Quark-hadronic molecule hybrid picture of the exotic hadrons

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- Summary

Experimental status of X(3872)

- First observation: 2003, Belle, KEKB
  cited more than 1000 times
- Mass: (3871.69 ± 0.17) MeV (J/ψ X decay mode)
  about 0.11 MeV below $D^0\bar{D}^{*0}$ threshold
- Mass:3782.9(+0.6 -0.4)(+0.4 -0.5)MeV ($D^{0bar}D^{0*}$ decay mode: D^{0*} mass constraind for off-shell D^{0*})
- Width: less than 1.2 MeV
- Quantum Number: $J^{PC} = 1^{++}$ L = 0

Experimental status of X(3872)

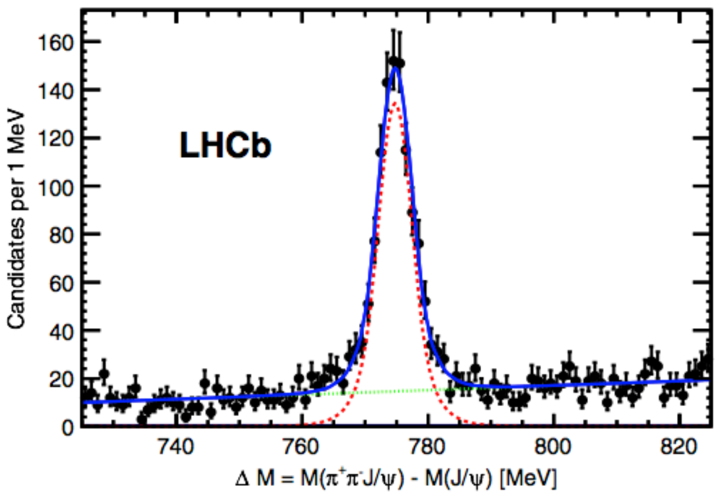


FIG. 1 (color online). Distribution of ΔM for $B^+ \to J/\psi K^+ \pi^+ \pi^-$ candidates. The fit of the $X(3872)$ signal is displayed. The solid (blue), dashed (red) and dotted (green) lines represent the total fit, signal component and background component, respectively.

R. Aaij et al. (LHCb Collaboration) Phys. Rev. D92 (2015) 011102 R

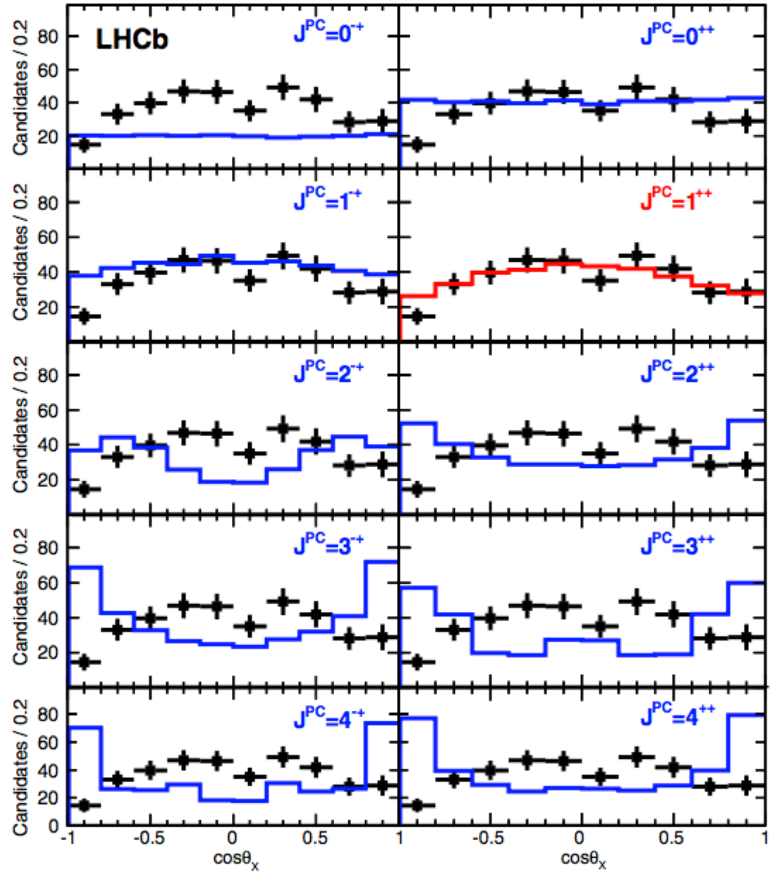


FIG. 5 (color online). Background-subtracted distribution of $\cos\theta_X$ for candidates with $|\cos\theta_\rho| > 0.6$ for the data (points with error bars) compared to the expected distributions for various $X(3872)$ J^{PC} assignments (solid histograms) with the B_{LS} amplitudes obtained by the fit to the data in the five-dimensional angular space. The fit displays are normalized to the observed number of the signal events in the full angular phase space.

