New States in Charmonium and Bottomonium Families

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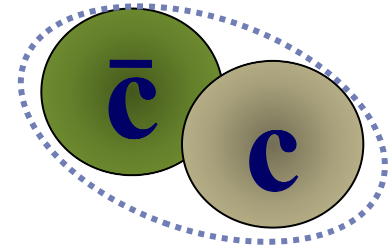
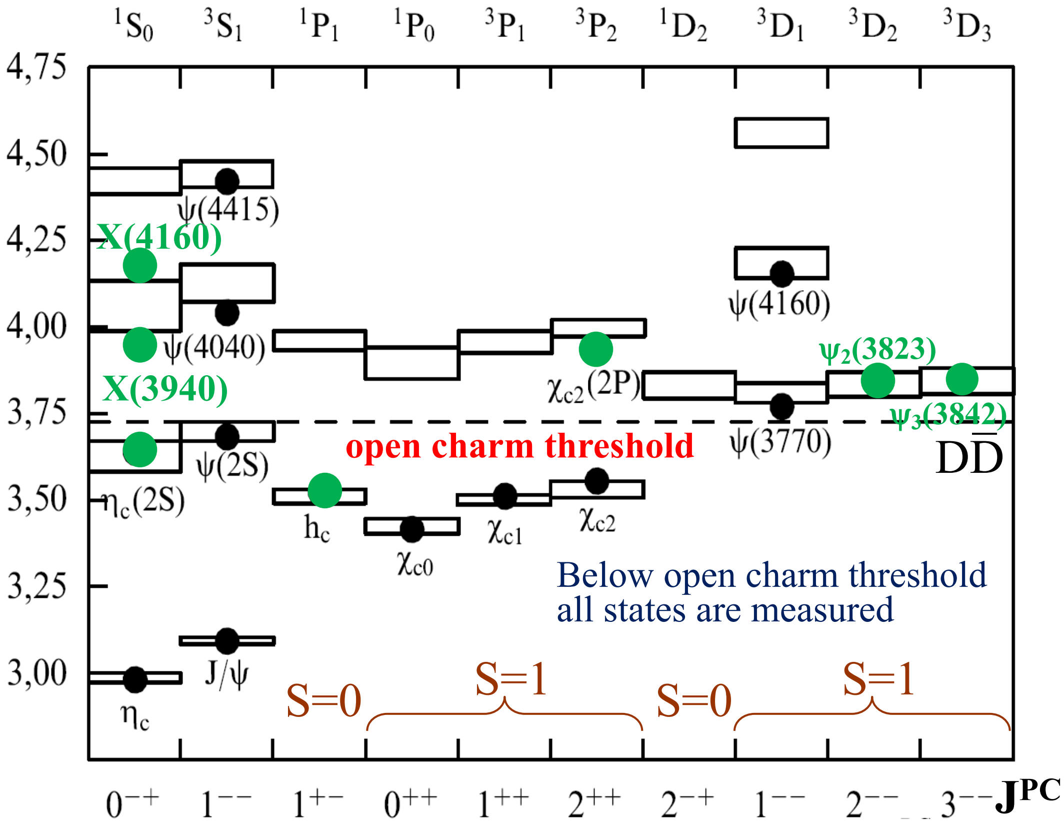
International Conference on Precision Physics and Fundamental Physical Constants FFK-2019
Tihany, Hungary, 10-14 June 2019

Charmonium in the standard quark model

Charmonium in the standard quark model





$(n+1)^{(2S+1)}L_J$

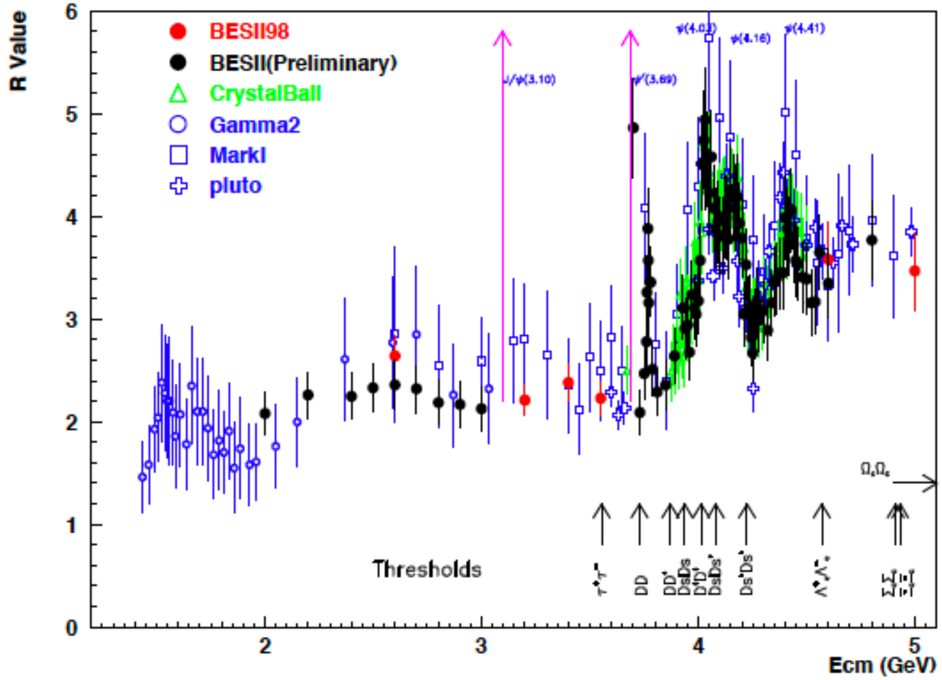
- n radial quantum number
- S total spin of quark-antiquark
- L relative orbital ang. mom. L = 0, 1, 2 ... corresponds to S, P, D...
- J = S + L
- $P = (-1)^{L+1}$ parity
- $C = (-1)^{L+S}$ charge conj.

1974-1980 Discovery of **10 standard charmonium states**

1980-2002 … nothing

2002-2019 Discovery of **7 new states that fit into charmonium table**

Below open charm threshold a good agreement between theory and experiment



Charm factory BESIII

Symmetric e^+e^- collider

Energy scan 2.0 - 4.6 GeV
L ~ 10^{33}/cm²/s

Direct production of vector charmonium ψ states with $J^{PC} = 1^{--}$

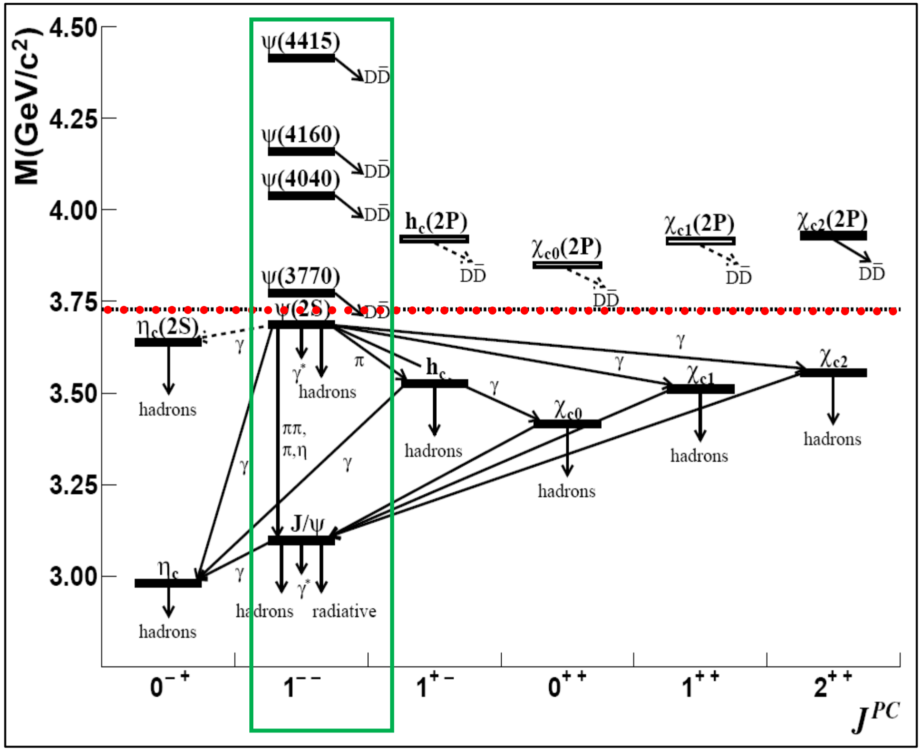
- Below open charm threshold
- Above open charm threshold ψ states decay mainly to D meson pairs

$\psi(3770) \Rightarrow D\bar{D};$

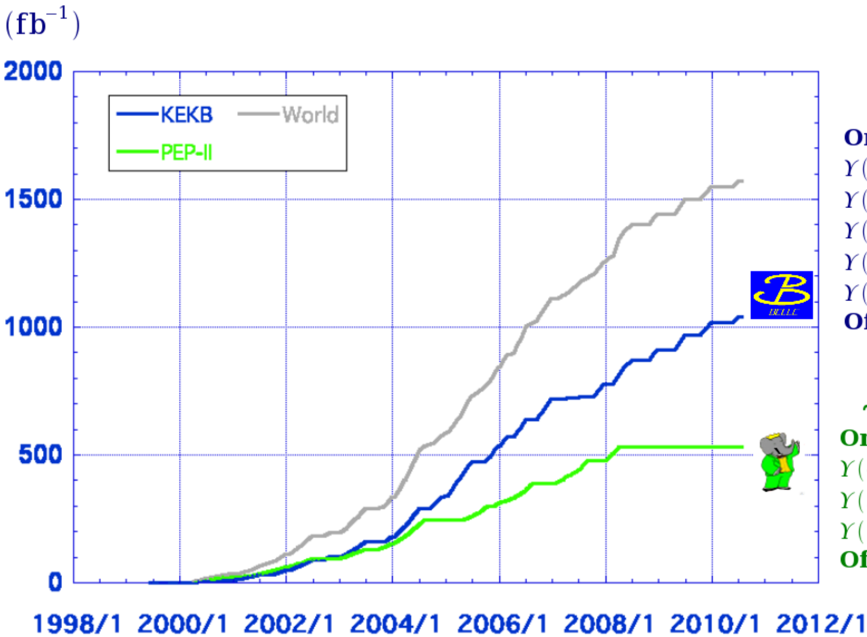
$\psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s;$

$\psi(4160) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*;$

$\psi(4415) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*.$

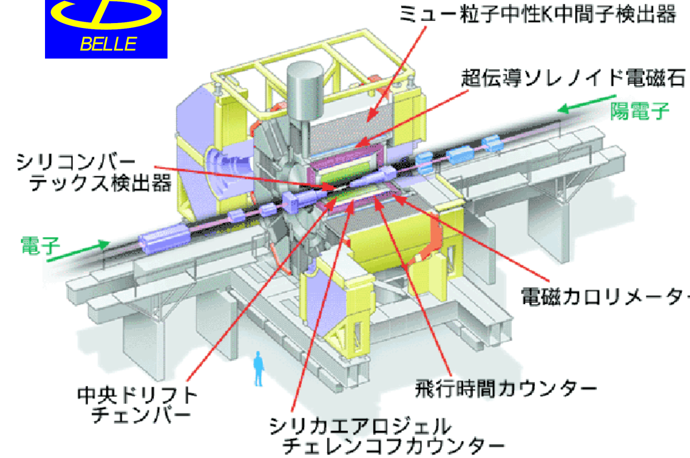


B factories Belle & BaBar



> 1 ab^{-1}
On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~100 fb^{-1}

~ 550 fb^{-1}
On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~54 fb^{-1}



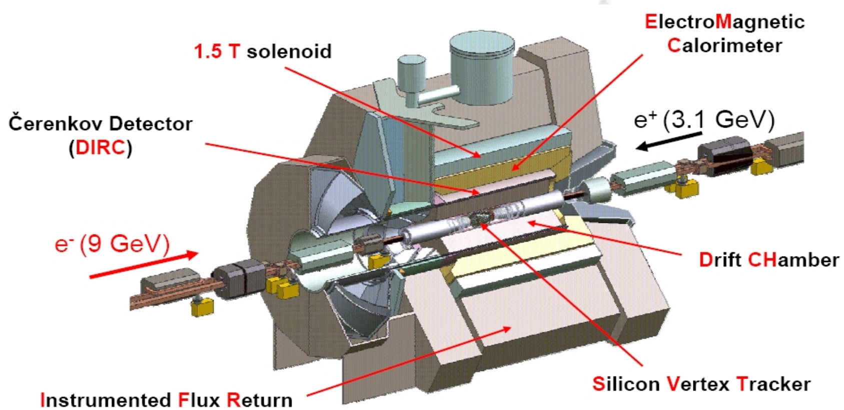
Asymmetric e^+e^- collider

Belle: 8 GeV (e^-) × 3.5 GeV (e^+)

designed luminosity: $10.0\times10^{33}\text{cm}^{-2}\text{s}^{-1}$

achieved $21.2\times10^{33}\text{cm}^{-2}\text{s}^{-1}$

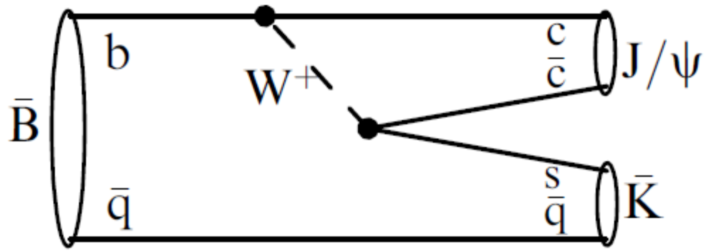
>2 times larger!



BaBar completed data taking in April, 2008
Belle completed data taking in June, 2010
to start SuperKEKB/Belle II upgrade

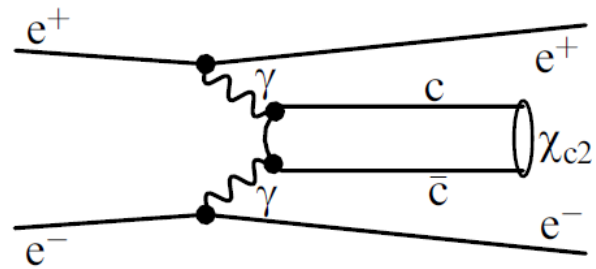
Charmonium production at B factories

B decays



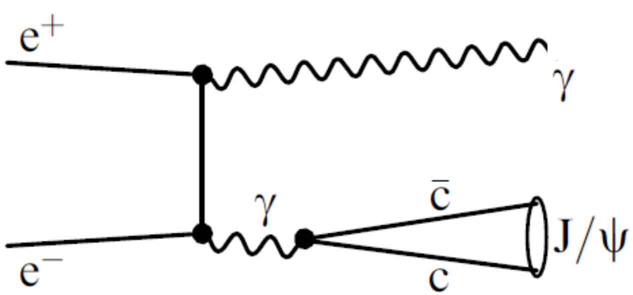
Any quantum numbers are possible,
can be measured in angular analysis

γγ fusion



$\mathbf{J^{PC} = 0^{\pm+}\ , 2^{\pm+}}$

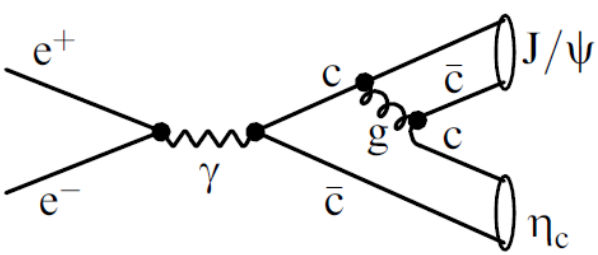
e+e− annihilation with ISR



$\mathbf{J^{PC} = 1^{--}}$

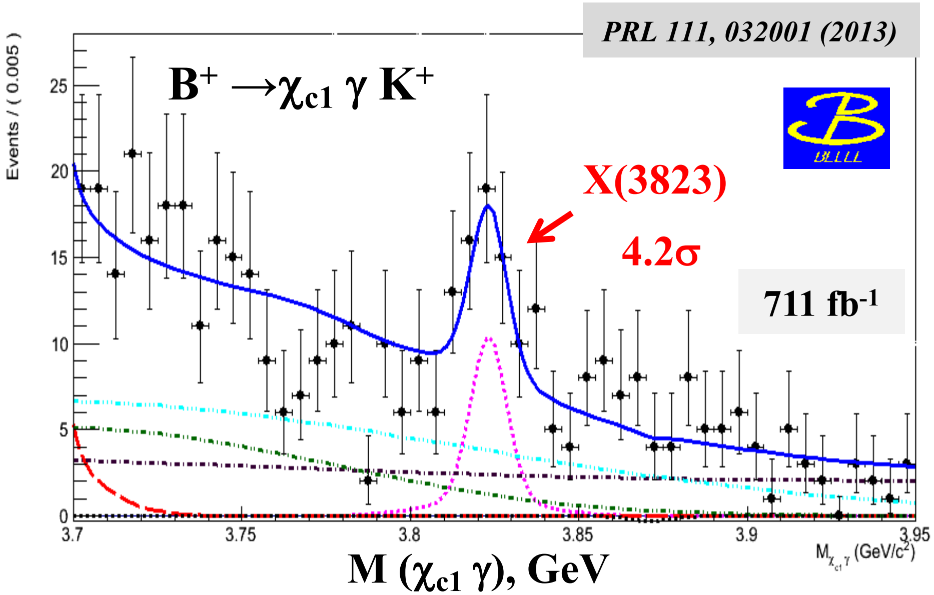
Study of vector charmonium states
from threshold in wide energy region

