Theoretical overview on Tetra-quark models

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The concept of exotic hadronic states was proposed at the birth of Quark model

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

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

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

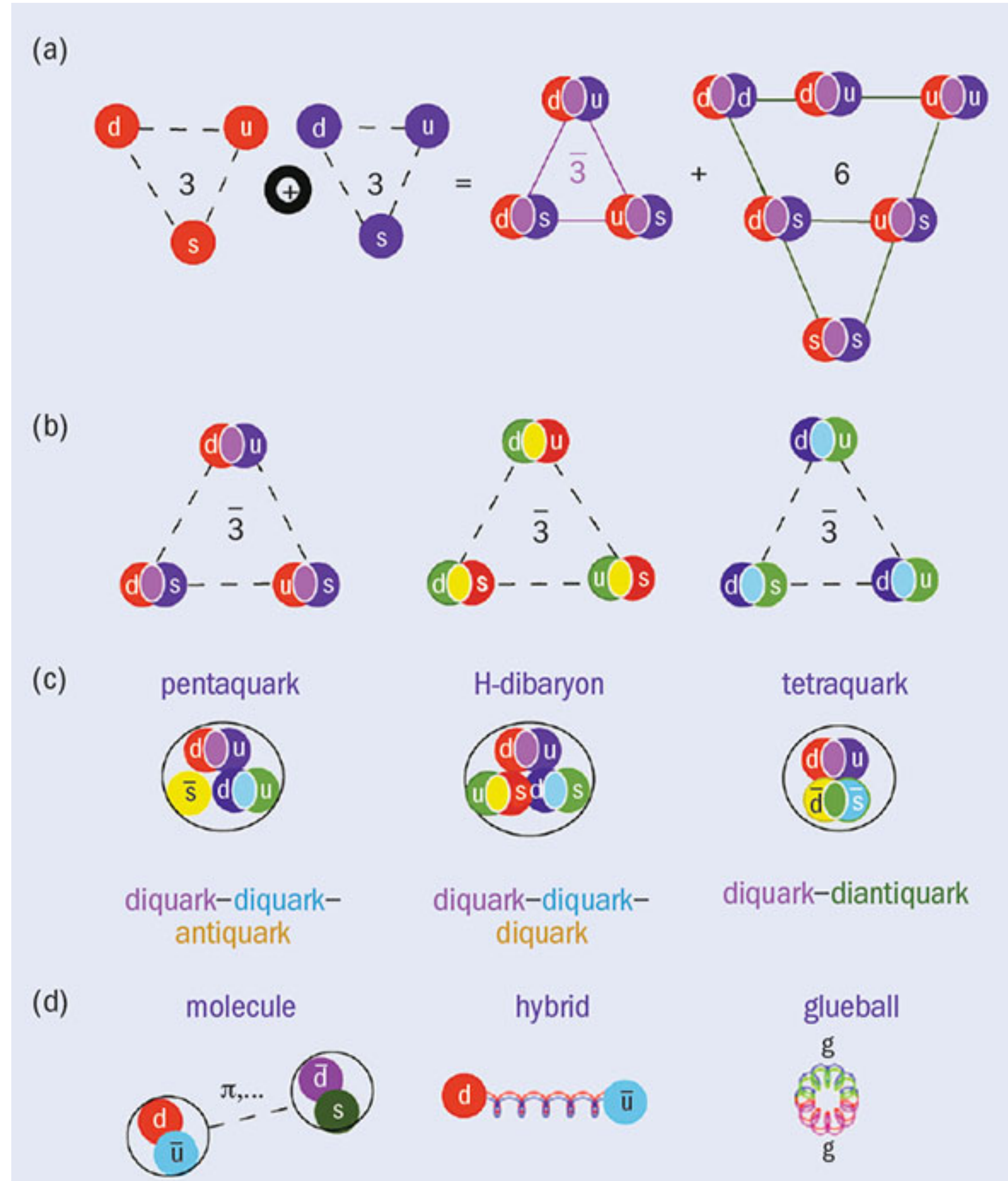
II *)

G. Zweig
CERN---Geneva

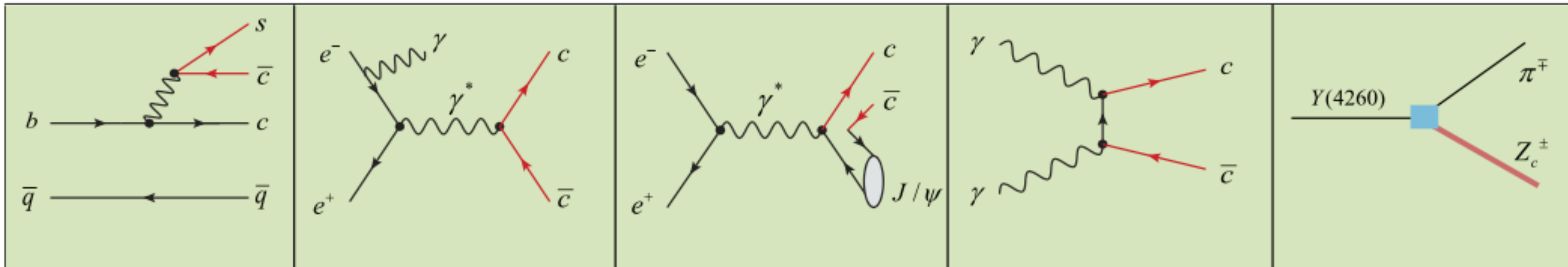
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".



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

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ELSEVIER

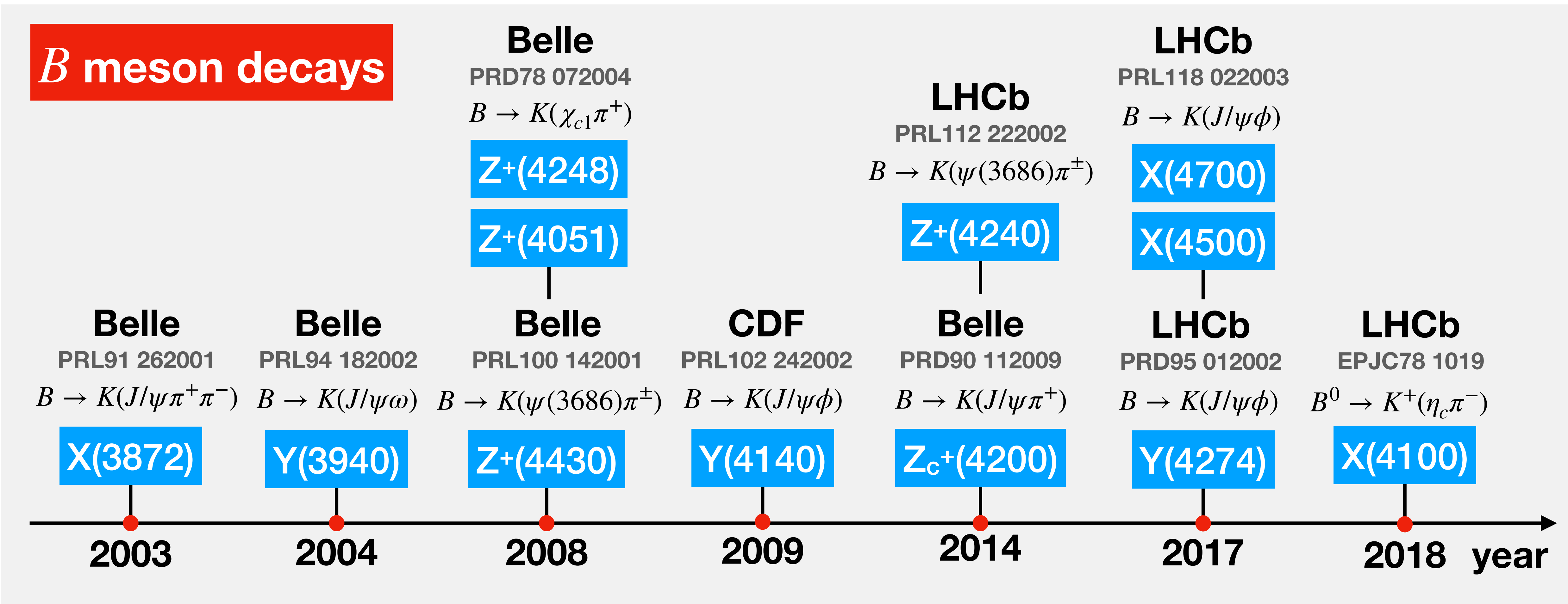
The hidden-charm pentaquark and tetraquark states

CrossMark

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

CESR CLEO, BABAR, BELLE, BESIII, CDF, DØ, LHCb, CMS

LHCb plays crucial role, especially for the observation of XYZ from B meson decays



Good platform to identify exotic tetraquark state

Full of challenges

Contents lists available at ScienceDirect

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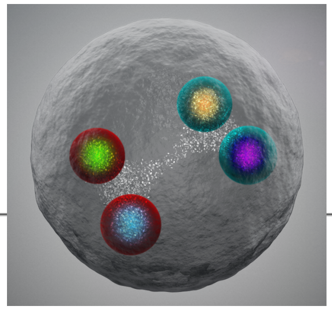
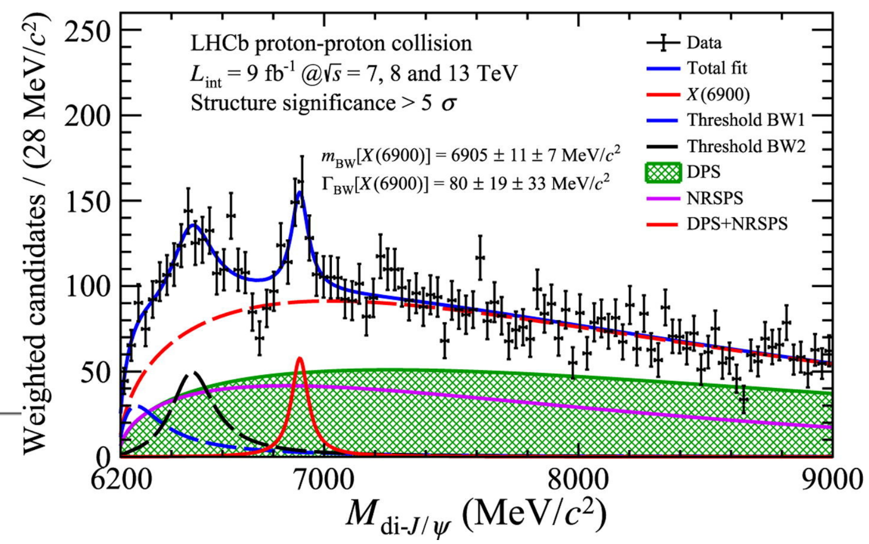
Article

Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration [1]

X(6900)





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ABSTRACT

Using proton-proton collision data at centre-of-mass energies of $\sqrt{s} = 7, 8$ and 13 TeV recorded by the LHCb experiment at the Large Hadron Collider, corresponding to an integrated luminosity of 9 fb^{-1}, the invariant mass spectrum of J/ψ pairs is studied. A narrow structure around 6.9 GeV/c^2 matching the lineshape of a resonance and a broad structure just above twice the J/ψ mass are observed. The deviation of the data from nonresonant J/ψ-pair production is above five standard deviations in the mass region between 6.2 and 7.4 GeV/c^2, covering predicted masses of states composed of four charm quarks. The mass and natural width of the narrow $X(6900)$ structure are measured assuming a Breit-Wigner lineshape.

CERN-EP-2020-158
LHCb-PAPER-2020-024
September 1, 2020

A model-independent study of resonant structure in $B^+ \to D^+ D^- K^+$ decays

LHCb collaboration†

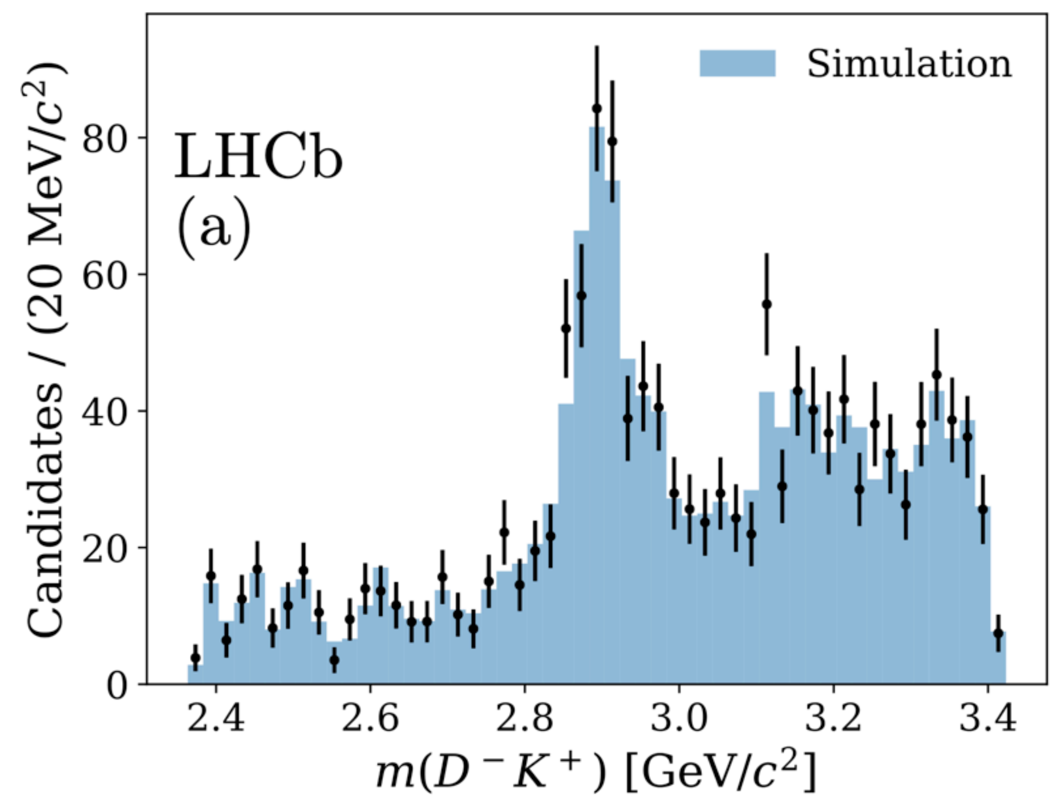
Abstract

The only anticipated resonant contributions to $B^+ \to D^+ D^- K^+$ decays are charmonium states in the $D^+ D^-$ channel. A model-independent analysis, using LHCb proton-proton collision data taken at centre-of-mass energies of $\sqrt{s} = 7, 8,$ and 13 TeV, corresponding to a total integrated luminosity of $9\,\text{fb}^{-1}$, is carried out to test this hypothesis. The description of the data assuming that resonances only manifest in decays to the $D^+ D^-$ pair is shown to be incomplete. This constitutes evidence for a new, exotic contribution to the decay, potentially one or more new charm-strange resonances in the $D^- K^+$ channel with masses around $2.9\,\text{GeV}/c^2$.

Submitted to Phys. Rev. Lett.

†Authors are listed at the end of this Letter.

