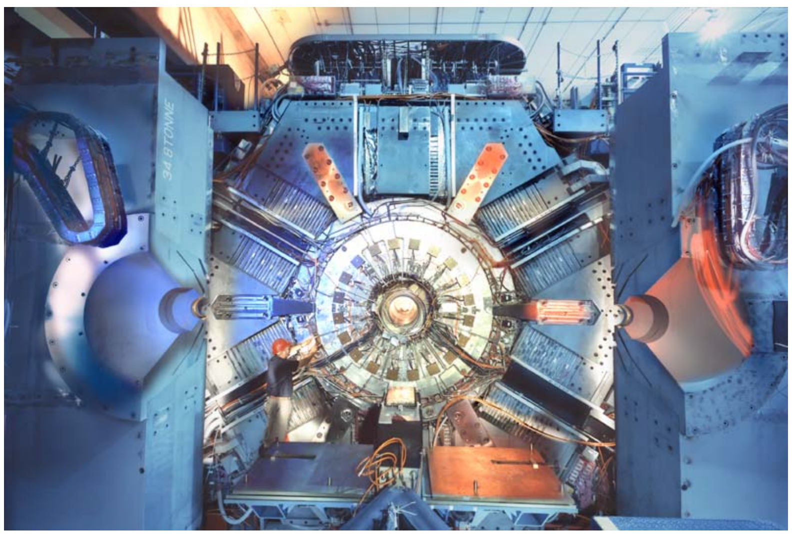
Quarkonium Physics and beyond at BaBar

RPM Seminar

LBNL, September 25th 2008



Philippe Grenier

SLAC/CNRS, and the BaBar Collaboration

Outline

1. Introduction to Quarkonium Physics

2. The B-Factory at SLAC

3. Charmonium and Exotics

4. Bottomonium: Observation of the η_b

5. Conclusion

Introduction to Quarkonium Physics

The B-Factory at SLAC

Charmonium and Exotics

Bottomonium: Observation of the η_b

Conclusion

Basics of Quarkonium Spectroscopy

$Q\bar{Q}$ bound state, with:

- Spin: $S_{Q\bar{Q}} = 1/2 \times 1/2 = 0 + 1$
- Parity: $P=(-1)^{L+1}$
- C-parity: $C=(-1)^{L+S}$
- Spectroscopy notation: $n^{2S+1}L_J$ (n, radial quantum number)

Some J^{PC} forbidden: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-},…

Charmonium spectrum:

	L	S	J^{PC}	$^{2S+1}L_J$	States(n=1,2….)
S-wave states	0	0	0^{-+}	$^1S_0$	$\eta_c(1S)$, $\eta_c(2S)$
		1	1^{--}	$^3S_1$	J/ψ, $\psi(2S)$
P-wave states	1	0	1^{+-}	$^1P_1$	$h_c(1P)$
		1	0^{++}	$^3P_0$	$\chi_{c0}(1P)$
			1^{++}	$^3P_1$	$\chi_{c1}(1P)$
			2^{++}	$^3P_2$	$\chi_{c2}(1P)$
D-wave states					

Heavy quarks: non-relativistic

Below open charm or bottom threshold: narrow states ($Q\bar{Q}$ annihilate through gluons or virtual photons; OZI rule)

Above: mostly broad states

Quarkonium and Beyond

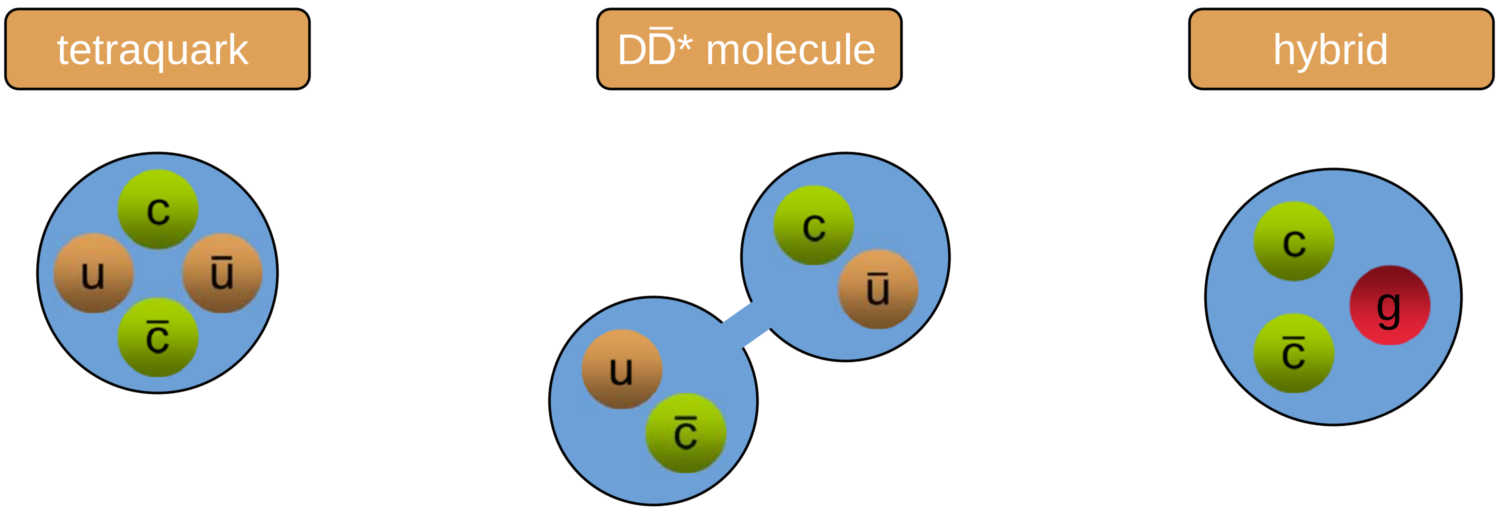
Studying Quarkonium… studying Strong Interactions:

- measure: masses, electromagnetic/hadronic transitions, other rates, splitting

  Test of NRQCD, LQCD, Potential models, etc…

- compare charmonium/bottomonium spectra
- new forms of aggregations mediated by the strong interaction

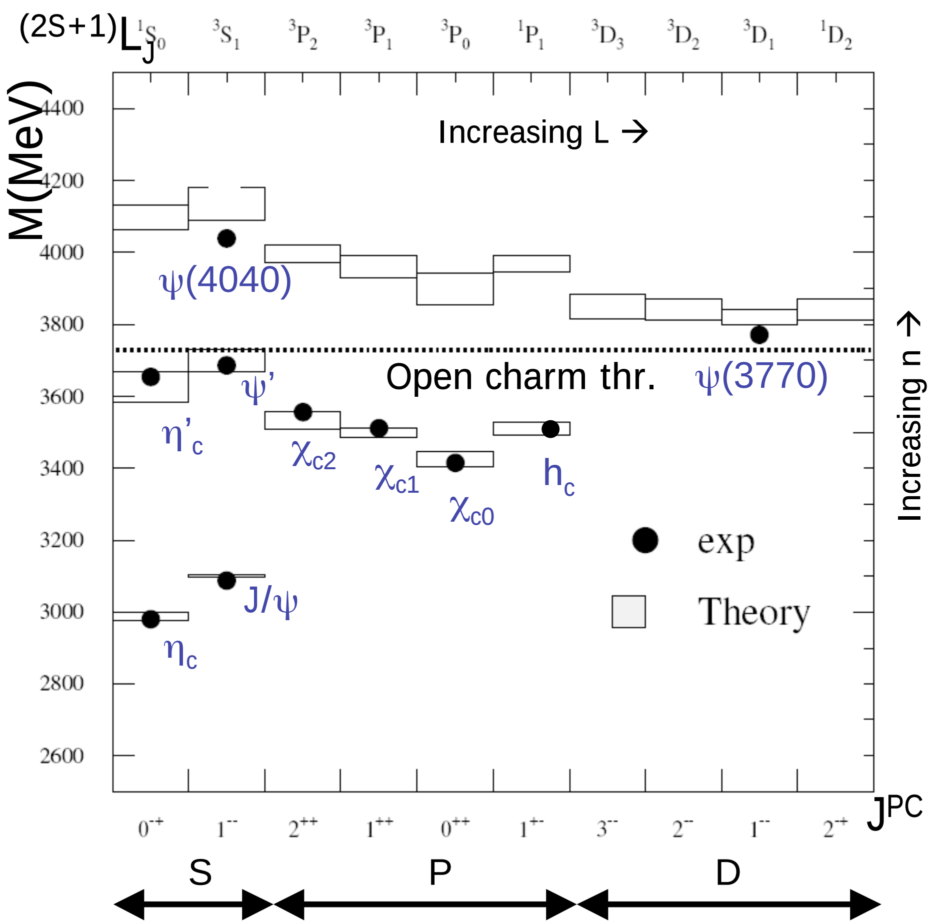
Beyond Quarkonium: $q\bar{q}$+"?", not forbidden… but never observed…



Search for resonances with: non-quarkonium $I^G(J^{PC})$, small width, non null charge,…

Charmonium ($c\bar{c}$) spectrum

State of the art a few years ago…



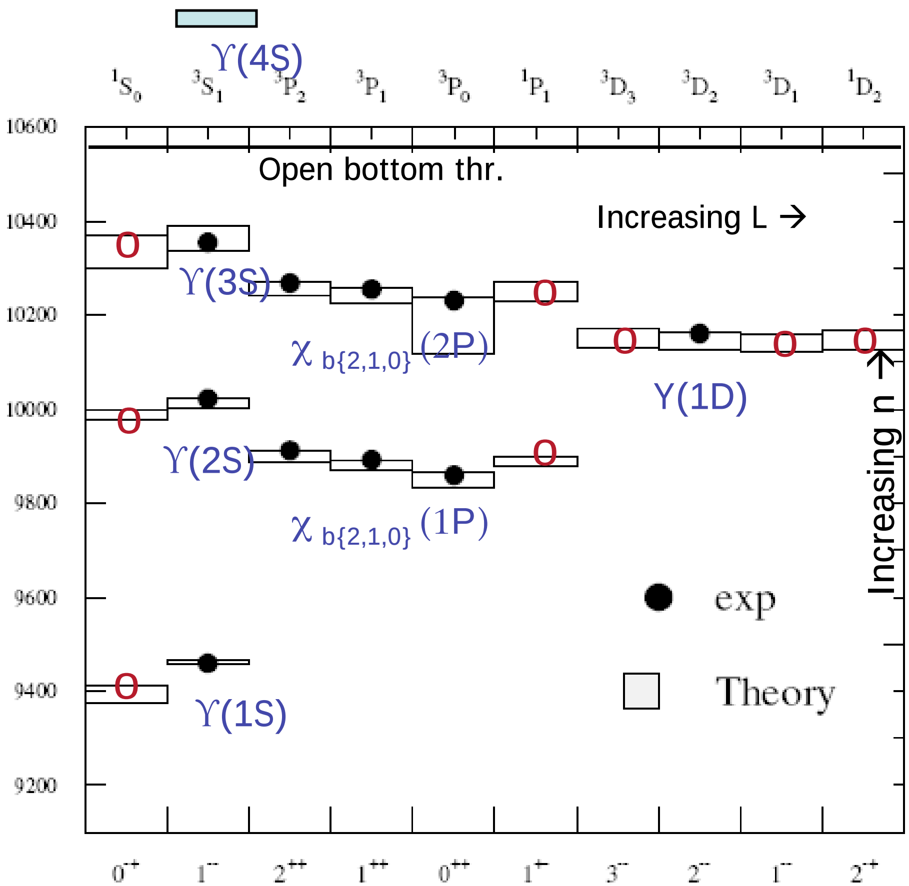
$\eta_c(2S)$ and $h_c(1P)$: recent additions

All states below $D\bar{D}$ threshold:consistent with theoretical expectations

Has the picture changed with B-Factories…?

Bottomonium ($b\bar{b}$) spectrum

State of the art a few weeks ago…



Still some work to do!

Below $B\bar{B}$ threshold, 8 states still missing: o

- S-wave η_b(1S,2S,3S)
- P-wave h_b(1P,2P)
- D-wave 1^3D_1, 1^1D_2 and 1^3D_3

…in particular the ground state!

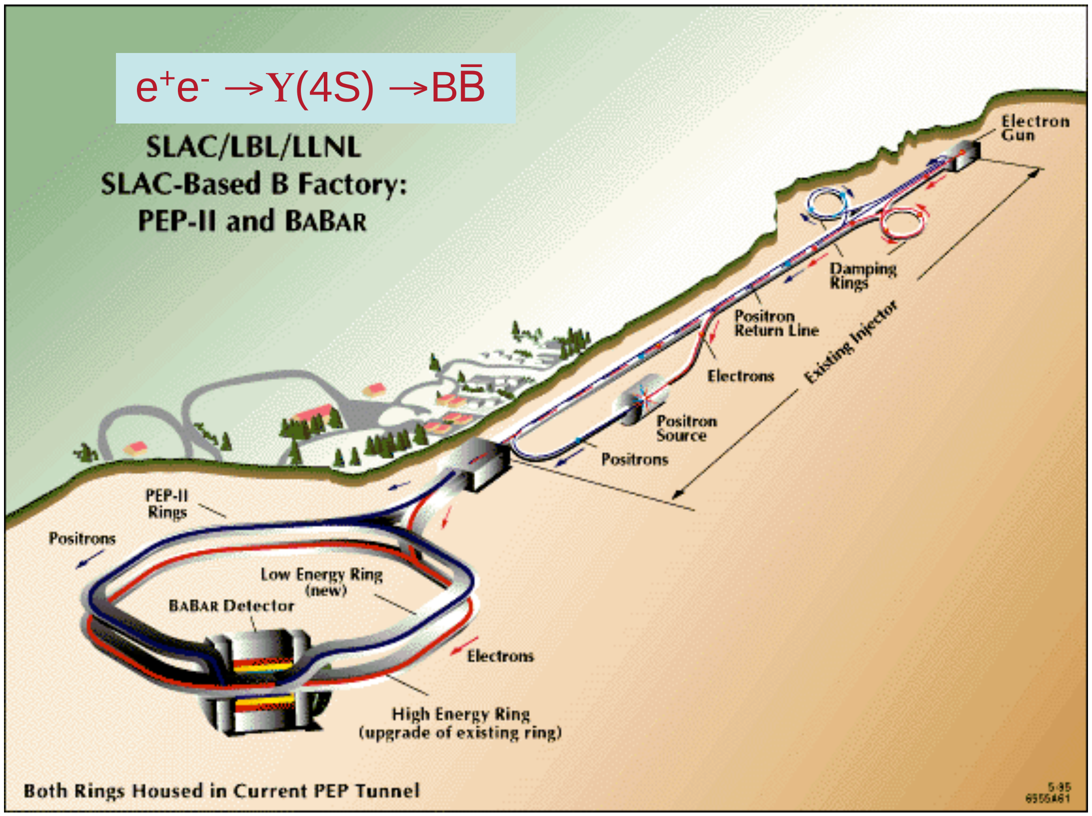
The B-factories may help…

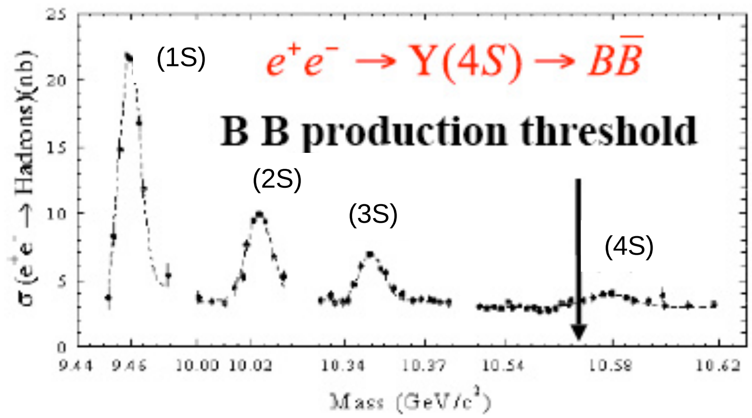
Aerial view of SLAC

The B-Factory

Study of CP violation in the B meson system

Asymmetric energy collider operating at the $\Upsilon(4S)$ resonance ($\sqrt{s}$=10.58 GeV), with 3.1 GeV positrons and 9.0 GeV electrons.



