隐粲多夸克态
求和规则研究

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第十四届重味物理与CP破坏研讨会

CONTENTS

- Experimental status of Pc(4380) and Pc(4450)
- Experimental status of other multiquark states
- The history of multiquark states
- Identifying exotic hidden-charm pentaquarks

  Rui Chen, Xiang Liu, Xue-Qian Li, Shi-Lin Zhu

  Method: one pion exchange (OPE) model
- Towards exotic hidden-charm pentaquarks in QCD

  Hua-Xing Chen, Wei Chen, Xiang Liu, T. G. Steele, Shi-Lin Zhu

  Method: QCD sum rule

Experimental status of Pc(4380) and Pc(4450)

Selected for a Viewpoint in *Physics*
PRL **115,** 072001 (2015) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2015

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays

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

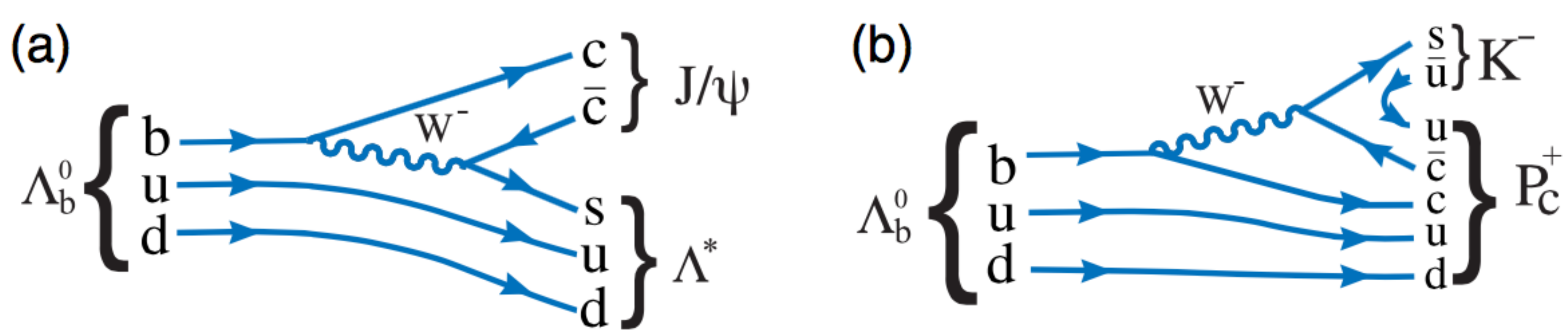

FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

The measured invariant mass spectra

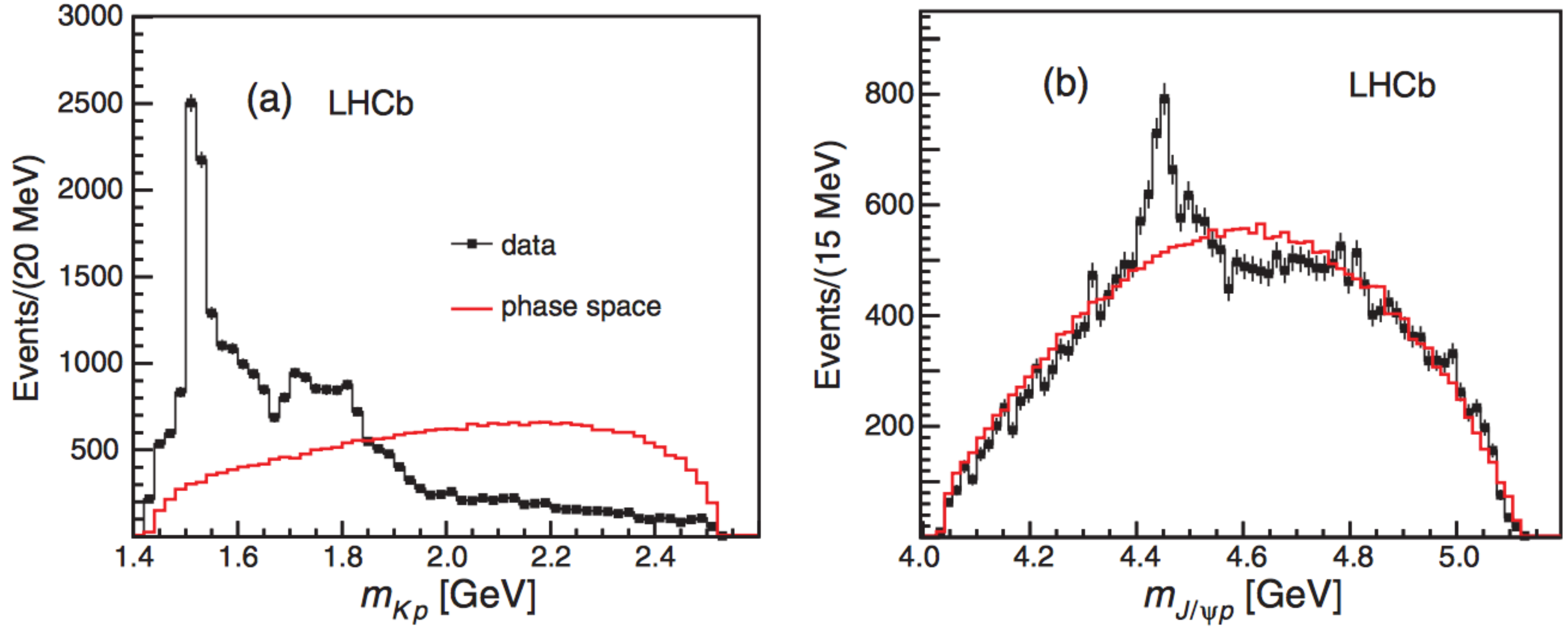

FIG. 2 (color online). Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

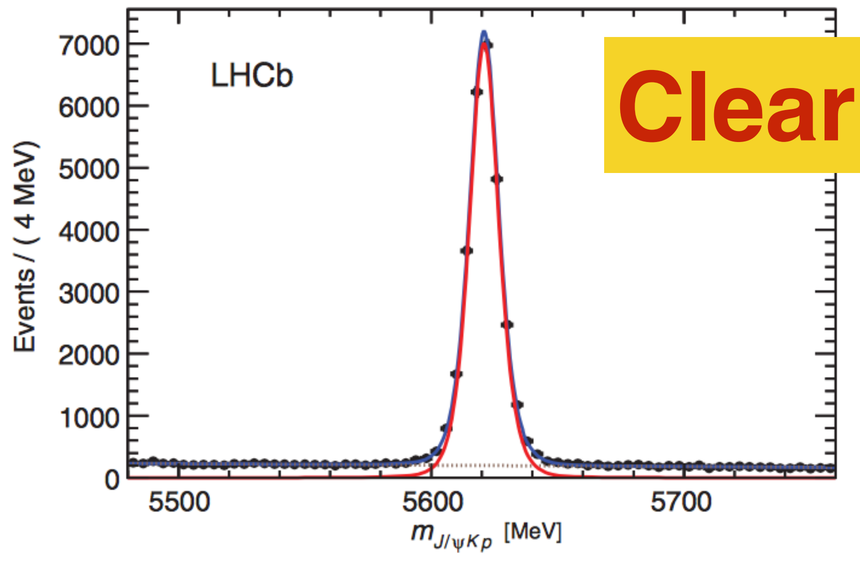

FIG. 4 (color online). Invariant mass spectrum of $J/\psi K^- p$ combinations, with the total fit, signal, and background components shown as solid (blue), solid (red), and dashed lines, respectively.