X(2900)



Outline

- Some lessons from X(3872)
- The challenge for molecular assignment to Y(4140) and Z(4430)
- Peculiar viewpoint to X(6900)
- Summary

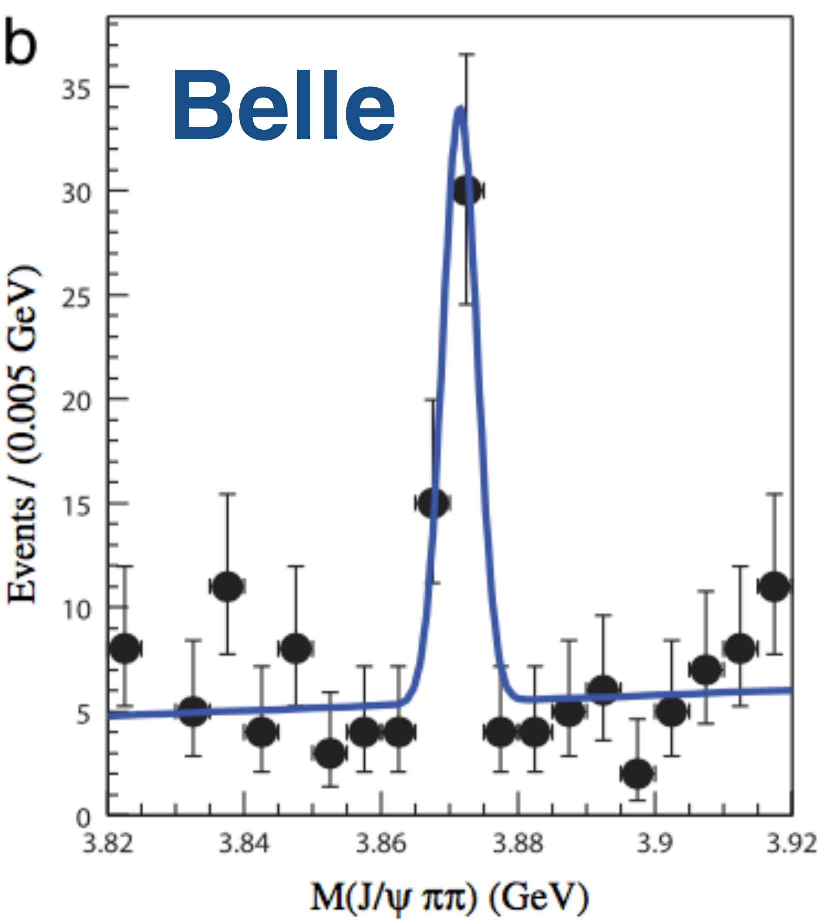
1

Some lessons from X(3872)

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						■		$3891.9 \pm 0.7 \pm 0.2$	

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

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

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

Is X(3872) a molecular state?

$D\bar{D}^*$ interaction

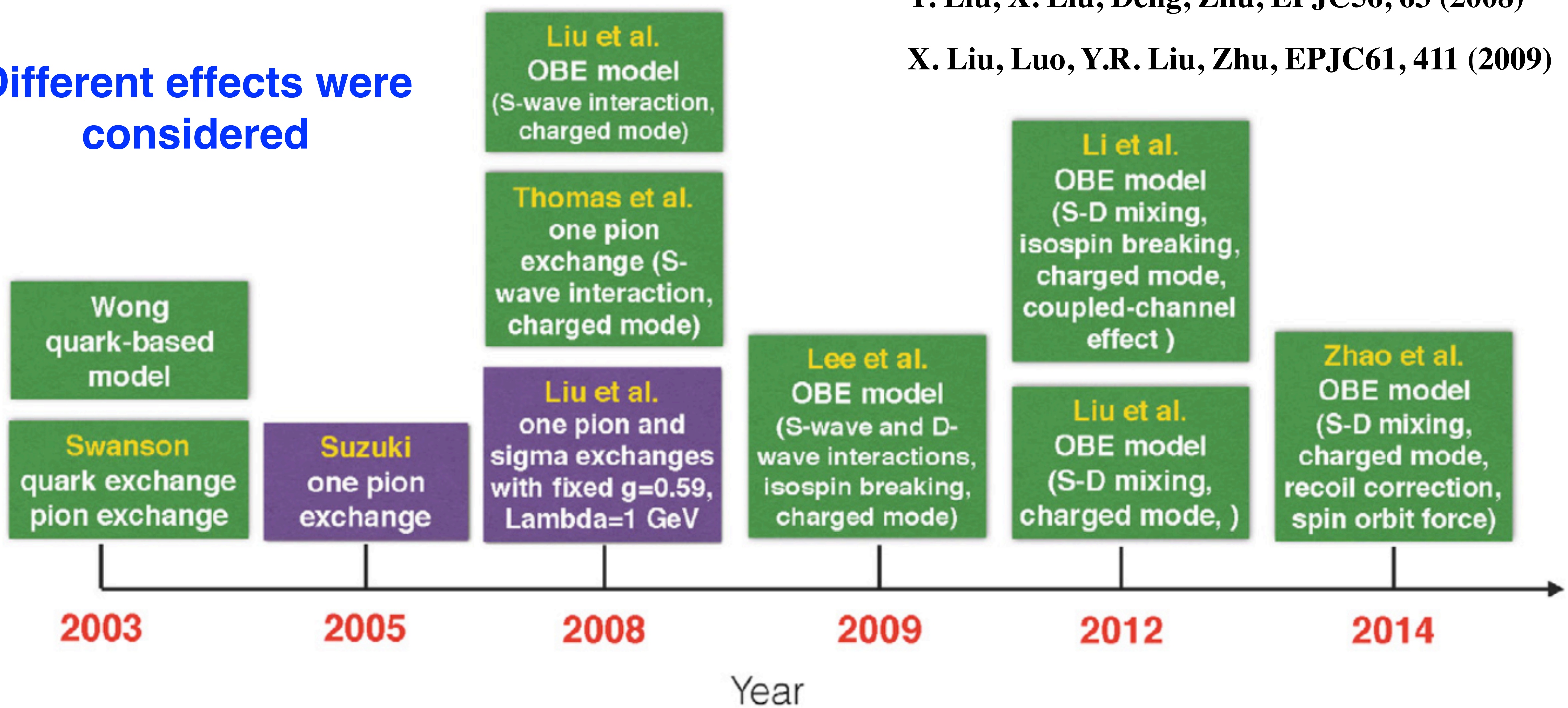
N. Li, S.L. Zhu, PRD86(2012)

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

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

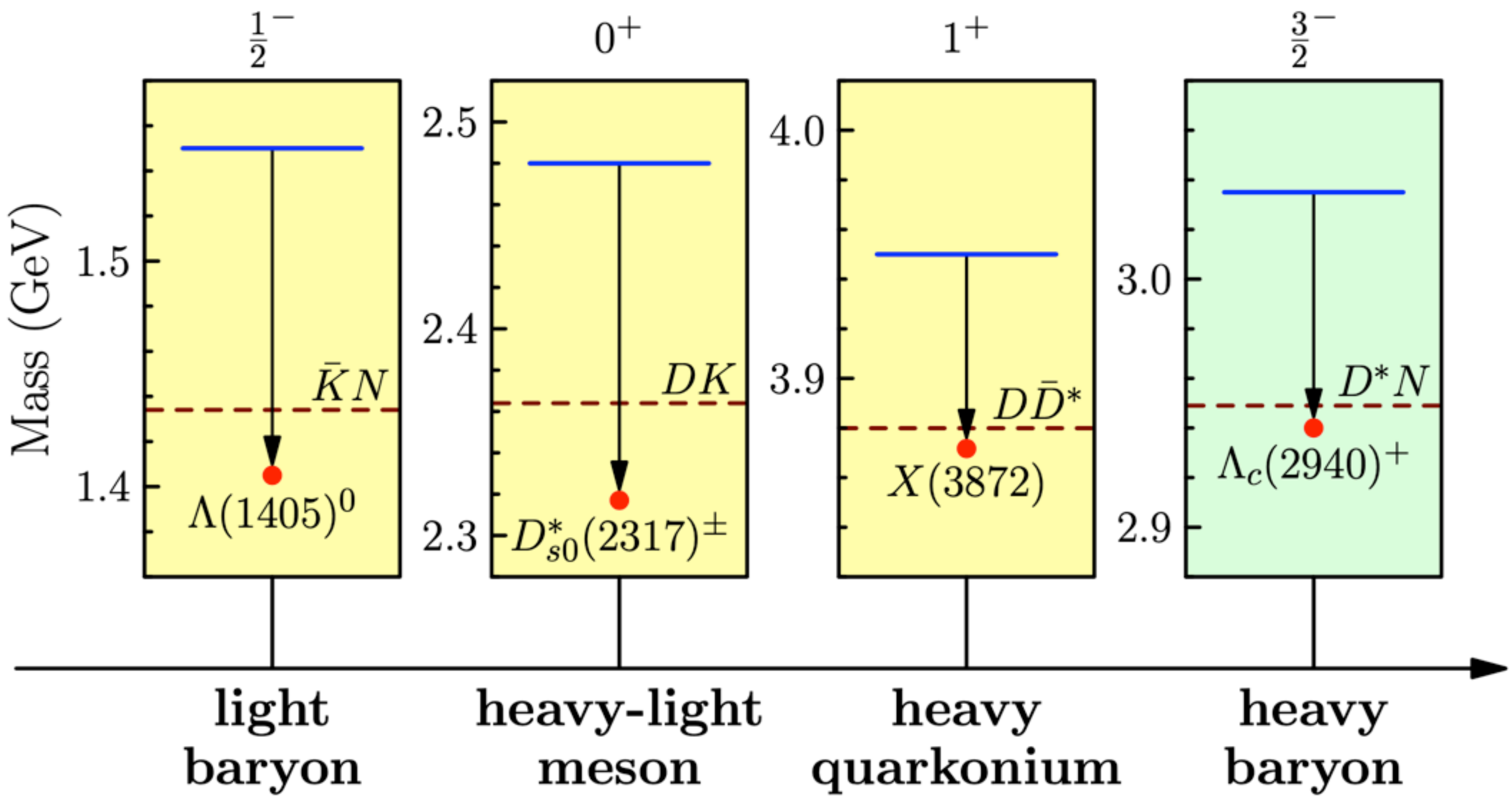
X. Liu, Luo, Y.R. Liu, Zhu, EPJC61, 411 (2009)

Different effects were considered



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

Coupled-channel effect as universal mechanism



Luo, Chen, Liu, Xiang Liu, Eur.Phys.J.C 80 (2020) 301

Start point: One boson exchange was extensively applied to the studies of observed XYZ states

Long list:

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

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

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

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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 pion exchange model to study XYZ states and predict P_c states

2

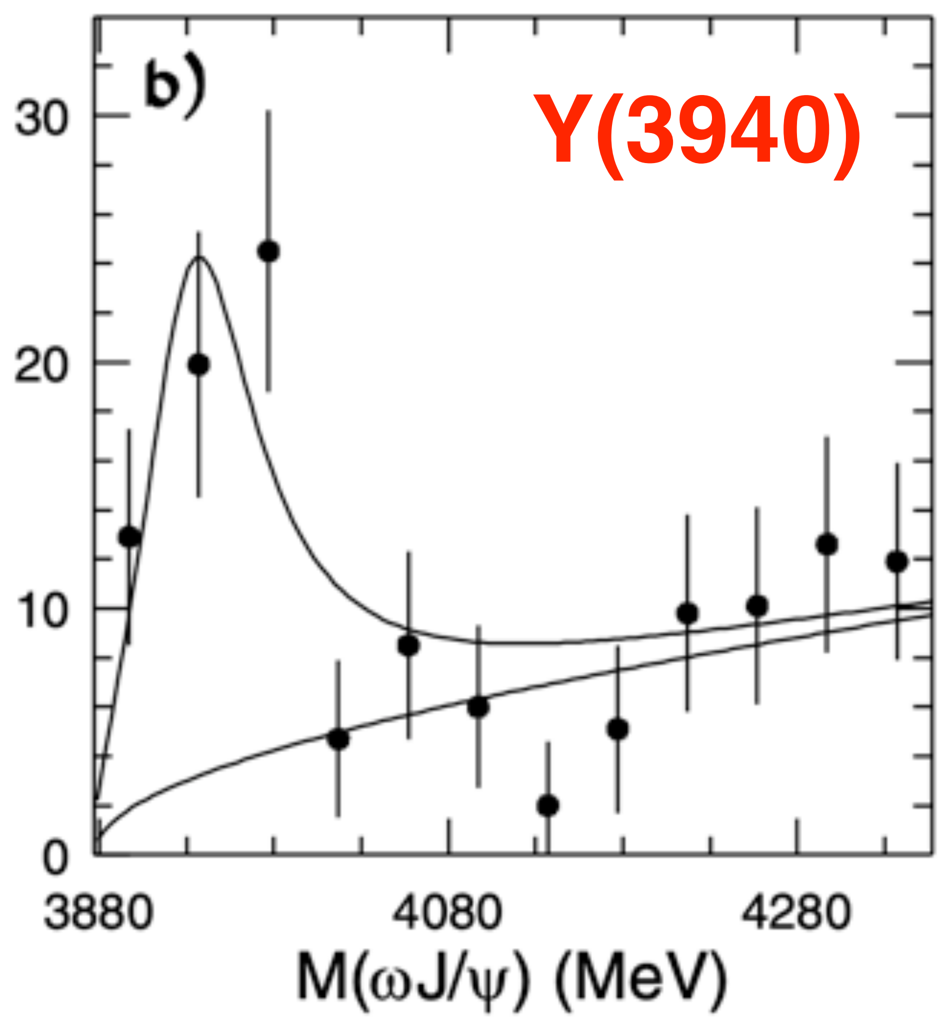
The challenge for molecular assignment to Y(4140) and Z(4430)

Spin-parity quantum number

The similarity between Y(3940) and Y(4140)

