Hidden-charm pentaquark states in QCD sum rules

Hua-Xing Chen

Beihang University

Collaborators: Wei Chen, Er-Liang Cui, Xiang Liu, Yan-Rui Liu, T. G. Steele, Shi-Lin Zhu

Guilin 2017/08/27

CONTENTS

- **Experimental status of Pc(4380) and Pc(4450)**
- History of multiquark states
- Various theoretical methods
- Our QCD sum rule studies

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)

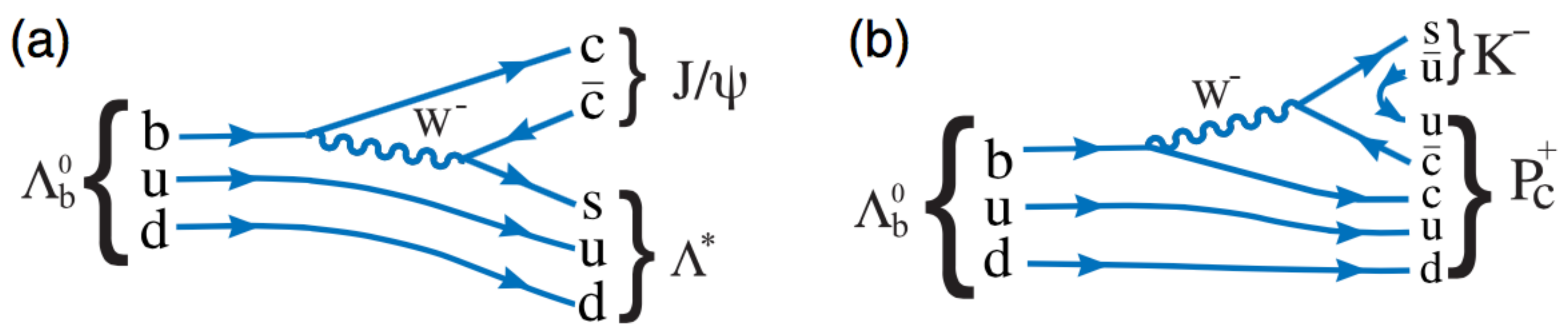


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

The measured invariant mass spectra

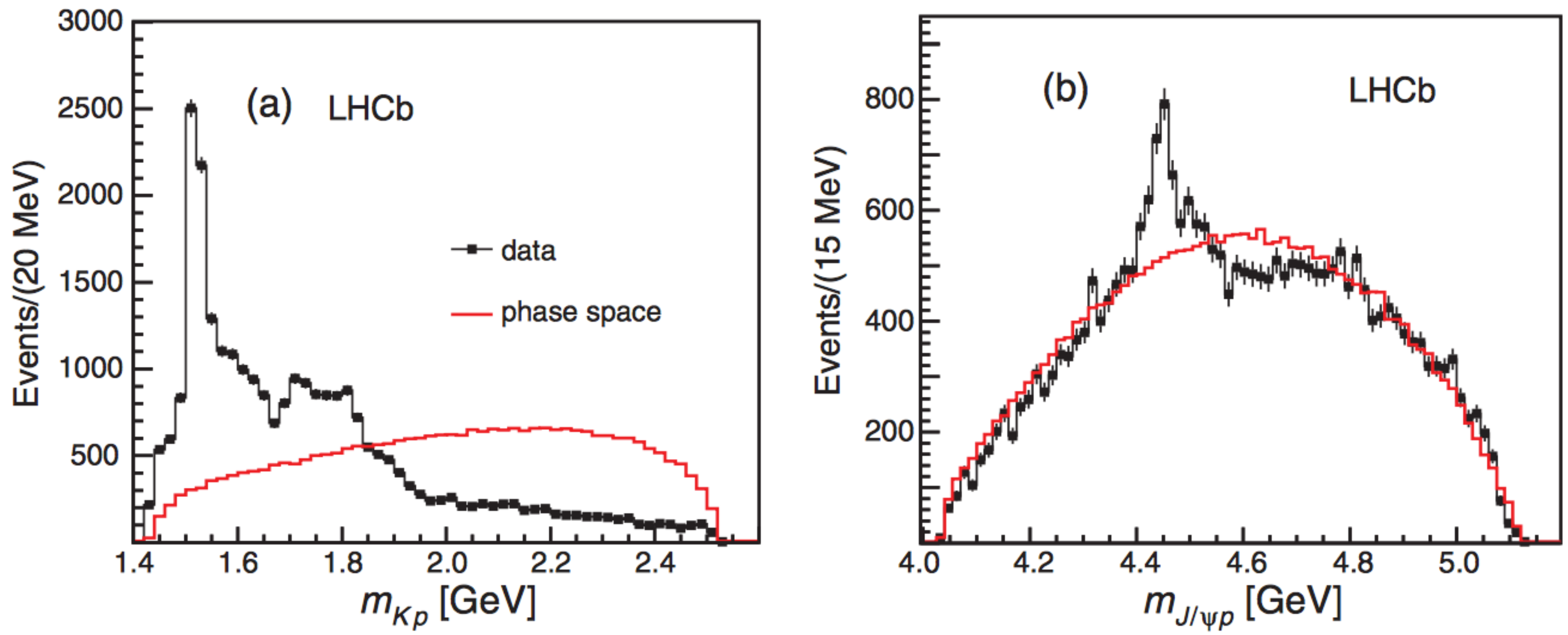


FIG. 2 (color online). Invariant mass of (a) $K^- p$ and (b) $J/\psi p$ combinations from $\Lambda_b^0 \to J/\psi K^- p$ decays. The solid (red) curve is the expectation from phase space. The background has been subtracted.

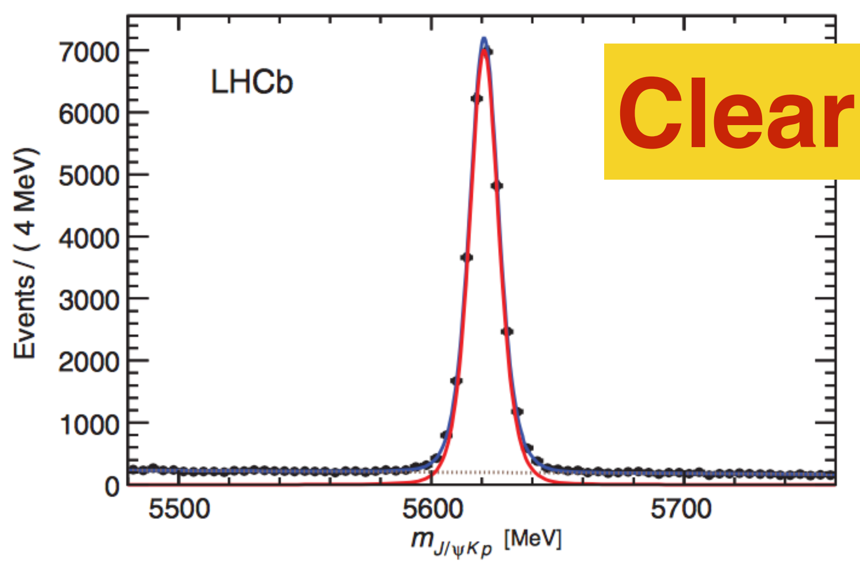


FIG. 4 (color online). Invariant mass spectrum of $J/\psi K^- p$ combinations, with the total fit, signal, and background components shown as solid (blue), solid (red), and dashed lines, respectively.

