Theoretical Progress of Heavy Hadrons

Hua-Xing Chen

Beihang University

Collaborators: Wei Chen, Atsushi Hosaka, Xiang Liu, Qiang Mao, Shi-Lin Zhu

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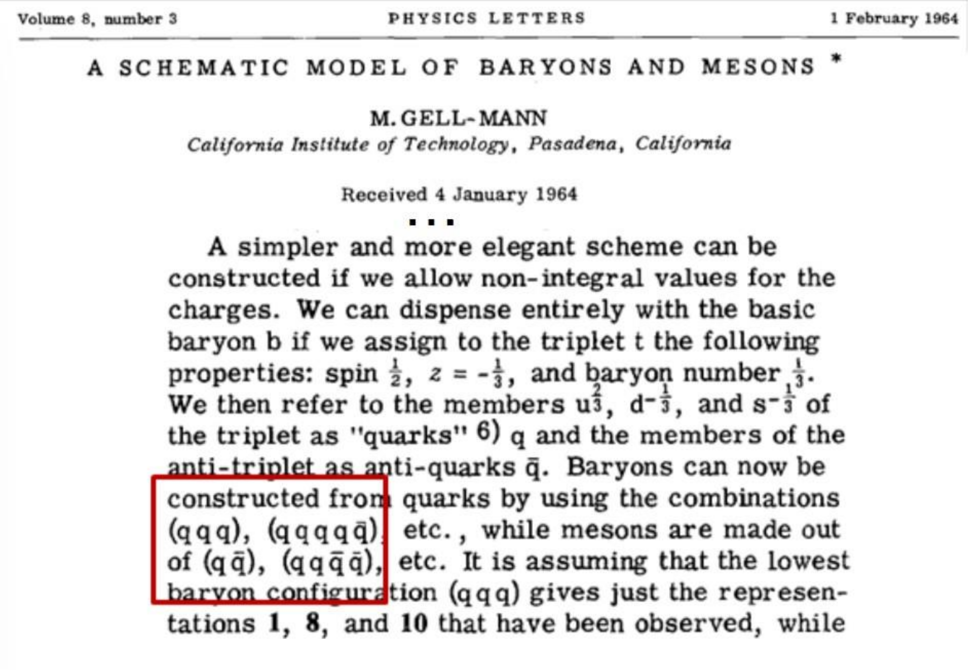
Phys.Lett. 8 (1964) 214-215



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

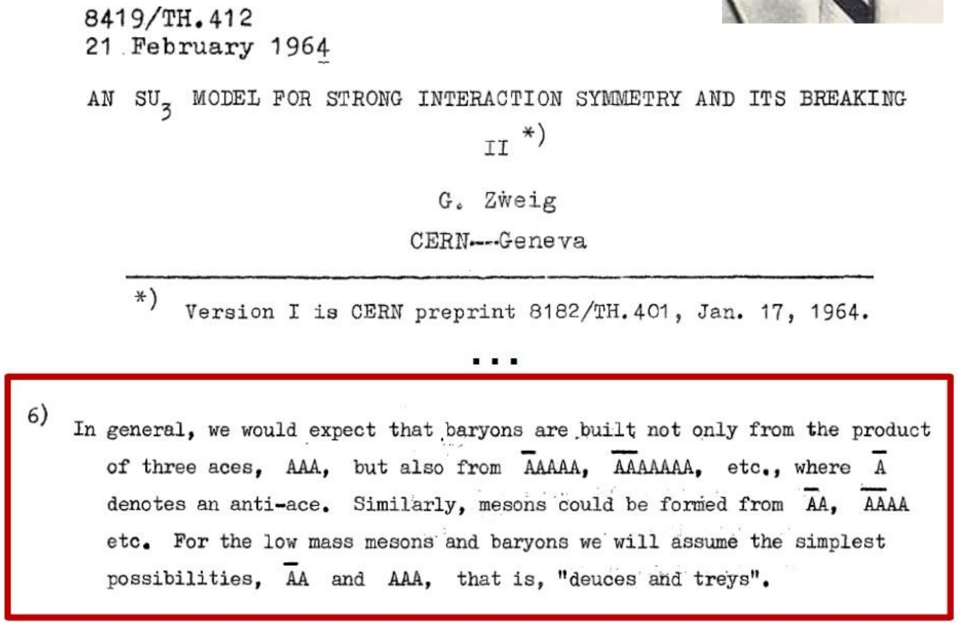
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

...

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING II *)

