北京大學

The hidden-charm multiquark states

Shi-Lin Zhu

School of Physics, Peking University

INPC 2016

Adelaide, Sep 13, 2016

Collaborators: X. Liu, H.X. Chen, Y.R. Liu, N. Li, Z.G. Luo, X.L. Chen, W.Z. Deng, W. Chen, M.L. Du, J. He, Z.F. Sun, L. Ma, X.H. Liu, L. Zhao

Outline

- Motivation
- Experimental status
- Theory
- Selected examples: Pc, X(3872), Zb/Zc, Y(4260)
- Summary

Not covered topics: Zc(4430), Zc(4200)...

Chen, Chen, Liu, Zhu, Phys. Rept. 639 (2016) 1-121

Why hadron physics?

- The motion and interaction of hadrons differ from those of nuclei and quark/gluons
- Hadron physics is the bridge between nuclear physics and particle physics
- Higgs mechanism contributes around 20 MeV to the nucleon mass through current quark mass
- Nearly all the mass of the visible matter in our universe comes from QCD interaction
- Study of hadron spectrum explores the mechanism of confinement and χSB

Types of hadrons in nature

No of quarks	Configurations	Matter
0	**gg/ggg**	Glueball ??
2	**qq**	Meson
3	**qqq**	Baryon
4	**qqqq**	Tetraquark ??
5	**qqqqq**	Pentaquark ??
6	**qqqqqq**	Deuteron
N → ∞		Nuclei → Neutron star

QED	QCD
No $e^-e^-e^-$ bound state	qqq (baryons)
No $\gamma\gamma$ bound state	gg/ggg (glueballs)
No $e^+e^-\gamma$ bound state	qqg (hybrid)

the QED analogues of the baryon, glueball and hybrid meson do NOT exist.

	QED	QCD
Positronium	**e+e-**	qq (π)
muonium	μ+μ-	ss (φ)
μe bound state	μ+e-	sq (K)
H	pe-	Qq/Qqq (D, Σ_c)
Positronium molecule	e+e-e+e-	qqqq (σ)??
H_2	pe-pe-	QqQq (tetraquark)??
Polarized atoms or molecules		
(van der Vaals force)		Deuteron√/**Hadronic**

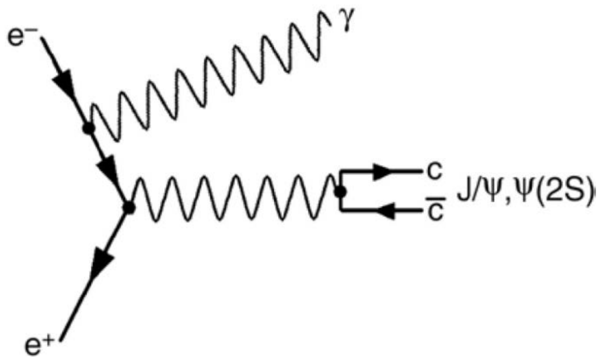
Molecules composed of Heavy hadrons ??

Why are nuclear physicists interested in the XYZ states?

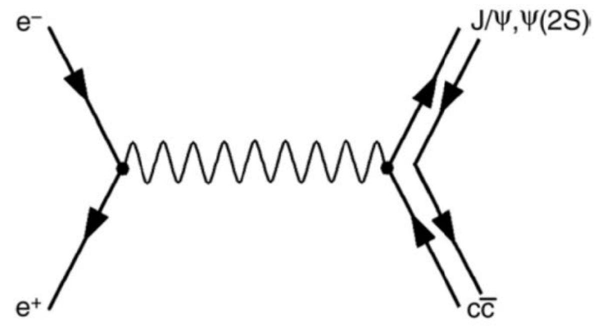
- Some XYZ state may be shallow deuteron-like states
- The chiral dynamics (pion-exchange force) and coupled channel effects are important
- We can use the same nuclear physics techniques to study some of the XYZ states
- I will focus on the XYZ states which the audience may have interest in

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), BABAR [87] (8.6)	2003
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [88–90] (np), DØ [91] (5.2)	
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), BABAR [93] (4.0)	
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), BABAR [96] (4.9)	
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), BABAR [97, 98] (3.6)	
				$B \to K(\gamma\psi(2S))$	BABAR [98] (3.5), Belle [99] (0.4)	
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), BABAR [101] (19)	2004
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)	
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [54] (5.0)	
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [27] (np), Belle [21] (np)	2007
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [108, 109] (8.0)	2005
					CLEO [110] (5.4)	
					Belle [104] (15)	
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)	
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [113] (np), Belle [114] (8.0)	2007
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010

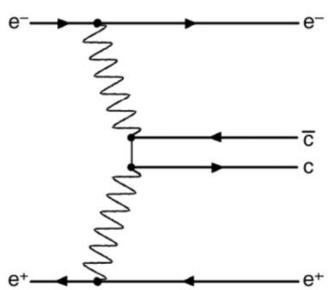
Production Mechanisms Include:



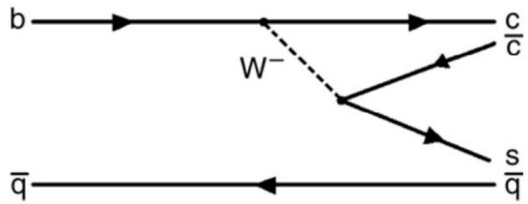
Initial State Radiation (ISR)



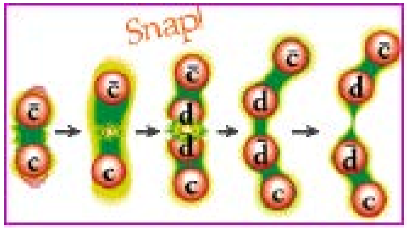
Double charmonium production



2γ production



B decay



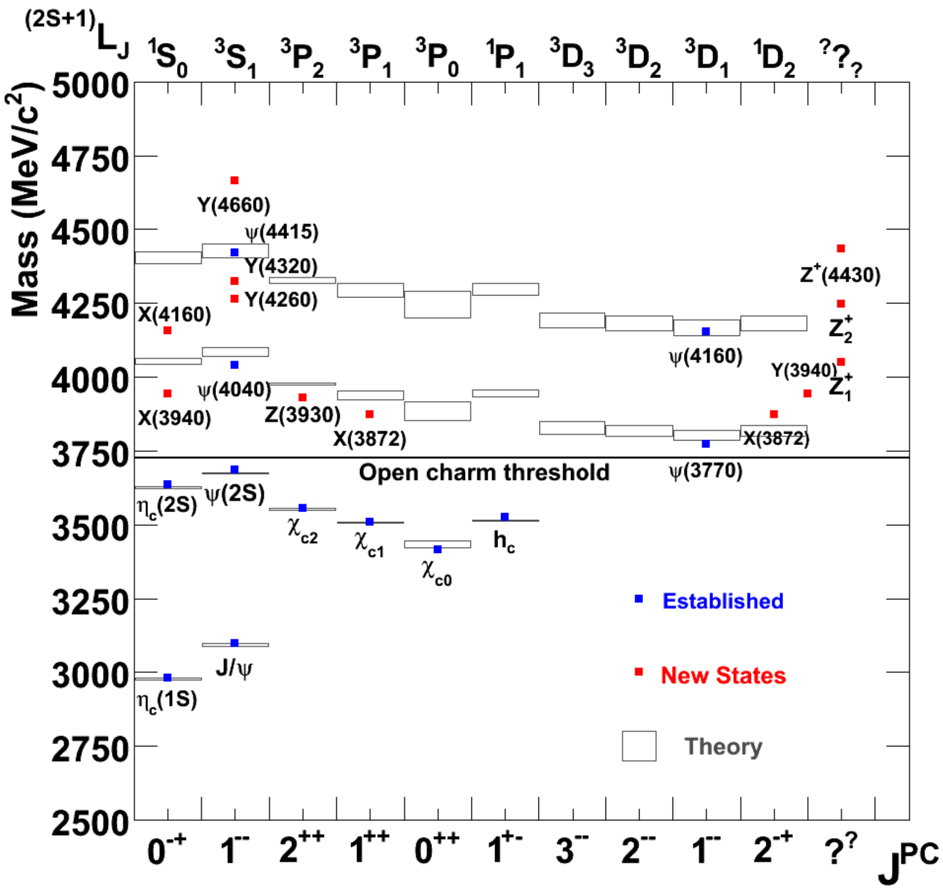
Excited Charmonium decay

Discovery Modes

		Hidden charm						Open charm			
	state	$J/\psi\pi\pi$	$J/\psi K\bar{K}$	$J/\psi\omega$	$J/\psi\phi$	$\psi(2S)\pi\pi$	$\chi_{c1}\pi^+$	$\psi(2S)\pi^+$	$D^0\bar{D}^{*0}$	$D\bar{D}$	$D^*\bar{D}^*$
neutral	$X(3872)$	■		■					■		
	$Y(4260)$	■	■								
	$Y(4320)$					■					
	$Y(3940)$			■							
	$X(3940)$ §								■		
	$Z(3940)$									■	
	$Y(4008)$	■									
	$X(4160)$										■
	$X(4664)$					■					
	$Y(4140)$				■						
	$Y(4274)$				■						
charge	$Z^+(4430)$							■			
	$Z^+(4050)$						■				
	$Z^+(4248)$						■				

Discovery modes include Hidden-charm and open charm

Charmonium Spectrum and XYZ



•Lattice QCD simulation reproduces the charmonium spectrum below the DD threshold very well

•Many new states above the DD threshold were discovered since 2003

•Some are even **charged.** They are good candidates of exotic mesons

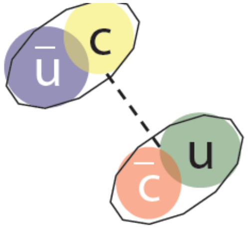
XYZ: resonant vs non-resonant

- Many XYZ states lie very close to open-charm threshold
- It's quite possible some threshold enhancements are not ***real*** resonances.
- They could arise from
  - 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
  - …

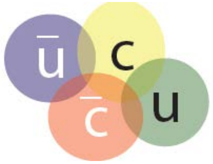
Possible Speculations

Many XYZ states do not fit into quark model spectrum easily. Theoretical speculations include:

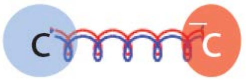
- **Molecular states:** loosely bound states composed of a pair of mesons, probably bound by the pion exchange



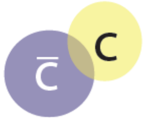
- **Tetraquarks:** bound states of four quarks, bound by colored-force between quarks, some are charged or carry strangeness, there are many states within the same multiplet



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



- **Conventional charmonium:** quark model spectrum could be distorted by the coupled-channel effects



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multi-quark states were discussed when the quark model was proposed

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.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

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 baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

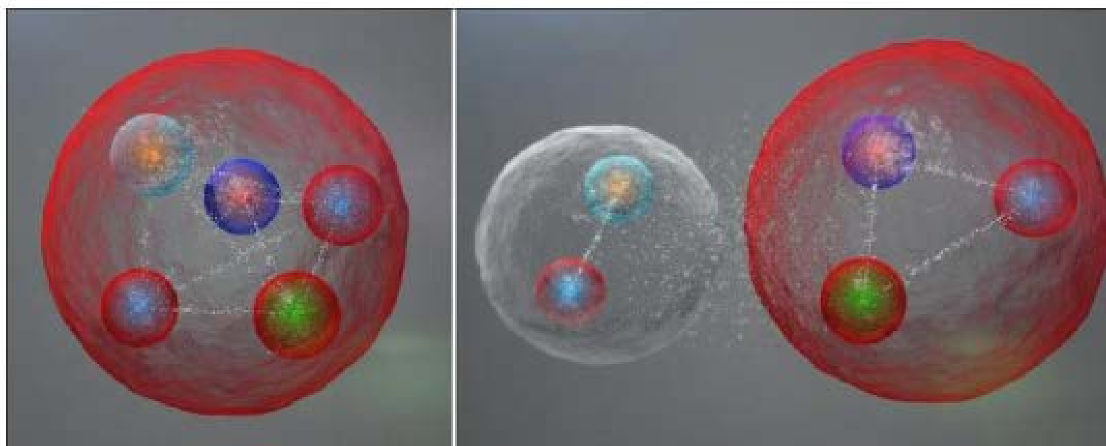
Prejudices

- No convincing states 50 years after Gell-Mann paper proposing $qqqq\bar{q}$ states
- Previous "observations" of several pentaquark states have been refuted
  - $\Theta^+ \to K^0 p, K^+ n, m = 1.54 \text{ GeV}, \Gamma \sim 10 \text{ MeV}$
  - Resonance in $D^{*-}p$ at $3.10 \text{ GeV}, \Gamma = 12 \text{ MeV}$
  - $\Xi^{--} \to \Xi^- \pi^-, m = 1.862 \text{ GeV}, \Gamma < 18 \text{ MeV}$
- Generally they were found/debunked by looking for "bumps" in mass spectra circa 2004

