QUARKONIUM: PRODUCTIONS & DECAYS

Emi Kou (LAL/In2p3)

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Introduction

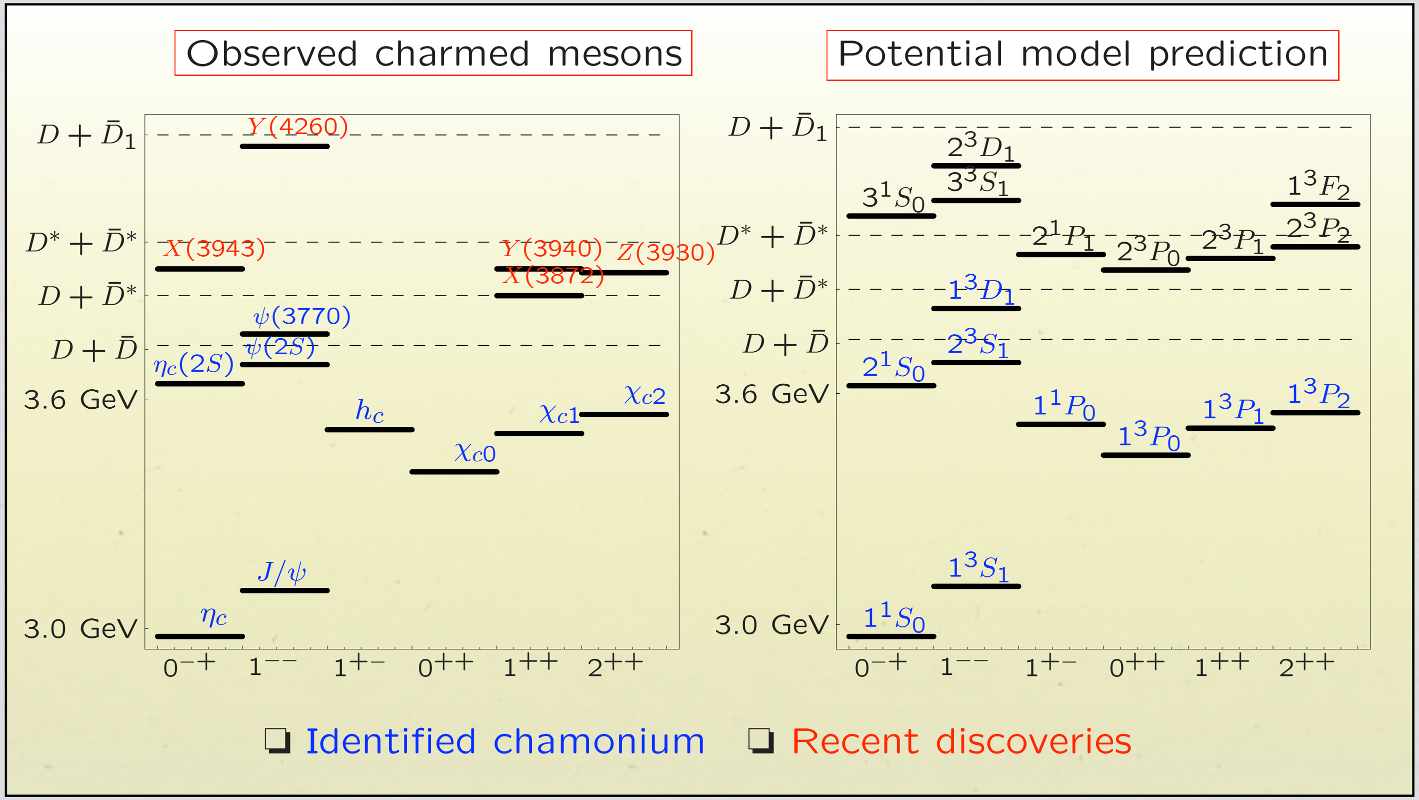
Charmonium spectrum: observation and prediction

Established charmonium below open-charm threshold ($2m_D$)

		$n\ ^{2s+1}l_J$	J^{PC}	mass MeV	width MeV	discovery
η_c	pseudoscalar	$1\ ^1S_0$	0^{-+}	2980	25.5	1980
J/ψ	vector	$1\ ^3S_1$	1^{--}	3097	0.093	1974
h_c	axial vector	$1\ ^1P_1$	1^{+-}	3524	<1	2005
χ_{c0}	scalar	$1\ ^3P_0$	0^{++}	3415	10.4	1975
χ_{c1}	axial vector	$1\ ^3P_1$	1^{++}	3511	0.89	1975
χ_{c2}	tensor	$1\ ^3P_2$	2^{++}	3556	2.06	1975
$\psi(3770)$	vector	$1\ ^3D_1$	1^{--}	3771	23.0	1977
$\eta_c(2S)$	pseudoscalar	$2\ ^1S_0$	0^{-+}	3637	10±4	2002
$\psi(2S)$	vector	$2\ ^3S_1$	1^{--}	3686	0.337	1974