G. Zweig
CERN---Geneva

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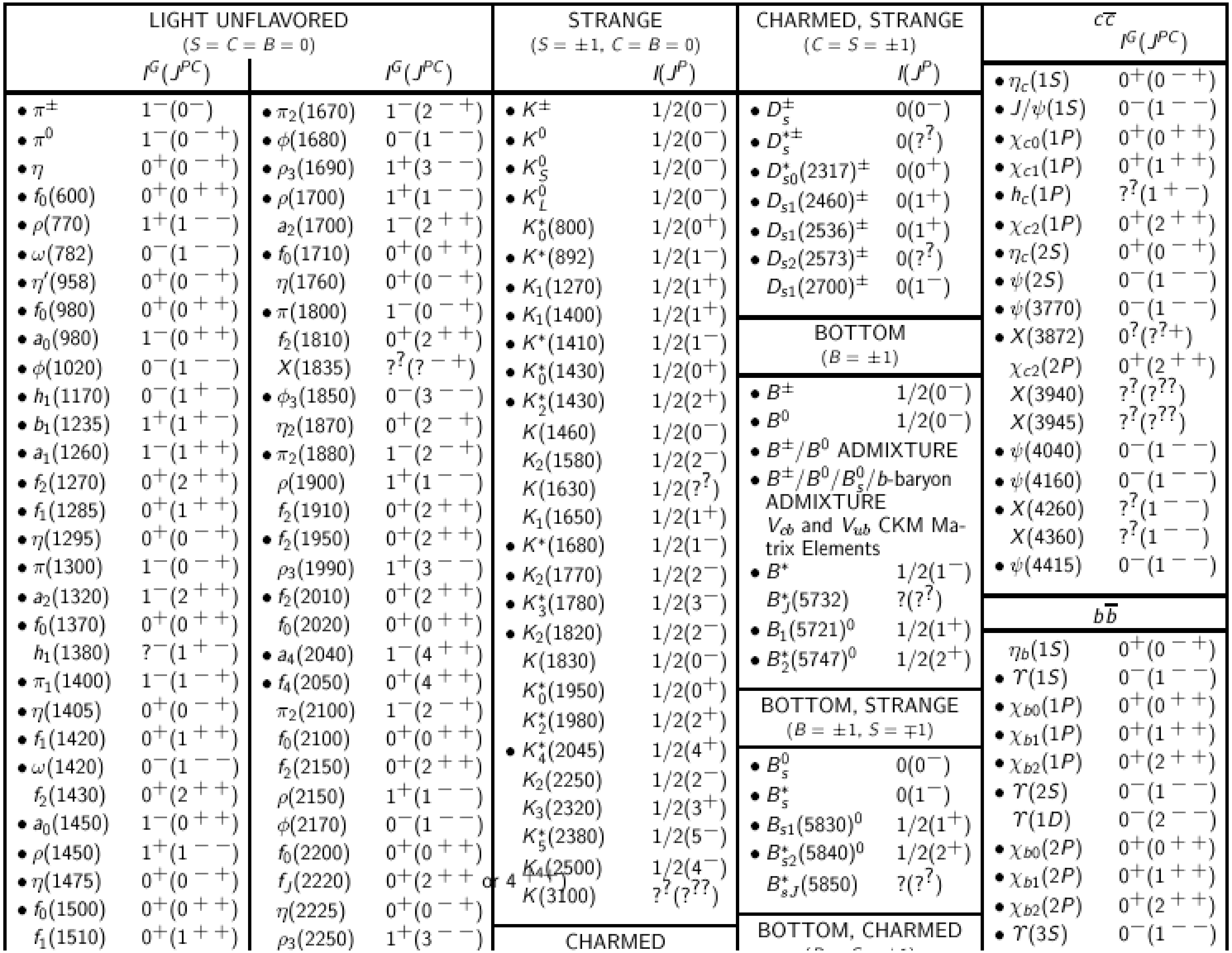
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

Quark Model



LIGHT UNFLAVORED
($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	• $\pi_2(1880)$	$1^-(2^{-+})$
• $f_2(1270)$	$0^+(2^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_1(1285)$	$0^+(1^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	• $f_2(1950)$	$0^+(2^{++})$
• $\pi(1300)$	$1^-(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $a_2(1320)$	$1^-(2^{++})$	• $f_2(2010)$	$0^+(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$	$f_0(2020)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $a_4(2040)$	$1^-(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	• $f_4(2050)$	$0^+(4^{++})$
• $\eta(1405)$	$0^+(0^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $f_1(1420)$	$0^+(1^{++})$	$f_0(2100)$	$0^+(0^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$f_2(2150)$	$0^+(2^{++})$
$f_2(1430)$	$0^+(2^{++})$	$\rho(2150)$	$1^+(1^{--})$
• $a_0(1450)$	$1^-(0^{++})$	$\phi(2170)$	$0^-(1^{--})$
• $\rho(1450)$	$1^+(1^{--})$	$f_0(2200)$	$0^+(0^{++})$
• $\eta(1475)$	$0^+(0^{-+})$	$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
• $f_0(1500)$	$0^+(0^{++})$	$\eta(2225)$	$0^+(0^{-+})$
$f_1(1510)$	$0^+(1^{++})$	$\rho_3(2250)$	$1^+(3^{--})$

STRANGE
($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K^*_0(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED

CHARMED, STRANGE
($C = S = \pm1$)

	$I(J^P)$
• $D^{\pm}_s$	$0(0^-)$
• $D^{*\pm}_s$	$0(?^?)$
• $D^*_{s0}(2317)^{\pm}$	$0(0^+)$
• $D_{s1}(2460)^{\pm}$	$0(1^+)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{s2}(2573)^{\pm}$	$0(?^?)$
$D_{s1}(2700)^{\pm}$	$0(1^-)$

BOTTOM
($B = \pm1$)

• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^{\pm}/B^0$ ADMIXTURE	
• $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B^*_2(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE
($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
• B^*_s	$0(1^-)$
• $B_{s1}(5830)^0$	$1/2(1^+)$
• $B^*_{s2}(5840)^0$	$1/2(2^+)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED

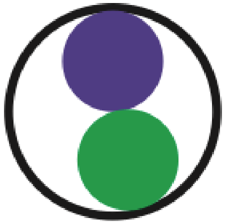
$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
$\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(3945)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
• $X(4260)$	$?^?(1^{--})$
$X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

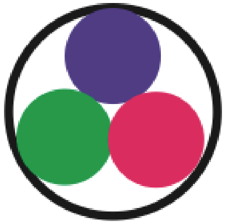
$b\overline{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$

