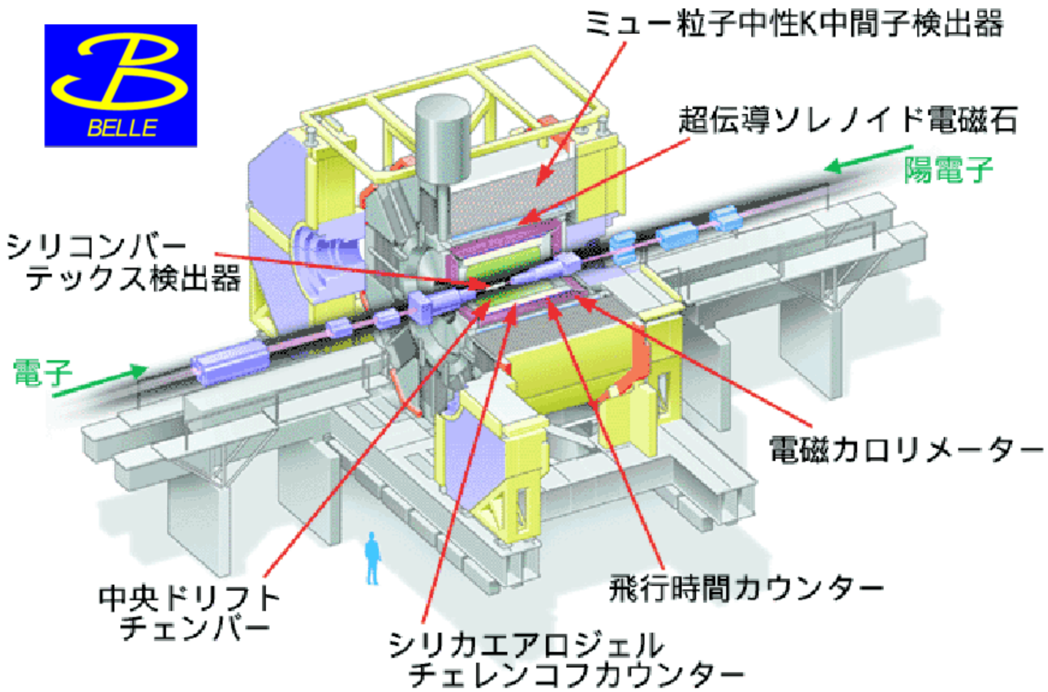
Exotic Hadron spectroscopy at Belle and BaBar

Pavel Pakhlov ITEP & Belle Collaboration



B-factories

$e^+e^- \to \Upsilon(4S)$ and nearby continuum:
$E_{cms} \sim 10.6$ GeV

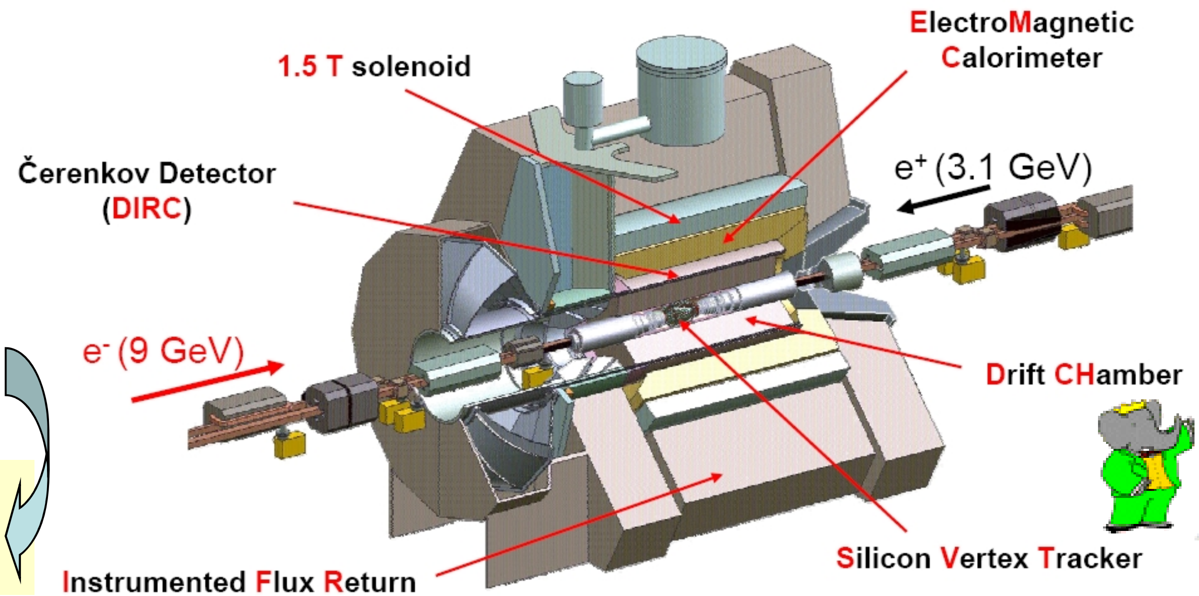
$L \sim 10^{34}/cm^2/s$

1000+530 fb^{-1} in total

(exotic) hadrons

from B-meson decays,
continuum,
initial state radiation (ISR),
and $\gamma\gamma$ fusion

more results in the talk by Fabio Anulli



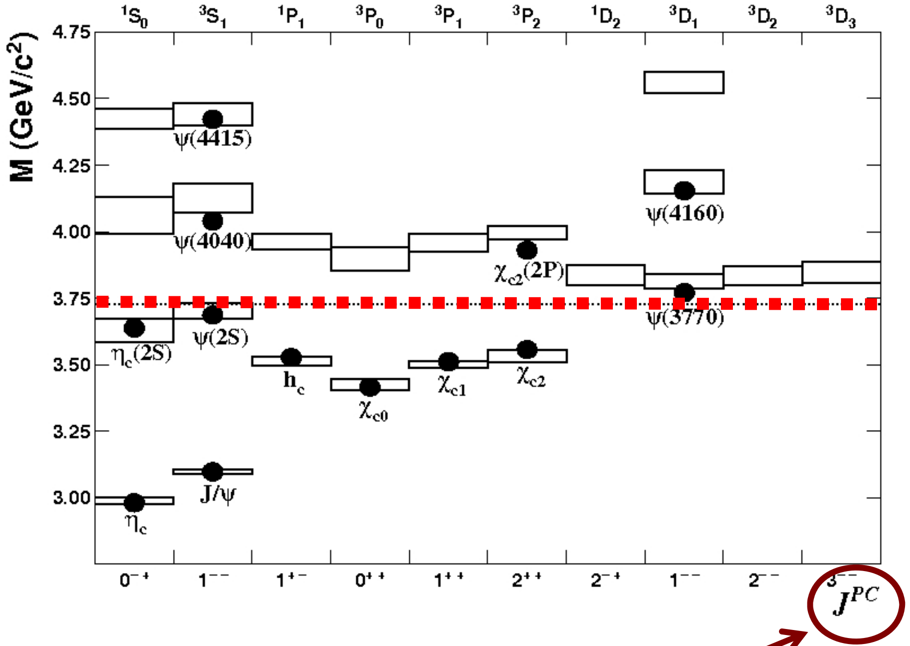
Many (>10) states poorly consistent with quark model

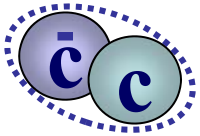
State	M (MeV)	Γ (MeV)	J^{PC}	Decay Modes	Production Modes
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$\phi f_0(980)$	e^+e^- (ISR) $J/\psi \to \eta Y_s(2175)$
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$\pi^+\pi^- J/\psi$, $\gamma J/\psi, D\bar{D}^*$	$B \to KX(3872)$, $p\bar{p}$
$X(3915)$	3914 ± 4	23 ± 9	$0/2^{++}$	$\omega J/\psi$	$\gamma\gamma \to X(3915)$
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$D\bar{D}$	$\gamma\gamma \to Z(3940)$
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	$e^+e^- \to J/\psi X(3940)$
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$\omega J/\psi$ (not $D\bar{D}^*$)	$B \to KY(3940)$
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$D^*\bar{D}^*$ (not $D\bar{D}$)	$e^+e^- \to J/\psi X(4160)$
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	e^+e^- (ISR)
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$\pi^+\pi^- \psi'$	e^+e^- (ISR)
$Z(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4050)$
$Z(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$\pi^\pm \chi_{c1}$	$B \to KZ^\pm(4250)$
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$\pi^\pm \psi'$	$B \to KZ^\pm(4430)$
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$\pi^+\pi^- \Upsilon(1,2,3S)$	$e^+e^- \to Y_b$

observed last 6 years by B-factories

Exotic charmonium-like states

Conventional charmonium





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

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

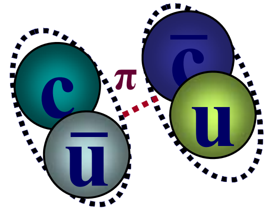
n radial quantum number

S total spin of q-antiq

L relative orbital ang. mom.