Clear signal of Λ_b

LHCb performed the analysis of the above experimental data

Resonance parameters of two Pc states

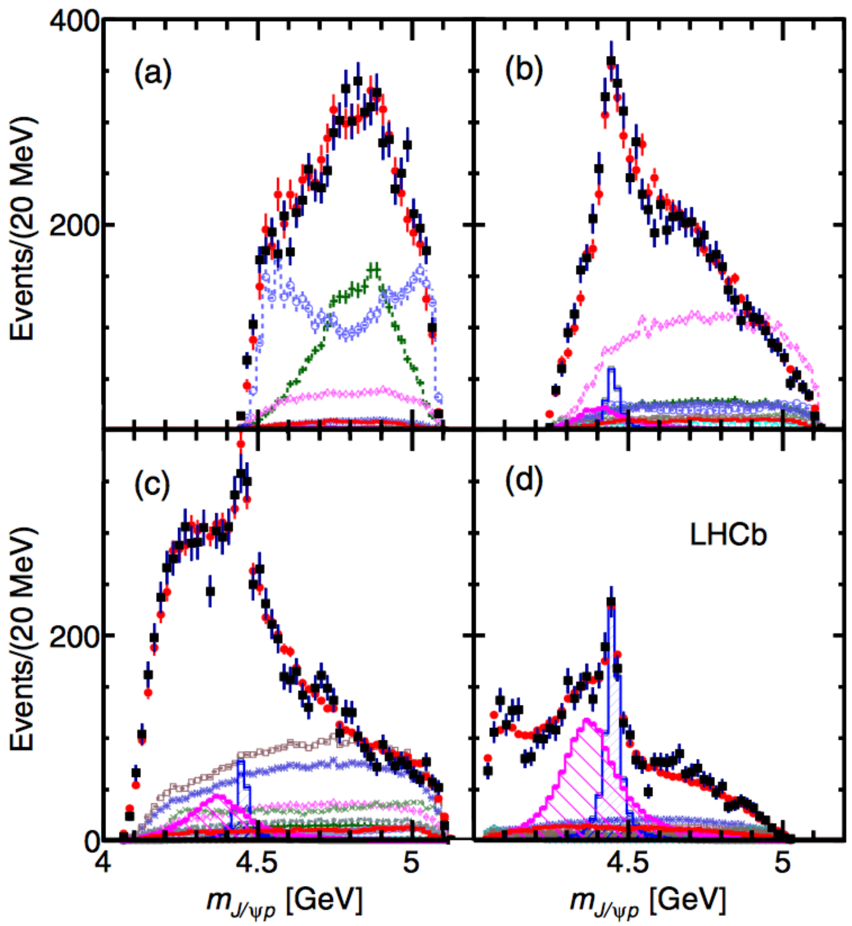


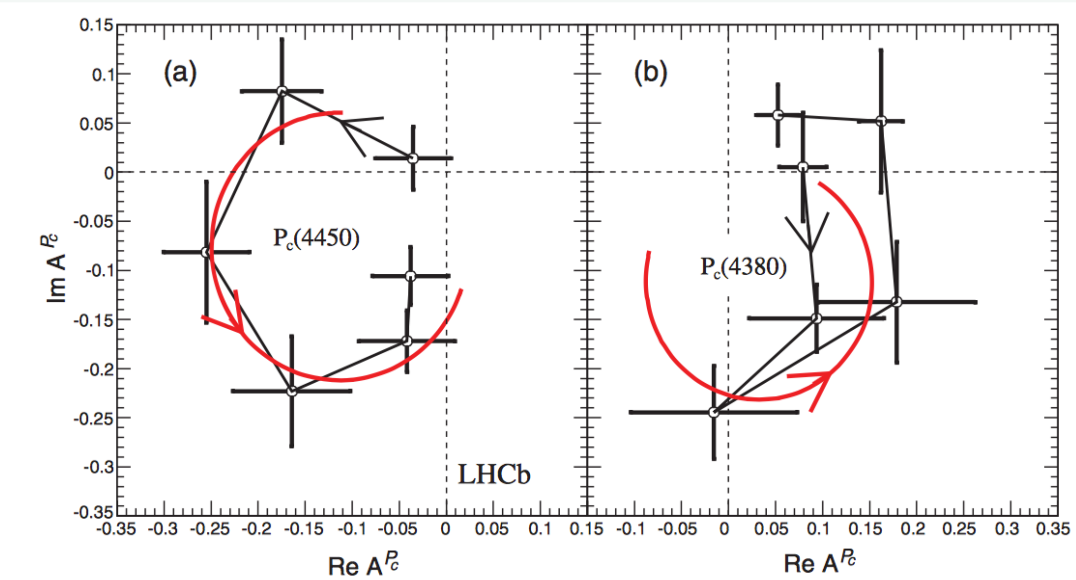
FIG. 8 (color online). $m_{J/\psi p}$ in various intervals of m_{Kp} for the fit with two P_c^+ states: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, and (d) $m_{Kp} > 2.00$ GeV. The data are shown as (black) squares with error bars, while the (red) circles show the results of the fit. The blue and purple histograms show the two P_c^+ states. See Fig. 7 for the legend.

	$P_c(4380)^+$	$P_c(4450)^+$
Significance	9σ	12σ
Mass (MeV)	4380 ± 8 ± 29	4449.8 ± 1.7 ± 2.5
Width (MeV)	205 ± 18 ± 86	39 ± 5 ± 19
Fit fraction(%)	8.4 ± 0.7 ± 4.2	4.1 ± 0.5 ± 1.1
$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-; P_c^+ \to J/\psi p)$	$(2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$	$(1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$

Branching ratio results are submitted to Chin. Phys. C (arXiv:1509.00292)

Ref: $\mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Argand diagrams show the resonance behavior of two Pc states



