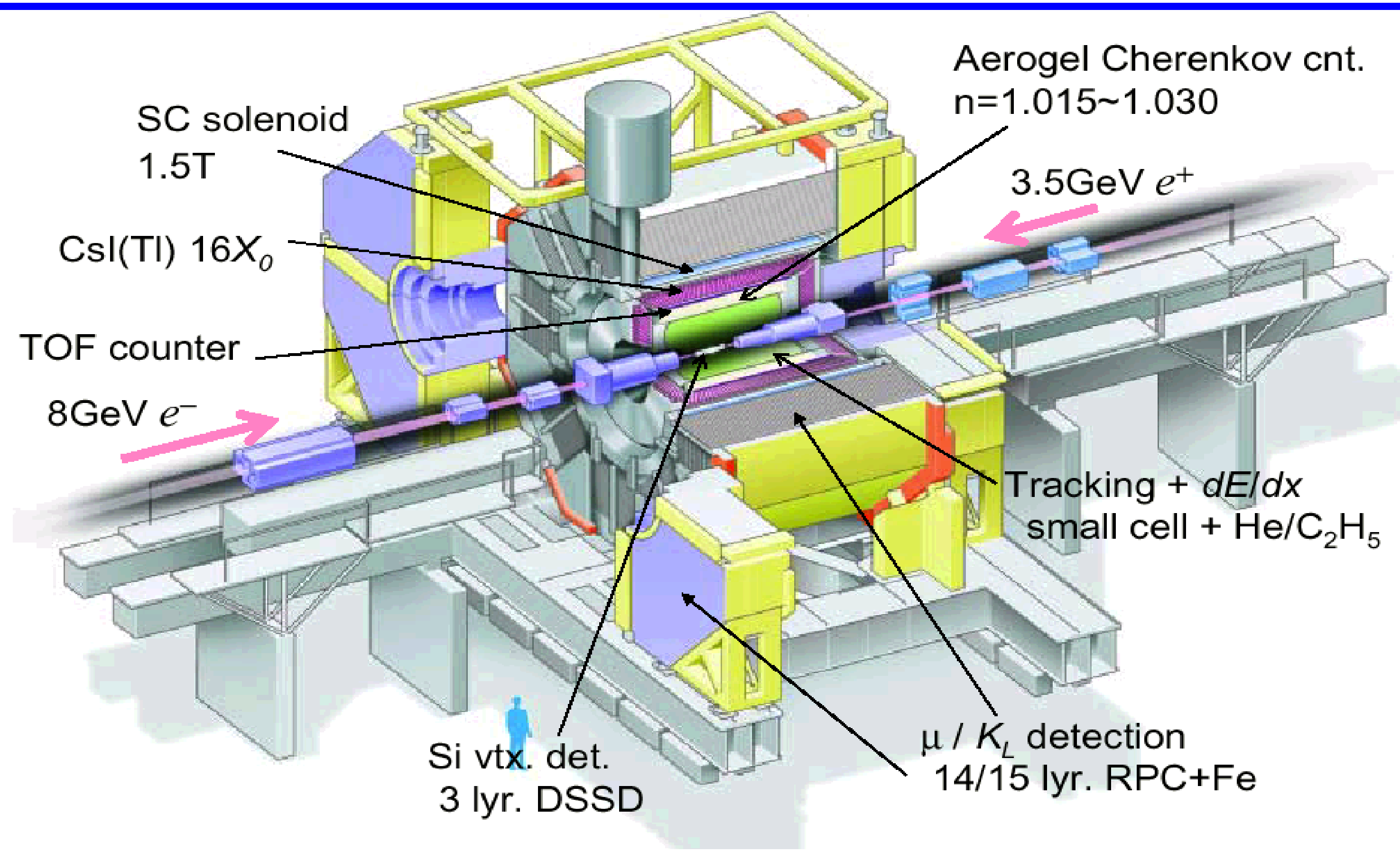
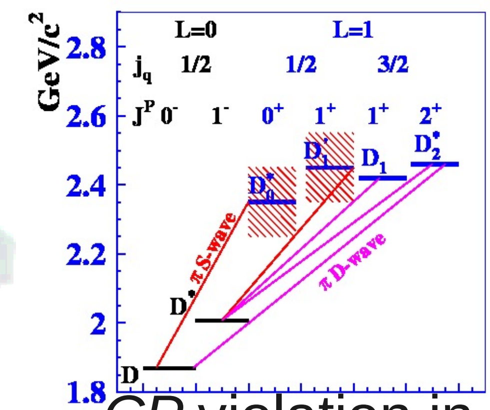
Belle