Clear signal of Λ_b

LHCb performed the analysis of the above experimental data

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- The LHCb experiment at CERN's Large Hadron Collider has reported **the discovery of a class of particles** known as **pentaquarks**.

Posted by Corinne Pralavorio on 14 Jul 2015. Last updated 14 Jul 2015, 10.19.

Voir en français

Possible layout of the quarks in a pentaquark particle. The five quarks might be tightly bound (left). They might also be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together (Image: Daniel Dominguez)

A summary of the observed XYZ states

$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10610)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$	–	–	–	–

X. Liu, Chin. Sci. Bull., 59: 3815–3830 (2014)

In past decade, more and more XYZ states have been reported by experiments

BaBar, Belle, CDF, D0, CLEOc, LHCb, CMS, BESIII

- **Below 1 GeV,** the multiquark exotic states do not exist individually but mix with regular structures. Moreover, in a pentaquark component might exist in the total wave function of a nucleon.

C. Amsler and F. E. Close, Phys. Lett. B **353**, 385 (1995)

K. T. Chao, X. G. He and J. P. Ma, Phys. Rev. Lett. **98**, 149103 (2007)

B. S. Zou and D. O. Riska, Phys. Rev. Lett. **95**, 072001 (2005)

- **States that decay into charmonium** may have particularly distinctive signatures.

X.-Q. Li and X. Liu, Eur. Phys. J. C74 (2014) 3198

Light sector

- Exotic in structure

light scalar mesons $\sigma(600)$, $\kappa(800)$, etc.

- Exotic in quantum numbers

$\pi_1(1400)$, $\pi_1(1600)$ with $I^G J^{PC} = 1^- 1^{-+}$

- Six-quark state d*(2380)

Heavy sector

- Exotic in structure

charmonium-like resonances X(3872), etc.

- Meson: Exotic in quantum numbers

charged charmonium-like resonances $Z_c(3900)$, Z(4430), etc.

- Baryon: Exotic in quantum numbers

hidden-charm pentaquarks $\boldsymbol{P_c(4380)}$ and $\boldsymbol{P_c(4450)}$

Theoretical studies

- Some earlier studies
- Studies at the hadron level

  one-boson exchange model

- Studies at the quark-gluon level

  QCD sum rule

The history of multiquark states

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

*) 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 $AAAA\bar{A}$, $AAAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

The muliquark states were predicted at the birth of Quark Model

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

$c\bar{c}$

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

$b\bar{b}$

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

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

截屏发图

PRD 15 (1977) 267

Multiquark hadrons. I. Phenomenology of $Q^2\bar{Q}^2$ mesons*

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and Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 15 July 1976)

The spectra and dominant decay couplings of $Q^2\bar{Q}^2$ mesons are presented as calculated in the quark-bag model. Certain known 0^+ mesons [$\epsilon(700), S^*, \delta, \kappa$] are assigned to the lightest cryptoexotic $Q^2\bar{Q}^2$ nonet. The usual quark-model 0^+ nonet ($Q\bar{Q}$ $L=1$) must lie higher in mass. All other $Q^2\bar{Q}^2$ mesons are predicted to be broad, heavy, and usually inelastic in formation processes. Other $Q^2\bar{Q}^2$ states which may be experimentally prominent are discussed.

The hadron with four quarks plus one antiquark was developed by Strottman in 1979

PHYSICAL REVIEW D VOLUME 20, NUMBER 3 1 AUGUST 1979

PRD 20 (1979)

Multiquark baryons and the MIT bag model

D. Strottman

Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545

(Received 4 December 1978)

The calculation of masses of $q^4\bar{q}$ and $q^5\bar{q}^2$ baryons is carried out within the framework of Jaffe's approximation to the MIT bag model. A general method for calculating the necessary SU(6)⊃SU(3) ⊗ SU(2) coupling coefficients is outlined and tables of the coefficients necessary for $q^4\bar{q}$ and $q^5\bar{q}^2$ calculations are given. An expression giving the decay amplitude of an arbitrary multiquark state to arbitrary two-body final states is given in terms of SU(3) Racah and 9-$\lambda\mu$ recoupling coefficients. The decay probabilities for low-lying $1/2^-$ $q^4\bar{q}$ baryons are given and compared with experiment. All low-lying $1/2^-$ baryons are found to belong to the same SU(6) representation and all known $1/2^-$ resonances below 1900 MeV may be accounted for without the necessity of introducing P-wave states. The masses of many exotic states are predicted including a $1/2^-$ Z_0^* at 1650 MeV and $1/2^-$ hypercharge -2 and $+3$ states at 2.25 and 2.80 GeV, respectively. The agreement with experiment for the $3/2^-$ and $5/2^-$ baryons is less good. The lowest $q^5\bar{q}^2$ state is predicted to be a $1/2^+$ Λ^* at 1900 MeV.

The name pentaquark was first proposed by Lipkin in 1987

WIS-87/32/May-PH

New Possibilities for Exotic Hadrons - Anticharmed Strange Baryons*

Harry J. Lipkin
Department of Nuclear Physics
Weizmann Institute of Science
76100 Rehovot, Israel

PLB 195 (1987) 484

Submitted to Physics Letters

May 20, 1987

ABSTRACT

$Y = 2$ STATES IN SU(6) THEORY*

Freeman J. Dyson† and Nguyen-Huu Xuong
Department of Physics, University of California, San Diego, La Jolla, California
(Received 30 November 1964)

Two-baryon states. —The SU(6) theory of strongly interacting particles[1,2] predicts a classification of two-baryon states into multiplets according to the scheme

$$\underline{56} \otimes \underline{56} = \underline{462} \oplus \underline{1050} \oplus \underline{1134} \oplus \underline{490}. \qquad (1)$$

We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the $\underline{490}$ multiplet.[3] This means that six zero-strangeness states shown in Table I should be observed. In all these states odd T goes with even J and vice versa.

Prediction of narrow N^* and Λ^* resonances with hidden charm above 4 GeV

Jia-Jun Wu[1,2], R. Molina[2,3], E. Oset[2,3] and B. S. Zou[1,3]
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3. Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China

(Dated: June 25, 2010) arXiv:1007.0573

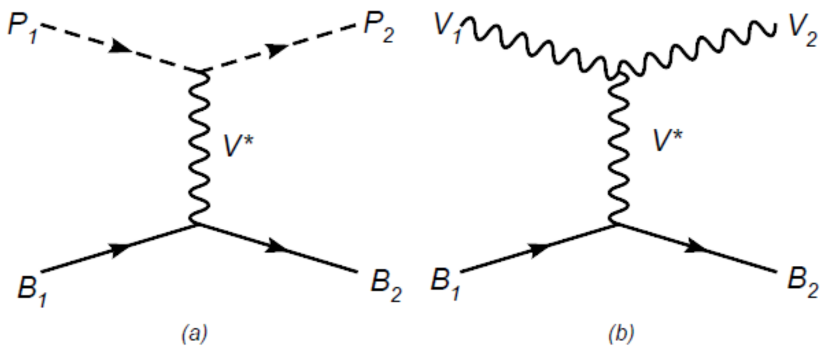

FIG. 1: The Feynman diagrams of pseudoscalar-baryon (
or vector- baryon (b) interaction via the exchange of a vect
meson. P_1, P_2 is D^-, $\bar{D}^0$ or D_s^-, and V_1, V_2 is D^{*-}, $\bar{D}^{*0}$
D_s^{*-}, and B_1, B_2 is Σ_c, Λ_c^+, Ξ_c, Ξ_c' or Ω_c, and V^* is ρ, K^*,
or ω.