CERN Accelerating science

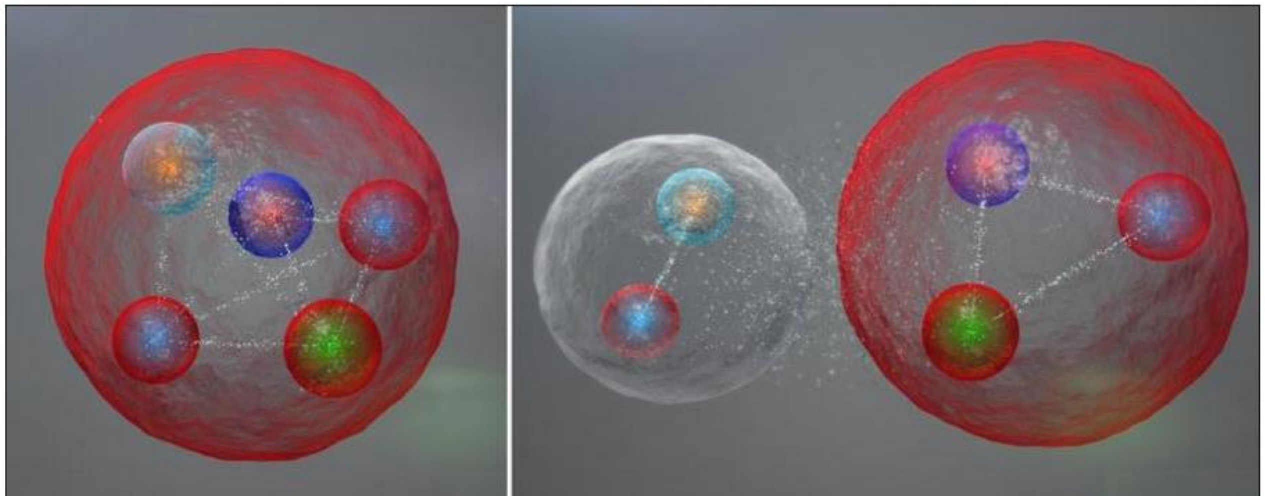
About CERN | Students & Educators | Scientists | CERN people

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)

CONTENTS

- Experimental status of Pc(4380) and Pc(4450)
- **History of multiquark states**
- Various theoretical methods
- Our QCD sum rule studies

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

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*

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 $1/2^+$ 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

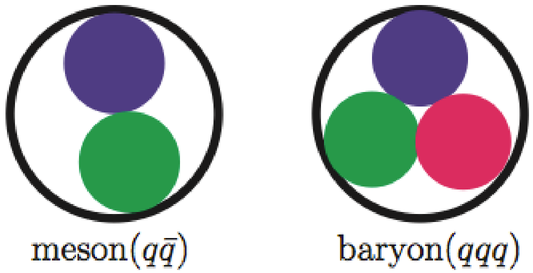
$$\underline{56}\otimes\underline{56}=\underline{462}\oplus\underline{1050}\oplus\underline{1134}\oplus\underline{490}. \qquad (1)$$

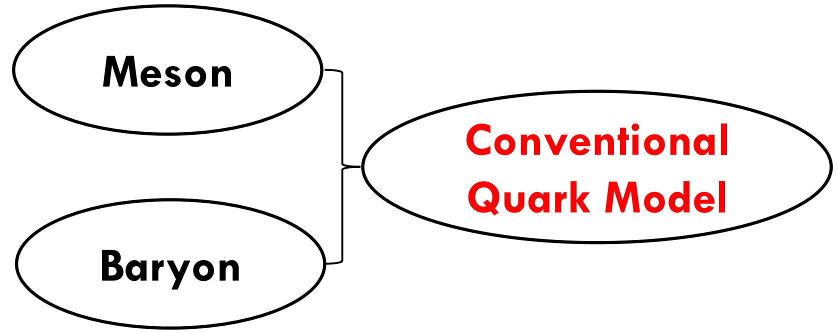
We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the $\underline{490}$ multiplet.[3] This means that six zero-strangeness states shown in Table I should be observed. In all these states odd T goes with even J and vice versa.

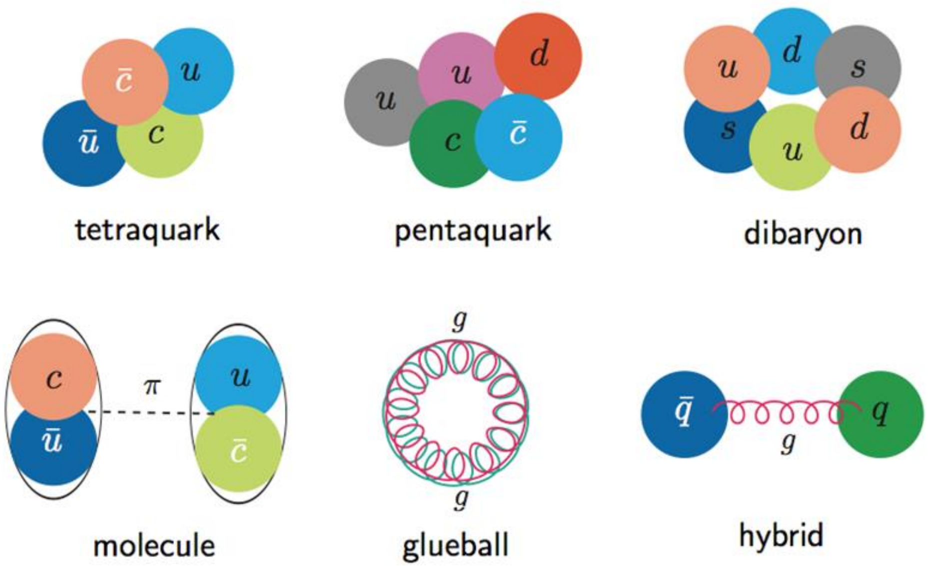
CONTENTS

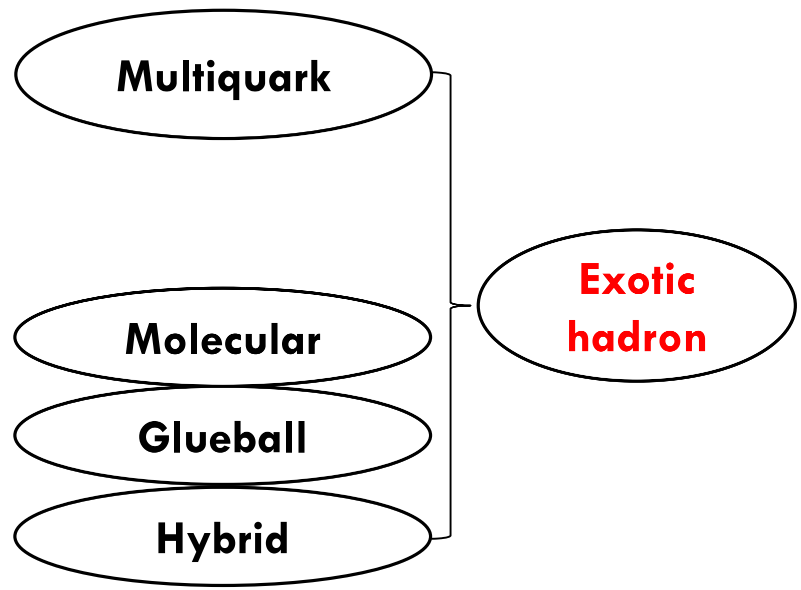
- Experimental status of Pc(4380) and Pc(4450)
- History of multiquark states
- **Various theoretical methods**
- Our QCD sum rule studies

Categorizations









- **Identifying exotic states is one of the most important issues of particle physics**
- **Various experimental signals provide us good platform to identify exotic state**

Theoretical explanations of experimental signals

Y(4260)

Resonant

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

Non-Resonant

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

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

Theoretical methods/models

- Various quark models
- Various effective methods
- Chiral unitary model
- One boson exchange model
- Diquark/triquark model
- **QCD sum rules**
- Lattice QCD

……

H.-X. Chen et al., Phys. Rept. 639, 1 (2016);
H.-X. Chen et al., ROPP 80, 076201(2017);
E. Klempt et al., RMP 82, 1095 (2010);
N. Brambilla et al., EPJC 74, 2981 (2014);
S. L. Olsen et al., Front. Phys. 10, 121 (2015);
E. Oset et al., IJMPE 25, 163001 (2016);
J. M. Richard, Few-Body Syst 57, 1185 (2016);
A. Hosaka et al., PTEP 6, 062C01 (2016);
R.A. Briceno et al. CPC 40, 042001 (2016);
R. F. Lebed et al., PPNP 93, 143 (2017);
A. Esposito et al., Phys. Rept. 668, 1 (2017);
Y. B. Dong et al., PPNP 94, 282 (2017);
F. K. Guo et al., arXiv:1705.00141.

