Hidden-charm pentaquark and beyond

刘 翔
xiangliu@lzu.edu.cn
兰州大学

“微扰量子场论及其应用”前沿讲习班暨前沿研讨会” 2025年7月10日

Many light hadrons

(1950’s &1960’s)

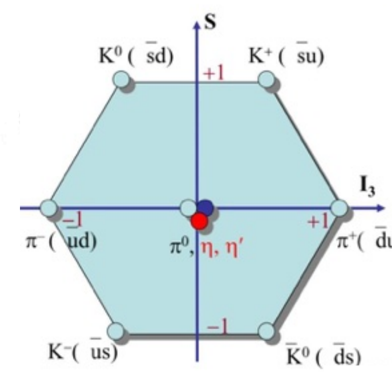
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS

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

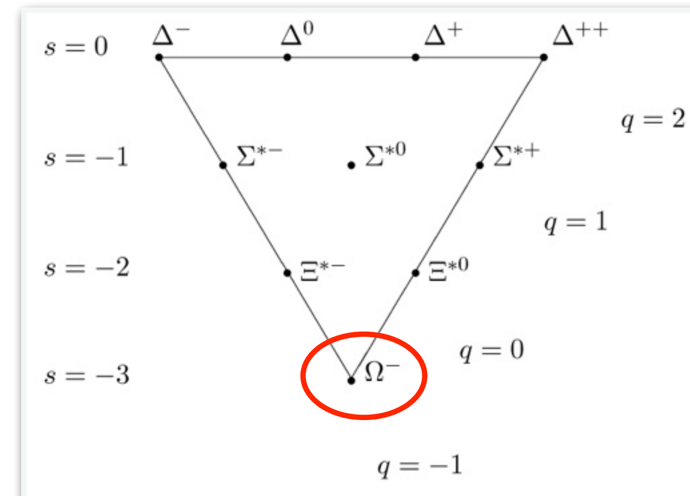
Received 4 January 1964

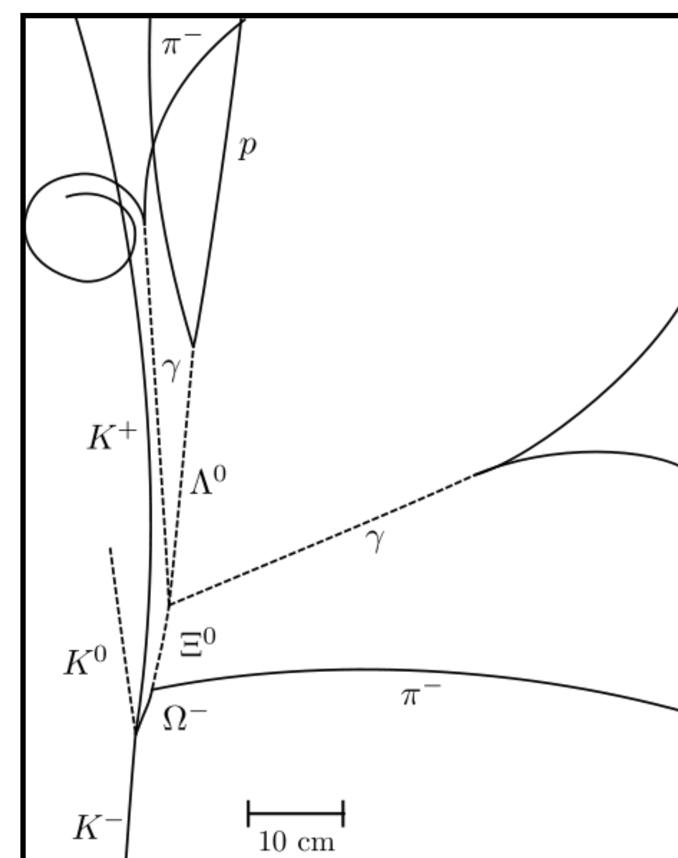


If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

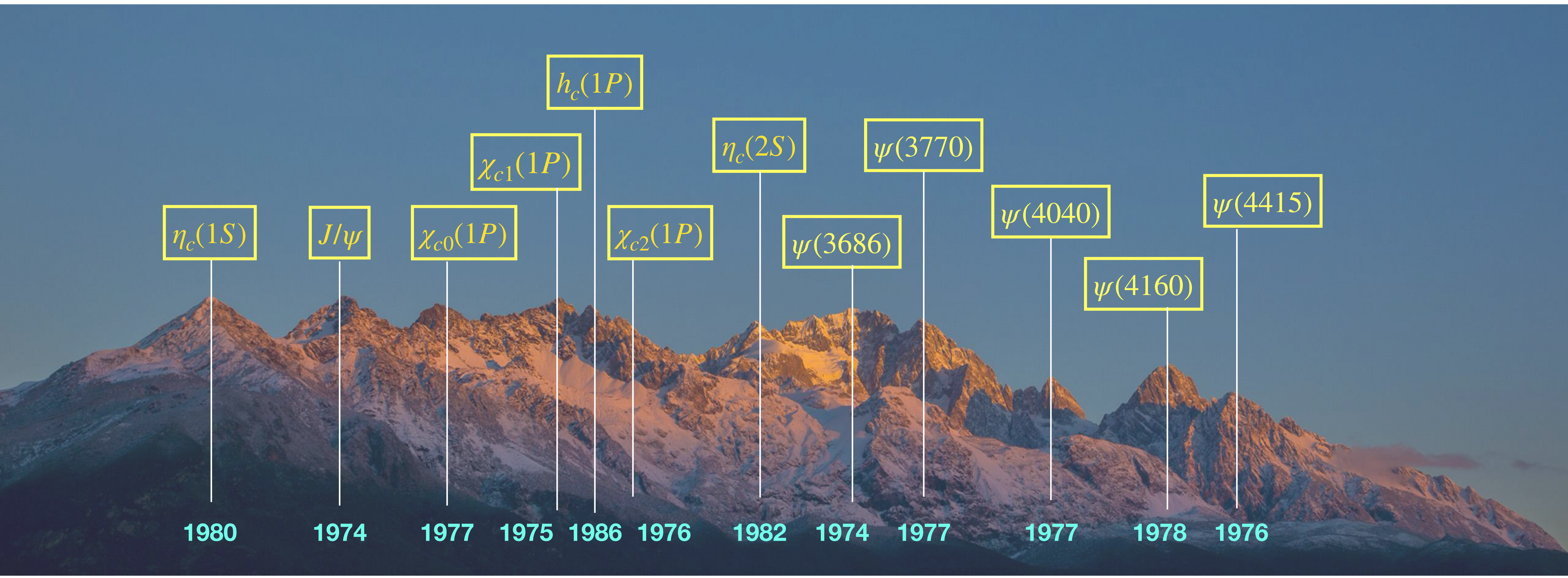
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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





Status of charmonium family

(1974-1982)



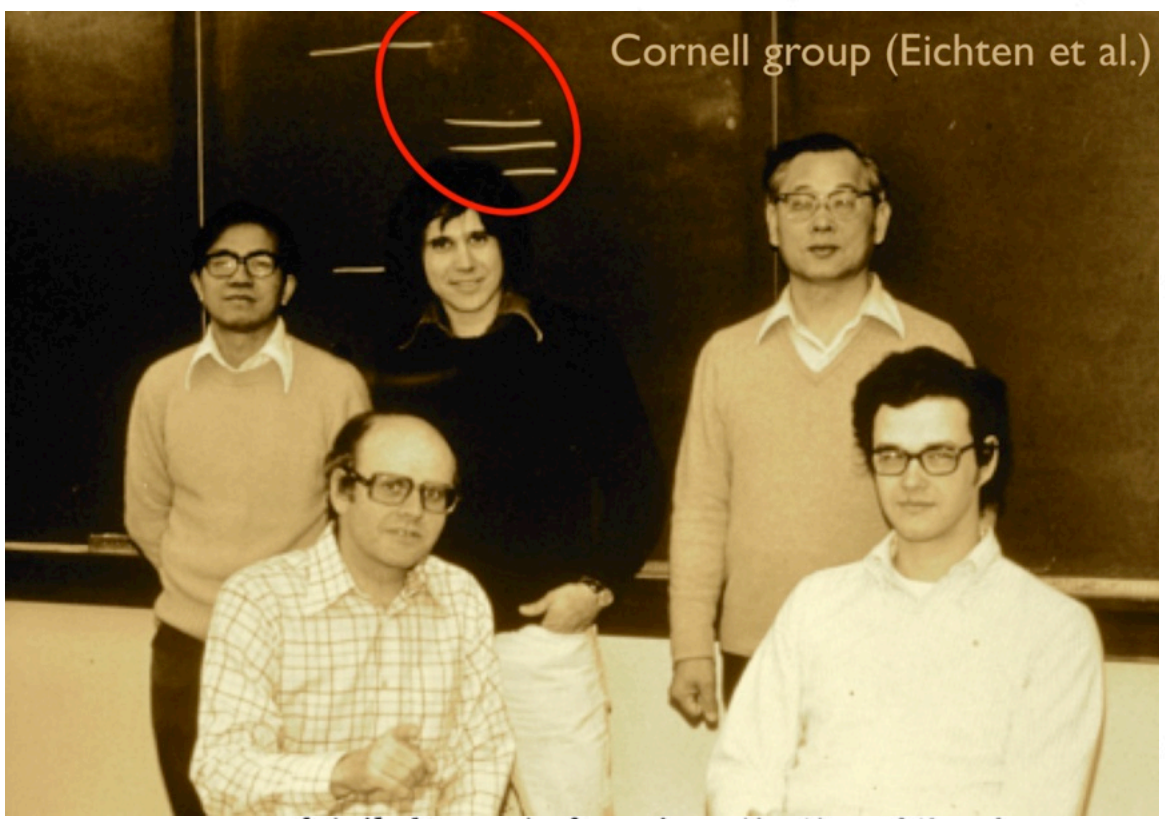
Most of charmonia listed in PDG were observed

PHYSICAL REVIEW D VOLUME 17, NUMBER 11 1 JUNE 1978

Charmonium: The model

E. Eichten,* K. Gottfried, T. Kinoshita, K. D. Lane,* and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853
(Received 9 February 1978)

A comprehensive treatment of the charmonium model of the ψ family is presented. The model's basic assumption is a flavor-symmetric instantaneous effective interaction between quark color densities. This interaction describes both quark-antiquark binding and pair creation, and thereby provides a unified approach for energies below and above the threshold for charmed-meson production. If coupling to decay channels is ignored, one obtains the "naive" model wherein the dynamics is completely described by a single charmed-quark pair. A detailed description of this "naive" model is presented for the case where the instantaneous potential is a superposition of a linear and Coulombic term. A far more realistic picture is attained by incorporating those terms in the interaction that couple charmed quarks to light quarks. The coupled-channel formalism needed for this purpose is fully described. Formulas are given for the inclusive e^+e^- cross section and for e^+e^- annihilation into specific charmed-meson pairs. The influence of closed decay channels on ψ states below charm threshold is investigated, with particular attention to leptonic and radiative widths.



color gauge interaction leads to forces that are so strong at large distances that quarks are permanently confined in color-neutral bound states—the mesons and baryons. We also adopt this assumption.

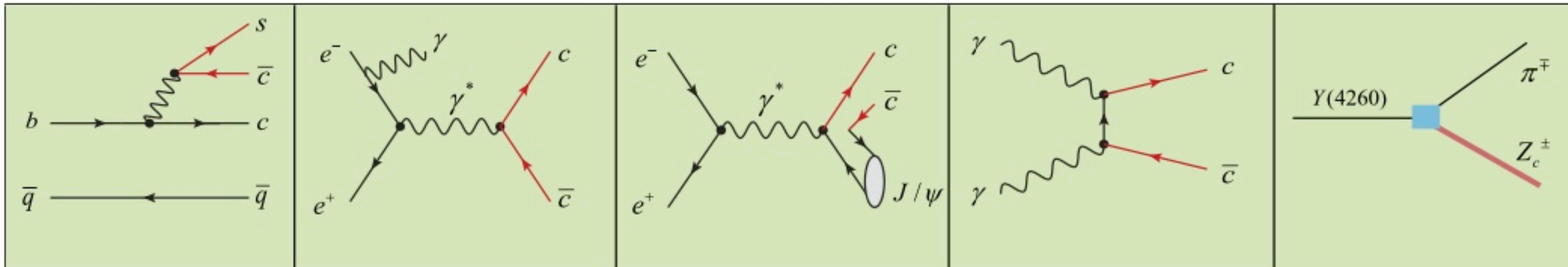
Secondly, the large masses of the ψ resonances and charmed mesons lead to the assumption that the charmed quarks are so heavy that they may be treated nonrelativistically.[4] No one has yet succeeded in calculating the effective form of the interquark forces from quantum chromodynamics,[16] even in the nonrelativistic limit. To fill this gap we postulate that in this limit many of the gross features of the potential between the charmed quarks can be simulated by the potential

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2} . \qquad (1.1)$$

Cornell potential

The observed charmonium-like XYZ states

(2003-now)



$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$				

see review

Physics Reports 639 (2016) 1–121

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

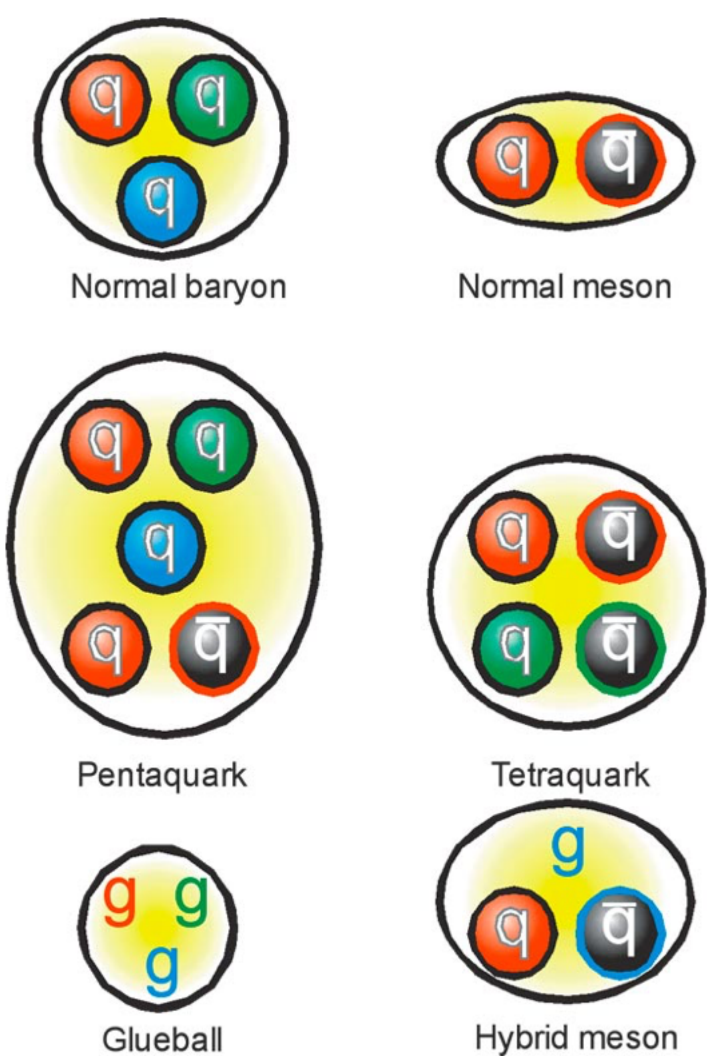
ELSEVIER

The hidden-charm pentaquark and tetraquark states

Hua-Xing Chen [a,b,1], Wei Chen [c,1], Xiang Liu [d,e,*], Shi-Lin Zhu [a,f,g,**]

"Particle Zoo 2.0"

Hadron
- Conventional QM states
  - Meson : $q\bar{q}$, $Q\bar{q}$, $Q\bar{Q}$
  - Baryon : qqq, Qqq, QQq, ...
- Exotic states
  - Molecular state
  - Hybrid meson
  - Glueball
  - Tetraquark
  - Pentaquark
  - ...



- **Identifying exotic states is one of the most important research issues of particle physics**
- **The observed XYZ states provide us good platform to identify exotic state**

Long reviews

1. The hidden-charm pentaquark and tetraquark states **1039 citations**
   H.X. Chen, W. Chen, X. Liu, S.L. Zhu
   Phys.Rept. 639 (2016) 1-121
2. Hadronic molecules **1057 citations**
   F.K. Guo, C. Hanhart, U.G. Msissner, Q. Wang, Q. Zhao, B.S. Zou
   Rev.Mod.Phys. 90 (2018) 015004
3. Multiquark resonances **615 citations**
   A. Esposito, A. Pilloni, A.D. Polosa
   Phys.Rept. 668 (2017) 1-97
4. A review of the open charm and open bottom systems **342 citations**
   H.X. Chen, W. Chen, X. Liu, Y.R. Liu, S.L. Zhu
   Rept.Prog.Phys.80 (2017) 076201
5. Pentaquark and tetraquark states **472 citations**
   Y.R. Liu, H.X. Chen, W. Chen, X. Liu, S.L. Zhu
   Prog.Part.Nucl.Phys. 107 (2019) 237-320
6. The XYZ states: experimental and theoretical status and perspectives **643 citations**
   N. Brambilla. S. Eidelman, C. Hanhart, A. Nefediev, C.P. Shen, C.E. Thomas, A. Vairo, C.Z. Yuan
   Phys.Rept. 873 (2020) 1-154
7. An updated review of the new hadron states **261 citations**
   H.X. Chen, W. Chen, X. Liu, Y.R. Liu, S.L. Zhu
   Rept.Prog.Phys.86 (2023) 026201

   ……

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   Rept.Prog.Phys.86 (2023) 026201

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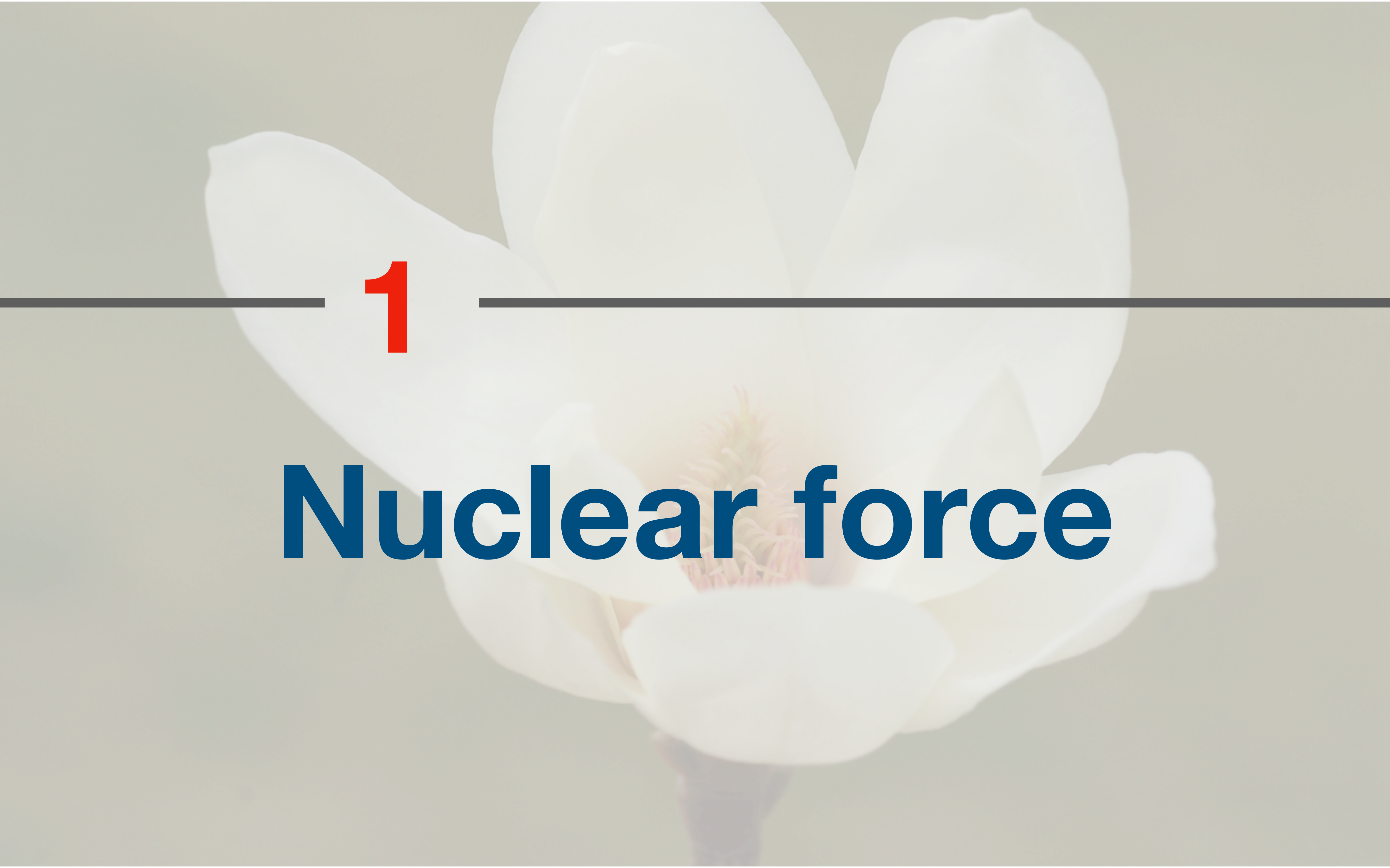
Long reviews

在过去十年中，强子物理取得了令人振奋的进展

Outline

- Nuclear force
- Lesson from $\Theta(1540)$
- XYZ charmoniumlike states
- Predicting hidden-charm molecular pentaquark and the LHCb observation @ 2015 @ 2019
- More predictions of heavy flavor pentaquark
- Electromagnetic properties
- Three-body and four-body systems
- Summary



1

Nuclear force

The Nobel Prize in Physics 1949

The Nobel Prize in Physics 1949 was awarded to Hideki Yukawa "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces."

I. The nuclear forces are described by a scalar field U, which satisfies the wave equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}-\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\varkappa^2\right)U=0 \qquad (1)$$

in vacuum, where x is a constant with the dimension of reciprocal length. Thus, the static potential between two nucleons at a distance r is proportional to exp $(-xr)/r$, the range of forces being given by $1/x$.

II. According to the general principle of quantum theory, the field U is inevitably accompanied by new particles or quanta, which have the mass

$$\mu=\frac{\varkappa\hbar}{c} \qquad (2)$$

and the spin 0, obeying Bose-Einstein statistics. The mass of these particles can be inferred from the range of nuclear forces. If we assume, for instance, $x = 5 \times 10^{12}$ cm^{-1}, we obtain $\mu \cong 200\ m_e$, where m_e is the mass of the electron.

Hideki Yukawa

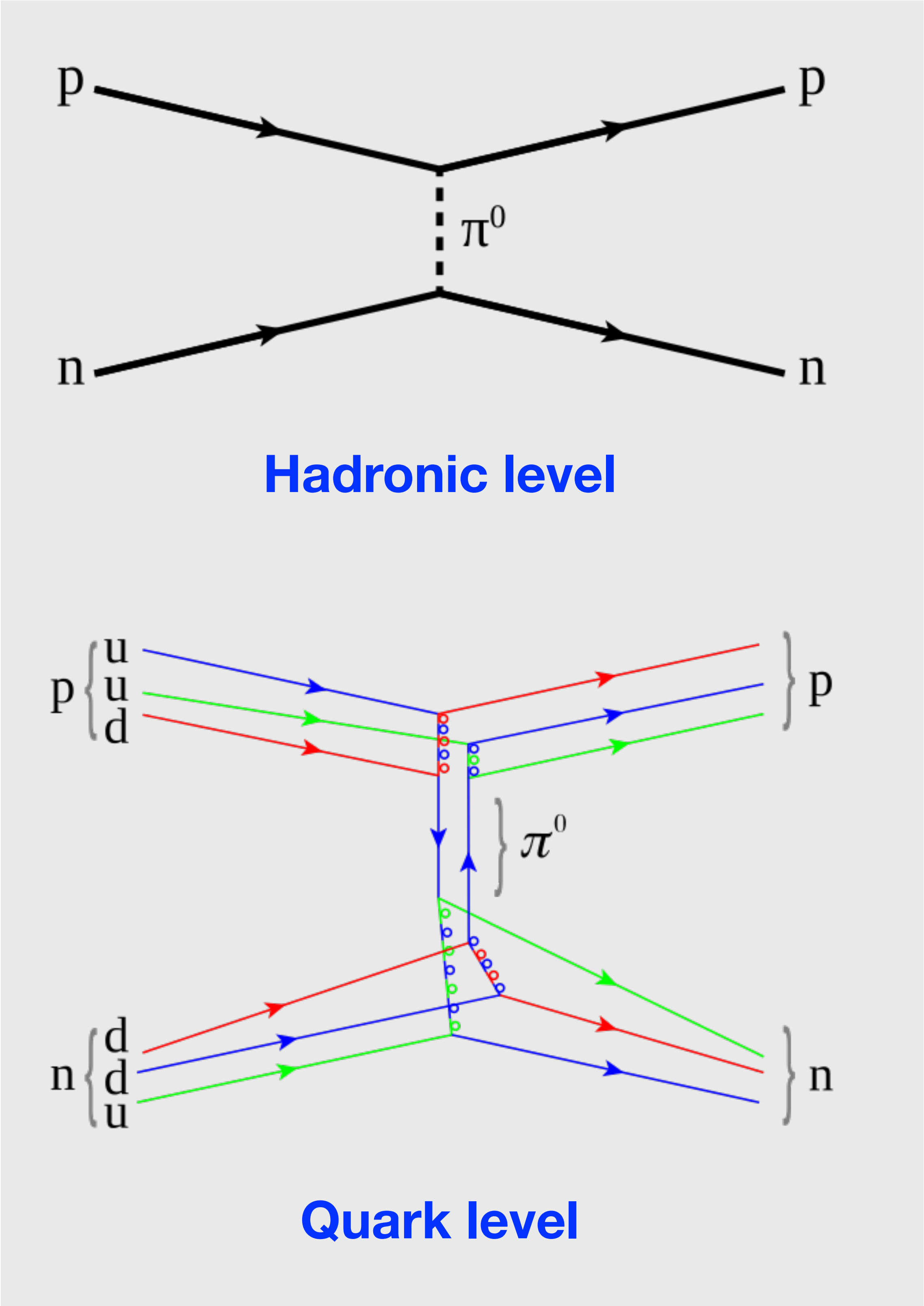
H I D E K I Y U K A W A

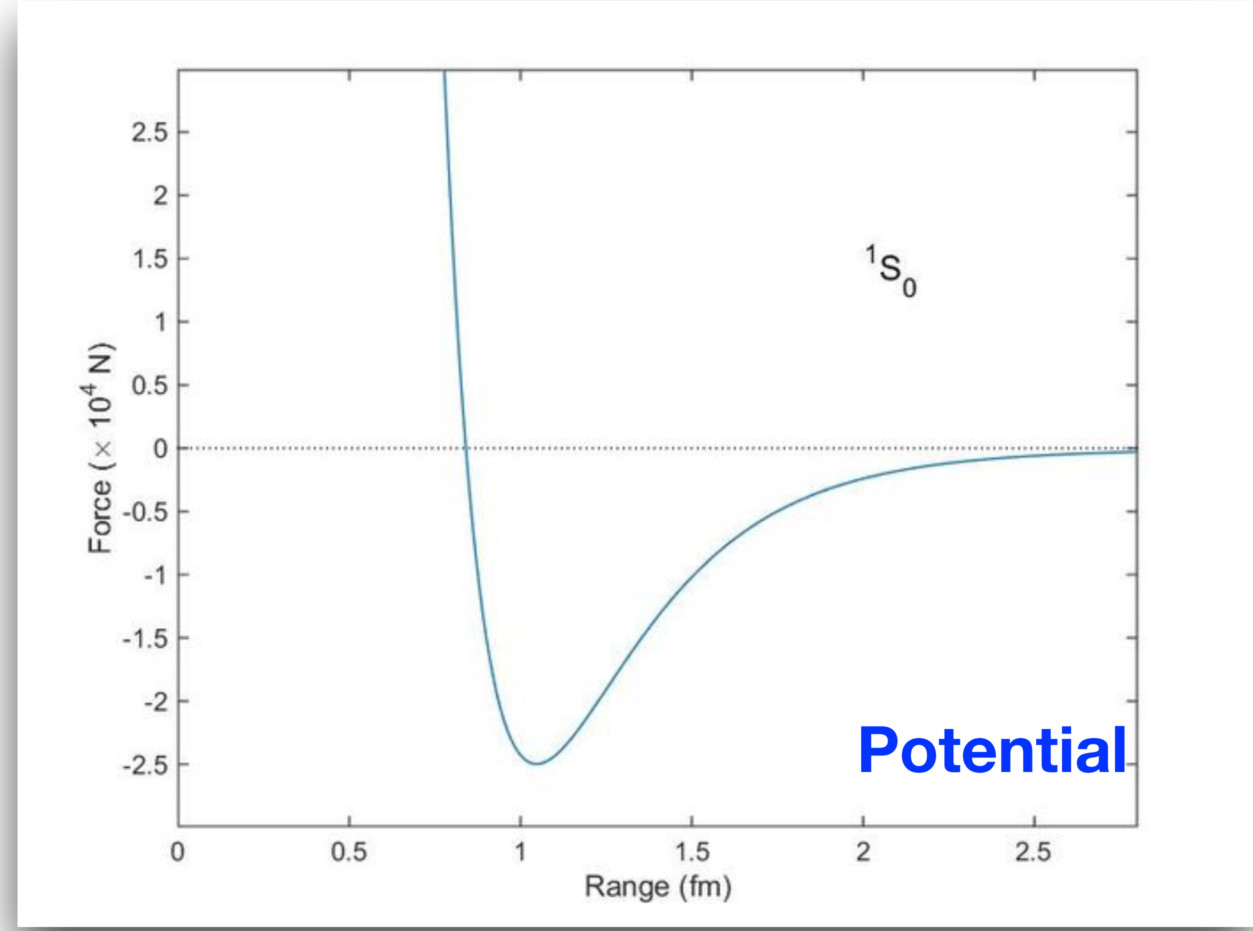
Meson theory in its developments

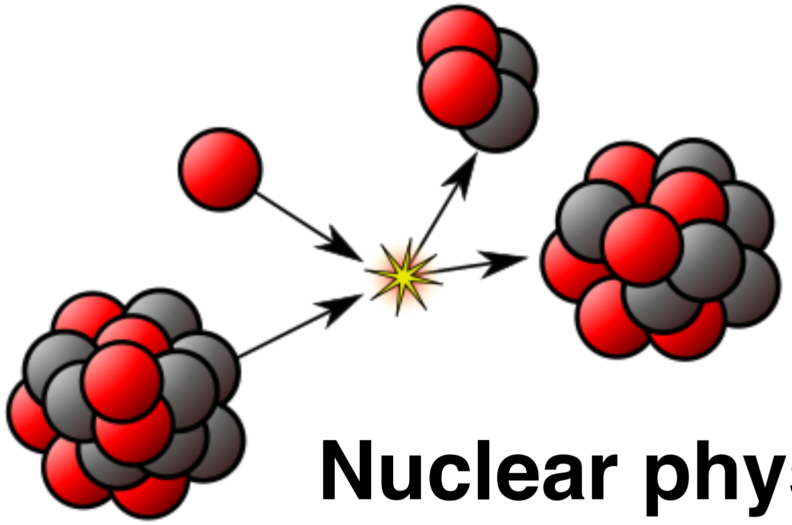
Nobel Lecture, December 12, 1949

https://www.nobelprize.org/uploads/2018/06/yukawa-lecture.pdf

Nuclear force



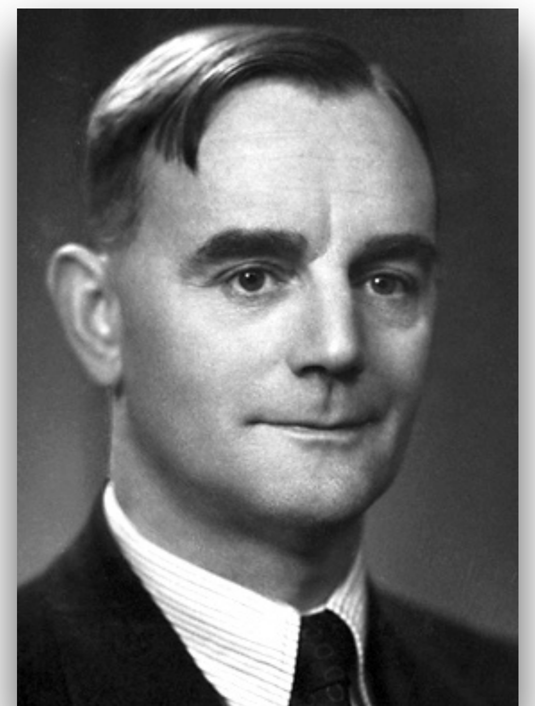




Nuclear physics

Observation of Pion

In 1947, the first true mesons, the charged pions, were found by the collaboration of Cecil Powell, César Lattes, Giuseppe Occhialini, *et al.*, at the University of Bristol, in England.