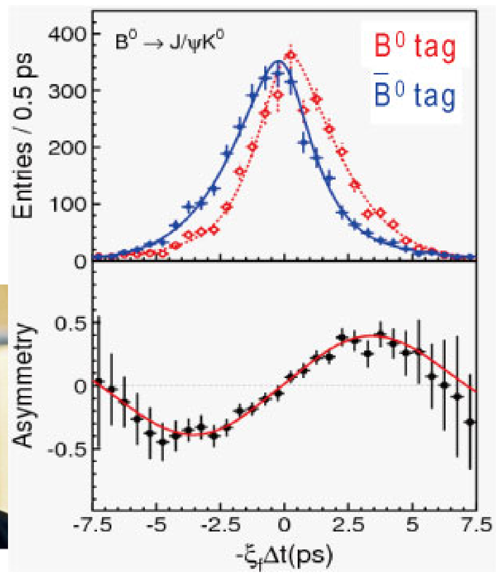
The Belle detector



Heavy hadrons spectroscopy



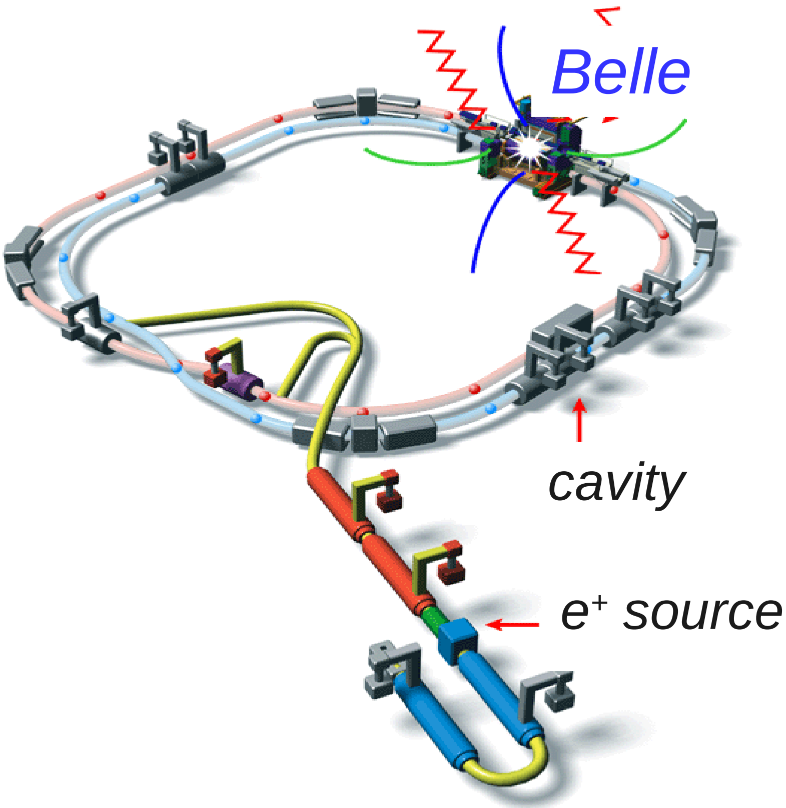
CP violation in B-mesons

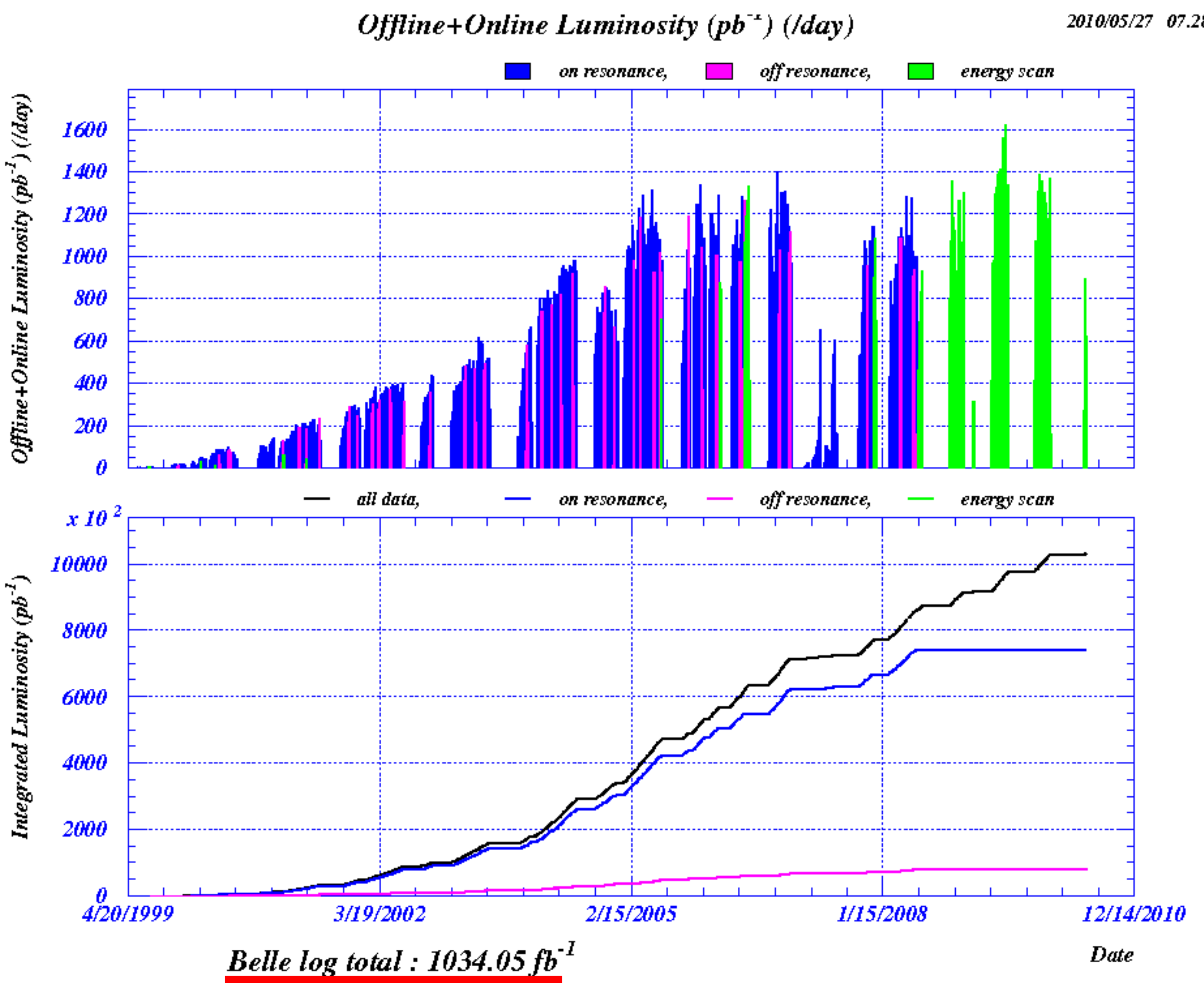


New charmonium-like states: X, Y, Z ...

$\int \mathcal{L}dt > 1000\ fb^{-1} = \sim 10^9\ BB$

KEKb accelerator





$\Upsilon(4S)$: ~710 fb^{-1}

$\Upsilon(5S)$: ~129 fb^{-1}

$\Upsilon(3S)$: 2.9 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 5.7 fb^{-1}`

KEKb operation stops in July 2010

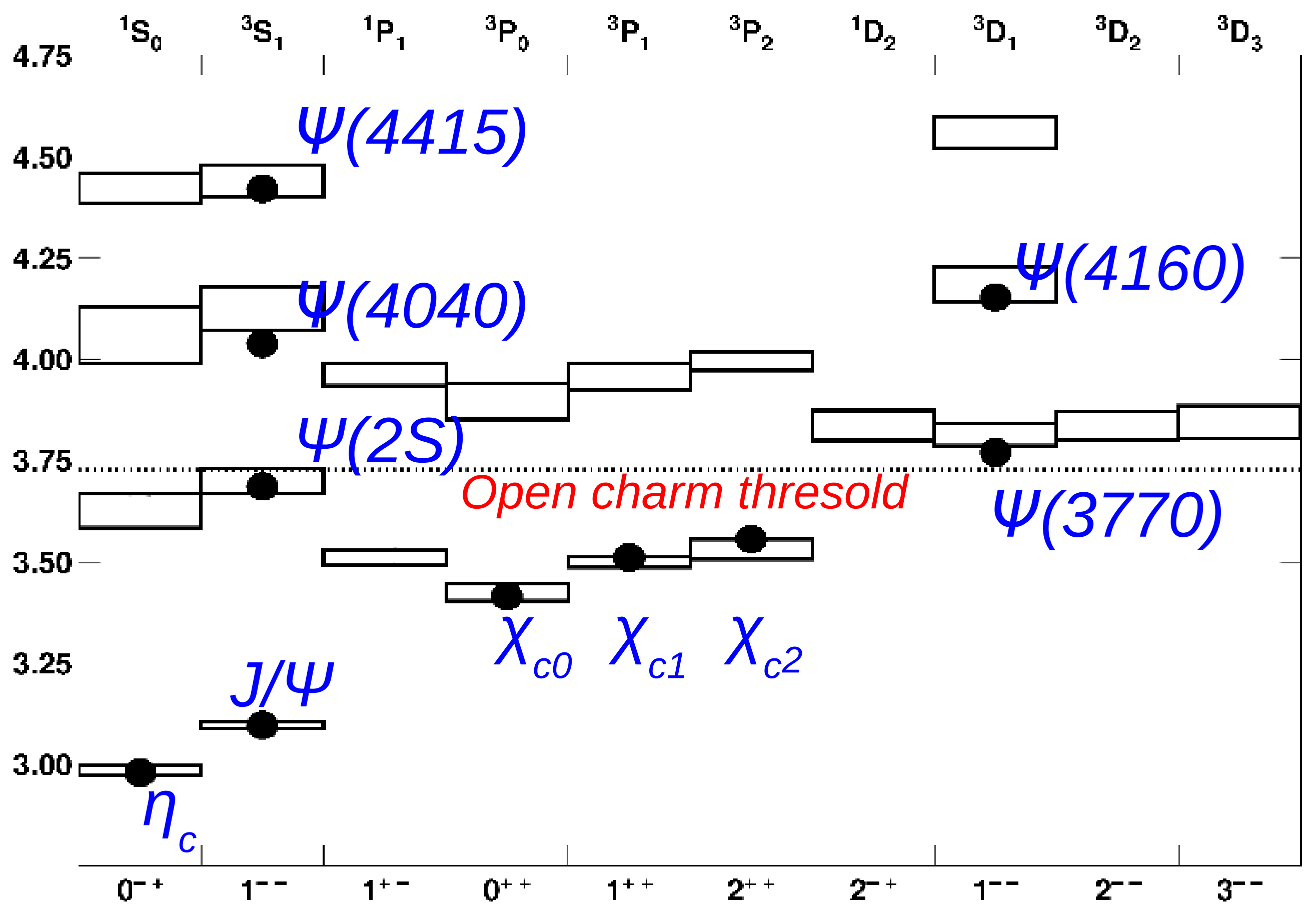
Charmonium: a long story

First cc state, J/Ψ, was discovered in 1974.

During next 6 years another 9 cc states were found:

Ψ(2S), η_c, χ_{c0},χ_{c1},χ_{c2},
Ψ(3770), Ψ(4040),
Ψ(4160), Ψ(4415)

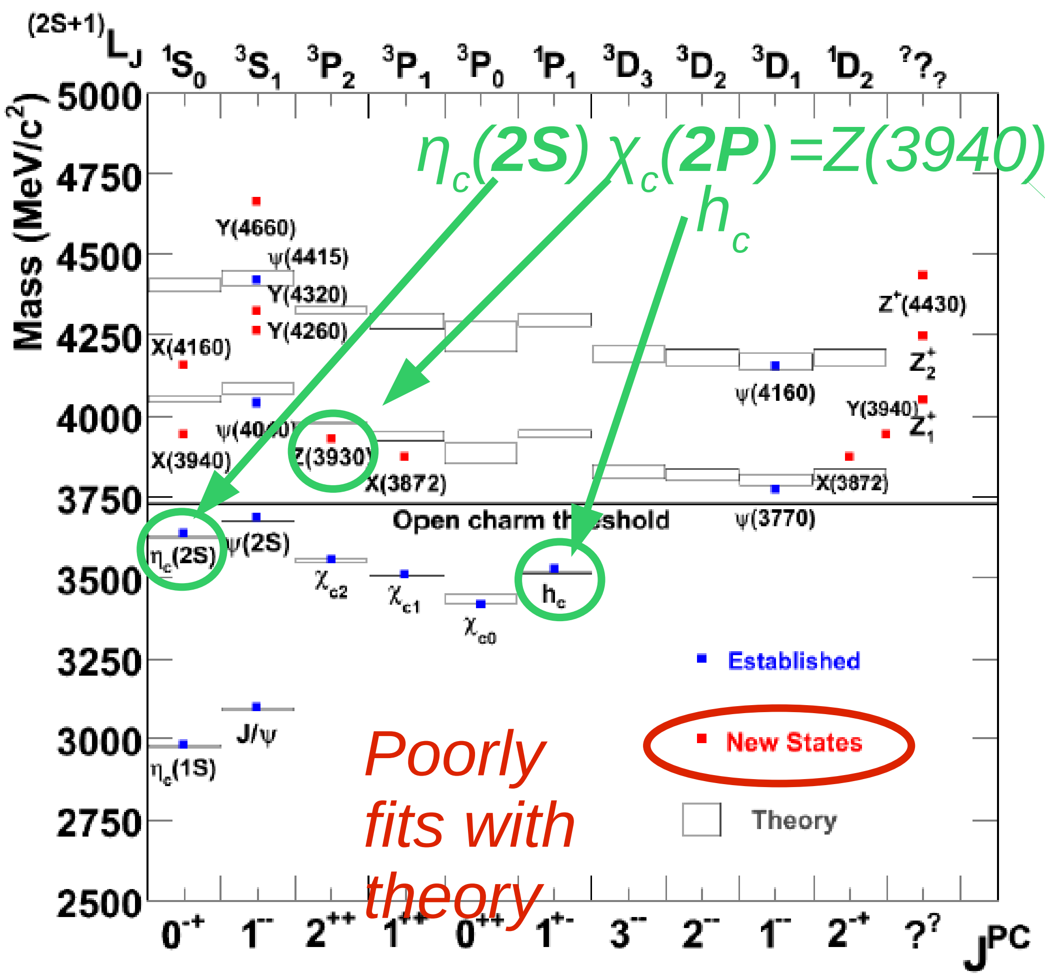
No new charmonium states was found during 1980-2002