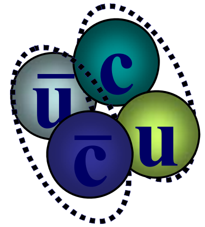
- **Multiquark states**
  - ***Molecular state***

    two loosely bound charm mesons
    - quark/color exchange at short distances
    - pion exchange at large distance

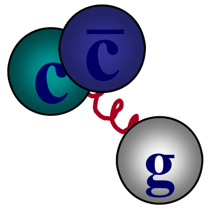


  - ***Tetraquark***

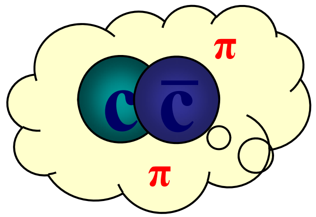
    tightly bound four-quark state



- **Charmonium hybrids**
  - States with excited gluonic degrees of freedom



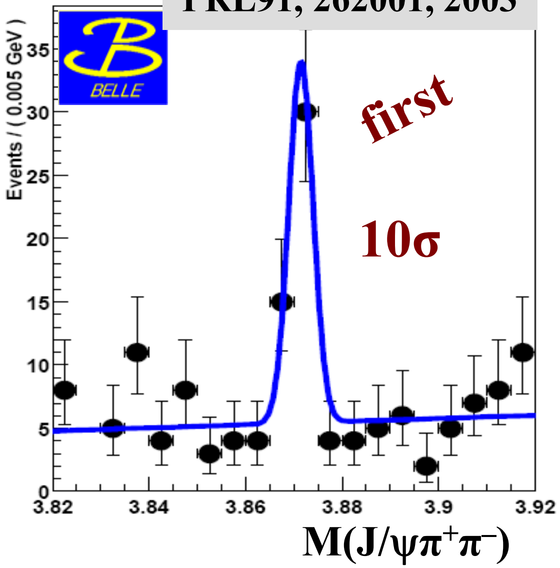
- **Hadro-charmonium**
  - Specific charmonium state "coated" by excited light-hadron matter



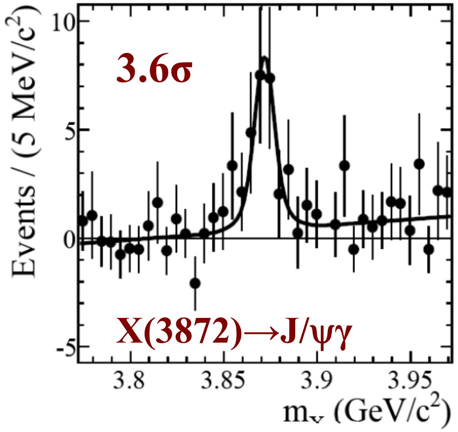
- **Threshold effects**
  - Virtual states at thresholds
  - Charmonium states with masses shifted by nearby $D_{(s)}^{(*)}D_{(s)}^{(*)}$ thresholds

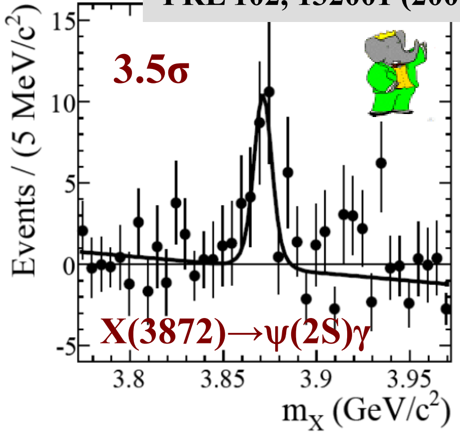
X(3872) first seen in B→K $J/\psi\pi^+\pi^-$

PRL91, 262001, 2003

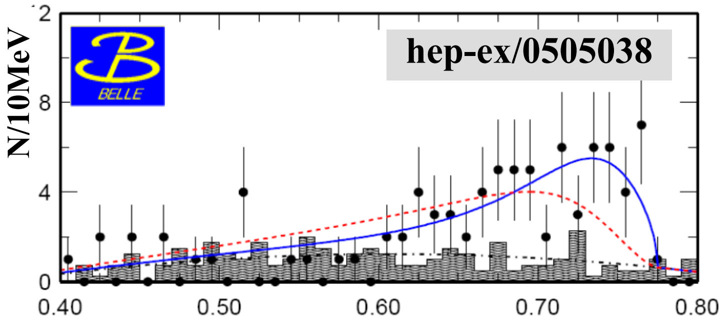


PRL 102, 132001 (2009)





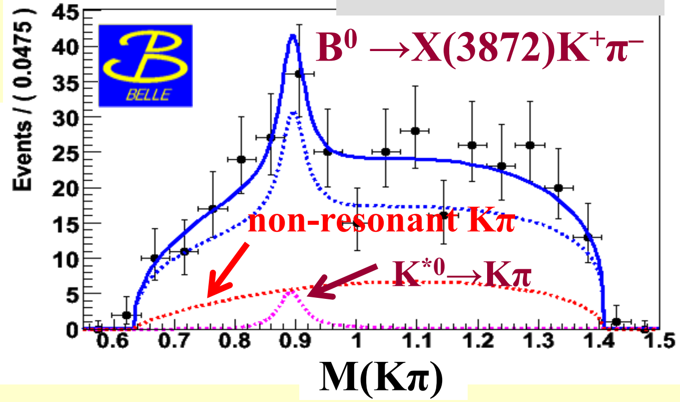
hep-ex/0505038

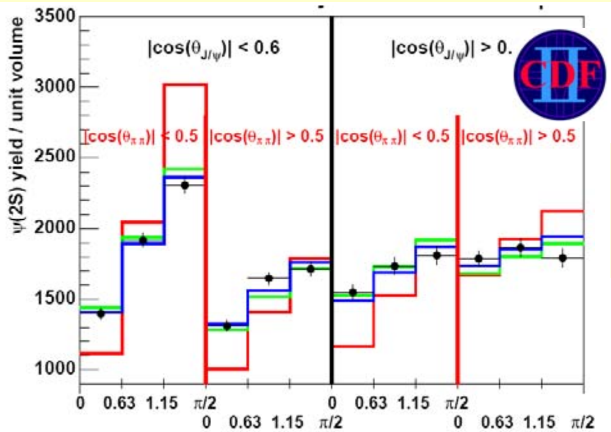


- $\pi\pi = \rho$. Isospin violation!
- X(3872) → $J/\psi\gamma$ is seen, but small
- X(3872) → $\psi'\gamma$ is also seen, surprisingly larger $J/\psi\gamma$

- M_X close to D^0D^{*0} threshold M = 3871.55 ± 0.20 MeV not clear below or above: Δm = – 0.25 ± 0.40 MeV
- surprisingly narrow: Γ_{tot} < 2.3 MeV at 90% CL

ArXiv: 0809.1224





- $J^{PC} = 1^{++}$ or 2^{-+}
- Br(X(3872) → $J/\psi\rho^0$) > 2.5% (90% C.L.)
- B→X(3872)Kπ non-resonant Kπ dominates! unlike B →Kπ+charmonium

X(3872): charmonium vs exotics

Conventional charmonium

χ_{c1}' ($J^{PC}=1^{++}$)

- expected $\Gamma(\chi_{c1}' \to J/\psi\gamma) / \Gamma(\chi_{c1}' \to J/\psi\pi\pi)$ ~ 30, measured ratio < 0.2
- ~ 100MeV/c^2 heavier

η_{c2} ($J^{PC}=2^{-+}$)

- expected large $\Gamma(\eta_{c2} \to gg)$ and tiny $\Gamma(\eta_{c2} \to J/\psi\pi\pi)$
- ~ 50MeV/c^2 lighter

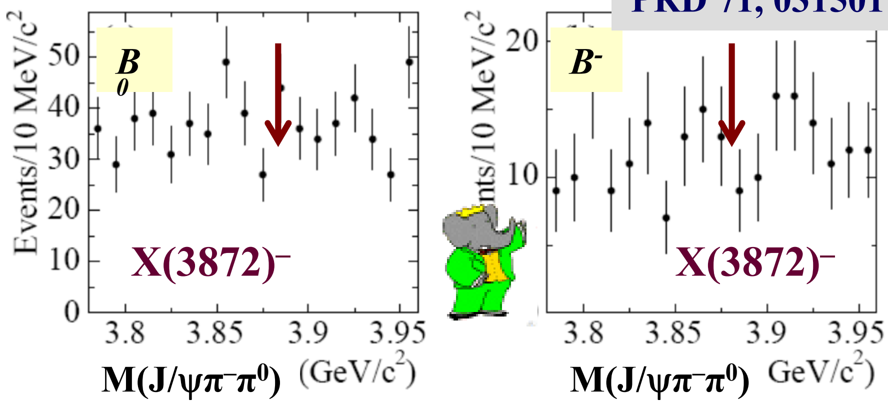
Tetraquark (cq)(cq):

+ 3 states (cu)(cu), (cd)(cu), (cd)(cd) with a few MeV mass splitting
    - no evidence of neither neutral doublet nor charged partner

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

- $M_X \sim M_{D^0} + M_{D^{*0}}$ is not accidental
- $J^{PC}=1^{++}$ (D^0D^{*0} in S-wave)
- DD^* decay
- Small rate for decay into $J/\psi\gamma$ is expected
- ***Problems:***
    - *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*
- ***Possible solution:*** Mixture of DD^* molecule and χ_{c1}' charmonium state?