Cecil Frank Powell

The Nobel Prize in Physics **1950** 'for his development of the photographic method of studying nuclear processes and his discoveries regarding mesons made with this method'.

Citation: M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

$\pi^{\pm}$ $\qquad I^G(J^P) = 1^-(0^-)$

We have omitted some results that have been superseded by later experiments. The omitted results may be found in our 1988 edition Physics Letters **B204** 1 (1988).

$\pi^{\pm}$ MASS

The most accurate charged pion mass measurements are based upon x-ray wavelength measurements for transitions in π^--mesonic atoms. The observed line is the blend of three components, corresponding to different K-shell occupancies. JECKELMANN 94 revisits the occupancy question, with the conclusion that two sets of occupancy ratios, resulting in two different pion masses (Solutions A and B), are equally probable. We choose the higher Solution B since only this solution is consistent with a positive mass-squared for the muon neutrino, given the precise muon momentum measurements now available (DAUM 91, ASSAMAGAN 94, and ASSAMAGAN 96) for the decay of pions at rest. Earlier mass determinations with pi-mesonic atoms may have used incorrect K-shell screening corrections.

Measurements with an error of > 0.005 MeV have been omitted from this Listing.

VALUE (MeV) $\qquad$ *DOCUMENT ID*

139.57061±0.00024 OUR FIT Error in[...]

139.57061±0.00023 OUR AVERAGE Error includes scale factor of 1.5. See the ideogram below.

139.57077±0.00018 $\quad$ [1] TRASSINELLI 16 $\quad$ CNTR $\quad$ X-ray transitions in pionic

Isoscalar pseudoscalar mesons listed in PDG

Mesons (pi, K, D, B, psi, Upsilon, ...)

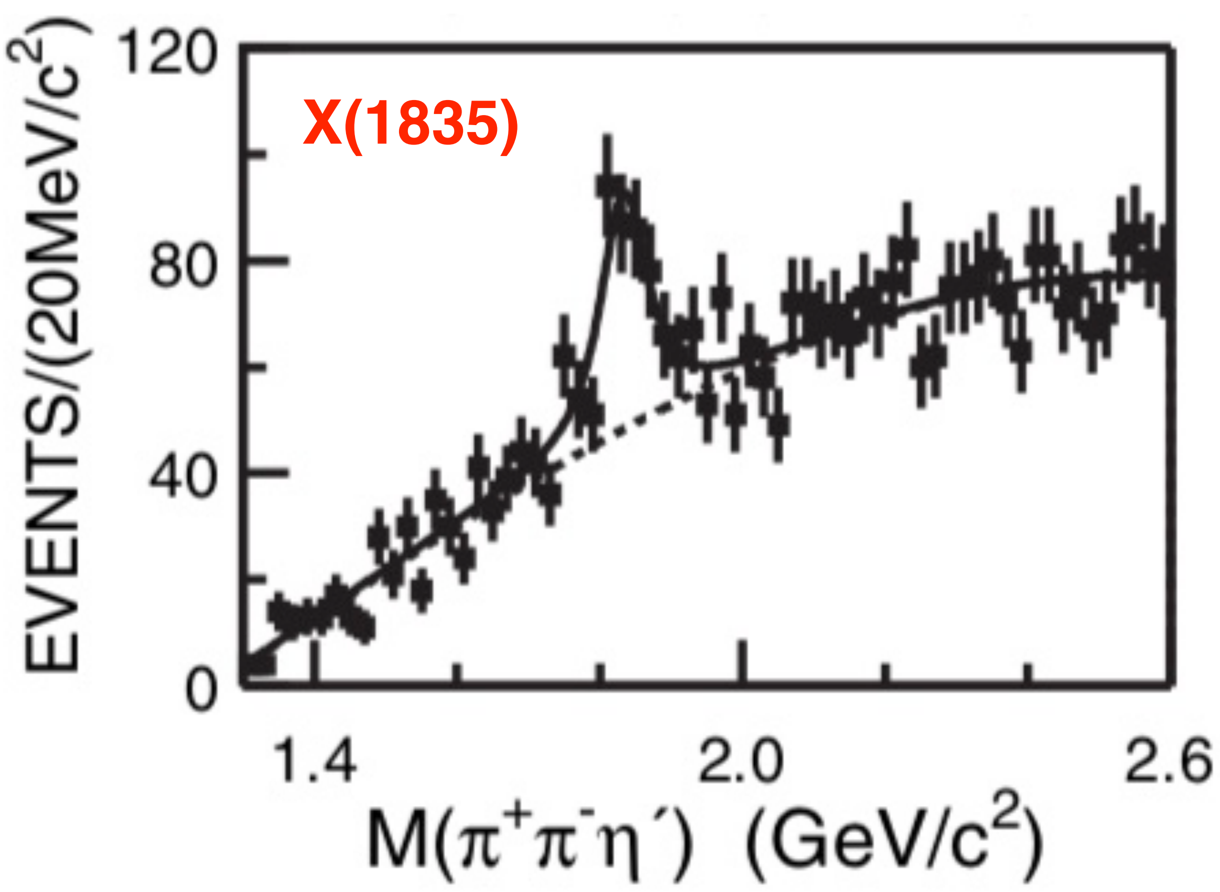
Light Unflavored Mesons (S = C = B = 0)

- Leptonic Decays of Charged Pseudoscalar Mesons
- pi+−
- pi0
- eta
- f(0)(500)
- rho(770)
- omega(782)
- eta'(958)
- f(0)(980)
- a(0)(980)
- phi(1020)
- h(1)(1170)
- eta(1295)
- pi(1300)
- a(2)(1320)
- f(0)(1370)
- h(1)(1380)
- pi(1)(1400)
- eta(1405)
- omega(1650)
- omega(3)(1670)
- pi(2)(1670)
- phi(1680)
- rho(3)(1690)
- rho(1700)
- a(2)(1700)
- f(0)(1710)
- eta(1760)
- pi(1800)
- f(2)(1810)
- X(1835)
- rho(1900)
- f(2)(1910)
- a(0)(1950)
- f(2)(1950)
- rho(3)(1990)
- f(2)(2010)
- f(0)(2020)
- a(1)(1420)
- f(2)(1430)
- a(0)(1450)
- rho(1450)
- eta(1475)
- f(0)(1500)
- f(1)(1510)
- f(2)'(1525)
- f(2)(1565)
- rho(1570)
- h(1)(1595)
- pi(1)(1600)
- a(1)(1640)
- f(2)(1640)
- pi(2)(2100)
- f(0)(2100)
- f(2)(2150)
- rho(2150)
- phi(2170)
- f(0)(2200)
- f(J)(2220)
- eta(2225)
- rho(3)(2250)
- f(2)(2300)
- f(4)(2300)
- f(0)(2330)
- f(2)(2340)
- rho(5)(2350)

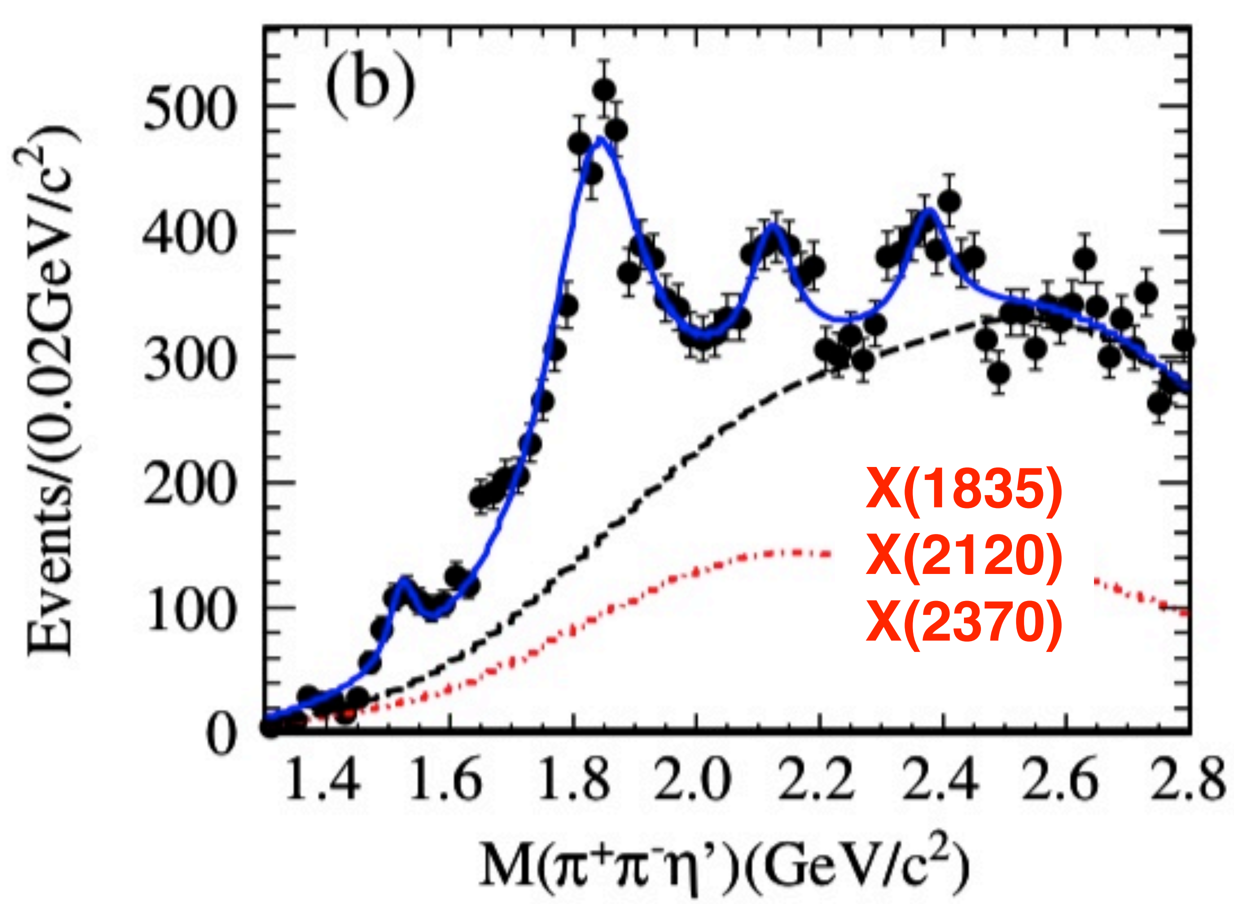
Seven pseudoscalar mesons were observed in the past decades

More observations

BESII PRL95 (2005) 262001



BESIII PRL106 (2011) 072002



Observation of an Anomalous Line Shape of the $\eta'\pi^+\pi^-$ Mass Spectrum near the $p\bar{p}$ Mass Threshold in $J/\psi \to \gamma\eta'\pi^+\pi^-$

Peak around 2640 MeV

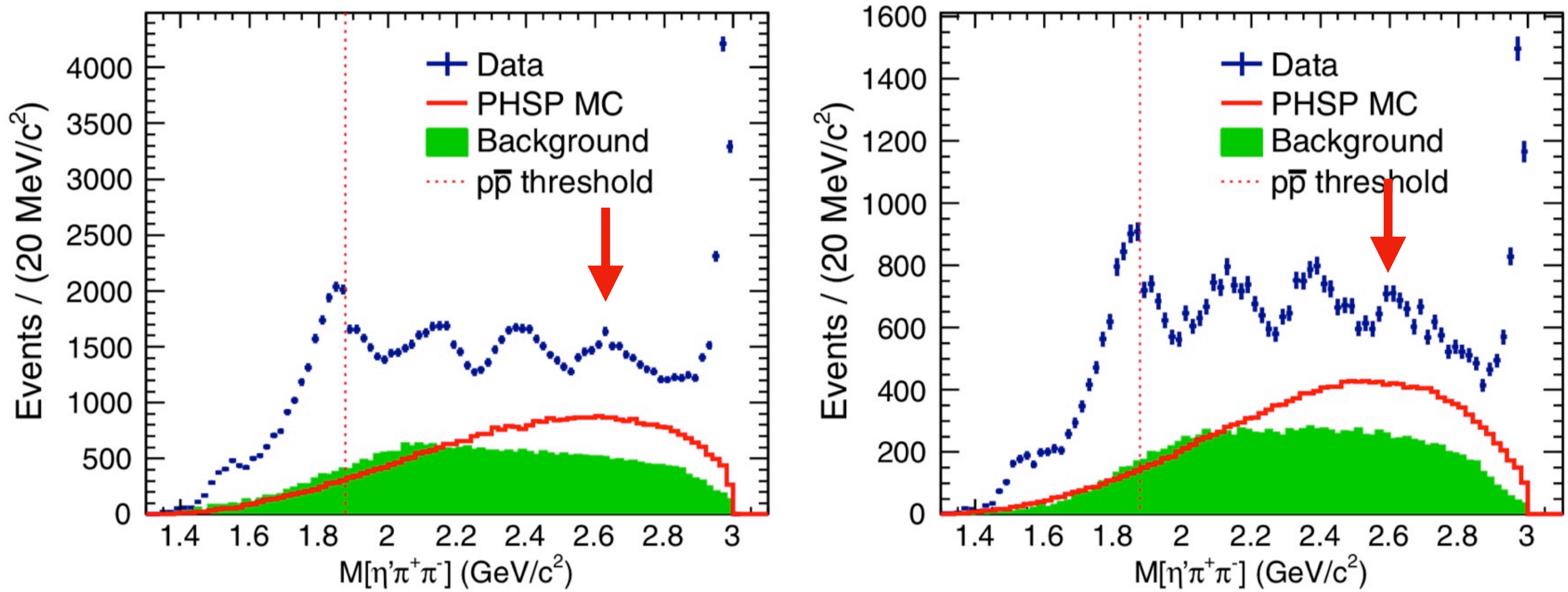
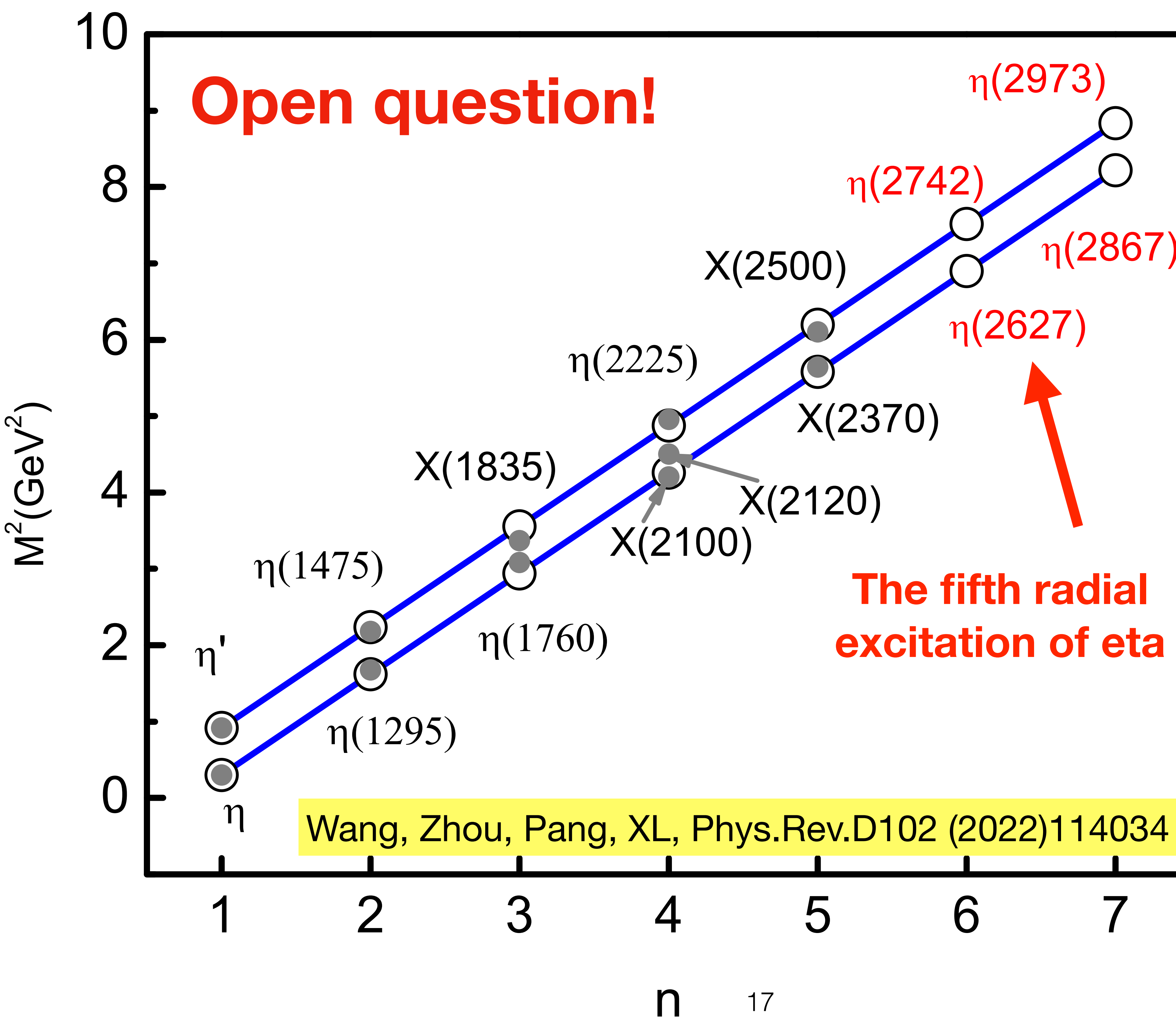
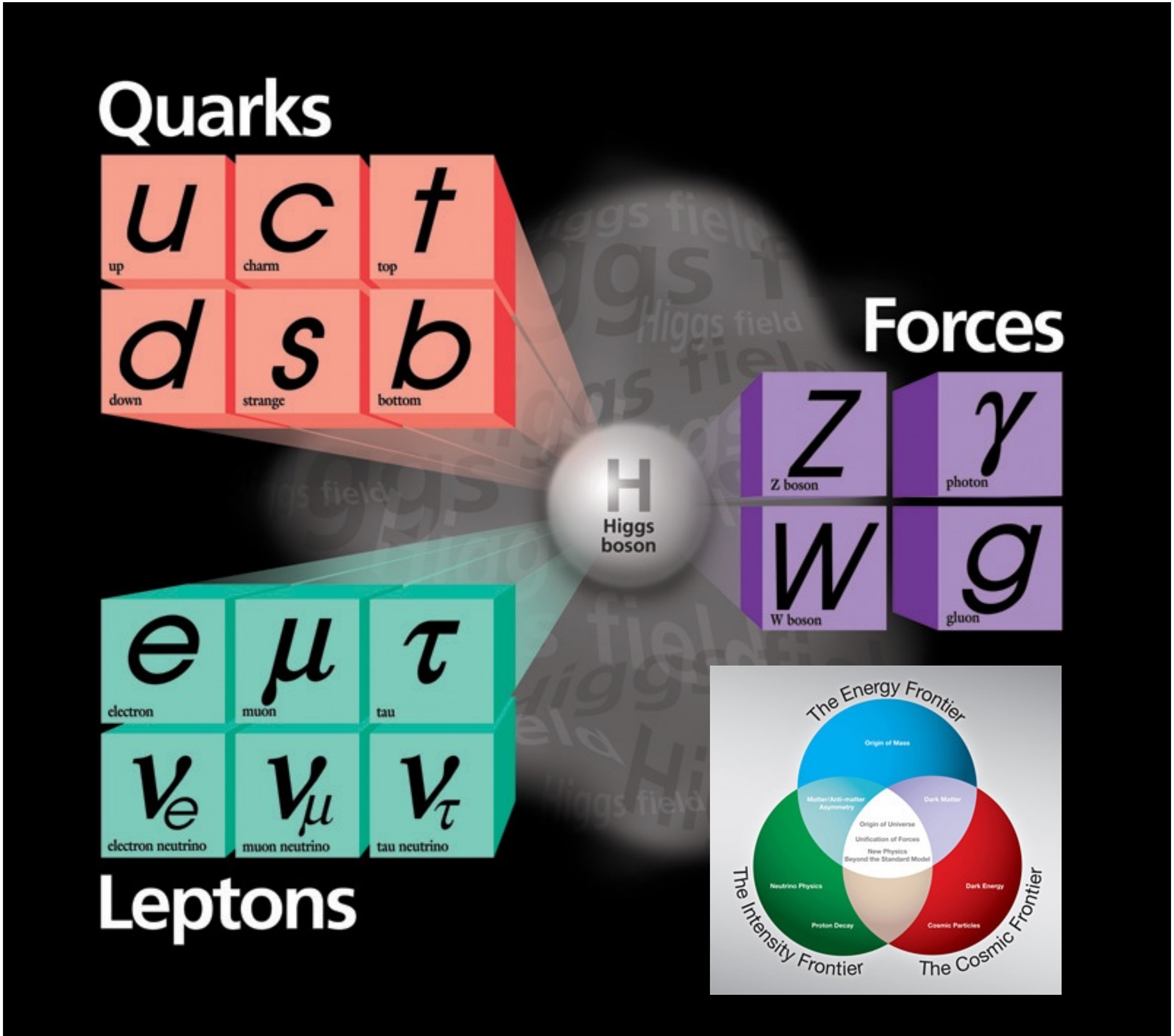


FIG. 1. The $\eta'\pi^+\pi^-$ invariant mass spectra after the application of all selection criteria. The plot on the left side shows the spectrum for events with the $\eta' \to \gamma\pi^+\pi^-$ channel, and that on the right shows the spectrum for the $\eta' \to \eta(\to \gamma\gamma)\pi^+\pi^-$ channel. In both plots, the dots with error bars are data, the shaded histograms are the background, the solid histograms are phase space (PHSP) MC events of $J/\psi \to \gamma\eta'\pi^+\pi^-$ (arbitrary normalization), and the dotted vertical line shows the position of the $p\bar{p}$ mass threshold.

Regge trajectory analysis





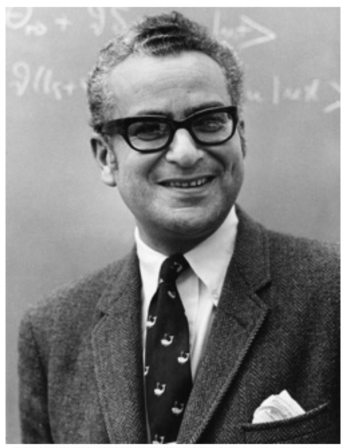
强子物理是精度前沿的代表

生命之柱

2

Lesson from $\Theta(1540)$

Who proposed multiquark state?



The concept of muliquark state was proposed at the birth of quark model

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 $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, 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".

PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

MIT Bag model

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
aboratory 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.

PHYSICAL REVIEW D VOLUME 20, NUMBER 3 1 AUGUST 1979

PRD 20 (1979) 748

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

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 $SU(6) \supset SU(3) \otimes SU(2)$ 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.

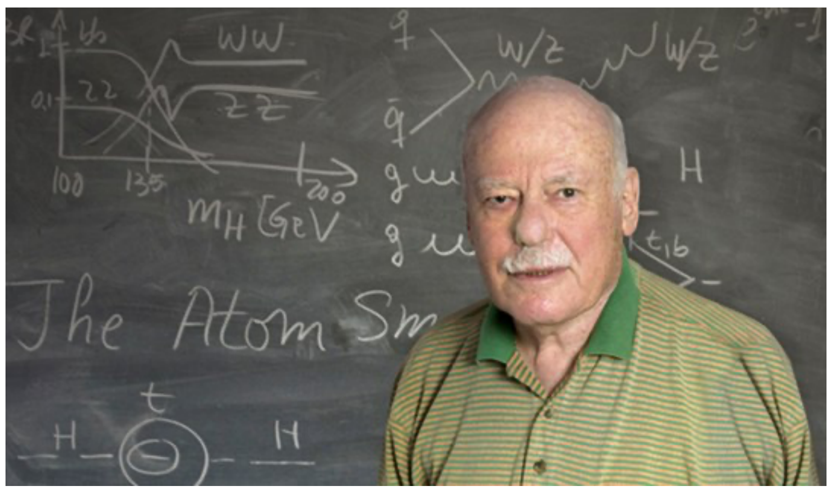
The name “pentaquark” was first introduced by Lipkin in 1987

高エ研図書室

PLB 195 (1987) 484

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

Submitted to Physics Letters

May 20, 1987

ABSTRACT

A new candidate for an exotic hadron is presented: an anticharmed strange baryon denoted by $P_{\bar{c}s}$, a bound state of a nucleon and an F (now called D_s). Theoretical estimates of the binding energy due to the hyperfine interaction give values comparable to the binding of the H dibaryon, but color-electric repulsive effects which may be present in the H are expected to be smaller in the $P_{\bar{c}s}$. The $P_{\bar{c}s}$ may be more easily detected than the H because it has several distinctive signatures detectable against a multiparticle background.

The prediction of $\Theta^+(\bar{s}uudd)$

Michal Praszalowicz

Predicting Θ^+ with mass around 1.54 GeV (skyrme model of baryons)

SKYRMIONS AND ANOMALIES. PROCEEDINGS, WORKSHOP, KRAKOW, POLAND, FEBRUARY 20-24, 1987

D. Diakonov, V. Petrov and M. Polyakov

Θ^+could have mass 1530 MeV and a narrow mass width of 15 MeV or less

(χQM and $1/N_c$ corrections)

Z. Phys. A 359, 305–314 (1997)

ZEITSCHRIFT FÜR PHYSIK A

© Springer-Verlag 1997

Exotic anti-decuplet of baryons: prediction from chiral solitons

Dmitri Diakonov[1,2], **Victor Petrov**[1], **Maxim Polyakov**[1,3]

[1] Petersburg Nuclear Physics Institute, Gatchina, St.Petersburg 188 350, Russia
[2] NORDITA, Blegdamsvej 17, 2100 Copenhagen, Denmark
[3] Inst. für Theor. Physik II, Ruhr-Universität Bochum, D-44780 Bochum, Germany (e-mail: maximp@hadron.tp2.ruhr-uni-bochum.de)

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Communicated by F. Lenz

Abstract. We predict an exotic Z^+ baryon (having spin 1/2, isospin 0 and strangeness +1) with a relatively low mass of about 1530 MeV and total width of less than 15 MeV. It seems that this region of masses has avoided thorough searches in the past.

