Theoretical studies on new hadron spectra

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IHEP 2018/02/09

CONTENTS

- **History of multiquark states**
- Various theoretical methods
- Our studies on exotic hadrons
- Our studies on heavy hadrons

The history of multiquark states

Phys.Lett. 8 (1964) 214-215

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

...

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

8419/TH.412
21 February 1964

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

G. Zweig
CERN---Geneva

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

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, 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 ($C = S = \pm1$)

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

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†

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

(Received 15 July 1976)

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

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

PHYSICAL REVIEW D VOLUME 20, NUMBER 3 1 AUGUST 1979

PRD 20 (1979)

Multiquark baryons and the MIT bag model

D. Strottman

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

(Received 4 December 1978)

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

The name pentaquark was first proposed by Lipkin in 1987

WIS-87/32/May-PH

New Possibilities for Exotic Hadrons - Anticharmed Strange Baryons*

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

PLB 195 (1987) 484

Submitted to Physics Letters

May 20, 1987

ABSTRACT

The name pentaquark was first proposed by Lipkin in 1987

WIS-87/32/May-PH

Volume 193, number 2,3 PHYSICS LETTERS B 16 July 1987

POSSIBILITY OF STABLE MULTIQUARK BARYONS

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Received 8 April 1987

The name pentaquark was first proposed by Lipkin in 1987

WIS-87/32/May-PH

Volume 193, number 2,3 PHYSICS LETTERS B 16 July 1987

POSSIBILITY OF STABLE MULTIQUARK BARYONS

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$Y = 2$ 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

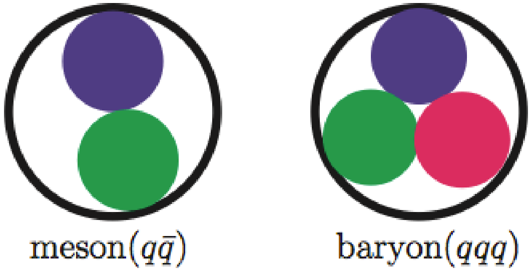
$$\underline{56} \otimes \underline{56} = \underline{462} \oplus \underline{1050} \oplus \underline{1134} \oplus \underline{490}. \qquad (1)$$

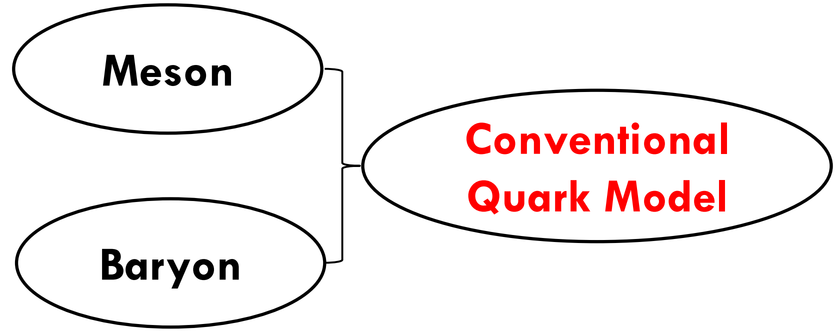
We now propose the hypothesis that all low-lying resonant states of the two-baryon system belong to the $\underline{490}$ multiplet.[3] This means that six zero-strangeness states shown in Table I should be observed. In all these states odd T goes with even J and vice versa.

CONTENTS

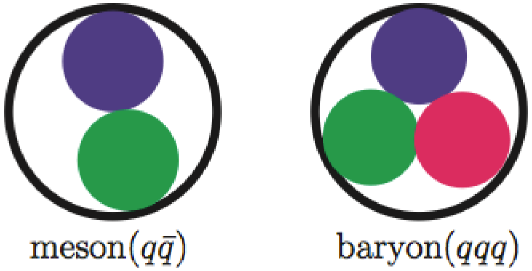
- History of multiquark states
- **Various theoretical methods**
- Our studies on exotic hadrons
- Our studies on heavy hadrons

