New states and charmonium spectroscopy at B factories

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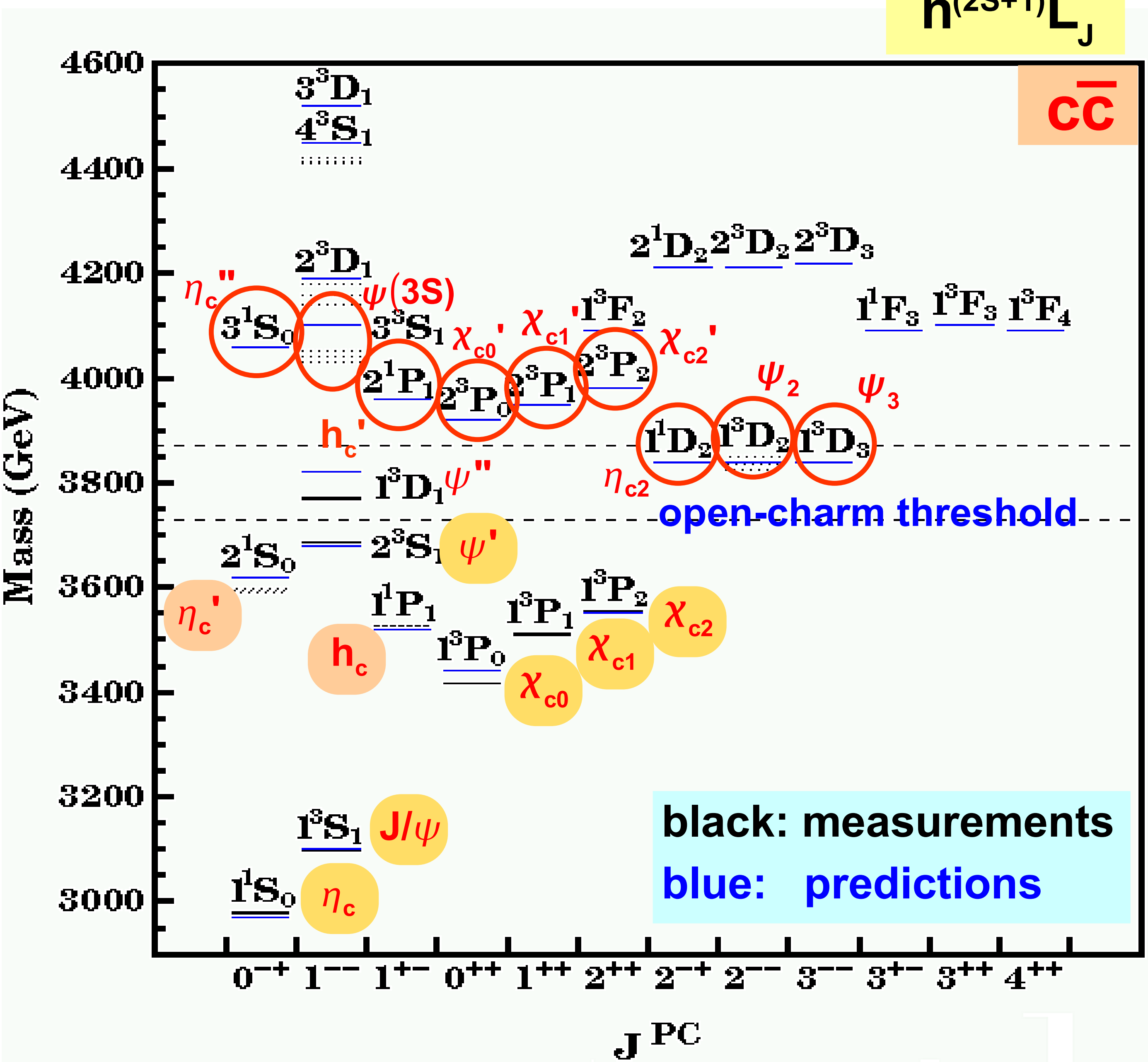
Standard Charmonium States

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



n radial quantum number

S total quark-antiquark spin

L relative orbital ang. mom.

(L = 0, 1, 2 ... S,P,D states)

$J = S + L$

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

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

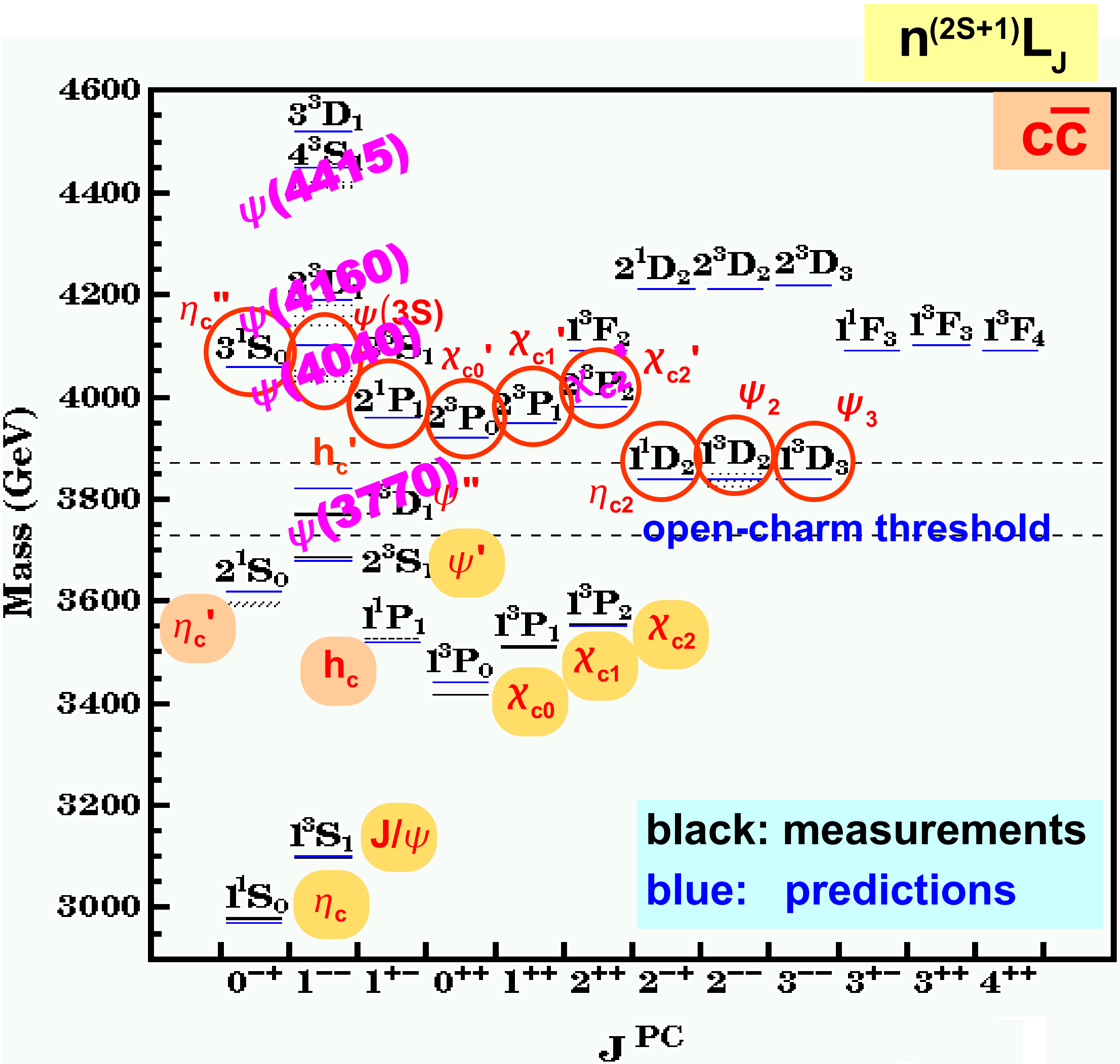
$M_D + M_{D^*} = 3871.8$ MeV/c^2

$2M_D$

Below the DD threshold:

- States are narrow
- All states observed
  - well measured
  - recently observed

Standard Charmonium States



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S total quark-antiquark spin

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(L = 0, 1, 2 ... S,P,D states)

$J = S + L$

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

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$M_D + M_{D^*} = 3871.8\ MeV/c^2$

$2M_D$

Above the DD threshold:

- States expected to be wide
- Only five states measured and identified

➡ Many candidates available

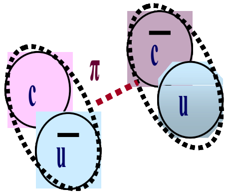
Exotic Charmonium-like States

Multiquark states

- *Molecular states*

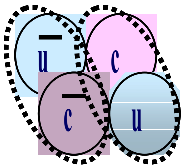
  Loosely bound pair of charm mesons

  (q,g/pion exchange at short/long distances)



- *Tetraquarks*

  Tightly bound diquark-diantiquark states

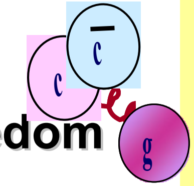


Exotic states:

- Are not forbidden in SM;
- Have exotic J^{PC}
  (0^{+-}, 1^{-+}, 2^{+-},... forbidden for $q\bar{q}$);
- exotic decay modes
  (not possible for $q\bar{q}$);
- strange properties (widths,...);
- Multiquark states could also have
  non-zero charge [$cu\bar{c}d$],
  strangeness [$cd\bar{c}s$]
  or both [$cu\bar{c}s$]

Charmonium hybrid states

States with excited gluonic degrees of freedom



Hadro-Charmonium

Compact charmonium states bound inside light hadronic matter

Threshold-effects

Virtual states at the threshold

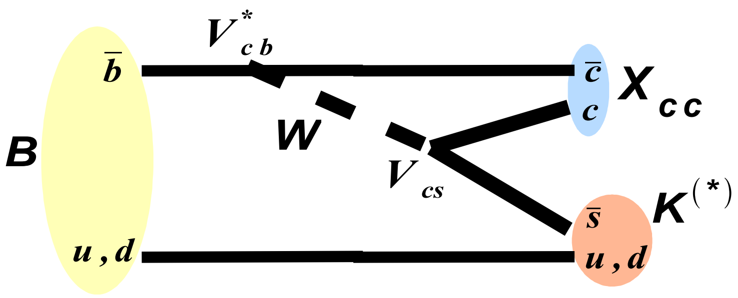
Charmonium states with shifted masses due to nearby $D^{(*)}D^{(*)}$ thresholds

Mixture of the above or something even more exotic?

$c\bar{c}$[-like] production at B-factories

- **Colour-suppressed B decays:**

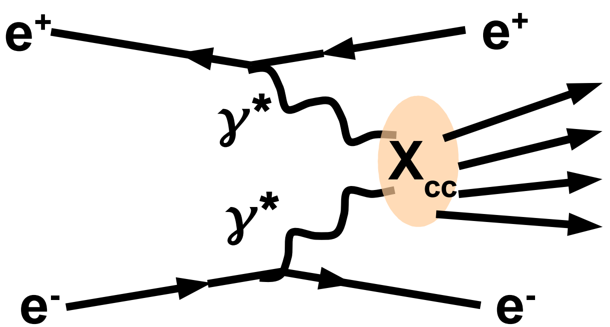
  e.g. $B \to X_{cc}\ K^{(*)}$



$0^{-+}, 1^{--}, 1^{++}$

- **Two-photon production:**

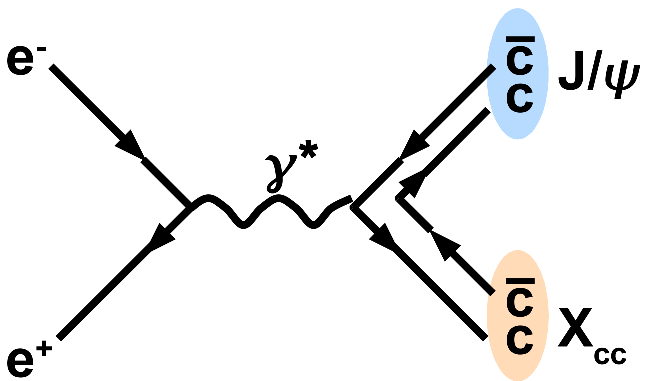
  $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X_{cc}$



$0^{-+}, 0^{++}, 2^{++}$

- **Double $c\bar{c}$ production:**

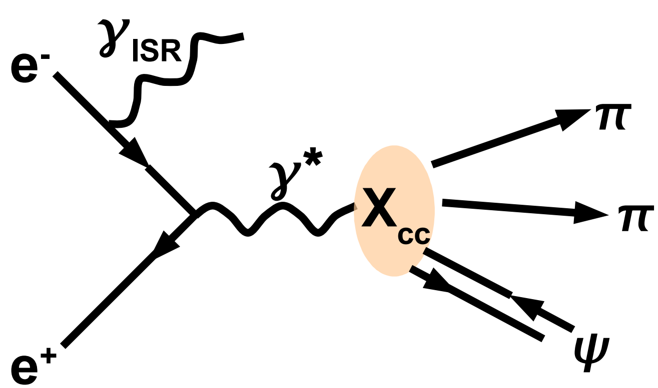
  e.g. $e^+e^- \to J/\psi\ \ X_{cc}$



states with C=+

- **e^+e^- radiative return (ISR):**

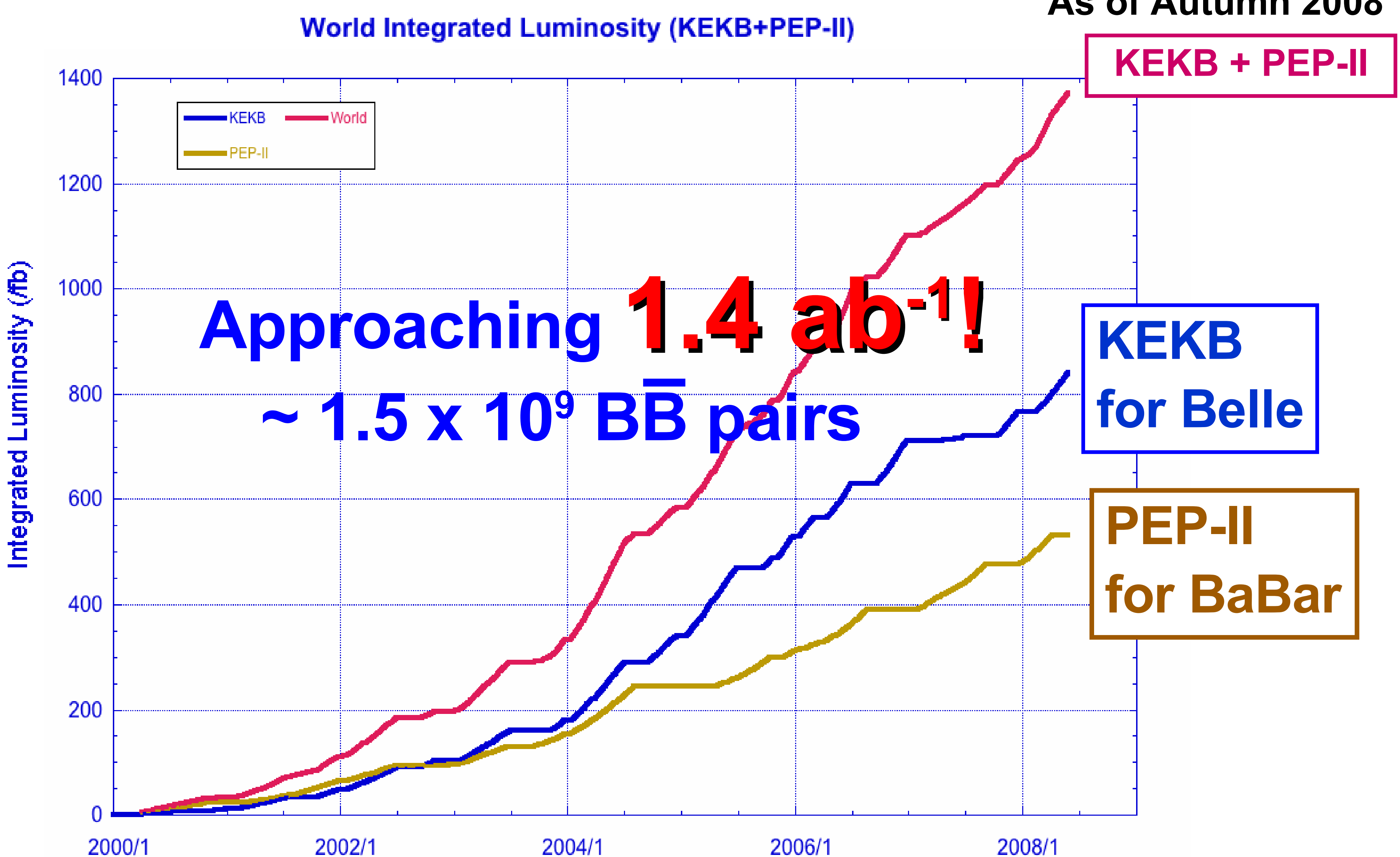
  e.g. $e^+e^- \to \gamma_{ISR}\ X_{cc} \to \gamma_{ISR}\psi\pi\pi$



1^{--} only

Asymmetric-Energy e^+e^- Colliders

As of Autumn 2008



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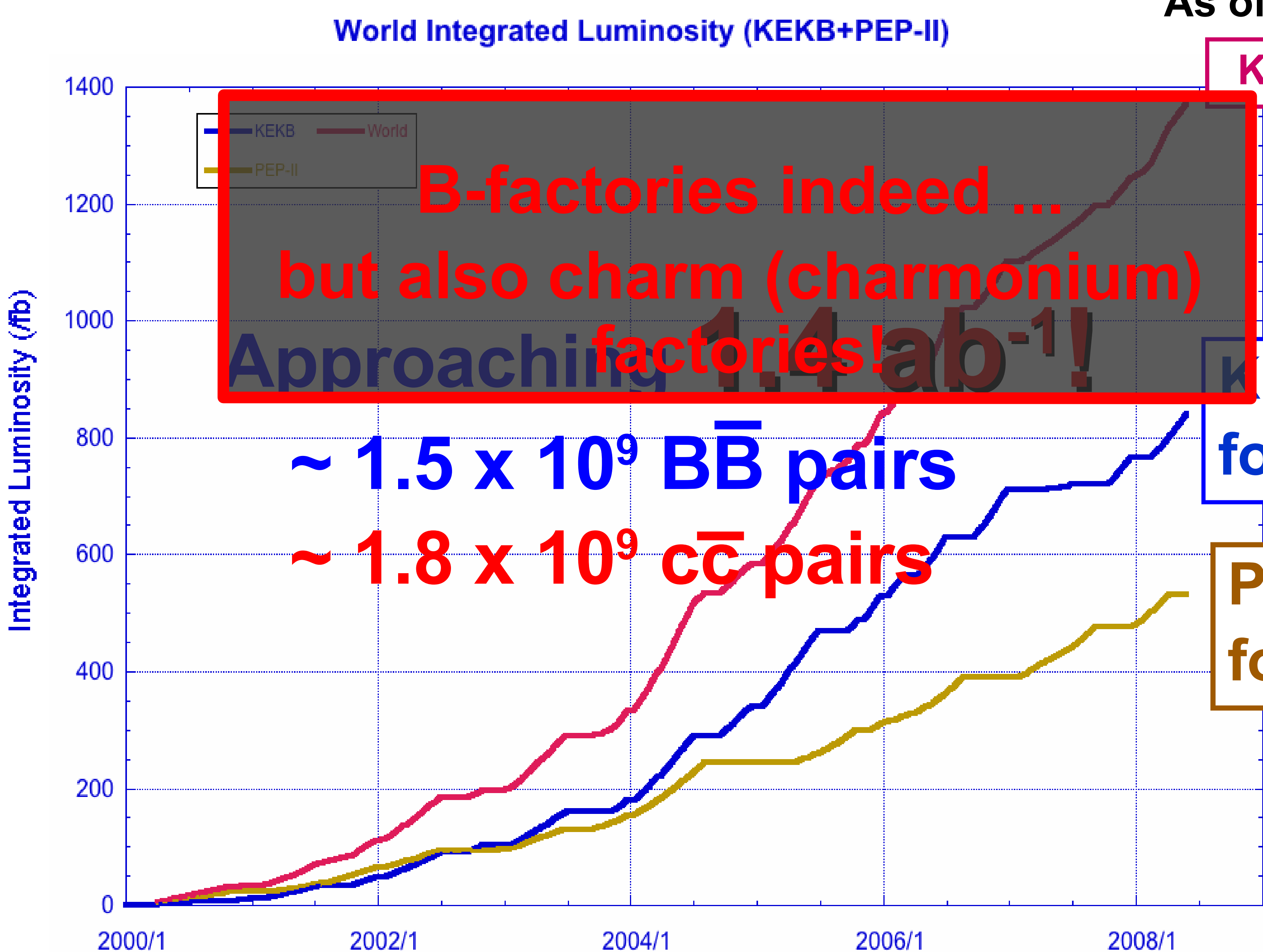


KEKB + PEP-II

Approaching $1.4\ ab^{-1}$!

B-factories indeed ...
but also charm (charmonium) factories!

$\sim 1.5 \times 10^9$ $B\bar{B}$ pairs

$\sim 1.8 \times 10^9$ $c\bar{c}$ pairs

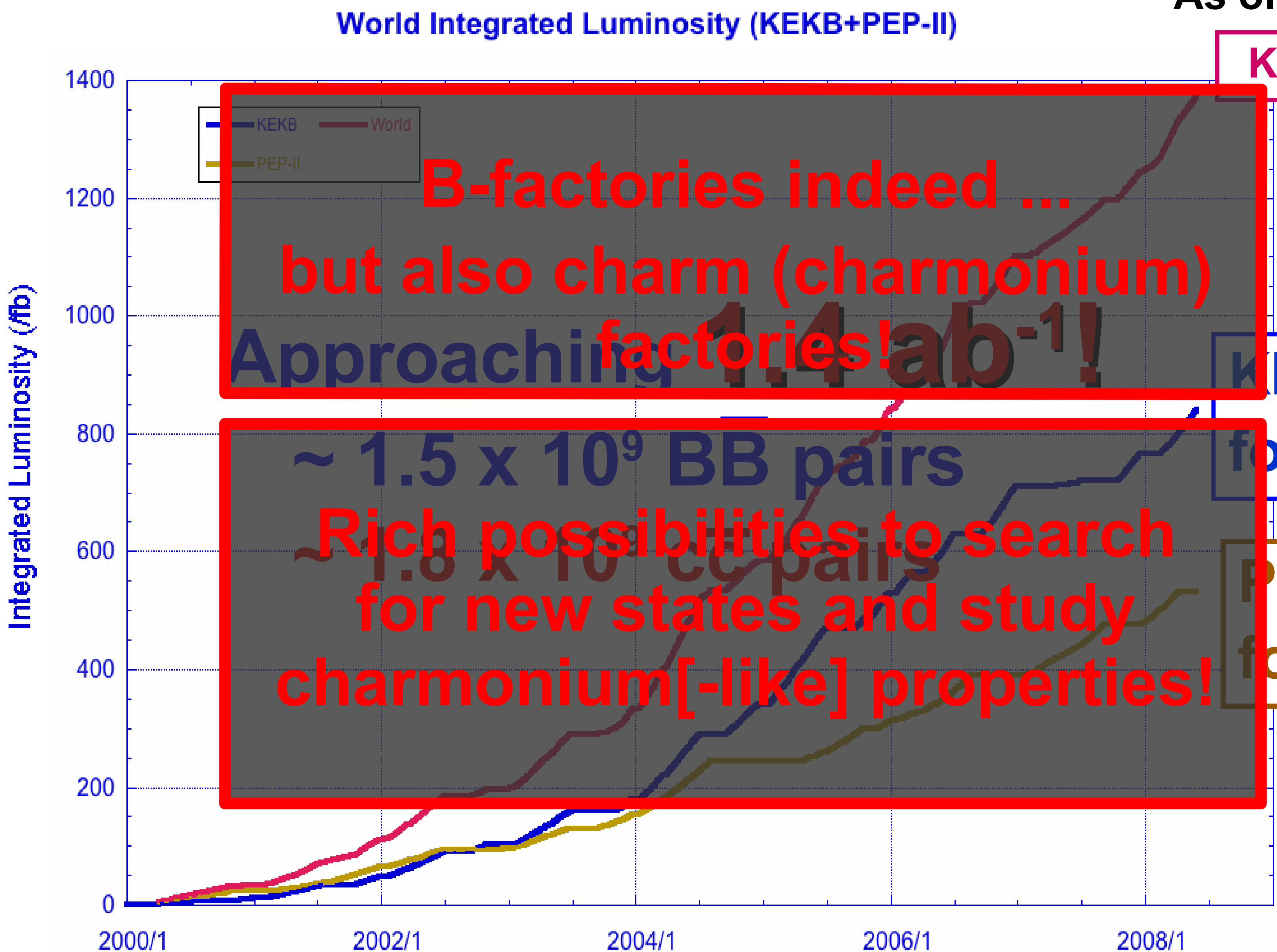
KEKB for Belle

PEP-II for BaBar

Asymmetric-Energy e⁺e⁻ Colliders

KEKB Quest for CPV kekb.jp

As of Autumn 2008



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Approaching 1.4 ab^{-1}!