PACS: 11.30.Rd, 12.39.Dc, 12.39.Mk, 13.75.Gx

to a great extent their dynamics (see, e.g. [3]), while the large N_c (= numbers of colours) argumentation by Witten [4] explains why the pion field inside the nucleon can be considered as a classical one, *i.e.* as a "soliton".

The generalization to hyperons [4, 5] makes the success of the chiral soliton idea even more impressive. The rotation can be now performed in the ordinary and in the flavour $SU(3)$ space. Its quantization shows [5, 6, 7, 8, 9] that the lowest

LEPS result of $\Theta^+(1540)$

VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

Evidence for a Narrow $S = +1$ Baryon Resonance in Photoproduction from the Neutron

T. Nakano,[1] D. S. Ahn,[2] J. K. Ahn,[2] H. Akimune,[3] Y. Asano,[4,5] W. C. Chang,[6] S. Daté,[7] H. Ejiri,[7,1] H. Fujimura,[8] M. Fujiwara,[1,5] K. Hicks,[9] T. Hotta,[1] K. Imai,[10] T. Ishikawa,[11] T. Iwata,[12] H. Kawai,[13] Z. Y. Kim,[8] K. Kino,[1] H. Kohri,[1] N. Kumagai,[7] S. Makino,[14] T. Matsumura,[1,5] N. Matsuoka,[1] T. Mibe,[1,5] K. Miwa,[10] M. Miyabe,[10] Y. Miyachi,[15,*] M. Morita,[1] N. Muramatsu,[5] M. Niiyama,[10] M. Nomachi,[16] Y. Ohashi,[7] T. Ooba,[13] H. Ohkuma,[7] D. S. Oshuev,[6] C. Rangacharyulu,[17] A. Sakaguchi,[16] T. Sasaki,[10] P. M. Shagin,[1,†] Y. Shiino,[13] H. Shimizu,[11] Y. Sugaya,[16] M. Sumihama,[16,5] H. Toyokawa,[7] A. Wakai,[18,‡] C. W. Wang,[6] S. C. Wang,[6,§] K. Yonehara,[3,||] T. Yorita,[7] M. Yoshimura,[19] M. Yosoi,[10] and R. G. T. Zegers[1]

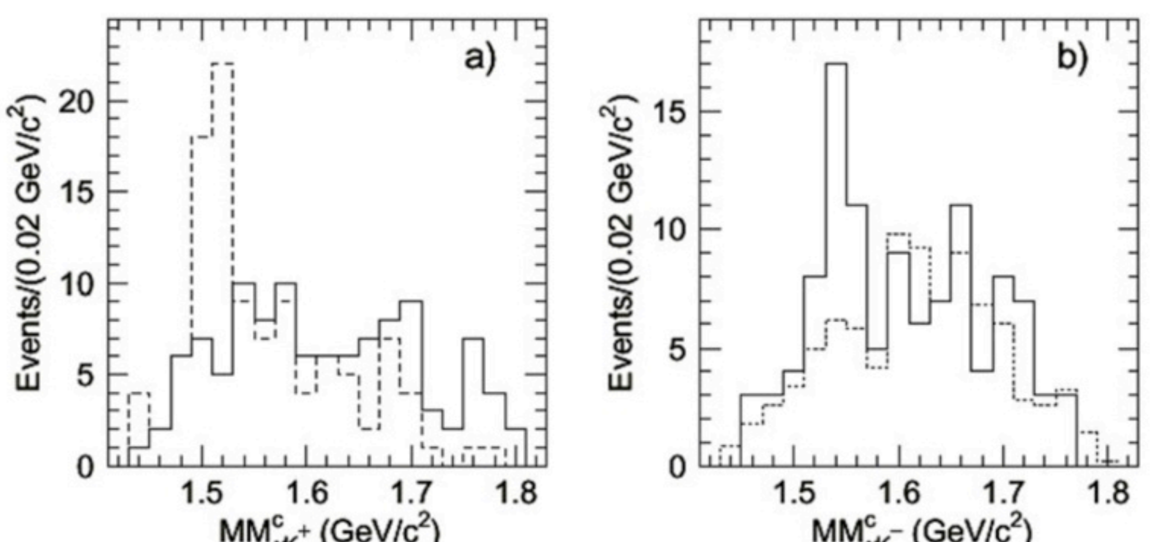


Fig. 4. Mass spectra for the reaction $\gamma C \to K^+K^-X$ where X is the undetected recoil nucleus, from reference [23]. A peak for the well-established $\Lambda(1520)$ is shown in the dashed histogram of the left panel, and for the purported Θ^+ by the solid histogram of the right panel.

T. Nakano

Dmitri Diakonov, Harry Lipkin and Robert Jaffe in discussion at the Pentaquark workshop.

Evidence for a narrow S = +1 baryon resonance in photoproduction from the neutron

#2

LEPS Collaboration • T. Nakano (Osaka U., Res. Ctr. Nucl. Phys.) et al. (Jan 15, 2003)

Published in: *Phys.Rev.Lett.* 91 (2003) 012002 • e-Print: hep-ex/0301020 [hep-ex]

pdf DOI cite 1,149 citations

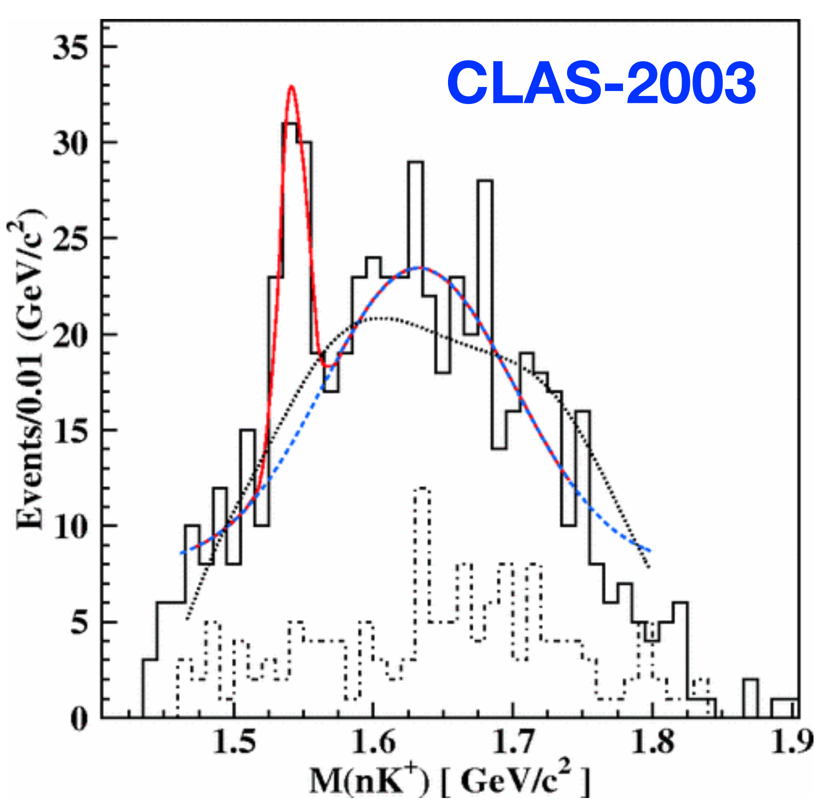
Stimulate extensive discussions of pentaquark

Negative experimental result

VOLUME 91, NUMBER 25 PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2003

Observation of an Exotic $S = +1$ Baryon in Exclusive Photoproduction from the Deuteron

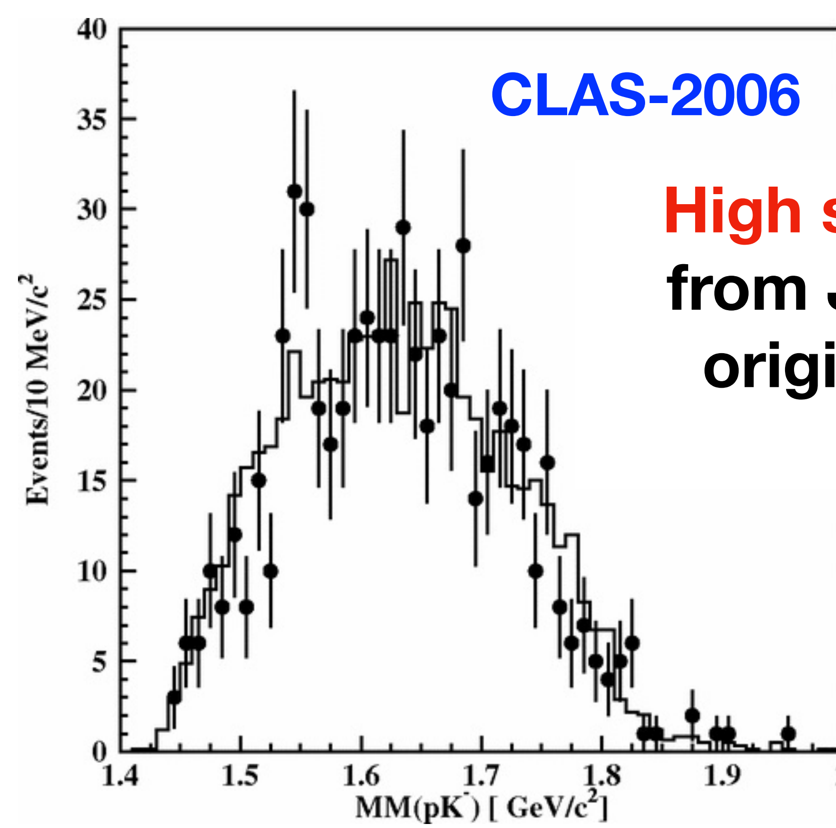
CLAS, Phys. Rev. Lett. **91** (2003) 252001



PRL **96,** 212001 (2006) PHYSICAL REVIEW LETTERS week ending 2 JUNE 2006

Search for the Θ^+ Pentaquark in the Reaction $\gamma d \rightarrow pK^- K^+ n$

CLAS, Phys. Rev. Lett. **996** (2006) 212001



High statistic repeated from JLab showed the original claims were fluctuation

PARTICLE PHYSICS https://www.nature.com/articles/435287a

Vanishing pentaquarks

Frank Close

After a first inconclusive sighting, the search for exotic particles that consist of five quarks has been hotly pursued in the past few years. But the weight of evidence is now shifting against their existence.

Correct perceptions differ from mistaken ones in that they become clearer when experimental accuracy is improved — Irving Langmuir's observation may have gained a new example with the latest report on the question of the 'pentaquark' particle. A high-statistics experiment at the Jefferson Laboratory in Virginia finds no evidence to support claims of the existence of this enigmatic object that have been made over the past three years. Final tests of the data remain to be completed, and a second independent experiment is still in progress. But this is a serious setback for the many who had hoped that this novel particle had revealed unexpected phenomena in quantum chromodynamics (QCD), the theory governing the 'strong' interactions of quarks — subatomic particles thought to be elemental and indivisible.

The story began in 1997 with the prediction[1] that an analogue of the proton should exist with a mass of "about 1,530 MeV" (some 50% more massive than the proton) and with both positive electric charge and a positive value for another fundamental quantum number, strangeness.

Such a correlation was not possible within the simplest quark model, where most strongly interacting particles (known as hadrons) are either mesons, which contain a quark and an antiquark, or baryons, which comprise three quarks. To make such a correlation of charge and strangeness requires a particle consisting of four quarks and one antiquark (hence dubbed a 'pentaquark'). Such combinations are allowed by QCD but are expected to be highly unstable, with 'widths' of many hundreds of MeV. (An inherent property of quantum mechanics is that short lifetimes are correlated with large uncertainties in energy. Thus the mass, or energy at rest, of a short-lived particle is actually a distribution with an intrinsic width — for strongly interacting unstable particles, such widths

287

0 MeV.
AS collaboration data show, at a level
on at least 50 times higher than the
SAPHIR result, that this particular
reaction produces no pentaquark. Researchers
at the Jefferson Lab are currently undertaking

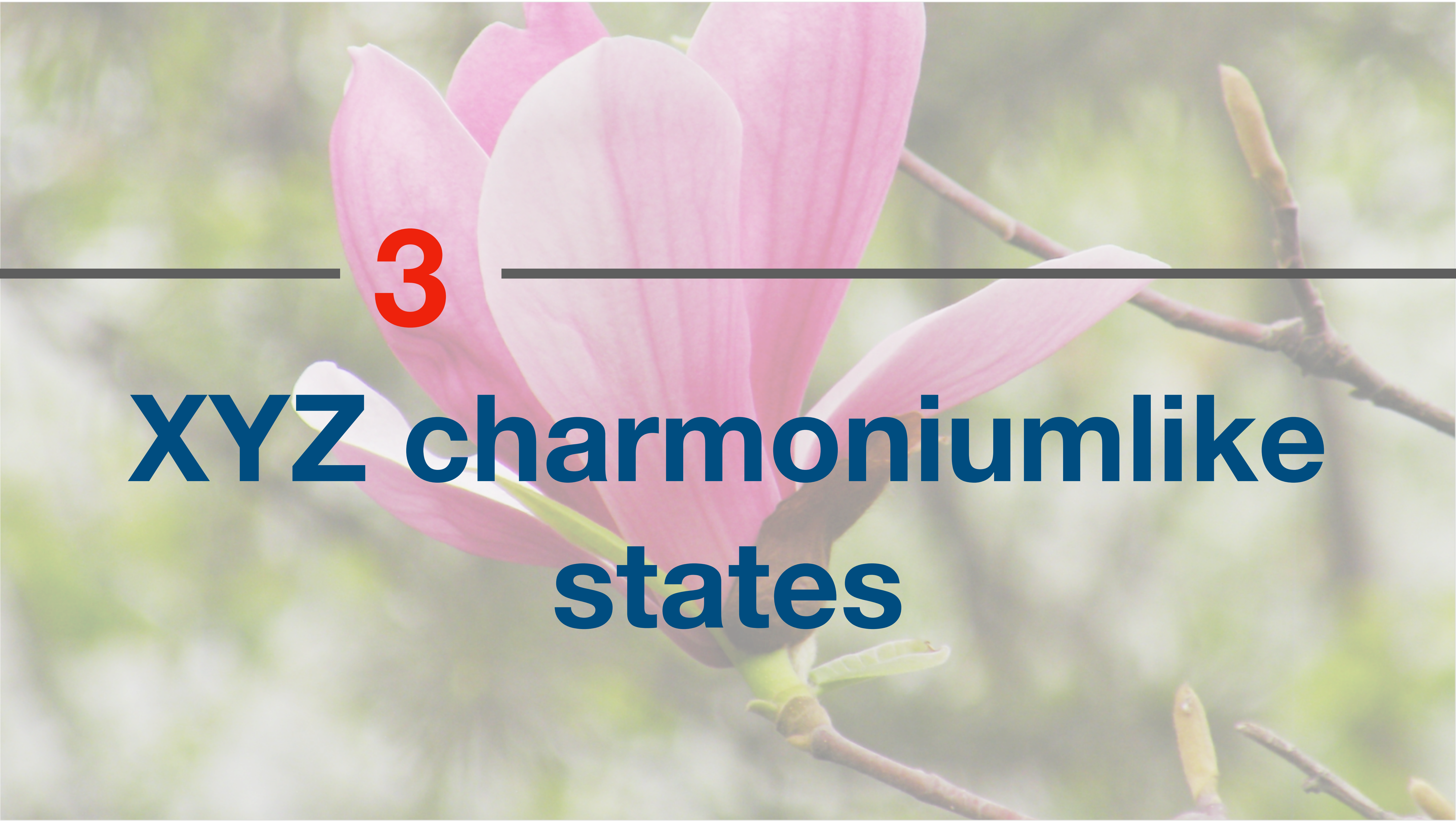
不久Θ^+五夸克态可能就不再是物理学家研究的课题了，而会成为研究科学史和科学哲学的学者的一个研究案例

are expected later this year. If they show a null result, the pentaquark story will probably have come to an end for physicists but will live on as a case-history for historians and philosophers of science. ■

up

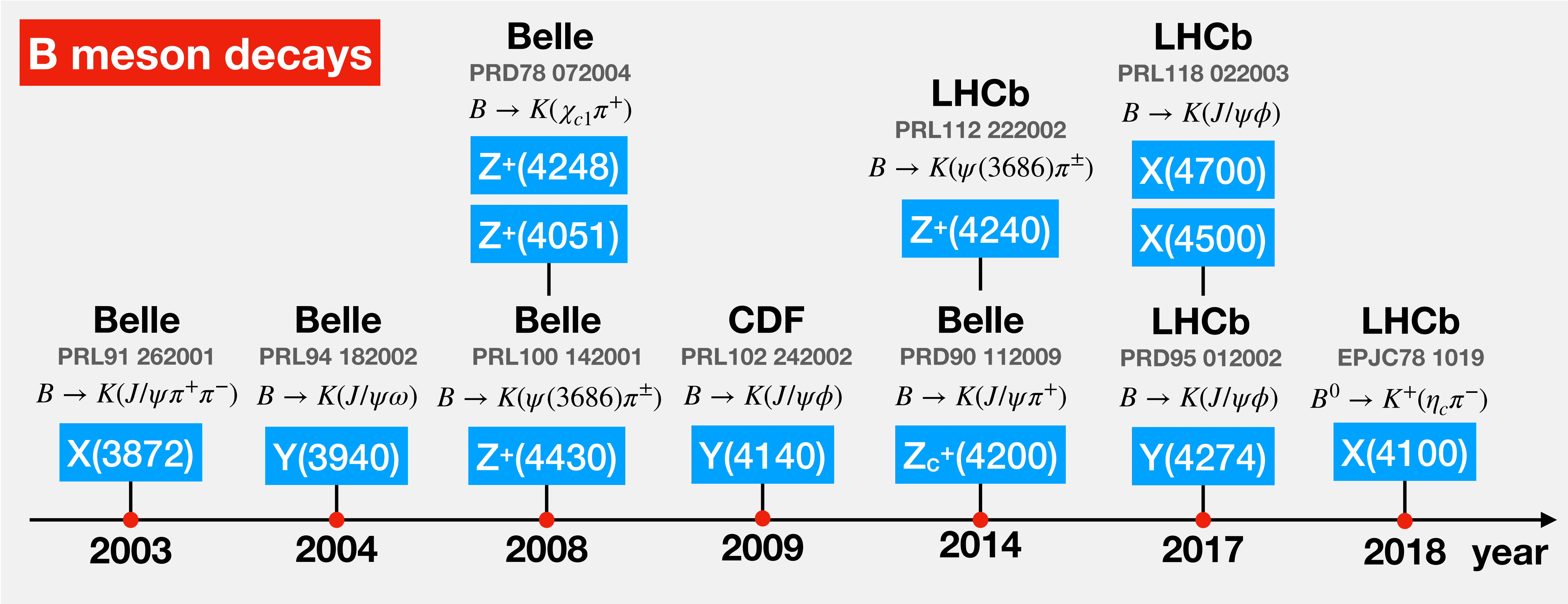
诺贝尔奖获得者维尔切克感叹道：五夸克态事件折射出我们对QCD的了解还是多么的贫乏

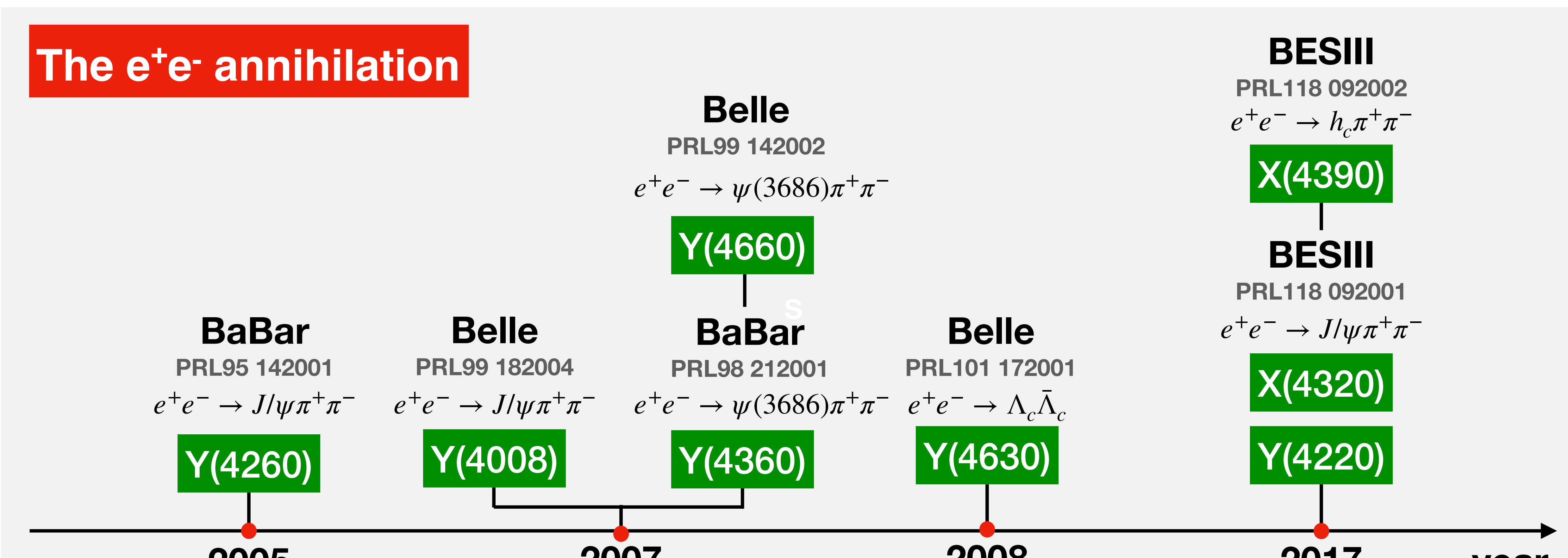
Θ^+(1540)充当了磨刀石的作用：对唯象模型的适用性和可靠性进行了检验，促进了理论的发展

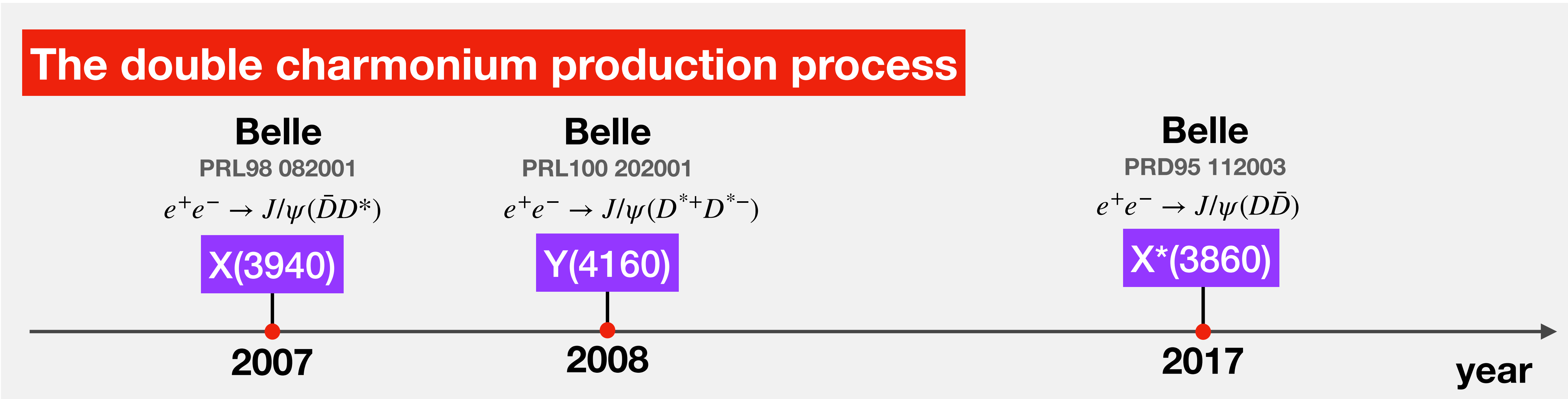


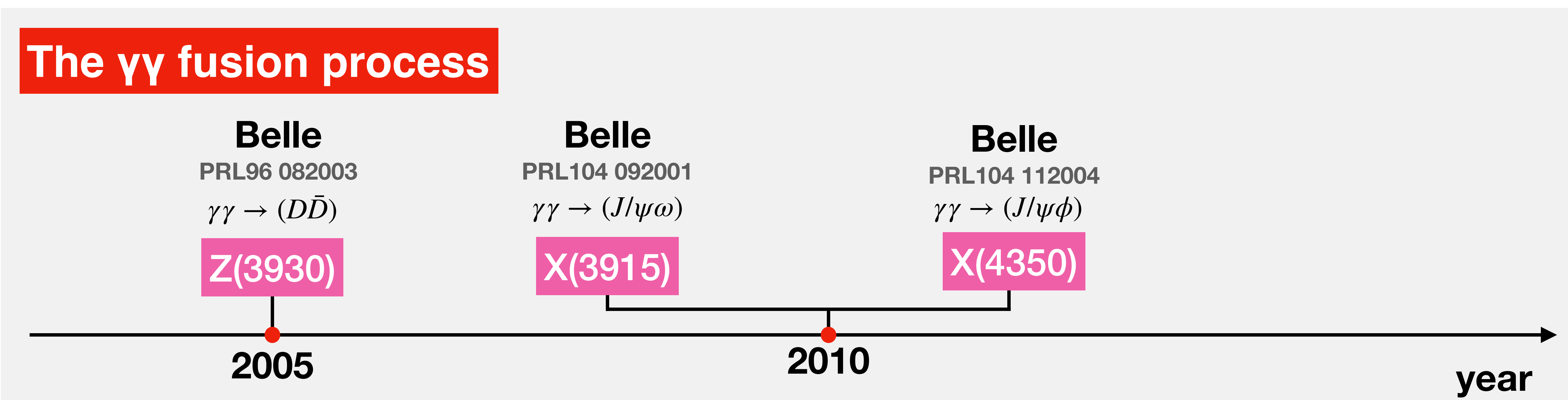
3

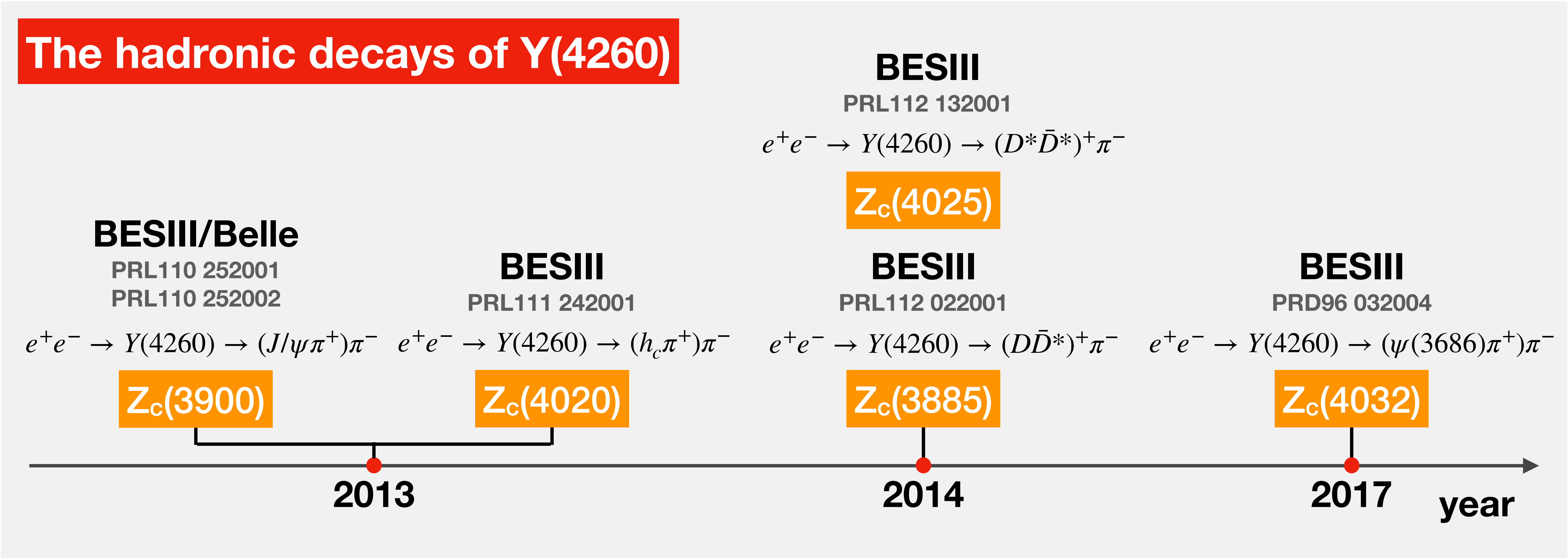
XYZ charmoniumlike states

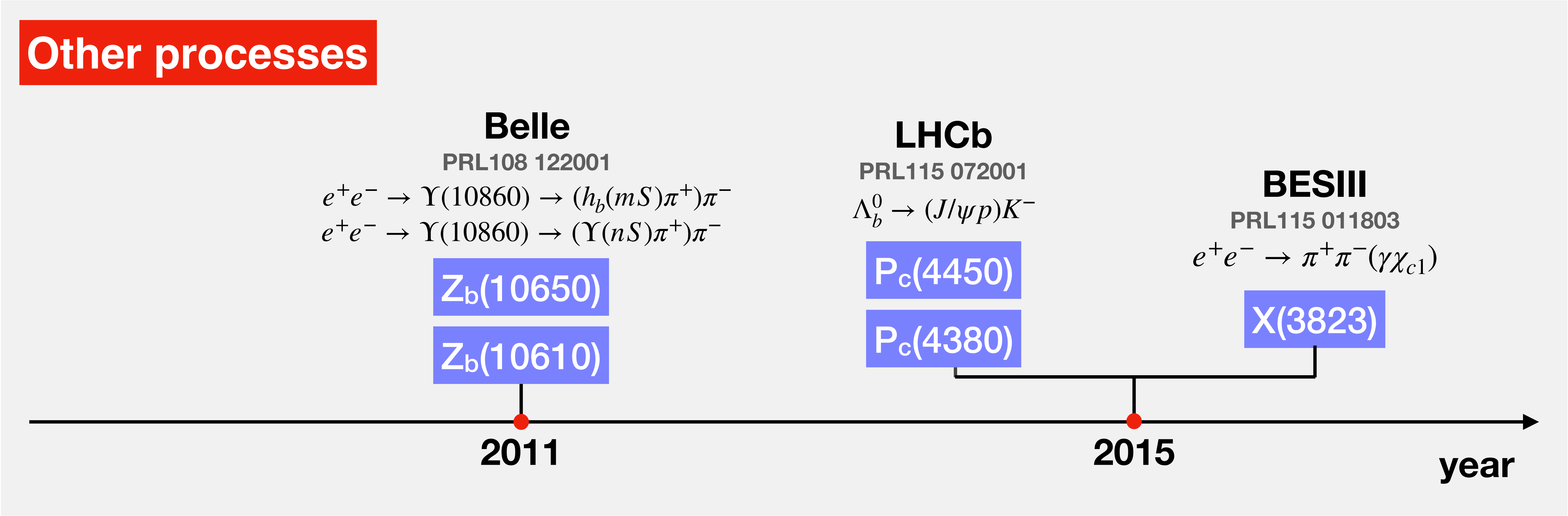

B meson decays
Belle
PRL91 262001
$B \to K(J/\psi\pi^+\pi^-)$
X(3872)
2003
Belle
PRL94 182002
$B \to K(J/\psi\omega)$
Y(3940)
2004
Belle
PRD78 072004
$B \to K(\chi_{c1}\pi^+)$
Z+(4248)
Z+(4051)
Belle
PRL100 142001
$B \to K(\psi(3686)\pi^\pm)$
Z+(4430)
2008
CDF
PRL102 242002
$B \to K(J/\psi\phi)$
Y(4140)
2009
LHCb
PRL112 222002
$B \to K(\psi(3686)\pi^\pm)$
Z+(4240)
Belle
PRD90 112009
$B \to K(J/\psi\pi^+)$
Zc+(4200)
2014
LHCb
PRL118 022003
$B \to K(J/\psi\phi)$
X(4700)
X(4500)
LHCb
PRD95 012002
$B \to K(J/\psi\phi)$
Y(4274)
2017
LHCb
EPJC78 1019
$B^0 \to K^+(\eta_c\pi^-)$
X(4100)
2018
year