Categorizations

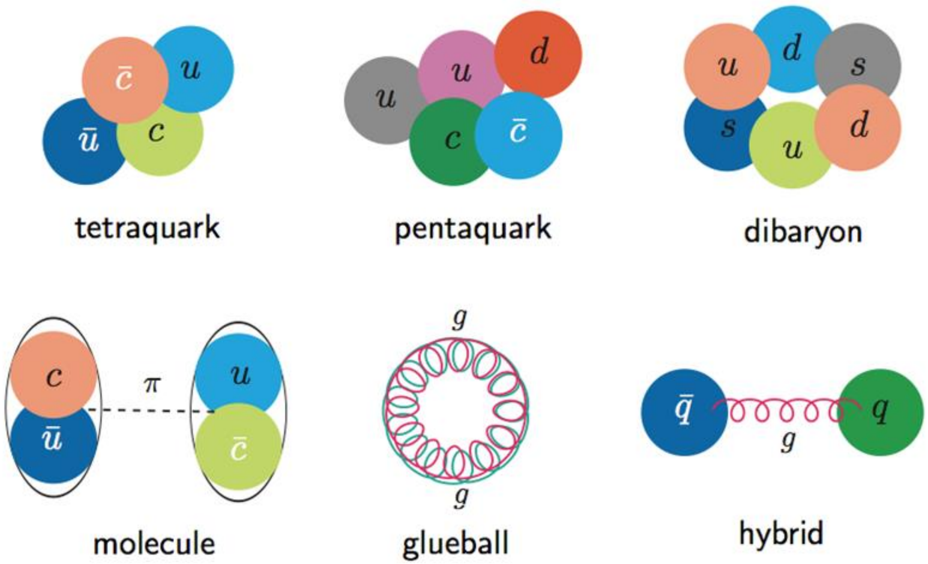




Categorizations



Meson
Baryon
Conventional Quark Model



Multiquark
Molecular
Glueball
Hybrid
Exotic hadron

- 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

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.

Y(4260)

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 explanations of experimental signals

Resonant

- **Conventional hadrons**

- **Exotic states**
  - **Molecular states:**
    loosely bound states composed of a pair of mesons/baryons; probably bounded by the pion exchange.
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Y(4260)

Y(4220)
Many Y's?

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

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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);
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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

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From Hadron Level

From Quark Level

- 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

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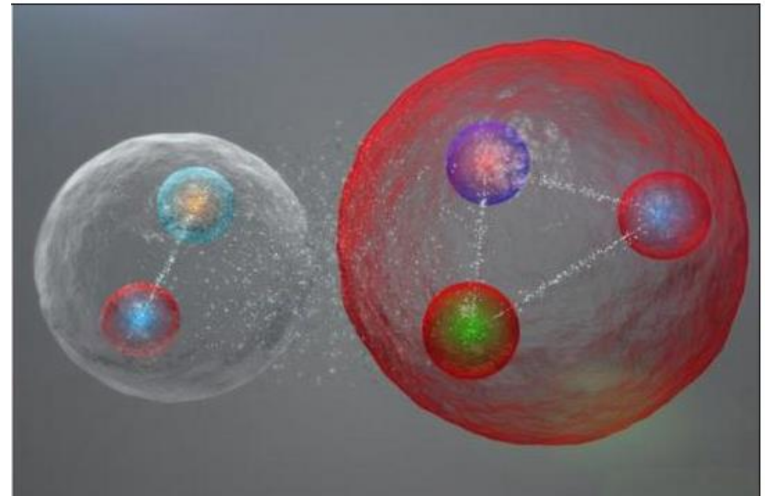


D mesons ⟷ Σ_c baryons

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.

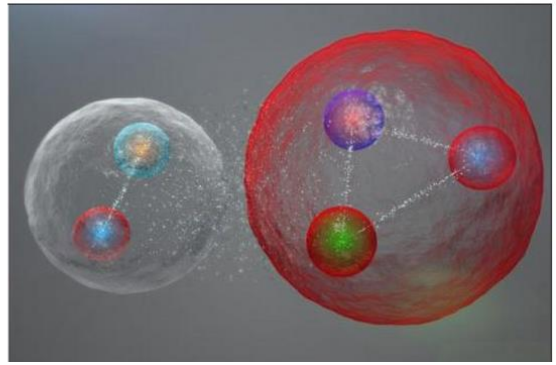
Deuteron: loosely bound state of proton and neutron

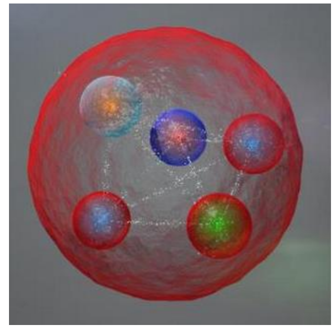
Nucleon force: short-range, mid-range, long-range