double charmonium production

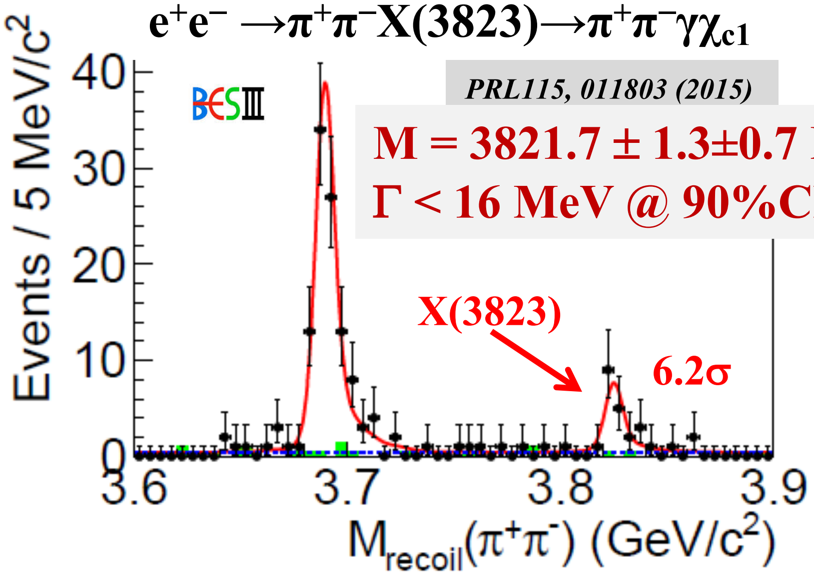


in association with **J/ψ**
only $\mathbf{J^{PC} = 0^{\pm+}}$ seen

$X(3823) = \psi_2(1^3D_2)$ PDG2018



M = 3823.5 ± 2.8 MeV
Γ < 14 MeV @ 90%CL

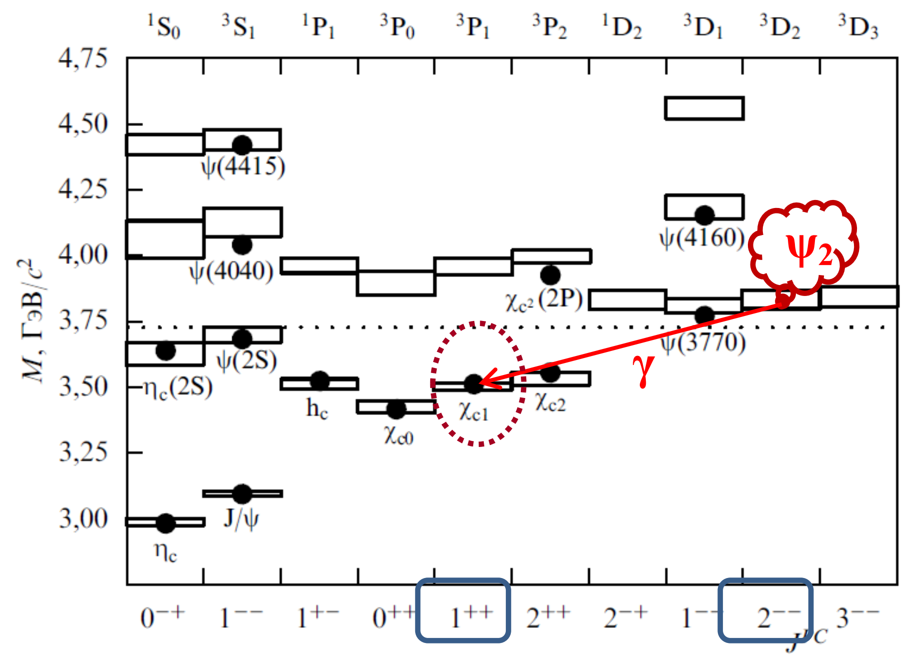


M = 3821.7 ± 1.3±0.7 MeV
Γ < 16 MeV @ 90%CL

$X(3823) \to \chi_{c1}\gamma \Longrightarrow C = -$

1^{--}	1^{+-}	2^{--}	3^{--}
$\psi(3770)$	$h_c(2P)$	ψ_2	$\psi_3 \to DD$

- decay to DD is forbidden due to unnatural spin-parity → small Γ
- decay to $\chi_{c1}\gamma$ should be prominent (E1)
- $\Gamma(\chi_{c1}\gamma) \sim O(10KeV)$ is typical for charmonium



Tevatron

LHC

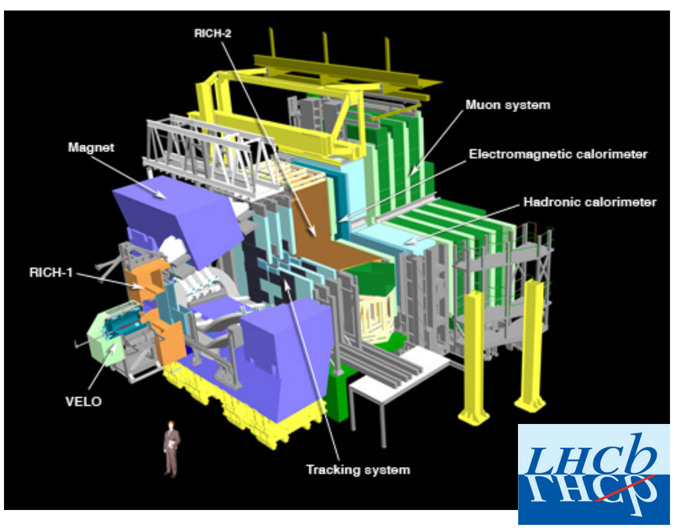
pp collider

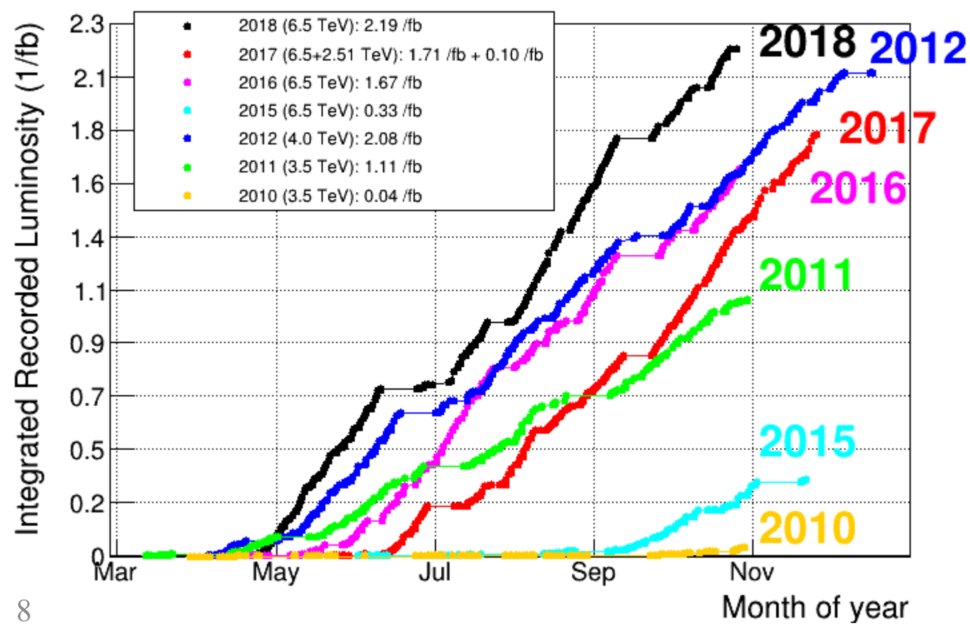
pp collider

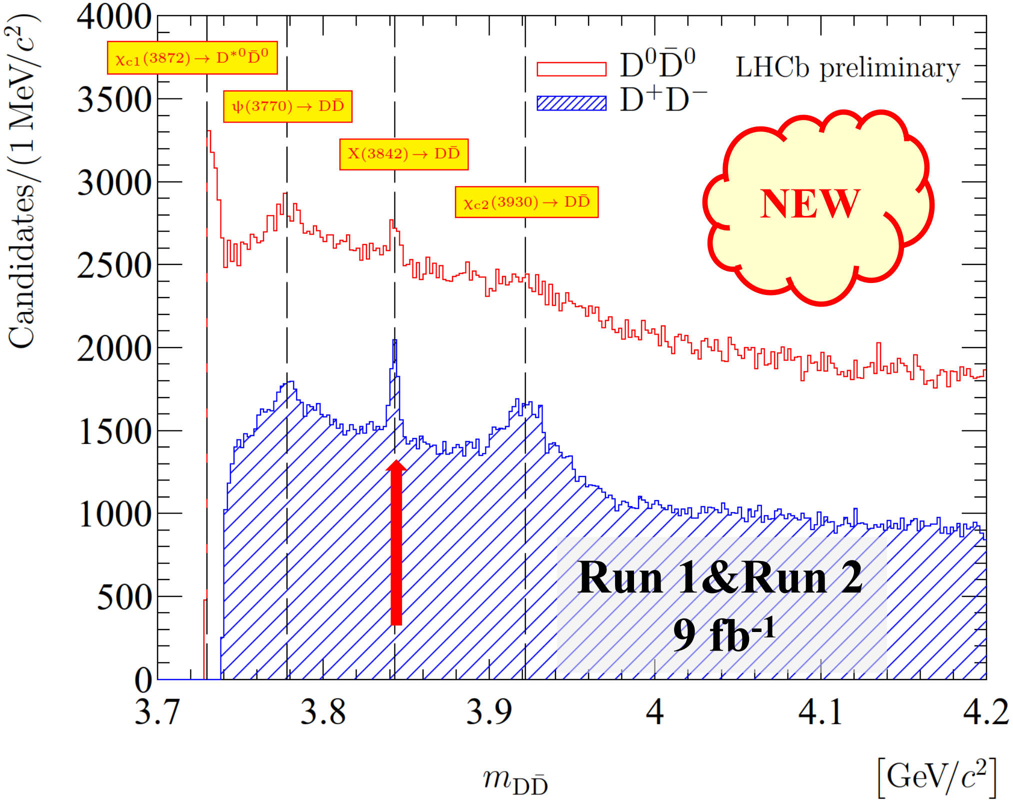
E ~ 1.8 TeV: L ~ 4fb^{-1} / experiment

Charmonium
- Prompt production
- B meson decays

Charmonium
- Prompt production
- Beauty hadrons decays







$X(3842) = \psi_3(1^3D_3)$

$X(3842) \to DD$

2^{--} 3^{--}

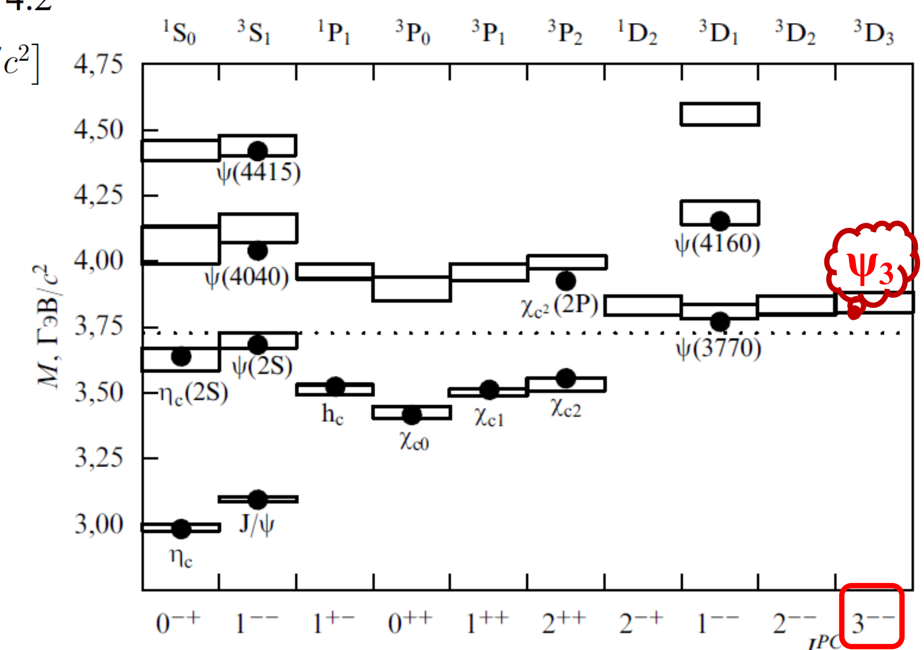
ψ_2 $\psi_3 \to DD$

- Decay to DD should be prominent
- $\Gamma(DD) \sim 1$ MeV, due to small decay phase-space and L=3 centrifugal barrier!

New narrow state X(3842) at open charm threshold is observed

$M = 3842.71 \pm 0.16 \pm 0.12$ MeV
$\Gamma = 2.79 \pm 0.51 \pm 0.35$ MeV

Consistent with expected 1^3D_3 state $\psi_3(1D)$ with $J^{PC}=3^{--}$



Exotic Charmoniumlike states

Multiquark states

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, Λ in the old Sakata model, for example 3) with all strong interactions ascribed to a neutral vector meson field interacting symmetrically with the three particles. Within such a framework, the

Hydronic molecules and the charmonium atom

M. B. Voloshin and L. B. Okun'
Institute of Theoretical and Experimental Physics

March 1976

(February 16, 1976)
Pis'ma Zh. Eksp. Teor. Fiz. **23**, No. 6, 369–372 (20 March 1976)

We consider the possible existence of levels in a system consisting of a charmed particle and a charmed antiparticle; these levels result from exchange of ordinary mesons (ω,ρ,ϵ,ϕ, etc.). An interpretation of the resonances in e^+e^- annihilation in the region 3.9–4.8 GeV is proposed.

Molecular Charmonium: A New Spectroscopy?*

A. De Rújula, Howard Georgi,† and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

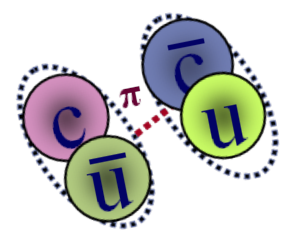
(Received 23 November 1976)

Recent data compel us to interpret several peaks in the cross section of e^-e^+ annihilation into hadrons as being due to the production of four-quark molecules, i.e., resonances between two charmed mesons. A rich spectroscopy of such states is predicted and may be studied in e^-e^+ annihilation.

November 1976

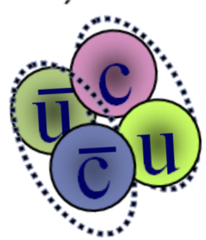
Molecular state

two loosely bound charm mesons



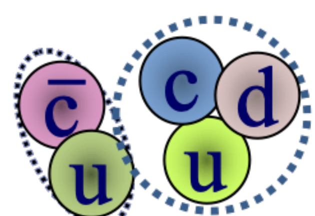
Tetraquark

tightly bound four-quark state



Pentaquark

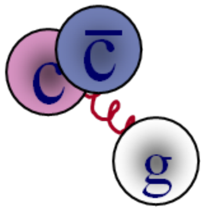
tightly bound five-quark state

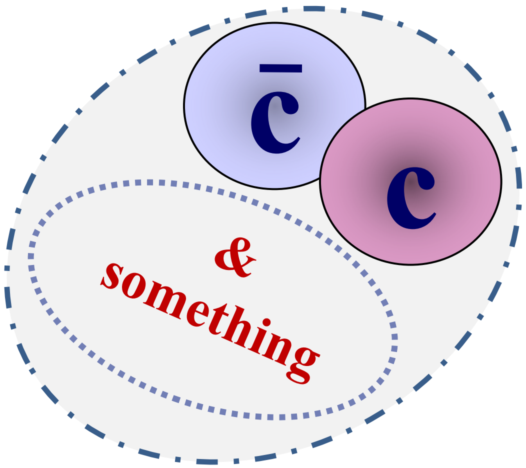


More charmoniumlike states

Charmonium hybrids

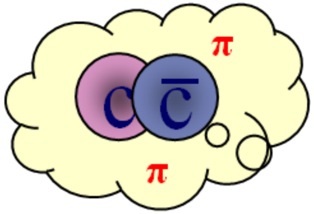
States with excited gluonic degrees of freedom





Hadrocharmonium

Specific charmonium state “coated” by excited light-hadron matter



Rescattering

Two D-mesons, produced closely, exchange quarks

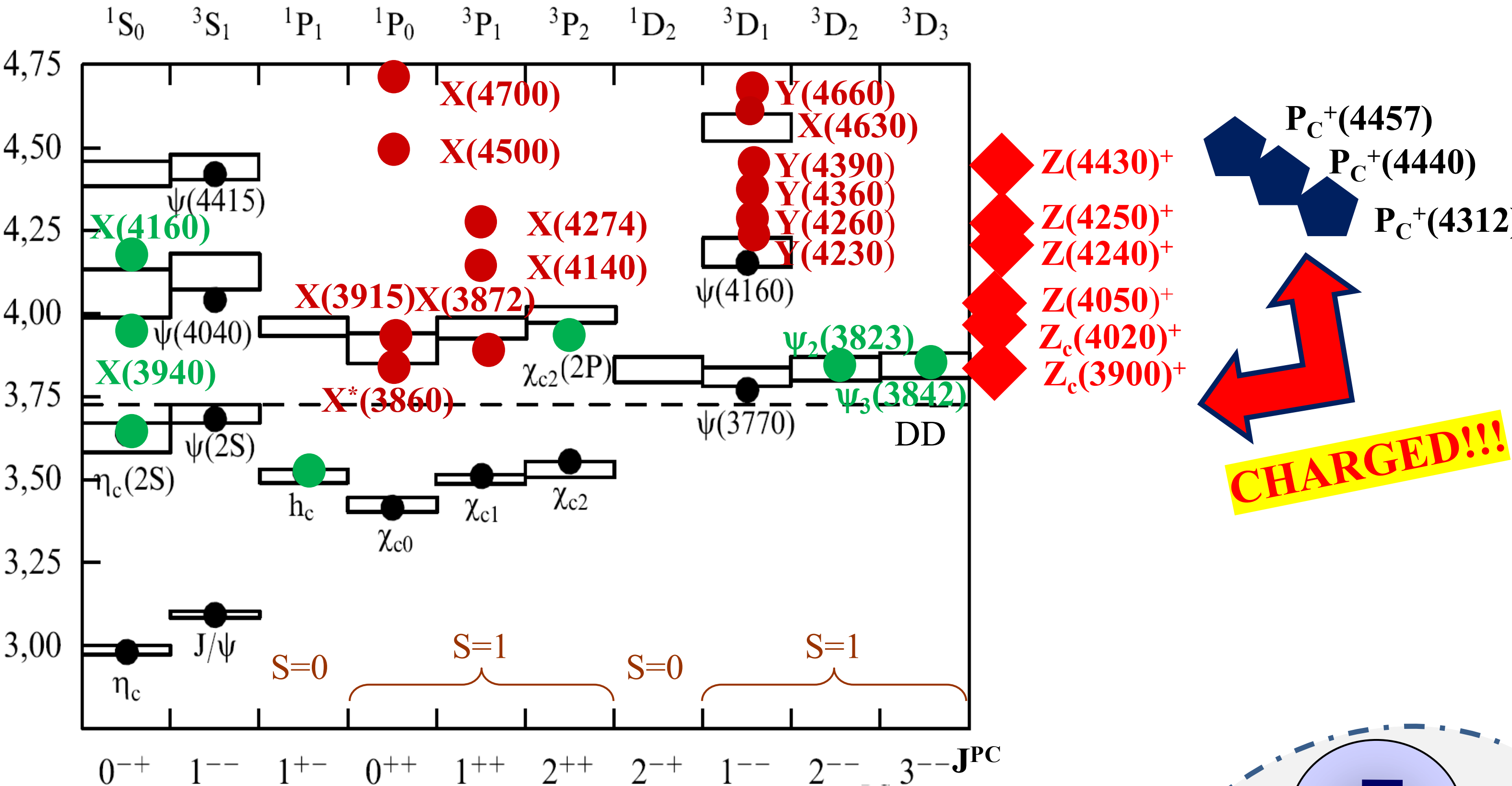
Threshold effects

Virtual states at thresholds

Charmonium states with masses shifted by nearby $\mathbf{D_{(s)}^{(*)}D_{(s)}^{(*)}}$ thresholds

