Quarkonium states at *B*-factories

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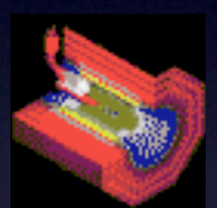
Quarkonium & *B*-factories

The study of quarkonium spectroscopy has been re-vitalized in recent years thanks to a series of new measurements performed by *B*-factories on their large data samples, mainly at $\Upsilon(4S)$ peak:



CLEO III (1989 - 2001): $\mathcal{L} \approx 9\ \mathrm{fb}^{-1}$

BABAR (1999 - 2008): $\mathcal{L} \approx 430\ \mathrm{fb}^{-1}$

Belle (1999 -): $\mathcal{L} \approx 800\ \mathrm{fb}^{-1}$

New results also from charm factories (BES, CLEO-c), Tevatron (CDF, D0), $p\bar{p}$ formation (E835)

Outline

Charmonium at *B*-factories:

- the first surprise: *X*(3872);
- new resonances at 3940 MeV/c^2;
- vector states: the '*Y*' series;
- and yet more...

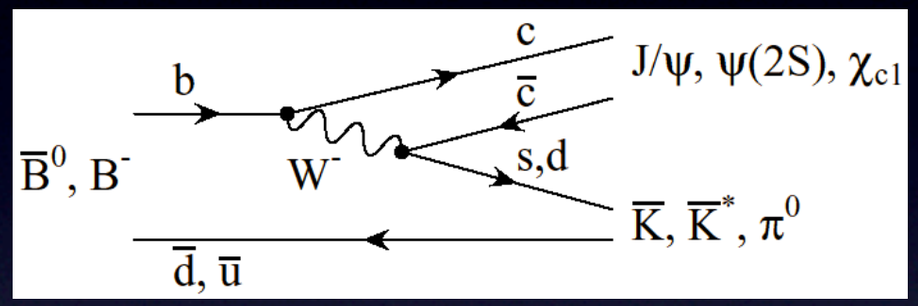
Bottomonium at *B*-factories:

- new decays of the Y(4*S*);
- anonalous decays of the Y(5*S*)

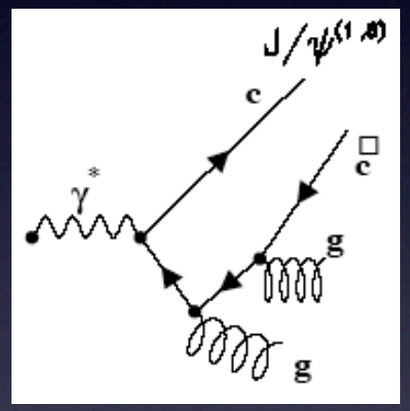
Charmonium production at *B*-factories

At B-factories, charmonium is copiously produced through a variety of processes:

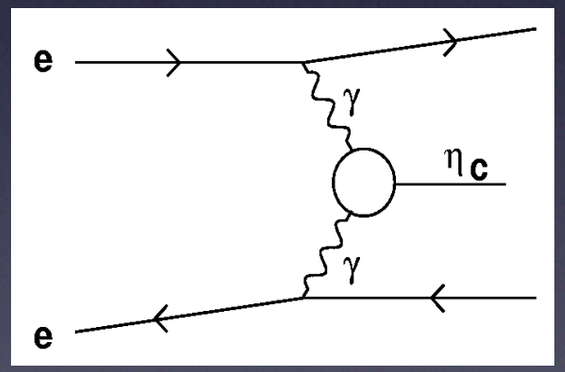
- production in B decays:
  $\mathcal{B}(B \to (c\,\bar{c})\,X) \sim 3\%$
  $\Rightarrow$ ~3M decays in 100 fb^{-1};



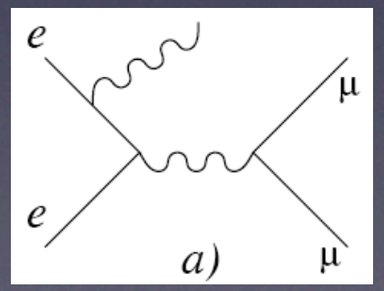
- production in continuum $e^+ e^-$ annihilation:
  $\sigma(e^+ e^- \to J/\psi\, X) \sim 2.5$ pb $\Rightarrow$ ~250k J/ψ in 100 fb^{-1};



- two-photon fusion
  $(e^+e^- \to e^+e^-\,\gamma\,\gamma \to e^+e^-\,(c\,\bar{c}))$:
  ~1M η_c in 100 fb^{-1};

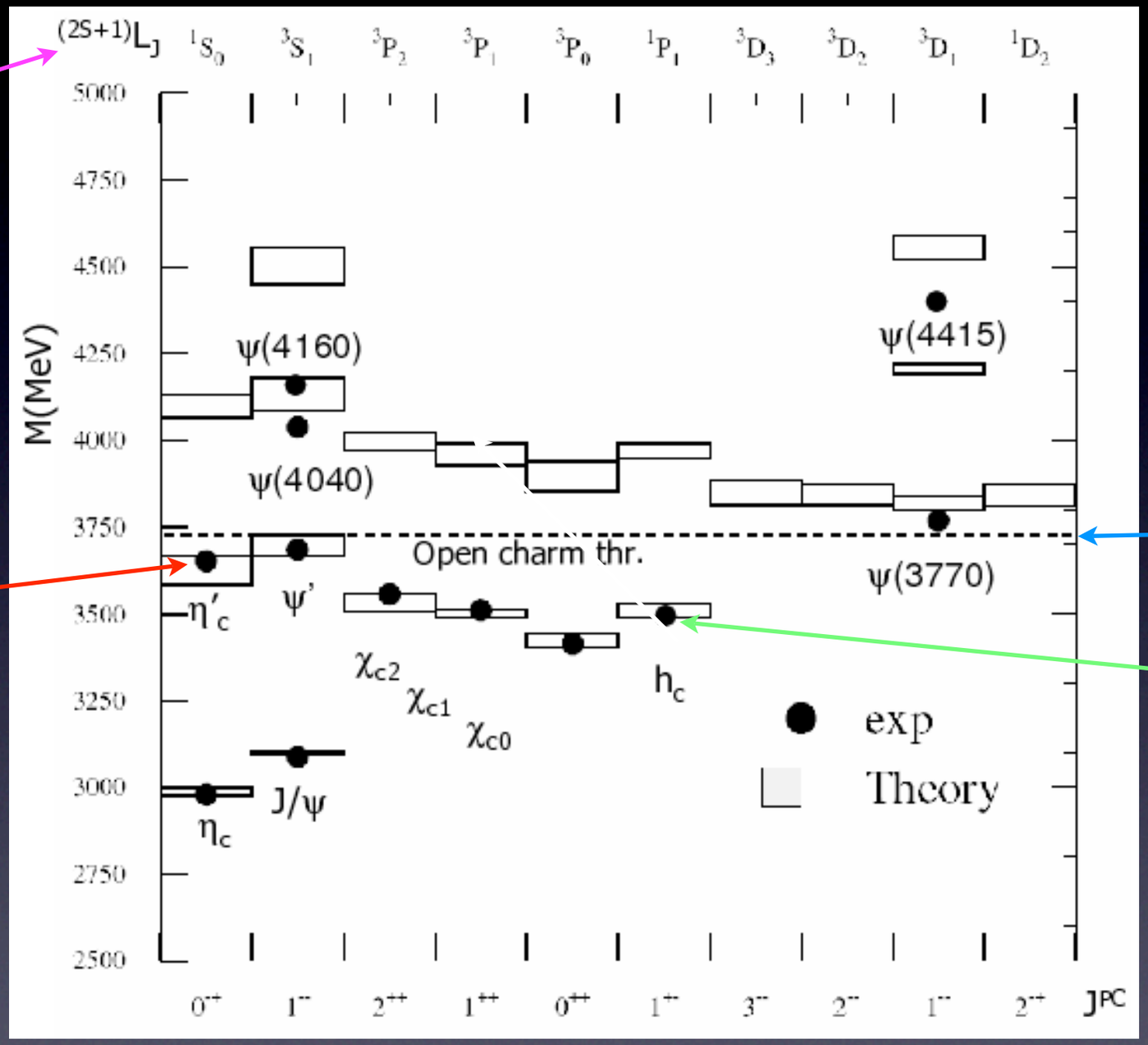


- production via initial state radiation:
  $\sigma(e^+ e^- \to J/\psi\,\gamma) \sim 2$ pb $\Rightarrow$ ~350k J/ψ in 100 fb^{-1}