Belle, PRL 94 (2005) 182002

$B \to J/\psi\omega K$

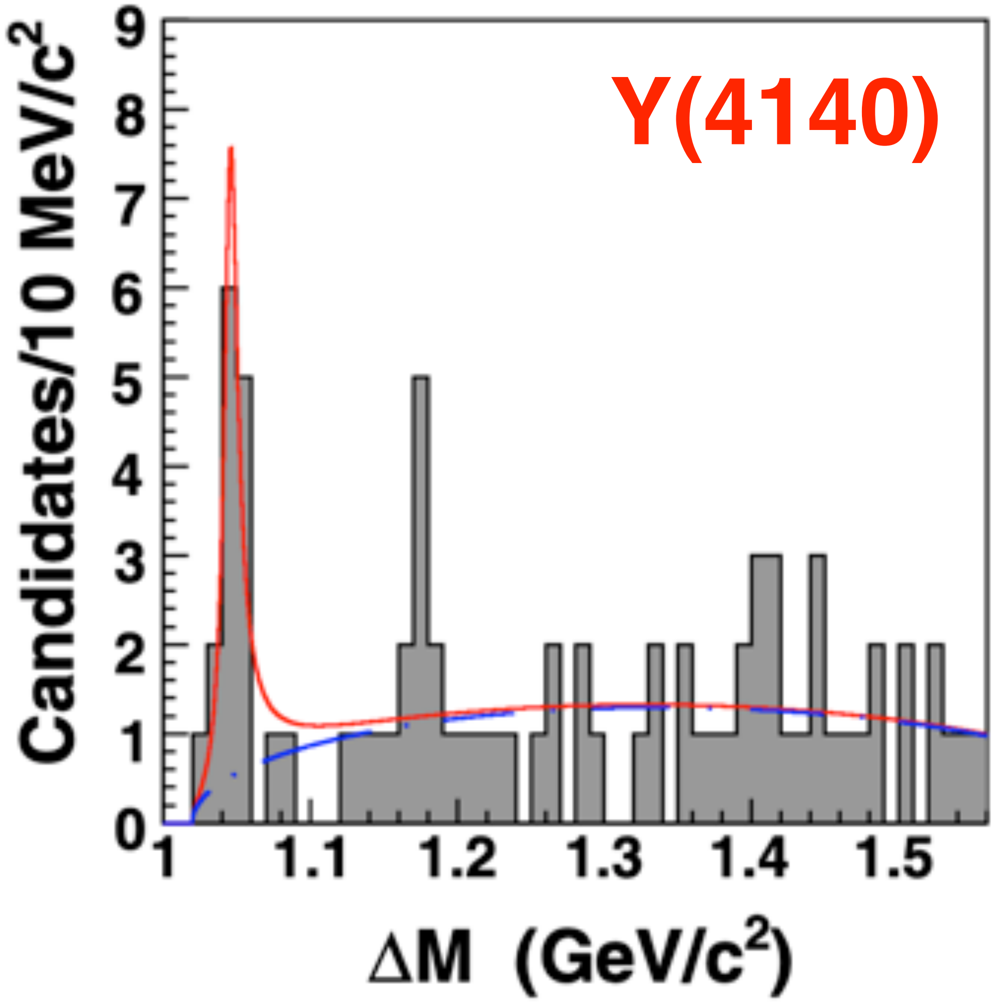


$M = 3943 \pm 11$ **MeV**

$\Gamma = 87 \pm 22$ **MeV**

CDF, PRL 102 (2005) 242002

$B^+ \to J/\psi\phi K^+$



$M = 4143.0 \pm 2.9(stat) \pm 1.2(syst)$ **MeV**

$\Gamma = 11.7^{+8.3}_{-5.0}(stat) \pm 3.7(syst)$ **MeV**

$J^P = 0^+$

$J^P = 2^+$

PHYSICAL REVIEW D **80,** 017502 (2009)

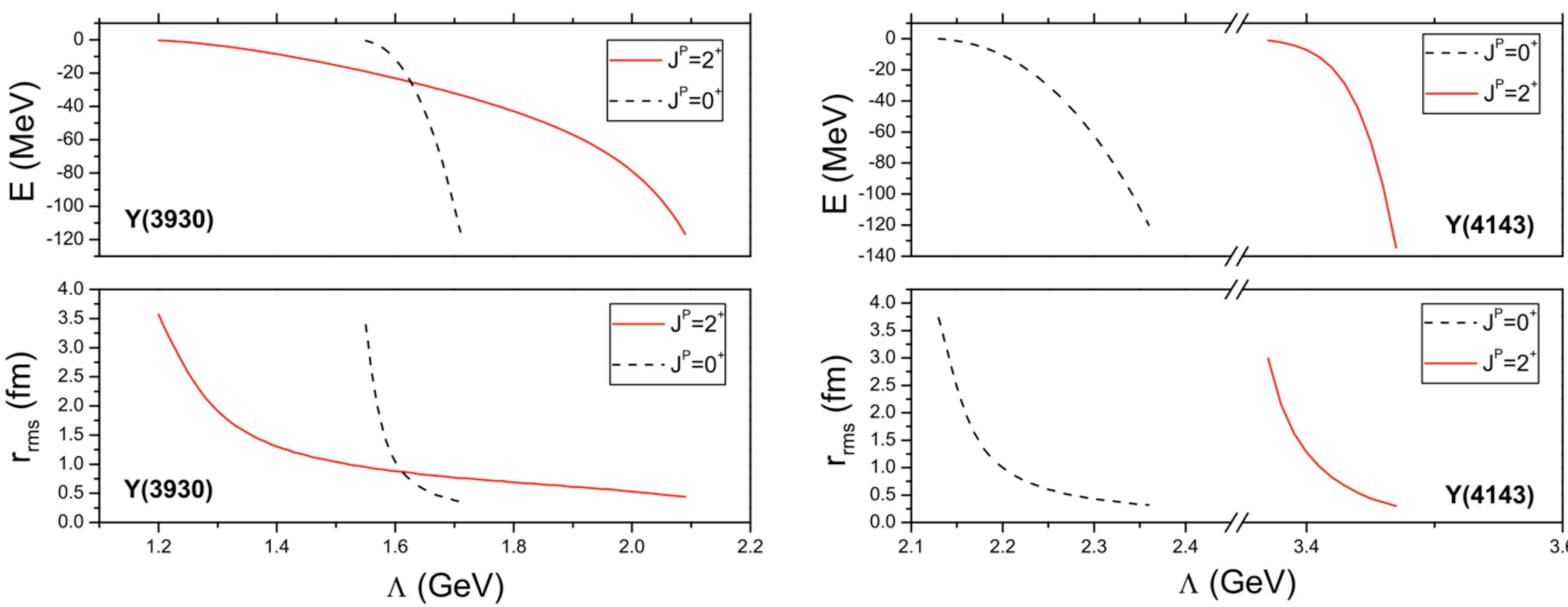
$Y(4143)$ is probably a molecular partner of $Y(3930)$

Xiang Liu[1,*] and Shi-Lin Zhu[2,†]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Department of Physics, Peking University, Beijing 100871, China*
(Received 20 March 2009; published 20 July 2009)

The Y(3940) and Y(4140) are close to the thresholds of $D^*\bar{D}^*$ and $D_s^*\bar{D}_s^*$, respectively, and satisfy an almost exact mass relation

$$M_{Y(4140)} - 2M_{D_s^*} \sim M_{Y(3940)} - 2M_{D^*}$$



The spin-parity quantum number of Y(4140) @ LHCb

LHCb, PRL 118 (2017) 022003

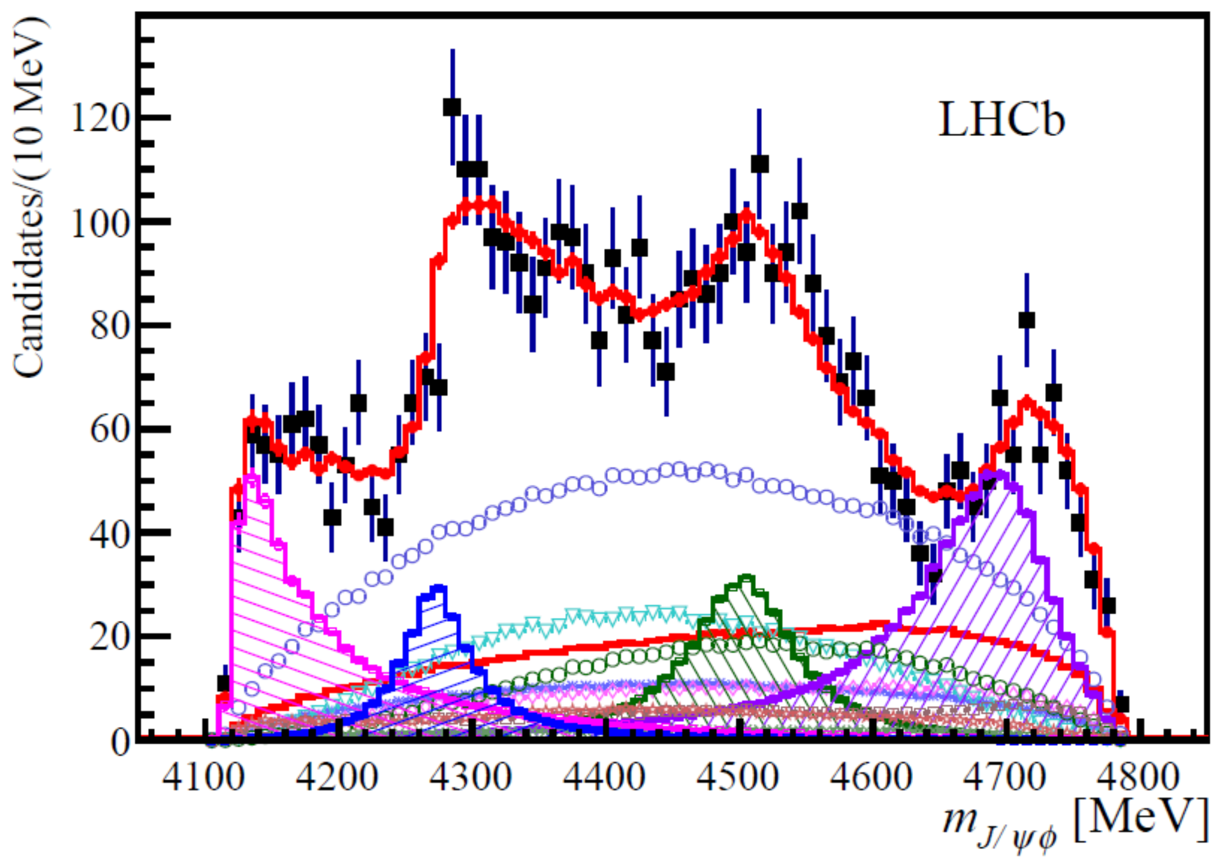


Figure 3: Distributions of (top left) ϕK^+, (top right) $J/\psi K^+$ and (bottom) $J/\psi\phi$ invariant masses for the $B^+ \to J/\psi\phi K^+$ candidates (black data points) compared with the results of the default amplitude fit containing eight $K^{*+} \to \phi K^+$ and five $X \to J/\psi\phi$ contributions. The total fit is given by the red points with error bars. Individual fit components are also shown.

LHCb, PRD 95 (2017) 012002

J^{PC}	$X(4140)$	$X(4274)$	$X(4500)$	$X(4700)$
0^{++}	10.3σ	7.8σ	Preferred	Preferred
0^{-+}	12.5σ	7.0σ	8.1σ	8.2σ
1^{++}	Preferred	Preferred	$\mathbf{5.2\sigma}$	$\mathbf{4.9\sigma}$
1^{-+}	10.4σ	$\mathbf{6.4\sigma}$	6.5σ	8.3σ
2^{++}	$\mathbf{7.6\sigma}$	7.2σ	5.6σ	6.8σ
2^{-+}	9.6σ	$\mathbf{6.4\sigma}$	6.5σ	6.3σ

- **LHCb suggests $J^{PC} = 1^{++}$ for Y(4140)**
- **Inconsistent with the S-wave $D_s^* \bar{D}_s^*$ molecular state assignment**

More structures existing in the $J/\psi\phi$ invariant mass spectrum

Challenge!

PRL 100, 142001 (2008) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2008

Observation of a Resonancelike Structure in the $\pi^{+-}\psi'$ Mass Distribution in Exclusive $B \to K\pi^{+-}\psi'$ Decays

Z(4430)

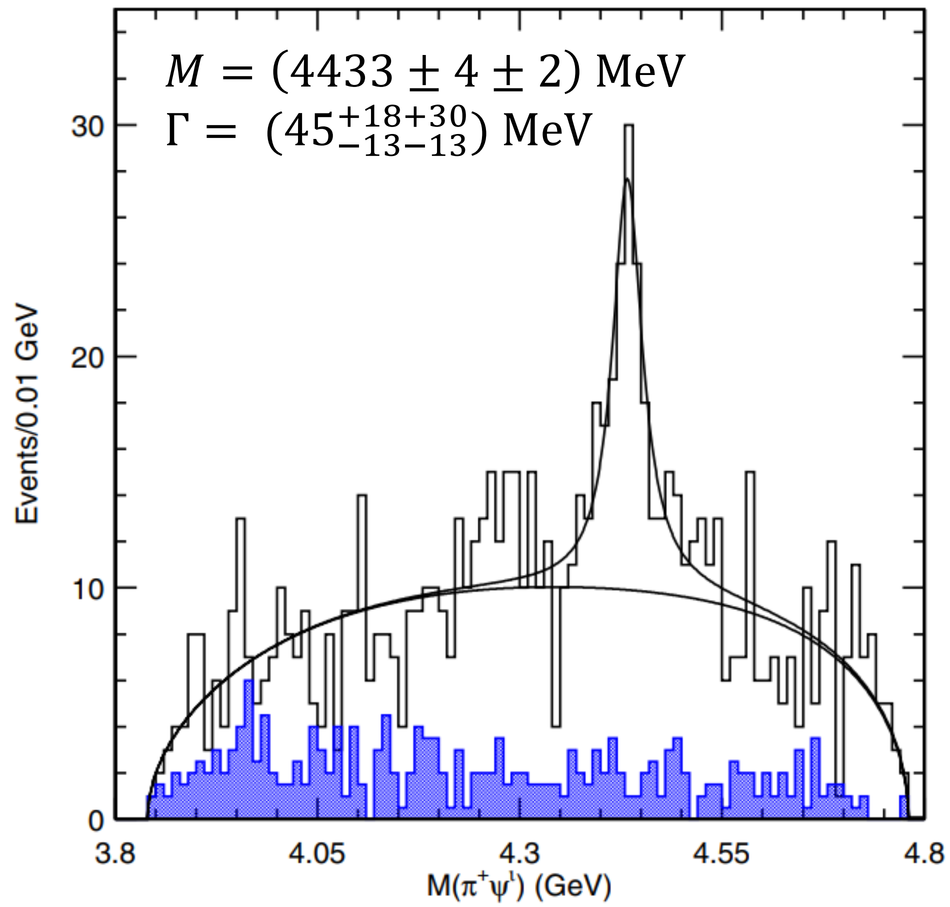


FIG. 2 (color online). The $M(\pi^+\psi')$ distribution for events in the $M_{bc} - \Delta E$ signal region and with the K^* veto applied. The shaded histogram show the scaled results from the ΔE sideband. The solid curves show the results of the fit described in the text.