ϱ and ω exchanges	Scalar σ with mass around 600 MeV	Pion exchange

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

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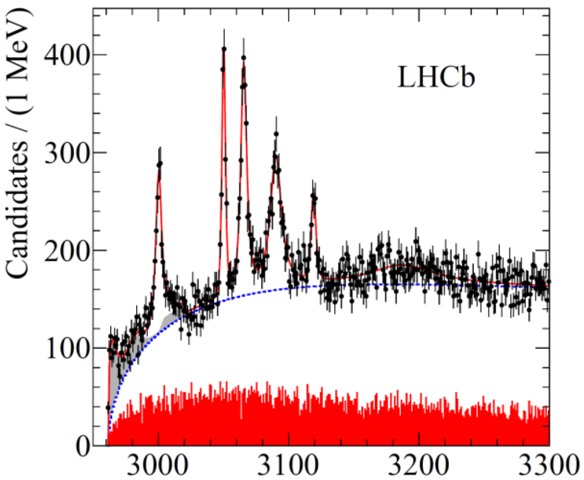
These studies help to understand **the internal structure** of hadrons



Recent LHCb Experiment [arXiv:1703.04639]

fine structure of QCD?

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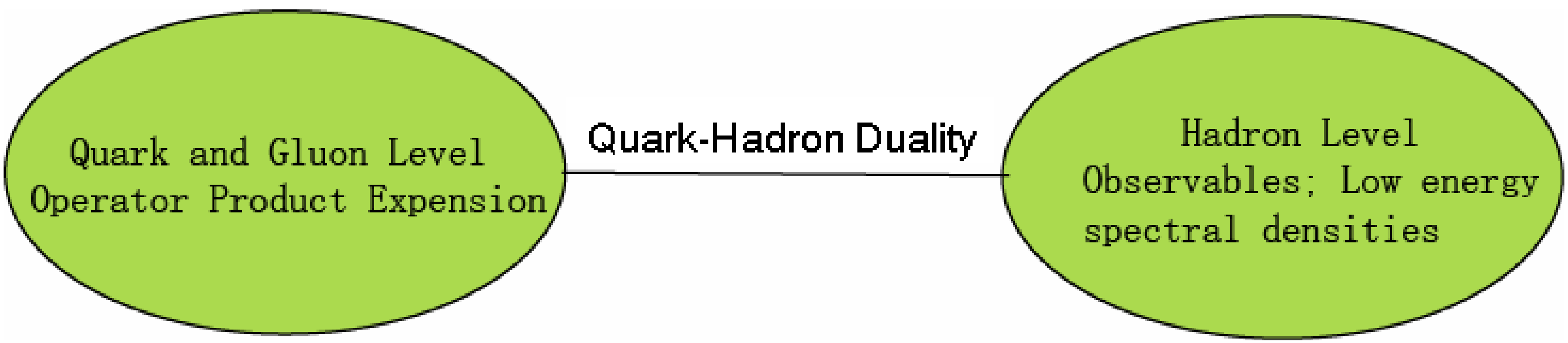
QCD SUM RULE

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

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



Hidden-Charm Pentaquarks $P_c(4380)$&$P_c(4450)$

- Final states $J/\psi\, p = \bar{c}cuud$

  $I = 1/2, SU(3)_F$ octet

- Spin-parity $J^P = 3/2^-$&$5/2^+$, $3/2^+$&$5/2^-$, or $5/2^+$&$3/2^-$.
- Masses and widths are known.

- We systematically construct all the hidden-charm pentaquark currents with the quark content $\bar{c}cuud$ and the spin $J = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}$.

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

We can construct various interpolating currents to reflect the internal structure of hadrons

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 a whole**, can be related to each other through (this suggests that decaying into $[J/\psi\ N]$ may be possible)

- **The Fierz transformation**

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

- **The color rearrangement**

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

However, each single current belonging to these two configurations lead to different QCD sum rule results.

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

- There are hundreds of currents belonging to this configuration.
- Due to the color structure, these currents well couple (quickly decay) to $[J/\psi\, N^{(*)}]$, etc.
- We can not use any of these currents to obtain reliable QCD sum rule results.
- This seems to be reasonable because J/ψ and $N^{(*)}$ do not have strong correlation.

