Exotic quarkonium in e^+e^- collisions

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The XXIV International Baldin Seminar on High Energy Physics Problems
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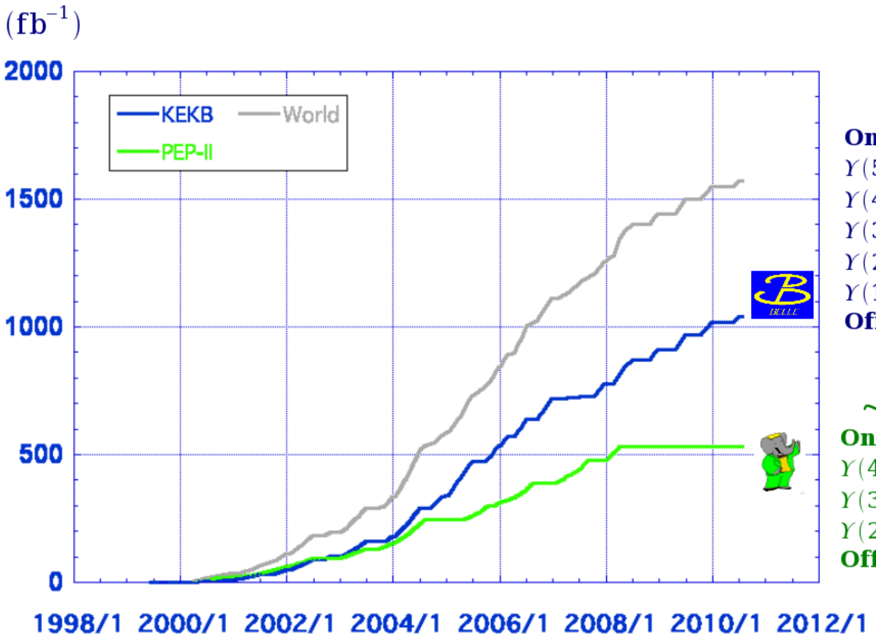
e^+e^- collisions at B factories



> 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:

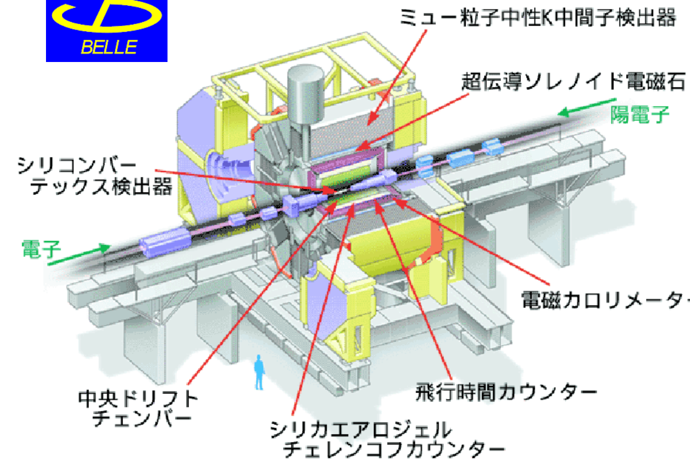
$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}

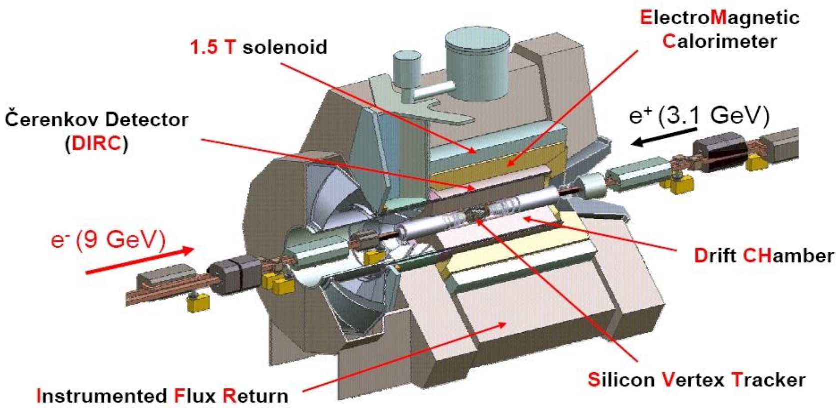


8 GeV (e^-) × 3.5 GeV (e^+)

designed luminosity: 10.0×10^{33}cm^{-2}s^{-1}

achieved 21.2×10^{33}cm^{-2}s^{-1}

>2 times larger!



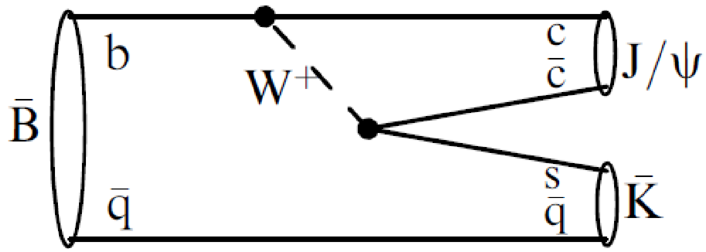
Belle

completed data taking on June, 2010

to start SuperKEKB/Belle II upgrade

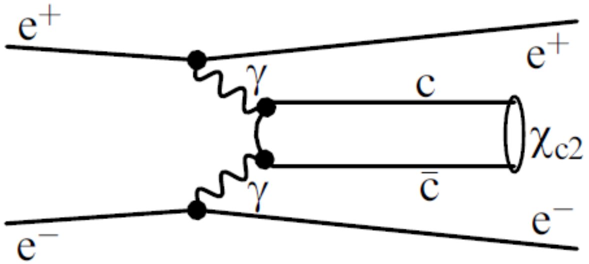
Charmonium (+like) production at B factories

B decays



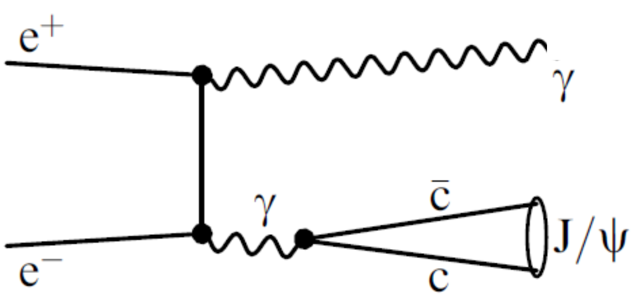
Any quantum numbers are possible, can be measured in angular analysis

γγ fusion



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

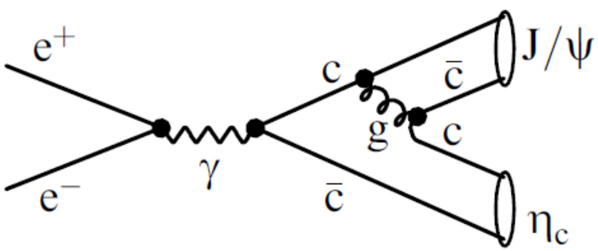
e^+e^- annihilation with ISR



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

Study of charmonium(+like) final states from threshold in wide energy region

double charmonium production



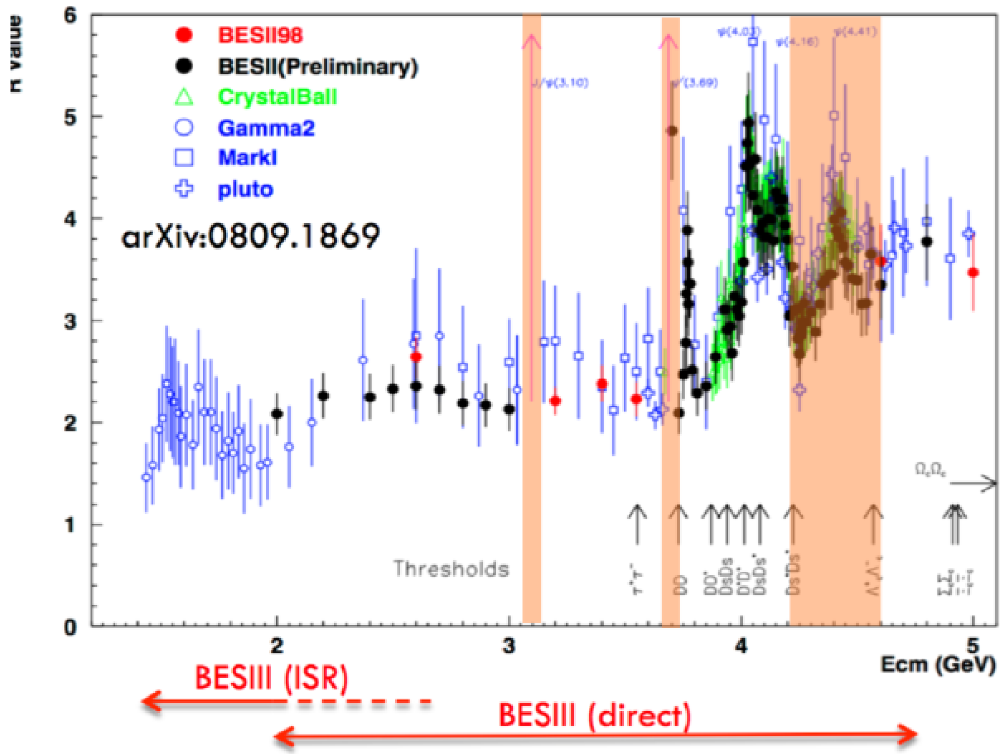
in association with J/ψ only $J^{PC} = 0^{\pm+}$ seen

e^+e^- collisions at Charm factory BESIII

BESIII

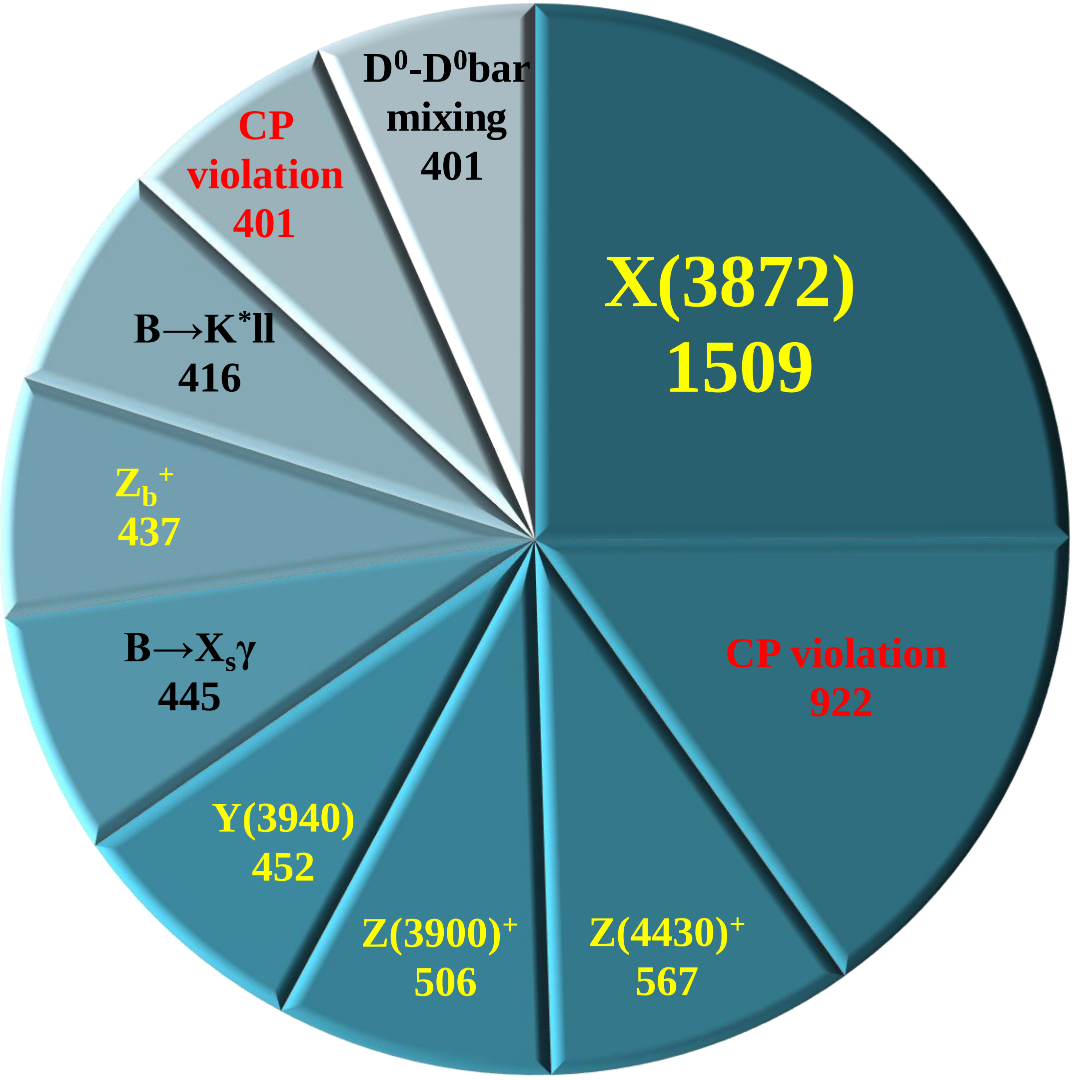
2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} at **ψ(3770)** *(total)*
482 pb^{-1} at **4.01 GeV**
2012: 0.45B **ψ(2S)** *(total)*
1.3B **J/ψ** *(total)*
2013: 1092 pb^{-1} at **4.23 GeV**
826 pb^{-1} at **4.26 GeV**
540 pb^{-1} at **4.36 GeV**
~50 pb^{-1} at **3.81, 3.90, 4.09, 4.19, 4.21, 4.22, 4.245, 4.31, 4.39, 4.42 GeV**
2014: 1029 pb^{-1} at **4.42 GeV**
110 pb^{-1} at **4.47 GeV**
110 pb^{-1} at **4.53 GeV**
48 pb^{-1} at **4.575 GeV**
567 pb^{-1} at **4.6 GeV**
0.8 fb^{-1} **R-scan** from 3.85 to 4.59 GeV (104 points)
2015: **R-scan** from 2-3 GeV + **2.175 GeV** data
2016: ~3fb^{-1} at 4.18 GeV (for **D_s**)
2017: 500/pb each for 7 energy points between 4.19~4.28 GeV
400/pb around chic_c1
200/pb around X(3872)

+ Initial State Radiation (ISR)



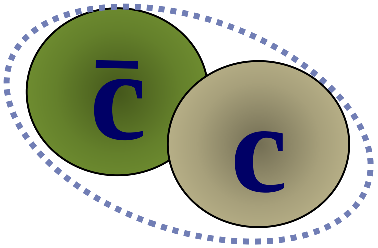
BESIII symmetric e^+e^- collider
scan 2.0 - 4.6 GeV; L ~ $10^{33}/cm^2/s$
$e^+e^- \rightarrow J/\psi$, $\psi(2S)$, $\psi(3770)$, etc…

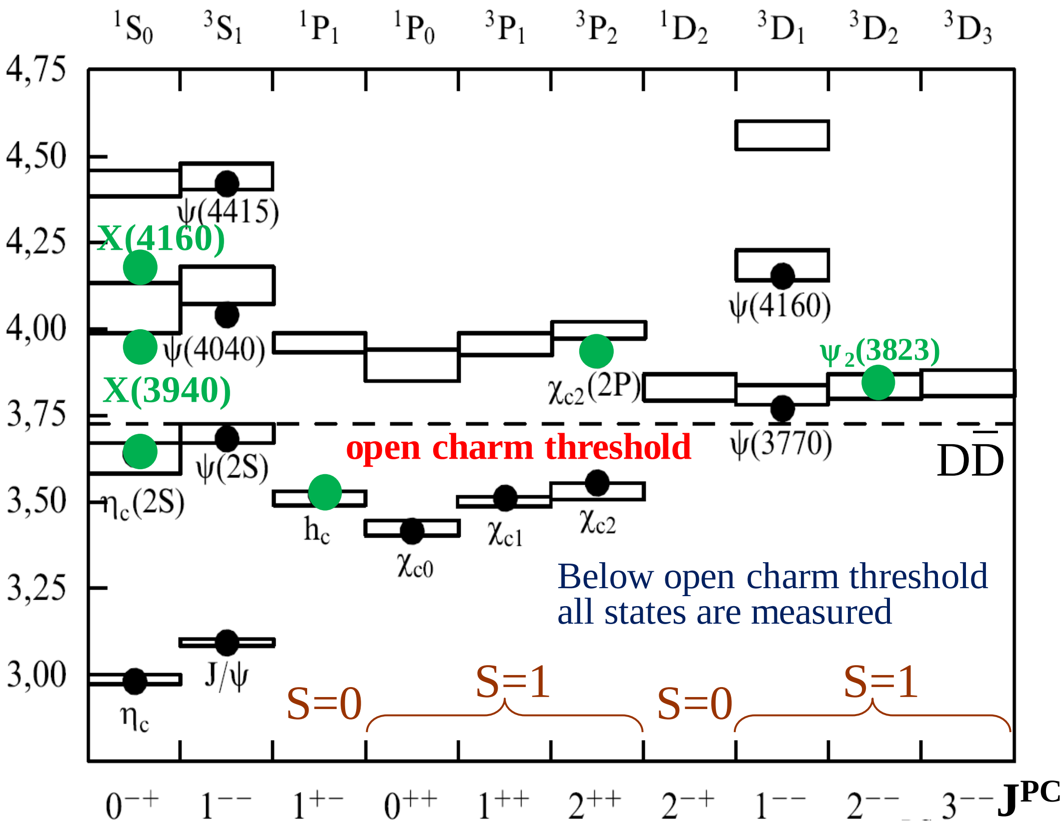
Belle citesummary 2018
Top 10



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.

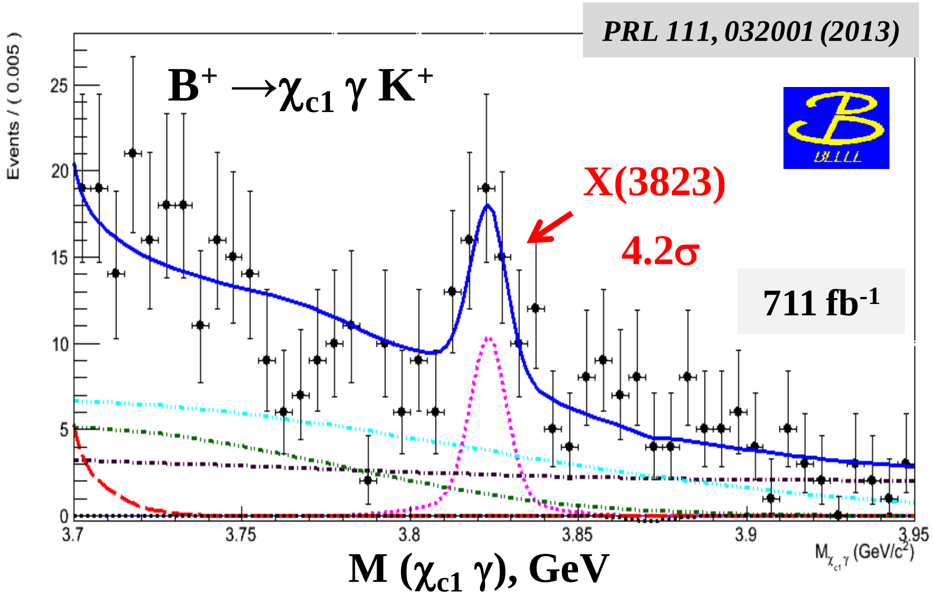
1974-1980 Discovery of **10 standard charmonium states**

1980-2002 … nothing

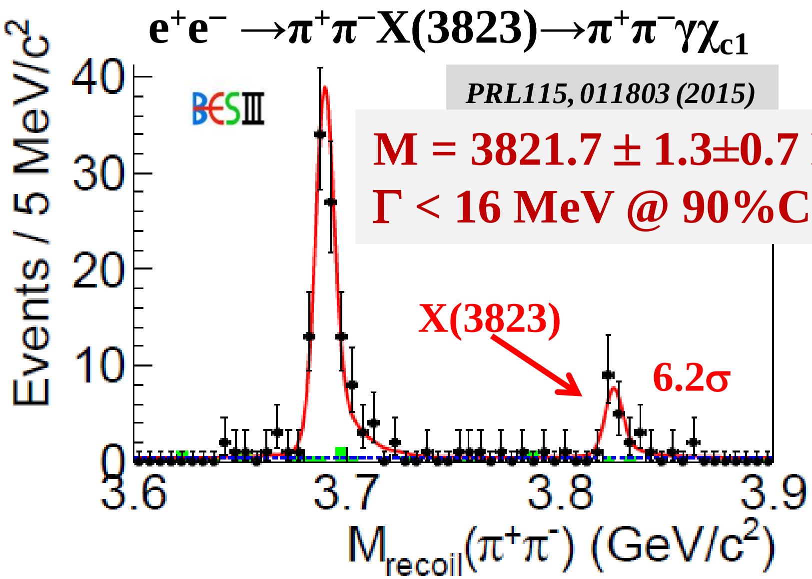
2002-2013 Discovery of **6 new states that can fit into charmonium table**

Below open charm threshold a good agreement between theory and experiment

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



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

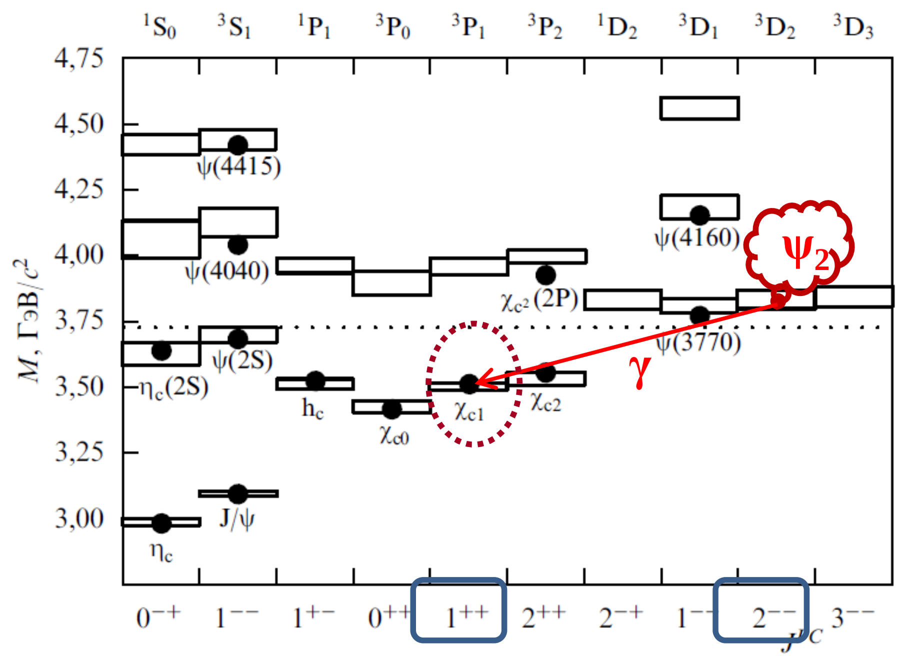


M = 3821.7 ± 1.3±0.7 MeV
Γ < 16 MeV @ 90%CL

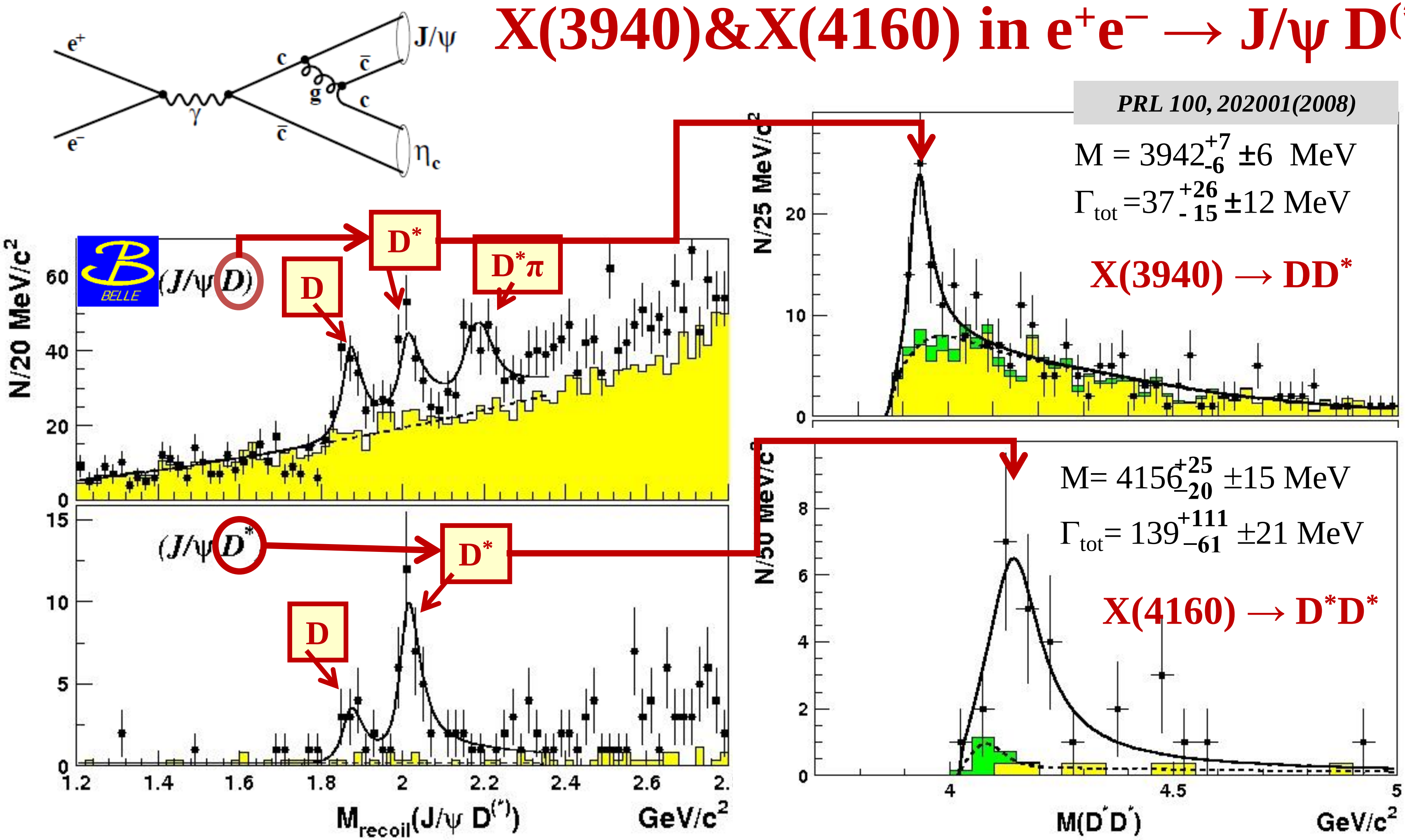
$X(3823)\to\chi_{c1}\gamma \Longrightarrow C = -$

1^{--}	1^{+-}	2^{--}	3^{--}
Ψ(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