Introduction

Charmonium spectrum: observation and prediction



- Good agreement below the threshold
- Difficulties above the threshold → appearance of exotic states

Quarkonium working group report: 1010.5827

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	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	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	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)		
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				$B \to K(\gamma \psi(2S))$	*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	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	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	NC!
				$e^+e^- \to J/\psi\ (...)$	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	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					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	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- \psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!

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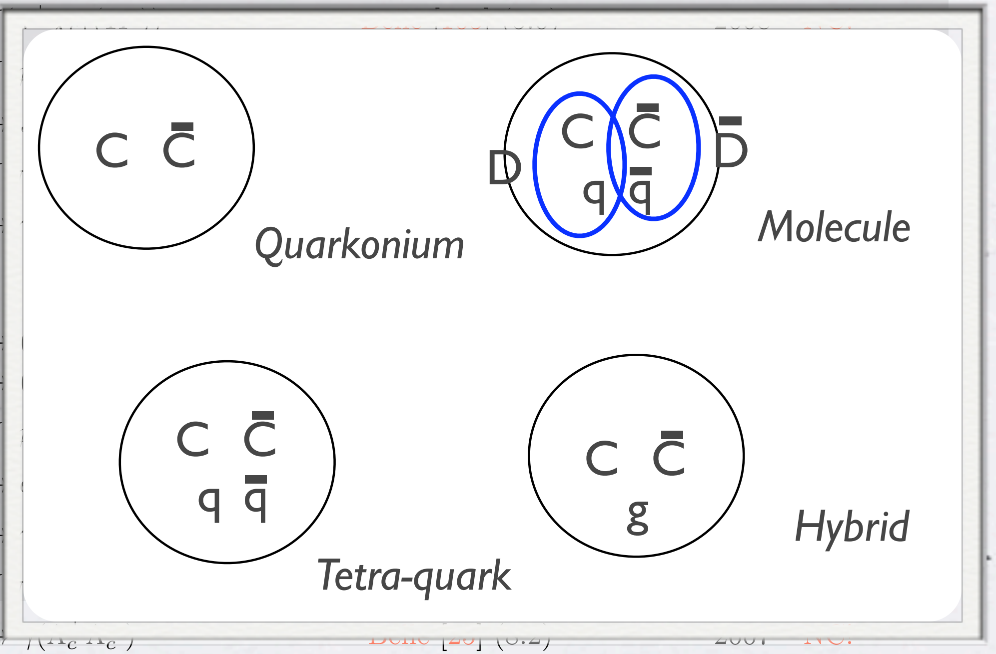

X(3872)

Discovery in 2003

It is observed firstly in Belle in 2003 and confirmed by Babar, CDF, D0...

- ☞ Mass: $3872.0 \pm 0.6 \pm 0.5$ MeV
- ☞ Width: < 2.3 MeV
- ☞ Discovery channel: $B \to KJ/\psi\pi\pi$
- ☞ Favoured quantum number: *How to determine it?*

X(3872)

Determining its spin parity

❏ C^- is excluded from radiative decays

S. Olsen hep-ph/0407033

Observation of radiative decays is important to identify the charge conjugation. $X(3872) \to J/\psi\gamma$ is observed, thus $C = +1$!

❏ $1^{-+}, 2^{-+}$ are ruled out from recoil mass distribution of $X \to J/\psi\rho$

$(1^{-+}, 2^{-+}) \to \rho J/\psi$ is only allowed for P-wave. Thus, the following result for the recoil mass distribution of $\pi\pi$ rules out this possibility:

$$\chi^2/\mathrm{dof} = 43/39 \quad S\text{-wave.} \qquad \chi^2/\mathrm{dof} = 71/39 \quad P\text{-wave}$$

❏ 0^{++} and 0^{-+} are ruled out from angular correlations

Angular correlations of $B \to KJ/\psi\pi\pi$

$$\frac{d\Gamma(B \to KJ/\psi\pi\pi)}{\Gamma d\cos\theta_{l\pi}} = \frac{3}{4}\sin^2\theta_{l\pi} \quad \text{while exp. peaks at} \quad |\cos\theta_{l\pi}| \simeq 1$$

$$\frac{d^2\Gamma(B \to KJ/\psi\pi\pi)}{\Gamma d\cos\theta d\phi d\cos\psi} = \sin^2\theta\sin^2\psi \quad \text{while exp. peaks at} \; |\cos\psi| \simeq 1$$

Two possibilities, 1++ or 2++, were left...