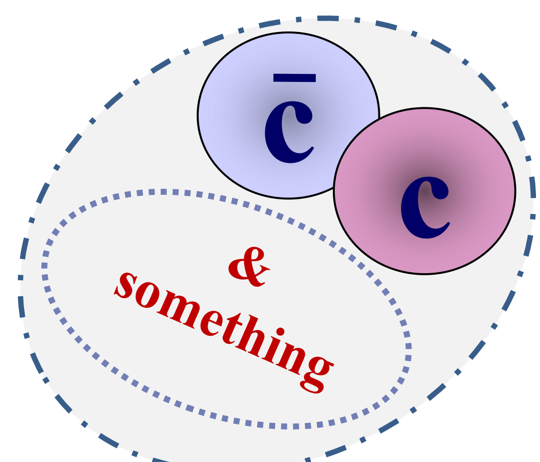
Charmoniumlike states

before PDG2018 naming scheme



2002-2019

Discovery of **two dozens exotic charmonium states or charmoniumlike states**



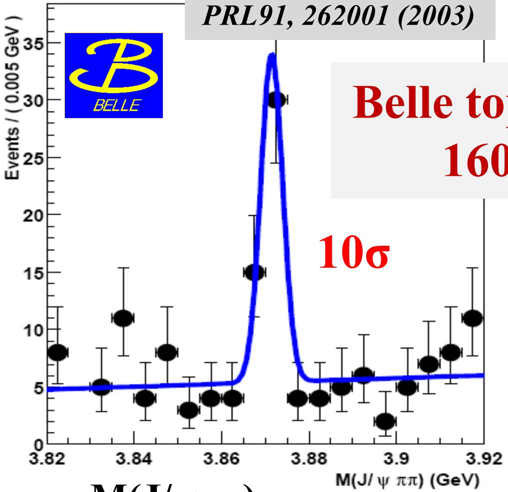
All of them above open charm threshold

X(3872)
as
χ_{c1}(3872) in PDG2018

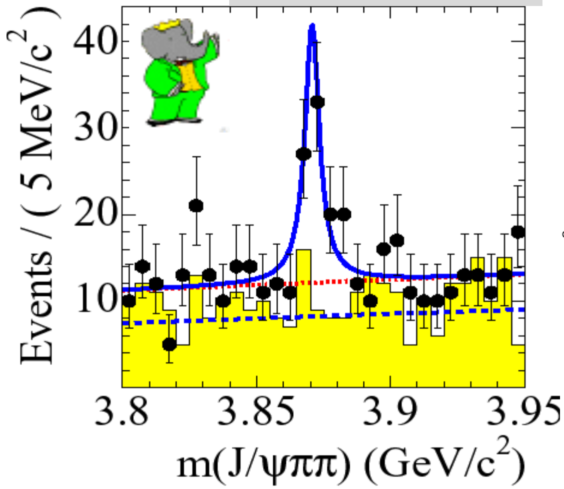
First observed by Belle in $B \to K\, J/\psi \pi^+\pi^-$

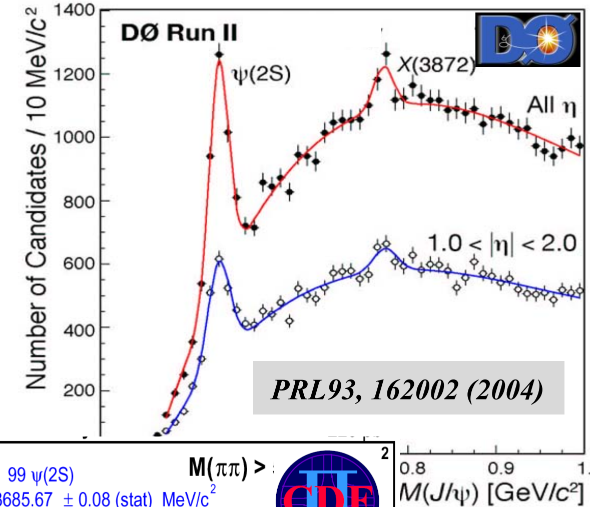
PRL91, 262001 (2003)

Belle top cited 1600+

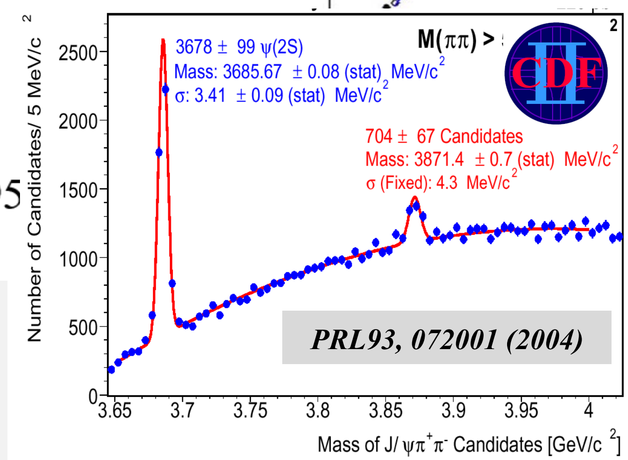


PRD73, 011101 (2006)



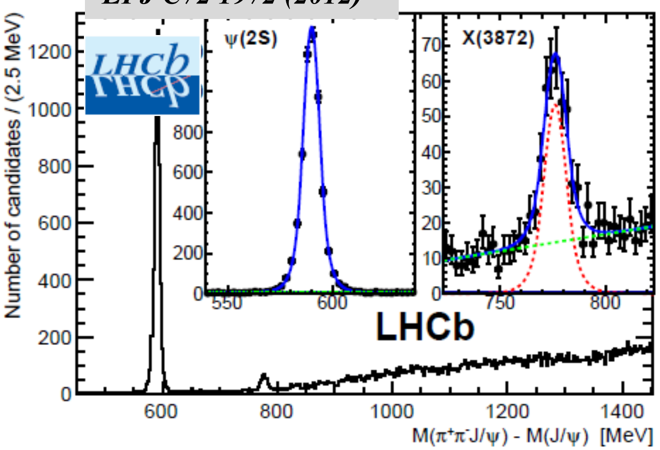


PRL93, 162002 (2004)



PRL93, 072001 (2004)

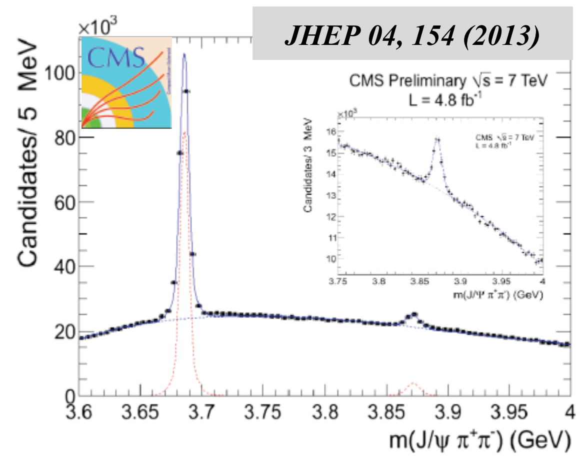
EPJ C72 1972 (2012)



$J^{PC} = 1^{++}$ finally established

Hadronic collisions: produced mostly promptly; only 0.263±0.023±0.016 from B-decays (CMS)

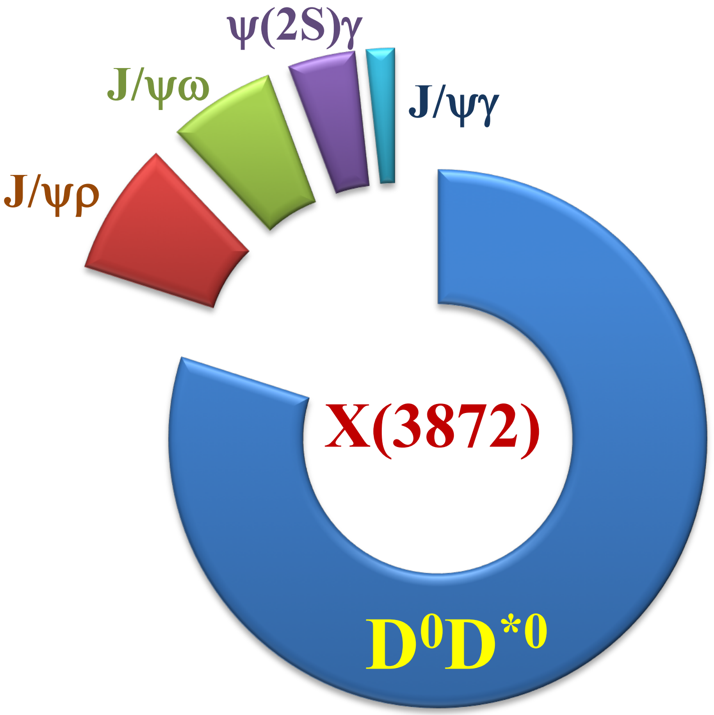
JHEP 04, 154 (2013)



M_X close to D^0D^{*0} threshold **M = 3871.69± 0.17 MeV**

not clear below or above: **Δm = – 0.01 ± 0.18 MeV**

Surprisingly narrow: **Γ_{tot}< 1.2 MeV** at 90% CL

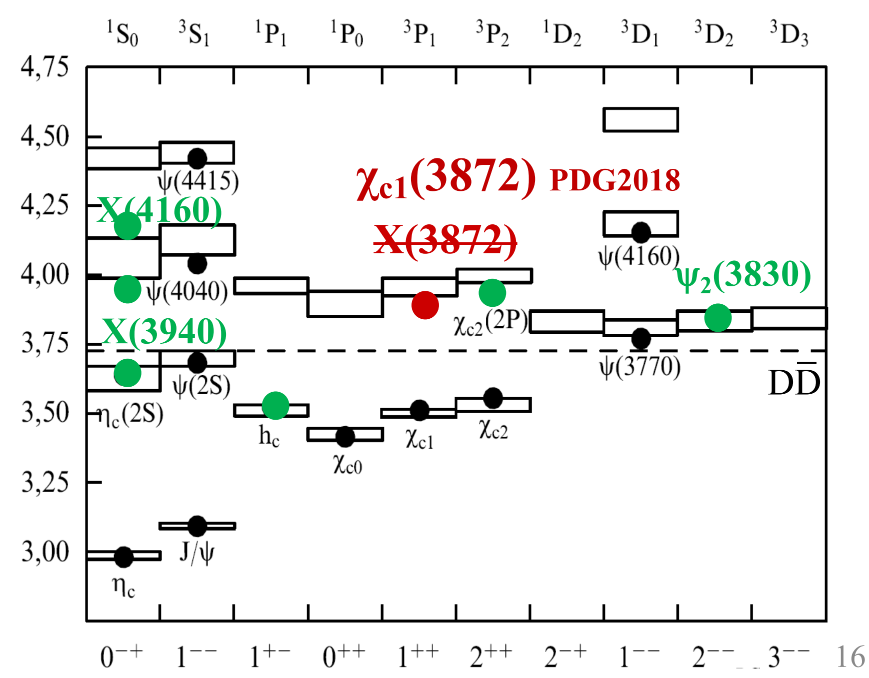


X(3872) interpretation

D^0D^{*0} molecular state: (the most popular today)

- $M_X \sim M_{D0} + M_{D^*0}$ is not accidental
- $J^{PC}=1^{++}$ (D^0D^{*0} in S-wave)
- DD^* decay
- Small rate for decay into $J/\psi\gamma$ is expected
- too large $X(3872) \to \psi(2S)\gamma$
- too small binding energy: D^0 and D^{*0} too far in space to be produced in high energy pp collisions

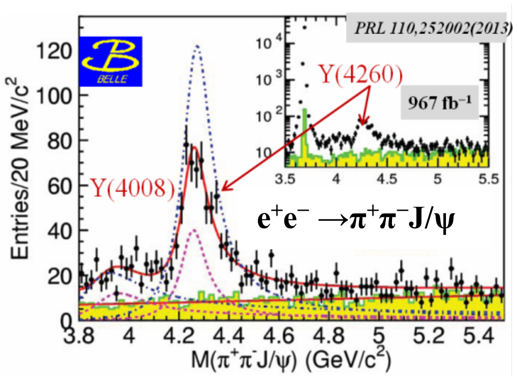
Mixture of P-wave charmonium $\chi_{c1}(2P)$ and S-wave DD^{*0} molecule

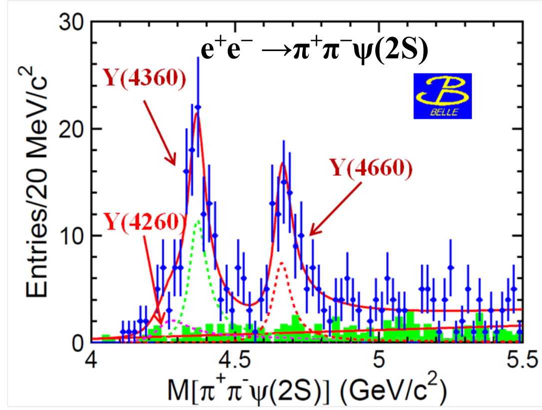


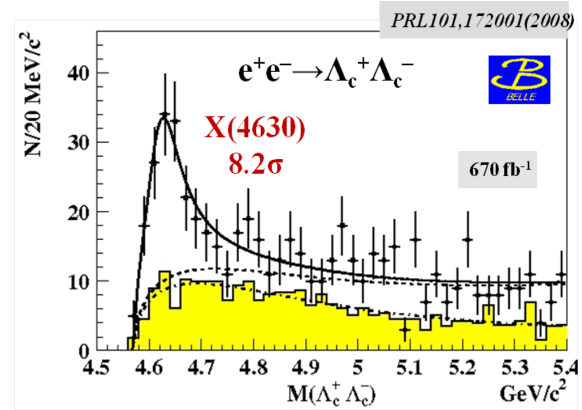
Search for X(3872) partners decays *Molecules with $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$...*	
$\chi_{c1}\gamma$ $\chi_{c2}\gamma$	Forbidden by C-parity conservation C-odd partners: tetraquark, molecule UL : $< 1/4$ from $J/\psi\,\pi^+\pi^-$
$J/\psi\,\eta$	C-odd partners: tetraquark UL : $< 1/2$ from $J/\psi\,\pi^+\pi^-$
$\eta_c\,\eta$ $\eta_c\,\pi^0$ $\eta_c\,\pi^+\pi^-$ $\eta_c\,\omega$	Search for other X-like molecular states UL : $\sim J/\psi\,\pi^+\pi$

BELLE


Y family of exotic
vector states

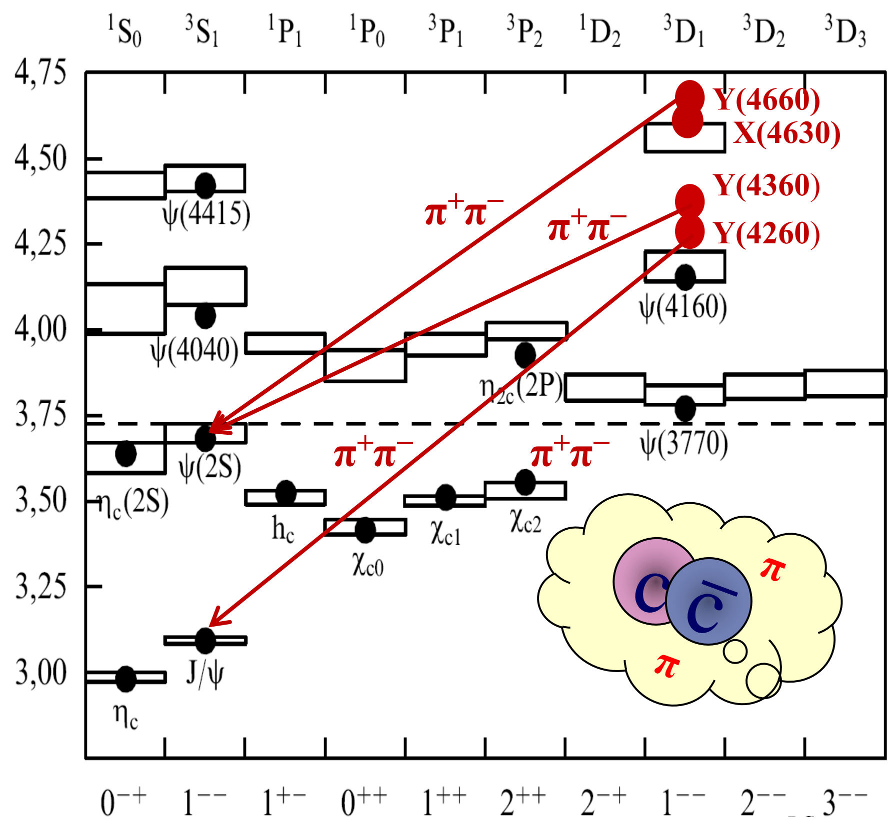






Y states at B factories via ISR

	M(MeV)	Γ(MeV)	decay mode	experiment
Y(4260)	4263^{+8}_{-9}	95±14	$J/\psi\pi\pi$	BaBar, Belle
Y(4360)	4361±13	74±18	$\psi(2S)\pi\pi$	BaBar, Belle
X(4630)	4634^{+9}_{-11}	92^{+41}_{-32}	$\Lambda_c^+\Lambda_c^-$	Belle
Y(4660)	4664±12	48±15	$\psi(2S)\pi\pi$	BaBar, Belle