The e+e- annihilation
BaBar
PRL95 142001
$e^+e^- \to J/\psi\pi^+\pi^-$
Y(4260)
2005
Belle
PRL99 182004
$e^+e^- \to J/\psi\pi^+\pi^-$
Y(4008)
Belle
PRL99 142002
$e^+e^- \to \psi(3686)\pi^+\pi^-$
Y(4660)
BaBar
PRL98 212001
$e^+e^- \to \psi(3686)\pi^+\pi^-$
Y(4360)
2007
Belle
PRL101 172001
$e^+e^- \to \Lambda_c\bar{\Lambda}_c$
Y(4630)
2008
BESIII
PRL118 092002
$e^+e^- \to h_c\pi^+\pi^-$
X(4390)
BESIII
PRL118 092001
$e^+e^- \to J/\psi\pi^+\pi^-$
X(4320)
Y(4220)
2017
year


The double charmonium production process
Belle
PRL98 082001
$e^+e^- \to J/\psi(\bar{D}D^*)$
X(3940)
2007
Belle
PRL100 202001
$e^+e^- \to J/\psi(D^{*+}D^{*-})$
Y(4160)
2008
Belle
PRD95 112003
$e^+e^- \to J/\psi(D\bar{D})$
X*(3860)
2017
year


The γγ fusion process
Belle
PRL96 082003
$\gamma\gamma \to (D\bar{D})$
Z(3930)
2005
Belle
PRL104 092001
$\gamma\gamma \to (J/\psi\omega)$
X(3915)
Belle
PRL104 112004
$\gamma\gamma \to (J/\psi\phi)$
X(4350)
2010
year


The hadronic decays of Y(4260)
BESIII
PRL112 132001
$e^+e^- \to Y(4260) \to (D^*\bar{D}^*)^+\pi^-$
$Z_c(4025)$
BESIII/Belle
PRL110 252001
PRL110 252002
$e^+e^- \to Y(4260) \to (J/\psi\pi^+)\pi^-$
$Z_c(3900)$
BESIII
PRL111 242001
$e^+e^- \to Y(4260) \to (h_c\pi^+)\pi^-$
$Z_c(4020)$
BESIII
PRL112 022001
$e^+e^- \to Y(4260) \to (D\bar{D}^*)^+\pi^-$
$Z_c(3885)$
BESIII
PRD96 032004
$e^+e^- \to Y(4260) \to (\psi(3686)\pi^+)\pi^-$
$Z_c(4032)$
2013
2014
2017
year


Other processes
Belle
PRL108 122001
$e^+e^- \to \Upsilon(10860) \to (h_b(mS)\pi^+)\pi^-$
$e^+e^- \to \Upsilon(10860) \to (\Upsilon(nS)\pi^+)\pi^-$
$Z_b(10650)$
$Z_b(10610)$
LHCb
PRL115 072001
$\Lambda_b^0 \to (J/\psi p)K^-$
$P_c(4450)$
$P_c(4380)$
BESIII
PRL115 011803
$e^+e^- \to \pi^+\pi^-(\gamma\chi_{c1})$
X(3823)
2011
2015
year

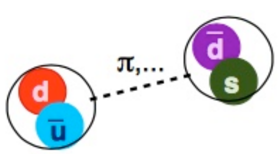
Abundant theoretical explanations

Resonant *vs* Non-resonant

Conventional hadrons

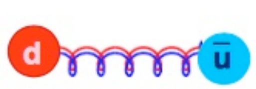
charmonium

Exotic states



- **Molecular states**: loosely bound states composed of a pair of mesons, probably bound by the pion exchange

- **Tetraquarks**: bound states of four quarks, bound by colored-force between quarks, some are charged or carry strangeness, there are many states within the same multiplet



- **Hybrid charmonium**: bound states composed of a pair of quarks and one excited gluon

Many XYZ states lie very close to open-charm threshold

It's quite possible some threshold enhancements are not ***real*** resonances.

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

One boson exchange (OPE) model

Deuteron: loosely bound state of proton and neutron

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

ρ **and** ω **exchanges**   **Scalar σ exchange** π **exchange**

Effective Lagrangian depicting $NN\pi$ **interaction**

$$\mathscr{L} = g_{NN\pi}\bar{\psi}i\gamma_5\tau\psi\cdot\pi$$

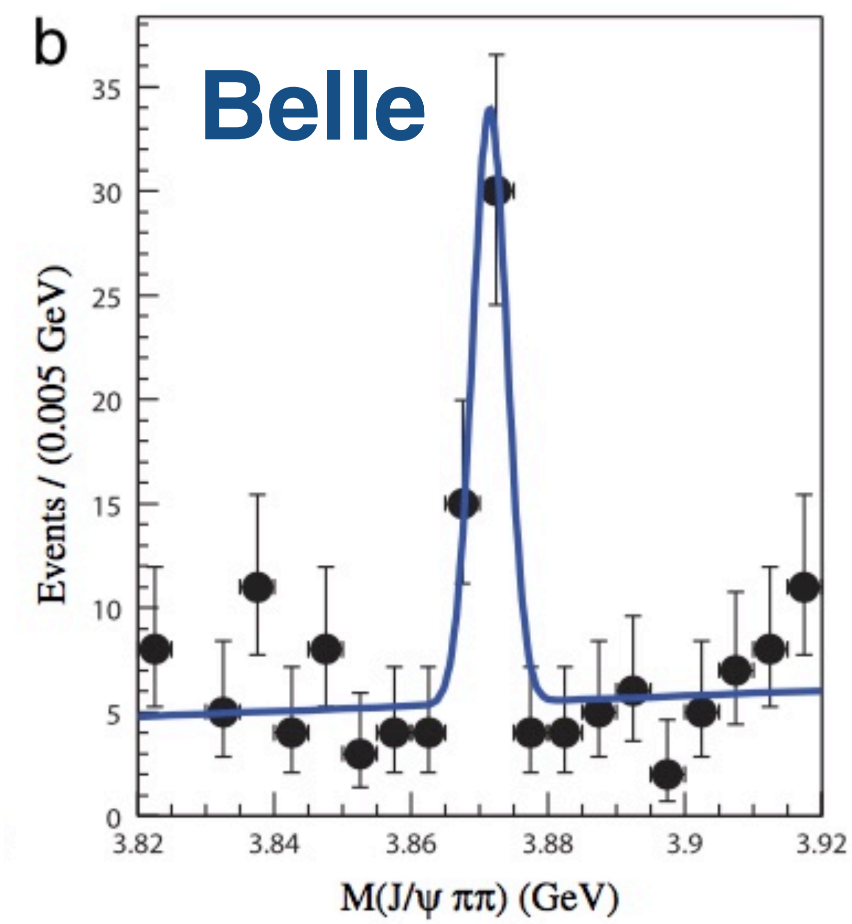
The non-relativistic nucleon-nucleon potential via π **exchange**

$$V_\pi = \frac{g_{NN\pi}^2}{4\pi}\frac{m_\pi^2}{12m_N^2}(\tau_1\cdot\tau_2)\left(\sigma_1\cdot\sigma_2 + \left[\frac{3(\sigma_1\cdot\mathbf{r})(\sigma_2\cdot\mathbf{r})}{r^2} - \sigma_1\cdot\sigma_2\right]\left[1 + \frac{3}{m_\pi r} + \frac{3}{m_\pi^2 r^2}\right]\right)\frac{e^{-m_\pi r}}{r}$$

X(3872)

Abundant experimental information

PRL 91 (2003) 262001



	Decay modes: $J/\psi\pi^+\pi^-$	$J/\psi\pi^+\pi^-\pi^0$ ($J/\psi\omega$)	$J/\psi\eta$	$D^0\bar{D}^0\pi^0$	$D^{*0}\bar{D}^0$	$\gamma J/\psi$	$\gamma\psi'$	Mass (MeV)	J^{PC}
Belle-1	■							$3872.0 \pm 0.6 \pm 0.5$	
Belle-2		■				■		–	
Belle-3				■				$3875.2 \pm 0.7^{+0.3}_{-1.6} \pm 0.8$	
Belle-4	■							$3871.46 \pm 0.37 \pm 0.07$	
Belle-5					■			$3872.9^{+0.3+0.5}_{-0.6-0.5}$	
Belle-6						■	■	–	
BaBar-1	■							3873.4 ± 1.4	
BaBar-2			□					–	
BaBar-3	■							–	
BaBar-4	■							$3871.3 \pm 0.6 \pm 0.1$ (B^-) $3868.6 \pm 1.2 \pm 0.2$ (B^0)	
BaBar-5				■				–	
BaBar-6						■		–	
BaBar-7					■			$3875.1^{+0.5}_{-0.7} \pm 0.5$	
BaBar-8	■							$3871.4 \pm 0.6 \pm 0.1$ (B^+) $3868.7 \pm 1.5 \pm 0.4$ (B^0)	
BaBar-9						■	■	–	
BaBar-10		■						$3873.0^{+1.8}_{-1.6} \pm 1.3$	2^{-+}
CDF-1	■							$3871.3 \pm 0.7 \pm 0.4$	
CDF-2	■							–	
CDF-3	■							–	$1^{++}/2^{-+}$
CDF-4	■							$3871.61 \pm 0.16 \pm 0.19$	
D0	■							$3871.8 \pm 3.1 \pm 3.0$	
LHCb-1	■							–	1^{++}
LHCb-2	■							$3871.95 \pm 0.48 \pm 0.12$	
CMS	■							–	
BESIII						■		$3891.9 \pm 0.7 \pm 0.2$	

$m(D^0D^{*0}) = (3871.81 \pm 0.36)$ MeV

PDG average mass of $X(3872)$: (3871.68 ± 0.17) MeV

Low mass puzzle:

The mass of X(3872) is 50-200 MeV lower than the prediction from potential model

Is X(3872) a molecular state?

$D\bar{D}^*$ interaction

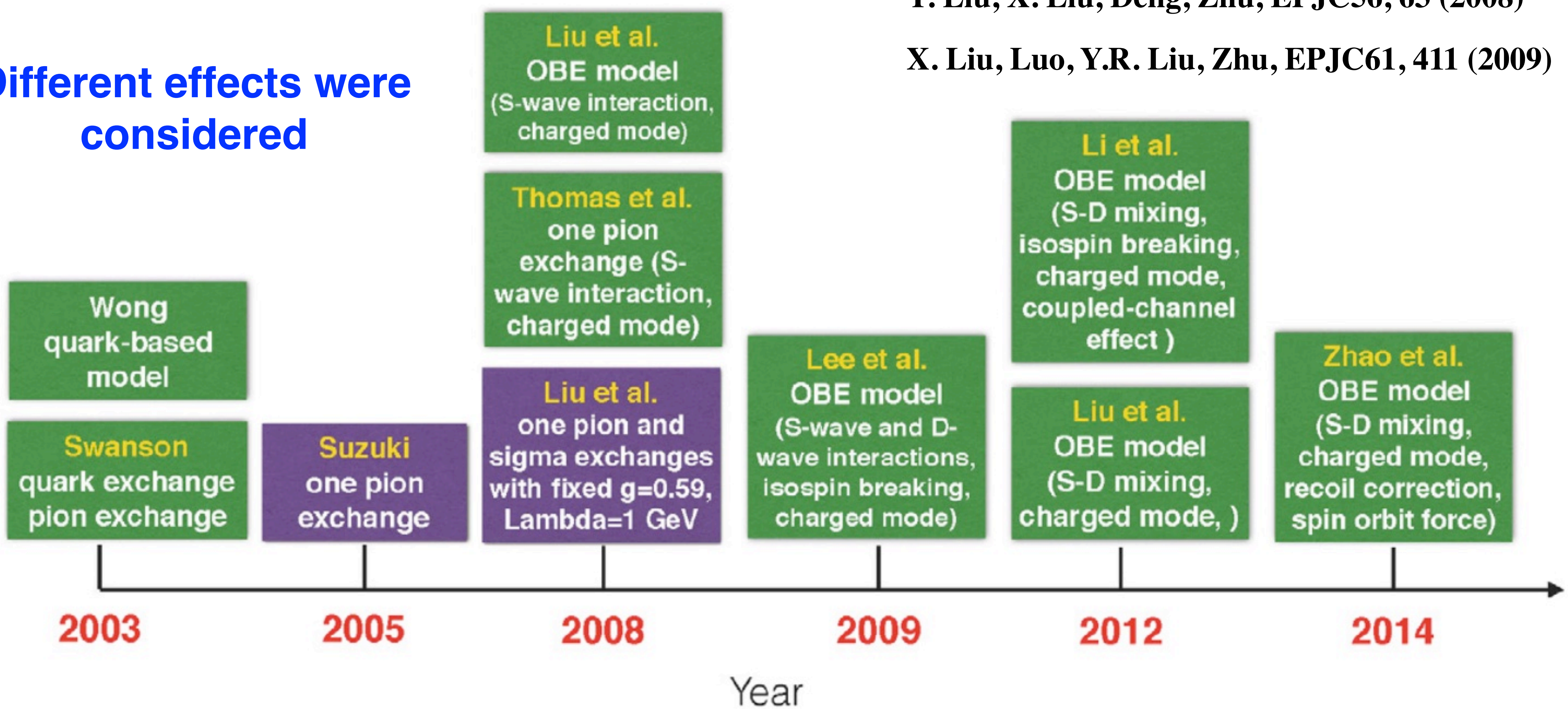
N. Li, S.L. Zhu, PRD86(2012)

L.Zhao, L.Ma, S.L.Zhu, PRD 89 (2014)

Y. Liu, X. Liu, Deng, Zhu, EPJC56, 63 (2008)

X. Liu, Luo, Y.R. Liu, Zhu, EPJC61, 411 (2009)

Different effects were considered



- Reproduce the mass of $X(3872)$
- Explain isospin violating $J/\psi\rho$ decay mode of $X(3872)$

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
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LIU X, LIU Y R, DENG W Z, ZHU S L. Phys. Rev. D, 2008, **77**: 034003
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Swanson E S. Phys. Lett. B, 2004, **598**: 197
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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
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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 plays crucial role to form heavy flavor molecular states

It is the reason why we adopt one boson exchange model to study XYZ states and predict P_c states

4

Predicting hidden-charm molecular pentaquark

The prediction of hidden-charm pentaquarks

PRL **105,** 232001 (2010) PHYSICAL REVIEW LETTERS week ending 3 DECEMBER 2010

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]

Hidden-charm pentaquarks are predicted in an extended hidden gauge symmetry approach

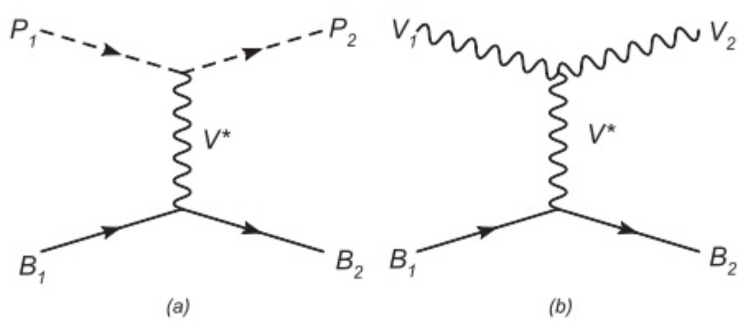


FIG. 1. Feynman diagrams of pseudoscalar-baryon (a) or vector-baryon (b) interaction via exchange of a vector meson. P_1, P_2 is D^-, $\bar{D}^0$, or D_s^-, V_1, V_2 is D^{*-}, $\bar{D}^{*0}$, or D_s^{*-}, B_1, B_2 is Σ_c, Λ_c^+, Ξ_c, Ξ_c', or Ω_c, and V^* is ρ, K^*, ϕ, or ω.

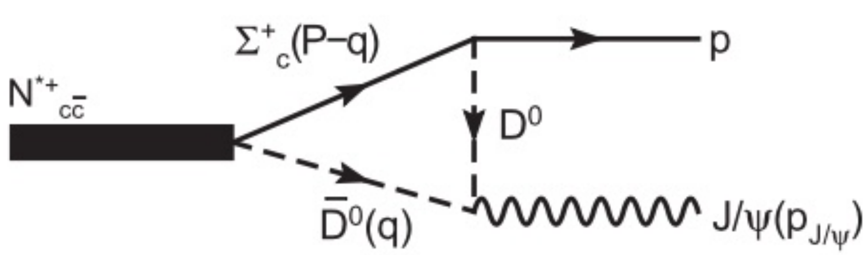


FIG. 2. Feynman diagram for $N_{c\bar{c}}^{*+}(4265) \to J/\psi p$.

TABLE II. 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)		$\bar{D}\Sigma_c$	$\bar{D}\Lambda_c^+$	
	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 position and coupling constants for the bound states from $VB \to VB$.

(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

The prediction of hidden-charm pentaquarks

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)]

[1] Department of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
[2] Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[3] Nuclear Theory Group, Institute of Modern Physics of Chinese Academy of Sciences, Lanzhou 730000, China
[4] School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China

OBE model

Abstract: Using the one-boson-exchange model, we studied the possible existence of very loosely bound hidden-charm molecular baryons composed of an anti-charmed meson and a charmed baryon. Our numerical results indicate that the $\Sigma_c\bar{D}^*$ and $\Sigma_c\bar{D}$ states exist, but that the $\Lambda_c\bar{D}$ and $\Lambda_c\bar{D}^*$ molecular states do not.

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

- **Explicitly indicate the existence of hidden-charm pentaquark with J=3/2**
- **Such prediction is confirmed by the LHCb measurement**

Eur. Phys. J. C (2014) 74:3198
DOI 10.1140/epjc/s10052-014-3198-3

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

A possible global group structure for exotic states

Xue-Qian Li[1,a], Xiang Liu[3,2,b]

Abstract Based on the fact that the long expected pentaquark which possesses the exotic quantum numbers of $B = 1$ and $S = 1$ was not experimentally found, although exotic states of XYZ have been observed recently, we conjecture that the heavy flavors may play an important role in stabilizing the hadronic structures beyond the traditional $q\bar{q}$ and qqq composites.

$$G = SU_c(3) \times SU_H(2) \times SU_L(3),$$

where the subscripts c, H, and L refer to color, heavy, and light, respectively. The $SU_L(3)$ corresponds to the regular quark model for the light quarks u, d, s and the newly introduced $SU_H(2)$ involves c and b quarks (antiquarks). This idea is inspired by the heavy quark effective theory (HQET) [27,28].

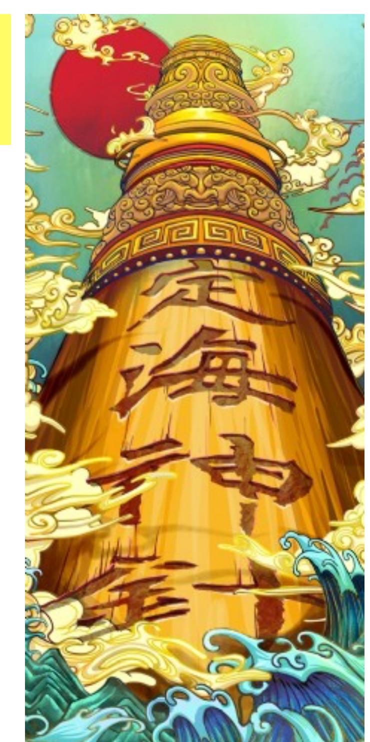
$$c\bar{b},\ (c\bar{c} + b\bar{b})/\sqrt{2},\ b\bar{c}, \quad \text{(triplet)},$$

$$(c\bar{c} - b\bar{b})/\sqrt{2}, \quad \text{(singlet)}.$$

Prediction:

隐粲量子数对五夸克态的稳定性的重要性

Therefore, we would predict that the pentaquarks should be $c\bar{c}qqq$ and $b\bar{b}qqq$. However, such baryons would have the same quantum numbers as the regular baryons, unlike their mass spectra, and it is hard to identify them as an exotic state. By contrast, the pentaquark $b\bar{c}qqq$ [38] would have



PRL 115, 122001 (2015) PHYSICAL REVIEW LETTERS week ending 18 SEPTEMBER 2015

New Exotic Meson and Baryon Resonances from Doubly Heavy Hadronic Molecules

Marek Karliner[1,*] and Jonathan L. Rosner[2,†]

Thus the conditions for existence of the resonance are as follows: (a) The state contains two heavy hadrons. They have to be heavy, as the repulsive kinetic energy is inversely proportional to the reduced mass (see, e.g., Ref. [26]). (For a more recent discussion see Ref. [27].) (b) The two hadrons carry isospin, so that they can couple to pions. Channels like $\Sigma_c \bar{\Lambda}_c$, in which one of the particles has zero isospin, can exchange a pion to become the equal-mass channel $\Lambda_c \bar{\Sigma}_c$. (c) The spin and parity of the two hadrons have to be such that they can bind through single pion exchange. (d) The hadrons making up the molecule have to

Consistent with our conclusion

[27] X. Q. Li and X. Liu, Eur. Phys. J. C **74**, 3198 (2014).

Notes added.—We thank X. Liu for informing us of an earlier calculation [37] of binding between a charmed baryon and anticharmed meson, obtaining—as we do—no binding between Λ_c and $\bar{D}^{(*)}$ but binding between Σ_c and $\bar{D}^*$ in all four spin-isospin channels, as well as—unlike us—between Σ_c and $\bar{D}$ with $I = 3/2$ and $J = 1/2$. We also

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

The consistency between their result and our former work published in CPC 36 (2012) 6-13

Observation of $P_c(4380)$ and $P_c(4450)$

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)

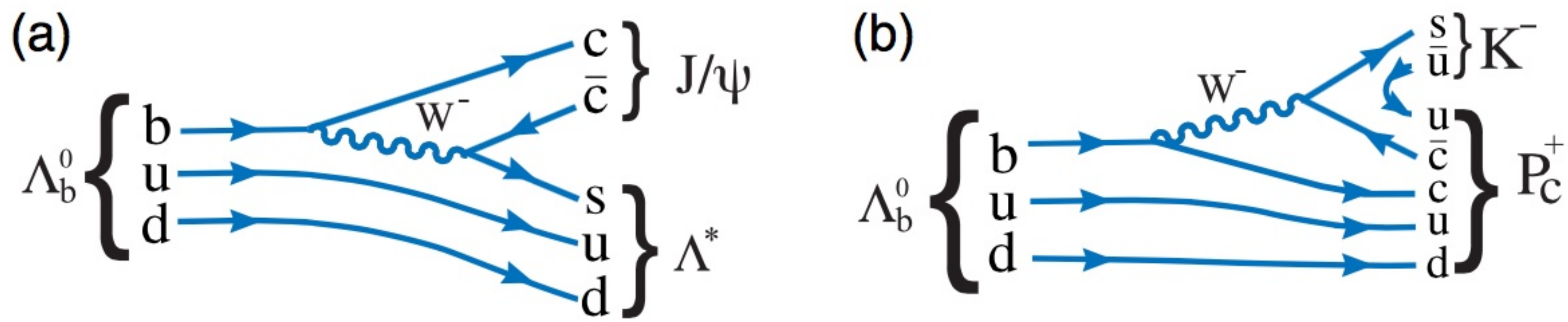


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

Resonance parameters of two P_c states

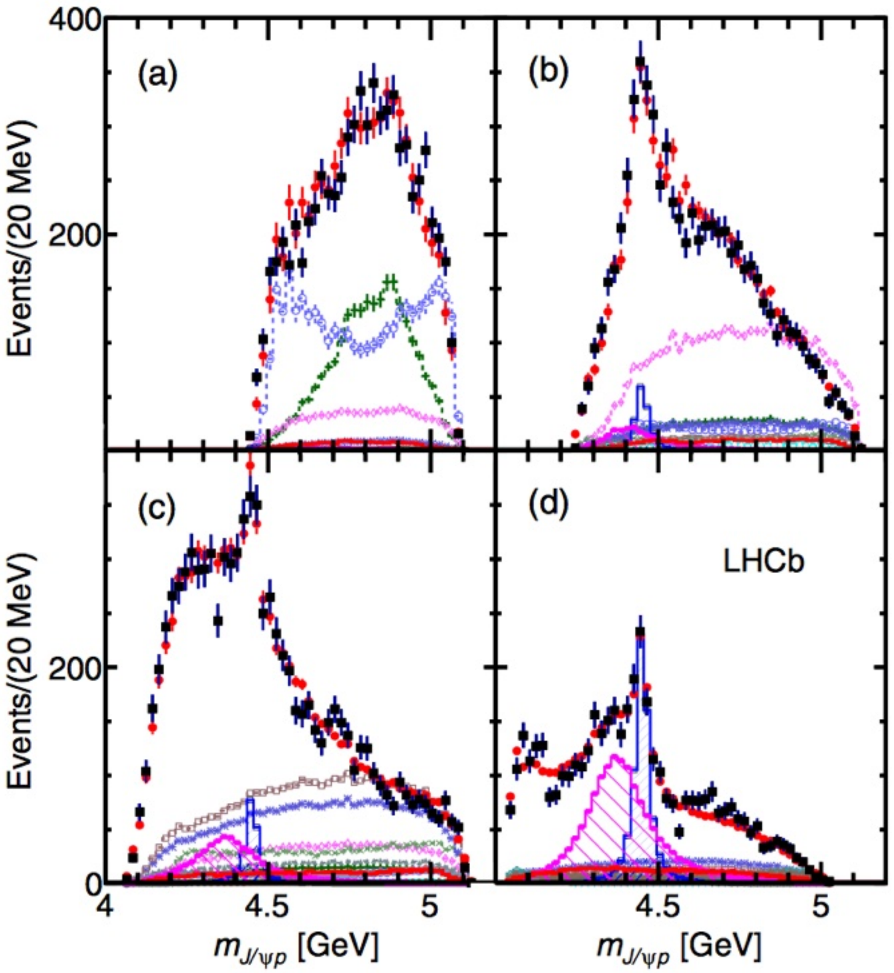


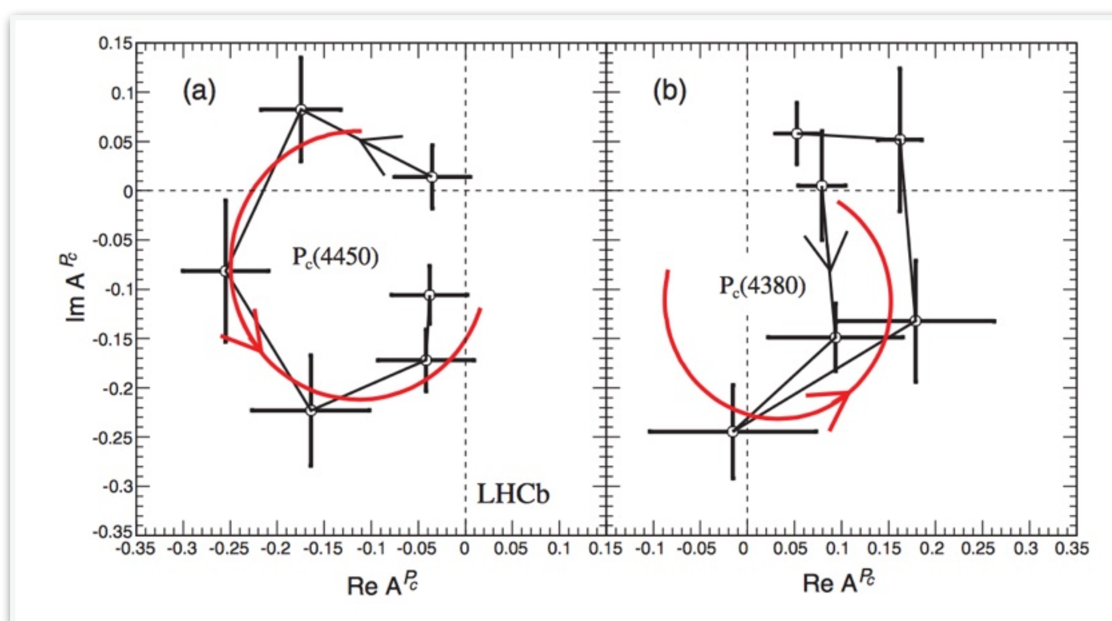
FIG. 8 (color online). $m_{J/\psi p}$ in various intervals of m_{Kp} for the fit with two P_c^+ states: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, and (d) $m_{Kp} > 2.00$ GeV. The data are shown as (black) squares with error bars, while the (red) circles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

