Exotic Particles From B-Factories

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EXHIC10 @ YITP, Kyoto, May 20, 2010

APOLOGIES

- The choice of subjects are limited
  - only results from Belle/BaBar
  - only for charmonium-like cases (i.e. no D_{SJ} ...)
  - + just a brief mention of a result in bb-like system

- Some slides are taken from other people's talks

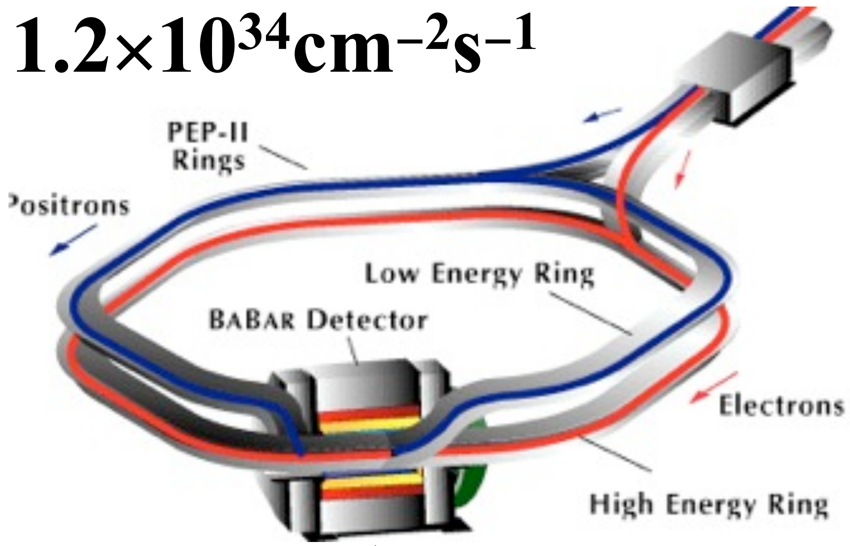
Outline

- A brief intro. to B-factory experiments
- The exotic particles
  - X(3872)
  - the family of Y(3940)
  - the charged exotics, a smoking gun?

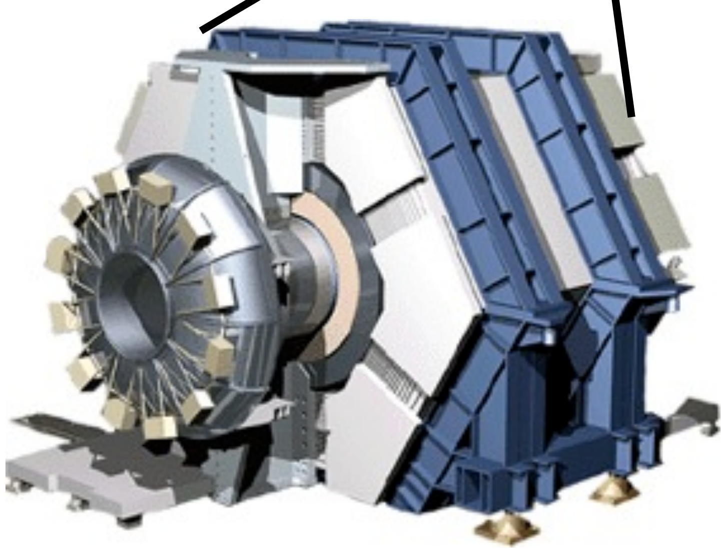
Two asymmetric B-factories

PEP-II at SLAC

9GeV (e^-) × 3.1GeV (e^+)
peak luminosity:
1.2×10^{34}cm^{-2}s^{-1}

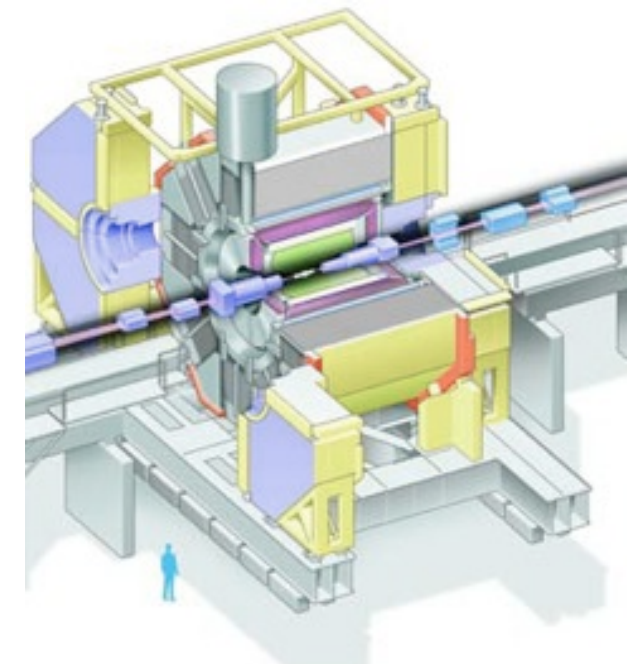


BaBar

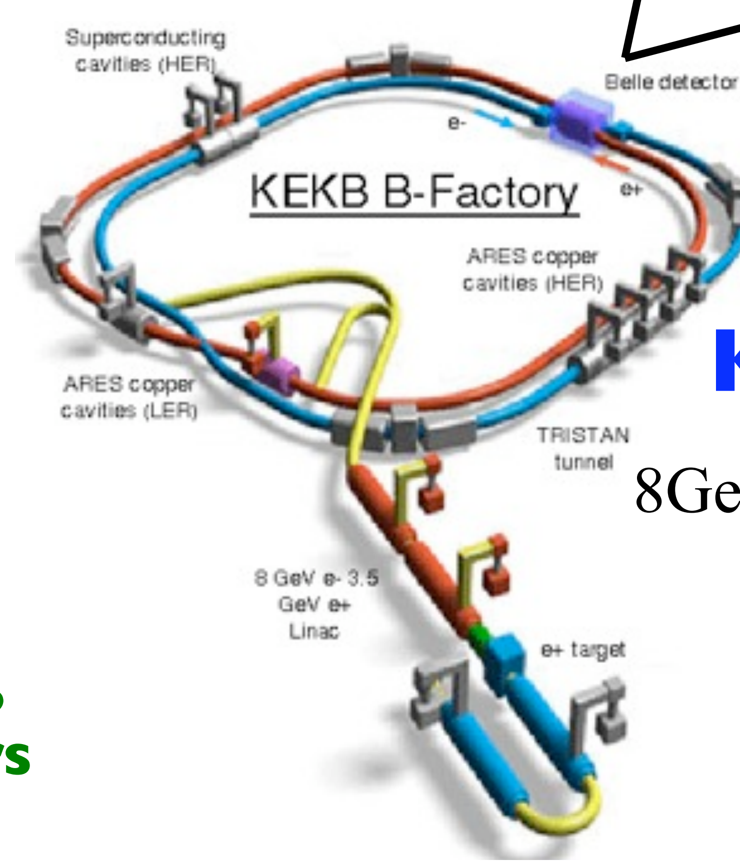


11 nations, 80 institutes, ~600 members

13 countries, 57 institutes, ~400 members



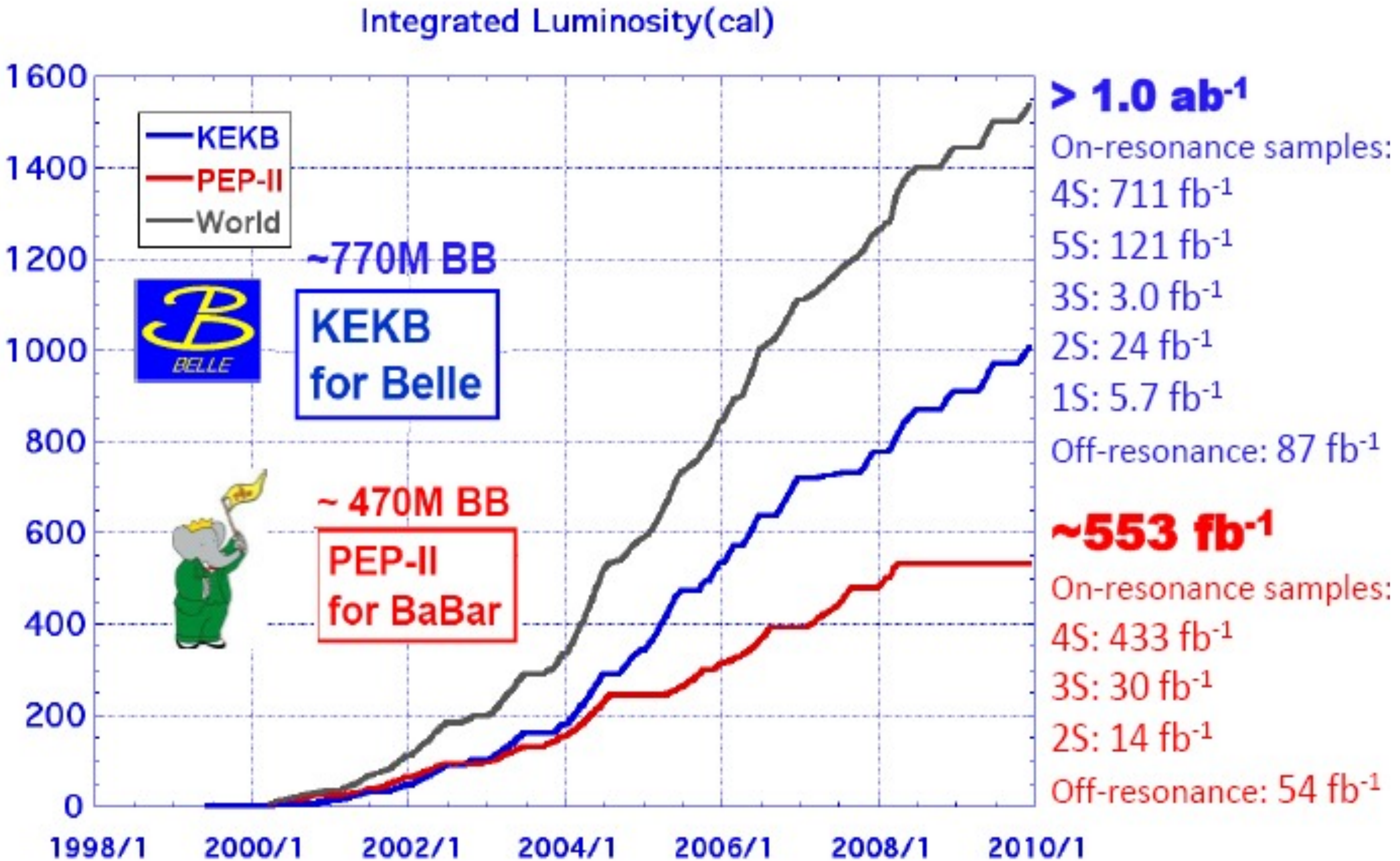
Belle

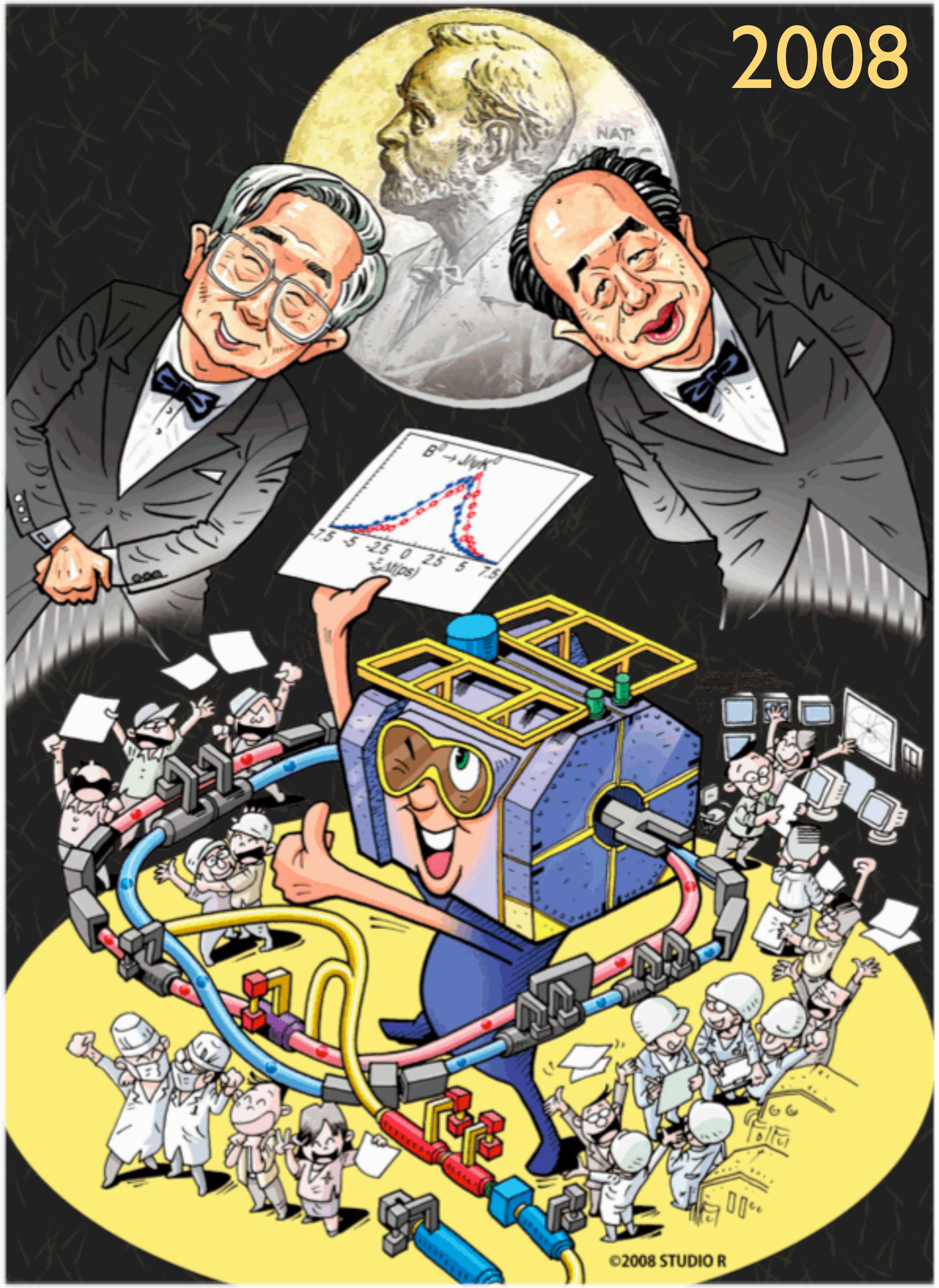


KEKB at KEK

8GeV (e^-) × 3.5GeV (e^+)
peak luminosity:
2.1×10^{34}cm^{-2}s^{-1}
world record

Belle/BaBar Luminosities





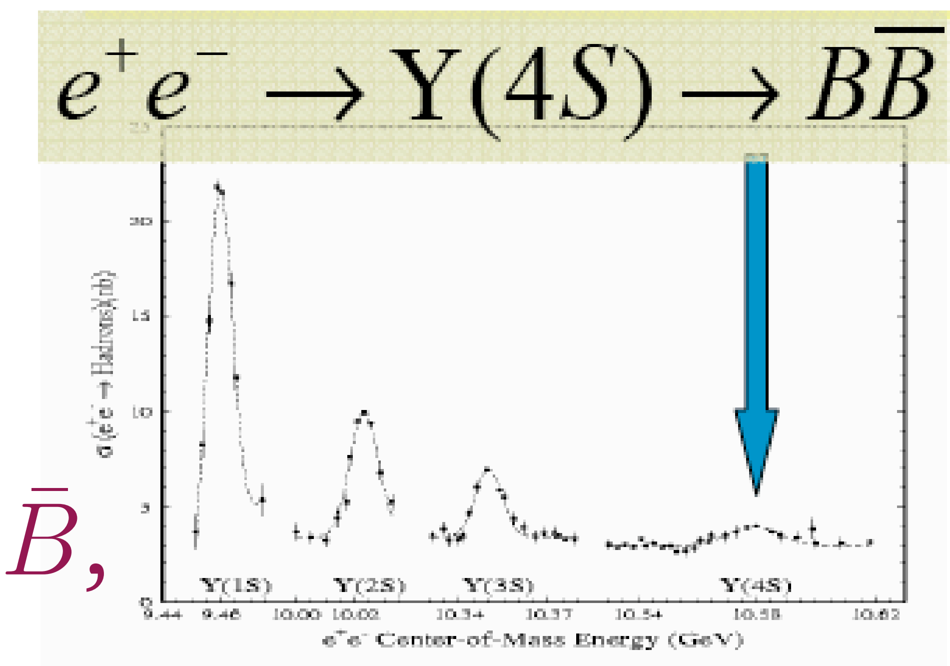
- Critical role of the B-factories in the verification of the KM hypothesis was recognized and cited by the Nobel Foundation
- A single irreducible phase in the weak int. matrix accounts for most of the CP violation observed in the K's and in the B's
- CP-violating effects in the B sector are $\mathcal{O}(1)$ rather than $\mathcal{O}(10^{-3})$ as in the K^0 system.