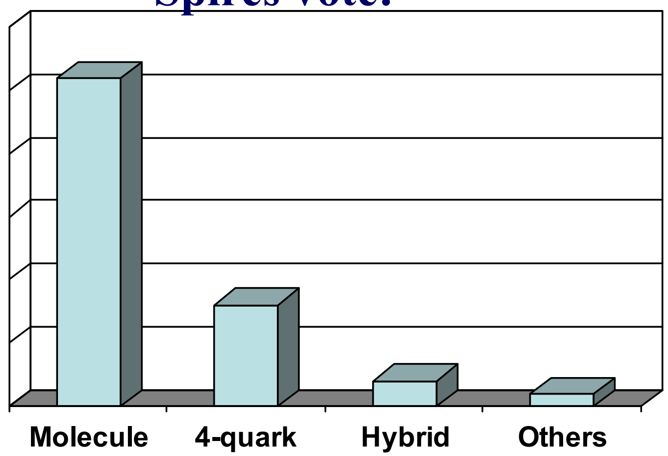
PRD 71, 031501 (2005)



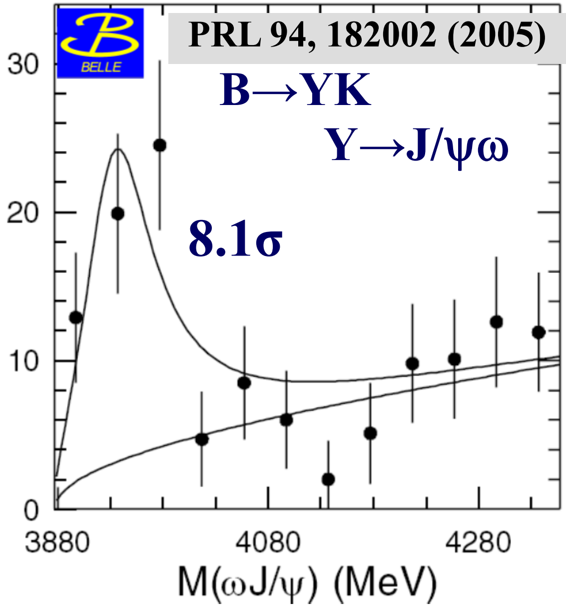
Moriond QCD

P Pakhlov, ITEP

Spires vote:

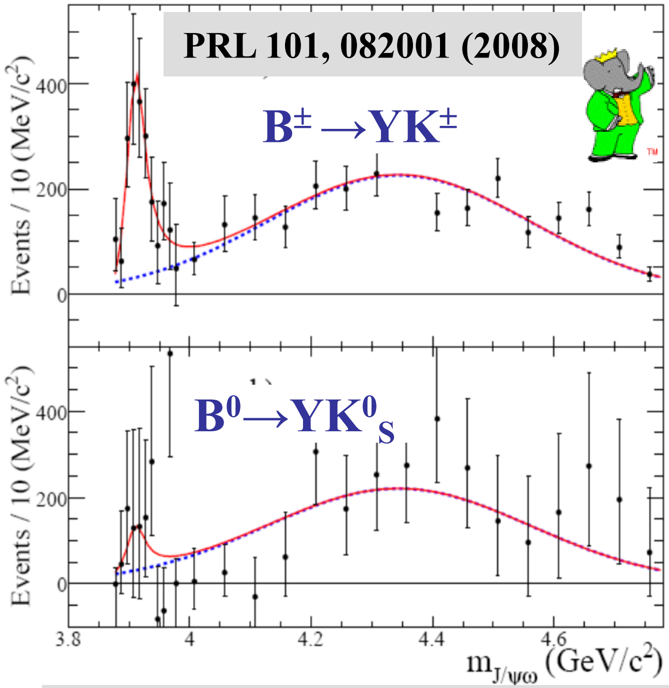


Y(3940) → J/ψω



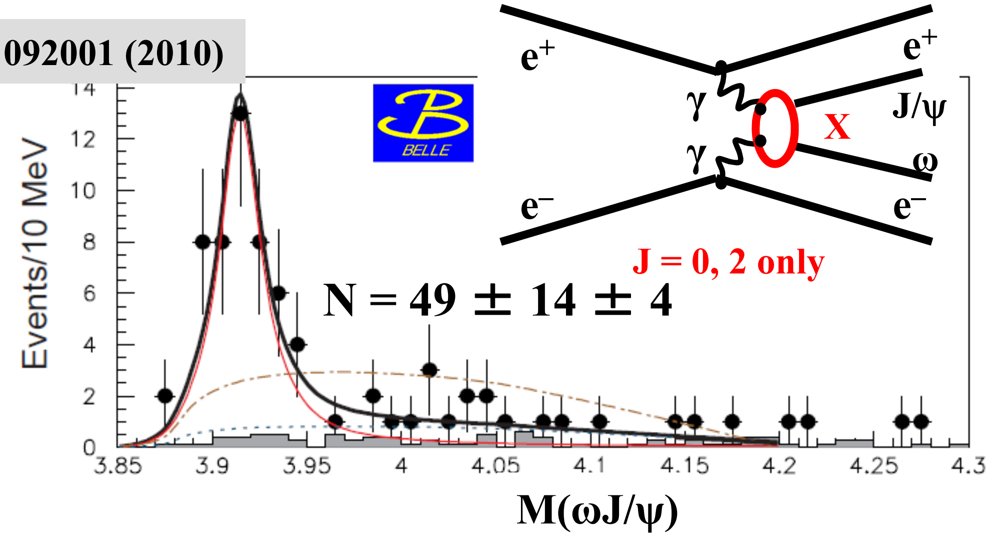
	Mass, MeV/c²	Width, MeV
B → YK	3943 ± 11 ± 13	87 ± 22 ± 26
B → YK	3914.6 ± 2 ± 1.9	34^{+12}_{-8} ± 6
γγ → Y	3914 ± 3 ± 2	17 ± 10 ± 3

Mass above DD threshold but J/ψω partial width is too large for conventional charmonium



$N_{B0}/N_{B+} = 0.27^{+0.28}_{-0.23}{}^{+0.04}_{-0.01}$

~3σ below isospin expectations



$\Gamma_{\gamma\gamma}(Y) \times B(Y \to \omega J/\psi) =$

(61 ± 17 ± 8) eV for $J^P = 0^+$

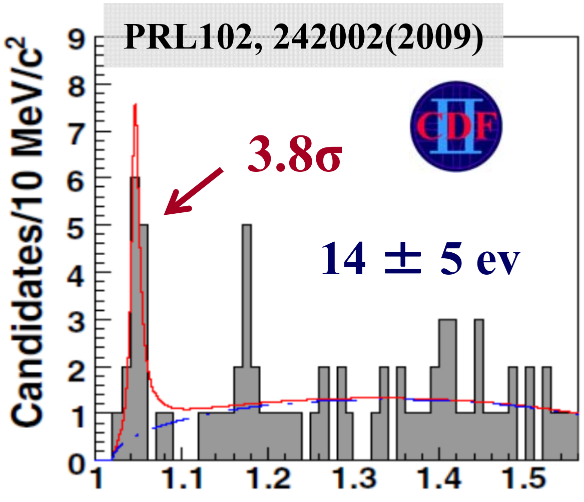
(18 ± 5 ± 2) eV for $J^P = 2^+$

if $\Gamma_{\gamma\gamma} \sim 1$ keV (typical for excited charmonium)

$\Gamma_{\omega J/\psi} \sim 1$ MeV is quite large for conventional charmonium

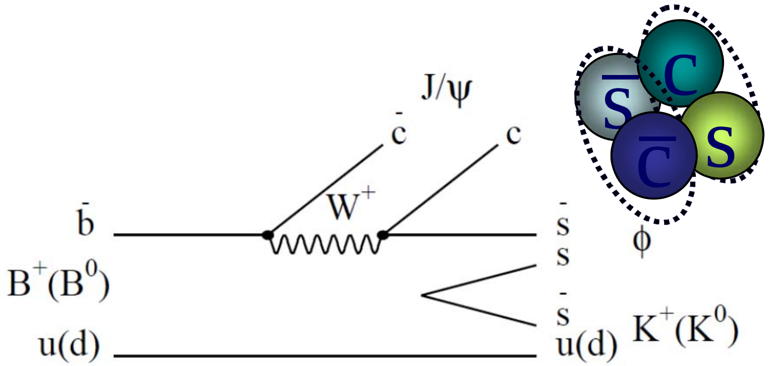
P Pakhlov, ITEP

$B^+ \to J/\psi\varphi K^+$, $Y(4140) \to J/\psi\varphi$



M(J/ψφ) – M(J/ψ)

Search for possible diquark-antidiquark state



$M = 4143.0 \pm 2.9 \pm 1.2 \text{MeV}/c^2$

$\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$ MeV

$Br(B^+ \to YK^+) \times Br(Y \to J/\psi\varphi)$

Belle: $< 6 \times 10^{-6}$ at 90% CL

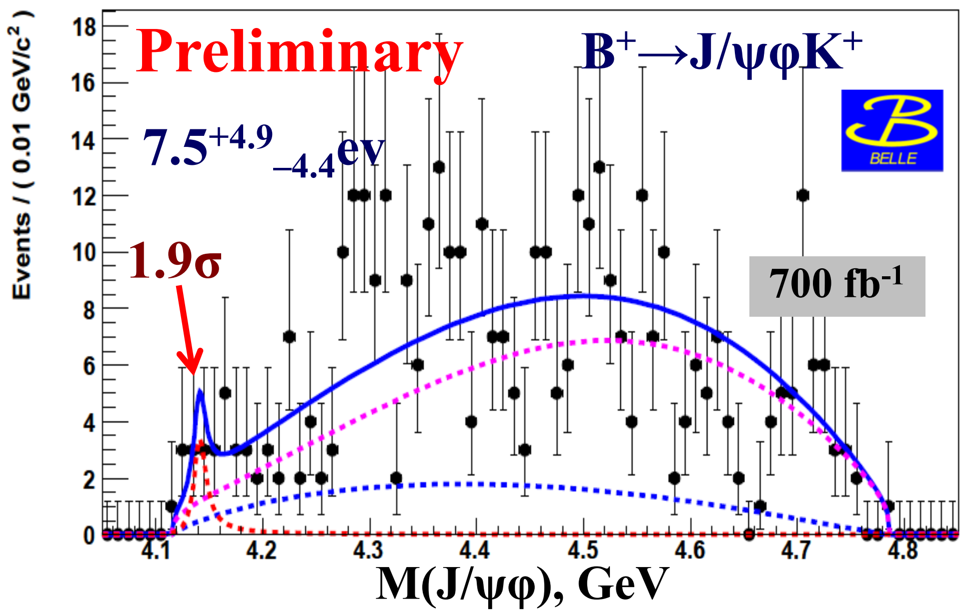
CDF: $(9.0 \pm 3.4 \pm 2.9) \times 10^{-6}$