Belle, PRD 80 (2009) 031104

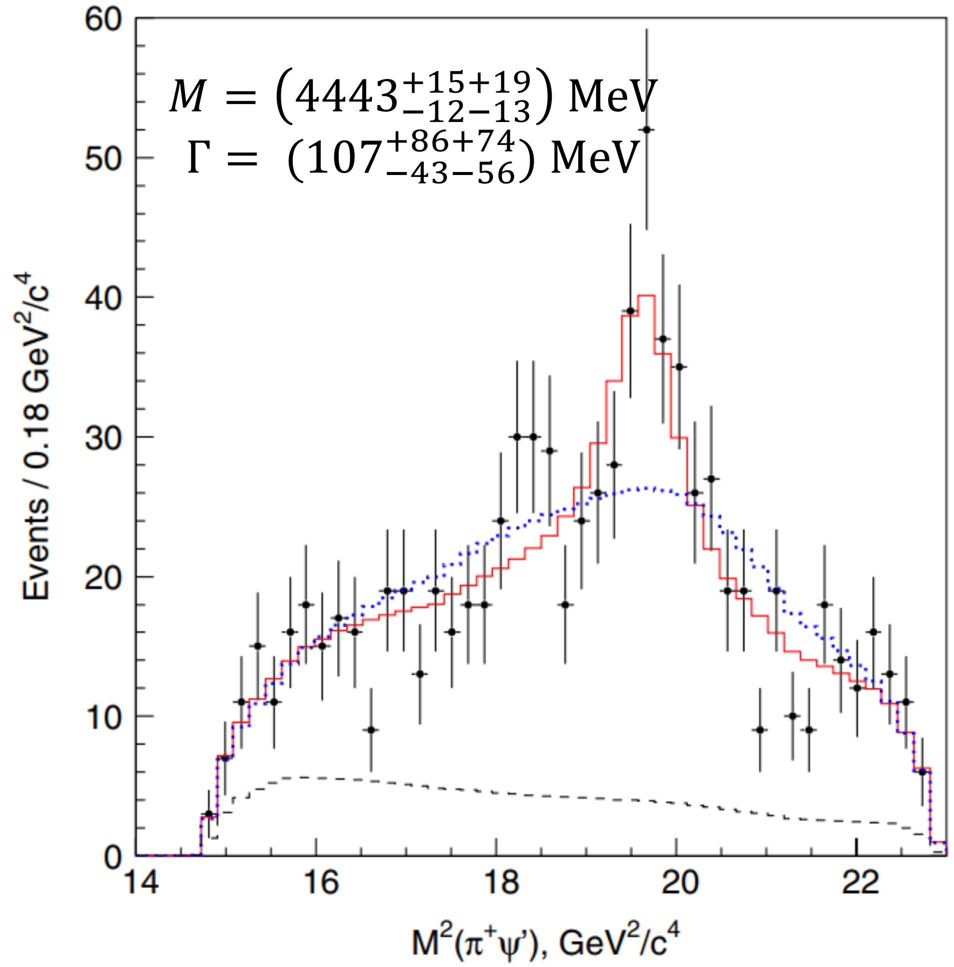


FIG. 3 (color online). The Dalitz plot projection with the K^* veto applied. The points with error bars represent data, the solid (dotted) histogram is the Dalitz plot fit result for the fit model with all $K\pi$ resonances and a single (without any) $\pi^+\psi'$ state, and the dashed histogram represents the background.

Z(4430) as the $D^*\bar{D}_1^{(\prime)}$ molecular state

One-pion-exchange model

Since $Z^+(4430)$ lies very close to the threshold of $D^*\bar{D}_1$, we investigate whether $Z^+(4430)$ could be a loosely bound S-wave state of $D^*\bar{D}_1$ or $D^*\bar{D}_1'$ with $J^P = 0^-, 1^-, 2^-$, i.e., a molecular state arising from the one-pion-exchange potential. The potential from the crossed diagram is much larger than that from the diagonal scattering diagram. With various trial wave functions, we notice that the attraction from the one-pion-exchange potential alone is not strong enough to form a bound state with realistic pionic coupling constants deduced from the decay widths of D_1 and D_1'.

X. Liu, Y.R. Liu, W.Z. Deng, and S.L. Zhu, PRD 77 (2008) 034003

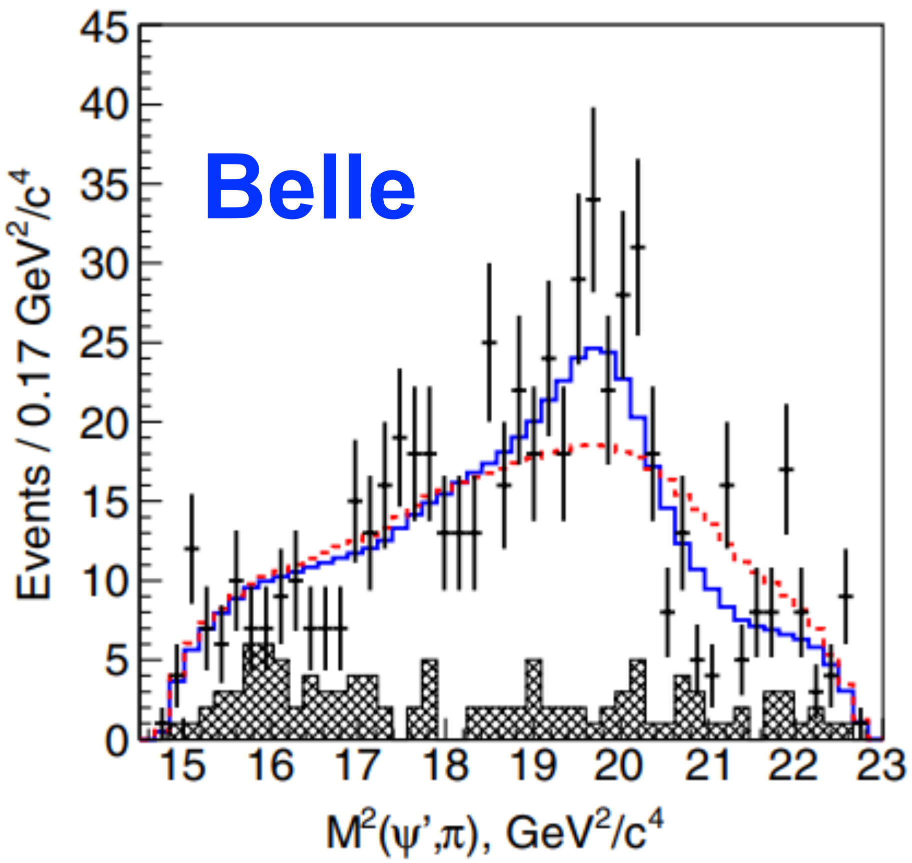
One-pion/sigma-exchange model

We reexamine whether $Z^+(4430)$ could be a $D_1' - D^*$ or $D_1 - D^*$ molecular state after considering both the pion and σ meson exchange potentials and introducing the form factor to take into account the structure effect of the interaction vertex. Our numerical analysis with Matlab package MATSLISE indicates the contribution from the sigma meson exchange is small for the $D_1' - D^*$ system and significant for the $D_1 - D^*$ system. The S-wave $D_1 - \bar{D}^*$ molecular state with only $J^P = 0^-$ and $D_1' - D^*$ molecular states with $J^P = 0^-, 1^-, 2^-$ may exist with reasonable parameters. One should investigate whether the broad width of D_1' disfavors the possible formation of molecular states in the future. The bottom analog Z_B of $Z^+(4430)$ has a larger binding energy, which may be searched at Tevatron and LHC. Experimental measurement of the quantum number of $Z^+(4430)$ may help uncover its underlying structure.

X. Liu, Y.R. Liu, W.Z. Deng, and S.L. Zhu, PRD 77 (2008) 094015

The spin-parity quantum number of Z(4430)

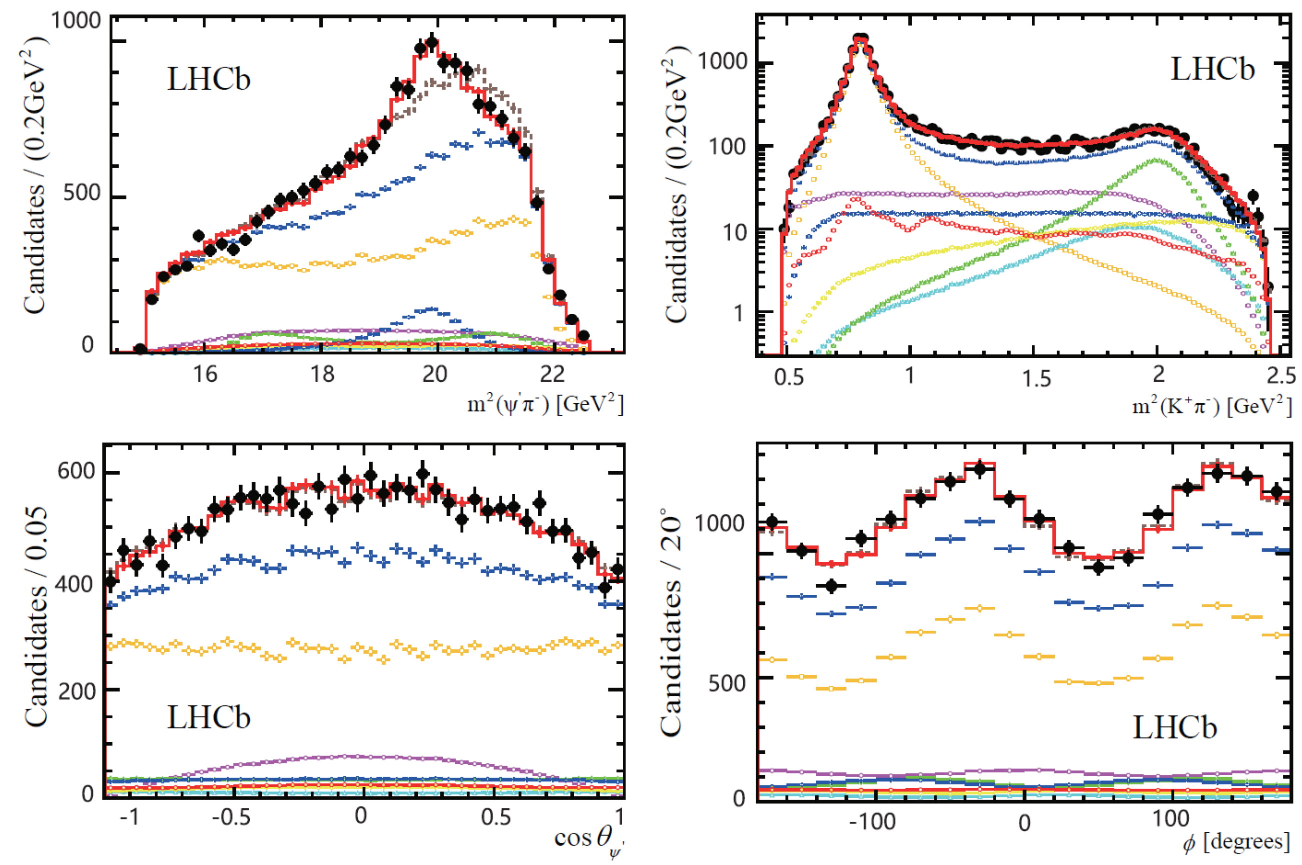
Belle, PRD 88 (2013) 074026



$M = 4485^{22+28}_{-22-11}$ MeV $\quad \Gamma = 200^{+41+26}_{-46-35}$ MeV

The $Z^+(4430)$ has quantum numbers $\boldsymbol{J^P = 1^+}$, this hypothesis being favored over the 0^-, 1^-, 2^- and 2^+ hypotheses at the levels of 3.4σ, 3.7σ, 4.7σ and 5.1σ, respectively.

LHCb, PRL 112 (2014) 222002



$M = 4475^{15}_{-18}$ MeV $\quad \Gamma = 172 + 13^{+37}_{-34}$ MeV

Its spin-parity to be $\boldsymbol{J^P = 1^+}$, both with very high significance. Moreover, they ruled out the 0^-, 1^-, 2^+ and 2^- hypotheses for its spin-parity by at least 9.7σ, 15.8σ, 16.1σ and 14.6σ, respectively.

Challenge!

The measured J^{PC} quantum number @Belle and @LHCb is inconsistent with molecular assignment to Z(4430)

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)

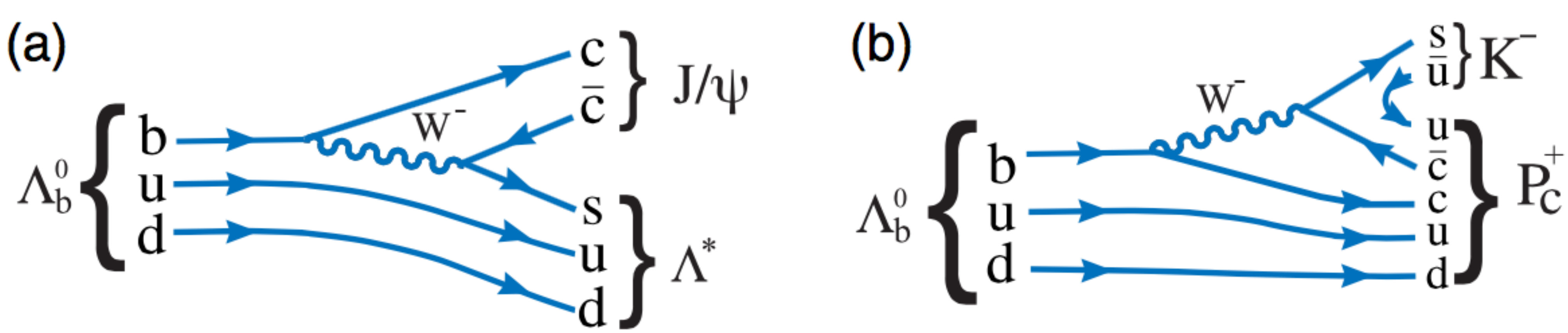


FIG. 1 (color online). Feynman diagrams for (a) $\Lambda_b^0 \to J/\psi \Lambda^*$ and (b) $\Lambda_b^0 \to P_c^+ K^-$ decay.