The charmonium spectrum

spectroscopic notation



observed by Belle, confirmed by *BABAR* and CLEO in 3 different production channels

$2\ m(D^0)$

recently observed by CLEO-c in $\psi(2S)$ decays

All states below open-charm thresholds have been observed

The $X(3872)$ state

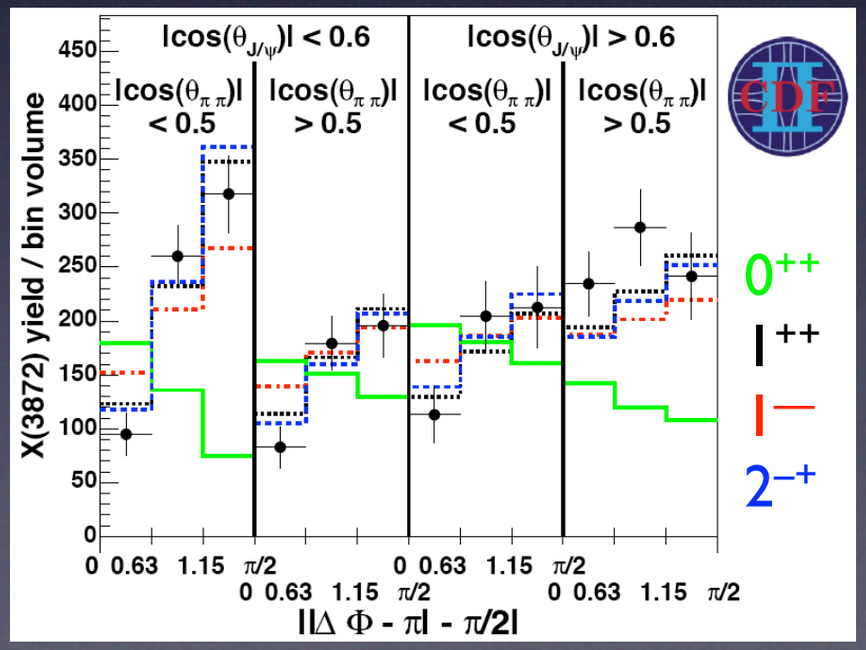
Discovered by Belle (2003) in $B^{\pm} \to X(3872)\, K^{\pm}, X \to J/\psi\, \pi^+ \pi^-$
Confirmed by CDF, D0, CLEO, *BABAR*

Production modes:

- B decays: $B \to X(3872)\, K$;
- prompt $p\bar{p}$;
- not seen in prompt e^+e^-, $\gamma\,\gamma$

Decay modes:

- $X \to J/\psi\, \pi^+ \pi^-$ (consistent with $X \to J/\psi\, \rho$);
- $X \to J/\psi\, \gamma$;
- $X \to D\, \bar{D}^*$



CDF angular analysis + decay modes
$\Rightarrow J^{PC}(X(3872)) = 1^{++}$ favoured

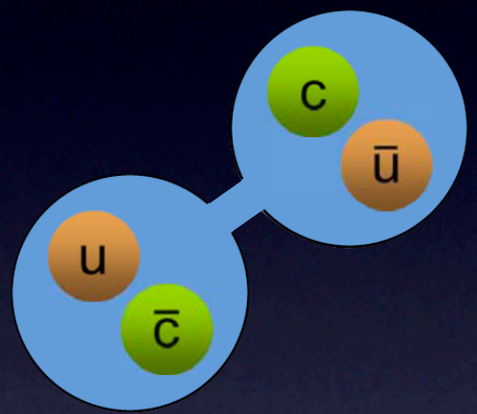
$X(3872)$: theoretical interpretations

Charmonium state:

- disfavoured: mass and BRs disagree with predictions

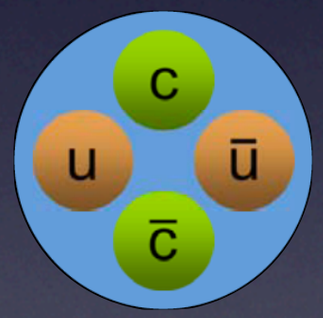
D^0-D^{*0} molecule:

- $J^{PC} = 1^{++}$ favoured, mass consistent with expected;
- accomodates competing decay modes



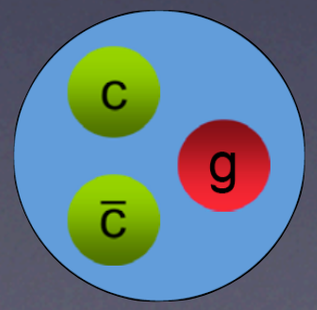
Tetraquark:

- small width expected;
- would imply 2 neutral + 2 charged states

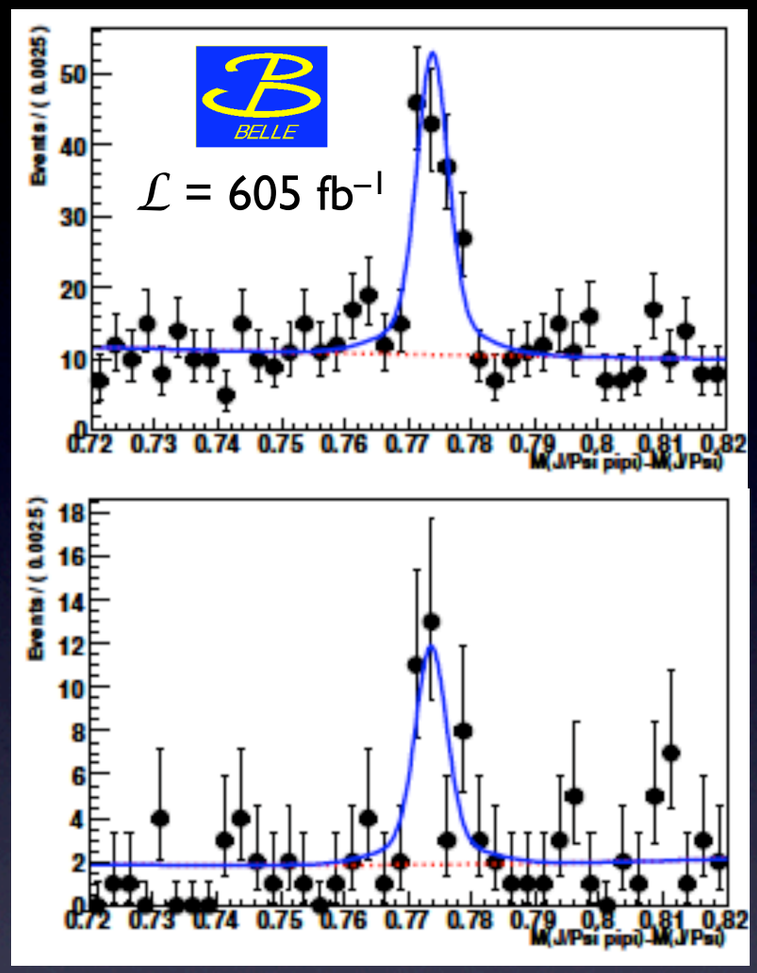


Hybrid:

