# 隐粲多夸克态
# 求和规则研究

陈华星

北京航空航天大学

2016手征有效场论研究会

# 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)

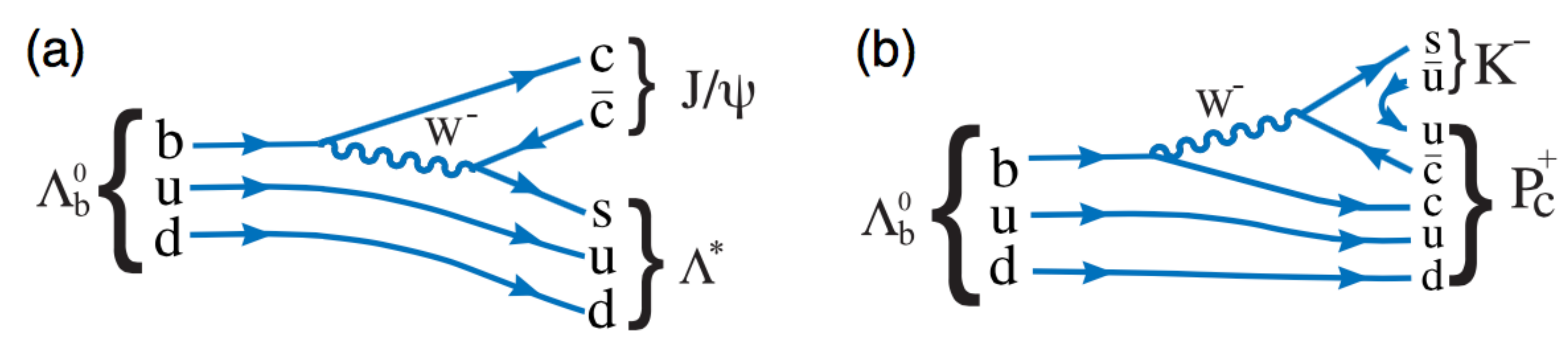



FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

# The measured invariant mass spectra

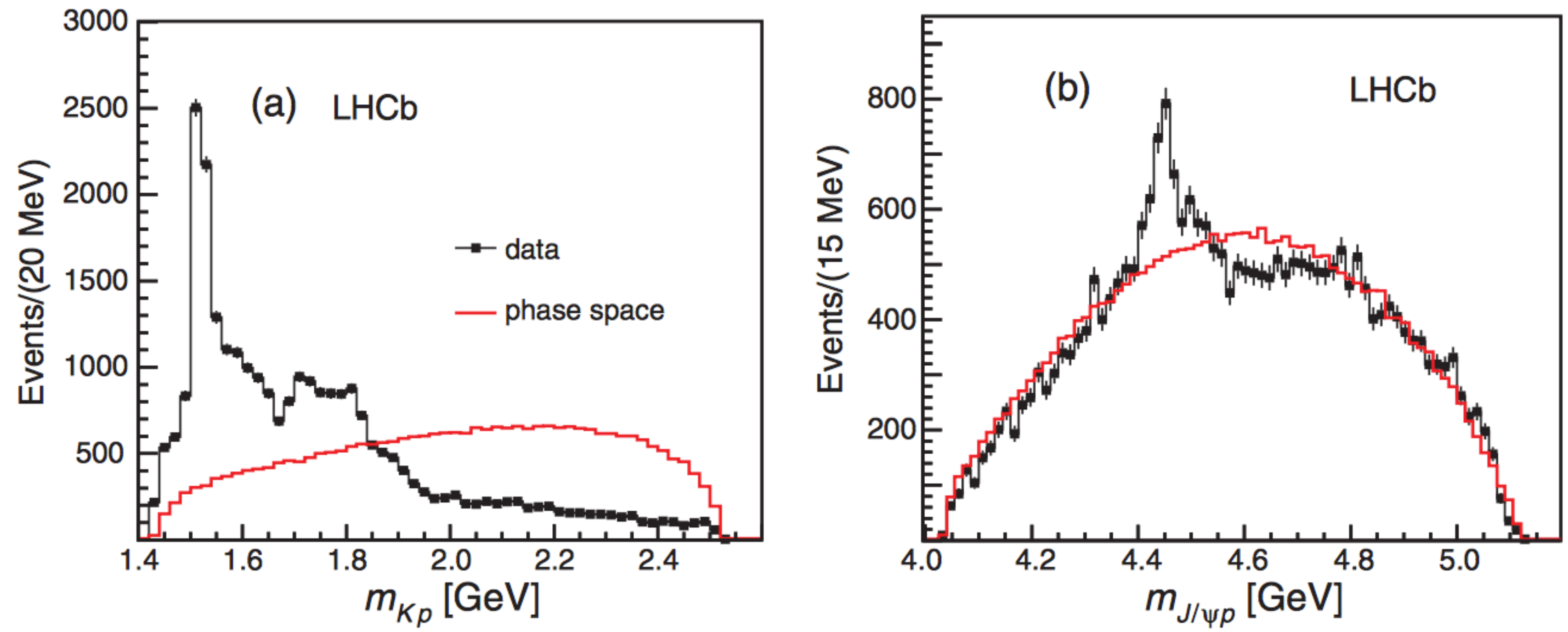



FIG. 2 (color online). Invariant mass of (a) $K^-p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