X(3940)&X(4160) in $e^+e^- \to J/\psi\, D^{(*)}D^{(*)}$



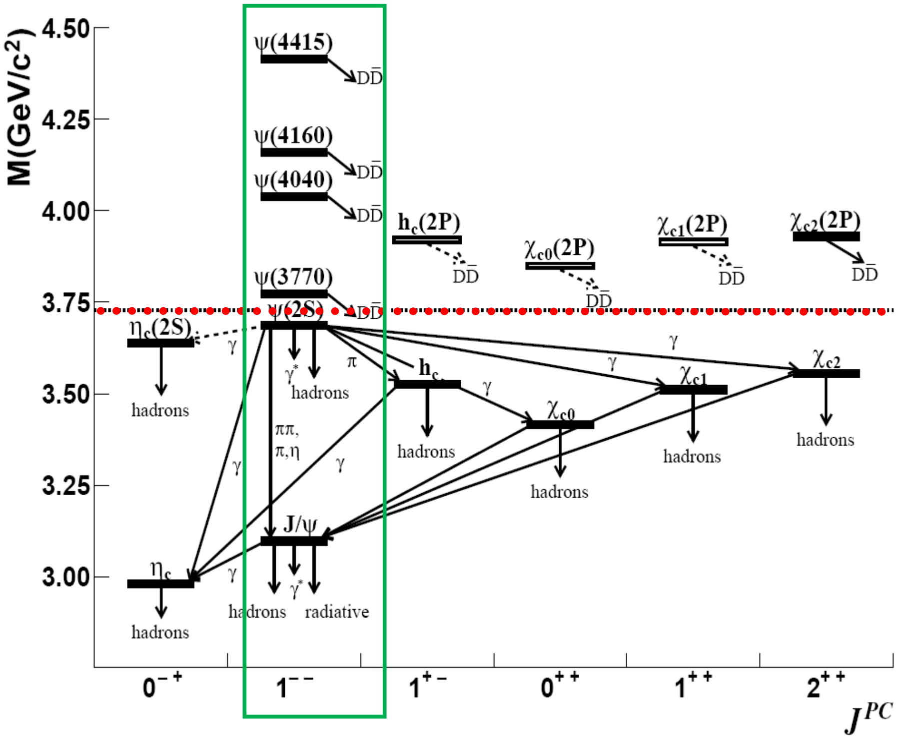
○ **Both observed states decay in open charm final states like standard charmonium**

○ Possible assignments are **η_c(3S)** and **η_c(4S)** , but **X(3940)&X(4160) PDG2018**

○ The masses predicted by the potential models are ~100-250 MeV higher than observed

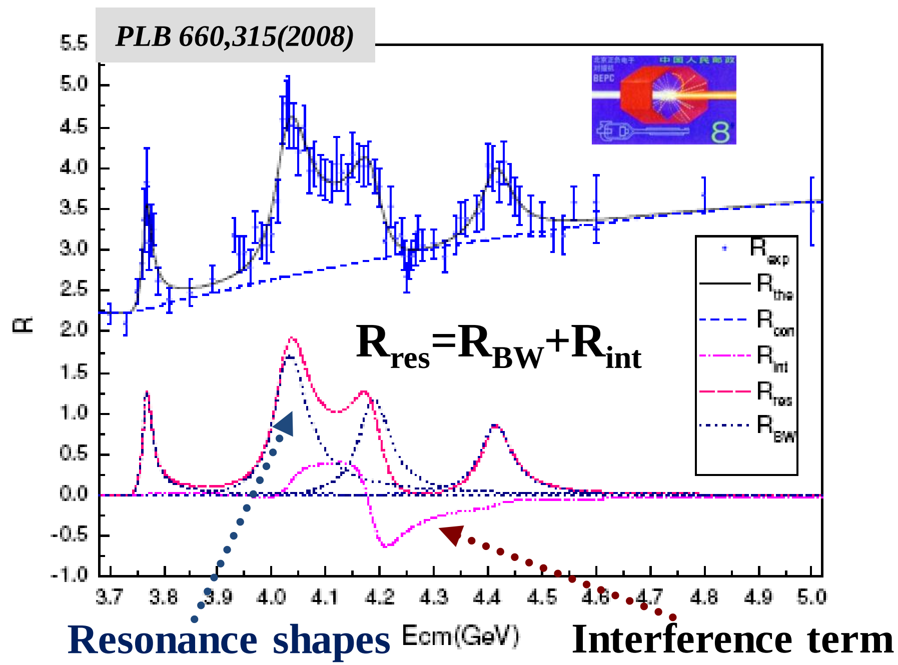
Theory probably needs more elaborated model to take into account charmonium coupling to charmed meson pairs

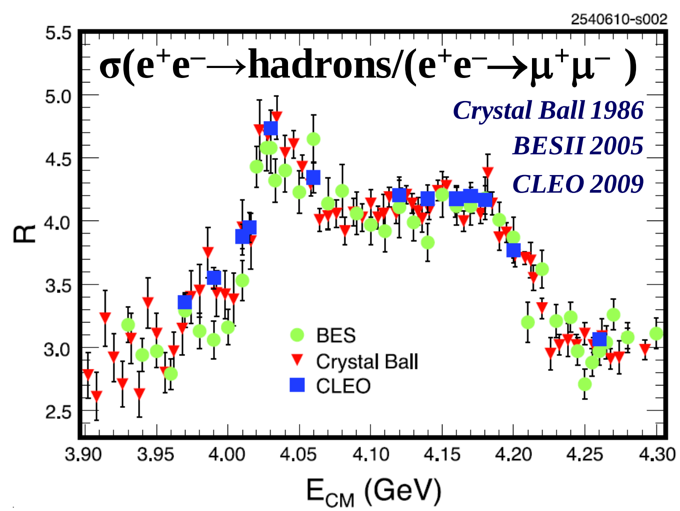
Vector charmonium states



Direct measurements at charm factories

ψ states: $J^{PC} = 1^{--}$



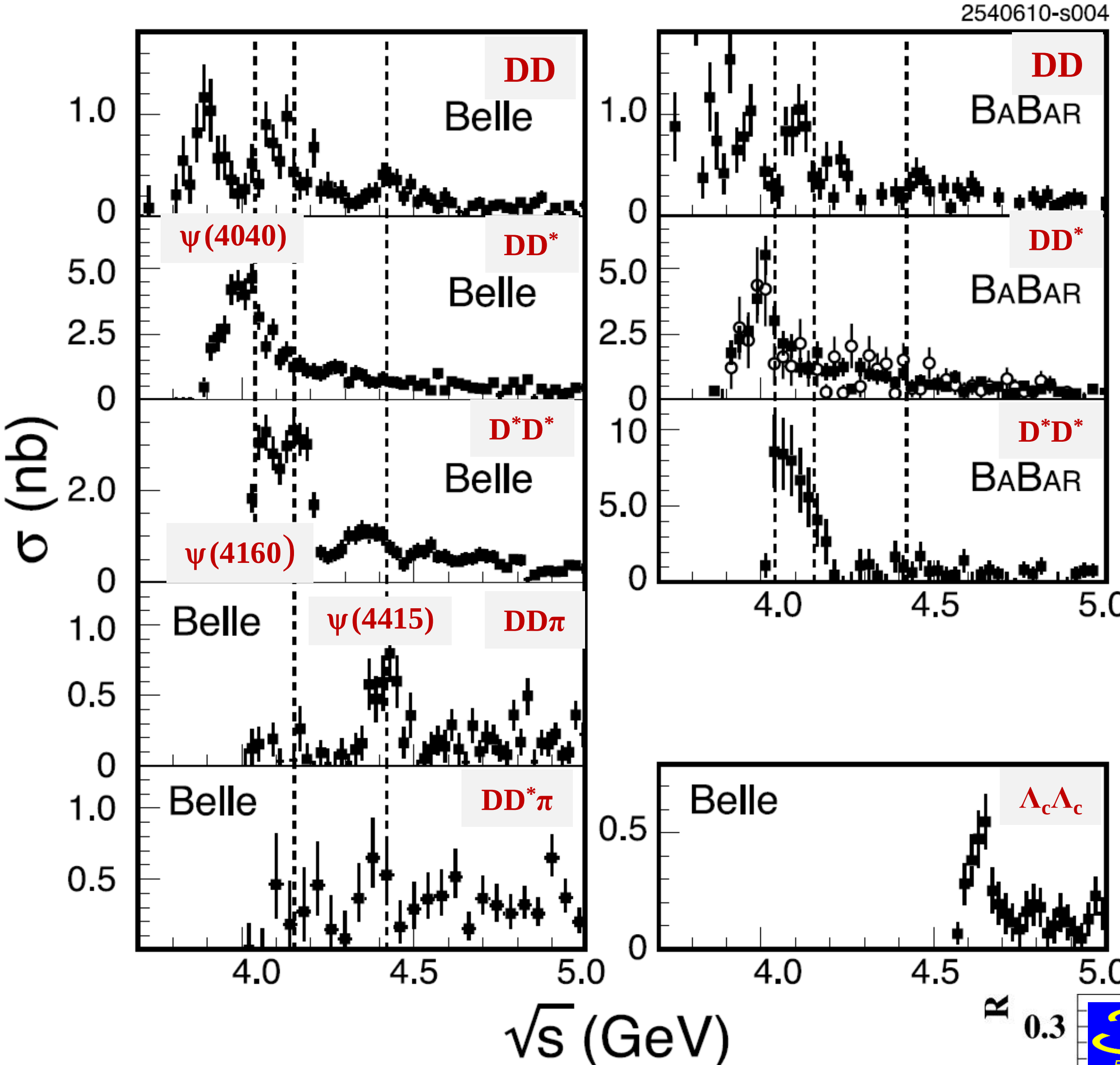


$$\psi(3770) \Rightarrow D\bar{D};$$
$$\psi(4040) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s;$$
$$\psi(4160) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*;$$
$$\psi(4415) \Rightarrow D\bar{D}, D^*\bar{D}^*, D\bar{D}^*, \bar{D}D^*, D_s\bar{D}_s, D_s\bar{D}_s^*, D_s^*\bar{D}_s^*.$$

Model dependent results

The interference is large & the total contribution differs from the simple sum of the Breit -Wigner resonances

$e^+e^- \to$ open charm



ISR measurements at B factories

Fixed quantum numbers of final state $J^{PC} = 1^{--}$

$\psi(4040)$ is seen in DD^*, D^*D^*, $D_s^+D_s^-$

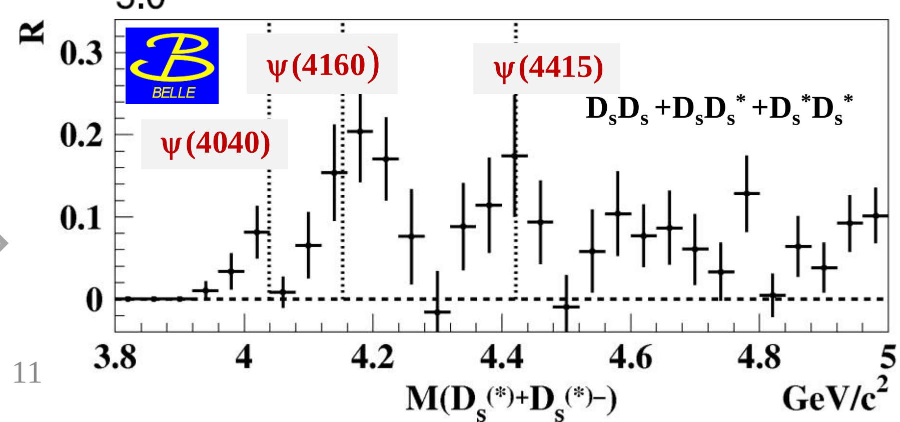
$\psi(4160)$ is seen in D^*D^*, $D_s^+D_s^{*-}$

$\psi(4415)$ is seen in $DD\pi$, $D_s^+D_s^{*-}$

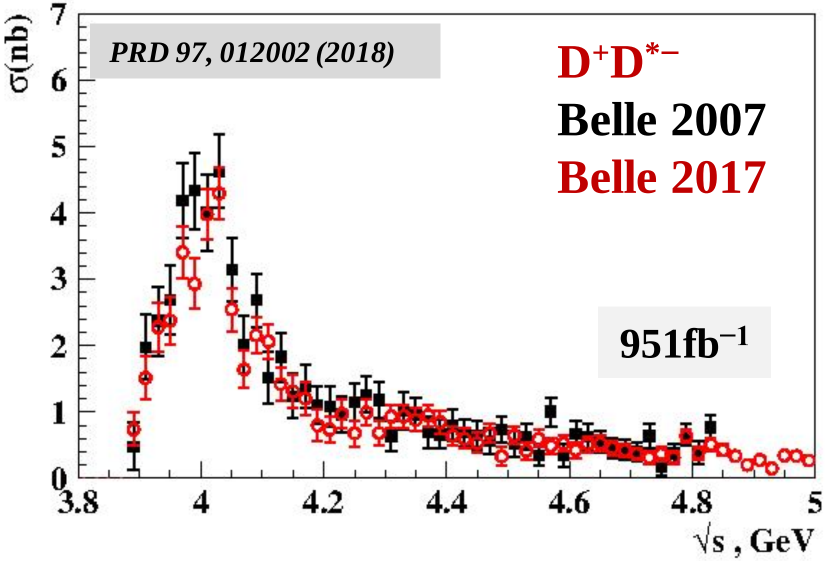
$e^+e^- \to DD$ peak at 3.9 GeV

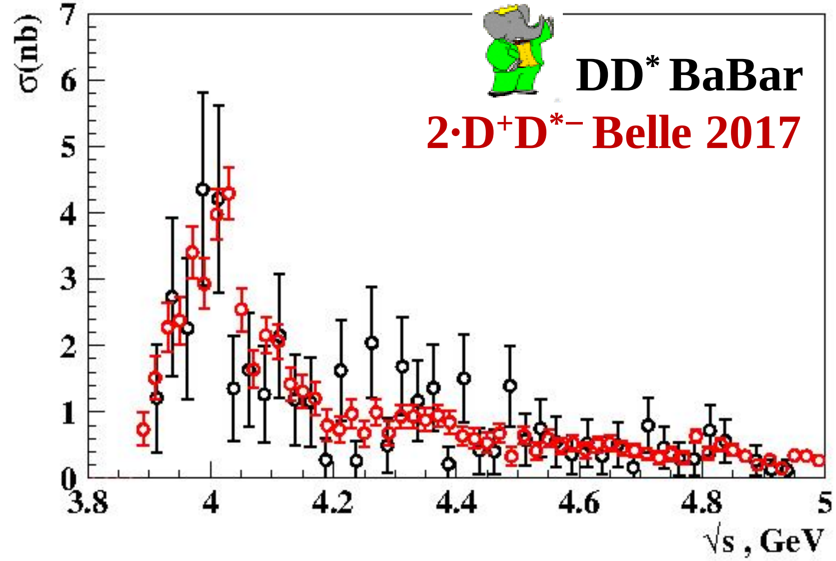
Y(4260) is seen as a dip

Sum of $e^+e^- \to D_s^{(*)+}D_s^{(*)-}$



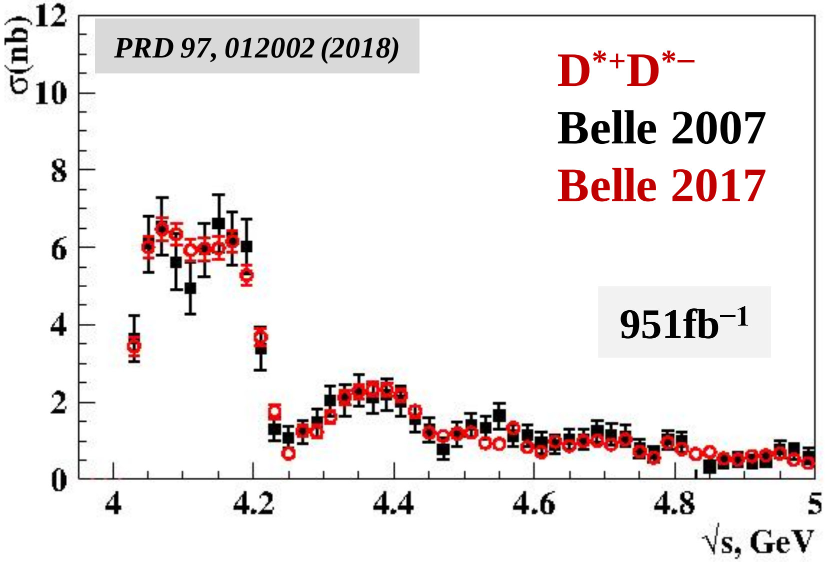
New measurements of $\sigma(e^+e^-\to D^{(*)+}D^{*-})$ via ISR

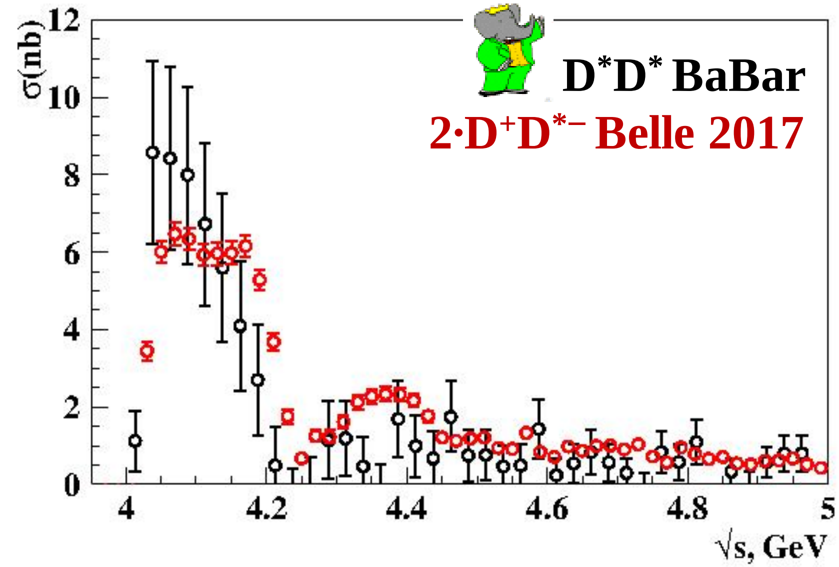




Ideal agreement with previous Belle and BaBar measurements

The accuracy is increased by a factor of two over the first Belle study





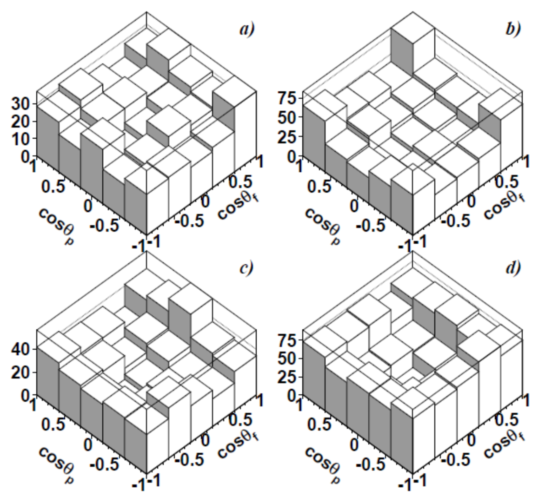
The first angular analysis of the $e^+e^- \to D^{*+}D^{*-}$ process

○ Study of the $D^{*\pm}$ helicity angle distribution in each bin of $M(D^{*+}D^{*-})$

○ Decomposition of the exclusive cross section into three components :

$D^{*+}_T D^{*-}_T$, $D^{*+}_L D^{*-}_T$ and **$D^{*+}_L D^{*-}_L$**

- ○ **D^*_T** transversely polarized D^* meson
- ○ **D^*_L** longitudinally polarized D^* meson



$\cos_f$ vs. $\cos_p$

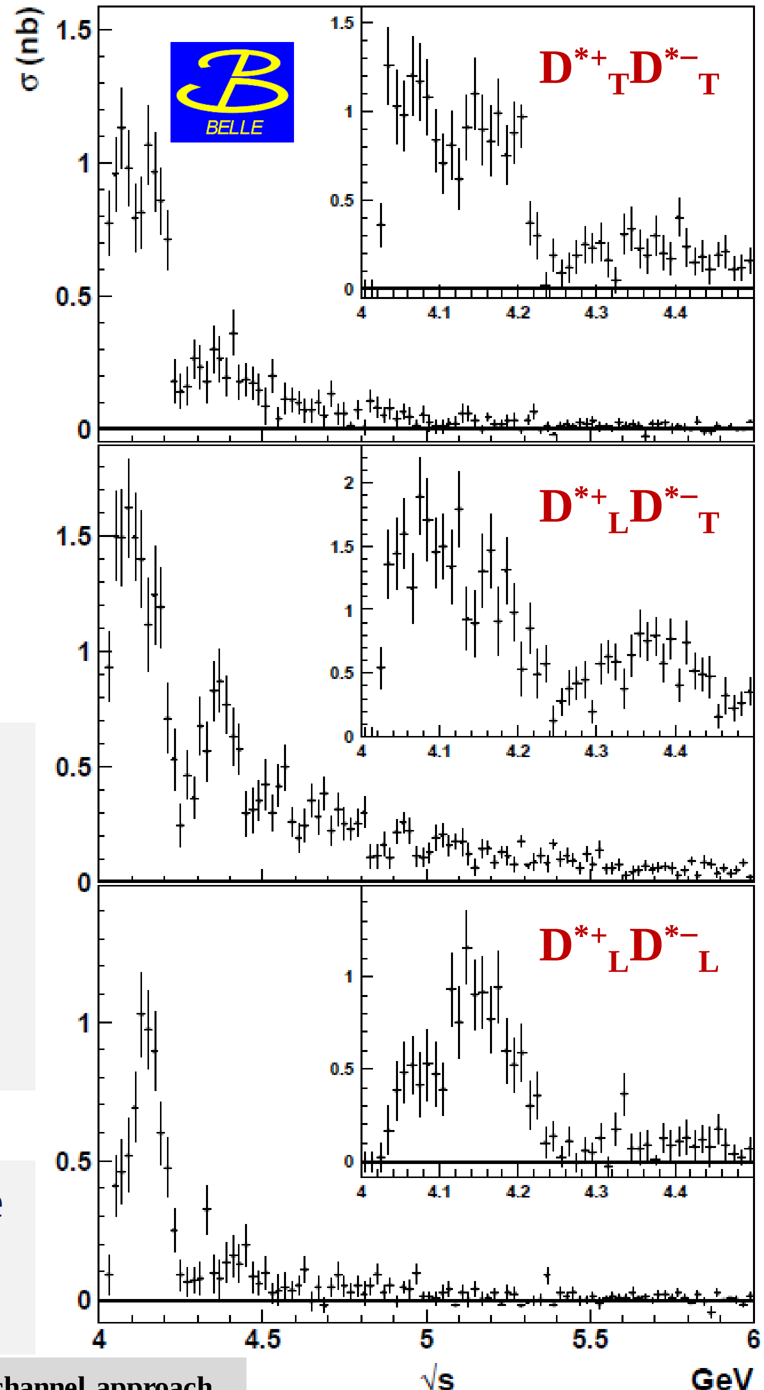
$M(D^{*+}D^{*-})$:

a) 4.0-4.1GeV/c^2

b) 4.1-4.25GeV/c^2

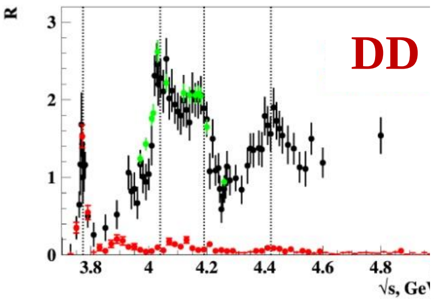
c) 4.25-4.6GeV/c^2

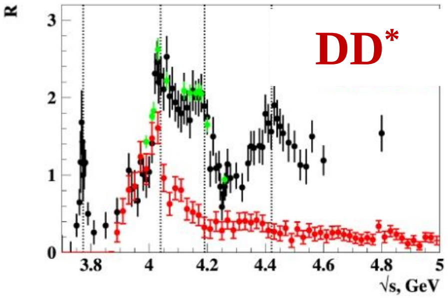
d) > 4.6GeV/c^2

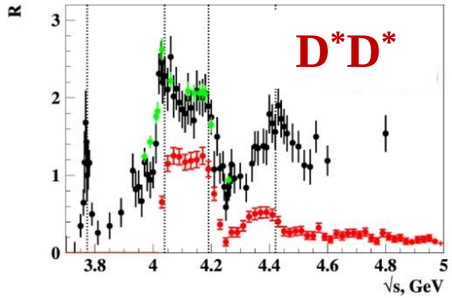


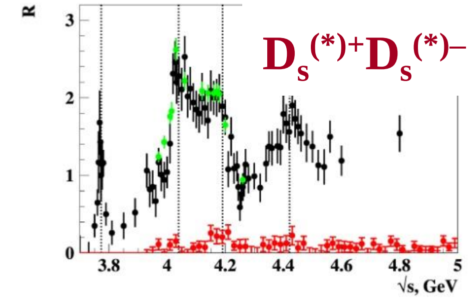
Obtained components should allow to describe all the measured exclusive cross-sections simultaneously in the framework of the coupled channel model

JETP L 105, 3 (2017) **Exclusive open-charm near-threshold cross sections in a coupled-channel approach**