Resonance parameters of two P_c states

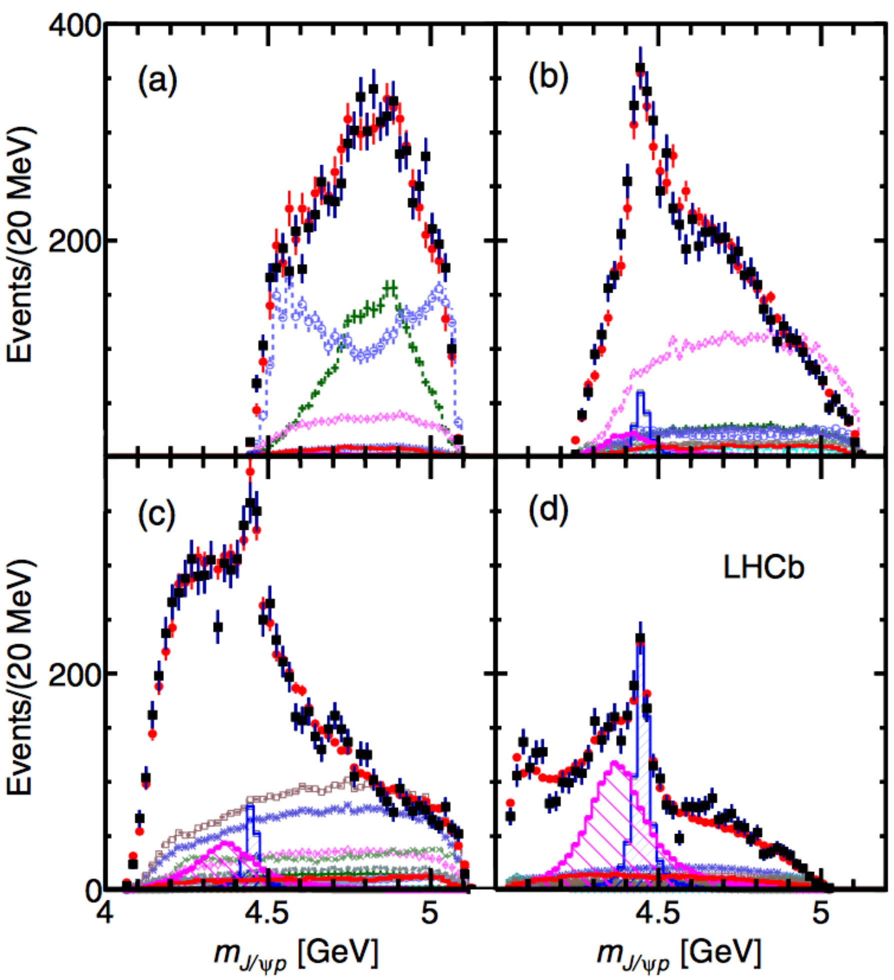


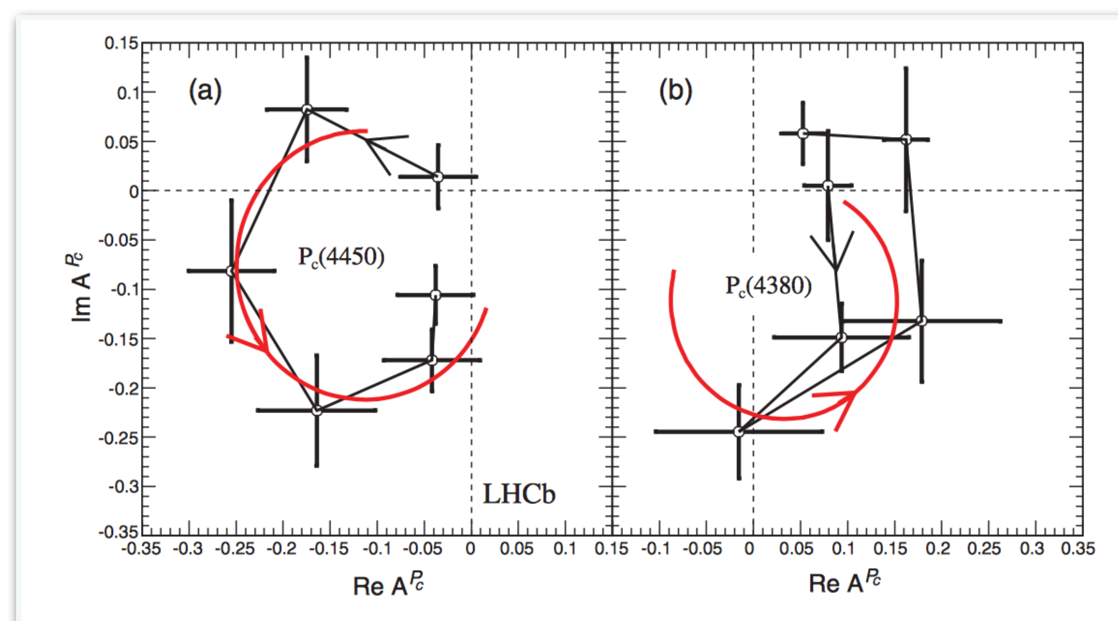
FIG. 8 (color online). $m_{J/\psi p}$ in various intervals of m_{Kp} for the fit with two P_c^+ states: (a) $m_{Kp} < 1.55$ GeV, (b) $1.55 < m_{Kp} < 1.70$ GeV, (c) $1.70 < m_{Kp} < 2.00$ GeV, and (d) $m_{Kp} > 2.00$ GeV. The data are shown as (black) squares with error bars, while the (red) circles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

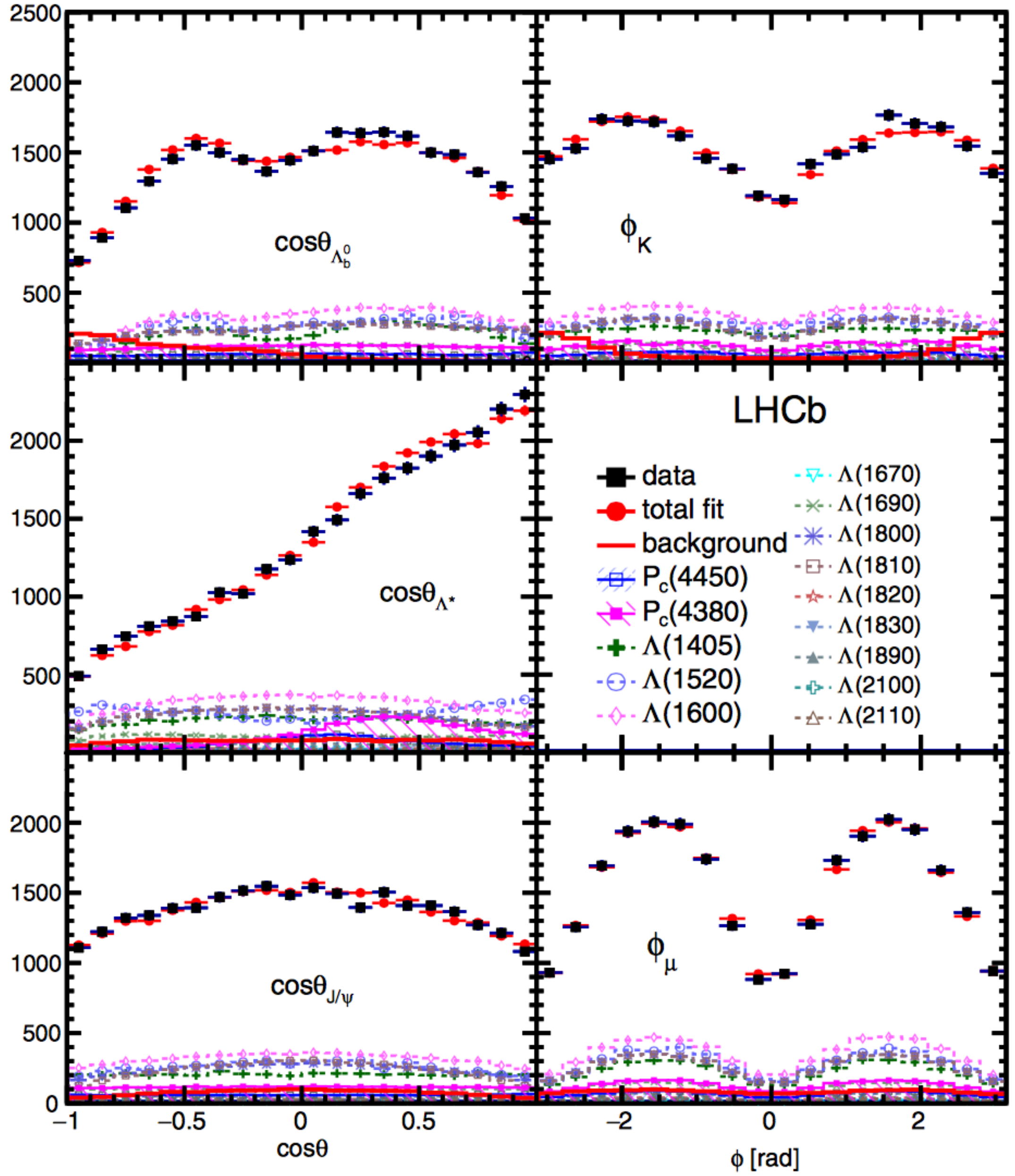
Ref: $\mathcal{B}(B^0 \to Z^-(4430)K^+; Z^- \to J/\psi\pi^-) = (3.4 \pm 0.5^{+0.9}_{-1.9} \pm 0.2) \times 10^{-5}$

Argand diagrams show the resonance behavior of two P_c states



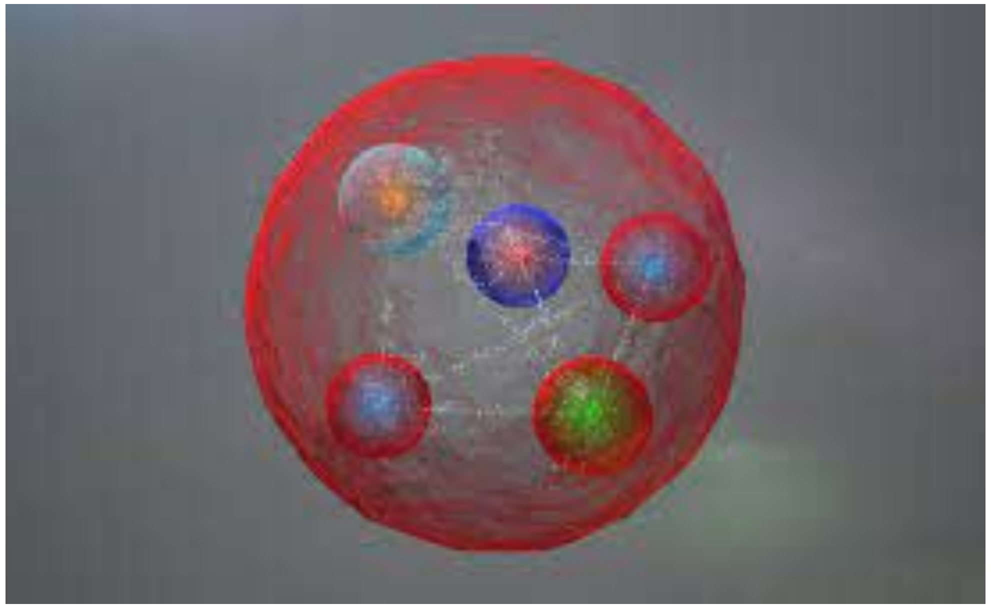
Decay angular distributions

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

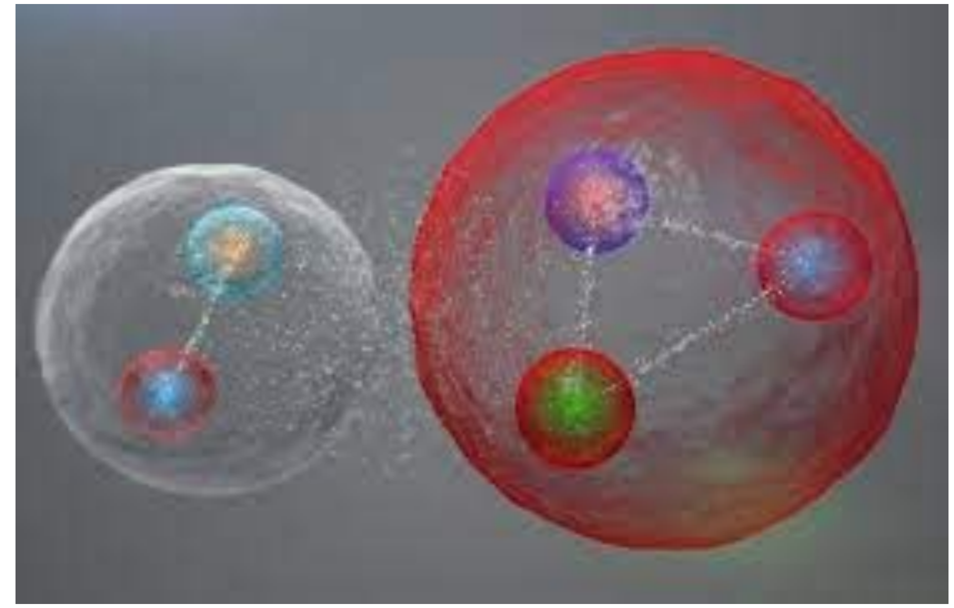


It is puzzling for us under the hadronic molecular assignment

LHCb@2015 cannot be applied distinguish different explanations



Compact pentaquark



Molecular state

Physics Reports 639 (2016) 1–121

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We need more data!

The hidden-charm pentaquark and tetraquark states

CrossMark

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.

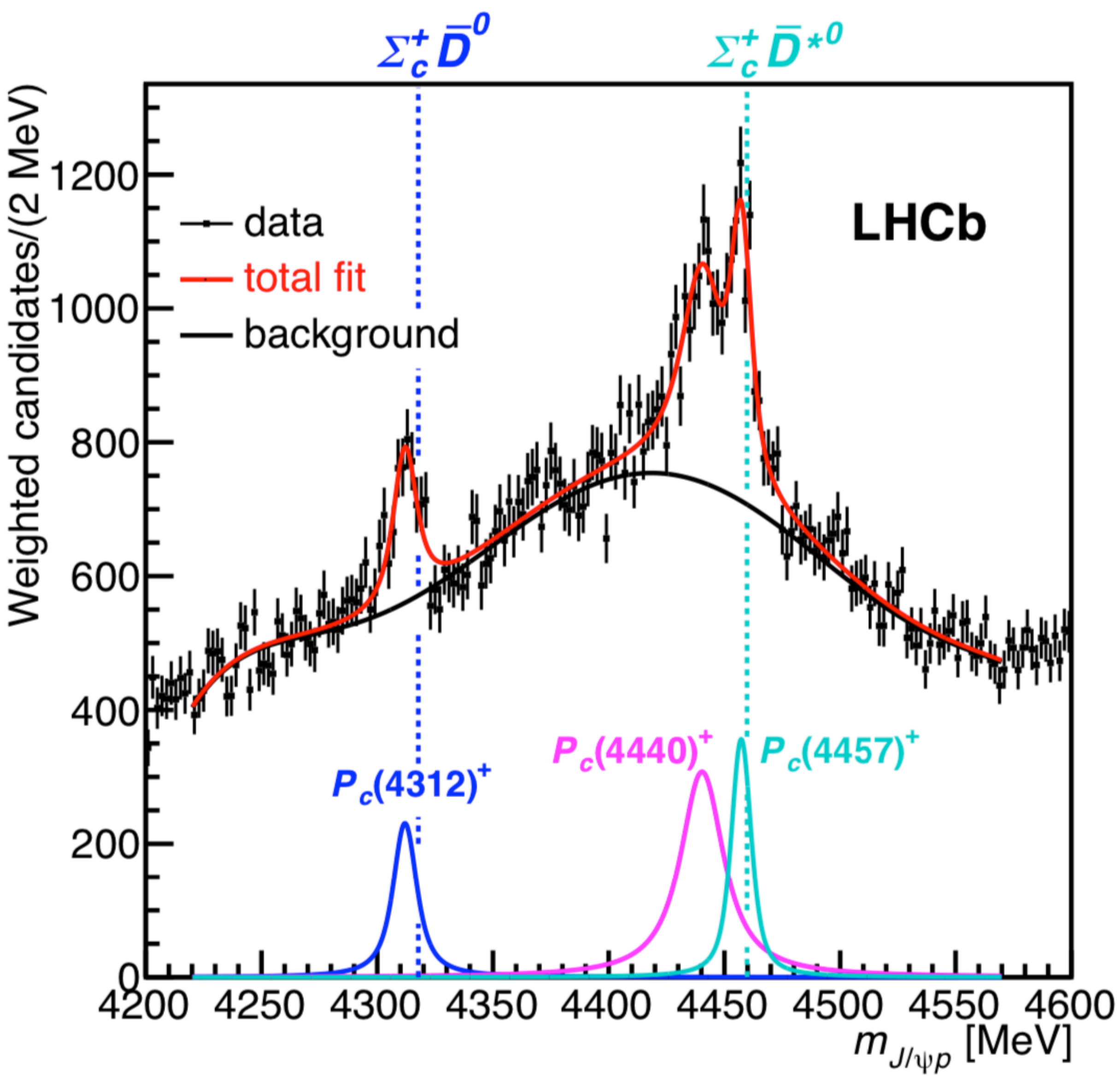
PHYSICAL REVIEW LETTERS **122**, 222001 (2019)