Experimental status of $Z(4430)^{\pm}$

- First observation: 2008, Belle, KEKB

  $$\bar{B}^0 \to \psi(2S)K^-\pi^+$$

  Invariant mass of $\psi(2S)\pi^+$ $c\bar{c}u\bar{d}$

  Mass: $4485 \pm 22^{+28}_{-11}$ MeV (Belle 2013)

  Width: $200\ ^{+41}_{-46}\ ^{+26}_{-35}$ MeV (Belle 2013)

- LHCb observation: 2014

  Mass: $4475 \pm 7^{+15}_{-25}$ MeV

  Width: $172 \pm 13^{+37}_{-34}$ MeV

- Quantum number: 1^+

Experimental status of Z(4430)$^{\pm}$

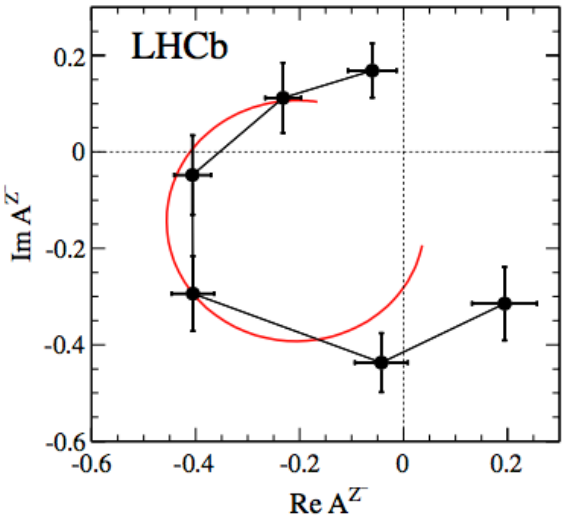


FIG. 3 (color online). Fitted values of the Z_1^- amplitude in six $m^2_{\psi'\pi^-}$ bins, shown in an Argand diagram (connected points with the error bars, $m^2_{\psi'\pi^-}$ increases counterclockwise). The red curve is the prediction from the Breit-Wigner formula with a resonance mass (width) of 4475 (172) MeV and magnitude scaled to intersect the bin with the largest magnitude centered at $(4477\ \text{MeV})^2$. Units are arbitrary. The phase convention assumes the helicity-zero $K^*(892)$ amplitude to be real.

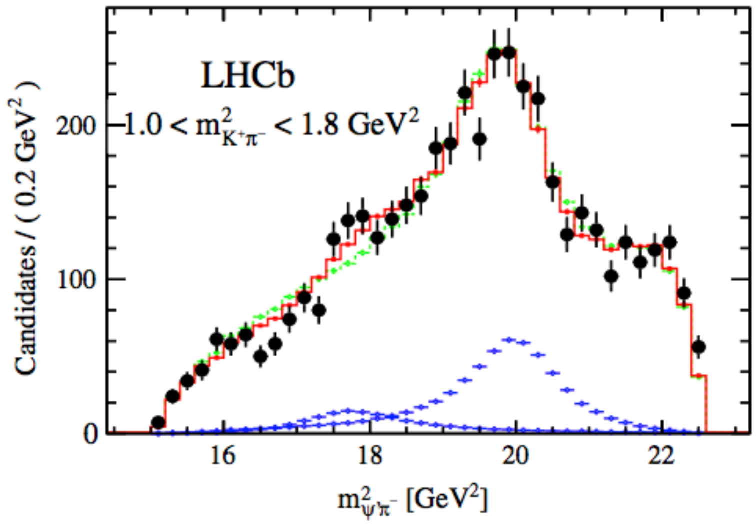


FIG. 4 (color online). Distribution of $m^2_{\psi'\pi^-}$ in the data (black points) for $1.0 < m^2_{K^+\pi^-} < 1.8\ \text{GeV}^2$ [$K^*(892)$, $K_2^*(1430)$ veto region] compared with the fit with two, 0^- and 1^+ (solid-line red histogram) and only one 1^+ (dashed-line green histogram) Z^- resonances. Individual Z^- terms (blue points) are shown for the fit with two Z^- resonances.

R. Aaij et al. (LHCb Collaboration) Phys. Rev. Lett. 112 (2014) 222002

Experimental status of other exotic mesons

名前	質量 [MeV]	幅 [MeV]	J^P	反応	崩壊モード	実験グループ (年)
$Z_c(4050)^+$	$4051 \pm 14^{+20}_{-41}$	82^{+21+47}_{-17-22}	$?^?$	$\bar{B}^0 \to \chi_{c1}(1P)K^-\pi^+$	$\chi_{c1}(1P)\pi^+$	Belle(2008)
$Z_c(4250)^+$	$4248^{+44+180}_{-29-35}$	$177^{+54+316}_{-39-61}$	$?^?$	$\bar{B}^0 \to \chi_{c1}(1P)K^-\pi^+$	$\chi_{c1}(1P)\pi^+$	Belle(2008)
$Z_b(10610)^\pm$	10607.2 ± 2.0	18.4 ± 2.4	1^+	$\Upsilon(5S) \to \pi^+\pi^-\Upsilon(1,2,3S)$	$\Upsilon(1,2,3S)\pi^\pm$	Belle(2012)
				$\Upsilon(5S) \to \pi^+\pi^- h_b(1,2P)$	$h_b(1,2P)\pi^\pm$	
$Z_b(10610)^0$	$10609 \pm 4 \pm 4$	18.4 (input)	1^+	$\Upsilon(5S) \to \pi^0\pi^0\Upsilon(2,3S)$	$\Upsilon(2,3S)\pi^0$	Belle(2013)
$Z_c(3900)^\pm$	3888.7 ± 3.4	35 ± 7	1^+	$Y(4260) \to \pi^+\pi^- J/\psi$	$J/\psi\pi^\pm$	BESIII(2013)
						Belle(2013)
				$\psi(4160) \to \pi^+\pi^- J/\psi$	$J/\psi\pi^\pm$	CLEO-c(2013)
				$Y(4260) \to (D\bar{D}^*)^\pm\pi^\mp$	$(D\bar{D}^*)^\pm$	BESIII(2014)
$Z_c(4020)^\pm$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$?^?$	$e^+e^- \to \pi^+\pi^- h_c$	$h_c\pi^\pm$	BESIII(2013)
$Z_c(4025)^\pm$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 2.6 \pm 7.7$	$?^?$	$Y(4260) \to (D^*\bar{D}^*)^\pm\pi^\mp$	$(D^*\bar{D}^*)^\pm$	BESIII(2014)
$Z_c(4200)^+$	4196^{+31+17}_{-29-13}	$370^{+70+70}_{-70-132}$	1^+	$\bar{B}^0 \to J/\psi K^-\pi^+$	$J/\psi\pi^+$	Belle(2014)