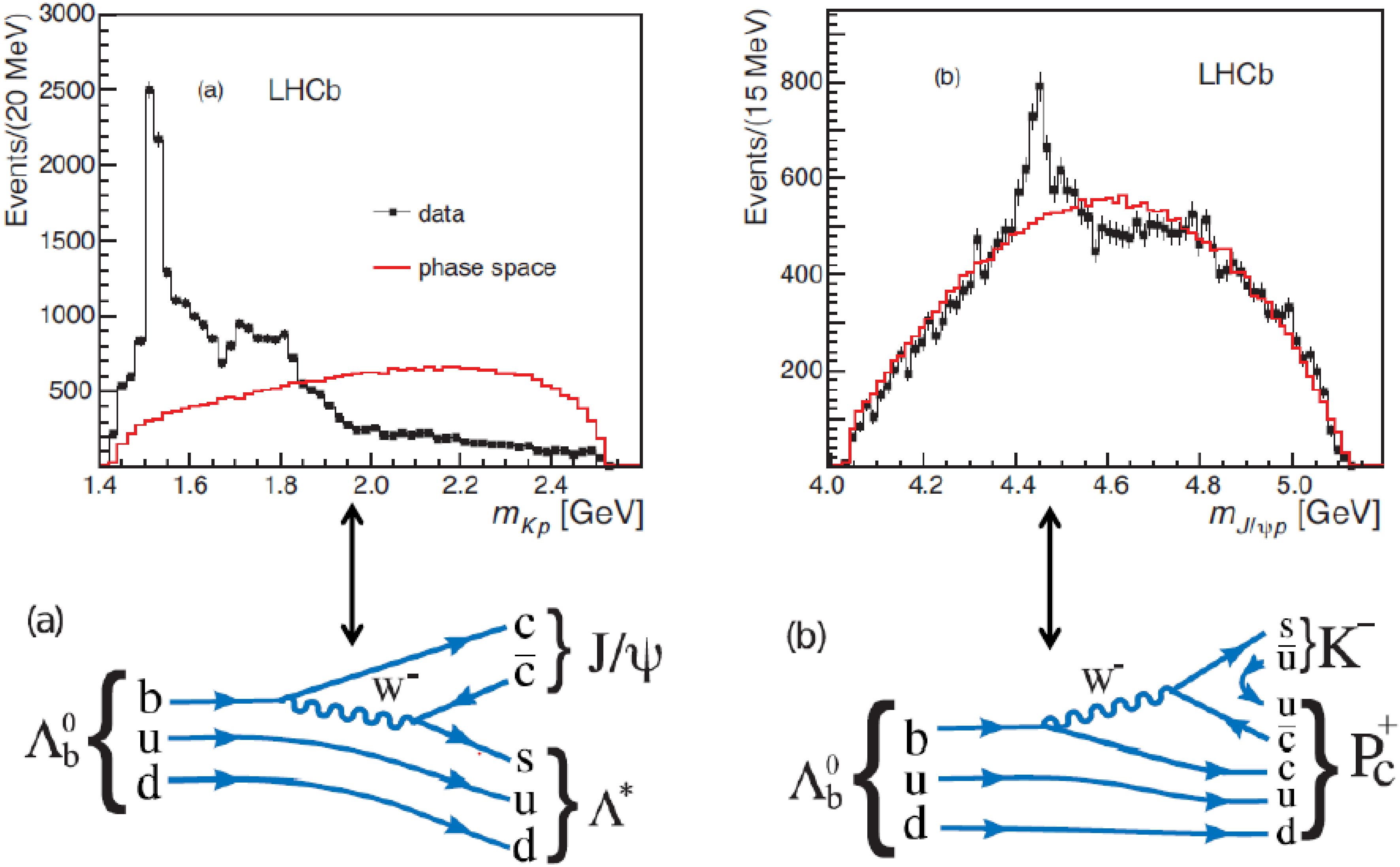
See summary by [K. H. Hicks, Eur. Phys. J. H37 (2012) 1]

- The LHCb experiment at CERN's Large Hadron Collider has reported **the discovery of a class of particles** known as **pentaquarks**.

Posted by Corinne Pralavorio on 14 Jul 2015. Last updated 14 Jul 2015, 10.19.
Voir en français



Possible layout of the quarks in a pentaquark particle. The five quarks might be tightly bound (left). They might also be assembled into a meson (one quark and one antiquark) and a baryon (three quarks), weakly bound together (Image: Daniel Dominguez)



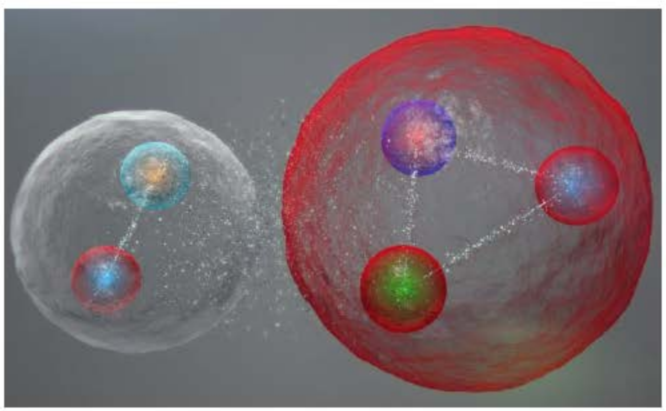
Events/(20 MeV)
3000
2500
2000
1500
1000
500
(a)
LHCb
data
phase space
1.4
1.6
1.8
2.0
2.2
2.4
m_Kp [GeV]
Events/(15 MeV)
800
600
400
200
(b)
LHCb
4.0
4.2
4.4
4.6
4.8
5.0
m_J/ψp [GeV]
(a)
Λb0
b
u
d
W-
c
c̄
J/ψ
s
u
d
Λ*
(b)
Λb0
b
u
d
W-
s
ū
K−
u
c̄
c
u
d
Pc+

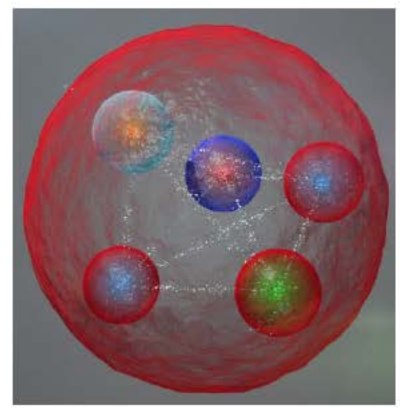
Summary

- Have performed a full amplitude fit to $\Lambda_b^0 \to J/\psi\, pK^-$
- Two Breit-Wigner shaped resonances in $J/\psi p$ mass are observed, with minimal quark content of $c\bar{c}uud$, therefore called pentaquark-charmonium states
  - The preferred J^P are of opposite parity, with one state having $J = \frac{3}{2}$ and the other $J = \frac{5}{2}$

	$P_c(4380)^+$	$P_c(4450)^+$
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
Best fit	3/2-	5/2+

- Different binding mechanisms are possible
  - Tightly-bound
  - Weakly bound “molecules” of baryon-meson





Deuteron & One-Boson-Exchange Model

- **The idea of the loosely bound molecular states is not new in nuclear physics since Yukawa proposed the pion in 1935**
- the deuteron is a very loosely bound state composed of a proton and neutron arising from the **meson exchange**
- Besides the **long-range pion exchange**, the **medium-range attraction** from the correlated two-pion exchange (or in the form of the **sigma meson exchange**), the **short-range interaction** in terms of the **vector meson exchange**, and the **S-D wave mixing** combine to form the loosely bound deuteron

- **We adopt the same one-meson-exchange formalism to discuss the possible molecular states composed of a pair of heavy hadrons**
- **To me, the charmed meson and baryon are the same as the proton and neutron**

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

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.

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

arXiv:1105.2901

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\mathbb{V}} = \frac{\beta_B g_V}{\sqrt{2}} \langle \bar{\mathcal{B}}_{\bar{3}}\; v\cdot\mathbb{V}\; \mathcal{B}_{\bar{3}}\rangle, \quad (24)$$

$$\mathcal{L}_{\mathcal{B}_{\bar{3}}\mathcal{B}_{\bar{3}}\sigma} = \ell_B \langle \bar{\mathcal{B}}_{\bar{3}}\; \sigma\; \mathcal{B}_{\bar{3}}\rangle, \quad (25)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{P}} = \frac{i g_1}{2 f_\pi} \epsilon^{\mu\nu\lambda\kappa} v_\kappa \langle \bar{\mathcal{B}}_6\; \gamma_\mu\gamma_\lambda\partial_\nu\mathbb{P}\; \mathcal{B}_6\rangle, \quad (26)$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\mathbb{V}} = -\frac{\beta_S g_V}{\sqrt{2}} \langle \bar{\mathcal{B}}_6\; v\cdot\mathbb{V}\; \mathcal{B}_6\rangle - \frac{i\lambda_S g_V}{3\sqrt{2}} \langle \bar{\mathcal{B}}_6\gamma_\mu\gamma_\nu(\partial^\mu\mathbb{V}^\nu$$

$$\mathcal{L}_{\mathcal{B}_6\mathcal{B}_6\sigma} = -\ell_S \langle \bar{\mathcal{B}}_6\; \sigma\; \mathcal{B}_6\rangle.$$

$$\mathcal{B}_{\bar{3}} = \begin{pmatrix} 0 & \Lambda_c^+ & \Xi_c^+ \\ -\Lambda_c^+ & 0 & \Xi_c^0 \\ -\Xi_c^+ & -\Xi_c^0 & 0 \end{pmatrix},$$

$$\mathcal{B}_6 = \begin{pmatrix} \Sigma_c^{++} & \frac{1}{\sqrt{2}}\Sigma_c^+ & \frac{1}{\sqrt{2}}\Xi_c^{\prime +} \\ \frac{1}{\sqrt{2}}\Sigma_c^+ & \Sigma_c^0 & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} \\ \frac{1}{\sqrt{2}}\Xi_c^{\prime +} & \frac{1}{\sqrt{2}}\Xi_c^{\prime 0} & \Omega_c^0 \end{pmatrix}.$$

cular baryons composed and a charmed baryon*

eng(孙志峰)[2,4] HE Jun(何军)[1,3;1)]
Shi-Lin(朱世琳)[1;3)]

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

Pc as dynamically generated resonance

(Wu, Molina, Oset and Zou, PRL2010)

- Through the S-wave charmed meson and baryon scattering, the hidden-charm baryons with negative parity can also be generated dynamically
- The total widths of the hidden-charm baryons were less than 60 MeV, quite narrow
- The charm-less decay modes are important within this formalism

- Decay channels with open charm or channels in the light sector still dominate
- Several hidden-charm baryons are generated dynamically for one set of J^P

Pc in the diquark model

(Maiani, Polosa, and Riquer, PLB2015)

$$P_c(4380, 3/2^-) = \bar{c}[cq]_{s=1}[qq]_{s=1}, \quad L = 0,$$
$$P_c(4450, 5/2^+) = \bar{c}[cq]_{s=1}[qq]_{s=0}, \quad L = 1,$$

- The authors assumed both quarks and diquarks as fundamental building blocks
- The mass difference between two Pc state is about 70 MeV

  - partly due to the orbital excitation around 280 MeV

  - partly due to the mass difference between scalar and axial-vector diquarks around 200 MeV

X(3872):

χ'_{c1} or **molecule** or **mixture**?

The X(3872) was seen in 2003 by Belle and soon confirmed by several experiment

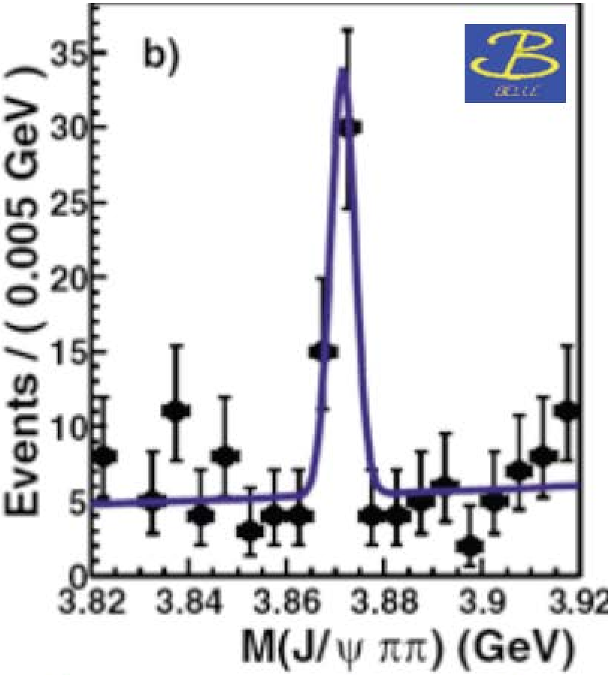
X(3872) interpretation

Conventional Charmonium: $\chi_{c1}(2^3P_1)$ (1^{++}) or $\eta_{c2}(1^1D_2)$ (2^{-+})

$D^0\bar{D}^{*0}$ Molecular interpretation:

$m(D^0) + m(\bar{D}^{*0}) = 3871.73 \pm 0.29$ MeV/c^2

Compatible with $J^{PC} = 1^{++}$ assignment;



PRL 91, 262001 (2003)

X(3872): the new state of play at October 2011

BY@QWG2011; adapted from Nucl. Phys. (Proc. Suppl.) 170, 248–253 (2007)

- narrow; prominent $\pi^+\pi^-\psi$ decay [Belle discovery; CDF, D0, BaBar]
  - $\mathcal{B}(X \to \pi^+\pi^-\psi) > 4.2\%$ [BaBar inclusive, *PRD* **71**, 031501]
  - $\Gamma < 1.2\,\mathrm{MeV}$ (90% C.L.) [Belle *PRD* **84**, 052004]
- $M = (3871.71 \pm 0.19)\mathrm{MeV} \overset{\Delta \lll \sigma}{=} (m_{\mathrm{D}^0} + m_{\mathrm{D}^*})$ [private WA; $S < 1$]
- $\mathrm{p\overline{p}}$ prod^n: $(16 \pm 5 \pm 2)\%$ b-decay, rest prompt; "ψ'-like" [CDF]
- $X^\pm$ still not seen: not an isovector [BaBar; Belle *PRD* **84**, 052004]
- C-even, from $X \to \gamma\psi$ [Belle, BaBar] and $\pi^0\pi^+\pi^-\psi$ [Belle]
  - $X \to \rho\psi$ dominates, $L = 0, 1$ [CDF & Belle $M(\pi^+\pi^-)$]
  - $J^{PC} = 1^{++}$ or 2^{-+} [CDF & Belle angular; note BaBar $\pi^0\pi^+\pi^-\psi$]
- B^+ *vs* $\mathrm{B}^0 \to \mathrm{K}\,X$: ΔM disfavoured [BaBar & Belle]
- large $\mathcal{B}(X \to (\{\gamma, \pi^0\}\mathrm{D}^0)_{\mathrm{D}^{*0}}\overline{\mathrm{D}}{}^0)$ [Belle & BaBar]
- loose ends: $\pi^0\pi^0\psi$, $\underline{\gamma\psi'}$, $\pi^+\pi^-\eta_c$, $\{\gamma, \pi^0\}\mathrm{D\overline{D}}$ lineshape

— radiative (disputed) & lineshape crucial for structure

Puzzles with X(3872)

- Very close to $\bar{D}D^*$ threshold. Mass difference less than 0.2 MeV
- Very narrow. Width less than 1 MeV
- Discovery mode $X(3872) \rightarrow J/\psi\ \rho \rightarrow J/\psi\ \pi\ \pi$ violates isospin symmetry, but its decay width is comparable to the decay width of $X(3872) \rightarrow J/\psi\ \omega \rightarrow J/\psi\ \pi\ \pi\ \pi$ decay mode
- → **1^{++} charmonium?**
- → **1^{++} molecular state?**

Could X(3872) be a molecule?