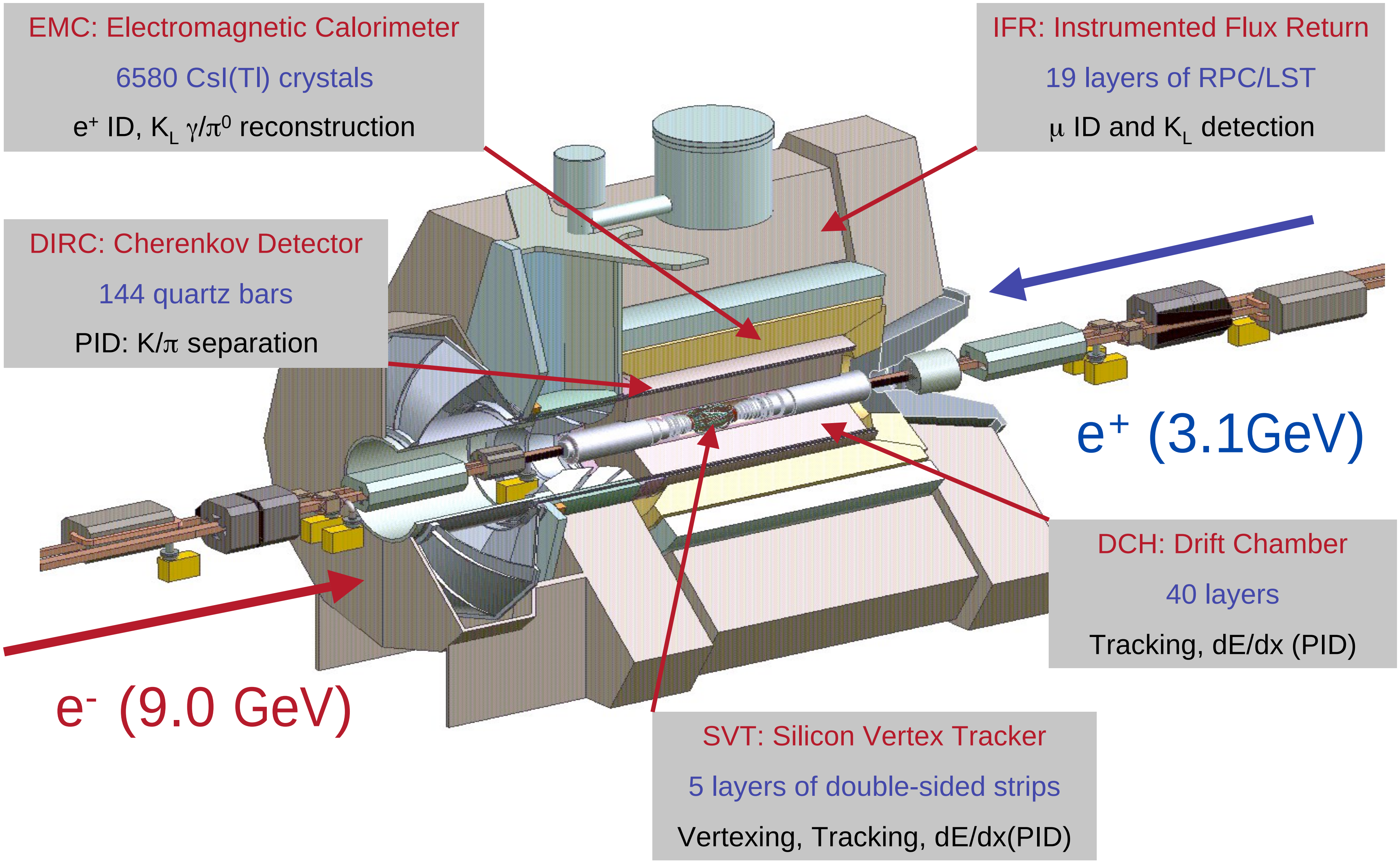


Cross sections at the $\Upsilon(4S)$:

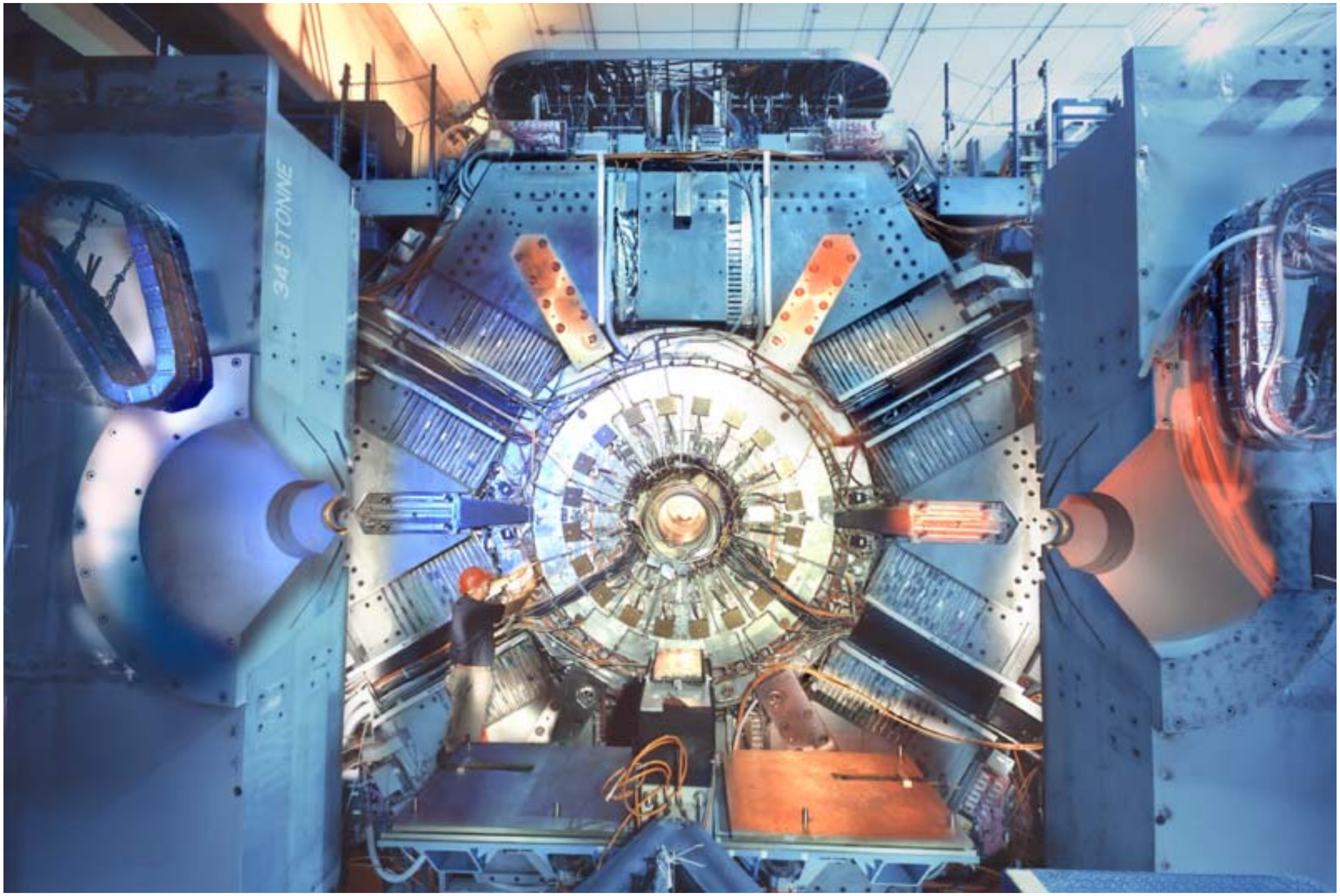
$$\begin{cases} \sigma(B\bar{B}) \approx 1.1 \text{ nb} \\ \sigma(c\bar{c}) \approx 1.3 \text{ nb} \end{cases}$$

Also a Charm-Factory!

The BABAR detector



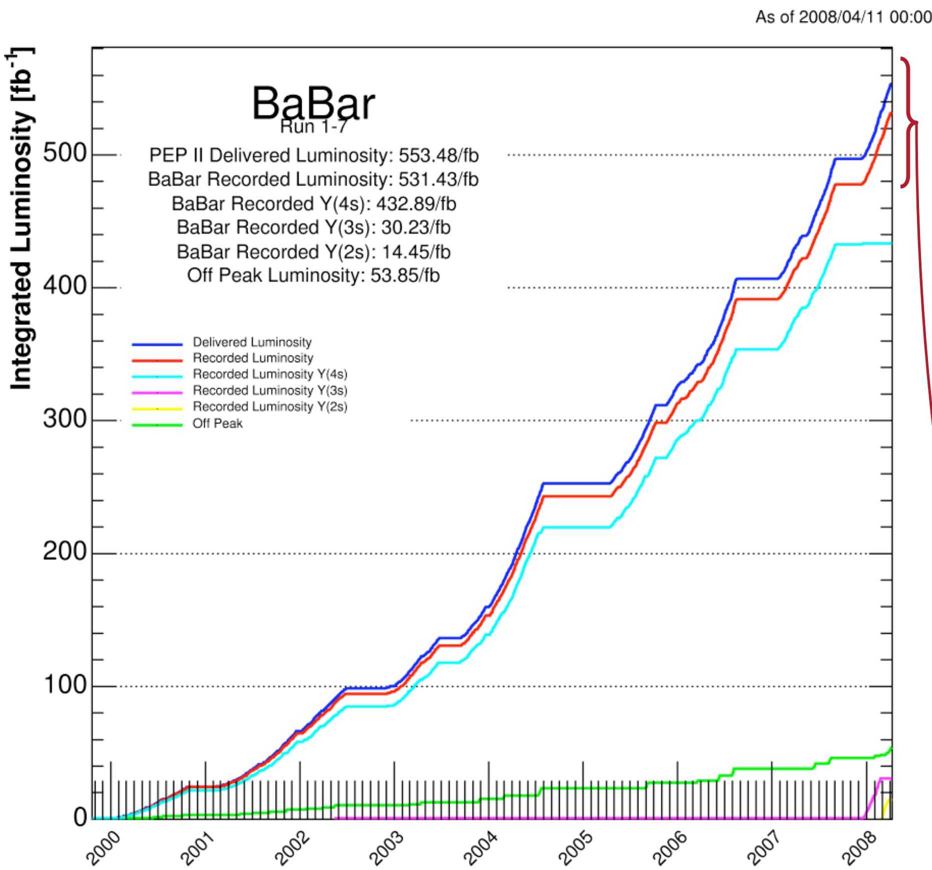
The BABAR detector



Front-end view

BaBar data sample

$\Upsilon(4S)$ data taking (Run 1-6) completed in December 2007: 433 fb^{-1}, plus 10% off-peak



Machine turned off… on Monday 2008 April 7th…

Run 7: $\Upsilon(3S)$, $\Upsilon(2S)$ and R-scan:

- October-November 2007: machine upgrade to L=2x10^{34} cm^{2}s^{-1}

→ First $\Upsilon(4S)$ collisions on December 15th

- December 19th: budget cut
- Faced with immediate shutdown, BaBar proposed to run at the $\Upsilon(3S)$:

  1- New Physics (Higgs and Dark Matter)

  2- Bottomonium (search for the η_b)

- $\Upsilon(3S)$ scan on December 22nd: all changes (machine, trigger, reconstruction and simulation software) implemented in just a few days!

- $\Upsilon(3S)$: 33 fb^{-1}
- $\Upsilon(2S)$: 14 fb^{-1}
- R-scan above $\Upsilon(4S)$: 4 fb^{-1}

Introduction to Quarkonium Physics

The B-Factory at SLAC

Charmonium and Exotics

X(3872)

$Y(1^{--})$ family

"3940", X,Y,Z family

$Z(4430)^+$

Most of the results from ICHEP 2008

Bottomonium : Observation of the η_b

Conclusion

The X(3872) …

Observation of a narrow charmonium - like state in exclusive B+- ---> K+- pi+ pi- J / psi decays.
By Belle Collaboration (S.K. Choi *et al.*). Sep 2003. 10pp.
Press release.
Published in **Phys.Rev.Lett.91:262001,2003**.
e-Print: **hep-ex/0309032**

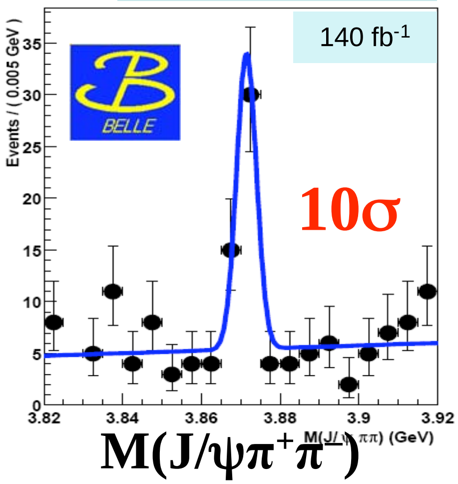
TOPCITE = 250+
References | LaTeX(US) | LaTeX(EU) | Harvmac | BibTeX | Keywords | Cited 372 times
Abstract and Postscript and PDF from arXiv.org (mirrors: au br cn de es fr il in it jp

BaBar: "Observation of CP violation in the B^0 meson system" PRL87:091801,2001: ….cited… 426 times

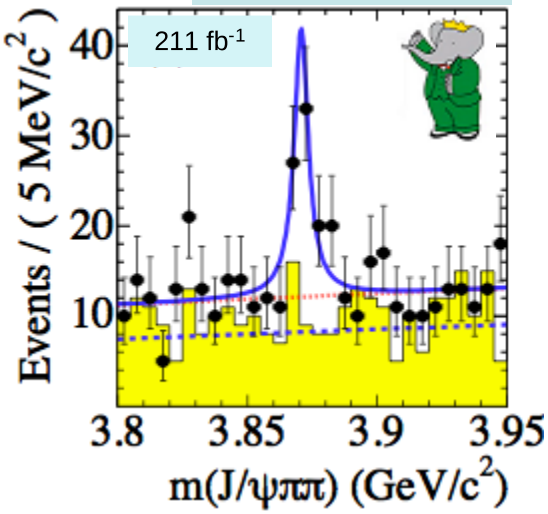
X(3872) observation

- X(3872) state reported by Belle (2003) in: B→X(3872)K, X(3872)→$J/\psi\pi^+\pi^-$
- Confirmed by CDF/D0 (in $p\bar{p}$ inclusive production), and Babar:

PRL 91, 262001(2003)



PRD 73, 011101(2006)



M = 3872.0±0.8 MeV/c^2

Γ< 2.3 MeV 90%CL

Close to DD* threshold 3871.8 (above, below ?)

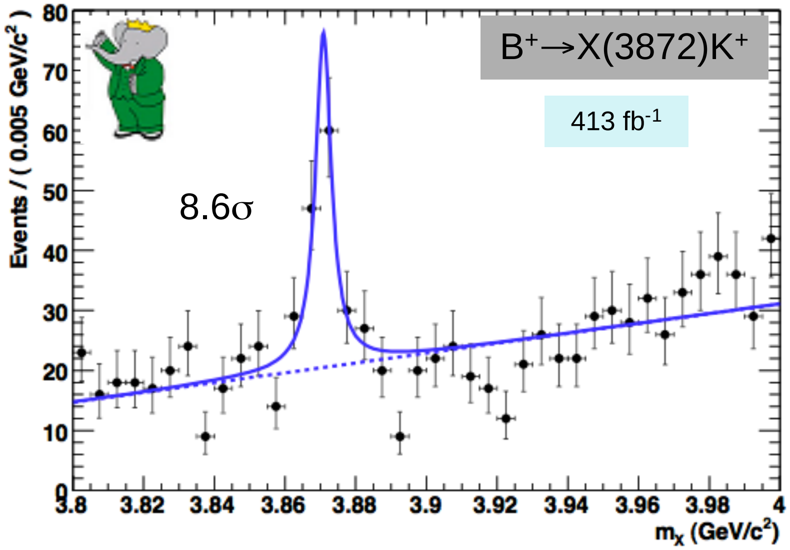
Small width for a state above $D\bar{D}$ threshold

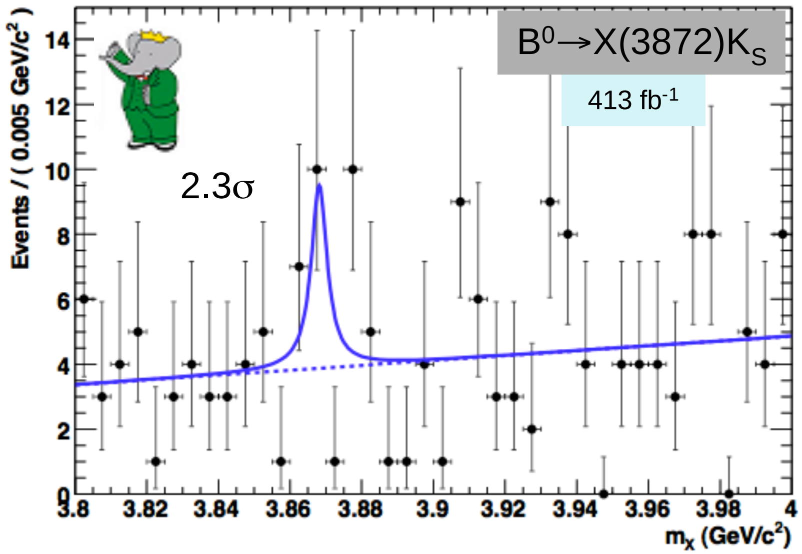
Then started the X(3872) saga…. Many theory papers… lots of experimental studies

BaBar update on X(3872)→$J/\psi\pi^+\pi^-$

PRD-RC 77, 111101(2008)

Updated measurements of X(3872) mass and width in B→X(3872)K decays, with X(3872)→$J/\psi\pi^+\pi^-$ with full dataset.





For neutral mode fit, width fixed to the charged mode result

$X(3872)\rightarrow J/\psi\pi^+\pi^-$: Comparison with Models and Belle

Measurements in B^0 and B^- decays separately: mass and branching fraction differences between neutral and charged B decays are important predictions from certain models

diquark-antiquark model:

- 2 neutral states: $X_u=[cu][\bar{c}\bar{u}]$ and $X_d=[cd][\bar{c}\bar{d}]$, with: $\Delta m=8\pm3$ MeV/c^2
- 2 charged states: $X^+=[cu][\bar{c}\bar{d}]$ and $X^-=[cd][\bar{c}\bar{u}]$

Molecule model: $R^{0/+}=BF(B^0\rightarrow XK_s)$ / $BF(B^+\rightarrow XK^+) < 0.1$

Natural width: $\Gamma=1.1\pm1.5\pm0.2$ MeV or $\Gamma<3.3$ MeV 90%CL

Masses:

$$m(X^0 \text{ in } B^0 \rightarrow X^0 K^0_S) = (3868.7 \pm 1.5 \pm 0.2)\,\text{MeV}/c^2$$
$$m(X^0 \text{ in } B^- \rightarrow X^0 K^-) = (3871.4 \pm 0.6 \pm 0.1)\,\text{MeV}/c^2$$

$\Delta m = (2.7\pm1.6\pm0.4)$MeV/$c^2$ (BaBar)

$\Delta m = (0.2\pm0.9\pm0.3)$MeV/$c^2$ (Belle)

Branching fractions

$$\mathcal{B}(B^- \rightarrow X^0 K^-, X^0 \rightarrow J/\psi\pi^+\pi^-) = (8.4 \pm 1.5 \pm 0.7) \times 10^{-6}$$
$$\mathcal{B}(B^0 \rightarrow X^0 K^0, X^0 \rightarrow J/\psi\pi^+\pi^-) = (3.5 \pm 1.9 \pm 0.4) \times 10^{-6}$$
$$< 6.0 \times 10^{-6}\ (90\%\ CL)$$

$R^{0/+} = 0.41\pm0.24\pm0.05$ (BaBar)

$R^{0/+} = 0.82\pm0.22\pm0.05$ (Belle)

1-2 σ agreement between experiments… hard to distinguish between models…

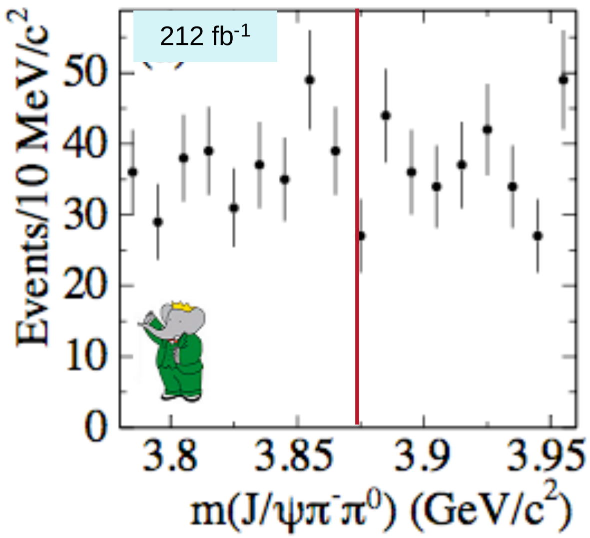
Search for a charged partner X(3872)$^+$

PRD 71, 031501(2005)

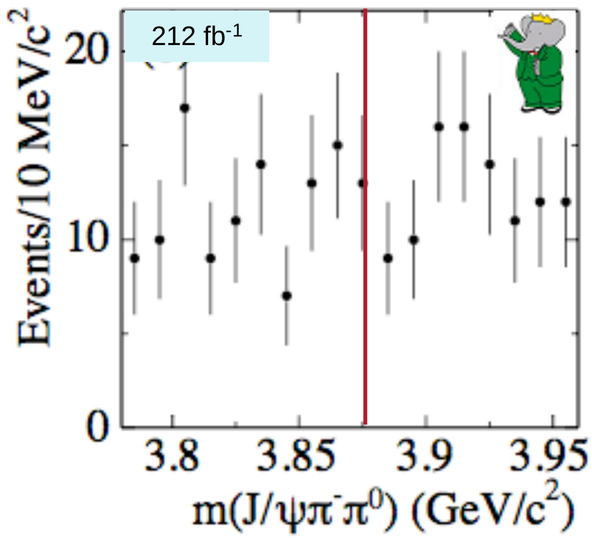
If X(3872) is isospin 1, then $B(B \to X^\pm K) = 2 \times B(B \to X^0 K)$

Search for $B \to X^\pm K$, with $X^+ \to J/\psi \pi^+ \pi^0$

$B^+ \to X(3872)^+ K_s$



$B^0 \to X(3872)^+ K^-$



No signal observed $\Rightarrow$ $I \neq 1$!