XYZ: new 'zoo'

Many new particles (>10) were discovered during last few years:

Conventional (3 states) | Exotic (still no conventional explanation)

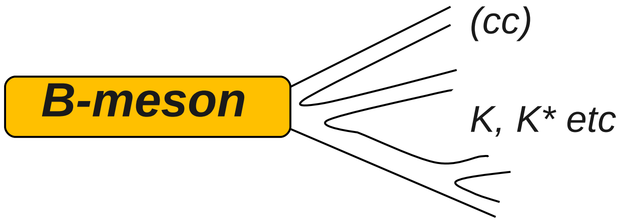


State	M (MeV)	Γ (MeV)	J^{PC}
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}

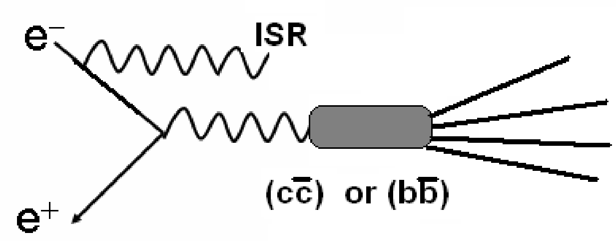
Charmonium production

There are several charmonium sources in the e^+e^- physics

Hadronic B-meson decays

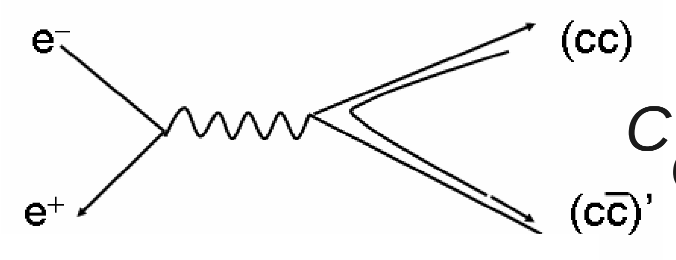


e^+e^- annihilation through virtual photon (including ISR)



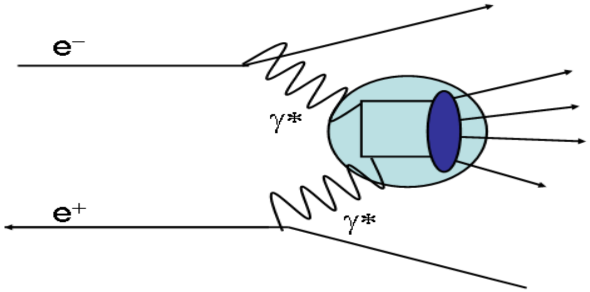
$\mathbf{1^{--}}$

Double charm production in e^+e^- annihilation



$C_{(cc)}C_{(cc)'}$**=-1**

Two photon collisions



C-even; J=1 is forbidden

Hunt for a New Spectroscopy

Direct indication of the New Spectroscopy in charmonium:

- *Observation of states with forbidden J^{PC}*
- *Extremely narrow width of the charmonium state*
- *Non-zero charge or strangeness (or both)*

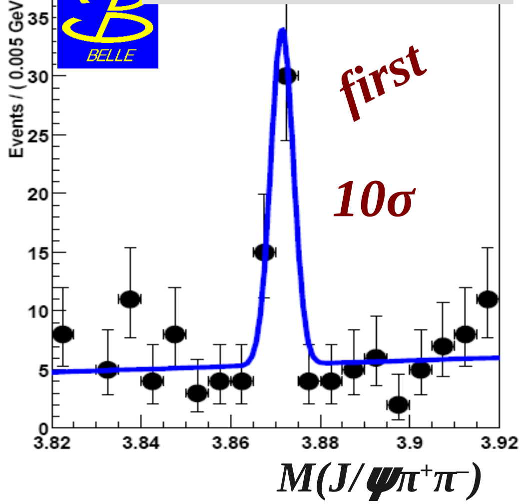
Indirect indication of the New Physics:

- *Mass and/or width which does not fit any model*

X(3872): unexpected puzzle

First observed by Belle in 2003 in $B \to J/\Psi\ \pi\pi K$ process

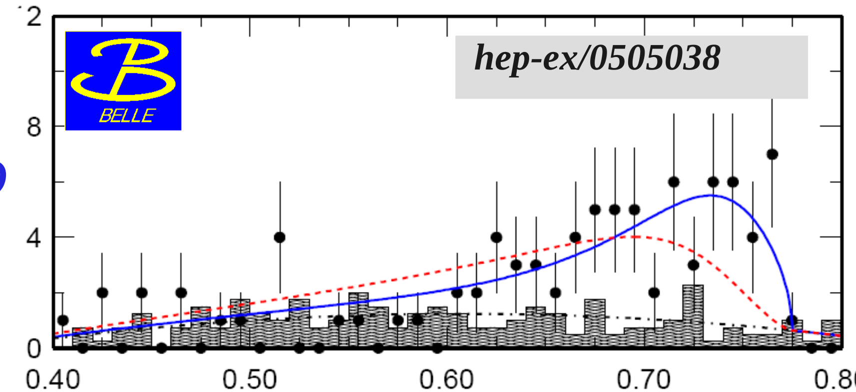
PRL91, 262001, 2003



charmonium $\to J/\Psi\ \rho$ violates isosopin

PRL 98 132002 (2007)

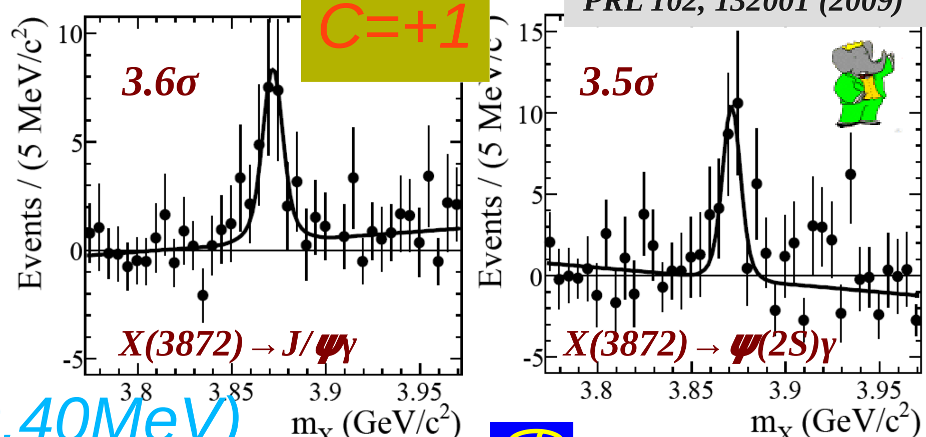
Angular analysis:
$J^{PC}=1^{++}$ or 2^{-+}