- predicted mass > 4200 MeV

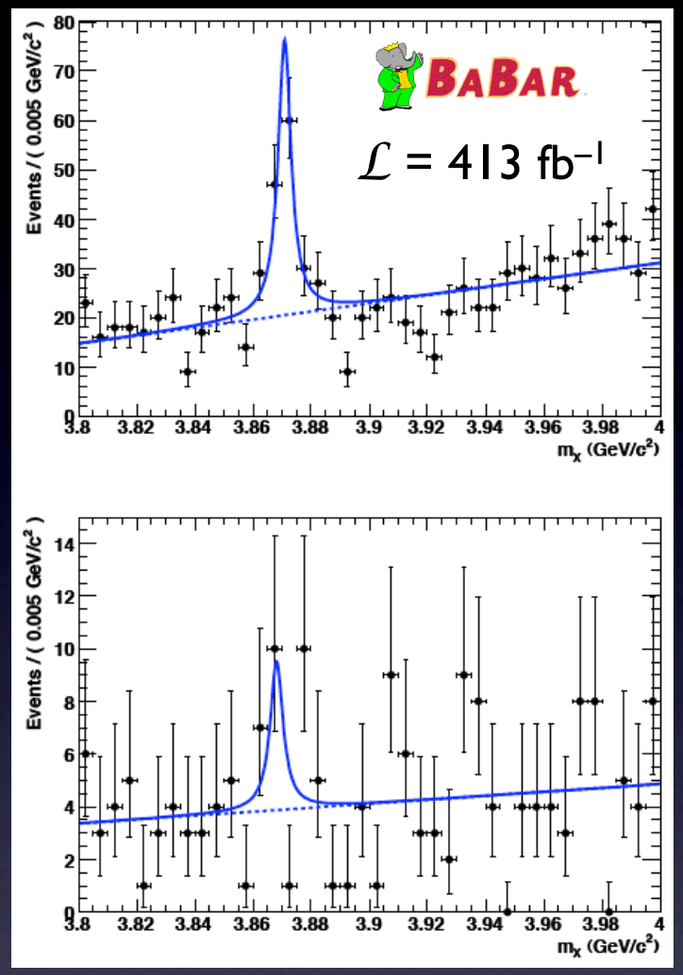


$X(3872) \to J/\psi\, \pi^+ \pi^-$



Belle-CONF-0711

$B^\pm \to (J/\psi\, \pi^+ \pi^-)\, K^\pm$



$B^0 \to (J/\psi\, \pi^+ \pi^-)\, K_S$

arXiv:0803.2838

M = (3872.0 ± 0.6 ± 0.5) MeV/c^2

ΔM = (0.22 ± 0.90 ± 0.27) MeV/c^2

$R(B^0/B^+)$ = 0.94 ± 0.24 ± 0.10

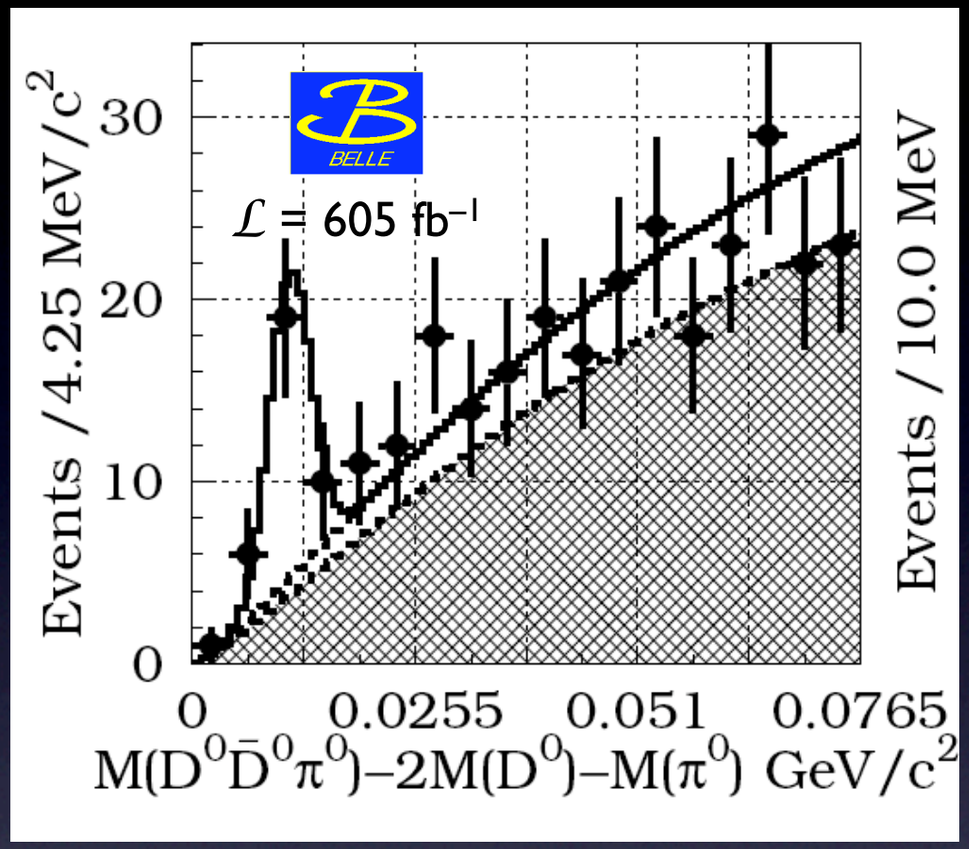
M = (3871.3 ± 0.6 ± 0.1) MeV/c^2

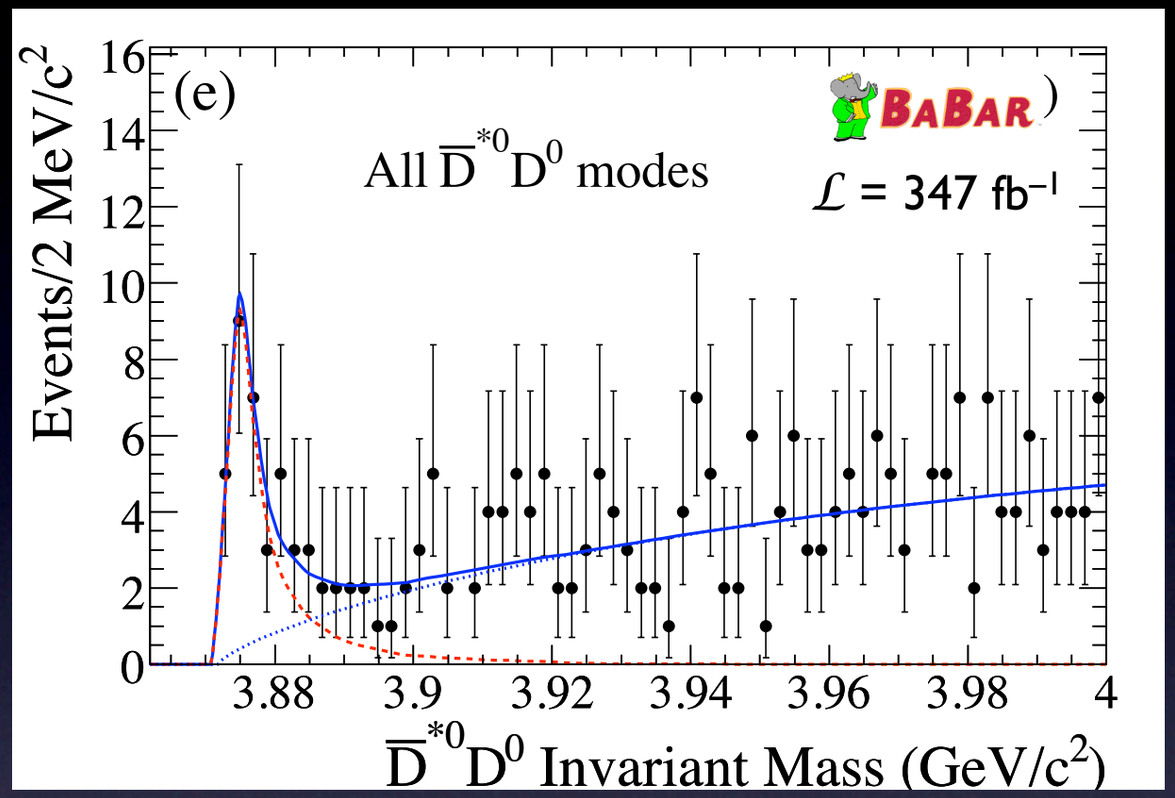
ΔM = (2.7 ± 1.6 ± 0.4) MeV/c^2

$R(B^0/B^+)$ = 0.41 ± 0.25 ± 0.05

No significant evidence of mass splitting expected in the tetraquark model

$X(3872) \to D\,\bar{D}^*$





Phys. Rev. Lett. 97, 162002

Phys. Rev. D 77, 011102

$M = (3875.4 \pm 0.7\ ^{+0.7}_{-1.7} \pm 0.8)$ MeV/c^2

$\mathcal{B} = (1.27 \pm 0.31\ ^{+0.22}_{-0.39}) \times 10^{-4}$

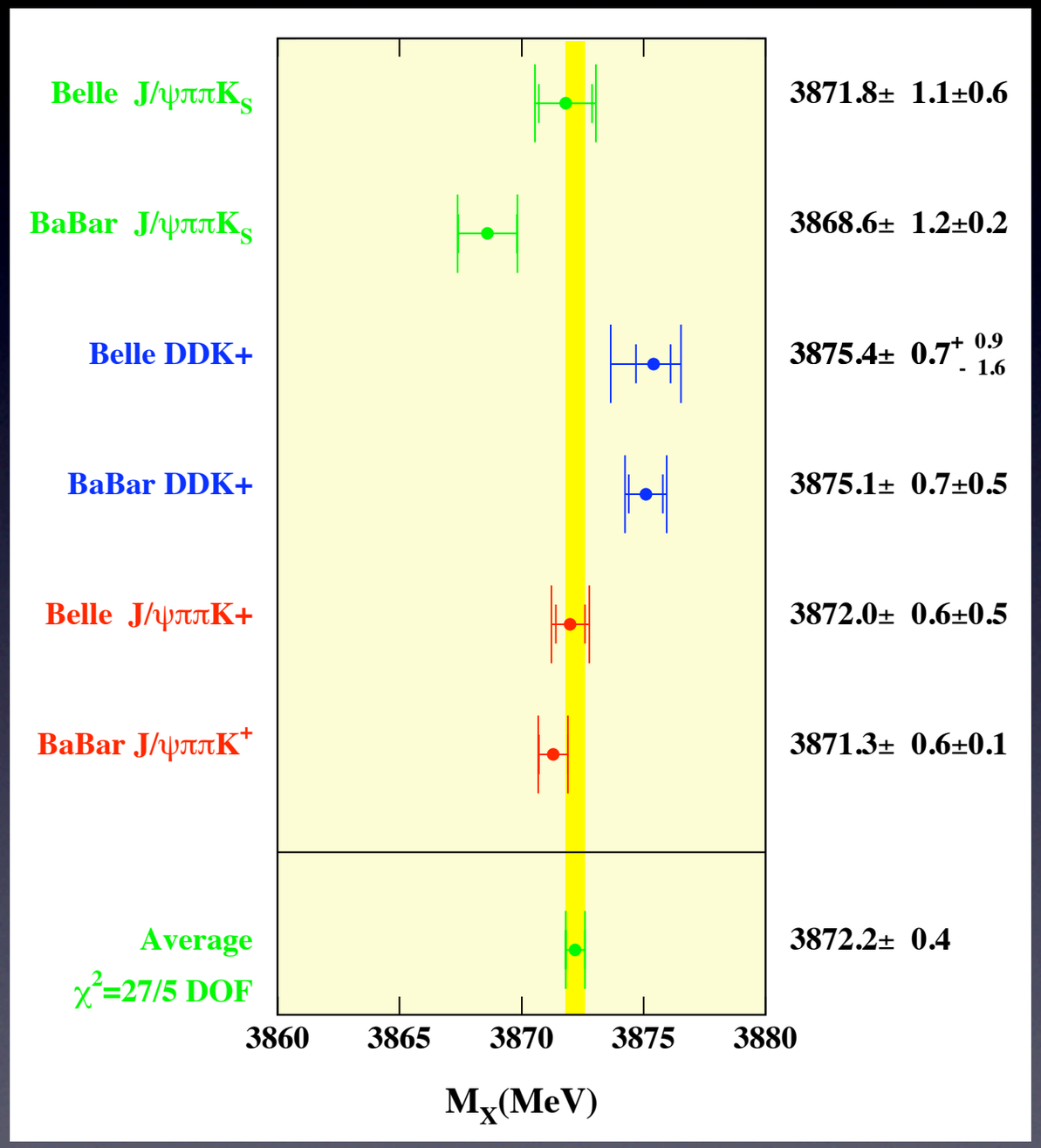
$M = (3875.1\ ^{+0.7}_{-0.5} \pm 0.5)$ MeV/c^2

$\mathcal{B} = (1.7 \pm 0.4 \pm 0.6) \times 10^{-4}$