We consider

- **the S-D wave mixing** which plays an important role in forming the loosely bound deuteron
- both the neutral $\bar{D}^0 D^{*0}$ and **charged $D^+ \bar{D}^{*-}$ component** in the flavor wave function
- the **mass difference** between the neutral and charged D/D* meson
- **the coupling of $\bar{D}D^*$ to $\bar{D}^*D^*$ channel**
- → **X(3872) is a good candidate of a loosely bound molecular state.**
- **In fact, if we replace the proton and neutron inside the deuteron by the D and D* mesons, we reproduce the X(3872).**

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)

When the Binding Energy is 0.3 MeV Branching Fraction Ratio Agrees With Data

$$R = R_{Phase} \times R_I = \mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0 J/\psi) / \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) = 0.42$$

0.8 ± 0.3 from BABAR Collaboration

$1.0 \pm 0.4(stat) \pm 0.3(syst)$ from Belle Collaboration

Isospin violating

TABLE IV: The variation of the branching fraction ratio, $R = \mathcal{B}(X(3872) \to \pi^+\pi^1\pi^0 J/\psi)/\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$, with the binding energy. "R_{Phase}" is the ratio of the phase space between $J/\psi\omega$ and $J/\psi\rho$. $R_I = \rho(I=0)/\rho(I=1)$ is the ratio of the isoscalar and isovector component.

B.E.(MeV)	R_{Phase}	R_I	R
0.10	0.151	65.76/34.04	0.29
0.20	0.150	70.05/29.95	0.35
0.30	0.149	73.76/26.24	0.42
0.60	0.147	79.81/20.19	0.57
1.00	0.144	84.32/15.68	0.78

Radiative decays

Babar: $$R_{\psi\gamma} \equiv \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.4 \pm 1.4,$$

Belle: <2.1

LHCb: $$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

- However, the E1 decay pattern suggests that X(3872) is a good candidate of the axial vector charmonium.
- If X(3872) is Chi'_c1, both the radial WFs of Chi_c1' and psi(2S) contain one node. Their overlapping is large. Chi_c1' will decay into psi(2S) gamma more esily.
- In fact, this rate is consistent with the quark model prediction for the Chi_c1'.

What's X(3872)?

- LHCb says: "The measured value agrees with expectations for a pure charmonium interpretation of X(3872) and a molecular-charmonium mixture interpretations"
- Moreover, the production cross section of X(3872) is comparable with that of φ(2S), which requires significant ($c\bar{c}$) component
- On the other hand, the isospin violating dipion decay of X(3872) requires the molecular component
- **X(3872) = mixture of χ'_{c1} and molecule ?**

Dynamical lattice QCD simulation

(Padmanath, Lang, and Prelovsek, PRD2015)

- recent dynamical lattice QCD simulation used many operators including ccbar, two-meson and diquark–antidiquark ones, Nf=2, m_π=260 MeV
- they found a lattice candidate for the X(3872) with $J^{PC} = 1^{++}$ and I = 0 only if both ccbar and DD^* operators are included
- this candidate cannot be found without ccbar
- no candidate for the neutral or charged X(3872), or any other exotic candidates are found in the I = 1 channel
- the most recent dynamical lattice QCD simulation strongly disfavors either the diquark–antidiquark or various four-quark interpretations of the X(3872)
- → Supports X(3872) as a mixture of ccbar and molecule

Common Feature: Couple-channel effects important

Λ(1405)

- Lower than quark model prediction for P-wave uds state
- Very close to KN threshold
- Dynamically generated resonance or genuine quark model state?
- Or mixture of uds and KN?
- Two poles with JP=1/2- near Λ(1405)?

D_{s0} (2317)

- Lower than quark model prediction for P-wave cs state
- Very close to DK threshold
- Dynamically generated resonance or genuine quark model state?
- Or mixture of cs and DK?

X(3872)

- Lower than quark model prediction for P-wave state χ'_{c1}
- Very close to DD* threshold
- Mixture of DD* and χ'_{c1} ?

Couple channel effects lower bare quark model level
S-wave continuum distorts QM spectrum

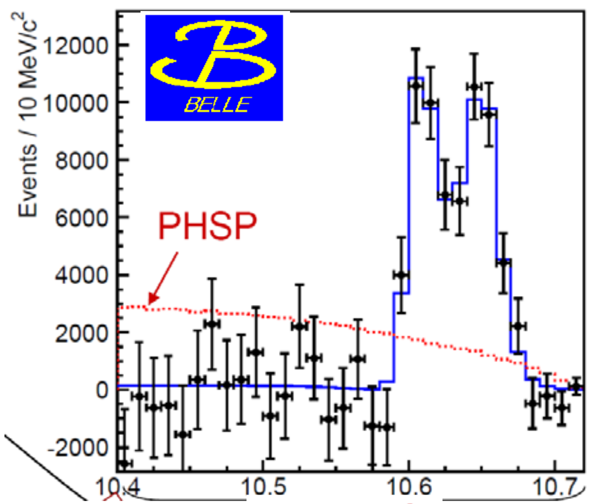
Its bottomonium analogue X_b not found since χ'_{b1} not close to BB* threshold

Belle Observed Two Charged Z_b States

$Z_b(10610)$

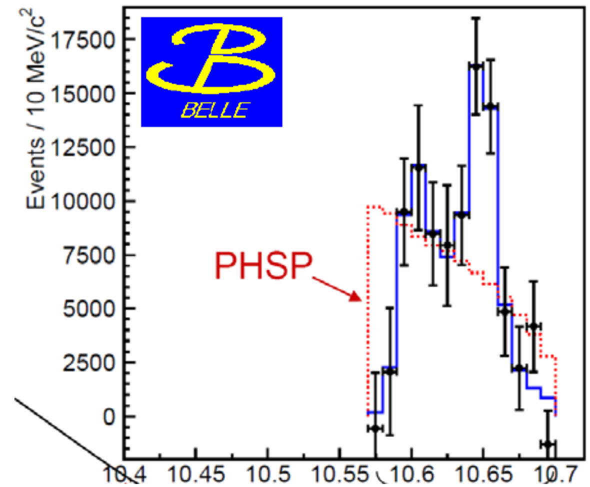
$Z_b(10650)$

$\Upsilon(5S) \to h_b(1P)\,\pi^+\pi^-$



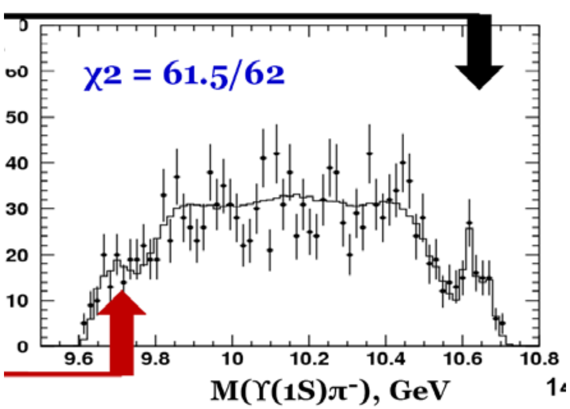
$M(h_b\pi^+)$

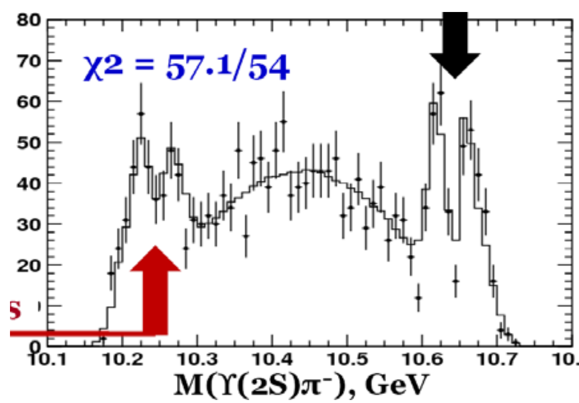
$\Upsilon(5S) \to h_b(2P)\,\pi^+\pi^-$

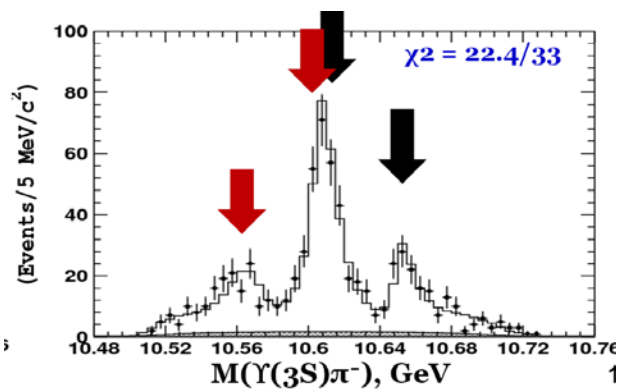


$M(h_b\pi^+)$

$\Upsilon(5S) \to \Upsilon(nS)\,\pi^+\pi^-$







Open-bottom decays dominant

$$\frac{\mathcal{B}(Z_b(10610) \to B\bar{B}^*)}{\sum_{n=1,2,3} \mathcal{B}(Z_b(10610) \to \Upsilon(nS)\pi) + \sum_{m=1,2} Z_b(10610) \to h_b(mP)\pi} = 6.2 \pm 0.7 \pm 1.3^{+0.0}_{-1.8},$$

and

$$\frac{\mathcal{B}(Z_b(10650) \to B^*\bar{B}^*)}{\sum_{n=1,2,3} \mathcal{B}(Z_b(10650) \to \Upsilon(nS)\pi) + \sum_{m=1,2} Z_b(10650) \to h_b(mP)\pi} = 2.8 \pm 0.4 \pm 0.6^{+0.0}_{-0.4},$$

Discovery of $Z_c(3900)^{\pm}$

PRL 110, 252001 (2013)

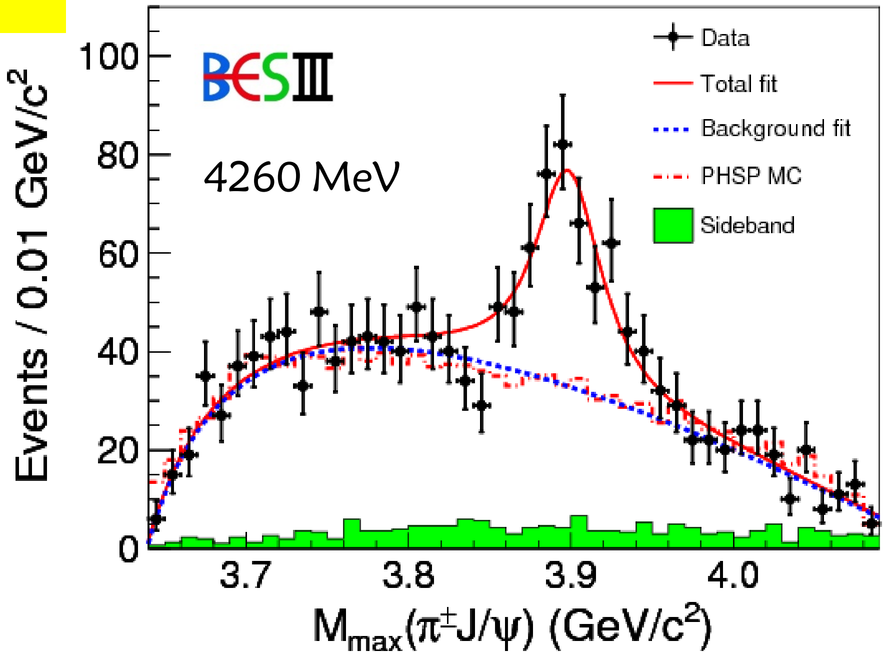
$Z_c(3900)^+$:

$m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$

$\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$

Mass close to $D\bar{D}^*$ threshold

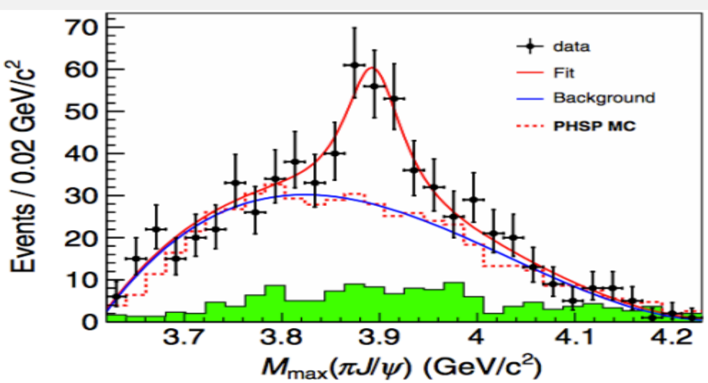
Decays to J/ψ → contains $c\bar{c}$
Electric charge → contains $u\bar{d}$