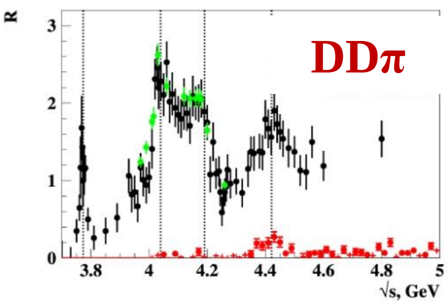


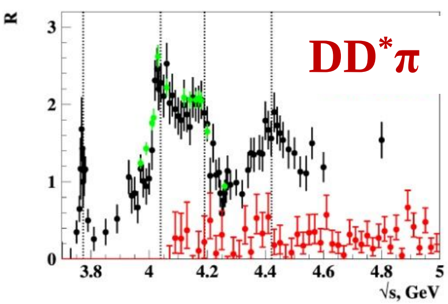


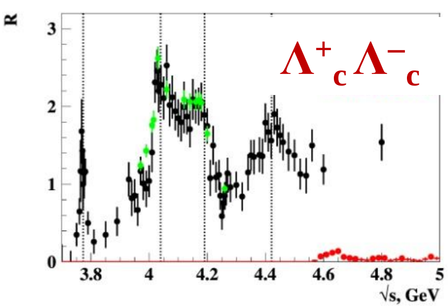


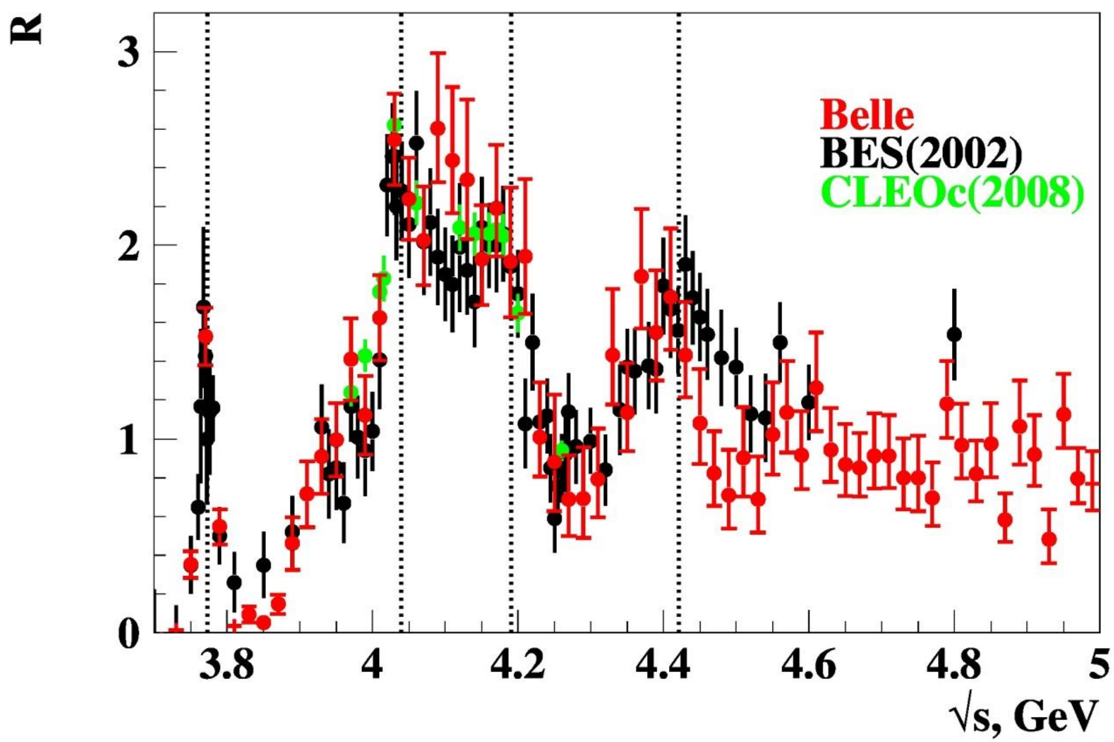


Sum of all measured exclusive cross-sections to open charm



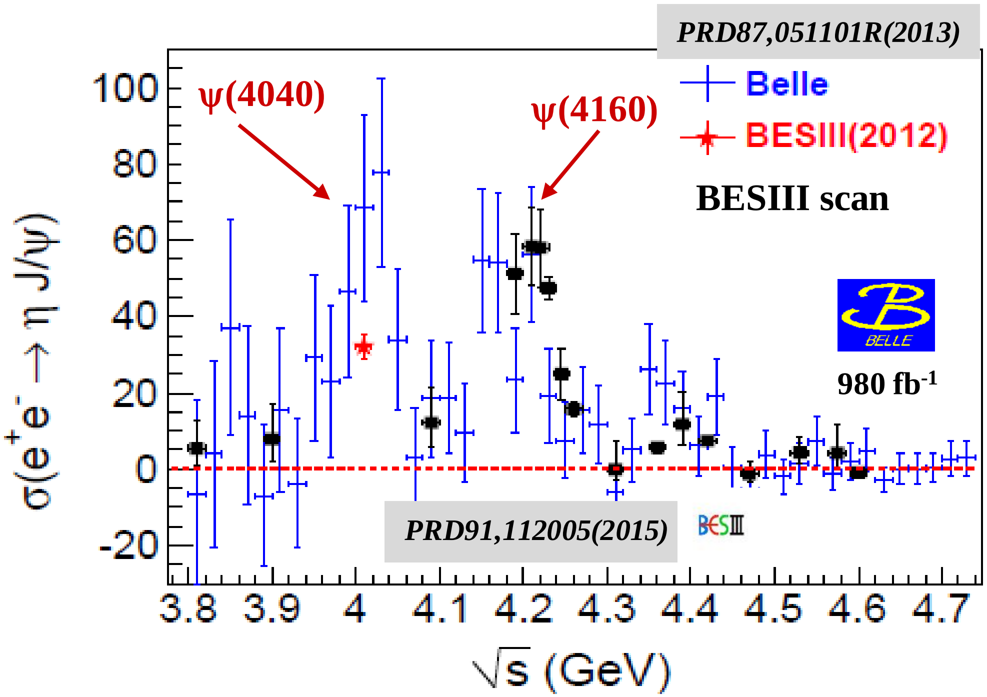




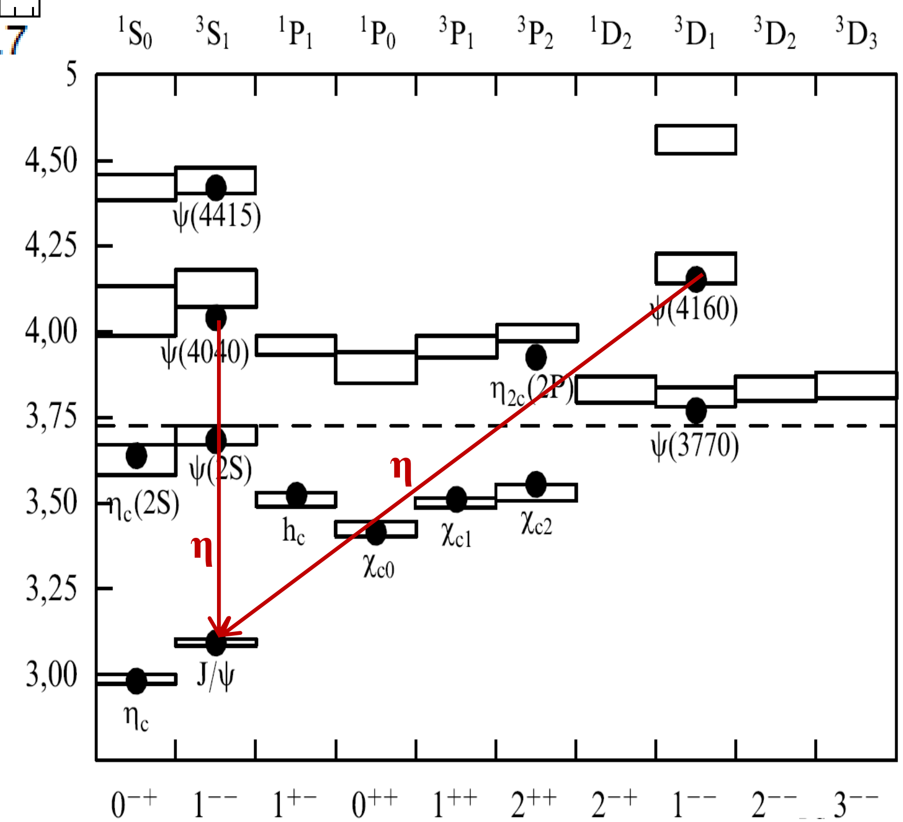


Contributions of D^+D^{*-}, $D^{*+}D^{*-}$, $D^0D^-\pi^+$ and $D^0D^{*-}\pi^+$ are scaled following isospin symmetry

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



- Peaks of ψ(4040) and ψ(4160)
- No sign of any Y state
- Γ (ψ(4040,4160) → J/ψη) ~ 1 MeV
  - Anomalous transitions: common feature of all 1^{--} states above threshold ?



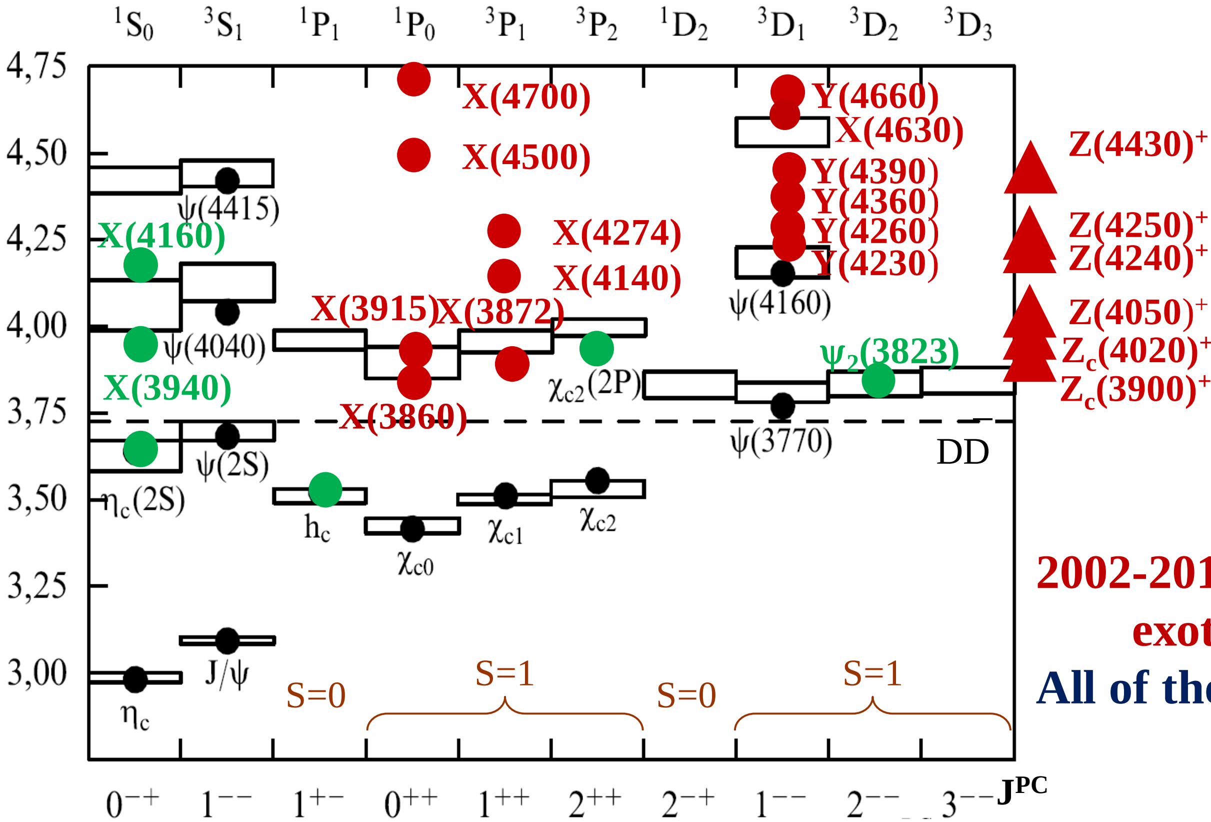
BESIII scan is in agreement with Belle ψ(4160) → J/ψη structure

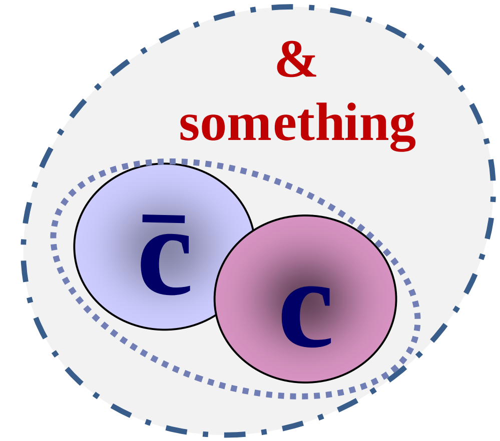
Do we understand conventional charmonium above DD threshold, in particular ψ states?

In fact, we even have not measured their parameters reliably…

Charmoniumlike states

Charmoniumlike states (before PDG2018 naming scheme)

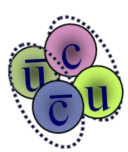




2002-2016 Discovery of **two dozens exotic charmonium states**

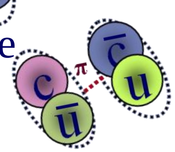
All of them above open charm threshold

Multiquark states



Tetraquark

tightly bound four-quark state

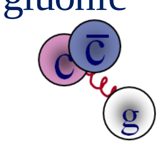


Molecular state

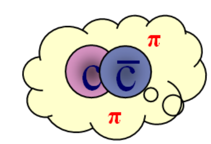
two loosely bound charm mesons

Charmonium hybrids

States with excited gluonic degrees of freedom



Hadrocharmonium



Specific charmonium state "coated" by excited light-hadron matter

Rescattering

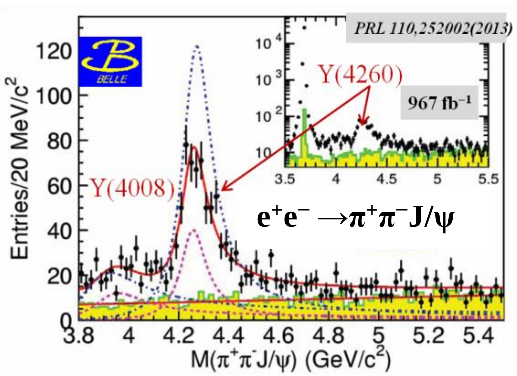
Two D-mesons, produced closely, exchange quarks

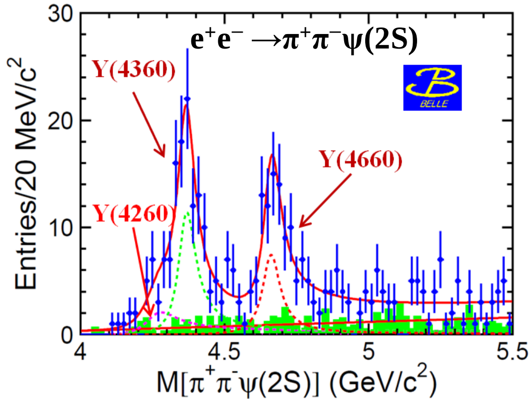
Threshold effects

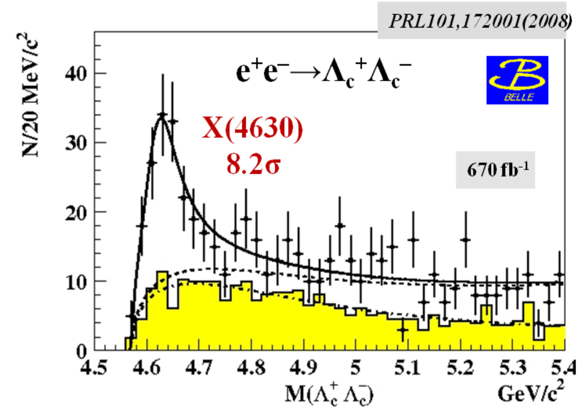
Virtual states at thresholds

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

Exotic vector states

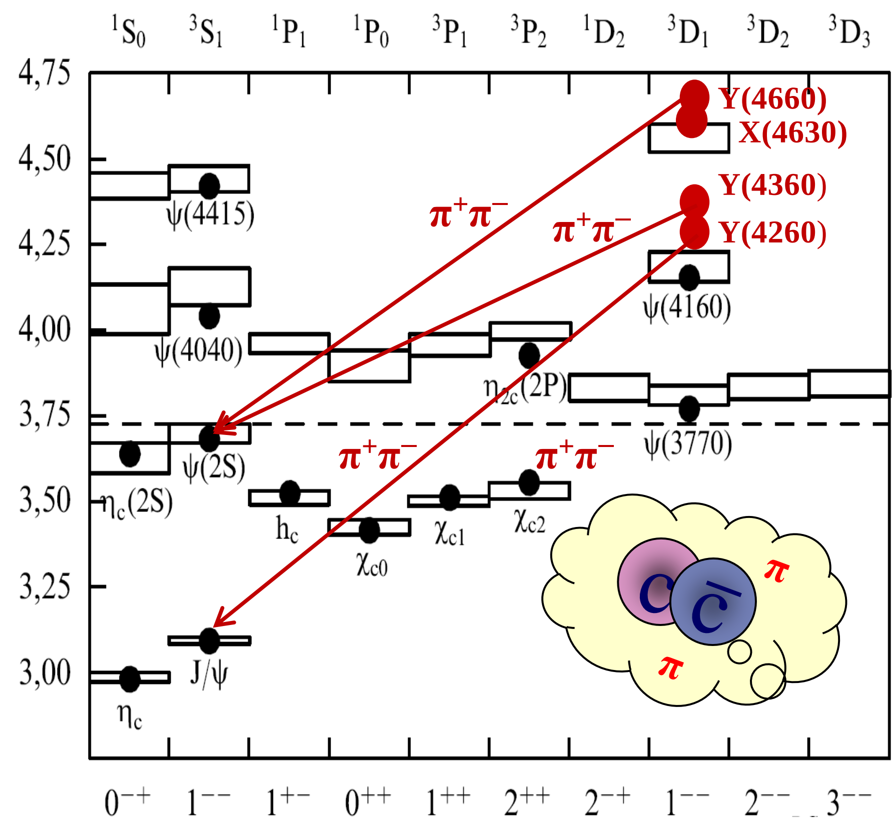






Y states at B factories via ISR

	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

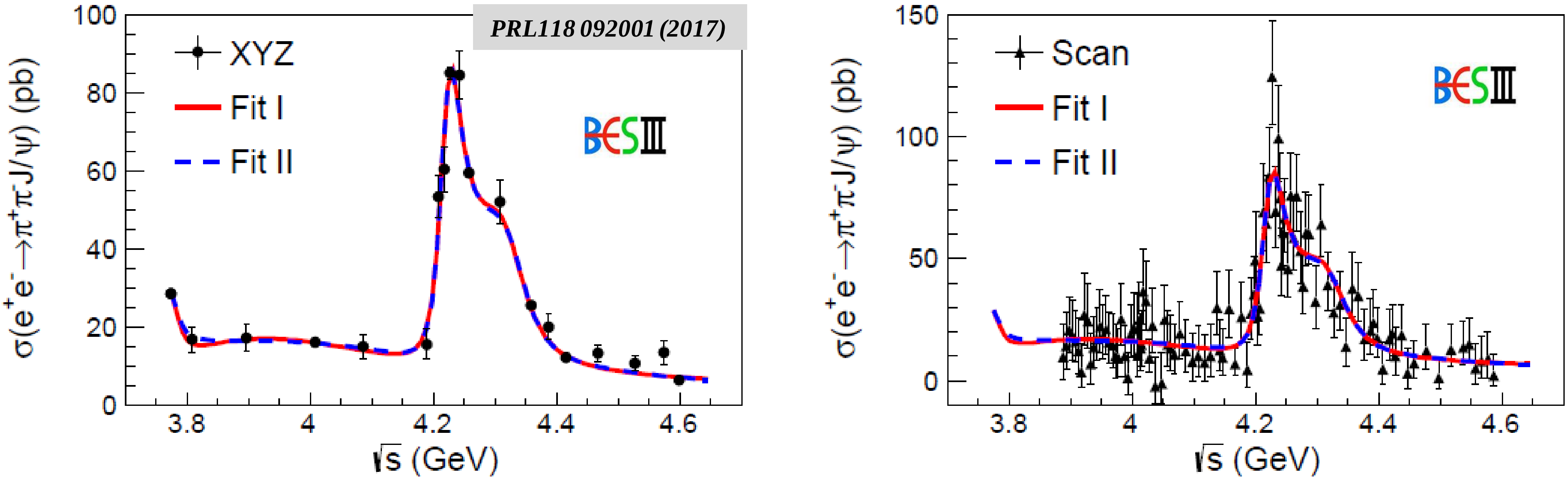
- No room for Y states among 1^{--} charmonium

  $3^3S_1 = \psi(4040)$; $2^3D_1 = \psi(4160)$; $4^3S_1 = \psi(4415)$; 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 + $\pi\pi$

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

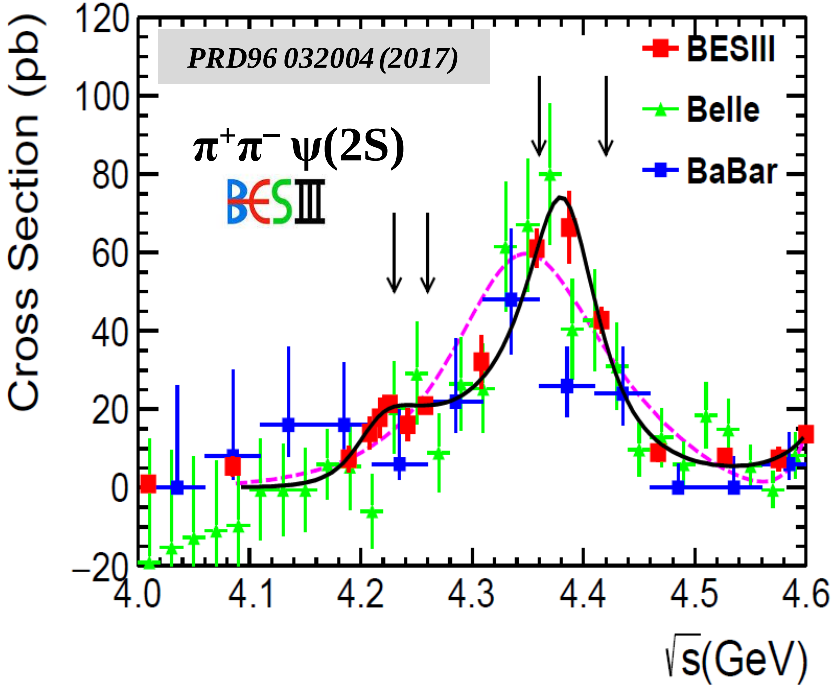


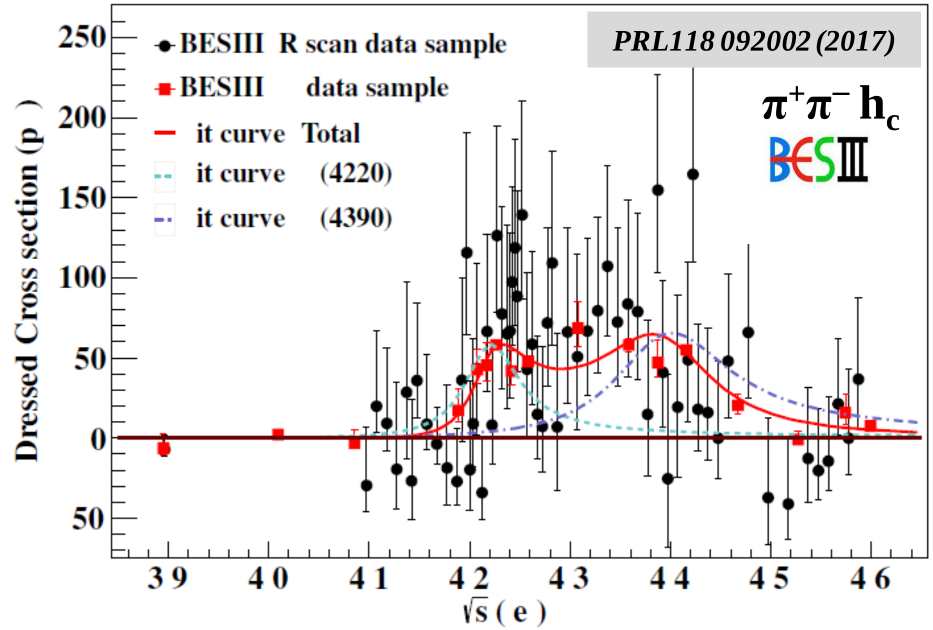
$e^+e^- \to \pi^+\pi^- J/\psi$ cross section is inconsistent with a single pick of Y(4260)

Two peaks are favored over one peak by 7.6 σ

	M, GeV/c²	**Γ, MeV**	**Decay mode**
X(4260), PDG	**4230±8**	**55±19**	**$\pi^+\pi^- J/\psi$**
Y(4220), BESIII	**4222.0±3.1±1.4**	**44.1±4.3±2.0**	**$\pi^+\pi^- J/\psi$**
X(4360), PDG	**4341±8**	**102±9**	**$\pi^+\pi^- \psi(2S)$**
Y(4360), BESIII	**4320.0±10.4±7.0**	**$101.4^{+25.3}_{-19.7}$±10.2**	**$\pi^+\pi^- J/\psi$**

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



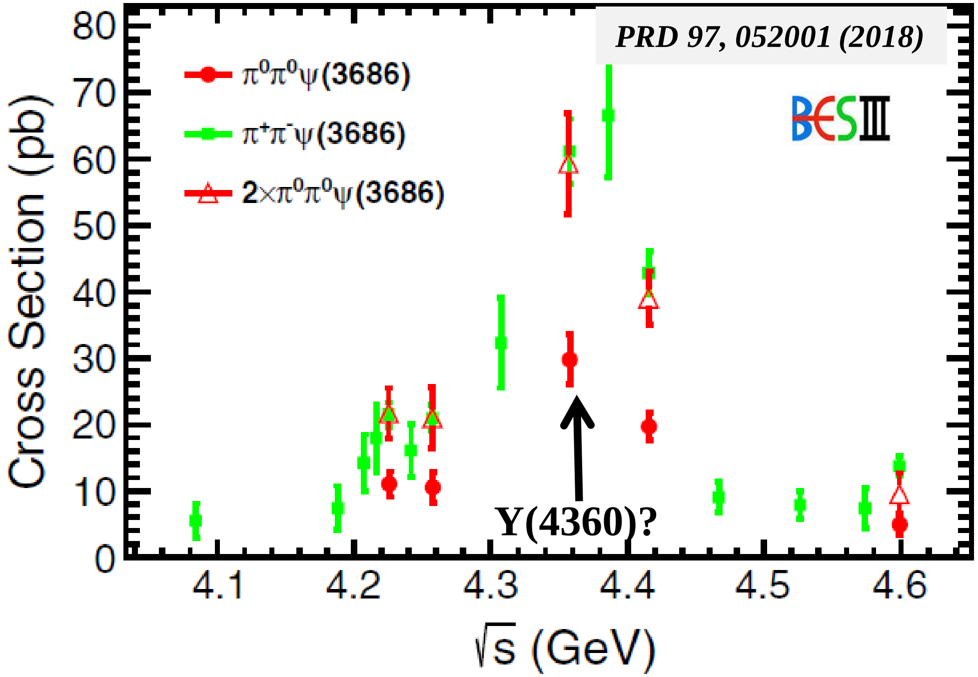


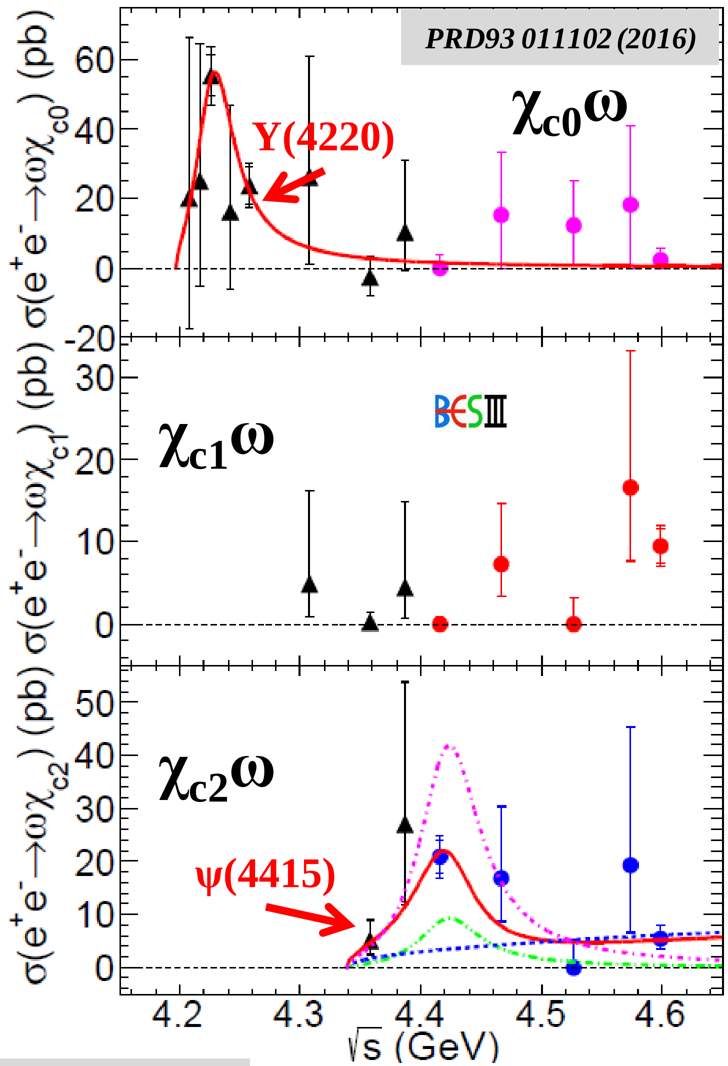
BESIII confirms lineshape in $e^+e^- \to \pi^+\pi^- \psi(2S)$