$B(B^0 \to X^+ K^-) . B(X \to J/\psi \pi^+ \pi^0) < 5.4 \times 10^{-6}$ 90% CL

$B(B^+ \to X^+ K_S) . B(X \to J/\psi \pi^+ \pi^0) < 22 \times 10^{-6}$ 90% CL

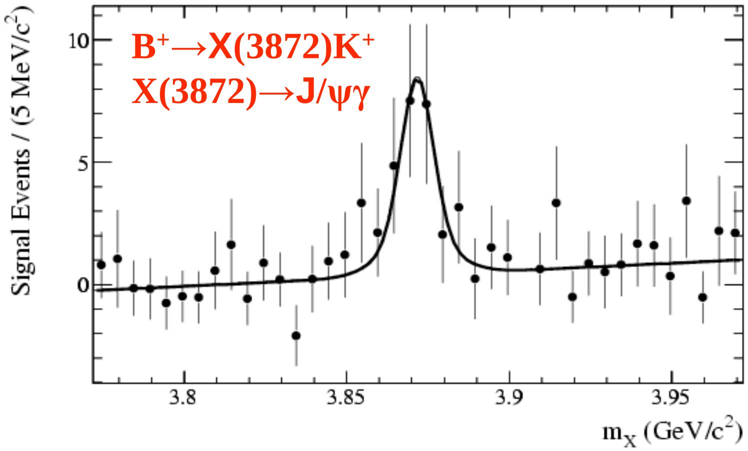
Observation of X(3872)→(J/ψ, ψ(2S))γ

hep-ex/0809.0042, submitted to PRL

We have updated B→X(3872)K, with X→J/ψ γ, and searched for B→X(3872)K, with X→ψ(2S) γ

- 3.6σ evidence for X(3872)→J/ψγ,
  BF(B^+→X(3872)K^+, X(3872)→J/ψγ) = (2.8±0.8±0.2)x10^{-6}

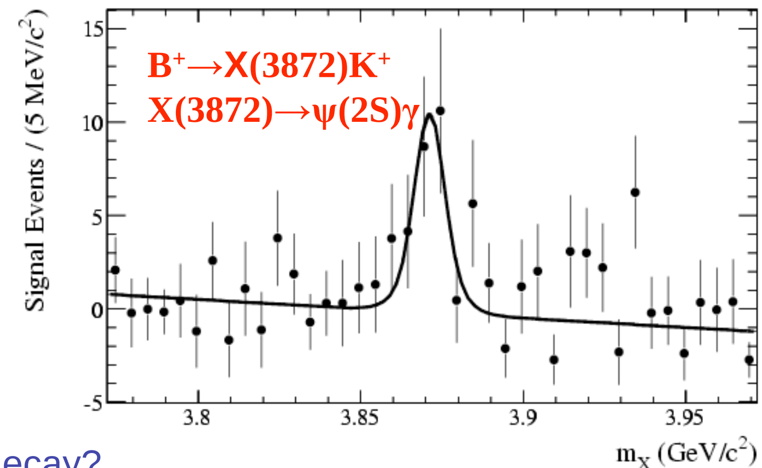
- 3.5σ evidence for X(3872)→ψ(2S)γ
  BF(B^+→X(3872)K^+, X(3872)→ψ(2S)γ) = (9.9±2.8±0.6)x10^{-6}



⇒ Implications of the measurements:

Molecular model DD*, decay X→ψ(2S)γ expected to be highly suppressed

Observation of X→J/ψγ implies: $C_{X(3872)}$=+1

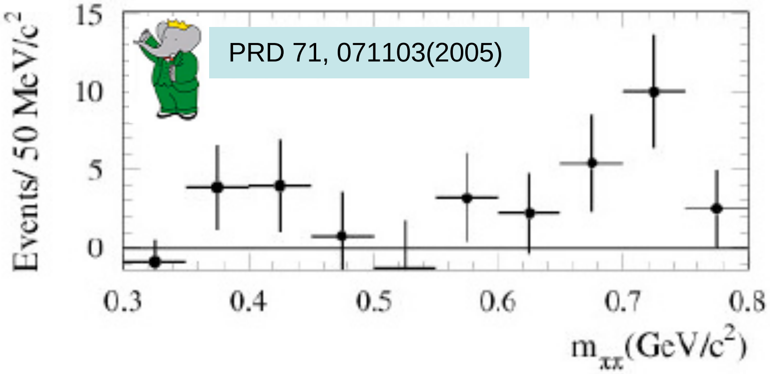


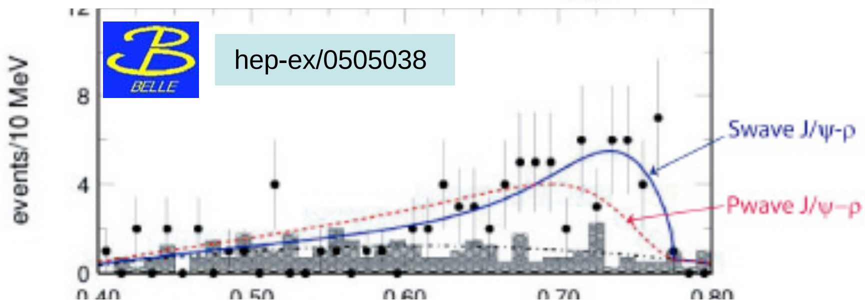
What do we learn for the $\pi^+\pi^-$ system, in the X→J/ψ$\pi^+\pi^-$ decay?

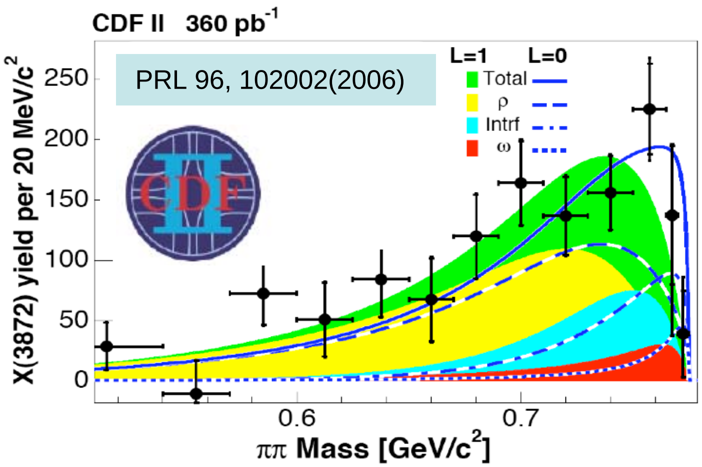
- C($\pi^+\pi$-) = -1 , and given C($\pi^+\pi$-) = $(-1)^{L+S}$, L($\pi^+\pi$-) odd, which indicates P-wave: ρ
- if X→J/ψ ρ, X→J/ψ$\pi^0\pi^0$ forbidden (nobody looked….)

X(3872)→J/ψπ⁺π⁻ : (π⁺π⁻) invariant mass

More on the $\pi^+\pi^-$ invariant mass distribution







- Di-pion mass consistent with $\rho^0 \to \pi^+\pi^-$
- Measurement of relative wave J/ψ-ρ: would help for parity determination: $P_X = P_{J/\psi}.P_\rho.(-1)^L$

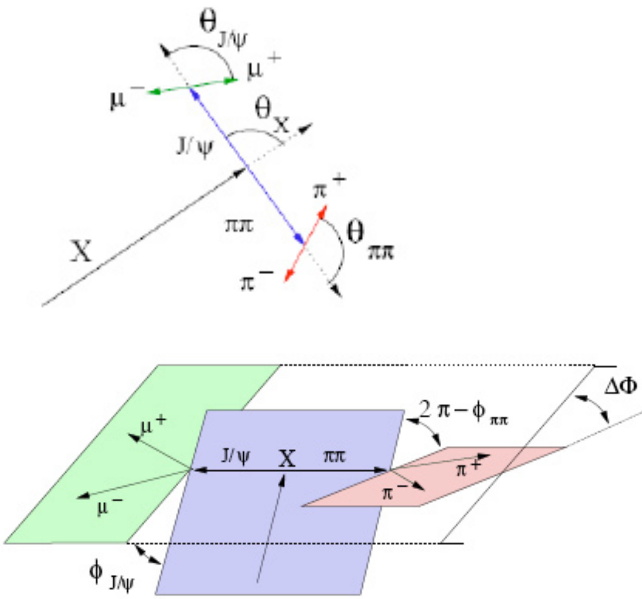
Best fit from CDF: data compatible with both S- and P-wave J/ψ-ρ

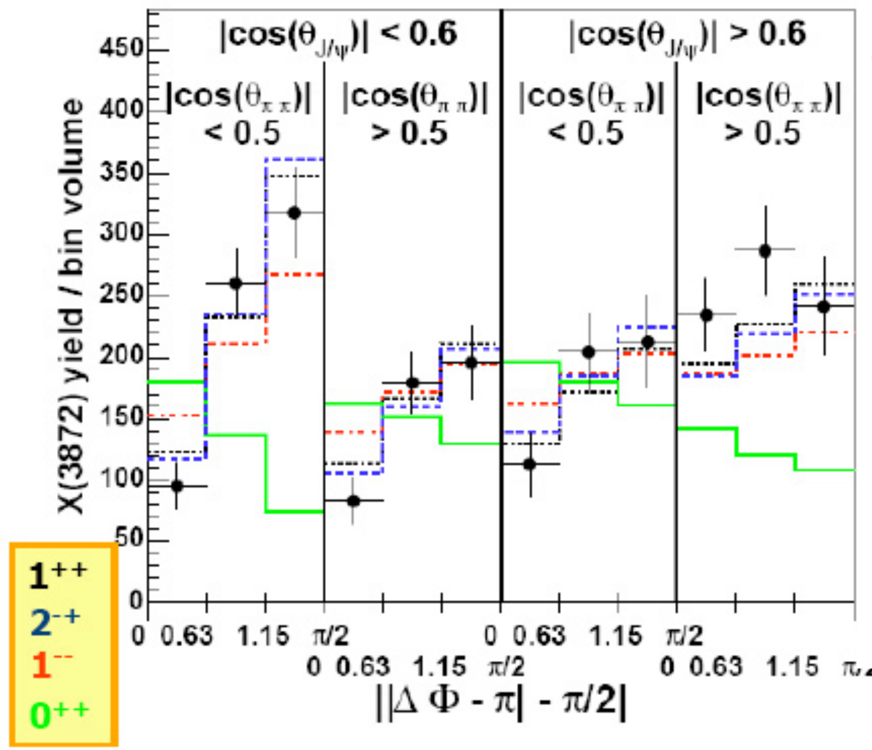
CDF X(3872) angular Analysis

PRL98, 1320002(2007)

CDF has performed a full angular analysis of $X \to J/\psi\pi\pi$ decays

Angles definition:





J^{PC}	χ^2 prob.
1^{++}	27.8%
2^{-+}	25.8%
1^{--}	0.02%
2^{+-}	$5.5\cdot10^{-5}$
1^{+-}	$3.8\cdot10^{-5}$
2^{--}	$3.8\cdot10^{-5}$
3^{+-}	$3.8\cdot10^{-5}$
3^{--}	$2.4\cdot10^{-5}$
2^{++}	$1.1\cdot10^{-5}$
1^{-+}	$4.1\cdot10^{-6}$
0^{-+}	$3.5\cdot10^{-17}$
0^{+-}	$<1\cdot10^{-20}$
0^{++}	$<1\cdot10^{-20}$

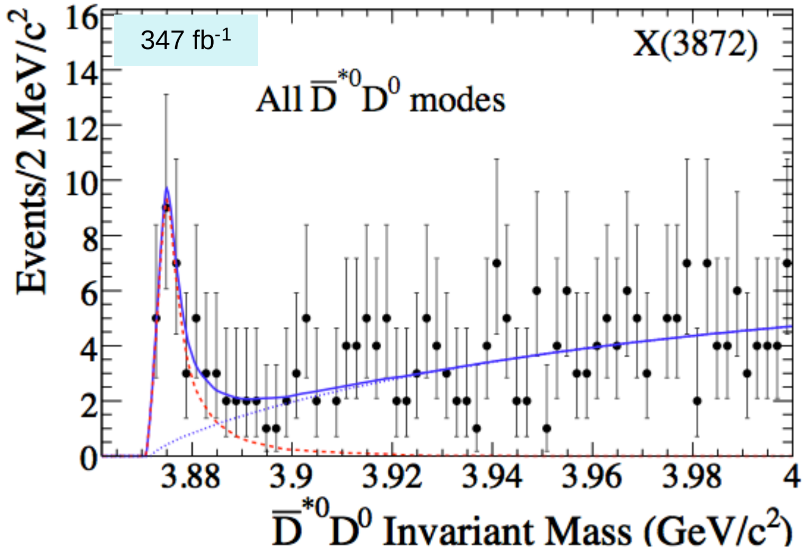
- Method tested using $\psi(2S) \to J/\psi\pi\pi$ decays
- Only $J^{PC} = 1^{++}$ and 2^{-+} compatible with data

X(3872) $J^{PC}=1^{++}$ or 2^{-+}

Observation of $X \to D^0 \bar{D}^{*0}$

Belle: $B \to XK$, $X \to \bar{D}^0 D^{*0}$ ($\bar{D}^0 D^0 \pi^0$) with m_X = 3875.4 MeV/c^2

BaBar confirmation with: $D^0 \bar{D}^{*0}$ and $\bar{D}^0 D^{*0}$ with $D^{*0} \to D^0 \pi^0$, $D^0 \gamma$



$M = 3875.1^{+0.7}_{-0.5} \pm 0.5$ MeV/c^2

$\Gamma = 3.0^{+1.9}_{-1.4} \pm 0.9$ MeV

$R = B^0/B^+ = 1.33 \pm 0.69 \pm 0.43$

$\Delta m = 0.7 \pm 1.9 \pm 0.3$ MeV/c^2

B mode		Yield	Efficiency (%)	$\mathcal{B}$ (10^{-4})	Limit (10^{-4})
$B^0 \to X(3872)K^0$	$[\bar{D}^{*0}D^0/\bar{D}^0D^{*0}]$	5.8 ± 2.7	0.5 - 5.3	$2.22 \pm 1.05 \pm 0.42$	4.37
$B^+ \to X(3872)K^+$	$[\bar{D}^{*0}D^0/\bar{D}^0D^{*0}]$	27.4 ± 5.9	1.5 - 10.2	$1.67 \pm 0.36 \pm 0.47$	-

- Excellent agreement with Belle (PRL97,162002(2006)): $M = 3875.4 \pm 0.7^{+1.2}_{-2.0}$ MeV/c^2
- However, mass is more than 4σ from the value measured in the $J/\psi\pi^+\pi^-$ decay modes!

Is the X(3875) a different state?

- Belle update at ICHEP (no Pub): $M = 3872.6^{+0.5}_{-0.4} \pm 0.4$ MeV/c^2 …. ?

What is the X(3872)?

Experimental facts

- X(3872)→DD*, (J/ψ,ψ(2S)) γ, J/ψππ(J/ψρ)
- Mass close to DD* threshold
- Small width
- $J^{PC}=1^{++}$ and 2^{-+} favored

Theoretical interpretation

Charmonium state ?

- 2^{-+} matched $^1D_2$?
- 1^{++}: $\chi_{c1}(2P)$ predicted at ≈3950 MeV/c^2
- small width ?

Tetraquark ?

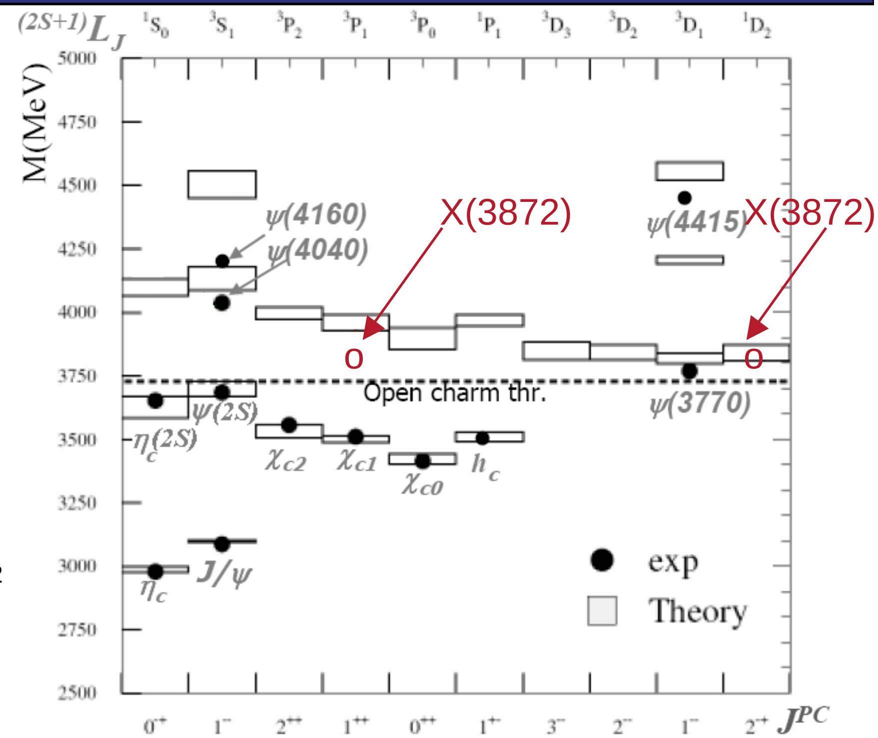
- would explain small width
- 4 states needed -including- 2 charged states!

Hybrid ?

- X too light wrt LQCD calculations (>4200 MeV)

$D\bar{D}^*$ molecule ?