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

- There are more currents belonging to this configuration.
- Due to the color structure, these currents well couple (quickly decay, if allowed) to $[\bar{D}^{(*)}\Sigma_c^{(*)}]$ and $[\bar{D}^{(*)}\Lambda_c^{(*)}]$, etc.
- We find some mixing currents, which lead reliable QCD sum rule results.
- The results suggests that the $P_c(4380)$ and $P_c(4450)$ can be interpreted as $[\bar{D}^{(*)}\Sigma_c^{(*)} \& \bar{D}^{(*)}\Lambda_c^{(*)}]$ molecules.

Hidden-charm pentaquark with **I = 1/2** and $\mathbf{J^P = 3/2^-}$

$$
\begin{aligned}
J_{\mu,3/2-} &= \cos\theta_1 \times \xi_{36\mu} + \sin\theta_1 \times \psi_{9\mu} \\
&= \cos\theta_1 \times [\epsilon^{abc}(u_a^T C\gamma_\nu\gamma_5 d_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu\gamma_5 u_d] \\
&\quad + \sin\theta_1 \times [\epsilon^{abc}(u_a^T C\gamma_\nu u_b)\gamma_\nu\gamma_5 c_c][\bar{c}_d\gamma_\mu d_d]\,,
\end{aligned}
$$

$\boxed{\bar{D}^{(*)}\Lambda_c^{(*)}}$

$\boxed{\bar{D}^{(*)}\Sigma_c^{(*)}}$

$$M_{3/2^-} = 4.40^{+0.16}_{-0.23}\ \mathrm{GeV}$$

- Our result suggests that the $P_c(4380)$ can be interpreted as hadronic molecule of $J^P = 3/2^-$.
- It may contains S-wave $[\bar{D}^*\Sigma_c]$, S-wave $[\bar{D}_1\Lambda_c(1P)]$, P-wave $[\bar{D}_1\Lambda_c]$, and D-wave $[\bar{D}\Lambda_c]$, etc.
- It can directly decay to $[J/\psi\ N]$.

Hidden-charm pentaquark with **I = 1/2** and $\mathbf{J^P = 5/2^+}$

$$\begin{aligned} J_{\mu\nu,5/2+} &= \cos\theta_2 \times \xi_{15\mu\nu} + \sin\theta_2 \times \psi_{4\mu\nu} \\ &= \cos\theta_2 \times [\epsilon^{abc}(u_a^T C\gamma_\mu\gamma_5 d_b)c_c][\bar{c}_d\gamma_\nu u_d] \\ &\quad + \sin\theta_2 \times [\epsilon^{abc}(u_a^T C\gamma_\mu u_b)c_c][\bar{c}_d\gamma_\nu\gamma_5 d_d] + \{\mu \leftrightarrow \nu\}\,, \end{aligned}$$

$\boxed{\bar{D}^{(*)}\Lambda_c^{(*)}}$

$\boxed{\bar{D}^{(*)}\Sigma_c^{(*)}}$

$$M_{5/2^+} = 4.50^{+0.26}_{-0.23}\ \mathrm{GeV}$$

- Our result suggests that the $P_c(4450)$ can also be interpreted as hadronic molecule of $J^P = 5/2^+$.
- It may contains P-wave $[\bar{D}\Sigma_c^*]$, S-wave $[\bar{D}^*\Lambda_c(1P)]$, and P-wave $[\bar{D}^*\Lambda_c]$, etc.
- It can directly decay to $[J/\psi\ N]$.

Hidden-charm pentaquark with **other spin-parity**

$$M_{3/2^+} = 4.40^{+0.14}_{-0.16}\ \mathrm{GeV}\,,$$
$$M_{5/2^-} = 4.43^{+0.26}_{-0.28}\ \mathrm{GeV}\,.$$

- These values are also consistent with the experimental masses of the Pc(4380) and Pc(4450), suggesting that they may also be interpreted as hadronic molecules of $J^P = 3/2^+$ and $5/2^-$ containing $[\bar{D}^{(*)}\Sigma_c^{(*)} \& \bar{D}^{(*)}\Lambda_c^{(*)}]$.