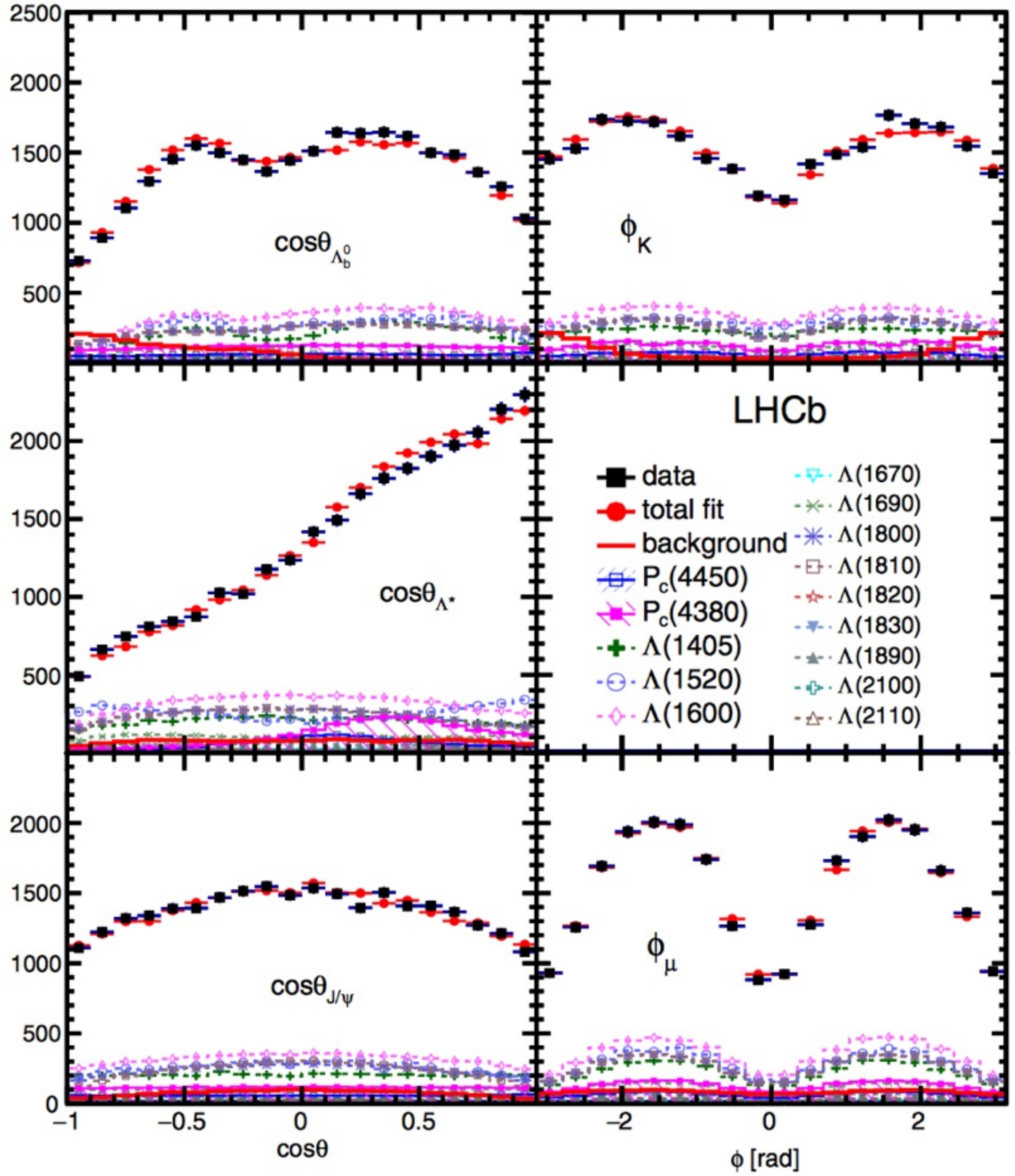
Ref: $\mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Argand diagrams show the resonance behavior of two P_c states



Decay angular distributions

The preferred J^P are of opposite parity, with one state having $J = 3/2$ and the other $5/2$



It is puzzling for us under the hadronic molecular assignment

PRL **115,** 132002 (2015) PHYSICAL REVIEW LETTERS week ending 25 SEPTEMBER 2015

Identifying Exotic Hidden-Charm Pentaquarks

Rui Chen and Xiang Liu*
Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China and 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‡
School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China; Collaborative Innovation Center of Quantum Matter, Beijing 100871, China and Center of High Energy Physics, Peking University, Beijing 100871, China

(Received 14 July 2015; published 25 September 2015)

The LHCb Collaboration at the Large Hadron Collider at CERN discovered two pentaquark states $P_c(4380)$ and $P_c(4450)$. These two hidden-charm states are interpreted as the loosely bound $\Sigma_c(2455)D^*$ and $\Sigma_c^*(2520)D^*$ molecular states in the boson exchange interaction model, which provides an explanation for why the experimental width of $P_c(4450)$ is much narrower than that of $P_c(4380)$. The discovery of the new resonances $P_c(4380)$ and $P_c(4450)$, indeed, opens a new page for hadron physics. The partners of $P_c(4380)$ and $P_c(4450)$ should be pursued in future experiments.

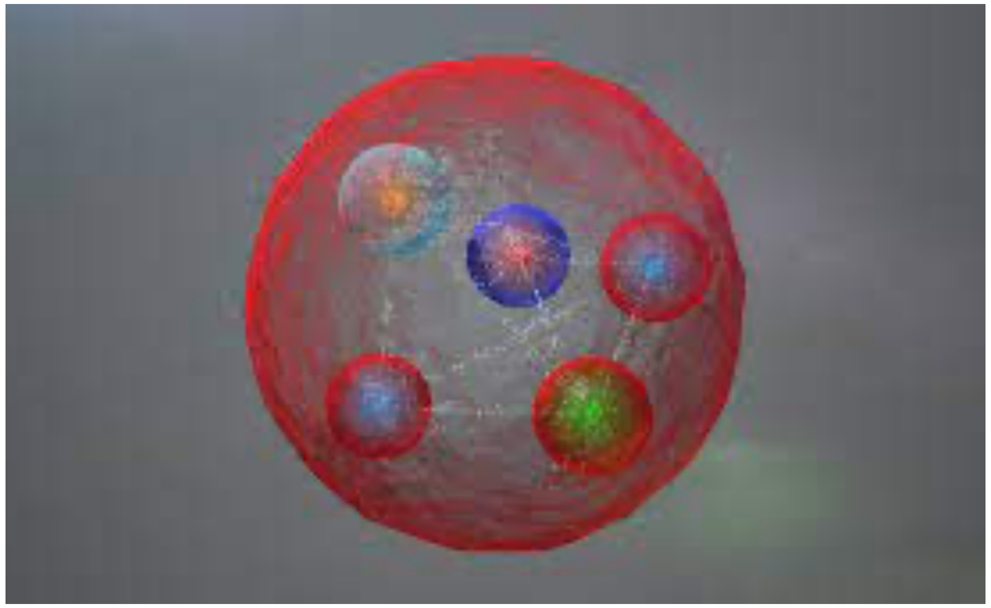
EDITORS' SUGGESTION

Identifying Exotic Hidden-Charm Pentaquarks

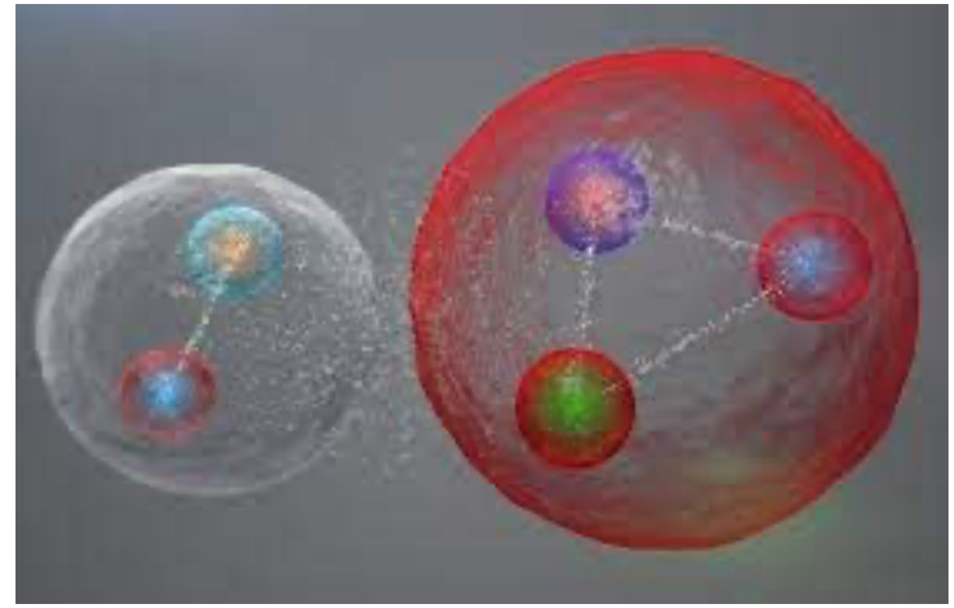
The pentaquarks discovered by the LHCb Collaboration could be molecular bound states of a charmed baryon and a meson. Observing the predicted isospin partners would allow for

Decode the properties of two observed P_c consistent with hadronic molecular states

LHCb@2015 cannot be applied distinguish different explanations



Compact pentaquark



Molecular state

Physics Reports 639 (2016) 1–121

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

ELSEVIER

We need more data!

The hidden-charm pentaquark and tetraquark states

Hua-Xing Chen[a,b,1], Wei Chen[c,1], Xiang Liu[d,e,*], Shi-Lin Zhu[a,f,g,**]

怀疑LHCb发现的P_c态还有子结构

As pointed out in Ref. [260], there may exist two or more resonant signals around 4380 MeV which are close to each other but may carry different parity. If the P-wave or higher excitation is very broad with a width around 500 MeV, such a state may easily be mistaken as the background. On the other hand, if an excitation lies several MeV within 4380 MeV but with a width as narrow as several MeV, then it may probably be buried by the $P_c(4380)$ resonance with a width around 205 MeV! The same situation may also occur around 4450 MeV.

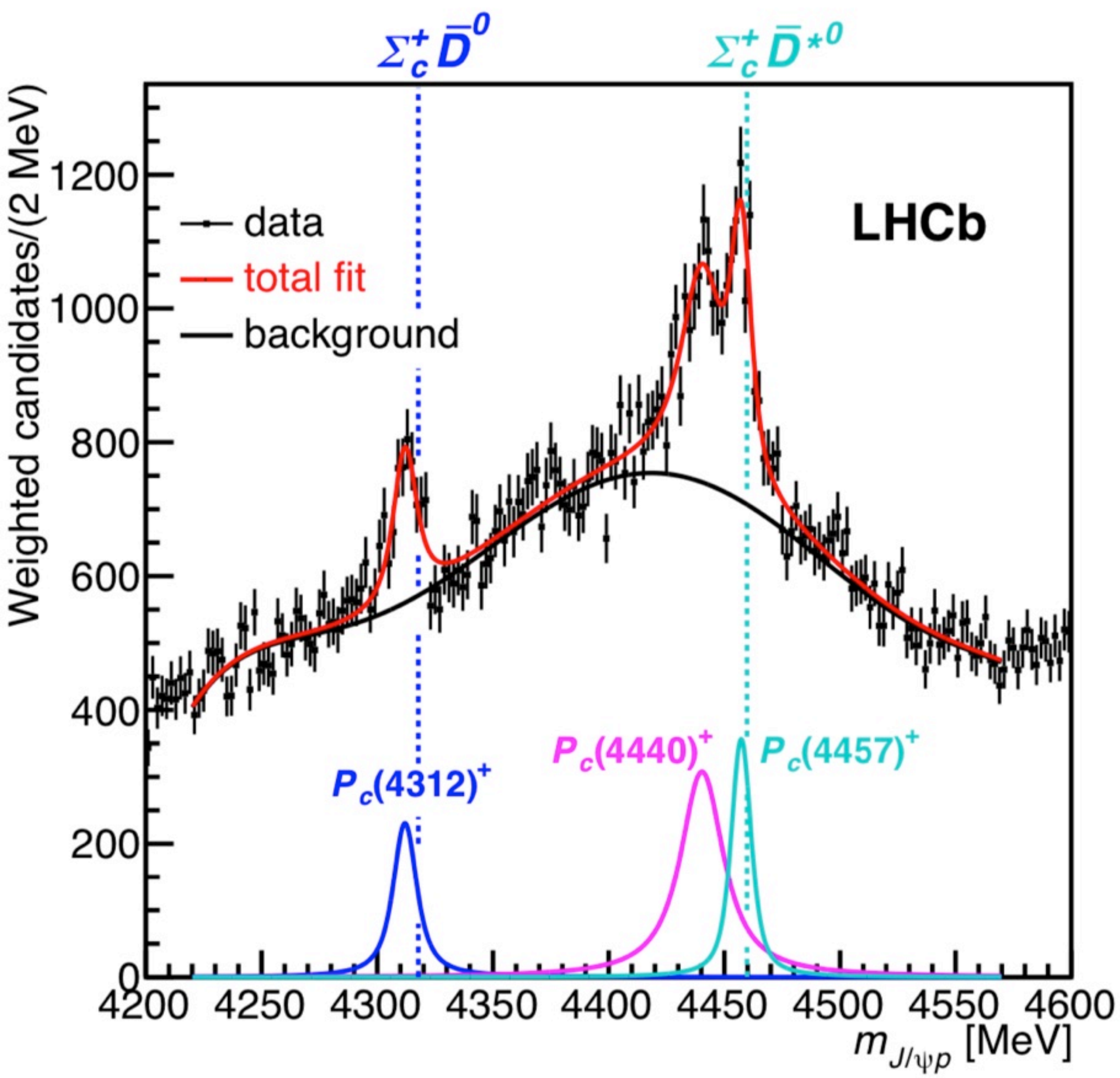
PHYSICAL REVIEW LETTERS **122,** 222001 (2019)

Editors' Suggestion | Featured in Physics

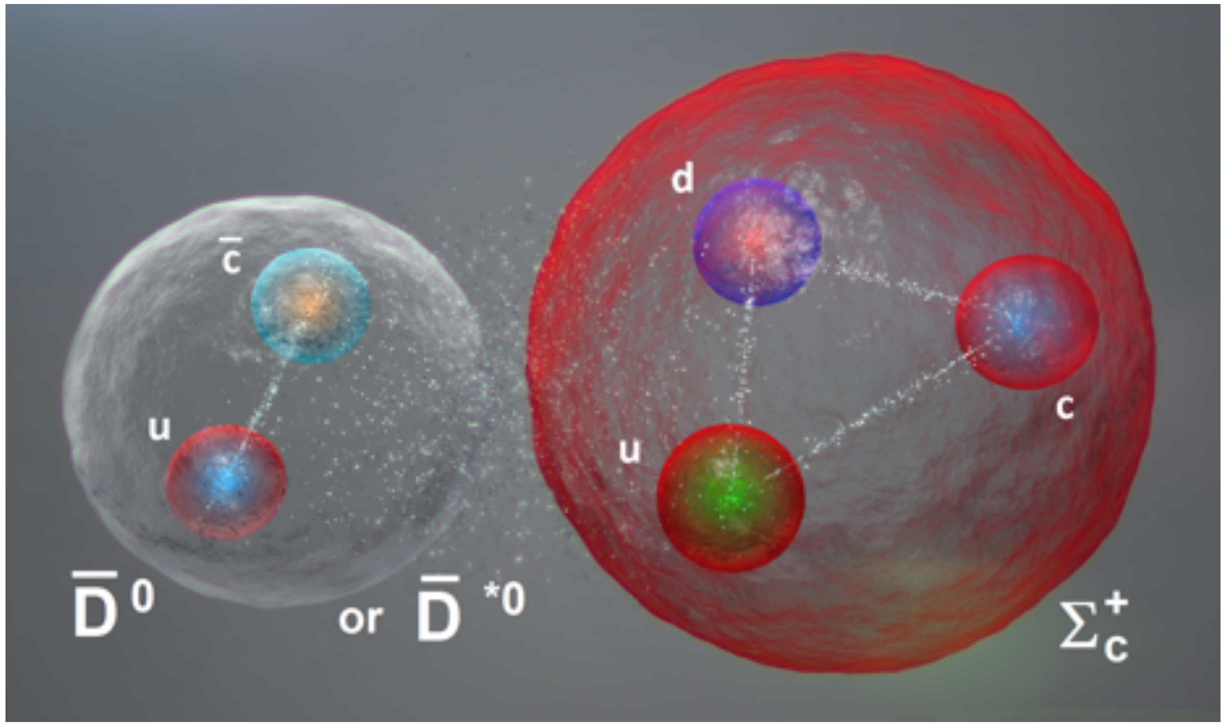
Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

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

(Received 6 April 2019; published 5 June 2019)



2019年高精度的实验数据支持分子态构型



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

2011

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)]

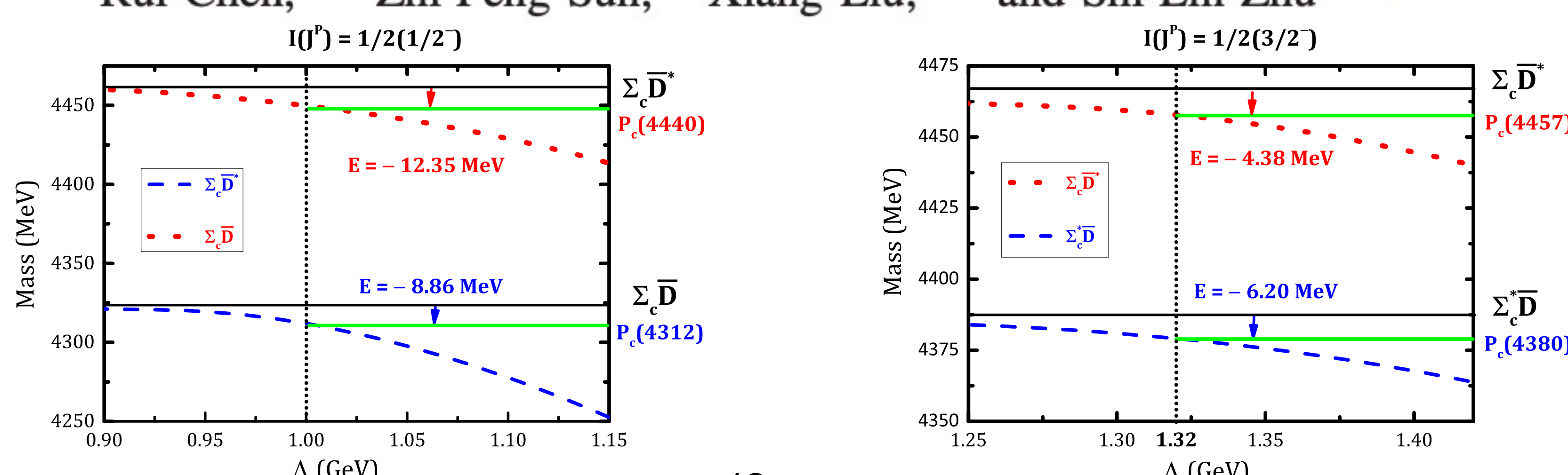
PHYSICAL REVIEW D **100**, 011502(R) (2019)

Rapid Communications

2019

Strong LHCb evidence supporting the existence of the hidden-charm molecular pentaquarks

Rui Chen,[1,2,3] Zhi-Feng Sun,[1,2] Xiang Liu,[1,2,*] and Shi-Lin Zhu[3,4,5,†]



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2019 Review of Particle Physics

Please use this **CITATION**:
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

在探索多夸克物质的征程上打下中国人的烙印

http://pdg.lbl.gov/2019/reviews/rpp2019-rev-pentaquarks.pdf

106. Pentaquarks

Revised September 2019 by M. Karliner (Tel Aviv U.) and T. Skwarnicki (Syracuse U.).

Experimental searches for pentaquark hadrons comprised of light flavors have a long and vivid history. No undisputed candidates have been found in 50 years. The first wave of observations of pentaquark candidates containing a strange antiquark occurred in the early seventies, see e.g. a review in the 1976 edition of Particle Data Group listings for $Z_0(1780)$, $Z_0(1865)$ and $Z_1(1900)$ [1]. The last mention of these candidates can be found in the 1992 edition [2] with the perhaps prophetic comment "the results permit no definite conclusion - the same story for 20 years. [...] The skepticism about baryons not made of three quarks, and lack of any experimental activity in this area, make it
likely that another 20 years will pass before th
observations occurred, possibly motivated by s
The evidence for pentaquarks was based on ob
of their decay products. More data, or more s
In the last mention of the best known candi
Data Group listing [7] included a statement: "
Θ^+, in particular, do not exist, appears com
the particle physics community until a study
(charge conjugate modes are implied). From a
LHC, the LHCb collaboration reported a sig
The exotic character of this structure, with th
in a nearly model-independent way in Ref. [9],
near 4450 MeV was too narrow to be accounte
Λ excitation), reinforcing the results from the
analysis of invariant masses and decay angles
though not apparent from the $m_{J/\psi p}$ distribu
broad $J/\psi p$ state to obtain a good description
a width of $205 \pm 18 \pm 86$ MeV and a fit fractio
The LHCb 6 fb^{-1} Run 2 LHC data at 1
selection for both runs, resulted in a nine-f
$J/\psi pK^-$ decays [10]. When fit with the same
sample gives consistent results for the P_c(44
compatibility of the data samples. However, t
by the observation of new narrow $J/\psi p$ struc
the Run 1 data analysis. Second horizontal
4312 MeV in the $J/\psi p$ mass. The 4450 MeV
peaks at 4440 and 4457 MeV. Performing a
faint $J/\psi p$ structures is challenging and has
observed peaks are so narrow that it is not
that these states are not artifacts of interfer
in Ref. [9]. Their masses and widths have
from one-dimensional fits to $J/\psi p$ mass distri
contributions, which peak at the lower pK^-
any broad $J/\psi p$ contributions like $P_c(4380)^+$.
in tabular form at https://www.hepdata.net/
The fit chosen by the LHCb for the centr
The $P_c(4312)^+$ state peaks right below the $\Sigma_c^+ \overline{D}^0$ threshold and has statistical significance over

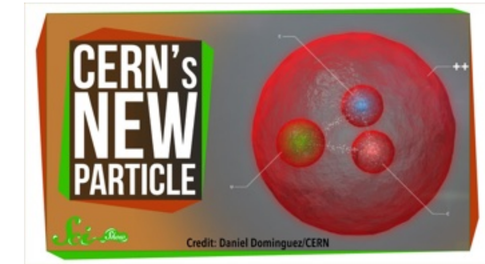
While $\Sigma_c \bar{D}^{(*)}$ states had been predicted [12–15] before the first LHCb results [8], after these results became known, many theoretical groups interpreted the $P_c(4450)^+$ and $P_c(4380)^+$ states in terms of diquarks and triquarks as building blocks of a compact pentaquark [16–22], or even of states below the lowest threshold for spontaneous dissociation [23]. In the first implementation of this approach [16], the pentaquark mass splitting was generated mostly by the change of angular momentum between the sub-components (L) from zero to one, which would also make the heavier state narrower and of opposite parity. Explicit modeling of multiquark systems [24] questions

[12] Z.-C. Yang *et al.*, Chin. Phys. **C36**, 6 (2012), [arXiv:1105.2901].
[13] J.-J. Wu *et al.*, Phys. Rev. Lett. **105**, 232001 (2010), [arXiv:1007.0573].
[14] J.-J. Wu, T. S. H. Lee and B. S. Zou, Phys. Rev. **C85**, 044002 (2012), [arXiv:1202.1036].
[15] M. Karliner and J. L. Rosner, Phys. Rev. Lett. **115**, 12, 122001 (2015), [arXiv:1506.06386].

4

More predictions of heavy flavor pentaquark

Selected for a Viewpoint in *Physics*
PRL **119,** 112001 (2017) PHYSICAL REVIEW LETTERS week ending 15 SEPTEMBER 2017



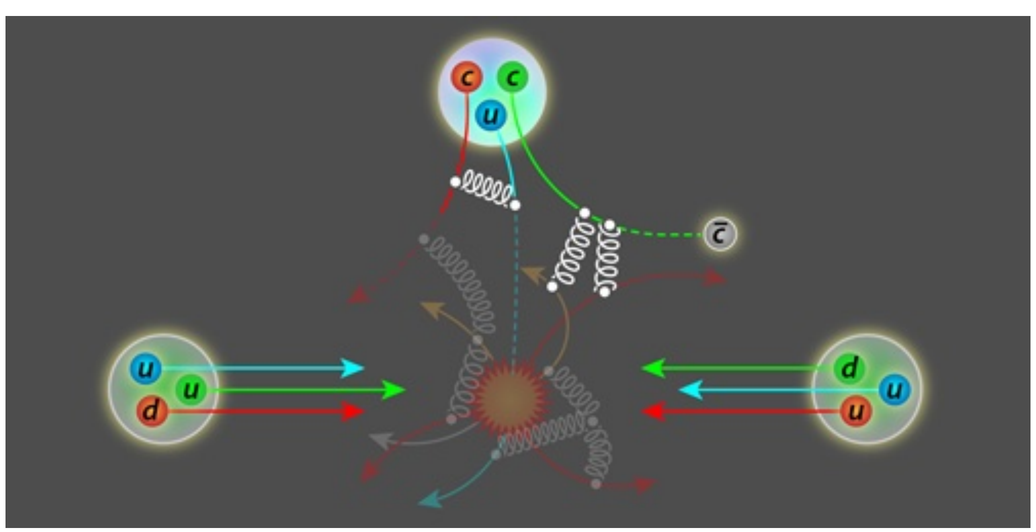
Observation of the Doubly Charmed Baryon Ξ_{cc}^{++}

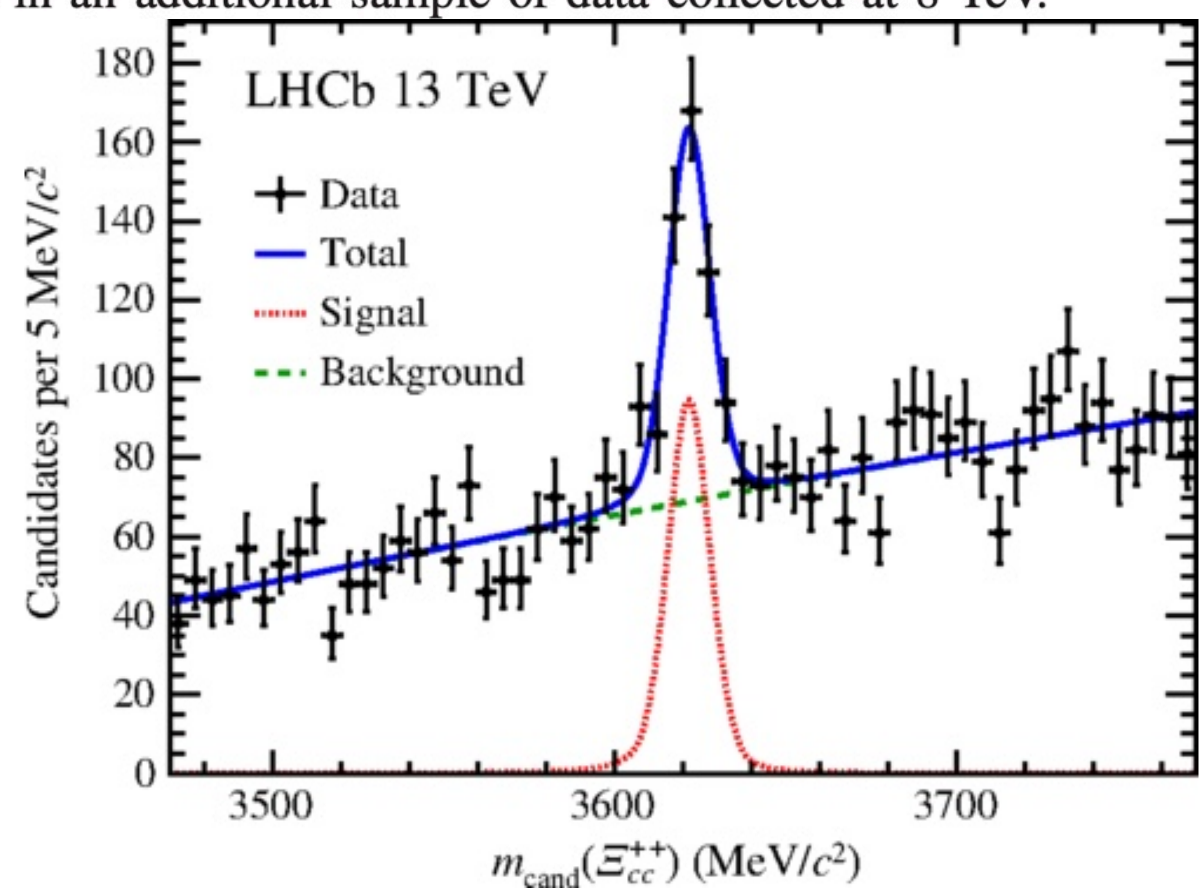
R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 6 July 2017; revised manuscript received 2 August 2017; published 11 September 2017)

A highly significant structure is observed in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum, where the Λ_c^+ baryon is reconstructed in the decay mode $pK^-\pi^+$. The structure is consistent with originating from a weakly decaying particle, identified as the doubly charmed baryon Ξ_{cc}^{++}. The difference between the masses of the Ξ_{cc}^{++} and Λ_c^+ states is measured to be $1334.94 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.})\ \text{MeV}/c^2$, and the Ξ_{cc}^{++} mass is then determined to be $3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$, where the last uncertainty is due to the limited knowledge of the Λ_c^+ mass. The state is observed in a sample of proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 1.7 fb^{-1}, and confirmed in an additional sample of data collected at 8 TeV.