- 1++ strongly favored by model
- Mass consistent with expected
- Accommodate more various decays - how about ψ(2S) γ decay mode?



Charmonium - $D\bar{D}^*$ molecule ?

Introduction to Quarkonium Physics

The B-Factory at SLAC

Charmonium and Exotics

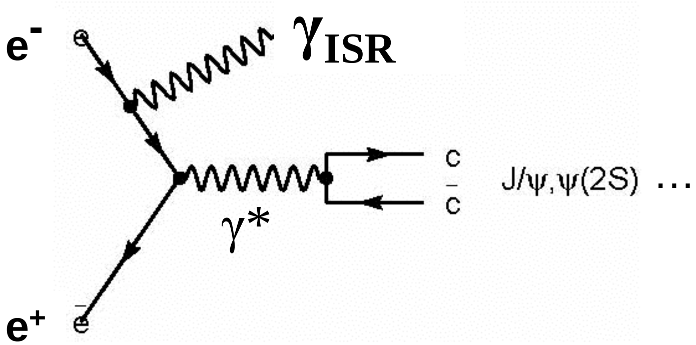
X(3872)

Y(1^{--}) family

"3940", X,Y,Z family

Z(4430)$^+$

$e^+e^- \rightarrow 1^{--}$ final states via ISR



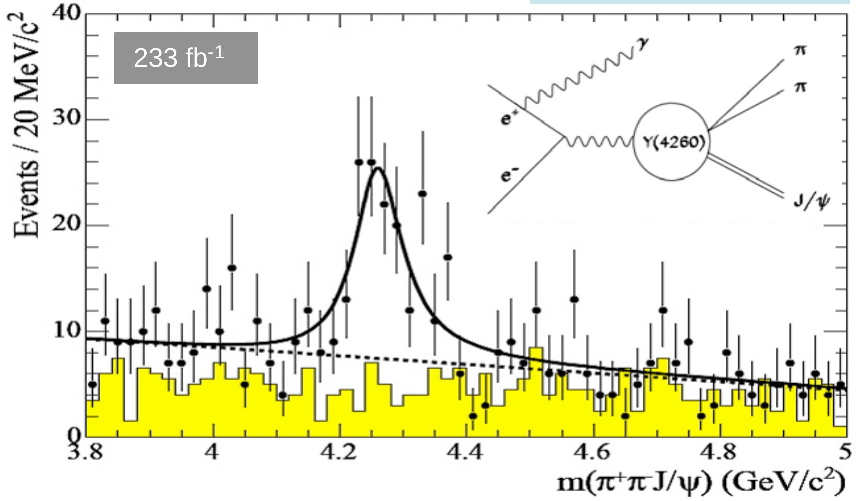
Bottomonium : Observation of the η_b

Conclusion

Observation of Y(4260) in ISR events

First observation from BaBar:

PRL 95, 142001(2005)



Main selection: $P_Y=(s-M_Y^2)/2\sqrt{s}$

M= (4259±8) MeV/c^2

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

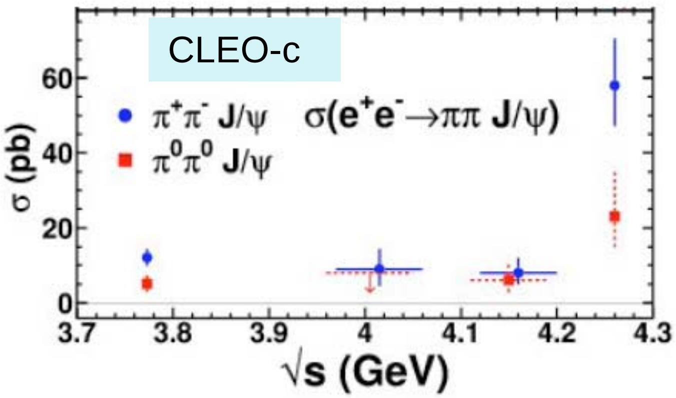
Γ = (88±23) MeV

Confirmation from other experiments: Belle, CLEO, CLEO-c (scan)

Belle: $M = 4295 \pm 10^{+10}_{-3}\ MeV/c^2$

$\Gamma = 133^{+26+13}_{-22-6}\ MeV$

$CLEO-III: M = 4283^{+17}_{-16} \pm 4\ MeV/c^2$



$J/\psi\pi^+\pi^-$ = 11σ

$J/\psi\pi^0\pi^0$ = 5.1σ

$(\pi^+\pi^-)/(\pi^0\pi^0)\approx 2 \rightarrow$ I=0

Search for Y(4260) in other channels

BaBar has searched for various decay modes, and other production process

PRD 76, 111105 (2007)
PRD 74, 091103 (2006)
PRD 73, 012005 (2006)
hep-ex/0608004

Study in ISR events

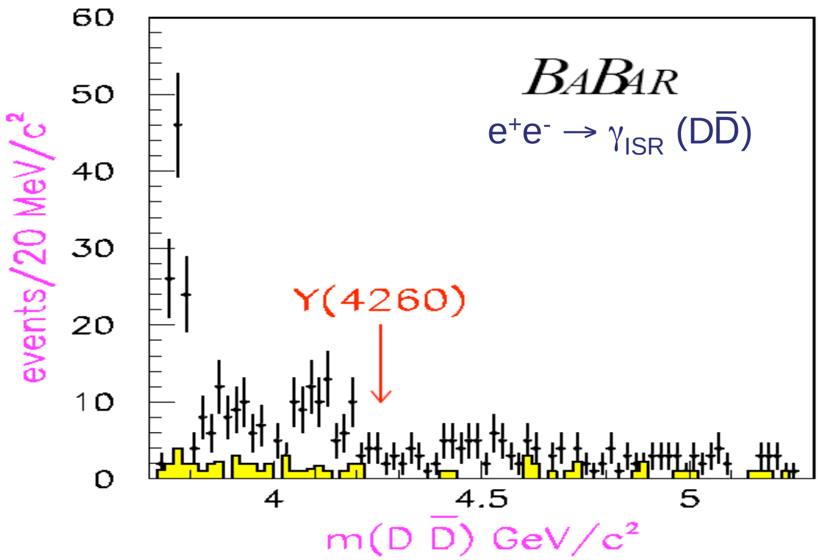
$e^+e^- \to \gamma_{ISR}\,(D\bar{D})$

$e^+e^- \to \gamma_{ISR}\,(\phi\pi^+\pi^-)$

$e^+e^- \to \gamma_{ISR}\,(p\bar{p})$

$e^+e^- \to \gamma_{ISR}\,(J/\psi\gamma\gamma)$

No evidence found…

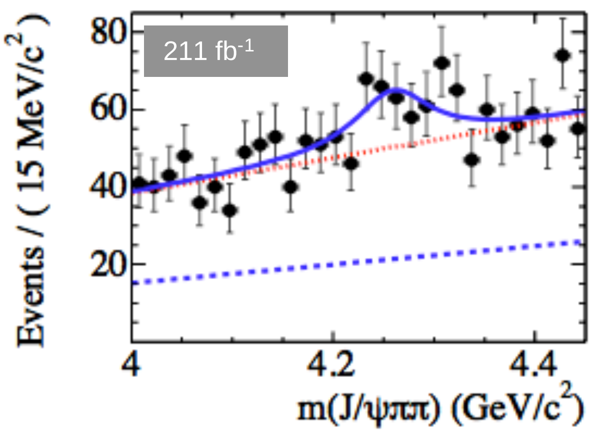


Search in B decay:

$B^{\pm}\to YK^{\pm}$, $Y\to J/\psi\pi\pi$

Hint (2σ) observed with 211fb^{-1}

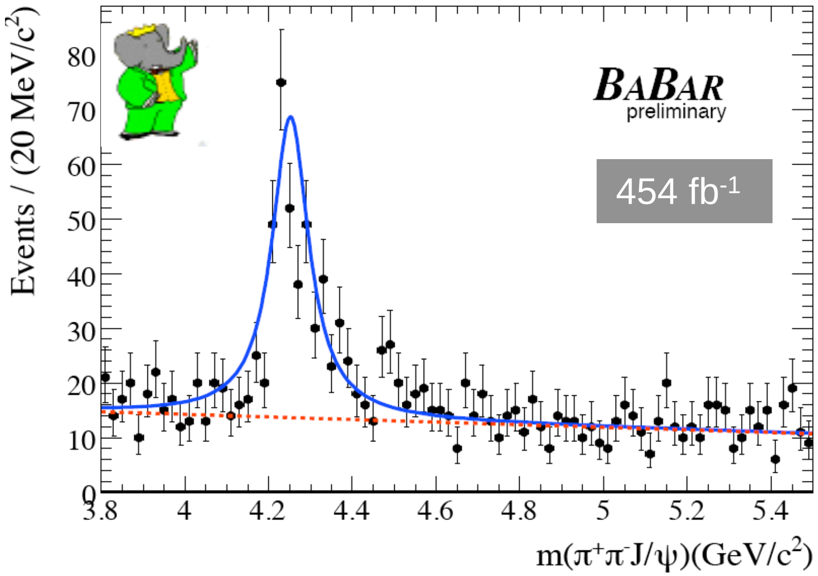
NOT yet confirmed



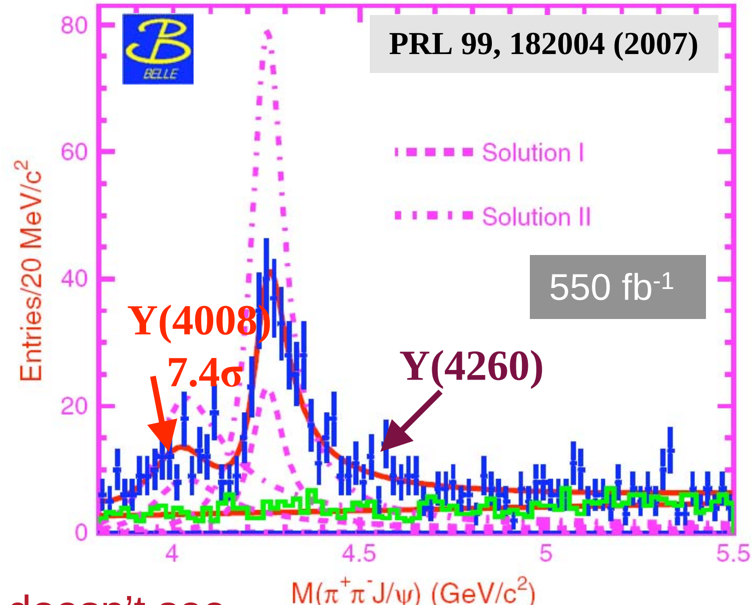
PRD 73, 011101 (2006)

Y(4260): updates from ICHEP

Update from BaBar with full statistics



Belle: a New resonance: Y(4008)?



Belle claims a new resonance… that BaBar doesn't see…

BaBar poor quality fit: analysis being improved…

Summary

of measurements

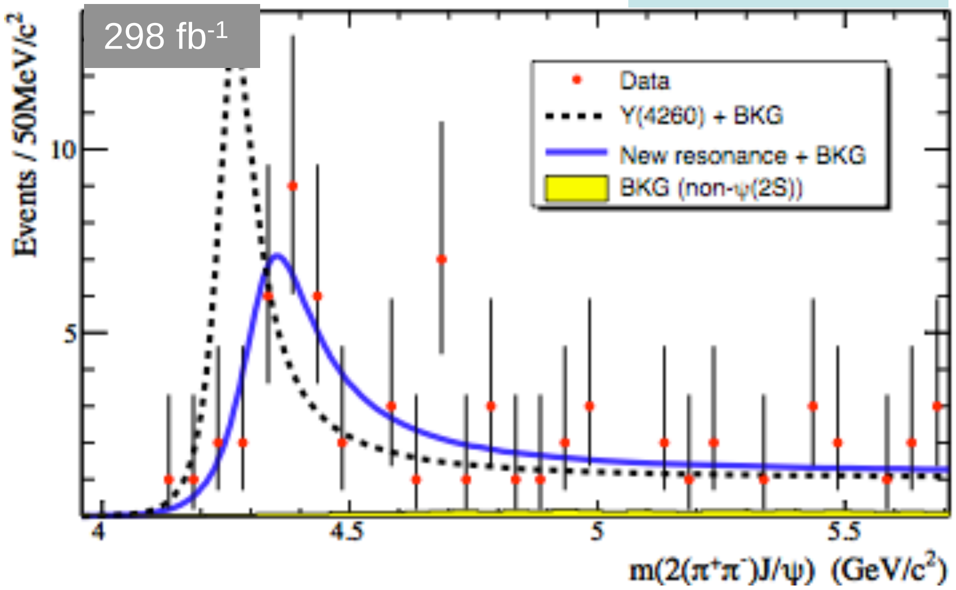
	State	M, MeV/c^2	Γ_{tot}, MeV
	Y(4008)	$4008 \pm 40^{+114}_{-28}$	$226 \pm 44 \pm 87$
	Y(4260)	$4259 \pm 8^{+2}_{-6}$	$88 \pm 23^{+6}_{-4}$
	Y(4260)	$4252 \pm 6^{+2}_{-3}$	$105 \pm 18^{+4}_{-6}$
	Y(4260)	$4284^{+17}_{-16} \pm 4$	$73^{+39}_{-25} \pm 5$
	Y(4260)	$4247 \pm 12^{+17}_{-32}$	$108 \pm 19 \pm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

Search for Y(4260) in $\psi(2S)\pi^+\pi^-$

Searching for the Y(4260), in ISR, decaying into $\psi(2S)\pi^+\pi^-$

Observation of a new state at 4325 MeV/c^2

PRL 98, 212001(2007)



Incompatible with BaBar Y(4260), $\psi(4415)$

BUT compatible with Belle Y("4295")

(problem resolved now….)

Assuming a single resonance:

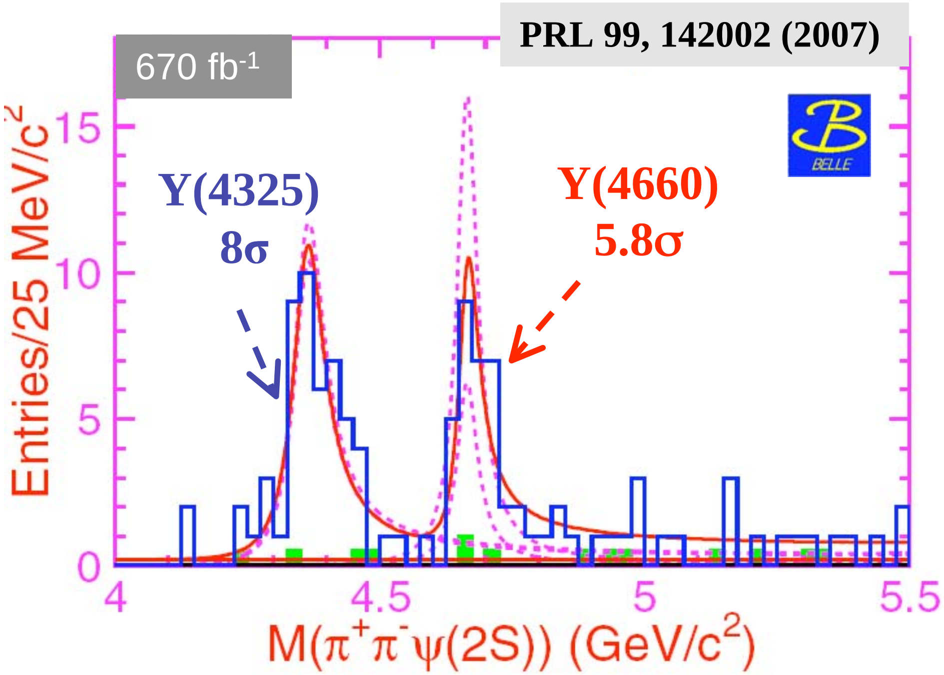
M= (4324±24) MeV/c^2

Γ = (172±33) MeV

Analysis on-going with
full statistics

Y(4325) confirmation and…

Belle: confirmation and observation of another new state



Hint of Y(4660) in BaBar data, but not significant enough….

Are the Y(4325) masses compatible between experiments?

Summary of measurements

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

Interpretation of the Y states

Conventional charmonium states:

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

(in some models, the Y(4260) mass consistent with predicted ψ(4S) state: 4^3S_1 .Some other models: 4S $\equiv$X(4415))

Hybrid interpretation most appealing:

Expected in the region M: 4.2 to 5 GeV/c^2

Dominant decay mode: $D\bar{D}_1$: threshold $\approx$ 4287 MeV/c^2 … ?

Is the Y(4260) a $D\bar{D}_1$ bound state?