- Various non-resonant explanations

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

Theoretical methods/models

- Various quark models
- Various effective methods
- Chiral unitary model
- One boson exchange model
- Diquark/triquark model
- **QCD sum rules**
- Lattice QCD

  ……

From Hadron Level (Chiral unitary model, One boson exchange model)

From Quark Level (Diquark/triquark model, QCD sum rules, Lattice QCD)

- Various non-resonant explanations

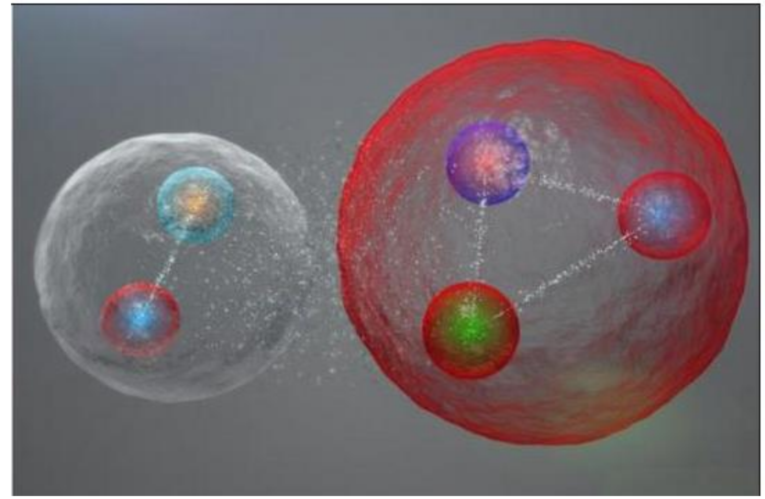
- Many methods/models to study productions and decay patterns of exotic hadrons

From Hadron Level

The methods/models at the **hadron** level usually take **the molecular picture**

- Chiral unitary model
- One boson exchange model

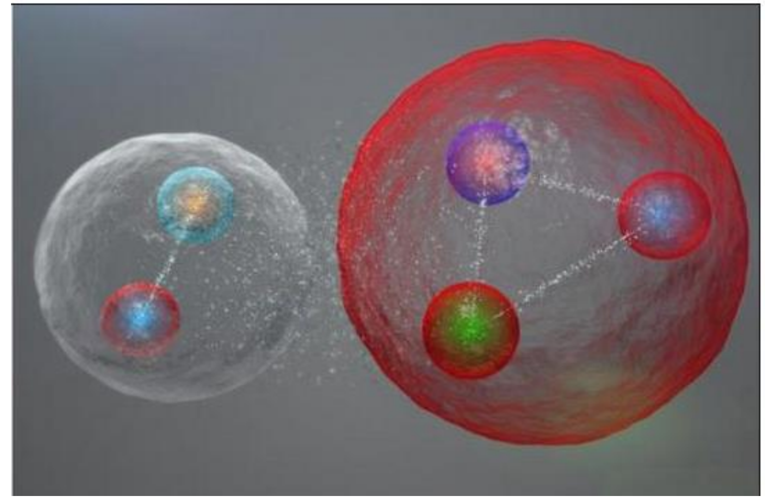
……



From **Hadron** Level

The methods/models at the **hadron** level usually take **the molecular picture**

- Chiral unitary model
- One boson exchange model
- ……



The **Molecular** Picture

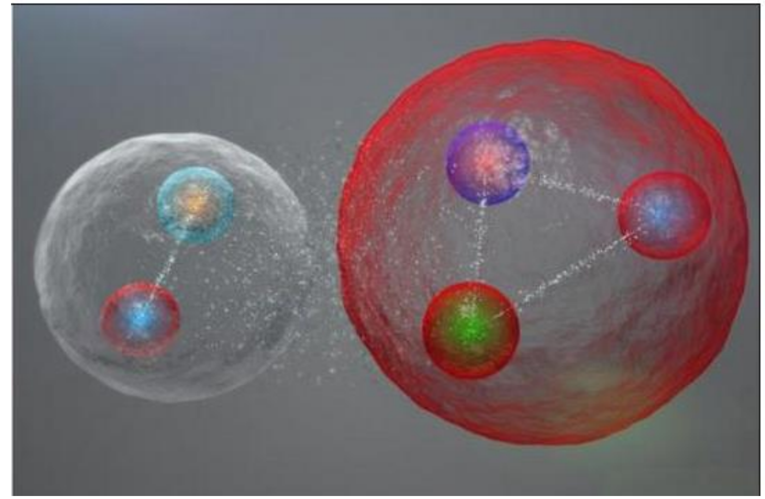
The masses of Pc(4380) and Pc(4450) are close to the $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ thresholds, respectively.

From **Hadron** Level

The methods/models at the **hadron** level usually take **the molecular picture**

- Chiral unitary model
- One boson exchange model

……



D mesons ⟷ Σ_c baryons

The **Molecular** Picture

The masses of Pc(4380) and Pc(4450) are close to the $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ thresholds, respectively.

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

Chiral unitary model

arXiv:1007.0573

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]
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)

The interaction between various charmed mesons and charmed baryons are studied within the framework of the coupled channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely

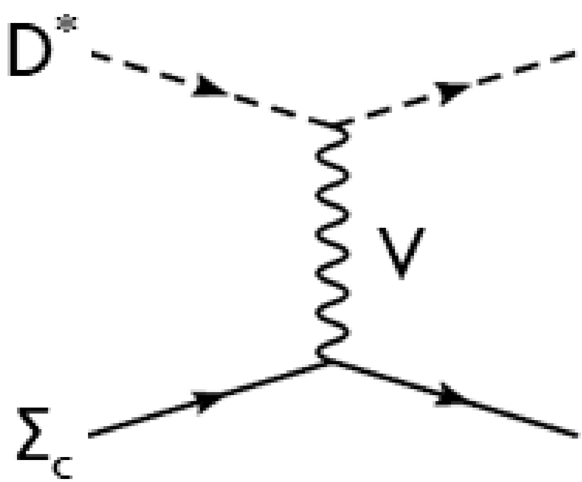
Chiral unitary model

arXiv:1007.0573

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]
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)