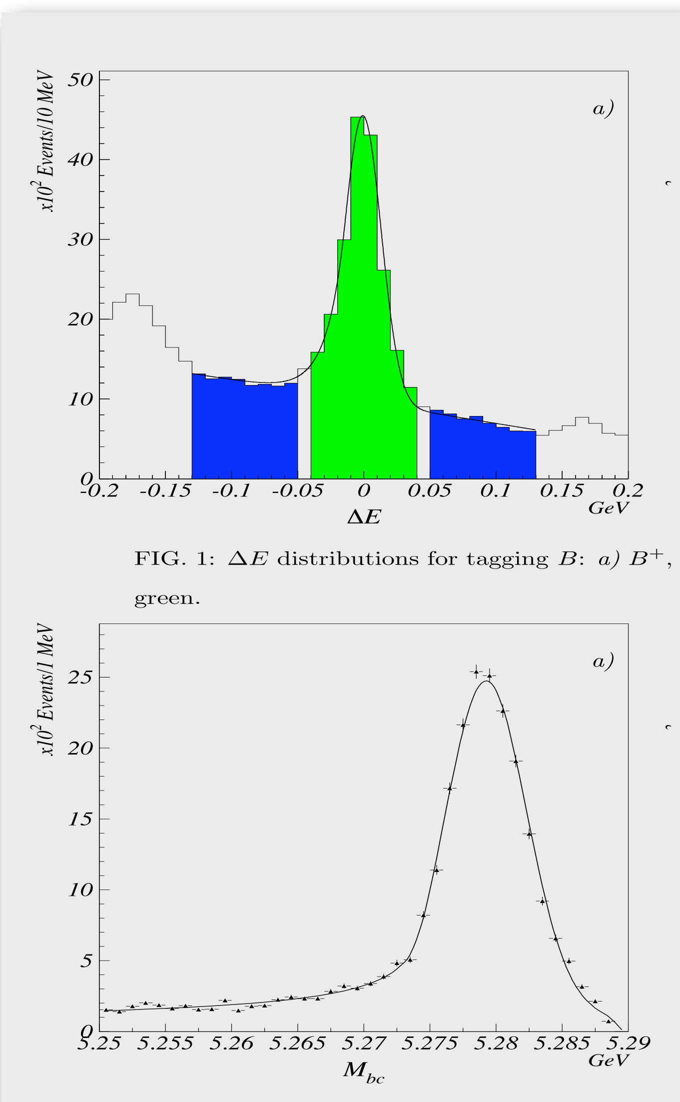
$m_{\rm ES}$ ~~$M_{\rm bc}$~~ & ΔE

"energy-substituted mass"

For a decay $B \to f_1 f_2 f_3$,

- $(E, \vec{p})_B = (\sum_i E_i, \sum_i \vec{p}_i)$
- $M_B^2 = (\sum_i E_i)^2 - |\sum_i \vec{p}_i|^2$





But for $\Upsilon(4S) \to B\bar{B}$,

- $\sum_i E_i = E_{\rm beam}$ in the CM frame
- Use $M_{\rm bc}^2 \equiv E_{\rm beam}^2 - |\sum_i \vec{p}_i|^2$
- and require $\Delta E \equiv \sum_i E_i - E_{\rm beam} \approx 0$

The coin toss

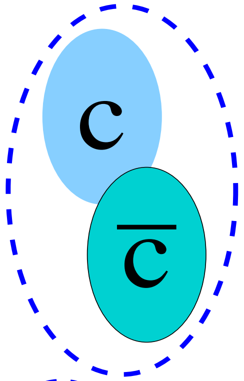
A reminder of our plan, agreed with both collaborations,
to decide between notation conventions for angles and other quantities:

- use one scheme; share the pain
- we will make a fair coin toss between
  1. $\{\phi_1, \phi_2, \phi_3, (S, C), m_{ES}, \ldots\}$
  2. $\{\beta, \alpha, \gamma, (S, A), M_{bc}, \ldots\}$
- I will toss
- Adrian will call “heads” or “tails” for scheme 2
- we will open the box

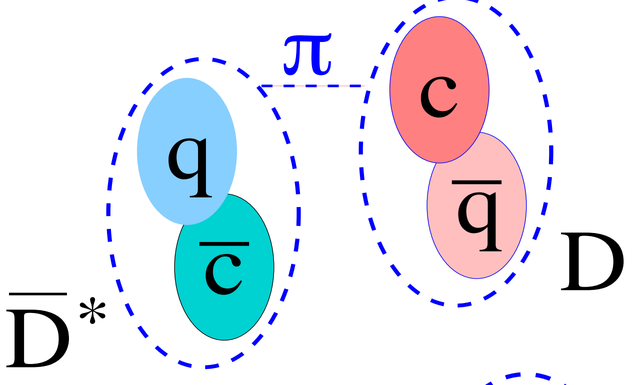
Drumroll please . . .

Exotic hadrons?

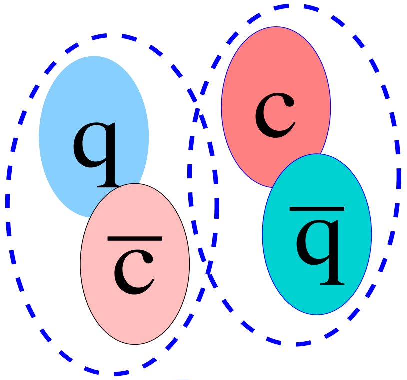
Conventional $c\bar{c}$: Reasonably well understood mesons, known for long time. Number of states fixed with masses rather well predicted.
Usually first choice for new state



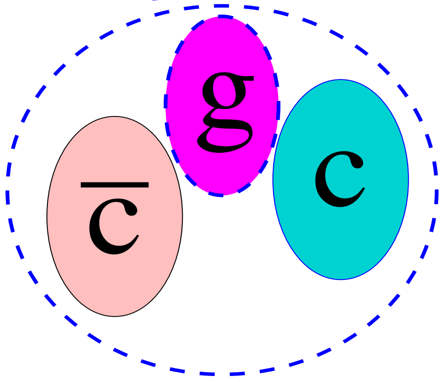
Molecule: Meson and antimeson loosely bound by pion exchange.
Mass slightly below sum of mesons masses.



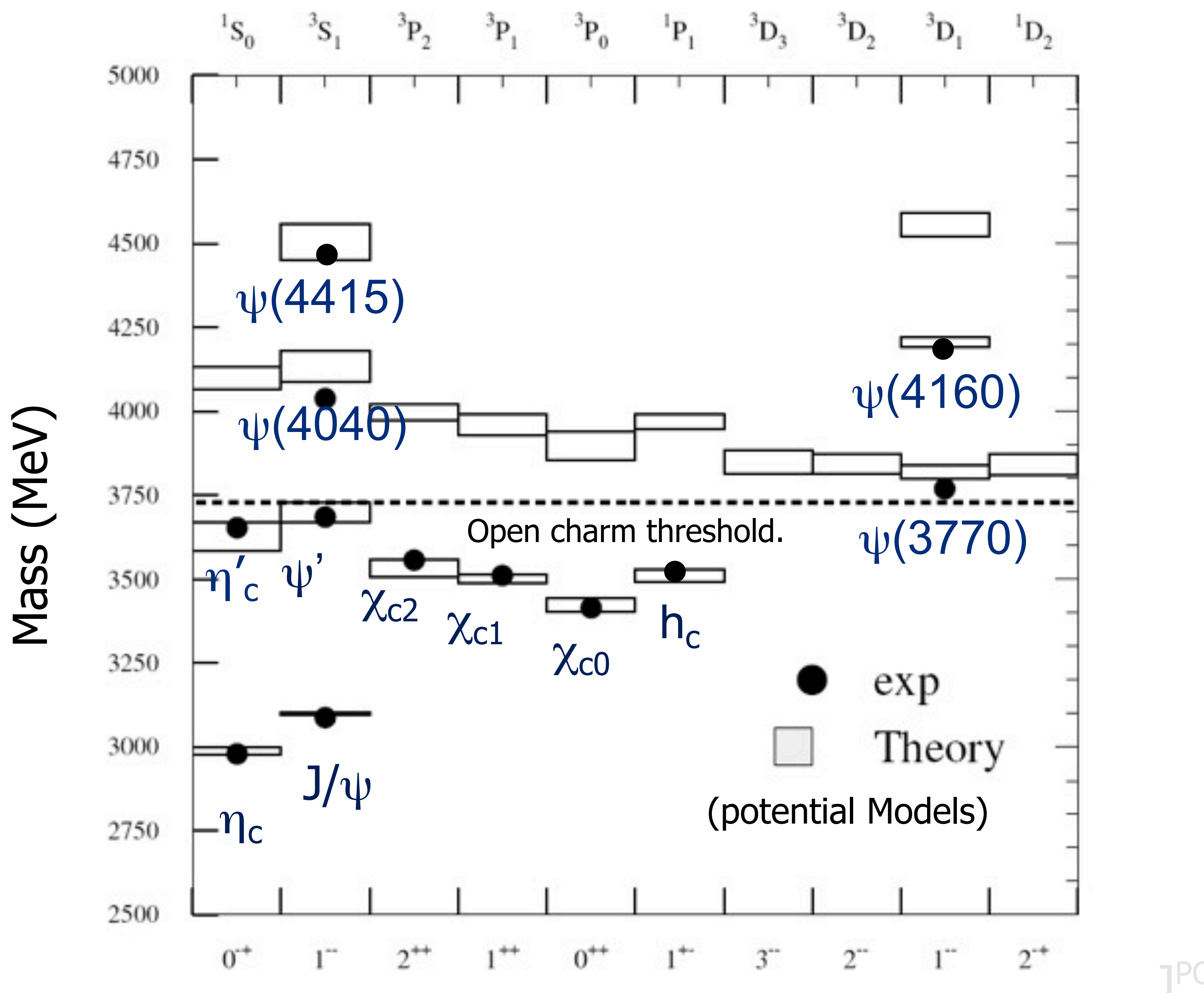
Tetraquark: Colored quarks tightly bound by gluon exchange.
Expect charged states in charmonium mass region

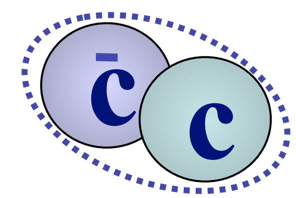


Hybrids: From LQCD $m > 4.2$ GeV, exotic J^{PC} possible, large hadronic transitions $\psi\pi\pi$, $\psi\omega$



Charmonium spectroscopy





$J = S + L$

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

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

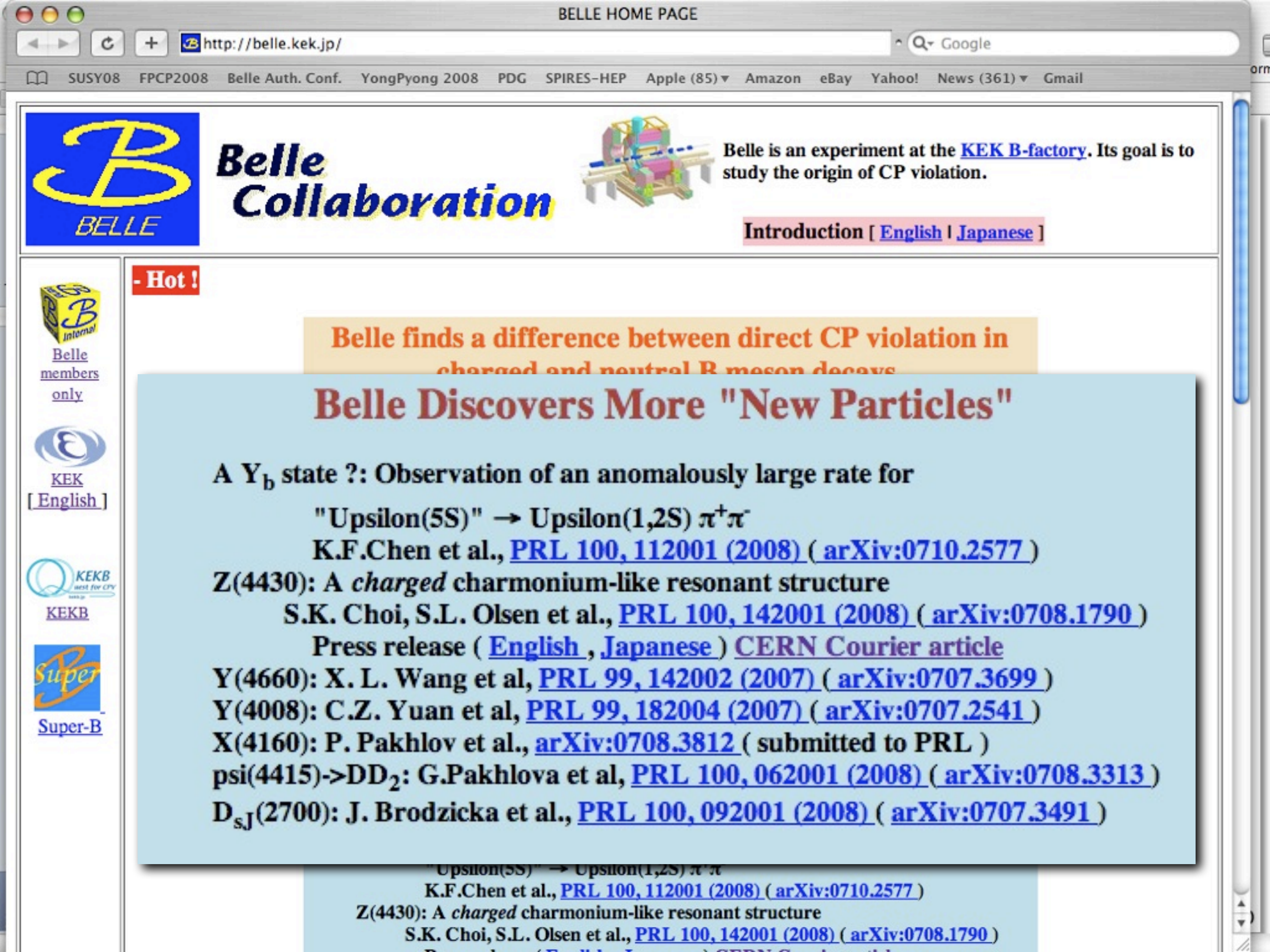
$$n^{(2S+1)}L_J$$

n radial quantum number

S total spin of q-antiq

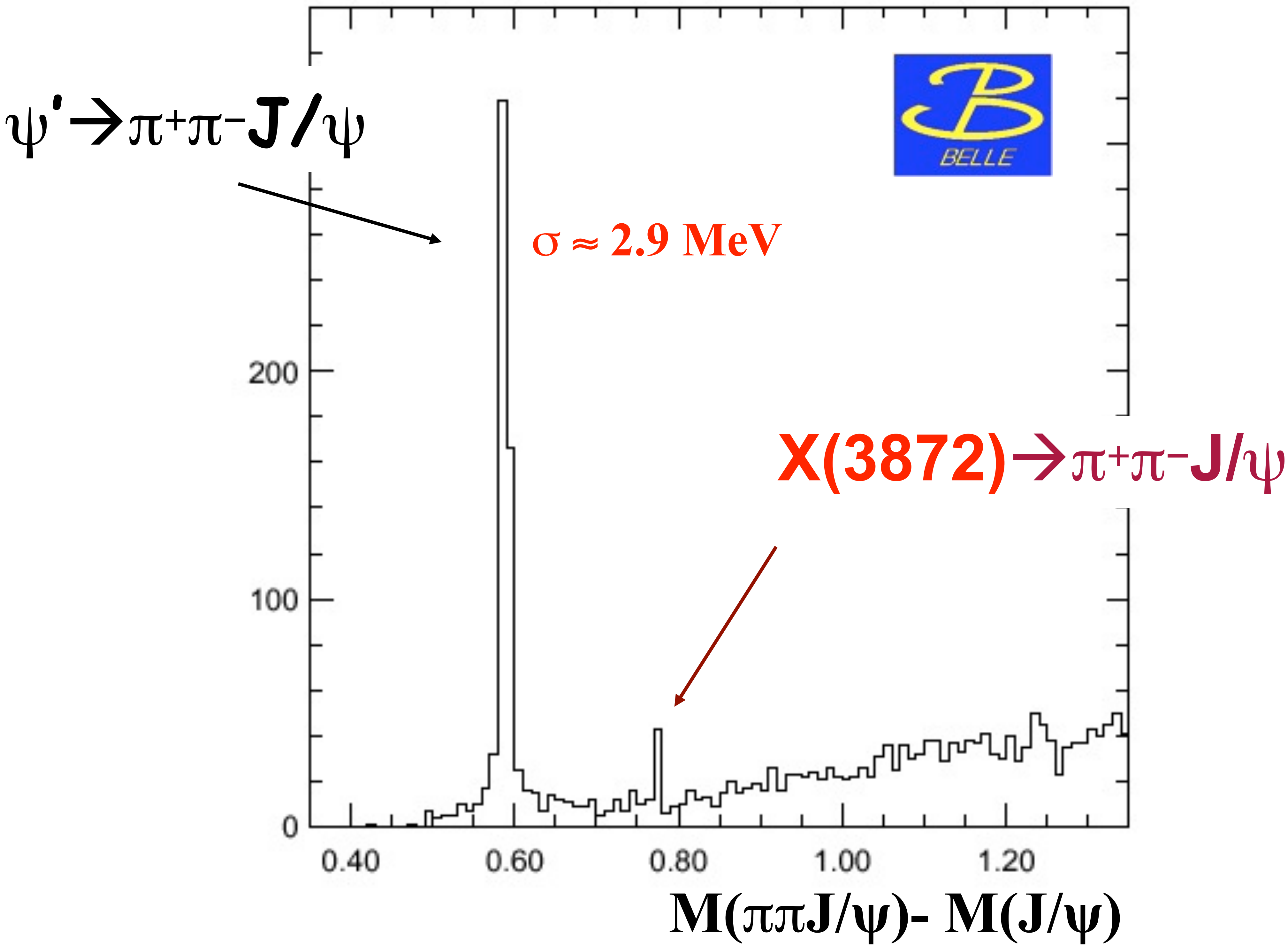
L relative orbital ang. mom.