DOI: 10.1103/PhysRevLett.119.112001





PHYSICAL REVIEW D **96,** 114030 (2017)

Prediction of triple-charm molecular pentaquarks

Rui Chen,[1,2,3,*] Atsushi Hosaka,[3,†] and Xiang Liu[1,2,‡]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*

(Received 29 November 2017; published 28 December 2017)

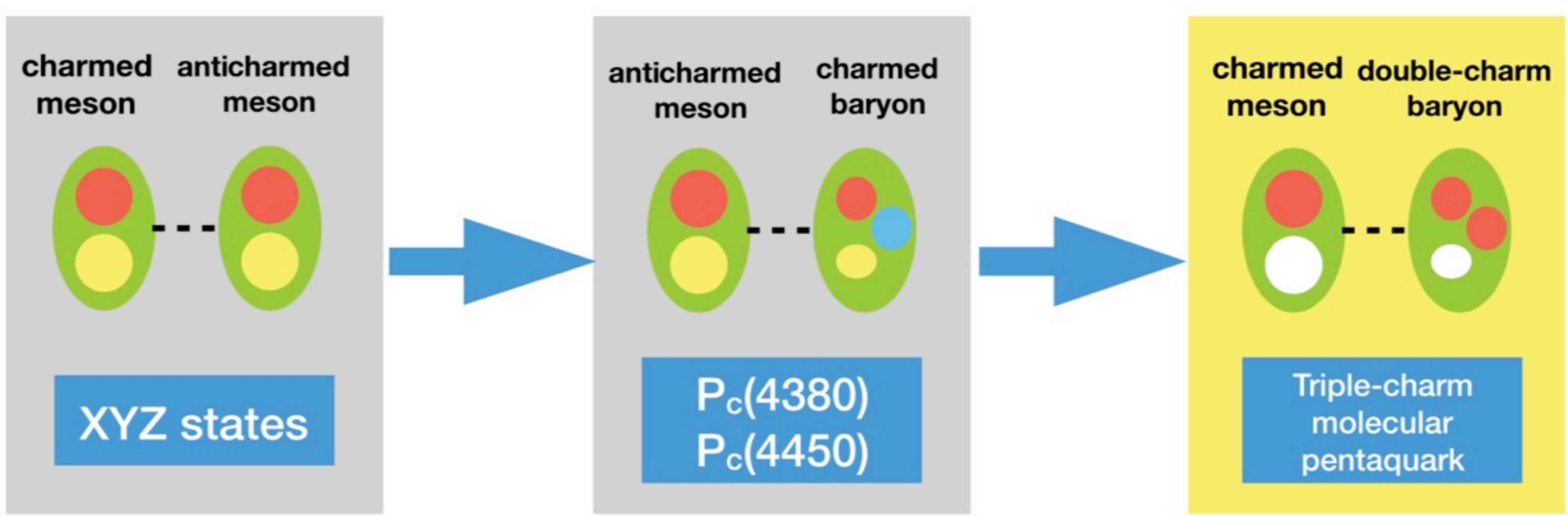
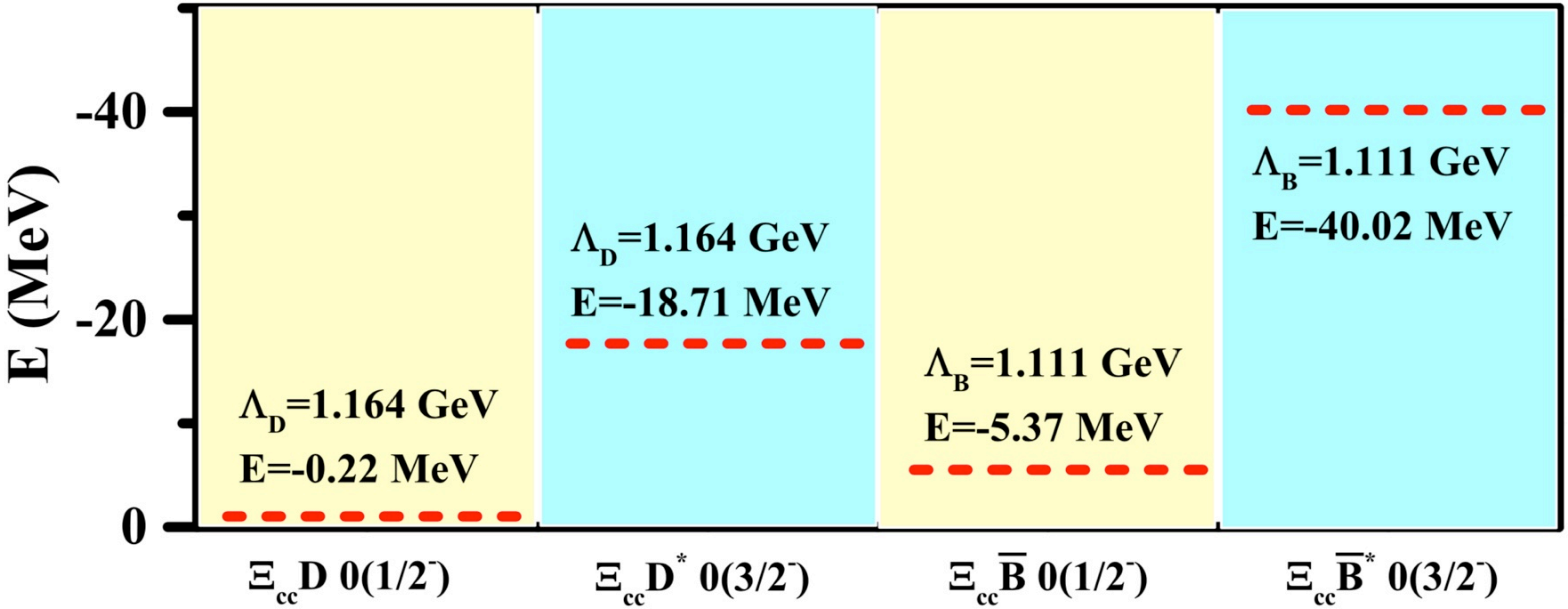


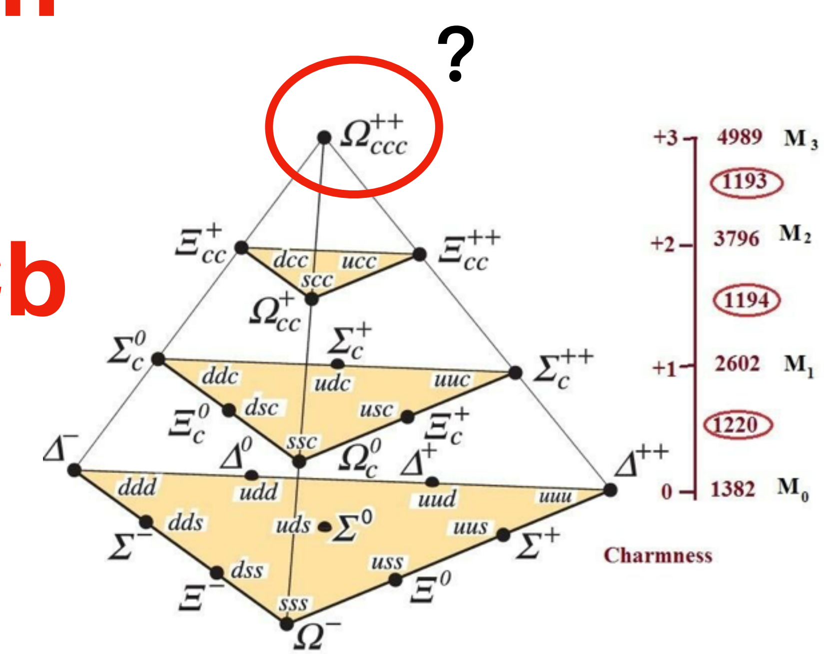
FIG. 1. Evolution of interaction of hadrons and the corresponding connections with charmoniumlike *XYZ* states, $P_c(4380)/P_c(4450)$, and triple-charm molecular pentaquark.

Chen, Hosaka, Liu, PRD96 (2017) 114030



Experimental search for triple-charm molecular pentaquarks will be interesting issue, especially for LHCb

Decay modes: $\Omega_{ccc}\sigma, \Omega_{ccc}\omega, \Omega_{ccc}\pi\pi$



PHYSICAL REVIEW D **99,** 054021 (2019)

Possible triple-charm molecular pentaquarks from $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ interactions

Fu-Lai Wang,* Rui Chen,† Zhan-Wei Liu,‡ and Xiang Liu§

School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China and Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

(Received 14 January 2019; published 25 March 2019)

In this work, we explore a systematic investigation on S-wave interactions between a doubly charmed baryon $\Xi_{cc}(3621)$ and a charmed meson in a T doublet (D_1, D_2^*). We first analyze the possibility for forming $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ bound states with the heavy quark spin symmetry. Then, we further perform a dynamical study on the $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ interactions within a one-boson-exchange model by considering both the $S-D$ wave mixing and coupled channel effect. Finally, our numerical results conform the proposals from the heavy quark spin symmetry analysis: the $\Xi_{cc}D_1$ systems with $I(J^P) = 0(1/2^+, 3/2^+)$ and the $\Xi_{cc}D_2^*$ systems with $I(J^P) = 0(3/2^+, 5/2^+)$ can possibly be loose triple-charm molecular pentaquarks. Meanwhile, we also extend our model to the $\Xi_{cc}\bar{D}_1$ and $\Xi_{cc}\bar{D}_2^*$ systems, and our results indicate the isoscalars of $\Xi_{cc}\bar{D}_1$ and $\Xi_{cc}\bar{D}_2^*$ can be possible molecular candidates.

TABLE V. Bound state solutions for the $\Xi_{cc}D_1/\Xi_{cc}D_2^*$ states with $I(J^P) = 0, 1(1/2^+, 3/2^+)$. Cutoff Λ, binding energy E, and root-mean-square radius $r_{\rm rms}$ are in units of GeV, MeV, and fm, respectively. $P(\%)$ denotes the probability for the different channels. Here, we label the probability for the corresponding channel in a bold manner.

(I, J^P)	Λ	E	$r_{\rm rms}$	$P(\Xi_{cc}D_1\|^2\mathbb{S}_{\frac{1}{2}}\rangle)$	$P(\Xi_{cc}D_1\|^2\mathbb{D}_{\frac{1}{2}}\rangle)$	$P(\Xi_{cc}D_2^*\|^4\mathbb{D}_{\frac{1}{2}}\rangle)$	$P(\Xi_{cc}D_2^*\|^6\mathbb{D}_{\frac{1}{2}}\rangle)$		
$(0, \frac{1}{2}^+)$	0.90	−0.47	3.84	**99.51**	0.43	$o(10^{-3})$	0.05		
	0.93	−3.76	1.60	**99.44**	0.46	$o(10^{-3})$	0.09		
	0.96	−10.78	1.04	**99.59**	0.32	$o(10^{-3})$	0.09		
$(1, \frac{1}{2}^+)$	2.30	−0.33	4.41	**99.62**	0.33	$o(10^{-3})$	0.05		
	3.15	−3.65	1.63	**98.46**	1.19	0.03	0.32		
	4.00	−10.24	1.04	**96.70**	2.30	0.09	0.92		
(I, J^P)	Λ	E	$r_{\rm rms}$	$P(\Xi_{cc}D_1\|^4\mathbb{S}_{\frac{3}{2}}\rangle)$	$P(\Xi_{cc}D_1\|^2\mathbb{D}_{\frac{3}{2}}\rangle)$	$P(\Xi_{cc}D_1\|^4\mathbb{D}_{\frac{3}{2}}\rangle)$	$P(\Xi_{cc}D_2^*\|^4\mathbb{S}_{\frac{3}{2}}\rangle)$	$P(\Xi_{cc}D_2^*\|^4\mathbb{D}_{\frac{3}{2}}\rangle)$	$P(\Xi_{cc}D_2^*\|^6\mathbb{D}_{\frac{3}{2}}\rangle)$
$(0, \frac{3}{2}^+)$	1.00	−0.53	3.64	**88.65**	0.17	0.81	10.35	$o(10^{-3})$	$o(10^{-3})$
	1.01	−2.44	1.68	**65.67**	0.14	0.67	**33.50**	$o(10^{-3})$	$o(10^{-3})$
	1.02	−6.49	0.96	**41.91**	0.08	0.34	**57.65**	$o(10^{-3})$	0.01
$(1, \frac{3}{2}^+)$	1.50	−0.22	4.87	**99.36**	0.05	0.24	0.29	$o(10^{-3})$	0.01
	1.63	−1.67	2.23	**95.76**	0.07	0.44	3.50	0.17	0.06
	1.76	−6.95	0.99	**57.95**	0.04	0.29	**40.91**	0.44	0.37

The most promising pentaquark moleculars

Isoscalar

$$\Xi_{cc}D_1(J^P = 1/2^+, 3/2^+)$$

$$\Xi_{cc}D_2^*(J^P = 3/2^+, 5/2^+)$$

PHYSICAL REVIEW D **97,** 114011 (2018)

Exotic triple-charm deuteronlike hexaquarks

Rui Chen,[1,2,3] Fu-Lai Wang,[1,2,*] Atsushi Hosaka,[3,†] and Xiang Liu[1,2,‡]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*Research Center for Nuclear Physics (RCNP), Osaka University, Ibaraki, Osaka 567-0047, Japan*

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Adopting the one-boson-exchange model, we perform a systematic investigation of interactions between a doubly charmed baryon (Ξ_{cc}) and an S-wave charmed baryon (Λ_c, $\Sigma_c^{(*)}$, and $\Xi_c^{(\prime,*)}$). Both the $S-D$ mixing effect and coupled-channel effect are considered in this work. Our results suggest that there may exist several possible triple-charm deuteronlike hexaquarks. Meanwhile, we further study the interactions between a doubly charmed baryon and an S-wave anticharmed baryon. We find that a doubly charmed baryon and an S-wave anticharmed baryon can be easily bound together to form shallow molecular hexaquarks. These heavy flavor hexaquarks predicted here can be accessible at future experiment like LHCb.

TABLE IV. Bound state properties (binding energy E and root-mean-square radius r_{RMS}) for the molecular hexaquarks composed of a doubly charmed baryon and an S-wave anticharmed baryon. Here, E, r_{RMS}, and Λ are in units of MeV, fm, and GeV, respectively.

$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}	$I(J^P)$	Λ	E	r_{RMS}
$\Xi_{cc}\bar{\Lambda}_c$								$\Xi_{cc}\bar{\Xi}_c$							
$1/2(0^+/1^+)$	1.00	−0.48	4.00					$0(0^+/1^+)$	0.95	−0.78	3.26	$1(0^+/1^+)$	1.10	−0.39	4.20
	1.10	−6.77	1.35						1.00	−5.09	1.50		1.30	−6.20	1.36
	1.20	−19.44	0.90						1.05	−13.06	1.04		1.50	−16.50	0.92
$\Xi_{cc}\bar{\Sigma}_c$				$\Xi_{cc}\bar{\Sigma}_c^*$				$\Xi_{cc}\bar{\Xi}_c'$				$\Xi_{cc}\bar{\Xi}_c^*$			
$1/2(0^+)$	0.80	−0.84	3.01	$1/2(1^+)$	0.80	−0.41	4.01	$0(0^+)$	0.85	−0.95	2.87	$0(1^+)$	0.85	−1.08	2.72
	0.95	−7.46	1.27		0.84	−3.86	1.60		0.95	−8.72	1.20		0.90	−7.14	1.24
	1.10	−10.97	1.18		0.88	−12.52	1.01		1.05	−19.52	0.93		0.95	−19.73	0.84
$1/2(1^+)$	0.92	−0.57	3.76	$1/2(2^+)$	0.95	−0.14	5.60	$0(1^+)$	0.95	−0.78	3.27	$0(2^+)$	1.00	−0.64	3.60
	0.96	−4.74	1.59		1.05	−4.93	1.65		1.00	−5.78	1.44		1.50	−6.90	1.31
	1.00	−13.93	1.06		1.15	−15.19	1.12		1.05	−16.19	0.98		1.80	−16.64	0.94
$3/2(0^+)$	1.35	−0.20	5.14	$3/2(1^+)$	1.00	−0.59	3.57	$1(0^+)$	1.20	−0.14	5.43	$1(1^+)$	1.20	−0.49	3.89
	1.70	−4.14	1.64		1.55	−4.40	1.60		1.50	−4.71	1.54		1.50	−4.71	1.54
	2.05	−9.94	1.16		1.85	−11.84	1.08		1.80	−11.84	1.07		1.80	−11.84	1.07
$3/2(1^+)$	1.00	−0.59	3.57	$3/2(2^+)$	1.00	−0.71	3.32	$1(1^+)$	1.10	−1.75	2.26	$1(2^+)$	1.00	−0.18	5.09
	1.10	−4.31	1.56		1.10	−4.42	1.54		1.20	−5.84	1.37		1.15	−5.16	1.43
	1.20	−11.00	1.08		1.20	−10.73	1.08		1.30	−11.81	1.04		1.30	−15.42	0.93

The prediction of hidden-charm pentaquarks with strangeness

Chinese Physics C Vol. 41, No. 10 (2017) 103105

Possible strange hidden-charm pentaquarks from $\Sigma_c^{(*)}\bar{D}_s^*$ and $\Xi_c^{(\prime,*)}\bar{D}^*$ interactions*

Rui Chen(陈锐)[1,3;1)] Jun He(何军)[2,3,4;2)] Xiang Liu(刘翔)[1,3,4;3)]

[1]School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China
[2]Department of Physics, Nanjing Normal University, Nanjing 210097, China
[3]Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China
[4]Nuclear Theory Group, Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Abstract: Using the one-boson-exchange model, we investigate the $\Lambda_c\bar{D}_s^*$, $\Sigma_c\bar{D}_s^*$, $\Sigma_c^*\bar{D}_s^*$, $\Xi_c\bar{D}^*$, $\Xi_c'\bar{D}^*$, and $\Xi_c^*\bar{D}^*$ interactions by considering the one-eta-exchange and/or one-pion-exchange contributions. We further predict the existence of hidden-charm molecular pentaquarks. Promising candidates for hidden-charm molecular pentaquarks include a $\Xi_c'\bar{D}^*$ state with $0(\frac{1}{2}^-)$ and the $\Xi_c^*\bar{D}^*$ states with $0(\frac{1}{2}^-)$ and $0(\frac{3}{2}^-)$. Experimental searches for these predicted hidden-charm molecular pentaquarks are an interesting future research topic for experiments like LHCb.

Table 6. Allowed decay channels for $\Xi_c'\bar{D}^*$ and $\Xi_c^*\bar{D}^*$ with different quantum numbers.

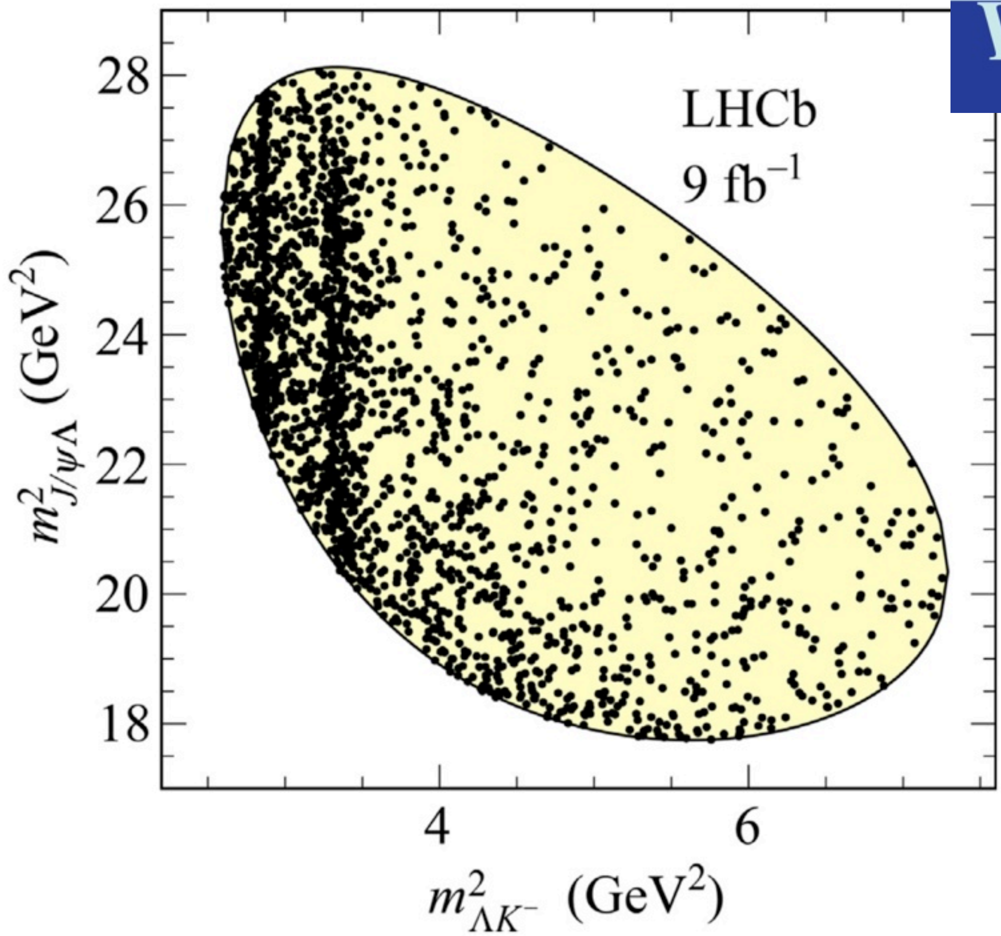
channels	$\Xi_c'\bar{D}^*$ $[I(J^P)]$		$\Xi_c^*\bar{D}^*$ $[I(J^P)]$		
	$0(\frac{1}{2}^-)$	$0(\frac{3}{2}^-)$	$0(\frac{1}{2}^-)$	$0(\frac{3}{2}^-)$	$0(\frac{5}{2}^-)$
$\Lambda_c\bar{D}_s$	✓	✓	✓	✓	✓
$\Lambda_c\bar{D}_s^*$	✓	✓	✓	✓	✓
$\Xi_c\bar{D}$	✓	✓	✓	✓	✓
$\Xi_c\bar{D}^*$	✓	✓	✓	✓	✓
$\Xi_c'\bar{D}$	✓	✓	✓	✓	✓
$\Xi_c'\bar{D}^*$			✓	✓	✓
$\Xi_c^*\bar{D}$	✓	✓	✓	✓	✓
$\eta_c\Lambda$	✓	✓	✓	✓	✓
$J/\psi\Lambda$	✓	✓	✓	✓	✓
$\Xi_{cc}(\frac{1}{2}^+)\bar{K}$	✓	✓	✓	✓	✓
$\Xi_{cc}(\frac{1}{2}^+)\bar{K}^*$	✓	✓	✓	✓	✓
$\Omega_{cc}(\frac{1}{2}^+)\eta$	✓	✓	✓	✓	✓
$\Omega_{cc}(\frac{1}{2}^+)\omega$	✓	✓	✓	✓	✓

If only considering one pion exchange contribution, the $\Xi_c\bar{D}^*$ system cannot be bound

Suggest to search for strange hidden-charm pentaquark via the $J/\psi\Lambda$ channel

Evidence of possible P_{cs} signal recently from LHCb

$\Xi_b^- \to (J/\psi\Lambda)K^-$

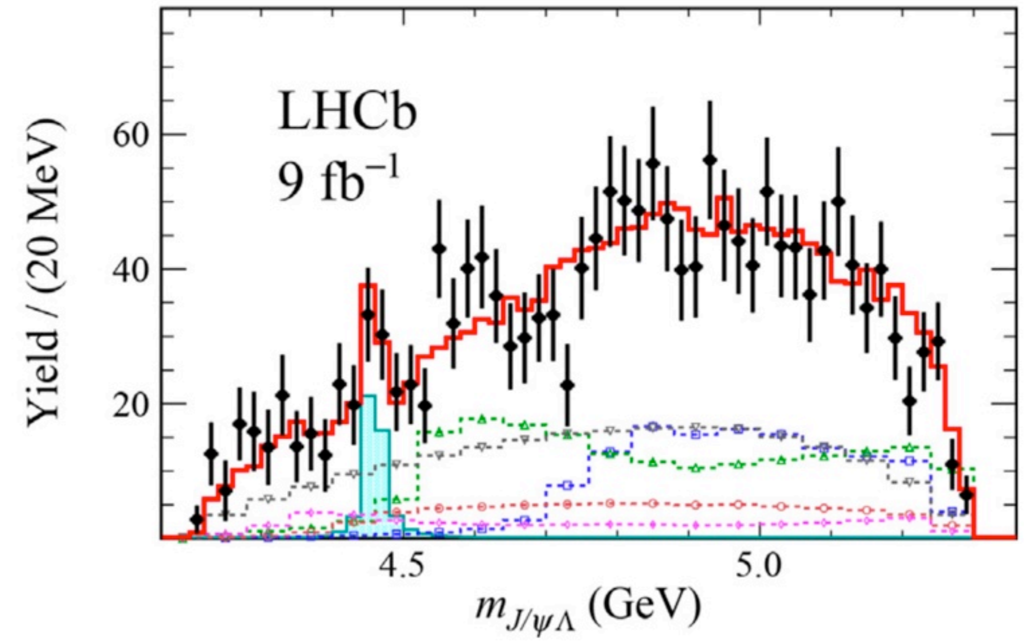


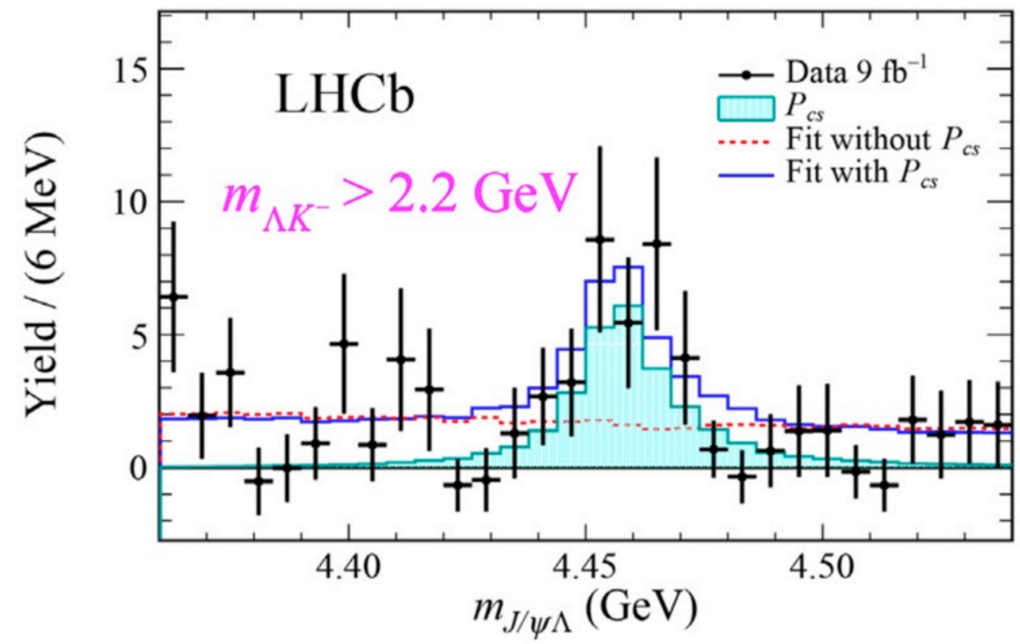
$$M = 4458 \pm 2.9^{+4.7}_{-1.1}\ \text{MeV}$$

$$\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}\ \text{MeV}$$

4.3σ significance

$P_{cs}(4459)$





LHCb: Sci.Bull. 66 (2021) 1278-1287

Another strange partner

$$B^- \to (J/\psi\Lambda)\bar{p}$$

$P_{cs}(4338)$

Amplitude contributions:

- $NR(\bar{p}\Lambda)$
- $NR(\bar{p}J/\psi)$
- $P^{\Lambda}_{\psi s}(J/\psi\Lambda)$