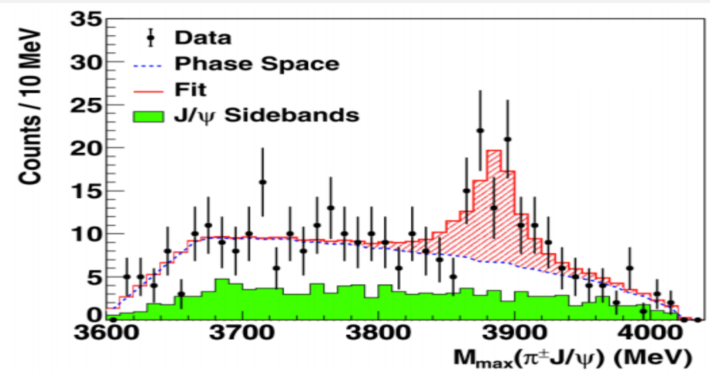
$$\sigma[e^+e^- \to \pi^+\pi^- J/\psi] = 62.9 \pm 1.9 \pm 3.7 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^{\pm} Z_c(3900)^{\mp} \to \pi^+\pi^- J/\psi]}{\sigma[e^+e^- \to \pi^+\pi^- J/\psi]} = (21.5 \pm 3.3 \pm 7.5)\% \text{ at } 4.26 \text{ GeV}$$

Belle with ISR data (PRL 110, 252002)



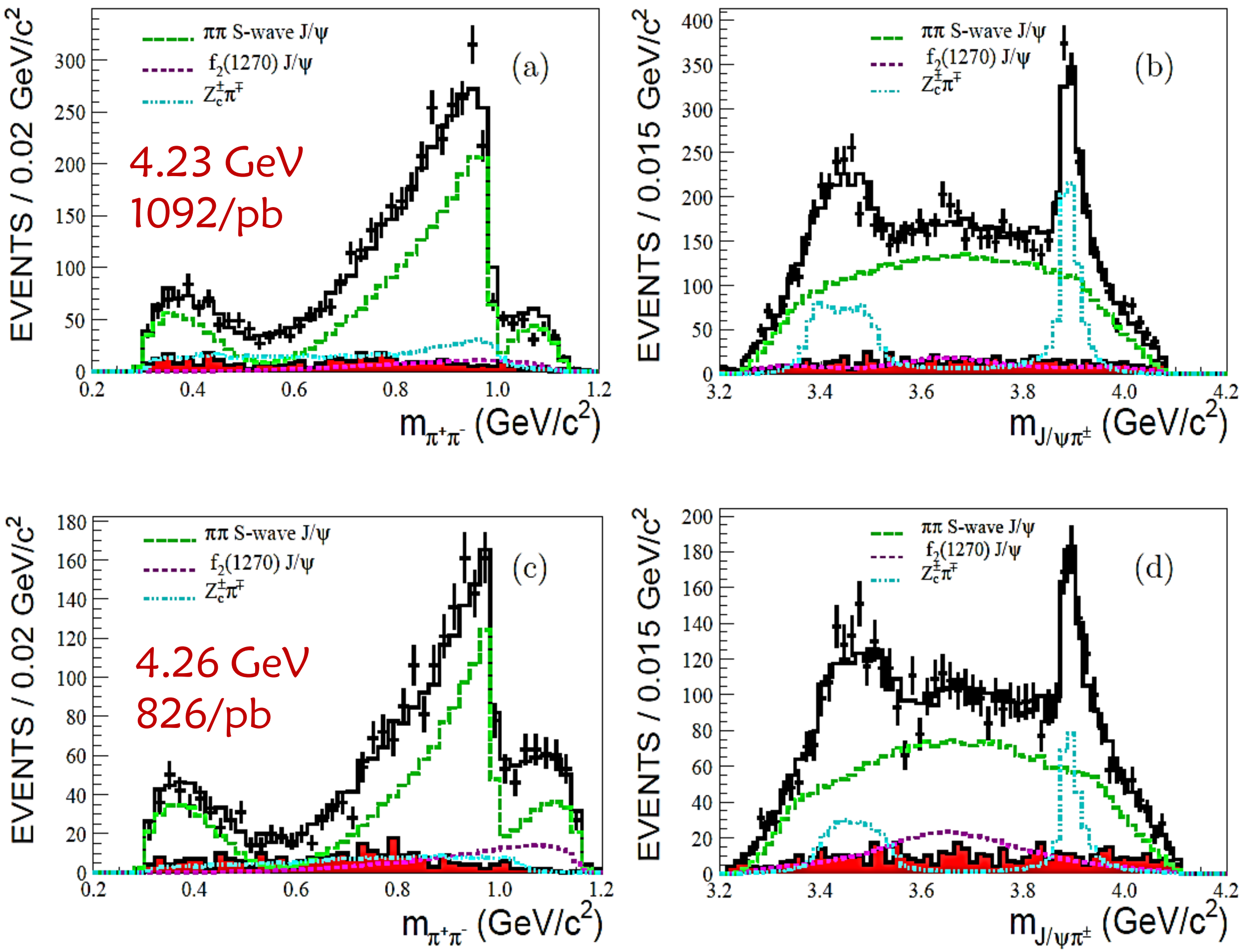
CLE0c data at 4.17 GeV (PLB 727, 366)



BESIII

preliminary

Spin-parity of $Z_c(3900)$



- Asymmetric line shape
- JP=1+ preferred over 0-, 1-, 2-, 2+ by at least 7σ.
- Significant $f_0(980)$ contribution
- $\pi\pi$ D-wave fraction increases as Ecm increases

[large data samples at 4.23, 4.26, 4.36, and 4.42 GeV]

Observation of $Z_c(3885)^{\pm}$ in $e^+e^- \to \pi^{\pm}(D\bar{D}^*)^{\mp}$ at $\sqrt{s} = 4.26\text{GeV}$ using single D tag method

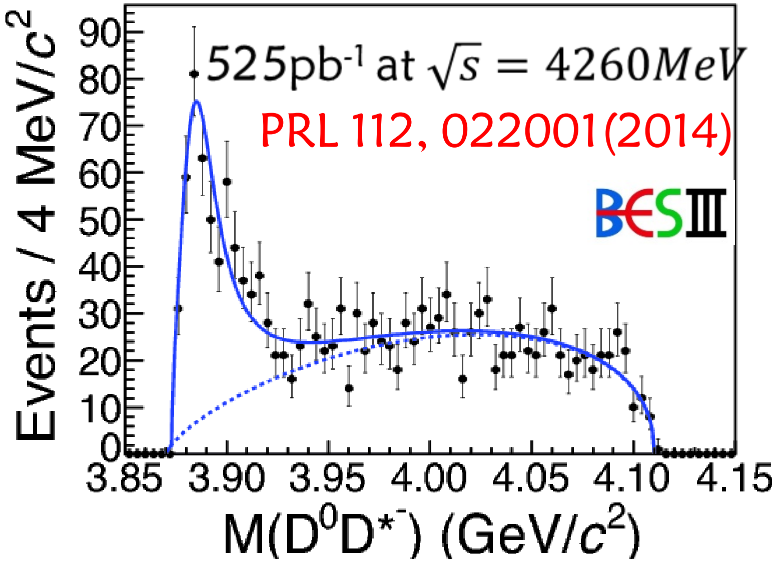
Reconstruct the π^+ and $D^0 \to K^-\pi^+$ and infer the D^{*-}.

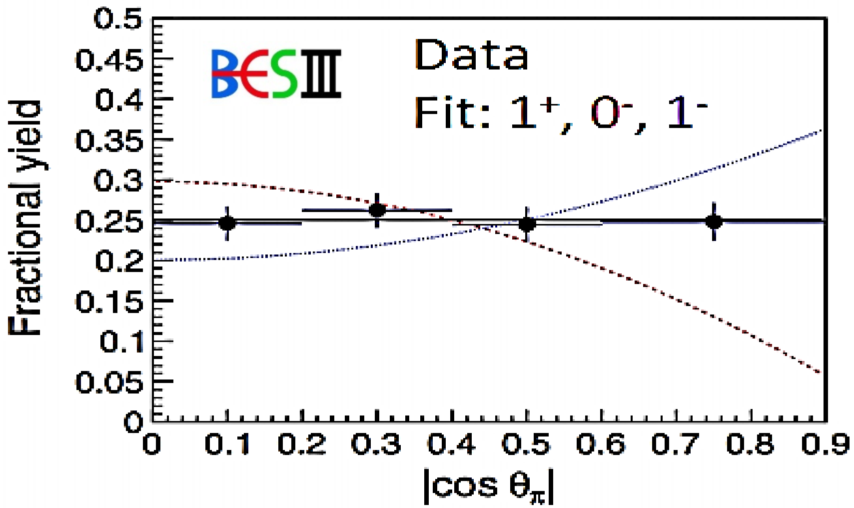
(Also analyze $\pi^+ D^- D^{*0}$ with the same method.)

Enhancement at $D\bar{D}^*$ threshold in both channels ($Z_c(3885)^+$):

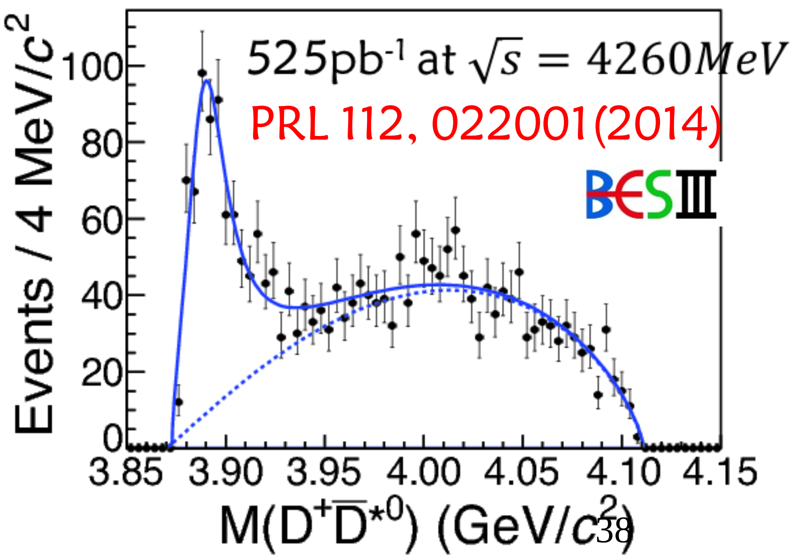
Mass = 3883.9 ± 1.5 ± 4.2 MeV, (fit with BW function)

Width = 24.8 ± 3.3 ± 11.0 MeV





Fit to angular distribution favors $J^P = 1^+$ over 0^- and 1^-



Comparison between $Z_c(3885)^{\pm}$ and $Z_c(3900)^{\pm}$

Single D tag results,
PRL 112, 022001(2014)

	$Z_c(3885) \to D\bar{D}^*$	$Z_c(3900) \to \pi J/\psi$
Mass (MeV/c^2)	$3883.9 \pm 1.5 \pm 4.2$	$3899.0 \pm 3.6 \pm 4.9$
Γ (MeV)	$24.8 \pm 3.3 \pm 11.0$	$46 \pm 10 \pm 20$
$\sigma \times \mathcal{B}$ (pb)	$83.5 \pm 6.6 \pm 22.0$	$13.5 \pm 2.1 \pm 4.8$

- The mass and width are consistent within **2σ!**

- If this is $Z_c(3900)^+$, open charm decays are suppressed, since

$$\frac{\mathcal{B}(Z_c \to D^* \bar{D})}{\mathcal{B}(Z_c \to J/\psi\,\pi)} = 6.2 \pm 1.1 \pm 2.7$$

Compared to e.g.

$$\frac{\mathcal{B}(\psi(4040) \to D^{(*)} \bar{D}^{(*)})}{\mathcal{B}(\psi(4040) \to J/\psi\,\eta)} = 192 \pm 27$$

⇒ Different dynamics in Y(4260)-Zc(3900) system!

Summary of the Z_c states at BESIII

$Z_c^{\pm}(3900)$	$Z_c^{\pm}(4020)$
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ M=3899.0±3.6±4.9MeV Γ = 46±10±20 MeV	$e^+e^- \rightarrow \pi^+\pi^- h_c$ M= 4022.9±0.8±2.7MeV Γ = 7.9±2.7±2.6 MeV
Z_c^0 (3900)	**$Z_c^0(4020)$**
$e^+e^- \rightarrow \pi^0\pi^0 J/\psi$ M=3894.8±2.3 MeV Γ =29.6±8.2 MeV	$e^+e^- \rightarrow \pi^0\pi^0 h_c$ M=4023.9±2.2±3.8 MeV Γ Fixed at $Z_c^{\pm}(4020)$

$Z_c^{\pm}(3885)$	$Z_c^{\pm}(4025)$
$e^+e^- \rightarrow \pi(D^*D)^{\pm}$ M=3882.2±1.1±1.5 MeV Γ =26.5±1.7±2.1 MeV	$e^+e^- \rightarrow \pi(D^*D^*)^{\pm}$ M= 4026.3±2.6±3.7 MeV Γ = 24.8±5.6±7.7 MeV
$Z_c^0(3885)$	**$Z_c^0(4025)$**
$e^+e^- \rightarrow \pi^0(D^*D)^0$ M=3885.7±5.7±8.4 MeV Γ = 35±12±15 MeV	$e^+e^- \rightarrow \pi^0(D^*D^*)^0$ M= 4025.5±4.7±3.1 MeV Γ = 23.0±6.0 ±1.0MeV

Z_b and Z_c Are Very Similar

- **Charged Upsilon-like structure**
- **Z_b are very close to $\bar{B}B^*$, $B^*\bar{B}^*$ threshold**
- **$I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$**
- **Observed both in the hidden-bottom modes: $\pi\Upsilon(1S,2S,3S)$, $\pi\, h_b(1P,2P)$ and open-bottom modes: $\bar{B}B^*$, $B^*\bar{B}^*$**
- **$B(^*)\bar{B}^*$ domonate Z_b decays with the branching ratio 86% and 73%**

- **Charged charmonium-like structure**
- **Z_c are very close to $\bar{D}D^*$, $D^*\bar{D}^*$ threshold**
- **$I^G J^{P(C)} = 1^+ \, 1^{+\,(-)}$**
- **Observed both in the hidden-charm modes: $\pi\, J/\psi$, $\pi\, h_c$ and open-charm modes: $\bar{D}D^*$, $D^*\bar{D}^*$**
- **$\bar{D}D^*$ dominates $Z_c(3900)$ decay**

$$\frac{\Gamma(Z_c(3885)\to D\bar{D}^*)}{\Gamma(Z_c(3900)\to \pi J/\psi)} = 6.2 \pm 1.1 \pm 2.7$$

Could Z_c/Z_b be tetraquarks?