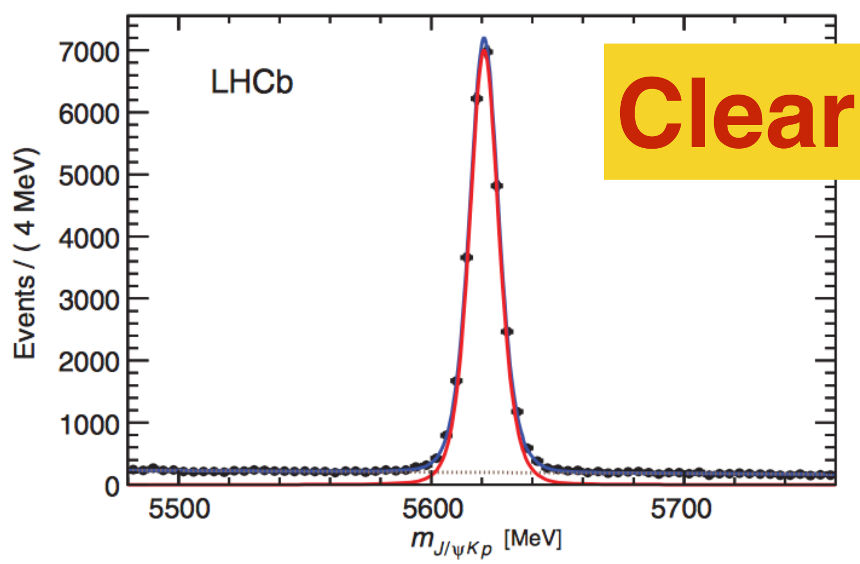



FIG. 4 (color online). Invariant mass spectrum of $J/\psi K^- p$ combinations, with the total fit, signal, and background components shown as solid (blue), solid (red), and dashed lines, respectively.

**Clear signal of $\Lambda_b$**

**LHCb performed the analysis of the above experimental data**

CERN Accelerating science

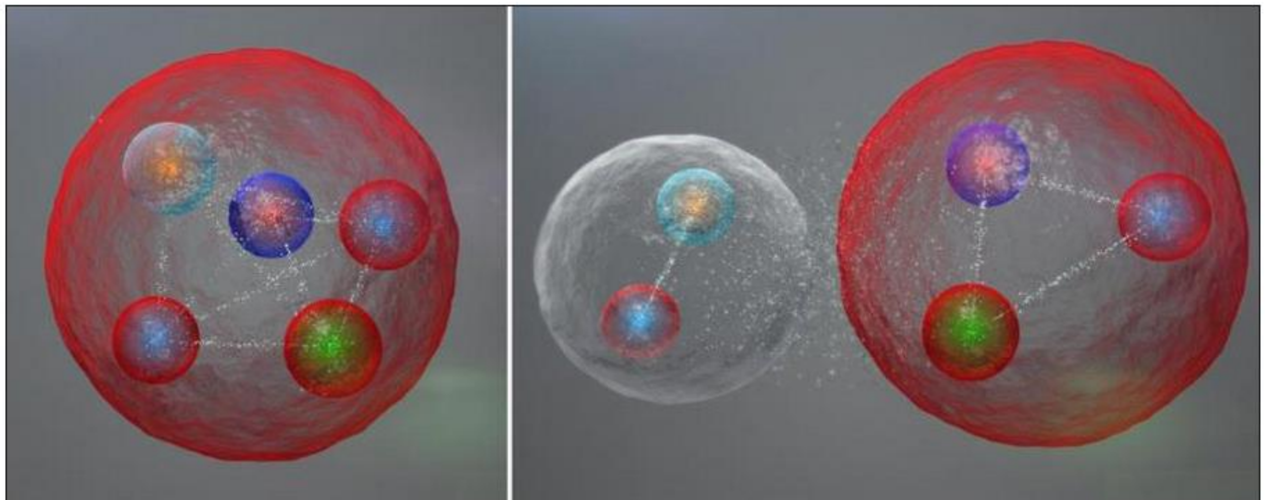
About CERN | Students & Educators | Scientists | CERN people