Potential model worked well for charmonia until the era of B-factories


BELLE HOME PAGE
http://belle.kek.jp/
Google
SUSY08 FPCP2008 Belle Auth. Conf. YongPyong 2008 PDG SPIRES-HEP Apple (85) Amazon eBay Yahoo! News (361) Gmail
BELLE
Belle Collaboration
Belle is an experiment at the KEK B-factory. Its goal is to study the origin of CP violation.
Introduction [English | Japanese]
- Hot !
Belle finds a difference between direct CP violation in charged and neutral B meson decays
Belle members only
KEK [English]
KEKB
KEKB
Super-B
Belle Discovers More "New Particles"
A Y_b state ?: Observation of an anomalously large rate for
"Upsilon(5S)" → Upsilon(1,2S) $\pi^+\pi^-$
K.F.Chen et al., PRL 100, 112001 (2008) (arXiv:0710.2577)
Z(4430): A *charged* charmonium-like resonant structure
S.K. Choi, S.L. Olsen et al., PRL 100, 142001 (2008) (arXiv:0708.1790)
Press release (English , Japanese) CERN Courier article
Y(4660): X. L. Wang et al, PRL 99, 142002 (2007) (arXiv:0707.3699)
Y(4008): C.Z. Yuan et al, PRL 99, 182004 (2007) (arXiv:0707.2541)
X(4160): P. Pakhlov et al., arXiv:0708.3812 (submitted to PRL)
psi(4415)->DD_2: G.Pakhlova et al, PRL 100, 062001 (2008) (arXiv:0708.3313)
D_{sJ}(2700): J. Brodzicka et al., PRL 100, 092001 (2008) (arXiv:0707.3491)
K.F.Chen et al., PRL 100, 112001 (2008) (arXiv:0710.2577)
Z(4430): A *charged* charmonium-like resonant structure
S.K. Choi, S.L. Olsen et al., PRL 100, 142001 (2008) (arXiv:0708.1790)

$X(3872)$

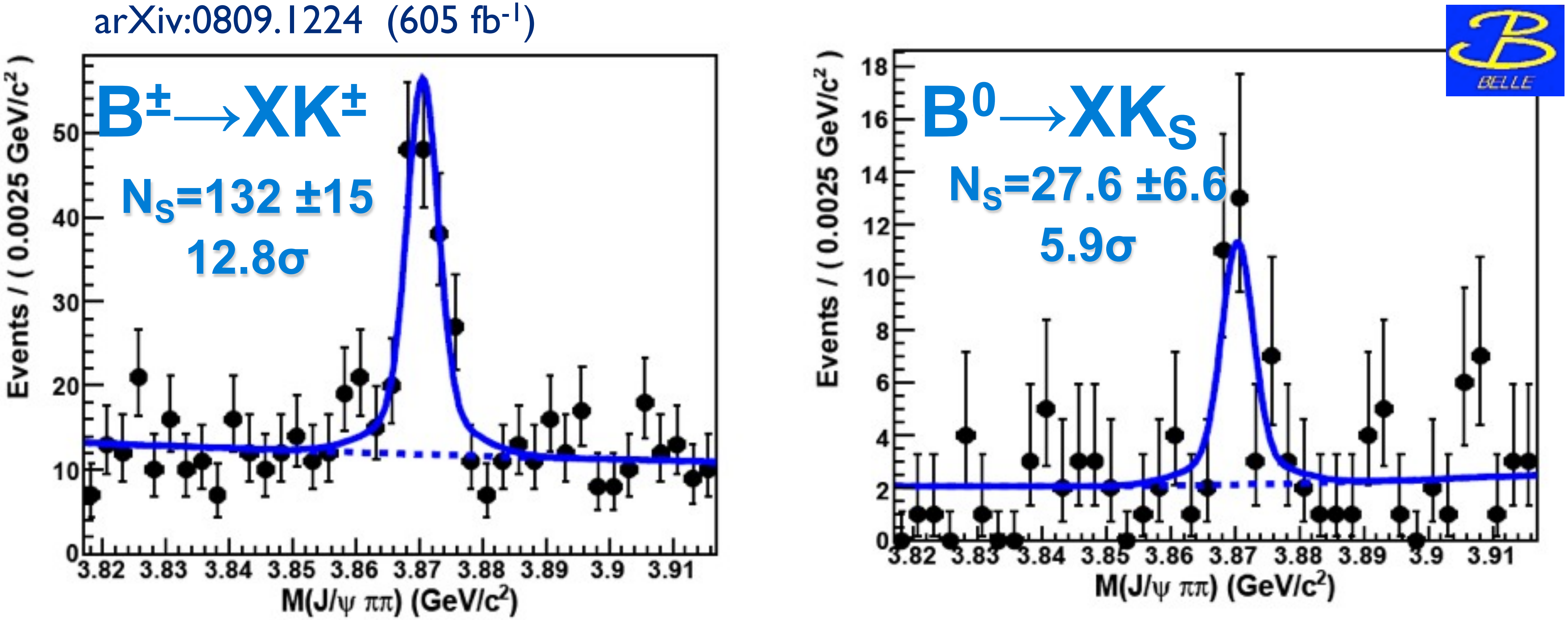
$X(3872)$ in $B^0 \to K\pi^+\pi^- J/\psi$



S. K. Choi et al, PRL 91, 262001 (2003)

$X(3872) \to \pi^+\pi^- J/\psi$

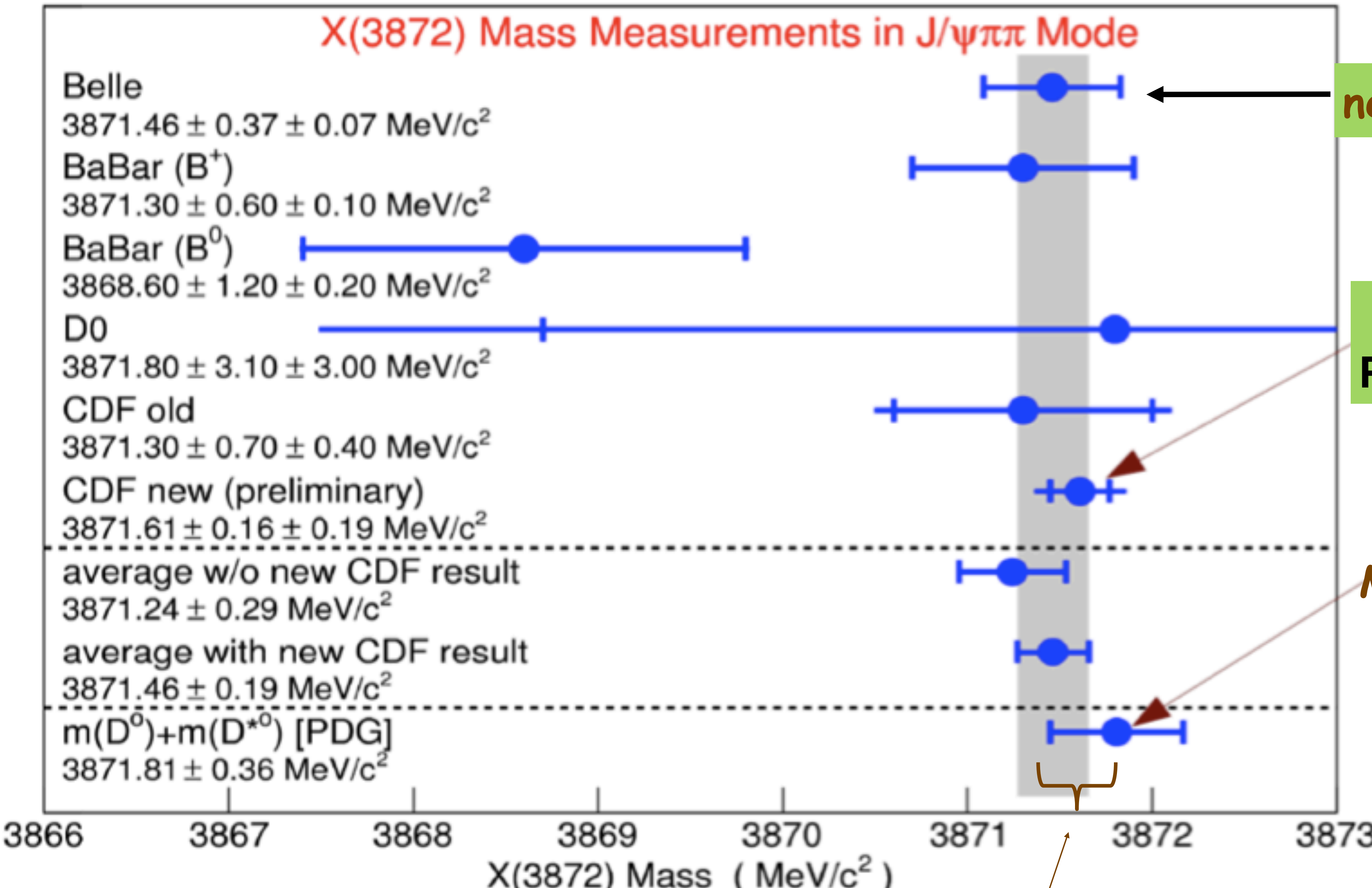
arXiv:0809.1224 (605 fb^{-1})



M(X(3872))=(3871.46±0.37±0.07) MeV
by combining two modes together

$m(X(3872))$ ($\pi^+\pi^- J/\psi$ mode only)

$\langle m_X \rangle$= 3871.46 ± 0.19 MeV



new Belle meas.

new CDF meas PRL103.152001.

$M_{D0} + M_{D^*0}$.

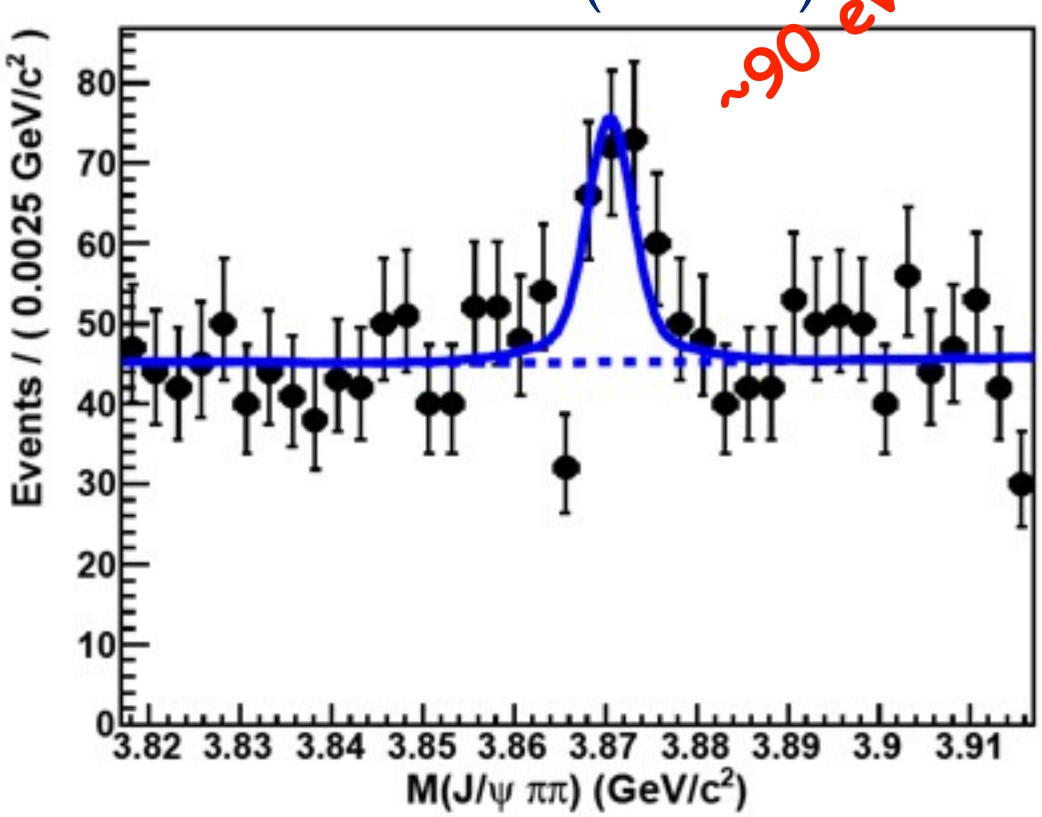
BES III can improve on this

Δm(deuteron) = -2.2 MeV

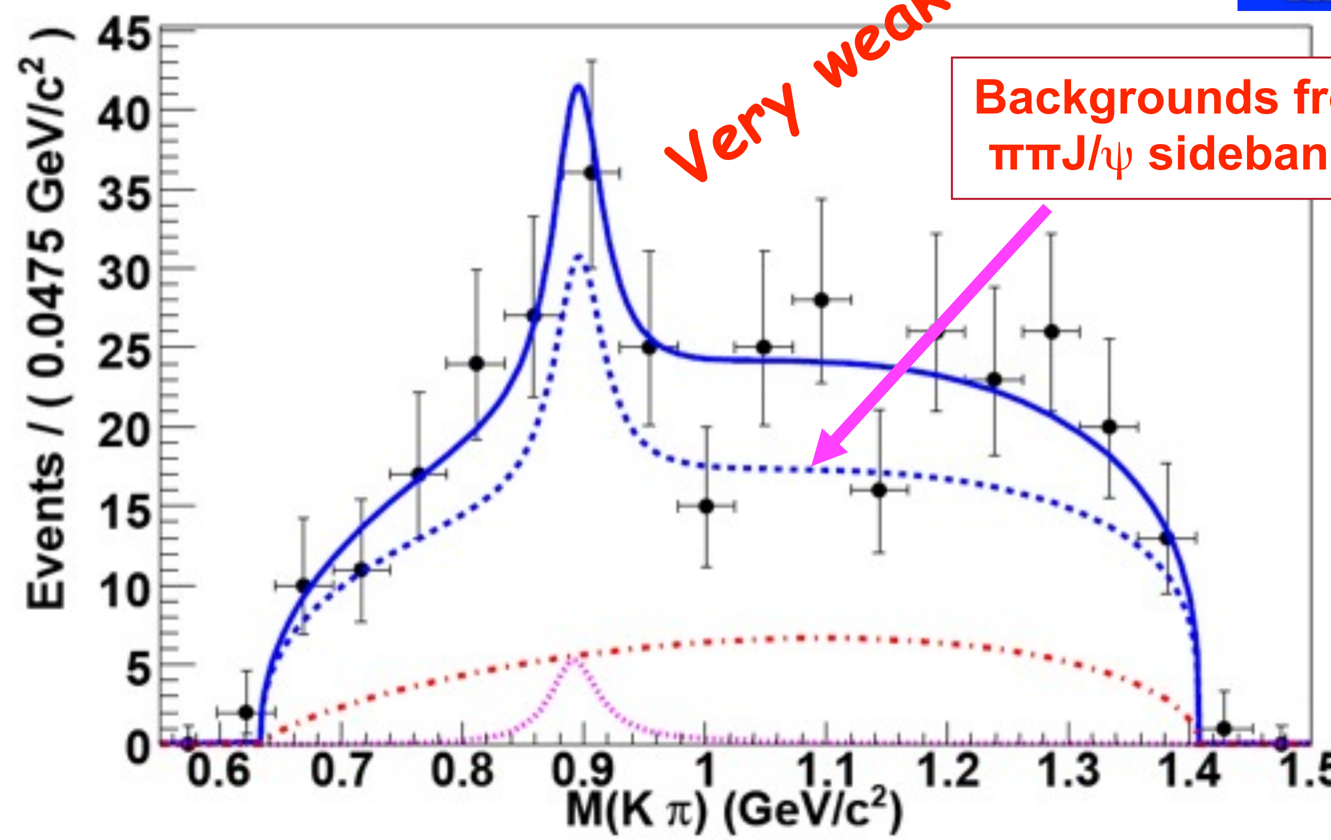
Δm = -0.35 ± 0.41 MeV

$B \to K\pi X(3872)$

arXiv:0809.1224 (605 fb^{-1})



M(ππJ/ψ) in GeV



M(Kπ) in GeV

$$\mathcal{B}(B^0 \to X(3872)K^*(892)^0) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$$

$$\mathcal{B}(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

Bf(B→J/ψ K^{*0})/Bf(B→J/ψ Kπ_{NR}) ~ 4. **Similar ratios for χ_{c1}, ψ(2S)!**

X(3872) is very different from other charmonia.

What is the X(3872) ?

The mass, width and decay modes do ***NOT*** appear to correspond to those of any predicted charmonium state.

One possibility suggested by a number of authors is a loosely bound S-wave molecule of charm mesons. $1/\sqrt{2}(D^0\ D^{*0}bar + D^0bar\ D^{*0})$

F. Close, P.R. Page, Phys. Lett. B 578, 119 (2003)

N.. A. Tornqvist, Phys Lett. B 590, 209(2004)

E. Braaten, M. Kusunoki, S. Nussinov, Phy. Rev. Lett. 93, 162001 (2004)

Another intriguing idea: X(3872)= c cbar u ubar state. In such a 4-quark picture there should be two neutral states, X^0, c cbar u ubar, c cbar d dbar as well as charged states, X^+, c cbar u dbar, c cbar d ubar etc….