~ 1.5 x 10^9 BB pairs

~ 1.8 x 10^9 cc pairs

Rich possibilities to search for new states and study charmonium[-like] properties!

KEKB + PEP-II

KEKB for Belle

PEP-II for BaBar

Many new charmonium-like states (X, Y, Z)

State	EXP	M + i Γ (MeV)	J^{PC}	Decay Modes Observed	Production Modes Observed
X(3872)	Belle,CDF, D0, Cleo, BaBar	3871.2±0.5 + i(<2.3)	1^{++}	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$, $\gamma J/\psi$	B decays, ppbar
	Belle BaBar	$3875.4 \pm 0.7^{+1.2}_{-2.0}$ $3875.6 \pm 0.7^{+1.4}_{-1.5}$		$D^0 \bar{D}^0 \pi^0$	B decays
Z(3930)	Belle	3929±5±2 + i(29±10±2)	2^{++}	$D^0 \bar{D}^0$, $D^+ D^-$	$\gamma\gamma$
Y(3940)	Belle BaBar	3943±11±13 + i(87±22±26) $3914.3^{+3.8}_{-3.4}$ ±1.6+ i(33^{+12}_{-8} ±0.60)	1^{--}	$\omega J/\psi$	B decays
X(3940)	Belle	3942^{+7}_{-6}±6 + i(37^{+26}_{-15}±8)	J^{P+}	DD^*	e^+e^- (recoil against J/ψ)
Y(4008)	Belle	$4008 \pm 40^{+72}_{-28}$ + i($226 \pm 44^{+87}_{-79}$)	1^{--}	$\pi^+\pi^- J/\psi$	e^+e^- (ISR)
X(4160)	Belle	4156^{+25}_{-20}±15+ i(139^{+111}_{-61}±21)	J^{P+}	D^*D^*	B decays
Y(4260)	BaBar Cleo Belle	$4259 \pm 8^{+8}_{-6}$ + i($88 \pm 23^{+6}_{-4}$) 4284^{+17}_{-16} ±4 + i(73^{+39}_{-25}±5) $4247 \pm 12^{+17}_{-32}$ + i(108±19±10)	1^{--}	$\pi^+\pi^- J/\psi$, $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$	e^+e^- (ISR), e^+e^-
Y(4350)	BaBar Belle	4324±24 + i(172±33) 4361±9±9 + i(74±15±10)	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)
Z^+(4430)	Belle	4433±4±1+ i($44^{+17}_{-13}{}^{+30}_{-11}$)	J^P	$\pi^+ \psi(2S)$	B decays
Y(4620)	Belle	4664±11±5 + i(48±15±3)	1^{--}	$\pi^+\pi^- \psi(2S)$	e^+e^- (ISR)

E. Eichten QWG -- 5th International Workshop on Heavy Quarkonia DESY October 17-20, 2007

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Z(3930)	[illegible]	[illegible]	[illegible]	[illegible]	$\gamma\gamma$
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$Z^+(4430)$	Belle	4433±4±1+ i($44^{+17}_{-13}$$^{+30}_{-11}$)	J^P	$\pi^+\psi(2S)$	B decays
Y(4620)	Belle	4664±11±5 + i(48±15±3)	1^{--}	$\pi^+\pi^-\psi(2S)$	e^+e^- (ISR)

Even more new states observed since then ...

... only some of these will be mentioned.

E. Eichten QWG -- 5th International Workshop on Heavy Quarkonia DESY October 17-20, 2007

Charged charmonium-like states ($Z^{\pm}$)

$Z^{\pm}(4430)$

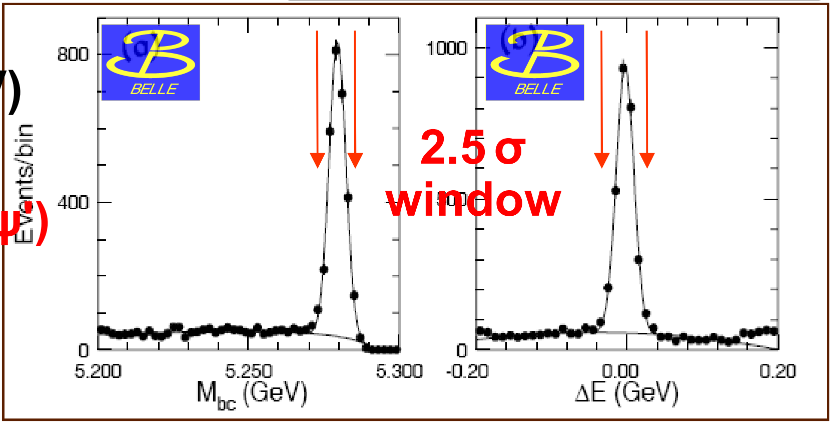
$Z^{\pm}(4050)$ & $Z^{\pm}(4250)$

$Z^+(4430)$ observation by Belle

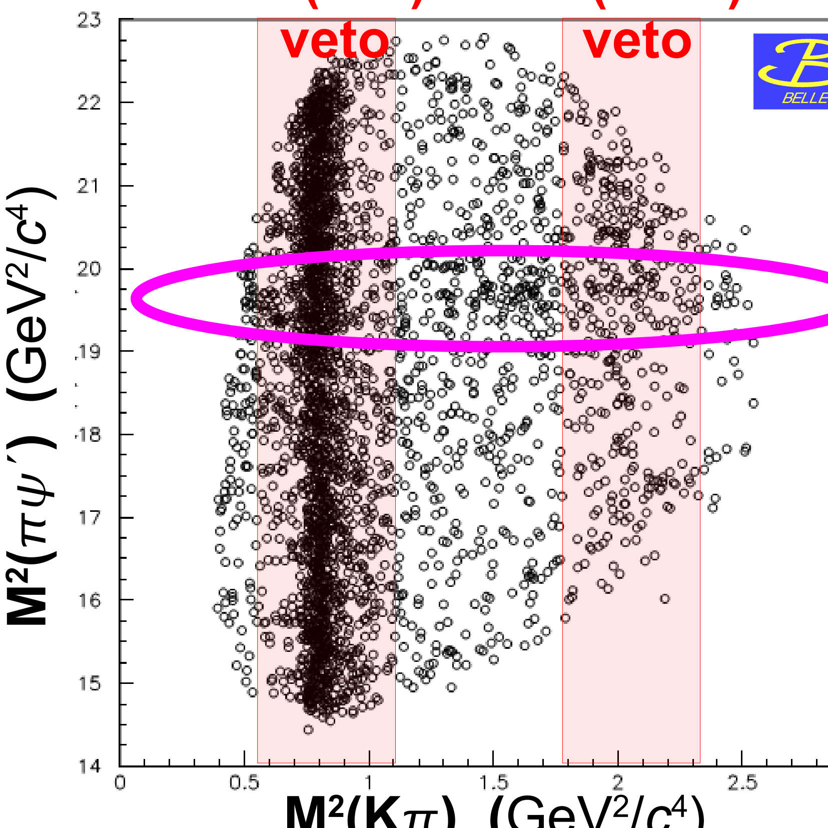
PRL 100, 142001(2008)
657 $B\bar{B}$

New state observed in $B \to K\pi^{\pm}\psi(2S)$ decays

- $B \to K\pi^{\pm}\psi'$ ($K=K^{\pm}$, K_S^0;
  $\psi' \to \ell^+\ell^-$ or $J/\psi(\to \ell^+\ell^-)\pi^+\pi^-$ with $m_{\pi^+\pi^-} > 0.44$GeV)
- Clear signals in both ΔE and M_{bc} seen
- $m_{K\pi\psi'}$ kinemat. constrained to m_B → $\sigma \sim 2.5$MeV for $M(\pi\psi')$
- $M(\pi^{\pm}\psi')$ fit: S-wave Breit-Wigner and PS-like function

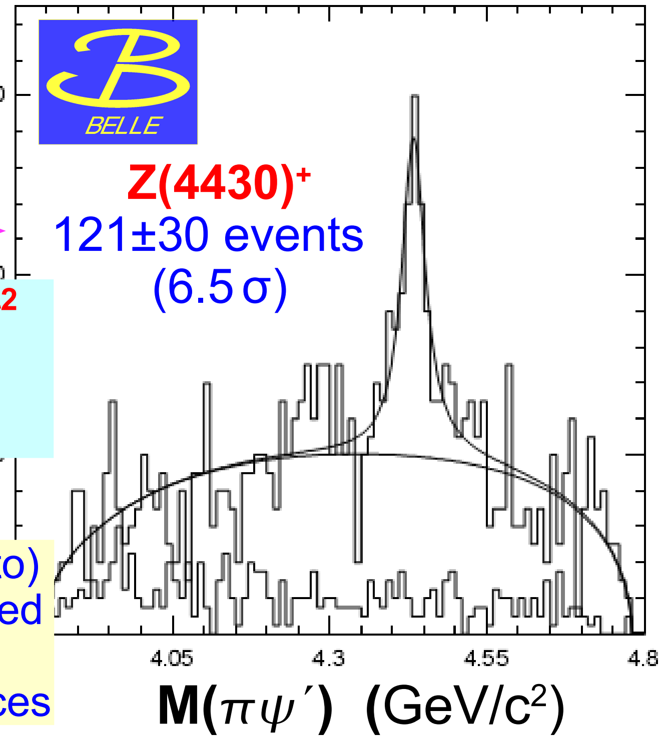


K*(890) K*(1430)



$M = (4433 \pm 4 \pm 2)$ MeV/c^2

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



→robust signal (subsamples;veto)
→too narrow state to be explained by interference of known S-, P- D-wave $K\pi$ resonances

$Z^+(4430)$ observation by Belle

PRL 100, 142001(2008)
657 $B\overline{B}$

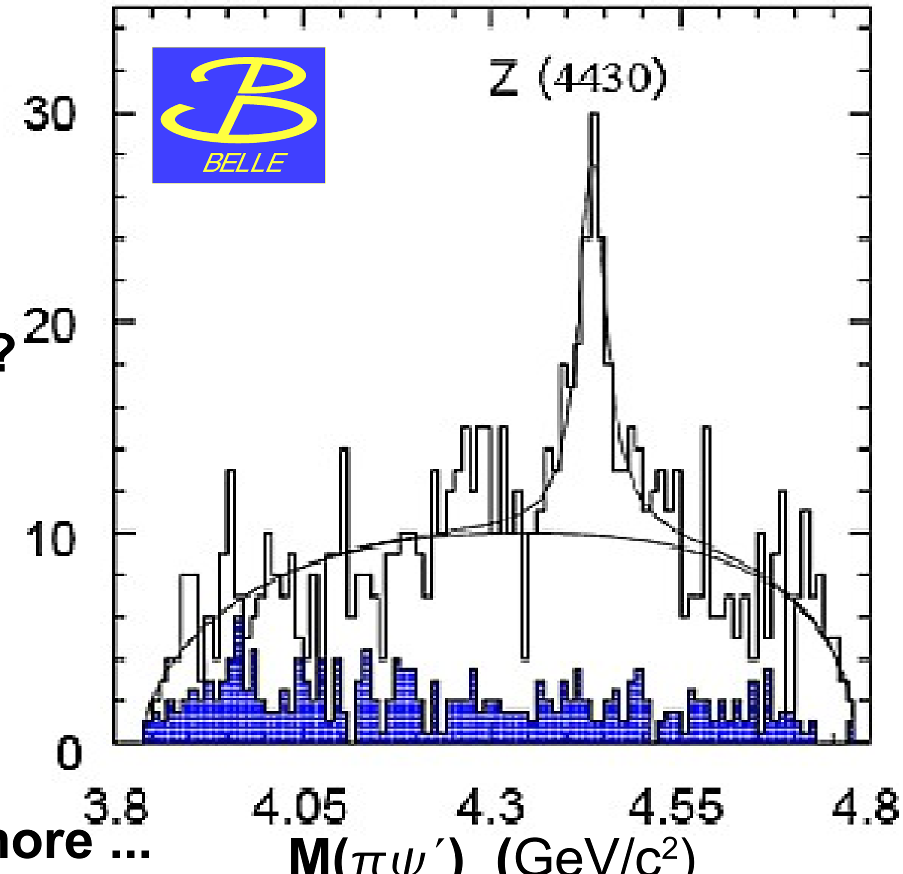
$Z(4430)^+ \rightarrow \psi(2S)\pi^+$:

- Charged state that decays like charmonium (= charged charmonium-like state)

$$Br(\overline{B}^0 \rightarrow K^- Z^+(4430)) \times Br(Z^+(4430) \rightarrow \pi^+\psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

- Not enough statistics to determine J^P

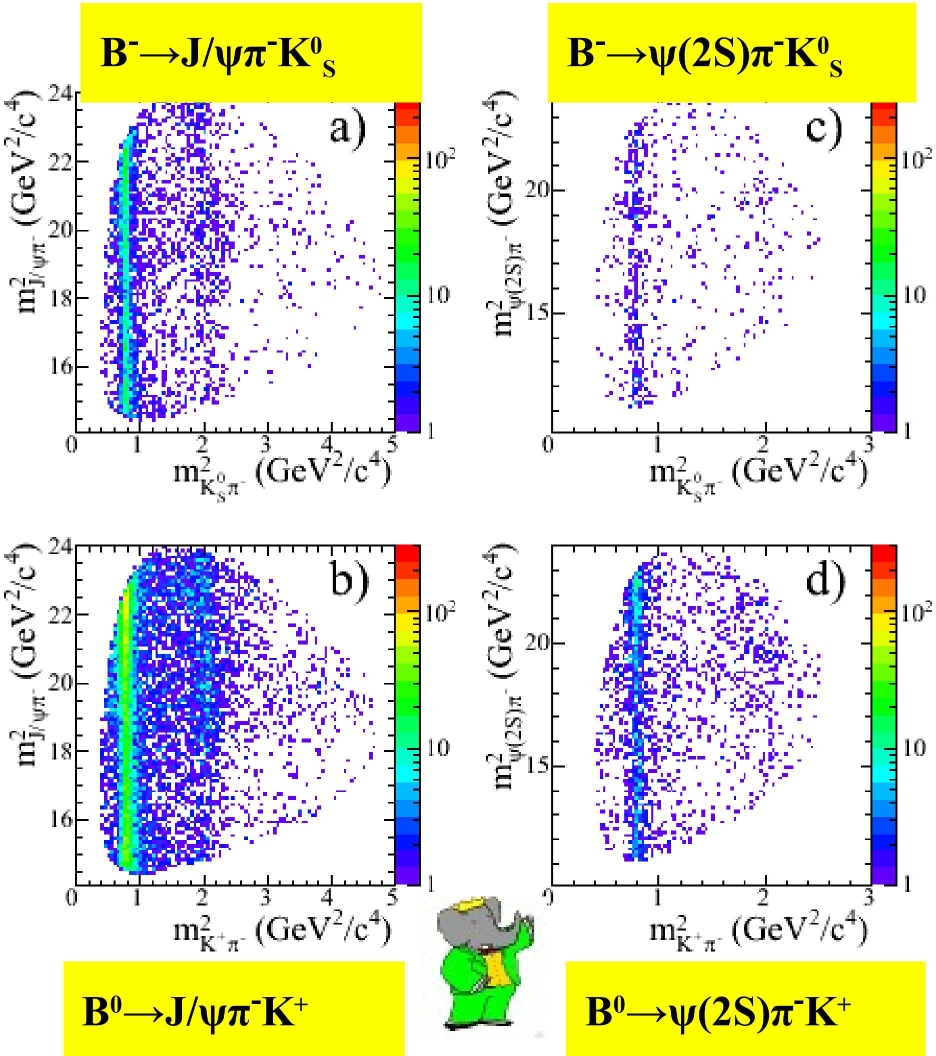
- (Some) possible interpretations:
  - [cu][$\bar{c}\bar{d}$] tetraquark with $J^P=1^+$
    (Radial excitation of X(3872) family?)
    - Neutral partner in decays: $\psi'\pi^0/\eta$, $\eta_c'\rho^0/\omega$?
    - Charged 1S state in decays: $\psi\pi^\pm$, $\eta_c\rho^\pm$?
    { Maiani et al., arXiv:hep-ph/0708.3997 }
  - $D^*\overline{D}_1(2420)$ threshold effect
    { Rosner, PRD 76, 114002 (2007) }
  - $D^*\overline{D}_1(2420)$ molecule with $J^P=0^-, 1^-$
    Decay to $D^*D^*\pi$ expected.
    { Meng et al., hep-ph/0708.4222 } ... and more ...



First serious tetraquark candidate → Confirmation needed

Search for the $Z^-(4430)$ by BaBar

arXiv:0811.0564v1[hep-ex]
413 fb^{-1} (subm. to PRD)



$B^{-,0} \to J/\psi \pi^- K^{0,+}$

and **$B^{-,0} \to \psi(2S) \pi^- K^{0,+}$**

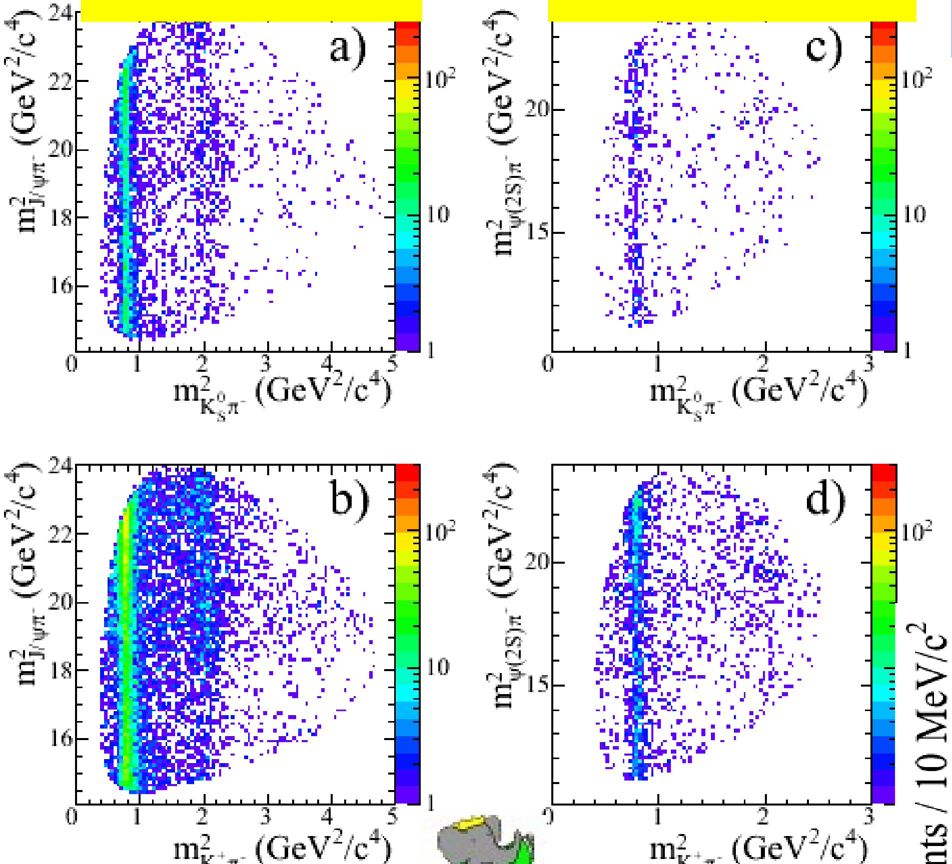
- **Detailed study of $K\pi^-$ system:**

- mass & angular distribution structures dominate the Dalitz plots
- correct for the efficiency over the DP
- include S, P and D wave

Search for the $Z^-(4430)$ by BaBar

arXiv:0811.0564v1[hep-ex]
413 fb^{-1} (subm. to PRD)

$B^- \to J/\psi \pi^- K^0_S$ $B^- \to \psi(2S) \pi^- K^0_S$



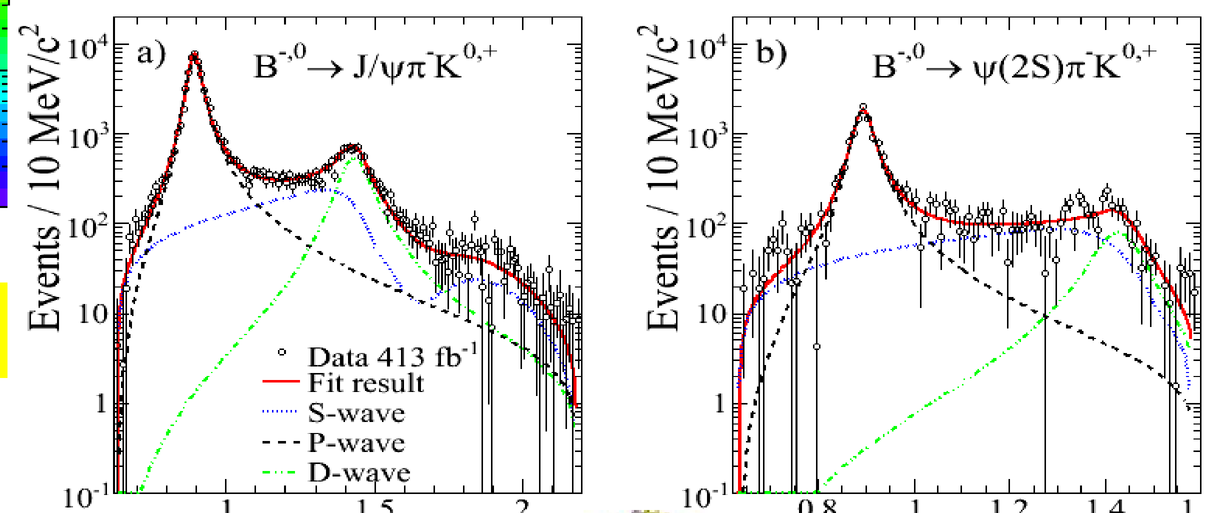
$B^0 \to J/\psi \pi^- K^+$

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

$B^{-,0} \to J/\psi \pi^- K^{0,+}$

and $B^{-,0} \to \psi(2S) \pi^- K^{0,+}$

- Detailed study of $K\pi^-$ system:
- mass & angular distribution structures dominate the Dalitz plots
- correct for the efficiency over the DP
- include S, P and D wave
- combine charged and neutral modes



$m_{K\pi^-}$ (GeV/c^2) $m_{K\pi^-}$ (GeV/c^2)