Accelerators | Experiments | Physics | Computing | Engineering | Updates

- 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 $P_c(4380)$ and $P_c(4450)$

# 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 $(qqq)$, $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration $(qqq)$ 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 $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, 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 ($S = C = B = 0$)

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

R. J. Jaffe†

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*
*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 $1/2^+$ $\Lambda^*$ 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 $\Lambda^*$ 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]
1. *Institute of High Energy Physics, CAS, Beijing 100049, China*
2. *Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain*
3. *Theoretical Physics Center for Science Facilities, CAS, Beijing 100049, China*

(Dated: June 25, 2010) arXiv:1007.0573

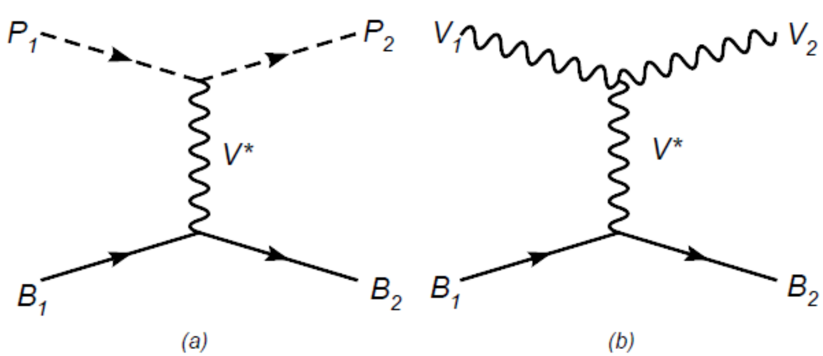



FIG. 1: The Feynman diagrams of pseudoscalar-baryon ( or vector- baryon (b) interaction via the exchange of a vect meson. $P_1$, $P_2$ is $D^-$, $\bar{D}^0$ or $D_s^-$, and $V_1$, $V_2$ is $D^{*-}$, $\bar{D}^{*0}$ $D_s^{*-}$, and $B_1$, $B_2$ is $\Sigma_c$, $\Lambda_c^+$, $\Xi_c$, $\Xi_c'$ or $\Omega_c$, and $V^*$ is $\rho$, $K^*$, or $\omega$.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\bar{D}_s\Lambda_c^+$ | 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 |

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

| | | | | |
|---|---|---|---|---|
| $(0,-1)$ | | $D_s\Lambda_c^+$ | $D\Xi_c$ | $D\Xi_c'$ |
| | 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 *

YANG Zhong-Cheng(杨忠诚)[1] SUN Zhi-Feng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
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

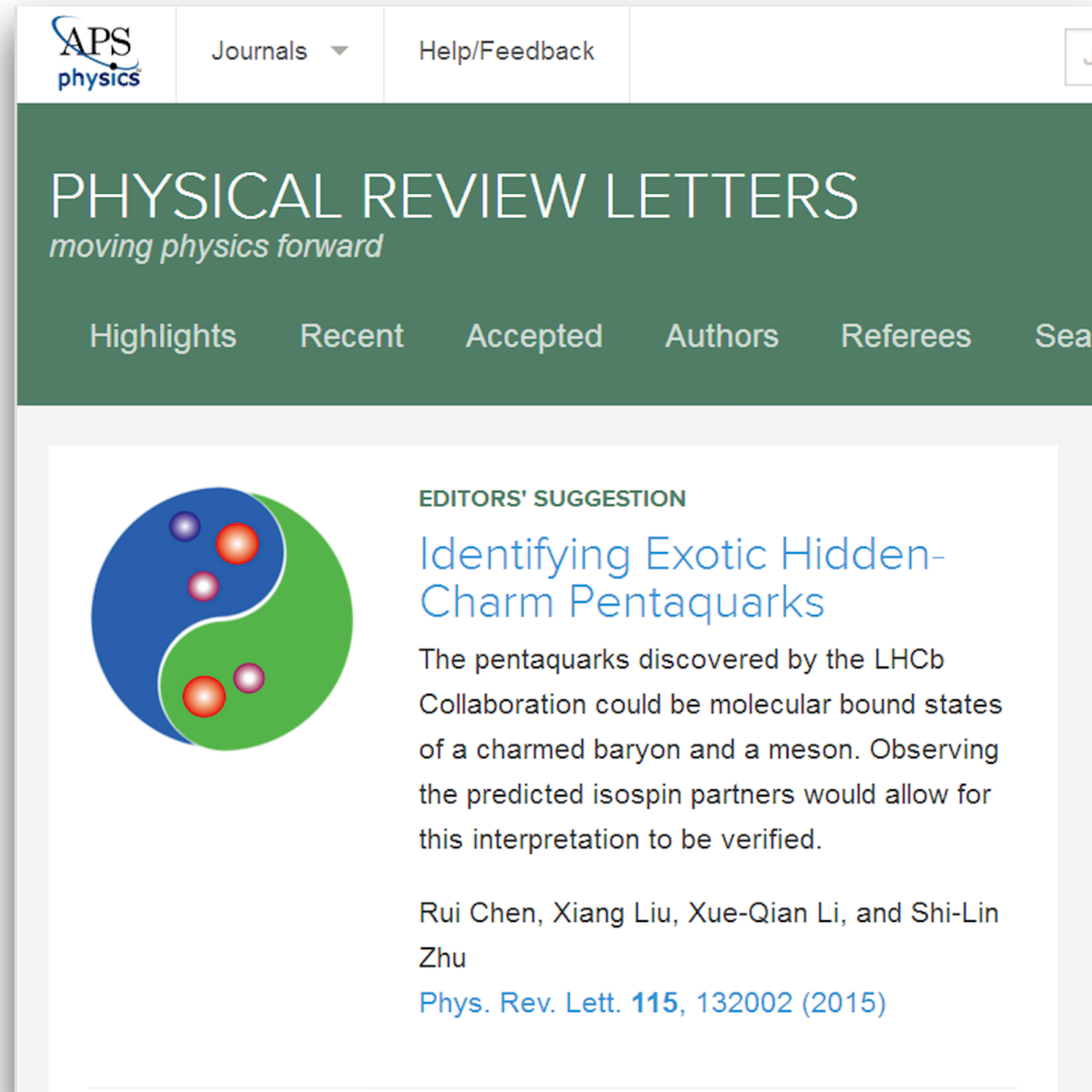
- Especially, the **hidden-charm molecular baryons** of $I(J^P) = \frac{1}{2}(\frac{3}{2}^-)$ were first investigated and predicted to exist within the one boson exchange model in