L. Maiani, F. Piccinini, A. D. Polosa, V. Riquer, Phys Rev. D71: 014028 (2005)

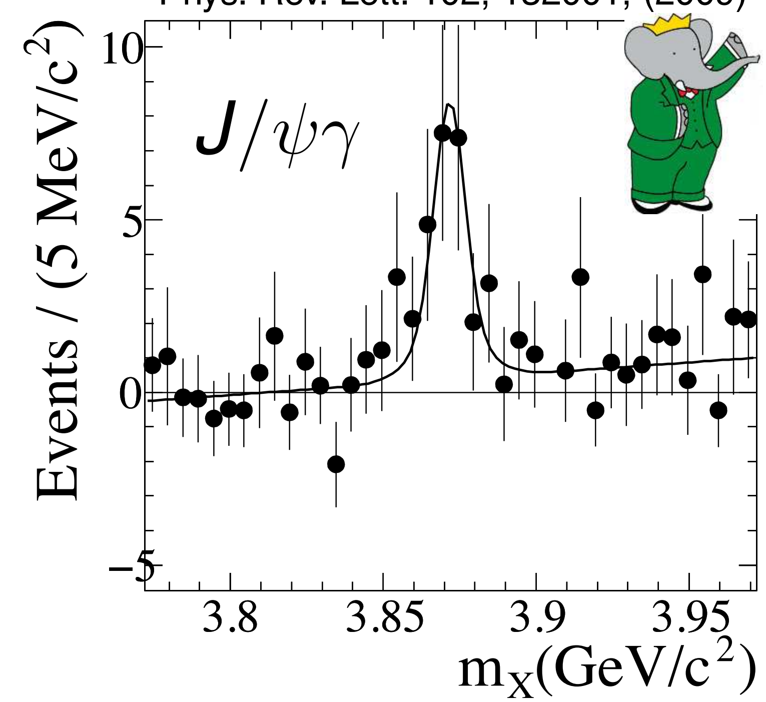
$X(3872) \to \psi(2S)\gamma$

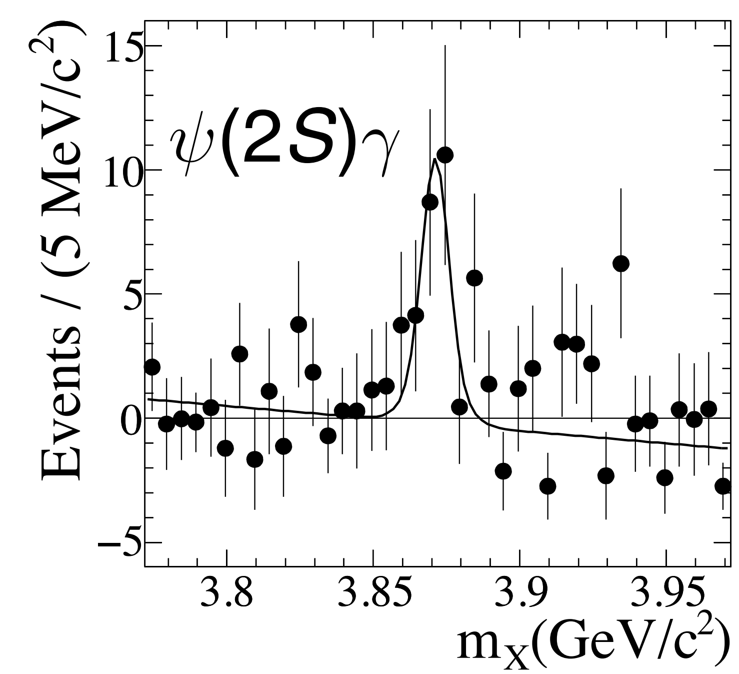
- $X(3872) \to (c\bar{c})\gamma$ can help distinguish molecule from conventional $c\bar{c}$
- $C = +1$ for such decays
- found evidences for decays to both $J/\psi\gamma$ and $\psi(2S)\gamma$; sig. $\sim 3.5\sigma$ for each
- obtained the ratio

$$\frac{\mathcal{B}(X \to \psi(2S)\gamma)}{\mathcal{B}(X \to J/\psi\gamma)} = 3.4 \pm 1.4$$

- generally inconsistent with pure DD^* molecule; may imply mixing with a significant $c\bar{c}$ component

Phys. Rev. Lett. 102, 132001, (2009)

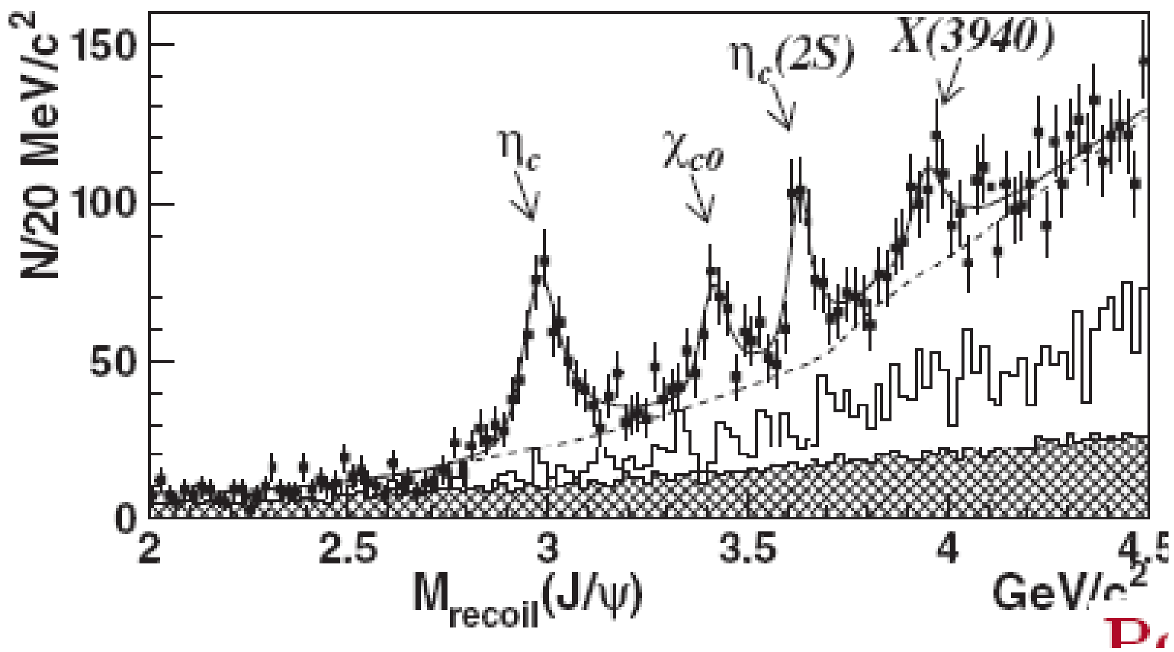




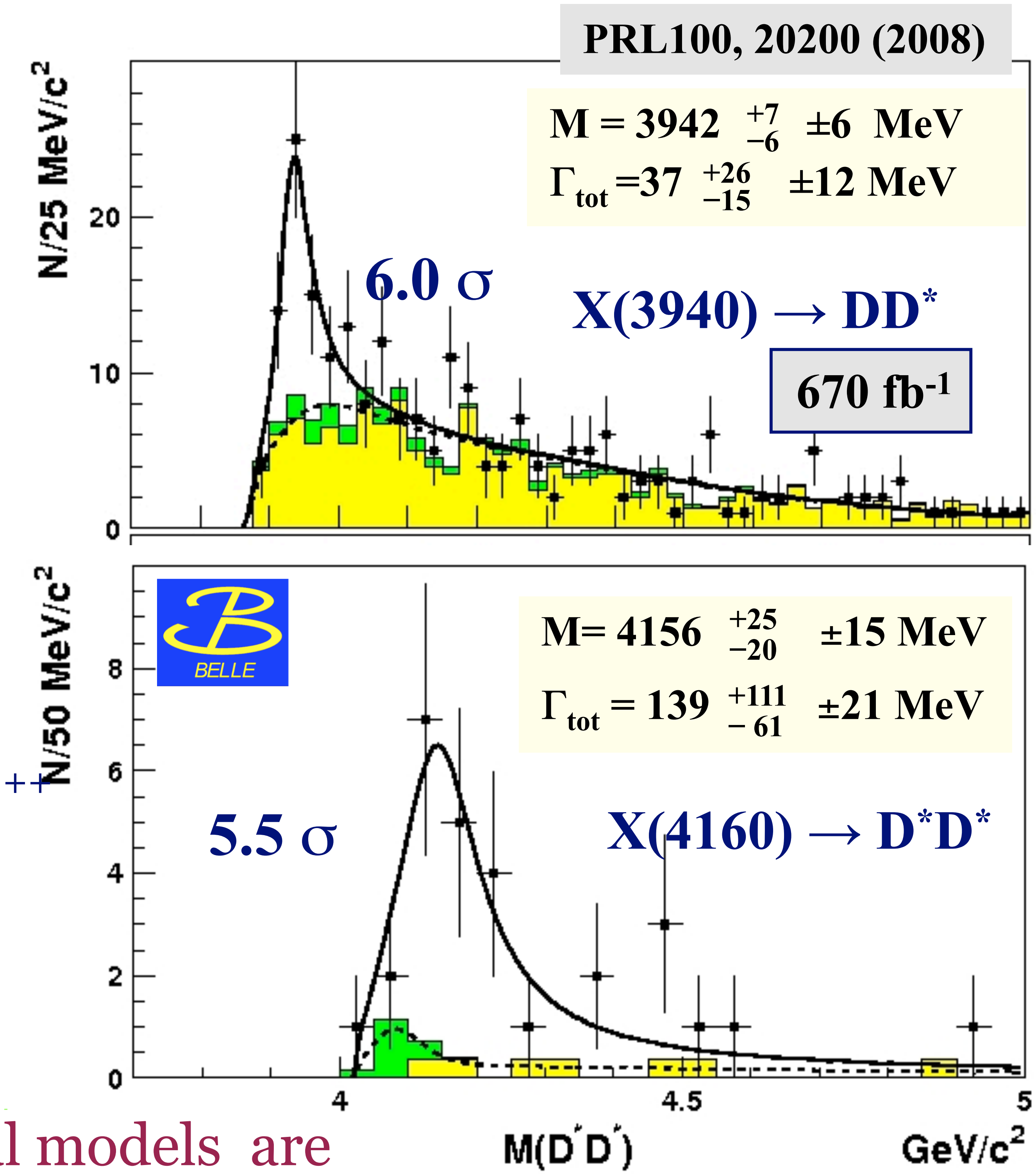
the $Y(3940)$ family

X(3940), *Y*(3940), *Z*(3930)

PRL 98, 082001 (2007)