$$\mathcal{L}_{VVV} = ig\langle V^\mu[V^\nu, \partial_\mu V_\nu]\rangle$$
$$\mathcal{L}_{PPV} = -ig\langle V^\mu[P, \partial_\mu P]\rangle$$
$$\mathcal{L}_{BBV} = g(\langle \bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle)$$

$\bar{D}_s\Lambda_c^+$	0	$-\sqrt{2}$	0	1	0	$\sqrt{\frac{1}{3}}$	$\sqrt{\frac{2}{3}}$	$-\sqrt{}$
$\bar{D}\Xi_c$		-1	0	$\sqrt{\frac{1}{2}}$	$-\frac{3}{2}$	$\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{12}}$	0
$\bar{D}\Xi_c'$			-1	$-\sqrt{\frac{3}{2}}$	$\sqrt{\frac{3}{4}}$	$-\sqrt{\frac{1}{2}}$	$\frac{1}{2}$	0
$\eta_c\Lambda$				0	0	0	0	0

$(0,-1)$		$D_s\Lambda_c^+$	$D\Xi_c$	$D\Xi_c'$
	4213	1.37	3.25	0
	4403	0	0	2.64

TABLE III: Pole positions z_R and coupling constants g_a for the states from $PB \to PB$.

(I,S)	z_R (MeV)		g_a	
$(1/2,0)$		$\bar{D}^*\Sigma_c$	$\bar{D}^*\Lambda_c^+$	
	4418	2.75	0	
$(0,-1)$		$\bar{D}_s^*\Lambda_c^+$	$\bar{D}^*\Xi_c$	$\bar{D}^*\Xi_c'$
	4370	1.23	3.14	0
	4550	0	0	2.53

TABLE IV: Pole position and coupling constants for the bound states from $VB \to VB$.

CPC(HEP & NP), 2012, **36**(1): 6–13 Chinese Physics C Vol. 36, No. 1, Jan., 2012

arXiv:1105.2901

Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon*

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LIU Xiang(刘翔)[2,4;2)] ZHU Shi-Lin(朱世琳)[1;3)]

$\mathcal{L}_{\mathcal{B}_{\bar{3}}}$

$\mathcal{L}_{\mathcal{B}_{\bar{3}}}$

$\mathcal{L}_{\mathcal{B}_6}$

$\mathcal{L}_{\mathcal{B}_6}$

$$-\frac{i\lambda_S g_V}{3\sqrt{2}}\langle\bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} = -\ell_S\langle\bar{\mathcal{B}}_6\ \sigma\ \mathcal{B}_6\rangle.$$

$$\mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

$$\mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c'^+ \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c'^0 \\ \frac{1}{\sqrt{2}}\Xi_c'^+ & \frac{1}{\sqrt{2}}\Xi_c'^0 & \Omega_c^0 \end{pmatrix}.$$

In this work, we have employed the OBE model to study whether there exist the loosely bound hidden-charm molecular states composed of an S-wave anti-charmed meson and an S-wave charmed baryon. Our numerical results indicate that there do not exist $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states due to the absence of bound state solution, which is an interesting observation in this work. Additionally, we notice the bound state solutions only for five hidden-charm states, i.e., $\Sigma_c\bar{D}^*$ states with $I(J^P)=\frac{1}{2}(\frac{1}{2}^-)$, $\frac{1}{2}(\frac{3}{2}^-)$, $\frac{3}{2}(\frac{1}{2}^-)$, $\frac{3}{2}(\frac{3}{2}^-)$ and $\Sigma_c\bar{D}$ state with $\frac{3}{2}(\frac{1}{2}^-)$. We also extend the same

- There **hidden-charm pentaquarks** are studied in the chiral unitary appraoch:

J. J.Wu, R.Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010)

T. Uchino, W. H. Liang and E. Oset, arXiv:1504.05726

- Especially, the **hidden-charm molecular baryons** of $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ were first investigated and predicted to exist within the one boson exchange model in

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C 36, 6 (2012)

- More references:

chiral quark model	W.L. Wang, F. Huang, Z.Y. Zhang, and B.S. Zou, Phys.Rev. C84 (2011) 015203
hyperfine interaction	S. G. Yuan, K. W. Wei, J. He, H. S. Xu, B. S. Zou, Eur.Phys.J. A48 (2012) 61
photoproduction	Yin Huang, Jun He, Hong-Fei Zhang, Xu-Rong Chen, J.Phys. G41 (2014) 11, 115004
kaon-induced reaction	Xiao-Yun Wang, Xu-Rong Chen, Eur.Phys.J. A51 (2015) 7, 85
isospin-exchange attraction	M. Karliner and J. L. Rosner, arXiv:1506.06386

Identify exotic hidden-charm pentaquarks

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EDITORS' SUGGESTION

Identifying Exotic Hidden-Charm Pentaquarks

The pentaquarks discovered by the LHCb Collaboration could be molecular bound states of a charmed baryon and a meson. Observing the predicted isospin partners would allow for this interpretation to be verified.

Rui Chen, Xiang Liu, Xue-Qian Li, and Shi-Lin Zhu

Phys. Rev. Lett. **115**, 132002 (2015)

The peculiarity of two Pc states:

- The masses of $P_c(4380)$ and $P_c(4450)$ are **close to the $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ thresholds**, respectively.
- According to their final state $J/\psi+p$, we conclude that the **two observed P_c must not be an isosinglet state**, and the two P_c states **contain hidden-charm quantum numbers**.
- The discovery of $P_c(4380)$ and $P_c(4450)$ inspires us interest in revealing their underlying structures under molecular state assignment

The corresponding flavor wave functions

I I₃

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|\Sigma_c^{(*)++}D^{*-}\rangle - \frac{1}{\sqrt{3}}|\Sigma_c^{(*)+}\bar{D}^{*0}\rangle,$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}|\Sigma_c^{(*)+}D^{*-}\rangle - \sqrt{\frac{2}{3}}|\Sigma_c^{(*)0}\bar{D}^{*0}\rangle,$$

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle = |\Sigma_c^{(*)++}\bar{D}^{*0}\rangle,$$

$$\left|\frac{3}{2},\frac{1}{2}\right\rangle = \frac{1}{\sqrt{3}}|\Sigma_c^{(*)++}D^{*-}\rangle + \sqrt{\frac{2}{3}}|\Sigma_c^{(*)+}\bar{D}^{*0}\rangle,$$

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle = \sqrt{\frac{2}{3}}|\Sigma_c^{(*)+}D^{*-}\rangle + \frac{1}{\sqrt{3}}|\Sigma_c^{(*)0}\bar{D}^{*0}\rangle,$$

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle = |\Sigma_c^{(*)0}D^{*-}\rangle,$$

These favor wave functions with I=1/2 match the discussed $P_c(4380)$ and $P_c(4450)$

We need to perform a dynamical calculation of the structures of $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$

One pion exchange (OPE) model

Deuteron: loosely bound state of proton and neutron

Nucleon force: short-range, mid-range, long-range

ϱ and ω exchanges

Scalar σ with mass around 600 MeV

Pion exchange

The coupling of π with nucleons reads

$$\mathcal{L} = g_{NN\pi}\bar{\psi} i\gamma_5 \boldsymbol{\tau}\psi \cdot \boldsymbol{\pi},$$

the non-relativistic nucleon-nucleon potential via π meson exchange can be obtained as

$$V_\pi = \frac{g_{NN\pi}^2}{4\pi}\frac{m_\pi^2}{12m_N^2}(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\left\{\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 + \left[\frac{3(\boldsymbol{\sigma}_1\cdot\boldsymbol{r})(\boldsymbol{\sigma}_2\cdot\boldsymbol{r})}{r^2} - \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2\right]\left[1+\frac{3}{m_\pi r}+\frac{3}{m_\pi^2 r^2}\right]\right\}\frac{e^{-m_\pi r}}{r}$$

In the past decade, one boson exchange was extensively applied to the studies of newly observed hadron states

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...