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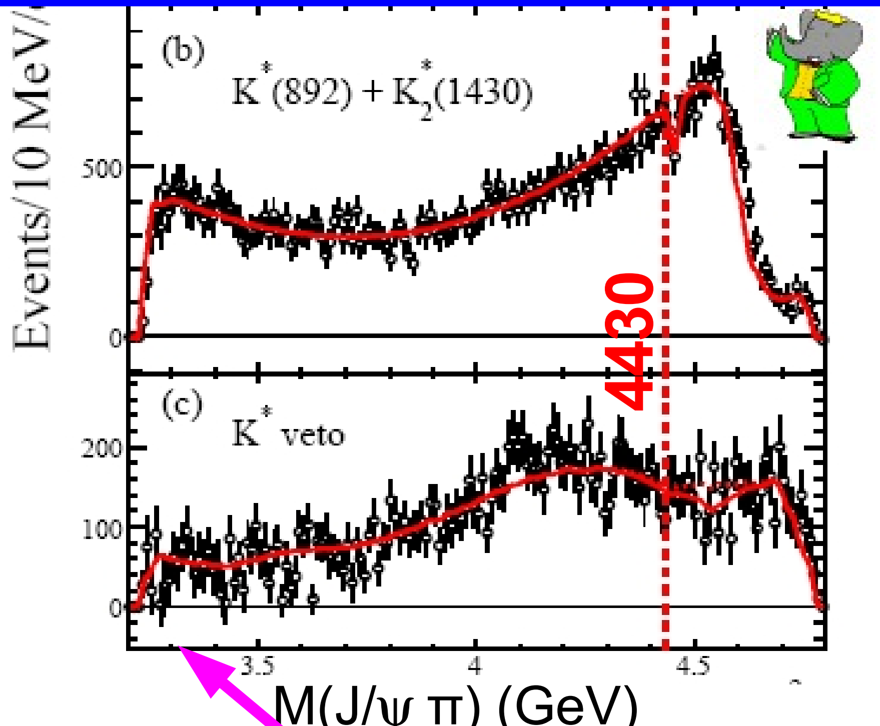


$B^{-,0} \rightarrow J/\psi \pi^- K^{0,+}$ and $B^{-,0} \rightarrow \psi(2S) \pi^- K^{0,+}$

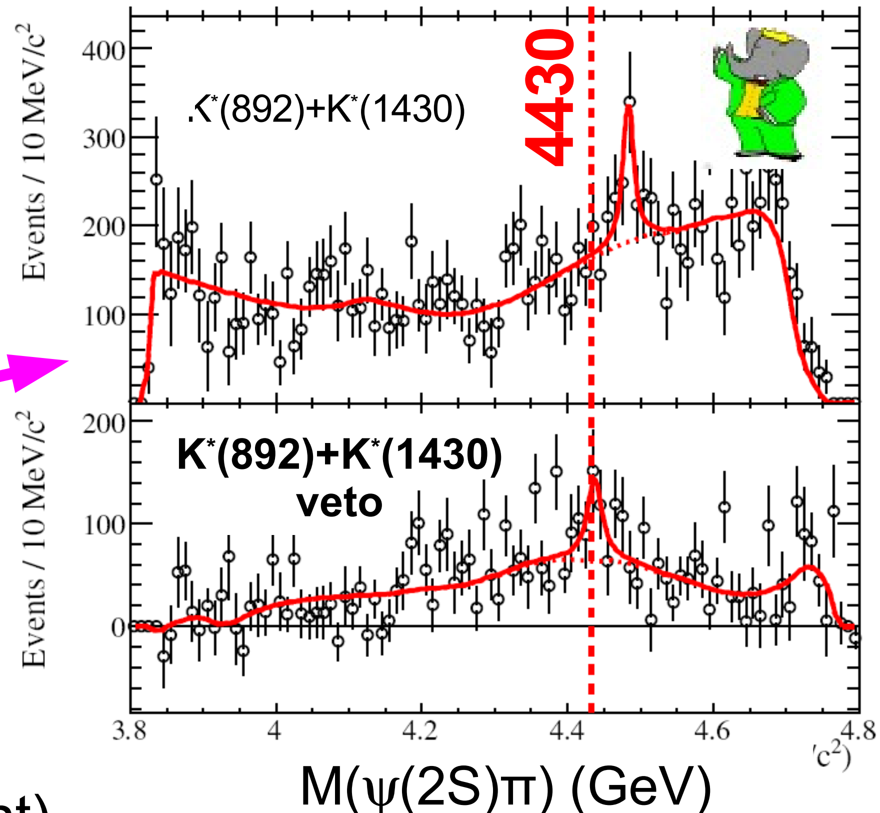
- $K\pi^-$ reflections into $J/\psi\pi^-$ / $\psi(2S)\pi^-$ mass distributions (σ~4-7MeV) describe the background

M($J/\psi\pi^-$) and M($\psi(2S)\pi^-$) fits:

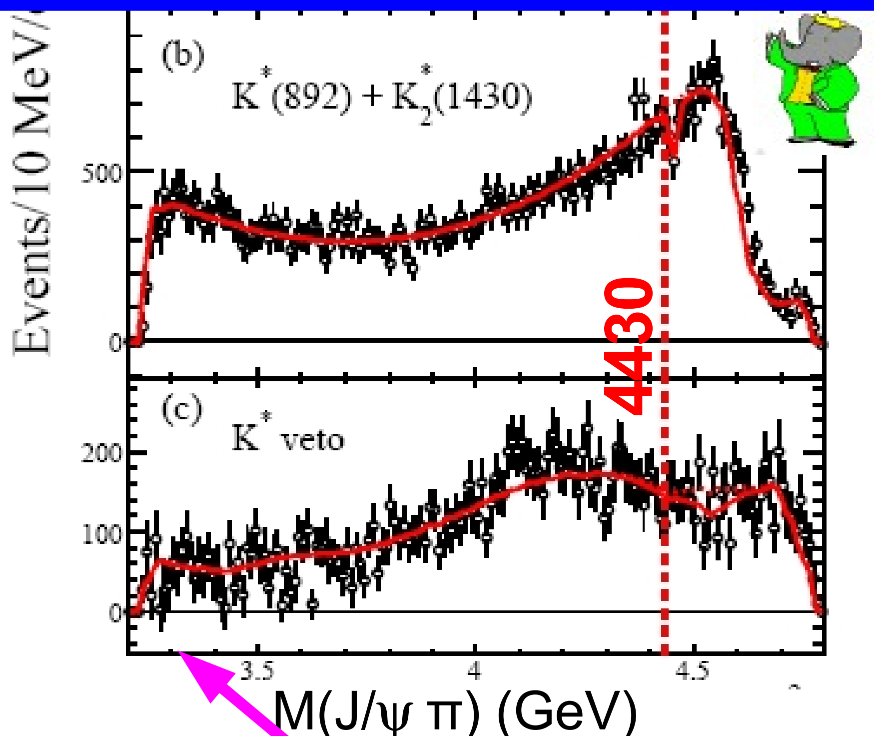
- **Background + S-wave BW (free M & Γ)**
  ⇨ **Observed ~ -2σ / ~ +2σ fluctuations wrt. the bckg. in J/ψ / ψ(2S) modes.**
- **For fixed M=4430 MeV/c² & Γ=45 MeV (Belle):**

BF($B^0 \rightarrow Z^- K^+$, $Z^- \rightarrow \psi(2S)\pi^-$)<3.1x10^{-5} @ 95% CL

BaBar and Belle values differ by 1.7σ
(without taking systematics into account)



Search for the $Z^-(4430)$ by BaBar



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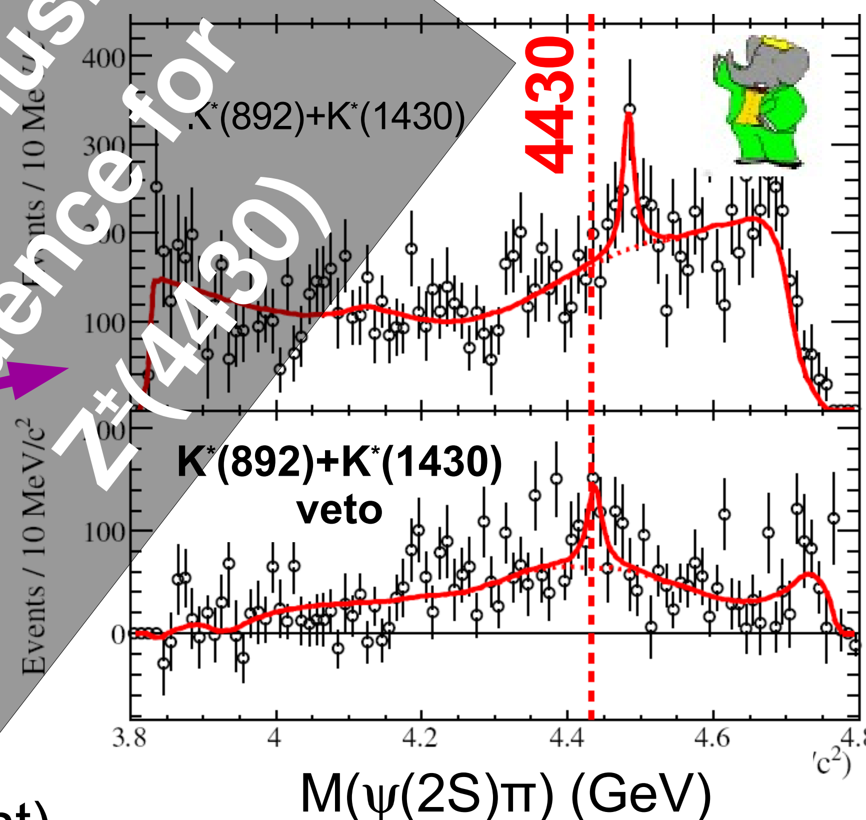
- $K\pi^-$ reflections into $J/\psi\pi^-$ / $\psi(2S)\pi^-$ mass distributions (σ~4-7MeV) describe the background

No conclusive evidence for $Z^{\pm}(4430)$



M($J/\psi\pi^-$) and M($\psi(2S)\pi^-$) fits:

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BaBar and Belle values differ by 1.7σ (without taking systematics into account)

$Z^+(4430)$: Complete Dalitz analysis by Belle

The default Dalitz fit model used:

All known K* resonances with J=0,1,2 below 1780 MeV/c^2

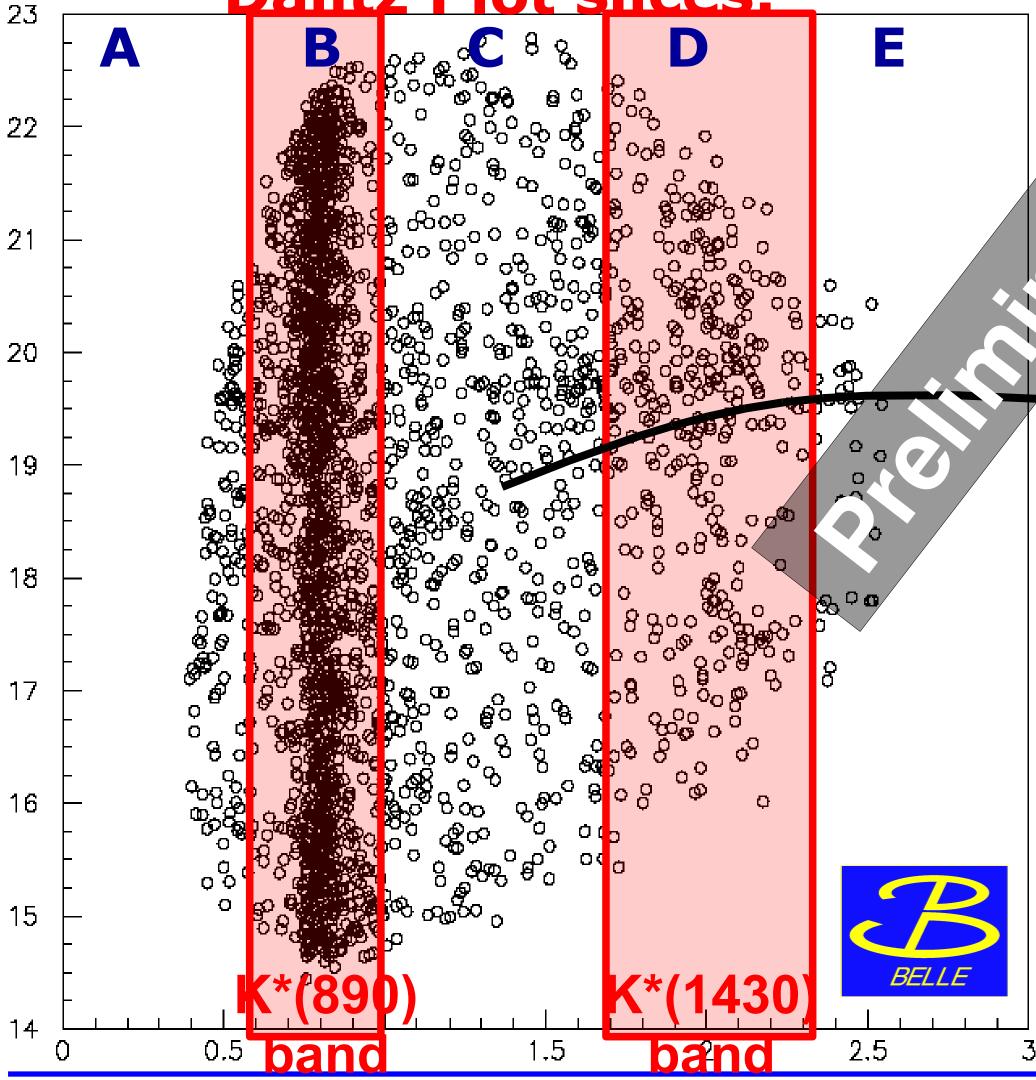
$B \to K\pi^{\pm}\psi(2S)$

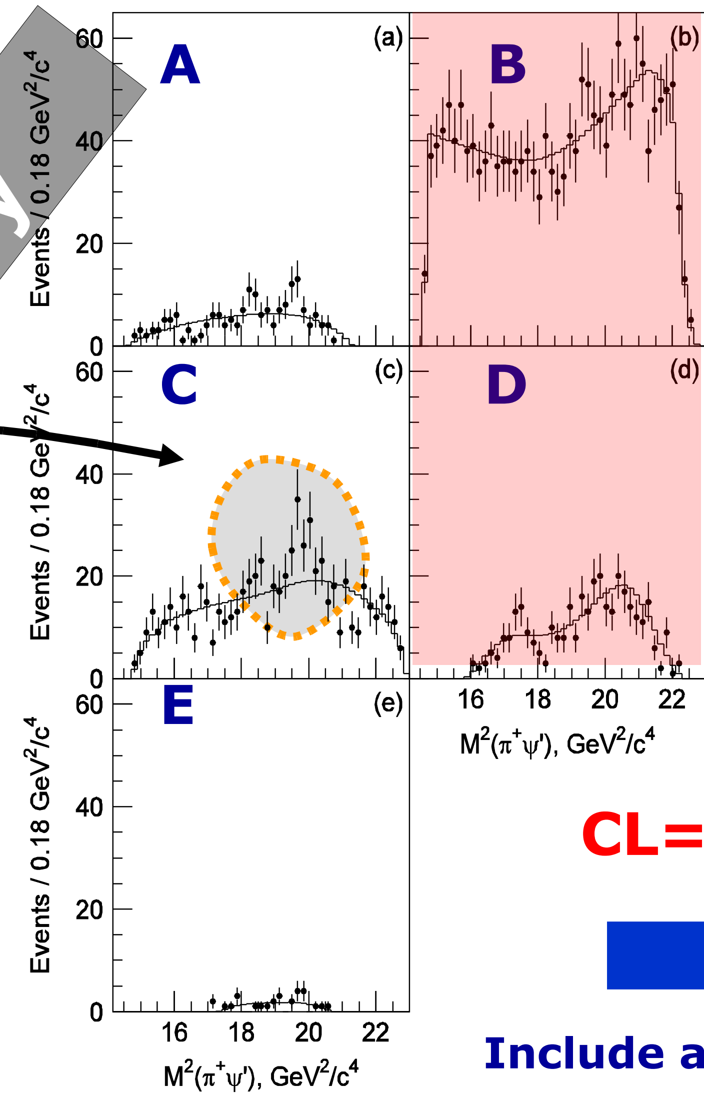
Presented @ QWG '08
2nd - 5th December 2008

NEW

Fit without a Z resonance:

Dalitz Plot slices:





CL=0.1%

Include a Z reson.

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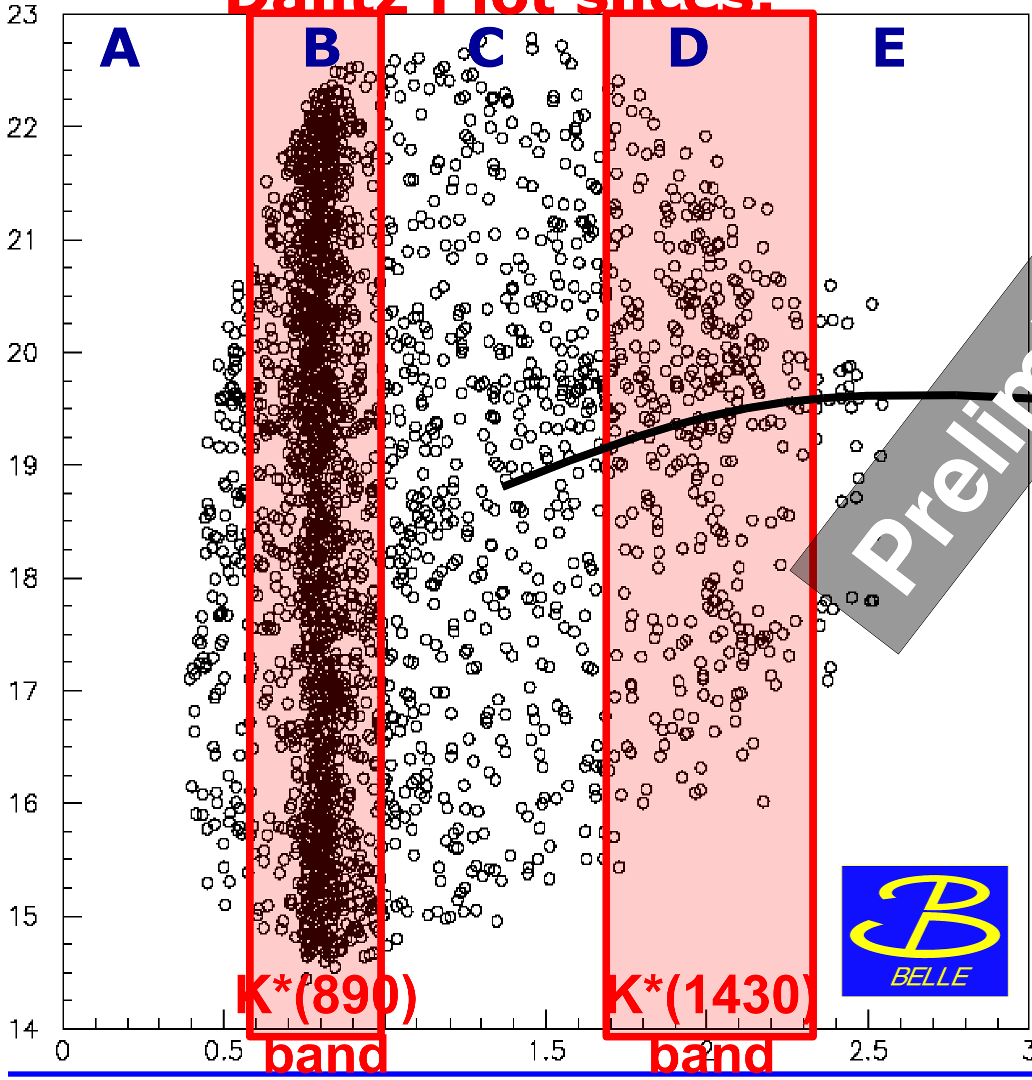

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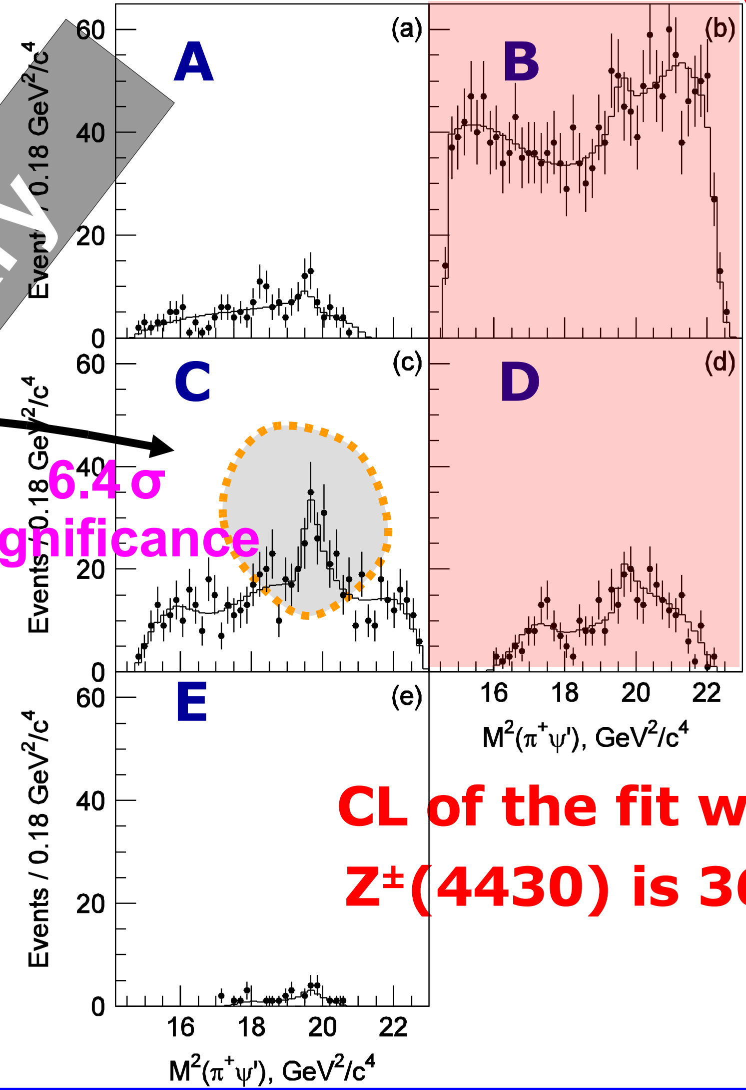

CL of the fit with $Z^{\pm}(4430)$ is 36%

$Z^+(4430)$: Complete Dalitz analysis by Belle

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2nd - 5th December 2008

Different fit models and the significance of $Z(4430)^+$:

TABLE I: Different fit models that are used to study systematic uncertainties and the significances of the $Z(4430)^+$.