Unlike conventional charmonium

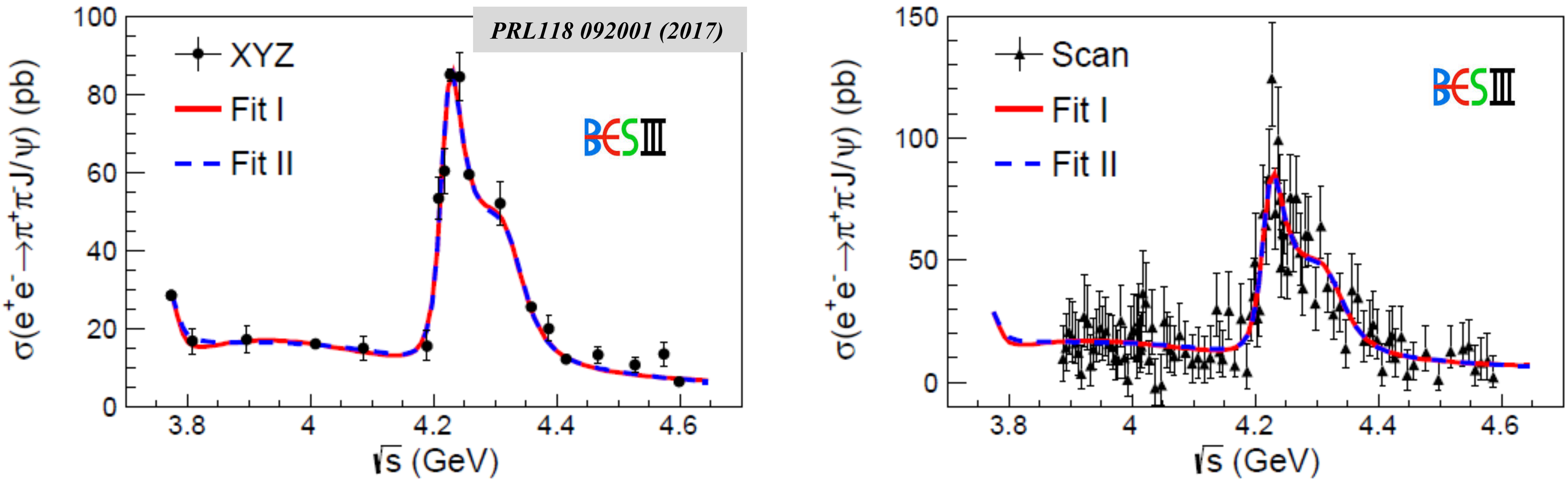
- No room for Y states among 1^{--} charmonium

  3^3S_1 = ψ(4040); 2^3D_1 = ψ(4160) ; 4^3S_1 = ψ(4415); masses of predicted 3^3D_1 (4520); 5^3S_1 (4760); 4^3D_1(4810) are higher (lower)
- Absence of open charm production
- Anomalous large partial width

  $\Gamma(Y \to J/\psi\pi\pi) > 1$ MeV
- Only one decay channel per one Y state:

  light charmonium + ππ

Precise measurements of $e^+e^- \to \pi^+\pi^- J/\psi$

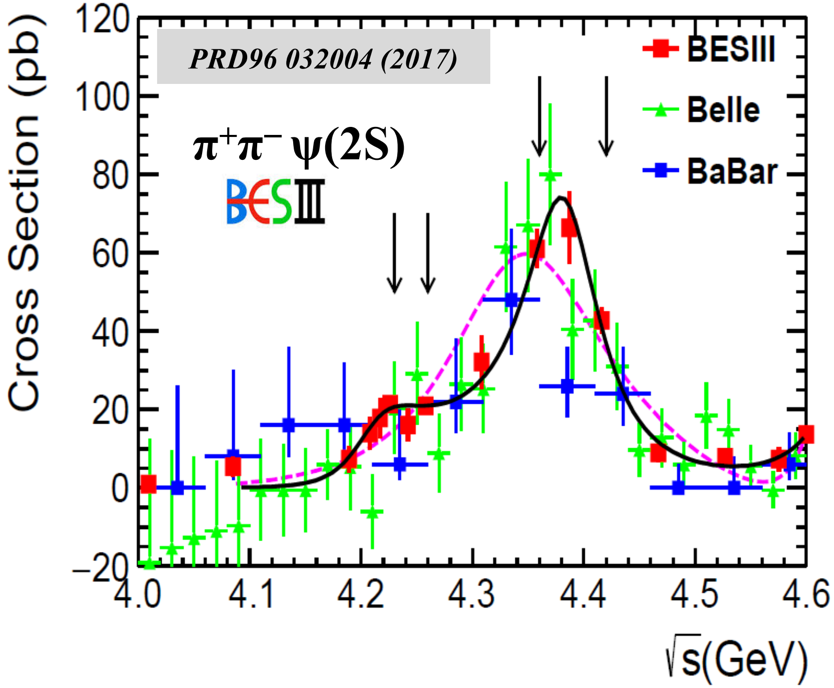


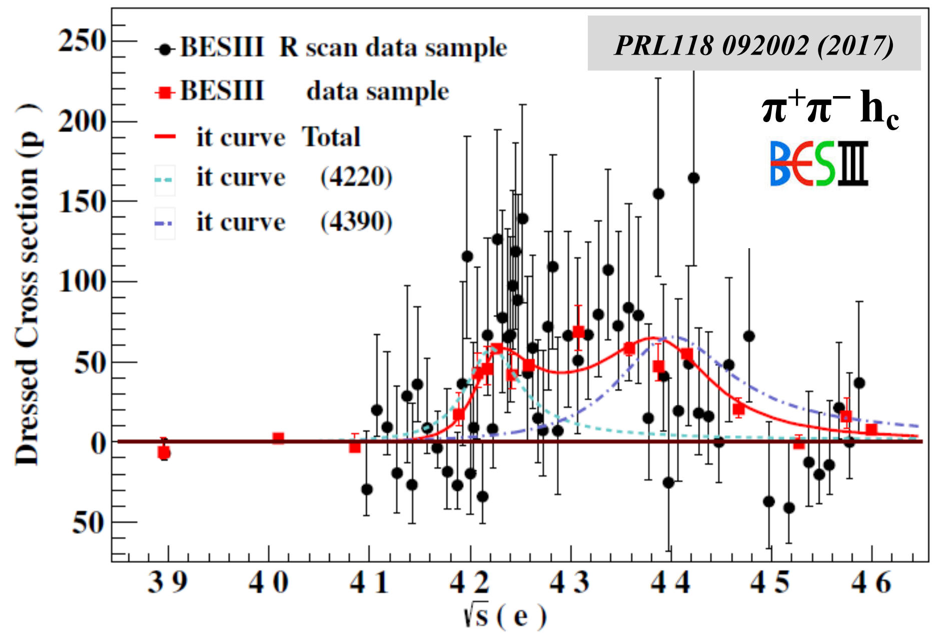
$e^+e^- \to \pi^+\pi^- J/\psi$ cross section is inconsistent with a single pick of Y(4260)

Two peaks are favored over one peak by 7.6 σ

	M, GeV/c²	Γ, MeV	Decay mode
Y(4220), BESIII	4222.0±3.1±1.4	44.1±4.3±2.0	$\pi^+\pi^- J/\psi$
Y(4360), BESIII	4320.0±10.4±7.0	$101.4^{+25.3}_{-19.7}\pm10.2$	$\pi^+\pi^- J/\psi$

Precise measurements of $e^+e^- \to \pi^+\pi^- \psi(2S)$, $\pi^+\pi^- h_c$

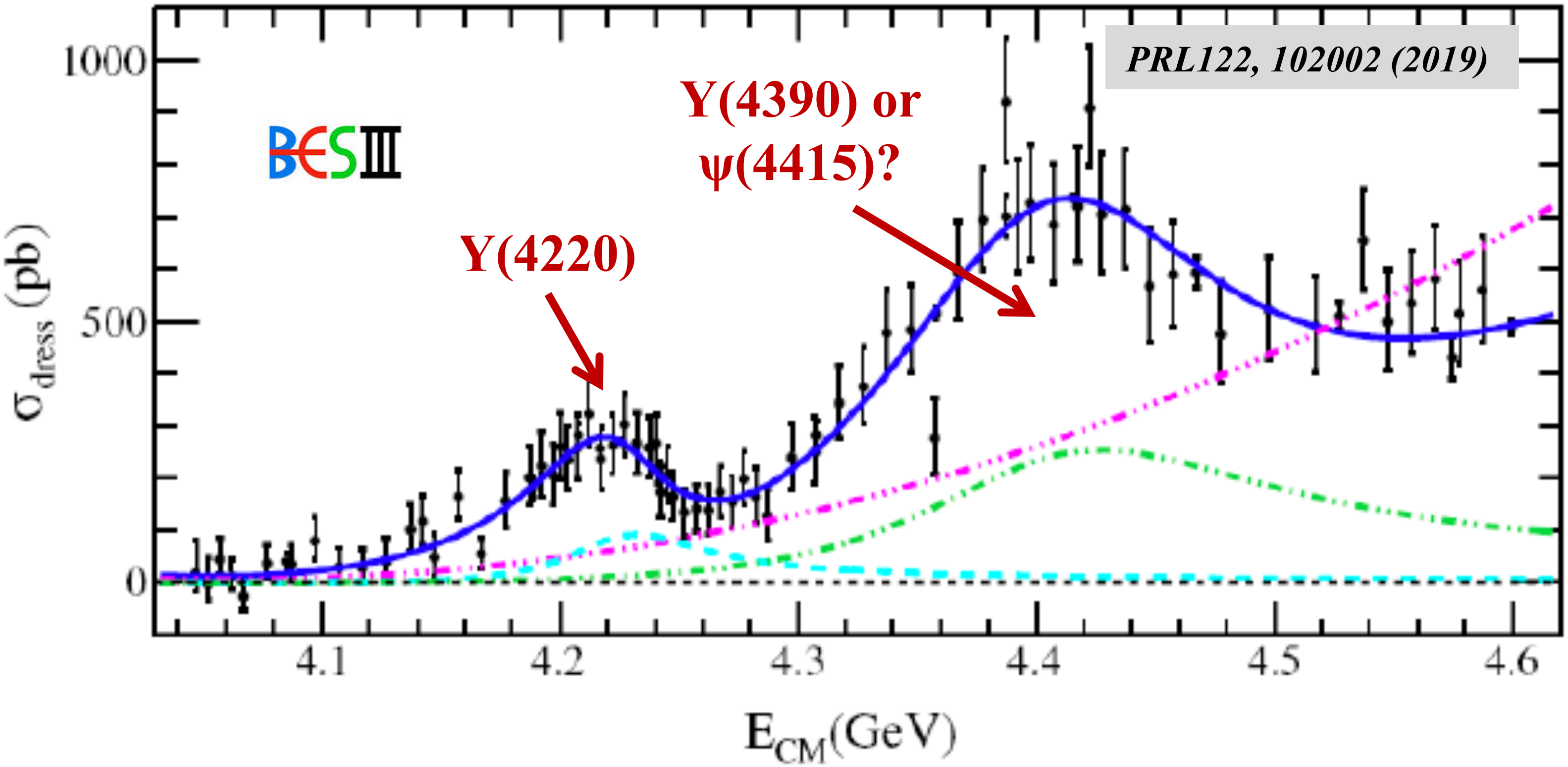




BESIII confirms lineshape in $e^+e^- \to \pi^+\pi^- \psi(2S)$

	M, GeV/c2	Γ, MeV	Decay mode
Y(4220)	4209.5±7.4±1.4	80.1±24.6±2.9	$\pi^+\pi^- \psi(2S)$
Y(4220)	$4218.4^{+5.5}_{-4.5}\pm0.9$	$66.0^{+12.3}_{-8.3}\pm0.4$	$\pi^+\pi^- h_c$
Y(4390)	4383.8±4.2±0.8	84.2±12.5±2.1	$\pi^+\pi^- \psi(2S)$
Y(4390)	$4391.5^{+6.3}_{-6.8}\pm0.9$	$139.5^{+16.2}_{-20.6}\pm0.6$	$\pi^+\pi^- h_c$

$e^+e^- \to D^0 D^{*-} \pi^+$



Two peaks are favored over one peak is greater 10 σ

	M, GeV/c2	Γ, MeV	Decay mode
Y(4220)	4228.6±4.1±6.3	77.0±6.8±6.3	$D^0 D^{*-} \pi^+$

$\psi(4415) \to D^0 D_2(2460)^0 \to D^0 D^- \pi^+$

$\psi(4415) \to D^0 D_2(2460)^0 \to D^0 D^{*-} \pi^+$

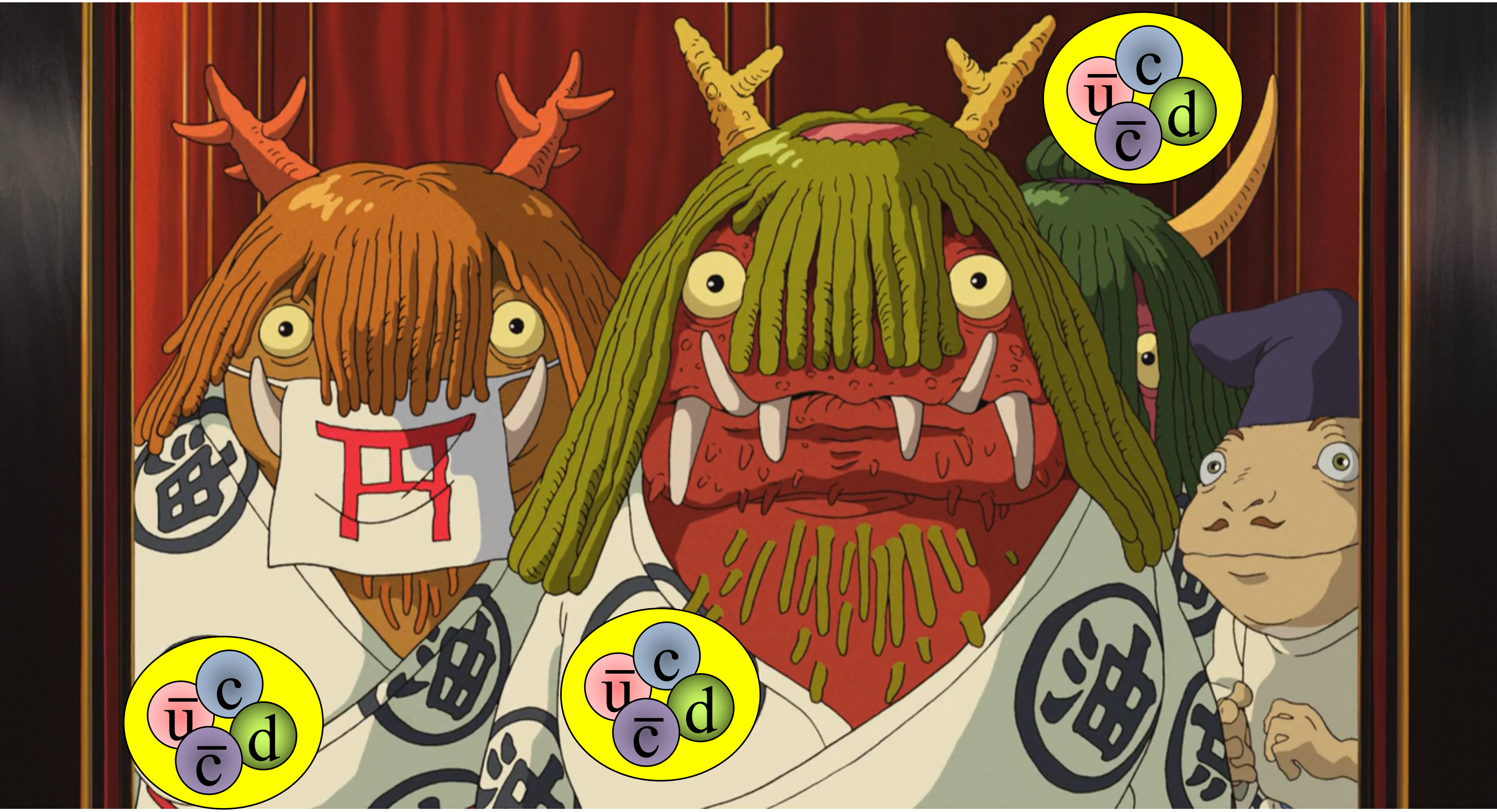
BELLE

Vector states summary 2019

	Open charm	$J/\psi\pi^+\pi^-$	$\psi(2S)\ \pi^+\pi^-$	$h_c\pi^+\pi^-$	$J/\psi\eta$	$\chi_{c0}\omega$	$\chi_{c2}\omega$	
ψ(3770)	+							
ψ(4040)	+				+			
ψ(4160)	+				+			
Y(4220) = ψ(4230) PDG 2018 Y(4260) = ψ(4260) PDG 2018	$DD^*\pi$ -	+ +		+		+		Same state?
Y(4390) = ψ(4390) PDG 2018 Y(4360) = ψ(4360) PDG 2018	 -	 +	+ +	+				Same state?
Y(4390)?	$DD^*\pi$							ψ(4415)?
ψ(4415)	$DD\pi$						+	
Y(4630) = ψ(4660) PDG 2018	$\Lambda_c^+\Lambda_c^-$							Same state ψ(4660)?
Y(4660) = ψ(4660) PDG 2018	-	+	+					

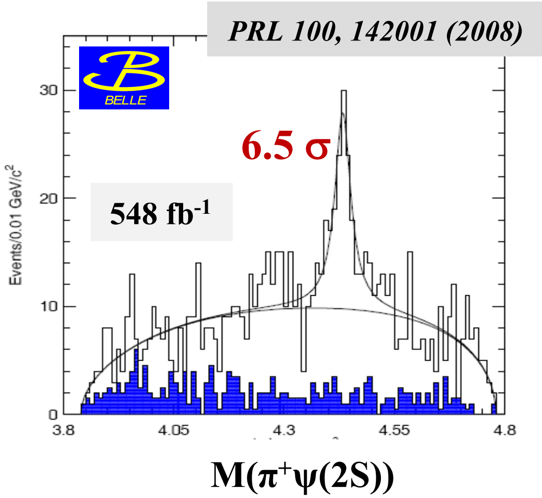
Y family contains three (five?) exotic vector states