- **Hidden-charm tetraquarks will fall apart into a pair of open-charm D mesons very easily**
- Width should be large while Z_c/Z_b states are quite narrow
- **The s-wave $\bar{D}D^*$mode should dominate the $\bar{D}^*D^*$ mode for higher Zc state because of the huge phase space difference**
- **But BESIII didn't observe $\bar{D}D^*$ mode for Zc(4025)**
- **Belle didn't observe $\bar{B}B^*$ mode for the higher Zb state**

- **Z_c/Z_b are not good candidates of tetraquarks**

Dynamical lattice QCD simulation

(Padmanath, Lang, and Prelovsek, PRD2015)

- **dynamical lattice QCD simulation, which used many operators**
- They didn't find any exotic candidates in the isovector channel
- Lattice QCD simulation strongly disfavors either the diquark–antidiquark or various tetraquark interpretations of the X(3872) and Zc(3900)

If resonant, one possible explanation

- Z_b states are S-wave $\bar{B}B^*$ and $\bar{B}^*B^*$ molecular states
- Z_c states are S-wave $\bar{D}D^*$ and $\bar{D}^*D^*$ molecular-type resonances??

Liu, Liu, Deng, Zhu, EPJC56, 63 (2008)

Liu, Luo, Liu, Zhu, EPJC61, 411 (2009)

> ergy decreases, which is helpful to the formation of the shallow $B\bar{B}$ bound state. In fact, our analysis indicates that there probably exists a loosely bound S-wave $B\bar{B}^*$ molecular state. Once produced, such a molecular state would be rather stable since its dominant decay mode is

Sun, He, Liu, Luo, Zhu, arXiv:1106.2968 [hep-ph], PRD84 (2011); Chin. Phy. C36 (2012)

He, Liu, Sun, Zhu, arXiv:1308.2999[hep-ph], EPJC

One-Boson-exchange model

Bondar, Garmash, Milstein, Mizuk, Voloshin, arXvi:1105.4473 [hep-ph]

Voloshin, arXiv:1105.5829 [hep-ph]

Ohkoda, Yamaguchi, Yasui, Sudoh, Hosaka, arXiv:1111.2921 [hep-ph]

Sun, He, Xiang Liu, Luo, Zhu, PRD84 (2011) 054002

$I^G(J^P)$	System	Remark	Experiment [1]	System	Remark	Experiment
$1^+(1^+)$	$Z^{(T)}_{B\bar{B}^*}$	✓	$Z_b(10610)$	$Z^{(T)}_{D\bar{D}^*}$	×	
$0^-(1^{+-})$	$Z^{(S)}_{B\bar{B}^*}$	✓		$Z^{(S)}_{D\bar{D}^*}$	✓	
$1^-(1^+)$	$Z^{(T)\prime}_{B\bar{B}^*}$	×		$Z^{(T)\prime}_{D\bar{D}^*}$	×	
$0^+(1^{++})$	$Z^{(S)\prime}_{B\bar{B}^*}$	✓		$Z^{(S)\prime}_{D\bar{D}^*}$	✓	$X(3872)$ [60]
$1^-(0^+)$	$Z^{(T)}_{B^*\bar{B}^*}[0]$	✓		$Z^{(T)}_{D^*\bar{D}^*}[0]$	×	
$0^+(0^{++})$	$Z^{(S)}_{B^*\bar{B}^*}[0]$	✓		$Z^{(S)}_{D^*\bar{D}^*}[0]$	✓	$Y(3930)$ [65–67]
$1^+(1^+)$	$Z^{(T)}_{B^*\bar{B}^*}[1]$	✓	$Z_b(10650)$	$Z^{(T)}_{D^*\bar{D}^*}[1]$	×	
$0^-(1^{+-})$	$Z^{(S)}_{B^*\bar{B}^*}[1]$	✓		$Z^{(S)}_{D^*\bar{D}^*}[1]$	✓	
$1^-(2^+)$	$Z^{(T)}_{B^*\bar{B}^*}[2]$	×		$Z^{(T)}_{D^*\bar{D}^*}[2]$	×	
$0^+(2^{++})$	$Z^{(S)}_{B^*\bar{B}^*}[2]$	✓		$Z^{(S)}_{D^*\bar{D}^*}[2]$	✓	$Y(3940)$ [65–67]

$I^G(J^{PC})$	State	Λ	E (MeV)	r_{RMS} (fm)
$1^+(1^+)$	$Z^{(T)}_{B\bar{B}^*}$	2.1	-0.22	3.05
		2.3	-1.64	1.31
		2.5	-4.74	0.84

$1^+(1^+)$	$Z^{(T)}_{B^*B^*}[1]$	2.2	-0.81	1.38
		2.4	-3.31	0.95
		2.6	-7.80	0.68
		2.8	-14.94	0.52

Both Z_b(10610) and Z_b(10650) can be explained as $\bar{B}B^*$ and $\bar{B}^*B^*$ molecular states. Besides Z_b states, there are also several loosely bound isoscalar molecular states.

However, within the same model, the Zc states are not bound. The potential is roughly the same for Zb and Zc. But the kinetic energy of the Zc systems is larger since $M_D<M_B$

Are Zb/Zc real resonances?

- Zc states lie above open-charm thresholds
- Their measured mass and width are channel dependent
- They could be non-resonant signals arising from

- open-charm/bottom thresholds,

- FSI such as DD*/ BB* rescattering

- Or triangle singularity …

All these non-resonant mechanisms could explain the current experimental data .

Vector charmonium family

- In PDG, there are three well-established vector charmonium above 4 GeV: **3S/ψ(4040), 2D/ψ(4160), 4S/ψ(4415)**
- In quark model, one expects two more states below 4.7 GeV at most: **3D, 5S**
- But **seven states** were observed: ψ(4008), ψ(4040), ψ(4160), ψ(4260), ψ(4360), ψ(4415), ψ(4660)
- What are these Y states?
- The current situation is very confusing

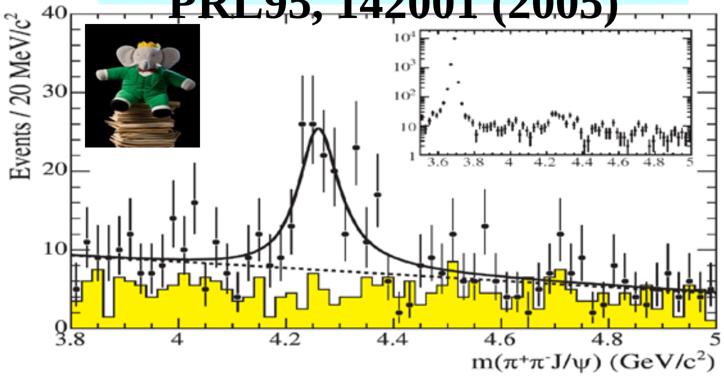
Y(4260) and Y(4360)

Spin-parity: $J^{PC}=1^{--}$

$$e^+e^- \rightarrow \gamma_{\rm ISR}\,\underline{\pi^+\pi^- J/\psi}$$

Experiment	Mass (MeV)	Width (MeV)
BaBar [1]	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
CLEO [3]	$4284^{+17}_{-16} \pm 4$	$73^{+39}_{-25} \pm 5$
Belle [4]	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$
Average [6]	4263^{+8}_{-9}	95 ± 14

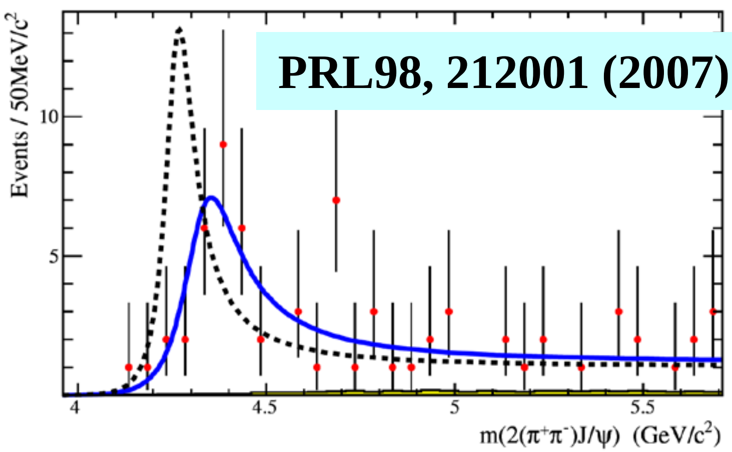
PRL95, 142001 (2005)



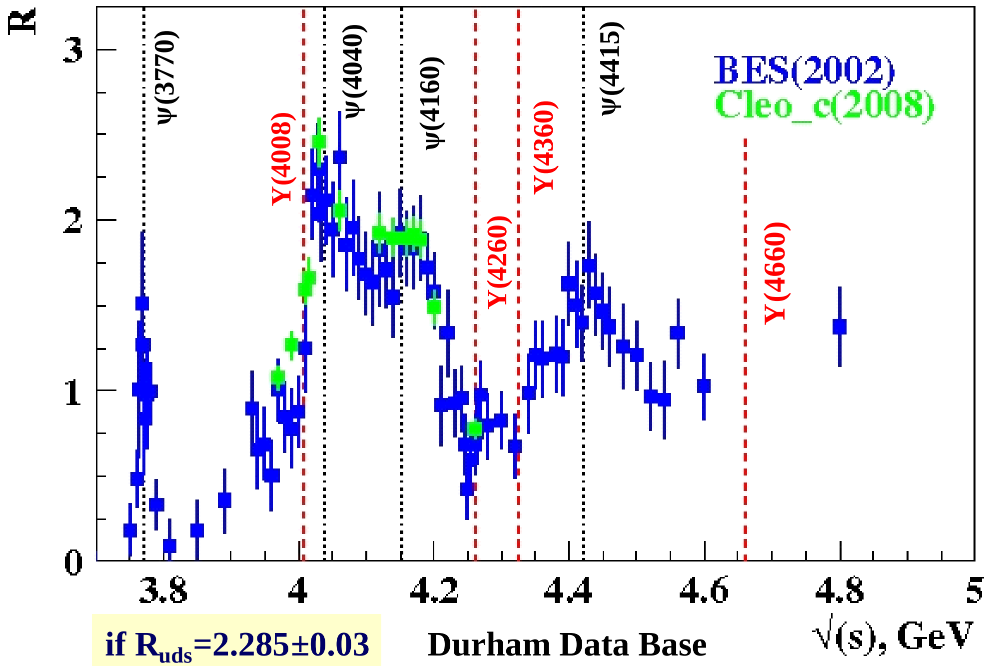
$$e^+e^- \rightarrow \gamma_{ISR}\,\underline{\psi(2S)\pi^+\pi^-}$$

M=4324±24 MeV

Γ=172±33 MeV

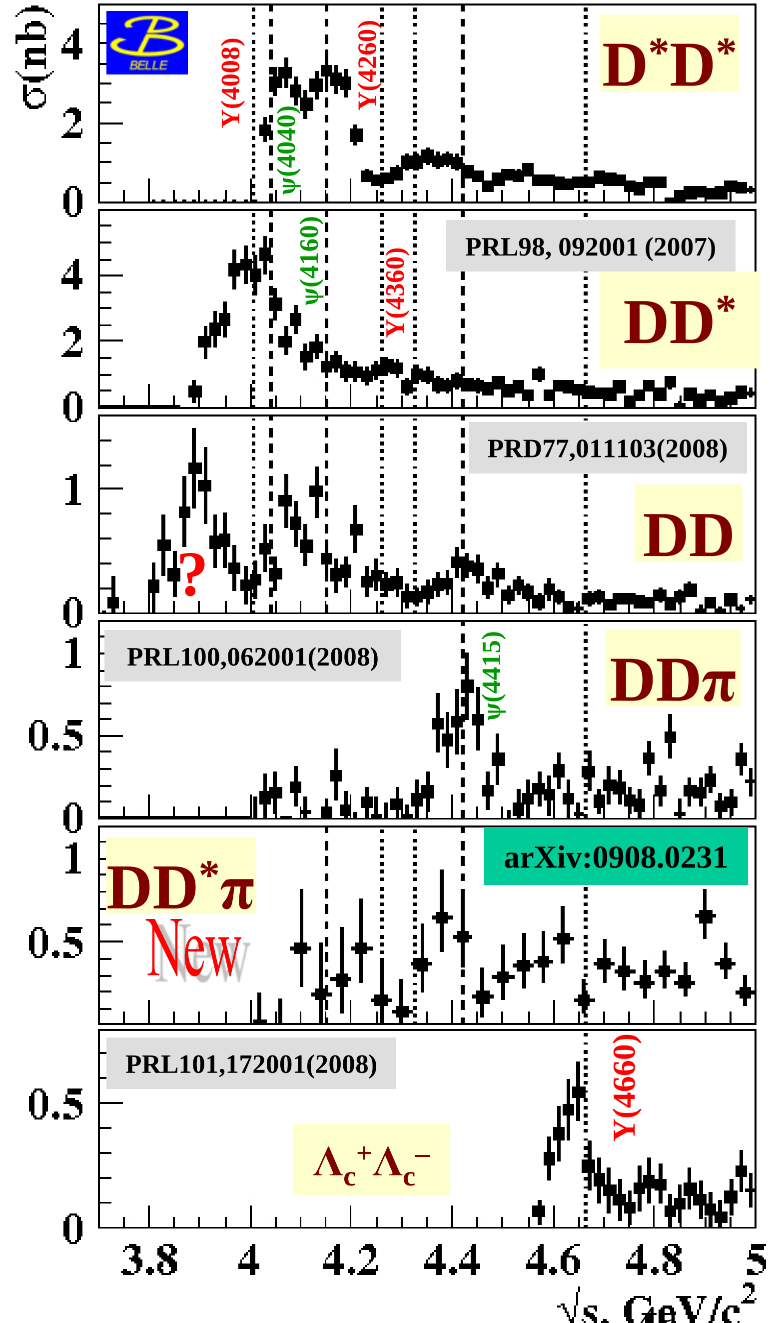


$$R(s) = \sigma(e^+e^- \to \textit{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-) - R_{uds}$$



No evidence of *Y*(4260)/*Y*(4360) in the open-charm process and *R*-value scan

Established vector charmonium appear as a peak.
But Y(4260) and Y(4360) show up as a dip.