	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)	$4391.5^{+6.3}_{-6.8}\pm0.9$	$139.5^{+16.2}_{-20.6}\pm0.6$	$\pi^+\pi^- h_c$
X(4360), PDG	4341±8	102±9	$\pi^+\pi^- \psi(2S)$

$e^+e^- \to \pi^0\pi^0\psi(2S)$

$e^+e^- \to \chi_{cJ}\omega$





$e^+e^- \to \pi^0\pi^0\psi(2S)$ consistent with the charged mode from isospin symmetry (scan five points)

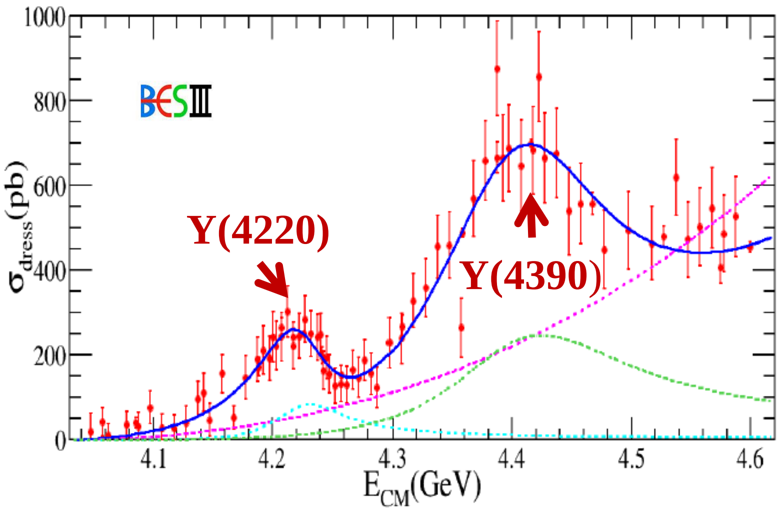
	M, GeV/c2	Γ, MeV	Decay mode
Y(4220)	4209.5±7.4±1.4	80.1±24.6±2.9	$\pi^+\pi^-\psi(2S)$
Y(4220)	$4218.4^{+5.5}_{-4.5}\pm0.9$	$66.0^{+12.3}_{-8.3}\pm0.4$	$\pi^+\pi^- h_c$
Y(4220)	4230±8±6	38±12±2	$\chi_{c0}\omega$

PRL 114 092003 (2015)

First measurements of $\psi(4415) \to \chi_{cJ}\omega$

mass, width, Γ_{ee} for ψ(4415) are fixed to PDG parameters

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



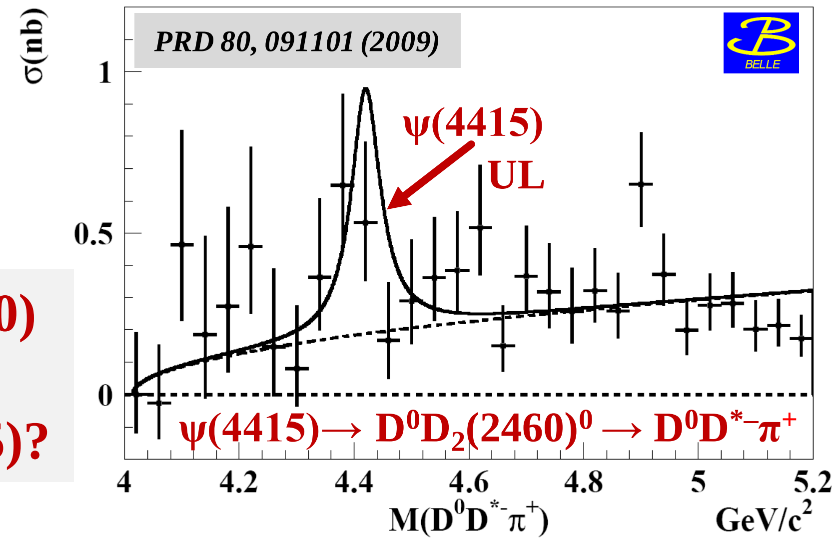
Parameters	SolutionI	SolutionII	SolutionIII	SolutionIV
c (10^{-4})	5.5±0.6			
M_1 (MeV/c^2)	4224.8±5.6			
Γ_1 (MeV)	72.3±9.1			
M_2 (MeV/c^2)	4400.1±9.3			
Γ_2 (MeV)	181.7±16.9			
Γ_1^{el} (eV)	62.9±11.5	7.2±1.8	81.6±15.9	9.3±2.7
Γ_2^{el} (eV)	88.5±15.8	55.3±8.7	551.9±85.3	344.9±70.6
ϕ_1	-2.1±0.1	2.8±0.3	-0.9±0.1	-2.3±0.2
ϕ_2	1.9±0.3	2.3±0.2	2.3±0.1	-1.9±0.1

Y(4220) — M_1; Y(4390) — M_2

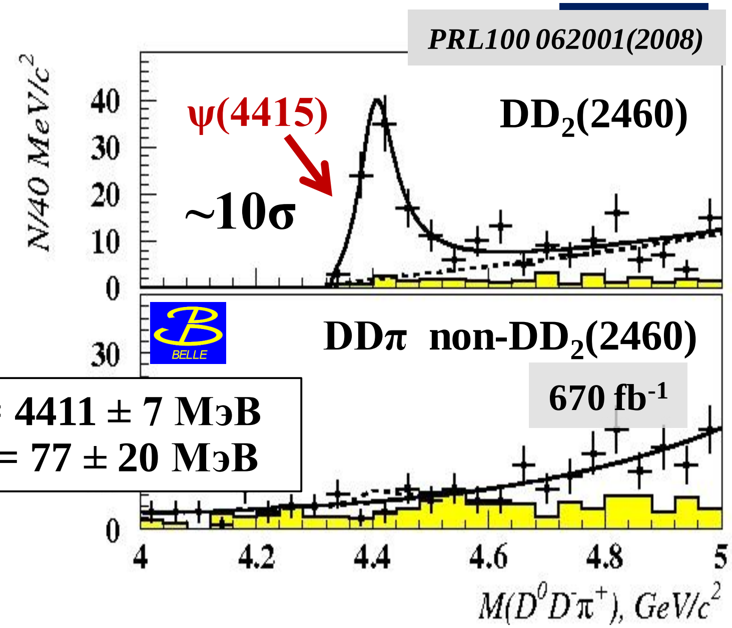
BESIII Preliminary

Y(4390) or ψ(4415)?

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



Belle: $e^+e^- \to D^0 D^- \pi^+$



M = 4411 ± 7 МэВ
Γ_{tot} = 77 ± 20 МэВ

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

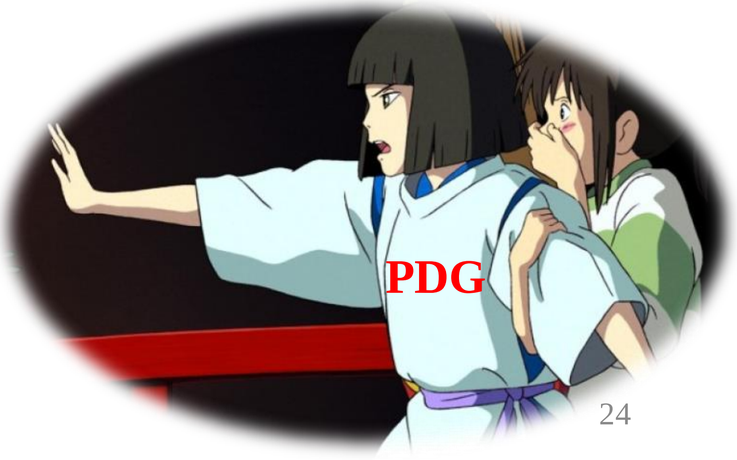
UL due to limited statistics

Vector states summary 2018

	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)	ok							
ψ(4040)	ok				ok			
ψ(4160)	ok				ok			
Y(4220) = ψ(4230) PDG 2018 Y(4260) = ψ(4260) PDG 2018	$DD^*\pi$ none	ok ok		ok		ok		Same state?
Y(4390) = ψ(4390) PDG 2018 Y(4360) = ψ(4360) PDG 2018	 none	 ok	ok ok	ok				Same state?
Y(4390)	$DD^*\pi$							ψ(4415)?
ψ(4415)	$DD\pi$						ok	
Y(4630) = ψ(4660) PDG 2018	$\Lambda_c^+\Lambda_c^-$							Same state ψ(4660)?
Y(4660) = ψ(4660) PDG 2018	none	ok	ok					

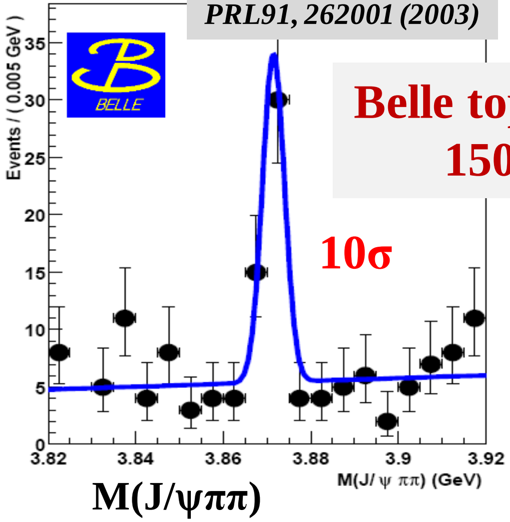
- Two newborns in Y family: Y(4220), Y(4390)
- ~~Only one~~ Few decay channels per one Y state
  - hadrocharmonium is excluded!
- Nature of Y states?
- PDG revolution 2018

Y states with $J^{PC} = 1^{--}$ turn into ψ states



X(3872)
as
χ_{c1}(3872) in
PDG2018

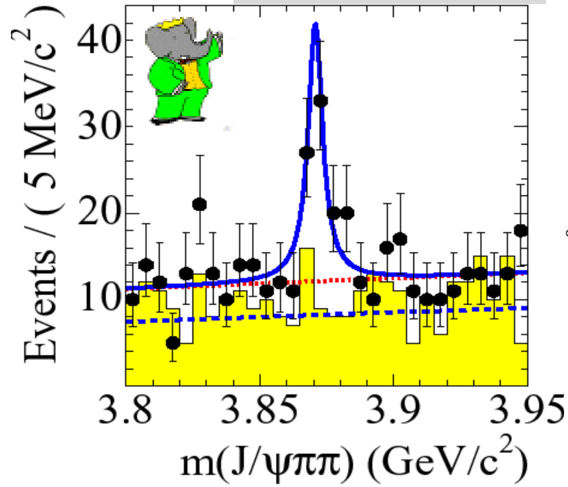
PRL91, 262001 (2003)

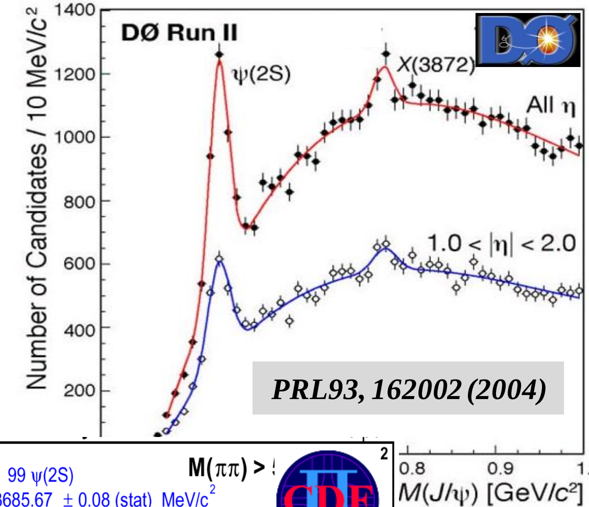


Belle top cited 1500+

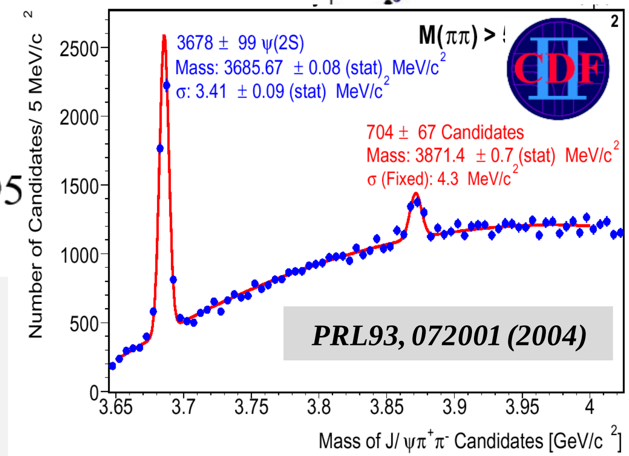
First observed by Belle in B→K J/ψπ⁺π⁻

PRD73, 011101 (2006)



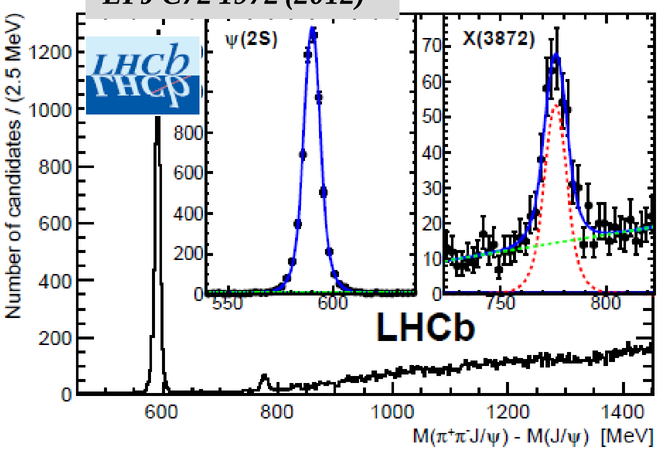


PRL93, 162002 (2004)



PRL93, 072001 (2004)

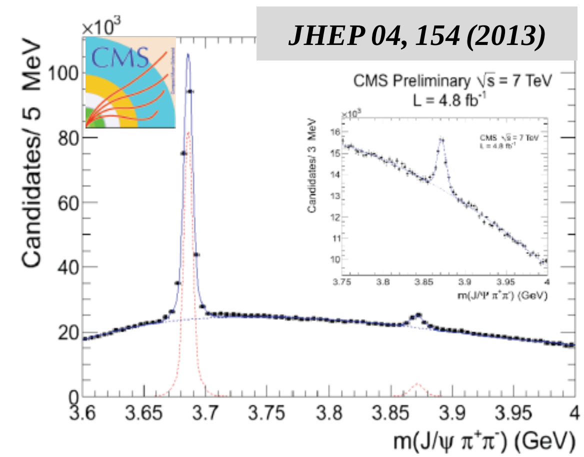
EPJ C72 1972 (2012)



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

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

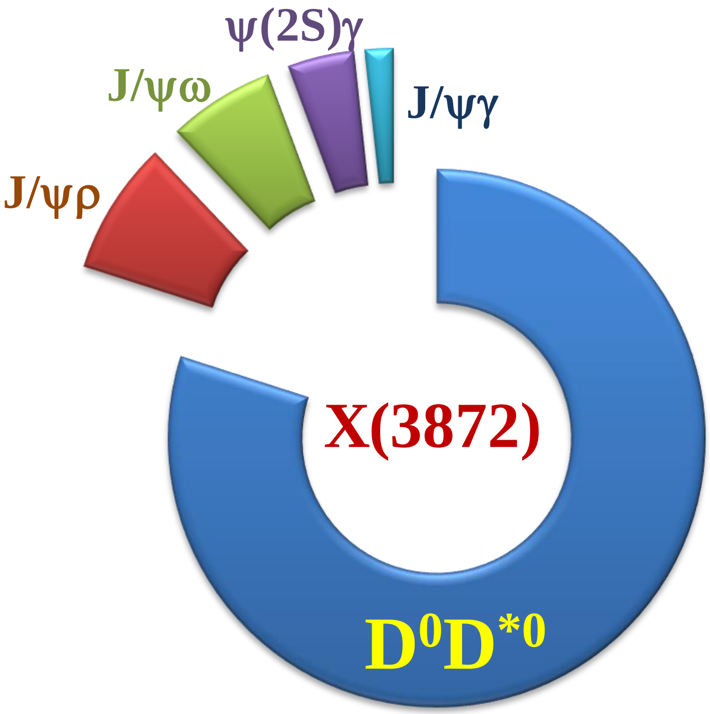
JHEP 04, 154 (2013)



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

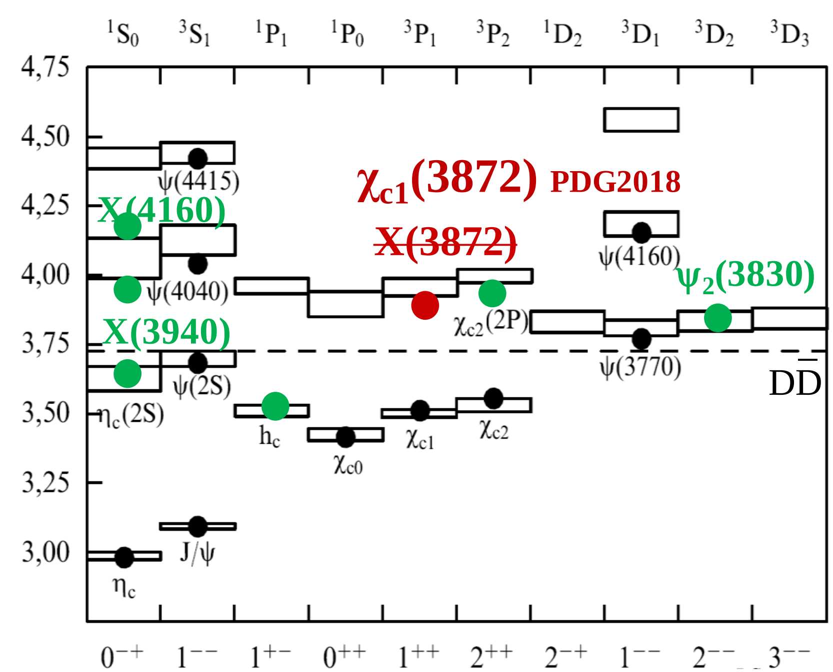


X(3872) interpretation

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

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

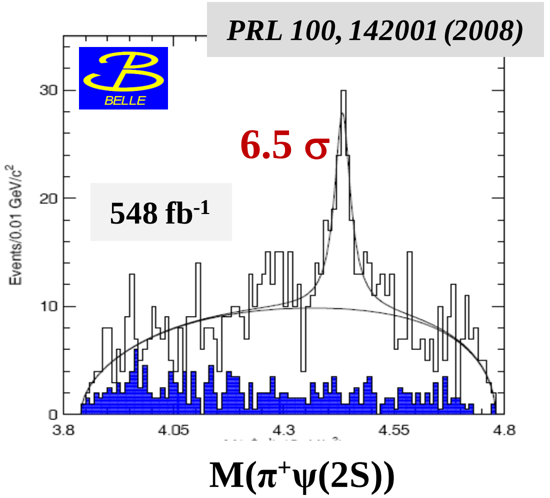
Mixture of P-wave charmonium $\chi_{c1}(2P)$ and S-wave DD^{*0} molecule

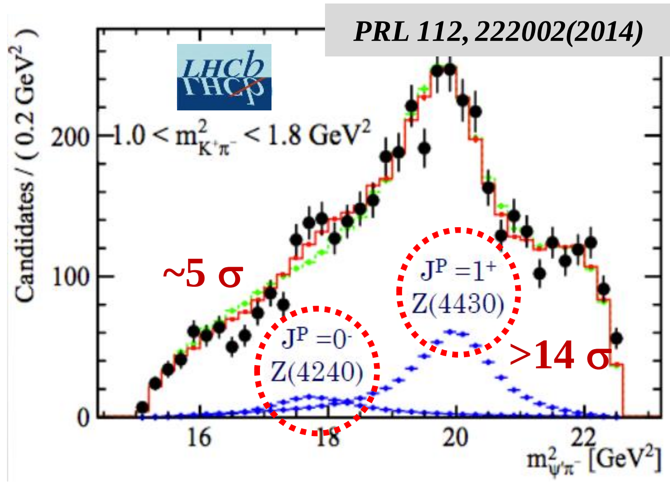


Search for X(3872) partners decays *Molecules with $J^{PC} = 0^{++}, 1^{+-}, 2^{++}$...*	
$\chi_{c1}\,\gamma$ $\chi_{c2}\,\gamma$	Forbidden by C-parity conservation C-odd partners: tetraquark, molecule UL : < 1/4 from $J/\psi\ \pi^+\pi^-$
$J/\psi\ \eta$	C-odd partners: tetraquark UL : < 1/2 from $J/\psi\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

Charged charmoniumlike states

Charged Z_c^+ states in B decays

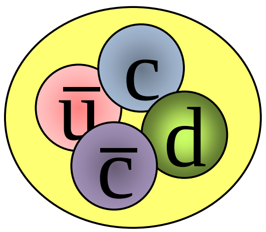




$Z(4430)^+ \to \psi(2S)\,\pi^+$

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

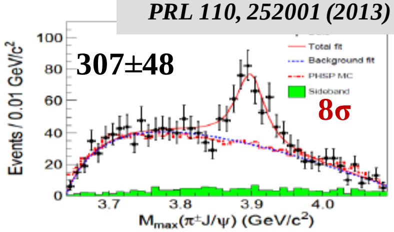
Z_c^+ cannot be conventional charmonium

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

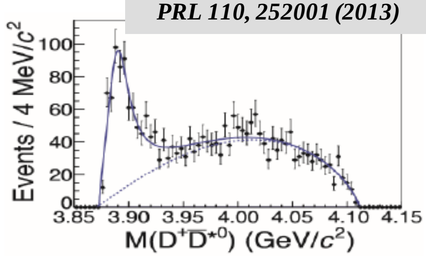
Z_c family in e^+e^- annihilation

PRL 110, 252001 (2013)



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

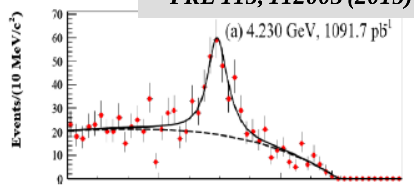
PRL 110, 252001 (2013)



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

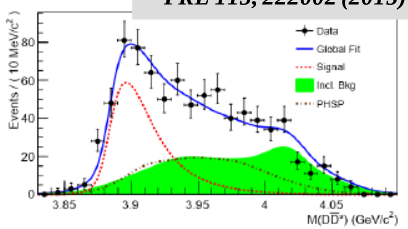
$Z_c(3900)^{\pm}$?

PRL 115, 112003 (2015)



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

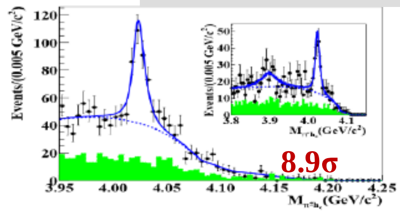
PRL 115, 222002 (2015)



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

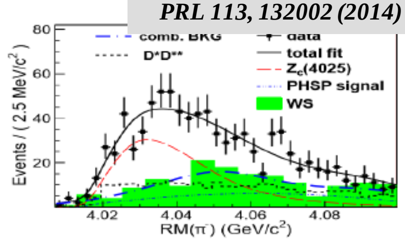
$Z_c(3900)^0$?

PRL 111, 242002 (2013)



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

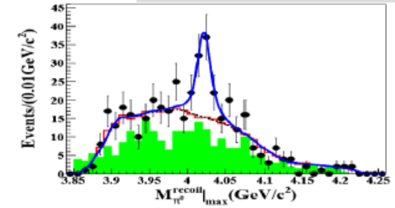
PRL 113, 132002 (2014)



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

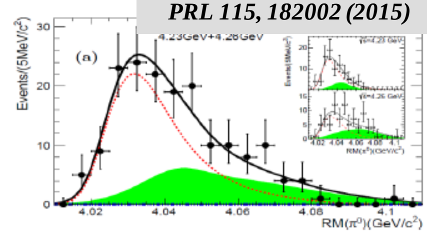
$Z_c(4020)^{\pm}$?

PRL 113, 212002 (2014)



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

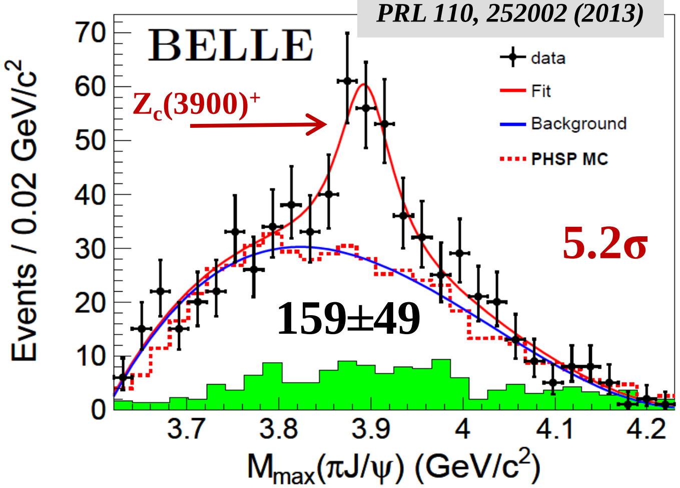
PRL 115, 182002 (2015)



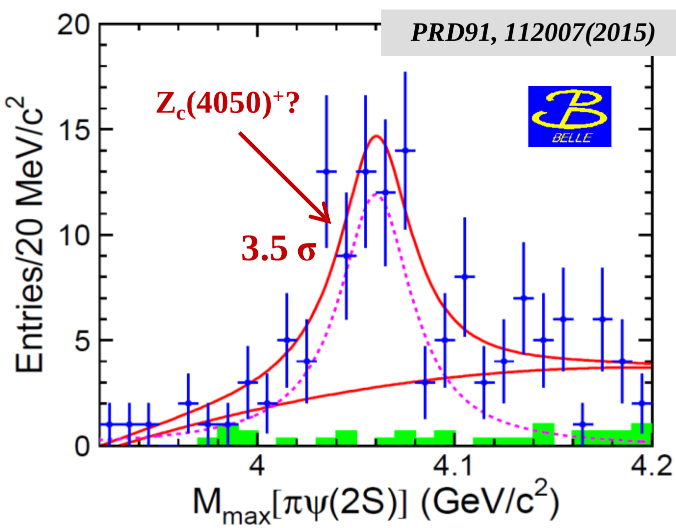
$e^+e^- \rightarrow \pi^0 (D^*\bar{D}^*)^0$

$Z_c(4020)^0$?