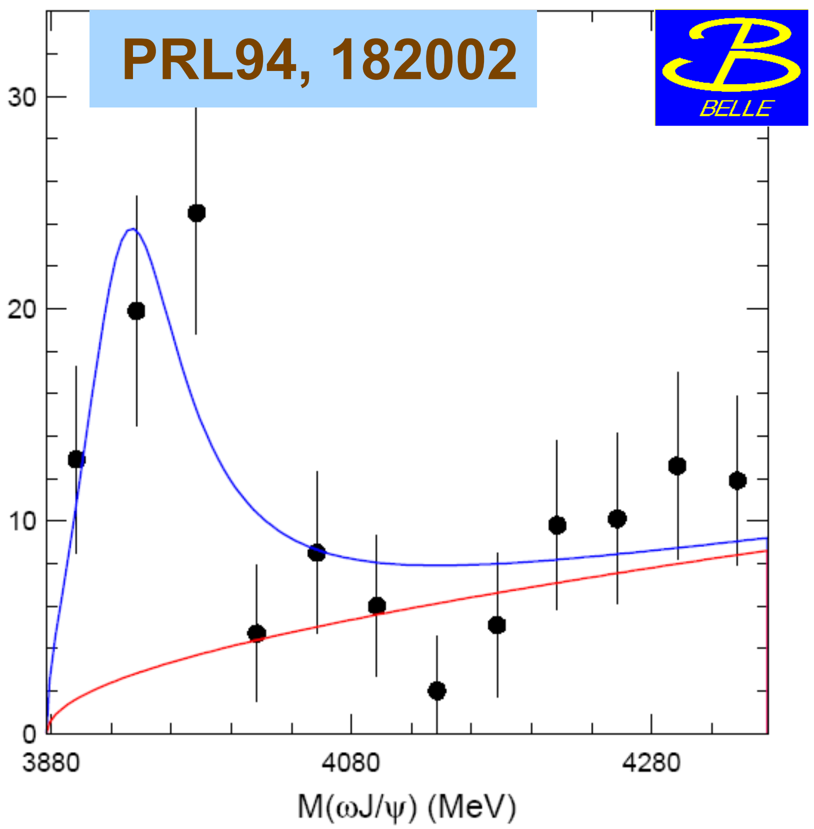


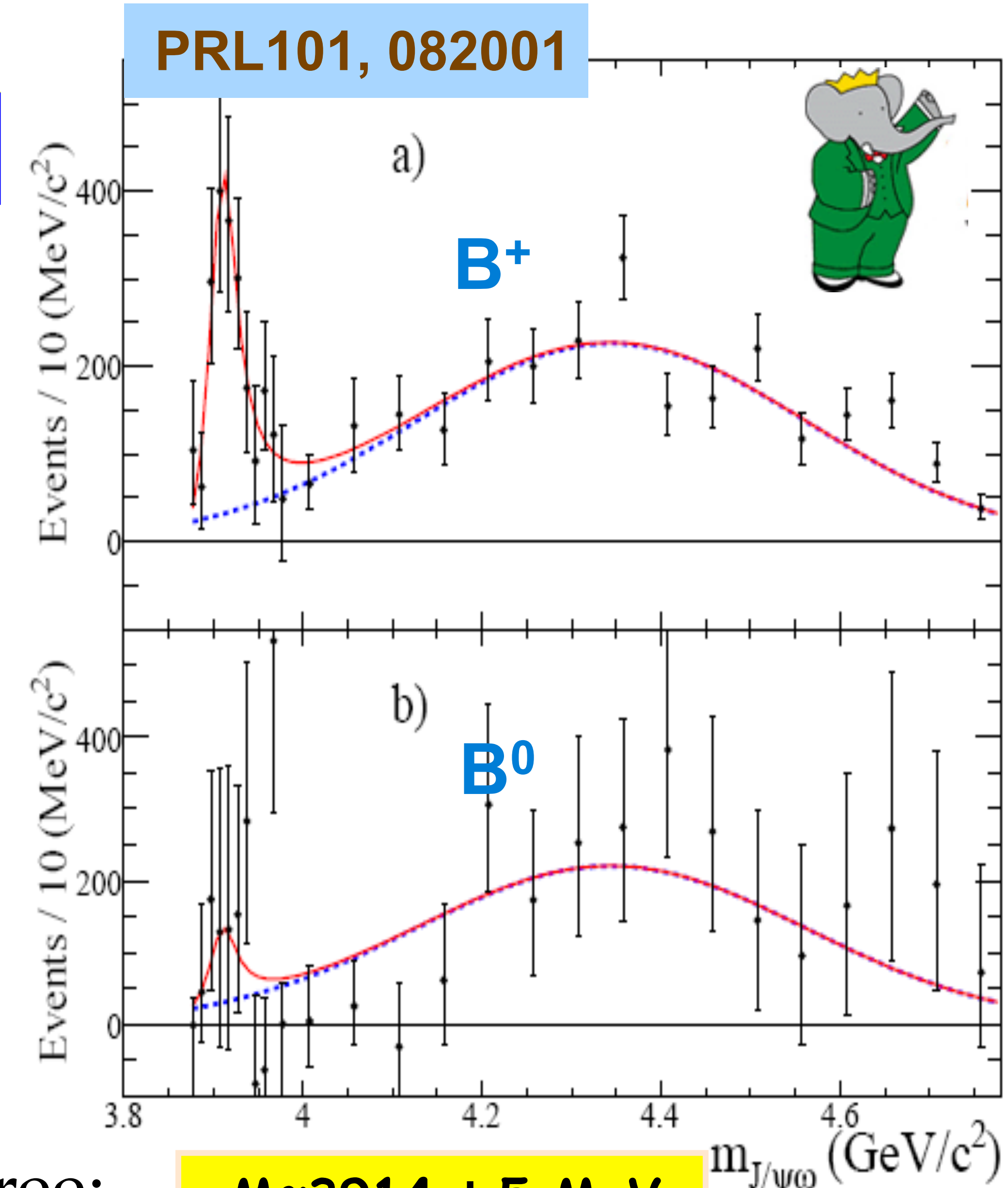
1st observed in the J/ψ recoil



* 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

$X(3940)$, $Y(3940)$, $Z(3930)$





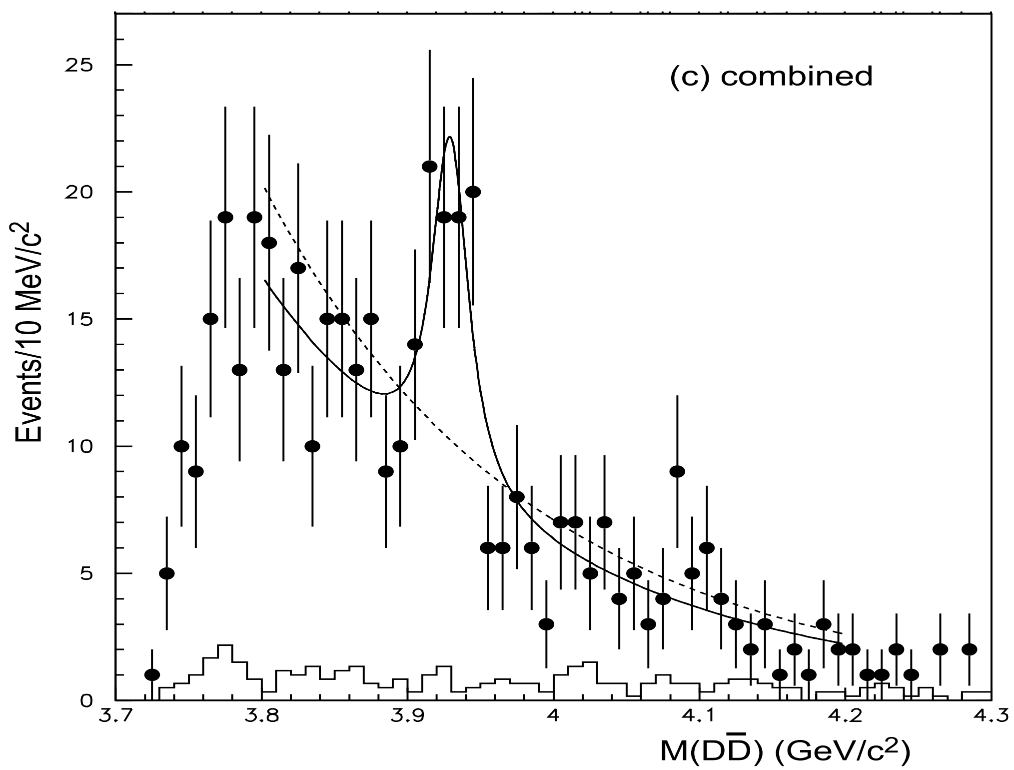
M≈3943 ± 17 MeV
Γ≈ 87 ± 34 MeV

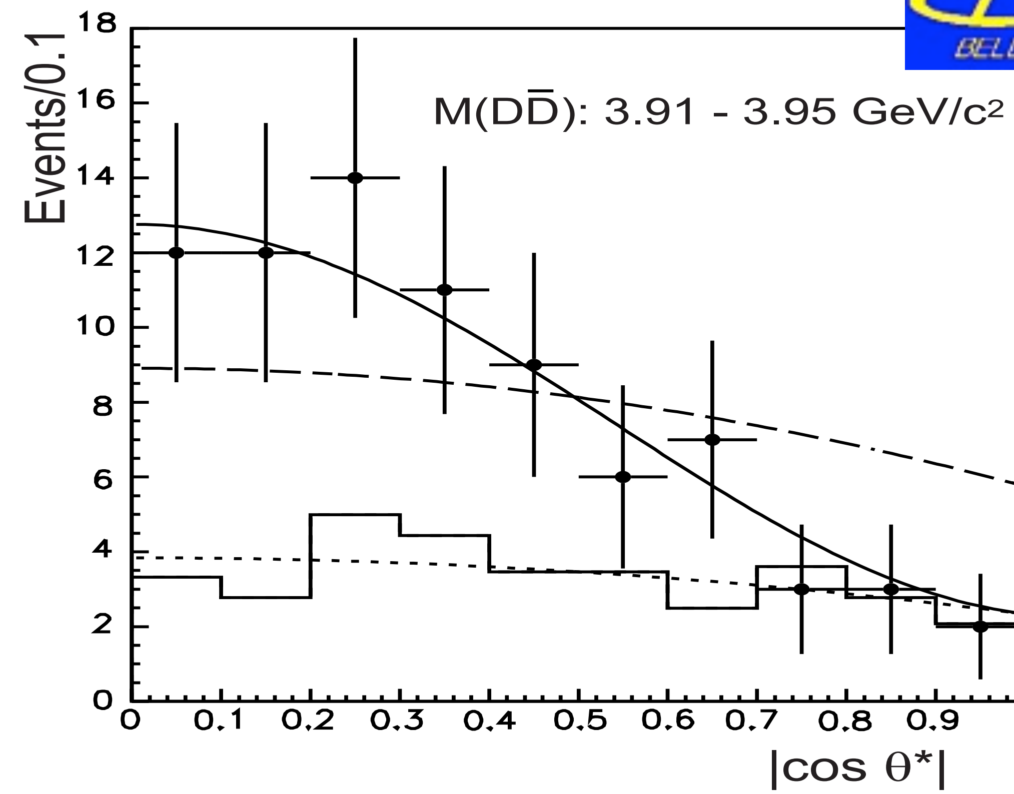
M≈3914 ± 5 MeV
Γ≈ 34 ± 13 MeV

* general featueres agree;
  but different M, Γ

* X(3940) --> D D* mostly; Y(3940) --> $\psi\omega$ dominantly
* X(3940) ≠ Y(3940)

X(3940), *Y*(3940), *Z*(3930)

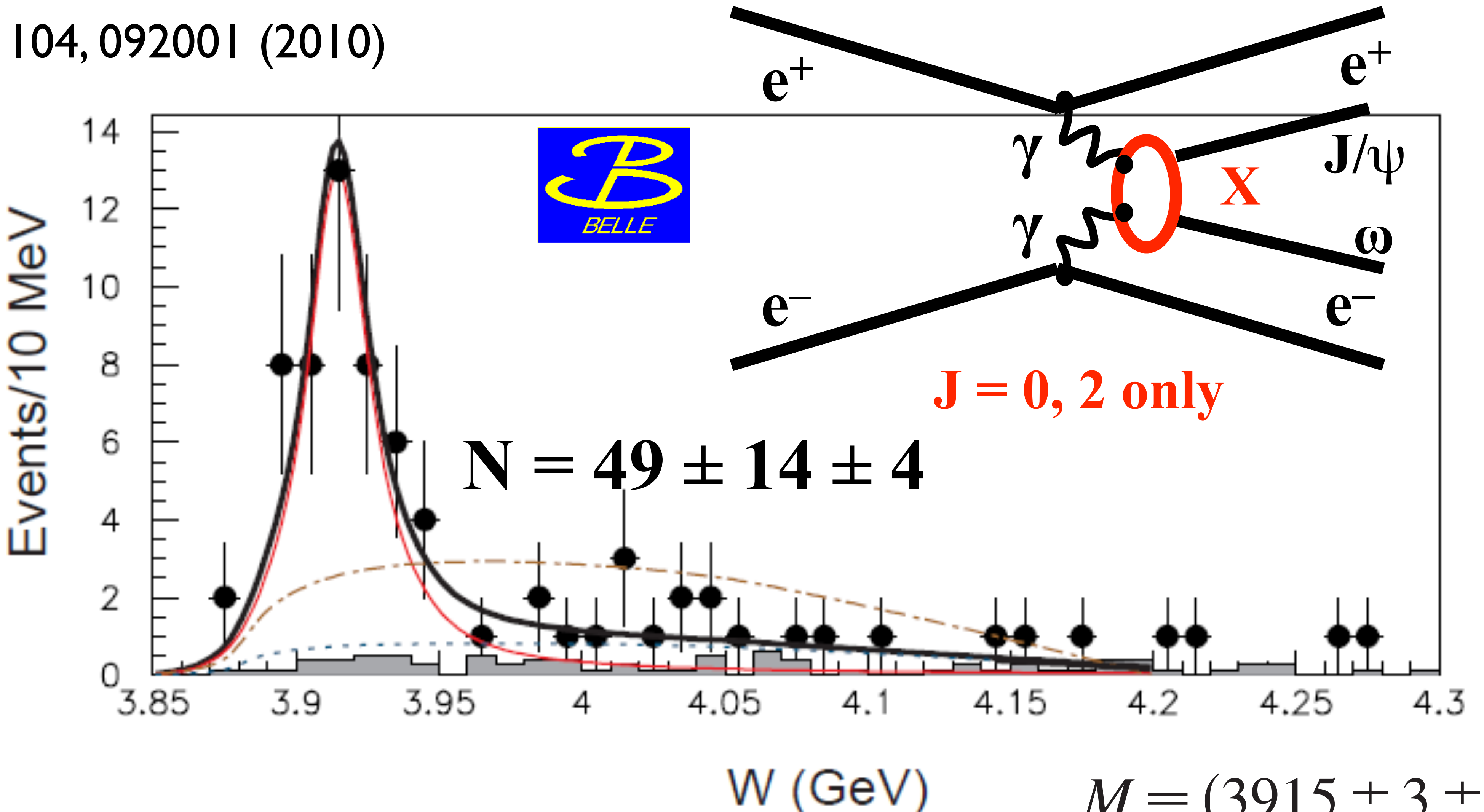




* observed in two-photon process
* doesn't seem to be exotic + Belle / BaBar agree
* consistent with $J^{PC} = 2^{++}$ --> a prime candidate for $\chi_{c2}(2P)$

yet another in the Y(3940) family

PRL 104, 092001 (2010)



$$M = (3915 \pm 3 \pm 2)\ \mathrm{MeV}/c^2$$

$$\Gamma = (17 \pm 10 \pm 3)\ \mathrm{MeV}$$

$\Gamma_{\gamma\gamma}$ (X) × B(X → ωJ/ψ) =

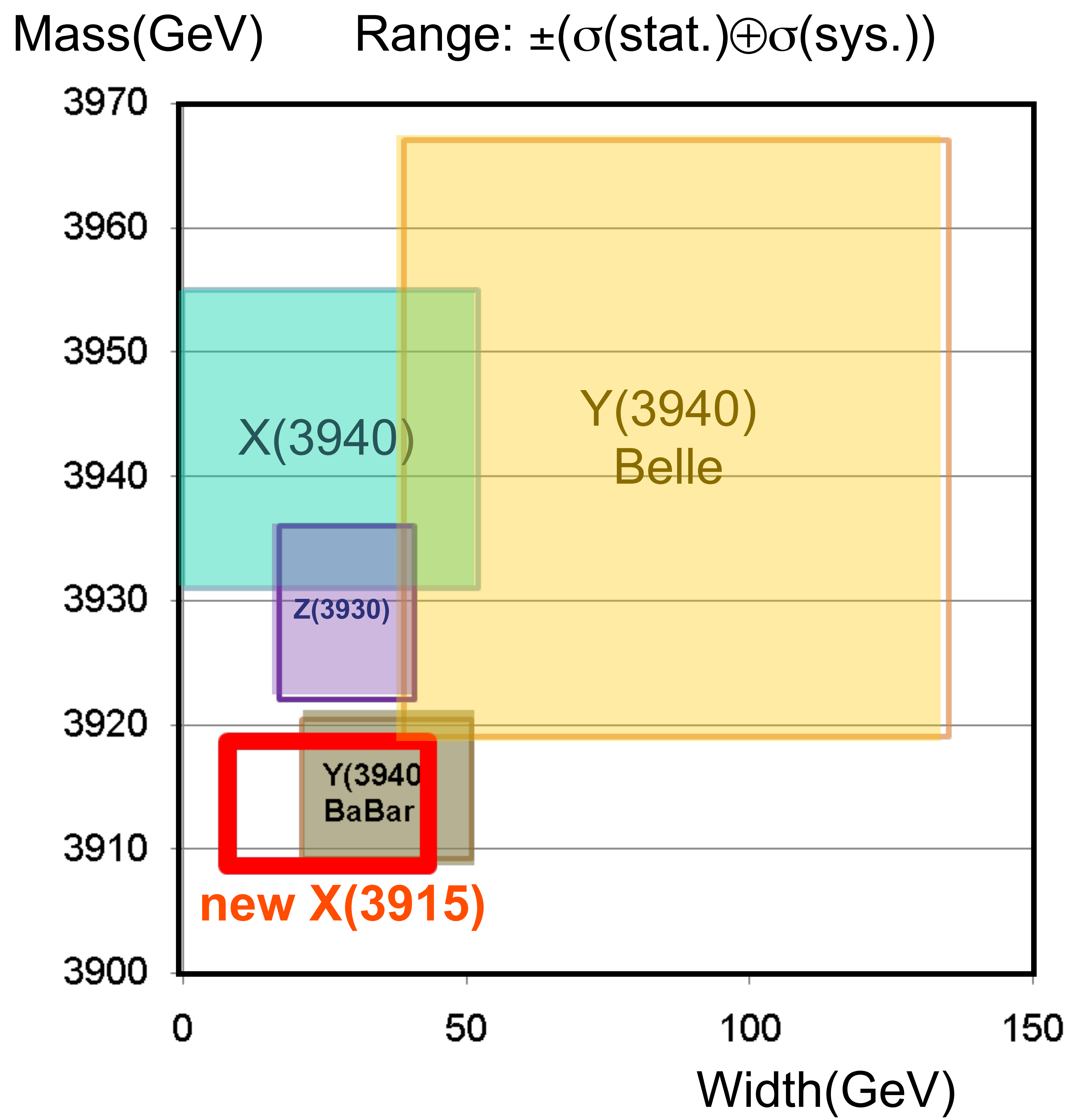
(61 ± 17 ± 8) eV for $J^P = 0^+$

(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

4 states in the *Y*(3940) family



Charged exotic -- the Z^+ family

a smoking gun?

- Most of the new resonances are "charmonium-like", but does not quite fit the charmonium spectra
- All these new resonances have one thing in common: charge = neutral
- Any charged ones?

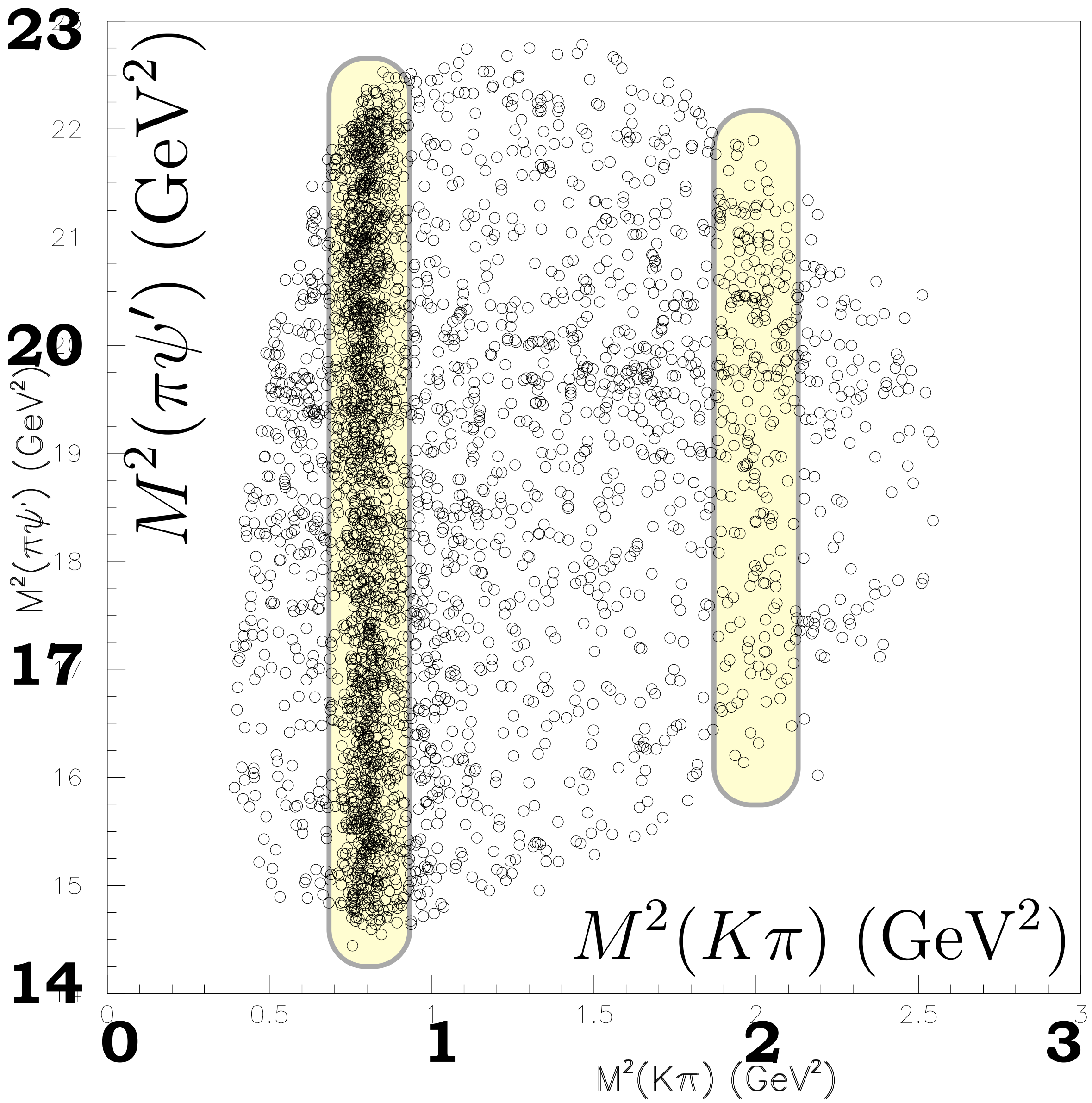
$Z(4430)^+$

- Charmonium-like states with non-zero charge will clearly distinguish multi-quark states from charmonia or hybrids
- Search for charged states in

$$B^+ \to K^+\pi^0\psi' \quad \text{and} \quad B^+ \to K^0\pi^+\psi'$$

Dalitz plot for signal events

$Z(4430)^+$



S.K. Choi et al., PRL 100, 142001 (2008)