Should be a multiplet

Introduction to Quarkonium Physics

The B-Factory at SLAC

Charmonium and Exotics

- X(3872)
- $Y(1^{--})$ family
- **“3940”, X,Y,Z family**
- $Z(4430)^{+}$

Bottomonium : Observation of the η_b

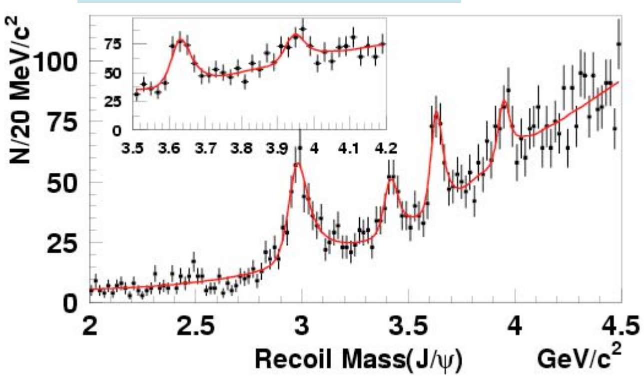
Conclusion

The X,Y,Z states at 3940 MeV/c^2

Belle has reported 3 states near 3940 MeV/c^2

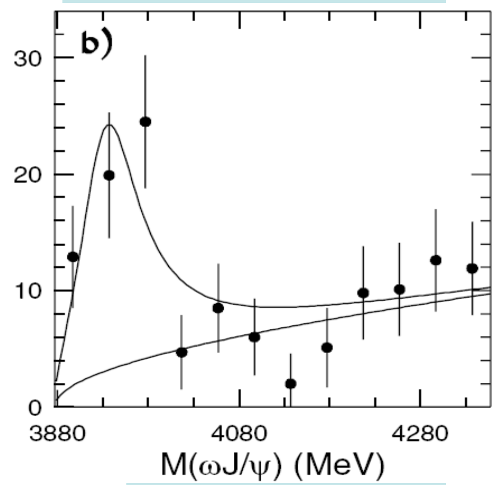
State	Process	M(MeV/c^2)	Γ(MeV)
X	$e^+e^- \to J/\psi X$	3943±8	<39
Y	$B \to YK$, $Y \to J/\psi\omega$	3943±17	87±34
Z	$\gamma\gamma \to Z$, $Z \to D\bar{D}$	3929±5	29±10

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



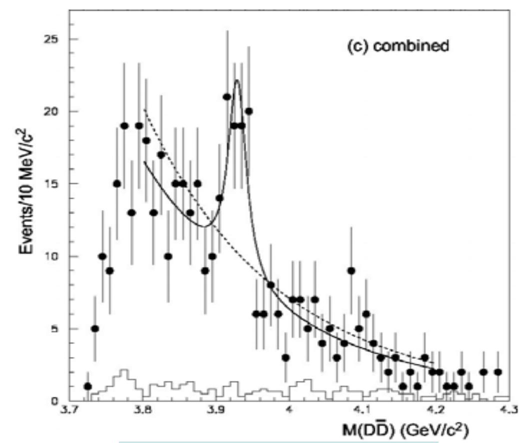
PRD 98, 082001(2007)

$B \to YK$, $Y \to J/\psi\omega$



PRD 94, 182002(2005)

$\gamma\gamma \to Z$, $Z \to D\bar{D}$

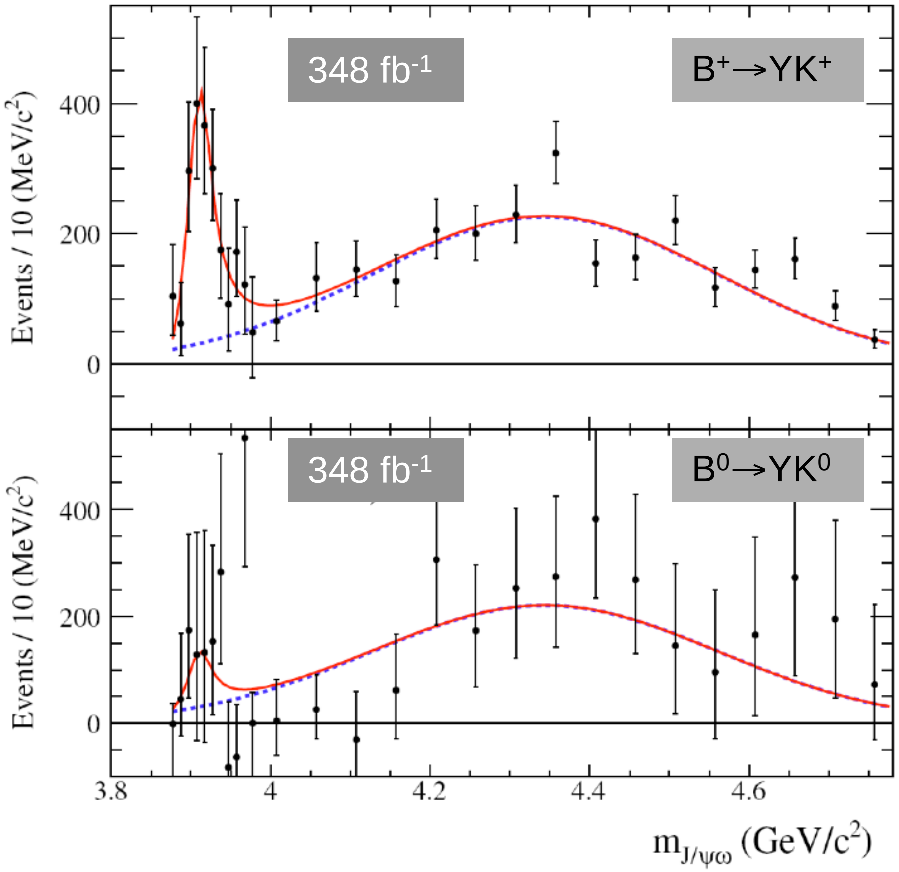


PRD 96, 082003(2006)

The Y(3940) at BaBar

PRL 101, 082001 (2008)

BaBar confirmation: B→Y(3940)K, Y(3940)→J/ψω



Branching Fractions:

$$\mathcal{B}(B^+) = (4.9^{+1.0}_{-1.0}(stat)^{+0.5}_{-0.5}(syst)) \times 10^{-5}$$
$$\mathcal{B}(B^0) = (1.5^{+1.4}_{-1.2}(stat)^{+0.2}_{-0.2}(syst)) \times 10^{-5}$$

Mass and Width:

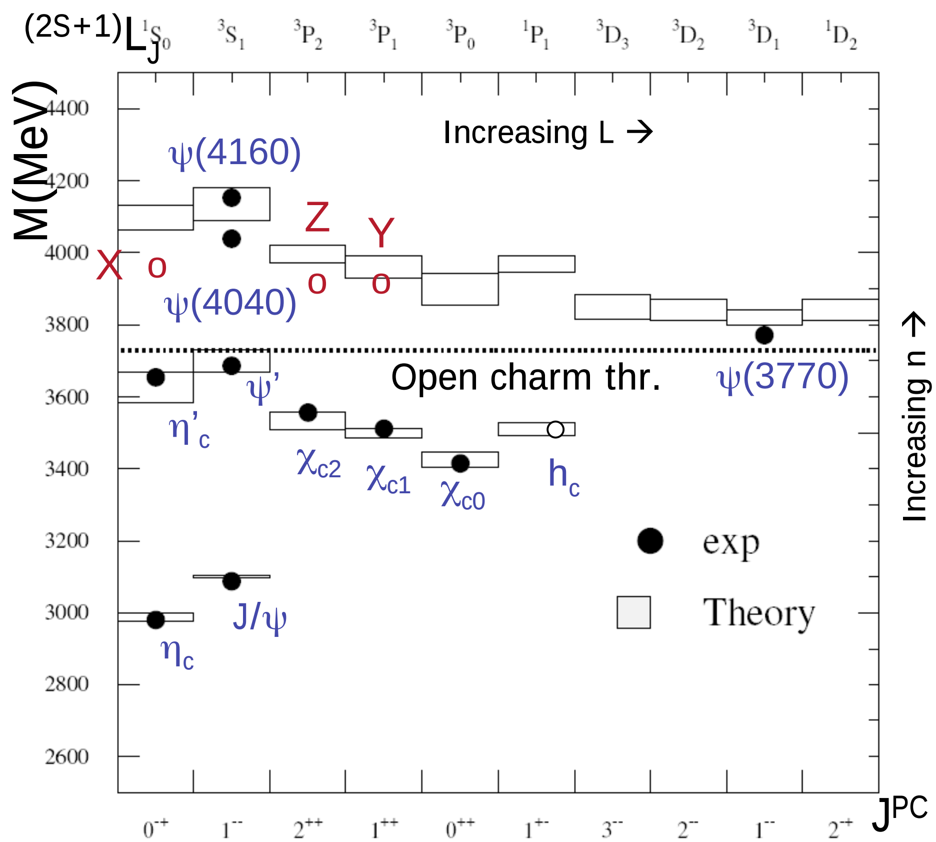
$$M(Y) = (3914.6^{+3.8}_{-3.4}(stat)^{+1.9}_{-1.9}(syst))\ \mathrm{MeV}/c^2$$
$$\Gamma(Y) = (33^{+12}_{-8}(stat)^{+5}_{-5}(syst))\ \mathrm{MeV}\,.$$

Y(3940/3915) confirmed by BaBar:

- Mass: 30 MeV/c^2 lower
- Width: narrower

The X,Y,Z states: Interpretation

Are all these states regular Charmonium states?



X(3940): possible candidate: η_c'' (3^1S_0)

Y(3940): possible candidate: $\chi_{c1}'(2^3P_1)$

Z(3930): likely candidate: $\chi_{c2}'(2^3P_2)$

Masses do not match predictions …?

All states should have E1 transitions to lower $c\bar{c}$

X(3940)/Z(3930) analysis on-going at BaBar

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- $Y(1^{--})$ family
- "3940", X,Y,Z family
- **$Z(4430)^+$**

Bottomonium : Observation of the η_b

Conclusion

Belle's observation of a charged state

Belle has reported the first observation of a charged state:

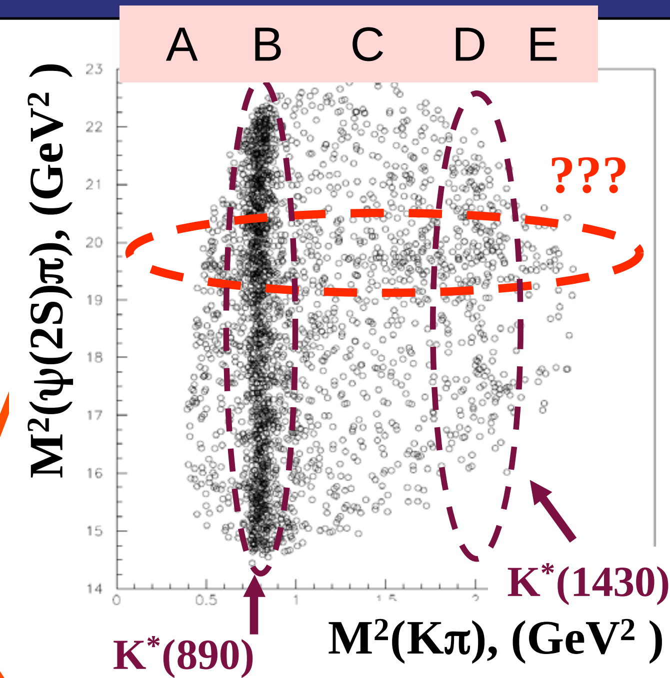
$B \to Z^- K$, with $Z^- \to \psi(2S)\pi^-$

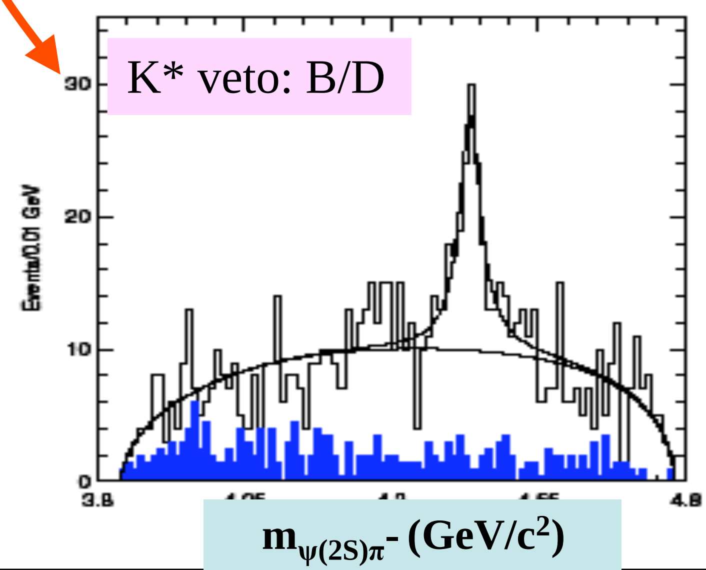
PRL 100, 142001 (2008)

Total significance: 6.5σ

$M = (4433 \pm 4)$ MeV/c^2
$\Gamma = (44^{+17}_{-13})$ MeV

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





If confirmed, first observation of $(c\bar{c}u\bar{d})$ tetraquark state:

Maiani: 0708.3997 (hep-ph)
Karliner & Lipkin: 0802.0649 (hep-ph)

Other hypothesis not ruled out ($D^*(2010)D_1(2420)$ Molecule, etc…)

Experimental questions: neutral mode? $J/\psi\pi^+$ mode ?

Search for the $Z(4430)^+$ at BaBar

To be submitted to PRD

Searched for 4 decay modes:

1. $B^- \to \psi(2S)\pi^- K_S$ where: $\psi(2S) \to e^+e^-, \mu^+\mu^-, J/\psi\pi^+\pi^-$
2. $B^- \to J/\psi\pi^- K_S$ $J/\psi \to e^+e^-, \mu^+\mu^-$
3. $B^0 \to \psi(2S)\pi^- K^+$
4. $B^0 \to J/\psi\pi^- K^+$

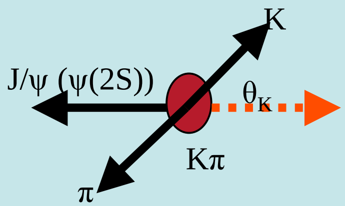
Key point of the analysis: understand the $K\pi$ reflections in the $\psi\pi$ system

$\rightarrow$ both $K\pi$ mass and angular distribution to taken into account

Detailed description of the $K\pi$ system in terms of S,P and D wave intensities

Legendre polynomial moments to parameterize angular structure

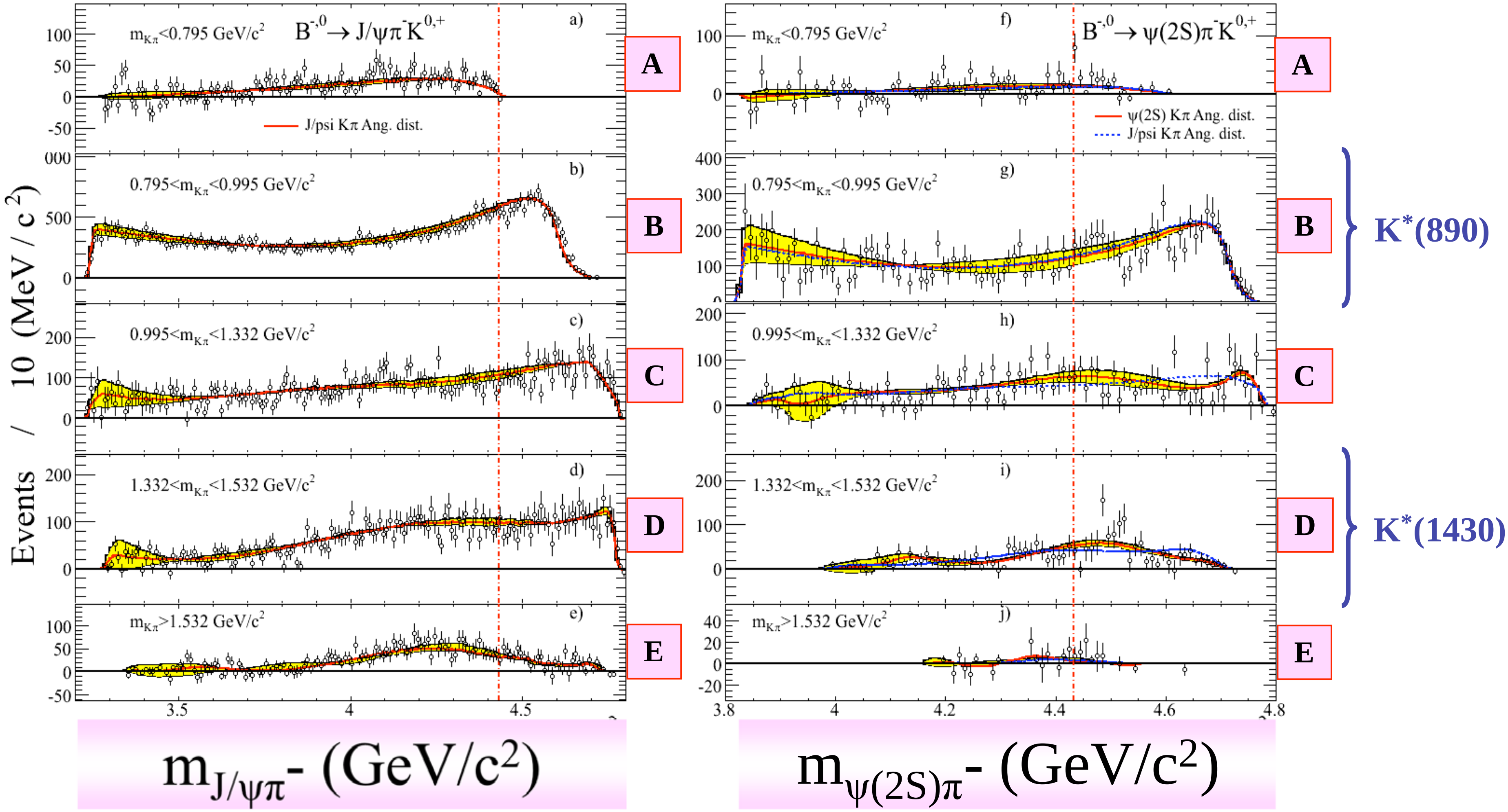
$$\frac{dN}{d\cos\theta_K} = N\sum_{i=0}^{i=L} < P_i > P(\cos\theta_K) = \frac{N}{2} + \sum_{i=1}^{i=L} \underbrace{(N < P_i >)}_{\text{Un-normalized Moments}} P_i(\cos\theta_K)$$



Moments used to describe $K\pi$ reflections into the $\psi\pi$ system

ψπ mass distribution in Kπ intervals

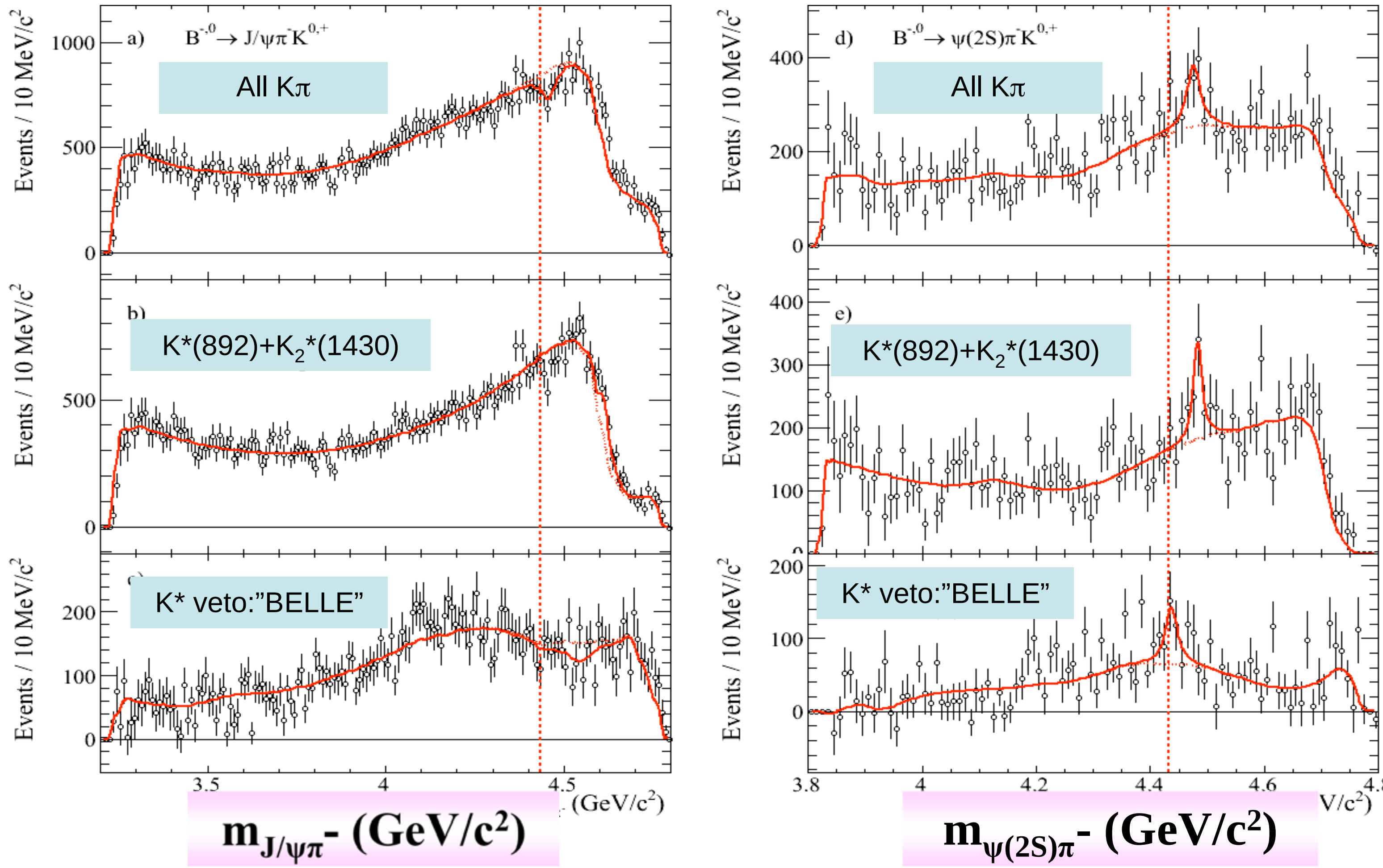
Five Kπ intervals defined (A,B,C,D,E) by BELLE: K* veto (B/D)



Background shape well modeled - No evidence of any structure

Fits to the $\psi\pi$ mass distributions

Fit allowing for a Z signal: BW (m_Z, Γ_Z, N_Z).