One conclusion:

Pion exchange play crucial role to form heavy flavor molecular states

It is the reason why we adopt one pion exchange model to study two P_c states

The effective Lagrangian relevant to the deduction of OPE potential:

$$\mathcal{L}_{\bar{D}^*\bar{D}^*\mathbb{P}} = i\frac{2g}{f_\pi} v^\alpha \varepsilon_{\alpha\mu\nu\lambda} \bar{D}_a^{*\mu\dagger} \bar{D}_b^{*\lambda} \partial^\nu \mathbb{P}_{ab},$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = i\frac{g_1}{2f_\pi} \varepsilon^{\mu\nu\lambda\kappa} v_\kappa \mathrm{Tr}[\bar{\mathcal{B}}_6 \gamma_\mu \gamma_\lambda \partial_\nu \mathbb{P} \mathcal{B}_6],$$

$$\mathcal{L}_{\mathcal{B}_6^*\mathcal{B}_6^*\mathbb{P}} = -i\frac{3g_1}{2f_\pi} \varepsilon^{\mu\nu\lambda\kappa} v_\kappa \mathrm{Tr}[\bar{\mathcal{B}}_{6\mu}^* \partial_\nu \mathbb{P} \mathcal{B}_{6\nu}^*],$$

where $g = 0.59 \pm 0.07 \pm 0.01$ is extracted from the width of D^* [25] as is done in Ref. [26], and $g_1 = 0.94$ was fixed in Refs. [12,24].

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The effective potential in momentum space

Scattering amplitude

$$V(\mathbf{Q}) \approx -\frac{\mathcal{M}}{\sqrt{2E_A}\sqrt{2E_B}\sqrt{2E_C}\sqrt{2E_D}}.$$

Fourier transformation

$\mathbf{V(r)}$ The effective potential in coordinate space

The effective potentials of $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ systems

$$V_{\Sigma_c\bar{D}^*}(r) = \frac{1}{3}\frac{gg_1}{f_\pi^2}\nabla^2 Y(\Lambda, m_\pi, r)\mathcal{J}_0\mathcal{G}_0,$$

$$V_{\Sigma_c^*\bar{D}^*}(r) = \frac{1}{2}\frac{gg_1}{f_\pi^2}\nabla^2 Y(\Lambda, m_\pi, r)\mathcal{J}_1\mathcal{G}_1,$$

$$Y(\Lambda, m, r) = \frac{1}{4\pi r}(e^{-mr} - e^{-\Lambda r}) - \frac{\Lambda^2 - m^2}{8\pi\Lambda}e^{-\Lambda r}.$$

TABLE I. The values of the $\mathcal{J}_i$ and $\mathcal{G}_i$ coefficients. Here, S, L, and J denote the spin, orbital, and total angular quantum numbers, respectively. $\mathbb{S}$ denotes $L = 1$ since we are interested in the S-wave interaction of the $\Sigma_c(2455)\bar{D}^*$ and $\Sigma_c^*(2520)\bar{D}^*$ systems.

I	$\mathcal{G}_0$	$\mathcal{G}_1$	$\vert{}^{2S+1}L_J\rangle$	$\mathcal{J}_0$	$\mathcal{J}_1$
1/2	1	−1	$\vert{}^2\mathbb{S}_{(1/2)}\rangle$	−2	5/3
3/2	−1/2	1/2	$\vert{}^4\mathbb{S}_{(3/2)}\rangle$	1	2/3
...	...	...	$\vert{}^6\mathbb{S}_{(5/2)}\rangle$	...	−1

By solving Shrouding equation, we try to find bound state solutions

Numerical results

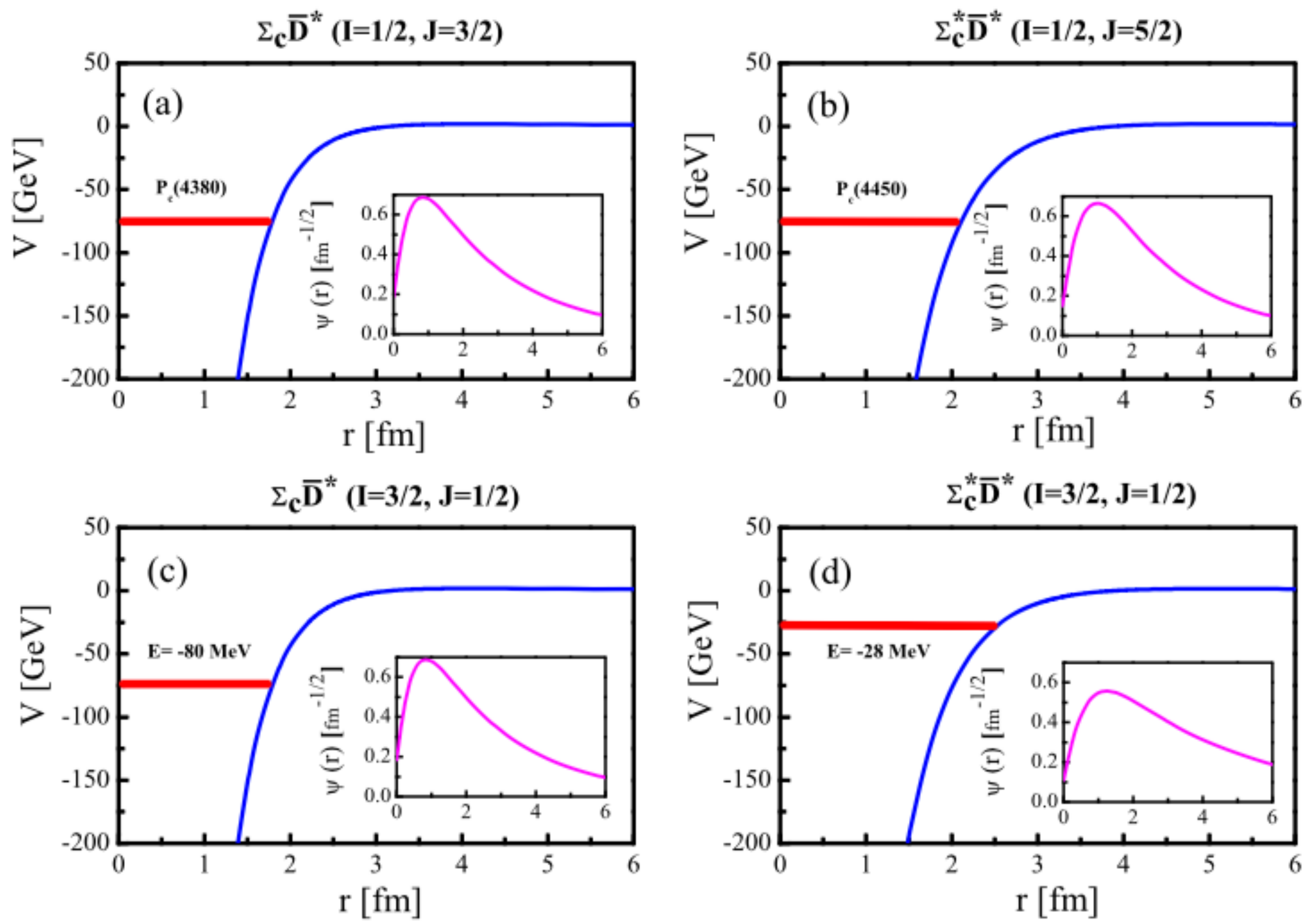

FIG. 1 (color online). The variations of the obtained OPE effective potentials for the $\Sigma_c^{(*)}\bar{D}^*$ systems to r, and obtained bound state solutions. Here, the masses of $P_c(4380)$ and $P_c(4450)$ can be reproduced well under the $\Sigma_c\bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^*\bar{D}^*$ with $(I = 1/2, J = 5/2)$ molecular assignments, respectively. $\Lambda = 2.35$ GeV and $\Lambda = 1.77$ GeV are taken for the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ systems, respectively. The blue curves are the effective potentials, and the red line stands for the corresponding energy levers. Additionally, the obtained spatial wave functions are given here.