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


APS physics | Journals | Help/Feedback

PHYSICAL REVIEW LETTERS

*moving physics forward*

Highlights | Recent | Accepted | Authors | Referees | Sear

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**

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

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

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

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

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

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

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

**We need to perform a dynamical calculation of the structures of Σc(2455)D* and Σc*(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 $\pi$ 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 $\pi$ 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

## Long list:


LIU X, ZENG X Q, DING Y B, LI X Q, SHEN H, SHEN P N. arXiv:hep-ph/0406118

HE X G, LI X Q, LIU X, ZENG X Q. Eur. Phys. J. C, 2007, **51**: 883–889

LIU X. Eur. Phys. J. C, 2008, **54**: 471–474

LIU X, LIU Y R, DENG W Z, ZHU S L. Phys. Rev. D, 2008, **77**: 034003

LIU X, ZHANG B. Eur. Phys. J. C, 2008, **54**: 253–258

Tornqvist N A. arXiv:hep-ph/0308277

Swanson E S. Phys. Lett. B, 2004, **598**: 197

LIU Y R, LIU X, DENG W Z, ZHU S L. Eur. Phys. J. C, 2008, **56**: 63–73

Close F, Downum C. Phys. Rev. Lett., 2009, **102**: 242003

Close F, Downum C, Thomas C E. Phys. Rev. D, 2010, **81**: 074033

Lee I W, Faessler A, Gutsche T, Lyubovitskij V E. Phys. Rev. D, 2009, **80**: 094005

XU Q, LIU G, JIN H. arXiv:1012.5949

LIU X, LIU Y R, DENG W Z. arXiv:0802.3157

LIU X, LIU Y R, DENG W Z, ZHU S L. Phys. Rev. D, 2008, **77**: 094015

LIU X, LUO Z G, LIU Y R, ZHU S L. Eur. Phys. J. C, 2009, **61**: 411–428

LIU X, ZHU S L. Phys. Rev. D, 2009, **80**: 017502

HU B, CHEN X L, LUO Z G, HUANG P Z, ZHU S L, YU P F, LIU X. Chin. Phys. C (HEP & NP), 2011, **35**: 113–125

SHEN L L, CHEN X L, LUO Z G, HUANG P Z, ZHU S L, YU P F, LIU X. Eur. Phys. J. C, 2010, **70**: 183–217

HE J, LIU X. Phys. Rev. D, **82**: 114029

LIU X, LUO Z G, ZHU S L. Phys. Lett. B, 2011, **699**: 341–344

LIU Y R, ZHANG Z Y. Phys. Rev. C, 2009, **80**: 015208

LIU Y R, ZHANG Z Y. Phys. Rev. C, **79**: 035206

LIU Y R, ZHANG Z Y. arXiv:0908.1734

DING G J. arXiv:0711.1485

DING G J, HUANG W, LIU J F, YAN M L. Phys. Rev. D, 2009, **79**: 034026

DING G J. Phys. Rev. D, 2009, **79**: 014001

DING G J. Phys. Rev. D, 2009, **80**: 034005

Lee N, LUO Z G, CHEN X L, ZHU S L. arXiv:1104.4257

CHEN Y D, QIAO C F. arXiv:1102.3487


...