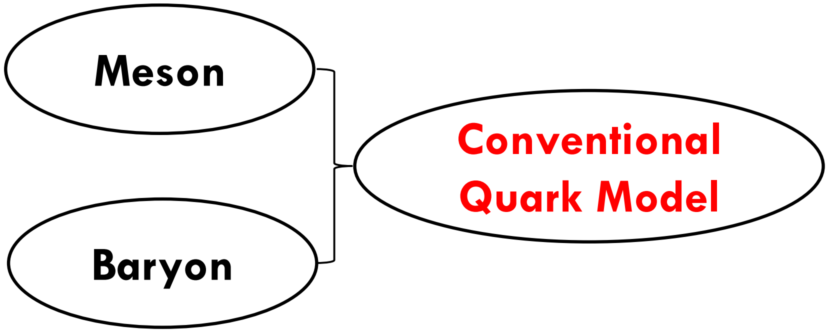
Categorizations



meson($q\bar{q}$)



baryon(qqq)

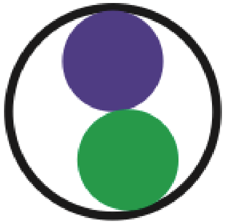


Meson

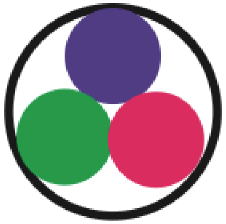
Baryon

Conventional Quark Model

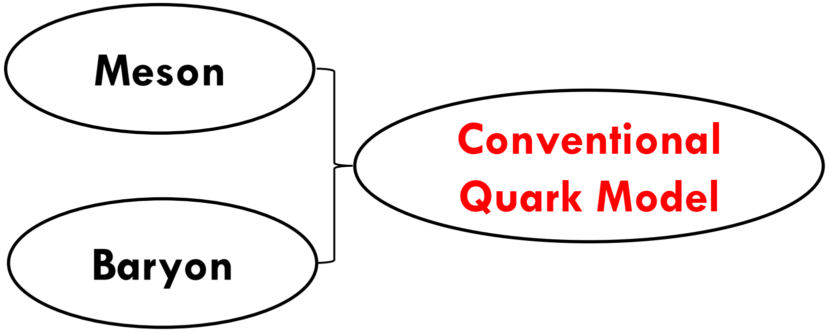
Categorizations



meson($q\bar{q}$)



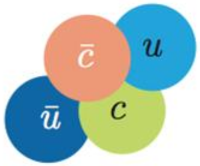
baryon(qqq)



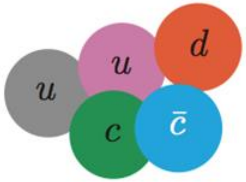
Meson

Baryon

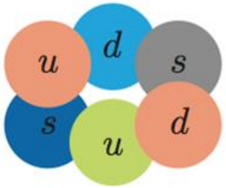
Conventional Quark Model



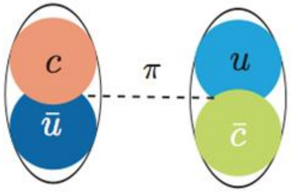
tetraquark



pentaquark

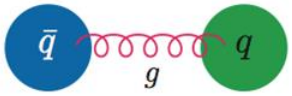


dibaryon

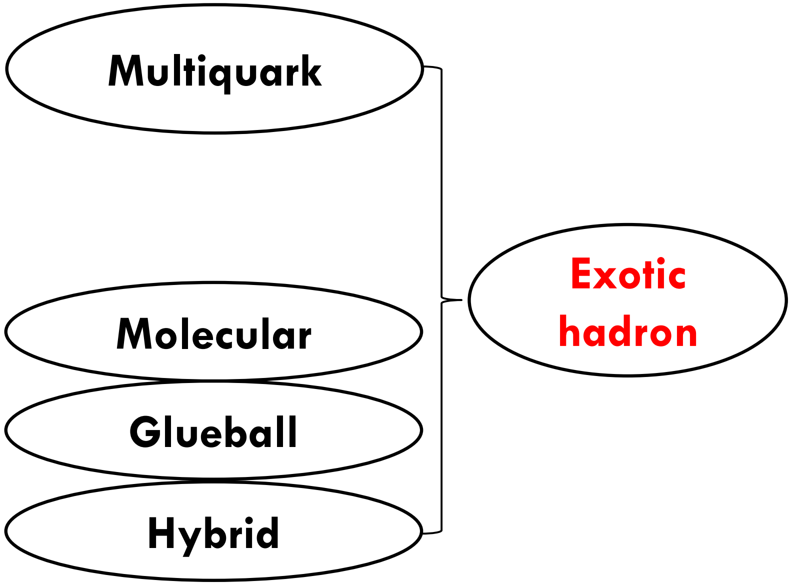


molecule

glueball



hybrid



Multiquark

Molecular

Glueball

Hybrid

Exotic hadron

Theoretical explanations of experimental signals

Resonant

- **Conventional hadrons**
- **Exotic states**
  - **Molecular states:**
    loosely bound states composed of a pair of mesons/baryons; probab bounded by the pion exchange.
  - **Multiquark states:**
    bound states of four/five/six quarks; bounded by colored-force between quarks; there are many states within the same multiplet.
  - **Hybrids:**
    bound states composed of a pair of quarks and one valance gluon.

$D_{s0}^{*}(2317)$

$D_{s1}(2460)$

…

Non-Resonant

Many exotic states lie very close to open-charm threshold; It's quite possible that some threshold enhancements are not real resonances.

