P = (1/2^-, 3/2^-) \quad \bar{3}_F \begin{cases} (\Lambda_c(2595), \Lambda_c(2625)) \\ (\Xi_c(2790), \Xi_c(2815)) \end{cases}$$

$$1/2^- \qquad 3/2^-$$

P-wave bottom baryons of the flavor $\bar{\mathbf{3}}_F$

$$1/2^- \qquad 3/2^-$$

$$L = 1, \boldsymbol{j_l = 1}, J^P = (1/2^-, 3/2^-) \quad \bar{3}_F \begin{cases} (\Lambda_b(5912), \Lambda_b(5920)) \\ (\Xi_b(?), \Xi_b(6100)) \end{cases}$$

missing

Heavy baryons possibly known

D-wave charmed baryons of the flavor $\bar{3}_F$

$$L = 2, j_l = 2, J^P = (3/2^+, 5/2^+) \quad \bar{3}_F \begin{cases} (\Lambda_c(2860), \Lambda_c(2880)) \\ (\Xi_c(3055), \Xi_c(3080)) \end{cases}$$

$3/2^+$ $5/2^+$

D-wave bottom baryons of the flavor $\bar{3}_F$

$3/2^+$ $5/2^+$

$$L = 2, j_l = 2, J^P = (3/2^+, 5/2^+) \quad \bar{3}_F \begin{cases} (\Lambda_b(6146), \Lambda_b(6152)) \\ (\Xi_b(6327), \Xi_b(6333)) \end{cases}$$

Heavy baryons not well known

P-wave charmed baryons of the flavor 6_F

$L = 1, j_l = ?, J^P = ?^-$

$$6_F \begin{cases} \Sigma_c(2800) \\ \Xi_c(2923), \Xi_c(2939), \Xi_c(2965) \\ \Omega_c(3000), \Omega_c(3050), \Omega_c(3066), \Omega_c(3090), \Omega_c(3119) \end{cases}$$

Many of them are missing

P-wave bottom baryons of the flavor 6_F

$L = 1, j_l = ?, J^P = ?^-$

$$6_F \begin{cases} \Sigma_b(6097) \\ \Xi_b(6227) \\ \Omega_b(6316), \Omega_b(6330), \Omega_b(6340), \Omega_b(6350) \end{cases}$$

Many of them are missing

Summary

- Thanks to the efforts of experimentalists, various signals of heavy baryons and exotic hadrons were observed in recent years, making hadron physics popular once more.

- Different from exotic hadrons, we know the internal structure of heavy mesons and heavy baryons much better. Especially, the heavy quark effective theory plays an important role.

- All the above assignments are just possible assignments. We propose to search for more excited heavy hadrons in future experiments.

Thank you very much!