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$= 71/39$ P-wave

❑ 0^{++} rrelations

Angula

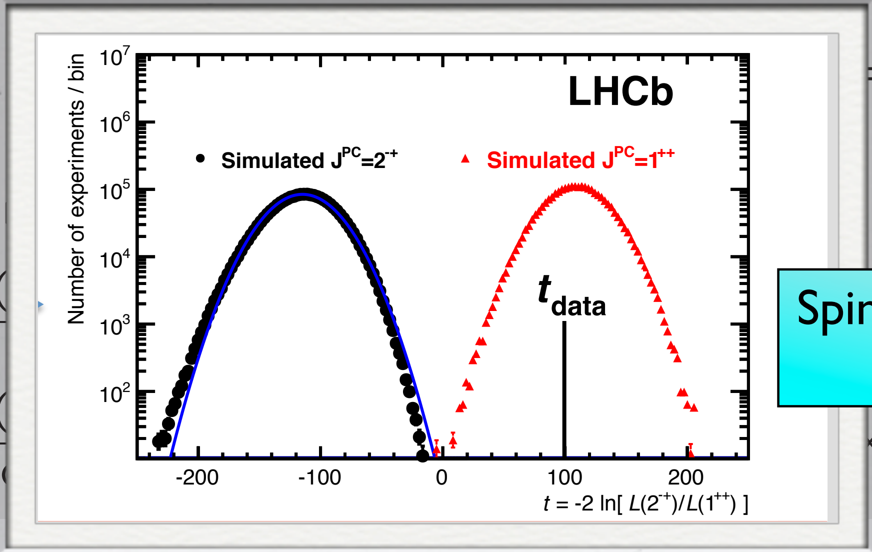
LHCb, 1302.6269

$d\Gamma($

$d^2\Gamma($

Γd

xp. peaks at $|\cos\psi| \simeq 1$



Spin 2++ excluded by LHCb at 8 σ level!

X(3872)

Discovery in 2003

It is observed firstly in Belle in 2003 and confirmed by Babar, CDF, D0...

- ☞ Mass: $3872.0 \pm 0.6 \pm 0.5$ MeV
- ☞ Width: < 2.3 MeV
- ☞ Discovery channel: $B \to KJ/\psi\pi\pi$
- ☞ Favoured quantum number: 1++
- ☞ Decay characteristics: large isospin breaking

$$\frac{Br(X \to \pi^+\pi^-\pi^0 J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 1.0 \pm 0.5$$

X(3872)

It's not charmonium ?!

❑ Can $X(3872)$ be a conventional charmonium?
A possible 1^{++} is the excited state of P-wave charmonium, χ'_{1c}. However, the predicted mass for χ'_{1c} is 3956 MeV, which is too high comparing to $X(3872)$. Moreover, the large isospin breaking decay is impossible for charmonium... So $X(3872)$ is unlikely a charmonium

❑ Various theoretical models as an interpretation of $X(3872)$:

✍ $D^0\bar{D}^{*0}$ Molecule (Deuson) Model N. A. Tornqvist PLB (2004)
$X(3872)$ might be a $D\bar{D}^*$ a D and $\bar{D}^*$ loosely bounded by a π exchange.

✍ Tetraquark Model L. Maiani, F. Piccinini, A. Polosa, V. Riquer, PRD (2005)
$X(3872)$ is one of the mixing states of

$$X_u = [cu][\bar{c}\bar{u}], \qquad X_d = [cd][\bar{c}\bar{d}]$$

$$\begin{pmatrix} X_h \\ X_l \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} X_u \\ X_d \end{pmatrix}$$

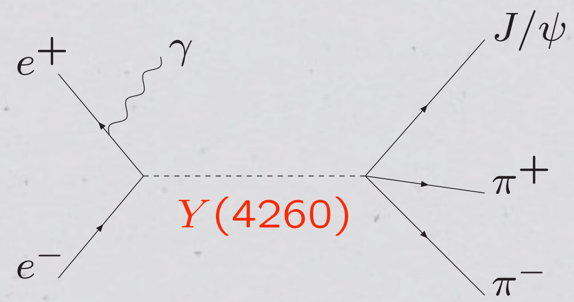
Where are the charged partners?