- **Kinematical effect**

  Opening of new threshold

  Cusp effect
- **Final state interaction**
- **Interference between continuum and charmonium states**
- **Triangle singularity due to the special kinematics**

Theoretical methods/models mostly from **Quark** Level

- Various quark models
- Various effective methods
- Lattice QCD
- **QCD sum rules**

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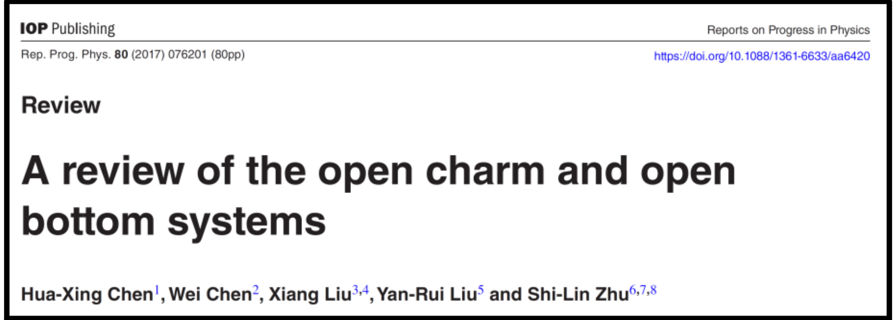

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Reports on Progress in Physics

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

https://doi.org/10.1088/1361-6633/aa6420

Review

A review of the open charm and open bottom systems

Hua-Xing Chen[1], Wei Chen[2], Xiang Liu[3,4], Yan-Rui Liu[5] and Shi-Lin Zhu[6,7,8]

Frontiers of Physics

December 2015, 10:101406 | Cite as

Charmed baryons circa 2015

Authors

Authors and affiliations

Hai-Yang Cheng

- Some non-resonant explanations

- Many methods/models to study productions and decay patterns of exotic hadrons

Theoretical methods/models mostly from Quark Level

- Various quark models
- Various effective methods
- Lattice QCD
- **QCD sum rules**

……

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Review

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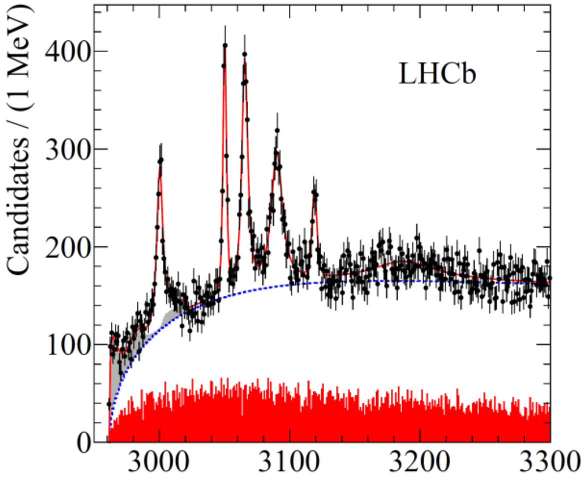
Hai-Yang Cheng

These studies help to understand **the internal structure** of hadrons



The LHCb Experiment [arXiv:1703.04639]

fine structure of QCD?

Internal structure of hadrons

- The internal structure of hadrons is complicated.

- We can construct various interpolating currents to reflect this using the method of

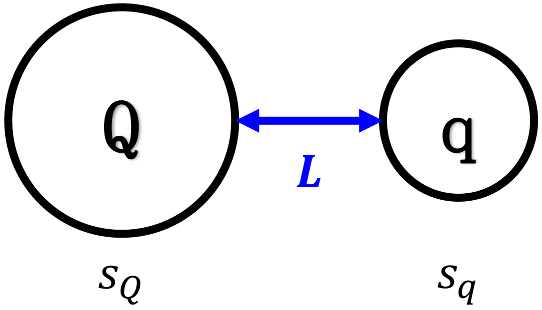
QCD sum rules within

heavy quark effective theory (HQET)

CONTENTS

Internal structure of heavy mesons

heavy meson (Q-q):



$$J = s_Q + s_q + L$$

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 (Q-q): $$\boldsymbol{J} = \boldsymbol{s_Q} + \left(\boldsymbol{L} + \boldsymbol{s_q}\right)_{\boldsymbol{j_l}}$$

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 (Q-q):

$$\boldsymbol{J} = \underbrace{\boldsymbol{s_Q}}_{\boxed{=1/2}} + \left(\boldsymbol{L} + \underbrace{\boldsymbol{s_q}}_{\boxed{=1/2}}\right)_{\boldsymbol{j_l}}$$

Internal structure of heavy mesons

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

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

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 (Q-q): $$\boldsymbol{J} = \underbrace{\boldsymbol{s_Q}}_{\boxed{=1/2}} + \big(\boldsymbol{L} + \underbrace{\boldsymbol{s_q}}_{\boxed{=1/2}}\big)_{j_l}$$

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

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

Internal structure of heavy mesons

- 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 (Q-q): $$\boldsymbol{J} = \underbrace{\boldsymbol{s_Q}}_{\boxed{=1/2}} + \left(\boldsymbol{L} + \underbrace{\boldsymbol{s_q}}_{\boxed{=1/2}}\right)_{\boldsymbol{j_l}}$$

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

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

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

Internal structure of heavy mesons

- We can construct relevant interpolating fields with derivatives to well describe the above internal structure:

$L = 2:$

$j_l = 3/2$

$J^P = (1^-, 2^-)$

$$J^{\dagger\alpha}_{1,-,3/2} = \sqrt{\frac{3}{4}}\bar{h}_v(-i)\left(\mathcal{D}^{\alpha}_t - \frac{1}{3}\gamma^{\alpha}_t \not{\mathcal{D}}_t\right)\not{\mathcal{D}}_t q,$$

$$J^{\dagger\alpha_1\alpha_2}_{2,-,3/2} = \sqrt{\frac{1}{2}}\bar{h}_v\gamma^5 \frac{(-i)^2}{2}\left(\gamma^{\alpha_1}_t \mathcal{D}^{\alpha_2}_t \not{\mathcal{D}}_t + \gamma^{\alpha_2}_t \mathcal{D}^{\alpha_1}_t \not{\mathcal{D}}_t - \frac{2}{3} g^{\alpha_1\alpha_2}_t \mathcal{D}_t \cdot \mathcal{D}_t\right) q,$$