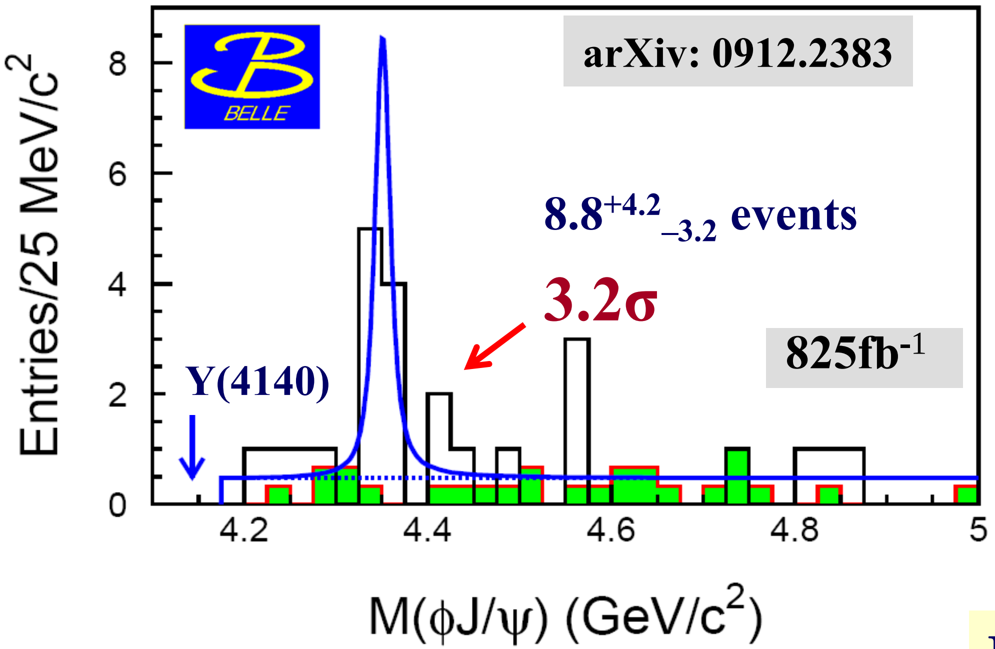
No big contradiction

small efficiency at threshold

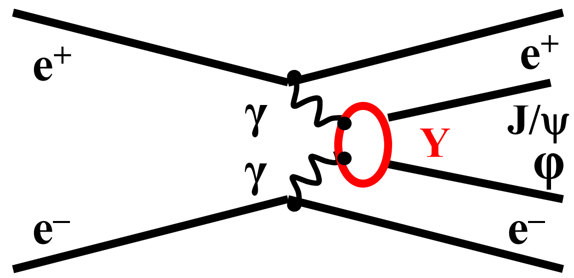
M(J/ψφ) fit with fixed parameters of Y(4140)

Y(4140) is not confirmed





$\gamma\gamma \to \varphi J/\psi$



J = 0, 2 only

$\Gamma_{\gamma\gamma}$ (Y(4140) × B(Y(4140) → φJ/ψ)
< 40 eV at 90% CL for $J^P=0^+$
< 5.9 eV at 90% CL for $J^P=2^+$
disfavor $D_s^{*+}D_s^{*-}$ molecule scenario for Y(4140) with $J^{PC} = 0^{++}$ or 2^{++}

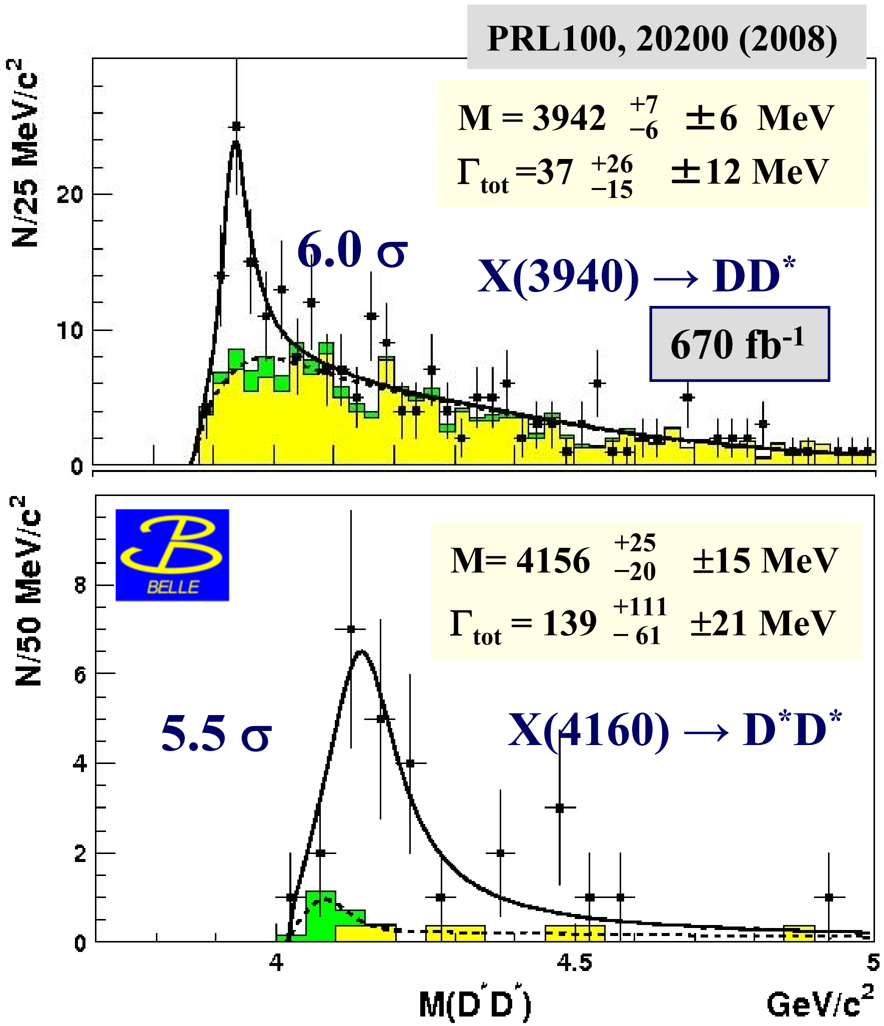
M = (4150.6 ± 5.1 ± 0.7) MeV/c²

$\Gamma = (13.3^{+17.9}_{-9.1} \pm 4.1)$ MeV

$\Gamma_{\gamma\gamma}$ (Y(4350) × B(Y(4350) → φJ/ψ) =
$(6.7^{+3.2}_{-2,4} \pm 1.1)$ eV for $J^P=0^+$
$(1.5^{+0.7}_{-0.6} \pm 0.3)$ eV for $J^P=2^+$

interpretations: $D_s^{*+}D_{s0}^{*-}$ molecule or sscc tetraquark with $J^{PC} = 2^{++}$; P-wave charmonium $\chi_{c2}(3P) = 3^3P_2$

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



- **decay to open charm final states like conventional charmonium**
- **production mechanism fix C=+1**
- **known states produced in $e^+e^- \to J/\psi\ cc$ have J=0**
- **not seen in DD decay, exclude $J^{PC}=0^{++}$**

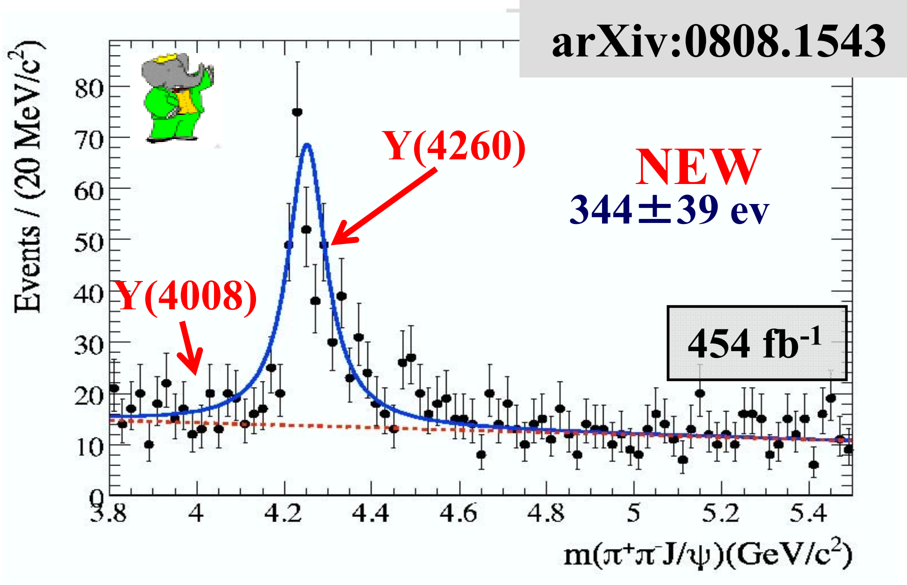
⇩

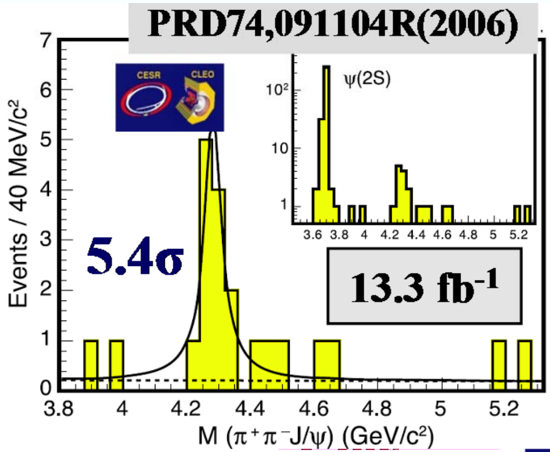
Plausible assignments are $J^{PC}=0^{-+}$
$X(3940) = 3^1S_0 = \eta_c(3S)$
$X(4160) = 4^1S_0 = \eta_c(4S)$