The interaction between various charmed mesons and charmed baryons are studied within the framework of the coupled channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and Λ^* resonances with hidden charm are predicted with mass above 4 GeV and width smaller than 100 MeV. The predicted new resonances definitely



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

$$V_{ab(P_1 B_1 \to P_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{P_1} + E_{P_2}),$$
$$V_{ab(V_1 B_1 \to V_2 B_2)} = \frac{C_{ab}}{4f^2}(E_{V_1} + E_{V_2})\vec{\epsilon}_1 \cdot \vec{\epsilon}_2,$$

Chiral unitary model

arXiv:1007.0573

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]

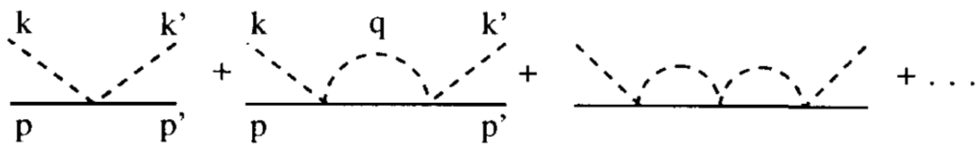
1. Institute of High Energy Physics, CAS, Beijing 100049, China

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)

The interaction between various charmed mesons and charmed baryons are studied within the framework of the coupled channel unitary approach with the local hidden gauge formalism. Several meson-baryon dynamically generated narrow N^* and
with mass above 4 GeV and width smaller than 100



$$T = V + VGT = (1 - VG)^{-1}V,$$

TABLE I: Coefficients C_{ab} in Eq. (2) for $(I, S) = (1/2, 0)$

	$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	$\eta_c N$	πN	ηN	$\eta' N$	$K\Sigma$	$K\Lambda$
$\bar{D}\Sigma_c$	-1	0	$-\sqrt{3/2}$	$-1/2$	$-1/\sqrt{2}$	$1/2$	1	0
$\bar{D}\Lambda_c^+$		1	$\sqrt{3/2}$	$-3/2$	$1/\sqrt{2}$	$-1/2$	0	1

(I, S)	z_R (MeV)	g_a		
$(1/2, 0)$		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	4269	2.85	0	
$(0, -1)$		$\bar{D}_s\Lambda_c^+$	$\bar{D}\Xi_c$	$\bar{D}\Xi_c'$
	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 $VB \to VB$.

One boson exchange model

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)]

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

One boson exchange model

arXiv:1507.03704

A new page for hadron physics: Identifying exotic hidden-charm pentaquarks

Rui Chen[1,2] and Xiang Liu[1,2*]

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

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

Xue-Qian Li[†]

School of Physics, Nankai University, Tianjin 300071, China

Shi-Lin Zhu[1,2,3‡]

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

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

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

One boson exchange model

arXiv:1507.03704

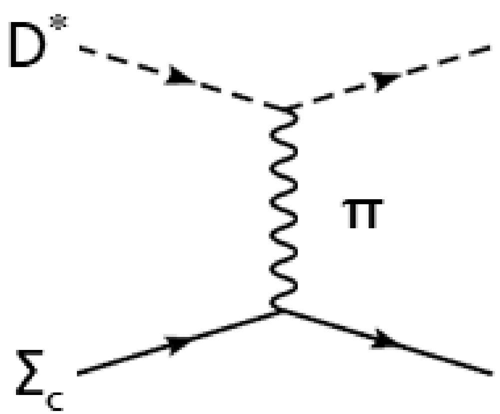
A new page for hadron physics: Identifying exotic hidden-charm pentaquarks

Rui Chen[1,2] and Xiang Liu[1,2*]
[1]*Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China*
[2]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*

Xue-Qian Li[†]
School of Physics, Nankai University, Tianjin 300071, China

Shi-Lin Zhu[1,2,3‡]
[1]*School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[2]*Collaborative Innovation Center of Quantum Matter, Beijing 100871, China*
[3]*Center of High Energy Physics, Peking University, Beijing 100871, China*

The authors investigated the **one-pion-exchange-based potentials** for the $\Sigma_c\bar{D}^*$ and $\Sigma_c^*\bar{D}^*$ systems:



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

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

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

One boson exchange model

arXiv:1507.03704

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

One boson exchange model

arXiv:1507.03704

The effective potential in momentum space

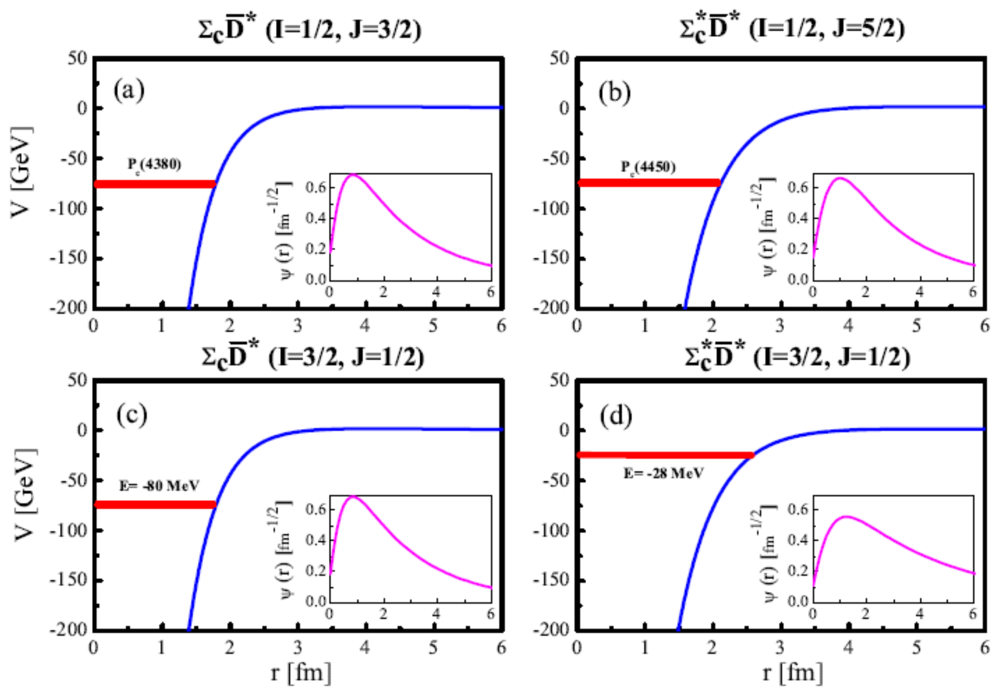
Scattering amplitude

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

Fourier transformation

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

Solving Schrödinger equation



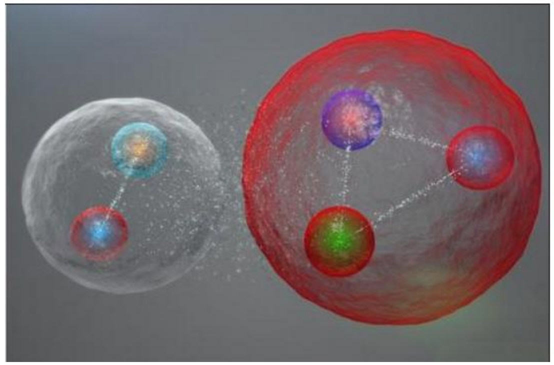
- $P_c(4380)$ and $P_c(4450)$ are first identified as the hidden-charm molecular pentaquarks $\Sigma_c\bar{D}^*$ with (I=1/2, J=3/2), and $\Sigma_c^*\bar{D}^*$ with (I=1/2, J=3/2), respectively.
- Their study indicates that there should exist a $\Sigma_c\bar{D}^*$ state with (I=3/2, J=1/2) and a $\Sigma_c^*\bar{D}^*$ state with (I=3/2, J=1/2).