Cmp. $\mathcal{B}(B^+ \to X\,K^+, J/\psi\,\pi^+\,\pi^-) = (1.14 \pm 0.20) \times 10^{-5}$ (PDG '06)

Significant mass difference with what measured in $X \to J/\psi\,\pi^+\,\pi^-$

Two *X*?



The mass values measured in the two decay modes $X \to J/\psi\, \pi^+ \pi^-, X \to D\, \bar{D}\, \pi$ show a poor consistency

$\Longrightarrow$ two different states?

(as predicted by the tetraquark model)

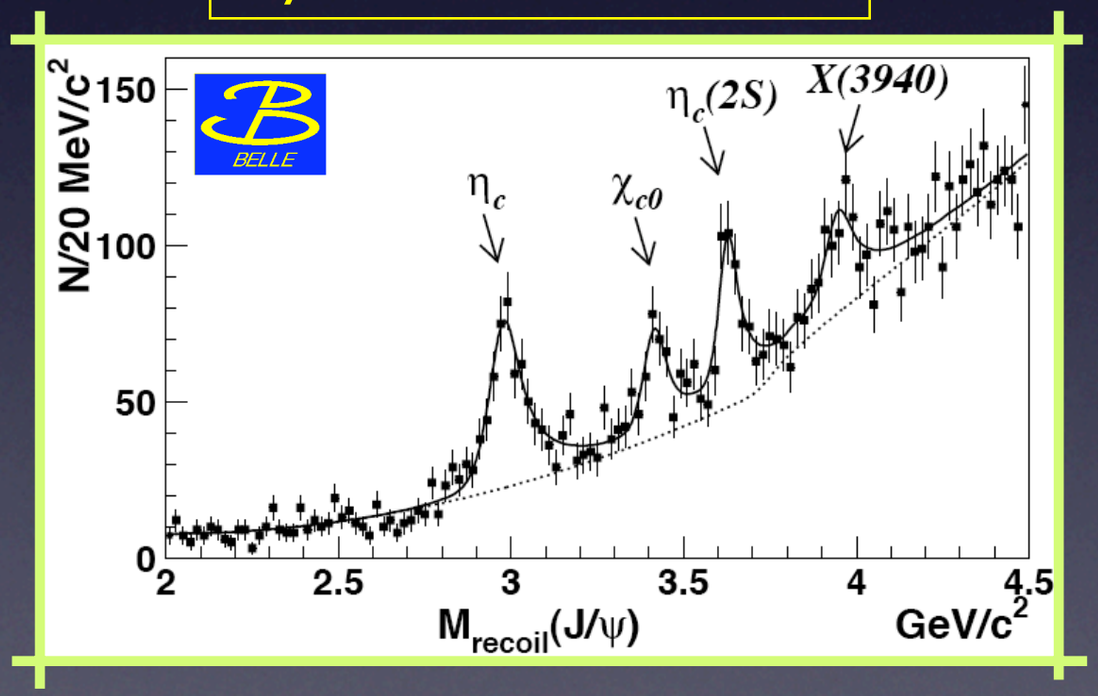
A simple model explains the observed mass shift as a consequence of the proximity of the $D^0 D^{0*}$ threshold

W. Dunwoodie, V. Ziegler, Phys. Rev. Lett. 100, 062006

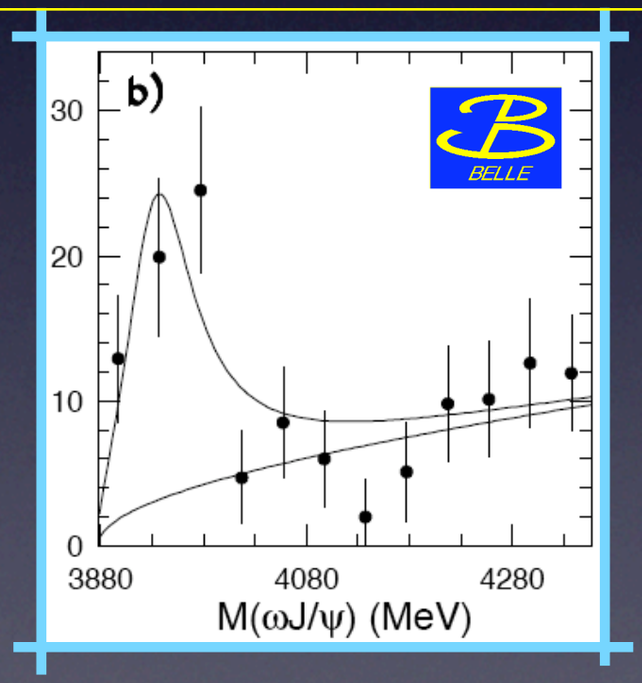
Three states at 3940 MeV/c^2

	Production/decay mode	J^{PC}	Mass (MeV)	Γ (MeV)
X	$e^+e^- \to J/\psi\, X,\ X \to D\bar{D}^*$	$0^{-+}, 1^{++}$	3943 ± 6 ± 6	< 52
Y	$B \to Y\, K,\ Y \to J/\psi\, \omega$	1^{++},...	3943 ± 11 ± 13	87 ± 22 ± 26
Z	$\gamma\gamma \to Z,\ Z \to D\bar{D}$	2^{++}	3929 ± 5 ± 2	29 ± 10 ± 2