Hidden-charm pentaquark with **other isospin: I = 3/2**

$M_{1/2^-} = 4.60^{+0.15}_{-0.14}$ GeV -- S-wave $[\bar{D}\Sigma_c]$

$M_{3/2^-} = 4.77^{+0.14}_{-0.13}$ GeV -- S-wave $[\bar{D}\Sigma_c^* \& \bar{D}^*\Sigma_c]$

$M_{5/2^-} = 4.95^{+0.13}_{-0.13}$ GeV -- S-wave $[\bar{D}^*\Sigma_c^*]$

- All the above mass values are significantly larger than the masses of the Pc(4380) and Pc(4450).
- They can not decay to $[J/\psi\ N]$ due to isospin symmetry, so their widths may not be very large.

Exotic Hadrons

- Every signal of exotic hadrons is of particular interest.
- We still know little about them. Especially, their internal structure are quite complicated and difficult to be understood.

- To know more about the internal structure of hadrons, we also study heavy mesons and heavy baryons.

CONTENTS

- History of multiquark states
- Various theoretical methods
- Our studies on exotic hadrons
- **Our studies on heavy hadrons**

Internal structure of heavy mesons

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

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

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

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

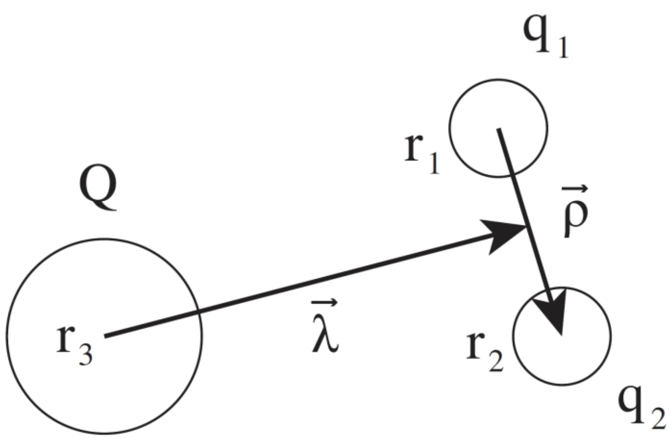
$$L = 2 : \begin{cases} j_l = 3/2, J^P = (1^-, 2^-) \\ j_l = 5/2, J^P = (2^-, 3^-) \end{cases}$$

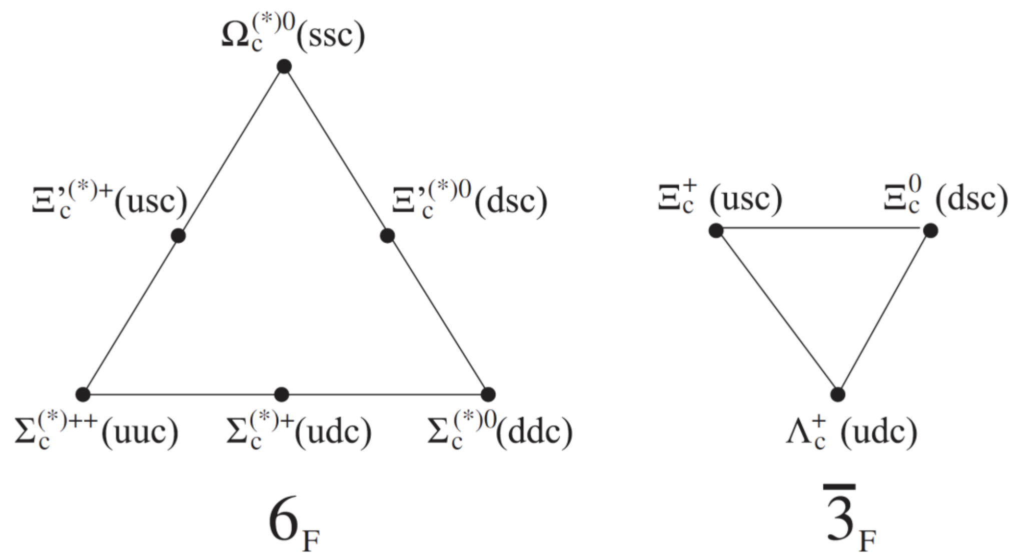
Internal structure of heavy mesons

- We can construct relevant interpolating fields to well describe the above internal structure, and use the method of QCD sum rules to study the mass spectra of heavy mesons.
- Using our method, the mass splitting within the same doublet can be evaluated quite well with much less uncertainties.
- We propose to observe higher excited heavy mesons in future experiments.