ππ mass spectrum

C=+1

PRL 102, 132001 (2009)



arXiv:0810.0358

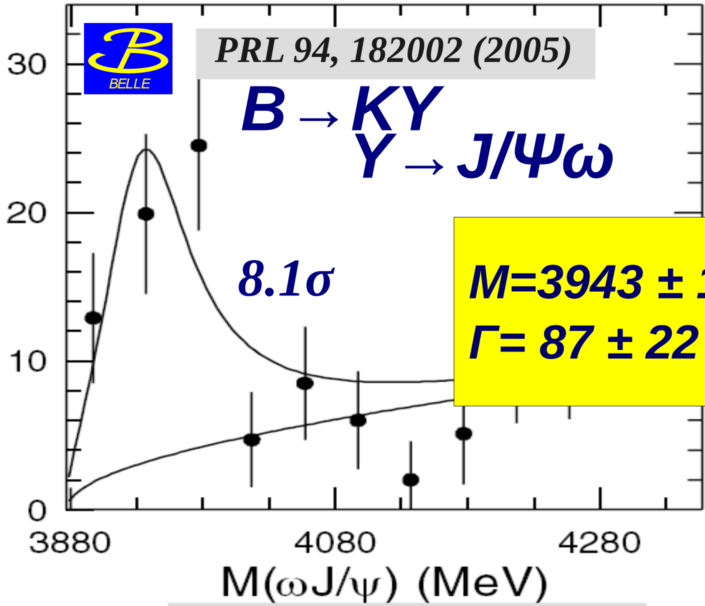
M X(3872) is close to D^0D^{*0} threshold
M=3871±0.20MeV
Not clear below or above (Δm=-0.25±0.40MeV)
surprisingly narrow Γ_{tot}<2.3 MeV @ 90% CL

PRL93, 051803, 2004

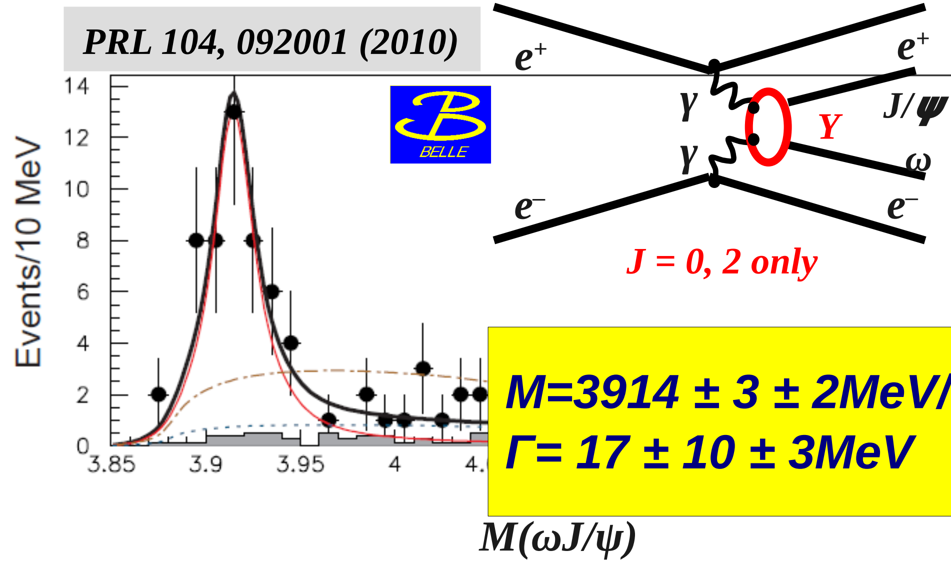
$\Gamma(X \to DD)\ /\ \Gamma(X \to J/\Psi\pi\pi)<7$ @ 90% CL

$B \to KD^0D^0\pi$ is also seen, M(X(3872)) is now the same as from $B \to KJ/\Psi\pi\pi$

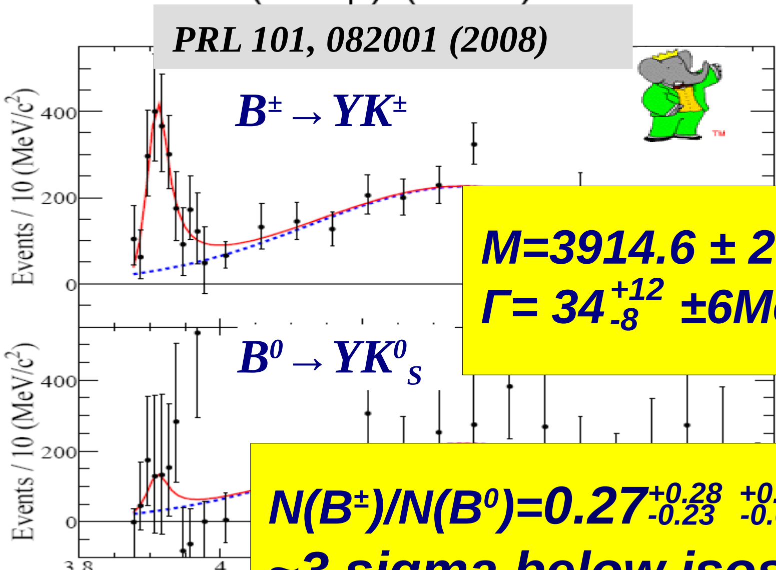
Y(3940)



M=3943 ± 11 ± 13MeV/c²
Γ= 87 ± 22 ± 2MeV



M=3914 ± 3 ± 2MeV/c²
Γ= 17 ± 10 ± 3MeV



M=3914.6 ± 2 ± 1.9MeV/c²
$\Gamma = 34^{+12}_{-8}$ ±6MeV

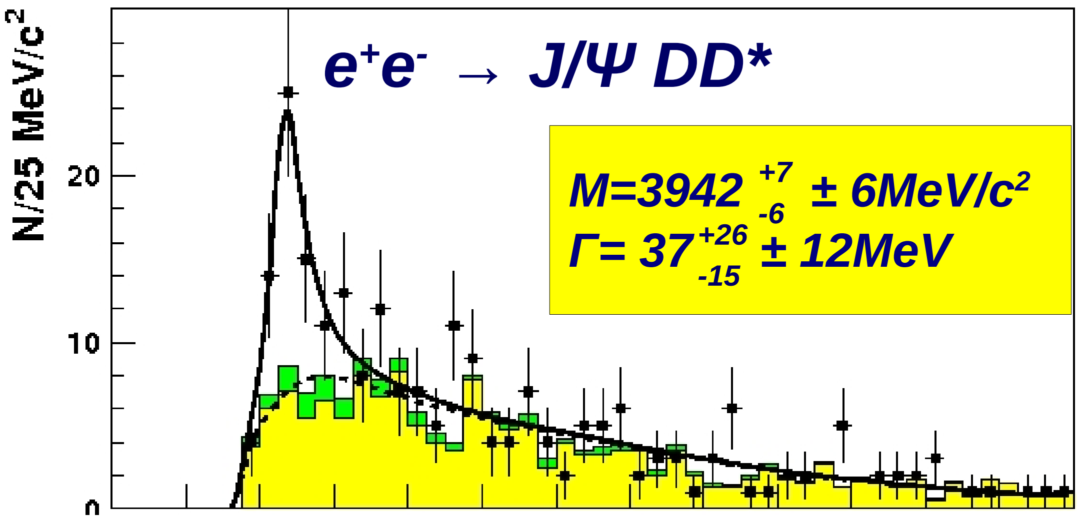
$N(B^{\pm})/N(B^{0})=0.27^{+0.28}_{-0.23}\,{}^{+0.04}_{-0.01}$
~3 sigma below isospin expectation

$\Gamma_{\gamma\gamma}(Y) \times B(Y \to \omega J/\psi)$ =
(61 ± 17 ± 8) eV for $J^P = 0^+$
(18 ± 5 ± 2) eV for $J^P = 2^+$
if $\Gamma_{\gamma\gamma}$ ~ 1 keV (typical for excited charmonium) $\Gamma_{\omega J/\psi}$ ~ 1 MeV is quite large for conventional charmonium

If $B(B \to YK)$~10^{-3} (OK for conv. charmonium) then $\Gamma_{\omega J/\psi}$~1MeV

No DD or DD* decays

Double charm: X(3940) & X(4160)