Conclusions

- The masses of Pc(4380) and Pc(4450) can be reproduced
- **Pc(4380) and Pc(4450) as Σ_c(2455)D* and Σ_c*(2520)D* molecular states with (I=1/2,J=1/2) and (I=1/2,J=3/2), respectively.**
- Qualitatively explain why the width of Pc(4450) is much narrower than that of Pc(4380)

  S-wave: **Pc(4380)—> J/ψ+p**

  D-wave: **Pc(4450)—> J/ψ+p**
- **Predict two isospin partners** of Pc(4380) and Pc(4450)

  Σ_c(2455)D* with (**I=3/2,J=1/2**) and binding energy **-80** MeV

  Σ_c*(2520)D* with (**I=3/2,J=1/2**) and binding energy **-28** MeV

  Decay modes: $\Delta(1232)J/\psi$ and $\Delta(1232)\eta_c$

Our Study through QCD Sum Rule

Towards exotic hidden-charm pentaquarks in QCD

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Inspired by the $P_c(4380)$ and $P_c(4450)$ recently observed by LHCb, a QCD sum rule investigation is performed, by which $P_c(4380)$ and $P_c(4450)$ can be identified as exotic hidden-charm pentaquarks composed of an anti-charmed meson and a charmed baryon. Our results suggest that the $P_c(4380)$ and $P_c(4450)$ states have quantum numbers $J^P = 3/2^-$ and $5/2^+$, respectively. As an important extension, the mass predictions of hidden-bottom pentaquarks are given. Searches for these partners of $P_c(4380)$ and $P_c(4450)$ is especially accessible at future experiments like LHCb.

Internal structure of hadrons

- The internal structure of hadrons is of interest, but we do not know much.
- An example: There are many excited heavy mesons well observed in experiments, such as $\Lambda_c(2595)$ of $J^P = 1/2^-$ and $\Lambda_c(2625)$ of $J^P = 3/2^-$.
- They both contain one orbital excitation, but we do not know whether this orbital excitation is between the two light quarks or between the light quarks and the heavy quark.
- We can construct different interpolating currents to study this subject using the method of QCD sum rule.

A $[J/\psi\, p]$ current

$$[\bar{c}_d(x)\gamma_\mu c_d(x)][\varepsilon^{abc}(u_a^T(x)Cd_b(x))\gamma_5 u_c(x)]$$

flavor contents

color indices

Lorentz indices

Two Configurations:

$$[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c] \text{ and } [\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$$

These two configurations, **as if they are local**, can be related to each other through

- **The Fierz transformation**

$$\begin{aligned}(\bar{s}_a u_b)(\bar{s}_b d_a) \;=\; & -\frac{1}{4}\{(\bar{s}_a u_a)(\bar{s}_b d_b) + (\bar{s}_a \gamma_\mu u_a)(\bar{s}_b \gamma^\mu d_b) + \frac{1}{2}(\bar{s}_a \sigma_{\mu\nu} u_a)(\bar{s}_b \sigma^{\mu\nu} d_b) \\ & -(\bar{s}_a \gamma_\mu \gamma_5 u_a)(\bar{s}_b \gamma^\mu \gamma_5 d_b) + (\bar{s}_a \gamma_5 u_a)(\bar{s}_b \gamma_5 d_b)\}\,.\end{aligned}$$

- **The color rearrangement**

$$\delta^{de}\epsilon^{abc} = \delta^{da}\epsilon^{ebc} + \delta^{db}\epsilon^{aec} + \delta^{dc}\epsilon^{abe}$$

Configuration $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$

- There are three independent local light baryon fields of flavor-octet and having a positive parity:

H. X. Chen, V. Dmitrasinovic, A. Hosaka, K. Nagata and S. L. Zhu, Phys. Rev. D 78, 054021 (2008)

$$
\begin{aligned}
N_1^N &= \epsilon_{abc}\epsilon^{ABD}\lambda_{DC}^N(q_A^{aT} C q_B^b)\gamma_5 q_C^c \,, \\
N_2^N &= \epsilon_{abc}\epsilon^{ABD}\lambda_{DC}^N(q_A^{aT} C\gamma_5 q_B^b) q_C^c \,, \\
N_{3\mu}^N &= \epsilon_{abc}\epsilon^{ABD}\lambda_{DC}^N(q_A^{aT} C\gamma_\mu\gamma_5 q_B^b)\gamma_5 q_C^c \,,
\end{aligned}
$$

- Together with light baryon fields having negative parity and the charmonium fields:

$$
\begin{gathered}
\bar{c}_d c_d\,[0^+]\,, \bar{c}_d\gamma_5 c_d\,[0^-]\,, \\
\bar{c}_d\gamma_\mu c_d\,[1^-]\,, \bar{c}_d\gamma_\mu\gamma_5 c_d\,[1^+]\,, \bar{c}_d\sigma_{\mu\nu} c_d\,[1^\pm]\,,
\end{gathered}
$$

- We can construct the currents of the configuration $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$.
- Those containing $J=3/2$ components are

$$
\begin{gathered}
[\bar{c}_d c_d][N_{3\mu}^N]\,, [\bar{c}_d\gamma_5 c_d][N_{3\mu}^N]\,, [\bar{c}_d\gamma_\mu c_d][N_{1,2}^N]\,, \\
[\bar{c}_d\gamma_\mu\gamma_5 c_d][N_{1,2}^N]\,, [\bar{c}_d\gamma_\mu c_d][N_{3\nu}^N]\,, [\bar{c}_d\gamma_\mu\gamma_5 c_d][N_{3\nu}^N]\,, \\
[\bar{c}_d\sigma_{\mu\nu} c_d][N_{1,2}^N]\,, [\bar{c}_d\sigma_{\mu\nu} c_d][N_{3\rho}^N]\,,
\end{gathered}
$$

- Three of them of $J=3/2\&5/2$ couple well to the combination of J/ψ and ***proton***

$$
\begin{aligned}
\eta_{1\mu}^{\bar{c}cuud} &= [\bar{c}_d\gamma_\mu c_d][\epsilon_{abc}(u_a^T C d_b)\gamma_5 u_c]\,, \\
\eta_{2\mu}^{\bar{c}cuud} &= [\bar{c}_d\gamma_\mu c_d][\epsilon_{abc}(u_a^T C\gamma_5 d_b) u_c]\,, \\
\eta_{3\{\mu\nu\}}^{\bar{c}cuud} &= [\bar{c}_d\gamma_\mu c_d][\epsilon_{abc}(u_a^T C\gamma_\nu\gamma_5 d_b) u_c] + \{\mu \leftrightarrow \nu\}\,.
\end{aligned}
$$

Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$

2. Currents of $[\bar{c}_d u_d][\epsilon^{abc} u_a d_b c_c]$

In this subsection, we construct the currents of the color configuration $[\bar{c}_d u_d][\epsilon^{abc} u_a d_b c_c]$. We find the following currents having $J^P = 3/2^-$ and quark contents $uudc\bar{c}$:

$$
\begin{aligned}
\xi_{1\mu} &= [\epsilon^{abc}(u_a^T C d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d u_d] ,\\
\xi_{2\mu} &= [\epsilon^{abc}(u_a^T C d_b)\gamma_\mu c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{3\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\gamma_\mu c_c][\bar{c}_d u_d] ,\\
\xi_{4\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{5\mu} &= [\epsilon^{abc}(u_a^T C d_b)\gamma_5 c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{6\mu} &= [\epsilon^{abc}(u_a^T C d_b) c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{7\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b) c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{8\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\gamma_5 c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{9\mu} &= [\epsilon^{abc}(u_a^T C d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{10\mu} &= [\epsilon^{abc}(u_a^T C d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{11\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{12\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{13\mu} &= [\epsilon^{abc}(u_a^T C d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{14\mu} &= [\epsilon^{abc}(u_a^T C d_b)\gamma_\nu c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{15\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\gamma_\nu c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{16\mu} &= [\epsilon^{abc}(u_a^T C\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{17\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\gamma_5 c_c][\bar{c}_d u_d] ,\\
\xi_{18\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b) c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{19\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b) c_c][\bar{c}_d u_d] ,\\
\xi_{20\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)\gamma_5 c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{21\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d u_d] ,\\
\xi_{22\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{23\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\sigma_{\mu\nu} c_c][\bar{c}_d u_d] ,\\
\xi_{24\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{25\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{26\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\gamma_\nu c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{27\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)\gamma_\nu c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{28\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{29\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{30\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_\mu c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{31\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\mu c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{32\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{33\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{34\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_\nu c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{35\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\nu c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{36\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{37\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b)\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{38\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu d_b) c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{39\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b) c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{40\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{41\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{42\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{43\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{44\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{45\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{46\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{47\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho\gamma_5 d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{48\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho\gamma_5 d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{49\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{50\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{51\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho\gamma_5 d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \sigma_{\mu\nu} u_d] ,\\
\xi_{52\mu} &= [\epsilon^{abc}(u_a^T C\gamma_\rho\gamma_5 d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \sigma_{\mu\nu}\gamma_5 u_d] ,\\
\xi_{53\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d u_d] ,\\
\xi_{54\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\gamma_\nu c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{55\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\gamma_\nu c_c][\bar{c}_d u_d] ,\\
\xi_{56\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d \gamma_5 u_d] ,\\
\xi_{57\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\gamma_5 c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{58\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b) c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{59\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b) c_c][\bar{c}_d \gamma_\nu u_d] ,\\
\xi_{60\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\gamma_5 c_c][\bar{c}_d \gamma_\nu\gamma_5 u_d] ,\\
\xi_{61\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \gamma_\rho u_d] ,\\
\xi_{62\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \gamma_\rho\gamma_5 u_d] ,\\
\xi_{63\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \gamma_\rho u_d] ,\\
\xi_{64\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \gamma_\rho\gamma_5 u_d] ,\\
\xi_{65\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \gamma_\rho u_d] ,\\
\xi_{66\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \gamma_\rho\gamma_5 u_d] ,\\
\xi_{67\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\sigma_{\mu\nu} c_c][\bar{c}_d \gamma_\rho u_d] ,\\
\xi_{68\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\sigma_{\mu\nu}\gamma_5 c_c][\bar{c}_d \gamma_\rho\gamma_5 u_d] ,\\
\xi_{69\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{70\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{71\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\sigma_{\nu\rho} c_c][\bar{c}_d \gamma_\mu u_d] ,\\
\xi_{72\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\sigma_{\nu\rho}\gamma_5 c_c][\bar{c}_d \gamma_\mu\gamma_5 u_d] ,\\
\xi_{73\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\gamma_\rho\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{74\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu} d_b)\gamma_\rho c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{75\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\gamma_\rho c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{76\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\mu\nu}\gamma_5 d_b)\gamma_\rho\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{77\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{78\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho} d_b)\gamma_\mu c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] ,\\
\xi_{79\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\gamma_\mu c_c][\bar{c}_d \sigma_{\nu\rho} u_d] ,\\
\xi_{80\mu} &= [\epsilon^{abc}(u_a^T C\sigma_{\nu\rho}\gamma_5 d_b)\gamma_\mu\gamma_5 c_c][\bar{c}_d \sigma_{\nu\rho}\gamma_5 u_d] .
\end{aligned}
$$

- The currents of this type are more complicated.
- The physical states are probably their mixings.
- Some currents may well couple to the physical states, but the problem is that we do not know this at the beginning.
- Hence, we select some of them to perform the QCD sum rule to see whether we can obtain reliable/stable sum rule results.
- In the present work we selected altogether 30 currents.

Configuration $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$

- The currents of this type can not be systematically constructed so easily, so we just transform the previous currents to this configuration, and select those related to D/D^* and $\Lambda_c/\Sigma_c/\Sigma_c^*$.
- We shall investigate the following currents of J=3/2

$$
\begin{aligned}
J_\mu^{\bar{D}^*\Sigma_c} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma^\nu \gamma_5 c_c]\,, \\
J_\mu^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\mu u_b) c_c]\,,
\end{aligned}
$$

- We shall investigate the following currents of J=5/2

$$
\begin{aligned}
J_{\{\mu\nu\}}^{\bar{D}^*\Sigma_c^*} &= [\bar{c}_d \gamma_\mu d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b)\gamma_5 c_c] + \{\mu \leftrightarrow \nu\}\,, \\
J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*} &= [\bar{c}_d \gamma_\mu \gamma_5 d_d][\epsilon_{abc}(u_a^T C \gamma_\nu u_b) c_c] + \{\mu \leftrightarrow \nu\}\,, \\
J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c} &= [\bar{c}_d \gamma_\mu u_d][\epsilon_{abc}(u_a^T C \gamma_\nu \gamma_5 d_b) c_c] + \{\mu \leftrightarrow \nu\}\,,
\end{aligned}
$$

QCD SUM RULE

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

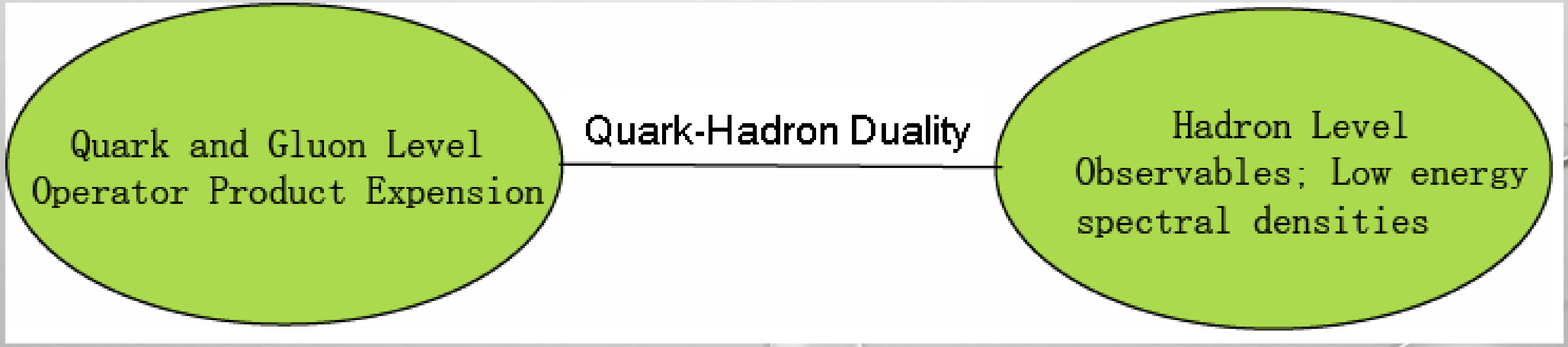
$$\Pi\left(q^2\right) \stackrel{\text{def}}{=} i \int d^4 x e^{iqx} \langle 0|T\eta(x)\eta^{+}(0)\,|0\rangle$$
$$\approx \sum_{n} \langle 0|\eta|n\rangle\langle n|\eta^{+}|0\rangle$$

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

- 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.