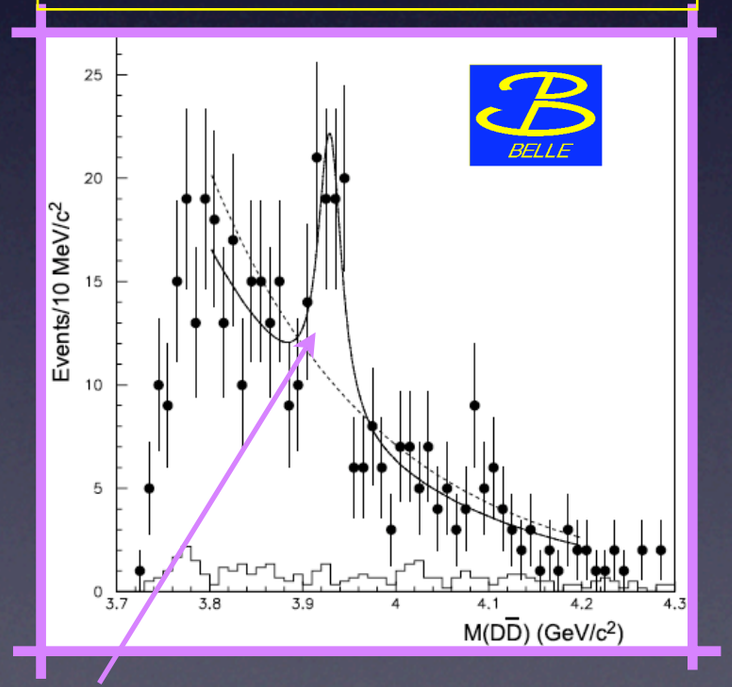
Phys. Rev. Lett. 98, 082001



Phys. Rev. Lett. 94, 182002



Phys. Rev. Lett. 96, 082003



good $\chi_{c2}(2P)$ candidate

$Y(3940) \to J/\psi\ \omega$ at BABAR

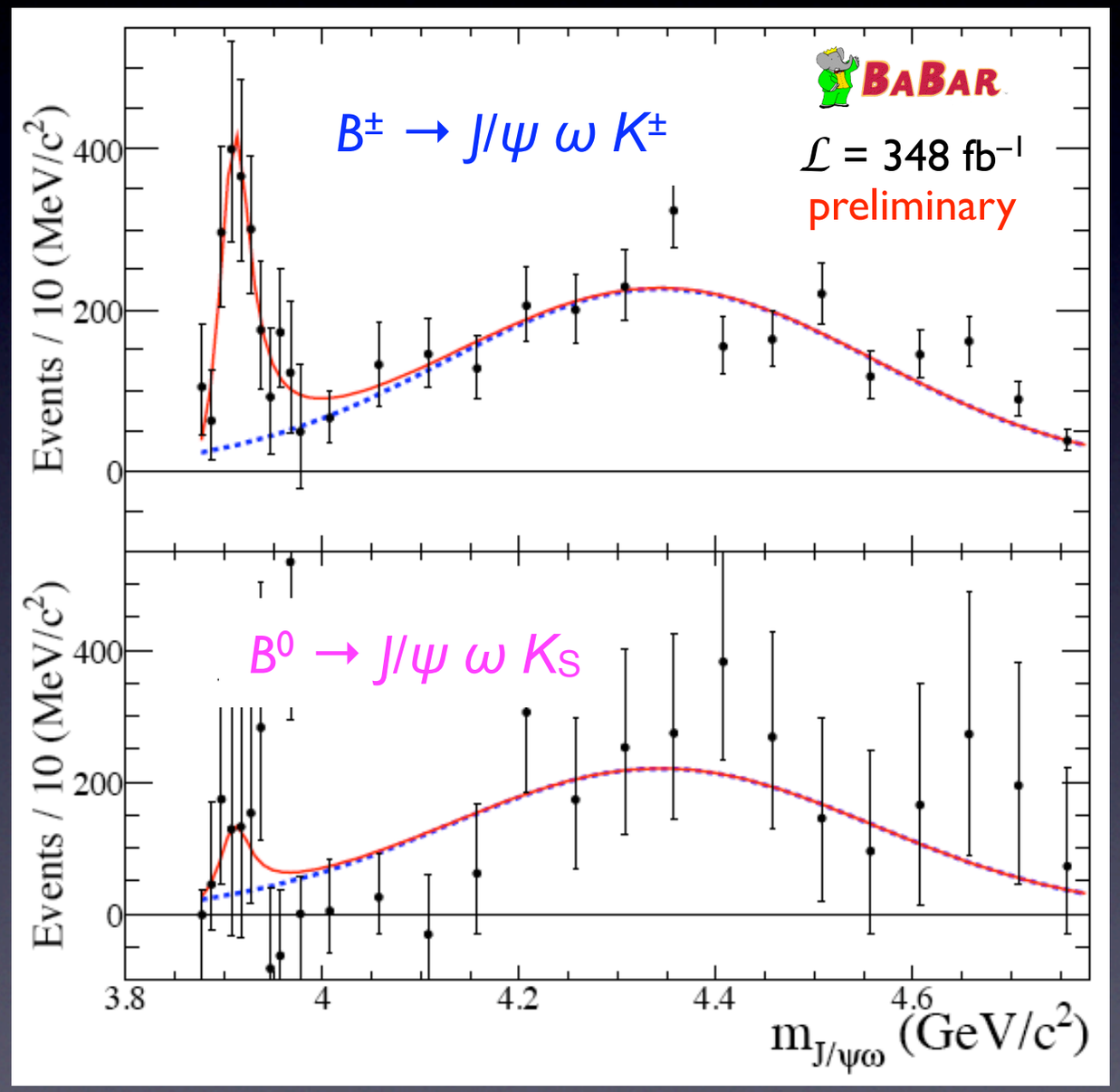
Correlation between B signal (using m_{ES}) and ω signal verified using projections in the angular distributions $\Rightarrow$ close to 100%

Results extracted fitting number of signal events in slices of $m(J/\psi\ \omega)$

$M = (3914.6\ ^{+3.8}_{-3.4} \pm 1.9)\ \mathrm{MeV}/c^2$
$\Gamma = (34\ ^{+12}_{-8} \pm 5)\ \mathrm{MeV}/c^2$

Mass lower, width narrower than Belle
$\Rightarrow$ same state as $X(3940)$?