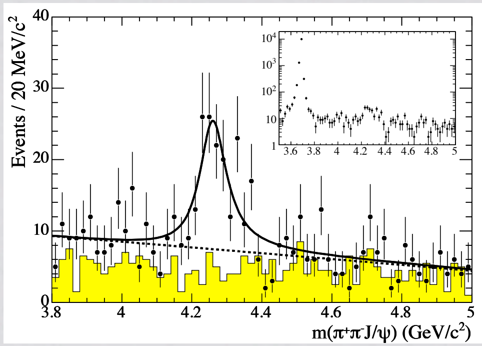
Y(4260)

Discovery in 2005!

A resonance observed in initial-state radiation process $e^+e^- \to (\gamma_{\rm IR})\pi^+\pi^- J/\psi$

Babar collab., PRL 95 (2005) Confirmed by CLEO, Belle, BES.





- Mass: $4259 \pm 8^{+2}_{-6}$ MeV
- Width: $88 \pm 23^{+2}_{-6}$ MeV
- Significance: 125 ± 23 events (8σ signal)

  Also found in $B^\pm \to K^\pm \pi^+\pi^- J/\psi$ decays (3.1σ signal)

  Babar collab., hep-ex/0507090.
- Decay characteristics: Decay to $D^{(*)}\bar{D}^{(*)}$ is suppressed?

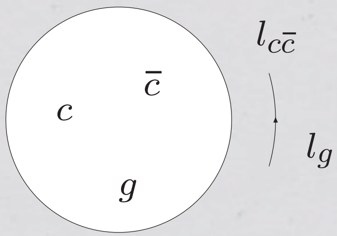
$\longrightarrow$ $\boxed{\textbf{Typical signature of hybrid!}}$

EK, O. Pene, PLB631 ('05)

Y(4260)

Is it a Hybrid?

$(c\bar{c})$+constituent gluon



$P = (-1)^{l_g + l_{c\bar{c}}} \quad C = (-1)^{l_{c\bar{c}} + s_{c\bar{c}} + 1}$

☞ Unnatural quantum number is possible
e.g. $(0^{+-}, 1^{-+}, 2^{+-})$

- ➢ The 1^{--} meson can be composed in two ways, $(l_g,\ l_{c\bar{c}},\ s_{c\bar{c}}) =$ $(0,\ 1,\ 1)$ or by $(1,\ 0,\ 0)$.
- ➢ The state $(l_g,\ l_{c\bar{c}},\ s_{c\bar{c}}) = (0,\ 1,\ 1)$ has been excluded due to its strong coupling to the continuum $D^{(*)}\bar{D}^{(*)}$ (the width exceeds 1 GeV). F. Iddir, S. Safir and O. Pene, PLB (1998)

Y(4260)

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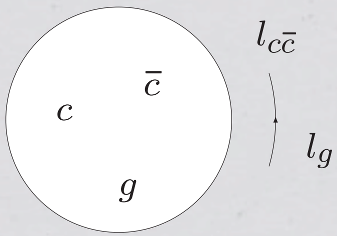

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Spacial symmetry forbids $(l_g,\ l_{c\bar{c}},\ s_{c\bar{c}})$=(1, 0, 0) decaying into any two S-wave final states.

✍ The selection rule was first proven by using the chromo-harmonic model
see e.g. A. Le Yaouanc, L. Oliver, O. Pene, J. C. Raynal and S. Ono, Z. Phys. C (1985)

Y(4260)

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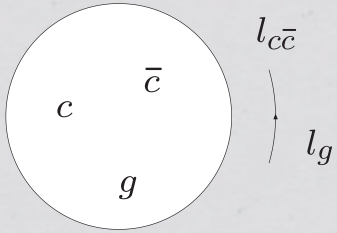

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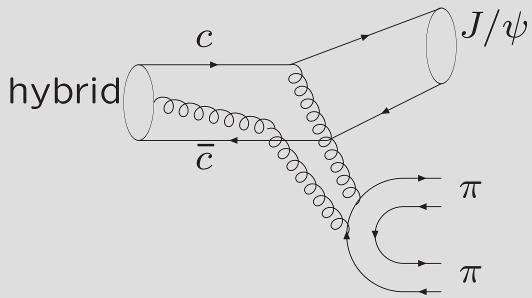
Main decay channel



- The suppression of Y(4260) decaying into the $D^{(*)}D^{(*)}$ final states can be understood by assuming Y(4260) to be a hybrid, due to its selection rule.
- After various experimental attempts (CLEO, BES etc...), the suppression of the $D^{(*)}D^{(*)}$ final states are still observed...
- Further tests at LHC will be interesting!