**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].


[12] Z. C. Yang, Z. F. Sun, J. He, X. Liu, and S. L. Zhu, Possible hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon, Chin. Phys. C 36, 6 (2012).

[24] Y. R. Liu and M. Oka, $\Lambda_c N$ bound states revisited, Phys. Rev. D 85, 014015 (2012).

[25] C. Isola, M. Ladisa, G. Nardulli, and P. Santorelli, Charming penguin contributions in $B \to K^*\pi, K(\rho,\omega,\phi)$ decays, Phys. Rev. D 68, 114001 (2003).

[26] X. Liu, Y.-R. Liu, W.-Z. Deng, and S.-L. Zhu, $Z^+(4430)$ as a $D_1' D^* (D_1 D^*)$ molecular state, Phys. Rev. D 77, 094015 (2008).


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

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

# Numerical results

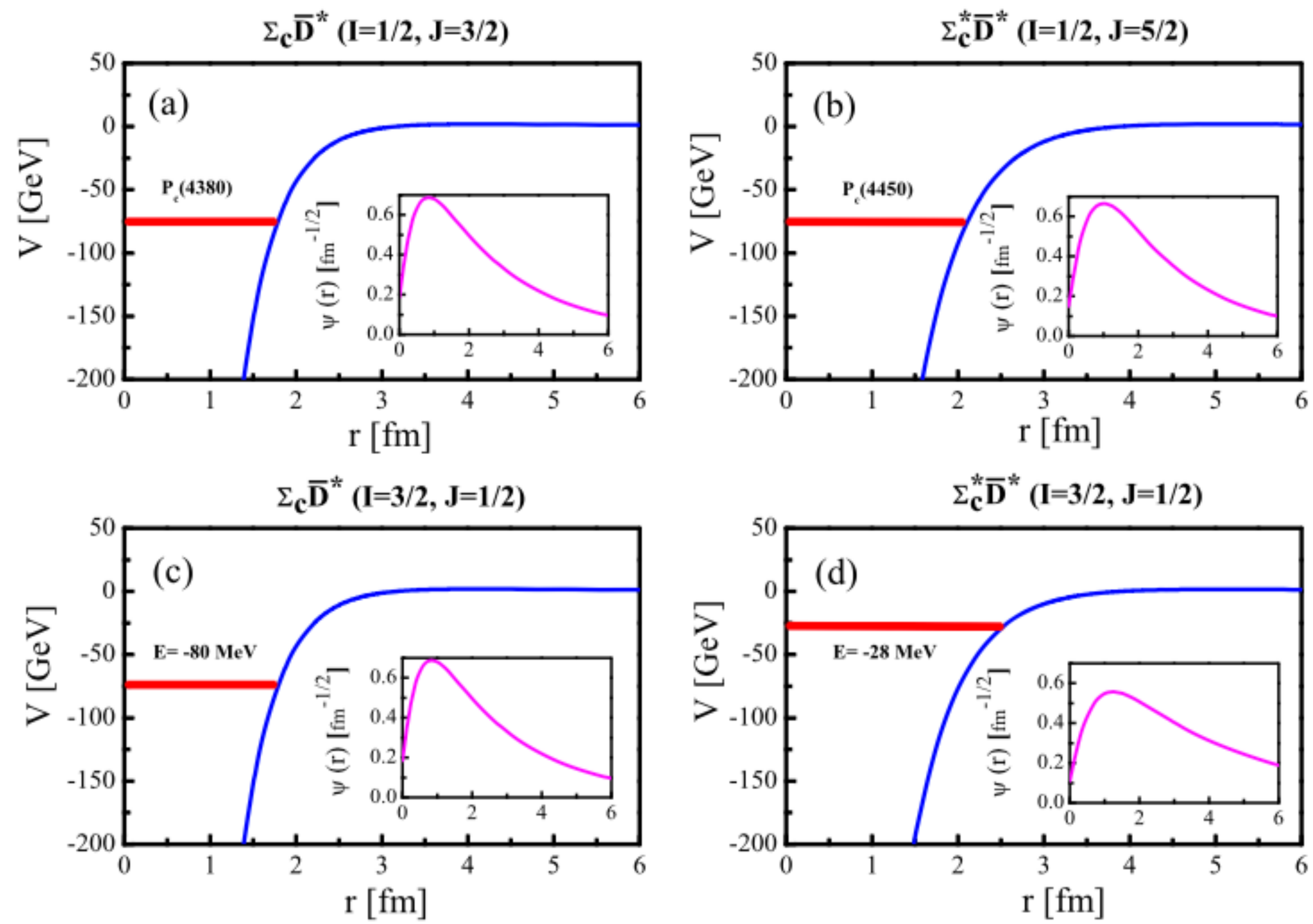



FIG. 1 (color online). The variations of the obtained OPE effective potentials for the $\Sigma_c^{(*)}\bar{D}^*$ systems to $r$, and obtained bound state solutions. Here, the masses of $P_c(4380)$ and $P_c(4450)$ can be reproduced well under the $\Sigma_c\bar{D}^*$ with $(I = 1/2, J = 3/2)$ and $\Sigma_c^*\bar{D}^*$ 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.

# Our Study through QCD Sum Rule

## Towards exotic hidden-charm pentaquarks in QCD

Hua-Xing Chen[1], Wei Chen[2,*] Xiang Liu[3,4,†] T. G. Steele[2,‡] and Shi-Lin Zhu[5,6,7§]

[1]*School of Physics and Nuclear Energy Engineering and International Research Center for Nuclei and Particles in the Cosmos, Beihang University, Beijing 100191, China*