Editors' Suggestion | Featured in Physics

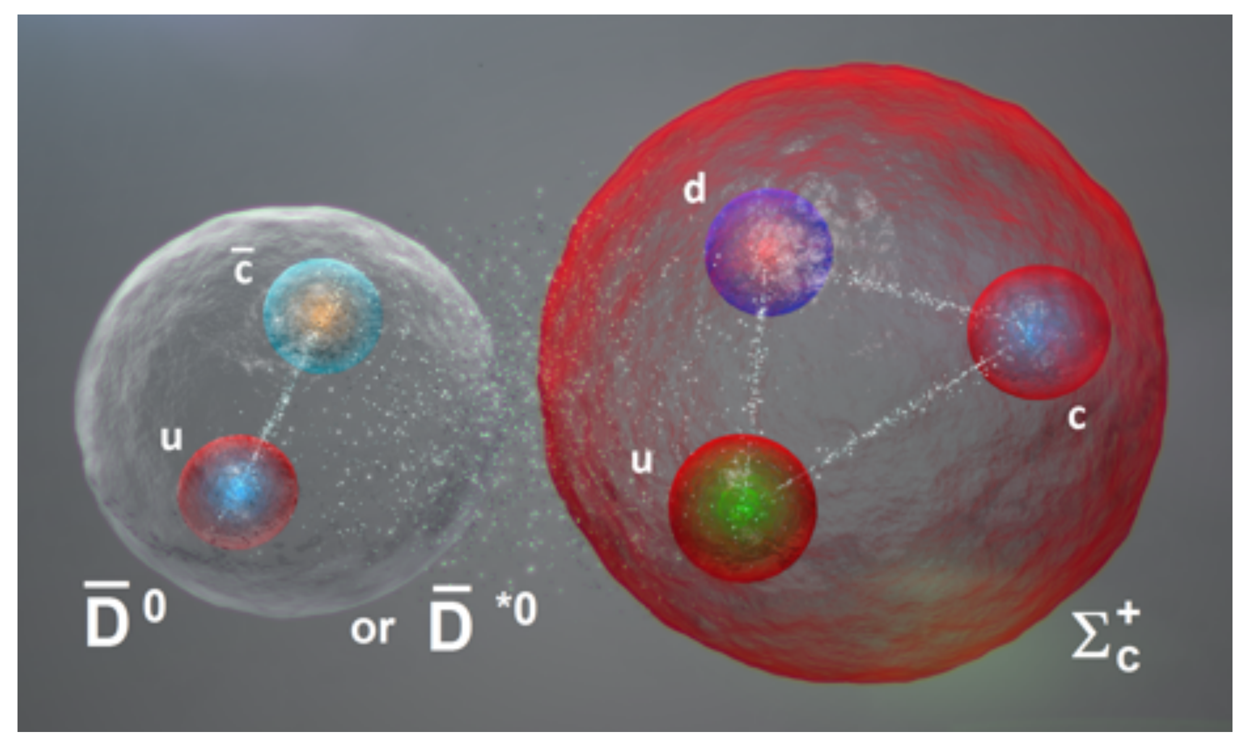
Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$

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

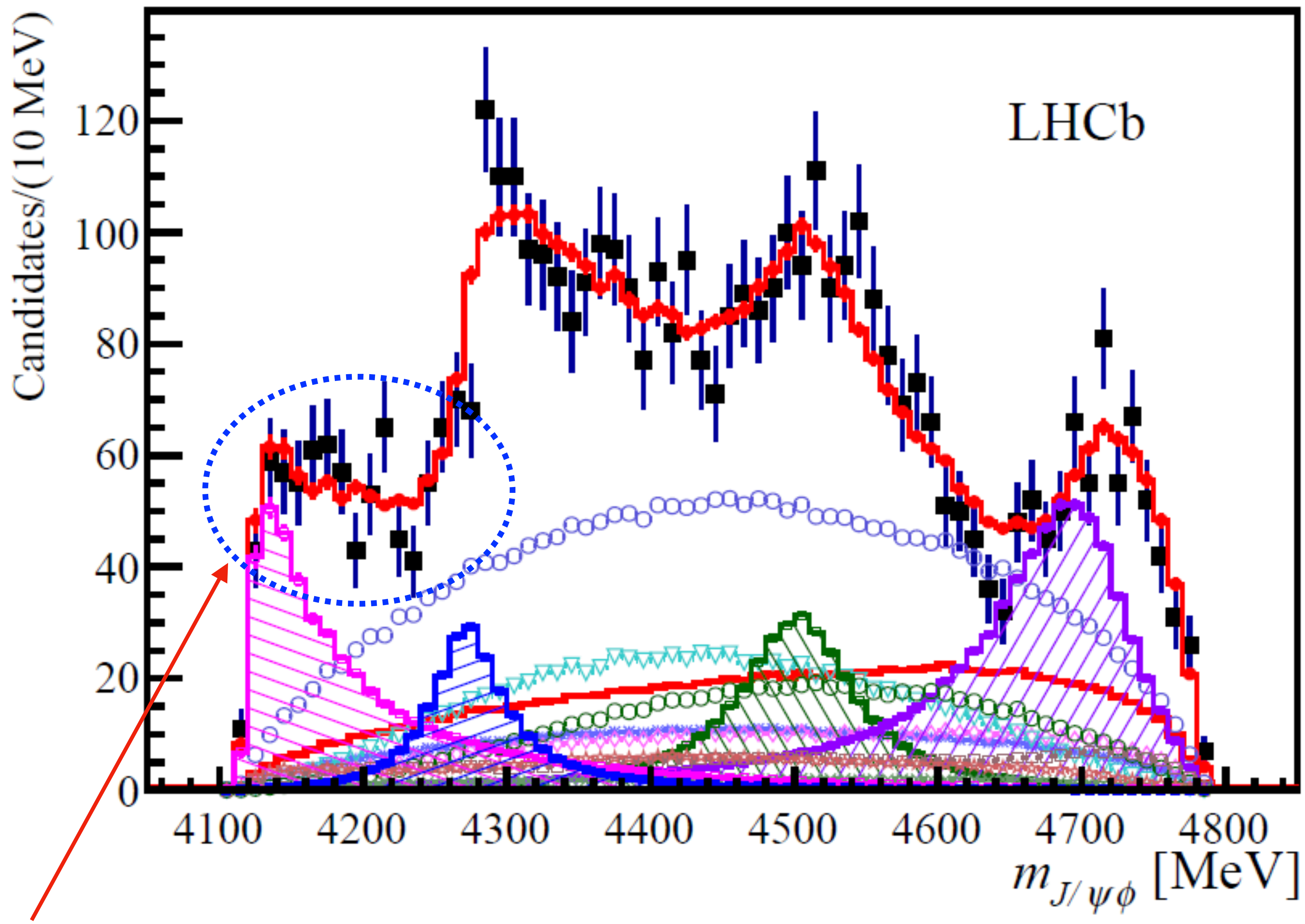
(Received 6 April 2019; published 5 June 2019)



2019年高精度的实验数据支持分子态构型

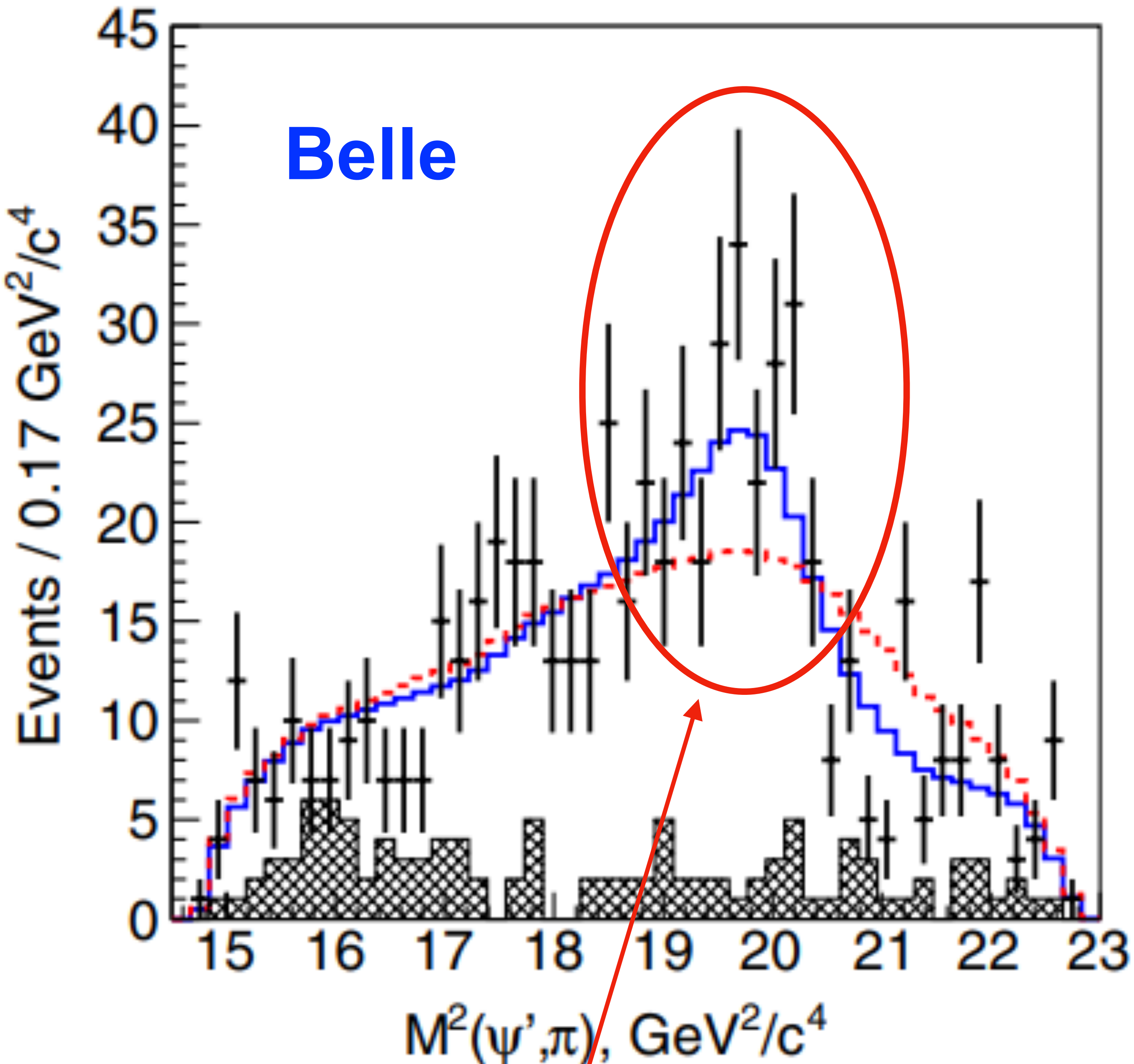


LHCb, PRL 118 (2017) 022003



More structures?

Belle, PRD 88 (2013) 074026



More structures?

LHCb should emphasize this point of measuring the spin-parity quantum numbers for Y(4140) and Z(4430)!

New task @ LHCb

Run I+Run II+RunIII

3

Peculiar viewpoint to X(6900)

1981

Z. Physik C, Particles and Fields 7, 317–320 (1981)

Zeitschrift für Physik C Particles and Fields

The (cc)–$(\overline{cc})$ (Diquark-Antidiquark) States in e^+e^- Annihilation

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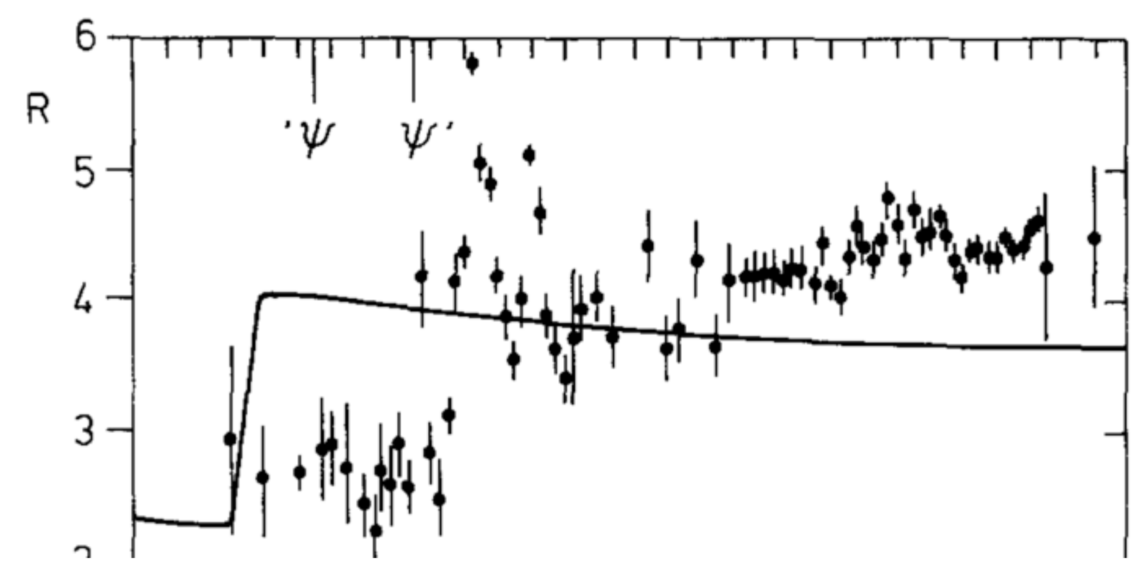
Received 10 September 1980

Abstract. The mass spectrum and decay modes of the (cc)–$(\overline{cc})$ states are estimated in a quark-gluon model. We argue that the peculiar resonance-like structures of $R(e^+e^- \to \text{hadrons})$ for $\sqrt{s} = 6$–$7\,\text{GeV}$ may be due to production of the P-wave (cc)–$(\overline{cc})$ states. They are predicted to lie in the range 6.4–6.8 GeV and mainly decay into charmend mesons.



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Long list from different models for the same issue

The existence of fully heavy quark hadrons was questioned in some papers

J. M. Richard, A. Valcarce and J. Vijande, String dynamics and metastability of all-heavy tetraquarks, Phys. Rev. D **95**, no.5, 054019 (2017).
A. Czarnecki, B. Leng and M. B. Voloshin, Stability of tetrons, Phys. Lett. B **778**, 233-238 (2018).