表 1: $Z_c(4430)^\pm$ 以降に発見された電荷又はアイソスピンを持ったチャーモニウム及びボトモニウム様状態

Summary of experimental status of exotic mesons (1)

- Only X(3872), $Z(4430)^{\pm}$, $Z_c(3900)^{\pm}$ have been observed by more than two experimental groups.
- Especially, LHCb observation of $Z_b(10610)^{\pm}$ and $Z_b(10650)^{\pm}$ is desirable.
- Measured quantum numbers of the exotic mesons were all $J^P=1^+$, Why?

Summary of experimental status of exotic mesons (2)

- BESIII observations in 2014

$$Z_c(3900)^{\pm} \to (D\bar{D}^*)^{\pm}$$
$$Z_c(4025)^{\pm} \to (D^*\bar{D}^*)^{\pm}$$

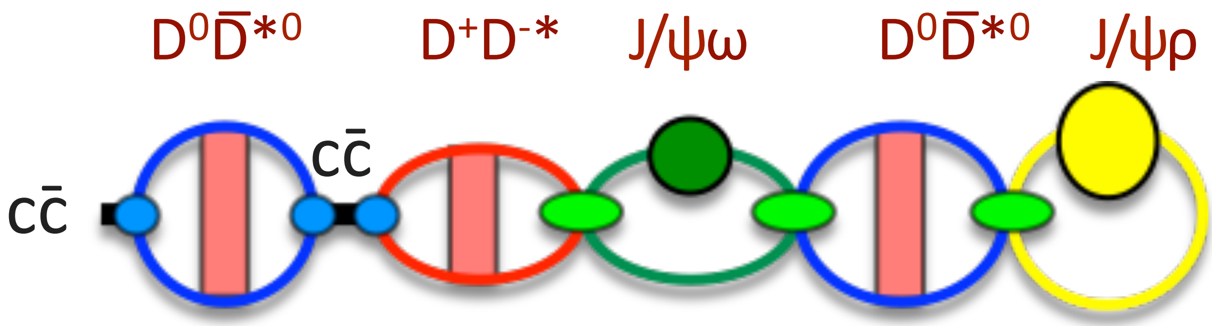
are interesting. Both states are about 10 MeV above the corresponding threshold.
How about $Z_b(10610)^{\pm} \to (B\bar{B}^*)^{\pm}$?

Summary of experimental status of exotic mesons (3)

- What does the Argand diagram tell us about the structure of the exotic hadrons?
- Further theoretical and experimental studies are necessary.

X(3872) as charmonium-hadronic molecule hybrid (1)

- Our picture of X(3872)



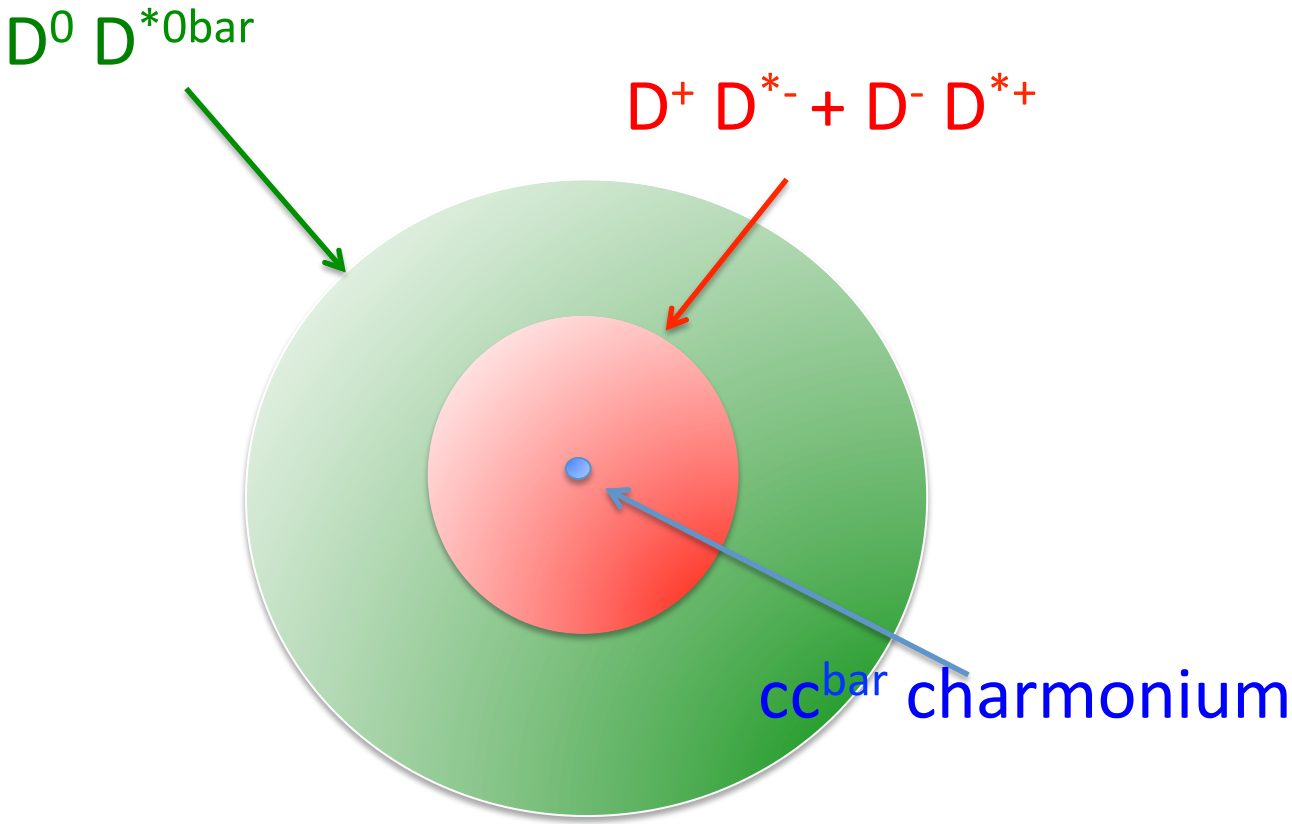
Two-meson molecule with a $c\bar{c}$ core:

$c\bar{c}$ - $D^0\bar{D}^{*0}$ - D^+D^{-*} - $J/\psi\omega$ – $J/\psi\rho$

ω and ρ have width.

J/ψ ω and J/ψ ρ couple to $c\bar{c}$ only via $D\bar{D}^*$ channels (OZI).

X(3872) as charmonium-hadronic molecule hybrid (2)



M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 0903D01
S.Takeuchi, K.Shimizu, and M.Takizawa, Prog. Theor. Exp. Phys. 2014, 123D01

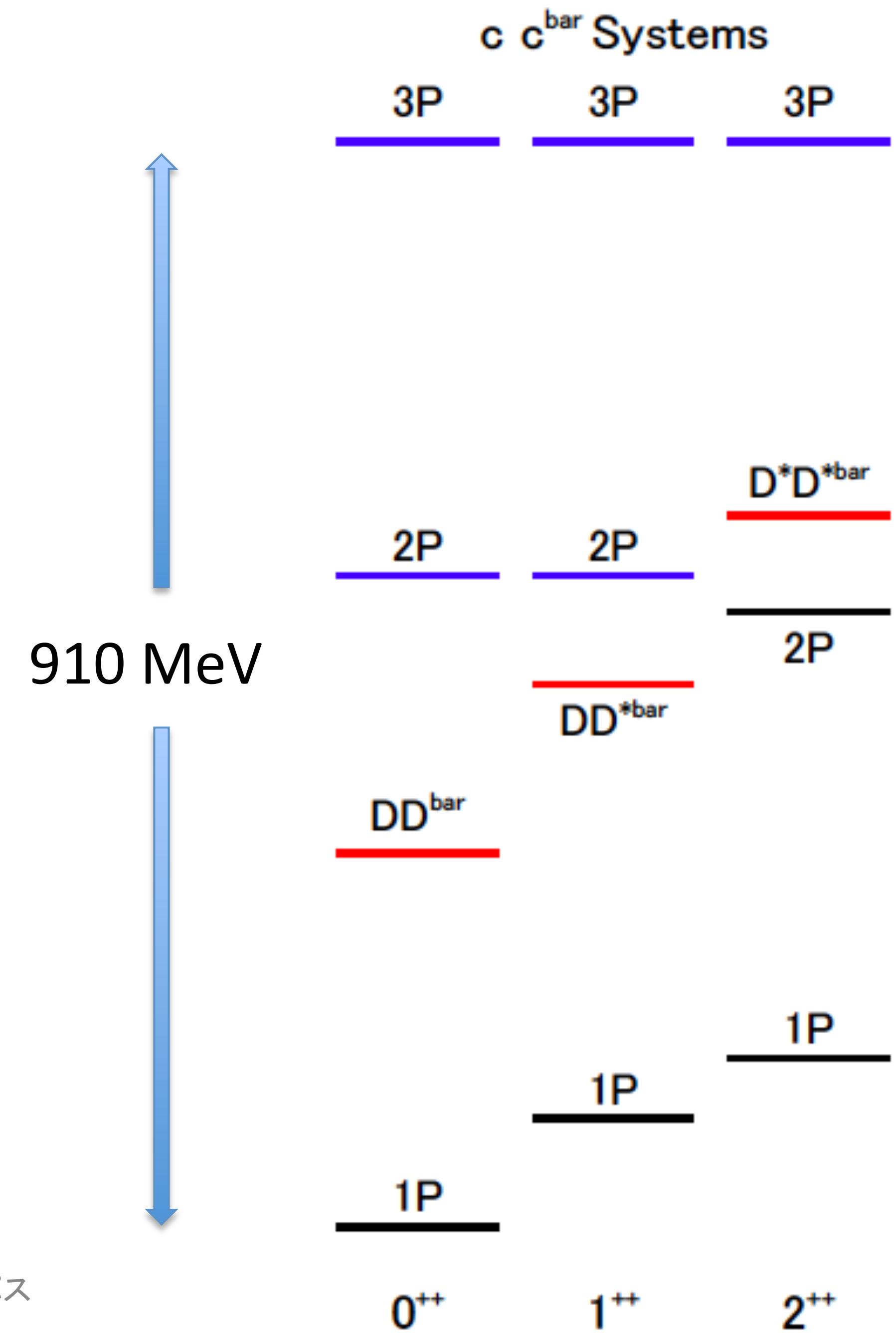
X(3872) as charmonium-hadronic molecule hybrid (3)

- Coupling between cc^{bar} core and DD^{*bar} gives rise to attraction between D and D^{*bar}, that explains non-existence of the charged partner of X(3872).