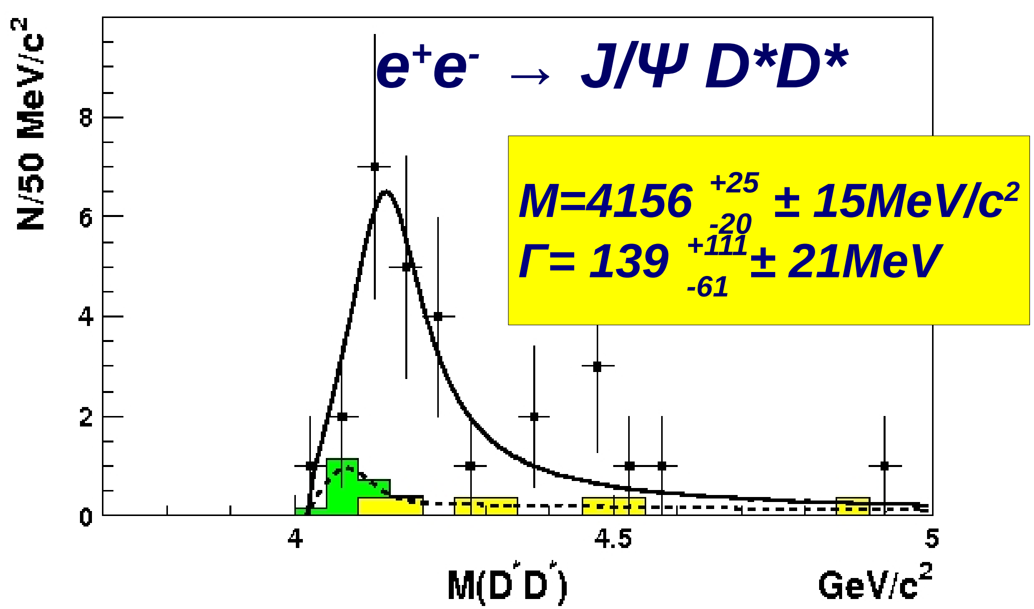
decay to open charm final states like conventional charmonium

production mechanism fix C=+1

known states produced in $e^+e^- \to J/\psi\ c\bar{c}$ have J=0

not seen in DD decay, exclude $J^{PC}=0^{++}$

Plausible assignments are $J^{PC}=0^{-+}$
$X(3940) = 3^1S_0 = \eta_c(3S)$
$X(4160) = 4^1S_0 = \eta_c(4S)$

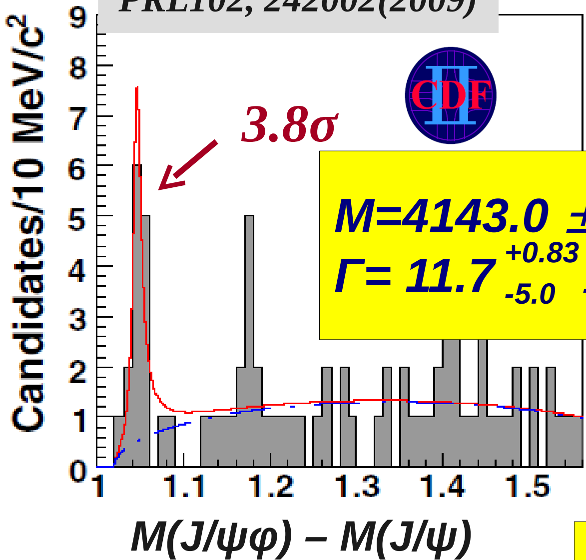


For both X(3940) and X(4160) the masses predicted by the potential models are ~100–250 MeV higher

$J/\Psi\varphi$: Y(4140) & Y(4350)

$B^+ \rightarrow J/\Psi\varphi K^+$

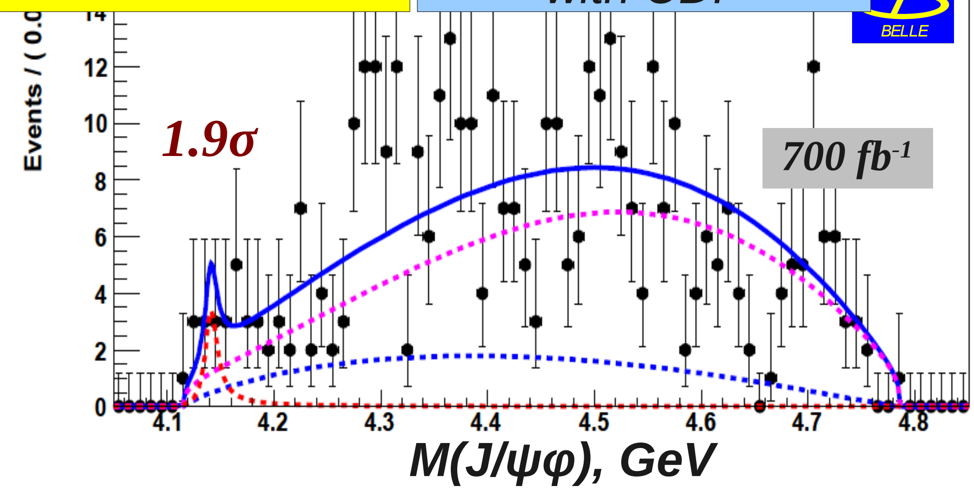
PRL102, 242002(2009)



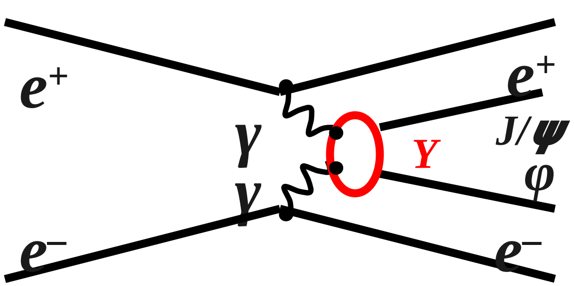
$M = 4143.0 \pm 2.9 \pm 1.2\,MeV/c^2$
$\Gamma = 11.7^{+0.83}_{-5.0} \pm 3.7\,MeV$

Belle does not confirm $Y(4140) \rightarrow J/\Psi\varphi$

Low efficiency at threshold: No big contradiction with CDF

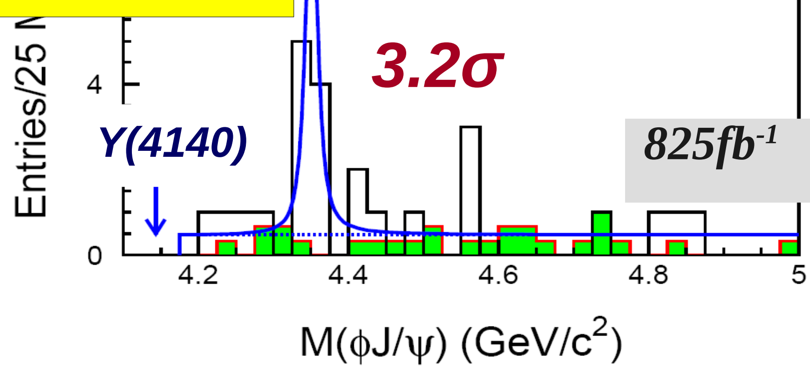


$\gamma\gamma \rightarrow J/\Psi\varphi$



Unexpected peak at 4350 MeV/c²

arXiv: 0912.2383



$\Gamma_{\gamma\gamma}(Y(4350)) \times B(Y(4350) \rightarrow \phi J/\psi) =$

$J^P = 0^+$: $(6.7^{+3.2}_{-2.4} \pm 1.1)$ eV

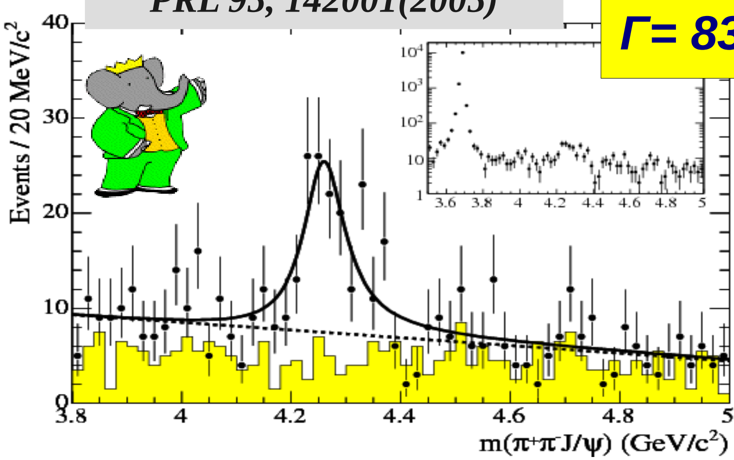
$J^P = 2^+$: $(1.5^{+0.7}_{-0.6} \pm 0.3)$ eV

Y in ISR: 4008,4260,4350 & 4660

$e^+e^- \to J/\Psi\pi\pi\ \gamma_{ISR}$

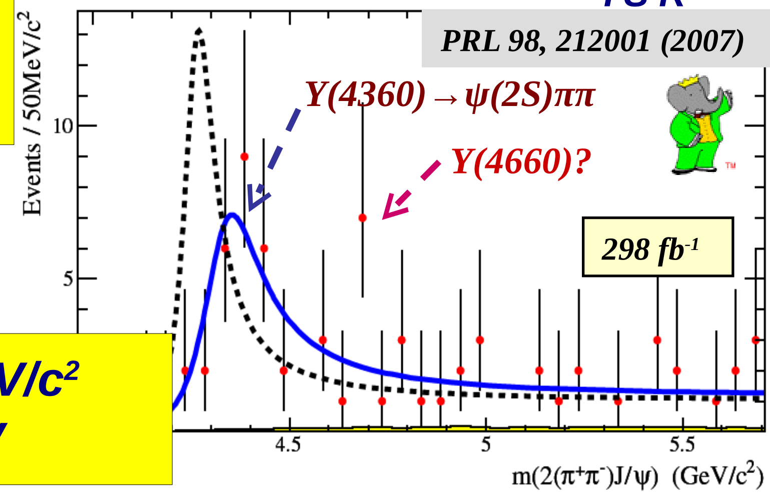
PRL 95, 142001(2005)