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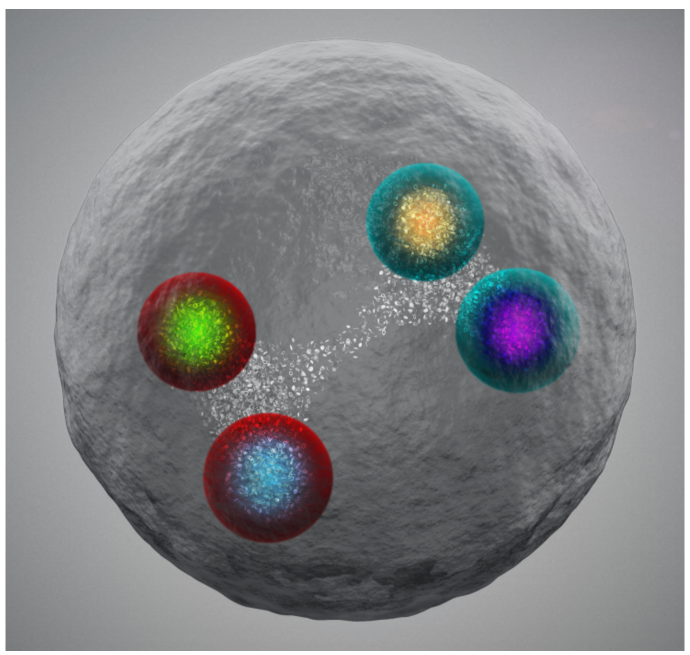
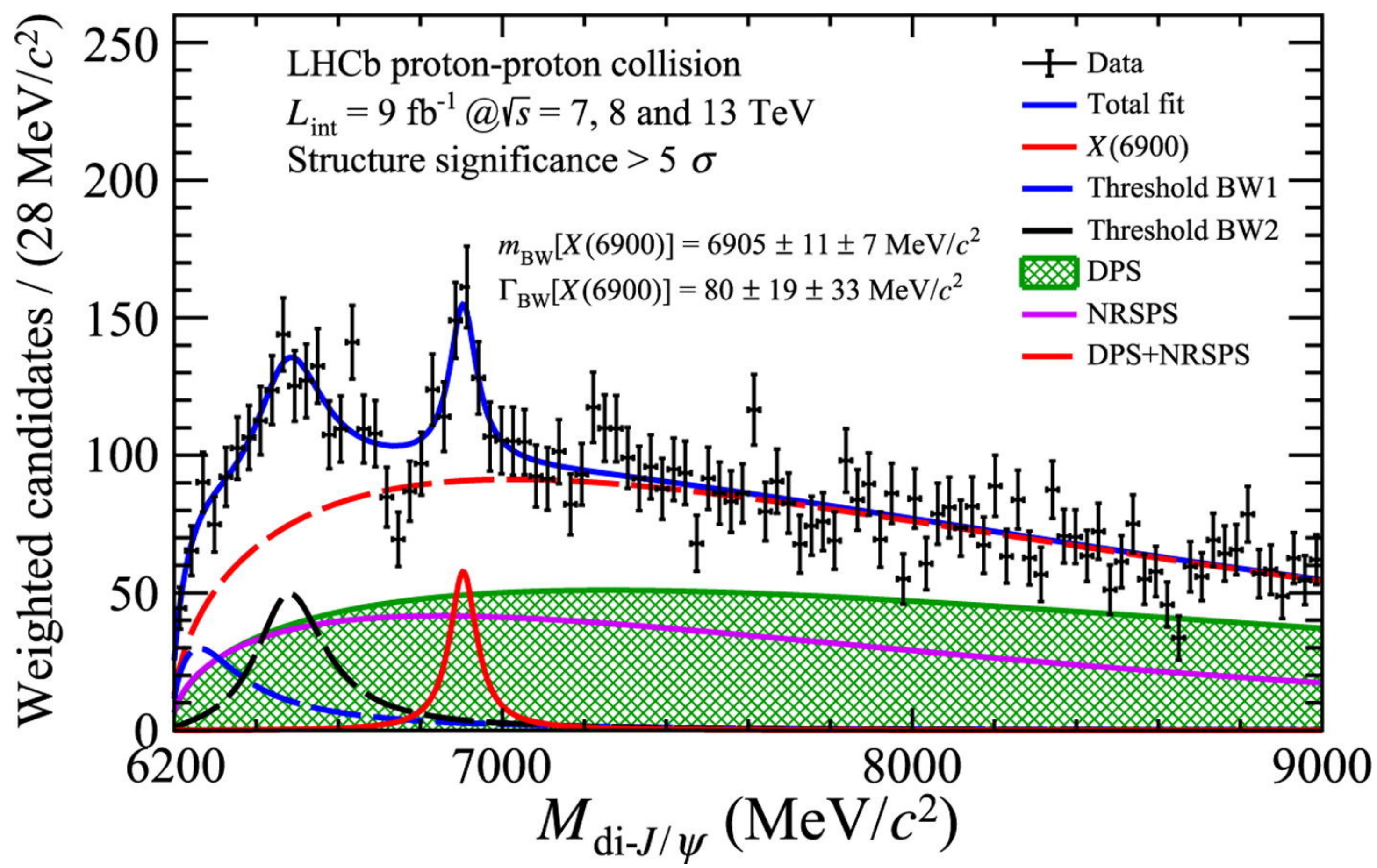
Article

Observation of structure in the J/ψ-pair mass spectrum

LHCb collaboration [1]





Observation of structure in the J/ψ-pair mass spectrum

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Jun 30, 2020)

Published in: *Sci.Bull.* 2020 65 • e-Print: 2006.16957 [hep-ex]

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52 citations

Attract extensive attention

Producing fully-charm structures in the J/ψ-pair invariant mass spectrum

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[2]Research Center for Hadron and CSR Physics, Lanzhou University & Institute of Modern Physics of CAS, Lanzhou 730000, China
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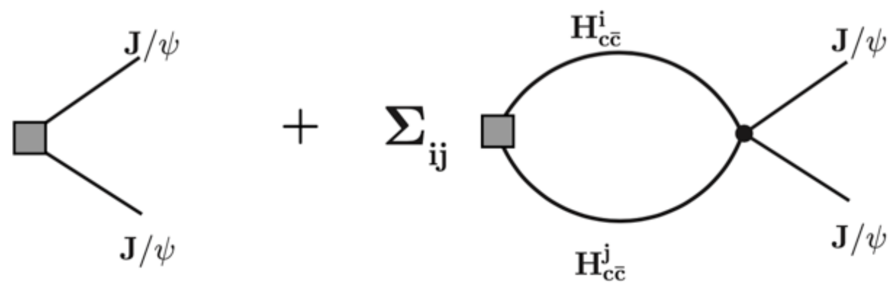
(Dated: September 18, 2020)

aXiv: 2008.07430

Focusing on the novel phenomenon of several enhancement structures existing in the invariant mass spectrum of a J/ψ pair, which was reported by LHCb very recently, we find a new dynamical mechanism based on the special reactions, where all the possible combinations of a double charmonium directly produced by a proton-proton collision are transitted into final state $J/\psi J/\psi$. Under this framework, totally different from the popular tetraquark explanation, the LHCb experimental data of the line shape of J/ψ-pair invariant mass spectrum can be well mimicked. Since the proposed dynamical mechanism is universal enough, we further predict the possible enhancement structures existing in the $\Upsilon(1S)$-pair invariant mass spectrum, which may provide a realistic approach to test this new mechanism proposed in this work and form a new task for the LHCb and CMS experiments.



$$L_{ij}(m_{J/\psi J/\psi}) = \int \frac{dq^4}{(2\pi)^4} \frac{e^{-(2\vec{q})^2/\alpha^2}}{(q^2 - m_i^2 + i\epsilon)((P-q)^2 - m_j^2 + i\epsilon)}$$

$$= \frac{i}{4 m_i m_j} \left\{ \frac{-\mu\alpha}{\sqrt{2}(2\pi)^{3/2}} + \frac{\mu\sqrt{2\mu m_0}\left(\mathrm{erfi}\left[\frac{\sqrt{8\mu m_0}}{\alpha}\right] - i\right)}{2\pi / e^{-\frac{8\mu m_0}{\alpha^2}}} \right\}, \quad (1)$$

$$\mathcal{A}^2_{direct} = g^2_{direct}\, e^{c_0 m_{ij}} \frac{1}{8\pi} \frac{\sqrt{\lambda(m_{ij}^2, m_i^2, m_j^2)}}{m_{ij}^2}, \quad (2)$$

where $\lambda(x^2, y^2, z^2) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$ is the Källen function, and m_{ij} is the corresponding invariant mass. For the rescattering processes with two types of intermediate charmonium pairs $H^i_{c\bar{c}} H^j_{c\bar{c}} = J/\psi J/\psi, \chi_{cJ}\chi_{cJ}, \chi_{c0}\chi'_{c1}$ and $H^i_{c\bar{c}} H^j_{c\bar{c}} = \eta_c \chi_{cJ}, J/\psi h_c$ in Fig. 1, the line shapes on the invariant mass spectrum of $m_{J/\psi J/\psi}$ are given by

$$\mathcal{A}^2_{ij}(m_{J/\psi J/\psi}) = g^2_{ij} L^2_{ij}(m_{J/\psi J/\psi}) \frac{e^{c_0 m_{J/\psi J/\psi}} p_{J/\psi}}{m_{J/\psi J/\psi}} \quad (3)$$

and

$$\mathcal{A}'^2_{ij}(m_{J/\psi J/\psi}) = g^2_{ij} L^2_{ij}(m_{J/\psi J/\psi}) \frac{e^{c'_0 m_{J/\psi J/\psi}} p^3_{J/\psi}}{m_{J/\psi J/\psi}}, \quad (4)$$

$$\begin{aligned}\mathcal{A}^2 =& \mid \mathcal{A}_{direct}(m_{J/\psi J/\psi}) + \textstyle\sum_{mn} e^{i\phi^{mn}} \mathcal{A}_{mn}(m_{J/\psi J/\psi}) \mid^2 \\ &+ \mid \mathcal{A}'_{direct}(m_{J/\psi J/\psi}) + \textstyle\sum_{mn} e^{i\phi^{mn}} \mathcal{A}'_{mn}(m_{J/\psi J/\psi}) \mid^2 \quad (5)\end{aligned}$$

The experimental data can be reproduced

without introducing exotic $c\bar{c}c\bar{c}$ states

Rescattering mechanism

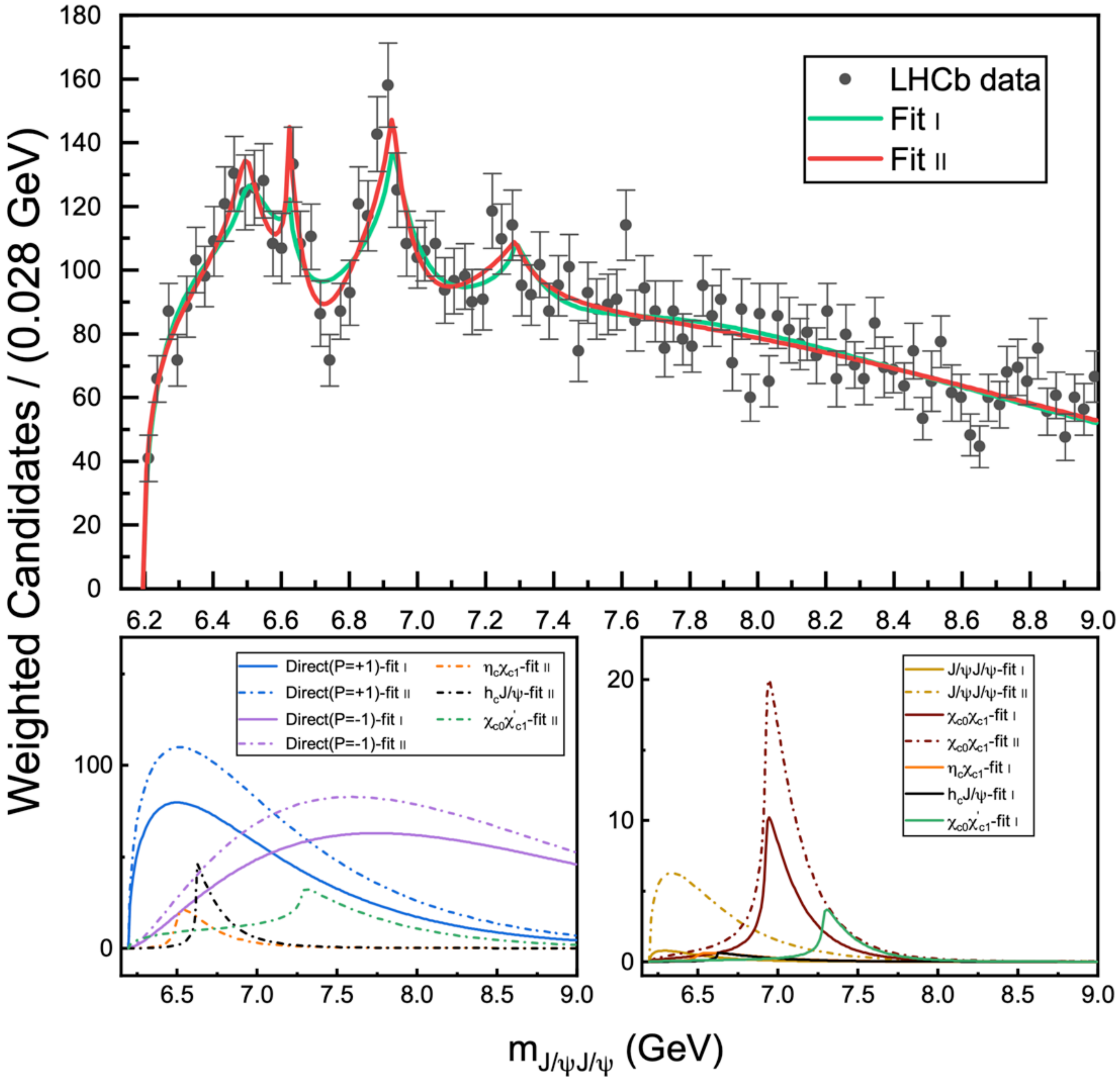


TABLE I: The parameters for reproducing the line shape of LHCb data in two fitting schemes of fit I and fit II.