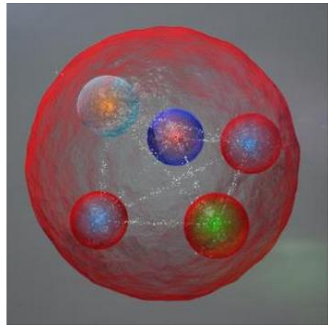
From **Quark** Level

The methods/models at the **quark** level can take both **the molecular picture** and **the (compact) multiquark picture**

- Diquark/triquark model
- QCD sum rules
- Lattice QCD

  ……



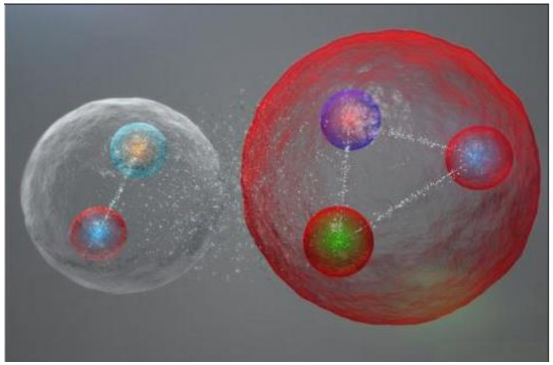


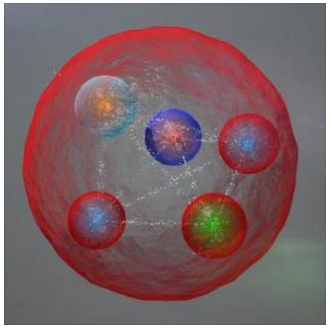
From **Quark** Level

The methods/models at the **quark** level can take both **the molecular picture** and **the (compact) multiquark picture**

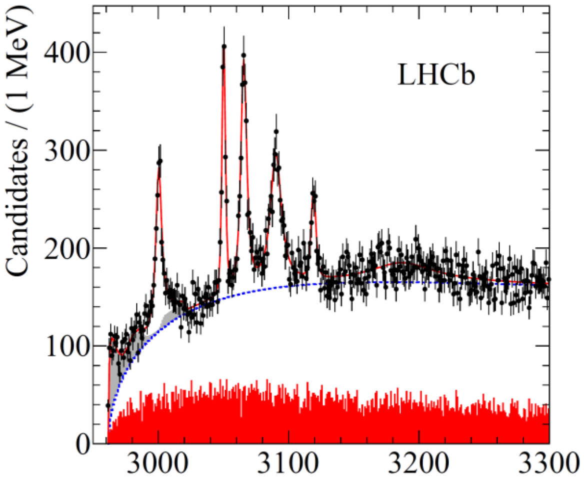
- Diquark/triquark model
- QCD sum rules
- Lattice QCD

……





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



Recent LHCb Experiment [arXiv:1703.04639]

fine structure of QCD?

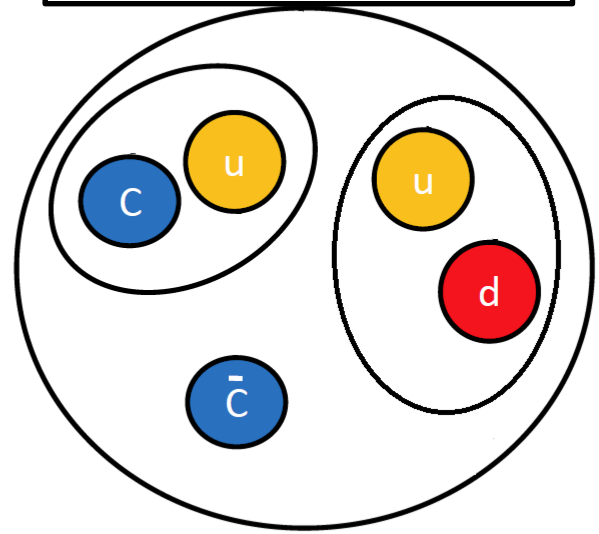
Diquark/triquark model

arXiv:1507.03704

The New Pentaquarks in the Diquark Model

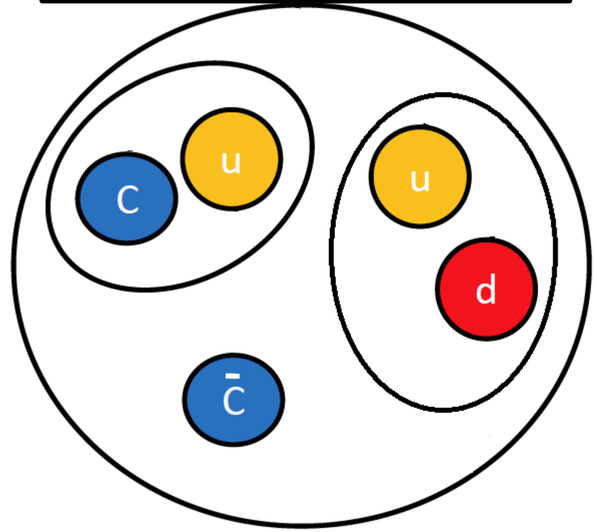
L. Maiani,[1] A.D. Polosa,[1] and V. Riquer[1]
[1] *Dipartimento di Fisica and INFN, 'Sapienza' Università di Roma*
P.le Aldo Moro 5, I-00185 Roma, Italy

Pentaquark baryons are a natural expectation of an extended picture of hadrons where
and diquarks are the fundamental units. The parity/mass pattern observed, when compared
of exotic mesons, appears as the footprint of a compact five-quark structure. What has been
from the X, Y, Z phenomenology informs about the newly found pentaquark structure and
further experimental tests and directions to be explored.