$M=4264 \pm 12\ MeV/c^2$
$\Gamma= 83 \pm 22\ MeV$



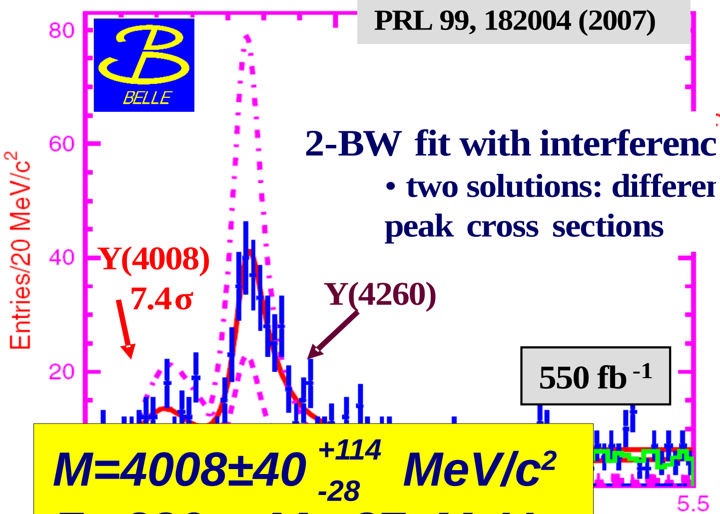
$e^+e^- \to \Psi(2S)\pi\pi\ \gamma_{ISR}$

PRL 98, 212001 (2007)



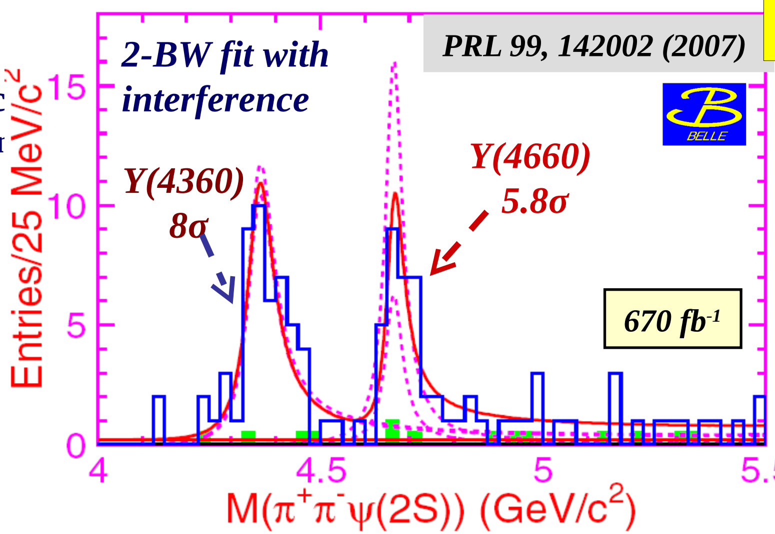
$M=4661\ ^{+9}_{-8} \pm 6\ MeV/c^2$
$\Gamma= 42\ ^{+17}_{-12} \pm 6\ MeV$

PRL 99, 182004 (2007)



$M=4008 \pm 40\ ^{+114}_{-28}\ MeV/c^2$
$\Gamma= 226 \pm 44 \pm 87\ MeV$

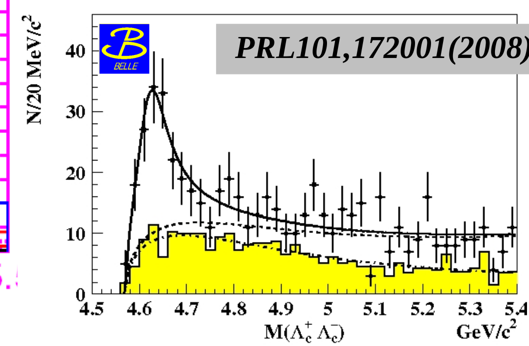
PRL 99, 142002 (2007)



$M=4355\ ^{+9}_{-10} \pm 9\ MeV/c^2$
$\Gamma= 103\ ^{+17}_{-15} \pm 11\ MeV$

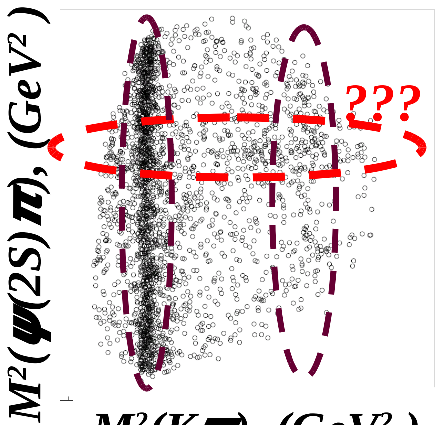
$e^+e^- \to \Lambda_c\Lambda_c\ \gamma_{ISR}$

PRL101,172001(2008)

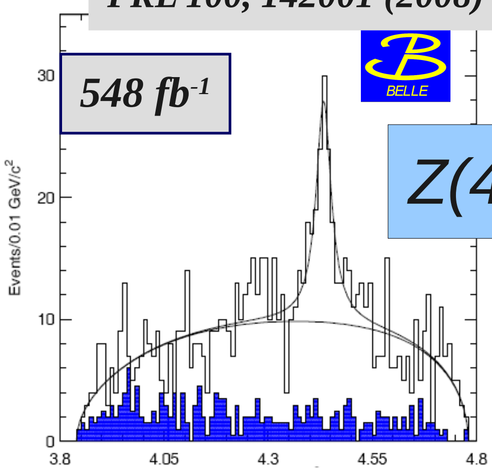


Z: charged charmonium?

$B \to K\pi^+\psi(2S)$



PRL 100, 142001 (2008)

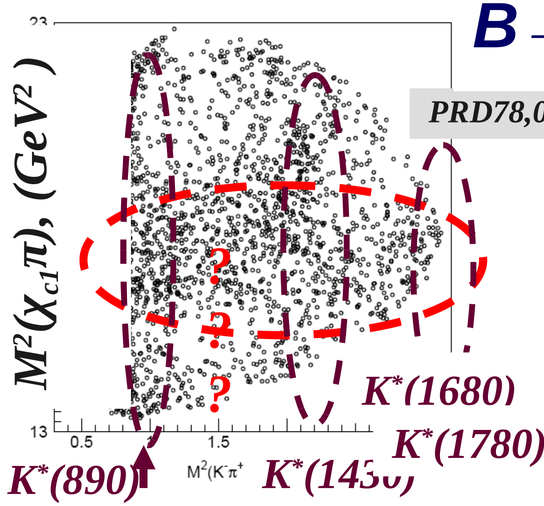


Z(4430)

Significance:1.9σ

$B(B\to ZK)B(Z\to \Psi(2S)\pi)<3.1\ 10^{-5}$ @ 95%CL

$B \to K\pi^+\chi_{c1}$



PRD78,072004 (2008)

Z(4050),Z(4250)

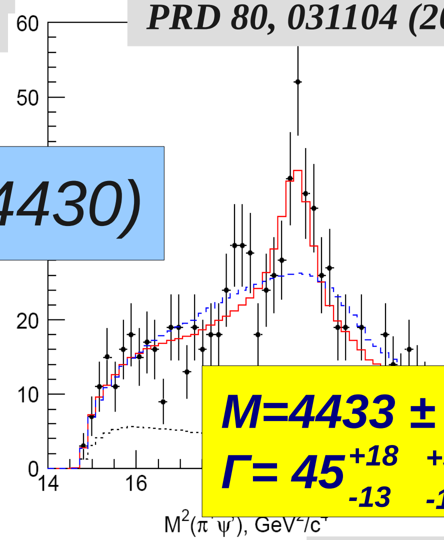
$M_1 = (4051\pm14^{+20}_{-41})$ MeV/c²

$\Gamma_1 = (82^{+21}_{-17}{}^{+47}_{-22})$ MeV

$M_2 = (4248^{+44}_{-29}{}^{+180}_{-35})$ MeV/c²

$\Gamma_1 = (177^{+54}_{-39}{}^{+316}_{-61})$ MeV

PRD 80, 031104 (2009)