$Z_c^{\pm}(3900)$

More surprise?!

symmetry dimensions of particle physics

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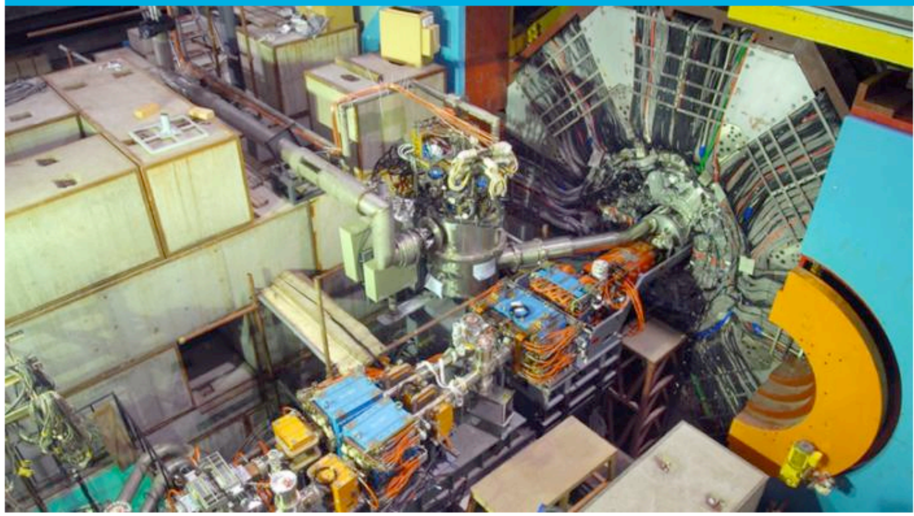

Photo: IHEP Beijing

breaking

March 26, 2013

BESIII collaboration catches new particle

A new particle spotted at China's Beijing Electron Positron Collider raises more questions than it answers.

- While BESIII investigates Y(4260) in details, they found a decay of Y(4260) into "charged charmonium" $Z_c^{\pm}(3900)$!
- There are theoretical papers indicating it might be the missing charged partner of X(3872)!!!

BESIII, 1303.5949

BELLE, 1304.0121

Faccini et al. 1303.6857

Voloshin, 1304.0380

Wang et al, 1303.6355

....

Conclusions

- Charmonium spectrum below threshold is well established and well understood while the above threshold is more puzzling.
- X(3872) and Y(4260) are rather well-established exotic states: they have decay characteristics which is not possible from the conventional charmonium.
- LHC study of XYZ states will be useful to further clarify the situation.

Suppression of S-wave final state

The spacial overlap of $H_B \to D\overline{D}$ can be written in terms of three independent parameters $\pm p_f$ ($D(\bar{D})$ meson mom.), $p_{c\bar{c}}$ (reltv. mom. between $c-\bar{c}$), k (reltv. mom. between $c\bar{c}-g$)

$$I = \int \frac{d\vec{p_{c\bar{c}}}\ d\vec{k}}{\sqrt{2\omega}(2\pi)6} d\Omega_f \boxed{\Psi_{l_H}^{m_H}(\vec{p}_{c\bar{c}},\ \vec{k})} \boxed{\Psi_{l_B}^{m_B\ *}(\vec{p}_B)\ \Psi_{l_C}^{m_C\ *}(\vec{p}_C)} \boxed{Y_l^{m\ *}(\Omega_f)}$$

Let us consider the change of variable

$$\boxed{\vec{k} \ \to\ -\vec{k}} \qquad \longrightarrow (\vec{p}_B \leftrightarrow -\vec{p}_C).$$

- The hybrid wave function is odd in k since $l_g = 1$.
- In the case of S-wave final mesons, the wave functions are even in p_B and p_C. Thus, their product remains unchanged.
- The spherical harmonic function $Y_l^{m\ *}(\Omega_f)$ is a function of the unit vector $\widehat{p}_f$ and is thus unchanged.

$$\boxed{\text{The decay } H_B \to D^{(*)}\overline{D}^{(*)} \text{ is forbidden in any potential model.}}$$

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