Diquark/triquark model

arXiv:1507.03704



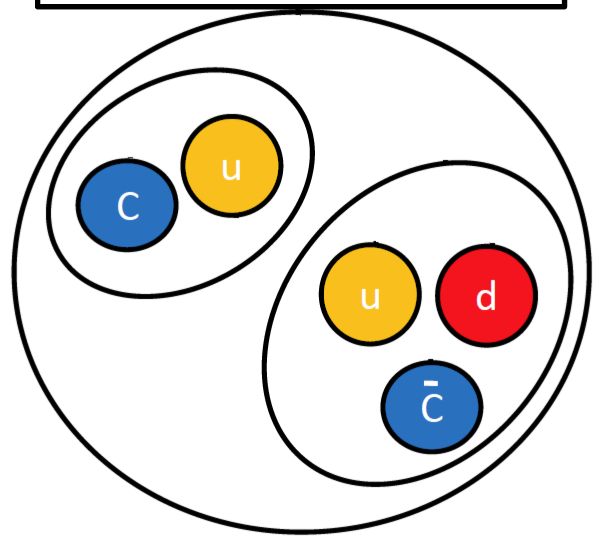
The New Pentaquarks in the Diquark Model

L. Maiani,[1] A.D. Polosa,[1] and V. Riquer[1]

[1] *Dipartimento di Fisica and INFN, 'Sapienza' Università di Roma P.le Aldo Moro 5, I-00185 Roma, Italy*

Pentaquark baryons are a natural expectation of an extended picture of hadrons where and diquarks are the fundamental units. The parity/mass pattern observed, when compared of exotic mesons, appears as the footprint of a compact five-quark structure. What has been from the X, Y, Z phenomenology informs about the newly found pentaquark structure and further experimental tests and directions to be explored.

arXiv:1507.05867



The Pentaquark Candidates in the Dynamical Diquark Picture

Richard F. Lebed*

Department of Physics, Arizona State University, Tempe, Arizona 85287-1504, USA

(Dated: July, 2015)

Starting with the dynamical picture of the exotic $c\bar{c}$-containing states XYZ as the confinement-induced hadronization of a rapidly separating pair of a compact diquark and antidiquark, we describe the pentaquark candidates $P_c^+(4380)$ and $P_c^+(4450)$ in terms of a confined but rapidly separating color-antitriplet diquark cu and color-triplet "triquark" $\bar{c}(ud)$. This separation explains the relatively small P_c^+ widths, despite these 5-quark systems lying far above both the $J/\psi\, p$ and $\Lambda_c \bar{D}^{(*)0}$ thresholds. The P_c^+ states are predicted to form isospin doublets with neutral partners P_c^0.

CONTENTS

- Experimental status of Pc(4380) and Pc(4450)
- History of multiquark states
- Various theoretical methods
- **Our QCD sum rule studies**

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

flavor contents

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

color indices

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

flavor contents

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

color indices

The Pauli principle is automatically satisfied

Two Configurations:

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

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

- **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:

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

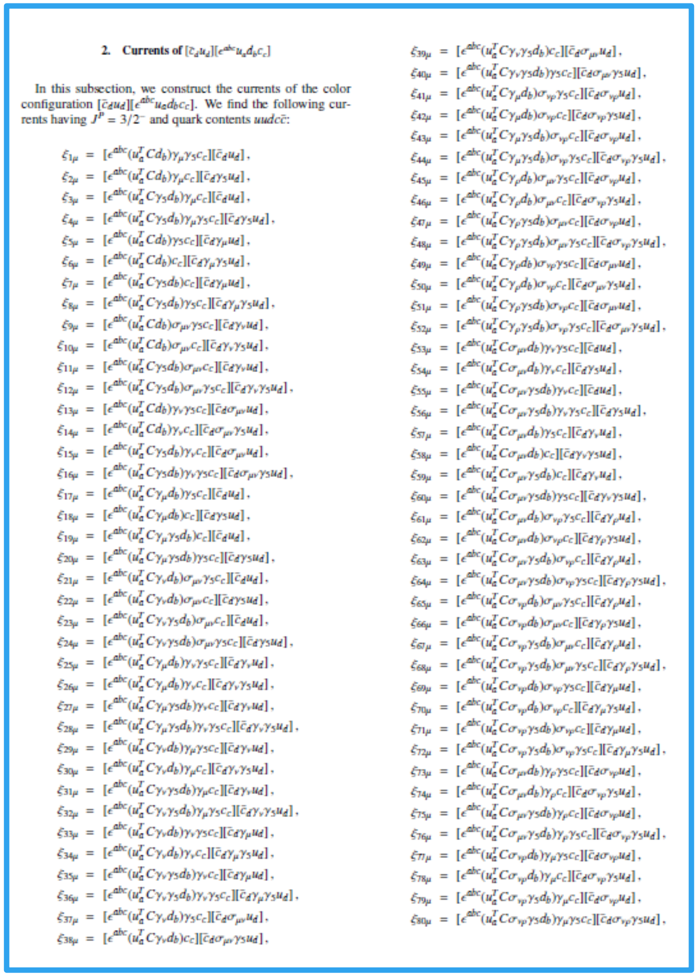
- We can construct the currents of the configuration $[\bar{c}_d c_d][\epsilon^{abc} q_a q_b q_c]$.
- Those containing $J=3/2$ components are

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

- 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.
- We select some of them to perform the QCD sum rules to see whether we can obtain reliable/stable sum rule results.

QCD SUM RULE

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

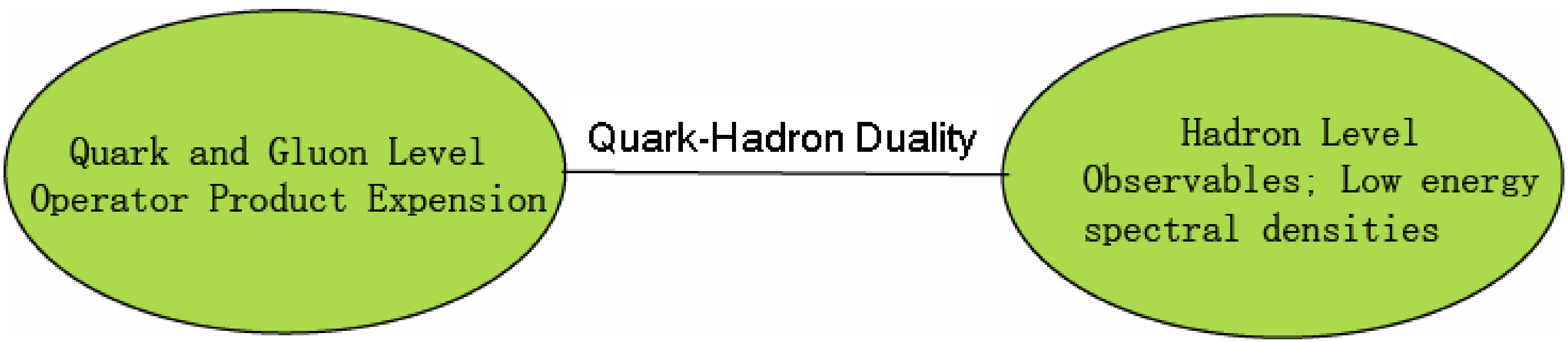
$$\Pi\left(q^2\right) \stackrel{\text{def}}{=} i\int d^4x e^{iqx}\langle 0|T\eta(x)\eta^+(0)\,|0\rangle$$
$$\approx \Sigma_n\langle 0|\eta|n\rangle\langle n|\eta^+|0\rangle$$