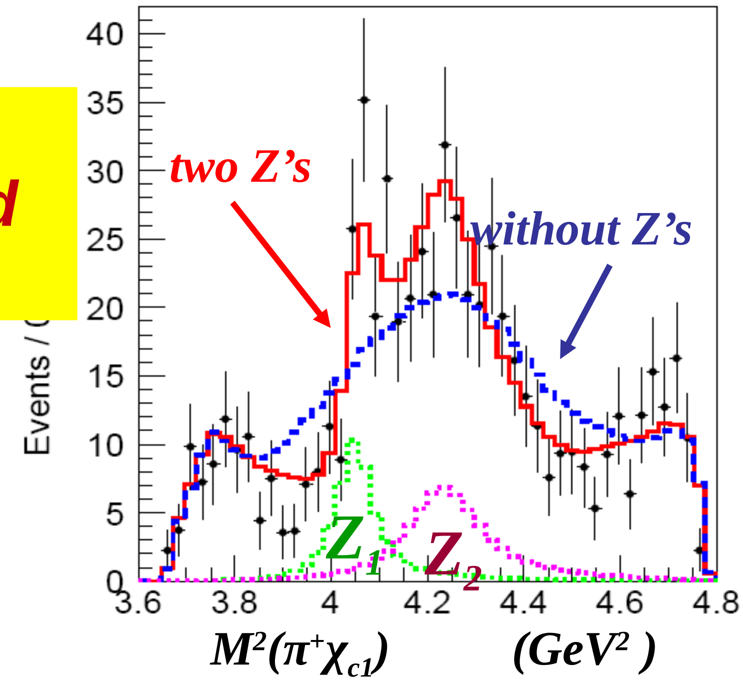


$M = 4433 \pm 4 \pm 2$ MeV/c²

$\Gamma = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV

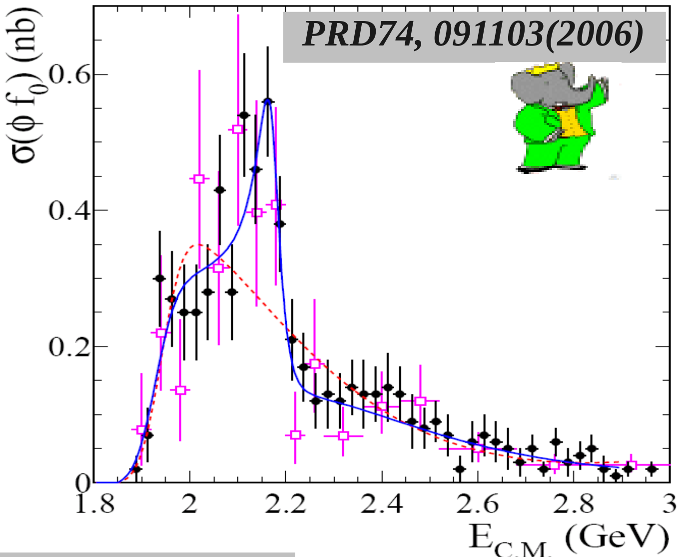
PRD 79, 112001 (2009)

two Z's favoured by 5.7σ

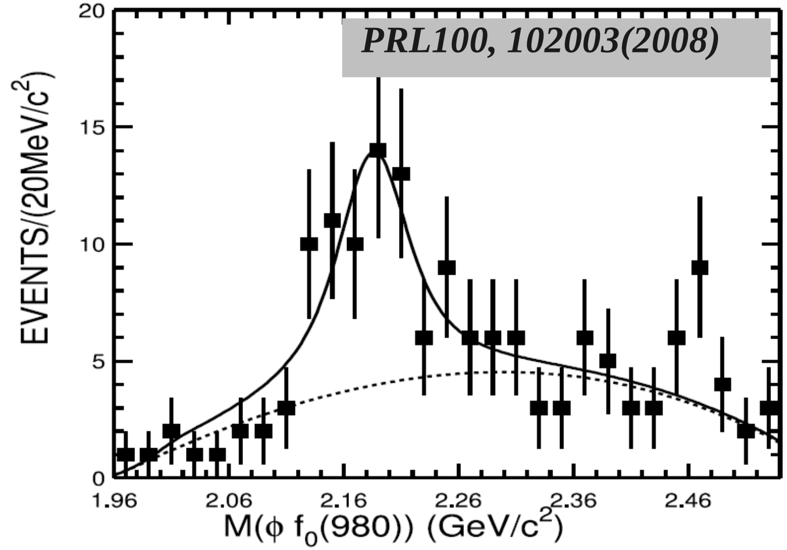


$Y_s(2175)$

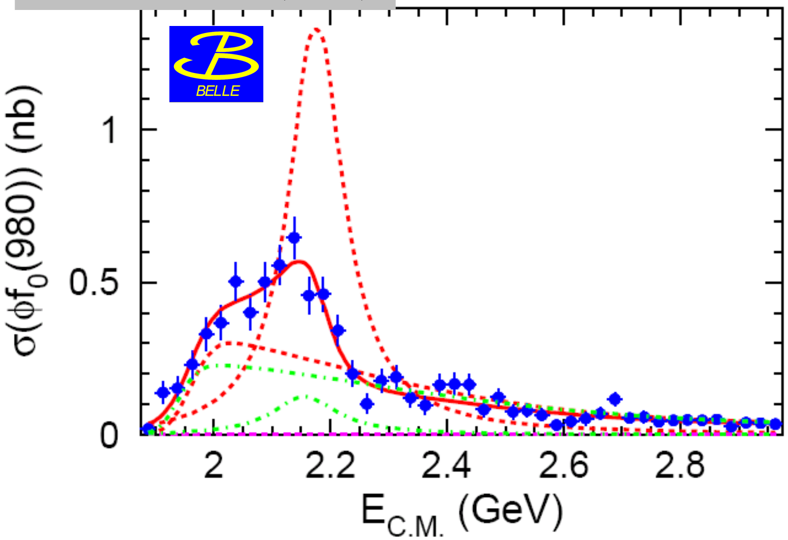
$e^+e^- \to \varphi f_0\, \gamma_{ISR}$



BESII: $J/\Psi \to \varphi f_0\, \eta$



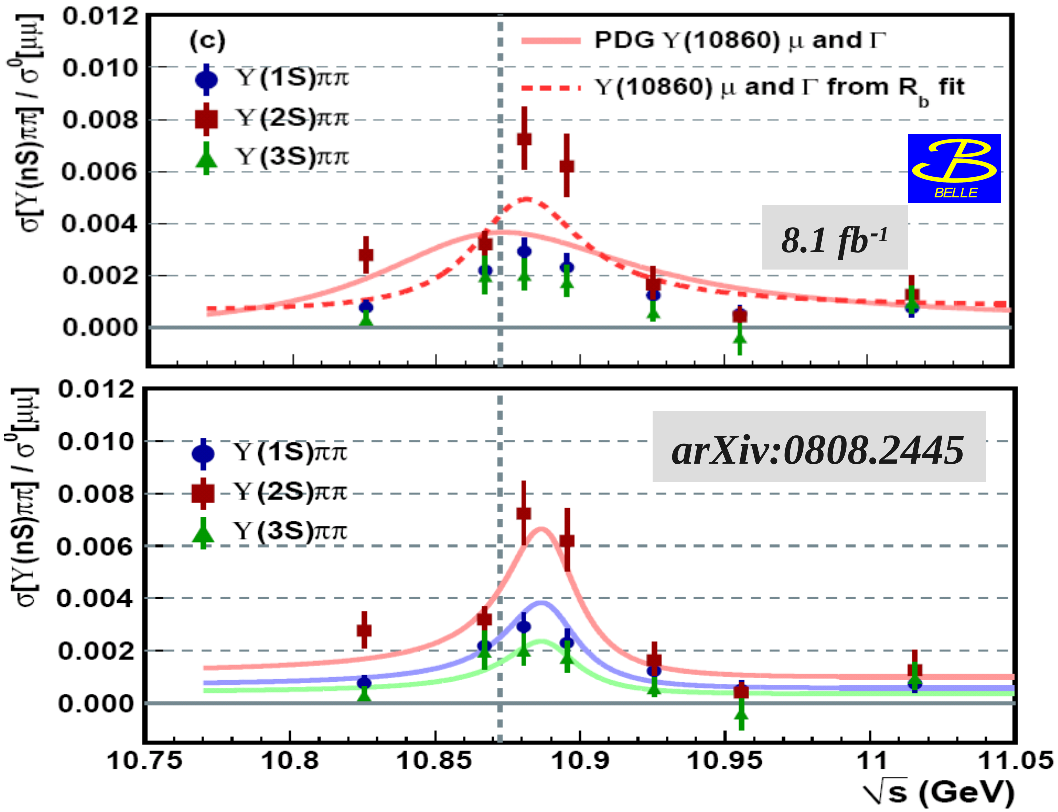
PRD80, 031101(2009)



Experiment	Channel	Mass (MeV/c^2)	Width (MeV/c^2)
BaBar [23]	$Y(2175) \to \phi f_0(980)$	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BES [25]	$Y(2175) \to \phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
Belle [26]	$Y(2175) \to \phi\pi^+\pi^-, \phi f_0(980)$	2133^{+69}_{-115}	169^{+105}_{-92}
Belle [26]	$\phi(1680) \to \phi\pi^+\pi^-$	1687 ± 21	212 ± 29
BaBar [28]	$\phi(1680) \to K^*K$ and $\phi\eta$	$1709 \pm 20 \pm 43$	$322 \pm 77 \pm 160$
PDG [3]	$\phi(1680)$	1680 ± 20	150 ± 50