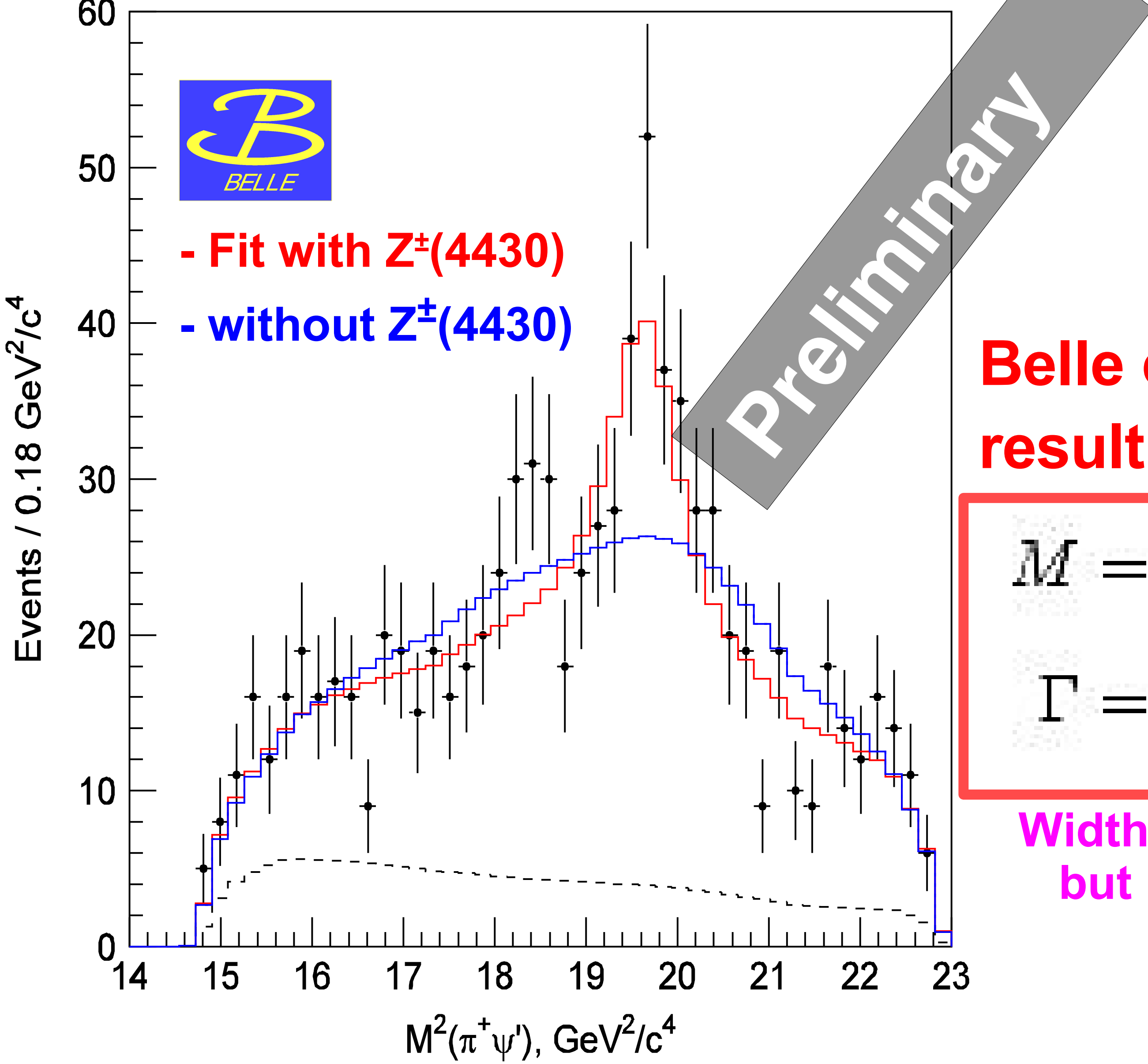
	Model	Significance
1	default*	6.4σ
2	no $K_0^*(1430)$	6.6σ
3	no $K^*(1680)$	6.6σ
4	release constraints on κ mass & width	6.3σ
5	new K^* $(J=1)$	6.0σ
6	new K^* $(J=2)$	5.5σ
7	add non-resonant $\psi'(2S)K^-$ term	6.3σ
8	add non-resonant $\psi'(2S)K^-$ term, release constraints on κ mass & width	5.8σ
9	add non-resonant $\psi'(2S)K^-$ term, new K^* $(J=1)$	5.5σ
10	add non-resonant $\psi'(2S)K^-$ term, new K^* $(J=2)$	5.4σ
11	add non-resonant $\psi'(2S)K^-$ term, no $K^*(1410)$	6.3σ
12	add non-resonant $\psi'(2S)K^-$ term, no $K^*(1680)$	6.6σ
13	LASS parameterization of S-wave component	6.5σ

Significance of $Z(4430)^+$ in different fit models is always larger than 5σ

$Z^+(4430)$: Updated parameters

Presented @ QWG '08
2^{nd} - 5^{th} December 2008

Sum of A, C, D slices (K*'s veto) :



Belle confirms the original result on $Z^{\pm}(4430)$:

$$M = (4443^{+15+17}_{-13-13})\ \mathrm{MeV}/c^2,$$

$$\Gamma = (109^{+86+57}_{-43-52})\ \mathrm{MeV},$$

Width larger than original (45MeV), but uncertainties are also large

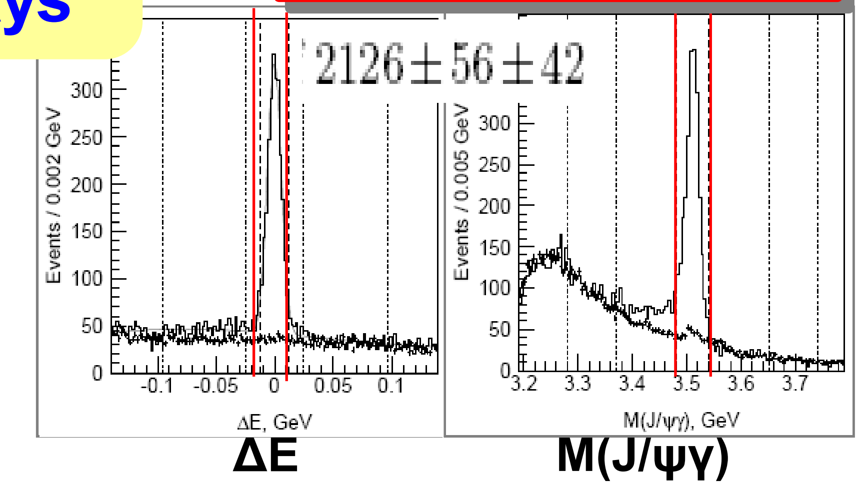
Observation of $Z^+(4050)$ & $Z^+(4250)$ by Belle

PRD 78, 072004 (2008)
657 BB

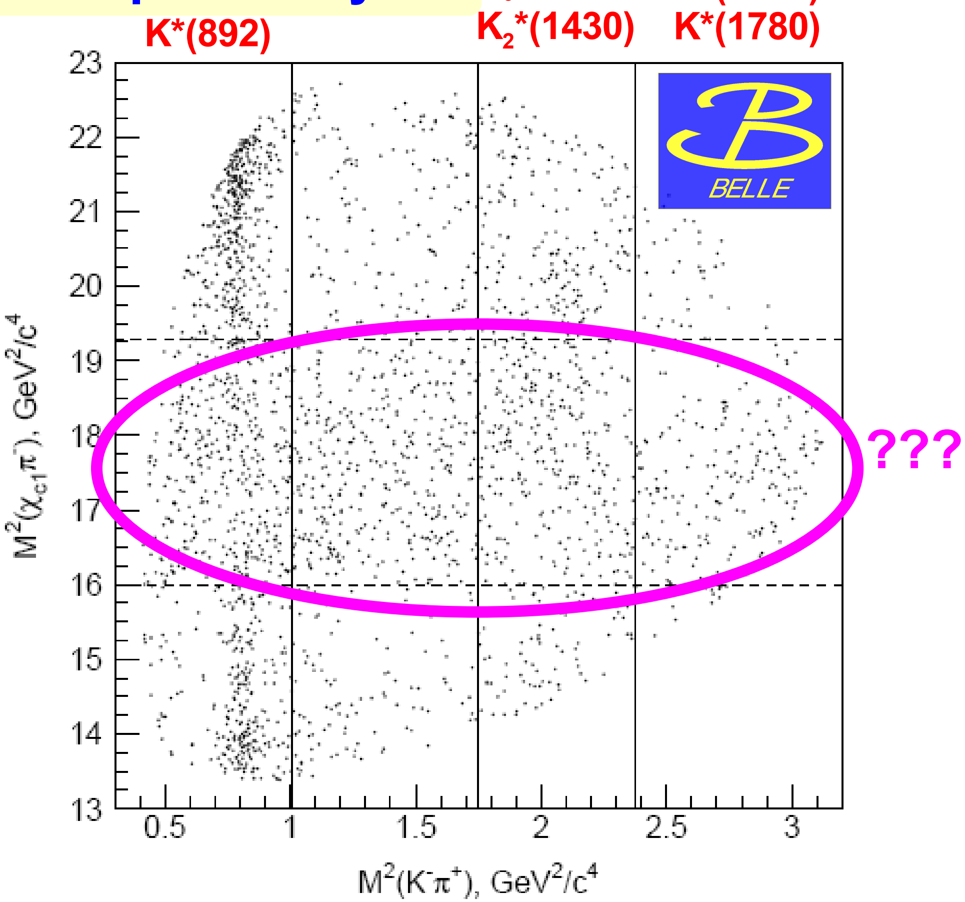
Another $B \to K^- \pi^+ (c\bar{c})$ mode :

New states observed in $\bar{B}^0 \to K^- \pi^+ \chi_{c1}$ decays

- $B^0 \to K^- \pi^+ \chi_{c1}$ ($\chi_{c1} \to J/\psi \gamma$; $J/\psi \to l^+ l^-$)
- Clear signals in ΔE, M_{bc}, $M(J/\psi\gamma)$



Dalitz plot analysis:



- Fit model: Include all K* resonances below 1900 MeV/c^2
- Integrated χ_{c1}, J/ψ angular distributions (no sensitivity)
- Correction for Lorentz non-invariance of helicity
- Binned (400x400) maximum likelihood fit
- Fit results depicted in M_1^2 for M_2^2 bands

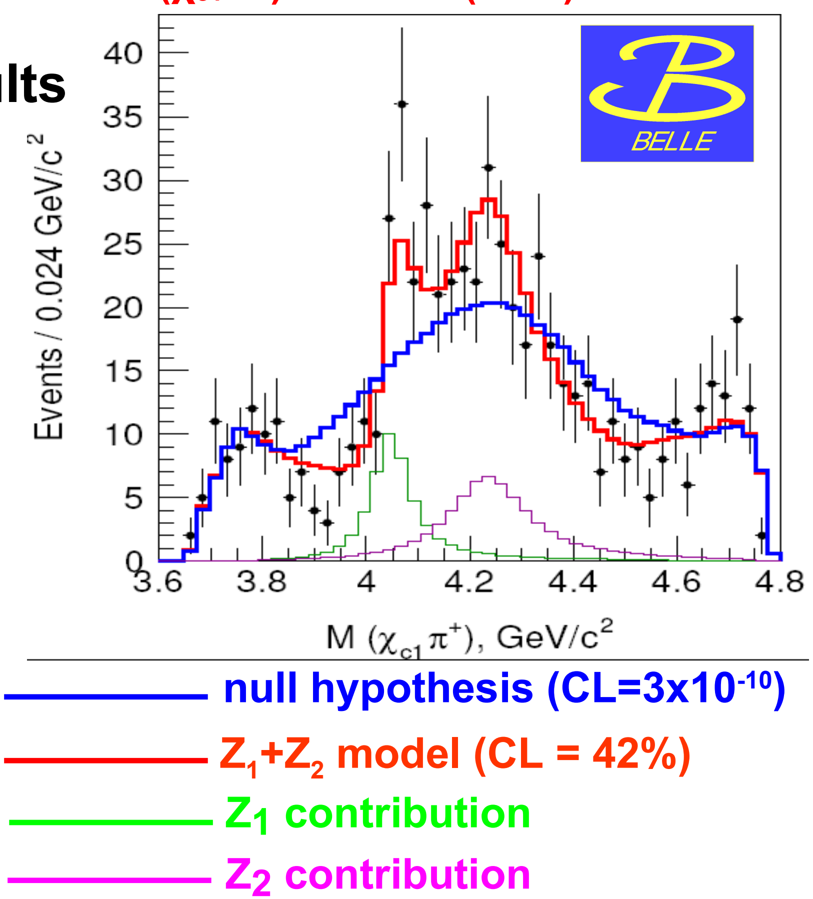
Observation of $Z^+(4050)$ & $Z^+(4250)$ by Belle

PRD 78, 072004 (2008)
657 $B\overline{B}$

- Data favour fit with 2 resonant structures:
  one Z (10.7σ) ; Z_1 and Z_2 (13.2σ ; 5.7σ wrt. one Z)
- Spin of $Z_{1,2}$ is not determined:
  J=0 and J=1 hypotheses give comparable results
- $Z_{1,2}$ parameters:
  large syst. errors due to model uncertainties

	Z_1^+	Z_2^+
M/MeV	$4051 \pm 14^{+20}_{-41}$	$4248^{+44}_{-29}{}^{+180}_{-35}$
Γ/MeV	$82^{+21}_{-17}{}^{+47}_{-22}$	$177^{+54}_{-39}{}^{+316}_{-61}$
$\mathcal{B}_{\overline{B}^0} \times \mathcal{B}_{Z^+}$	$(3.1^{+1.5}_{-0.9}{}^{+3.7}_{-1.7}) \times 10^{-5}$	$(4.0^{+2.3}_{-0.9}{}^{+19.7}_{-0.5}) \times 10^{-5}$

M($\chi_{c1}\pi^+$) for 1<M²($K^-\pi^+$)<1.75GeV



BF product comparable to $Z^+(4430)$, X(3872)…

- $Z^+(4050)$, $Z^+(4250)$ join $Z^+(4430)$ as charged charmonium-like exotics:

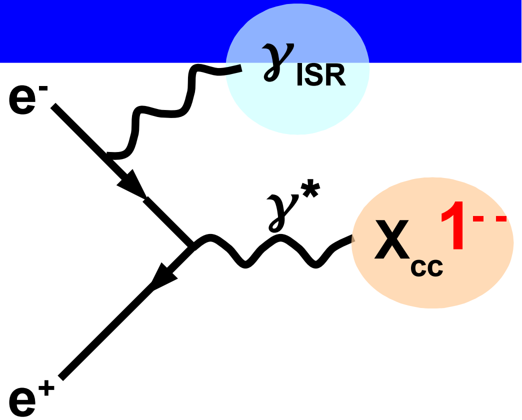
Tetraquark candidates

→ Experimental confirmation is needed

Many Y states with Initial State Radiation

Study of 1^{--} states with ISR

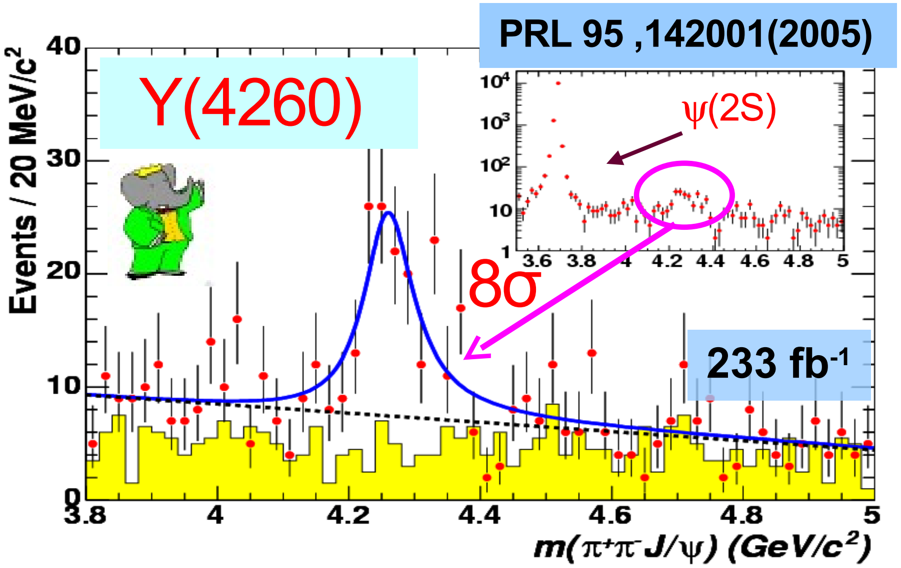
- Initial state radiation(ISR) gives access to $J^{PC} = 1^{--}$ states



- Two main characteristics of ISR physics at B-factories:
  - Continuous ISR spectrum gives access to the wide √s range
  - High luminosity "compensates" for the emission of hard photons

➡ Sensitivity comparable to direct energy scan (e.g. CLEO-c, BES III)

- Y(4260) → $J/\psi\pi^+\pi^-$ observed via ISR by BaBar (confirmed first by CLEO)



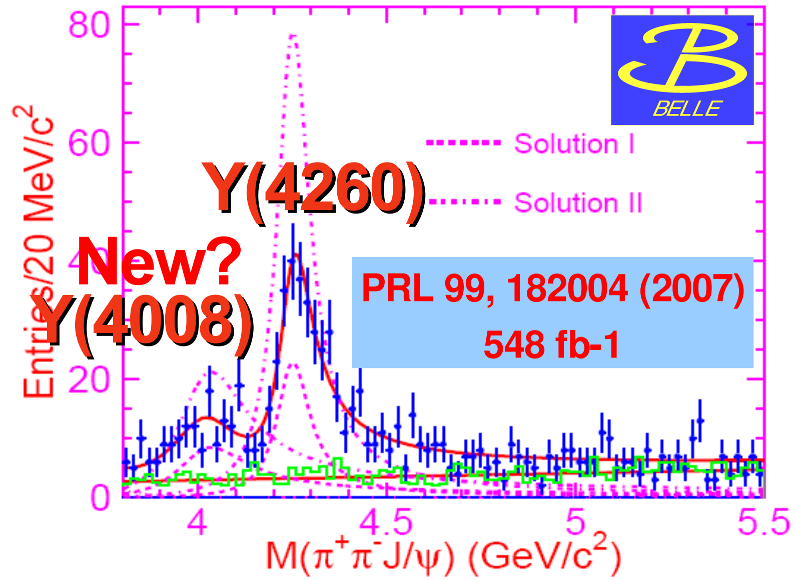
Study of 1^{--} states in $e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$

➡ **Using BaBar's approach**

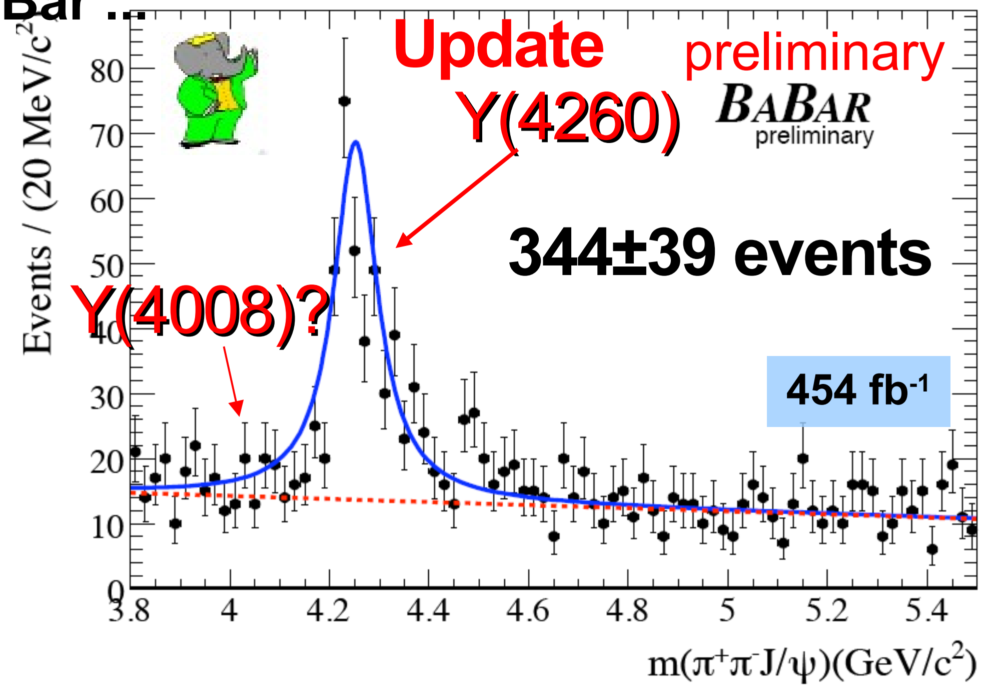
- **Study of $e^+e^- \to \gamma_{ISR} J/\psi\pi^+\pi^-$ also by Belle**
- **Reconstruction: $\pi^+\pi^-$ & $J/\psi(\to e^+e^-, \mu^+\mu^-)$**
  (no extra tracks allowed; γ_{ISR} not detected)
- **Missing(recoil) mass identifies ISR:**

$$M_{rec} = \sqrt{(E_{cms} - E^*_{J/\psi\pi^+\pi^-})^2 - p^{*\,2}_{J/\psi\pi^+\pi^-}}$$

- **Fit to $M(J/\psi\pi^+\pi^-)$ with two coherent BW curves**
- **Y(4260) is confirmed also by Belle**
- **New Y(4008) resonance? Not seen by BaBar ...**



	State	M, MeV/c²	Γ_{tot}, MeV
Belle	Y(4008)	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$
BaBar	Y(4260)	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
BaBar	Y(4260)	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$
CLEO	Y(4260)	$4284^{+17}_{-16} \pm 4$	$73^{+39}_{-25} \pm 5$
Belle	Y(4260)	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm 10$



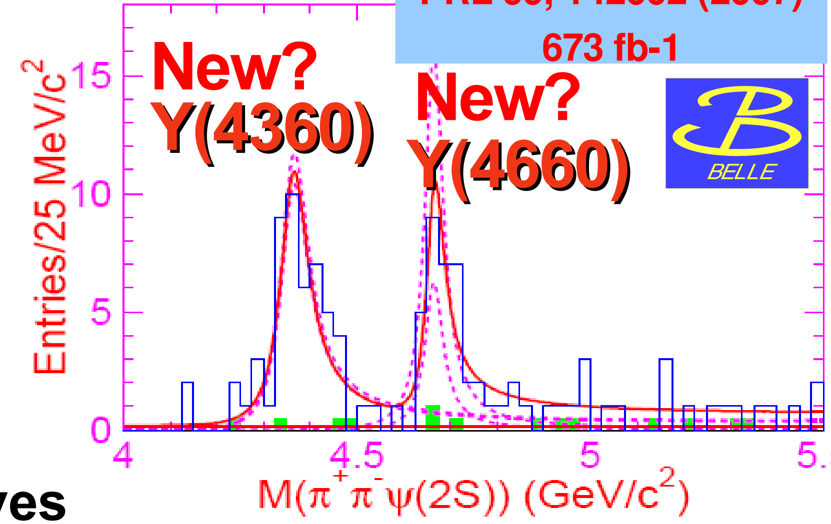
Study of 1^{--} states in $e^+e^- \to \gamma_{ISR} \psi' \pi^+\pi^-$

Similar approach also for:

- Study of $e^+e^- \to \gamma_{ISR}\, \psi(2S)\pi^+\pi^-$
- Reconstruction: $\pi^+\pi^-$ & $\psi(2S)(\to \pi^+\pi^- J/\psi(\to e^+e^-, \mu^+\mu^-))$
  (no extra tracks allowed; γ_{ISR} not detected)
- Missing(recoil) mass identifies ISR:

$$M_{rec} = \sqrt{(E_{cms} - E^*_{\psi(2S)\pi^+\pi^-})^2 - p^{*\,2}_{\psi(2S)\pi^+\pi^-}}$$

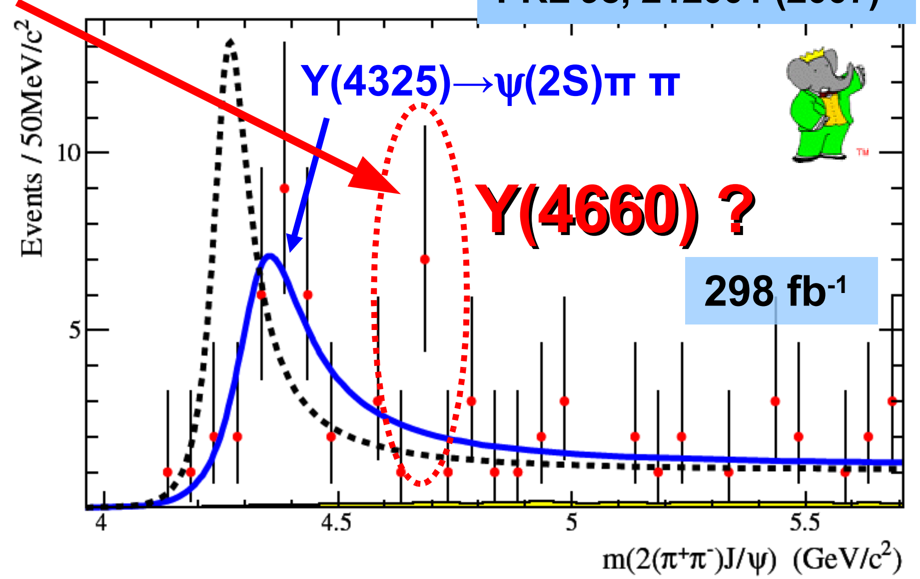
PRL 99, 142002 (2007)
673 fb-1



- Fit to $M(\psi(2S)\pi^+\pi^-)$ with two coherent BW curves
- Belle's Y(4360) resonance:
  close to BaBar's Y(4325), but narrower
- New Y(4660) resonance by Belle? (Seen also by BaBar?)