J/ψ: No signal

ψ(2S): 2.3σ

(mass shift!)

J/ψ: No signal

ψ(2S): 2.5σ

(mass shift!)

J/ψ: No signal

ψ(2S): 1.7σ

No need of a resonance to describe the data…

Search for the Z(4430)$^+$ at BaBar: conclusions

The $\psi\pi$ mass distributions can be understood as the mass and angular structure of the $K\pi$ system

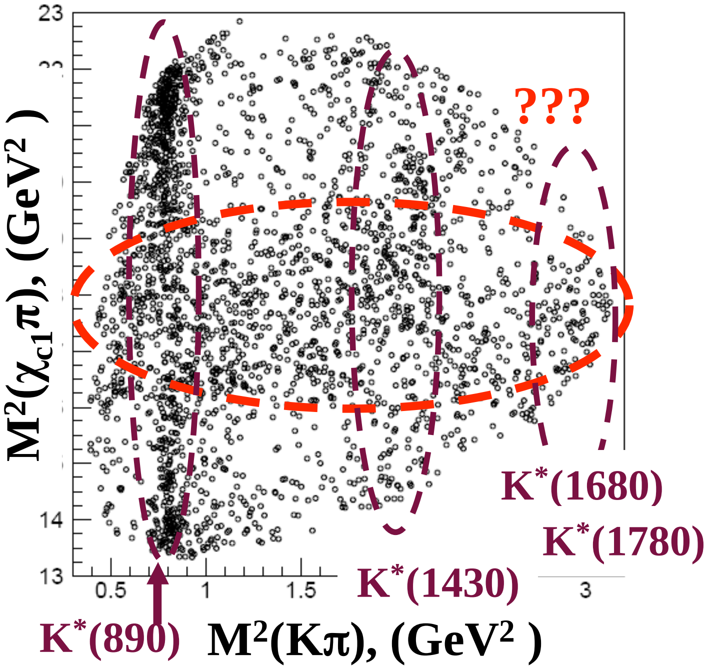
No significant Z(4430)$^+$ is observed in any of the studied decay modes

Belle's new resonances $Z^+_{1,2}$?

hep-ex/0806.4098

Belle has reported the observation of two new charged resonances:

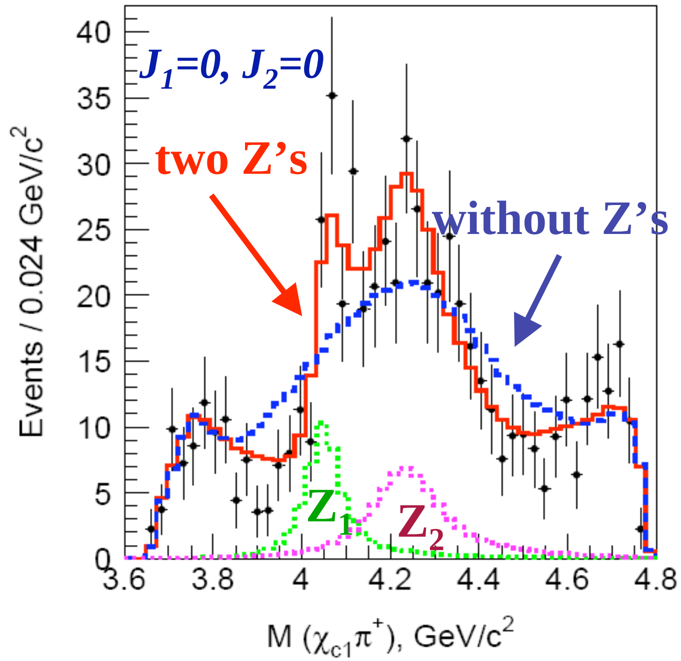
$B \to Z^+_{1,2} K$, with $Z^+ \to \chi_{c1}\pi^+$



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

Dalitz analysis : fit $B^0 \to \chi_{c1}\pi^\pm K^\mp$ 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



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

…Needs confirmation….

Introduction to Quarkonium Physics

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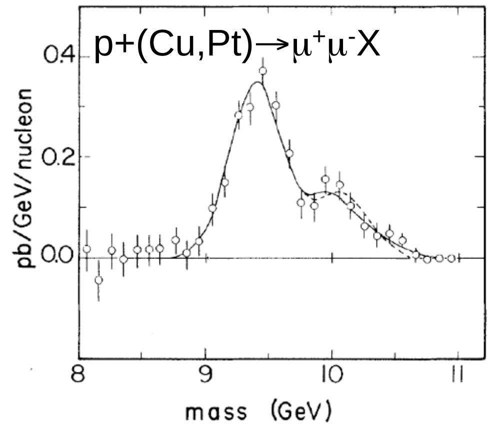
Bottomonium: Observation of the η_b

Conclusion

Bottomonium spectrum … until a few weeks ago

Bottomonium history started 30 years ago

(PRL 39, 242 (1977) and PRL 39,1240 (1977))

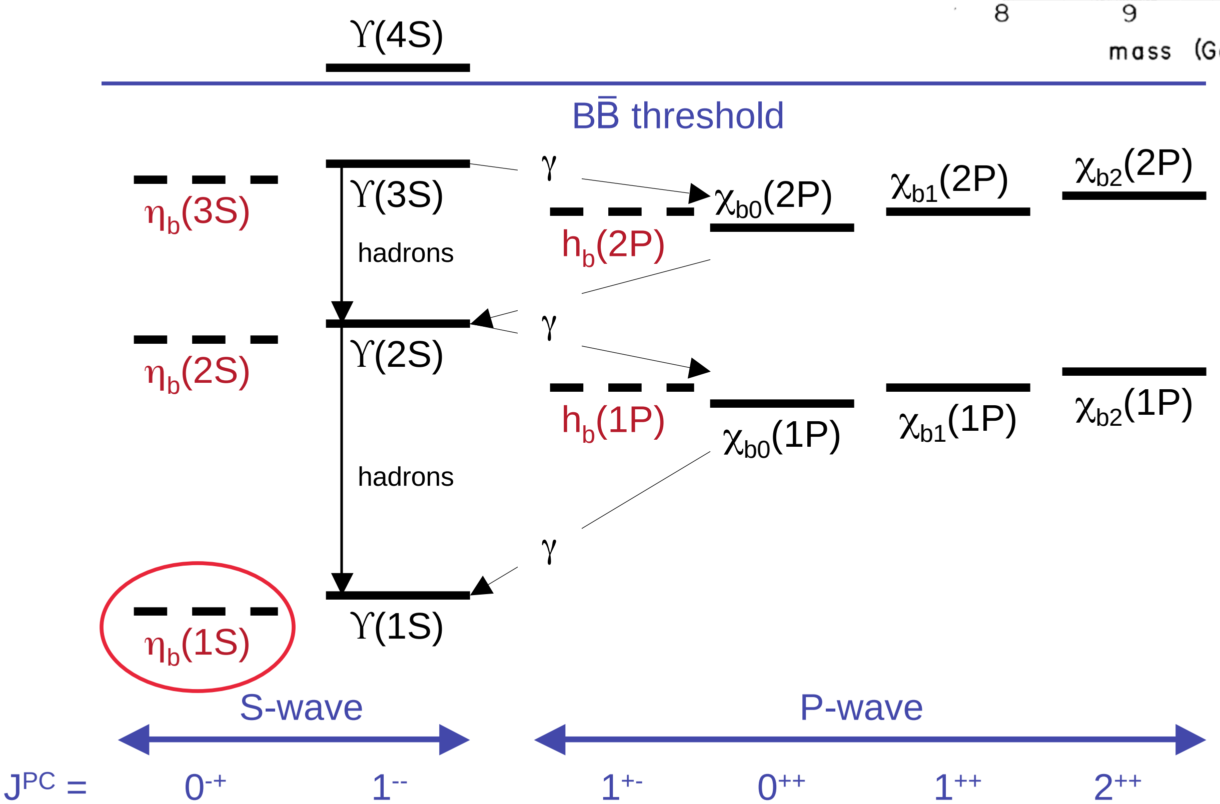


M(ϒ)=9.40±0.013

M(ϒ')=10.00±0.04

M(ϒ'')=10.43±0.12

30 years later….



ϒ(nS) confirmed and χ_{bJ}(1,2P) states observed

Below BB̄, several states not yet observed: 3 S-wave (η_b), 2 P-wave (h_b), D-wave,etc…

Among them, the ground state, the η_b(1S), expected between 20-100 MeV/c^2 below the ϒ(1S)

The bottomonium ground state

Beyond observation of the η_b:

Measurement of mass and width helpful to test Lattice QCD, pNRQCD and Potential models

Hyperfine splitting $M(\Upsilon(1S))-M(\eta_b)$: role of spin-spin interaction in heavy meson system

Hyperfine splitting very sensitive to α_s: measurement of $M(\eta_b)$ with a few MeV error sufficient to improve $\alpha_s(M_Z)$ accuracy.

Previous searches

ALEPH: 1 candidate compatible with background in $\gamma\gamma\rightarrow\eta_b$

(PL B530(2002) 56)

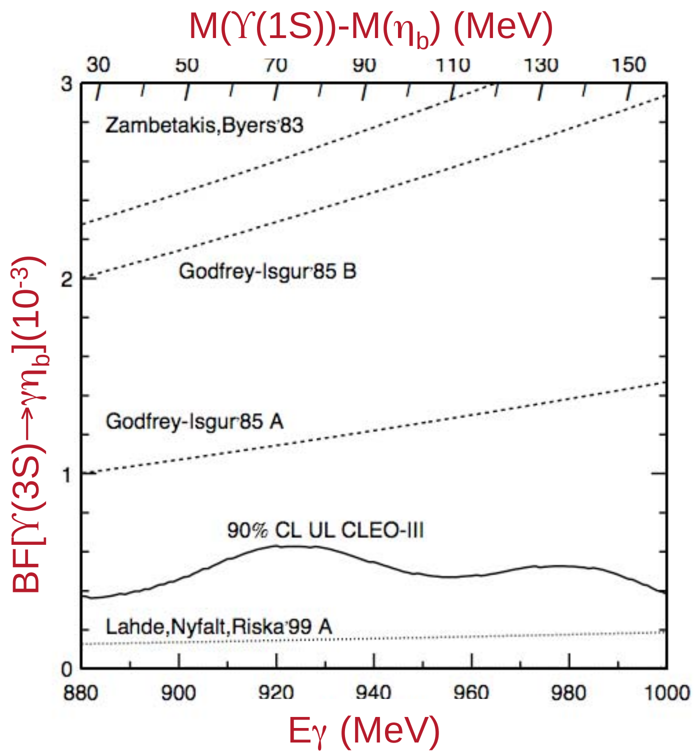
DELPHI (2006): $\gamma\gamma\rightarrow\eta_b$ in 4-6-8 prong final states

CDF(2006): $\eta_b \rightarrow J/\psi J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$

CLEO: Upper Limit on $BF[\Upsilon(3S)\rightarrow\gamma\eta_b]<4.3\times10^{-4}$ @ 90% CL

Upper Limit on $BF[\Upsilon(2S)\rightarrow\gamma\eta_b]<5.1\times10^{-4}$ @ 90% CL

(PRL 94(2005) 032001)



Predictions:

- BF $[\Upsilon(3S)\rightarrow\gamma\eta_b]$: 10^{-4} - 20×10^{-4}
- $M(\Upsilon(1S))-M(\eta_b)$: 20-100 MeV/c^2
- Width: 4-20 MeV

Search Strategy

General Strategy: inclusive search

o Decay modes of η_b not known or predicted

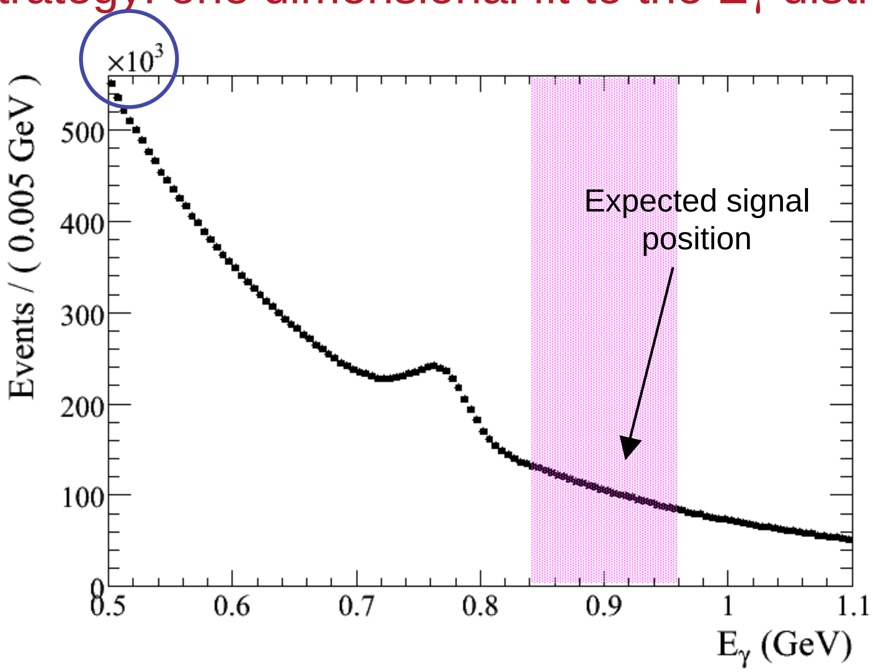
o Search for the radiative transition $\Upsilon(3S)\to\gamma\eta_b$, with $e^+e^-\to\Upsilon(3S)$

o Monochromatic photon in Eγ spectrum: $M(\eta_b)$=9.4 GeV $\to$ Eγ = 911 MeV

$$E_\gamma = \frac{s - m^2}{2\sqrt{s}}$$

$\to$ look for a bump near 900 MeV in inclusive photon energy spectrum

Analysis strategy: one dimensional fit to the Eγ distribution



Huge background

Blind analysis

Signal Selection

Selection criteria aimed at reducing background while retaining high efficiency in signal

Optimization using: $S/\sqrt{B}$

o S: Signal yield from Monte Carlo (MC)

o B: Background from Data: no reliable event generator

$\rightarrow$ use 1/10th of full Data statistics (not used in final results): $\approx 10\times10^6$ of $\Upsilon(3S)$!

Hadronic selection:

o η_b expected to decay mainly via two gluons: high track multiplicity

o sphericity cut to remove QED background

Candidate photon:

o isolated from charged tracks

o shape compatible with electromagnetic shower

o photon detected in calorimeter barrel

o veto against photons from π^0

o use of angle between photon and rest of the event

Total efficiencies:

ε(signal)=37%

ε(bkgd)=6%

Background to the Eγ spectrum

1- Non-peaking (continuous):

- $q\bar{q}$(uds)
- Υ(3S) generic decays

All contributions fitted to a single component:

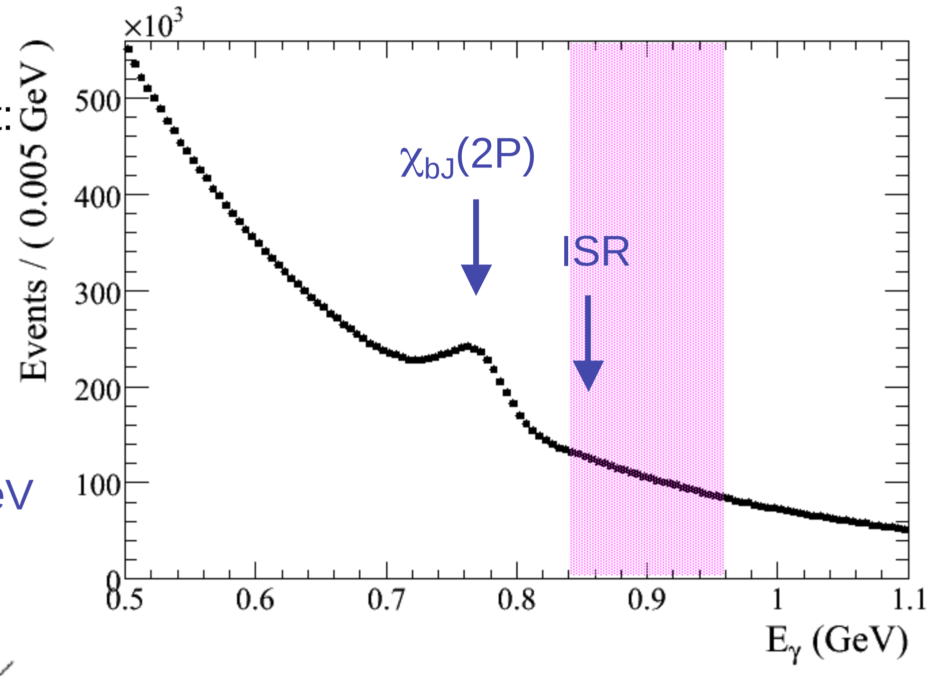
$$A\left(C + e^{-\alpha E_\gamma - \beta E_\gamma^2}\right)$$