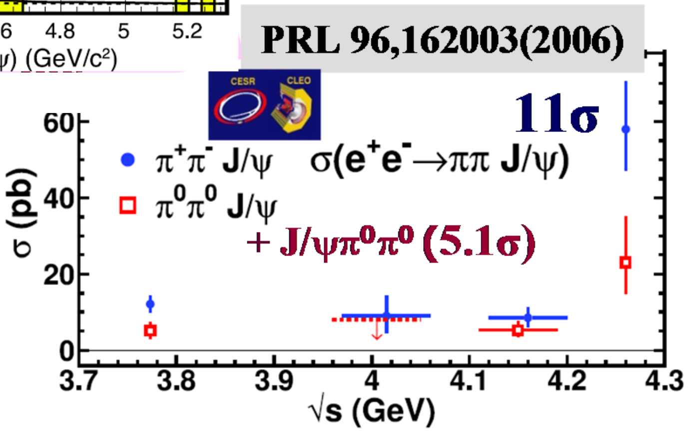
For both X(3940) and X(4160) the masses predicted by the potential models are ~100–250 MeV higher

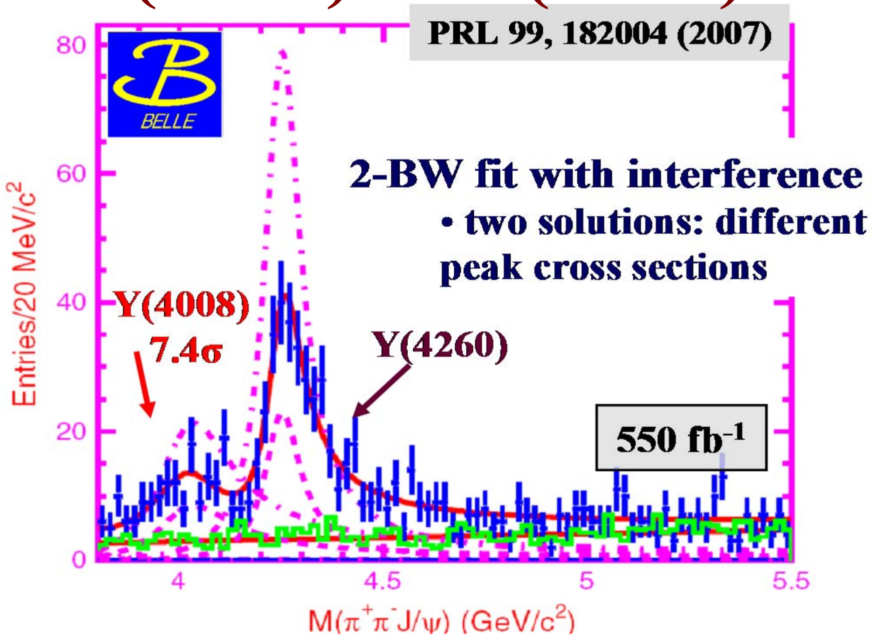
$e^+e^- \to J/\psi\, \pi^+\pi^-\, \gamma_{ISR}$

Y(4260) ... Y(4008)?

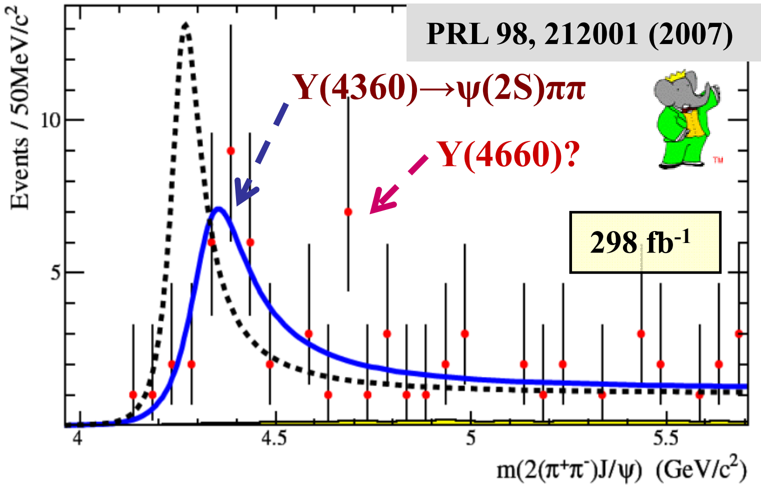


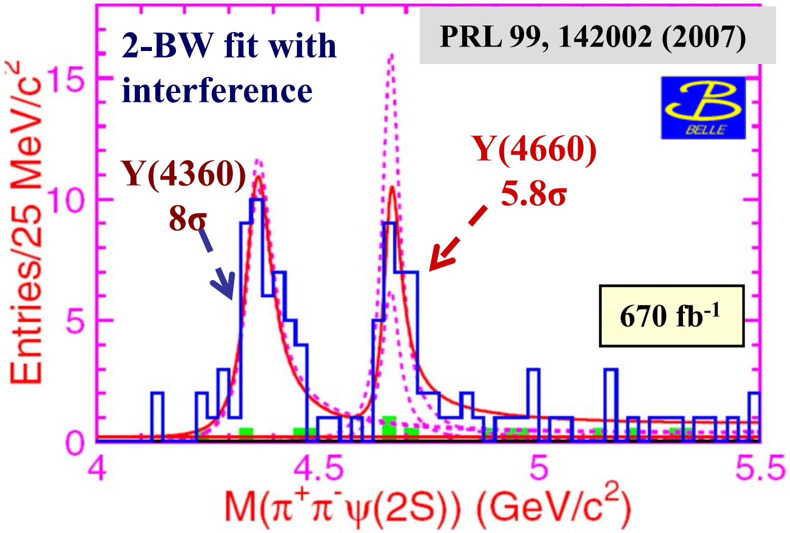






State	M, MeV/c^2	Γ_{tot}, MeV
Y(4008)	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$
Y(4260)	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
Y(4260)	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$
Y(4260)	$4284^{+17}_{-16} \pm 4$	$73^{+39}_{-25} \pm 5$
Y(4260)	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$





$e^+e^- \to \psi(2S)\,\pi^+\pi^-\,\gamma_{ISR}$
Y(4360), Y(4660) ...

B&B combined PRD 78, 014032 (2008)

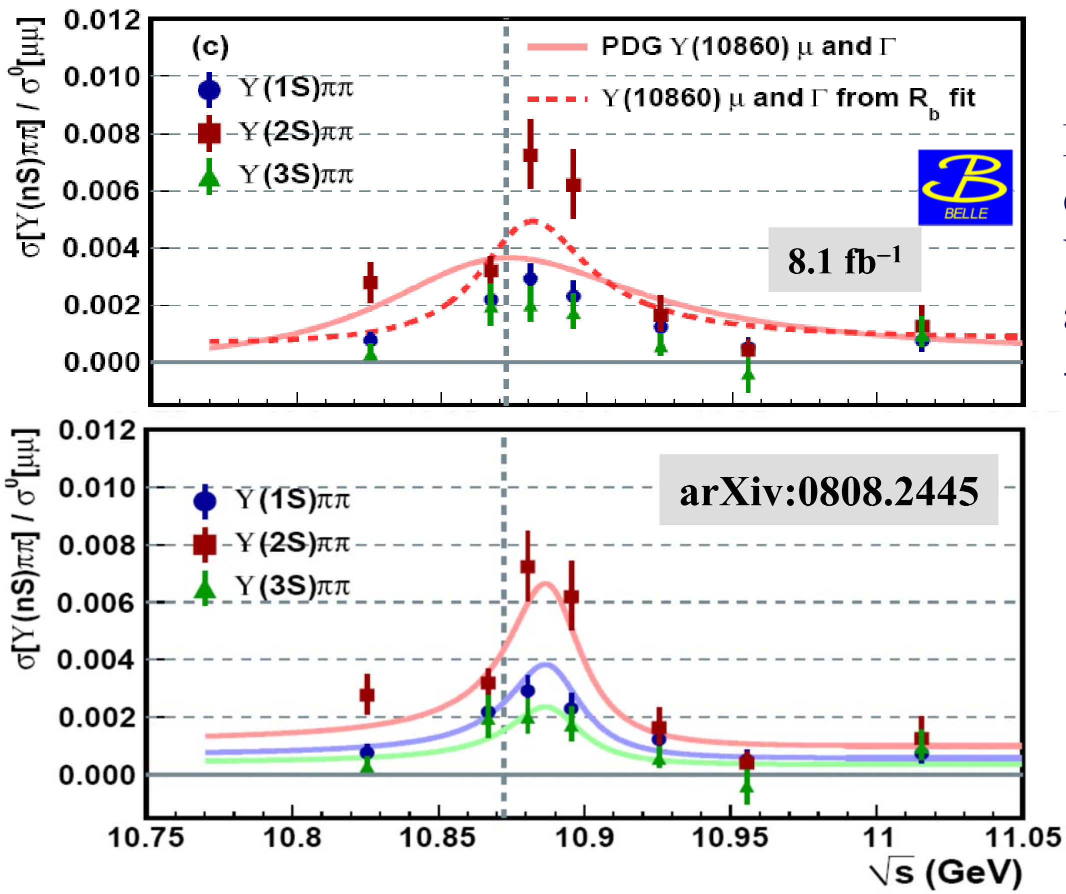
State	M, [MeV/c^2]	Γ_{tot}, [MeV]
Y(4360)	4324 ± 24	172 ± 33
Y(4360)	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4360)	$4355^{+9}_{-10} \pm 9$	$103^{+17}_{-15} \pm 11$
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$
Y(4660)	$4661^{+9}_{-8} \pm 6$	$42^{+17}_{-12} \pm 6$