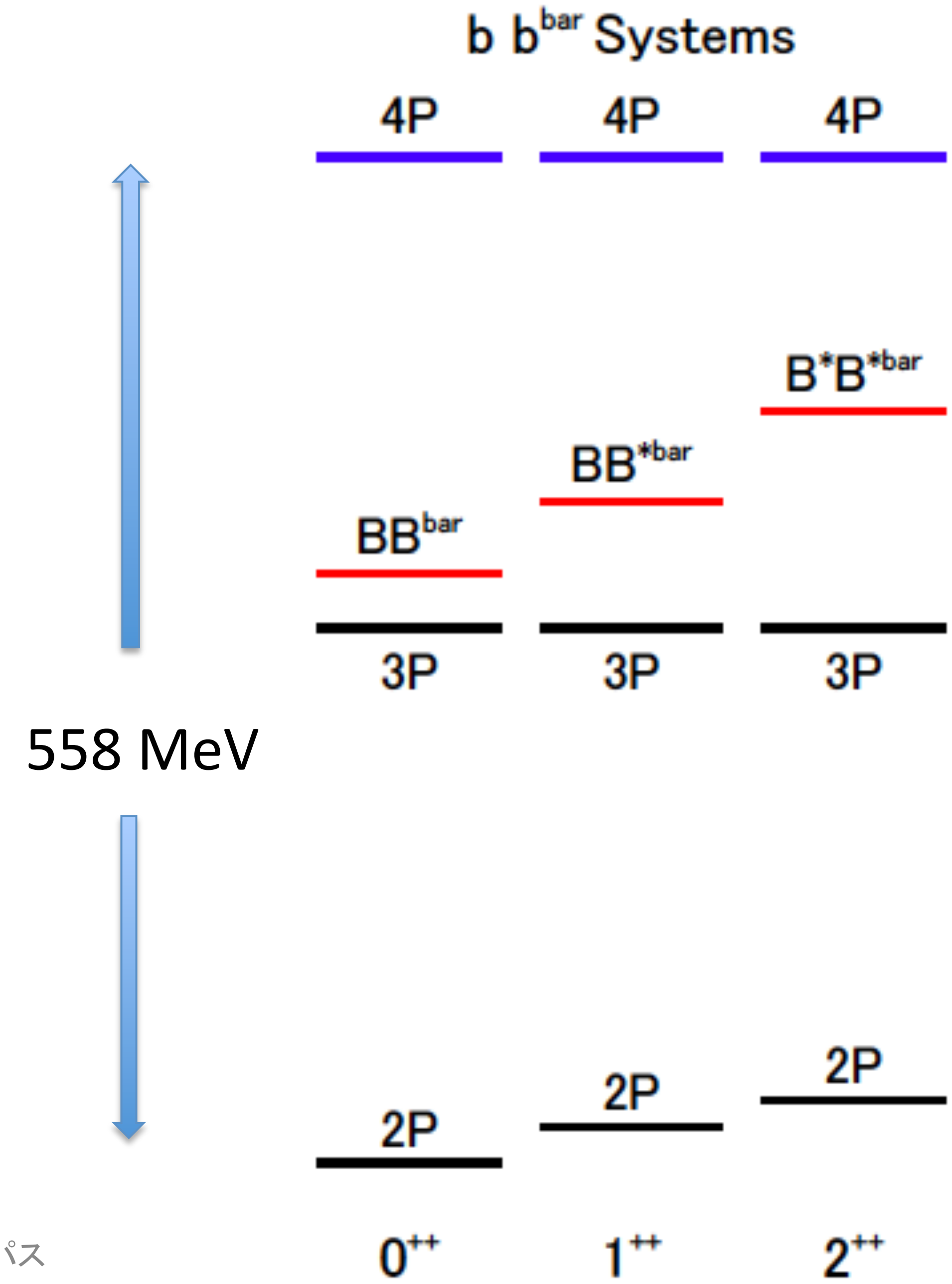
- Existence of compact cc^{bar} component can explain production rate of X(3872) in the high-energy pp colider experiment.

- Existence of compact cc^{bar} component can explain radiative decay rates of X(3872).

Possibility of other exotic hadrons by same mechanism as X(3872)



How about bb^{bar} systems?



Possibility of other exotic hadrons by same mechanism as X(3872)

- There is little chance to have exotic hadrons by same mechanism as X(3872)