$j_l = 5/2$

$J^P = (2^-, 3^-)$

$$\begin{aligned} J^{\dagger\alpha_1\alpha_2}_{2,-,5/2} = \sqrt{\frac{5}{6}}\bar{h}_v\gamma^5 \frac{(-i)^2}{2}\Big(&\mathcal{D}^{\alpha_2}_t \mathcal{D}^{\alpha_1}_t + \mathcal{D}^{\alpha_1}_t \mathcal{D}^{\alpha_2}_t - \frac{2}{5}\mathcal{D}^{\alpha_2}_t \gamma^{\alpha_1}_t \not{\mathcal{D}}_t \\ &- \frac{2}{5}\mathcal{D}^{\alpha_1}_t \gamma^{\alpha_2}_t \not{\mathcal{D}}_t - \frac{2}{5} g^{\alpha_1\alpha_2}_t \mathcal{D}_t \cdot \mathcal{D}_t\Big) q, \end{aligned}$$

$$J^{\dagger\alpha_1\alpha_2\alpha_3}_{3,-,\frac{5}{2}} = \sqrt{\frac{1}{2}}\bar{h}_v \mathcal{S}_1[\gamma^{\alpha_1}_t (-i)^2 \mathcal{D}^{\alpha_2}_t \mathcal{D}^{\alpha_3}_t] q\,,$$

- Through QCD sum rules, the mass splitting within the same doublet can be evaluated quite well with much less uncertainties.

			D mesons (c-q)		Ds mesons (c-s)	
	Multiplets	J^P	**Experiments**	Ours	**Experiments**	Ours
S-wave	$L=0, j_l=\frac{1}{2}$	0^-	$\mathbf{D}$	--	$\mathbf{D_s}$	--
		1^-	$\mathbf{D^*}$	--	$\mathbf{D_s^*}$	--
P-wave	$L=1, j_l=\frac{1}{2}$	0^+	$\mathbf{D_0^*(2400)}$	--	$\mathbf{D_{s0}^*(2317)}$	--
		1^+	$\mathbf{D_1(2420)}$	--	$\mathbf{D_{s1}(2460)}$	--
	$L=1, j_l=\frac{3}{2}$	1^+	$\mathbf{D_1(2430)}$	--	$\mathbf{D_{s1}(2536)}$	--
		2^+	$\mathbf{D_2^*(2460)}$	--	$\mathbf{D_{s2}^*(2573)}$	--
D-wave	$L=2, j_l=\frac{3}{2}$	1^-	$\mathbf{D_1^*(2760)}$	2.75 GeV	$\mathbf{D_{s1}^*(2860)}$	2.81 GeV
		2^-	$\mathbf{D(2750)?}$	2.78 GeV	**--**	2.82 GeV
	$L=2, j_l=\frac{5}{2}$	2^-		2.72 GeV	**--**	2.81 GeV
		3^-	$\mathbf{D_3^*(2760)}$	2.78 GeV	$\mathbf{D_{s3}^*(2860)}$	2.85 GeV
F-wave	$L=3, j_l=\frac{5}{2}$	2^+	--	--	--	3.45 GeV
		3^+	--	--	--	3.50 GeV
	$L=3, j_l=\frac{7}{2}$	3^+	--	--	--	3.20 GeV
		4^+	--	--	--	3.26 GeV

			D mesons (c-q)		**Ds mesons (c-s)**	
	Multiplets	J^P	**Experiments**	Ours	**Experiments**	Ours
S-wave	$L=0, j_l=\frac{1}{2}$	0^-	$\mathbf{D}$	--	$\mathbf{D_s}$	--
		1^-	$\mathbf{D^*}$	--	$\mathbf{D_s^*}$	--
P-wave	$L=1, j_l=\frac{1}{2}$	0^+	$\mathbf{D_0^*(2400)}$	--	$\mathbf{D_{s0}^*(2317)}$	--
		1^+	$\mathbf{D_1(2420)}$	--	$\mathbf{D_{s1}(2460)}$	--
	$L=1, j_l=\frac{3}{2}$	1^+	$\mathbf{D_1(2430)}$	--	$\mathbf{D_{s1}(2536)}$	--
		2^+	$\mathbf{D_2^*(2460)}$	--	$\mathbf{D_{s2}^*(2573)}$	--
D-wave	$L=2, j_l=\frac{3}{2}$	1^-	$\mathbf{D_1^*(2760)}$	2.75 GeV	$\mathbf{D_{s1}^*(2860)}$	2.81 GeV
		2^-	$\mathbf{D(2750)?}$	2.78 GeV	**--**	2.82 GeV
	$L=2, j_l=\frac{5}{2}$	2^-		2.72 GeV	**--**	2.81 GeV
		3^-	$\mathbf{D_3^*(2760)}$	2.78 GeV	$\mathbf{D_{s3}^*(2860)}$	2.85 GeV
F-wave	$L=3, j_l=\frac{5}{2}$	2^+	--	--	--	3.45 GeV
		3^+	--	--	--	3.50 GeV
	$L=3, j_l=\frac{7}{2}$	3^+	--	--	--	3.20 GeV
		4^+	--	--	--	3.26 GeV