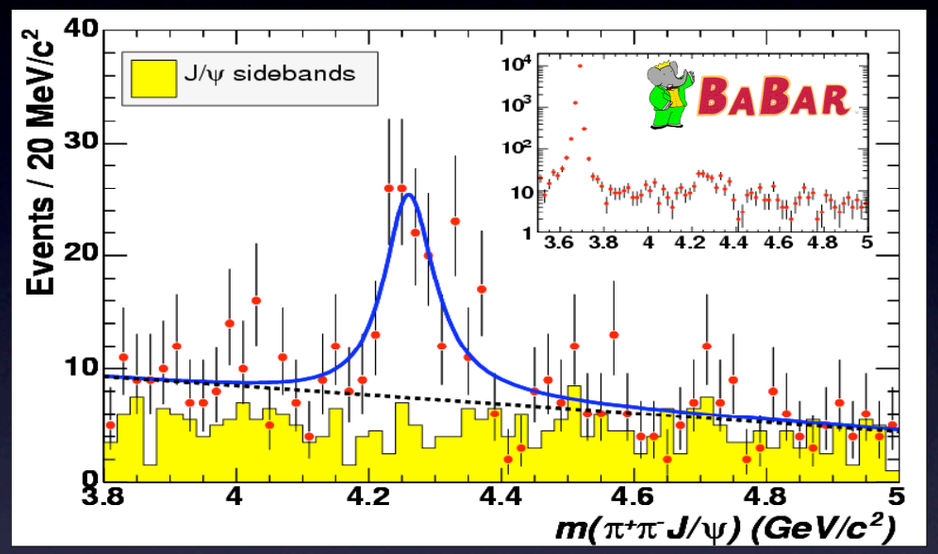
arXiv:0711.2047
sumbm. to PRL



The 'Y' vector states

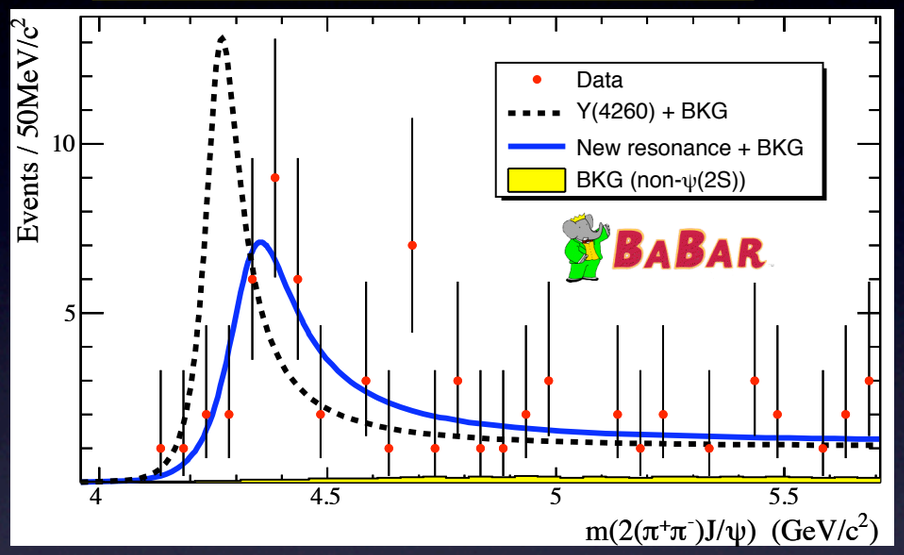
Two $J^{PC} = 1^{--}$ states observed by *BABAR* in ISR production:

Phys. Rev. Lett 95, 142001



$Y(4260) \rightarrow J/\psi\ \pi^+\ \pi^-$

Phys. Rev. Lett. 98, 212001

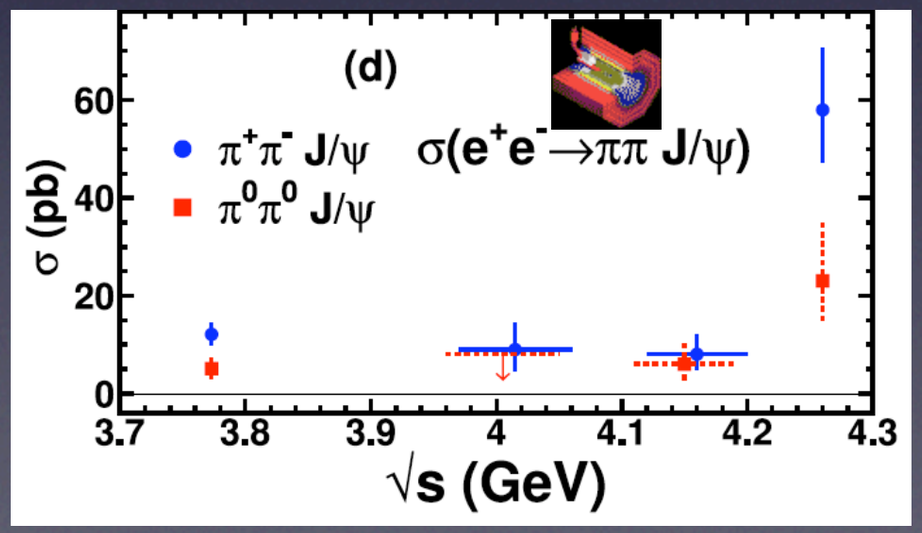


$Y(4350) \rightarrow \psi(2S)\ \pi^+\ \pi^-$

Y(4260) confirmed by CLEO and CLEO-c (also $Y(4260) \rightarrow J/\psi\ \pi^0\ \pi^0$)