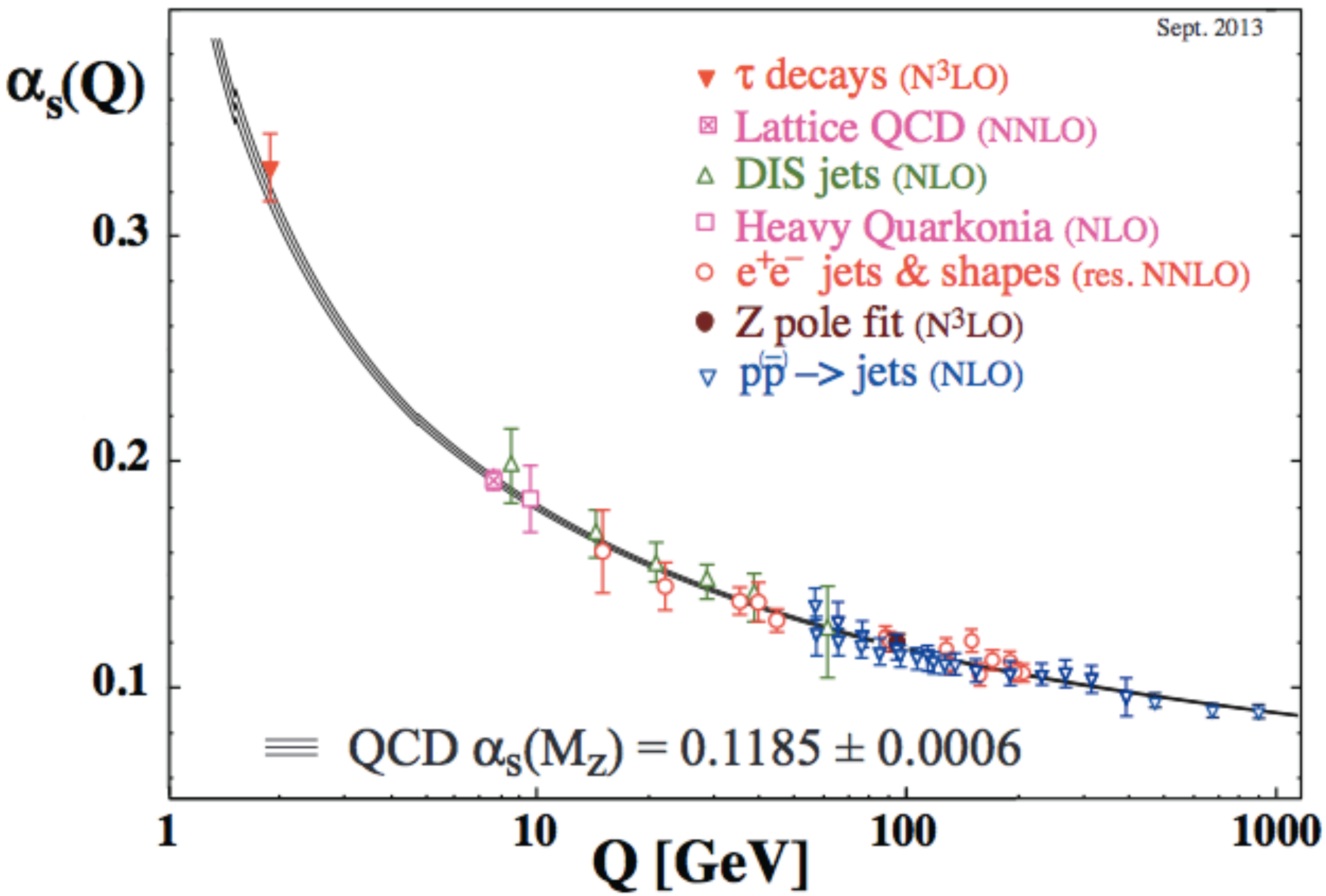
- X(3872) seems to be rather special

Are J/psi and psi(2S) the pure charmonia? (1)

- First of all, what is charm quark mass?
  $m_c\,(\mu^2=m_c^2) = 1.27$ GeV

  current quark mass or constituent quark mass?
- $\alpha_S(\mu^2=m_c^2)$ is small enough?

Are J/psi and psi(2S) the pure charmonia? (2)



Are J/psi and psi(2S) the pure charmonia? (3)

- psi(2S)
  Mass: $3686.109^{+0.012}_{-0.014}$ MeV

  Width: 299 ± 8 keV

  $M_{psi(2s)} - M_{J/psi} = 589.188 \pm 0.028$ MeV

Are J/psi and psi(2S) the pure charmonia? (4)

Psi(2S) decays

Decays into $J/\psi(1S)$ and anything

Γ_9	$J/\psi(1S)$anything	(60.9 ± 0.6) %
Γ_{10}	$J/\psi(1S)$neutrals	(25.10 ± 0.33) %
Γ_{11}	$J/\psi(1S)\pi^+\pi^-$	(34.45 ± 0.30) %
Γ_{12}	$J/\psi(1S)\pi^0\pi^0$	(18.13 ± 0.31) %
Γ_{13}	$J/\psi(1S)\eta$	(3.36 ± 0.05) %
Γ_{14}	$J/\psi(1S)\pi^0$	$(1.268 \pm 0.032) \times 10^{-3}$

Are J/psi and psi(2S) the pure charmonia? (5)

Width: 20.32 keV

$\Upsilon(3S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\Upsilon(2S)$anything	(10.6 ± 0.8) %	
Γ_2	$\Upsilon(2S)\pi^+\pi^-$	(2.82 ± 0.18) %	S=1.6
Γ_3	$\Upsilon(2S)\pi^0\pi^0$	(1.85 ± 0.14) %	
Γ_4	$\Upsilon(2S)\gamma\gamma$	(5.0 ± 0.7) %	
Γ_5	$\Upsilon(2S)\pi^0$	$< 5.1 \times 10^{-4}$	CL=90%
Γ_6	$\Upsilon(1S)\pi^+\pi^-$	(4.37 ± 0.08) %	
Γ_7	$\Upsilon(1S)\pi^0\pi^0$	(2.20 ± 0.13) %	
Γ_8	$\Upsilon(1S)\eta$	$< 1 \times 10^{-4}$	CL=90%
Γ_9	$\Upsilon(1S)\pi^0$	$< 7 \times 10^{-5}$	CL=90%

Are J/psi and psi(2S) the pure charmonia? (6)

Width: 31.98 keV

$\Upsilon(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	$\Upsilon(1S)\pi^+\pi^-$	(17.85 ± 0.26) %	
Γ_2	$\Upsilon(1S)\pi^0\pi^0$	(8.6 ± 0.4) %	
Γ_3	$\tau^+\tau^-$	(2.00 ± 0.21) %	
Γ_4	$\mu^+\mu^-$	(1.93 ± 0.17) %	S=2.2
Γ_5	e^+e^-	(1.91 ± 0.16) %	
Γ_6	$\Upsilon(1S)\pi^0$	$< 4 \times 10^{-5}$	CL=90%
Γ_7	$\Upsilon(1S)\eta$	$(2.9 \pm 0.4) \times 10^{-4}$	S=2.0

Are J/psi and psi(2S) the pure charmonia? (7)

- psi(2s) -> J/psi + pi + pi decays

  by just multi-gluon interactions?

  or light quark contents, DD^{bar} contents in psi(2S) and J/psi?