Fit results:

$m = 4338.2 \pm 0.7$ MeV

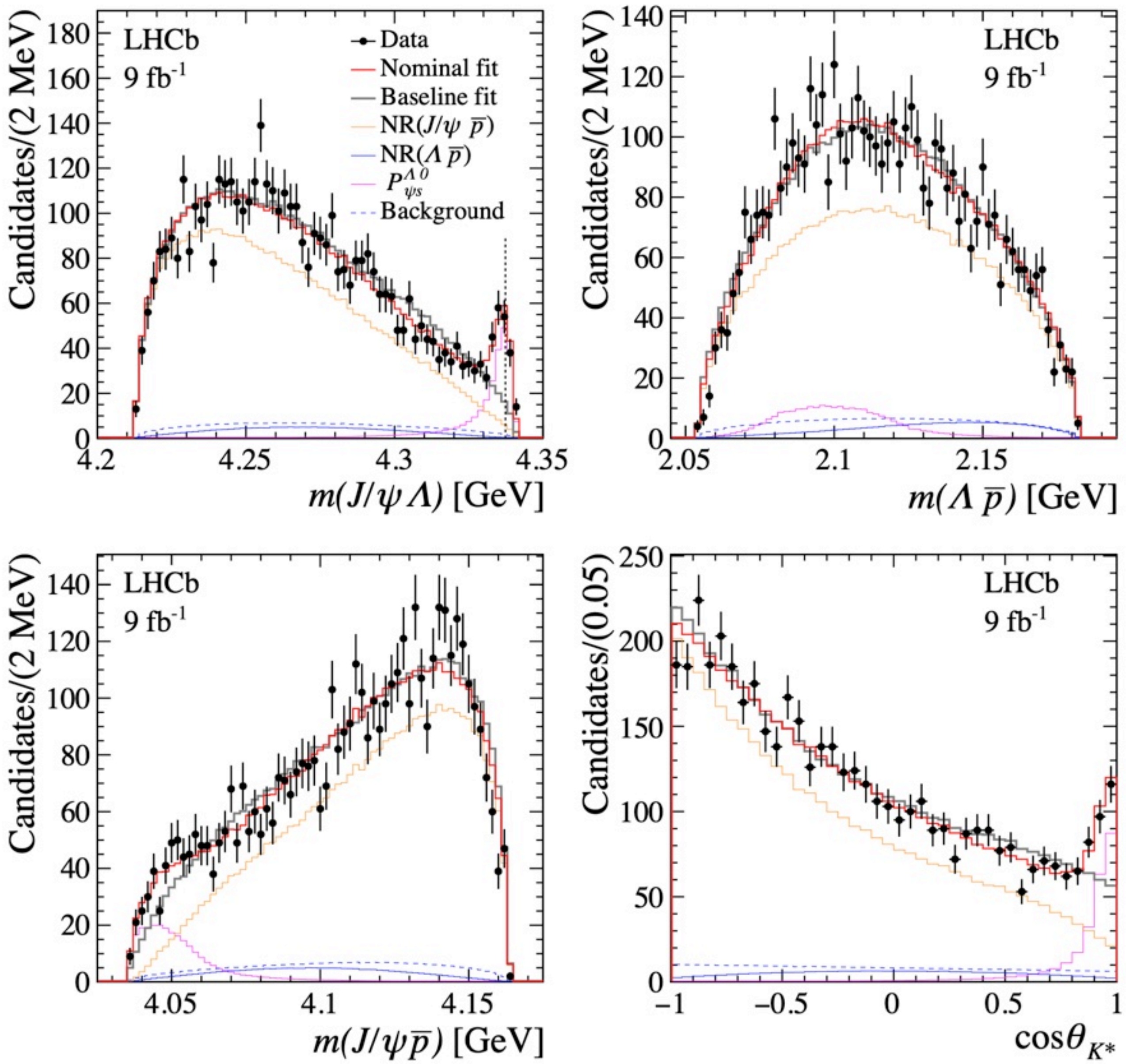
$\Gamma = 7.0 \pm 1.2$ MeV

Spin-parity:

$J^P = 1/2^-$ is preferred

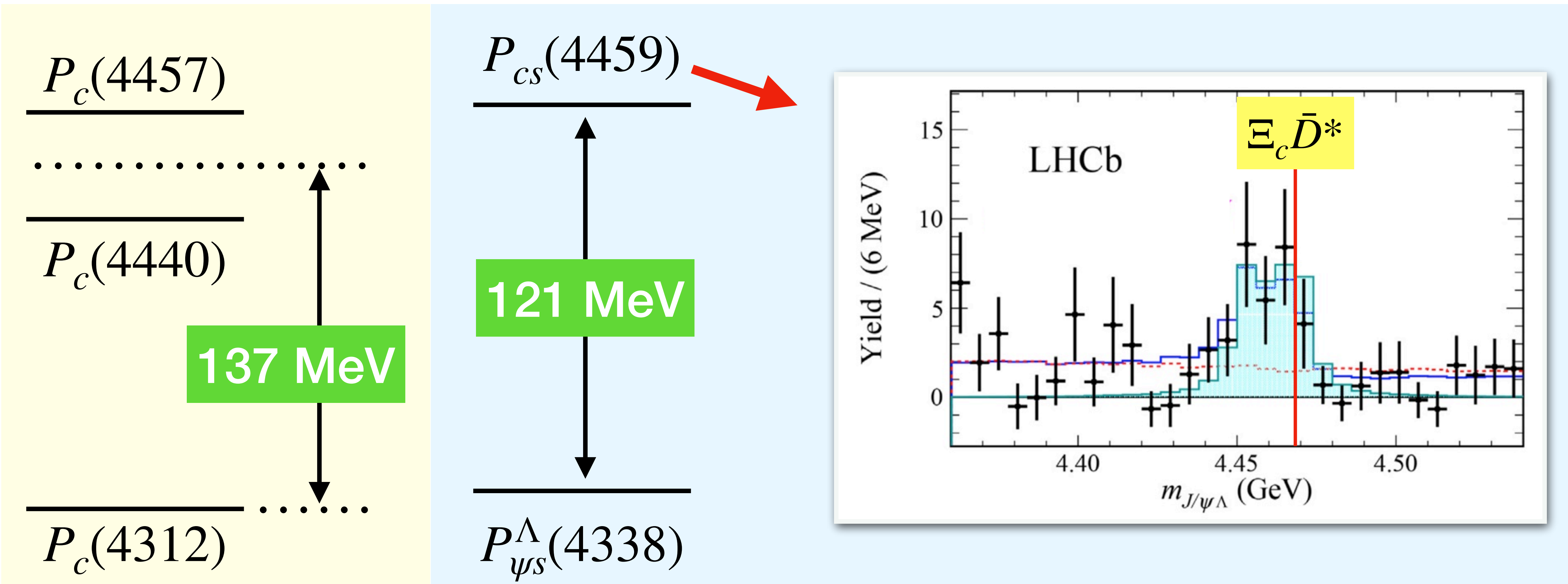
Significance:

$> 10\sigma$



LHCb: Phys.Rev.Lett. 131 (2023) 031901

Similarity between P_ψ^N and $P_{\psi s}^\Lambda$



$$\Xi_b^- \to J/\psi \Lambda K$$

F.L. Wang, Xiang Liu, Phys.Lett.B 835 (2022)137583

Bound state properties for the S-wave isoscalar $\Xi_c\bar{D}^{(*)}$ systems by considering the S-D wave mixing effect. Here, the cutoff Λ, binding energy E, and root-mean-square radius $r_{\rm RMS}$ are in units of GeV, MeV, and fm, respectively.

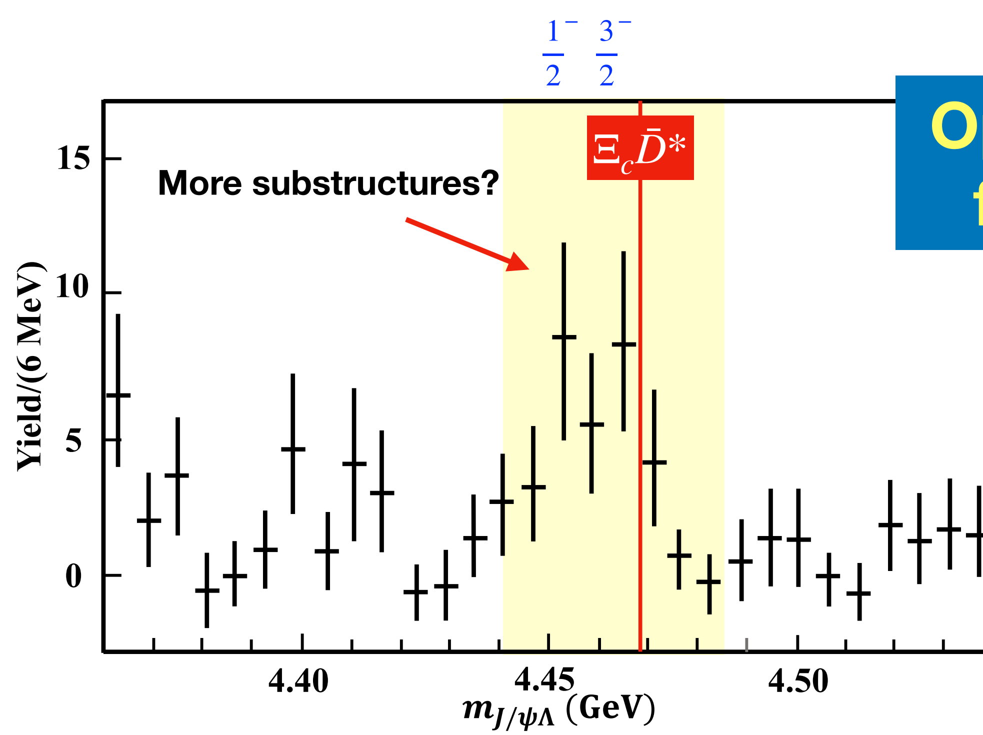
$\Xi_c\bar{D}(J^P=1/2^-)$			
Λ	E	$r_{\rm RMS}$	
1.41	−0.35	4.73	
1.61	−4.82	1.64	
1.79	−12.49	1.10	
$\Xi_c\bar{D}^*(J^P=1/2^-)$			
Λ	E	$r_{\rm RMS}$	$P(^2\mathbb{S}_{\frac{1}{2}}/^4\mathbb{D}_{\frac{1}{2}})$
1.39	−0.34	4.70	**100.00**/o(0)
1.57	−4.71	1.63	**100.00**/o(0)
1.74	−12.21	1.10	**100.00**/o(0)
$\Xi_c\bar{D}^*(J^P=3/2^-)$			
Λ	E	$r_{\rm RMS}$	$P(^4\mathbb{S}_{\frac{3}{2}}/^2\mathbb{D}_{\frac{3}{2}}/^4\mathbb{D}_{\frac{3}{2}})$
1.39	−0.34	4.70	**100.00**/o(0)/o(0)
1.57	−4.71	1.63	**100.00**/o(0)/o(0)
1.74	−12.21	1.10	**100.00**/o(0)/o(0)

Bound state properties for the S-wave isoscalar $\Xi_c\bar{D}^*$ system by performing the coupled channel analysis. Here, the cutoff Λ, binding energy E, and root-mean-square radius $r_{\rm RMS}$ are in units of GeV, MeV, and fm, respectively. Additionally, Λ and Λ' denote the cutoff parameters of the $\Xi_c\bar{D}^*$ and $\Xi_c'\bar{D}^*$ channels, respectively.

Λ	Λ'	E	$r_{\rm RMS}$	$P(\Xi_c\bar{D}^*/\Xi_c'\bar{D}^*)$
$\Xi_c\bar{D}^*(J^P=1/2^-)$				
1.12	0.92	−0.30	4.74	**97.75**/2.25
1.16	0.96	−4.33	1.58	**89.46**/10.54
1.20	1.00	−14.67	0.89	**77.76**/22.24
$\Xi_c\bar{D}^*(J^P=3/2^-)$				
1.31	1.11	−0.29	4.87	**99.73**/0.27
1.43	1.23	−4.52	1.64	**98.54**/1.46
1.56	1.36	−15.01	0.98	**96.48**/3.52

There exists mass degeneration for the S-wave isoscalar $\Xi_c\bar{D}^*$ states with $J^P=1/2^-$ and $J^P=1/2^-$ when adopting same cutoff value.
Coupled-channel may result in the violation of mass degeneration.

Double-peak structure can be tested with more precise data



Opportunity for LHCb

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Similar behavior may happen for the $\Xi_c'\bar{D}^{(*)}$ systems

$\Xi_c'\bar{D}$: $J^P = 1/2^-$

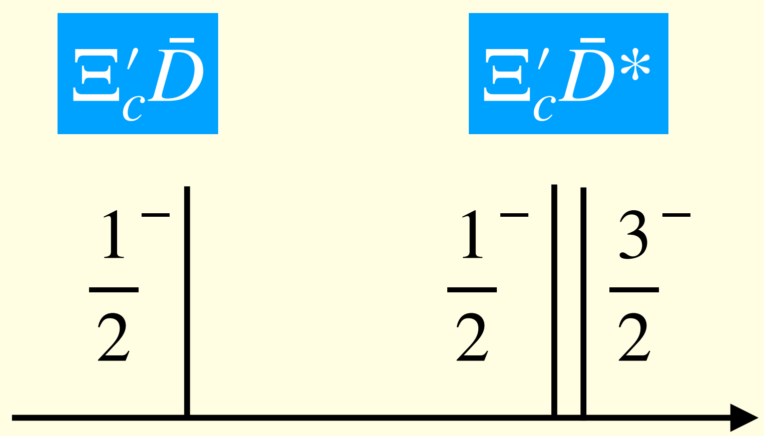
Λ	E	r_{RMS}
1.45	-0.29	4.92
1.65	-4.62	1.65
1.84	-12.14	1.10

$\Xi_c'\bar{D}^*$: $J^P = 1/2^-$

Λ	E	r_{RMS}	$P\left({}^2S_{\frac{1}{2}}/{}^4D_{\frac{1}{2}}\right)$
0.92	-0.50	4.02	99.63/0.37
0.97	-4.18	1.64	99.45/0.55
1.02	-11.90	1.06	99.45/0.55

$\Xi_c'\bar{D}^*$: $J^P = 3/2^-$

Λ	E	r_{RMS}	$P\left({}^4S_{\frac{3}{2}}/{}^2D_{\frac{3}{2}}/{}^4D_{\frac{3}{2}}\right)$
1.63	-0.33	4.87	98.49/0.17/1.18
2.09	-4.79	1.75	96.63/0.32/3.05
2.55	-12.42	1.21	95.65/0.35/4.00



Characteristic spectrum

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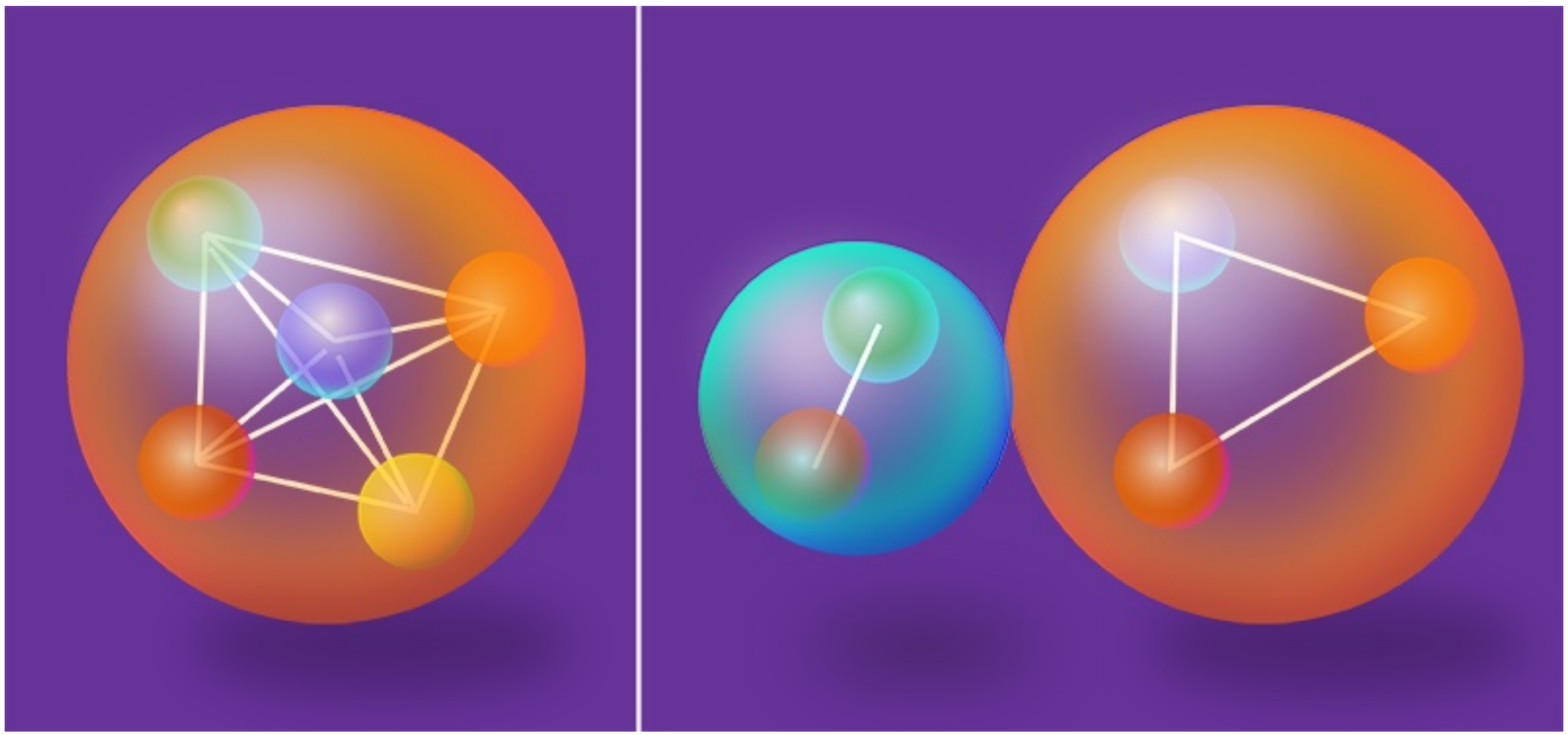
5

Electromagnetic properties

How to distinguish different configurations of hadrons with the same J^P?



Magnetic moments of the baryon octet

Particle	Experiment [52]
p	2.79 ± 10^{-7}
n	-1.91 ± 10^{-7}
Σ^+	2.42 ± 0.05
Σ^-	-1.157 ± 0.025
Λ	-0.613 ± 0.004
Ξ^0	-1.250 ± 0.014
Ξ^-	-0.679 ± 0.031
$\Sigma^0\Lambda$	1.61 ± 0.08

Magnetic momentum can reflect their inner structures

But it is difficult to directly measure this physical quantity

PHYSICAL REVIEW D **107,** 114017 (2023)

B_c-like tetraquarks

Radiative decays and magnetic moments of the predicted B_c-like molecules

Fu-Lai Wang,* Si-Qiang Luo,† and Xiang Liu‡

School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China;
Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, Lanzhou University, Lanzhou 730000, China;
Key Laboratory of Quantum Theory and Applications of MoE, Lanzhou University, Lanzhou 730000, China;
Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China and Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China

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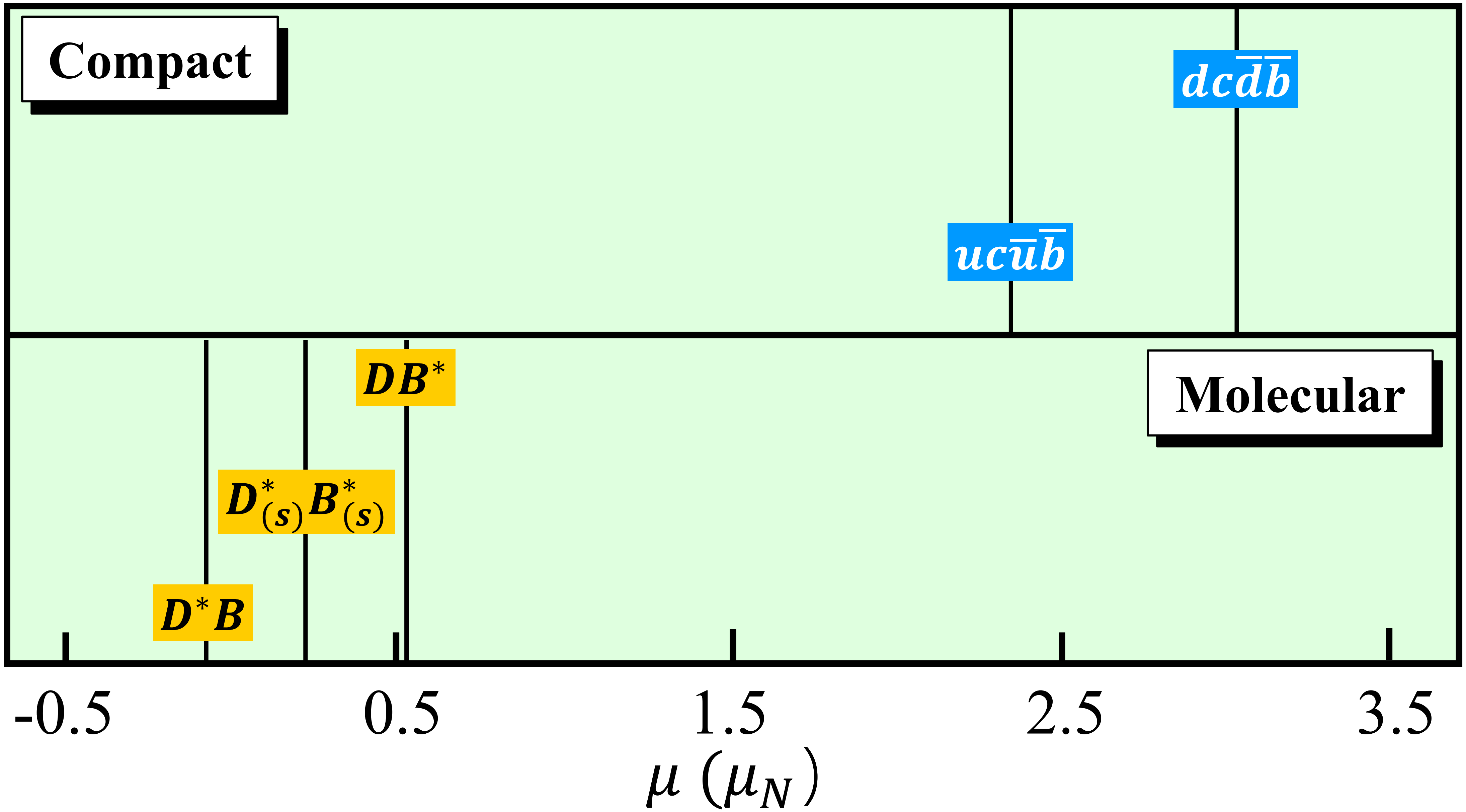
In this work, we first perform a systematic study of the transition magnetic moments and the corresponding radiative decay behaviors of the B_c-like molecular states associated with their mass spectra, where the constituent quark model is adopted by considering the S-D wave mixing effect. Our numerical results show that the radiative decay properties can be considered as the effective physical observable to reflect the inner structures of these B_c-like molecular states. Meanwhile, we also discuss the magnetic moments of the B_c-like molecular states, and we find that the magnetic moment properties can be used to distinguish the B_c-like molecular states from the conventional B_c mesonic states, which have the same quantum numbers and similar masses. We expect that the present study can inspire the interest of the experimentalist in exploring the electromagnetic properties of the B_c-like molecular states, especially the radiative decay properties.

PHYSICAL REVIEW D **107**, 114017 (2023)

B_c-like tetraquarks

Radiative decays and magnetic moments of the predicted B_c-like molecules

Fu-Lai Wang,[*] Si-Qiang Luo,[†] and Xiang Liu[‡]



The radiative decay width can be linked to the transition magnetic moment

$$\Gamma_{H\to H'\gamma} = \frac{k^3}{m_p^2}\frac{\alpha_{\rm EM}}{2J_H+1}\frac{\sum_{J_{H'z},J_{Hz}}\begin{pmatrix} J_{H'} & 1 & J_H \\ -J_{H'z} & 0 & J_{Hz}\end{pmatrix}^2}{\begin{pmatrix} J_{H'} & 1 & J_H \\ -J_z & 0 & J_z\end{pmatrix}^2}\frac{|\mu_{H\to H'}|^2}{\mu_N^2}. \quad (3.4)$$

Here, $m_p = 0.938$ GeV [106], $\alpha_{\rm EM} \approx 1/137$, $\mu_N = e/2m_p$, and the constants $\begin{pmatrix} J_{H'} & 1 & J_H \\ -J_{H'z} & 0 & J_{Hz}\end{pmatrix}$ and $\begin{pmatrix} J_{H'} & 1 & J_H \\ -J_z & 0 & J_z\end{pmatrix}$ are the 3-j coefficients.

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$$\mu_{H\to H'} = \langle J_{H'}, J_z|\sum_j \hat{\mu}_{zj}^{\rm spin} e^{-i\mathbf{k}\cdot\mathbf{r}_j} + \hat{\mu}_z^{\rm orbital}|J_H, J_z\rangle. \quad (3.1)$$

Here, $\mu_{H\to H'}$ is the transition magnetic moment between the hadrons H and H', J_z is the lowest value between J_H and $J_{H'}$, the spatial wave function of the emitted photon for the $H \to H'\gamma$ process is denoted by $e^{-i\mathbf{k}\cdot\mathbf{r}_j}$, and $\mathbf{k}$ refers to the momentum of the emitted photon, which is $k = (m_H^2 - m_{H'}^2)/2m_H$. Within the constituent quark model, the magnetic moment operator is composed of the spin magnetic moment operator and the orbital magnetic moment operator, which can be written explicitly as [50–95]

$$\hat{\mu}_{zj}^{\rm spin} = \frac{e_j}{2m_j}\hat{\sigma}_{zj}, \quad (3.2)$$

$$\hat{\mu}_z^{\rm orbital} = \left(\frac{m_m}{m_b+m_m}\frac{e_b}{2m_b} + \frac{m_b}{m_b+m_m}\frac{e_m}{2m_m}\right)\hat{L}_z. \quad (3.3)$$

Magnetic moments of the hadrons within the constituent quark model

$$\mu_H = \langle J_H, J_H|\sum_j \hat{\mu}_{zj}^{\rm spin} + \hat{\mu}_z^{\rm orbital}|J_H, J_H\rangle.$$

$\Omega_c^* D_s^{(*)}$

New type of doubly charmed molecular pentaquarks containing most strange quarks

TABLE VI. The obtained transition magnetic moments and radiative decay widths between the $\Omega_c D_s^*$ molecule with $J^P = 1/2^-$, the $\Omega_c^* D_s^*$ molecule with $J^P = 1/2^-$, and the $\Omega_c^* D_s^*$ molecule with $J^P = 3/2^-$. The units of the transition magnetic moments and the radiative decay widths between the hadrons are μ_N and keV, respectively. Here, Case I, Case II, and Case III correspond to the results obtained based on the single channel analysis, the S-D wave mixing analysis, and the coupled channel analysis, respectively.

Electromagnetic properties	Decay processes	Case I	Case II	Case III
$\mu_{H\to H'}$	$\Omega_c^* D_s^* \vert 1/2^-\rangle \to \Omega_c D_s^* \vert 1/2^-\rangle \gamma$	0.629, 0.664, 0.665	0.629, 0.663, 0.665	0.538, 0.369, 0.265
	$\Omega_c^* D_s^* \vert 3/2^-\rangle \to \Omega_c D_s^* \vert 1/2^-\rangle \gamma$	−0.702, −0.742, −0.744	−0.702, −0.741, −0.743	−0.804, −1.053, −1.152
	$\Omega_c^* D_s^* \vert 3/2^-\rangle \to \Omega_c^* D_s^* \vert 1/2^-\rangle \gamma$	−1.301, −1.301, −1.301	−1.301, −1.300, −1.300	…
$\Gamma_{H\to H'\gamma}$	$\Omega_c^* D_s^* \vert 1/2^-\rangle \to \Omega_c D_s^* \vert 1/2^-\rangle \gamma$	1.135, 1.263, 1.270	1.134, 1.260, 1.267	0.831, 0.390, 0.201
	$\Omega_c^* D_s^* \vert 3/2^-\rangle \to \Omega_c D_s^* \vert 1/2^-\rangle \gamma$	0.708, 0.789, 0.793	0.706, 0.787, 0.791	0.926, 1.590, 1.902

TABLE VII. The obtained magnetic moments of the $\Omega_c D_s^*$ molecule with $J^P = 1/2^-$, the $\Omega_c^* D_s^*$ molecule with $J^P = 1/2^-$, and the $\Omega_c^* D_s^*$ molecule with $J^P = 3/2^-$. The units of the magnetic moments of the hadrons are μ_N. Here, Case I, Case II, and Case III correspond to the results obtained based on the single channel analysis, the S-D wave mixing analysis, and the coupled channel analysis, respectively.