Absence of open charm production, too large partial widths in charmonium and light mesons are inconsistent with conventional charmonium

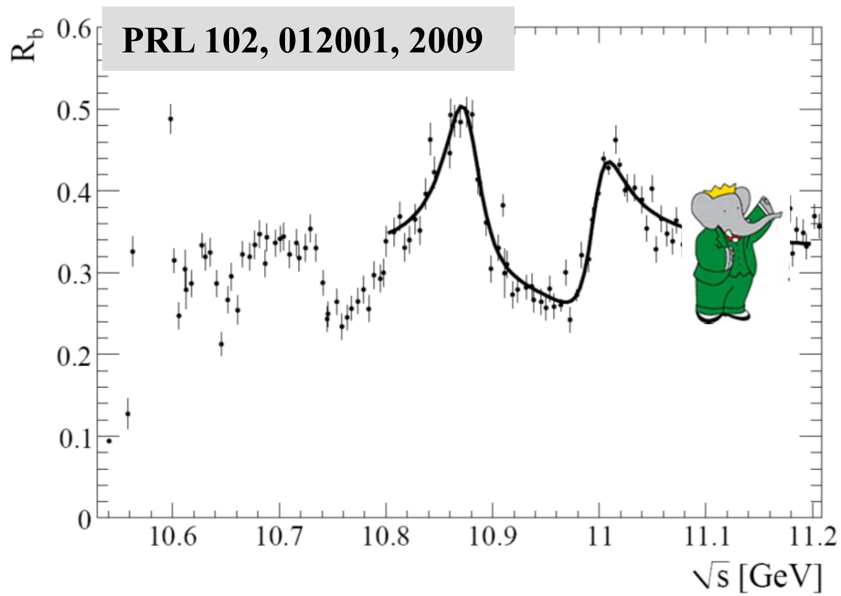
Another problem is absence of vacant $J^{PC}=1^{--}$ charmonium states

- **Charmonium hybrids** (LQCD expect ~ 4.2 GeV; the dominant decays to $D^{(*)}D^{(*)}\pi$)
- **Hadro-charmonium** -specific charmonium state "coated" by excited light-hadron matter
- **Multiquark states** ([cq][cq] tetraquark or DD_1/D^*D^0 molecules)
- **S-wave charm meson thresholds**

$b\bar{b}$ counterpart of Y?



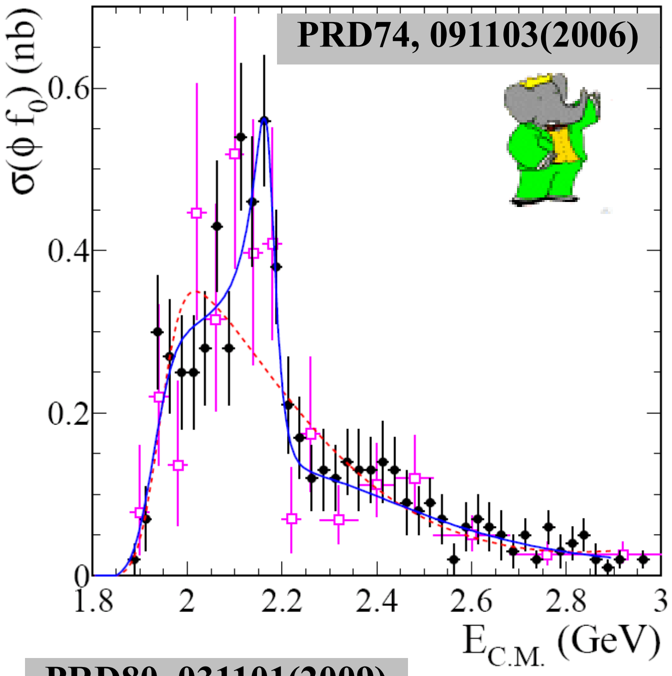
Energy scan above Y(4S) to search for counterpart of Y(4260) in bottomonium sector: study anomalously large cross section of $e^+e^- \to Y(nS)\pi^+\pi^-$, (n = 1, 2, 3)



Fit to inclusive cross section $e^+e^- \to$ hadrons coherent Y(5S) +Y(6S) + continuum

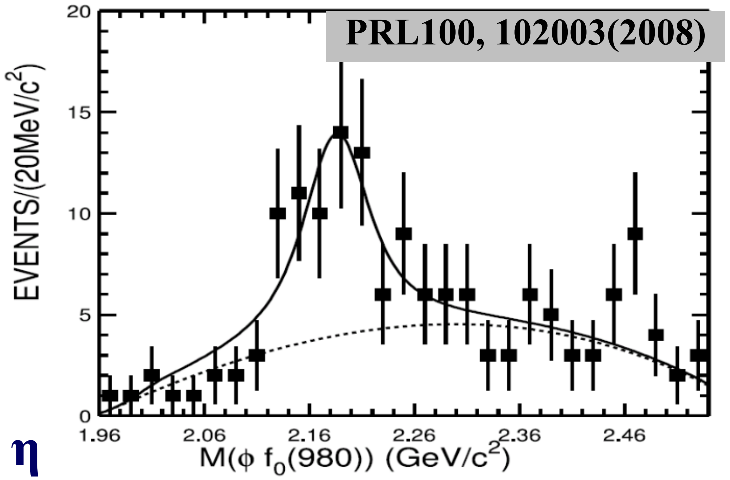
	$\Upsilon(10860)$	$\Upsilon(11020)$
mass (GeV)	10.876 ± 0.002	10.996 ± 0.002
width (MeV)	43 ± 4	37 ± 3
ϕ (rad)	2.11 ± 0.12	0.12 ± 0.07
PDG mass (GeV)	10.865 ± 0.008	11.019 ± 0.008
PDG width (MeV)	110 ± 13	79 ± 16

Both inclusive and exclusive dipion cross-sections are inconsistent with PDG Y(5,6S) parameters and poorly agree each other.

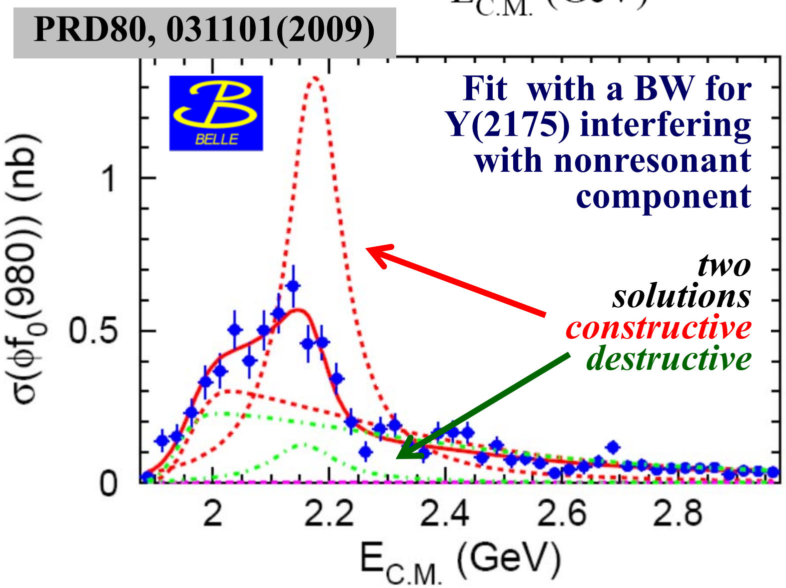


$s\bar{s}$ counterpart of Y?

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



BESII:
$J/\psi \to \varphi f_0 \eta$



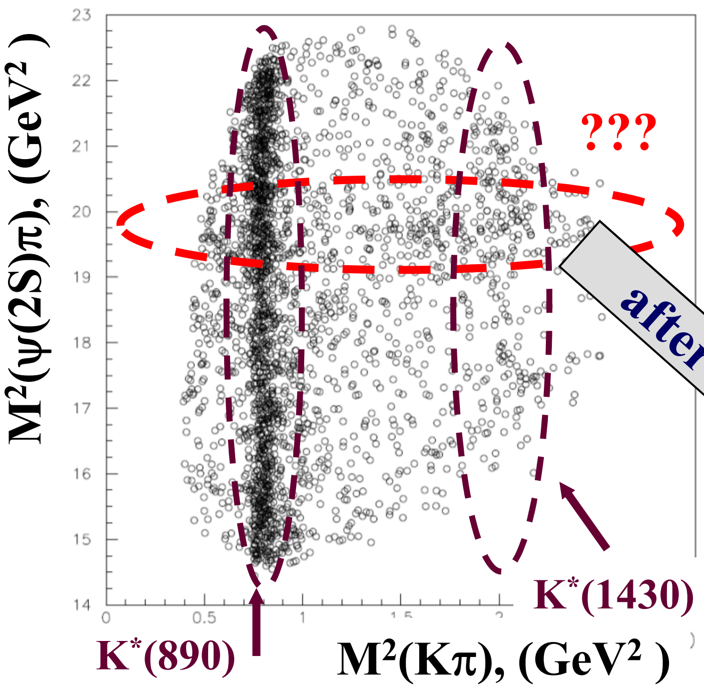
Experiment	Channel	Mass (MeV/c^2)	Width (MeV/c^2)
BaBar [23]	$Y(2175) \to \phi f_0(980)$	$2175 \pm 10 \pm 15$	$58 \pm 16 \pm 20$
BES [25]	$Y(2175) \to \phi f_0(980)$	$2186 \pm 10 \pm 6$	$65 \pm 23 \pm 17$
Belle [26]	$Y(2175) \to \phi\pi^+\pi^-, \phi f_0(980)$	2133^{+69}_{-115}	169^{+105}_{-92}
Belle [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

Interpretations:

PDG 09: φ(2170) 3^3S_1 ss state? but predicted width ~380MeV!
hybrid similar to Y(4260)? tetraquark? ....