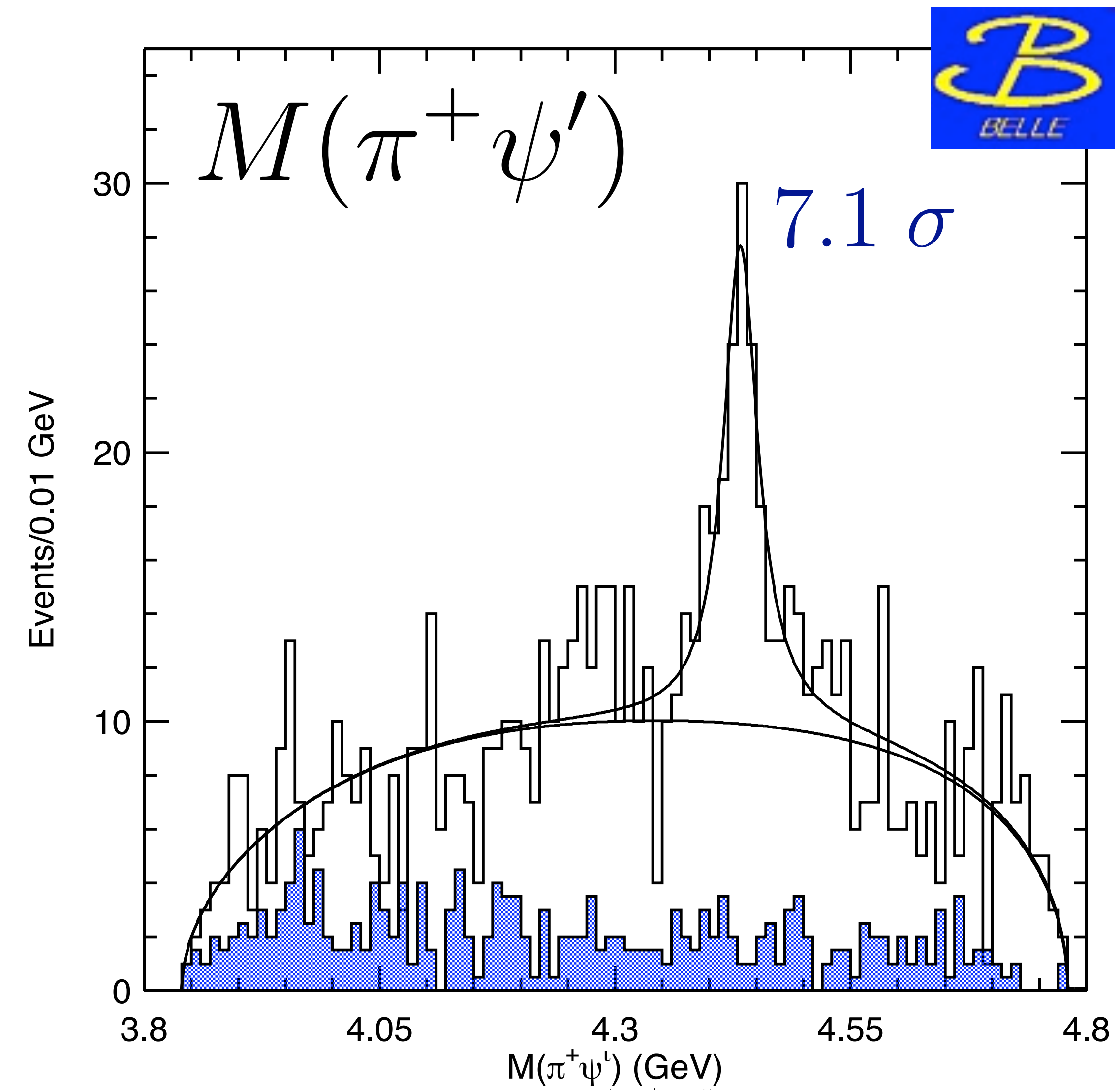
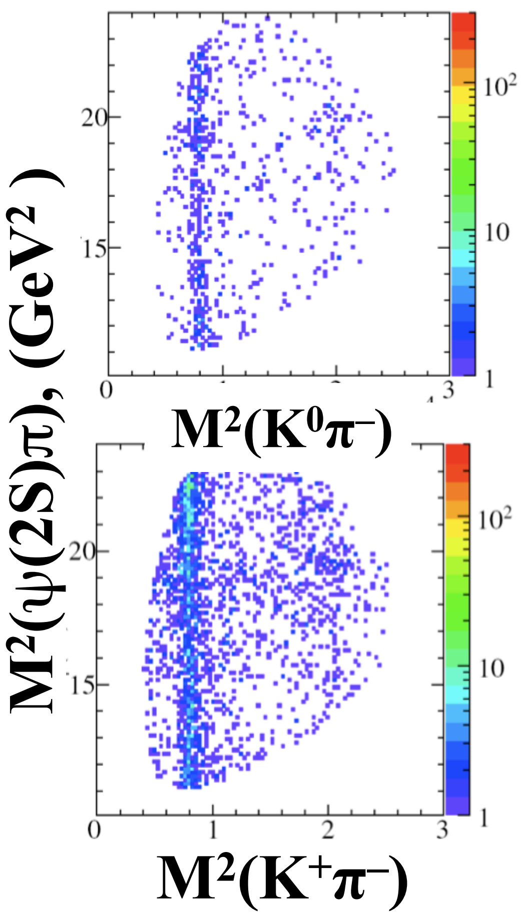


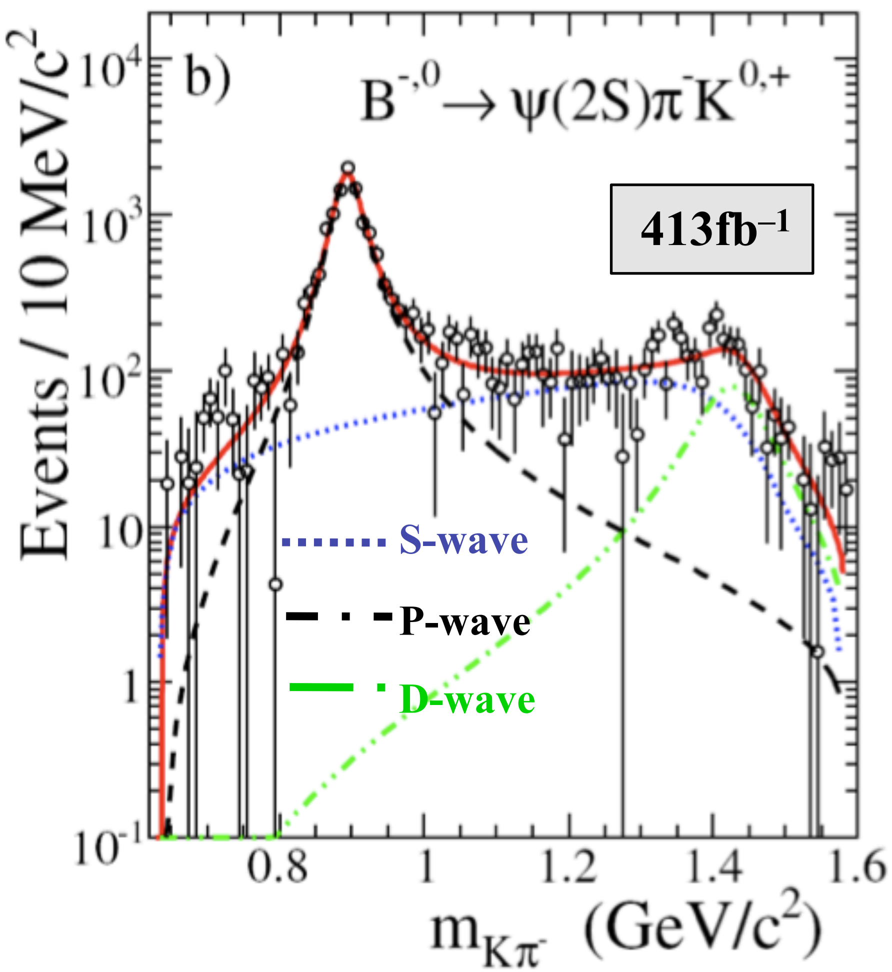
FIG. 2 (color online). The $M(\pi^+\psi')$ distribution for events in the $M_{bc} - \Delta E$ signal region and with the K^* veto applied. The shaded histogram show the scaled results from the ΔE sideband. The solid curves show the results of the fit described in the text.

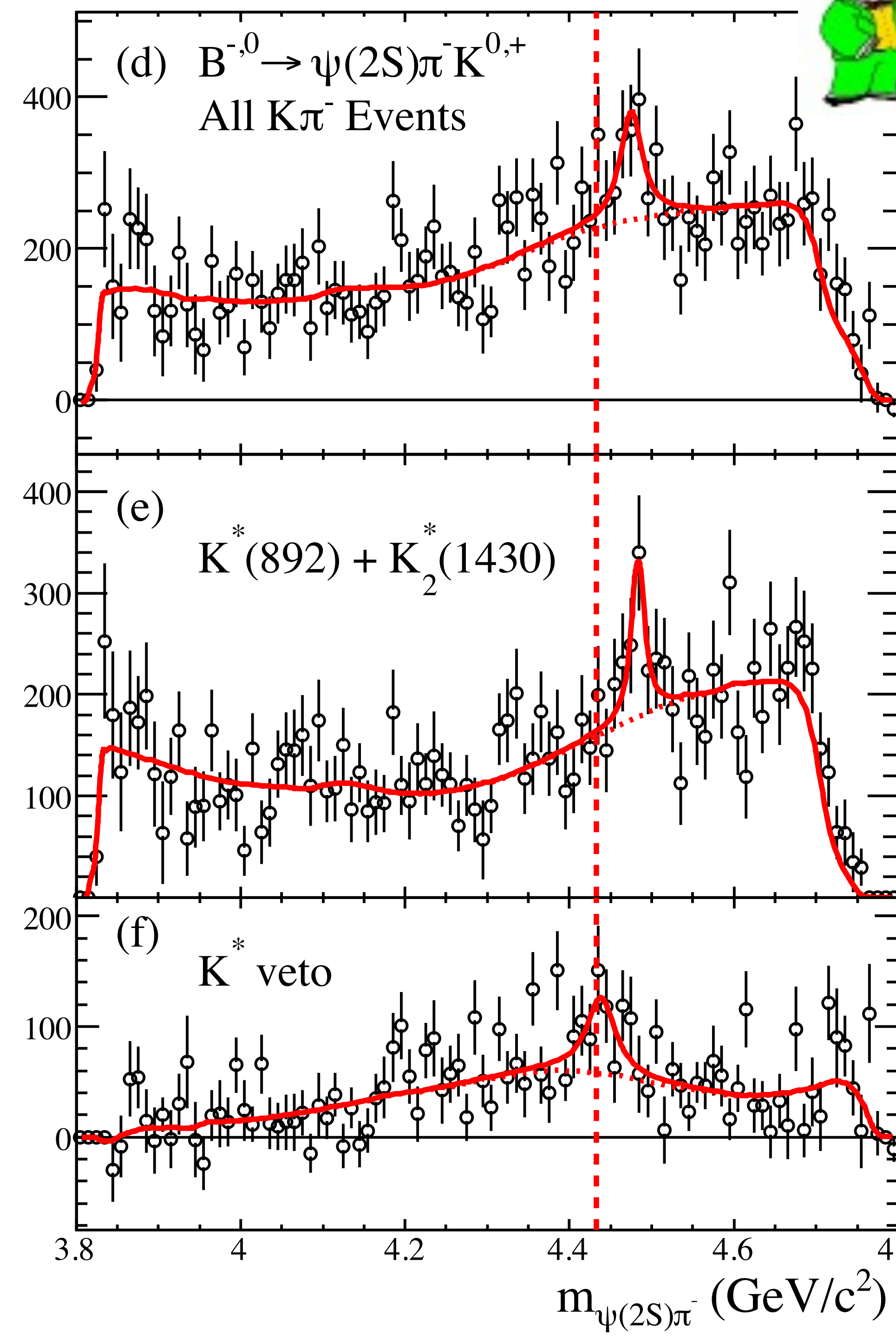
$$\mathcal{B}(\bar{B}^0 \to K^- Z^+(4430)) \times \mathcal{B}(Z^+(4430) \to \pi^+\psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5},$$

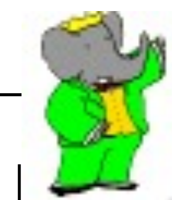
N_{sig}	$\mathcal{N}_{cont}$	BW Mass (GeV)	Γ (GeV)
121 ± 30	766 ± 39	4.433 ± 0.004	$0.045^{+0.018}_{-0.013}$