2- Peaking, next to signal

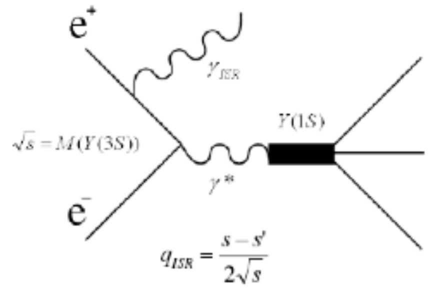
(expected around 900 MeV):

- $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(1S)$: 760 MeV
- $e^+e^- \to \gamma_{ISR}\ \Upsilon(1S)$: 856 MeV ("ISR")

Full data set distribution



Initial State Radiation:



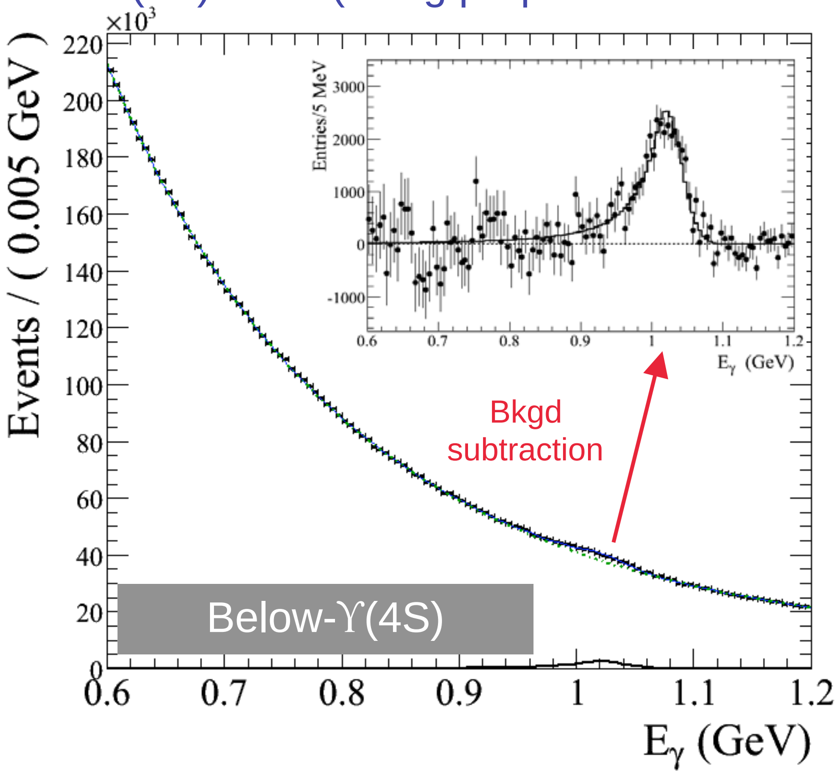
Extremely important to understand (yield and line-shape)

Background to the Eγ spectrum: Peaking $\gamma_{ISR}\Upsilon(1S)$

Photon energy for γ_{ISR} $\Upsilon(1S)$ production at $\Upsilon(3S)$: 856 MeV

⇒ both line-shape and yield are very important to determine: depending on η_b mass, both peaks are going to overlap.

- line-shape estimated from signal MC
- yield estimated using $\Upsilon(4S)$ Off-Peak data (40 MeV below resonance, 40fb^{-1}): extrapolate to $\Upsilon(3S)$ data (using proper cross-sections, efficiencies and integrated luminosities)



Fitted yield: 35800±1600

Extrapolated yield to $\Upsilon(3S)$: 25200±1700

Extrapolated yiled from $\Upsilon(3S)$ Off-Peak data: 29400±5000 : good agreement

At $\Upsilon(4S)$ Off-Peak, Eγ=1.03 GeV

Background to the Eγ spectrum: Peaking χ_b

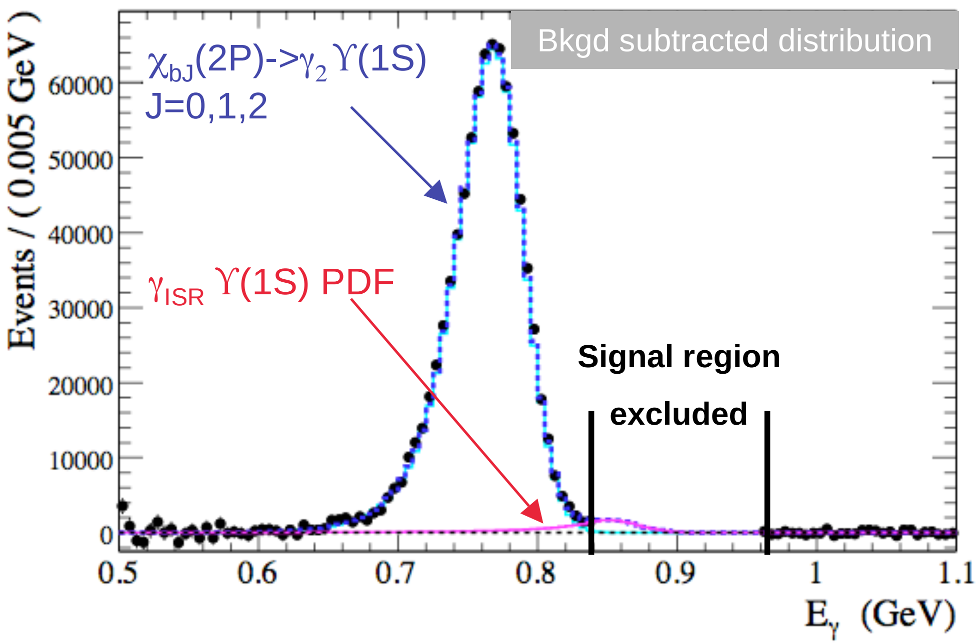
Second transition in Υ(3S)->$\gamma_1\chi_{bJ}$(2P), χ_{bJ}(2P)->$\gamma_2\,\Upsilon$(1S) : J=0,1,2: three radiative transitions

Model each as a Gaussian+power-law tail (Crystal Ball function)

- o Transition point and power law tail parameter fixed to same value for each peak
- o Peak positions fixed to PDG values minus a common offset
- o Ratio of yields taken from PDG (χ_{b0} highly suppressed)

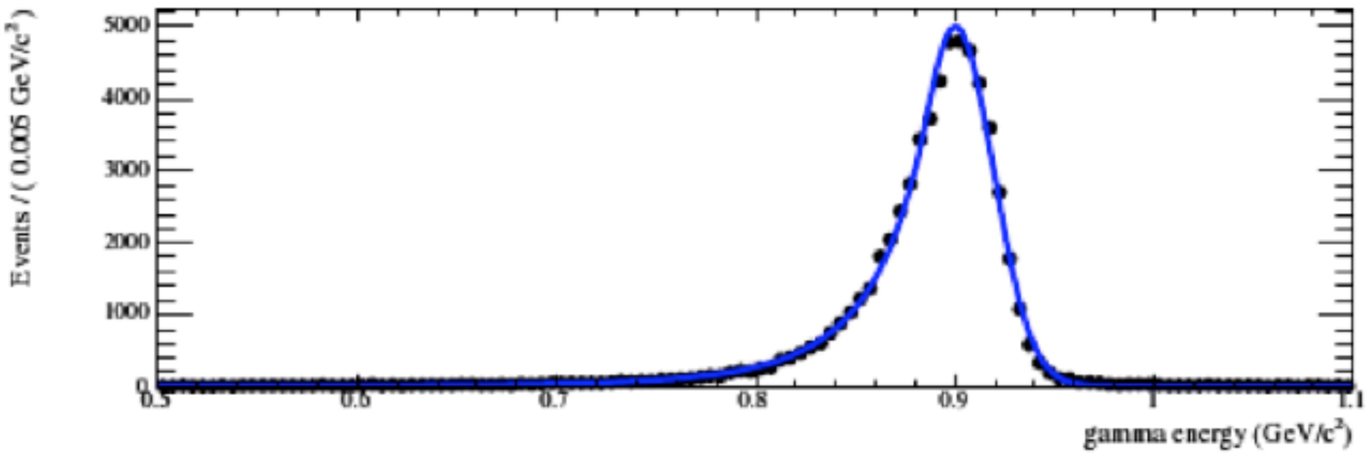
Detector resolution and Doppler broadening: three peaks overlap: <Eγ>≈760 MeV

PDF parameters obtained from a fit to the full data, with the ISR Y(1S) and signal regions excluded



Offset of 3.8 MeV observed: used to correct all other peaks

The η_b signal model



Signal model determined from MC simulation

Functional form: $P(E\gamma) = CB(E\gamma) \otimes BW(E\gamma, \Gamma\eta_b)$

- CB: Crystal Ball function (Gaussian + power-law low side)

  Models the detector energy resolution

  CB shape, determined with signal MC generated with Γ=0.0 MeV

- BW: Breit-Wigner function, the natural shape of the η_b

  width set to 10 MeV, and varied as a systematic

Fit Strategy

Developed using a large number of MC experiments: no bias in fitting method

Signal extraction: binned maximum likelihood fit to the $E\gamma$ distribution

- Non-peaking background:

→ float all parameters

- χ_b peak:

→ line-shape parameters determined from the signal-region blinded fit and fixed in the final lfit, but float yield

- $\gamma_{ISR}\Upsilon(1S)$ peak:

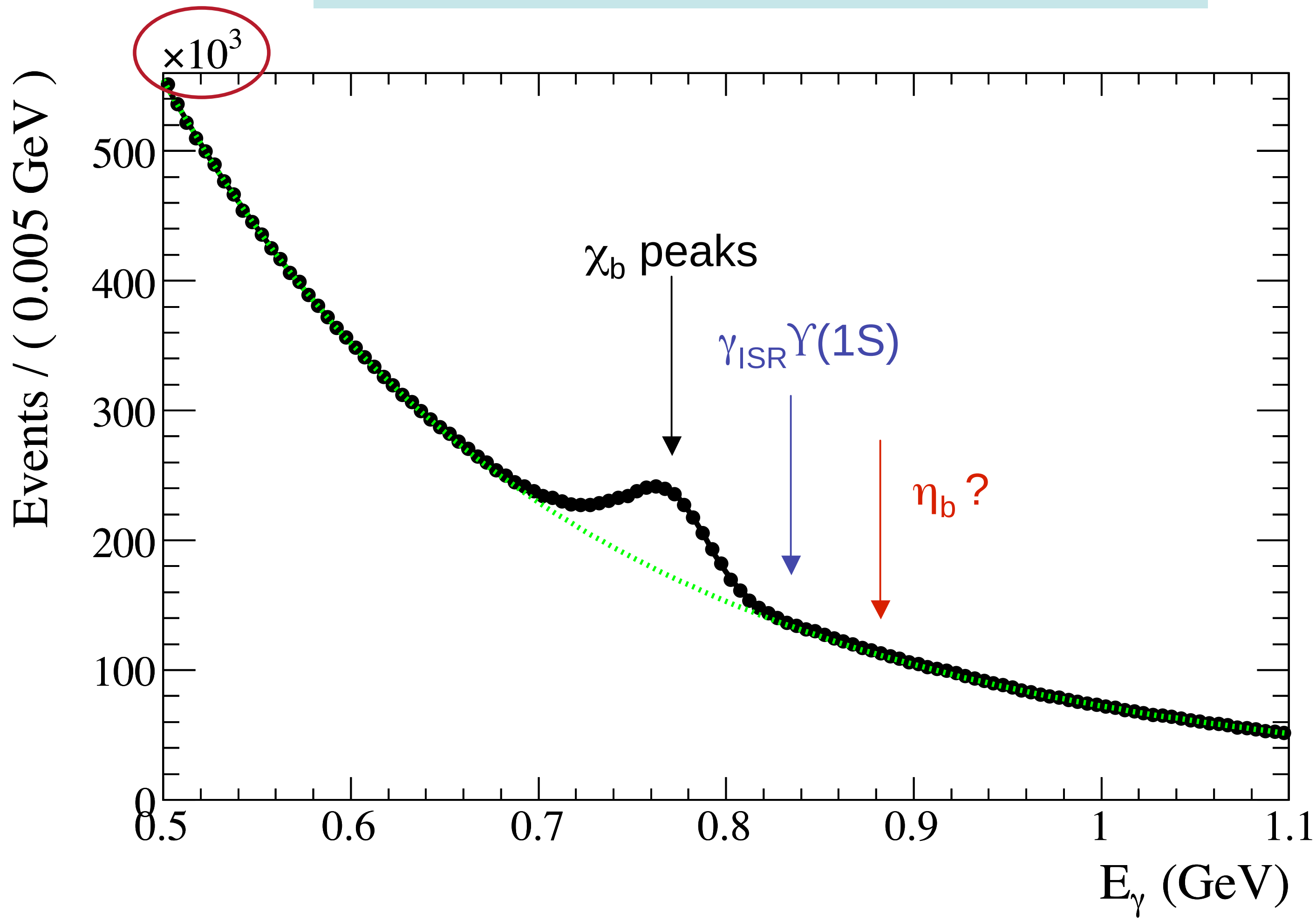
→ fix line-shape from MC, and yield from $\Upsilon(4S)$ Off-Peak data

- Signal:

→ line-shape fixed from MC, only yield and mean floated (width set to 10 MeV)

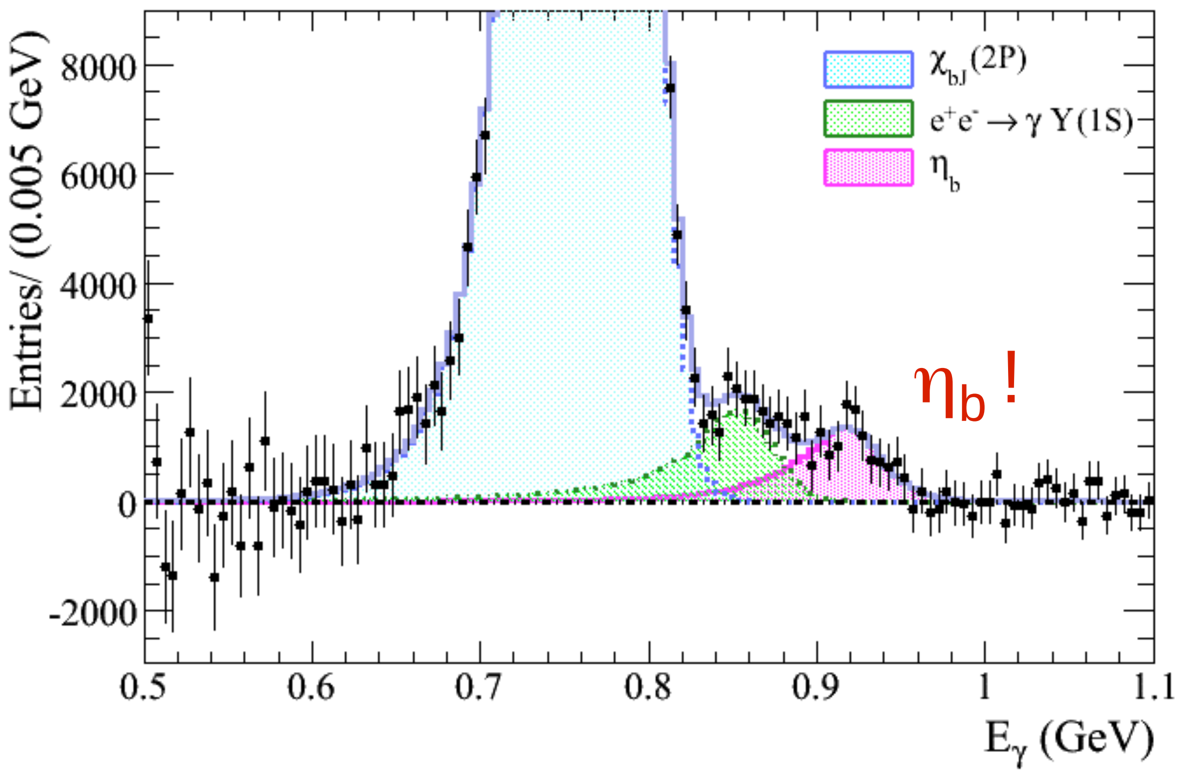
Fit to the Eγ spectrum

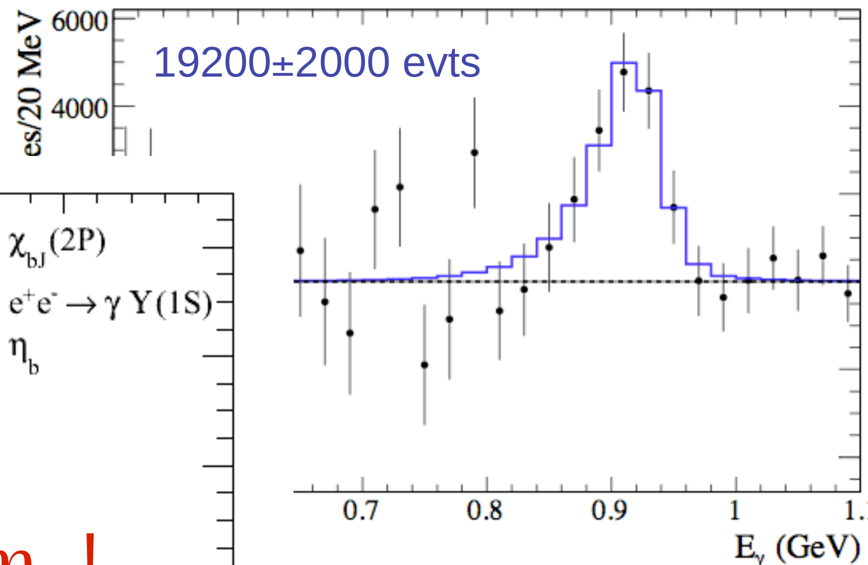
Fit to the full dataset: 109 x 10^6 $\Upsilon(3S)$



Observation of the η_b

Non-peaking background subtracted data





η_b signal observed with a statistical significance of 10 σ

Peak position: $921.2^{+2.1}_{-2.8}$ (stat only) MeV

Systematic uncertainties

Signal yield:

o vary ISR yield by $\pm 1\sigma$ (stat + syst)

o vary all PDF parameters by $\pm 1\sigma$

o fits with BW width set to 5,15 and 20 MeV

Largest systematic error: 10%

$\rightarrow$ total error: 11%

Mass: main error from uncertainty in $\chi_b(2P)$ peak: 2.0 MeV

Branching fraction:

o efficiency: data/MC comparison on $\chi_b(2P)$: 12.6%

o PDG branching fractions: 18%

$\rightarrow$ total error: 25%

Study of significance: varied all systematic parameters (including BW width) in the worst direction in terms of significance: no significant change of significance!