			D mesons (c-q)		Ds mesons (c-s)	
	Multiplets	J^P	**Experiments**	Ours	**Experiments**	Ours
S-wave	$L=0, j_l=\frac{1}{2}$	0^-	$\mathbf{D}$	--	$\mathbf{D_s}$	--
		1^-	$\mathbf{D^*}$	--	$\mathbf{D_s^*}$	--
P-wave	$L=1, j_l=\frac{1}{2}$	0^+	$\mathbf{D_0^*(2400)}$	--	$\mathbf{D_{s0}^*(2317)}$	--
		1^+	$\mathbf{D_1(2420)}$	--	$\mathbf{D_{s1}(2460)}$	--
	$L=1, j_l=\frac{3}{2}$	1^+	$\mathbf{D_1(2430)}$	--	$\mathbf{D_{s1}(2536)}$	--
		2^+	$\mathbf{D_2^*(2460)}$	--	$\mathbf{D_{s2}^*(2573)}$	--
D-wave	$L=2, j_l=\frac{3}{2}$	1^-	$\mathbf{D_1^*(2760)}$	2.75 GeV	$\mathbf{D_{s1}^*(2860)}$	2.81 GeV
		2^-	$\mathbf{D(2750)?}$	2.78 GeV	**--**	2.82 GeV
	$L=2, j_l=\frac{5}{2}$	2^-		2.72 GeV	**--**	2.81 GeV
		3^-	$\mathbf{D_3^*(2760)}$	2.78 GeV	$\mathbf{D_{s3}^*(2860)}$	2.85 GeV
F-wave	$L=3, j_l=\frac{5}{2}$	2^+	--	--	--	3.45 GeV
		3^+	--	--	--	3.50 GeV
	$L=3, j_l=\frac{7}{2}$	3^+	--	--	--	3.20 GeV
		4^+	--	--	--	3.26 GeV

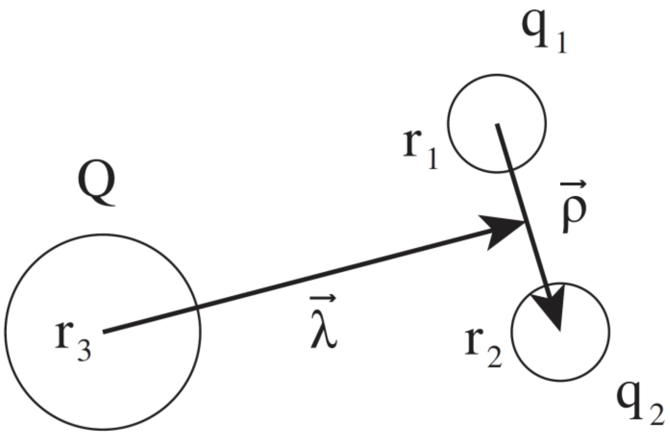
CONTENTS

What is more interesting: heavy baryons

The internal structure of heavy baryons is more complicated than heavy mesons, and more interesting:

λ-excitation and ρ-excitation

heavy baryon (Q-q_1-q_2):



$$J = s_Q + s_{q1} + s_{q2} + l_\rho + l_\lambda$$

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

What is more interesting: heavy baryons

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

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

What is more interesting: heavy baryons

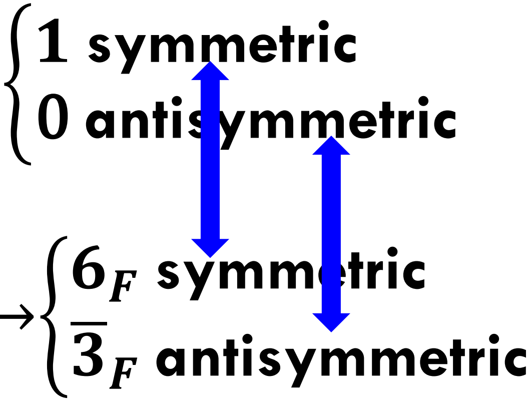
S-wave heavy baryons:

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

What is more interesting: heavy baryons

S-wave heavy baryons:

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



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

What is more interesting: heavy baryons

S-wave heavy baryons:

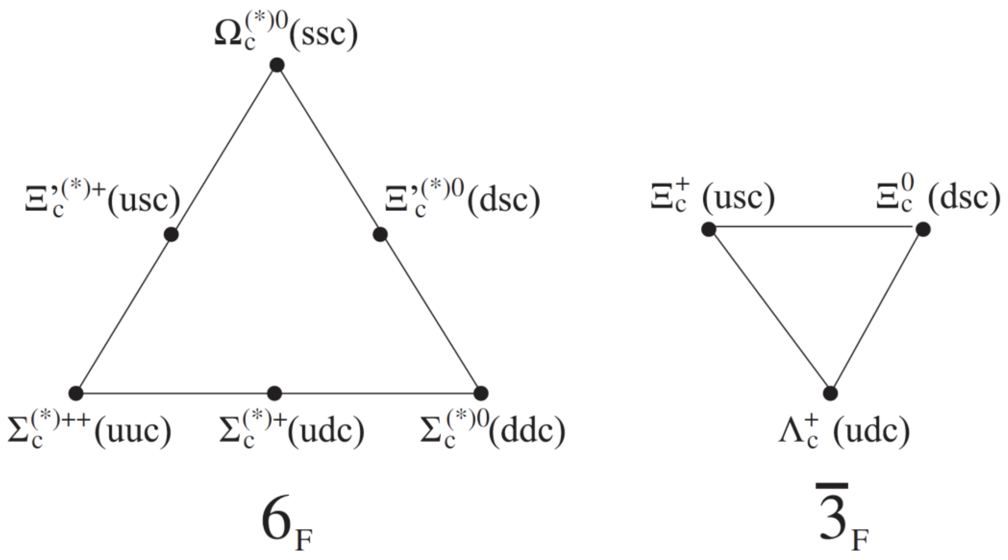
- color$\longrightarrow \bar{3}_C$ **antisymmetric**
- orbital$\longrightarrow \boldsymbol{l_\rho = 0}$ **symmetric**
- spin$\longrightarrow \boldsymbol{s_{qq}} = \begin{cases} \mathbf{1}\ \textbf{symmetric} \\ 0\ \textbf{antisymmetric} \end{cases}$
- SU(3) flavor$\longrightarrow \begin{cases} \boldsymbol{6_F}\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