Are J/psi and psi(2S) the pure charmonia? (8)

- psi(2S) -> J/psi + pi^0 (SU(2) breaking)
  psi(2S) -> J/psi + eta (SU(3) breaking)

  Axial anomaly type decays.
  -> Quark triangle diagram
  ->light quark contents DD^{bar} contents in psi(2S) and J/psi?
  ->or charm quark contents in pi^0 and eta?

Summary

- Exotic hadron era has just started.

- From the viewpoint of the exotic hadron, we should reconsider the structure of the ordinary hadrons.

Summary

- In order to understand the structure of the charged charmonium(bottomonium)-like exotic hadrons, we would like to know the interactions between D and D^{bar}, D and D^{*bar}, D^{*} and D^{*bar} (B's).

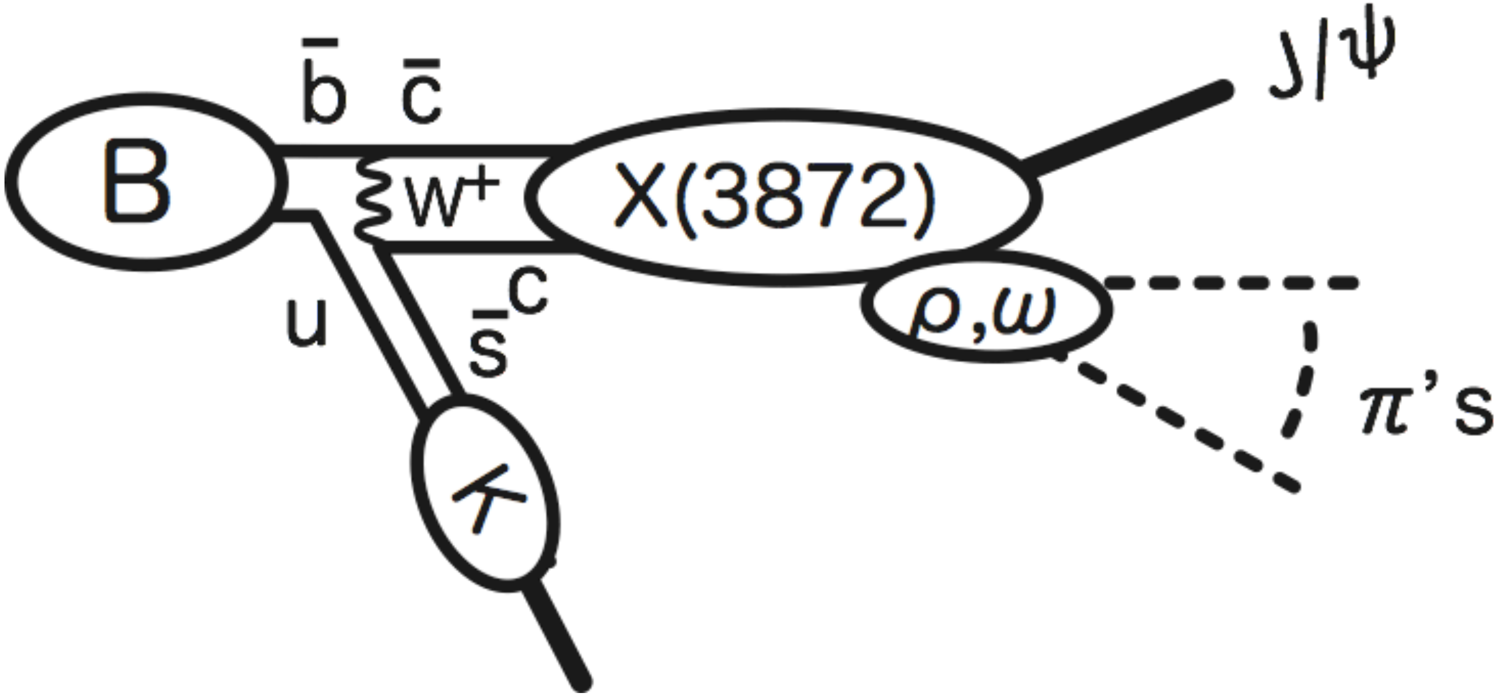
  If $Z_c(3900)$ is DD^{*bar} molecule and $Z_b(10610)$ is BB^{*bar} molecule, then interaction between B and B^{*bar} should be much weaker than that between D and D^{*bar}, since the kinetic energy of BB^{*bar} system is about 1/3 of DD^{*bar} system. However, from the heavy quark symmetry these two interaction may be similar.