[2]*Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK, S7N 5E2, Canada*

[3]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*

[4]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*

[5]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[6]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*

[7]*Center of High Energy Physics, Peking University, Beijing 100871, China*

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 $J/\psi$ 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 $uudc\bar{c}$:

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

- 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 $J=3/2$

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

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

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

# QCD SUM RULE

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

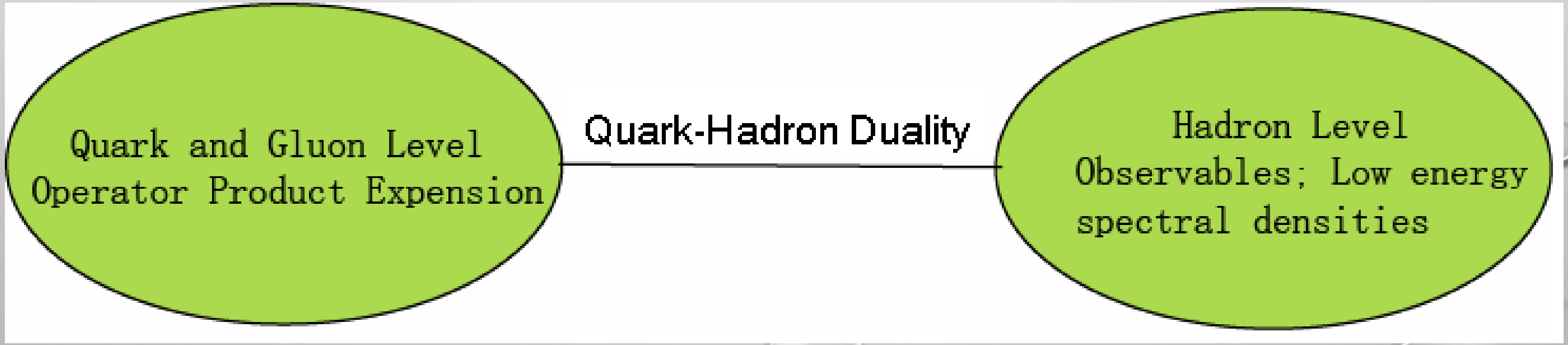
$$\Pi(q^2) \stackrel{\text{def}}{=} i \int d^4x e^{iqx} \langle 0 | T\eta(x)\eta^+(0) | 0 \rangle$$
$$\approx \sum_n \langle 0 | \eta | n \rangle \langle n | \eta^+ | 0 \rangle$$

where $\eta$ is the current which can couple to hadronic states.

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

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

- 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

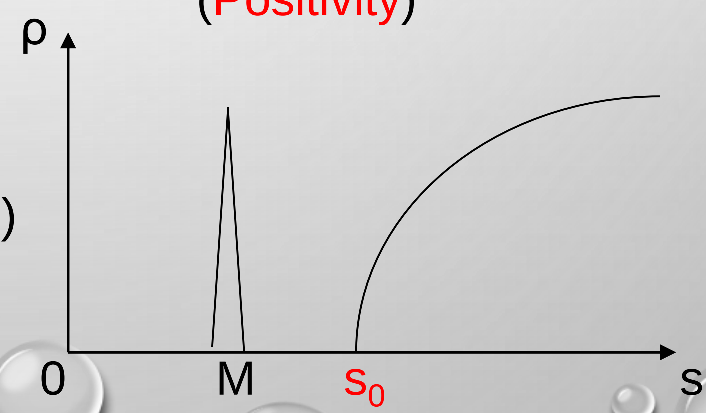
## Hadron Level

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

(Positivity)