PRL 110, 252002 (2013)



PRD91, 112007(2015)



New signal in
$Y(4360) \rightarrow \pi^- Z(4050)^+$
$M = 4054 \pm 3 \pm 1$ MeV/c^2
$\Gamma = 45 \pm 11 \pm 6$ MeV

BESIII *PRD96,032004(2017)*

$Z_c(4030)^+$
$M = 4032.1 \pm 2.4$ MeV/c^2
$\Gamma = 26.1 \pm 5.3$ MeV

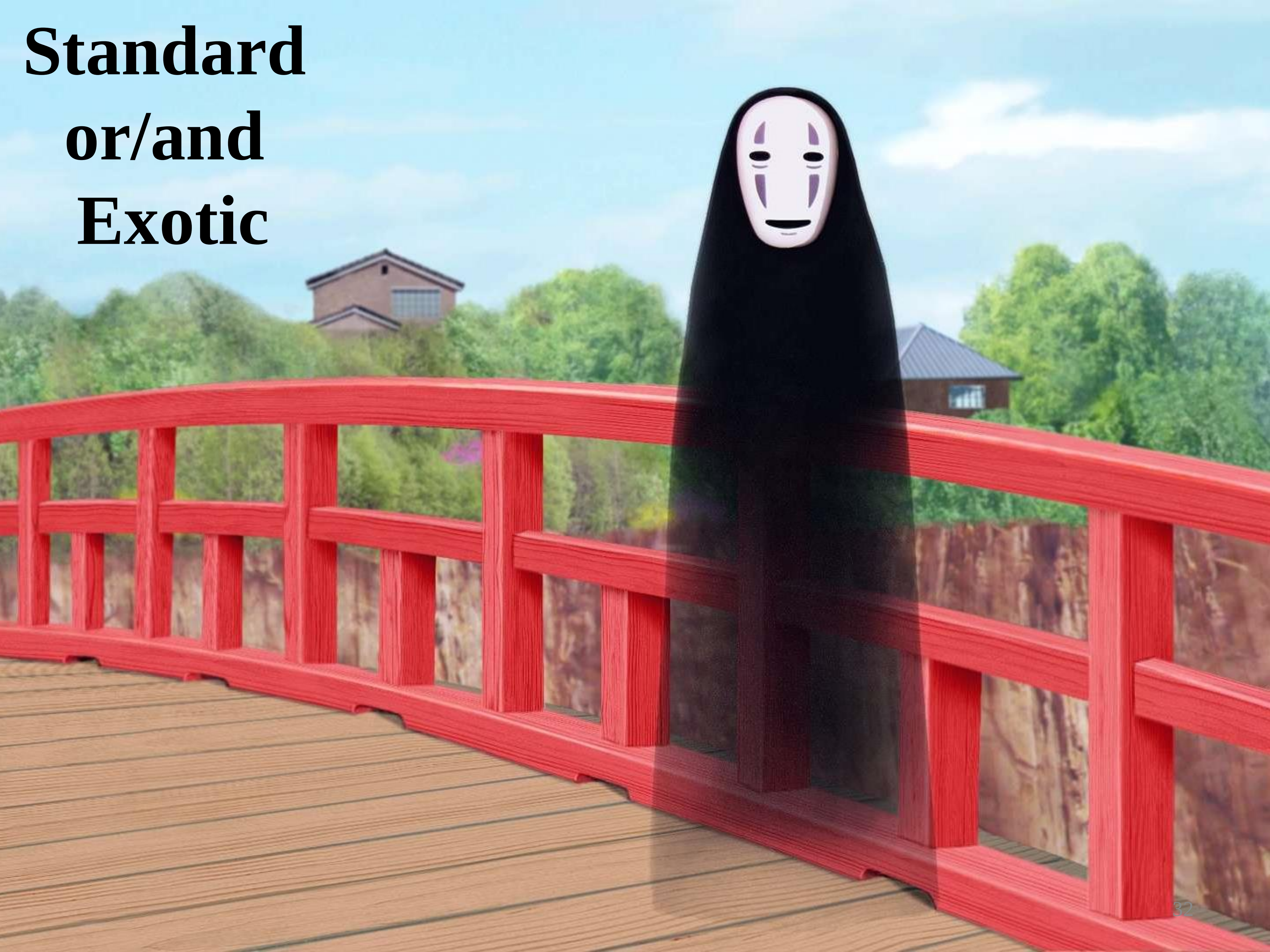
Z_c summary

BESIII

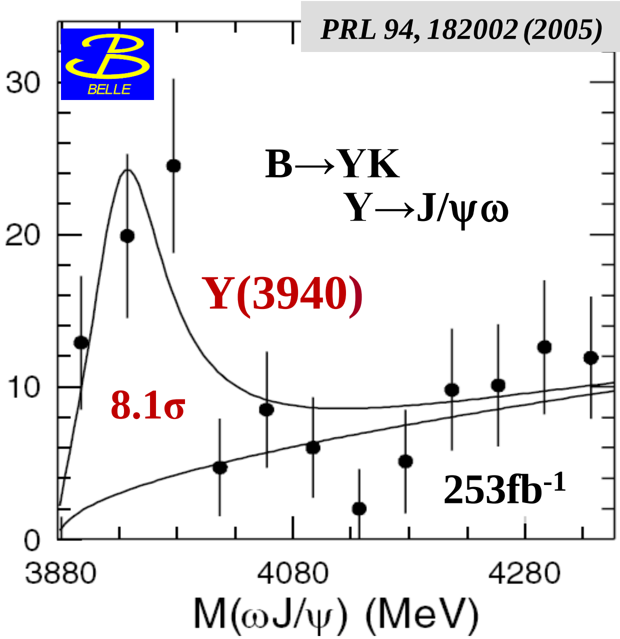
State	Mass (MeV/c²)	Width (MeV)	Decay	Process
$Z_c(3900)^{\pm}$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$	$\pi^{\pm} J/\psi$	$e^+e^- \to \pi^+\pi^- J/\psi$
$Z_c(3900)^0$	$3894.8 \pm 2.3 \pm 2.7$	$29.6 \pm 8.2 \pm 8.2$	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$
$Z_c(3885)^{\pm}$	$3883.9 \pm 1.5 \pm 4.2$ 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? $Z_c(4050)^+ = Z_c(4030)^+$?**

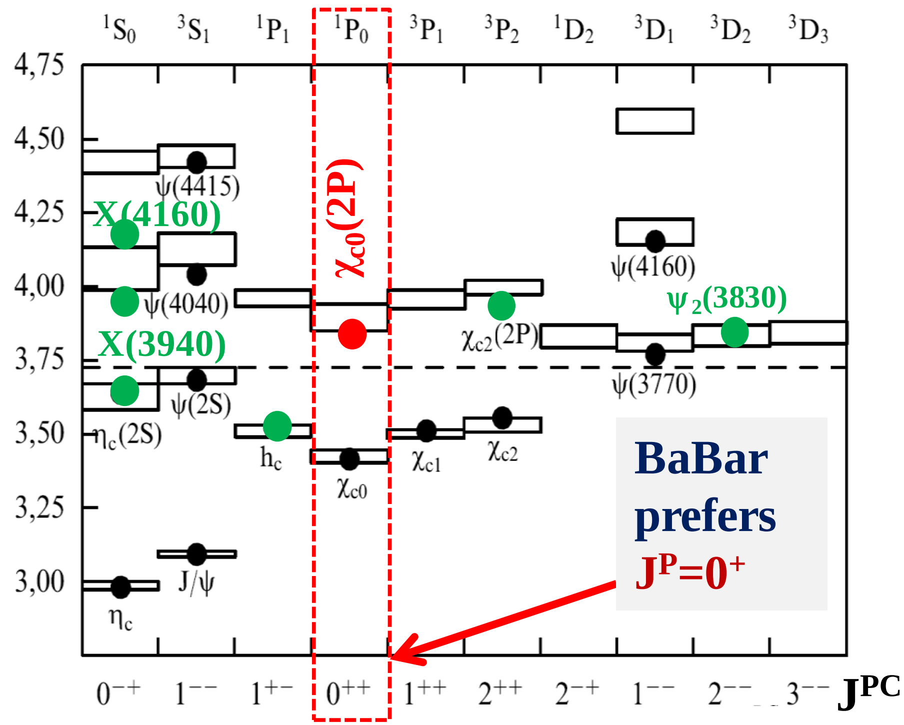
Standard or/and Exotic



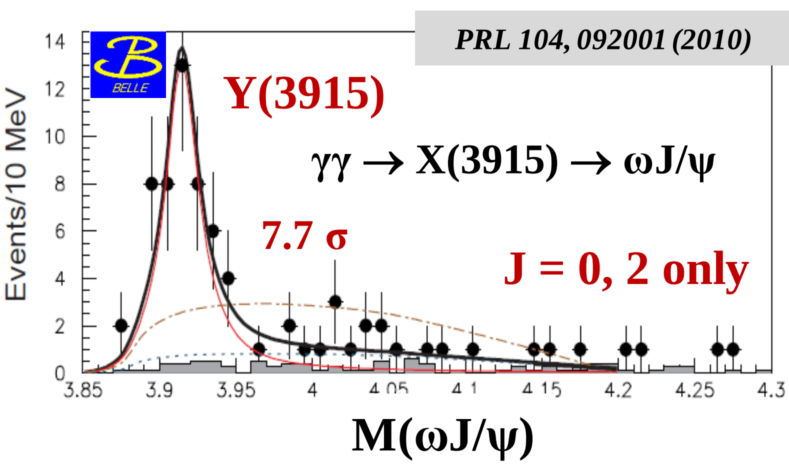
X (3915) ≡ Y(3940)



Particle Data Group 2016
Y(3940) ≡ X(3915) ≡ χ_{c0}(3915)



- The same decay mode
- Similar masses and widths
- Different production mechanisms
- Found by Belle & confirmed by BaBar



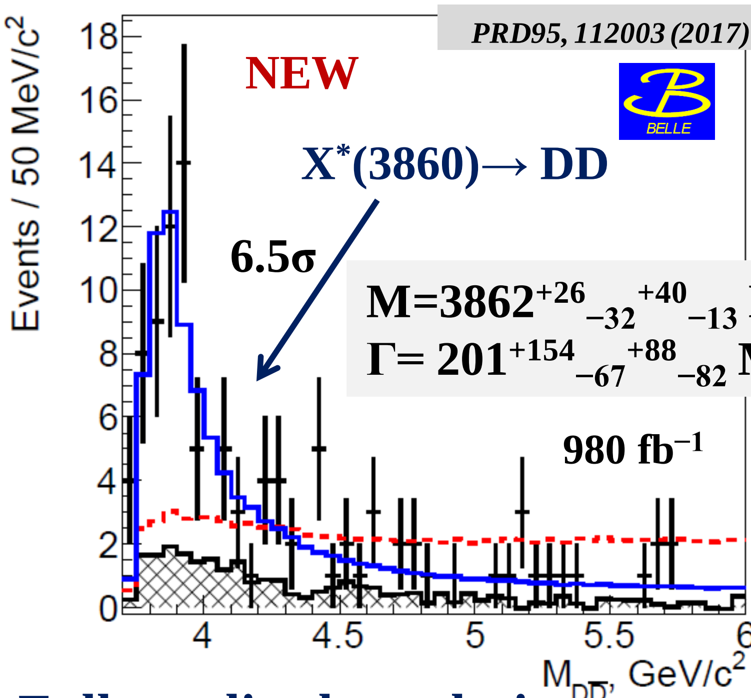
Theory

- χ_{c0}(2P) production in two body B decays is suppressed
- χ_{c0}(2P) → DD should be dominant

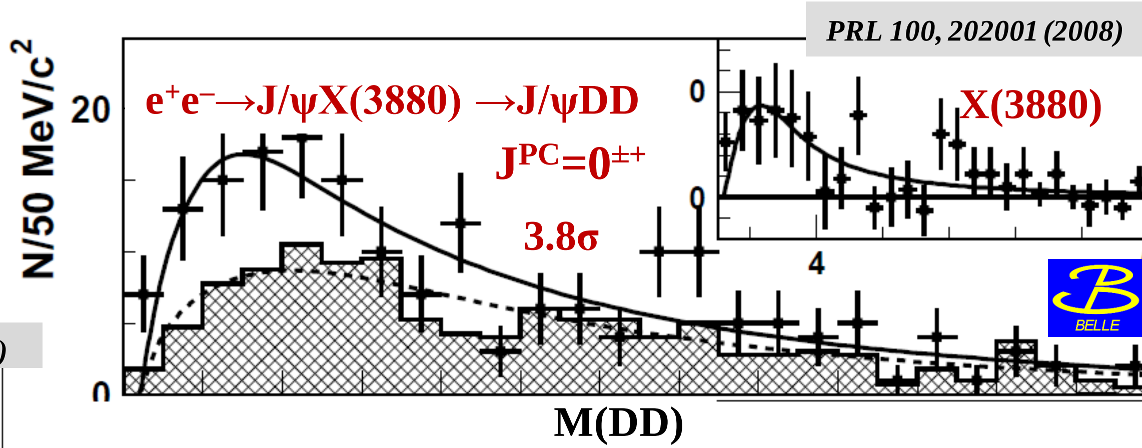
Better $\chi_{c0}(2P)$ candidate in $e^+e^- \to J/\psi DD$

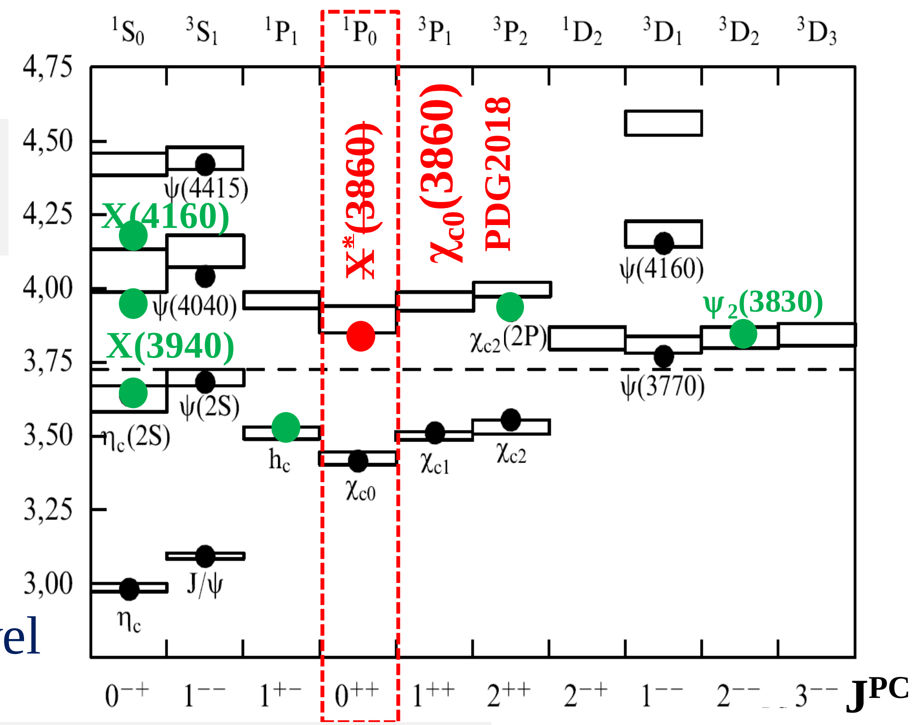
New ideas:

- BaBar angular analysis based on non strict exclusion of $J^P=2^+$
- New better candidate for $\chi_{c0}(2P)$ is seen in $X^*(3860) \to DD$



$M = 3862^{+26}_{-32}{}^{+40}_{-13}$ MeV/c^2
$\Gamma = 201^{+154}_{-67}{}^{+88}_{-82}$ MeV





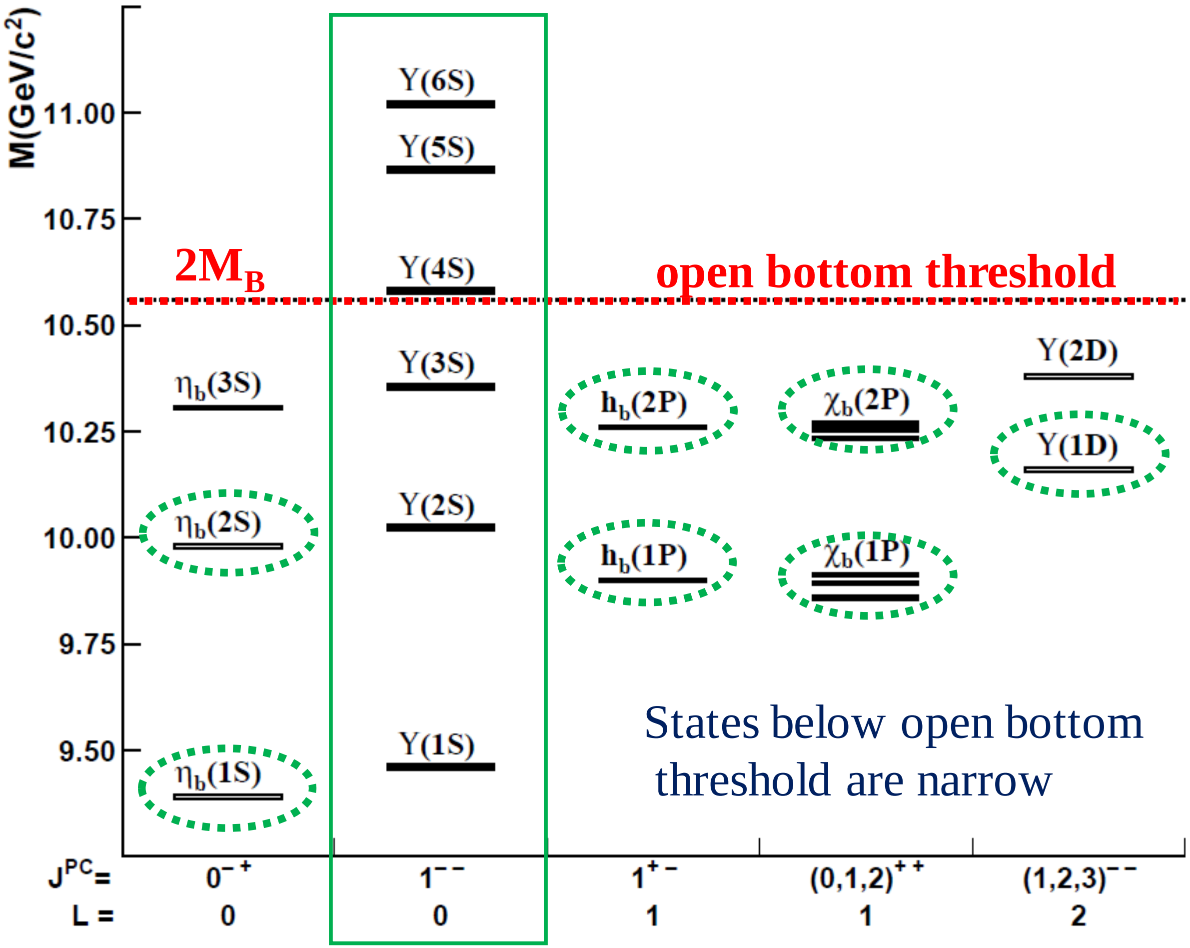
Full amplitude analysis

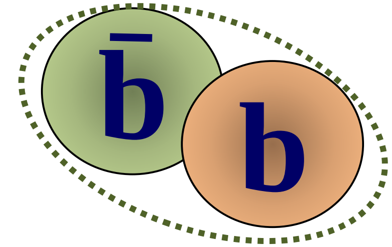
$J^{PC}=0^{++}$ is favored over the 2^{++} at 2.5σ level

Nature of X(3915) is the open question… again

Bottomonium

Bottomonium in 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

$J = S + L$

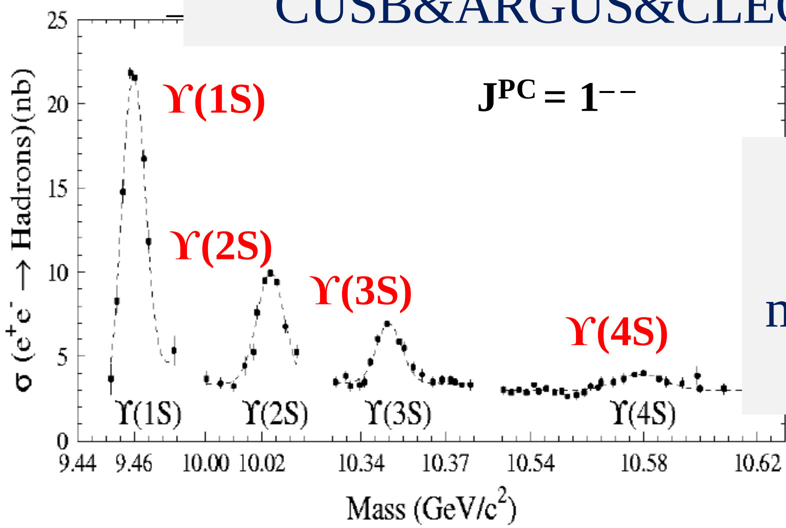
$P = (-1)^{L+1}$ parity

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

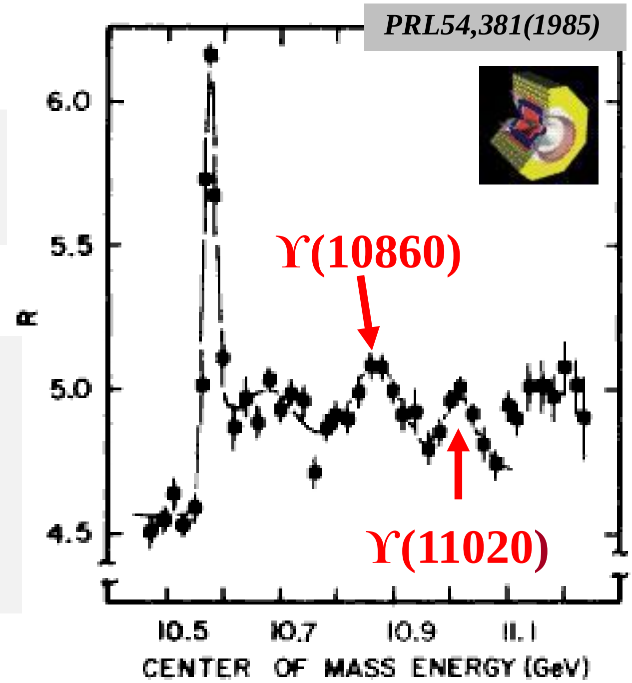
The heaviest quarkonium provide a unique non-relativistic system for QCD testing

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:

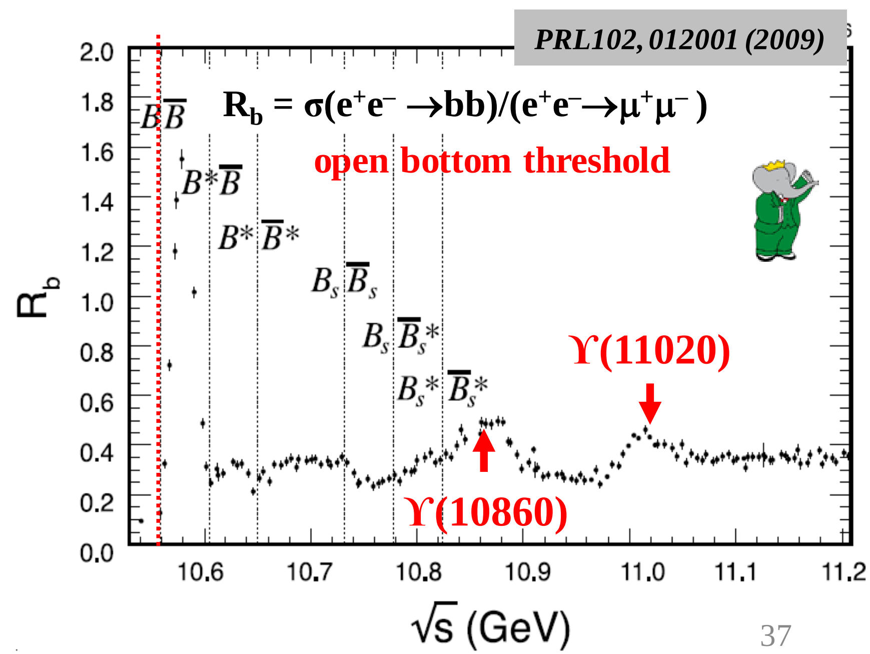
Υ(1S), Υ(2S), Υ(3S), Υ(4S), but…Υ(10860) and Υ(11020) [Common names Υ(5S), Υ(6S)]