Search for $Z(4430)^+$ by BaBar



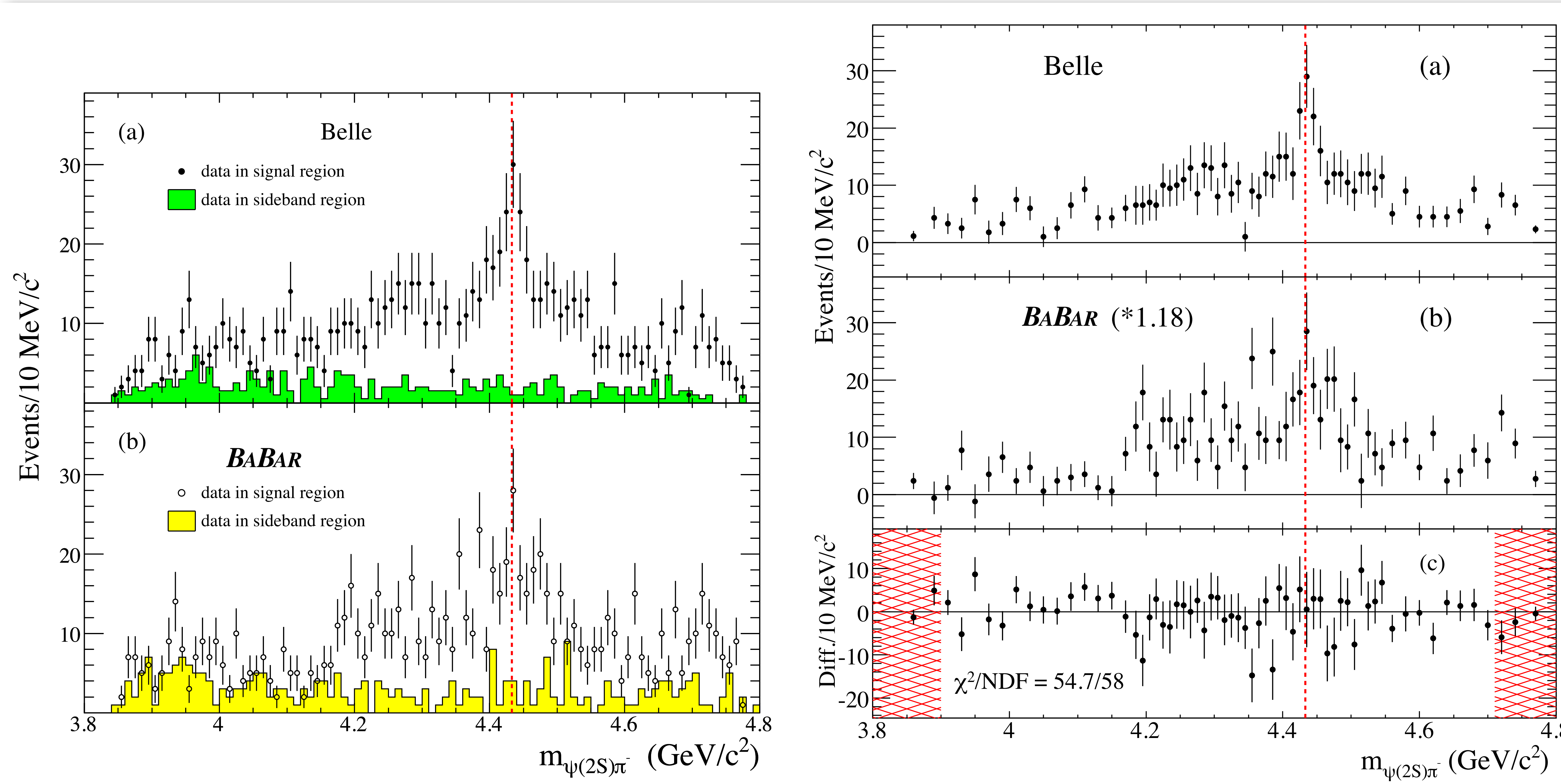






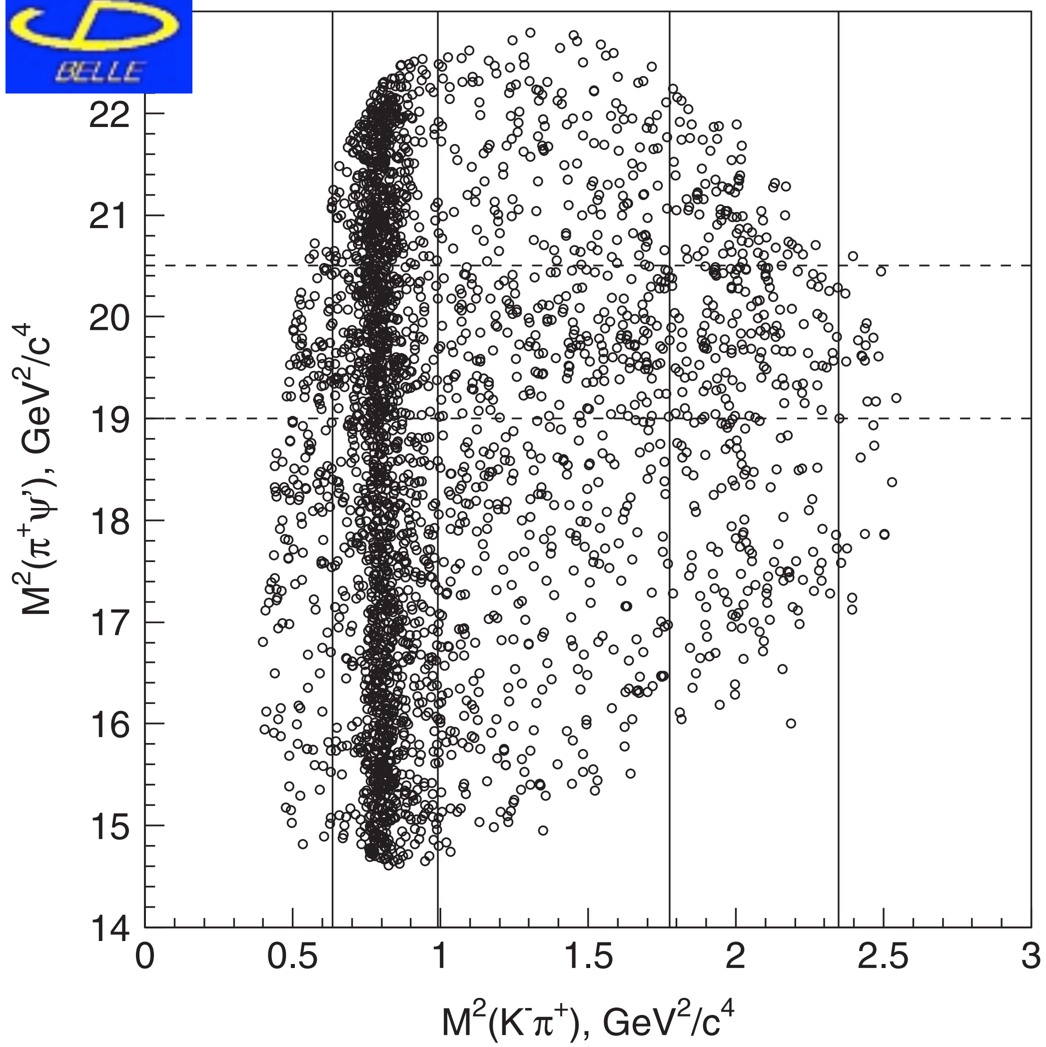
* very detailed study of (Kπ) background
* Z(4430) signal only 1.9σ

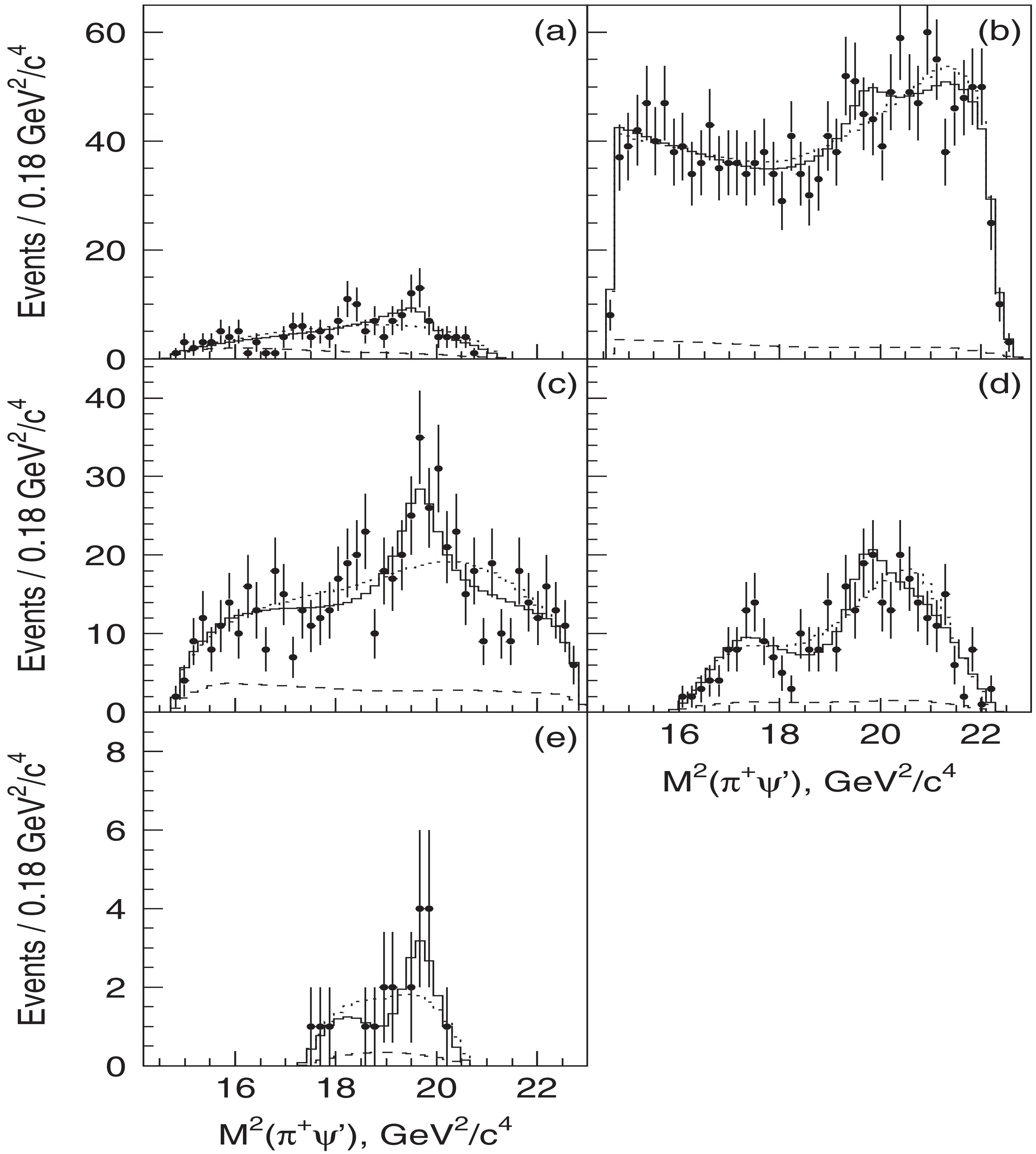
Z(4430)$^+$ -- BaBar vs. Belle



- Not inconsistent with each other!

$Z(4430)^+$ Dalitz analysis (Belle)

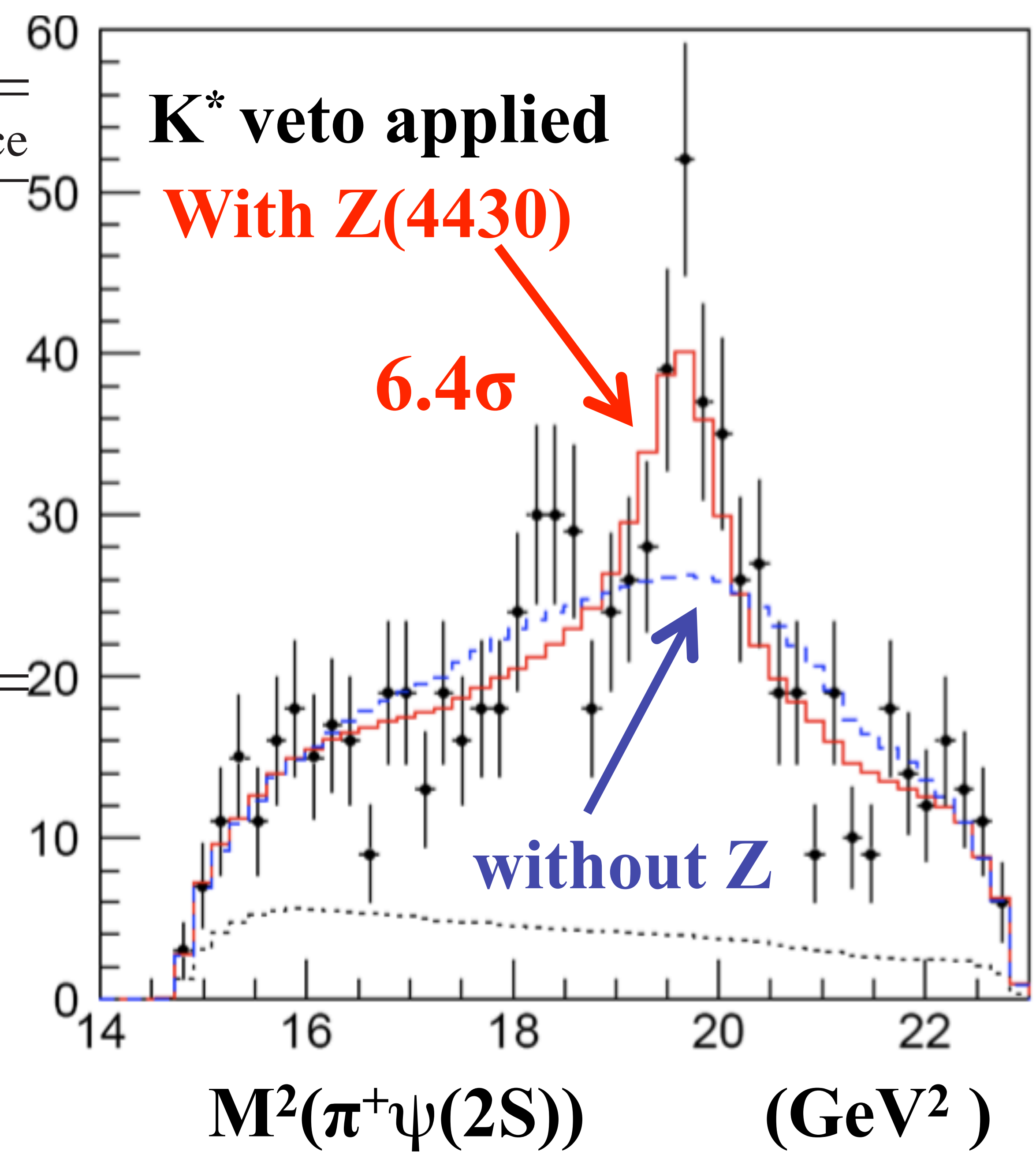




$Z(4430)^+$ Dalitz analysis (Belle)

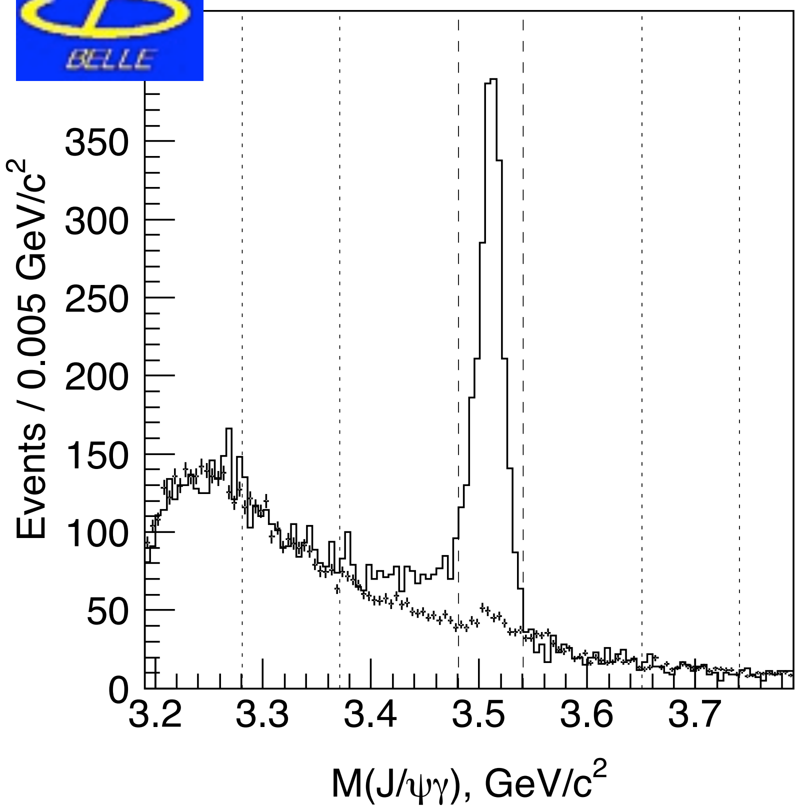
TABLE I. The fit fractions and significances of all contributions for the fit models with the default set of $K\pi^+$ resonances and a single $\pi^+\psi'$ resonance.

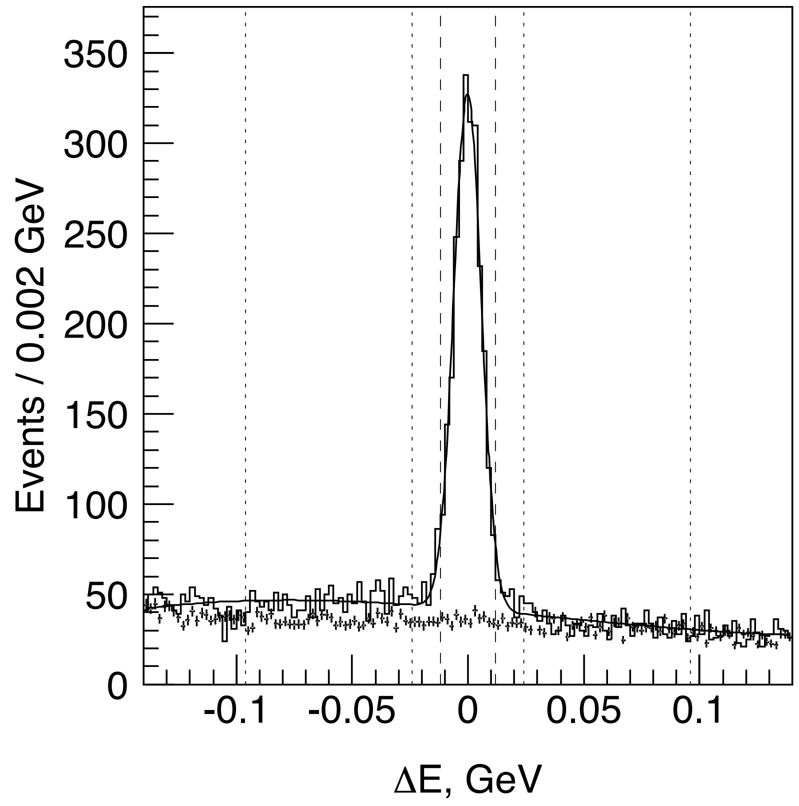
Contribution	Fit fraction (%)	Significance
$Z(4430)^+$	$5.7^{+3.1}_{-1.6}$	6.4σ
κ	$4.1^{+3.4}_{-1.1}$	1.5σ
$K^*(892)$	$64.8^{+3.8}_{-3.5}$	large
$K^*(1410)$	$5.5^{+8.8}_{-1.5}$	0.5σ
$K_0^*(1430)$	5.3 ± 2.6	1.3σ
$K_2^*(1430)$	$5.5^{+1.6}_{-1.4}$	3.1σ
$K^*(1680)$	$2.8^{+5.8}_{-1.0}$	1.2σ