Observation of the η_b :Summary of Results

PRL 101, 071801 (2008)

Is this indeed the η_b ? this state is below the Υ(1S): the only candidate is the η_b , but other interpretations, such as a low-mass Higgs are not excluded (and would make us happy!)…

Applying the bottomonium hypothesis:

η_b mass:

$$9388.9^{+3.1}_{-2.3}(\mathrm{stat}) \pm 2.7(\mathrm{syst})\ \mathrm{MeV}/c^2$$

Υ(1S) - η_b hyperfine splitting:

$$71.4^{+2.3}_{-3.1}(\mathrm{stat}) \pm 2.7(\mathrm{syst})\ \mathrm{MeV}/\mathrm{c}^2$$

Υ(3S) $\rightarrow\gamma\eta_b$ branching fraction:

$$[4.8 \pm 0.5(\mathrm{stat}) \pm 1.2(\mathrm{syst})] \times 10^{-4}$$

Wide range of LQCD: results agrees with some…

Splitting larger than most predictions from Potential models

- Introduction to Quarkonium Physics
- The B-Factory at SLAC
- Charmonium and Exotics
- Bottomonium: Observation of the η_b

Conclusion

Conclusions

Many new charmonium-like states observed at the B-Factories…

Z(4430)+

X(3940)

Y(4008)

Y(4660)

Z_1+

Y(4325)

X(4160)

X(3872)

Z_2+

Z(3930)

Y(3940)

Y(4260)

Few are understood, most of them are likely exotic states…

More statistics needed.

Observation of the bottomonium ground state

More bottomonium results to come !

Backup slides

PEP-II Performance

The machine has been performing much better than original design

Parameter	Unit	Design	Best
$I(e^+)$	mA	2140	3213
$I(e^-)$	mA	750	2069
N bunches		1658	1722
β_Y^*	mm	15-20	10
Bunch length	mm	12	11
Peak Lumi	$x10^{33}$	3	12
$\int L$ /day	pb^{-1}	130	911

- ✓ best shift: 339 pb^{-1}
- ✓ best day: 911 pb^{-1}
- ✓ best week: 5.4 fb^{-1}
- ✓ best month: 19.7 fb^{-1}
- ✓ Peak L: $12.1\times10^{33}cm^{2}s^{-1}$

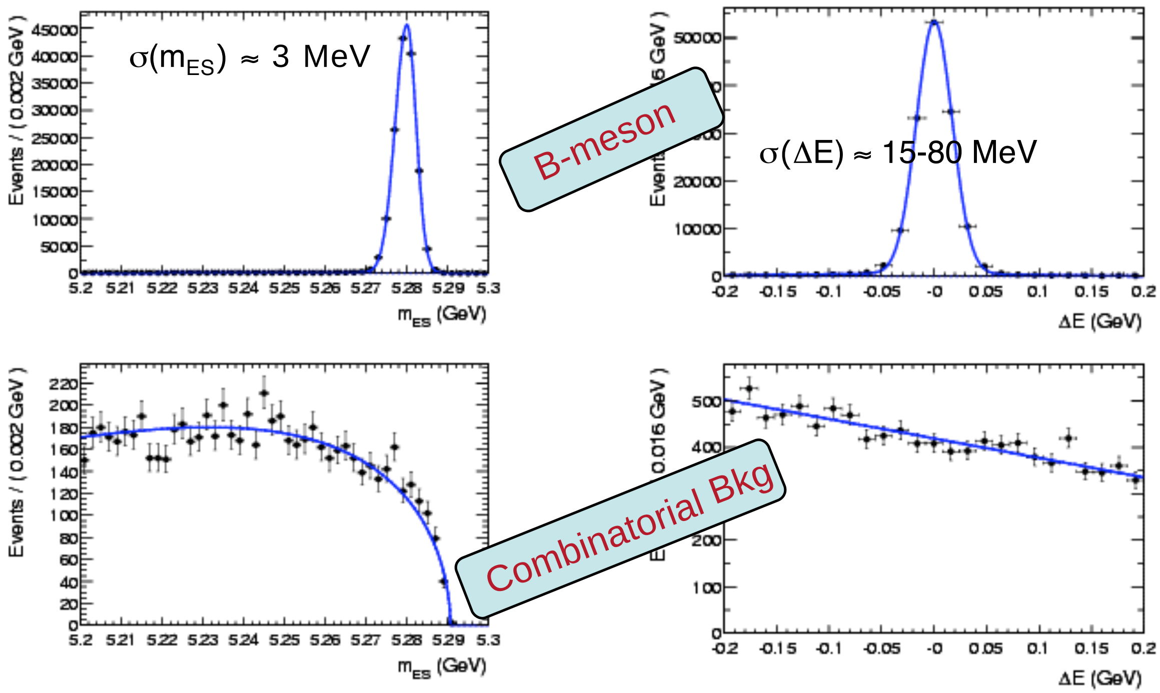
Since 1999, continuous and tremendous effort to upgrade the B-factory, on the accelerator side (many beam elements replaced RF cavities added, etc…) and on the detector side (electronics to cope with higher rates, occupancies and background, Trigger).

Selecting B mesons

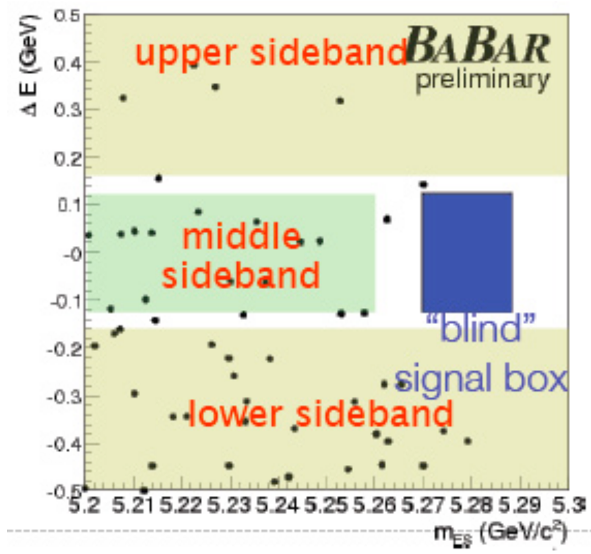
For charmonium studies in B decays, most of the background is from combinatorics: use of two weakly correlated variables that reflects energy and momentum conservation.

$$m_{ES} = \sqrt{E^{*2}_{beam} - p^{*2}_{B}}$$

$$\Delta E = E^{*}_{B} - E^{*}_{beam}$$



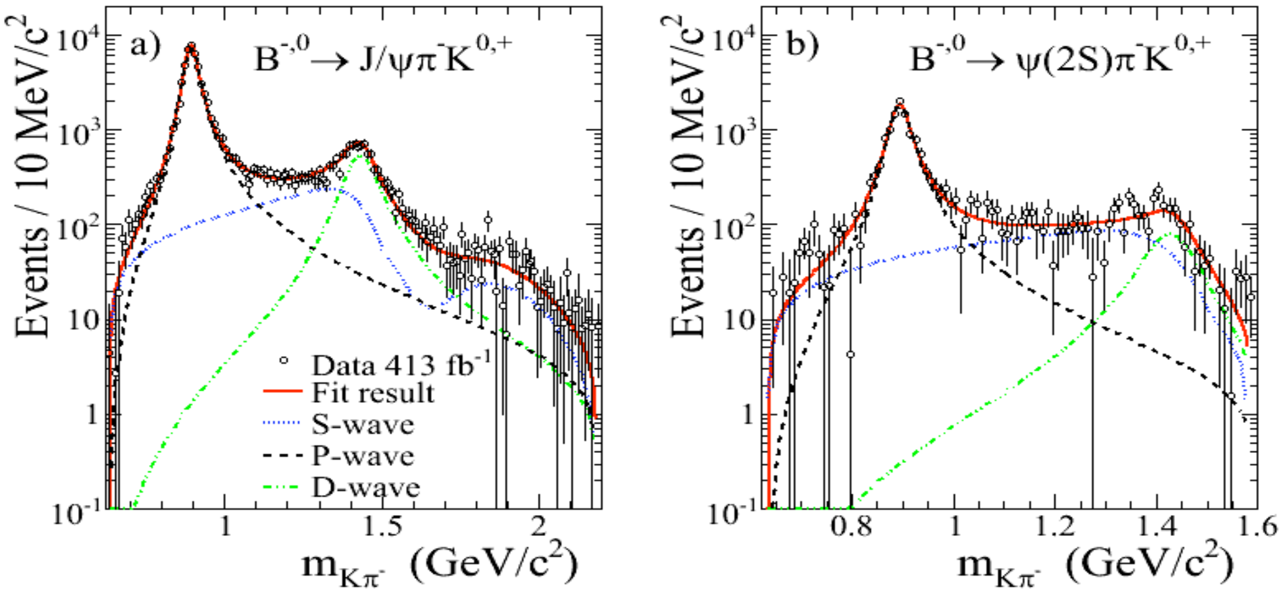
Blind Analysis



- Define signal region and background sidebands
- Signal box blind until analysis strategy determined (cuts, signal extraction, etc…)

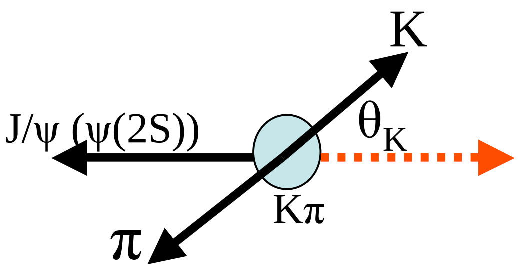
Z(4430) at BaBar: Kπ mass system

Kπ mass distribution fitted with S- (LASS), P-, and D-wave intensity

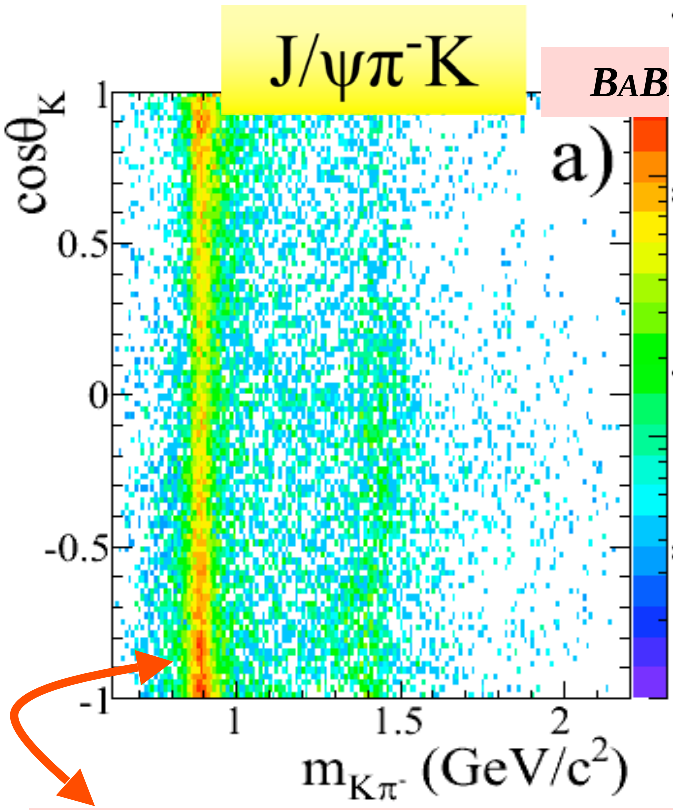


Mode	Events	m(K*(892)) (MeV/c2)	Γ(K*(892)) (MeV)	S-wave (%)	P-wave (%)	D-wave (%)
$B^0 \to J/\psi\pi^- K^+$	57231±561	895.5±0.4	48.9±1.0	15.7±0.8	73.5±0.7	10.8±0.5
$B^- \to J/\psi\pi^- K^0_S$	20985±393	892.9±0.8	49.0±1.9	17.0±1.6	72.5±1.3	10.5±1.0
$B^0 \to \psi(2S)\pi^- K^+$	13237±377	895.8±1.0	43.8±3.0	25.4±2.2	68.2±2.0	6.4±1.2
$B^- \to \psi(2S)\pi^- K^0_S$	5016±292	891.6±2.1	44.8±6.0	23.4±4.5	71.3±4.4	5.3±2.7

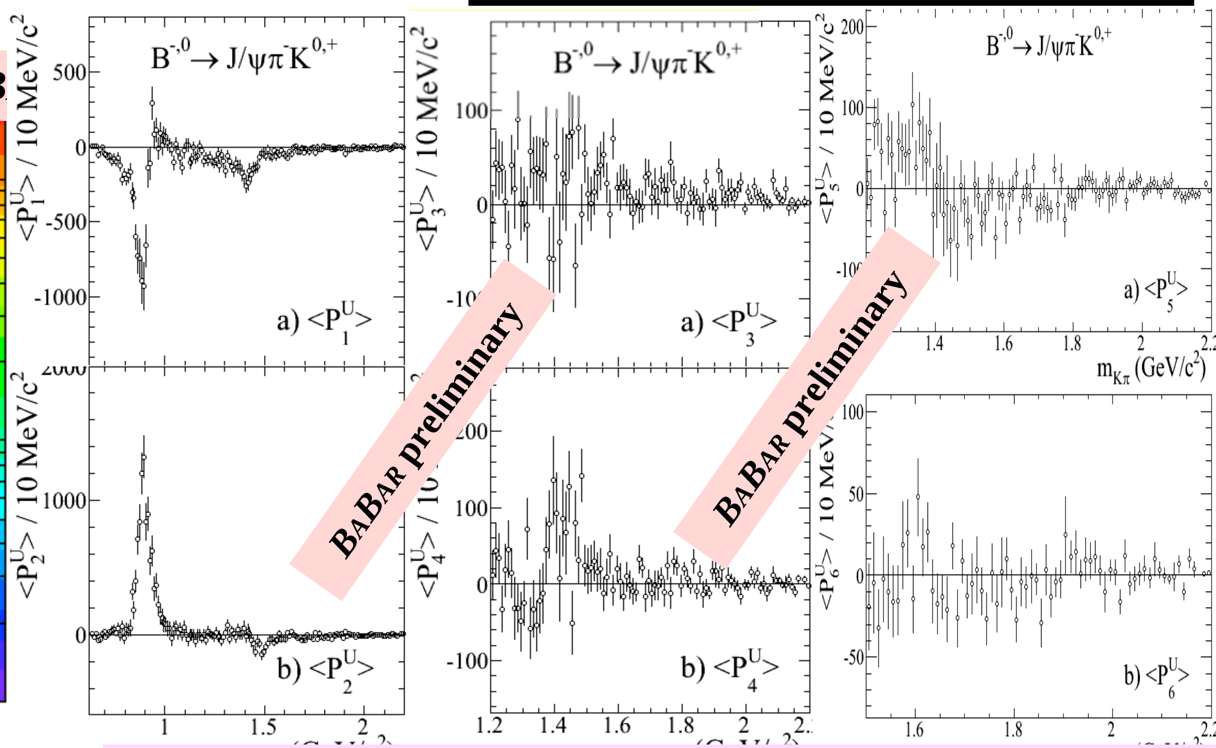
Z(4430) at BaBar: Legendre polynomial Moments



$$\frac{dN}{d\cos\theta_K} = N\sum_{i=0}^{i=L} \langle P_i \rangle P(\cos\theta_K) = \frac{N}{2} + \sum_{i=1}^{i=L} \underbrace{(N \langle P_i \rangle)}_{\text{Un-normalized moment } \langle P_i^U \rangle} P_i(\cos\theta_K)$$

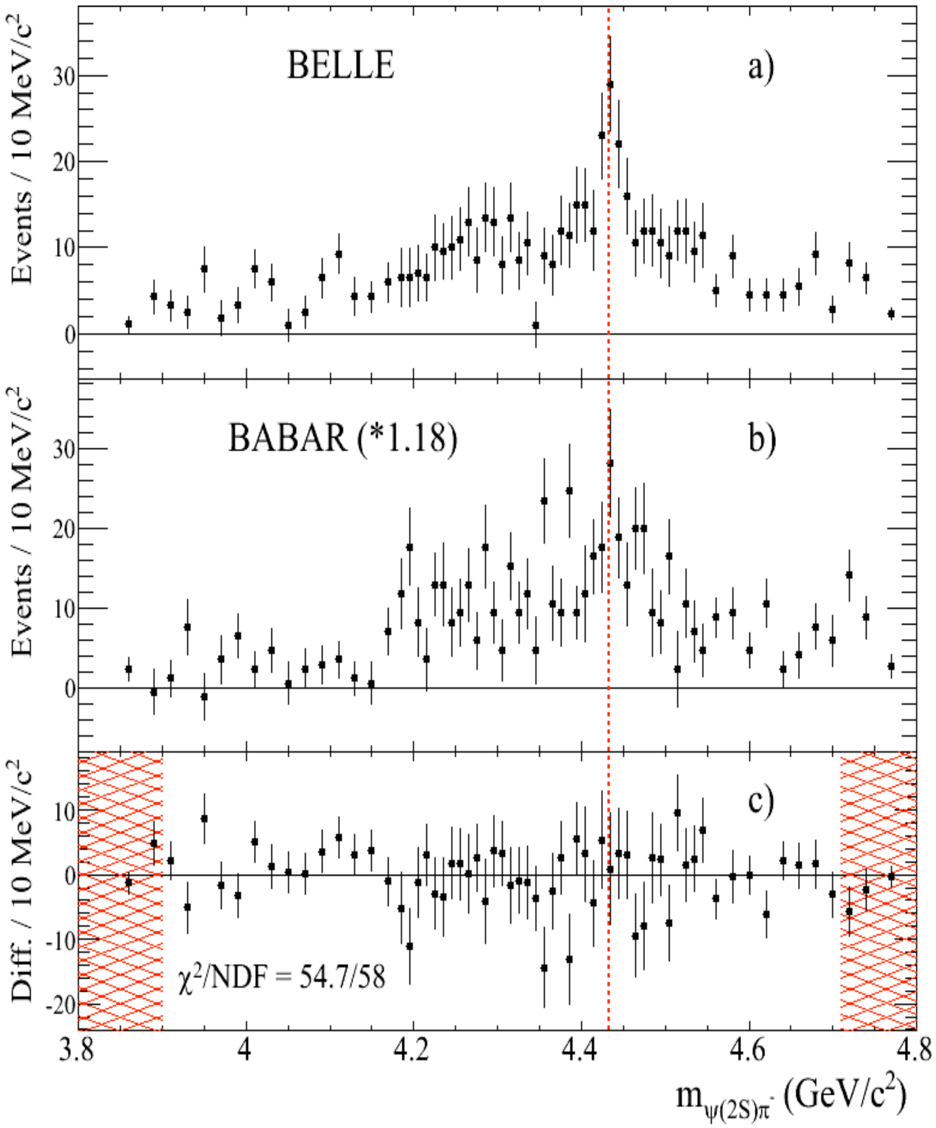


More backward than forward



$m_{K\pi^-}$ (GeV/c²)

Z(4430) at BaBar: direct comparison with Belle



Belle and BaBar data are consistent!

Importance of background modeling

(simple phase space in Belle)