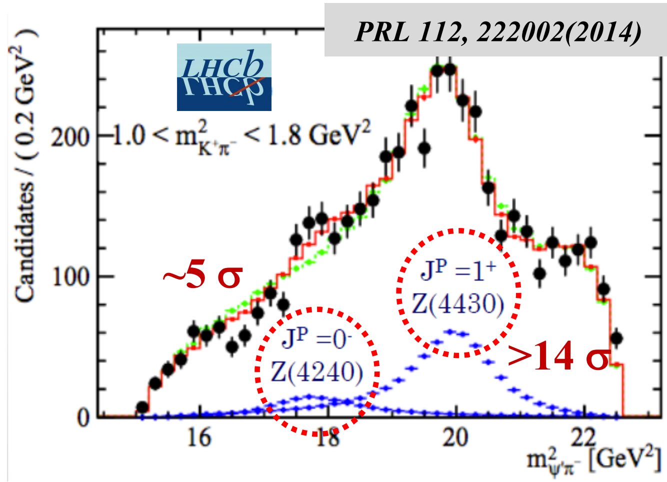
- ~~Only one~~ **Few decay channels per one Y state**
  - **hadrocharmonium is excluded!**
- **Nature of Y states?**
- **PDG naming 2018: Y states with $J^{PC} = 1^{--}$ turn into ψ states**



Charged charmoniumlike states

Charged Z_c^+ states in B decays

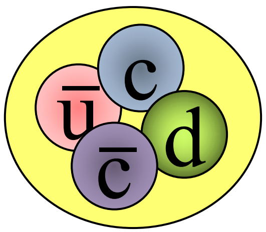




$Z(4430)^+ \to \psi(2S)\ \pi^+$

LHCb: Parameters (including quantum numbers) are consistent with the Belle results

Another peak at **4240 MeV** with significance ~5 σ



Belle: $Z(4430)^+$ three different analysis, $J^P = 1^+$

- Discovery: fit to $M(\psi(2S)\pi^+)$ with $K^*(890)$&$K^*(1430)$ veto
- Dalitz analysis
- Full amplitude analysis to obtain spin-parity

Mass values are the same, width depends on method

Z_c^+ cannot be conventional charmonium

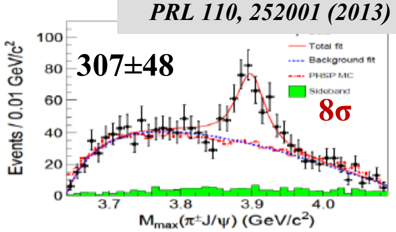
Four Z_c^+ states found by Belle

	PDG2018	M(MeV)	Γ(MeV)	J^{PC}	decay mode	production mode	experiment
$Z^+(4050)$	X(4050)	4051^{+24}_{-40}	82^{+50}_{-28}	?	$\chi_{c1}\pi$	$B\to KZ^+$	Belle
$Z^+(4250)$	X(4250)	4248^{+190}_{-50}	177^{+320}_{-70}	?	$\chi_{c1}\pi$	$B\to KZ^+$	Belle
$Z^+(4200)$	$Z_c^+(4200)$	$4196^{+31}_{-29}{}^{+17}_{-13}$	370^{+100}_{-150}	1^+	$J/\psi\pi$	$B\to KZ^+$	Belle/LHCb
$Z^+(4430)$	$Z_c^+(4430)$	4478^{+15}_{-18}	181±31	1^+	$\psi(2S)\pi$, $J/\psi\pi$	$B\to KZ^+$	Belle/LHCb

Z_c family in e^+e^- annihilation

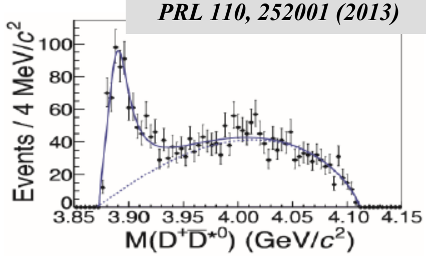
BESIII

PRL 110, 252001 (2013)



$e^+e^- \to \pi^+\pi^- J/\psi$

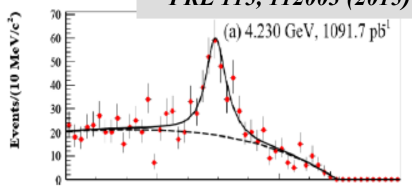
PRL 110, 252001 (2013)



$e^+e^- \to \pi^+ (D\bar{D}^*)^-$

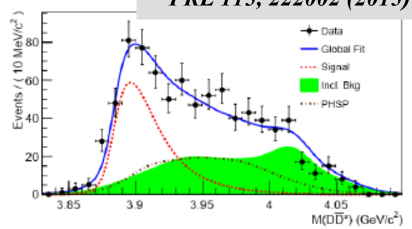
$Z_c(3900)^{\pm}$?

PRL 115, 112003 (2015)



$e^+e^- \to \pi^0\pi^0 J/\psi$

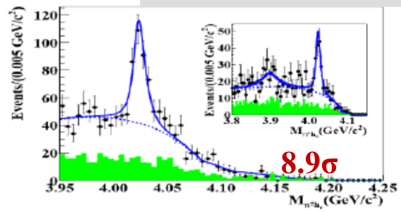
PRL 115, 222002 (2015)



$e^+e^- \to \pi^0 (D\bar{D}^*)^0$

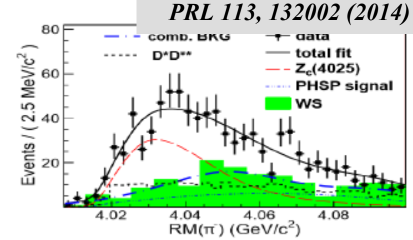
$Z_c(3900)^0$?

PRL 111, 242002 (2013)



$e^+e^- \to \pi^+\pi^- h_c$

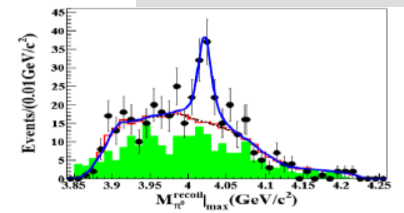
PRL 113, 132002 (2014)



$e^+e^- \to \pi^+ (D^*\bar{D}^*)^-$

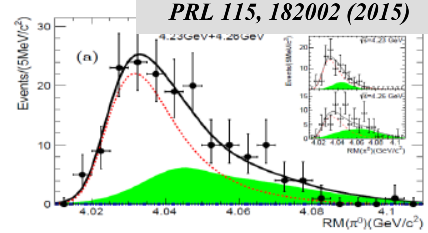
$Z_c(4020)^{\pm}$?

PRL 113, 212002 (2014)



$e^+e^- \to \pi^0\pi^0 h_c$

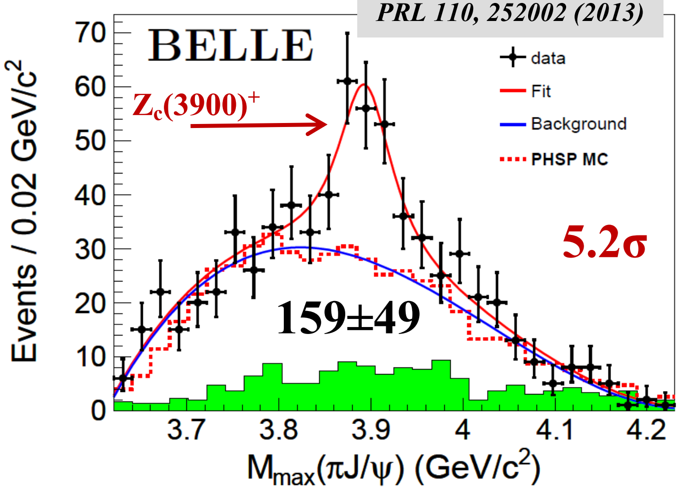
PRL 115, 182002 (2015)



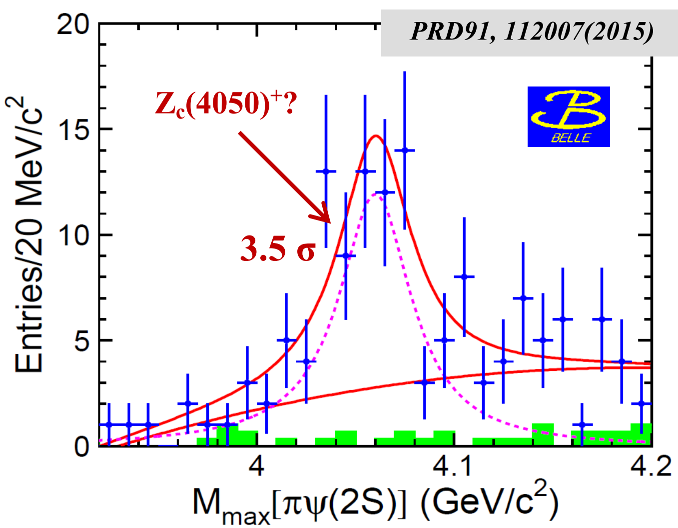
$e^+e^- \to \pi^0 (D^*\bar{D}^*)^0$

$Z_c(4020)^0$?

PRL 110, 252002 (2013)



PRD91, 112007(2015)



New signal in
$Y(4360) \to \pi^- Z(4050)^+$
$M = 4054 \pm 3 \pm 1$ MeV/c²
$\Gamma = 45 \pm 11 \pm 6$ MeV

BESIII *PRD96,032004(2017)*

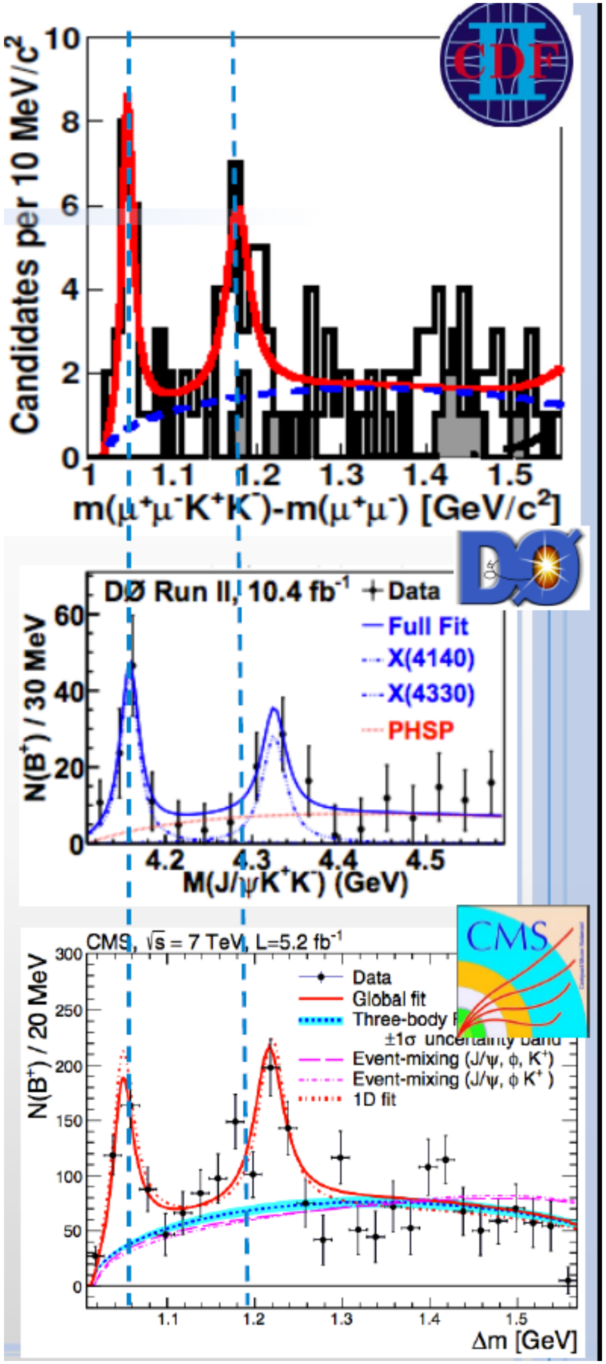
$Z_c(4030)^+$
$M = 4032.1 \pm 2.4$ MeV/c²
$\Gamma = 26.1 \pm 5.3$ MeV

Z_c summary

State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ Single D tag	$24.8 \pm 3.3 \pm 11.0$ Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
	$3881.7 \pm 1.6 \pm 2.1$ Double D tag	$26.6 \pm 2.0 \pm 2.3$ Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7} \pm 8.4$	$35^{+11}_{-12} \pm 15$	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$
$Z_c(4020)^{\pm}$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$	$\pi^{\pm} h_c$	$e^+e^- \to \pi^+\pi^- h_c$
$Z_c(4020)^0$	$4023.9 \pm 2.2 \pm 3.8$	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$
$Z_c(4025)^{\pm}$	$4026.3 \pm 2.6 \pm 3.7$	$24.8 \pm 5.6 \pm 7.7$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$
$Z_c(4025)^0$	$4025.5^{+2.0}_{-4.7} \pm 3.1$	$23.0 \pm 6.0 \pm 1.0$	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$

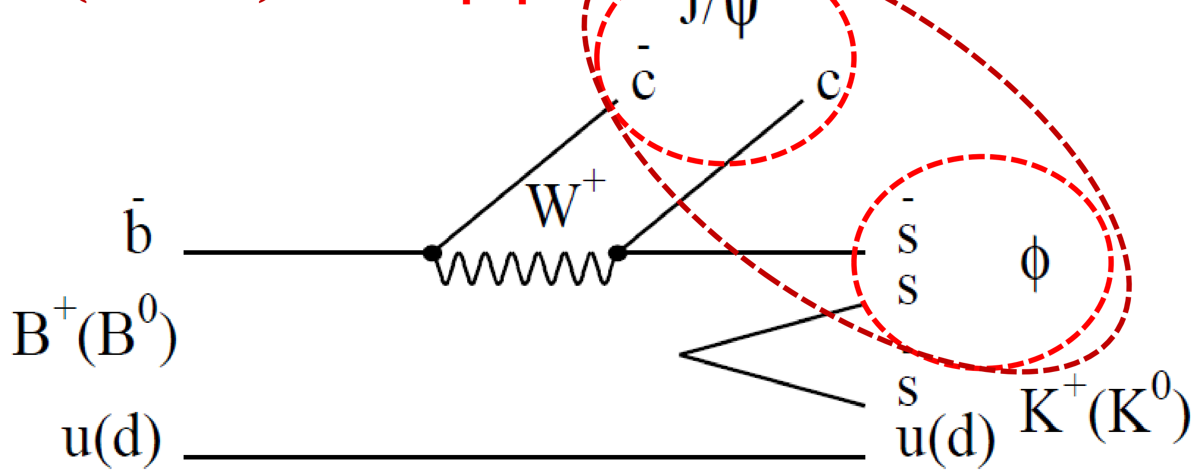
- Same states with different final states
- **Two isospin triplets: $Z_c(3900)^{\pm/0}$ and $Z_c(4200)^{\pm/0}$**
- Amplitude analysis on **$Z_c(3900)$: $J^P=1^+$**
- **Interpretation? Molecular states? $Z_c(4050)^+ = Z_c(4030)^+$?**

Tetraquarks



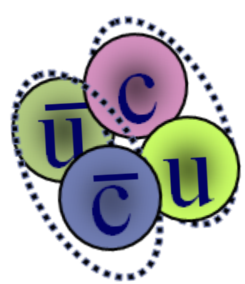
$B^+ \to J/\psi \phi K^+$

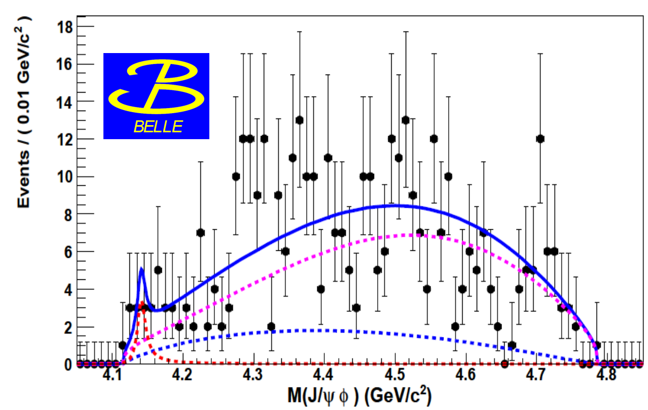
$X(4140) \to J/\psi \phi$



X(4140) & X(4274)

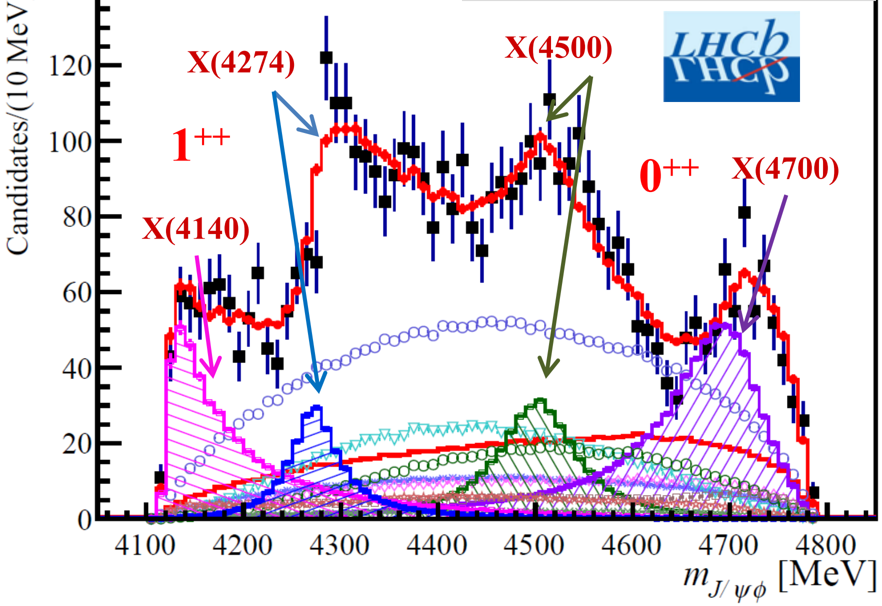
narrow peak at threshold and one more nearby

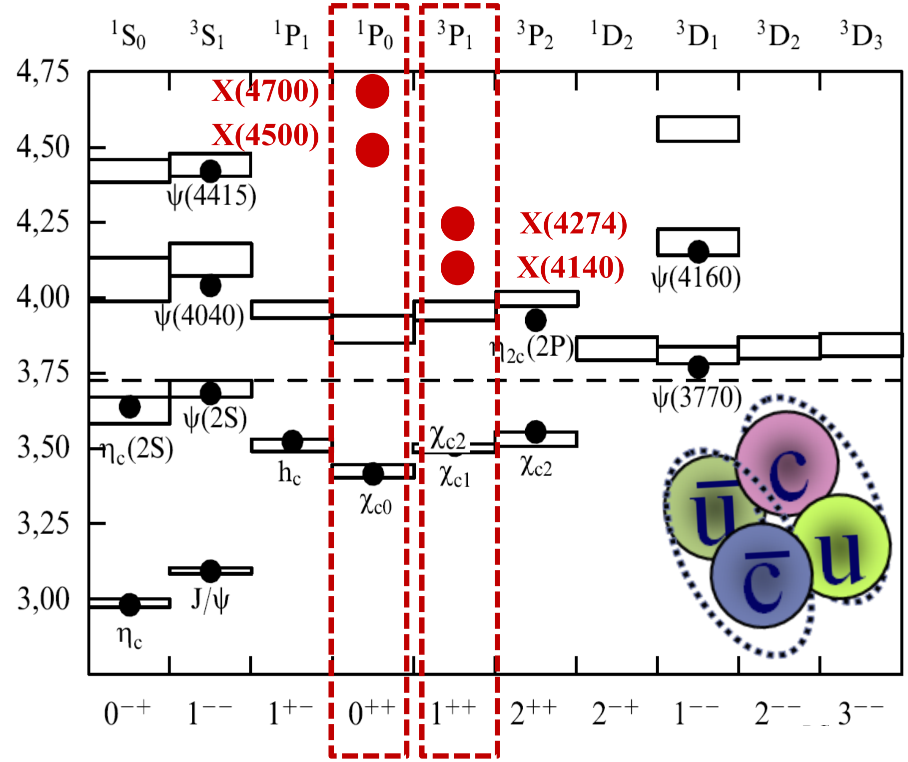




$B^+ \to J/\psi\phi K^+$ at LHCb

PRL 118, 022003 (2017)





Full amplitude analysis to obtain spin-parity

FOUR NEW STATES!!!