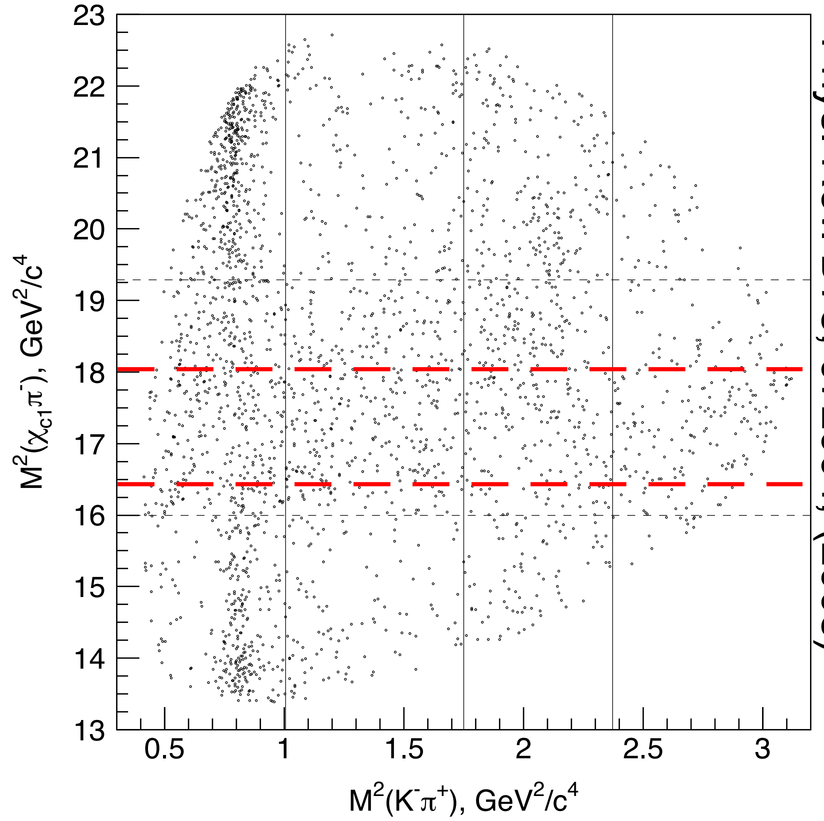


- $M = (4443^{+15+19}_{-12-13})\ \mathrm{MeV}/c^2$
- $\Gamma = (107^{+86+74}_{-43-56})\ \mathrm{MeV}$

more Z^+ states: $Z^+ \to \chi_{c1}\pi^+$







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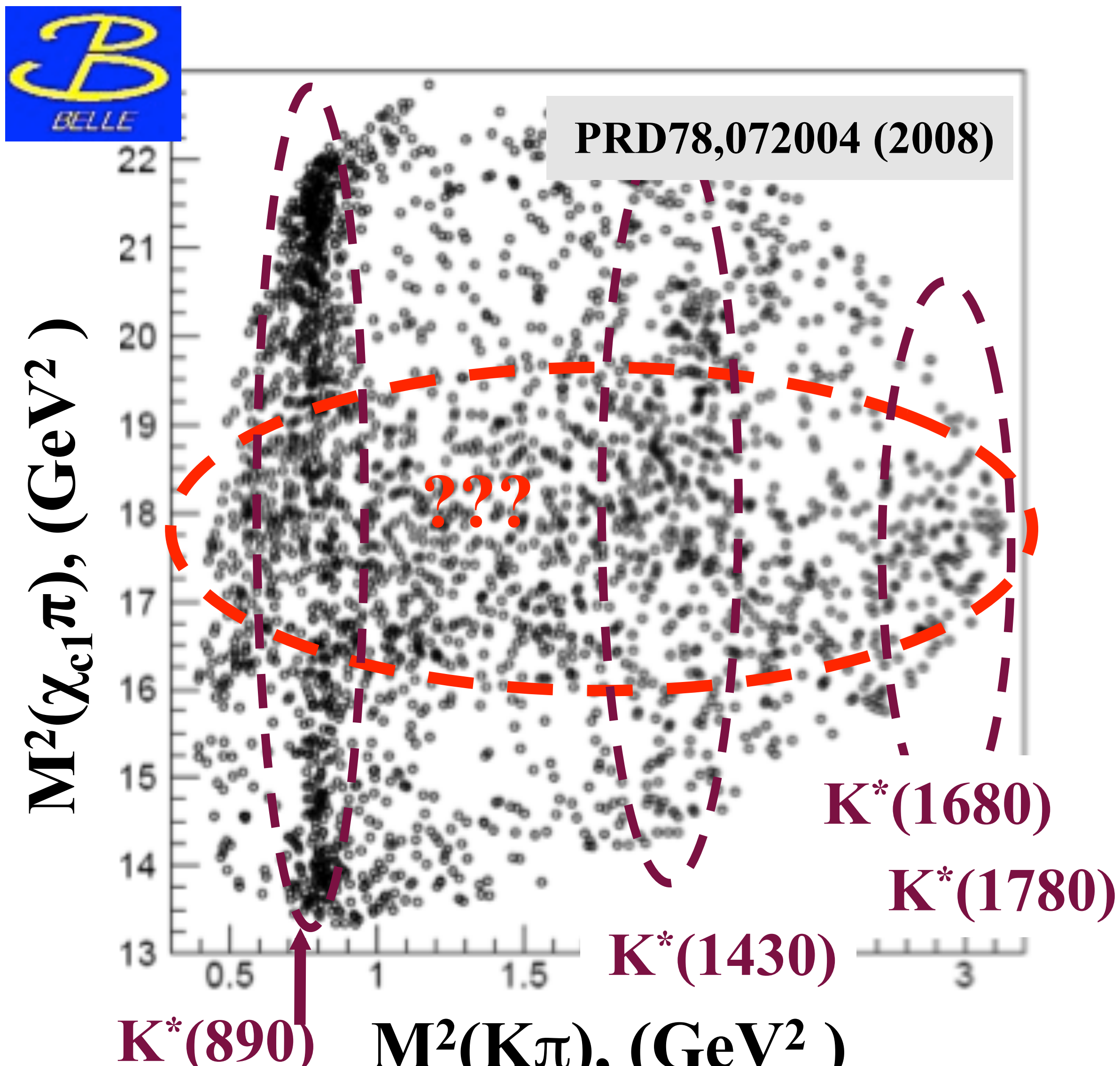
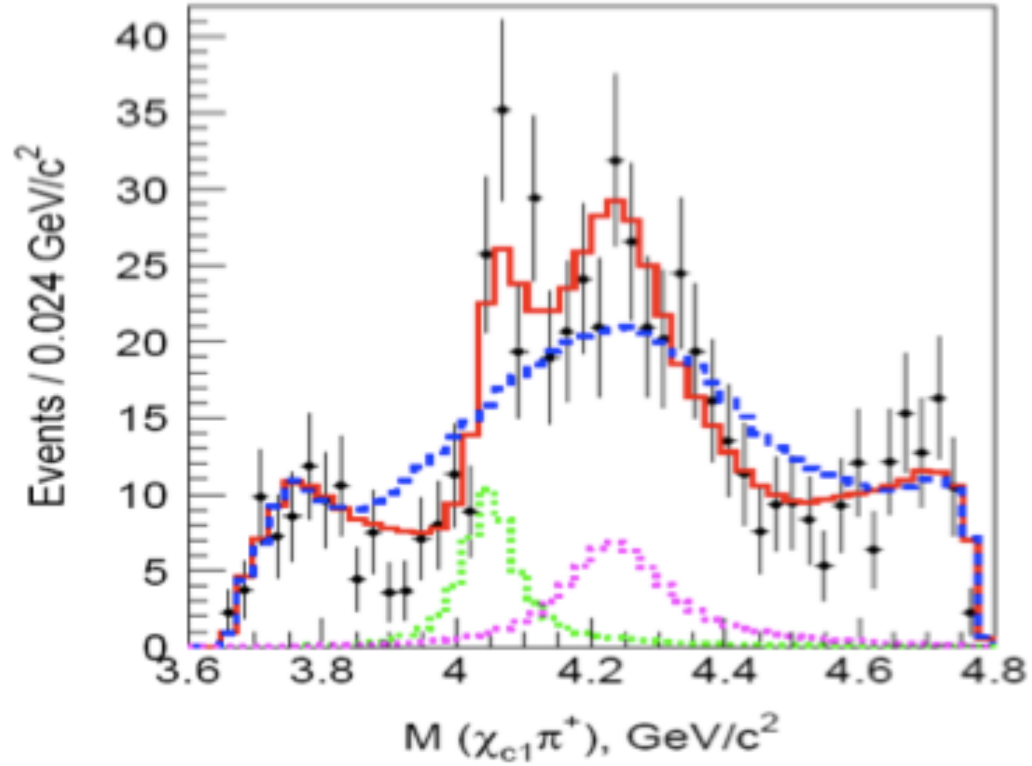
- Belle studied $B^0 \to \chi_{c1}\pi^+K^-$ with $\chi_{c1}J/\psi\gamma$
- observed clear signals for both B^0 and χ_{c1}

more Z^+ states: $Z^+ \to \chi_{c1}\pi^+$



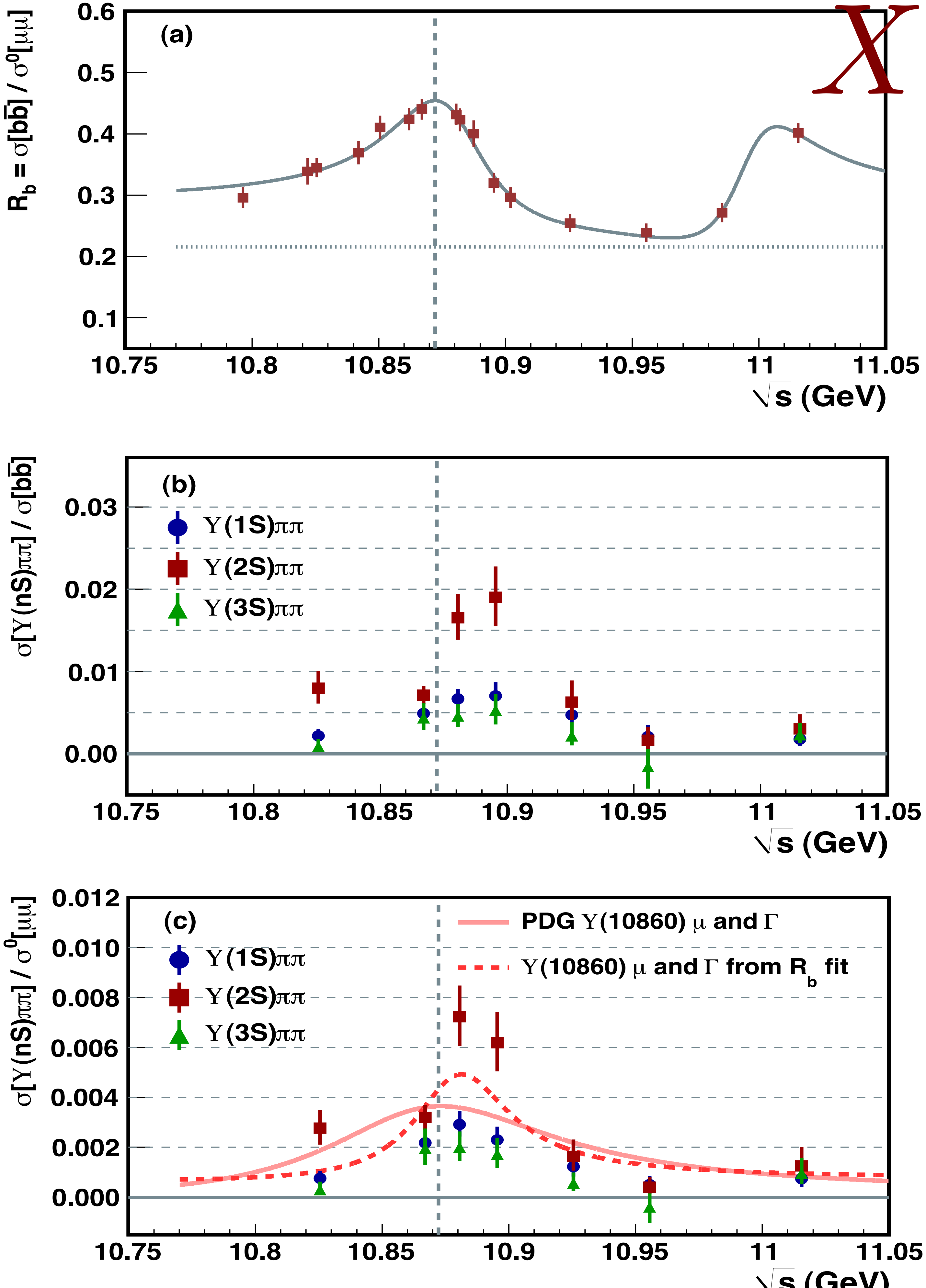


MeV	$Z(4050)$	$Z(4250)$
M	$4051 \pm 14^{+29}_{-41}$	$4248^{+44}_{-29}{}^{+180}_{-35}$
Γ	$82^{+21}_{-16}{}^{+47}_{-22}$	$177^{+54}_{-39}{}^{+316}_{-61}$
$\mathcal{B}_B \cdot \mathcal{B}_Z$	$3.0^{+1.5}_{-0.8}{}^{+3.7}_{-1.6} \times 10^{-5}$	$4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5} \times 10^{-5}$

- fit to the Dalitz plot strongly prefers two new resonances, $Z(4050)^+$ and $Z(4250)^+$; data favor two Z^+ against one at 5.7σ
- spins are not determined

Exotic states in $B\bar{B}$?

XYZ in $b\bar{b}$?



$\sqrt{s}$(GeV)	$\mathcal{L}(\mathrm{fb}^{-1})$
10.8255	1.73
10.8805	1.89
10.8955	1.46
10.9255	1.18
10.9555	0.99
11.0155	0.88
10.8670	21.74

XYZ in $b\bar{b}$?

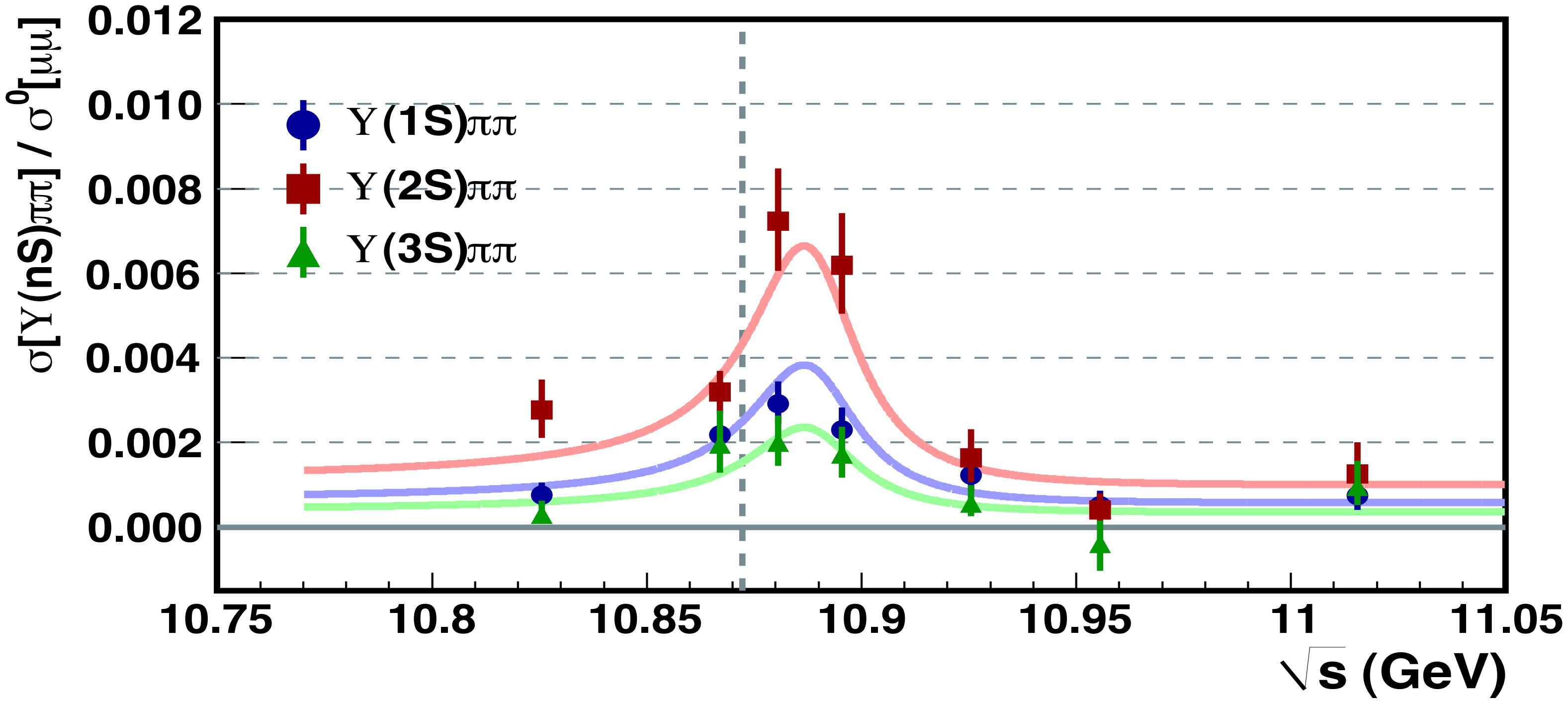


FIG. 2: The CM energy-dependent cross sections for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2, 3)$ processes normalized to the leading-order $e^+e^- \to \mu^+\mu^-$ cross sections. The results of the fits are shown as smooth curves. The vertical dashed line indicates the energy at which the hadronic cross section is maximal.

$\Upsilon(1S)\pi\pi$ σ at peak	$\left(2.78^{+0.42}_{-0.34} \pm 0.23\right)$ pb
$\Upsilon(2S)\pi\pi$ σ at peak	$\left(4.82^{+0.77}_{-0.62} \pm 0.66\right)$ pb
$\Upsilon(3S)\pi\pi$ σ at peak	$\left(1.71^{+0.35}_{-0.31} \pm 0.24\right)$ pb
μ	$\left(10888.4^{+2.7}_{-2.6} \pm 1.2\right)$ MeV$/c^2$
Γ	$\left(30.7^{+8.3}_{-7.0} \pm 3.1\right)$ MeV$/c^2$
ϕ	$(1.97 \pm 0.26 \pm 0.06)$ or $(-1.74 \pm 0.11 \pm 0.02)$ rad
R_0	$\left(1.98^{+0.72}_{-0.60} \pm 0.20\right)$ or $\left(0.87^{+0.29}_{-0.22} \pm 0.09\right)$ $(\mathrm{GeV})^{-2}$

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

Scoreboard

candidate	Molecule?	$cq\bar{c}\bar{q}$	$c\bar{c}$-gluon
X(3872)	☺	☹	☹
X(3940)	☹	??	☹
Y(3940)	☹	??	☹
X(4160)	☹	??	??
Y(4008)	☺	??	☹
Y(4260)	☺	??	☺
Y(4350)	☹	??	☹
Y(4660)	☹	??	☹
Z(4430)	☺	??	☹
Z_1(4050)	☹	??	☹
Z_2(4250)	☺	??	☹

table by S. Olsen