Study bottomonium states using transitions of Υ(nS) states

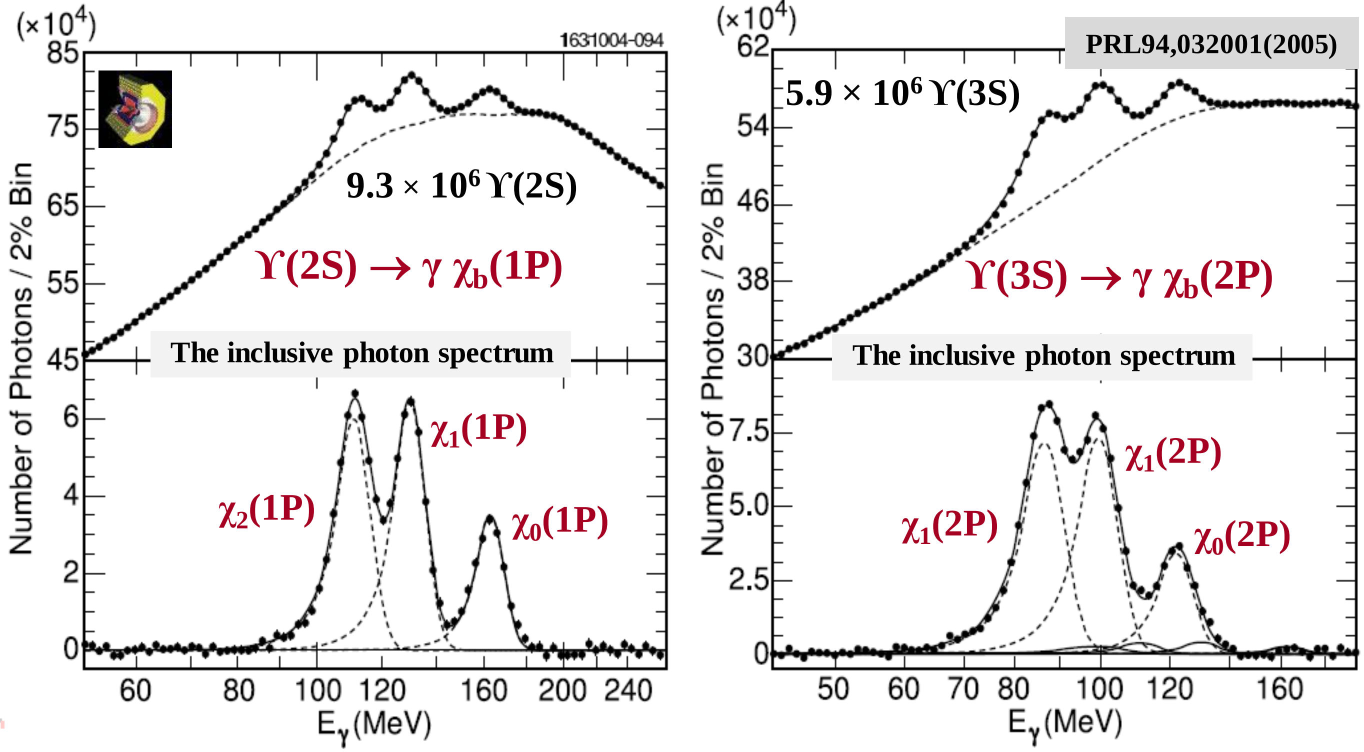
- Υ(4S)→BB (B = B^0 or B^+)

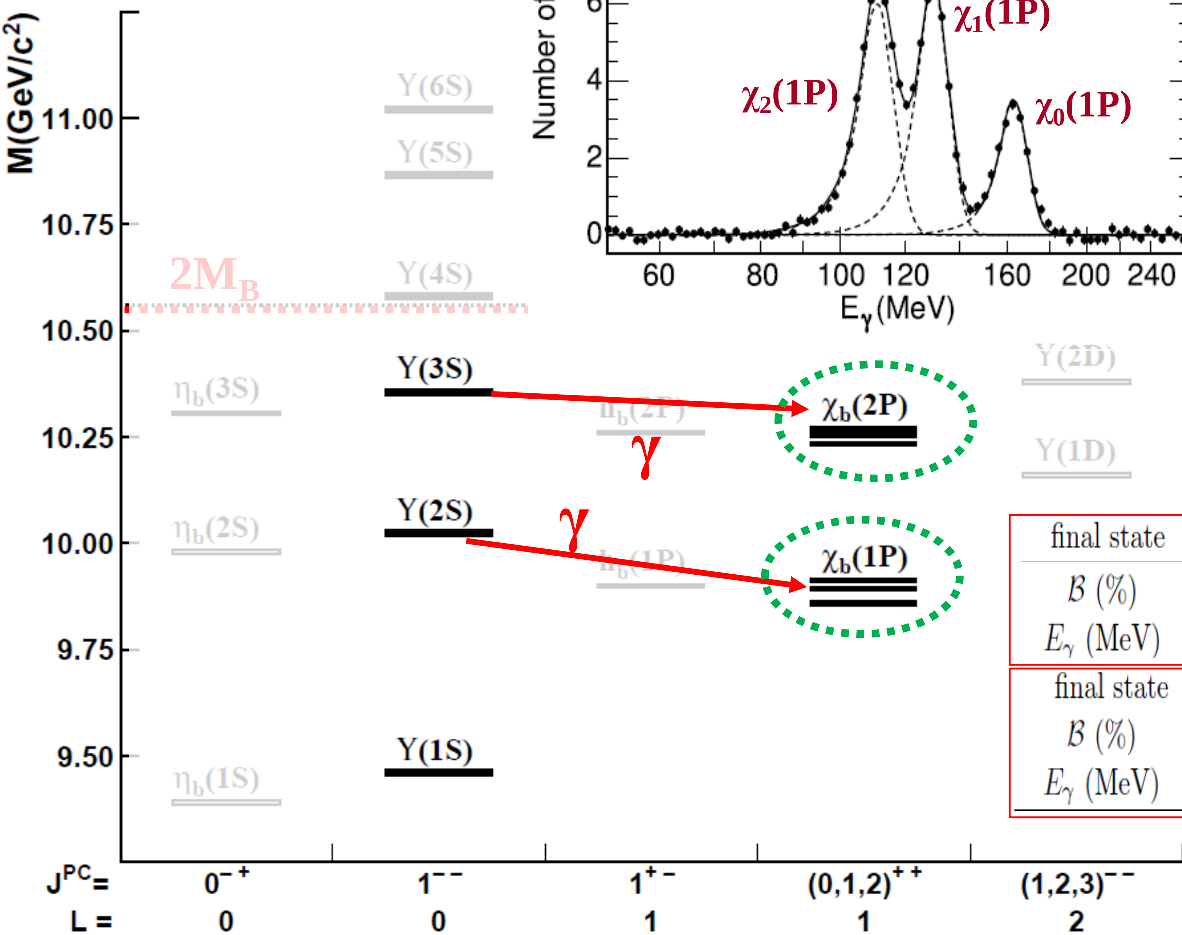
  <u>"B physics" at B-factories</u>

- 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



$\chi_{bJ}(1P)$
$\chi_{bJ}(2P)$





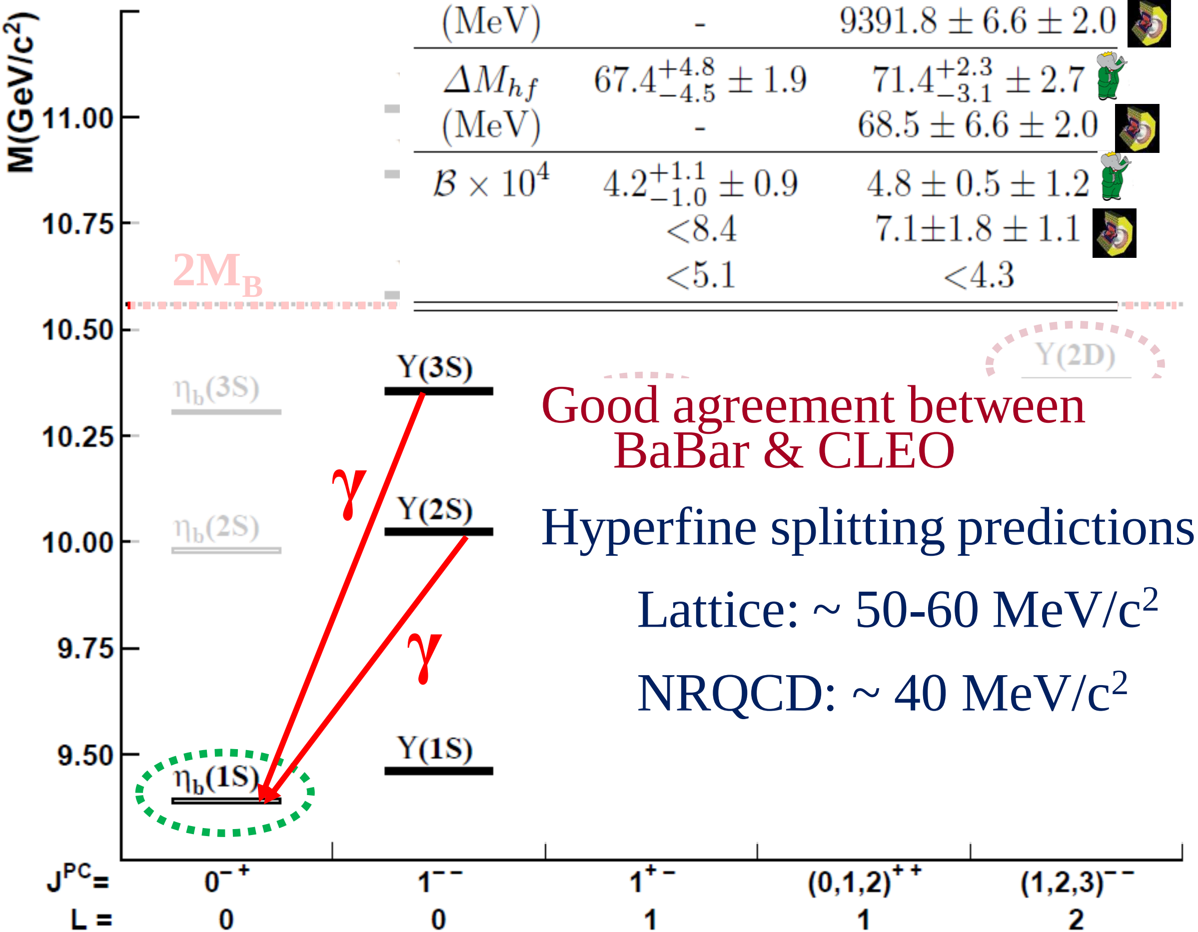
final state	$\chi_{b0}(1P)$	$\chi_{b1}(1P)$	$\chi_{b2}(1P)$
$\mathcal{B}$ (%)	3.75±0.12±0.47	6.93±0.12±0.41	7.24±0.11±0.40
E_γ (MeV)	162.56±0.19±0.42	129.58±0.09±0.29	110.58±0.08±0.30

final state	$\chi_{b0}(2P)$	$\chi_{b1}(2P)$	$\chi_{b2}(2P)$
$\mathcal{B}$ (%)	6.77±0.20±0.65	14.54±0.18±0.73	15.79±0.17±0.73
E_γ (MeV)	121.55±0.16±0.46	99.15±0.07±0.25	86.04±0.06±0.27

η_b (1S) the ground state of bottomonium

Measured η_b properties

Quantity	$\Upsilon(2S) \to \gamma\eta_b$	$\Upsilon(3S) \to \gamma\eta_b$
E_γ (MeV)	$610.5^{+4.5}_{-4.3} \pm 1.8$	$921.2^{+2.1}_{-2.8} \pm 2.4$
	-	$918.6 \pm 6.0 \pm 1.8$
$M(\eta_b)$ (MeV)	$9392.9^{+4.6}_{-4.8} \pm 1.8$	$9388.9^{+3.1}_{-2.3} \pm 2.7$
	-	$9391.8 \pm 6.6 \pm 2.0$
ΔM_{hf} (MeV)	$67.4^{+4.8}_{-4.5} \pm 1.9$	$71.4^{+2.3}_{-3.1} \pm 2.7$
	-	$68.5 \pm 6.6 \pm 2.0$
$\mathcal{B} \times 10^4$	$4.2^{+1.1}_{-1.0} \pm 0.9$	$4.8 \pm 0.5 \pm 1.2$
	<8.4	$7.1 \pm 1.8 \pm 1.1$
	<5.1	<4.3

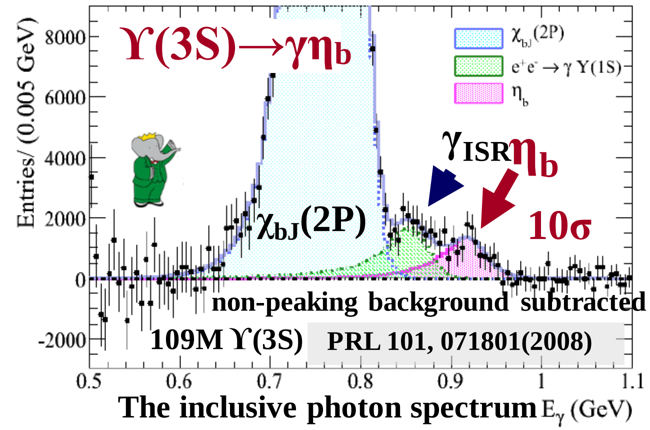


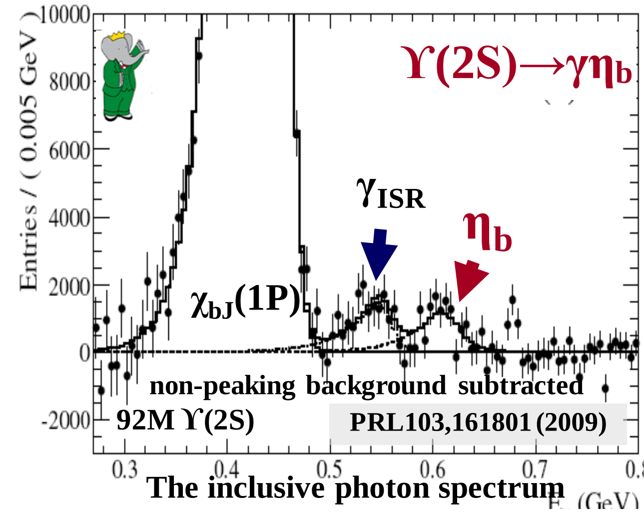
Good agreement between BaBar & CLEO

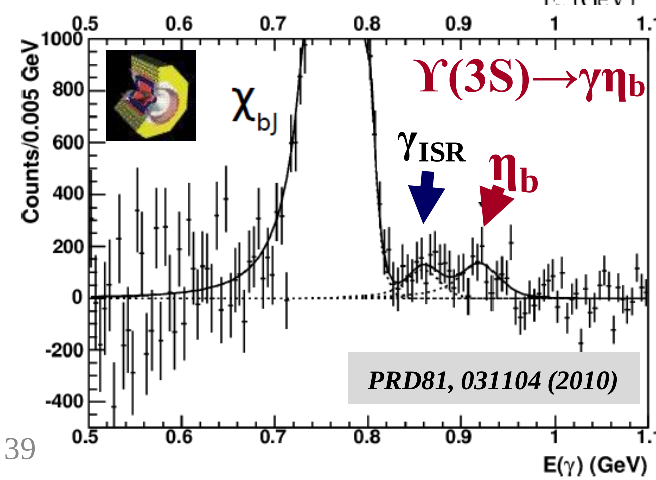
Hyperfine splitting predictions

Lattice: ~ 50-60 MeV/c^2

NRQCD: ~ 40 MeV/c^2

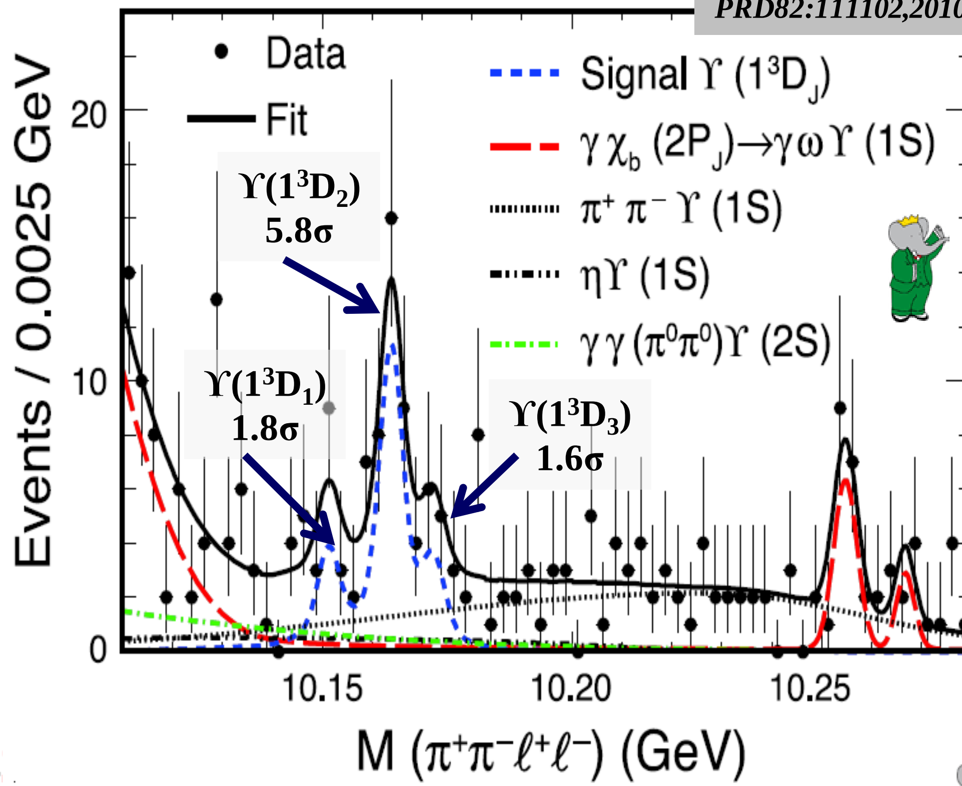




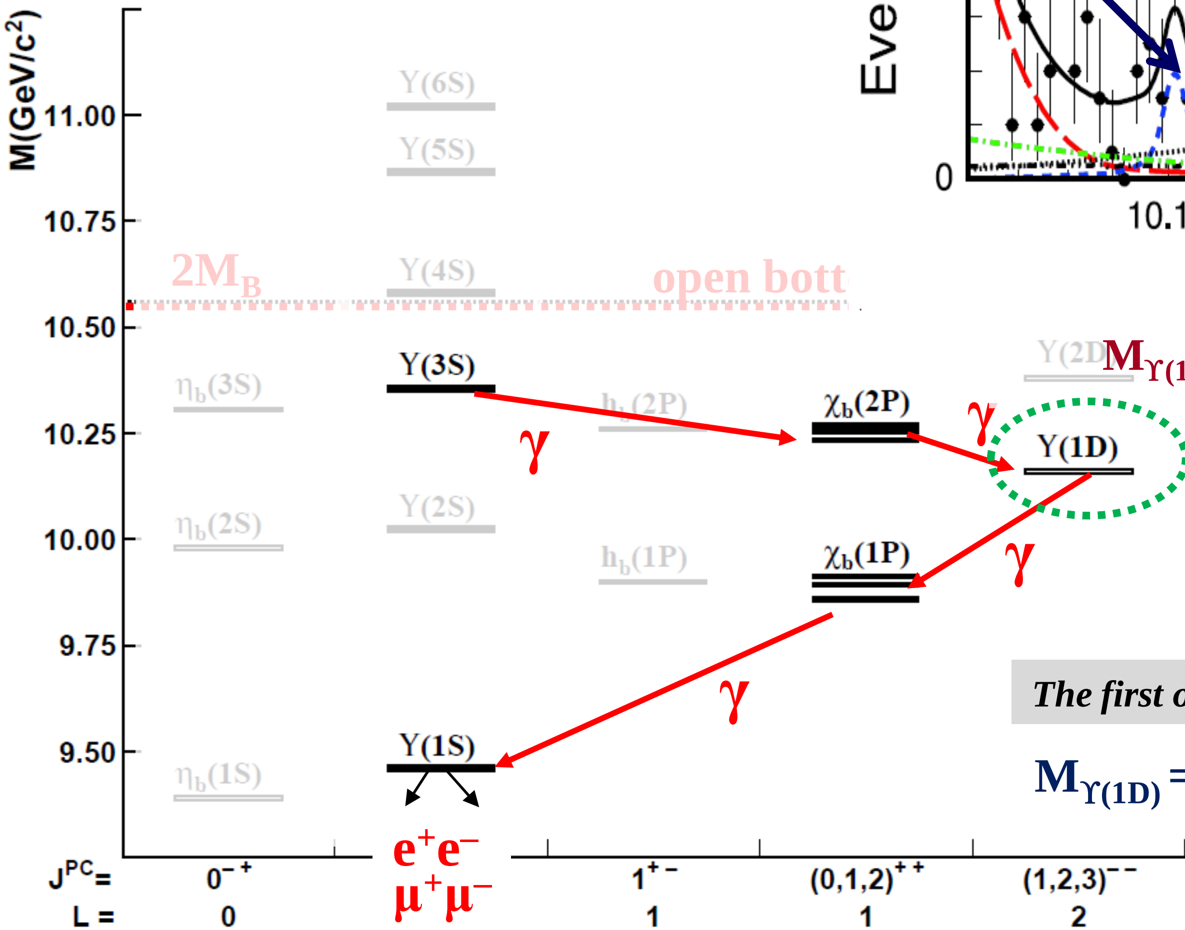


Search for $\Upsilon(1D)_J$

PRD82:111102,2010



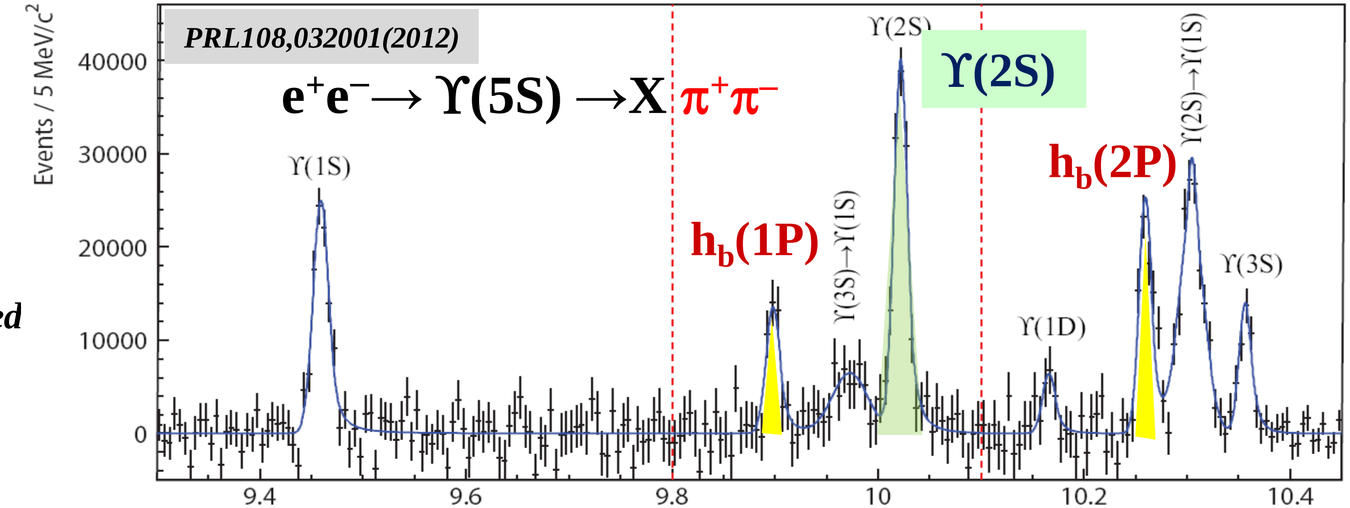
$M_{\Upsilon(1D_2)} = 10164.5 \pm 0.8 \pm 0.6$ MeV/c^2



The first observation of ϒ(1D) PRD70,032001 (2004)

$M_{\Upsilon(1D)} = 10161.1 \pm 0.6 \pm 1.6$ MeV/c^2

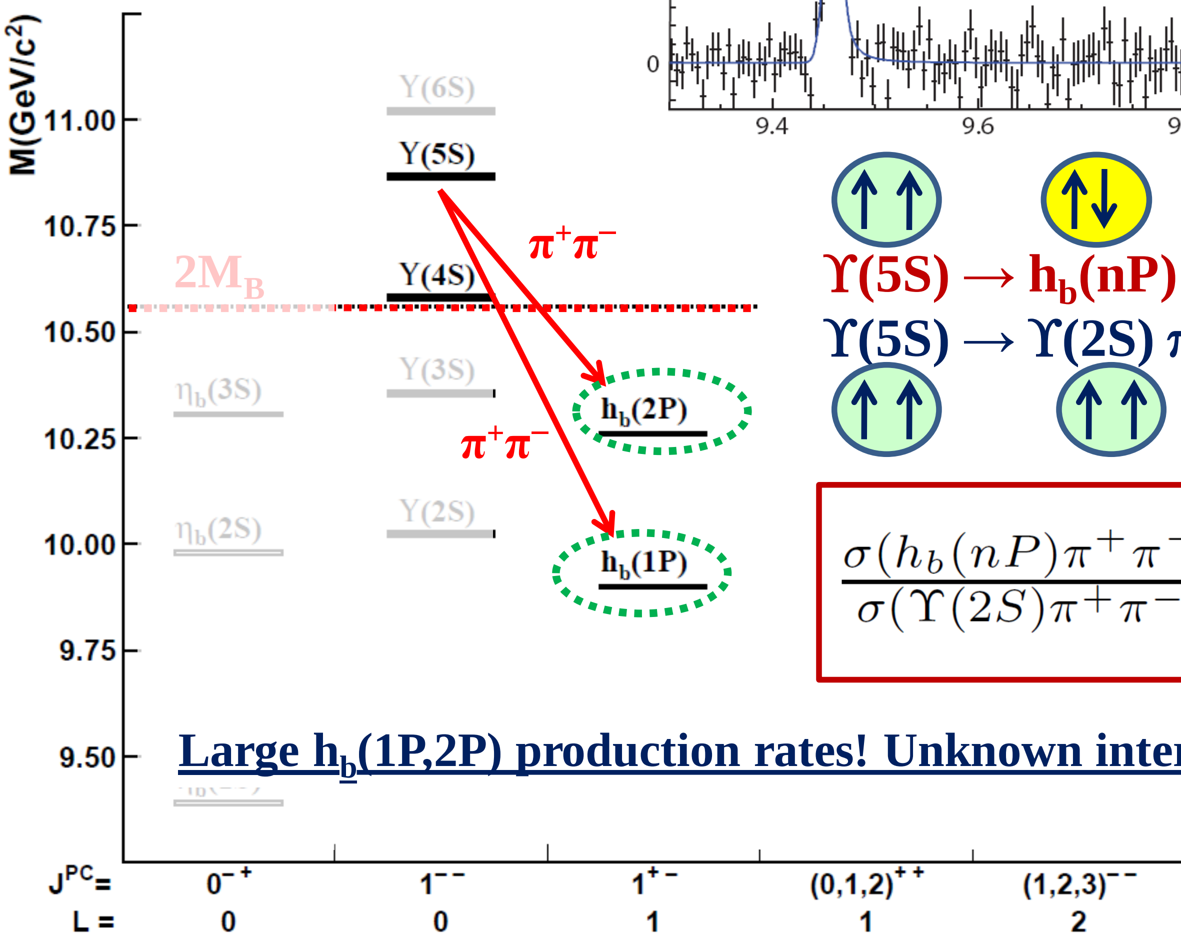
Observation of $h_b(1P,2P)$



$\Delta M_{HF}(1P) = 0.8 \pm 1.1$ 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 ~$(\Lambda_{QCD}/m_b)^2$**

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

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

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

CLEO

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

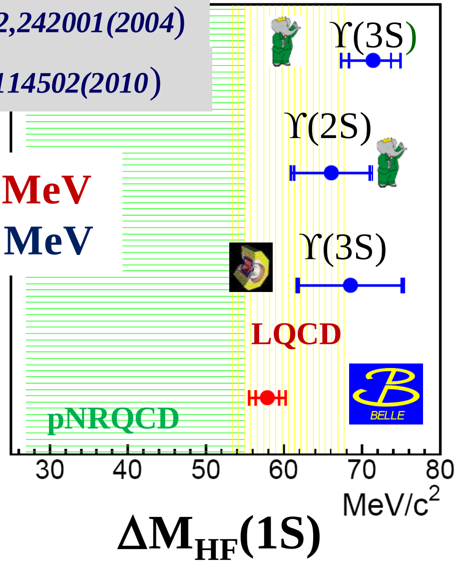
Observation of $h_b(1P,2P) \to \eta_b(1S)\,\gamma$