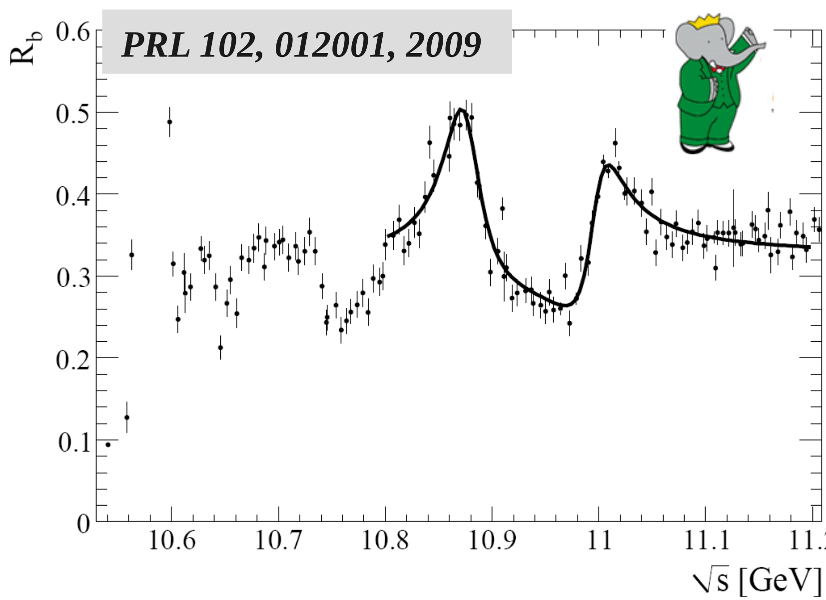
$Y_b(10890)$

energy scan



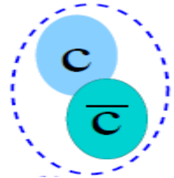
	Υ(10860)	Υ(11020)
mass (GeV) width (MeV) ϕ (rad)	10.876 ± 0.002 43 ± 4 2.11 ± 0.12	10.996 ± 0.002 37 ± 3 0.12 ± 0.07
PDG mass (GeV) PDG width (MeV)	10.865 ± 0.008 110 ± 13	11.019 ± 0.008 79 ± 16

Neither inclusive nor exclusive (dilepton) cross-section are consistent with Y(5S) and Y(6S)



New States: interpretation

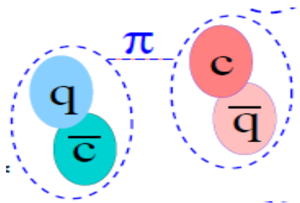
Conventional charmonium:



Very well known model

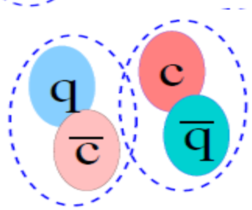
J^{PC}: J=L+S; P=$(-1)^{L+1}$; C=$(-1)^{L+S}$

Molecular state:



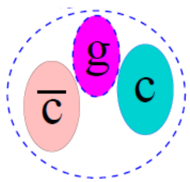
Loosely bound two charm mesons quark/color or pion exchange

Tetraquark:



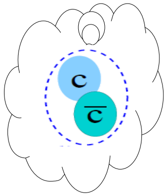
Tightly bound four-quark state

Hybrid state:



Excited gluonic degree of freedom

Hadrocharmonium:



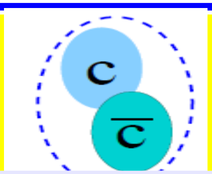
Charmonium coated by a cloud of excited hadronic matter

Threshold effects:

Virtual states near threshold

Interpretation: Conventional ($c\bar{c}$)

<u>Conventional charmonium:</u>



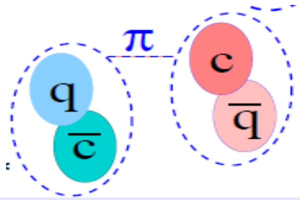
Very well known model

J^{PC}: $J=L+S$; $P=(-1)^{L+1}$; $C=(-1)^{L+S}$

X(3872):	***χ_{c1}':*** *Expected $\Gamma(J/\Psi\gamma)/\ \Gamma(J/\Psi\pi\pi)$~30; measured <0.2* *~100MeV/c^2 heavier*
	η_c(2S): *Expected large $\Gamma(gg)$ and tiny $\Gamma(J/\Psi\pi\pi)$* *~50 MeV/c^2 lighter*
Y(3940):	*$\Gamma(J/\Psi\omega)$ is too large*
Y(4260):	*3^3D_1? $Y\rightarrow D^{(*)}D^{(*)}$ not found*
X(3940):	*$\eta_c(3S)=3^1S_0$ ~100MeV/c^2 mass shift*
X(4160):	*$\eta_c(4S)=4^1S_0$ ~250MeV/c^2 mass shift (if $\psi(4415)=\psi(4S)$)*
Y_s(2175):	*$\varphi(2170)=3^3S_1$ ($s\bar{s}$) predicted width 380MeV*
Y(4360),Y(4660):	*no vacant 1^{--}; no open-charm production; too large Γ(charmonium)*

Interpretation: Molecule

Molecular state:



Loosely bound two charm mesons quark/color or pion exchange

X(3872):

Pro: *$M_X \sim M_{D^{*0}} + M_{D0}$ is not accidental; DD* decay; $J^{PC}=1^{++}$ allows S-wave; small rate for J/Ψγ is expected*

Contra: *too large X(3872) → ψ(2S)γ; too small binding energy: D's are too far to be produced in pp*

Y(4140): *not found in γγ; small Γ(γγ) disfavoures $D_s^*D_s^*$ molecula*

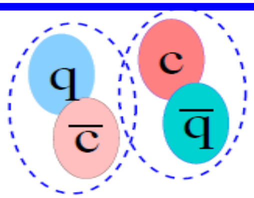
Y(4350): *$D_s^{*+}D_{s0}^{*-}$ molecule with $J^{PC}=2^{++}$*

Y(4360),Y(4660): *DD_1 or D^0D^* molecule ?*

Z's: *$D_{(s)}^{(*)}D_{(s)}^{(*)}$ combinations of proper charge*

Interpretation: Tetraquark

Tetraquark:



Tightly bound four-quark state

X(3872): *(cu)(cu), (cd)(cu), (cd)(cd) small mass splitting; no evidence neither for neutral nor for charged partners*

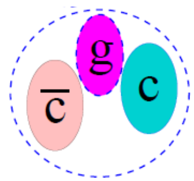
Y(4360),Y(4660): *(cq)(cq) tetraquark?*

Y(4140),Y(4350): *(ccss) diquark-antidiquark state ?*

Z's: *(ccq_1q_2) tetraquark ?*

Interpretation:Hybrids etc

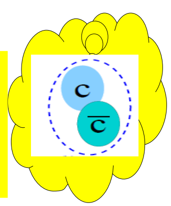
Hybrid state:



Excited gluonic degree of freedom

Y(4360),Y(4660): ***Hybrids:*** *supported by Lattice calculations*
$D^{(*)} D^{**}$ decays dominates

Hadrocharmonium:



Charmonium coated by a cloud of excited hadronic matter

Y(4360),Y(4660): ***Hadrocharmonium:*** *(cc)+ excited light meson*

Z's: ***Hadrocharmonium:*** *$\Psi(2S)$ / χ_{c1}+ excited charged light meson*

Interpretation: summary

Belle

State	M (MeV)	Γ (MeV)	J^{PC}	Popular interpretations
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\varphi(2170)=3^3S_1(s\bar{s})$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	Molecule, χ_{c1}', η_{c2}, tetraquark etc
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$Y(3940)$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\chi_c(2P)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$\eta_c(3S)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	Conventional $(c\bar{c})$, hybrid
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	non-res $J/\Psi\pi\pi$
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$\eta_c(4S)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	3^3D_1
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	Molecule, tetraquark, hadrocharmonium, hybrid
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$Y(4660)$
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	Molecule, tetraquark, hadrocharmonium, hybrid
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	Molecule, tetraquark, hadrocharmonium, hybrid
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$Y(5S)$ $Y(6S)$

Conclusions: a challenge

Results of B-factories (Belle and BaBar) as well as Tevatron experiments (CDF, D0) and many others (BES etc) start a new exciting era in hadron spectroscopy.

A lot of new states are opened, many of them remains unexplained.

New 'zoo' is a challenge:

- *For theoreticians to explain the origin of these states*
- *For experimentalists to measure characteristics at highest possible precision*

New Super B-factories could solve a XYZ puzzle