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

What is more interesting: heavy baryons

S-wave heavy baryons:

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



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

heavy baryons well known

S-wave charmed baryons

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

S-wave bottom baryons

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

heavy baryons well known

S-wave charmed baryons

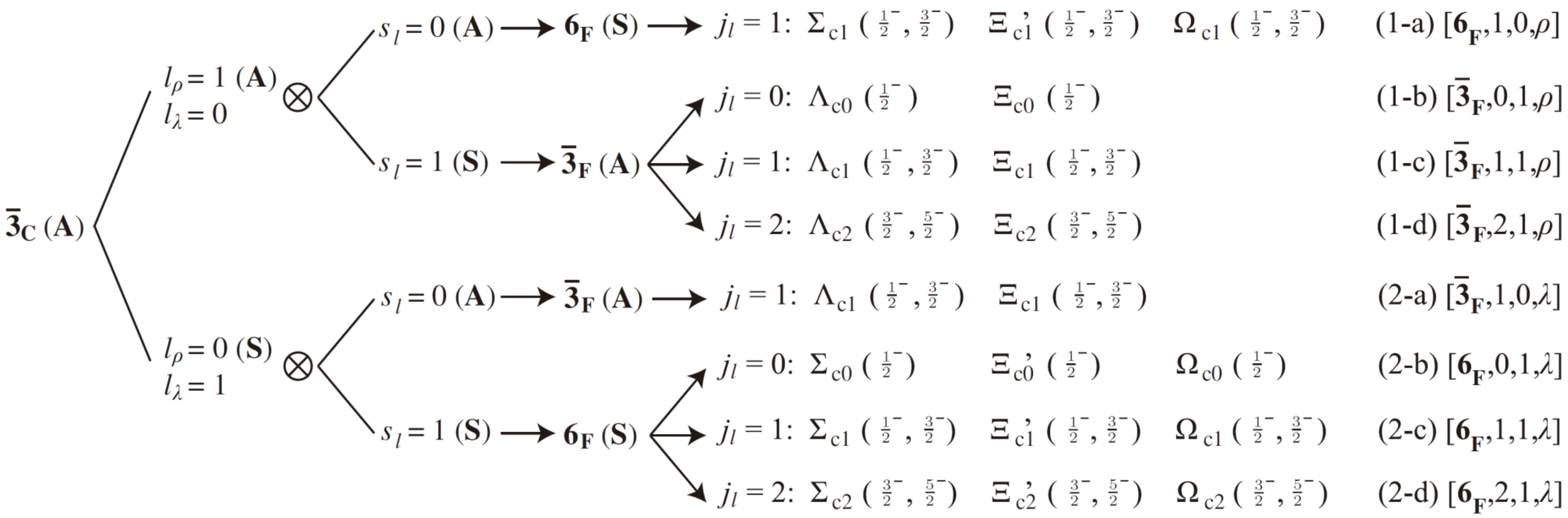
$$L=0\begin{cases}j_l=\mathbf{0}, J^P=1/2^+ & \bar{3}_F:\ \Lambda_c,\Xi_c\\ j_l=\mathbf{1}, J^P=(1/2^+,3/2^+) & 6_F:(\Sigma_c,\Sigma_c^*),(\Xi_c',\Xi_c^*),(\Omega_c,\Omega_c^*)\end{cases}$$

S-wave bottom baryons

$$L=0\begin{cases}j_l=\mathbf{0}, J^P=1/2^+ & \bar{3}_F:\ \Lambda_b,\Xi_b\\ j_l=\mathbf{1}, J^P=(1/2^+,3/2^+) & 6_F:(\Sigma_b,\Sigma_b^*),(\Xi_b',\Xi_b^*),(\Omega_b,\underset{\uparrow}{\Omega_b^*})\end{cases}$$

missing

P-wave charmed baryons



$\bar{\mathbf{3}}_{\mathrm{C}}$ (**A**)

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

$s_l = 0$ (**A**) $\longrightarrow$ $\mathbf{6}_{\mathrm{F}}$ (**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) $[\mathbf{6}_{\mathrm{F}},1,0,\rho]$

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

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

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

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

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

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

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

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

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

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

heavy baryons possibly known

P-wave charmed baryons

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

P-wave bottom baryons

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

heavy baryons possibly known

P-wave charmed baryons

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

P-wave bottom baryons

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

missing

heavy baryons possibly known

D-wave charmed baryons

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

D-wave bottom baryons

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

heavy baryons possibly known

D-wave charmed baryons

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

D-wave bottom baryons

$$L = 2, \boldsymbol{j_l = 2}, J^P = (3/2^+, 5/2^+) \quad \bar{3}_F \left\{ \begin{array}{l} (\Lambda_b(?\,), \Lambda_b(?\,)) \\ (\Xi_b(?\,), \Xi_b(?\,)) \end{array} \right.$$

missing

heavy baryons not well known

P-wave charmed baryons

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

$$6_F \begin{cases} \Sigma_c(2800), ? \\ \Xi_c(2930), \Xi_c(2980), ? \\ \Omega_c(3000), \Omega_c(3050), \Omega_c(3066), \Omega_c(3090), \Omega_c(3119)? \end{cases}$$

heavy baryons not well known

P-wave charmed baryons

$$L = 1, \boldsymbol{j_l} = ?, J^P = (?^-, ?^-)$$

Are there more $\Sigma_c(1P)$ and $\Xi_c(1P)$ states?