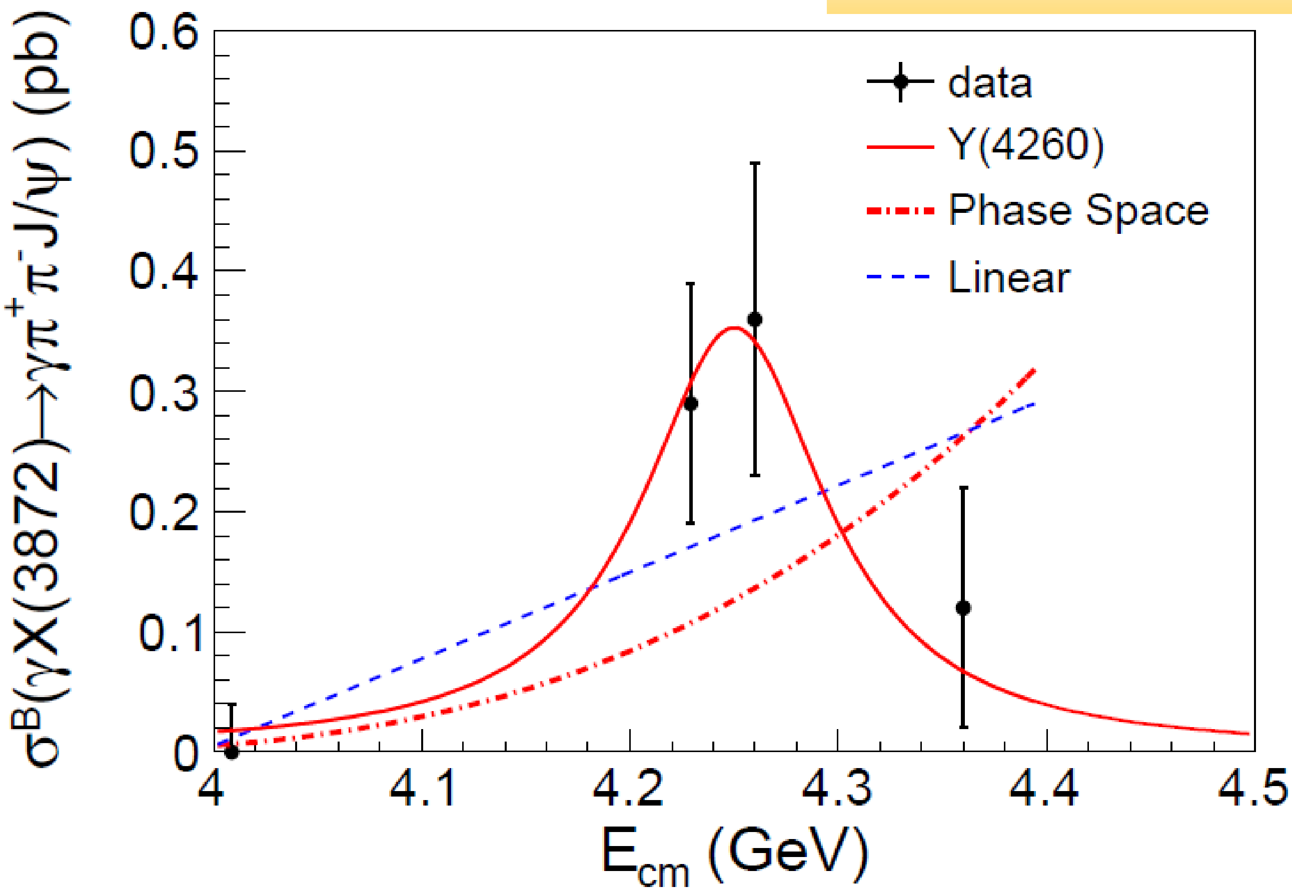
Y(4260) is a good candidate of charmonium hybrid

Zhu; Kou, Pene; Close, Page (2005)

- According to lattice QCD simulation, both the vector and exotic (1^{-+}) hybrid charmonium lie around 4260 MeV
- Because of the gluon, the 1^{--} hybrid charmonium does not couple to the virtual photon very strongly, which explains the dip in the R-value scan
- According to the flux tube model and QCD sum rule analysis, the favorable decay mode of hybrid states is p-wave + s-wave meson pair, which explains the non-observation in the open charm modes

Observation of Y(4260)→γX(3872)

PRL 112, 092001 (2014)



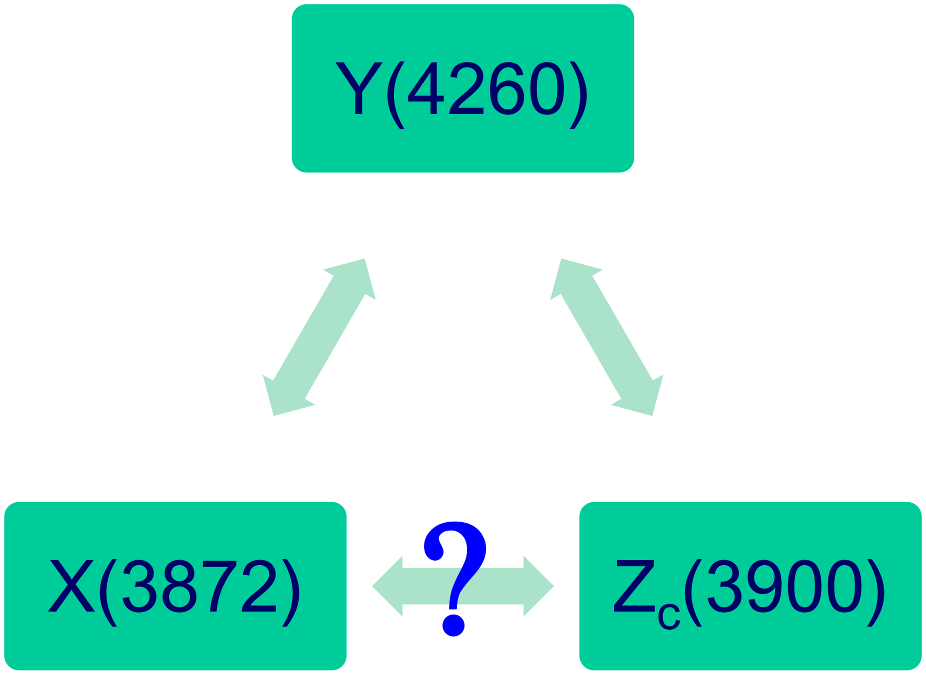
A new Y(4260) decay mode

A new X(3872) production mode

If we take $\mathcal{B}(X(3872)\to\pi^+\pi^- J/\psi)\sim 5\%$, (>2.6% in PDG)

$\frac{\sigma(e^+e^-\to\gamma X(3872))}{\sigma(e^+e^-\to\pi^+\pi^- J/\psi)}\sim$ 10%   Large transition ratio !

X、Y、Z states are correlated!



Both X(3872) and Zc(3900) can be produced from Y(4260) decays.

Summary

- Excited Upsilon states act as an exotic hadron factory

- M[Y(5S)]=**10.860** GeV
- M[$\bar{B}B^{*}+\pi$]=10.604+0.140=**10.744** GeV
- M[$\bar{B}^{*}B^{*}+\pi$]=10.650+0.140=**10.790** GeV
- **Phase space of Y(5S)→$B^{(*)}\bar{B}^{*}\pi$ is tiny**
- **Relative motion between the $\bar{B}^{(*)}B^{*}$ pair is very slow, which is favorable to the formation of the $B^{(*)}\bar{B}^{*}$ molecular states**
- **Y(5S) [or Y(6S)] is the ideal place to study either molecular states or the $B^{(*)}B^{*}$ interaction**
- **Similar signals will be produced abundantly at Belle2 next year!**

Summary

- **The vector charmonium spectrum is very puzzling at present.**

- Excited charmonium decay is ideal in the search of Zc signals
- The **γ, 1π, 2π, 3π** will act as a **quantum number filter**

- **X(3872), χ'_{c1}, Y(4260)** are the key states in revealing the underlying structure of the charmonium-like XYZ states

- Through the **decay pattern and possible partner states**, we can test the various theoretical picture
- Especially the experimental measurement of the **various pionic and electromagnetic transitions** between Y(4360), Y(4260), Z_c(4020), Z_c(3900) and X(3872) are crucial

Hearing Handicapped

Please speak loud and slowly
Thank you very much

Backup slides

Opening of new threshold

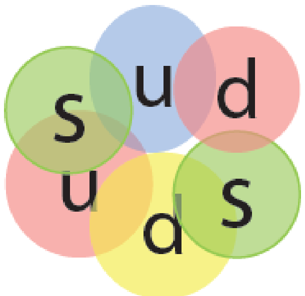
- Let's take e+ e- → D*s D*s as an example
- Y(4260) lies very close to D*s D*s threshold 4224 MeV
- With the opening of new threshold, the cross section

$$\sigma \sim (k\,\beta)^n * \mathrm{Exp}[-(k\,\beta)^2]$$

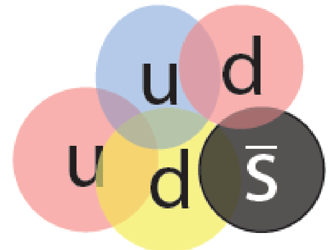
where k is the D*s momentum, β is a parameter, $n \geq 1$

- One would expect an enhancement slightly above the open charm threshold
- Does Y(4260) arise from this threshold enhancement?

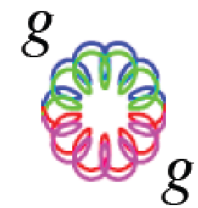
QCD: There are many other possible color singlets.



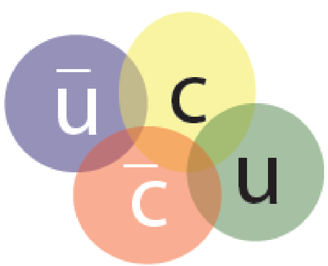
dibaryon



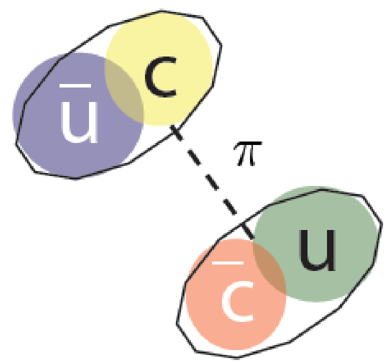
pentaquark



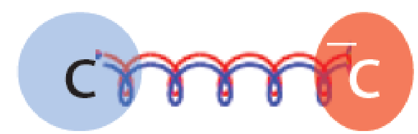
glueball



diquark + di-antiquark



dimeson molecule



$q\,\bar{q}\,g$ hybrid

Molecules in QED and QCD

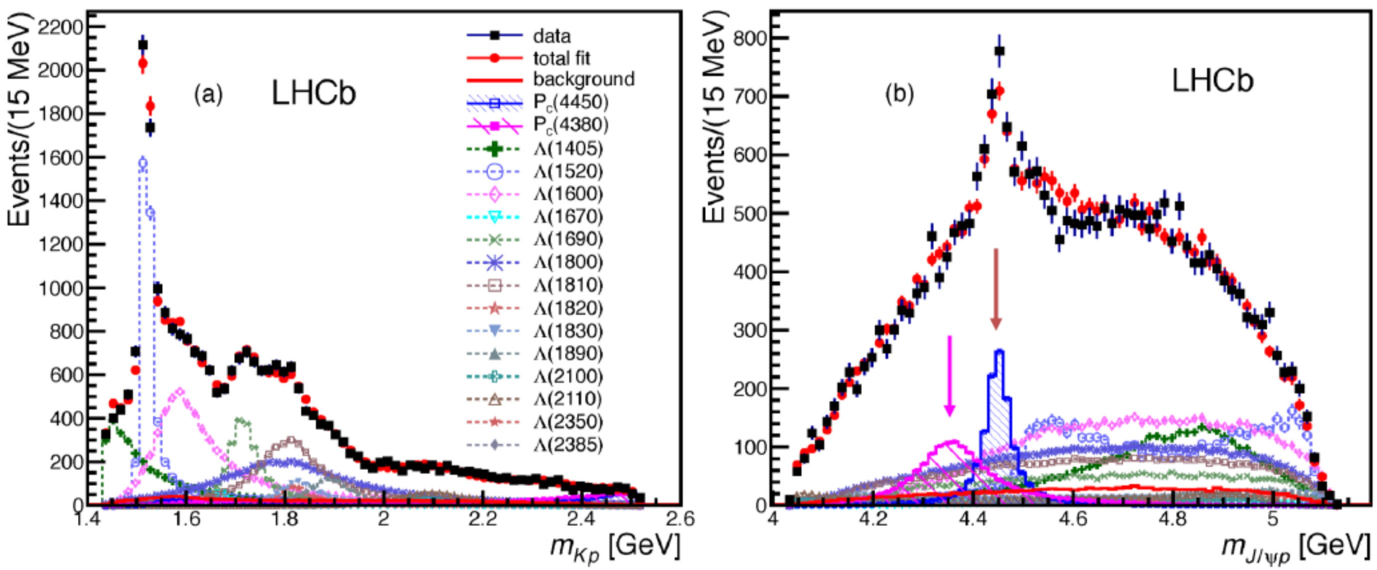
- **QED**
- **Hydrogen atom:**
  light electron circles around proton
- **Hydrogen molecule:**
  two electrons shared by two protons