Parameters	Fit I	Fit II
c_0 (GeV^{-1})	-1.52 ± 0.02	-1.45 ± 0.01
c_0' (GeV^{-1})	-0.946 ± 0.058	-1.05 ± 0.01
$\mid g'_{direct}/g_{direct} \mid$	0.0767 ± 0.0204	0.137 ± 0.042
$\mid g_{J/\psi J/\psi}/g_{direct} \mid$	8.53 ± 3.64	14.0 ± 1.4
$\mid g_{\eta_c\chi_{c1}}/g'_{direct} \mid$	91.6 ± 75.4	112 ± 28
$\mid g_{J/\psi h_c}/g'_{direct} \mid$	69.7 ± 16.1	109 ± 8
$\mid g_{\chi_{c0}\chi_{c1}}/g_{direct} \mid$	33.3 ± 8.2	38.5 ± 7.6
$\mid g_{\chi_{c0}\chi'_{c1}}/g_{direct} \mid$	25.8 ± 10.6	19.0 ± 4.3
$\phi_{J/\psi J/\psi}$ (rad)	1.53 ± 0.51	3.16 ± 0.19
$\phi_{\eta_c\chi_{c1}}$ (rad)	2.69 ± 0.20	2.80 ± 0.15
$\phi_{J/\psi h_c}$ (rad)	4.40 ± 0.33	2.95 ± 0.24
$\phi_{\chi_{c0}\chi_{c1}}$ (rad)	2.14 ± 0.18	2.89 ± 0.20
$\phi_{\chi_{c0}\chi'_{c1}}$ (rad)	2.00 ± 0.33	3.23 ± 0.20
$\alpha_{J/\psi J/\psi}$ (GeV)	1.71 ± 0.01	2.30 ± 0.21
$\alpha_{\eta_c\chi_{c1}}$ (GeV)	1.71 ± 0.01	1.20 ± 0.21
$\alpha_{J/\psi h_c}$ (GeV)	1.71 ± 0.01	1.20 ± 0.03
$\alpha_{\chi_{c0}\chi_{c1}}$ (GeV)	1.71 ± 0.01	1.73 ± 0.26
$\alpha_{\chi_{c0}\chi'_{c1}}$ (GeV)	1.71 ± 0.01	5.20 ± 0.05
$\chi^2/d.o.f$	1.41	1.25

Wang, Chen, XL, Matsuki, aXiv: 2008.07430

Similar phenomenon existing in di-$\Upsilon(1S)$ invariant mass spectrum

Opportunity for LHCb and CMS

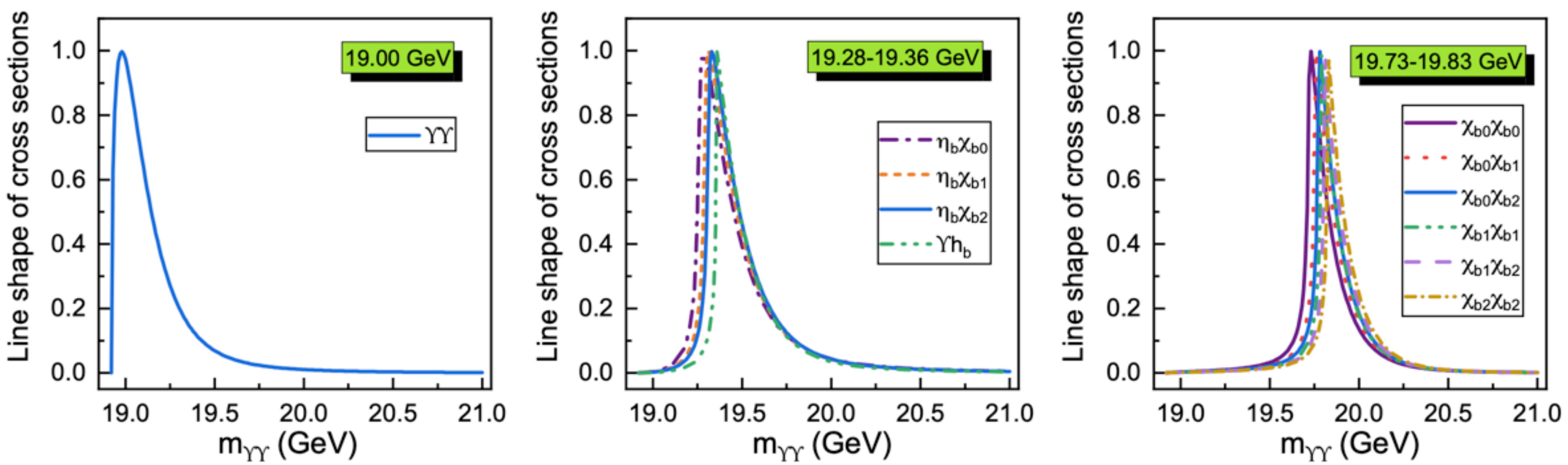
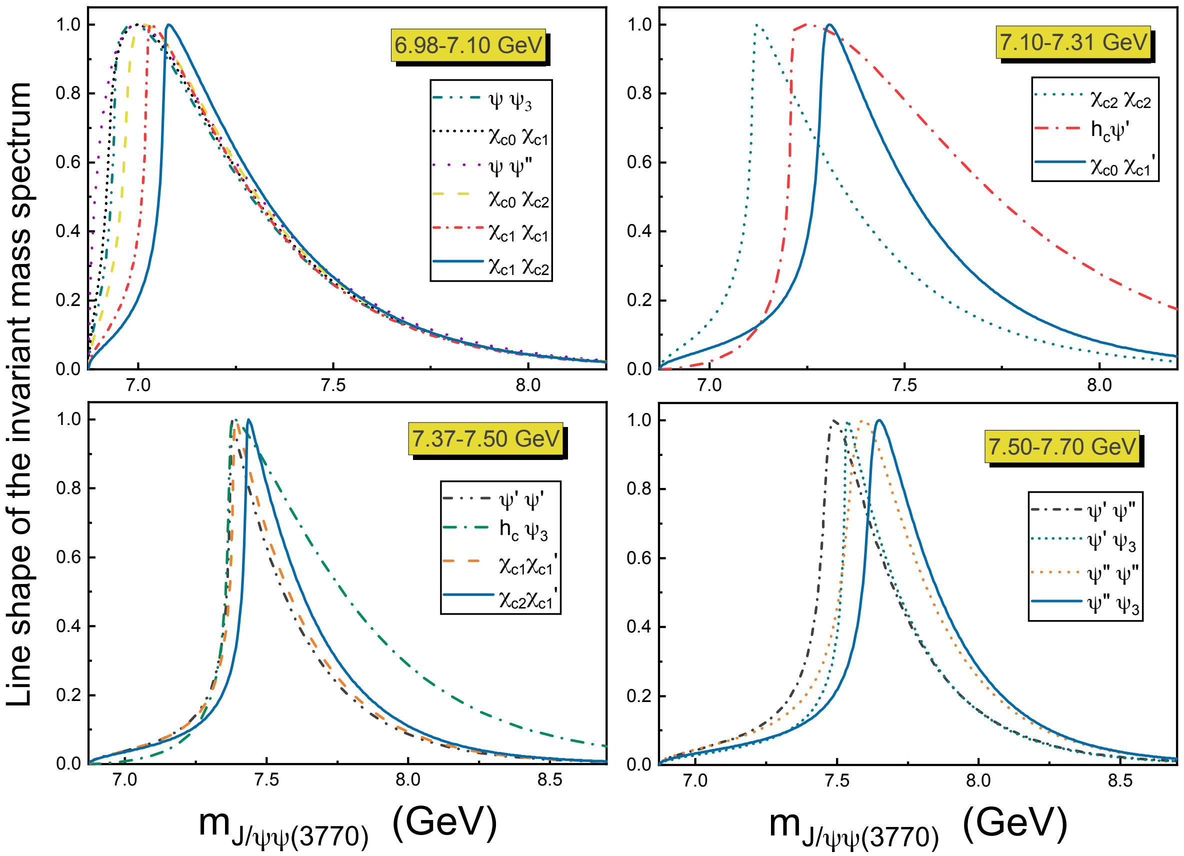
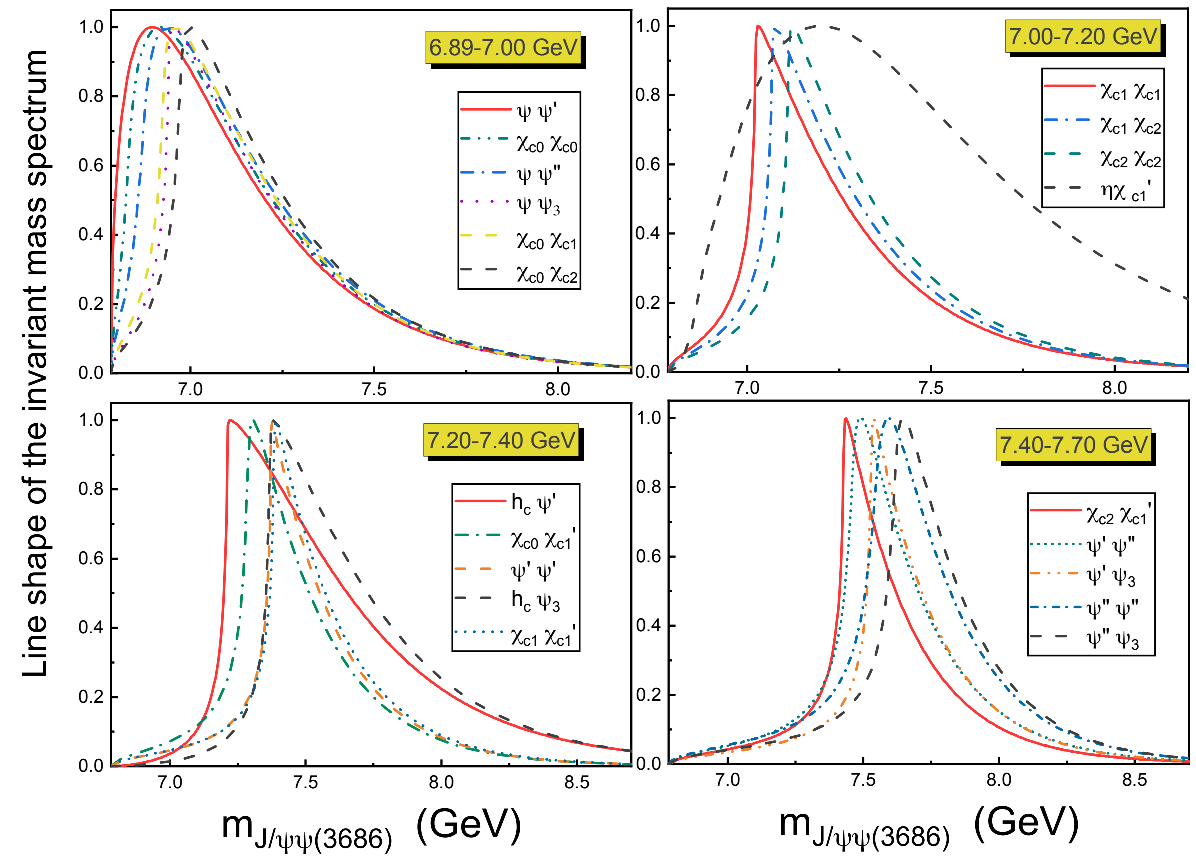


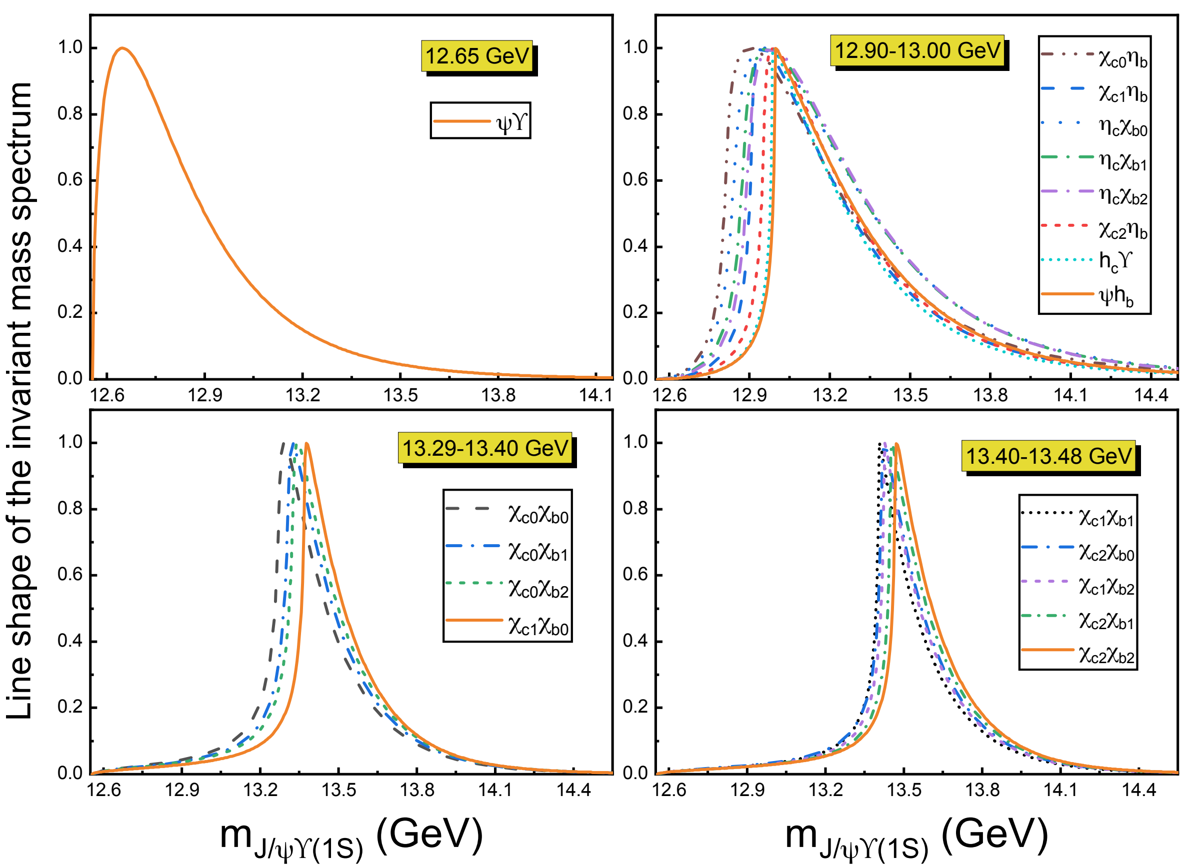
FIG. 4: The theoretical predictions for the peak line shapes from dynamical rescattering mechanism in the invariant mass spectrum of $m_{\Upsilon\Upsilon}$, in which the channels of $\Upsilon(1S)\Upsilon(1S)$, $\eta_b\chi_{bJ}$, $\Upsilon(1S)h_b$, $\chi_{bJ}\chi_{bJ}$ with $J = 0, 1, 2$ are considered. Here, the maximums are normalized to one.

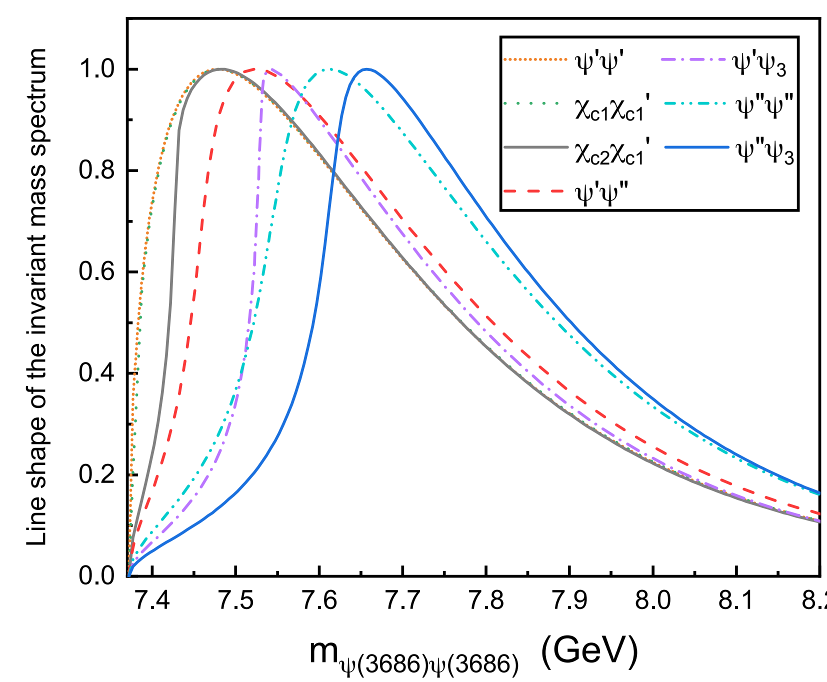
Wang, Chen, XL, Matsuki, aXiv: 2008.07430

More predictions









Wang, XL, Matsuki, aXiv: 2012.03281

4

Summary

How to establish an exotic state

Concept | Model | Experiment | Identify

- 奇特态研究可以提供启示—耦合道效应用于研究X(3872)
- B衰变中的XYZ类粲偶素态的研究应该予以重视
- 非共振态的解释是在确立奇特态的过程中的重要环节

Thank you for your attention