Molecules	Case I	Case II	Case III
$\Omega_c D_s^* \vert 1/2^-\rangle$	1.062	1.061, 1.061, 1.061	1.124, 1.186, 1.169
$\Omega_c^* D_s^* \vert 1/2^-\rangle$	−0.921	−0.921, −0.920, −0.920	…
$\Omega_c^* D_s^* \vert 3/2^-\rangle$	−0.319	−0.319, −0.319, −0.319	…

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Studying electromagnetic properties of different heavy flavor pentaquark systems

$\Xi_c^{(\prime,*)}\bar{D}_s^* / \Omega_c^{(*)}\bar{D}_s^{(*)}$

PRD108 (2023) 034006

$\Xi_c^{(\prime,*)}\bar{D}_1 / \Xi_c^{(\prime,*)}\bar{D}_2^*$

PRD108 (2023) 054028

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

PRD106 (2022) 034034

$\Omega_c^* D_s^{(*)}$

PRD108 (2023) 074022

$\Xi_c^{(\prime)}\bar{D}^{(*)}$

PRD106 (2022) 054020

$\Xi_c^{(\prime,*)}D^{(*)}$

PRD109 (2024) 014043

Suggest our experimental colleague to pay more attention to the radiative decays of heavy flavor pentaquark

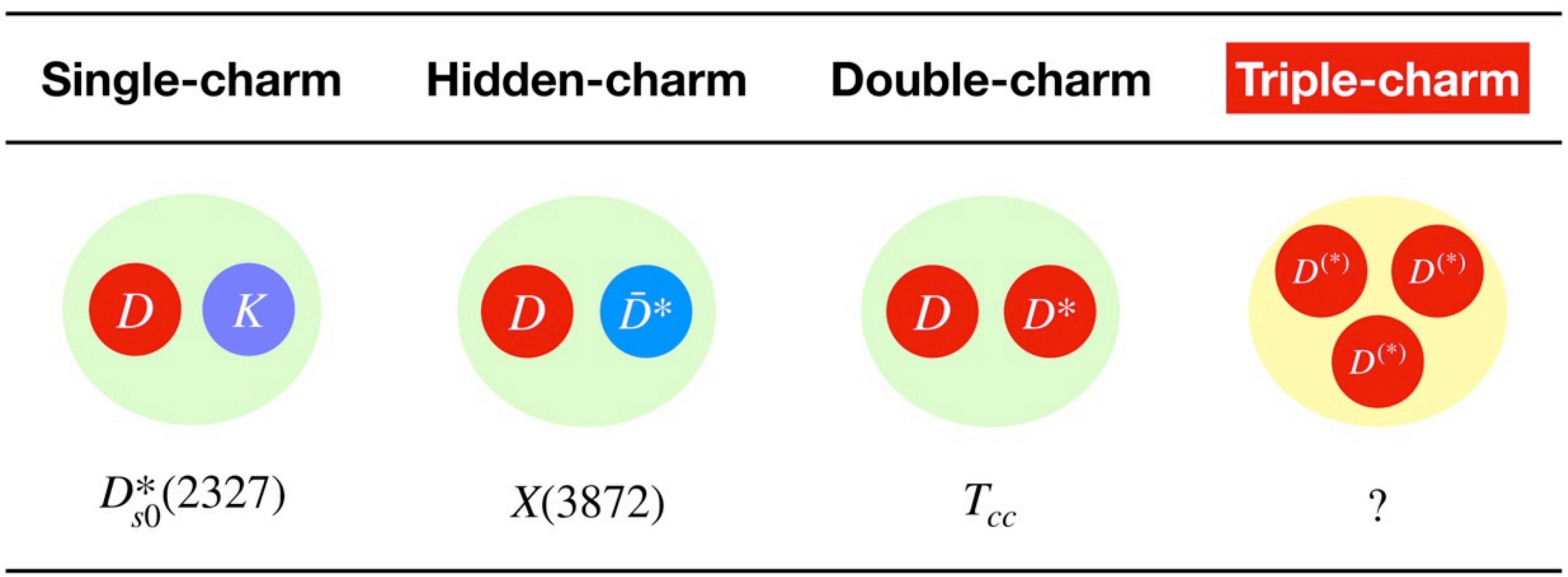
6

Three-body and four-body systems

Triple-charm molecular states composed of D^*D^*D and $D^*D^*D^*$

Si-Qiang Luo,[1,2] Tian-Wei Wu,[3] Ming-Zhu Liu,[4,5] Li-Sheng Geng,[5,6,7,8,*] and Xiang Liu[1,8,9,10,†]

Inspired by the newly observed T_{cc}^+ state, we systematically investigate the S-wave triple-charm molecular states composed of D^*D^*D and $D^*D^*D^*$. We employ the one-boson-exchange model to derive the interactions between $D(D^*)$ and D^* and solve the three-body Schrödinger equations with the Gaussian expansion method. The S-D mixing and coupled channel effects are carefully assessed in our study. Our results show that the $I(J^P)=\frac{1}{2}(0^-,1^-,2^-)D^*D^*D$ and $I(J^P)=\frac{1}{2}(0^-,1^-,2^-,3^-)D^*D^*D^*$ systems could form bound states, which can be viewed as three-body hadronic molecules. We present not only the binding energies of the three-body bound states, but also the root-mean-square radii of D-D^* and D^*-D^*, which further corroborate the molecular nature of these states. These predictions could be tested in the future at LHC or HL-LHC.



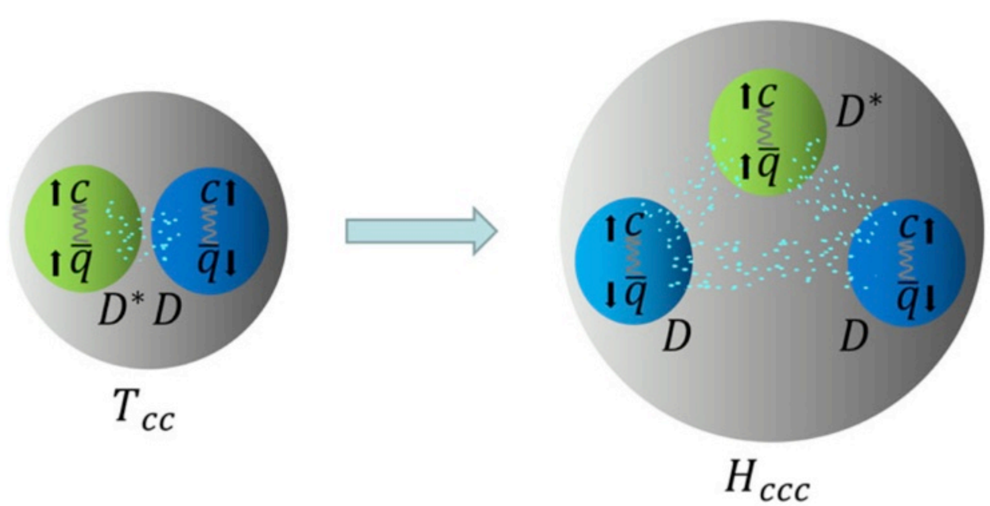
PHYSICAL REVIEW D **105**, L031505 (2022)

Letter

Discovery of the doubly charmed T_{cc}^{+} state implies a triply charmed H_{ccc} hexaquark state

Tian-Wei Wu,[1,2] Ya-Wen Pan,[1] Ming-Zhu Liu,[3,1] Si-Qiang Luo,[4]
Li-Sheng Geng,[1,5,6,7,*] and Xiang Liu[4,8,7,†]

The doubly charmed exotic state T_{cc} recently discovered by the LHCb Collaboration could well be a DD^* molecular state long predicted in various theoretical models, in particular, the DD^* isoscalar axial vector molecular state predicted in the one-boson-exchange model. In this work, we study the DDD^* system in the Gaussian expansion method with the DD^* interaction derived from the one-boson-exchange model and constrained by the precise binding energy of 273 ± 63 keV of T_{cc} with respect to the $D^{*+}D^0$ threshold. We show the existence of a DDD^* state with a binding energy of a few hundred keV, isospin $1/2$, and spin-parity 1^-. Its main decay modes are $DDD\pi$ and $DDD\gamma$. The existence of such a state could in principle be confirmed with the upcoming LHC data and will unambiguously determine the nature of the T_{cc}^{+} state and of the many exotic states of similar kind, thus deepening our understanding of the nonperturbative strong interaction.



PHYSICAL REVIEW D **106,** 014017 (2022)

Double-charm heptaquark states composed of two charmed mesons and one nucleon

Si-Qiang Luo,[1,2,3,*] Li-Sheng Geng,[4,5,6,7,†] and Xiang Liu[1,7,3,8,‡]

Inspired by the experimental discoveries of T_{cc}, $\Sigma_c(2800)$, and $\Lambda_c(2940)$ and the theoretical picture where they are DD^*, DN, and D^*N molecular candidates, we investigate the double-charm heptaquark system of DD^*N. We employ the one-boson-exchange model to deduce the pairwise D-D^*, D-N, and D^*-N potentials and then study the DD^*N system with the Gaussian expansion method. We find two good hadronic molecular candidates with $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ and $\frac{1}{2}(\frac{3}{2}^+)$ DD^*N with only S-wave pairwise interactions. The conclusion remains unchanged even taking into account the S-D mixing and coupled channel effects. In addition to providing the binding energies, we also calculate the root-mean-square radii of the DD^*N system, which further support the molecular nature of the predicted states. They can be searched for at the upcoming LHC run 3 and run 4.

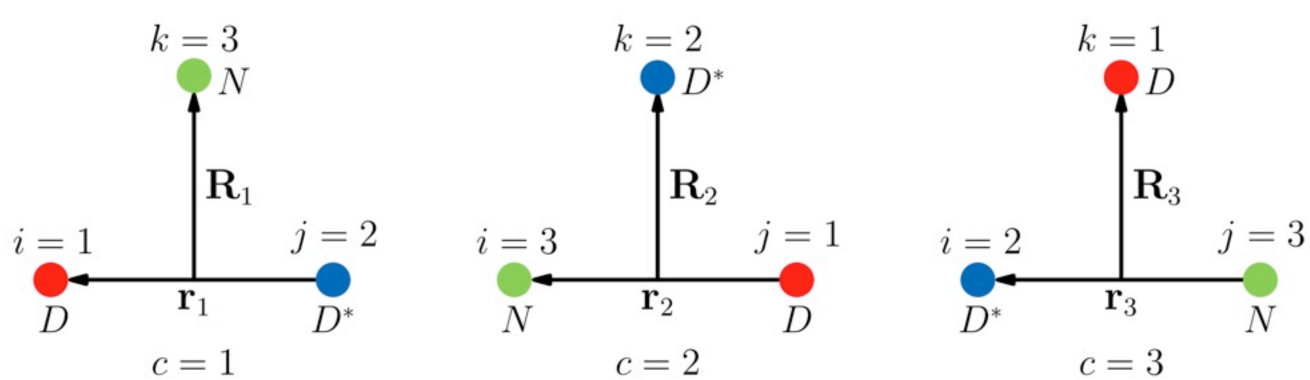
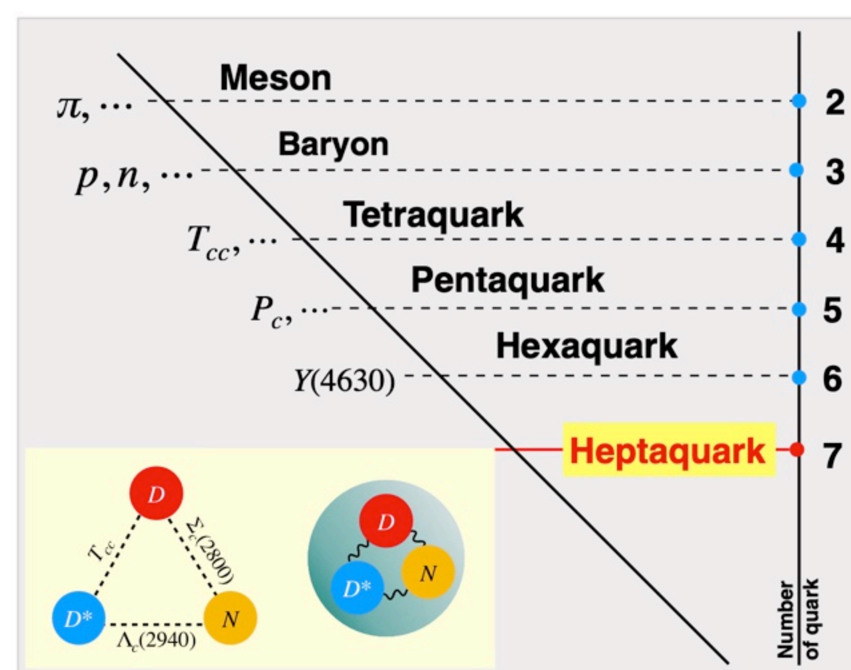


FIG. 2. Jacobi coordinates of the DD^*N system.



PHYSICAL REVIEW D **107,** 054022 (2023)

New type of hydrogenlike charm-pion or charm-kaon matter

Si-Qiang Luo,[1,2,3,4,5,*] Zhan-Wei Liu,[1,3,4,5,†] and Xiang Liu[1,3,4,5,‡]

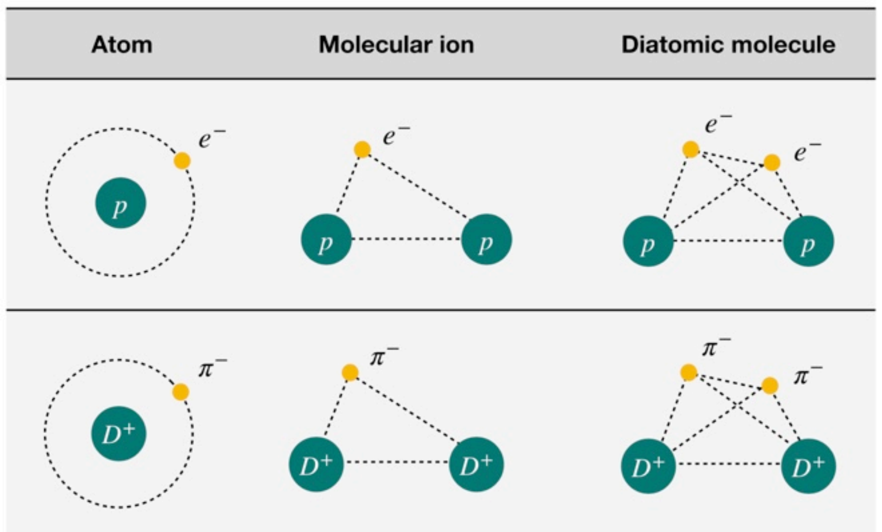
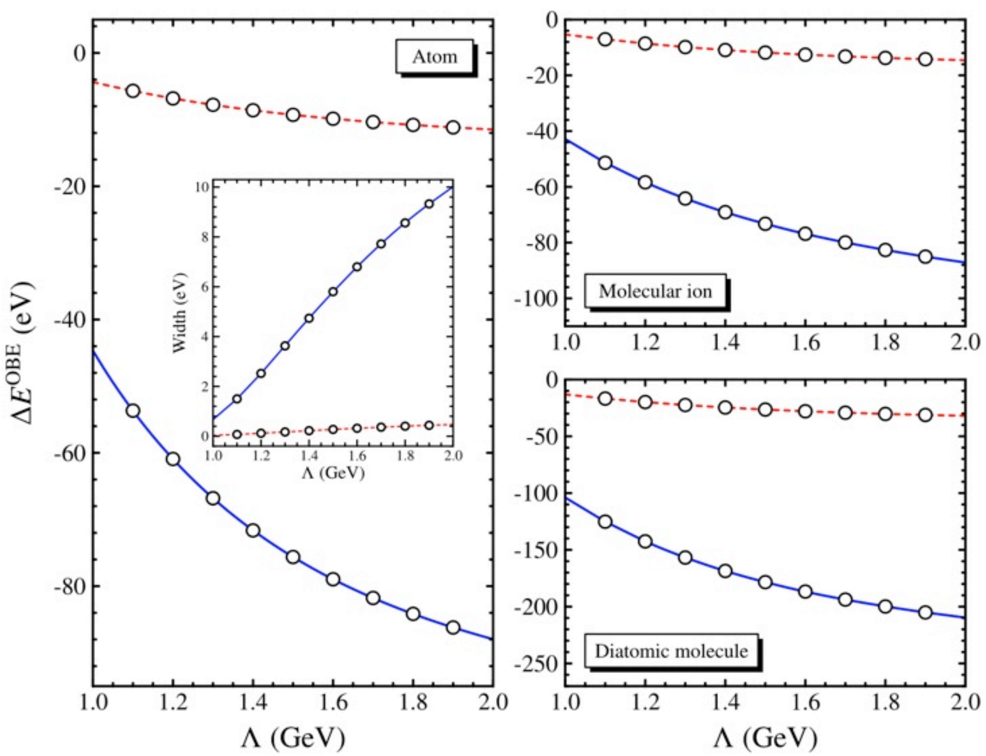
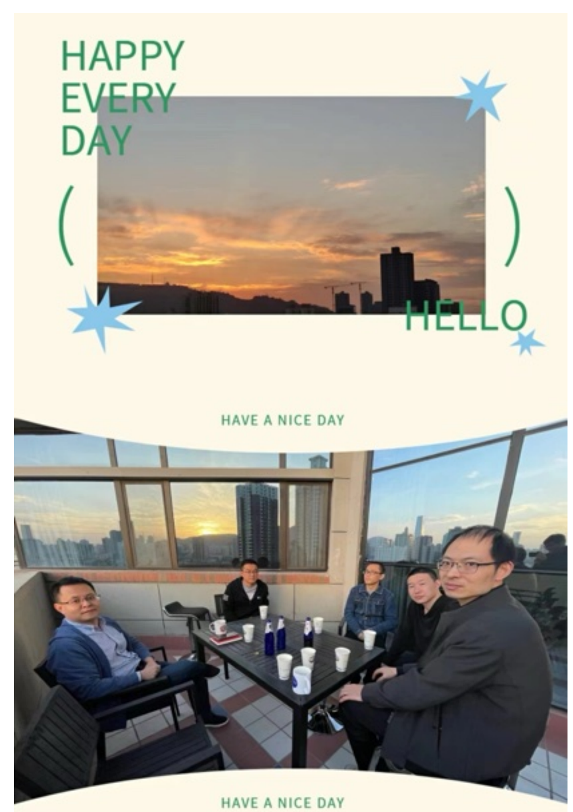
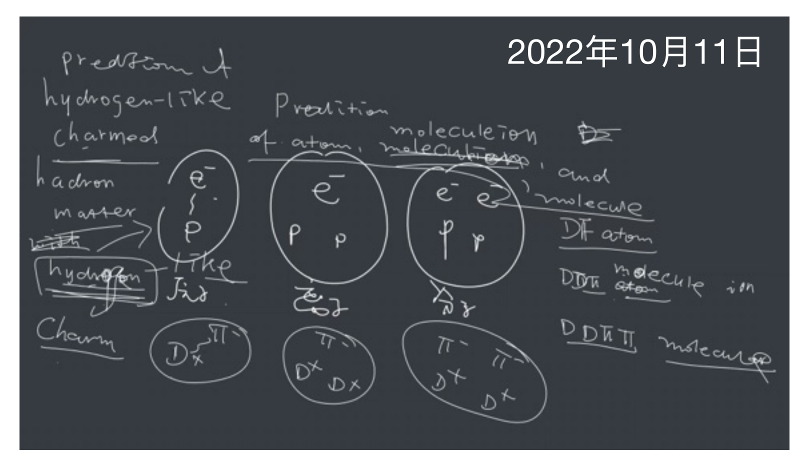


TABLE I. The binding energy E, root-mean-square radius R of the atom, molecular ion, and diatomic molecule type systems. For the charm-pion and charm-kaon atoms, the decay widths are also given.

		Hydrogen		Charm-pion		Charm-kaon	
		Experimental	Theoretical		Theoretical		Theoretical
Atom	E (eV)	−13.6	−13.6	$E^{\rm QED}$ (keV)	−3.458	$E^{\rm QED}$ (keV)	−10.421
	R (nm)		0.09	R (fm)	360.6	R (fm)	119.6
				$\Delta E^{\rm OBE}$ (eV)	−4.4 ∼ −11.5	$\Delta E^{\rm OBE}$ (eV)	−44.7 ∼ −88.0
				Γ (eV)	0.03 ∼ 0.47	Γ (eV)	0.7 ∼ 10.0
Molecular ion	B (eV)	−16.25	−16.20	$E^{\rm QED}$ (keV)	−3.848	$E^{\rm QED}$ (keV)	−11.182
	R^{pp} (nm)		0.11	$R^{D^+D^+}$ (fm)	613.0	$R^{D^+D^+}$ (fm)	259.2
	R^{pe^-} (nm)		0.10	$R^{D^+\pi^-}$ (fm)	496.0	$R^{D^+K^-}$ (fm)	197.2
				$\Delta E^{\rm OBE}$ (eV)	−5.3 ∼ −14.6	$\Delta E^{\rm OBE}$ (eV)	−42.8 ∼ −87.2
Diatomic molecule	E (eV)	−31.65	−31.60	$E^{\rm QED}$ (keV)	−7.517	$E^{\rm QED}$ (keV)	−21.889
	R^{pp} (nm)		0.127	$R^{D^+D^+}$ (fm)	574.3	$R^{D^+D^+}$ (fm)	187.3
	$R^{e^-e^-}$ (nm)		0.076	$R^{\pi^-\pi^-}$ (fm)	435.4	$R^{K^-K^-}$ (fm)	214.3
	R^{pe^-} (nm)		0.094	$R^{D^+\pi^-}$ (fm)	433.8	$R^{D^+K^-}$ (fm)	164.7
				$\Delta E^{\rm OBE}$ (eV)	−13.1 ∼ −32.0	$\Delta E^{\rm OBE}$ (eV)	−103.9 ∼ −209.7



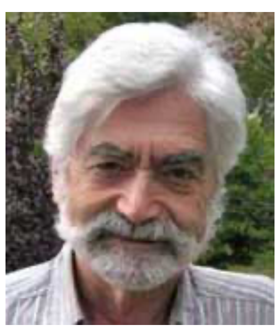




Summary

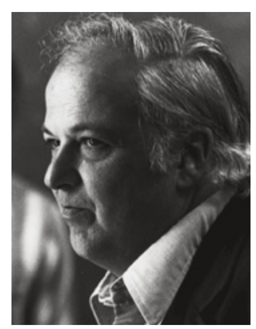
Roadmap of conventional hadrons

Quark model



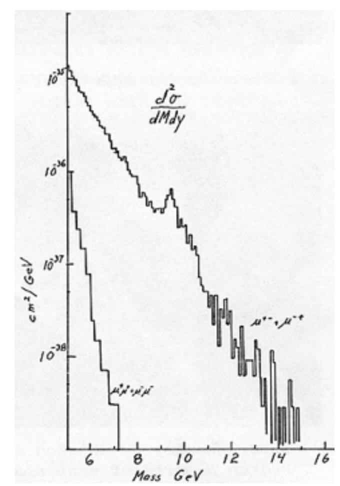
1964

J/Psi meson



1974

Upsilon meson

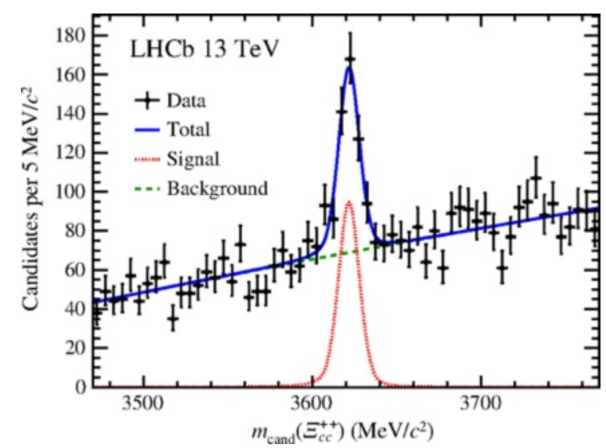


1977

Fermilab

PRL39 (1977) 252

Double-charm baryon



2017

LHCb

PRL119 (2017) 112001

Year

Identify exotic states
Experimental analysis
Lattice QCD
Phenomenological models

深度书评 | 只有坚持从事科学研究的半生才是值得记录和怀念的

原创 么辰 赛先生 2023-01-04 17:58 发表于北京

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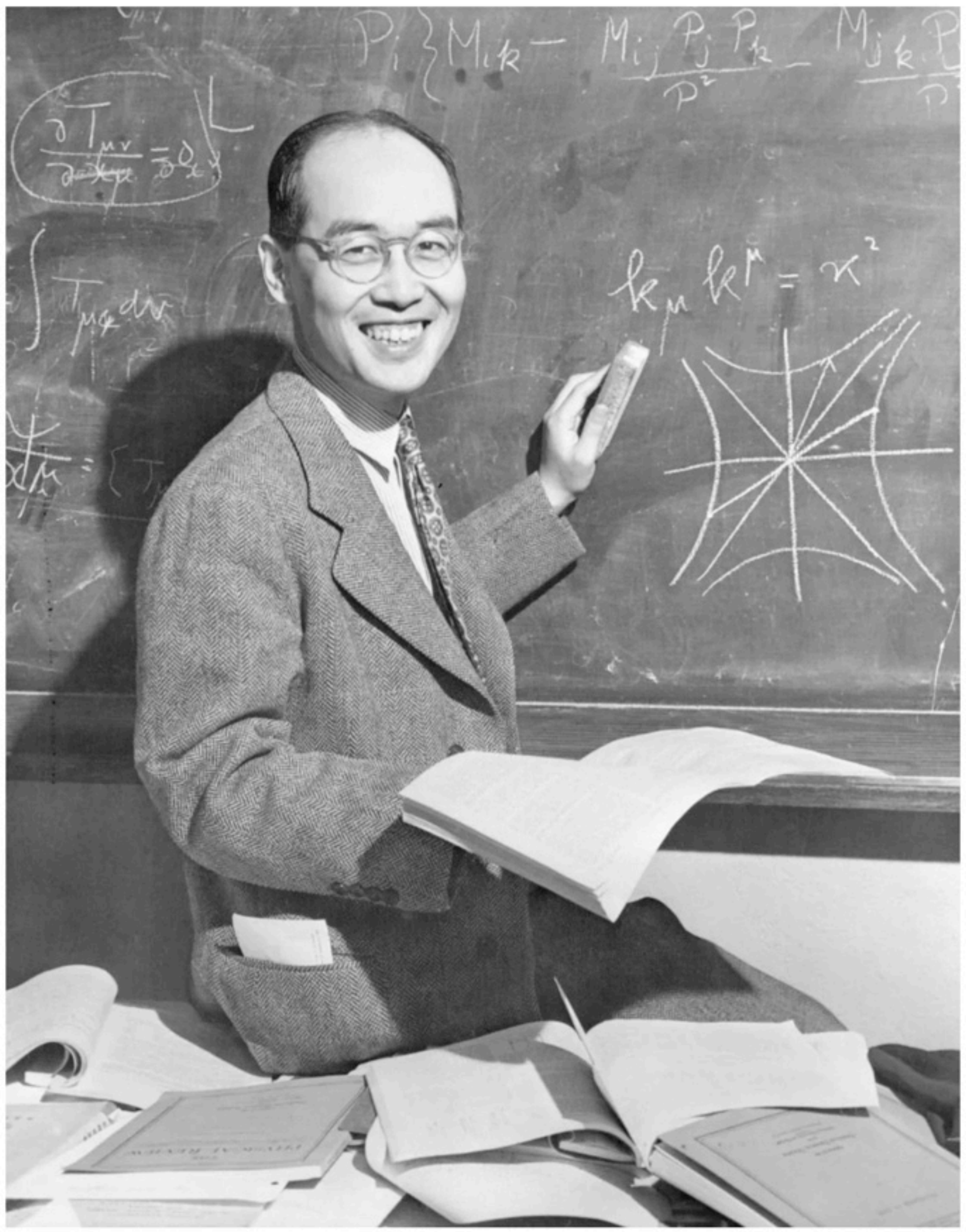

汤川秀树（1907.1.23-1981.9.8），物理学家，1935年提出了关于核子力的“介子理论”，并于1949年获得诺贝尔物理学奖，成为日本首位诺奖得主。

“我觉得自己像是一个在山坡顶上的一家小茶馆里歇脚的旅人。这时我并不去考虑前面是否还有更多的山山水水。”

——全书结束于汤川秀树27岁提出介子论的时间点，如前文所述，《旅人》写于作者50岁时，这本书写了当时一半的生命时光，对于后一半的人生旅程，汤川只字未提。他认为：“我不想再从这里往后写下去，因为我坚持不懈地从事研究的那些日子是值得我怀念的，而另一方面，当我想到自己如何日益被研究以外的事情所困扰时不免感到悲哀。”

他认为，作科学研究，或者说探索未知世界就像是一场不带地图，不知道目的地的旅行，有时需要旅人背负重物拼命爬坡，可能会有一些先前的探索者们留下的足迹，但并不意味着追随这些足迹就一定能到达目的地，有时旅人不得不重新开辟一条新路，一边开辟新路，一边绘制地图，一边寻找目的地，很多人甚至在开始动身时就走错了方向。而显然，这条探索之路尽管充满艰辛，却是最值得汤川怀念和记录的，于是就有了这本《旅人》。

而当作者功成名就之后，却也同时失去了享受孤独的自由：“很久以前，我就不是一个‘无名的权兵卫’（即‘无名小卒’，作者注）了，现在没有人让我独处了。想到自己还有某种价值，我并非不感到喜悦，但是我也不能否认这对我是一种沉重的负担。”所以，对于之后的那一半人生，汤川秀树认为并没有记录的必要，毕竟，在科学世界中的艰难探索，即使备尝艰辛，即使默默无闻，即使可能徒劳无功，即使只是一大段独自跋涉的旅程，却是最精彩、最幸福、最值得怀念的。

在科学世界中的艰难探索，即使备尝艰辛，即使默默无闻，即使可能徒劳无功，即使是一大段独自跋涉的旅程，却是最精彩、最幸福、最值得怀念的。

Thank you for your attention!