$$6_F \begin{cases} \Sigma_c(2800), ? \\ \Xi_c(2930), \Xi_c(2980), ? \\ \Omega_c(3000), \Omega_c(3050), \Omega_c(3066), \Omega_c(3090), \Omega_c(3119)? \end{cases}$$

Which Ω_c states are 1P states?

The doubly heavy baryon $\Xi_{cc}^{++}(3621)$

- The **heavy quark effective theory** may not be very appropriate to study doubly heavy baryons, but their internal structure is still interesting.
- We propose to search for the doubly heavy baryon Ξ_{cc}^{*} of $J^P = 3/2^+$ via its electromagnetic transition:

$$\Gamma(\Xi_{cc}^{*++} \to \gamma\Xi_{cc}^{++}) = 13.7_{-7.9}^{+17.7}\ keV.$$

Several Remarks

- Thanks to the efforts of experimentalists, various signals of heavy hadrons as well as exotic hadrons were observed in recent years, making hadron physics popular once more.
- Different from exotic hadrons, it seems that we well know the internal structure of heavy mesons and heavy baryons. Especially, the heavy quark effective theory plays an important role.
- All the above assignments are just possible assignments. We propose to search for higher excited heavy hadrons in future experiments to further understand them.

Thank you very much!

谢谢

QCD SUM RULE

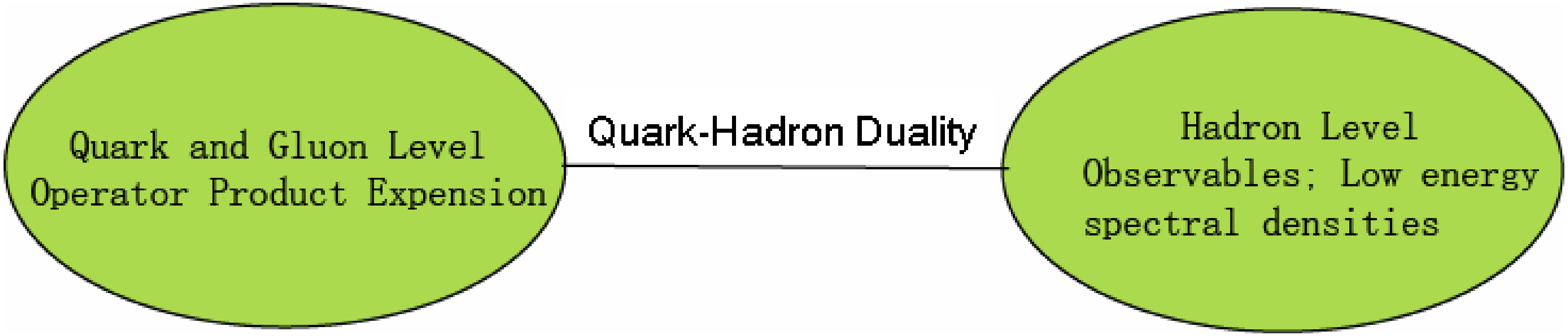
- In sum rule analyses, we consider two-point correlation functions:

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

$$\approx \sum_n \langle 0|\eta|n\rangle\langle n|\eta^+|0\rangle$$

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

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



SVZ sum rule (Shifman 1979)

Quark and Gluon Level

(Convergence of OPE)

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

Quark-Hadron Duality

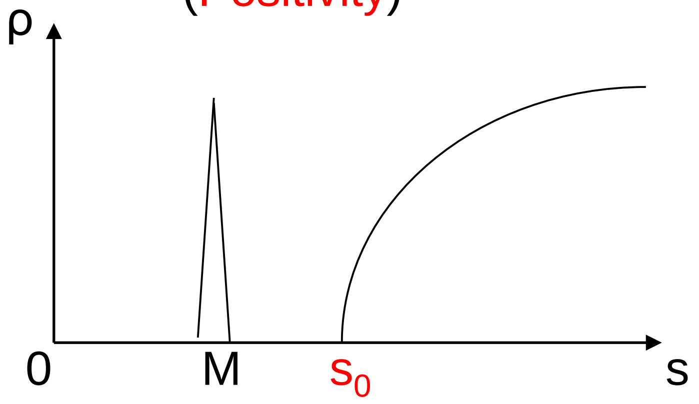
Hadron Level

$$\Pi_{phys}(q^2) = f_P^2\, \frac{\not{q} + M}{q^2 - M^2} \longleftrightarrow \rho_{phys}(s) = \lambda_x^2 \delta(s - M_x^2) + \cdots$$

(Positivity)

(for baryon case)

(Sufficient amount of Pole contribution)



QCD Sum Rule

- Borel transformation to suppress the higher order terms:

$$\boxed{\Pi(M_B^2) \equiv f^2\, e^{-M^2/M_B^2} = \int_{s_<}^{s_0} e^{-s/M_B^2}\rho(s)ds}$$

- Two parameters

M_B , s_0

We need to choose certain region of (M_B, s_0).

- **Criteria**

1. Stability
2. Convergence of OPE
3. Positivity of spectral density
4. Sufficient amount of pole contribution