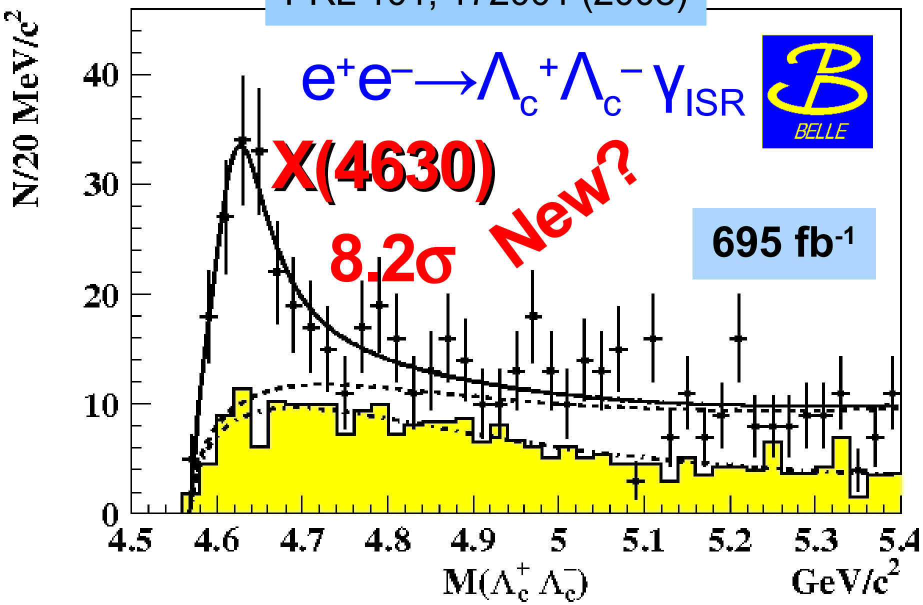
State	M, MeV/c^2	Γ_{tot}, MeV
Y(4325) (BaBar)	4324 ± 24	172 ± 33
Y(4325) (Belle)	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$
Y(4660) (Belle)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

PRL 98, 212001 (2007)



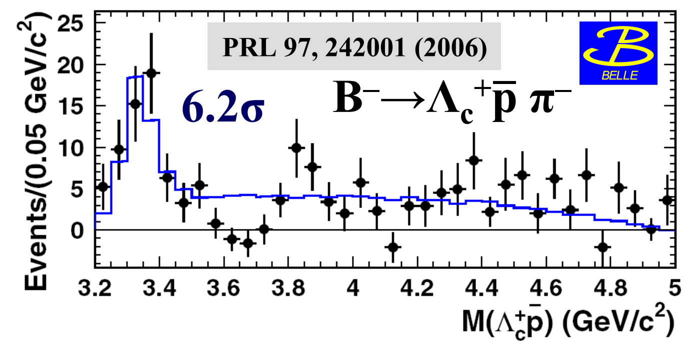
Study of $e^+e^- \to \gamma_{ISR} \Lambda_c^+ \Lambda_c^-$

PRL 101, 172001 (2008)



Interpretations for the new X(4630)

- Dibaryonic peak near the threshold
  seen e.g. in $B \to p\Lambda\pi$, $J/\psi \to \gamma pp$

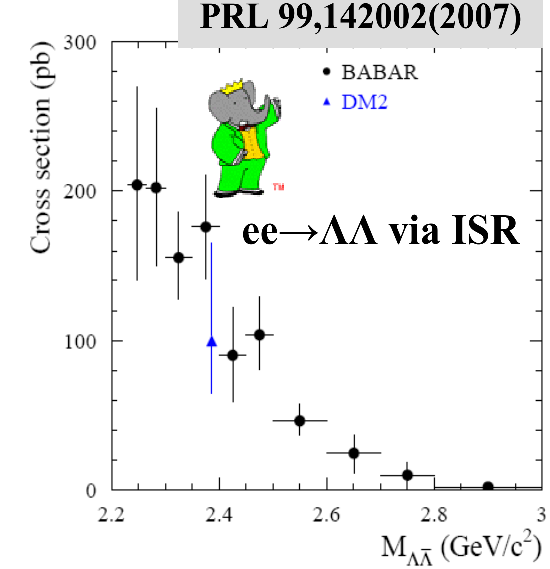


- Could be also: X(4630) = Y(4660)?

State	M, MeV/c^2	Γ_{tot}, MeV
X(4630)	4634^{+8+5}_{-7-8}	92^{+40+10}_{-24-21}
Y(4660)	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$

- But no peaking structure in:

PRL 99,142002(2007)

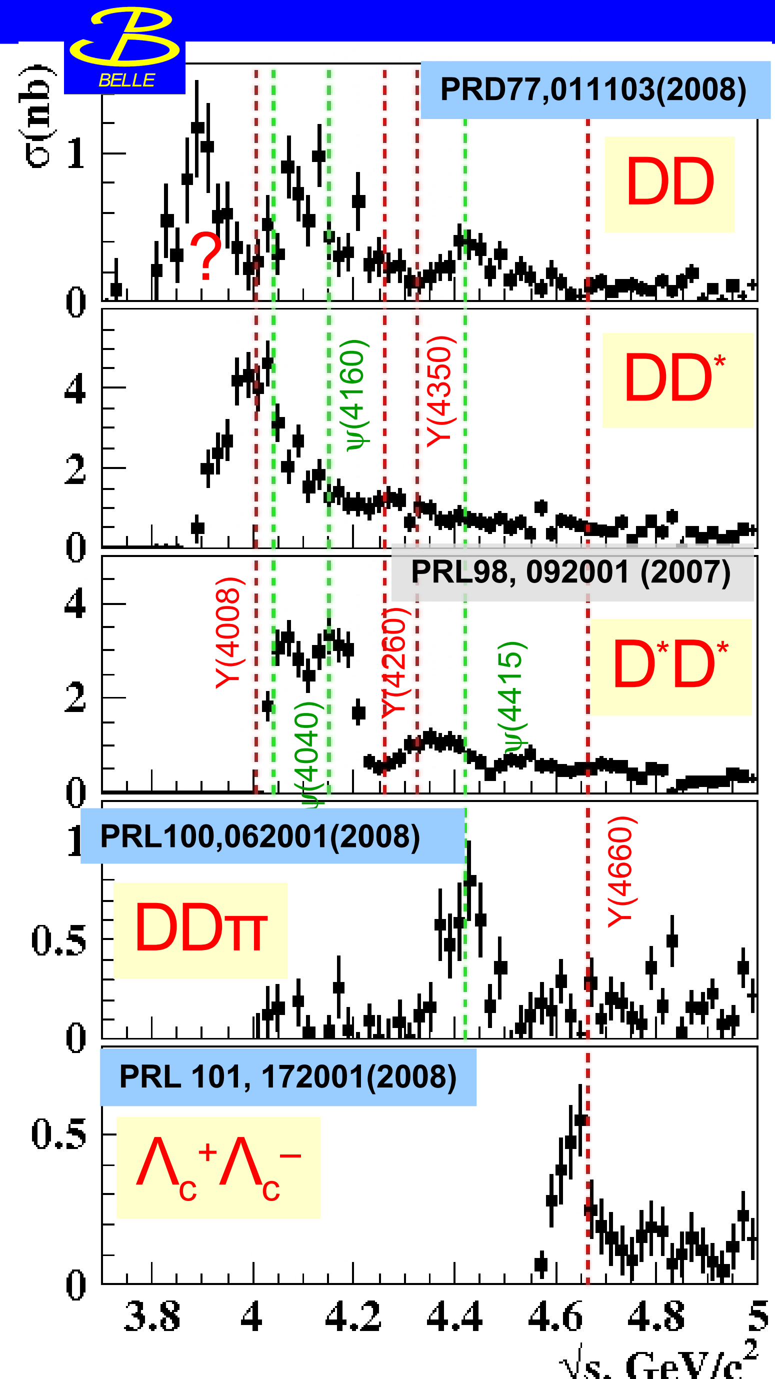


- Can not exclude 5^3S_1 charmonium :
  in some models M (5^3S_1) ~4670MeV

Exclusive $D^{(*)}D^{(*)}$ cross sections w. ISR

- $e^+e^- \to D\bar{D}$, $D\bar{D}^*$, $D^*\bar{D}^*$ cross sections measured with ISR
- $D\bar{D}^*$, $D^*\bar{D}^*$: using partial reconstruction; γ_{ISR} detected

  $D\bar{D}$: fully reconstructed; γ_{ISR} used if detected
- Recoil mass is again used to identify ISR events
- Method is well established
- Difficult interpretation in terms of resonances (there are many maxima/minima, model dependent coupled-channels and threshold effects…)



1^{--} Y states: What are they?

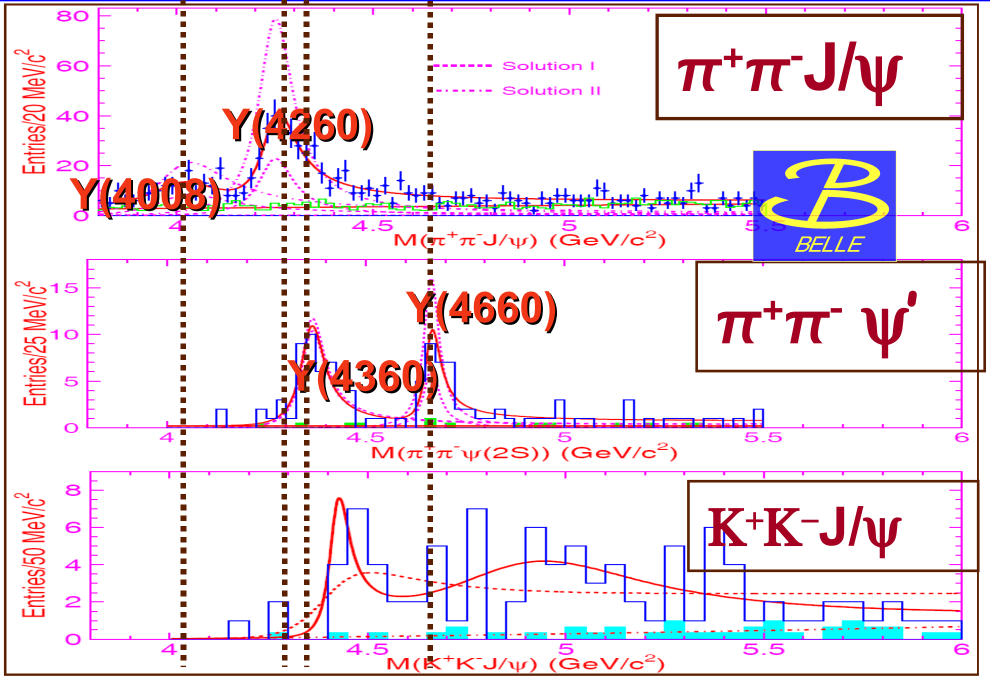
➡ Difficult interpretation

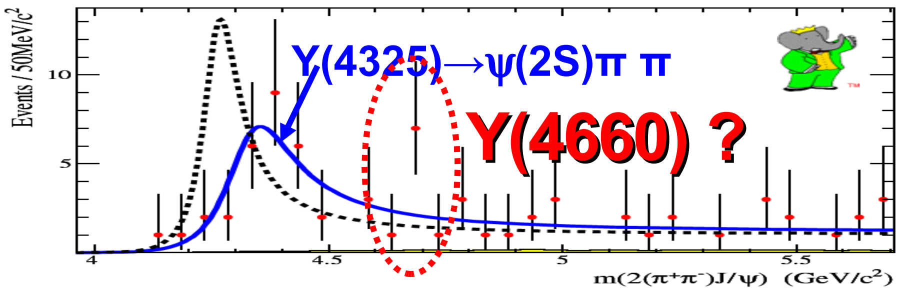
Charmonium options:

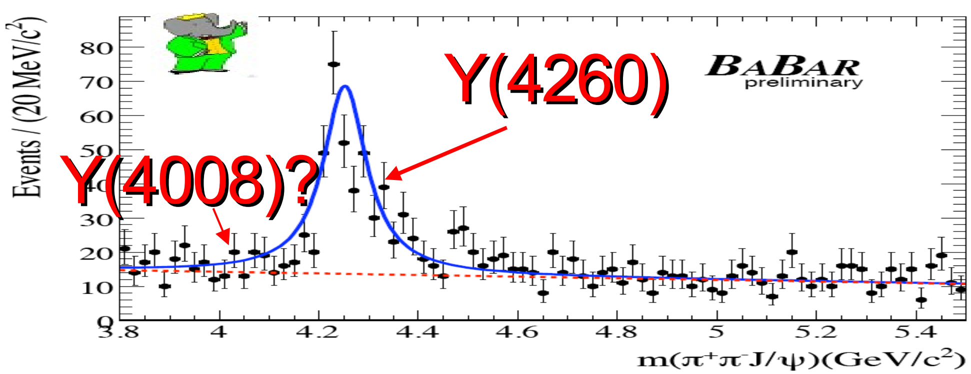
- Y states above $D\bar{D}$ threshold but don't match well the peaks in $D^{(*)}\bar{D}^{(*)}$ cross-sections
- Large widths for $\psi\pi\pi$ transition: not likely for conventional $c\bar{c}$
- No $c\bar{c}$ assignments available in this mass region (there are too many 1^{--} states)

Other options:

- Charm-meson threshold effects
- $D\bar{D}_1$ or $D^*\bar{D}_0$ molecules
- $cqc\bar{q}$ tetraquarks
- $c\bar{c}g$ hybrids predicted@4.2-5GeV $D\bar{D}_1$ mode should dominate
- Coupled-channel effects







Summary and conclusions

Charmonium(-like) states :

Following the exciting X(3872) discovery ...

... New exotic state observed in $B \to \psi(2S)\pi^{\pm}K$ decays:

$Z(4430)^+$ (charged charmonium-like state)

... also Z_1^+ and Z_2^+ in $B^0 \to K^- \pi^+ \chi_{c1}$ decays

New charmonium[-like] spectroscopy established at 4-5GeV?

Good candidates for molecular states; multiquarks; hybrids; ...

X(3872); $Z(4430)^+$, Z_1^+ and Z_2^+; Y's; ...

Same type of XYZ spectroscopy in b(s)-quark sector?

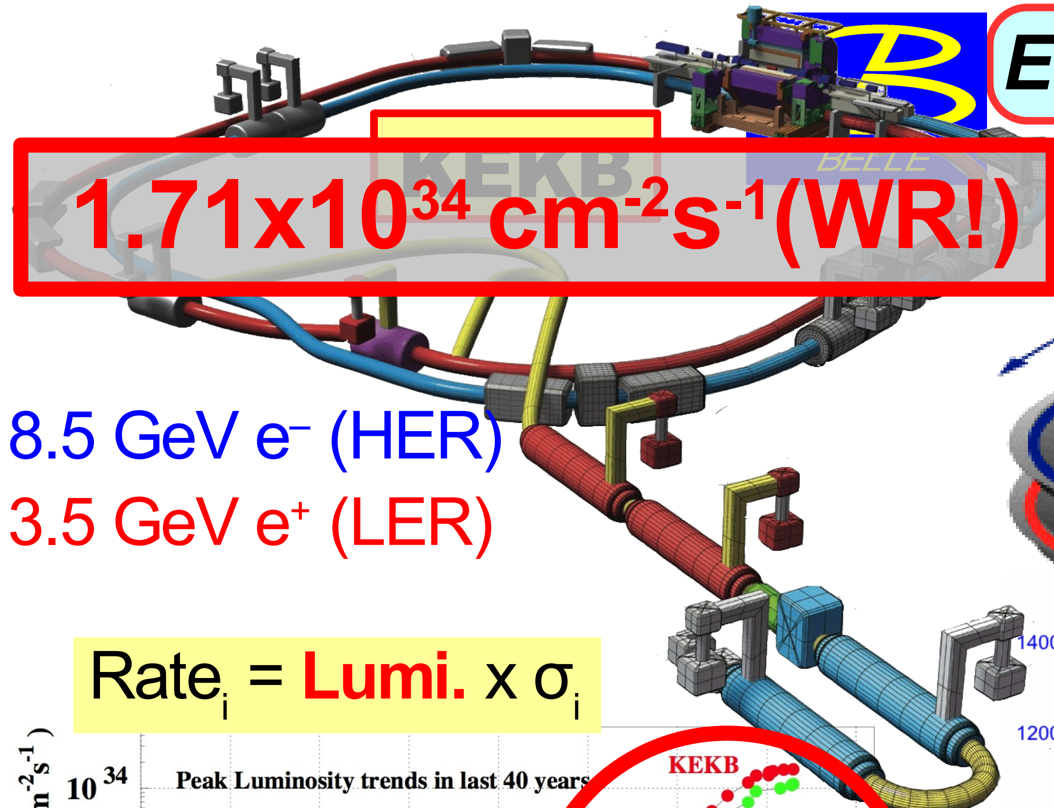
Many interesting results/new states still coming from B-factories

... stay tuned for more news!

Supplementary material

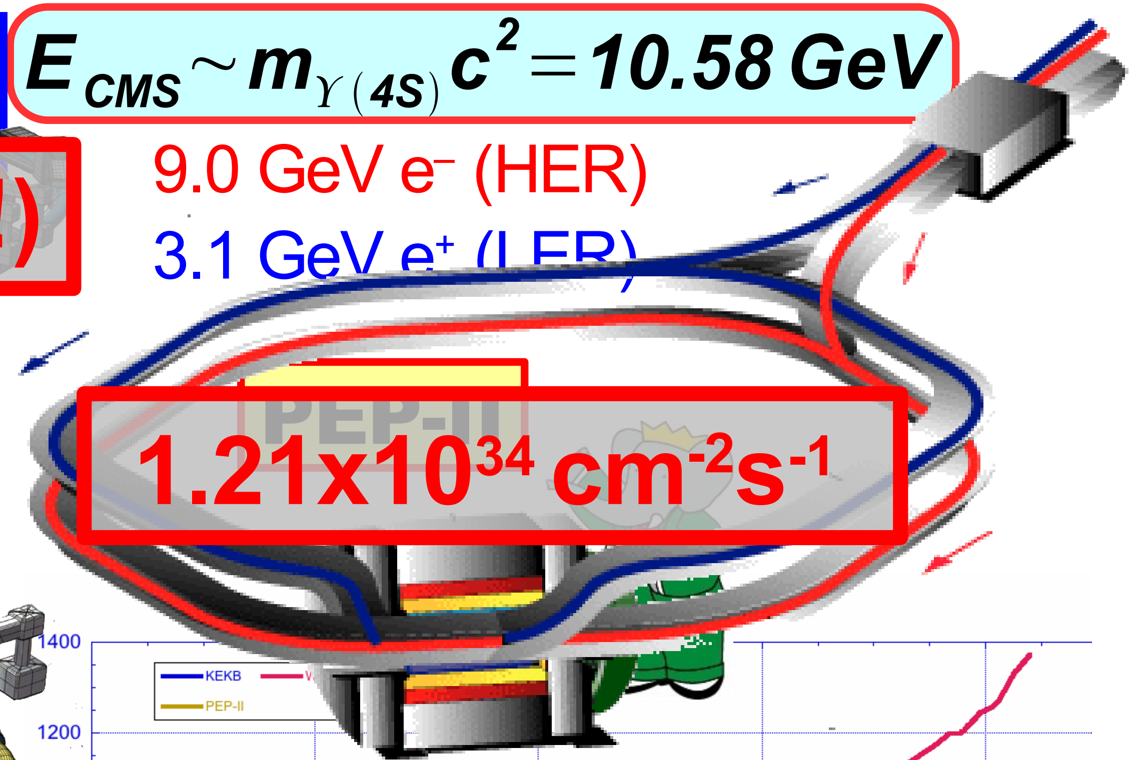
Asymmetric-Energy e^+e^- Colliders

$E_{CMS} \sim m_{\Upsilon(4S)} c^2 = 10.58\ GeV$



$1.71 \times 10^{34}\ cm^{-2}s^{-1}$ (WR!)

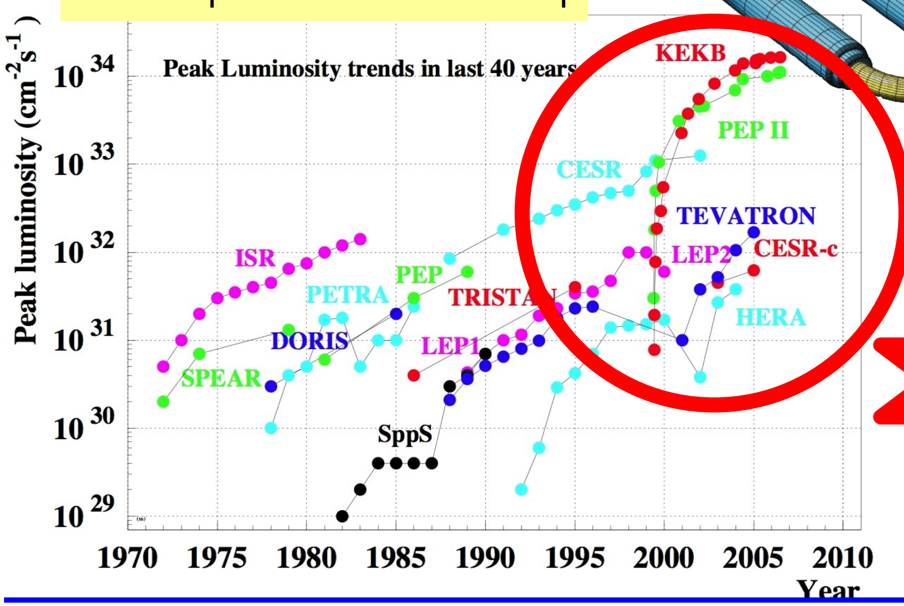
8.5 GeV e^- (HER)
3.5 GeV e^+ (LER)

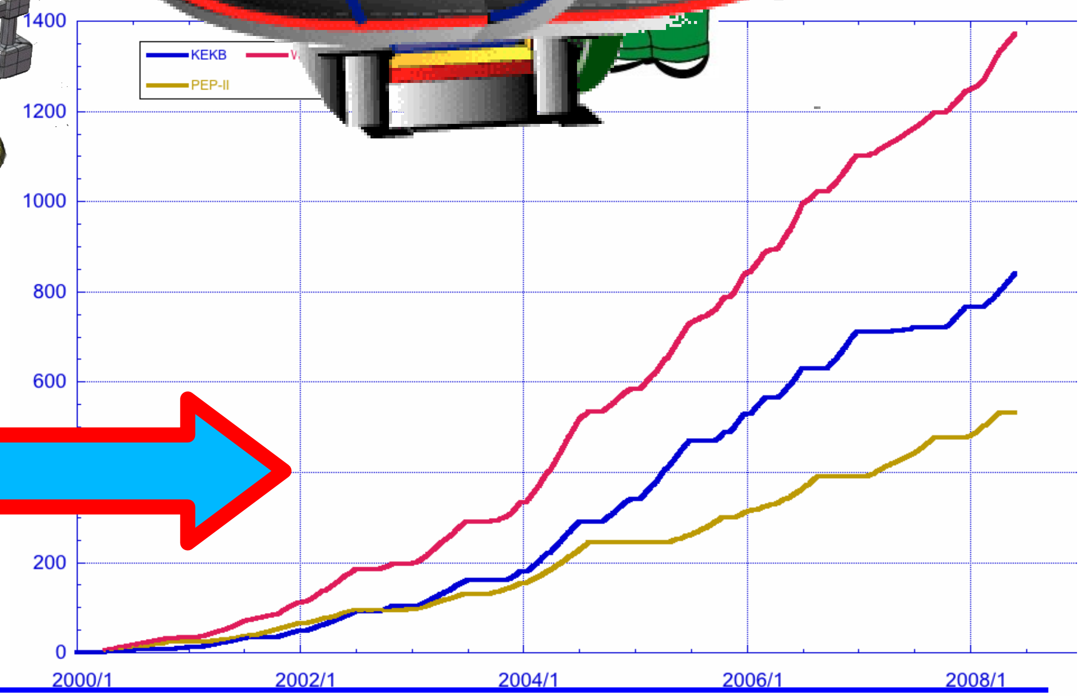


$1.21 \times 10^{34}\ cm^{-2}s^{-1}$

9.0 GeV e^- (HER)
3.1 GeV e^+ (LER)

$Rate_i$ = **Lumi.** x σ_i





Belle & BaBar Collaborations

BELLE

BABAR

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BELLE

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Hiroshima Tech.
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IHEP, Moscow
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13 countries, 55 institutes,