Other decay channels to be measured to clarify the nature of Y(2175)

$Z(4430)^+$ first charged charmoniumlike state



<u>Cannot be conventional charmonium or hybrid</u>

$B \to KZ$, $Z(4430)^+ \to \pi^+\psi(2S)$
$K=K^-$, K^0_s ; $\psi(2S) \to \ell^+\ell^-$, $\pi^+\pi^- J/\psi$

Fit: S-wave BW + phase space like function

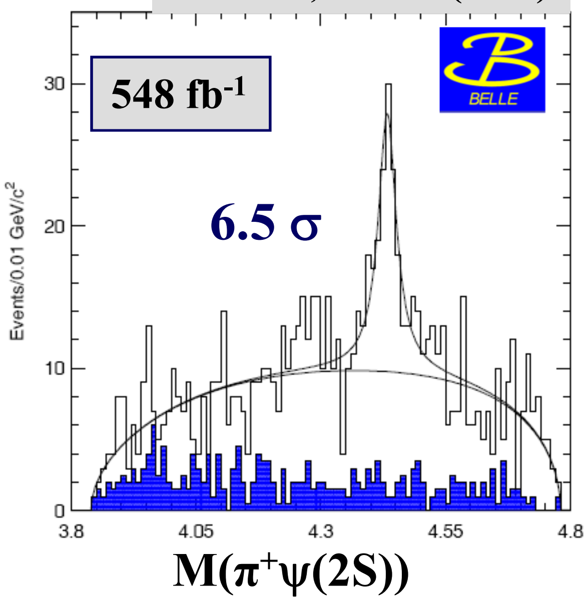
$M = (4433 \pm 4 \pm 2)$ MeV $\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV

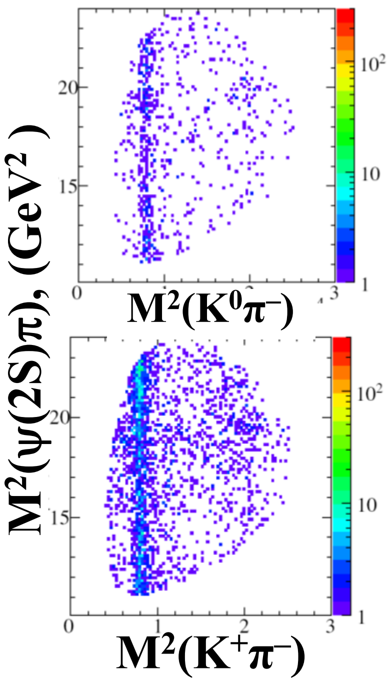
$Br(B\to KZ) \times Br(Z\to\psi(2S)\pi) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$ $Br_{\pm} / Br_0 = 1.0 \pm 0.4$

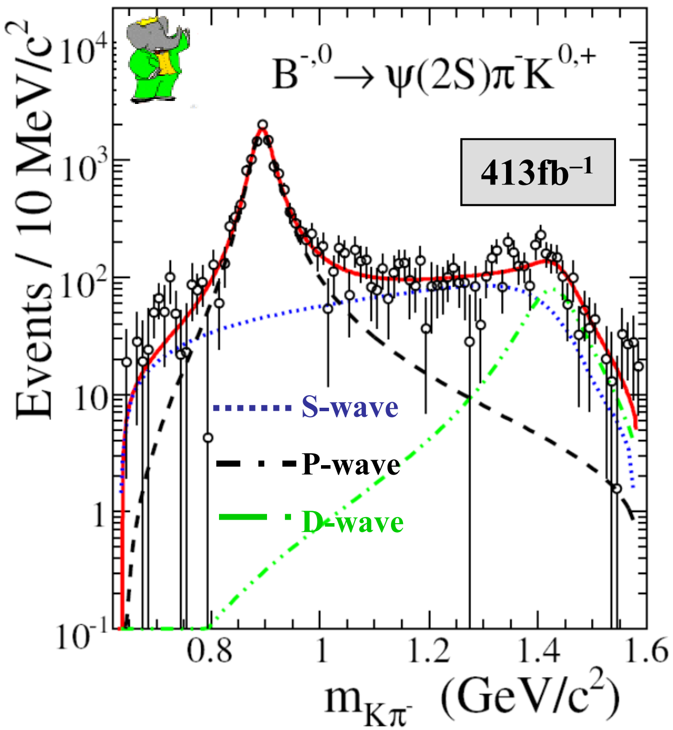
Shows up in all data subsamples

- **Could the Z(4430) be due to a reflection from the $K\pi$ channel?**
  - **S- P- & D-waves cannot make a peak (+ nothing else)**

PRL 100, 142001 (2008)





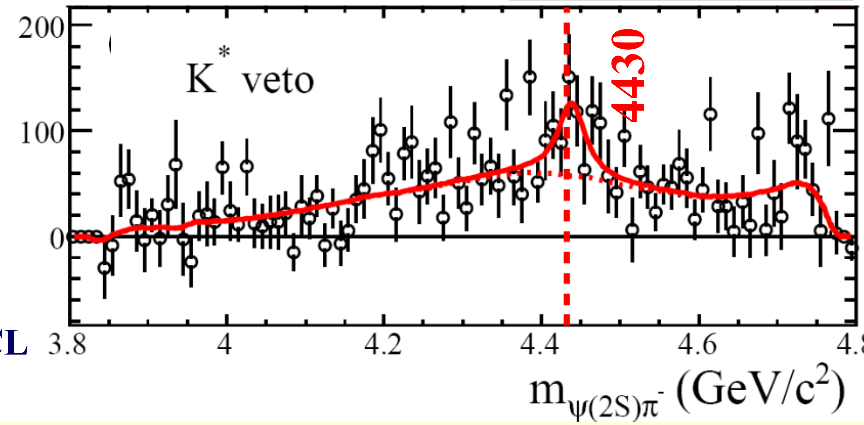


BaBar search for the Z(4430)⁻

$B^{-0} \rightarrow J/\psi\pi^- K^{0+}$; $B^{-0} \rightarrow \psi(2S)\pi^- K^{0+}$

- **Detailed study of K π^- reflections into the J/ψ π^- and ψ(2S) π^- masses (S, P, D waves) to describe background for both J/ψ and ψ(2S) modes**

PRD79:112001 (2009)

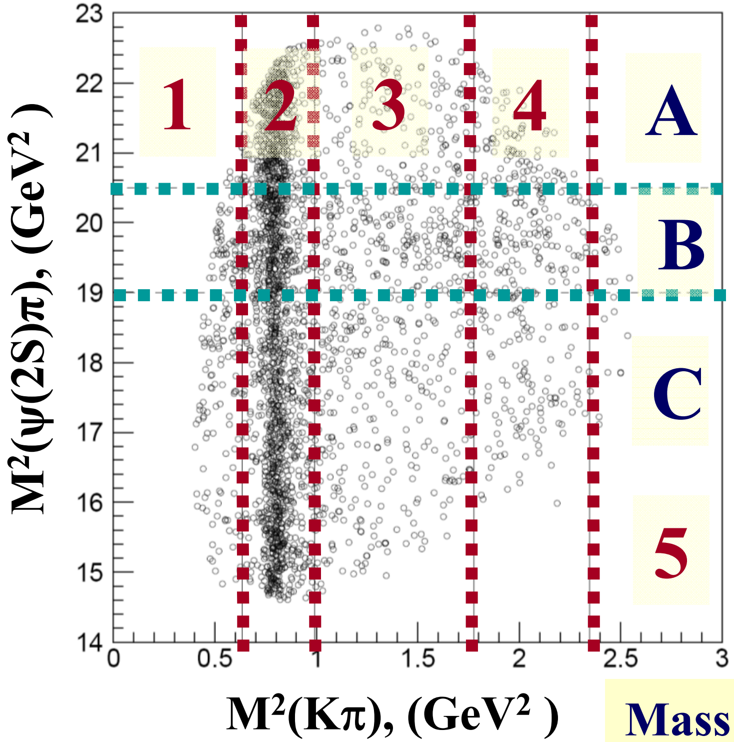


- **Fit to $J/\psi\pi^-$ and ψ(2S) π^- distributions: background + BW (free mass & width). Observe ~2σ fluctuations below/above background in J/ψ and ψ(2S) modes**

- **At M = 4430 MeV/c² & Γ = 45 MeV**

$Br(B^0 \rightarrow Z^- K^+, Z^- \rightarrow \psi(2S)\pi^-) < 3.1 \times 10^{-5}$ @ 95% CL