Phys. Rev. D 74, 091104

Phys. Rev. Lett. 96, 1620003

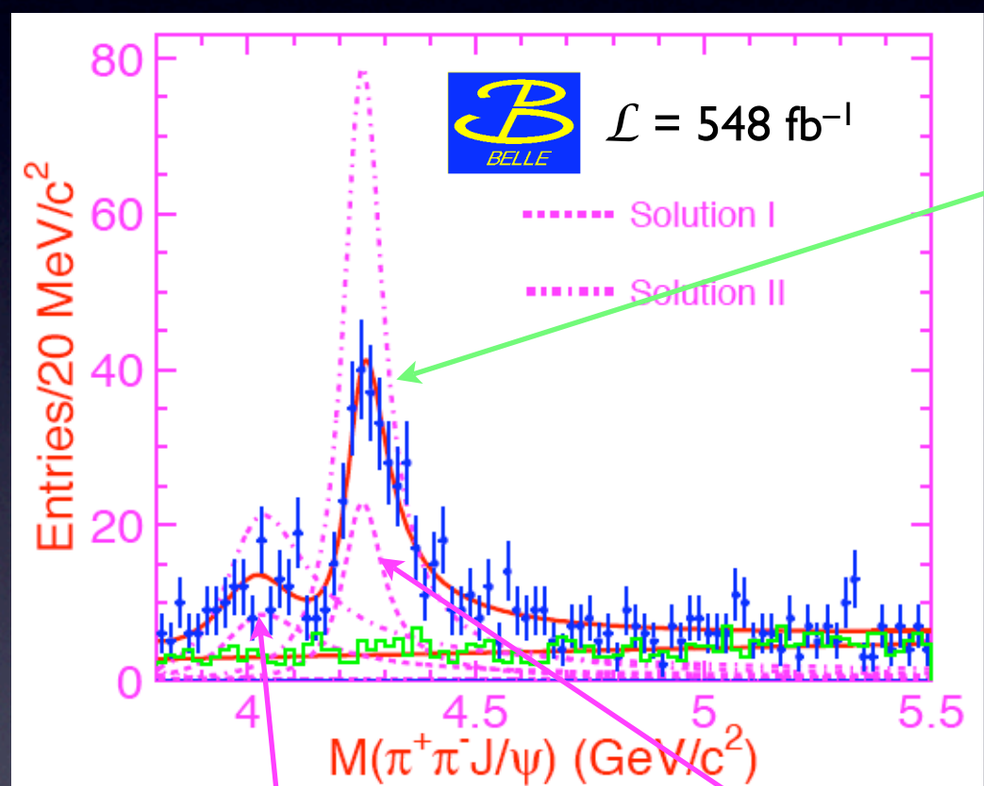


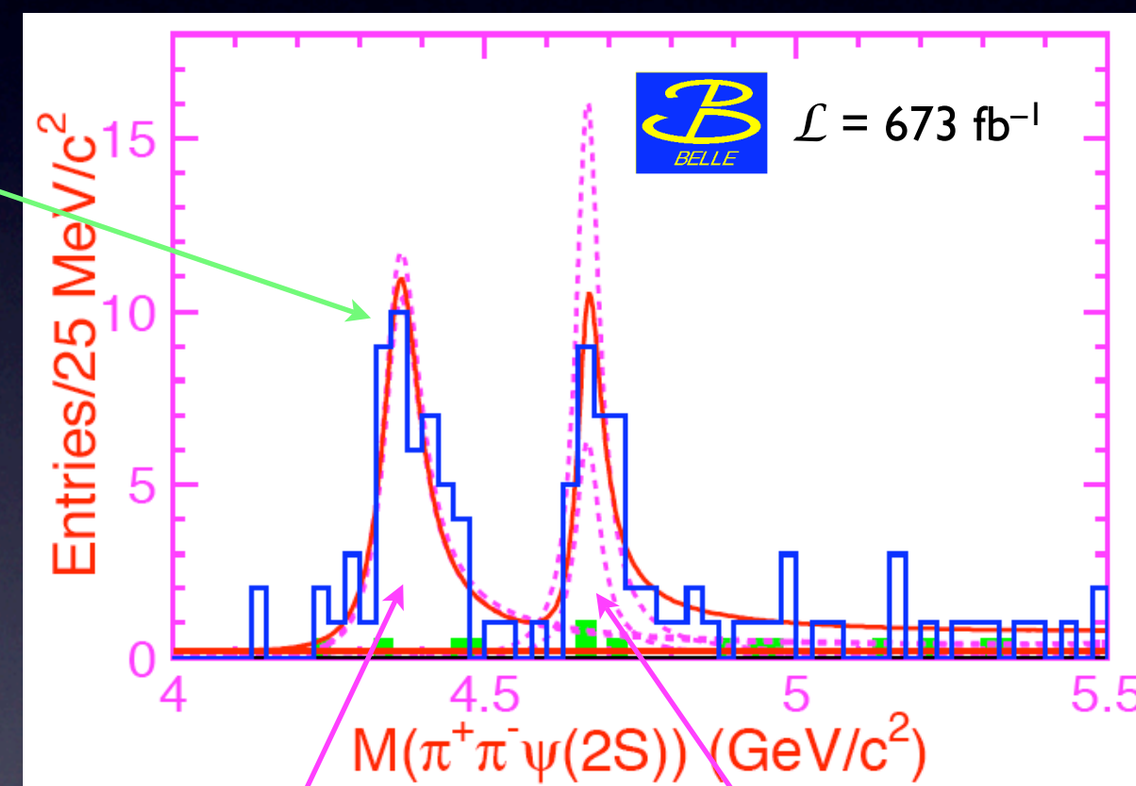
More *Y*s from Belle

From a similar analysis on ISR events, Belle found confirmation for the two states, and found evidence for two more vector states

Phys. Rev. Lett 99, 182004

Phys. Rev. Lett. 99, 142002





BABAR states

M (MeV)

Γ (MeV)

$4008 \pm 40\ ^{+114}_{-28}$	$4247 \pm 12\ ^{+17}_{-32}$	$4361 \pm 9 \pm 9$	$4664 \pm 11 \pm 5$
$226 \pm 44 \pm 87$	$108 \pm 19 \pm 10$	$74 \pm 15 \pm 10$	$48 \pm 15 \pm 3$

New states: summary

State	Experiment	M (MeV)	Γ (MeV)	J^{PC}	Production	Decay
$X(3872)$	Belle, CDF, D0, Cleo, BaBar	3871.2 ± 0.5	< 2.3	$1^{++}, 2^{-+}$	B decays, $p\bar{p}$	$J/\psi\ \pi^+\ \pi^-, J/\psi\ \gamma$
$X(3875)$	Belle, BaBar	3875.2 ± 0.7			B decays	$D^0\ \bar{D}^0\ \pi^0, D^0\ \bar{D}^{*0}$
$X(3940)$	Belle	$3943 \pm 6 \pm 6$	< 52	J^{P+}	$e^+\ e^-$ (J/ψ recoil)	$D\ D^*$
$Y(3940)$	Belle, BaBar	$3914.6\ ^{+3.8}_{-3.4} \pm 1.9$	$34\ ^{+12}_{-8} \pm 5$	J^{++}	B decays	$J/\psi\ \omega$
$Z(3930)$	Belle	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$	2^{++}	$\gamma\ \gamma$	$D^0\ \bar{D}^0, D^+\ D^-$
$Y(4008)$	Belle	$4008 \pm 40\ ^{+114}_{-28}$	$226 \pm 44 \pm 87$	1^-	$e^+\ e^-$	$J/\psi\ \pi^+\ \pi^-, J/\psi\ \pi^0\ \pi^0$
$Y(4260)$	BaBar, Cleo, Belle	$4247 \pm 12\ +17\ -32$	$108 \pm 19 \pm 10$	1^-	$e^+\ e^-$	$J/\psi\ \pi^+\ \pi^-$
$Y(4350)$	BaBar, Belle	$4361 \pm 9 \pm 9$	$74 \pm 15 \pm 10$	1^-	$e^+\ e^-$	$\psi(2S)\ \pi^+\ \pi^-$
$Y(4660)$	Belle	$4664 \pm 11 \pm 5$	$48 \pm 15 \pm 3$	1^-	$e^+\ e^-$	$\psi(2S)\ \pi^+\ \pi^-$
$Y(4160)$	Belle	$4156\ ^{+25}_{-20} \pm 15$	$139\ ^{+111}_{-61} \pm 21$	J^{P+}	$e^+\ e^-$ (J/ψ recoil)	$D^*\ D^*$
$Z^+(4430)$	Belle	$4433 \pm 4 \pm 2$	$44\ ^{+18}_{-13}\ ^{+30}_{-13}$		B decays	$\psi(2S)\ \pi^+$

charged!

Many new states, few new charmonia?

Bottomonium at *B*-factories

It is usually assumed that $\mathcal{B}(\Upsilon(4S) \to B\bar{B}) \approx 100\% \Rightarrow$ *B*-factories:

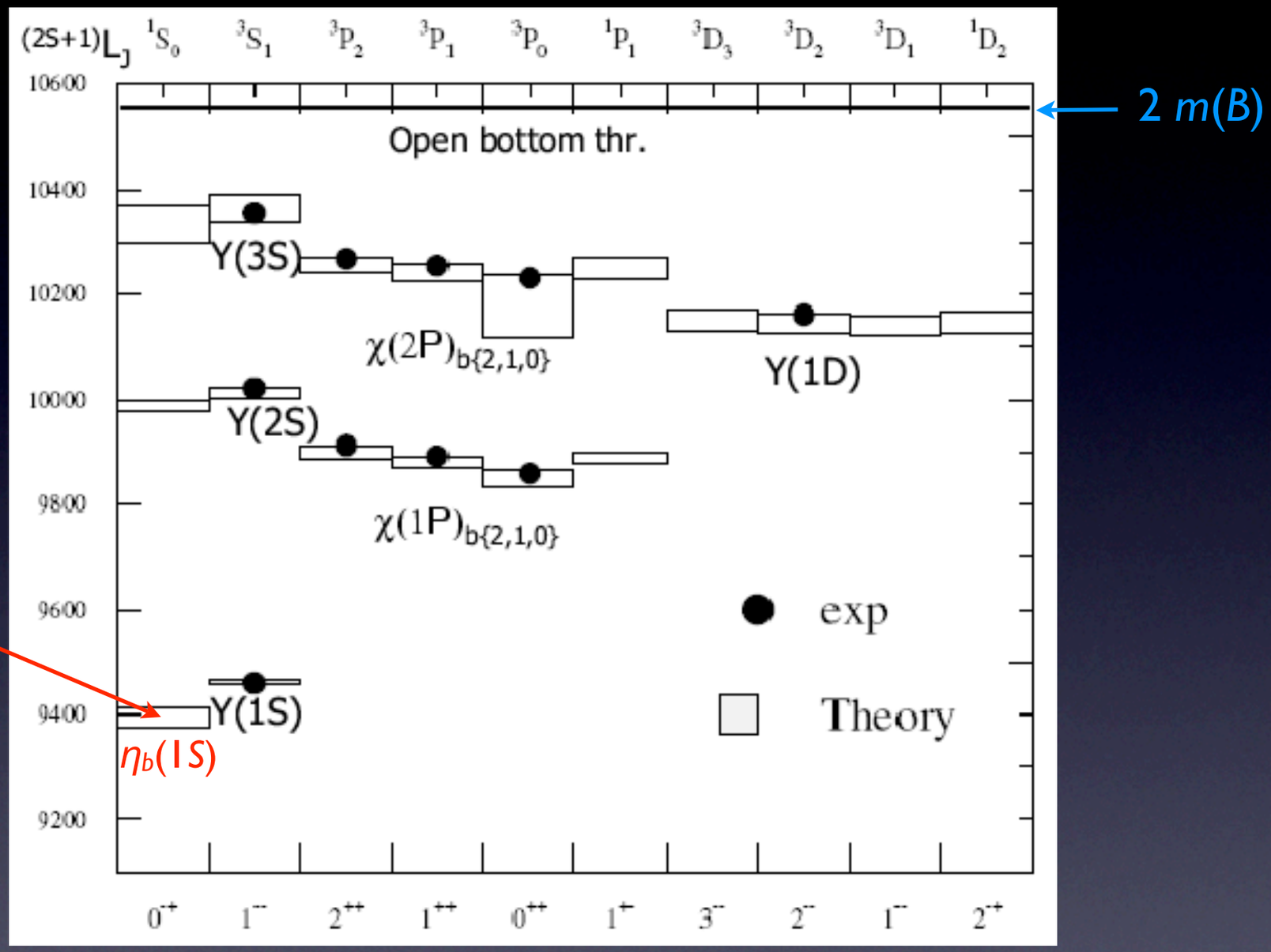
- however, the size of the data samples allows to search for rarer, non-$B\bar{B}$ decays;
- moreover, states below the open-*B* threshold can be reached via the ISR mechanism, providing some of the largest data sets recorded