Theory:

X(4140) $D_sD_s^*$ cusp? tetraquark?

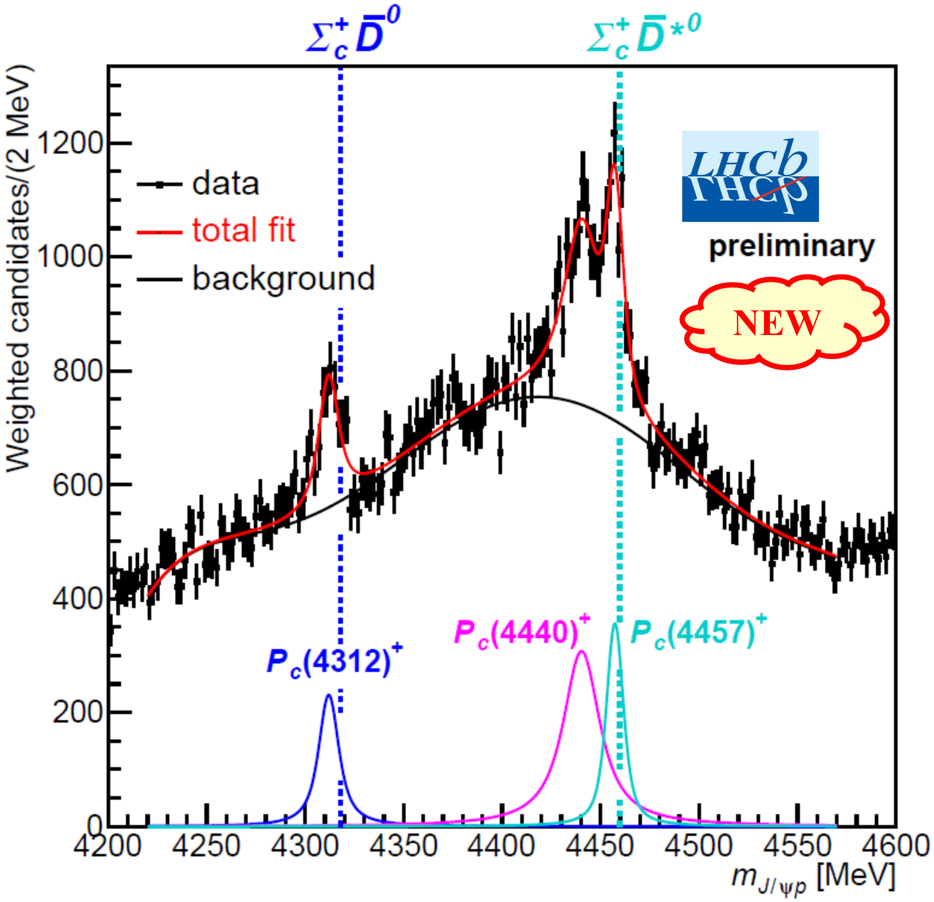
X(4274) tetraquark?

X(4500) $D_s^*D_s^*$ cusp?

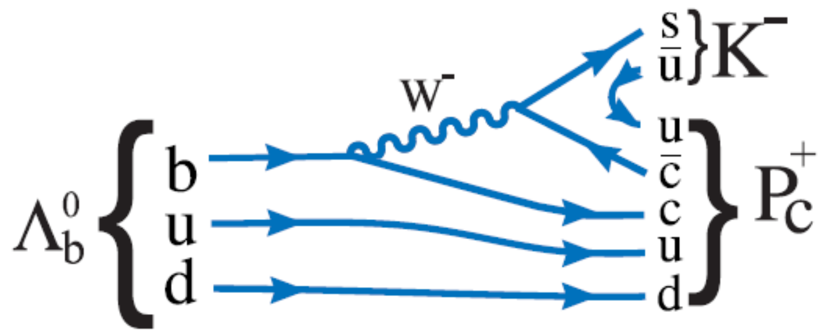
X(4700)?

	M, GeV/c²	Γ, MeV	J^{PC}
X(4140), χ_{c1} (4140) PDG2018	**4146.8±2.4**	**22^{+8}_{-7}**	**1^{++}**
X(4274), χ_{c1} (4274) PDG2018	**4274^{+8}_{-7}**	**49±12**	**1^{++}**
X(4500), χ_{c0} (4500) PDG2018	**4506^{+16}_{-19}**	**92±29**	**0^{++}**
X(4700), χ_{c0} (4700) PDG2018	**4704^{+17}_{-26}**	**120±50**	**0^{++}**

Pentaquarks

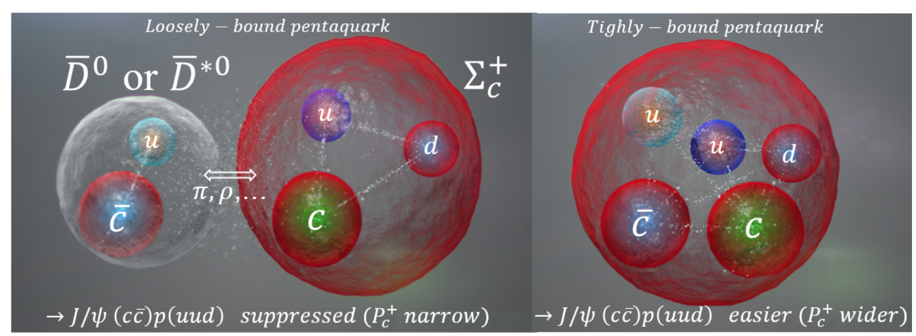


$\Lambda_b \rightarrow P_c^+ K^- \rightarrow J/\psi p\, K^-$



State	M [MeV]	Γ [MeV]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$

” …the near-threshold masses and the narrow widths of $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$ favor “molecular” pentaquarks with meson-baryon substructure!

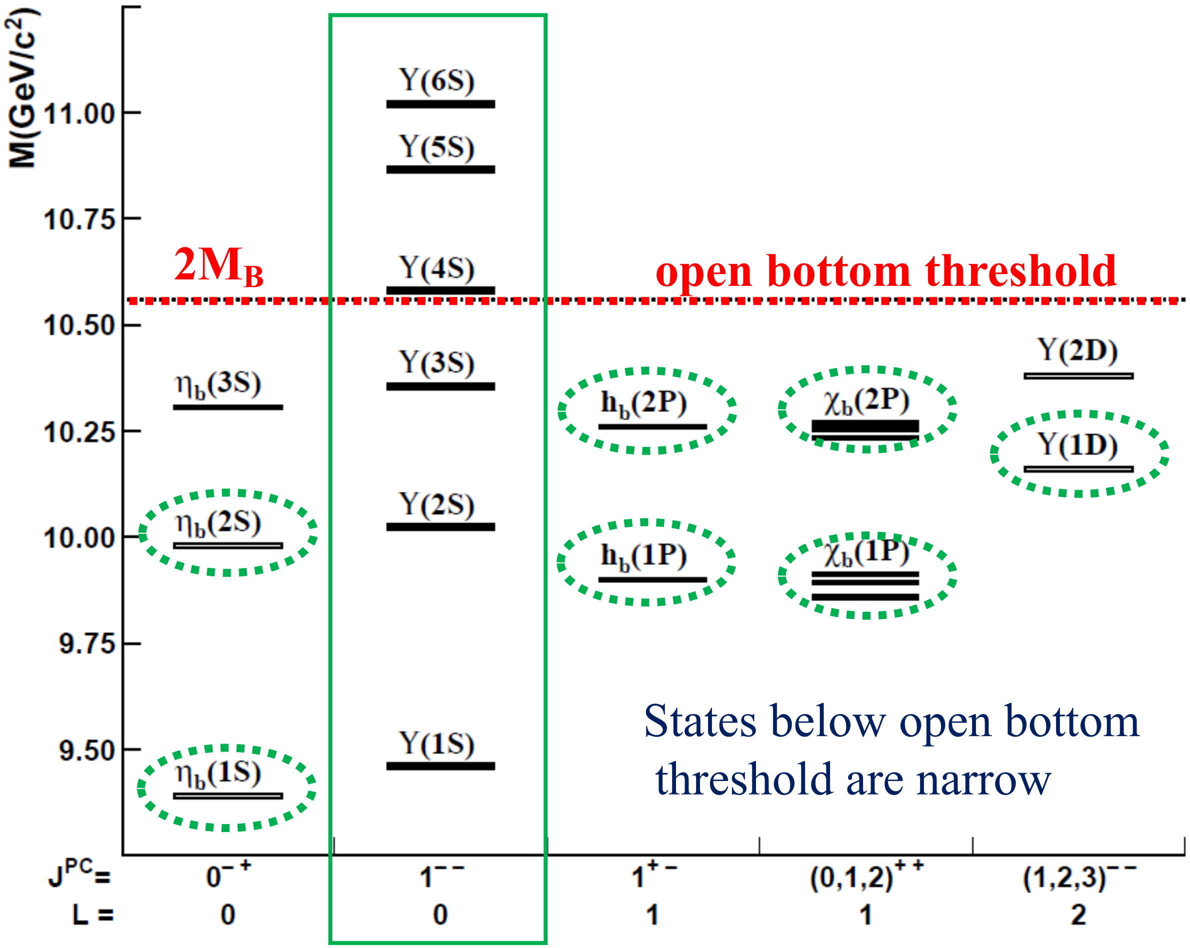


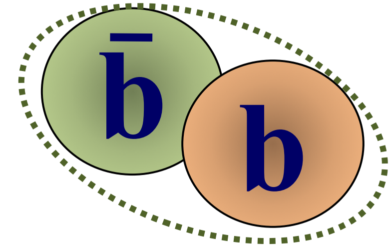
…we need to measure J^P to confirm molecular hypothesis, find isospin partners…”

Moriond QCD, Tomasz Skwarnicki, March 26, 2019

Bottomonium

Bottomonium
in the standard quark model





$n^{(2S+1)}L_J$

n radial quantum number

S total spin of q-antiq

L relative orbital ang. mom.

L = 0, 1, 2 ... correspond to S, P, D

$J = S + L$

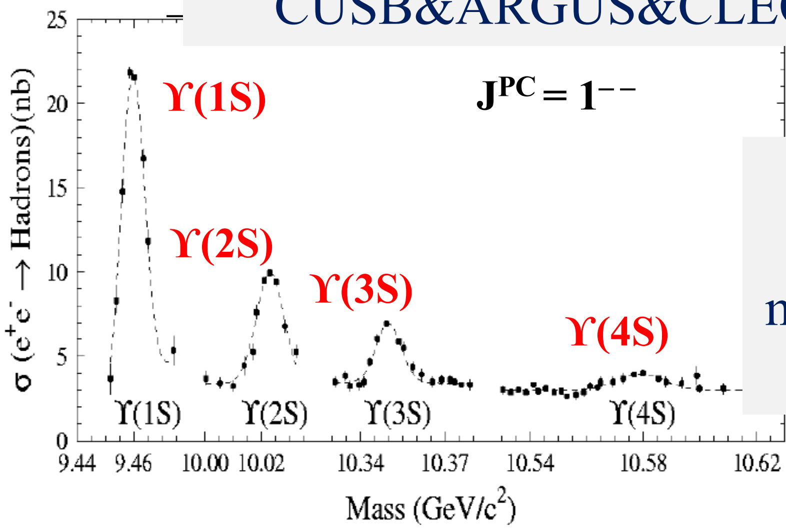
$P = (-1)^{L+1}$ parity

$C = (-1)^{L+S}$ charge conj.

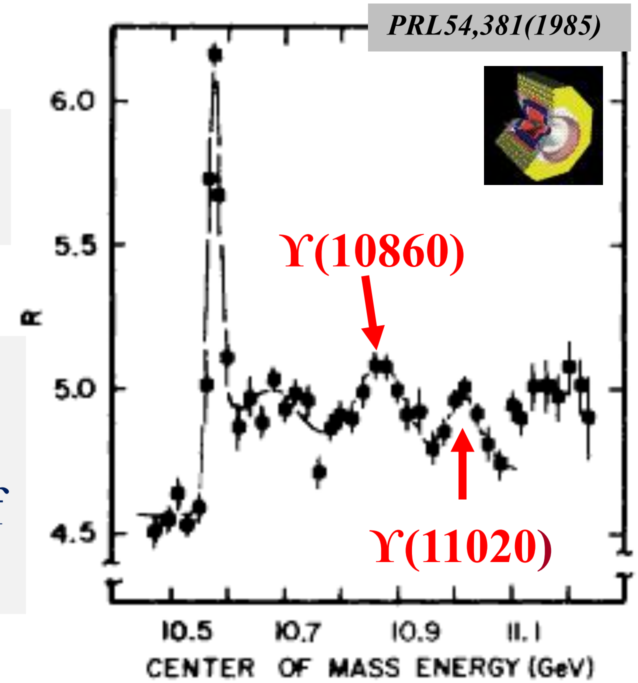
The heaviest quarkonium provide a unique non-relativistic system for QCD testing

Vector bottomonium states

Direct measurements at e^+e^- colliders from CUSB&ARGUS&CLEO to Belle & BaBar



The most accurate measurements of masses and widths of ϒ(nS) states



PDG:

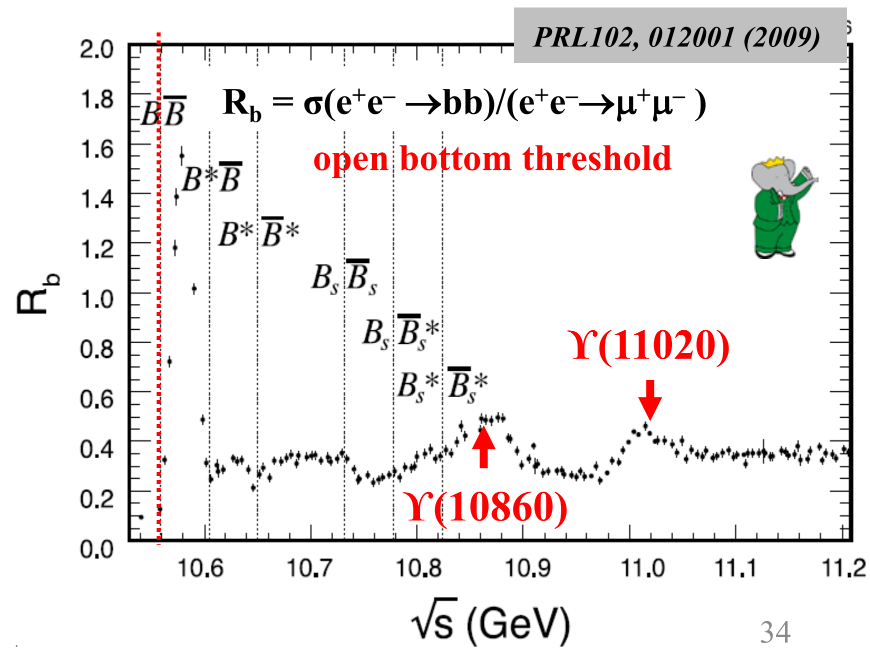
ϒ(1S), ϒ(2S), ϒ(3S), ϒ(4S), but…ϒ(10860) and ϒ(11020) [Common names ϒ(5S), ϒ(6S)]

Study bottomonium states using transitions of ϒ(nS) states

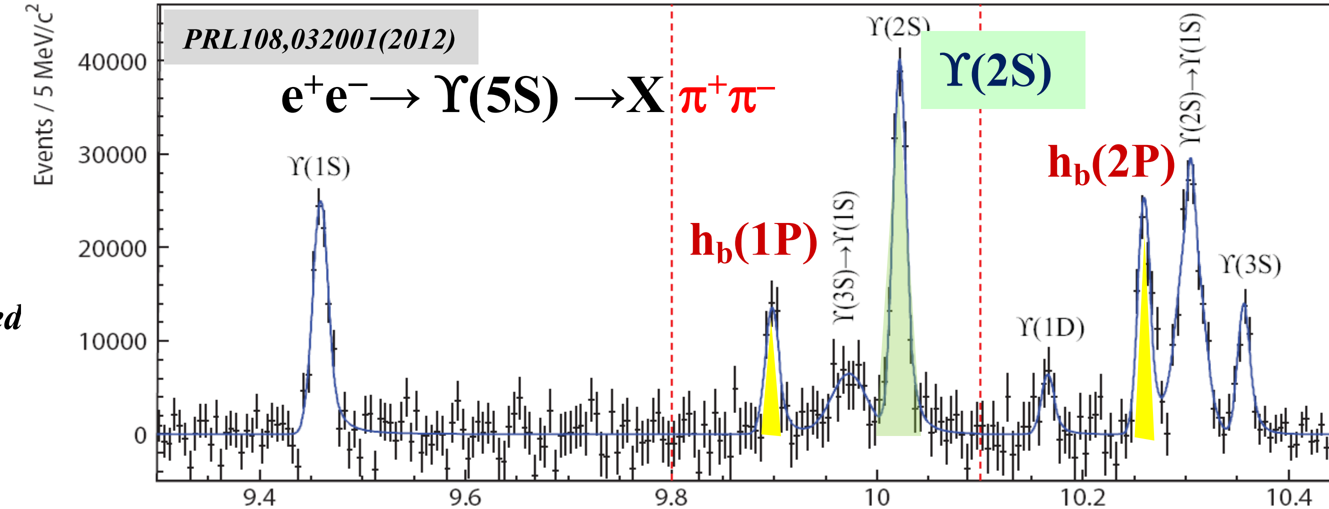
- ϒ(4S)→BB (B = B^0 or B^+)