"For the fit … equivalent to the Belle analysis…we obtain mass & width values that are consistent with theirs,… but only ~1.9σ from zero; fixing mass and width increases this to only ~3.1σ…"



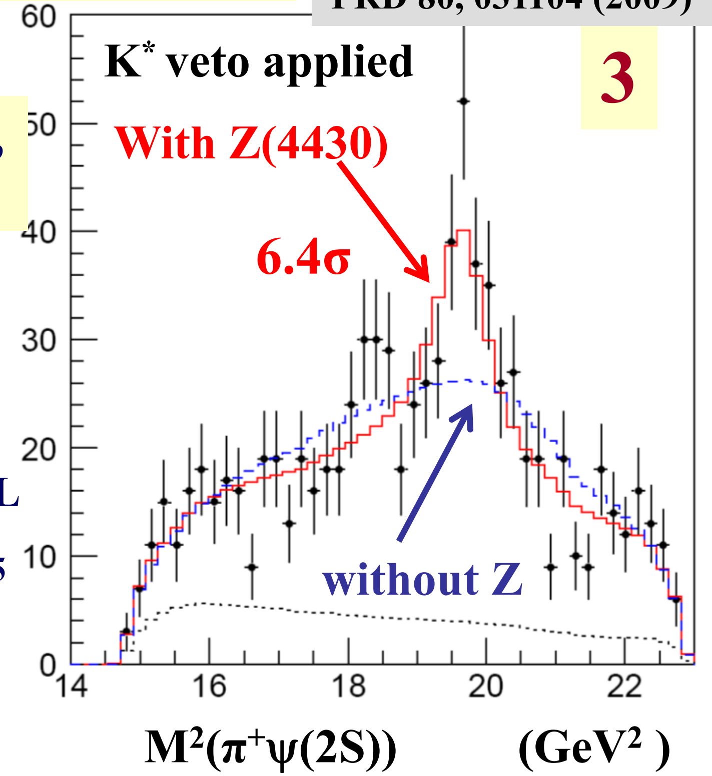
Reanalysis of $B \to K\pi\psi(2S)$ data using Dalitz fit

Fit $B^0 \to \psi(2S)\pi^+K^-$ amplitude by coherent sum of RBW contributions

- all known $K\pi$ resonances
- all known $K\pi$ resonances + $\psi(2S)\pi$ resonance

$M = (4443^{+15}_{-12}{}^{+17}_{-13})$ MeV/c^2
$\Gamma = (109^{+86}_{-43}{}^{+57}_{-52})$ MeV

PRD 80, 031104 (2009)



Mass & significance similar, width & errors are larger

PRL 100, 142001 (2008)

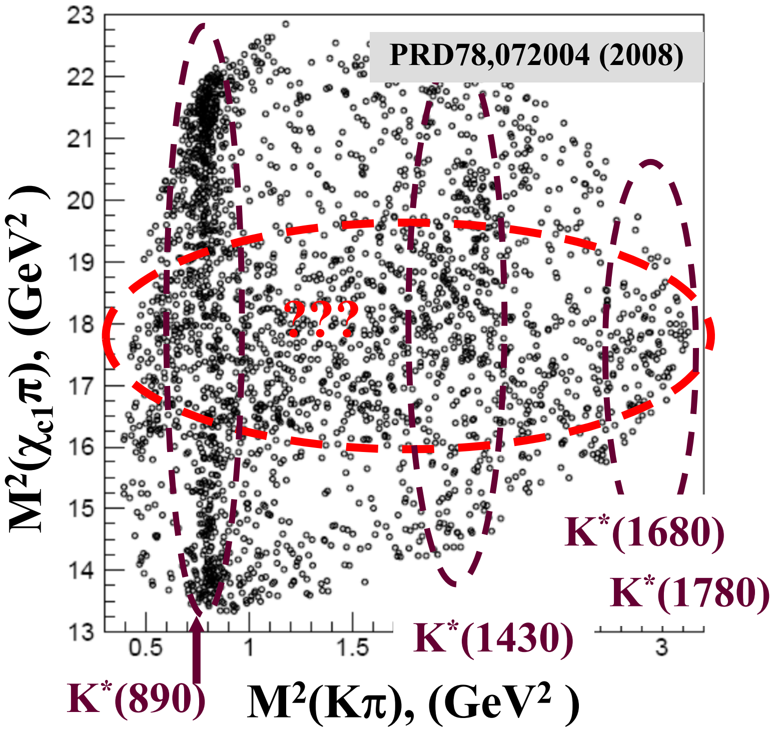
$M = (4433 \pm 4 \pm 2)$ MeV/c^2 $\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV

$Br(B^0 \to Z^- K^+, Z^- \to \psi(2S)\pi^-) < 3.1 \times 10^{-5}$ @ 95% CL

$= (3.2^{+1.8}_{-0.9}{}^{+5.3}_{-1.6}) \times 10^{-5}$

No big contradiction

$Z^+_{1,2} \rightarrow \chi_{c1}\pi^+$

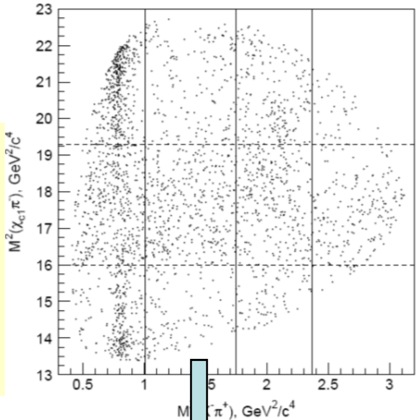


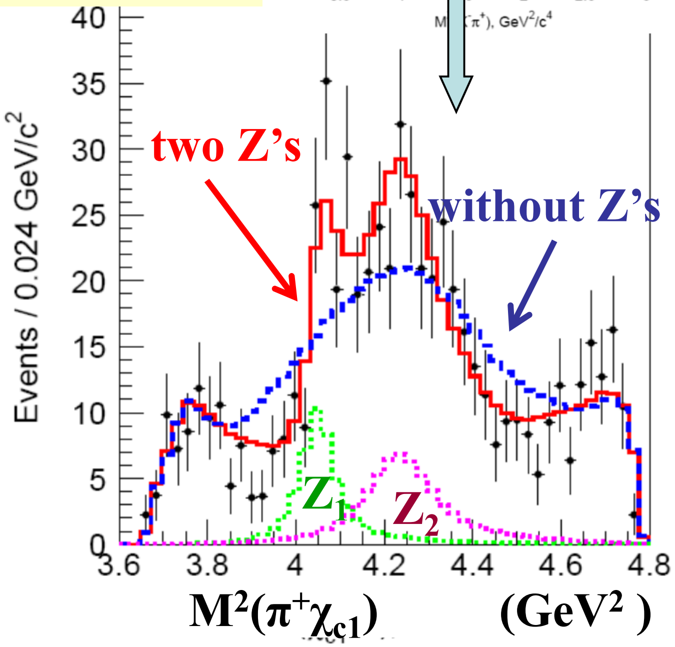
$B^0 \rightarrow \chi_{c1}\pi^+K^-$; $\chi_{c1} \rightarrow J/\psi\gamma$

Dalitz analysis: fit $B^0 \rightarrow \chi_{c1}\pi^+K^-$ amplitude by coherent sum of RBW contributions

- known $K\pi$ resonances
- K^*'s + one $(\chi_{c1}\,\pi)$ resonance
- K^*'s + two $(\chi_{c1}\,\pi)$ resonances

$M_1 = (4051 \pm 14^{+20}_{-41})$ MeV/c^2
$\Gamma_1 = (82^{+21}_{-17}{}^{+47}_{-22})$ MeV
$M_2 = (4248^{+44}_{-29}{}^{+180}_{-35})$ MeV/c^2
$\Gamma_1 = (177^{+54}_{-39}{}^{+316}_{-61})$ MeV





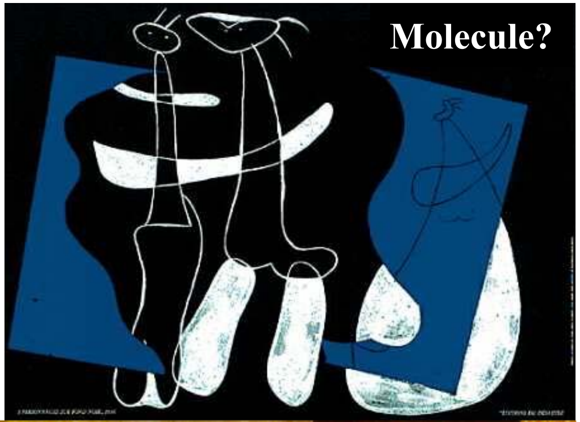
- Hypothesis of two Z's resonances is favored over one Z resonance at 5.7 σ

- Spin of $Z_{1,2}$ is not determined: J=0 and J=1 result in comparable fit qualities

$$\mathcal{B}(\overline{B}^0 \rightarrow K^- Z_1^+) \times \mathcal{B}(Z_1^+ \rightarrow \pi^+ \chi_{c1}) = (3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5},$$

$$\mathcal{B}(\overline{B}^0 \rightarrow K^- Z_2^+) \times \mathcal{B}(Z_2^+ \rightarrow \pi^+ \chi_{c1}) = (4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{-5}.$$

Summary



- Hard work have been done by BaBar & Belle teams
  - More than ten new states have been observed
  - PDG almost double its volume after 10 years of BaBar&Belle running

- Theorists work also hard, but many states remain unexplained
  - can theory solve all the problems at once?

New Super B-factories

Super KEKB Quest for BSM   SuperB

could help to resolve most of XYZ puzzles … but likely (hopefully) add more …