(for baryon case)

(Sufficient amount of Pole contribution)



Y. Chung, H. G. Dosch, M. Kremer and D. Schall, Nucl. Phys. B 197, 55 (1982)
D. Jido, N. Kodama and M. Oka, Phys. Rev. D 54, 4532 (1996)
Y. Kondo, O. Morimatsu and T. Nishikawa, Nucl. Phys. A 764, 303 (2006)
K. Ohtani, P. Gubler and M. Oka, Phys. Rev. D 87, no. 3, 034027 (2013)

# 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 $P_c(4380)$ and $P_c(4450)$, 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

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

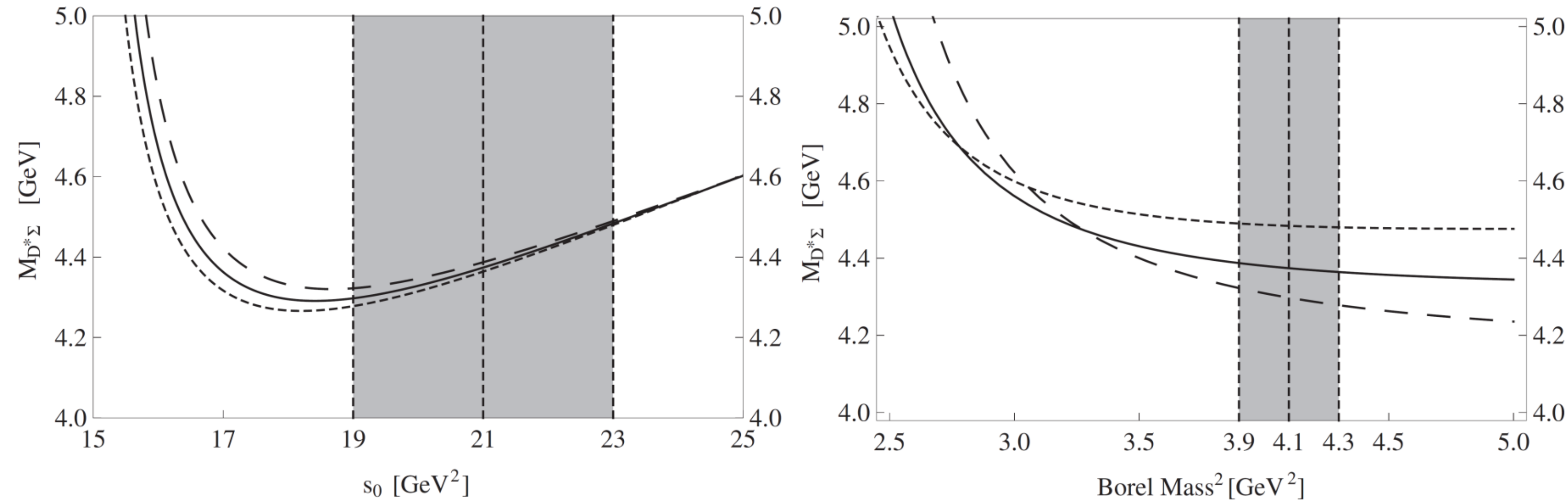



FIG. 1: The variation of $M_{[\bar{D}^*\Sigma_c],3/2^-}$ with respect to the threshold value $s_0$ (left) and the Borel mass $M_B$ (right). In the left figure, the