~400 collaborators

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80 Institutions
623 Physicists

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Harvard U
U of Iowa
Iowa State U
LBNL
LLNL
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INFN, Milano & Univ
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Brunel U
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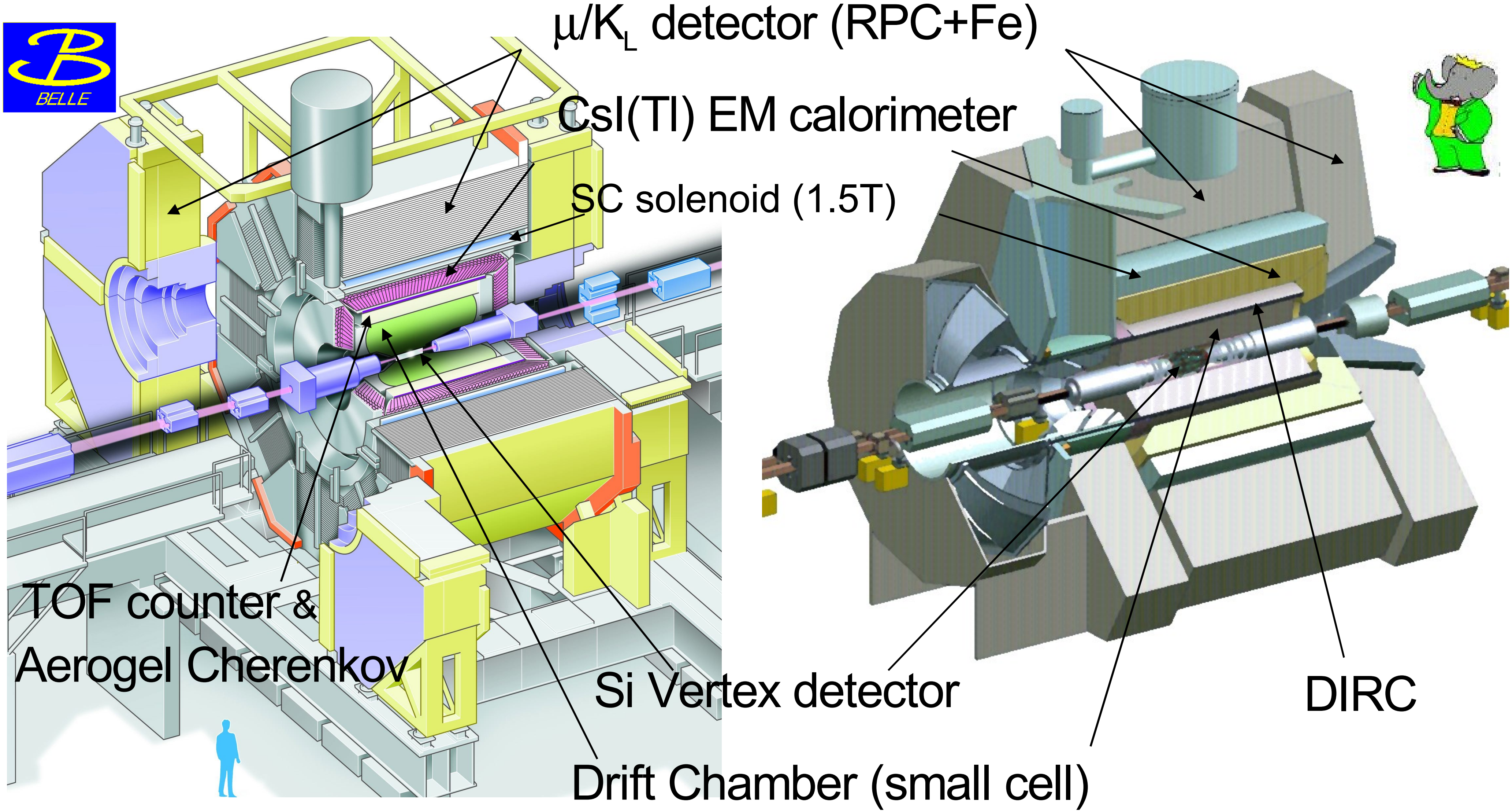
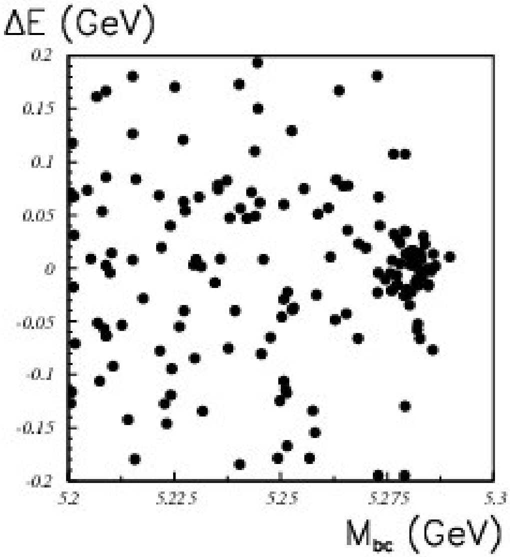
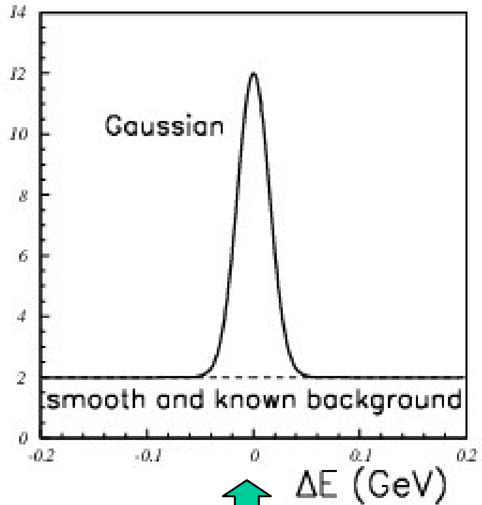
U of London, Rc
U of Mancheste
Rutherford App
U of Warwick

Belle & BaBar Detectors



Analysis tools: B-meson selection





Reconstructing B meson decays at Υ(4S):

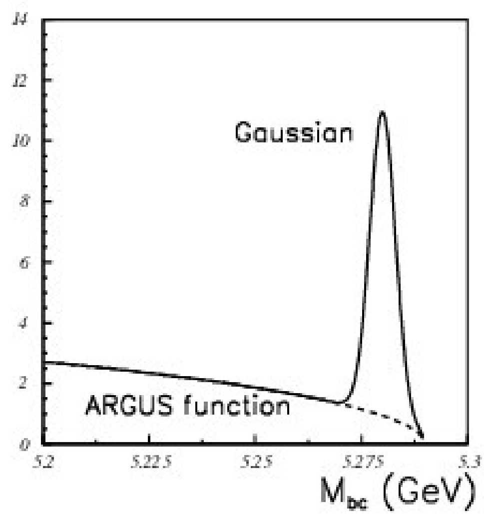
use two variables,

beam-constrained mass M_{bc}

(energy-substituted mass m_{ES})

and

energy difference ΔE



$$\Delta E \equiv \sum E_i - E_{beam}^{CMS}$$

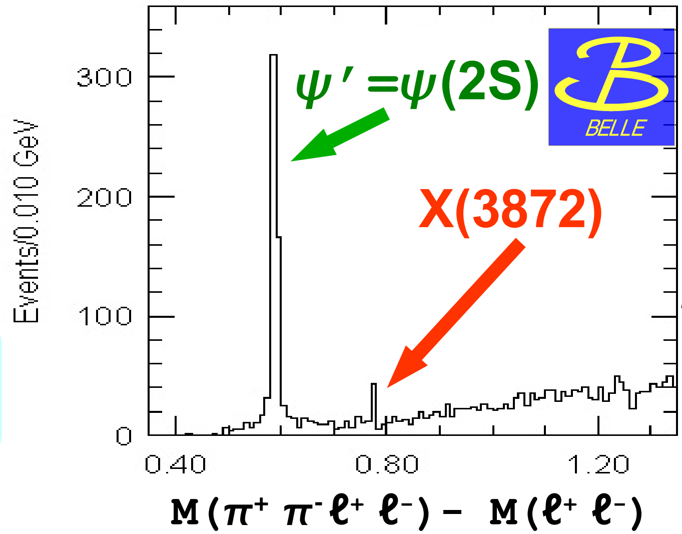
$$M_{bc} = \sqrt{(E_{CM}/2)^2 - (\sum \vec{p}_i)^2}$$

X(3872): observation in 2003

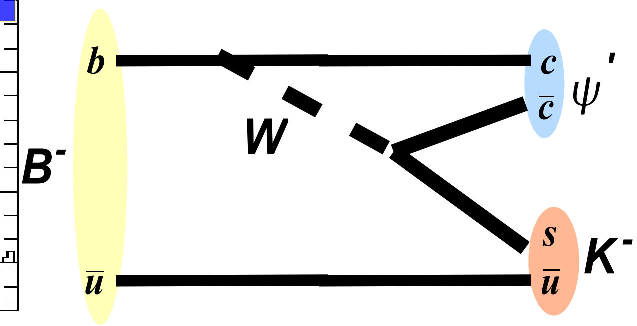
Observed first by Belle in:

$B^{\pm} \rightarrow K^{\pm} \pi^+ \pi^- J/\psi$, where $\pi^+ \pi^- J/\psi$ is X(3872) and $J/\psi \rightarrow \ell^+ \ell^-$

34 ± 7 events(~10σ)
M=(3872.0 ± 0.6 ± 0.5) MeV/c²

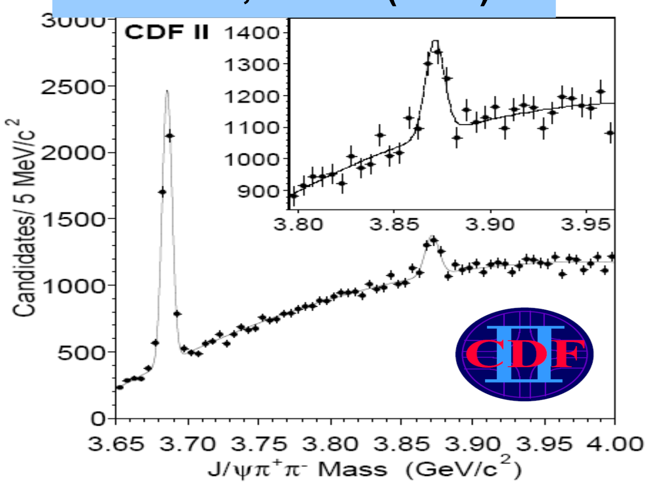


Belle : 152M BB
PRL 91, 262001 (2003)

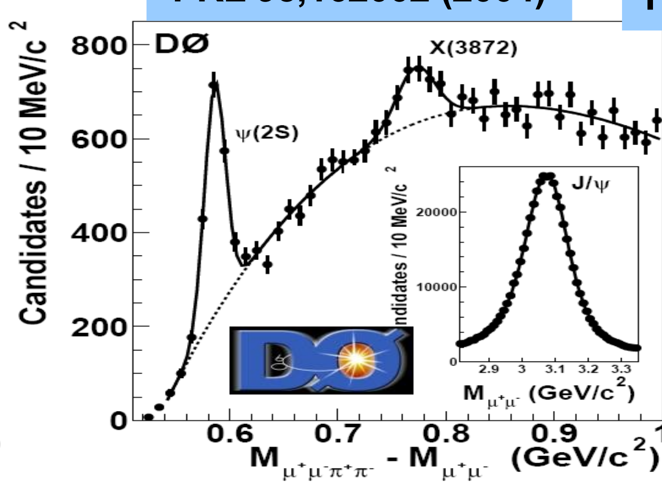


Confirmed soon by:

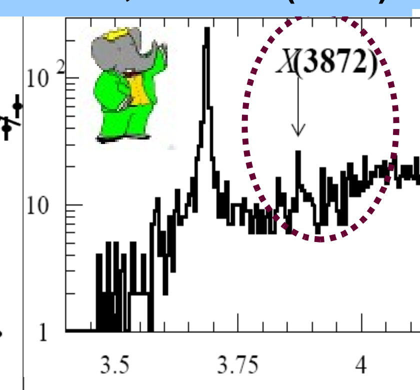
PRL 93,072001 (2004)



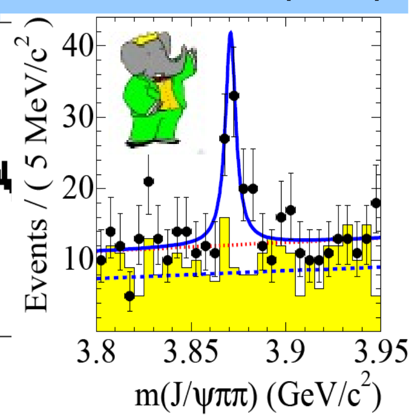
PRL 93,162002 (2004)



PRD71,071103R(2005)



PRD73,011101R(2006)

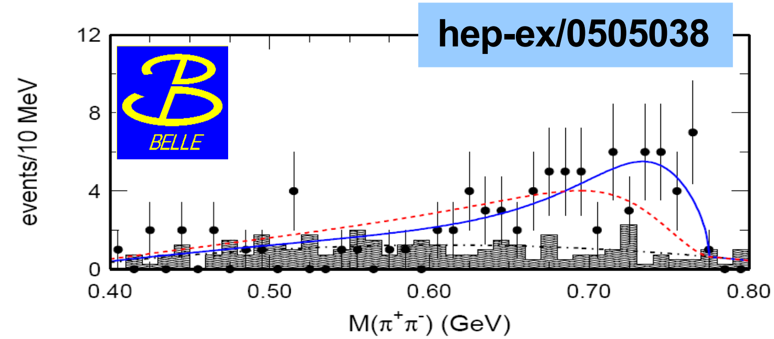


X(3872): properties

- PDG2008 mass: $M_X = (3872.2 \pm 0.8)\ \mathrm{MeV}/c^2$

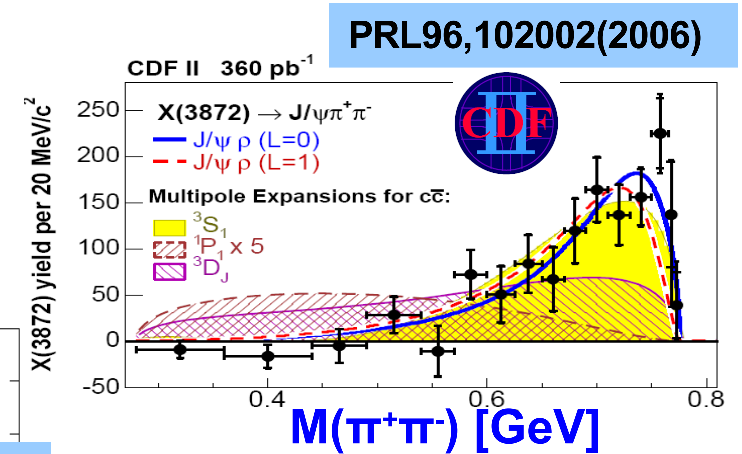
(close to $D^0\bar{D}^{*0}$ threshold: $M_X - M(D^0\bar{D}^{*0}) < 1\ \mathrm{MeV}/c^2$)

- Narrow: $\Gamma <$ 2.3 MeV (@ 90% CL)



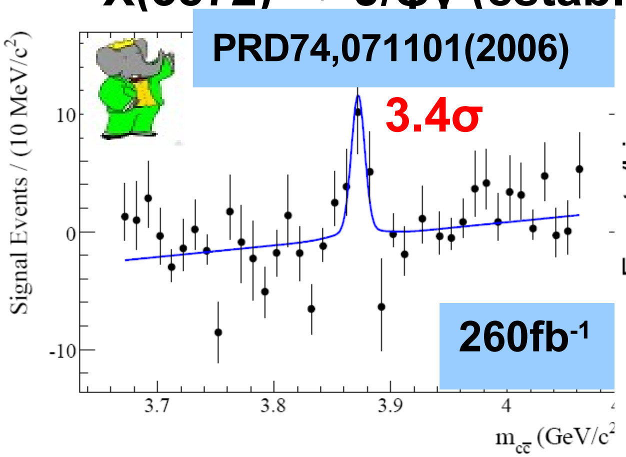
- From $M(\pi^+\pi^-)$: clustering on high end

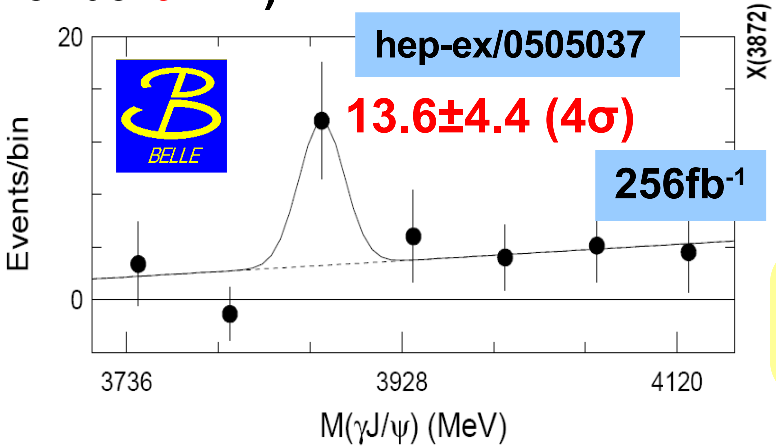
  X(3872) → J/ψ ρ (S or P wave) (J = 1 or 2)



- Decay modes:

  - X(3872)⟶ J/ψγ (establishes C=+1)





small

$$\frac{Br(X \to \gamma J/\psi)}{Br(X \to \pi^+\pi^- J/\psi)} = 0.14 \pm 0.05$$

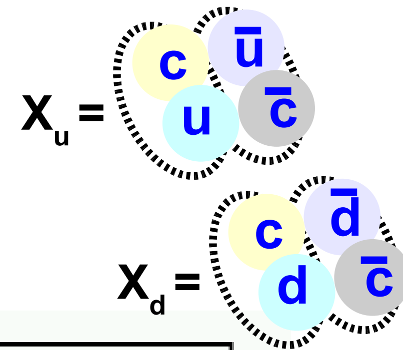
  - comparable rate J/ψω and J/ψρ (large isospin breaking – unlike charmonium)
  - $D\bar{D}\pi$ (but no $D\bar{D}$)

favoured $J^{PC} = 1^{++}$ or 2^{-+}

X(3872): interpretation

➡ **No standard charmonium assignment ...**

- **Other possible (popular) interpretations:**



➡ **[cu][$\bar{c}\bar{u}$] or [cd][$\bar{c}\bar{d}$] tetraquark:**

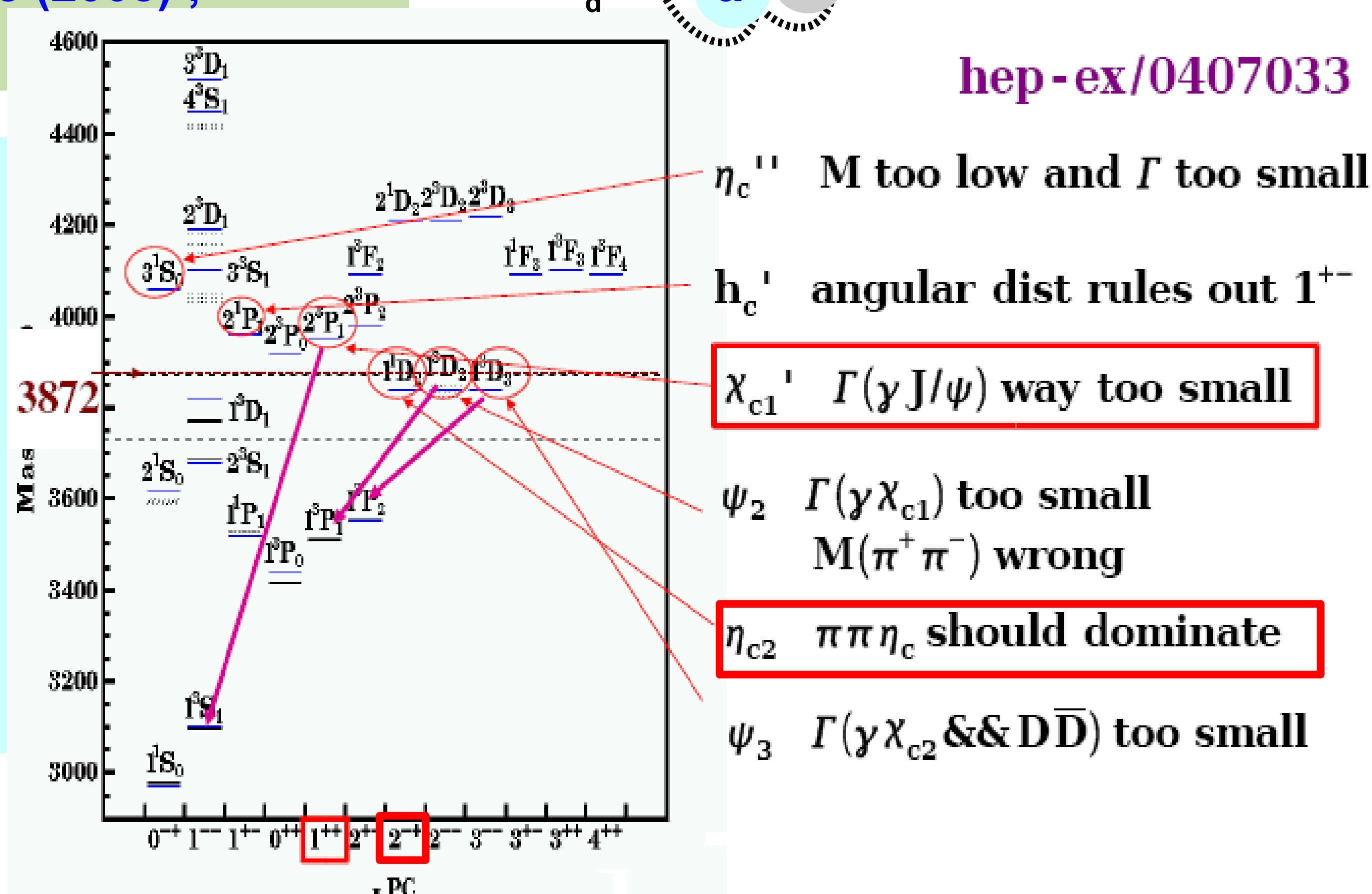
- Requires different X mass in B^+ and B^0 decays.
- Charged X[cu][$\bar{c}\bar{d}$] is expected.

{ Maiani et al., PRD 71, 014028 (2005) ; Ebert et al. }

➡ **$D^{*0}\bar{D}^0$ molecule:**

- $M_X \sim m(\bar{D}^0) + m(D^{*0})$
- Isospin breaking expected
- Favours DDπ over J/ψππ
- $J^{PC} = 1^{++}$ ($D^0\bar{D}^{*0}$ in S-wave)
- Production in B^0 suppressed wrt. B^+

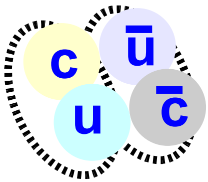
{ Braaten et al., hep-ph/0710.5482 }

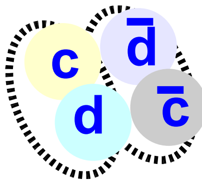


X(3872): charged & neutral partners?