  "B physics" at B-factories

- ϒ(nS)→γbb , n =2,3
- ϒ(10860) →$B^{(*)}B^{(*)}$, $B^{(*)}B^{(*)}\pi$, BBππ, $B_s^{(*)}B_s^{(*)}$, ϒ(nS) ππ, ϒ(nS)X… etc



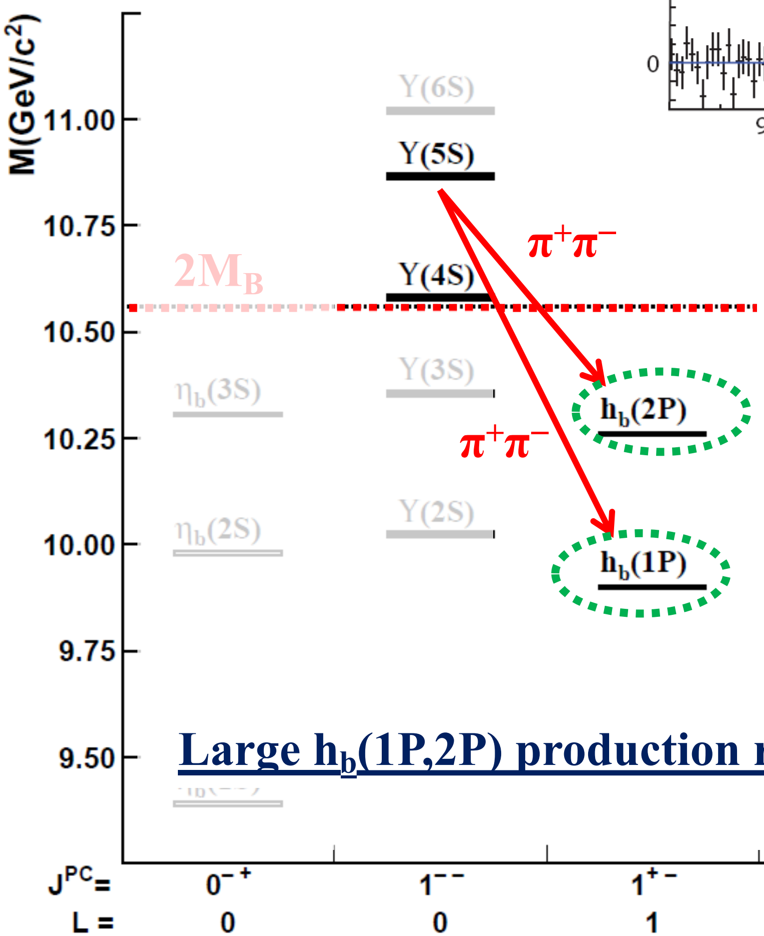
Observation of $h_b(1P,2P)$



$\Delta M_{HF}(1P) = 0.8 \pm 1.1$ MeV

$\Delta M_{HF}(2P) = 0.5 \pm 1.2$ MeV

consistent with zero, as expected



$\Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$ ← Due to spin flip to be suppressed as $\sim(\Lambda_{QCD}/m_b)^2$

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

$$\frac{\sigma(h_b(nP)\pi^+\pi^-)}{\sigma(\Upsilon(2S)\pi^+\pi^-)} = \begin{cases} 0.46 \pm 0.08^{+0.07}_{-0.12} & h_b(1P) \\ 0.77 \pm 0.08^{+0.22}_{-0.17} & h_b(2P) \end{cases}$$

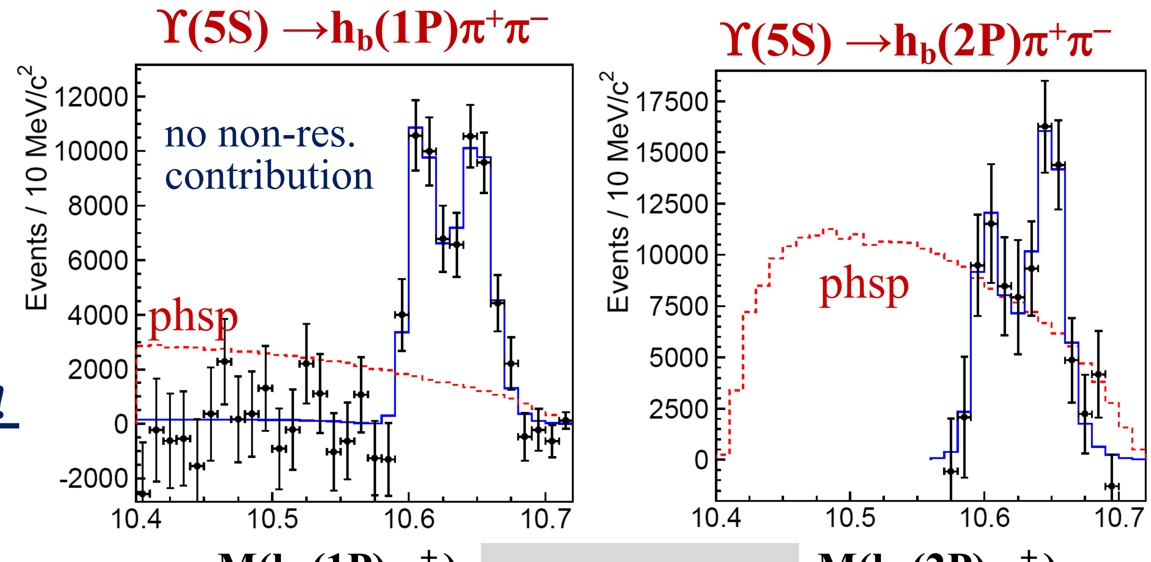
Large $h_b(1P,2P)$ production rates! Unknown intermediate state?

CLEO

large $e^+e^- \to Y(4260) \to h_c\pi^+\pi^-$

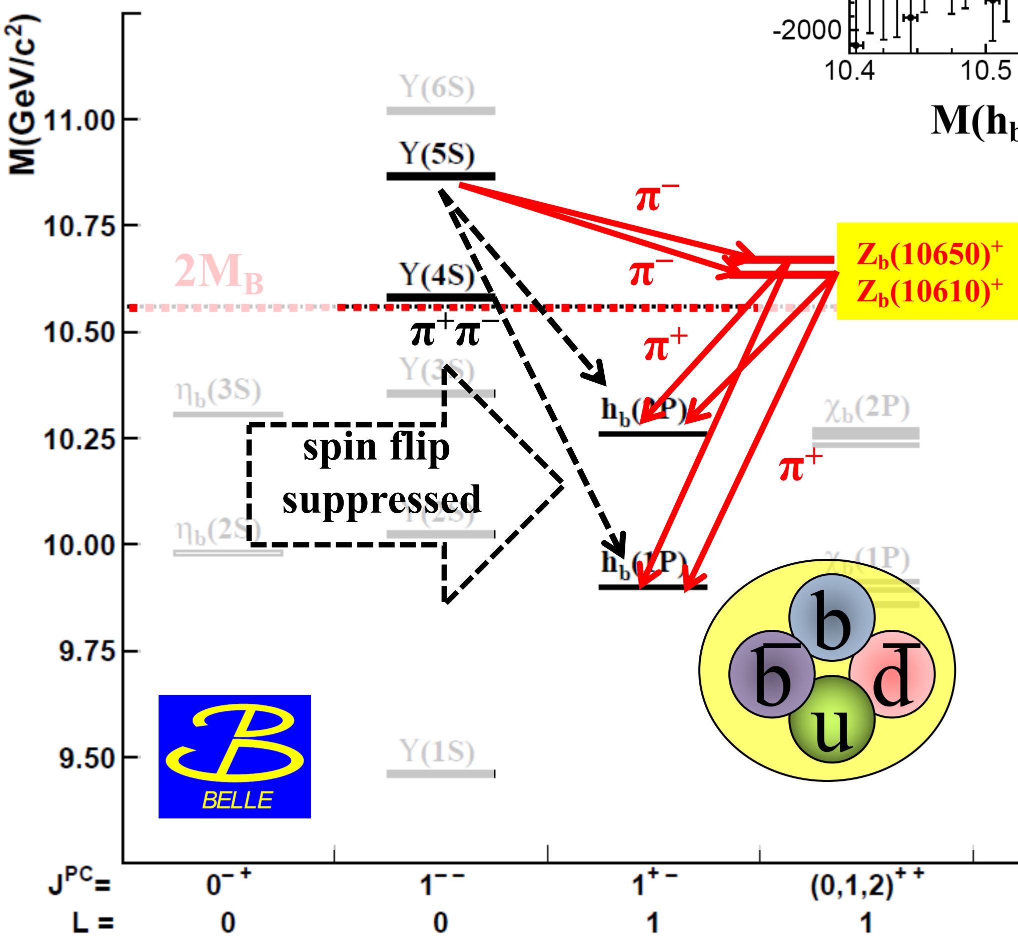

Charged
bottomoniumlike
states

Resonant structure of $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$



PRD88, 052016 (2013)

Large h_b(1P,2P) production rates!

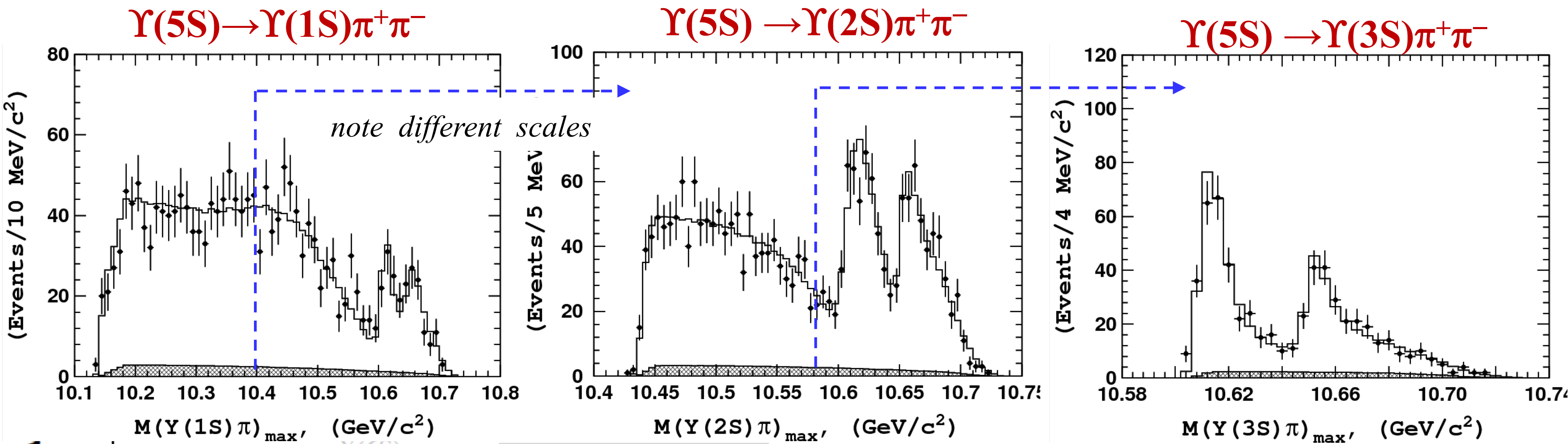


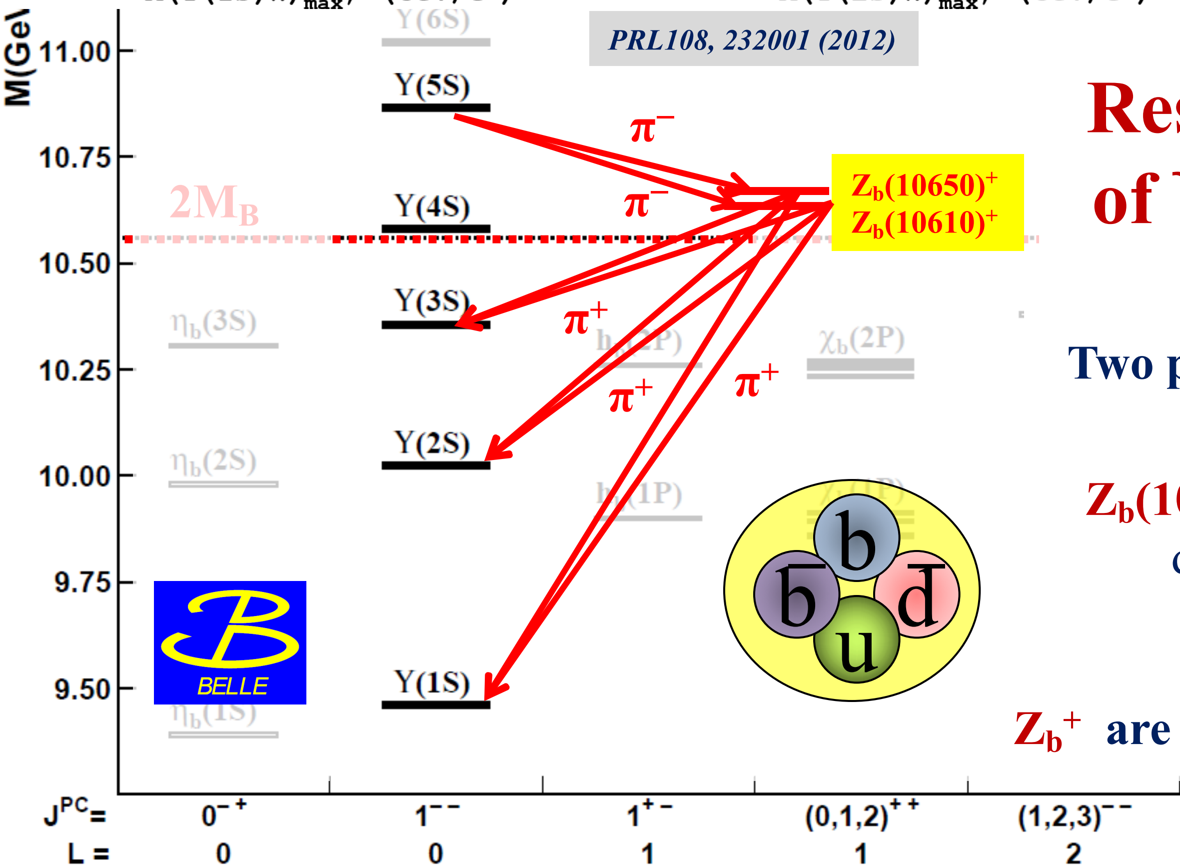
Dalitz plot analysis

Two peaks are observed in all modes

The first exotic bottomoniumlike $Z_b(10610)^+$ and $Z_b(10650)^+$ states were discovered in $h_b(1P)\pi^+$, $h_b(2P)\pi^+$ final states

Z_b^+ are multiquark states





Resonant structure of $\Upsilon(5S) \to (bb)\pi^+\pi^-$

Dalitz plot analysis

Two peaks are observed in all modes

The first exotic bottomoniumlike $Z_b(10610)^+$ & $Z_b(10650)^+$ states were discovered in $\Upsilon(1S)\pi^+$, $\Upsilon(2S)\pi^+$, $\Upsilon(3S)\pi^+$ final states

Z_b^+ are multiquark states

Summary of Z_b parameters

Average over 5 channels

M_1= 10607.2±2.0 MeV

Γ_1 = 18.4±2.4 MeV

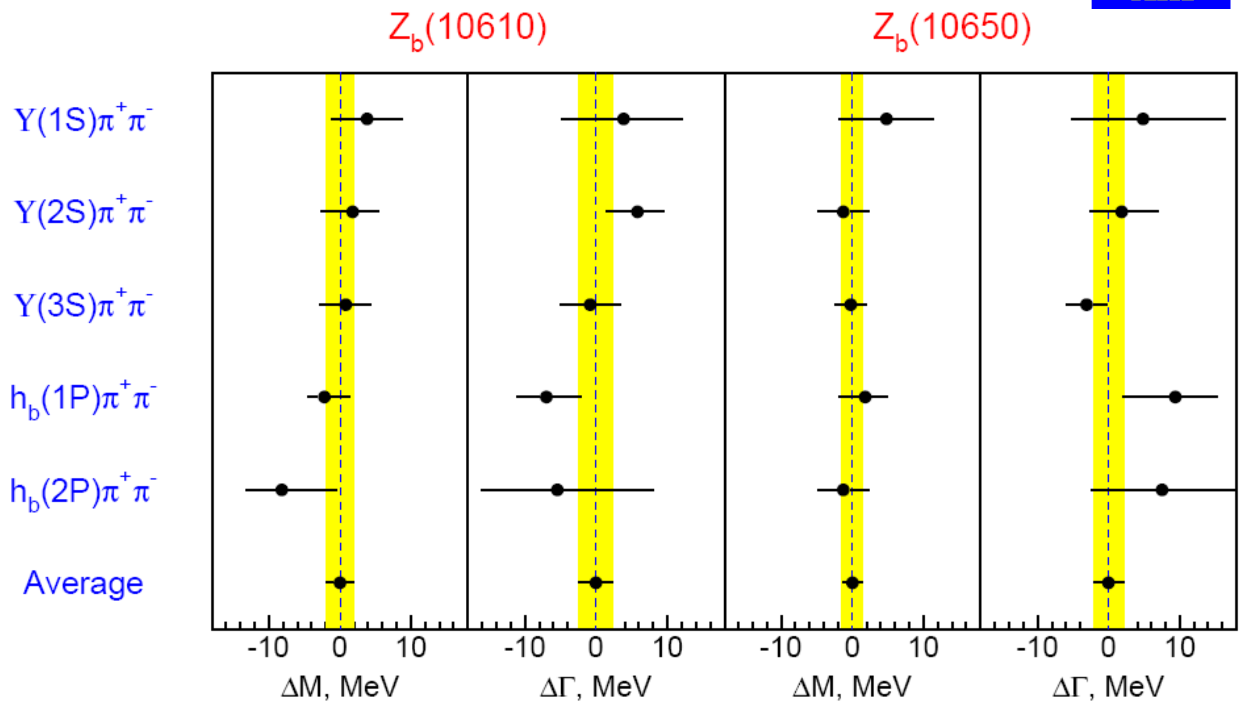
M_2 = 10652.2±1.5 MeV

Γ_2 = 11.5 ± 2.2 MeV

$J^P = 1^+$

PRD91,072003(2015)

6D amplitude analysis



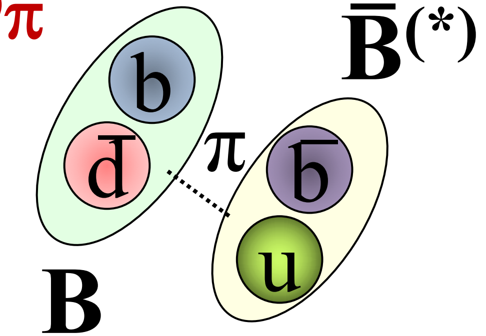
Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

h_b production mechanism:

$\Upsilon(5S) \rightarrow h_b(1,2P)\ \pi^+\pi^-$ are not suppressed due to Z_b intermediate states!