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

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

$$\tan\theta = -1.25$$

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

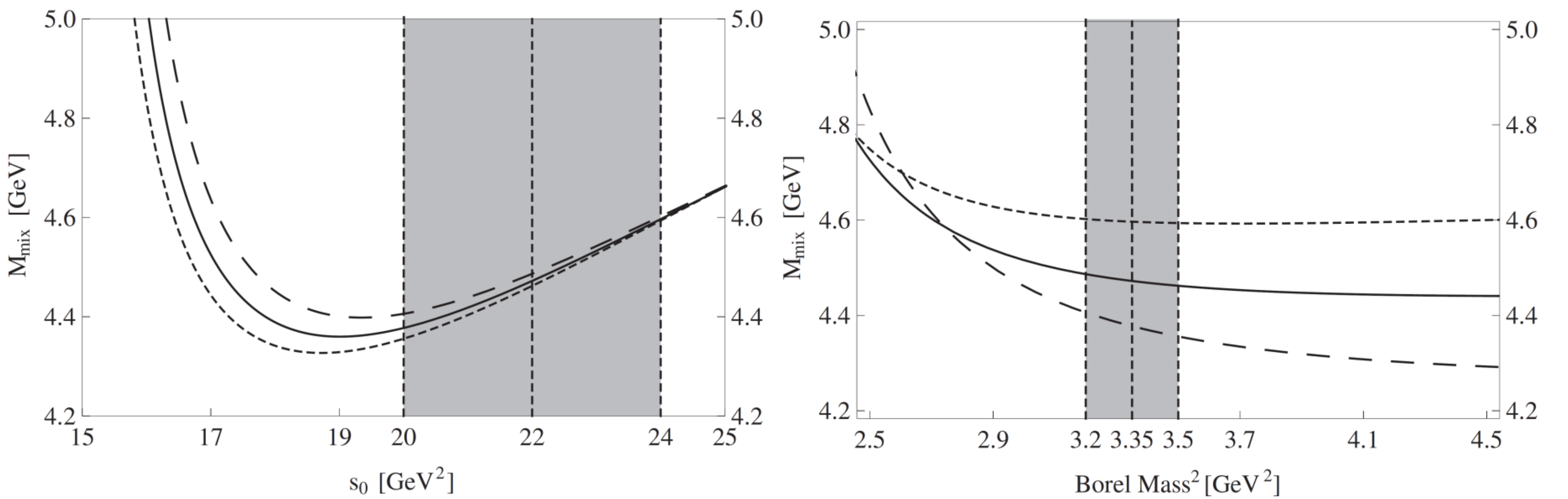



FIG. 2: The variation of $M_{[\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c],5/2^+}$ with respect to the threshold value $s_0$ (left) and the Borel mass $M_B$ (right).

# More: hidden-charm baryonium states

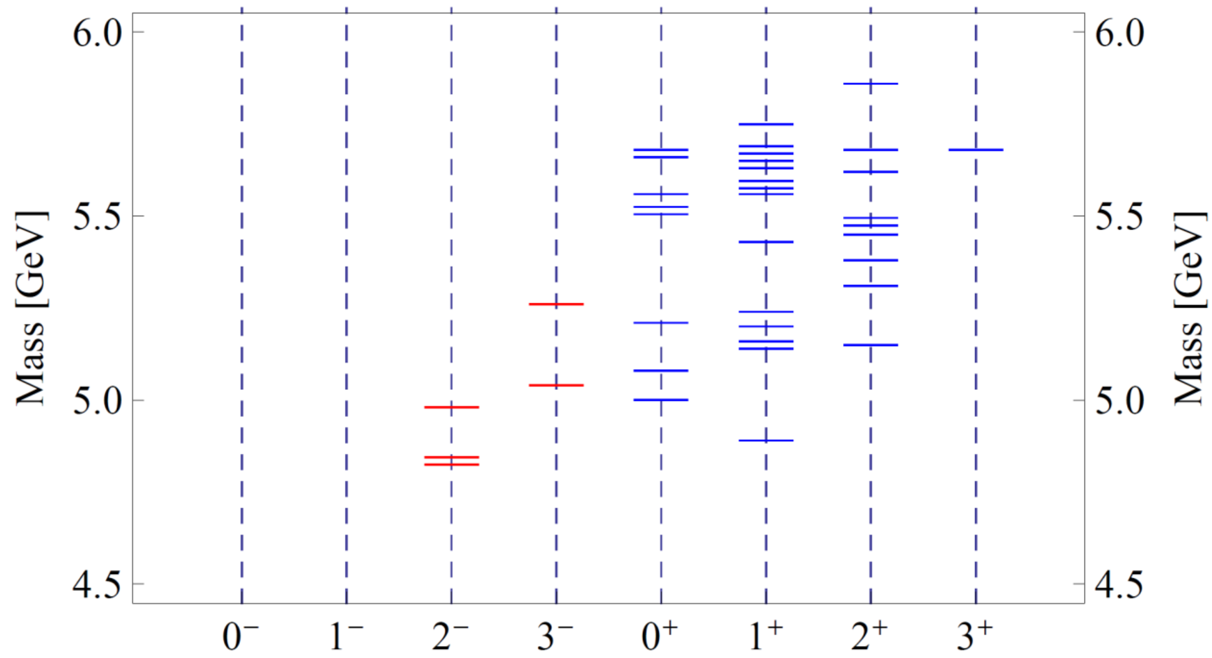



FIG. 5: Spectrum of hidden-charm baryonium states obtained using the method of QCD sum rules. The blue lines are obtained using the currents of Type D, and the red lines are obtained using the currents of Type F.

# Summary

**We still need more theoretical and experimental joint efforts**

# Thank you for your attention