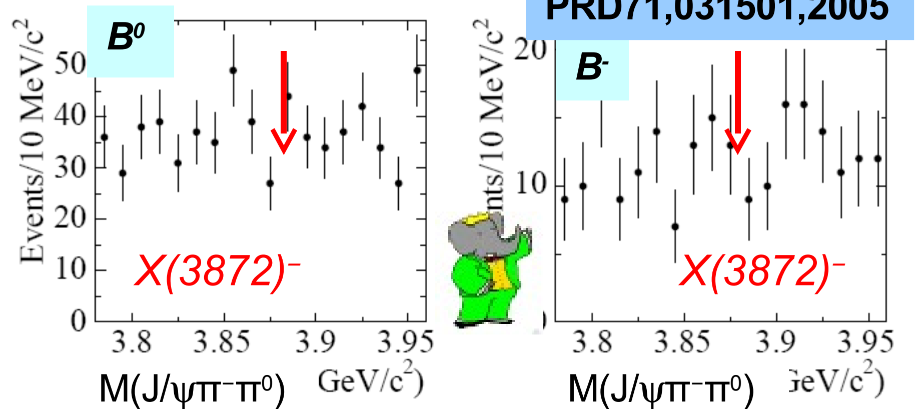
No evidence for $X^-(3872) \to J/\psi\pi^-\pi^0$

This excludes isovector hypothesis

X_u = 

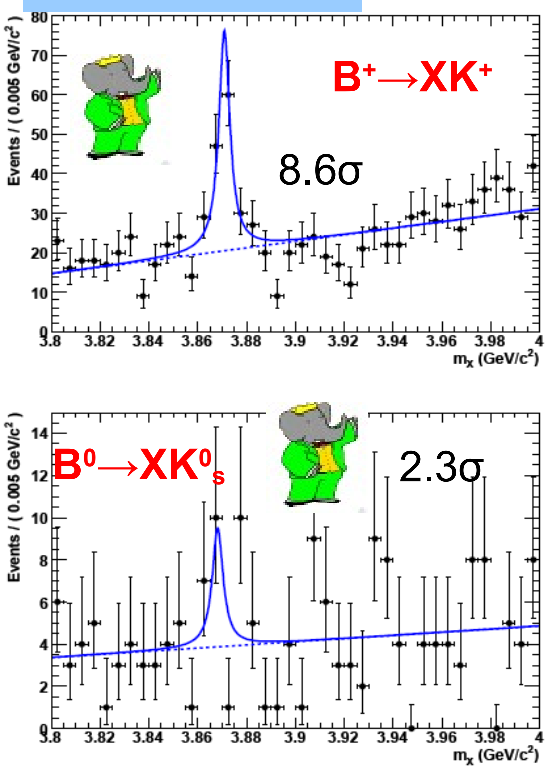
X_d = 

PRD71,031501,2005

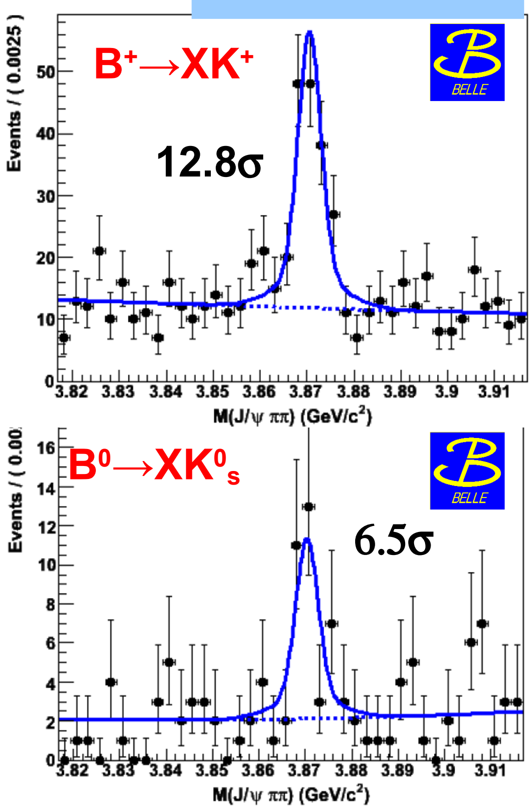


$X(3872) \to J/\psi\pi^+\pi^-$

PRD77,111101,2008



BELLE-CONF-0849



<u>diquark-antidiquark models</u>

X_u and X_d from B^0 and B^+ decays

ΔM_X= 8±3 MeV

{Maiani et al PRD71, 014028}

$\Delta M_X = (2.7 \pm 1.6 \pm 0.4)$ MeV/c²

$\Delta M_X = (0.18 \pm 0.89 \pm 0.26)$ MeV/c²

ΔM~0 : Not really supported by the 4-q hypothesis

$Br(B^0 \to XK^0) / Br(B^+ \to XK^+)$ =

0.41 ± 0.24 ± 0.05

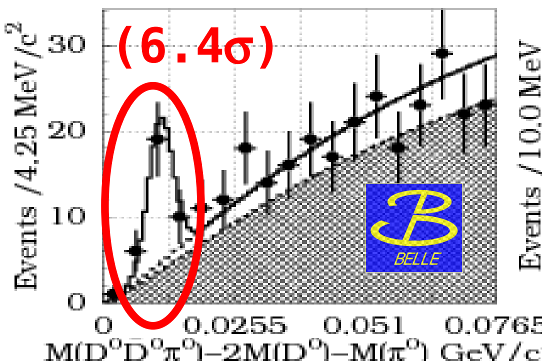
0.82 ± 0.22 ± 0.05

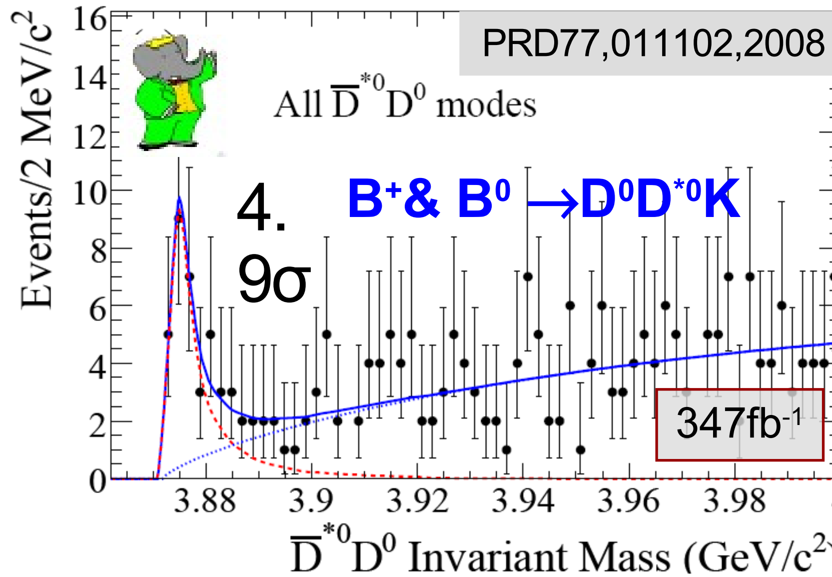
R~1: Not really supported by the molecular interpretation

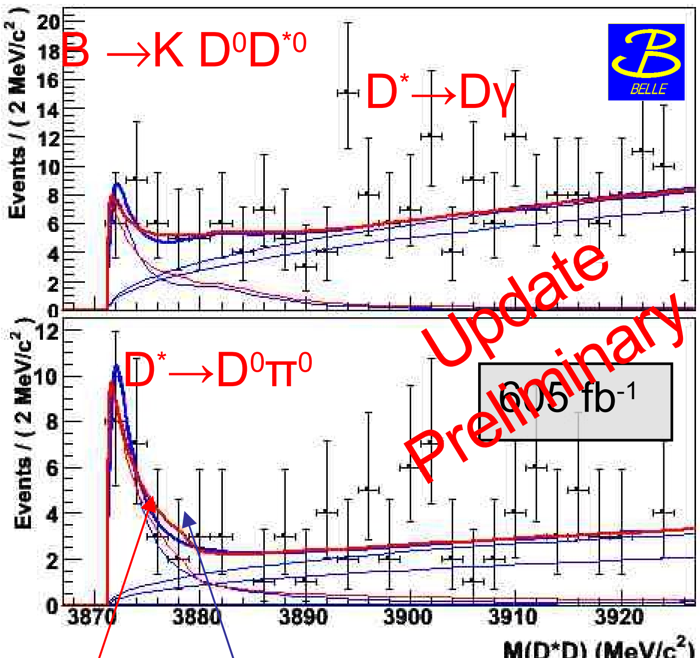
X(3872): $D^0D^0\pi^0$ decay mode

$B^+ \to K^+ D^0 \bar{D}^0 \pi^0 / B^0 \to K^0 D^0 \bar{D}^0 \pi^0$

Belle : 447M BB
PRL 97, 162002 (2006)







Flatte vs BW similar result: 8.8σ

New Belle vs New BaBar only ~2σ difference

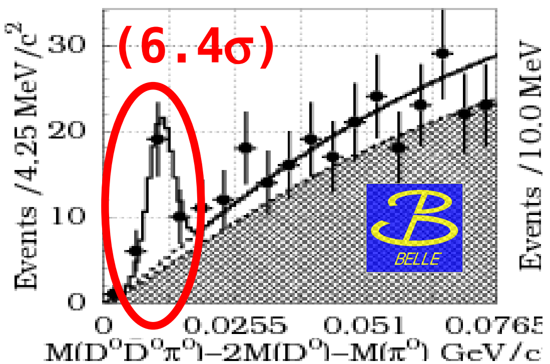
State	M, MeV/c²	Γ_{tot}, MeV	Decay Modes
X(3875)	$3875.2 \pm 0.7^{+0.9}_{-1.8}$	$1.22 \pm 0.31^{+0.23}_{-0.30}$	$D^0\bar{D}^0\pi^0$ (Belle)
X(3872)	$3872.6^{+0.5}_{-0.4} \pm 0.4$	$3.9^{+2.5+0.5}_{-1.3-0.3}$	$D^0\bar{D}^{*0}$ (Belle)
X(3875)	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$	$D^0\bar{D}^{*0}$ (BaBar)
X(3872)	3871.4 ± 0.6	< 2.3	$\pi^+\pi^- J/\psi$ PDG

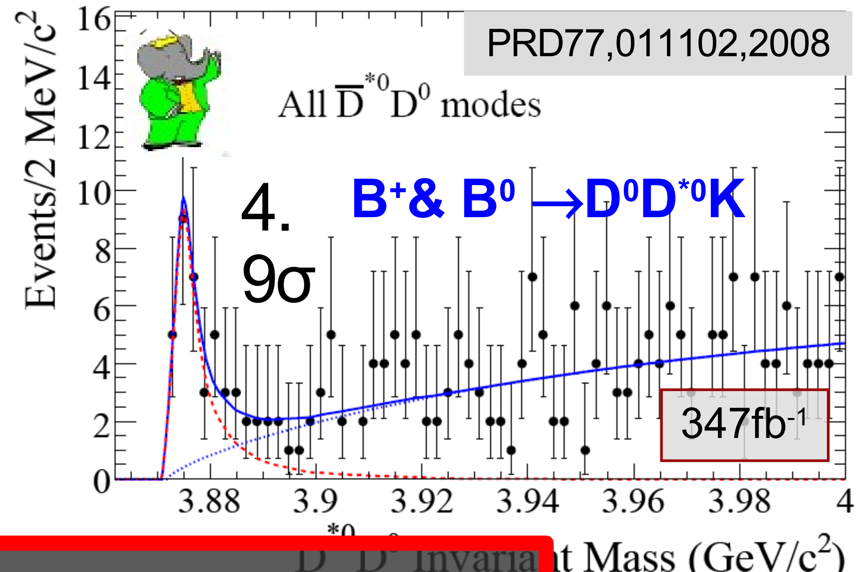
2 states X(3875) & X(3872)? Tetraquark interpretation {Maiani et al., hep-ph/0707.3354}: $X_u \to D^0\bar{D}^0\pi^0$(X(3875)) ; $X_d \to J/\psi\pi^+\pi^-$ (X(3872))

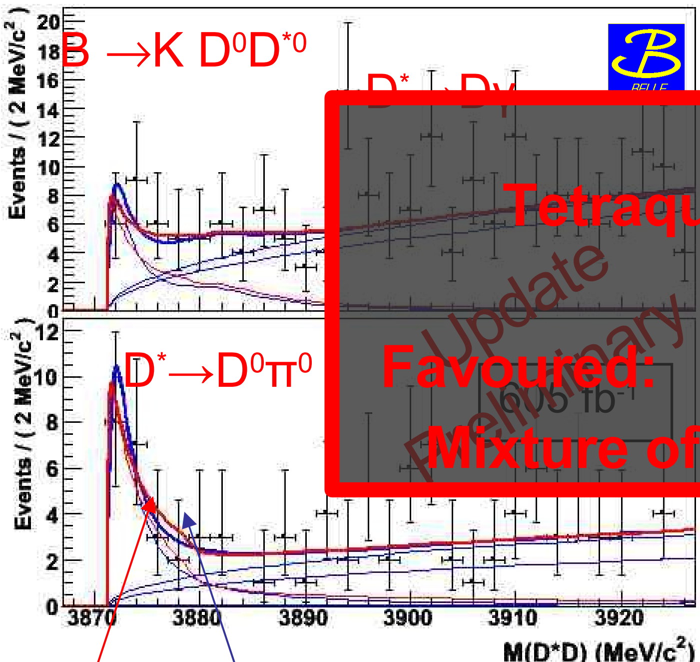
X(3872): $D^0D^0\pi^0$ decay mode

$B^+ \to K^+ D^0 \bar{D}^0 \pi^0 / B^0 \to K^0 D^0 \bar{D}^0 \pi^0$

Belle : 447M BB
PRL 97, 162002 (2006)







Flatte vs BW similar result: 8.8σ

New Belle vs New BaBar only ~2σ difference

Tetraquark hypothesis not favoured.

Favoured:

Mixture of D^0D^{*0} molecule and ccbar state

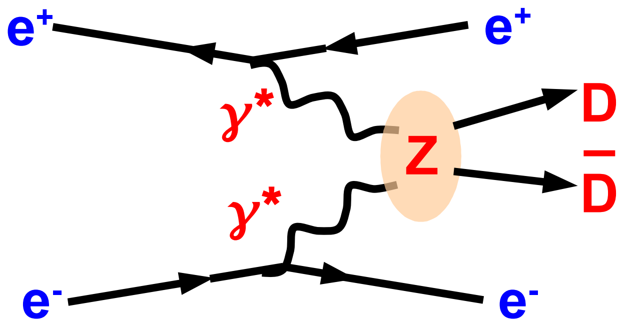
Update Preliminary

State	M, MeV/c²	Γ_{tot}, MeV	Decay Modes
X(3875)	$3875.2 \pm 0.7^{+0.9}_{-1.8}$	$1.22 \pm 0.31^{+0.23}_{-0.30}$	$D^0\bar{D}^0\pi^0$ (Belle)
X(3872)	[illegible]	[illegible]	$D^0\bar{D}^{*0}$ (Belle)
X(3875)	$3875.1^{+0.7}_{-0.5} \pm 0.5$	$3.0^{+1.9}_{-1.4} \pm 0.9$	$D^0\bar{D}^{*0}$ (BaBar)
X(3872)	3871.4 ± 0.6	< 2.3	$\pi^+\pi^- J/\psi$ PDG

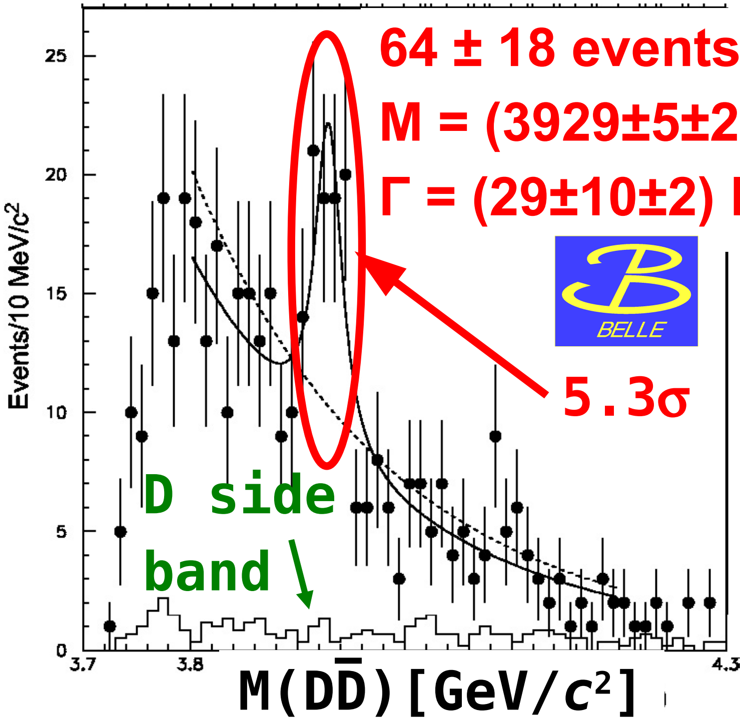
2 states X(3875) & X(3872)? Tetraquark interpretation {Maiani et al., hep-ph/0707.3354}: $X_u \to D^0\bar{D}^0\pi^0$(X(3875)) ; $X_d \to J/\psi\pi^+\pi^-$ (X(3872))

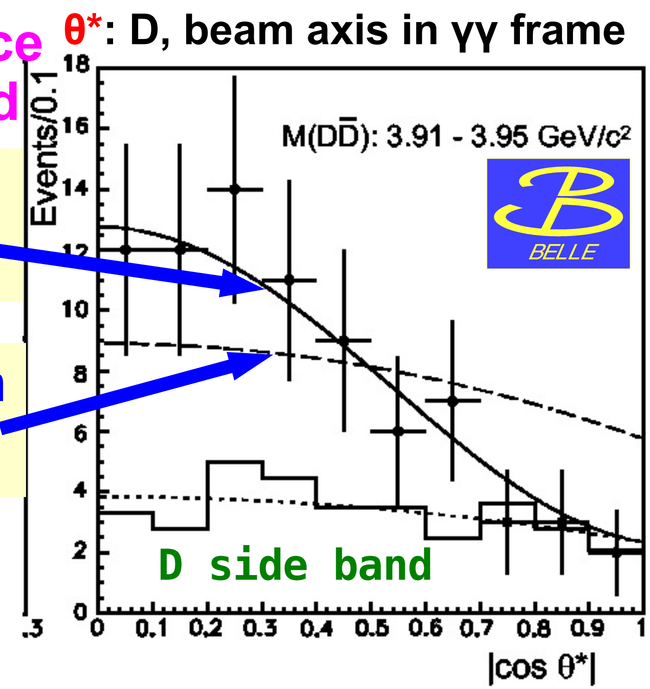
Z(3930): conventional $c\bar{c}$ (χ_{c2})

Belle : 395 fb^{-1}
PRL 96, 082003 (2006)



- un-tagged events (e^+,e^- undetected)
- $D^0 \to K^- \pi^+$, $K^- \pi^+ \pi^0$, $K^- \pi^+ \pi^+ \pi^-$
  $D^+ \to K^- \pi^+ \pi^+$
- $p_t(D\bar{D}) < 0.05$ GeV/c





$$\Gamma_{\gamma\gamma}(Z(3930))\,Br(Z(3930)\to D\bar{D}) = 0.18 \pm 0.05(stat.) \pm 0.03(syst.)\ keV$$

$Z \equiv \chi_{c2}'$

2^3P_2 $c\bar{c}$

S.Godfrey,N.Isgur,PRD32,189 (1985)

C.R.Münz,Nucl.Phys.A609,364 (1996)

$Z^+(4430)$ state: more info

PRL 100, 142001(2008)
657 $B\bar{B}$

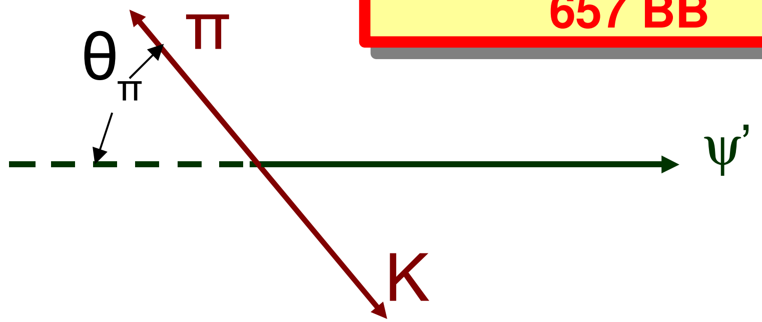
$Z^+(4430)$

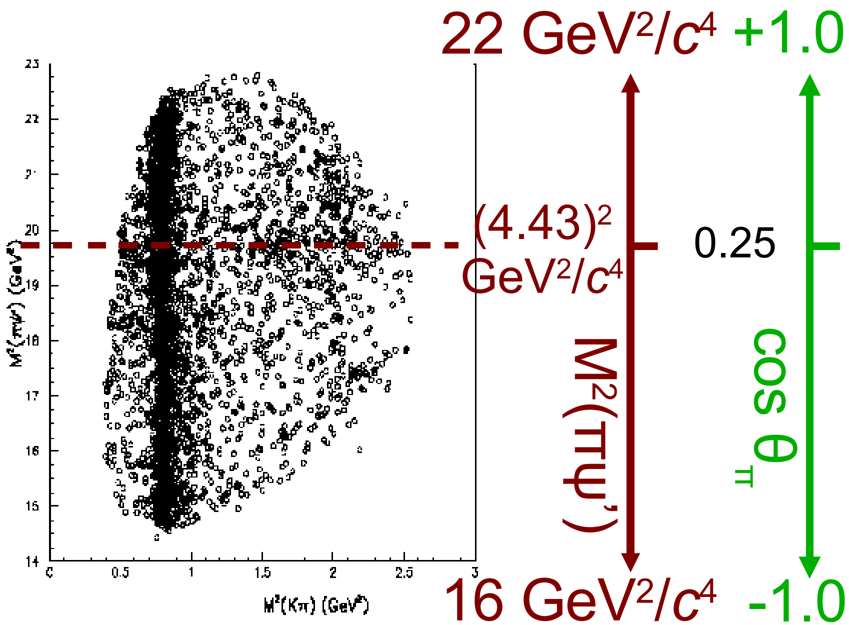
S-, P-, D-wave interference:

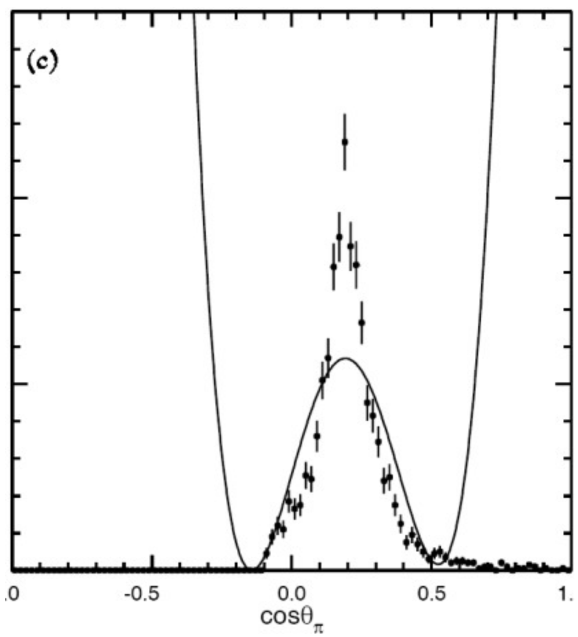
resonance	Longitudinal ψ'	Transverse ψ'
κ	constant	$--$
$K^*(890)$	$\cos\theta_\pi$	$\frac{1}{\sqrt{2}}\sin\theta_\pi$
$K_2^*(1430)$	$\frac{3}{2}\cos\theta_\pi^2 - \frac{1}{2}$	$\sqrt{\frac{3}{2}}\sin\theta_\pi\cos\theta_\pi$

interference (between rows)

incoherent (between columns)







cannot produce
a single narow peak
at $\cos\theta_\pi \sim 0.25$

$Z^-(4430)$ search: more info

arXiv:0811.0564v1[hep-ex]

413 fb^{-1}

TABLE VI: The $Z(4430)^-$ signal size, the branching fraction value, and its 95% c.l. upper limit for each decay mode; the errors quoted are statistical, and the upper limits were obtained using these values; the $Z(4430)^-$ mass and width have been fixed to the central values obtained by Belle [5].