  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

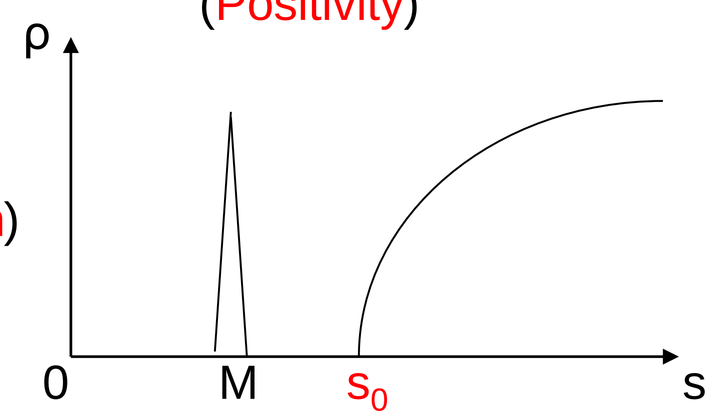
Hadron Level

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

(for baryon case)

(Positivity)

(Sufficient amount of Pole contribution)



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

Parity of Pentaquark

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)

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

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

- The same pentaquark current J can couple to states of both positive and negative parities through

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

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

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

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

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

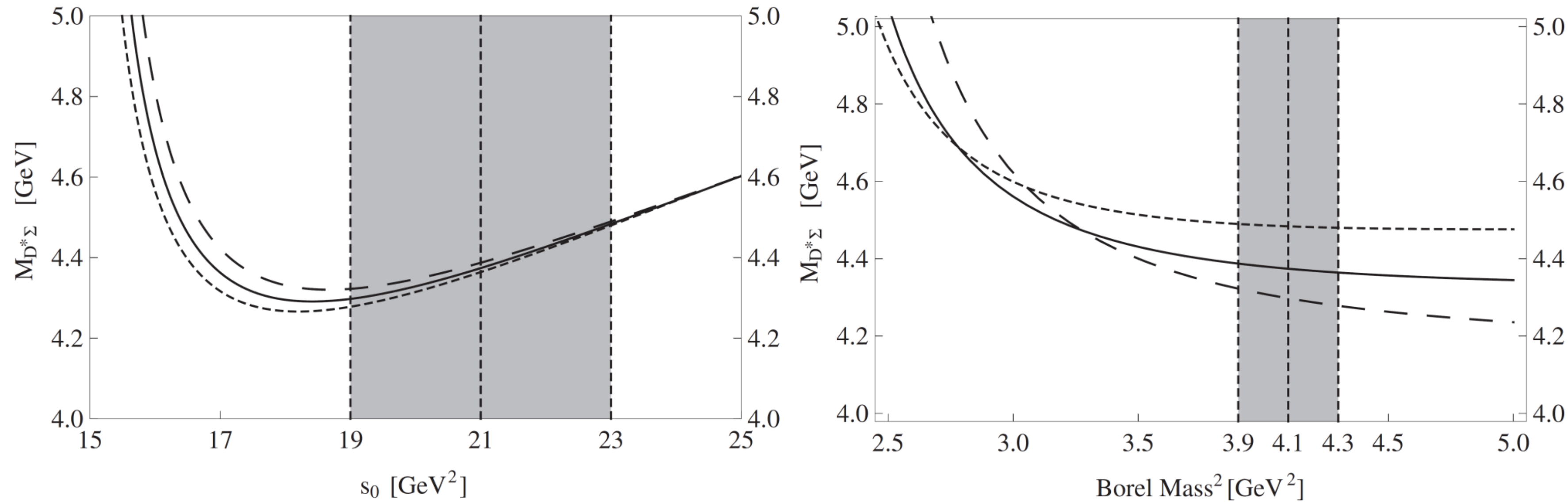


FIG. 1: The variation of $M_{[\bar{D}^*\Sigma_c],3/2^-}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right). In the left figure, the

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***)

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

$$\tan\theta = -1.25$$

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

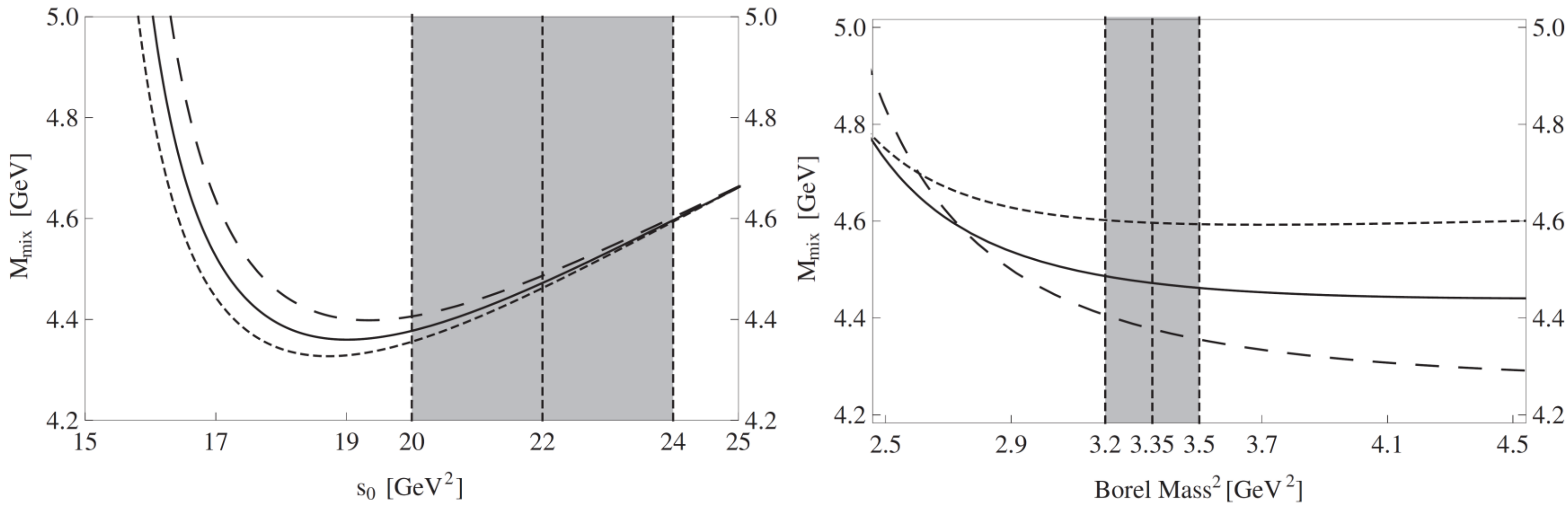


FIG. 2: The variation of $M_{[\bar{D}\Sigma_c^* \& \bar{D}^*\Lambda_c],5/2^+}$ with respect to the threshold value s_0 (left) and the Borel mass M_B (right).

Summary

- Besides the mass spectrum, production and decay properties are also important to understand **exotic hadrons**.
- We still need more theoretical and experimental joint efforts.
- This is a research field full of challenges and opportunities.

Thank you very much!