SVZ sum rule (Shifman 1979)

Quark and Gluon Level

(Convergence of OPE)

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

Quark-Hadron Duality

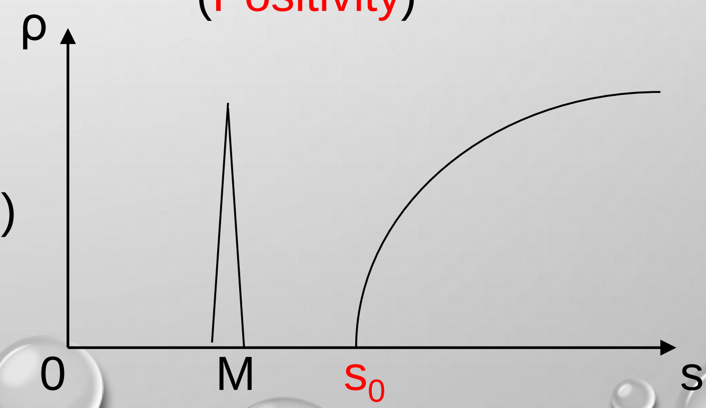
Hadron Level

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

(for baryon case)

(Positivity)

(Sufficient amount of Pole contribution)



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Parity of Pentaquark

- Assuming $\boldsymbol{J}$ is a pentaquark current, $\boldsymbol{\gamma_5 J}$ is its partner having the opposite parity.
- They can couple to the same physical state through

$$< 0|\, \boldsymbol{J}\, |P(q) > = f_P u(q)\,, \qquad < 0|\, \boldsymbol{\gamma_5 J}\, |P(q) > = f_P \boldsymbol{\gamma_5} u(q).$$

- The same pentaquark current $\boldsymbol{J}$ can couple to states of both positive and negative parities through

$$< 0|\, \boldsymbol{J}\, |P(q) > = f_P u(q)\,, \qquad < 0|\, \boldsymbol{J}\, |P'(q) > = f_{P'} \boldsymbol{\gamma_5} u'(q).$$

where $|P(q) >$ has the same parity as $\boldsymbol{J}$, while $|P'(q) >$ has the opposite parity.

$$f_P^2 \frac{\not{q} + M}{q^2 - M^2} \qquad\qquad f_P^2 \frac{-\not{q} + M}{q^2 - M^2}$$

QCD Sum Rule

- Borel transformation to suppress the higher order terms:

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

- 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

Numerical Results

- Technically, in the following analyses we use the terms proportional to $\mathbf{1}$ to evaluate the mass of $\boldsymbol{P_c(4380)}$ and $\boldsymbol{P_c(4450)}$, which are then compared with those proportional to $\not{q}$ to determine its parity.
- We perform QCD sum rule analyses using $\eta_{12\mu}^{\bar{c}cuud} = \eta_{1\mu}^{\bar{c}cuud} - \eta_{2\mu}^{\bar{c}cuud}$ and $\eta_{3\{\mu\nu\}}^{\bar{c}cuud}$ of the $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$ configuration, but the results are not useful.
- We also perform QCD sum rule analyses using $J_\mu^{\bar{D}^*\Sigma_c}$, $J_\mu^{\bar{D}\Sigma_c^*}$, $J_{\{\mu\nu\}}^{\bar{D}^*\Sigma_c^*}$, $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*}$, and $J_{\{\mu\nu\}}^{\bar{D}^*\Lambda_c}$ of the $[\bar{c}_d q_d][\epsilon^{abc} c_a q_b q_c]$ configuration.

The sum rule results obtained using $J_\mu^{\bar{D}^*\Sigma_c}$(**J=3/2**) are

$$M_{[\bar{D}^*\Sigma_c],3/2^-} = 4.37^{+0.18}_{-0.12}\ \text{GeV}\,.$$

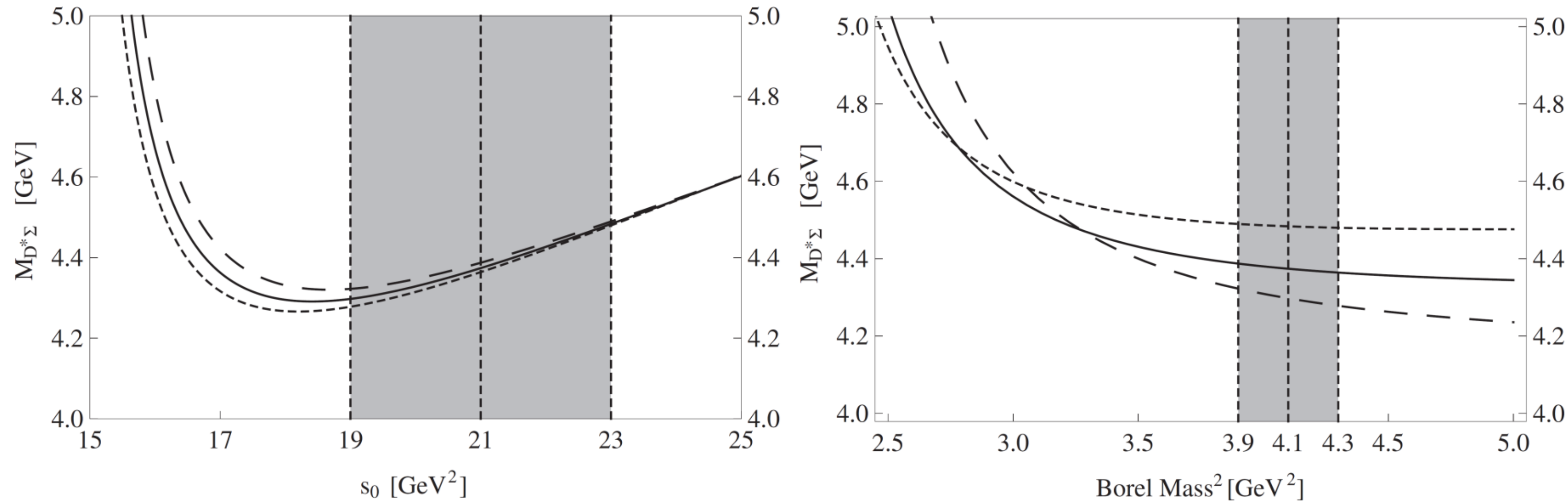

FIG. 1: The variation of $M_{[\bar{D}^*\Sigma_c],3/2^-}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right). In the left figure, the