Back up

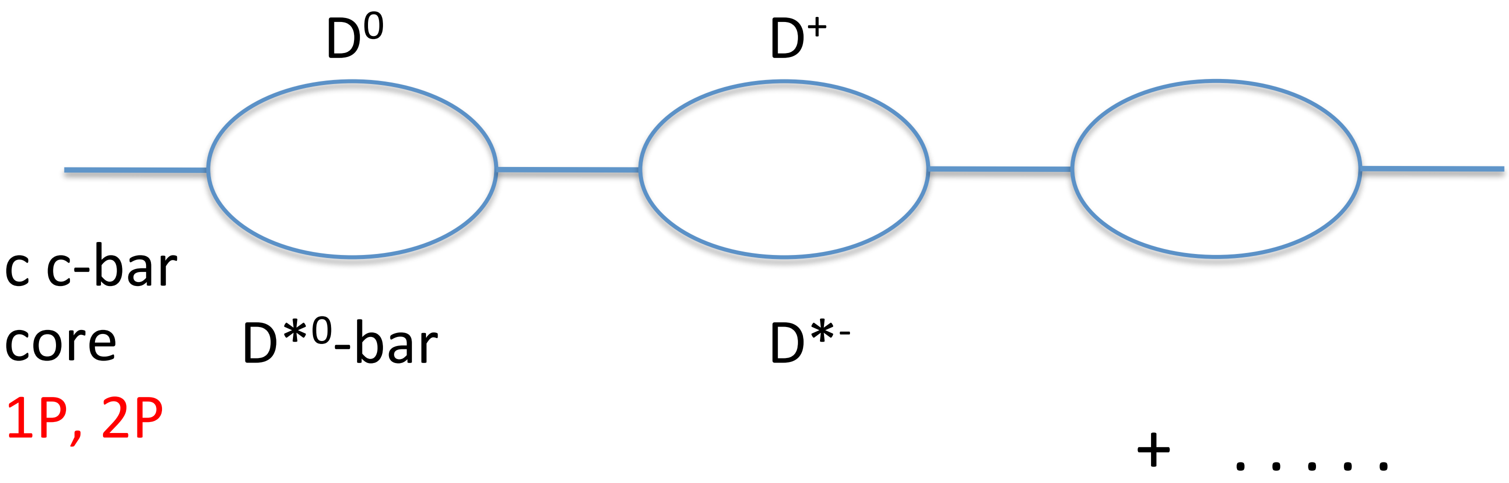
$B^+ \rightarrow K^+ + J/\psi + \pi\pi(\pi)$

- $B^+ \rightarrow$ <u>X(3872)</u> $+$ K^+

  $\rightarrow J/\psi +$ <u>vector meson</u> $\rightarrow \pi$'s



χ_{c1}(1P)の影響



χ_{c1}(1P)の影響

- Schroedinger Equation

$$\begin{pmatrix} m_{c\bar{c}(1P)} - E & 0 & V & V \\ 0 & m_{c\bar{c}(2P)} - E & V & V \\ V & V & m_{D^0} + m_{D^{*0}} + \frac{\hat{p}^2}{2\mu_0} + -E & 0 \\ V & V & 0 & m_{D^+} + m_{D^{*-}} + \frac{\hat{p}^2}{2\mu_+} - E \end{pmatrix} \begin{pmatrix} c_1 \left| c\bar{c}(1P) \right\rangle \\ c_2 \left| c\bar{c}(2P) \right\rangle \\ c_3 \left| D^0 \overline{D^{*0}} \right\rangle \\ c_4 \left| D^+ D^{*-} \right\rangle \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\frac{1}{\mu_0} = \frac{1}{m_{D^0}} + \frac{1}{m_{D^{*0}}}, \quad \frac{1}{\mu_+} = \frac{1}{m_{D^+}} + \frac{1}{m_{D^{*-}}}$$

X_{c1}(1P)の影響

- Charge conjugation + state is assumed
- Interaction: Isospin symmetric
- X_{c1}(1P)-DD^{*bar}とX_{c1}(2P)-DD^{*bar}は同じ結合

$$\left\langle D^0 \overline{D*^0}(\vec{q}) \middle| V \middle| c\bar{c}:1P \right\rangle = \left\langle D^0 \overline{D*^0}(\vec{q}) \middle| V \middle| c\bar{c}:2P \right\rangle$$

$$= \frac{g\Lambda^2}{\vec{q}^2+\Lambda^2} = \left\langle D^+ D^{*-}(\vec{q}) \middle| V \middle| c\bar{c}:1P \right\rangle = \left\langle D^+ D^{*-}(\vec{q}) \middle| V \middle| c\bar{c}:2P \right\rangle$$

X_{c1}(1P)の影響　計算結果: 質量

- Mass of the cc-bar core:
  1P: 3.51 GeV　　2P: 3.95 GeV
  from S. Godfrey, N. Isgur, Phys. Rev. D 32 (1985) 189.

- Cutoff Lambda = 0.5 GeV,
  Calculated bound states energy are
  3.492 GeV and <u>3.87157 GeV</u>

- χ_{c1}(1P) mass shift by coupling to DD* is about 20MeV

χ_{c1}(1P)の影響　計算結果: 波動関数

0.5%　　　11%

$$|X(3872)\rangle = 0.071|c\bar{c}(1P)\rangle - 0.326|c\bar{c}(2P)\rangle$$

$$+0.907\left|D^0\overline{D^{*0}}\right\rangle + 0.255\left|D^+D^{*-}\right\rangle$$

82%　　　6.5%

- cc^bar 1P component is small.

$D^* \bar{D}^*$ (D^*D^{*bar})の影響

- 簡単のために、isospin の破れは考えない。
- $\chi_{C1}(2P)$-DD^{*bar}結合と$\chi_{C1}(2P)$-D^*D^{*bar}は同じ値にしている。
- 質量はisospin平均を使った。

D^*D^{*bar}の影響　計算結果: 波動関数

30%

$$|X(3872)\rangle = 0.557|c\bar{c}(2P)\rangle$$

$$-0.818|D\overline{D^*}(I=0)\rangle - 0.143|D^*\overline{D^*}(I=0)\rangle$$

67%　　　　2%

- cc^{bar}成分が増えたのは、isospin平均質量を使ったため、束縛エネルギーが大きくなったので。
- D^*D^{*bar}の成分は2%と十分小さかった。