Resonant structure of $\Upsilon(5S)\to BB^{(*)}\pi$

Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23 \pm 2.88 \pm 2.28$
$h_b(2P)\pi^+$	$6.08 \pm 2.15 \pm 1.63$	$17.0 \pm 3.74 \pm 4.1$
$B^+\bar{B}^{*0} + \bar{B}^0 B^{*+}$	$82.6 \pm 2.9 \pm 2.3$	–
$B^{*+}\bar{B}^{*0}$	–	$70.6 \pm 4.9 \pm 4.4$



Phase space of $\Upsilon(5S)\to B^{(*)}B^*$ is tiny

Relative motion $B^{(*)}B^*$ is small

$Z_b(10610) \to BB^*$ dominantly

$Z_b(10650) \to B^*B^*$ dominantly

PRL108,122001(2012)

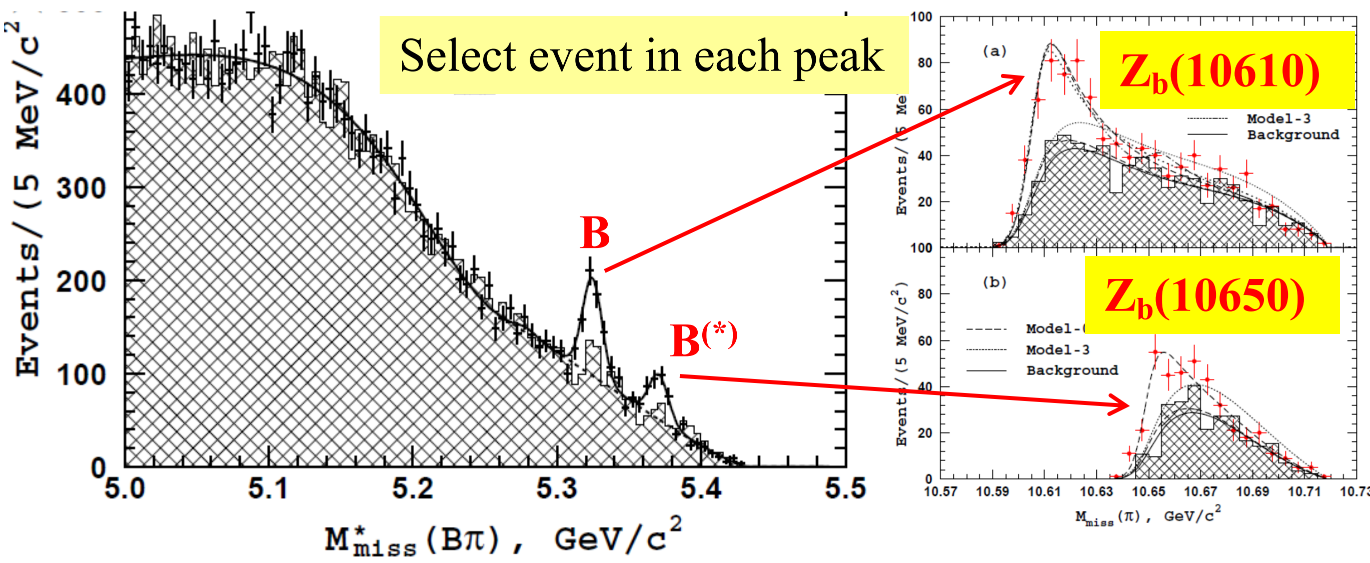
PRL116,212001(2016)

PRL117,142001(2016)

$$M_{Zb(10610)} - (M_B + M_{B^*}) = +2.6 \pm 2.1 \text{ MeV}$$

$$M_{Zb(10650)} - 2M_{B^*} = +1.8 \pm 1.7 \text{ MeV}$$

Favorable to the formation of the molecular states



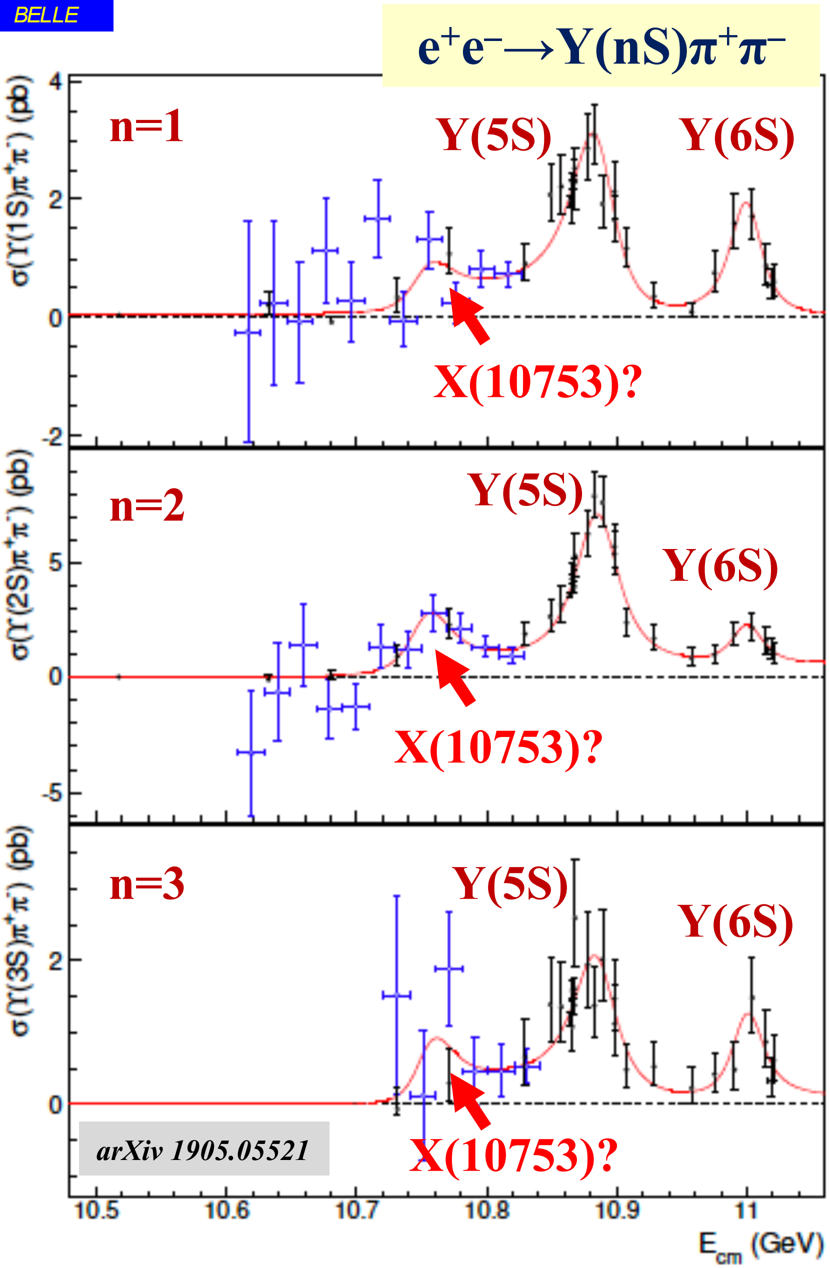
$J^P = 1^+$:

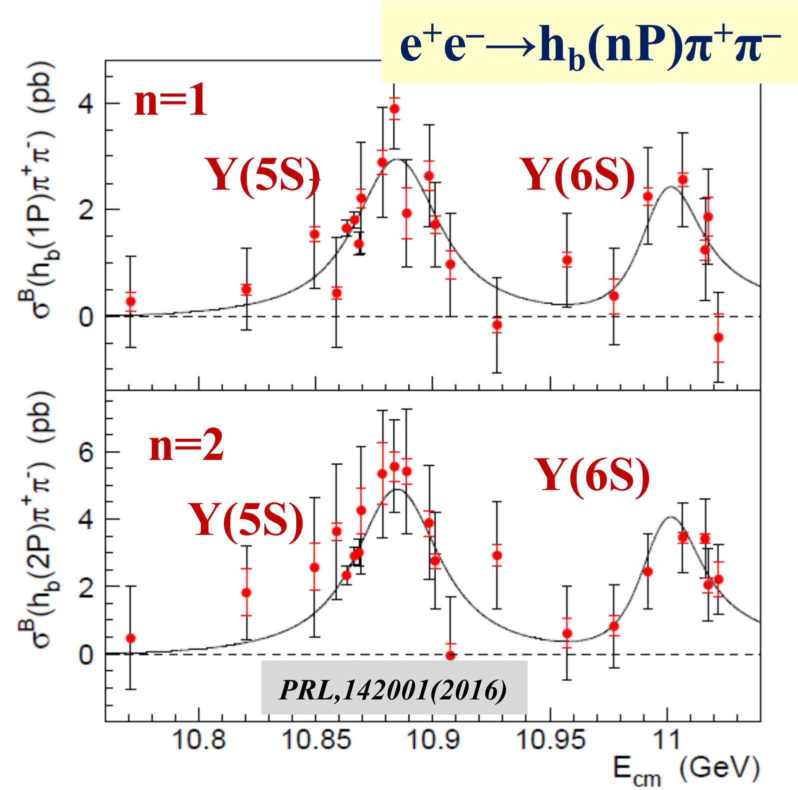
$B^{(*)}B^*$ in S-wave

$Z_b(10610) = |BB^*\rangle$

$Z_b(10650) = |B^*B^*\rangle$

Bottomonium cross sections





Cross sections of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ (n=1,2,3):

Υ(5S) and Υ(6S) & New structure (6.7 σ)

$M = 10752.7 \pm 5.9^{+0.1}_{-1.1}$ MeV/c^2

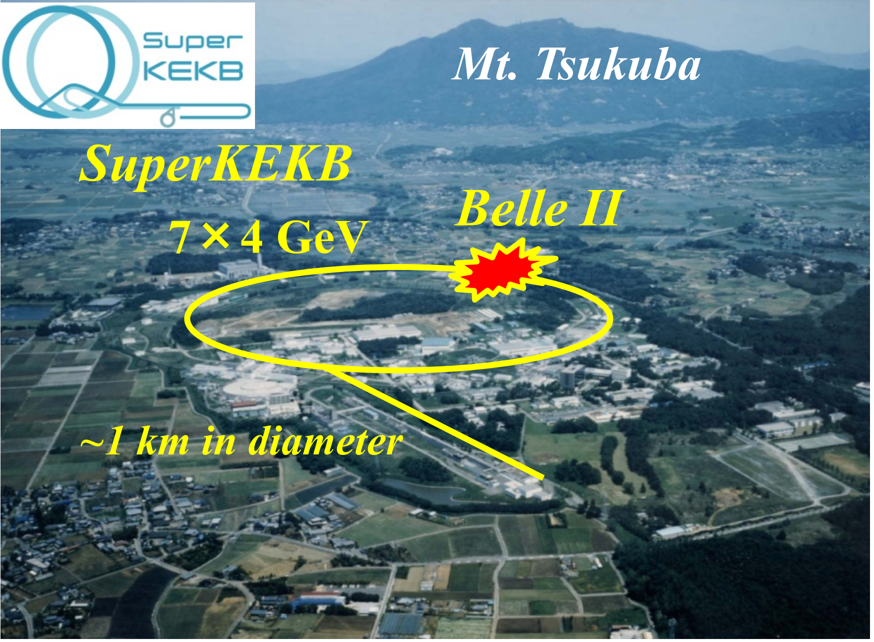
$\Gamma = 35.5^{+17.6}_{-11.3}{}^{+3.9}_{-3.3}$ MeV

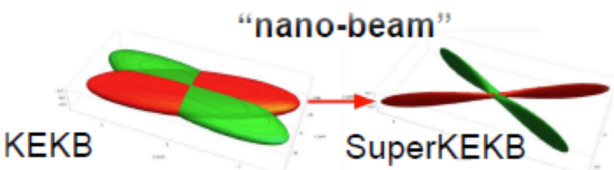
Cross sections of $e^+e^- \to h_b(nP)\pi^+\pi^-$ (n=1,2) & $e^+e^- \to \chi_{bJ}\pi^+\pi^-\pi^0$:

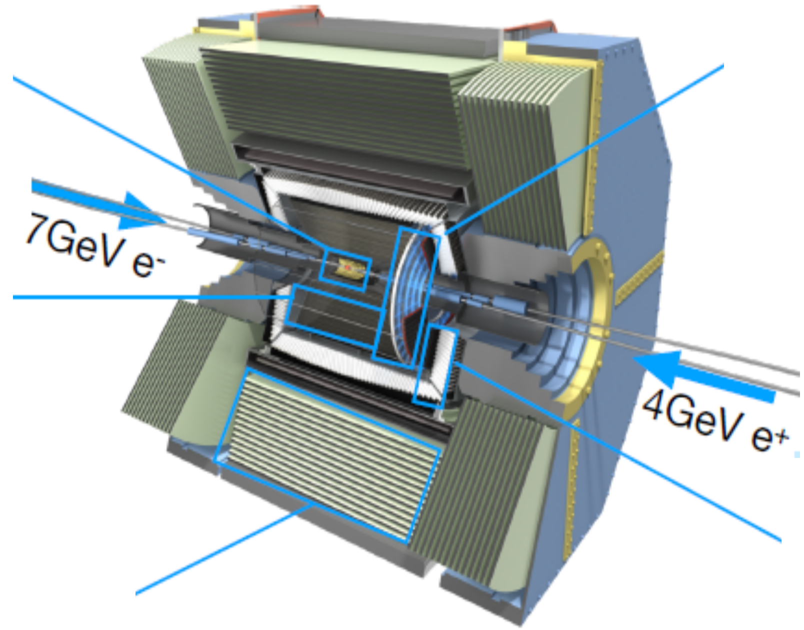
Υ(5S) and Υ(6S) peaks only

Future Super-B & c-τ Factories

KEKB & Belle upgrade
SuperKEKB &Belle II







SuperKEKB built inKEKB tunnel is almost entirely new machine

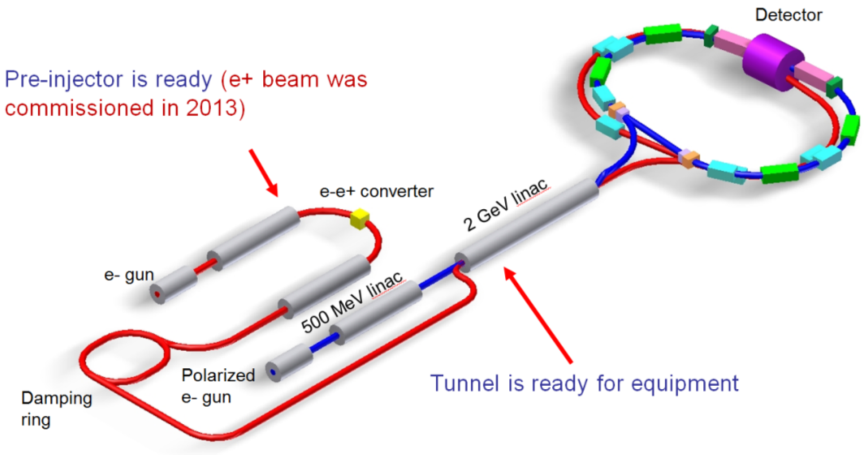
- ×20 smaller beam focus at interaction region
- twice higher beam current
- **×40 higher Luminosity**

Belle II detector as upgrade of the Belle is capable to work at much higher background environment

- Better tracking
- Better vertexing
- Better particle identification
- Better calorimeter resolution

First beam in 2016, physics data taking since March 25, 2019

Super Charm Tau Factory at BINP in Novosibirsk



- **Two rings, 800 m each**
- **Crab waist**
- **Collision energy from 2 GeV to 5 (6) GeV**
- **Luminosity: $5 \cdot 10^{34}$ cm^{-2}s^{-1} at 2 GeV**
- **and 10^{35} cm^{-2} s^{-1} at 4 GeV**
- **Longitudinally polarized electron beam at IP**

The concept of the new collider is based on a new method to increase the luminosity, which was proposed by physicists from INFN (Italy) and developed by INFN and BINP experts

- **Detailed physics program is developed**
- Preliminary CDR was issued (in 2011) and updated in 2018
- R&D for accelerator and detector is in progress, prototypes and key elements were designed and produced
- Preliminary civil engineering and infrastructure design is completed
- IT requirements are identified

Talk of P.V.Logachev, Director BINP at "Super c-tau factory workshop", May 26-27 2018, Novosibirsk

To be done at Super-B & Super c-τ Factories

Huge luminosity and significantly improved detector parameters (better tracking, vertexing, particle identification, resolution) should allow to perform a lot of new measurements and studies inaccessible to previous experiments because of lack of statistics

Detailed physics programs are developed. They include:

○ Search for and precise measurements of all predicted quarkonium states above open charm (bottom) threshold

○ Energy scan in 3.7-5.0 GeV energy region at Super c-τ Factory. Precise measurements of $\sigma(e^+e^- \to \text{hadrons})$, including exclusive cross-sections to open charm final states

○ Search for new and precise study of known quarkoiniumlike states including angular & Dalitz & amplitude analyses

In conclusion

- **Dozens of quarkonium states and quarkoniumlike states named as XYZ states were discovered since 2002 by Belle & BaBar & BES & LHC experiments and this list continues to grow**
  - **Particle Data Group 2018: instead of XYZ states new naming scheme of hadrons M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D 98, 030001 (2018).**

- **Charmonium & Bottomonium tables below open charm & bottom thresholds are (almost) completed. Good agreement between theory and experiment!**

- **Above open charm &bottom thresholds quarkonium physics is in deep crises! Observed states remain puzzling and can not be explained for many years!**

BUT….

- **The mysterious behavior of exotic states motivates us to create new experiments and theoretical models**
- **Super-B and Super-charm-tau factories have to shed light on unknown nature of quarkoniumlike states**