- **QCD**
- **Heavy meson:**
  light quark circles around heavy quark
- **Di-meson molecule:**
  two mesons bound by pions

Pc

Extended model with two P_c^+'s

- Leads to a good fit
  - The 2nd broad P_c^+ visible in other projections (shown later)
  - It also modifies the narrow P_c^+'s decay angular distribution via interference to match the data



Quantum numbers

- Tested all J^P combinations up to spin $\frac{7}{2}$
- **Best fit has $J^P = \left[\frac{3}{2}^- \text{(low)},\ \frac{5}{2}^+ \text{(high)}\right]$**
  - Plots shown correspond to this combination
- $\left[\frac{3}{2}^+ \text{(low)},\ \frac{5}{2}^- \text{(high)}\right]$ & $\left[\frac{5}{2}^+ \text{(low)},\ \frac{3}{2}^- \text{(high)}\right]$ are also possible: $\Delta(-2\ln\mathcal{L}) < 3^2$
- All others are ruled out: $\Delta(-2\ln\mathcal{L}) > 5.9^2$

Zb and Zc

Observation of $Z_c(4025)^{\pm}$

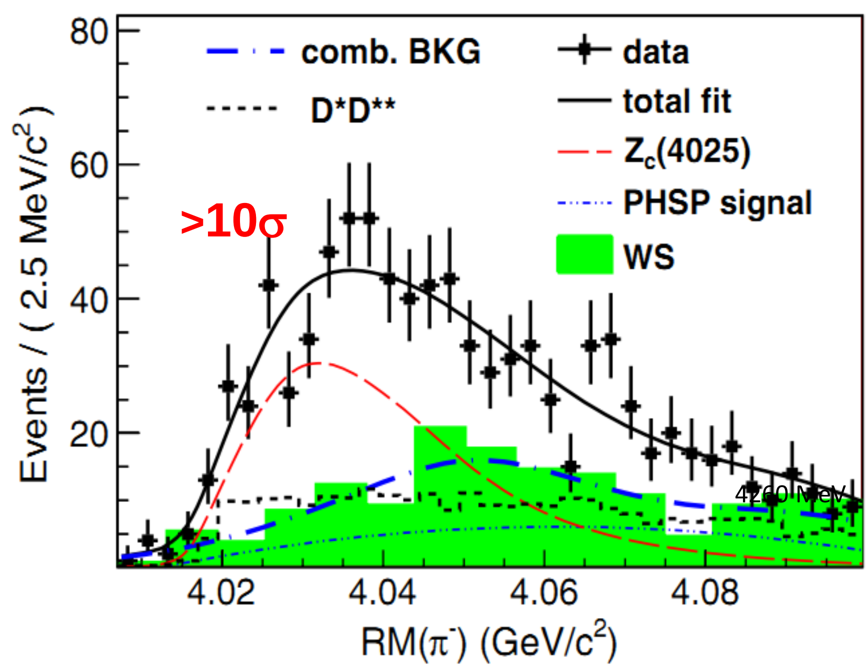
$e^+e^- \to \pi^{\pm}(D^*\bar{D}^*)^{\mp}$ *at* $\sqrt{s} = 4.26GeV$

PRL 112, 132001 (2014)

Tag a D^+ and a bachelor π^-, reconstruct one π^0 to suppress the background.

A structure, named as Zc(4025), can be observed in the recoil mass of the bachelor π^-.

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;
$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV



$$\sigma[e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}] = 137 \pm 9 \pm 15 \text{ pb at } 4.26 \text{ GeV}$$

$$\frac{\sigma[e^+e^- \to \pi^{\pm} Z_c(4025)^{\mp} \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}]}{\sigma[e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}]} = 0.65 \pm 0.09 \pm 0.06 \text{ at } 4.26 \text{ GeV}$$

Coupling to $\bar{D}^*D^*$ is much larger than to πh_c if $Z_c(4025)$ and $Z_c(4020)$ are the same state.

How To Test the OPE Model And Molecular Picture?

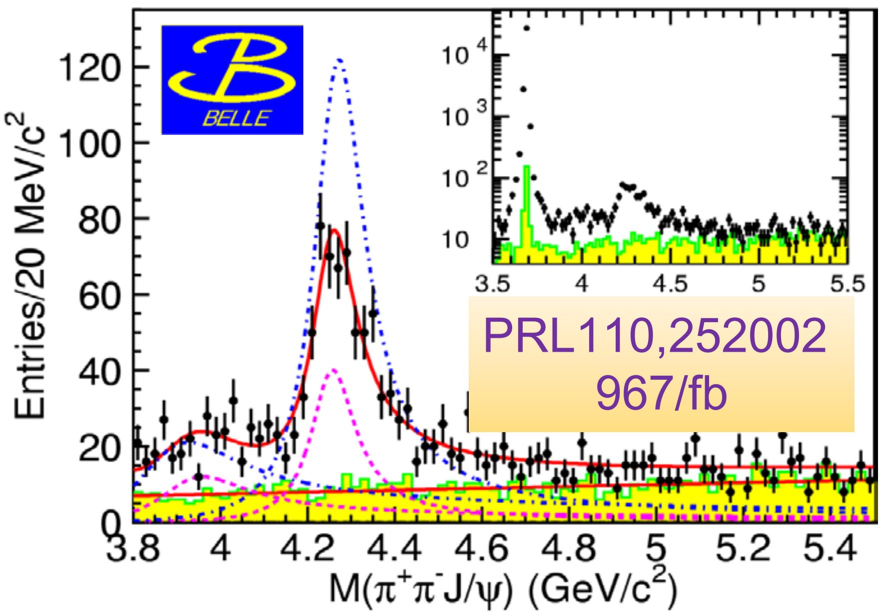
- Through the **partner states** of Z_b and Z_c
- Through the **decay pattern** of Z_b and Z_c

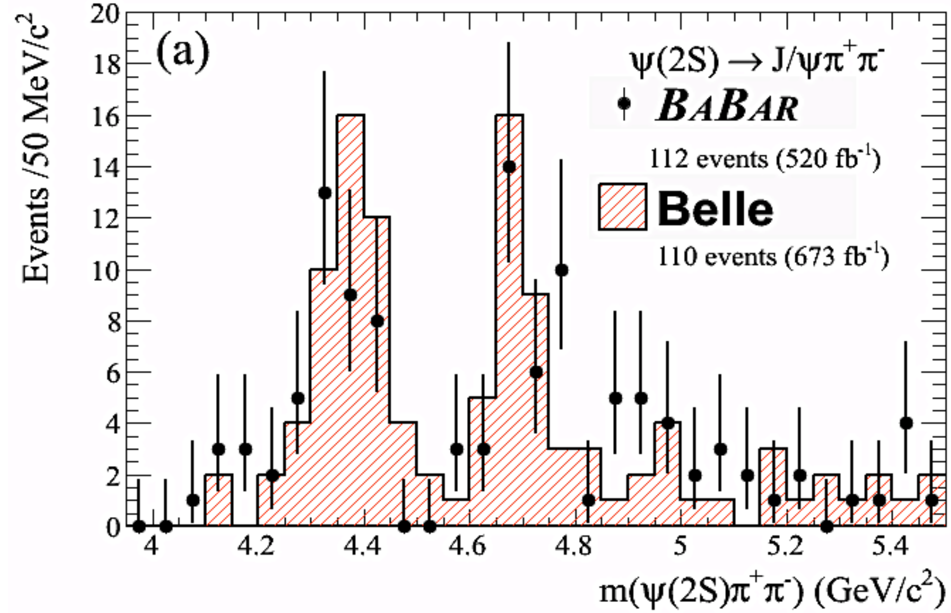
Ma, Sun, Liu, Deng, Liu, Zhu, arXiv:1403.7907
He, Liu, Sun, Zhu, arXiv:1308.2999, EPJC