<table>
<tr><th></th><th></th><th></th><th colspan="2">D mesons (c-q)</th><th colspan="2">Ds mesons (c-s)</th></tr>
<tr><th></th><th>Multiplets</th><th>J^P</th><th>Experiments</th><th>Ours</th><th>Experiments</th><th>Ours</th></tr>
<tr><td rowspan="6"></td><td rowspan="2">$L=0, j_l=\frac{1}{2}$</td><td>0^-</td><td>D</td><td>--</td><td>D_s</td><td>--</td></tr>
<tr><td>1^-</td><td>D^*</td><td>--</td><td>D_s^*</td><td>--</td></tr>
<tr><td rowspan="2">$L=1, j_l=\frac{1}{2}$</td><td>0^+</td><td>$D_0^*(2400)$</td><td>--</td><td>$D_{s0}^*(2317)$</td><td>--</td></tr>
<tr><td>1^+</td><td>$D_1(2420)$</td><td>--</td><td>$D_{s1}(2460)$</td><td>--</td></tr>
<tr><td rowspan="2">$L=1, j_l=\frac{3}{2}$</td><td>1^+</td><td>$D_1(2430)$</td><td>--</td><td>$D_{s1}(2536)$</td><td>--</td></tr>
<tr><td>2^+</td><td>$D_2^*(2460)$</td><td>--</td><td>$D_{s2}^*(2573)$</td><td>--</td></tr>
<tr><td rowspan="4">D-wave</td><td rowspan="2">$L=2, j_l=\frac{3}{2}$</td><td>1^-</td><td>$D_1^*(2760)$</td><td>2.75 GeV</td><td>$D_{s1}^*(2860)$</td><td>2.81 GeV</td></tr>
<tr><td>2^-</td><td rowspan="2">$D(2750)?$</td><td>2.78 GeV</td><td>--</td><td>2.82 GeV</td></tr>
<tr><td rowspan="2">$L=2, j_l=\frac{5}{2}$</td><td>2^-</td><td>2.72 GeV</td><td>--</td><td>2.81 GeV</td></tr>
<tr><td>3^-</td><td>$D_3^*(2760)$</td><td>2.78 GeV</td><td>$D_{s3}^*(2860)$</td><td>2.85 GeV</td></tr>
<tr><td rowspan="4">F-wave</td><td rowspan="2">$L=3, j_l=\frac{5}{2}$</td><td>2^+</td><td>--</td><td>--</td><td>--</td><td>3.45 GeV</td></tr>
<tr><td>3^+</td><td>--</td><td>--</td><td>--</td><td>3.50 GeV</td></tr>
<tr><td rowspan="2">$L=3, j_l=\frac{7}{2}$</td><td>3^+</td><td>--</td><td>--</td><td>--</td><td>3.20 GeV</td></tr>
<tr><td>4^+</td><td>--</td><td>--</td><td>--</td><td>3.26 GeV</td></tr>
</table>

What is more interesting: heavy baryons





- The internal structure of heavy baryons is more complicated than heavy mesons, but still understandable: λ-excitation and ρ-excitation.
- The Pauli principle can be directly applied to the two light quarks.

heavy baryons (Q-qq): $J = \underbrace{s_Q}_{\boxed{=1/2}} + \left(L + \underbrace{s_{q1}}_{\boxed{=1/2}} + \underbrace{s_{q2}}_{\boxed{=1/2}}\right)_{j_l}$

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

P-wave

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

D-wave

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

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

- The **heavy quark effective theory** may not be very appropriate to study the doubly heavy baryons, but their internal structure is still interesting.

- We propose to search for the doubly heavy baryon Ξ_{cc}^{*} of $J^P = 3/2^+$ via its electromagnetic transition:

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

Several Remarks

- Thanks to the efforts of experimentalists, various signals of exotic hadrons were observed in recent years, making hadron physics popular once more. However, it seems that we still know little about exotic hadrons.
- Oppositely, it seems that we well know the internal structure of heavy mesons and heavy baryons. Especially, the heavy quark effective theory plays an important role. We propose to search for higher excited heavy mesons and (doubly) heavy baryons in future experiments.