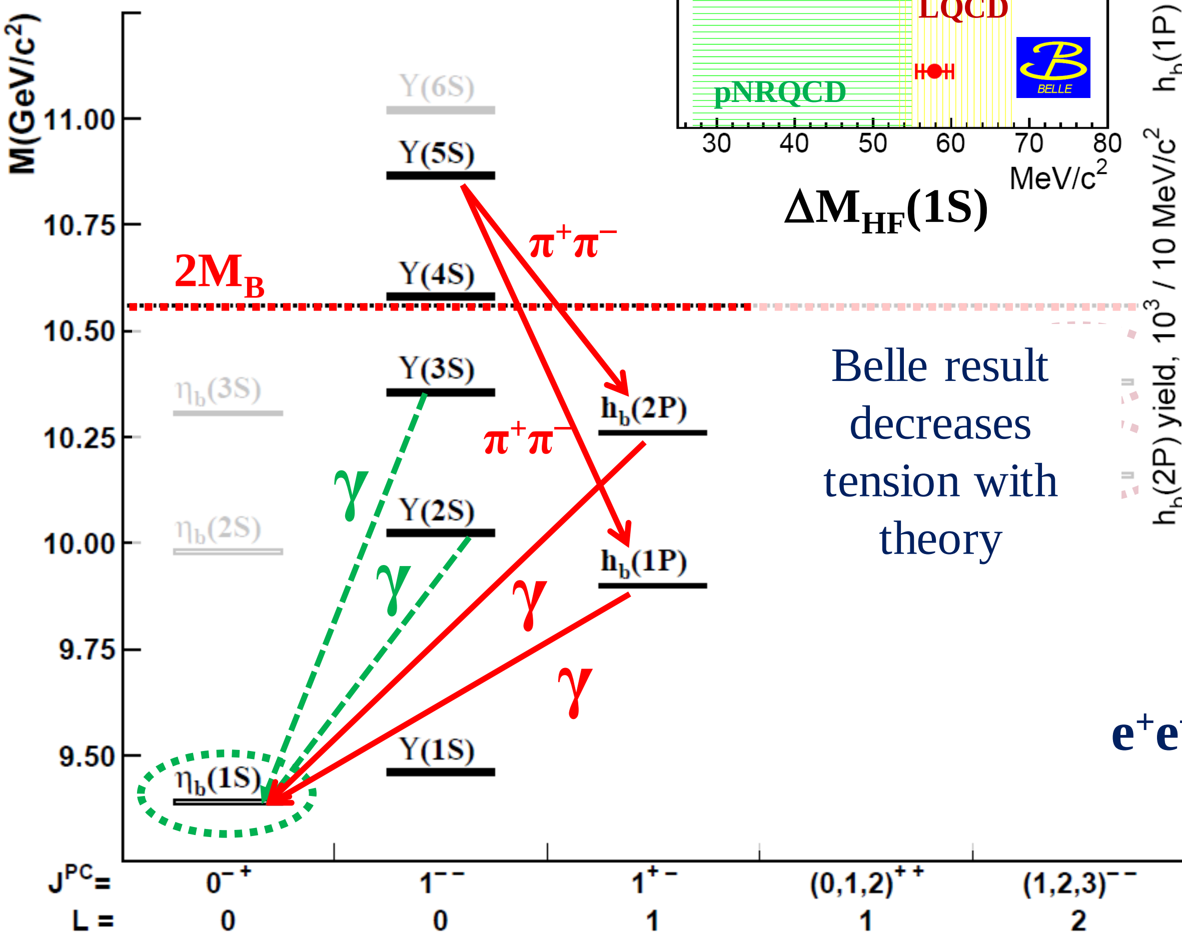
Kniehl et al, PRL92,242001(2004)

Meinel, PRD82,114502(2010)

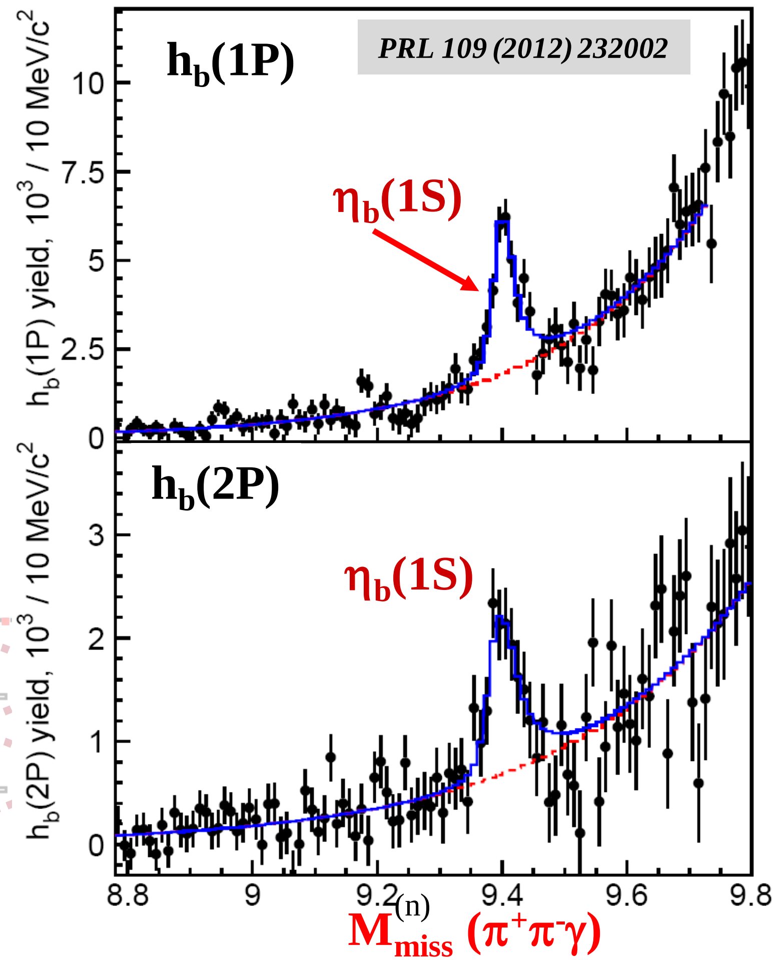
Belle : 57.9 ± 2.3 MeV

PDG'12 : 69.3 ± 2.8 MeV





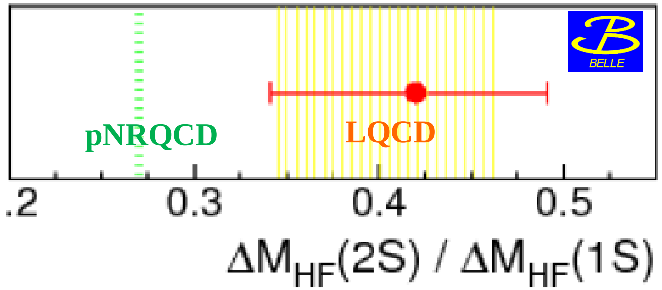
Belle result decreases tension with theory

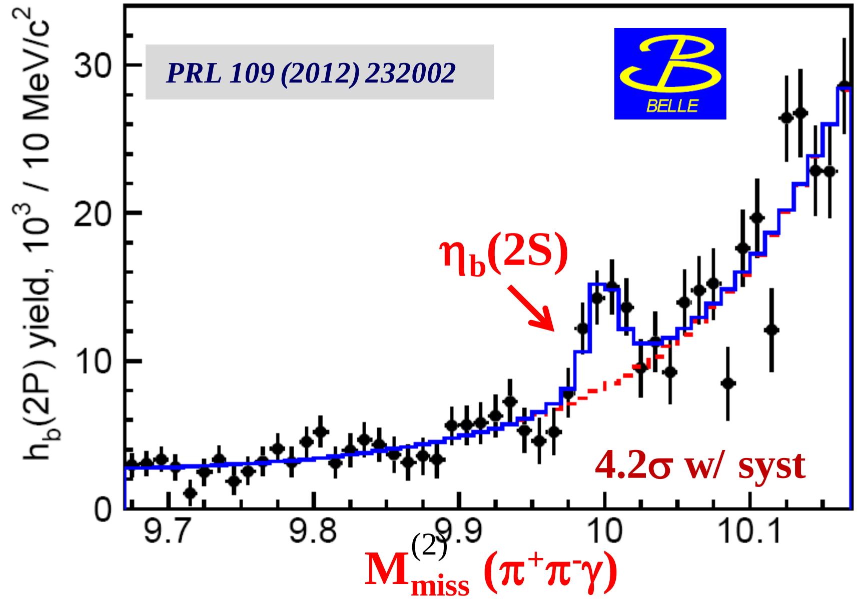


$e^+e^- \to \Upsilon(5S) \to h_b(nP)\ \pi^+\pi^-$

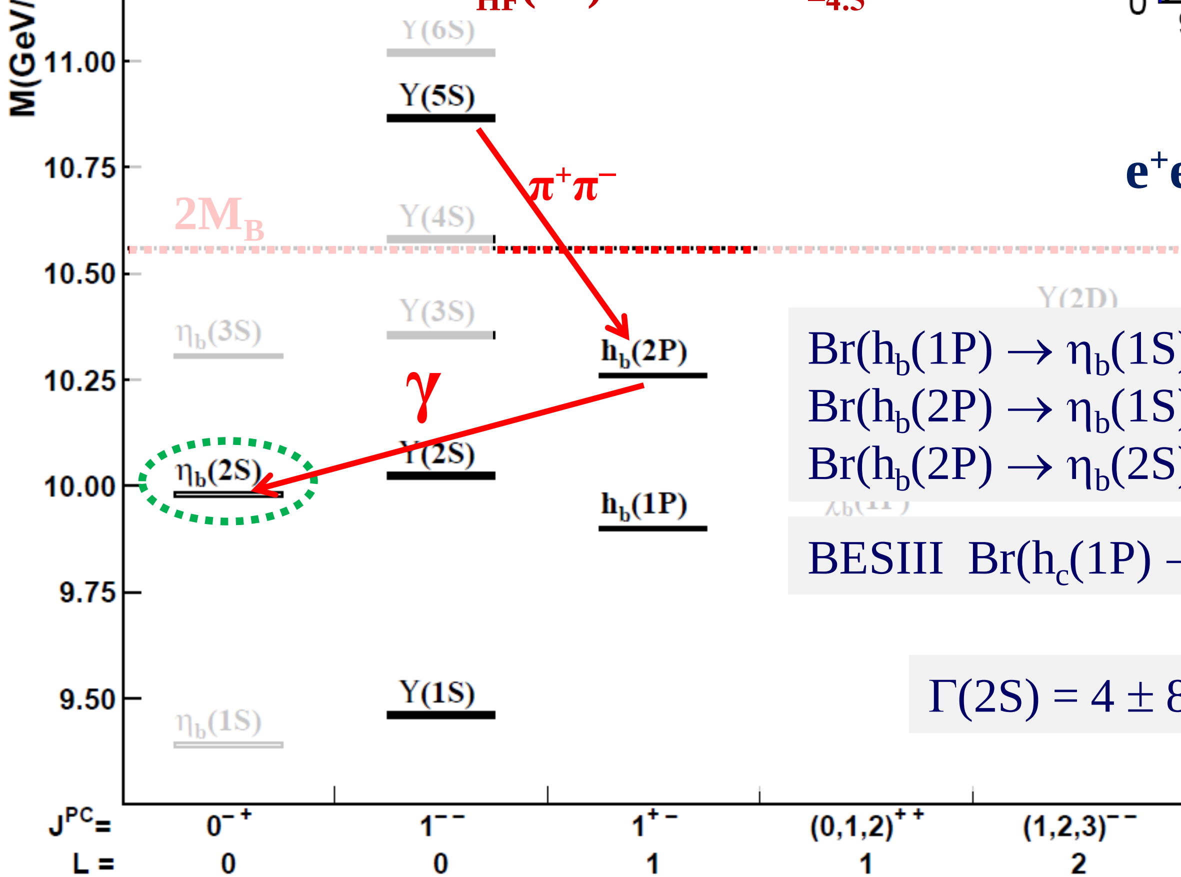
$h_b(nP) \to \eta_b(1S)\ \gamma$

First evidence for $\eta_b(2S)$





$\Delta M_{HF}(2S) = 24.3\ ^{+4.0}_{-4.5}$ MeV



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

$h_b(2P) \to \eta_b(2S)\ \gamma$

$Br(h_b(1P) \to \eta_b(1S)\gamma) = 49.2 \pm 5.7^{+5.6}_{-3.3}\%$	41%
$Br(h_b(2P) \to \eta_b(1S)\gamma) = 22.3 \pm 3.8^{+3.1}_{-3.3}\%$	13%
$Br(h_b(2P) \to \eta_b(2S)\gamma) = 47.5 \pm 10.5^{+6.8}_{-7.7}\%$	19%
BESIII $Br(h_c(1P) \to \eta_c(1S)\gamma) = 54.3 \pm 8.5\%$	39%

Godfrey Rosner PRD66,014012(2002)

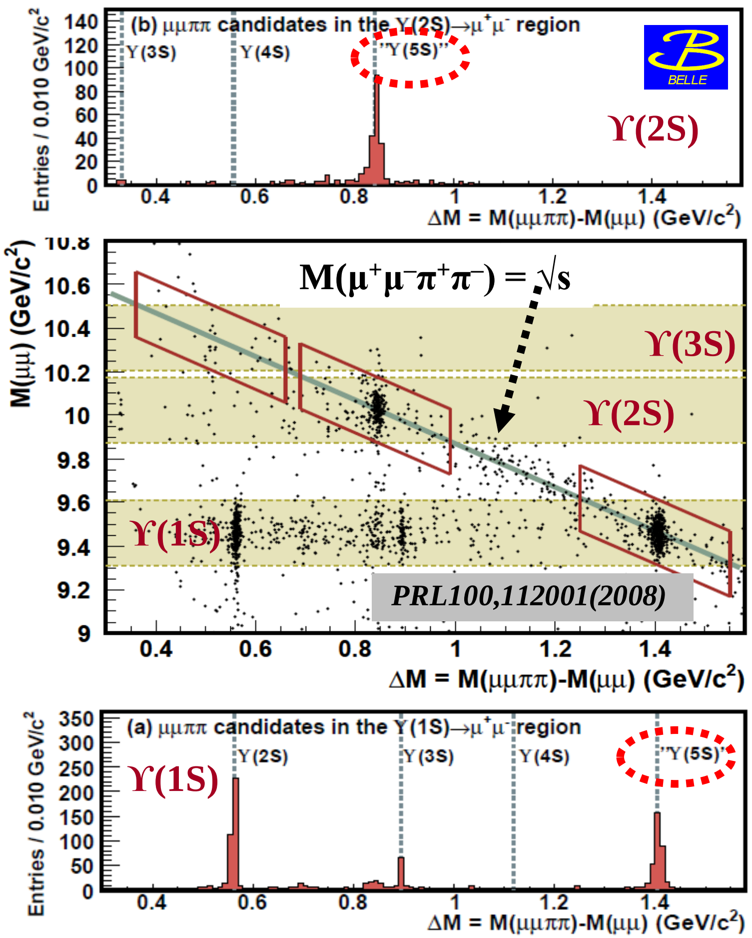
$\Gamma(2S) = 4 \pm 8$ MeV, < 24MeV @ 90% C.L.

expect ~4MeV

In agreement with theory


Charged
bottomoniumlike
states

Observation of large $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$ near $\Upsilon(10860)$



Partial widths for $\Upsilon(10860) \to \Upsilon(nS)\,\pi^+\pi^-$ more than **two orders of magnitude larger** than corresponding partial widths for $\Upsilon(4S)$, $\Upsilon(3S)$ or $\Upsilon(2S)$ decays

	$\Gamma(\Upsilon(nS)\,\pi^+\pi^-)$
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009

Possible explanations

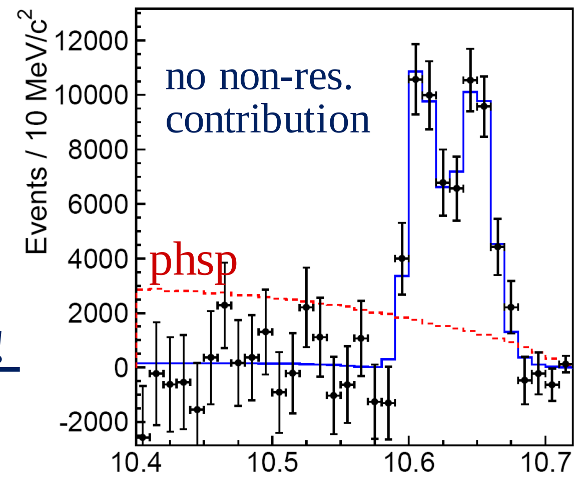
- ○ $\Upsilon(10860)$ has exotic properties
- ○ Reactions in fact proceed via **Y_b states** similar to exotic vector charmonium

To be done

- ○ **Study of resonant structure of $\Upsilon(5S) \to (bb)\pi^+\pi^-$**
- ○ **Measure energy dependence of $e^+e^- \to \Upsilon(nS)\,\pi^+\pi^-$**

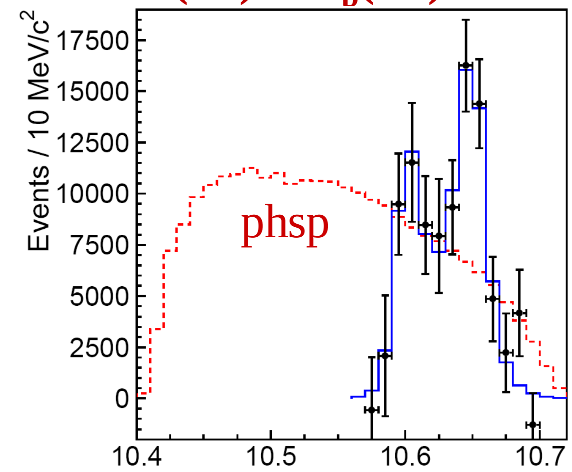
Resonant structure of $\Upsilon(5S)\to(b\bar{b})\pi^+\pi^-$

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



$M(h_b(1P)\,\pi^{\pm})$

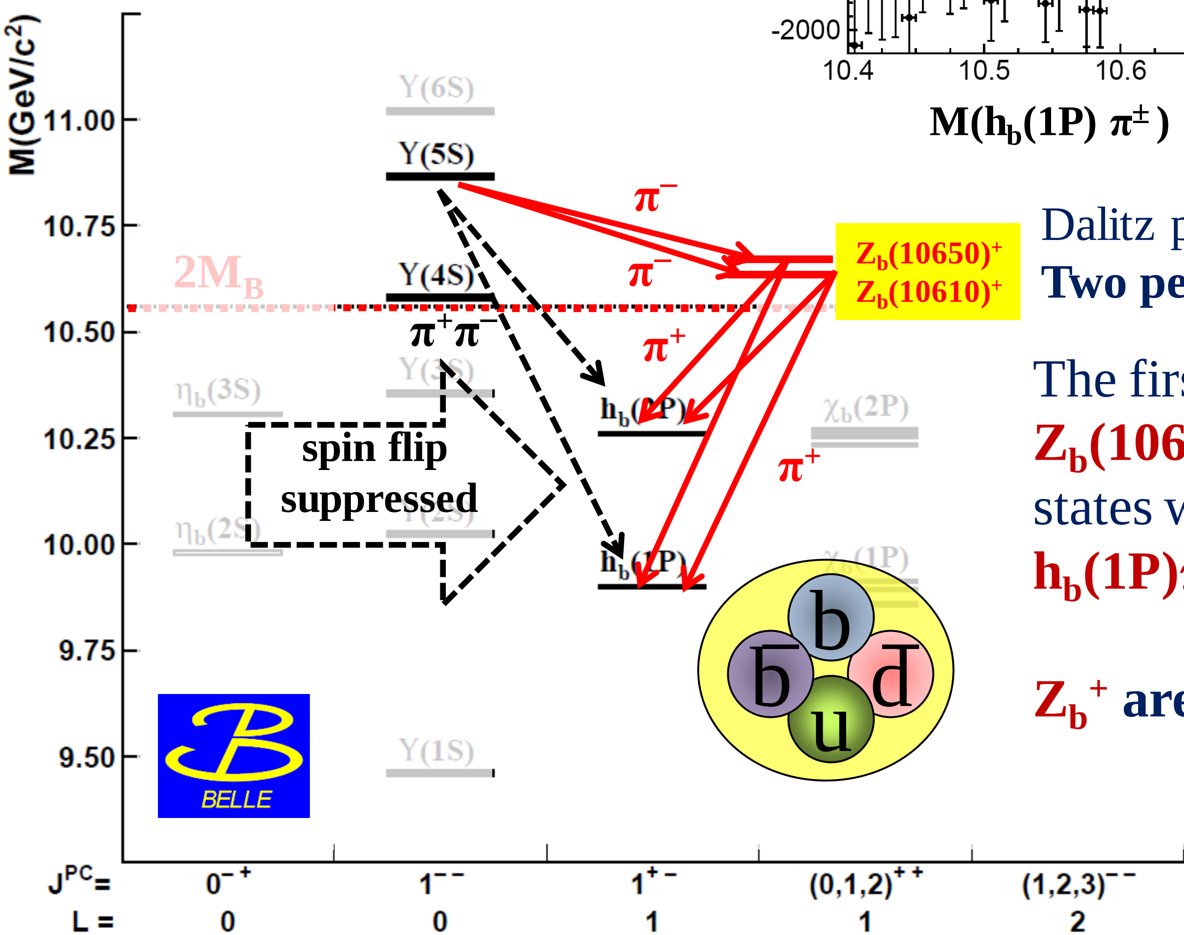
$\Upsilon(5S)\to h_b(2P)\pi^+\pi^-$



$M(h_b(2P)\,\pi^{\pm})$

PRD88, 052016 (2013)

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

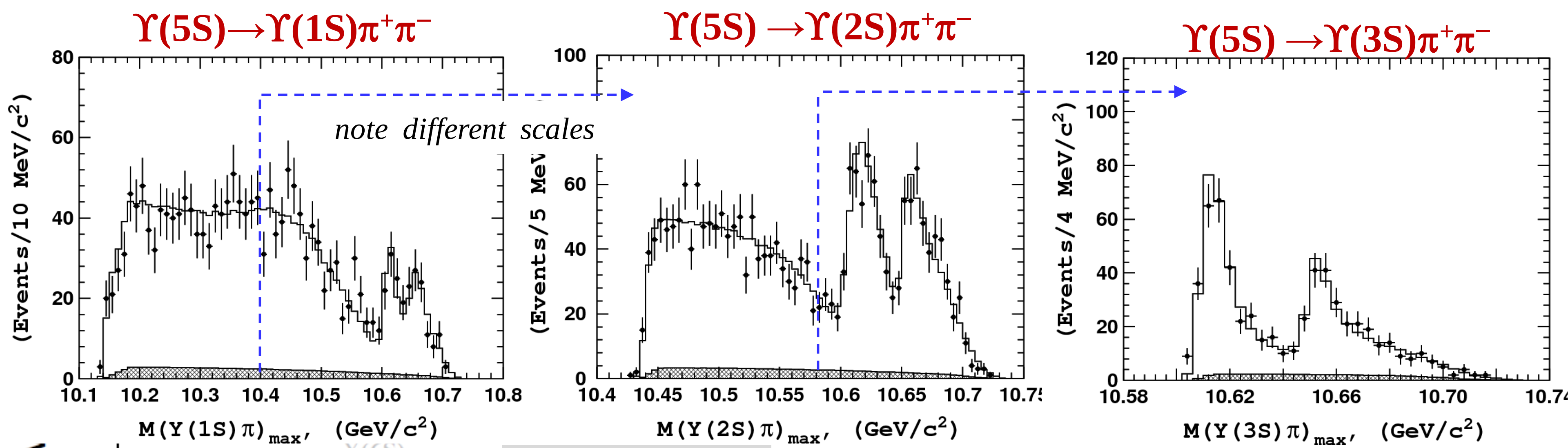


Dalitz plot analysis

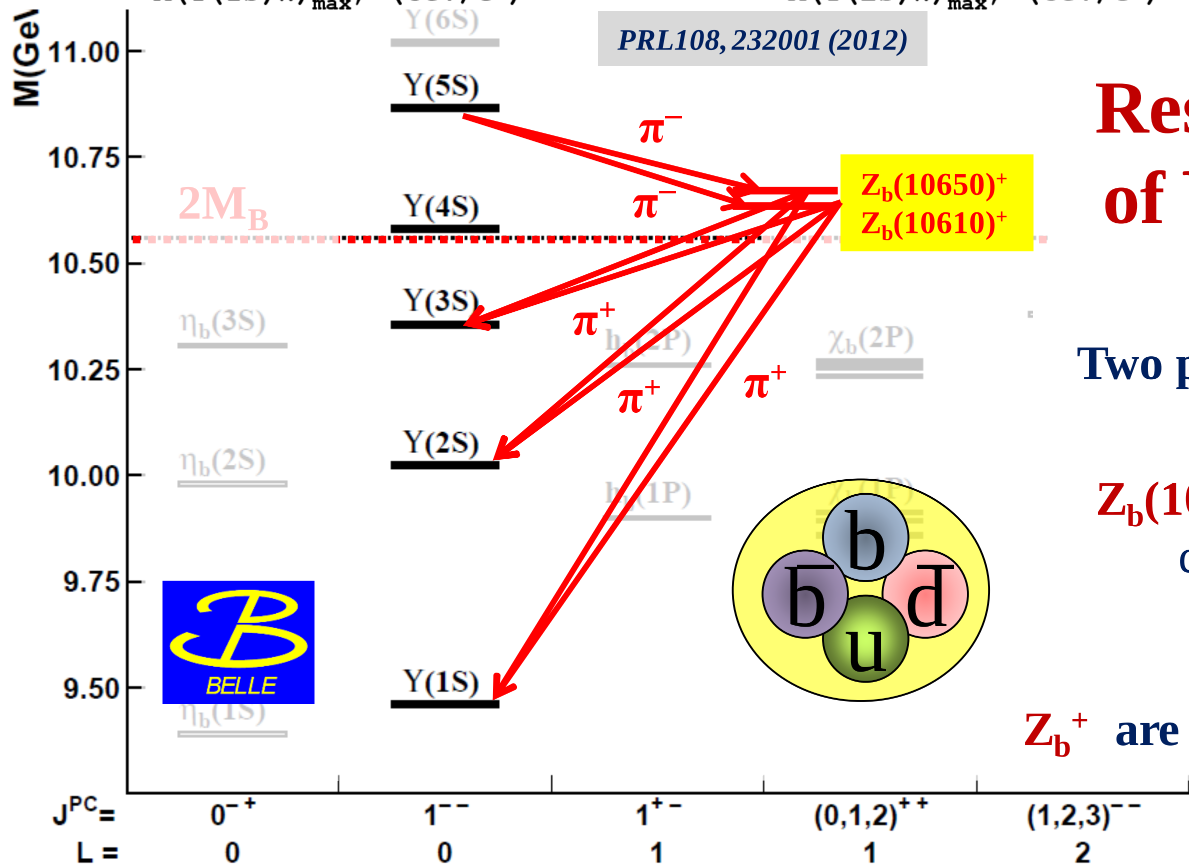
Two peaks are observed in all modes

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



PRL108, 232001 (2012)