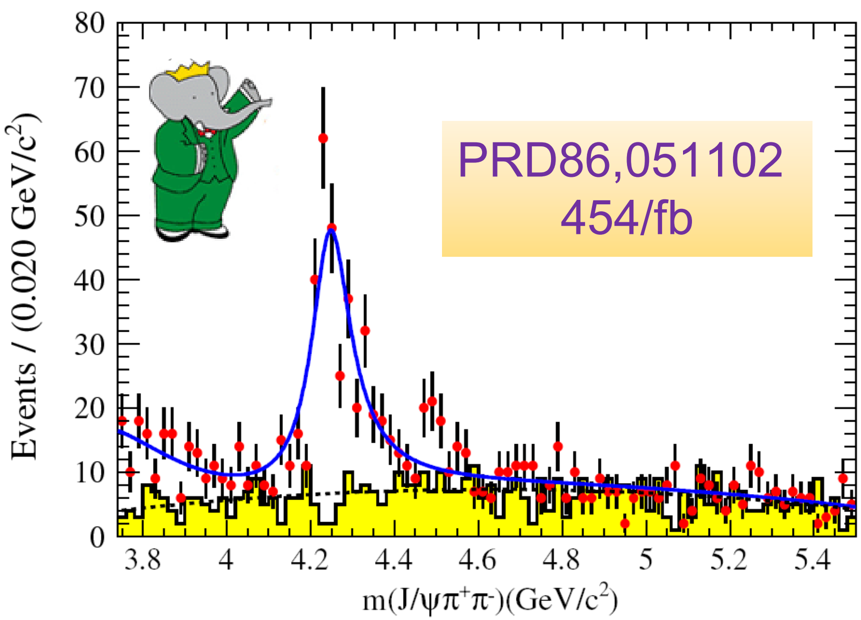
Vector Charmonium

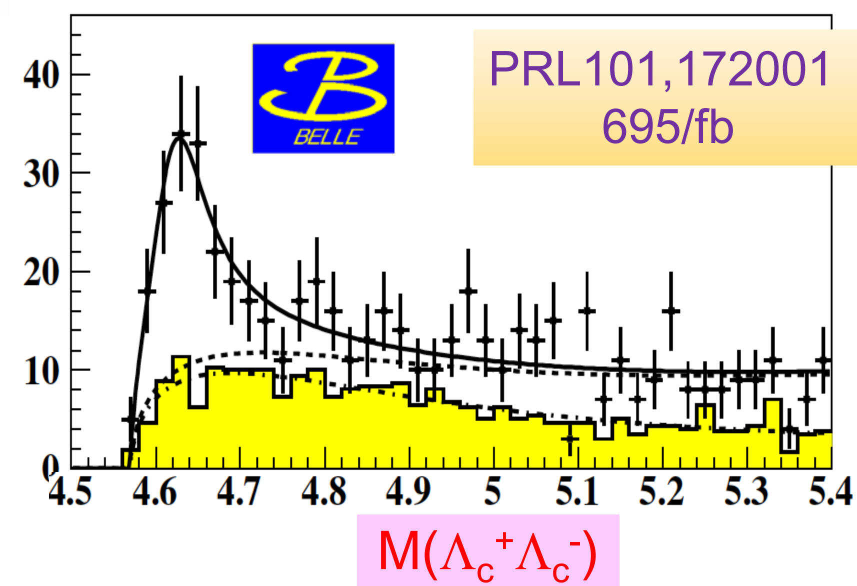
The Y states

Belle: PRL99,142002, 670/fb
BaBar: PRD89, 111103, 520/fb



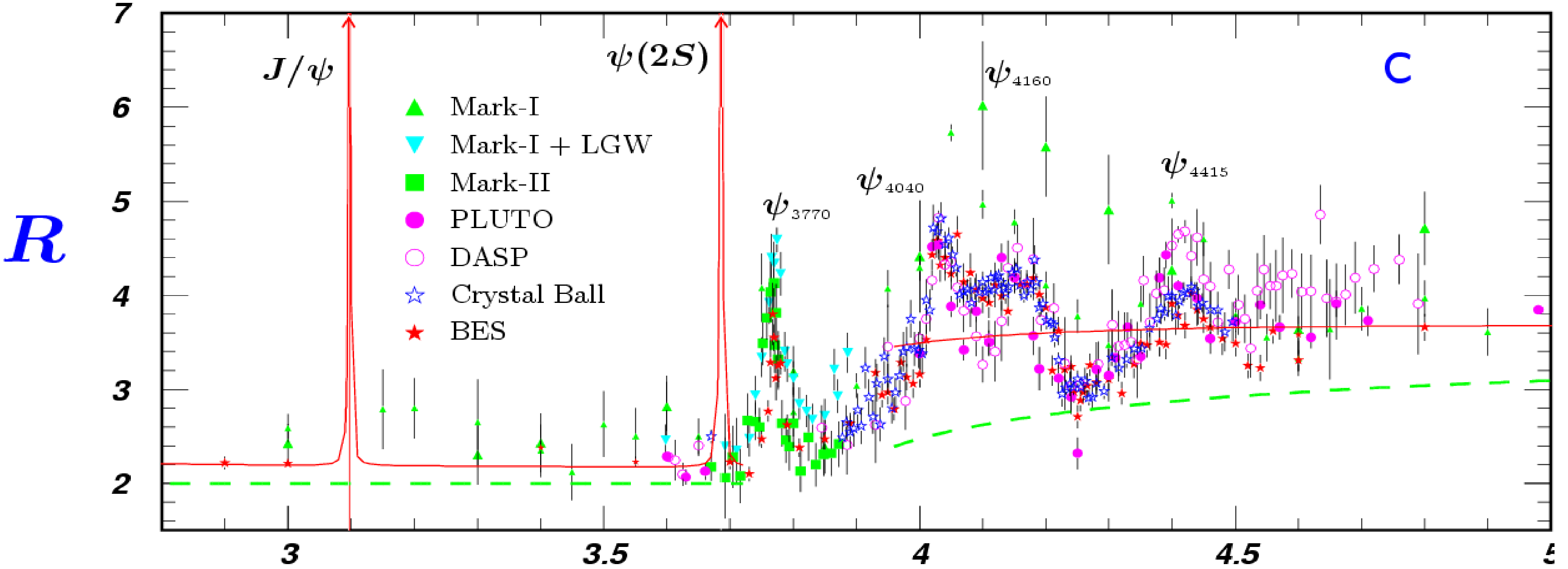


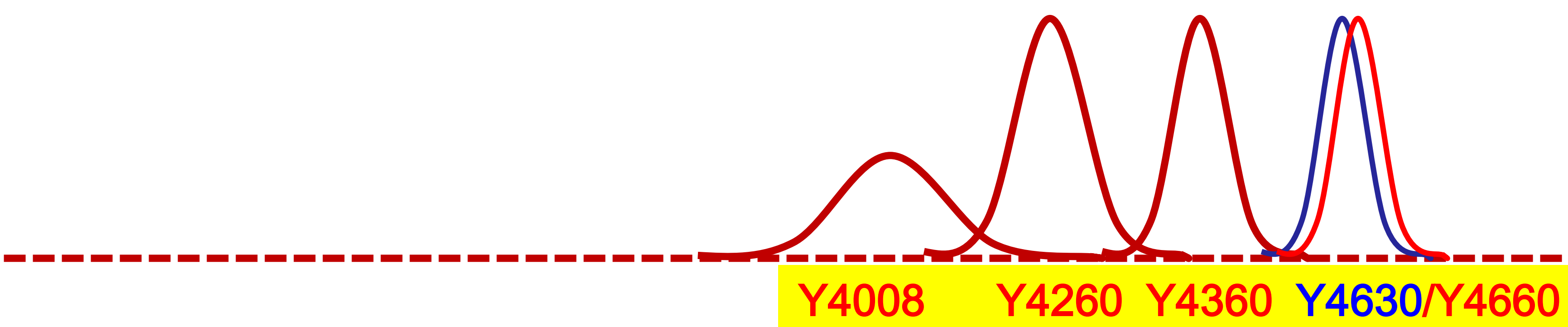




May BESIII help?

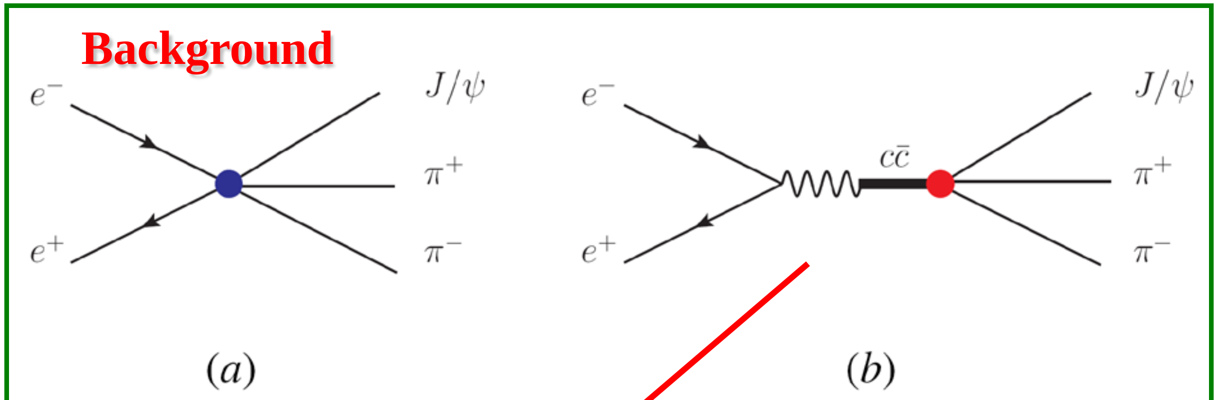
Excited ψ states and Y states

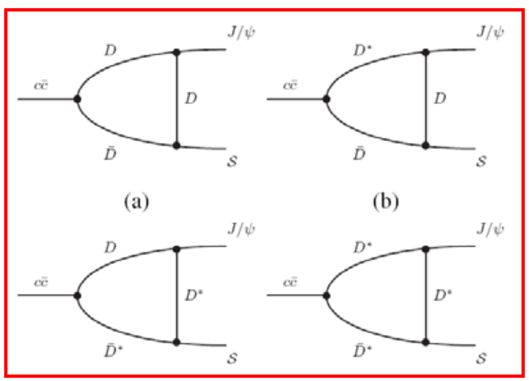




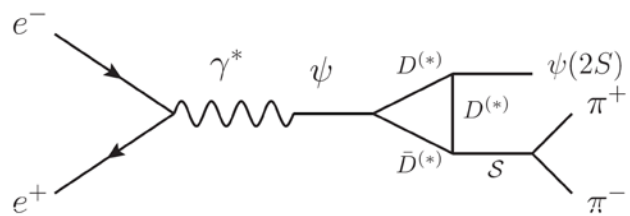
Possible Non-resonant Interpretation for Y(4260)/Y(4360)

The interference between **Continuum** and **Resonance**





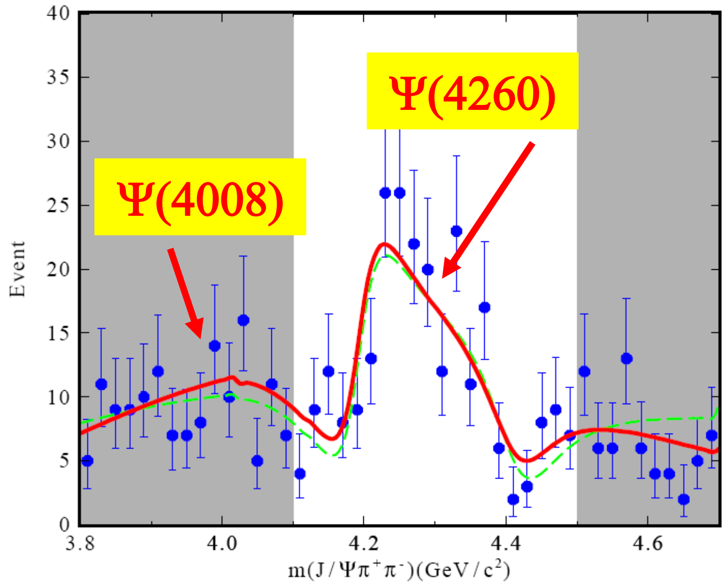
$$\psi = \{\psi_1 = \psi(4160), \psi_2 = \psi(4415)\}$$

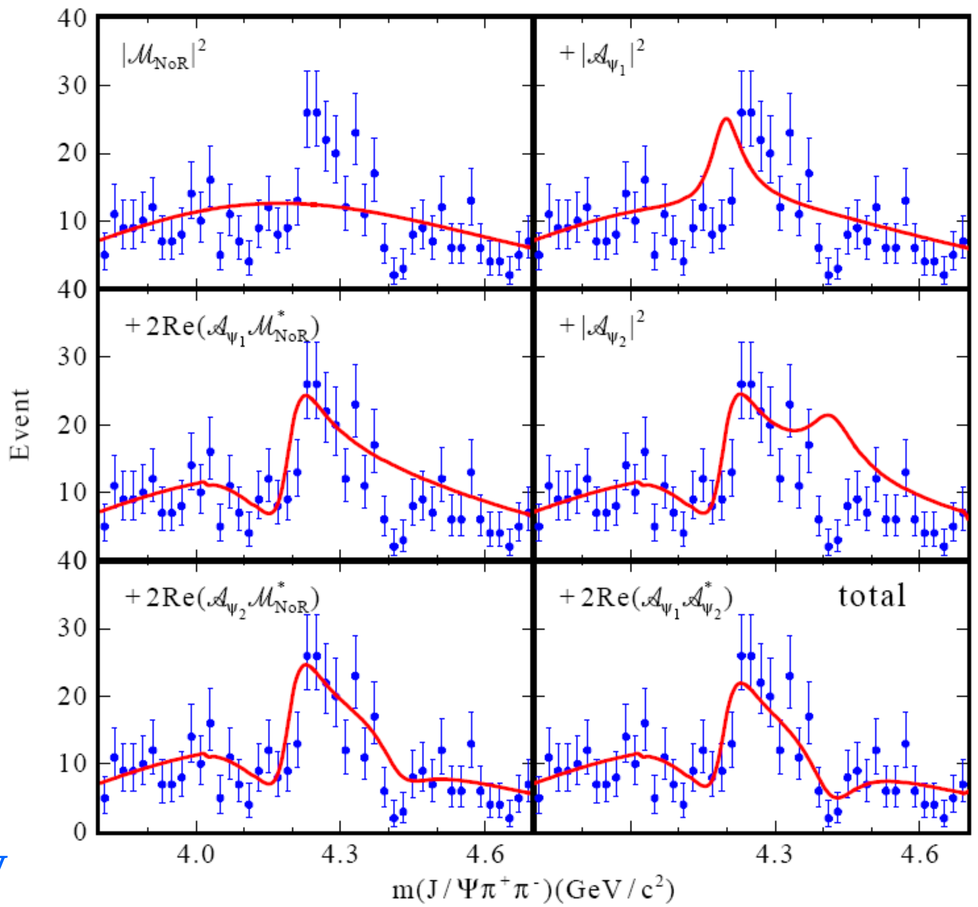


The lineshape is reproduced for Y(4260)/Y(4360) with the interference mechanism

D.Y. Chen, J. He and Xiang Liu, Phys.Rev.D83, 054021 (2011)

Parameter	Value (Rad)	Parameter	Value
ϕ_1	0.4545 ± 0.3535	g_{NoR}	0.0967 ± 0.0280 GeV
ϕ_2	-0.9789 ± 0.5146	a	0.7341 ± 0.0678 GeV^{-2}
ϕ_3	1.5983 ± 1.0922	β_1, β_2	1





M=4008±40 MeV Γ=226 ±44 MeV

Belle, Phys.Rev.Lett.99:182004 (2007)

Could some Y states be tetraquarks?

WEI CHEN AND SHI-LIN ZHU PHYSICAL REVIEW D **83**, 034010 (2011)

TABLE III. The threshold value, Borel window, mass and pole contribution corresponding to the currents with $J^{PC} = 1^{--}$ in the $qc\bar{q}\bar{c}$, $sc\bar{s}\bar{c}$, $qb\bar{q}\bar{b}$ and $sb\bar{s}\bar{b}$ systems.

	Currents	s_0 (GeV^2)	$[M^2_{min}, M^2_{max}]$ (GeV^2)	m_X (GeV)	PC(%)
$qc\bar{q}\bar{c}$ system	$J_{1\mu}$	5.0^2	$2.9 \sim 3.6$	4.64 ± 0.09	44.1
	$J_{4\mu}$	5.0^2	$2.9 \sim 3.6$	4.61 ± 0.10	46.4
	$J_{7\mu}$	5.2^2	$2.9 \sim 4.1$	4.74 ± 0.10	47.3

- Hidden-charm tetraquarks will fall apart into a pair of open-charm D mesons or hidden-charm plus light mesons very easily
- Their width is expected to be very large while Y states are not so broad
- Up to now, Y states have not been observed in the p-wave $D\bar{D}$ and $\bar{D}D^*$ mode

Y(4260) may be a conventional charmonium

- Bare $c\bar{c}$ quark model state may mix with the $D\bar{D}$ continuum through the $D\bar{D}$ hadron loop
- Charmonium spectrum might be distorted
- With the screened linear, energy level spacing above 4 GeV becomes narrower
- More vector states can exist between 4 and 4.7 GeV
- Y(4260) =ψ(4S), Y(4360) =ψ(3D),
- ψ(4415) =ψ(5S), Y(4660/4630) =ψ(6S)
- **Difficult to explain the dip in the R-value**
- **2D psi(4160) is 100 MeV lower than data**

Li, Chao (PRD 2009)

Y(4260) is a good candidate of charmonium hybrid

Zhu; Kou, Pene; Close, Page (2005)

- According to lattice QCD simulation, both the vector and exotic (1^{-+}) hybrid charmonium lie around 4.26 GeV
- Because of the gluon, the 1^{--} hybrid charmonium does not couple to the virtual photon very strongly, which explains the dip in the R-value scan
- According to the flux tube model and QCD sum rule analysis, the favorable decay mode of hybrid states is p-wave + s-wave meson pair → non-observation in the $\bar{D}D$, $\bar{D}D^*$, $\bar{D}^*D^*$ modes
- The $\bar{c}c$ pair is a spin-singlet while the gluon is color-magnetic →favorable to the spin-singlet hidden-charm decay mode?
- Recently BESIII observed Y(4260)→ hc π π; p-wave + s-wave D meson decay modes

Lessons Which We Should Keep in Mind

- In 1949, Fermi and Yang derived the $N\bar{N}$ potential based on $N\bar{N} \rightarrow N\bar{N}$ **elastic scattering and G-parity rule**
- **They obtained many deeply bound states in the OBE model, but none of them was observed. Why?**
- In the $N\bar{N}$ case, the **inelastic scattering or annihilation process $N\bar{N} \rightarrow$ mesons** is important, which renders the short-distance interaction very complicated
- The presence of the optical potential V(r)+i W(r) changes the whole picture

- **OBE model is reliable only in the case (1) when there is no annihilation; (2) or for very shallow bound states when there is annihilation**