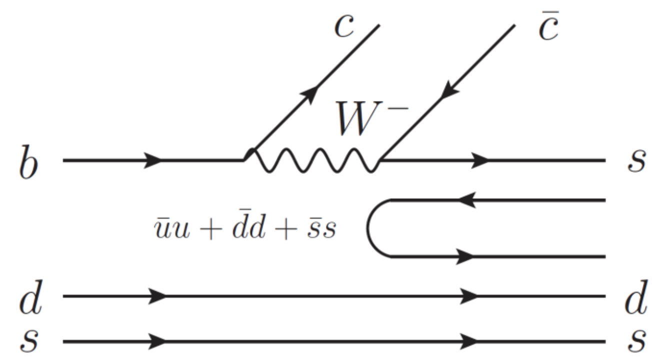
- **A hint from heavy baryons may be useful:** there are more heavy baryons containing strangeness than those not containing strangeness. Moreover, their widths are usually not large.
- However, no signals of exotic hadrons containing open strangeness are observed. We propose to search for them in future experiments:

Tetraquarks	**Pentaquarks**	**Dibaryon**
X(3872), Y(4260), Zc(3900), Zc(4020)…	Pc(4380), Pc(4450)…	d*(2380)…
↓	↓	
Tetraquarks with strangeness Zcs(4???) …	**Pentaquarks with strangeness** Pcs(4???) …	

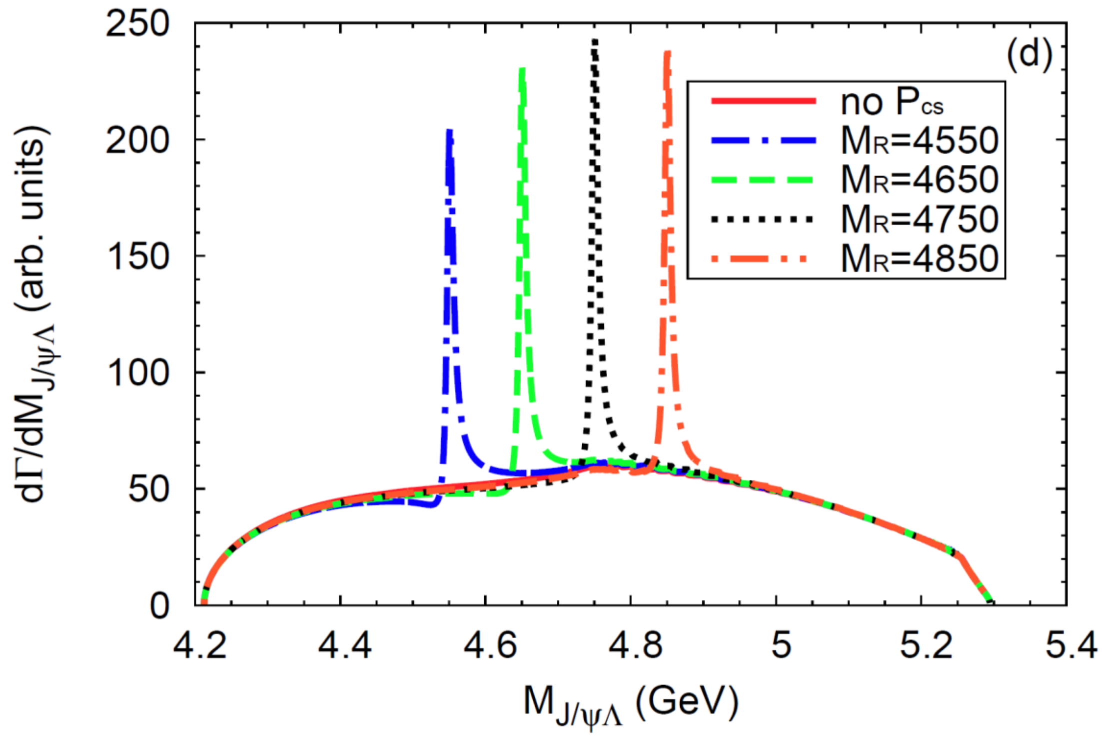
Pcs($c\bar{c}uds$) in $\Xi_b^- \to J/\psi\,\Lambda\,K^-$ decay

We need to consider

- **weak decay**
- **hadronization**
- **final state interactions**



Our result suggests that a strangeness hidden-charm pentaquark state, the counterpart of the Pc(4450), can be clearly seen.



Thank you very much!

谢谢