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

BELLE

Average over 5 channels

$\langle M_1 \rangle = 10607.2 \pm 2.0$ MeV

$\langle \Gamma_1 \rangle = 18.4 \pm 2.4$ MeV

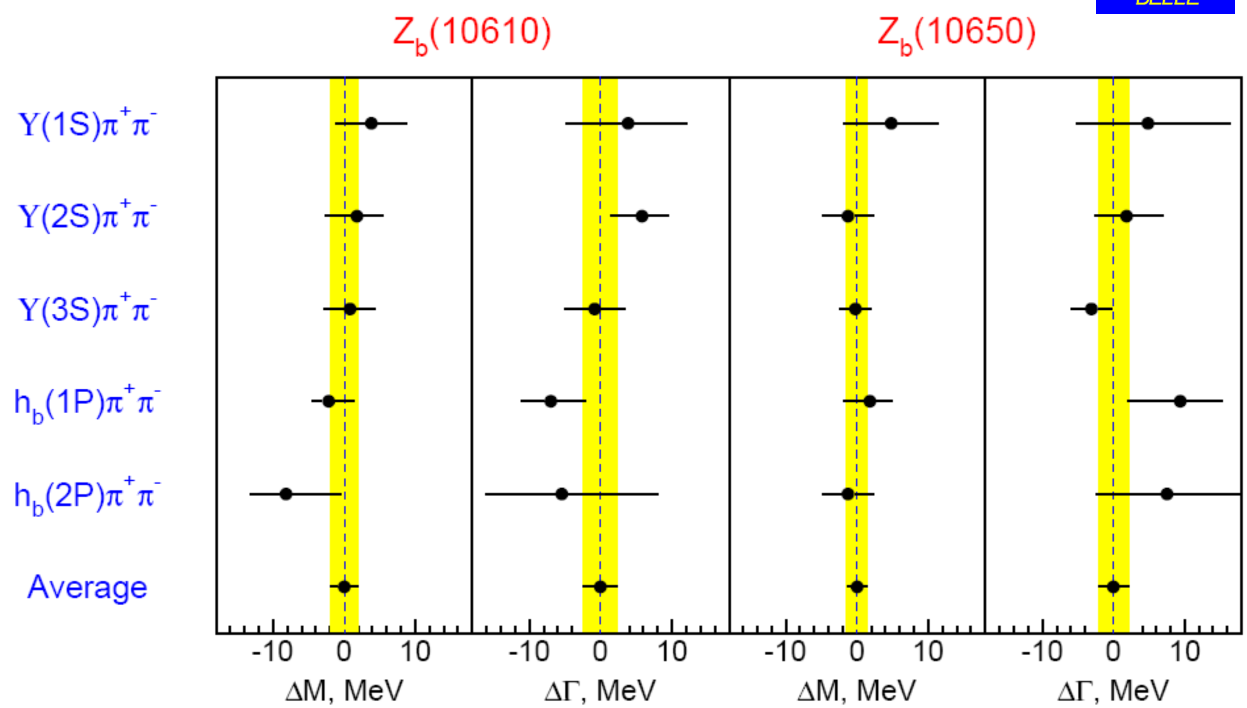
$\langle M_2 \rangle = 10652.2 \pm 1.5$ MeV

$\langle \Gamma_2 \rangle = 11.5 \pm 2.2$ MeV

$J^P = 1^+$

PRD91,072003(2015)

6D amplitude analysis

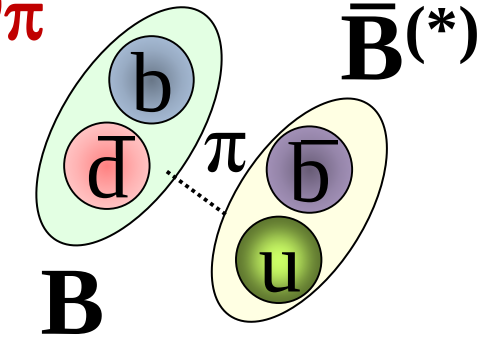


Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, 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:

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

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



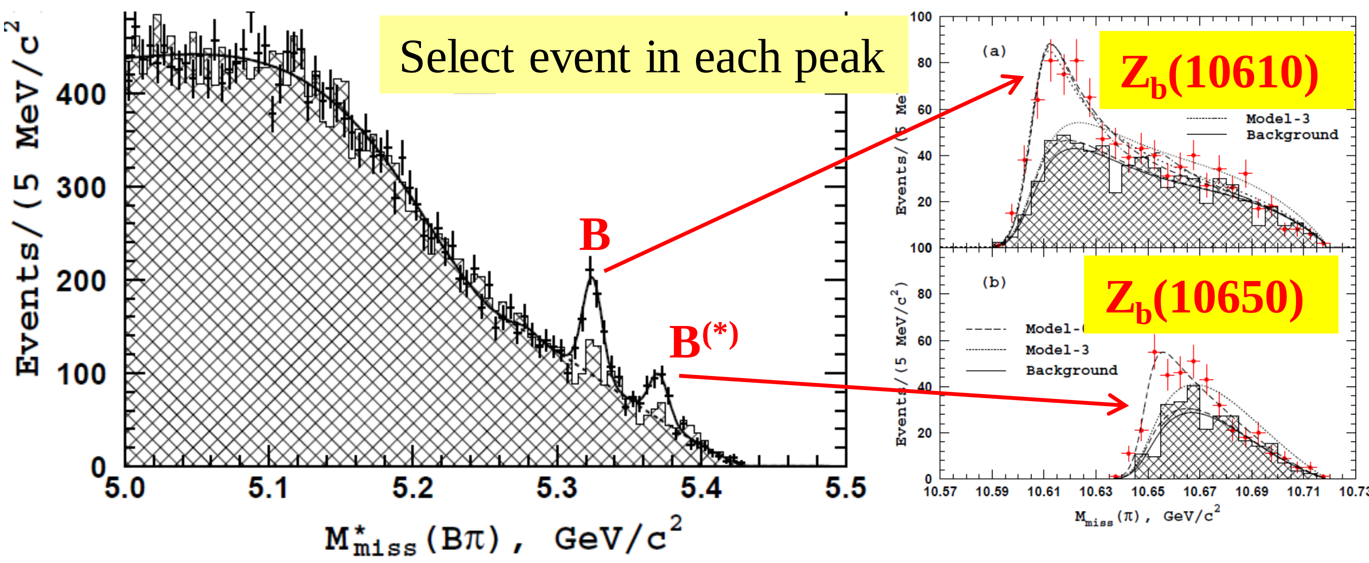
Channel	Fraction, %	
	$Z_b(10610)$	$Z_b(10650)$
$\Upsilon(1S)\pi^+$	$0.60 \pm 0.17 \pm 0.07$	$0.17 \pm 0.06 \pm 0.02$
$\Upsilon(2S)\pi^+$	$4.05 \pm 0.81 \pm 0.58$	$1.38 \pm 0.45 \pm 0.21$
$\Upsilon(3S)\pi^+$	$2.40 \pm 0.58 \pm 0.36$	$1.62 \pm 0.50 \pm 0.24$
$h_b(1P)\pi^+$	$4.26 \pm 1.28 \pm 1.10$	$9.23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

Phase space of $Y(5S) \to B^{(*)}B^*$ 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)

$M_{Zb(10610)} - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV
$M_{Zb(10650)} - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Favorable to the formation of the molecular states

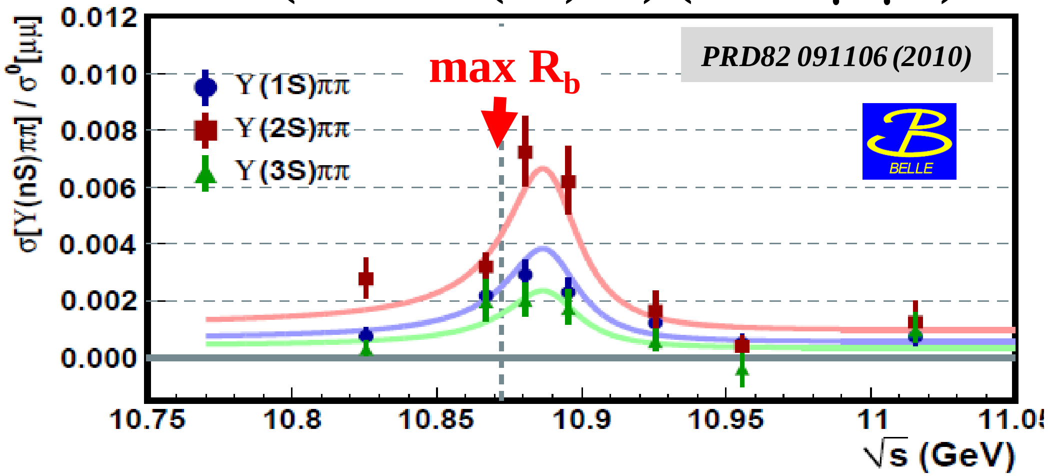


$J^P = 1^+$:
$B^{(*)}B^*$ in S-wave

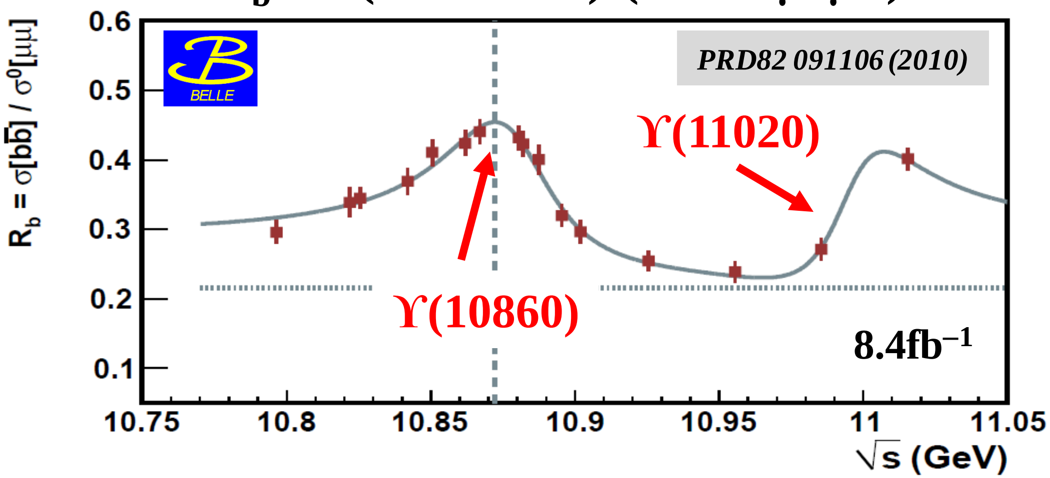
$Z_b(10610) = |BB^*\rangle$
$Z_b(10650) = |B^*B^*\rangle$

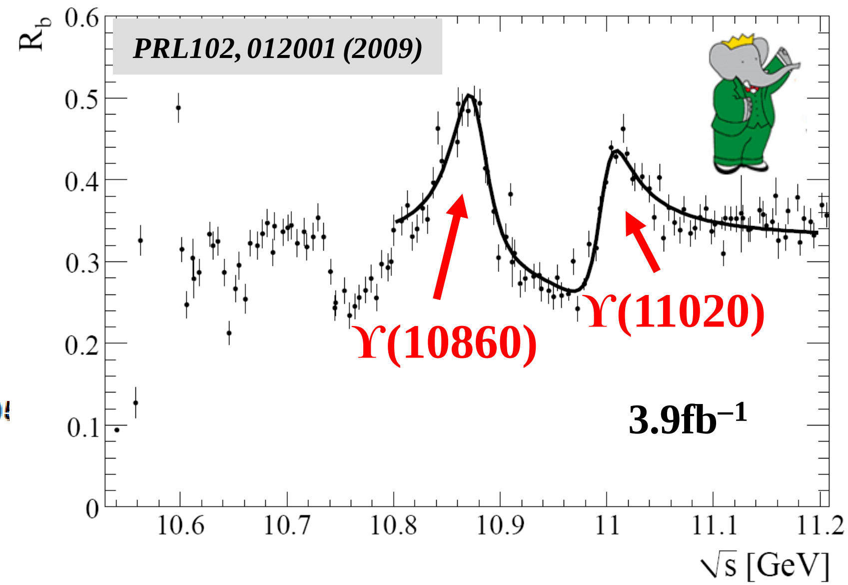
Energy scans: search for Y_b states

$\sigma(e^+e^- \to \Upsilon(nS)\pi\pi)/(e^+e^- \to \mu^+\mu^-)$



$R_b = \sigma(e^+e^- \to bb)/(e^+e^- \to \mu^+\mu^-)$



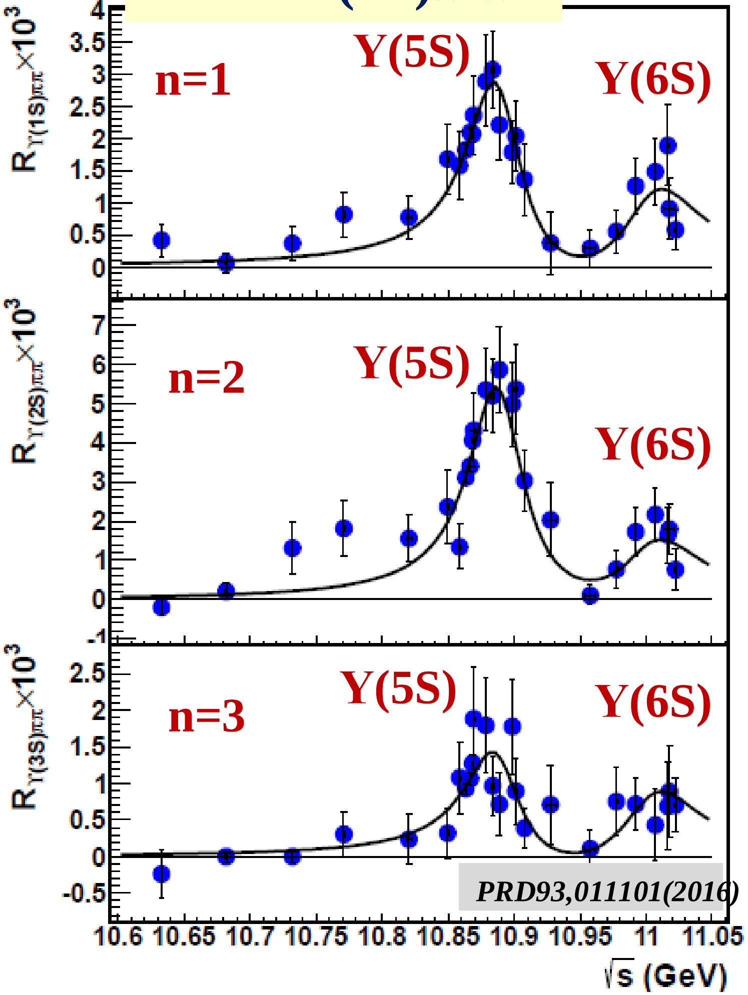


No evidence for new Y_b state

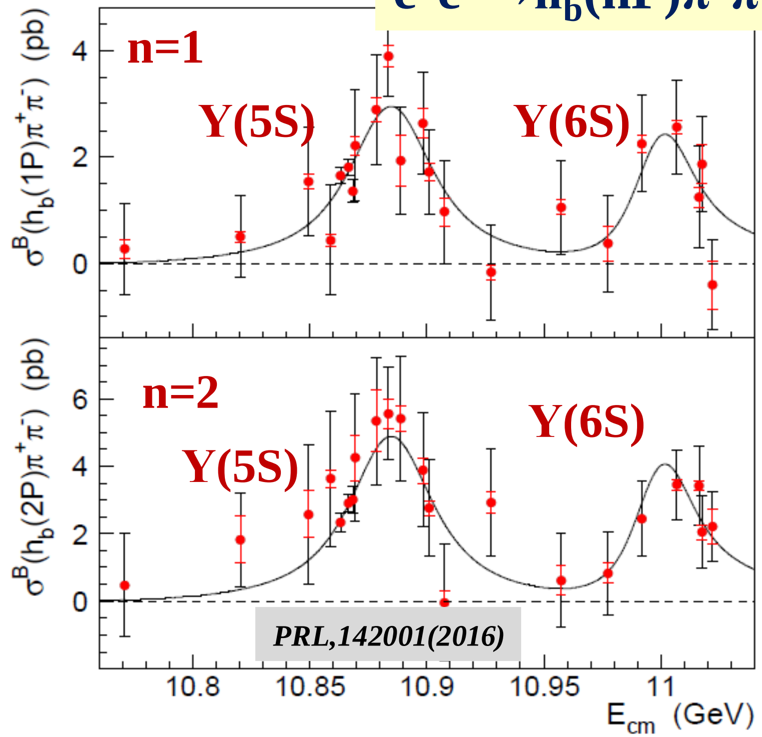
Belle & BaBar are in a good agreement

Bottomonium cross sections

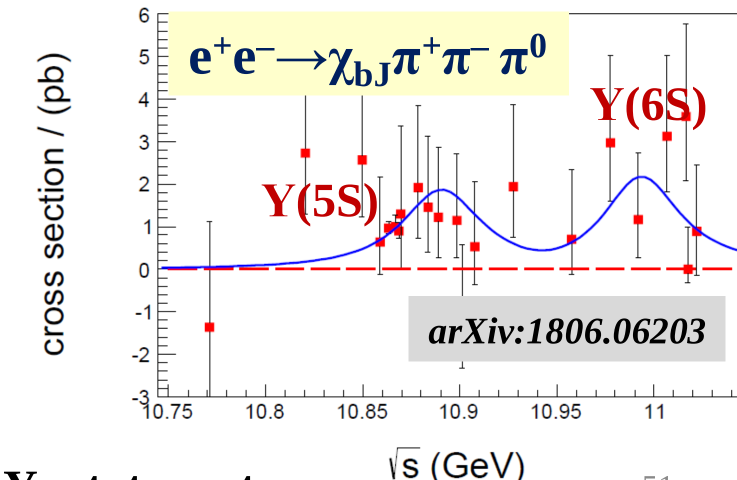
$e^+e^- \to \Upsilon(nS)\pi^+\pi^-$



$e^+e^- \to h_b(nP)\pi^+\pi^-$



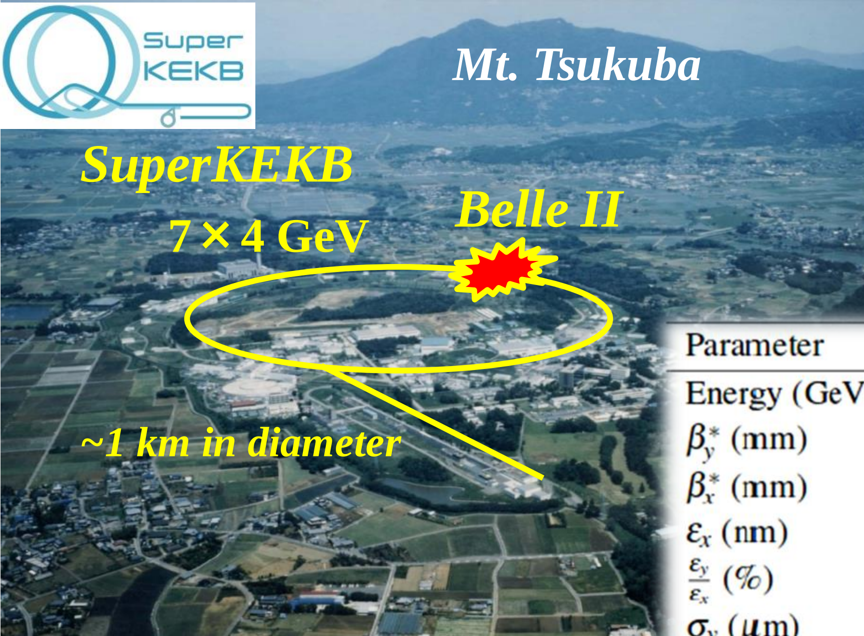
$e^+e^- \to \chi_{bJ}\pi^+\pi^-\pi^0$



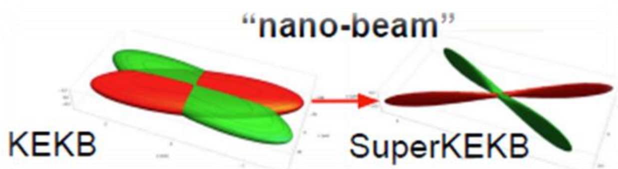
Cross sections of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ (n=1,2,3), $e^+e^- \to h_b(nP)\pi^+\pi^-$ (n=1,2) & $e^+e^- \to \chi_{bJ}\pi^+\pi^-\pi^0$:
Υ(5S) and Υ(6S) peaks only

No evidence for new Y_b states yet


Future
Super-
B & c-τ
Factories



KEKB upgrade
SuperKEKB(nano-beam)



Parameter	KEKB Design	KEKB Achieved	SuperKEKB Design
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\frac{\varepsilon_y}{\varepsilon_x}$ (%)	1	0.85/0.64	0.27/0.24
σ_y (μm)	1.9	0.94 → 1/20 →	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6/7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19 → x2 →	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity ($10^{34}cm^{-2}s^{-1}$)	1.0	2.11 → x40 →	80

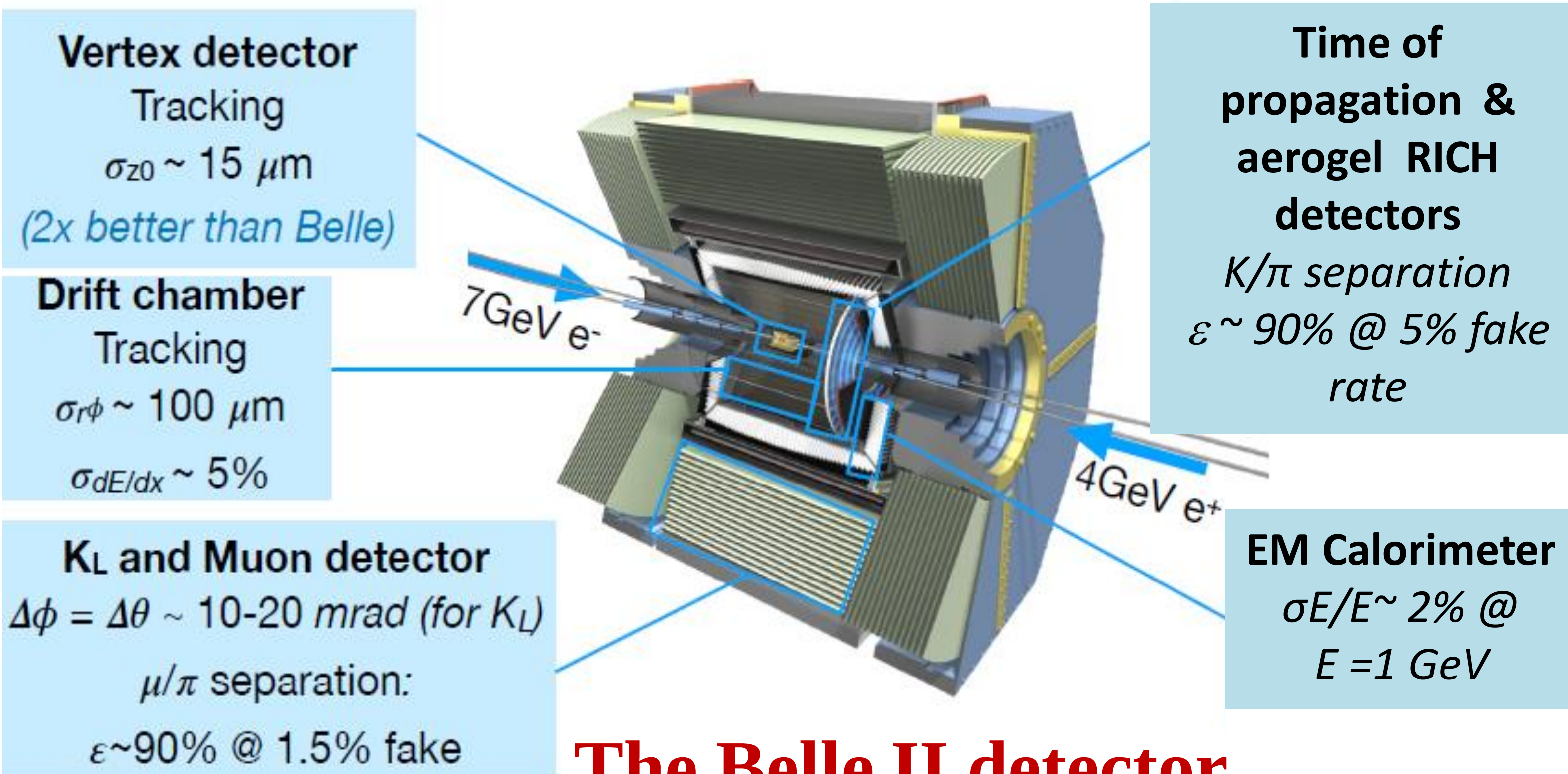
SuperKEKB built in of KEKB tunnel is almost entirely new machine

○ ×20 smaller beam focus at interaction region

○ twice higher beam current

○ **×40 higher Luminosity**

First beam in 2016， first collision in April 2018



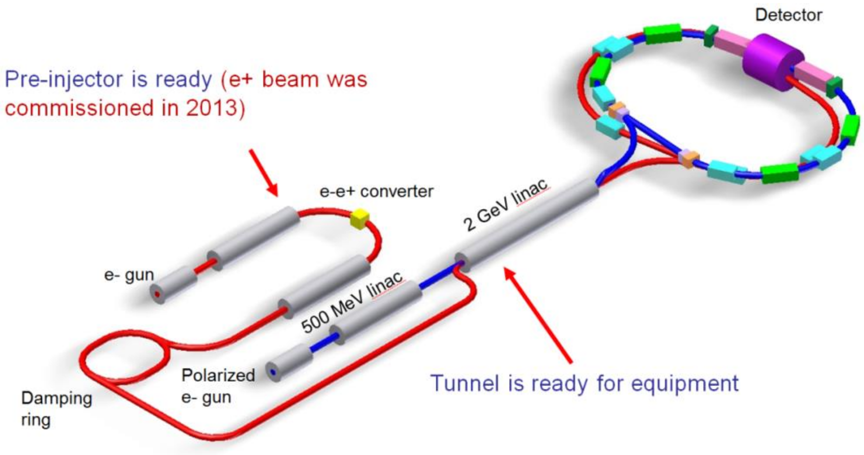
The Belle II detector

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

Highlights:
Vertex: 2 layers of pixels, 4 layers of DS Si strips with extended coverage
Drift chamber: smaller cell size + longer lever arm
PID: new TOP + ARICH

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

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 $\sigma(e^+e^- \to hadrons)$, 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 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**