The sum rule results obtained using $J^{\bar{D}\Sigma_c^*}_{\{\mu\nu\}}$ and $J^{\bar{D}^*\Lambda_c}_{\{\mu\nu\}}$ are not useful.
However, their mixing gives a reliable mass sum rule (***J=5/2***)

$$J^{\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c}_{\{\mu\nu\}} = \sin\theta \times J^{\bar{D}\Sigma_c^*}_{\{\mu\nu\}} + \cos\theta \times J^{\bar{D}^*\Lambda_c}_{\{\mu\nu\}}$$

$$\boxed{\tan\theta = -1.25}$$

$$M_{[\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c],5/2^+} = 4.47^{+0.19}_{-0.12}\ \mathrm{GeV}\,.$$

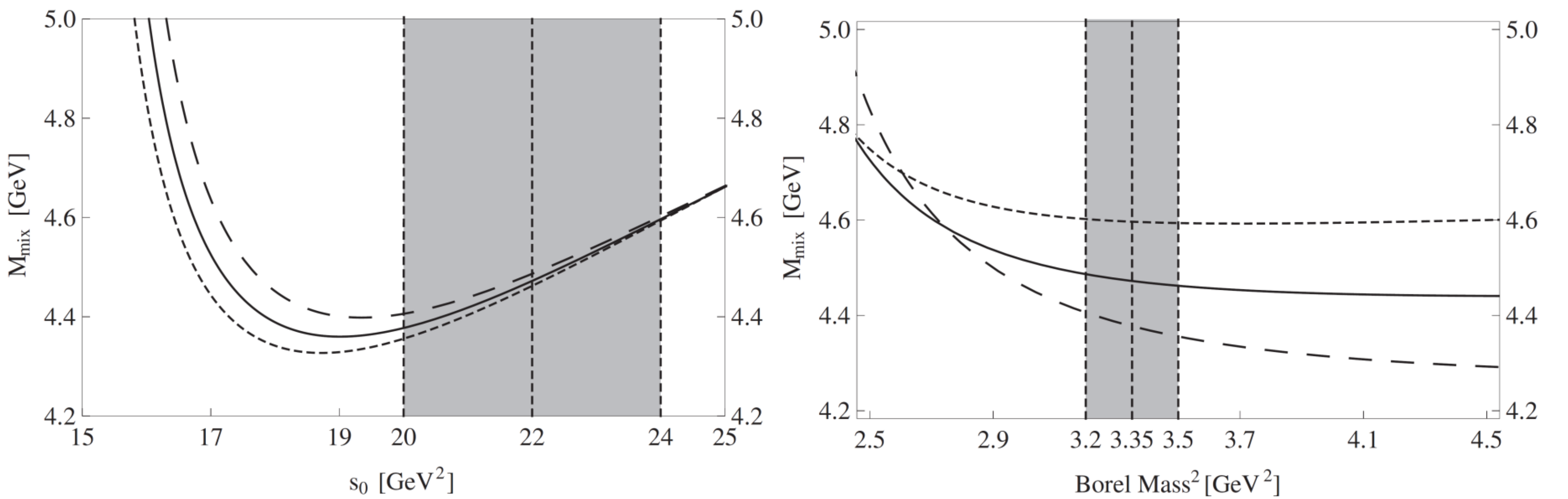

FIG. 2: The variation of $M_{[\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c],5/2^+}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right).

Summary

- We have performed a QCD sum rule investigation, by which the $\boldsymbol{P_c(4380)}$ and $\boldsymbol{P_c(4450)}$ states recently observed by LHCb are identified as **hidden-charm pentaquark states** composed of **anti-charmed meson** and **charmed baryon**.
- We use the interpolating current $J_\mu^{\bar{D}^*\Sigma_c}$ to perform QCD sum rule analysis. The result is consistent with the experimental mass of the $\boldsymbol{P_c(4380)}$ state, which supports the $\boldsymbol{P_c(4380)}$ state as a $[\bar{D}^*\Sigma_c]$ hidden-charm pentaquark, and of quantum numbers $\boldsymbol{J^P = 3/2^-}$.
- We use a mixed current $J_{\{\mu\nu\}}^{\bar{D}\Sigma_c^*\&\bar{D}^*\Lambda_c}$ to perform QCD sum rule analysis. The result is consistent the experimental mass of the $\boldsymbol{P_c(4450)}$ state, which implies a possible mixed hidden-charm pentaquark structure of the $\boldsymbol{P_c(4450)}$ state, as admixture of $[\bar{D}\Sigma_c^*]$ and $[\bar{D}^*\Lambda_c]$, and of quantum numbers $\boldsymbol{J^P = 5/2^+}$.

More: hidden-charm baryonium states

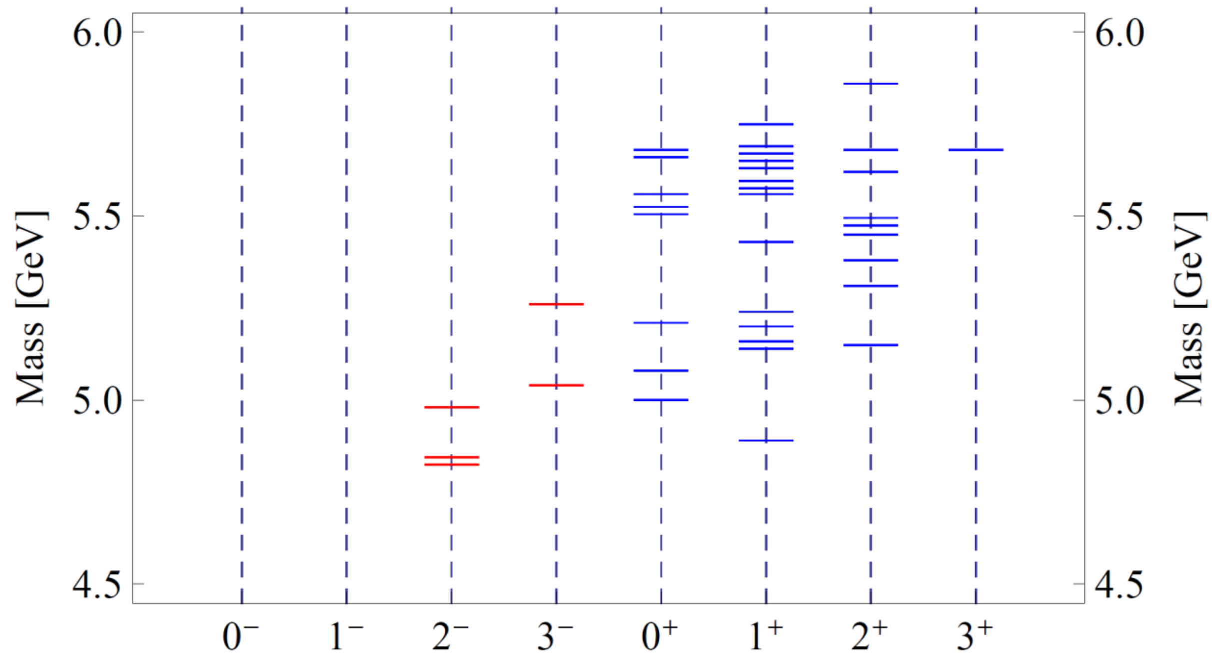

FIG. 5: Spectrum of hidden-charm baryonium states obtained using the method of QCD sum rules. The blue lines are obtained using the currents of Type D, and the red lines are obtained using the currents of Type F.

Summary

We still need more theoretical and experimental joint efforts

Thank you for your attention