Decay mode	$Z(4430)^-$ signal	Branching fraction ($\times 10^{-5}$)	Upper limit ($\times 10^{-5}$ at 95% c.l.)
$B^- \to Z(4430)^- \bar{K}^0, Z(4430)^- \to J/\psi \pi^-$	-17 ± 140	-0.1 ± 0.8	1.5
$B^0 \to Z(4430)^- K^+, Z(4430)^- \to J/\psi \pi^-$	-670 ± 203	-1.2 ± 0.4	0.4
$B^- \to Z(4430)^- \bar{K}^0, Z(4430)^- \to \psi(2S) \pi^-$	148 ± 117	2.0 ± 1.7	4.7
$B^0 \to Z(4430)^- K^+, Z(4430)^- \to \psi(2S) \pi^-$	415 ± 170	1.9 ± 0.8	3.1

BELLE

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

Z-(4430) search: more info

arXiv:0811.0564v1[hep-ex]

413 fb-1

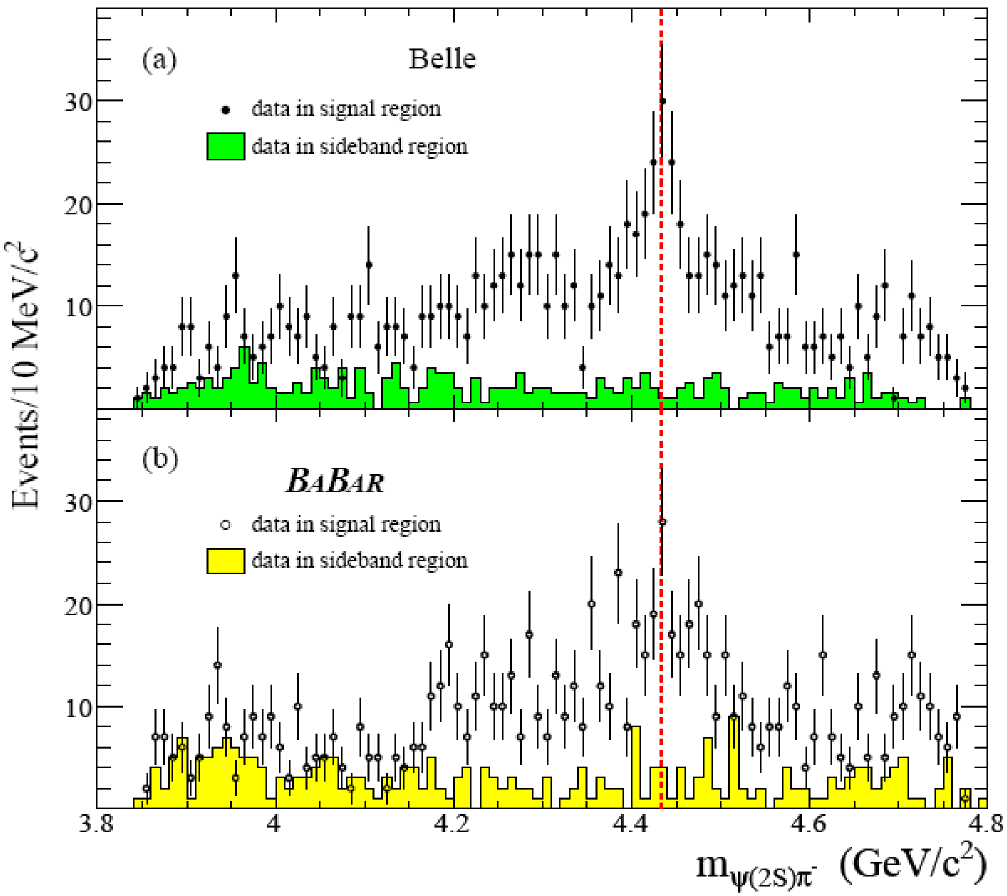


FIG. 28: a) The $\psi(2S)\pi^-$ mass distribution after K^* veto from Ref. [5]; the data points represent the signal region (we have assigned $\sqrt{N}$ errors at present), and the shaded histogram represents the background contribution estimated from the ΔE sideband regions; b) shows the corresponding distribution from the *BABAR* analysis. The dashed vertical line indicates $m_{\psi(2S)\pi^-} = 4.433$ GeV/c^2.

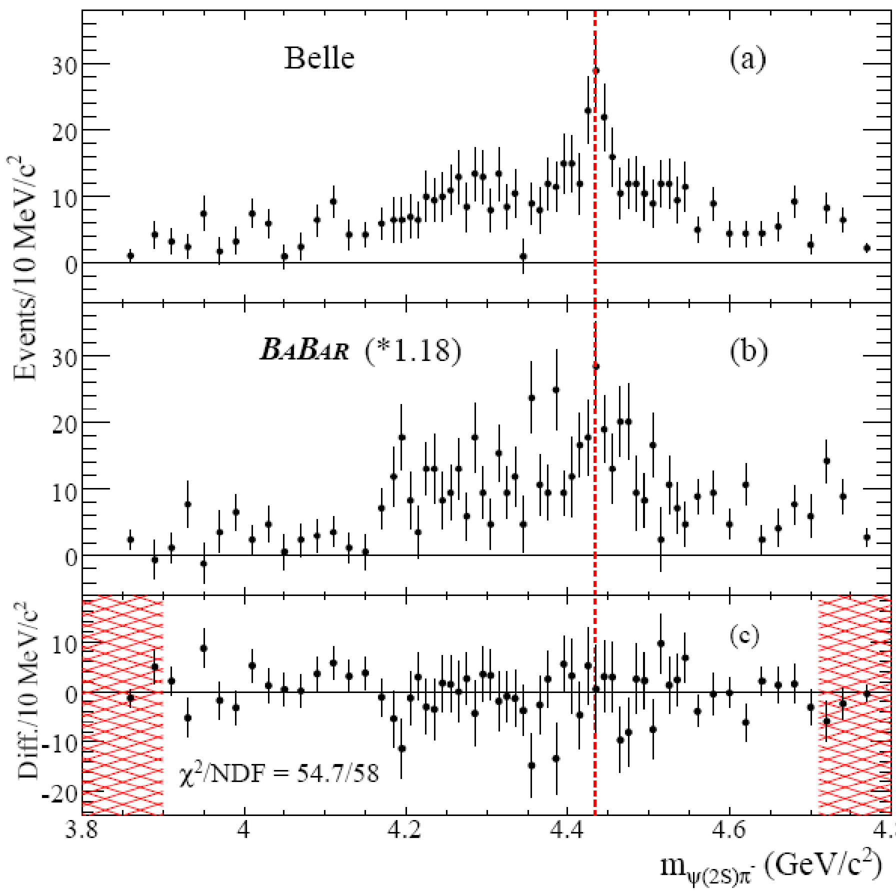


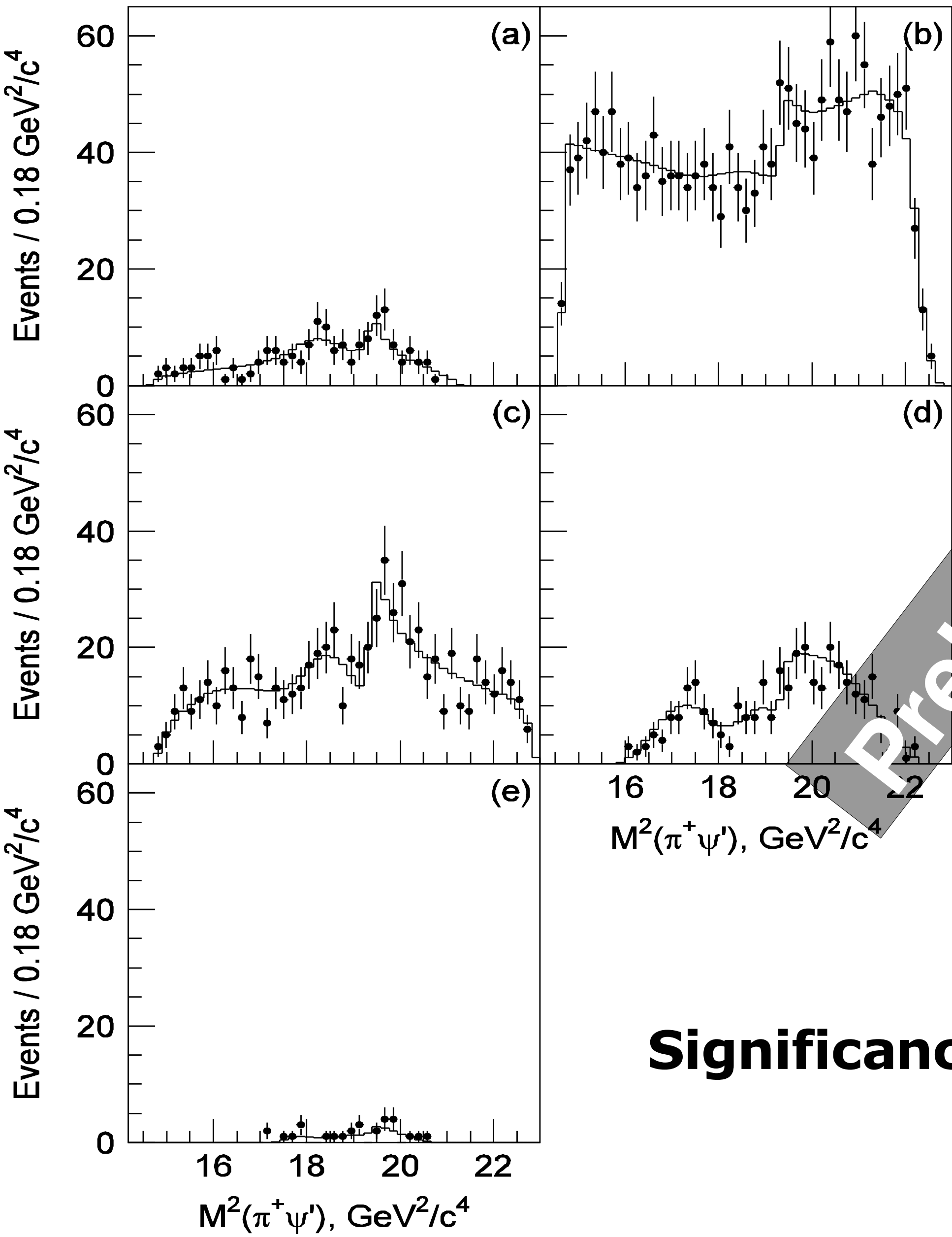
FIG. 29: a) The distribution of Fig. 28(a) after combining mass intervals for $m_{\psi(2S)\pi^-} < 4.18$ GeV/c^2 and $m_{\psi(2S)\pi^-} > 4.55$ GeV/c^2, and carrying out sideband subtraction. b) The distribution of Fig. 28(b) after following the same procedure, and in addition scaling by 1.18, as described in the text. c) The difference, (a)-(b), where the errors have been combined in quadrature; $\chi^2/NDF = 54.7/58$ (Probability=59.9%) excluding the low-efficiency regions (cross-hatched).

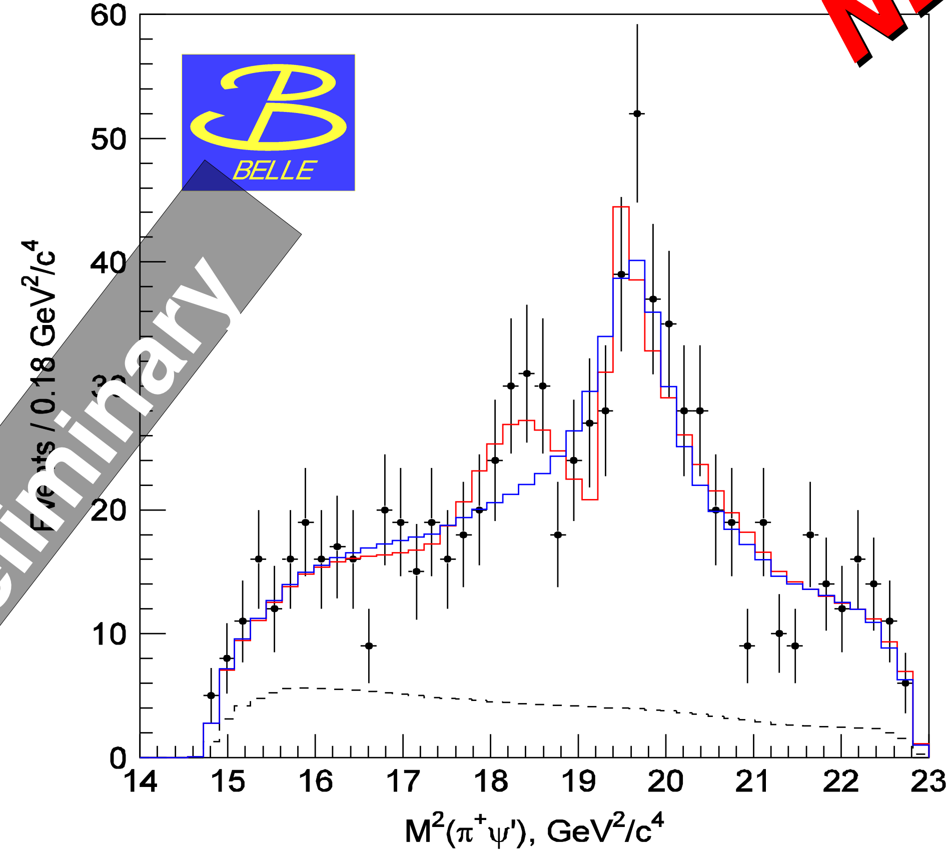
$Z^+(4430)$ update: Fit with two Z states?

Presented @ QWG '08
2nd - 5th December 2008

NEW

Results of Dalitz Plot fit with two Z's in $B \to K\pi^+\psi'$





Significance of two Z's over one Z is 3.9σ

Z_1^+ & Z_2^+ in $\bar{B}^0 \to K^- \pi^+ \chi_{c1}$ decays: fit

BELLE

- • data
- - - - background
- —— fit function
- ..... fit function without Z

Fit results: $M^2(\chi_{c1}\pi^+)$ projections in 4 $M^2(K^-\pi^+)$ bands

Null hypothesis:

all known K*'s;

poor fit :

C.L. ≤ 3×10^{-10}

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

signif. 10.7σ

$(\sqrt{-2\ln L/L_0})$,

C.L. = 0.5%

$M_Z = (4150^{+31}_{-16})$ MeV/c^2

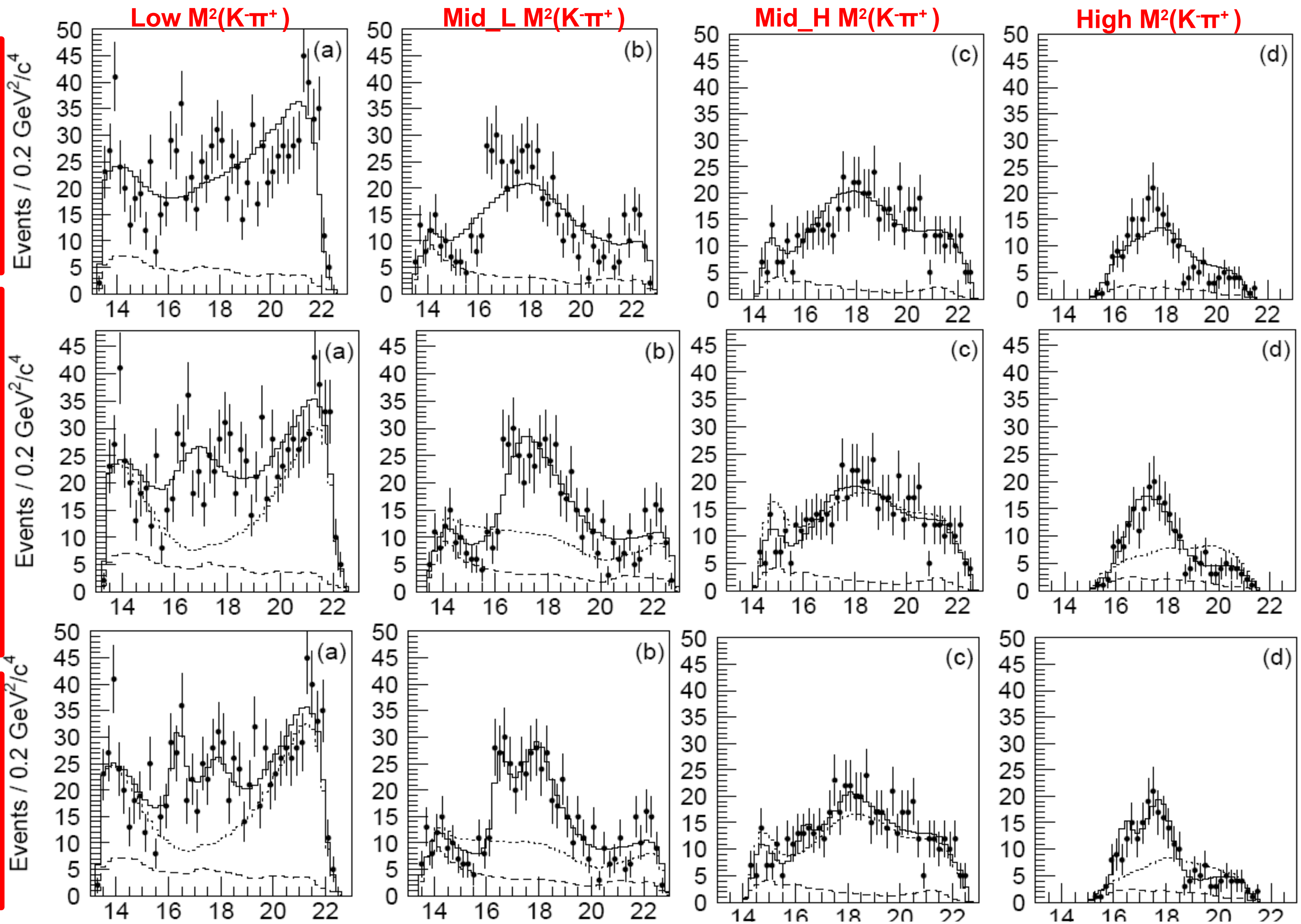
$\Gamma_Z = (352^{+99}_{-43})$ MeV

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

signif. wrt 1 Z:

5.7σ,

C.L. = 42%



Z_1^+ & Z_2^+ : fit fractions

	One Z^+		Two Z^+	
Contribution	Fit fraction	Signif.	Fit fraction	Signif.
$Z^+_{(1)}$	$(33.1^{+8.7}_{-5.8})\%$	$10.7\,\sigma$	$(8.0^{+3.8}_{-2.2})\%$	$5.7\,\sigma$
Z^+_2	–	–	$(10.4^{+6.1}_{-2.3})\%$	$5.7\,\sigma$
κ	$(1.9 \pm 1.8)\%$	$2.1\,\sigma$	$(3.6 \pm 2.6)\%$	$3.5\,\sigma$
$K^*(892)$	$(28.5 \pm 2.1)\%$	$10.6\,\sigma$	$(30.1 \pm 2.3)\%$	$9.8\,\sigma$
$K^*(1410)$	$(3.6 \pm 4.4)\%$	$1.3\,\sigma$	$(4.4 \pm 4.3)\%$	$2.0\,\sigma$
$K_0^*(1430)$	$(22.4 \pm 5.8)\%$	$3.4\,\sigma$	$(18.6 \pm 5.0)\%$	$4.5\,\sigma$
$K_2^*(1430)$	$(8.4 \pm 2.7)\%$	$5.2\,\sigma$	$(6.1 \pm 2.9)\%$	$5.4\,\sigma$
$K^*(1680)$	$(5.2 \pm 3.7)\%$	$2.2\,\sigma$	$(4.4 \pm 3.1)\%$	$2.4\,\sigma$
$K_3^*(1780)$	$(7.4 \pm 3.0)\%$	$3.6\,\sigma$	$(7.2 \pm 2.9)\%$	$3.8\,\sigma$
	110.5%		92.8%	

There is small net interference effect

$e^+e^- \to \gamma_{ISR}\psi'\pi^+\pi^-$: BaBar & Belle combined fit

Combined fit to BaBar and Belle data on $e^+e^- \to \pi^+\pi^-\psi(2S)$

Z. Q. Liu,[1,3] X. S. Qin,[1,2] and C. Z. Yuan[1,*]

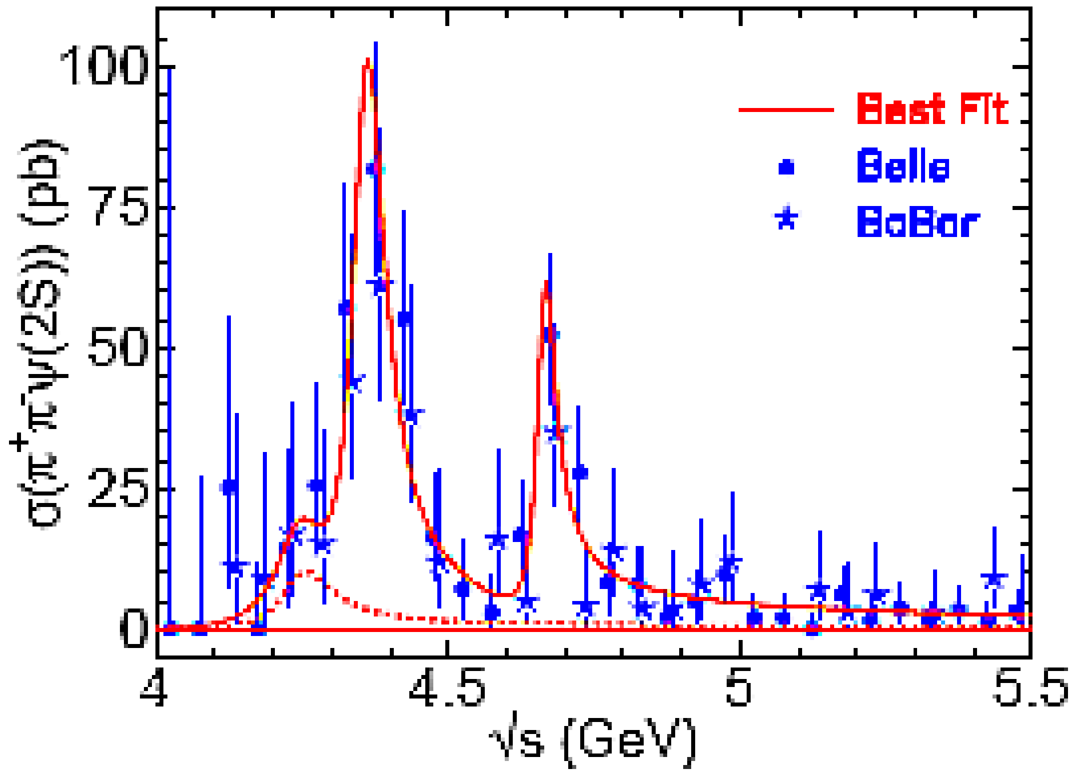


FIG. 4: The results of the fit to $e^+e^- \to \pi^+\pi^-\psi(2S)$ data from Belle and BaBar. The solid curve show the best fit with three coherent Breit-Wigners: the $Y(4260)$, $Y(4360)$, and $Y(4660)$, and the dashed curve is the signal shape of the $Y(4260)$.