Special data sets taken by Belle and *BABAR* at different energies:

- Belle: $\Upsilon(3S)$ peak, 3 fb^{-1}; $\Upsilon(5S)$ scan, 2 fb^{-1}; $\Upsilon(5S)$ peak 21.7 fb^{-1} (~40 × pre-existing sample)
- *BABAR*: $\Upsilon(2S)$ peak, 15 fb^{-1}; $\Upsilon(3S)$ peak, 30 fb^{-1}; R-scan $\Upsilon(4S) \to$ 11.3 MeV/c^2, 3 fb^{-1} (all ~10 × pre-existing sample)

$\Rightarrow$ quest for missing states and search for bottomonium-like equivalent of charmonium-like new states

The bottomonium spectrum



Several states below open-bottom threshold still missing: in particular, pseudo-scalar (η_b) states

Υ(4S) hadronic decays

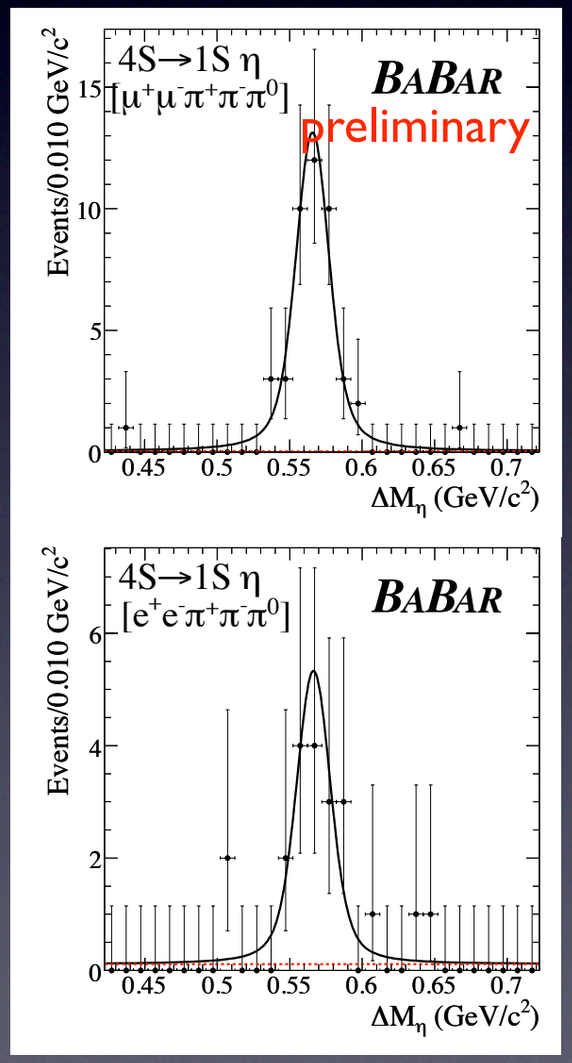
First non-$B\bar{B}$ hadronic decays of Υ(4S) observed by *BABAR* on 211 fb^{-1} of data: Υ(4S) → Υ(1S, 2S) $\pi^+ \pi^-$. Confirmed by Belle

Update on 347 fb^{-1}: new, improved measurements of:

- $\mathcal{B}$(Υ(4S) → Υ(1S, 2S) $\pi^+ \pi^-$);
- $\mathcal{B}$(Υ(3S) → Υ(2S) $\pi^+ \pi^-$);
- $\mathcal{B}$(Υ(3S, 2S) → Υ(1S) $\pi^+ \pi^-$);
- Γ(Υ(*mS*) → Υ(1S) $\pi^+ \pi^-$)/Γ(Υ(*mS*) → Υ(2S) $\pi^+ \pi^-$)

First observation of Υ(4S) → Υ(1S) η:

- anomalously large
  Γ(Υ(4S) → Υ(1S) η)/Γ(Υ(4S) → Υ(1S) $\pi^+ \pi^-$)
  = 2.41 ± 0.40 ± 0.12



Υ(4S) hadronic decays

preliminary

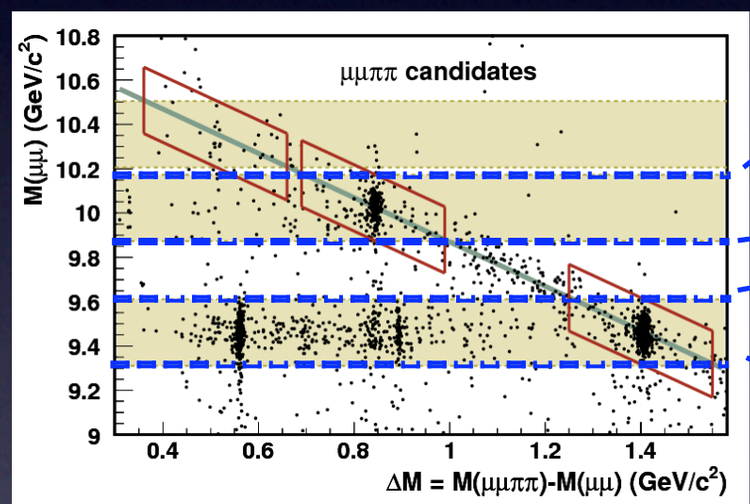
Transition	N_{cand}	N_{bck}	N_{corr}	Signif.	Our Measurement
$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)$ (meV)	9036	156±11	24319±268		2582±28±94
$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to e^+e^-)$ (meV)	3139	230±9	25202±574		2618±60±97
$\Gamma_{ee}(2S)\mathcal{B}(\Upsilon(2S)\to\eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ (meV)	0	2.5±1.1	<28		<3.1
$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)$ (meV)	4198	207±10	9945±174		457±8±18
$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to e^+e^-)$ (meV)	3604	1234±20	9821±261		441±12±18
$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S)\to\pi^+\pi^-\Upsilon(2S))\mathcal{B}(\Upsilon(2S)\to e^+e^-)$ (meV)	975	180±21	4477±241		206±11±12
$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S)\to\eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ (meV)	1	0.8±0.4	<41		<2.0
$\Gamma_{ee}(3S)\mathcal{B}(\Upsilon(3S)\to\eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to e^+e^-)\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ (meV)	4	2.8±0.8	<210		<9.6
$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)$ ($\times10^6$)	687	378±11	739± 60		1.99±0.16±0.07
$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to e^+e^-)$ ($\times10^6$)	1057	934±17	676±397		1.76±1.05±0.06
$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S))\mathcal{B}(\Upsilon(2S)\to\mu^+\mu^-)$ ($\times10^6$)	377	204±8	615± 78		1.65±0.21 ±0.11
$\mathcal{B}(\Upsilon(4S)\to\pi^+\pi^-\Upsilon(2S))\mathcal{B}(\Upsilon(2S)\to e^+e^-)$ ($\times10^6$)	251	206±8	669±392		1.76±1.03 ±0.11
$\mathcal{B}(\Upsilon(4S)\to\eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to\mu^+\mu^-)\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ ($\times10^6$)	40	0.2±0.4	387±60	11σ	1.08±0.17±0.05
$\mathcal{B}(\Upsilon(4S)\to\eta\Upsilon(1S))\mathcal{B}(\Upsilon(1S)\to e^+e^-)\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$ ($\times10^6$)	16	0.7±0.6	424±106	6.2σ	1.15±0.29±0.05

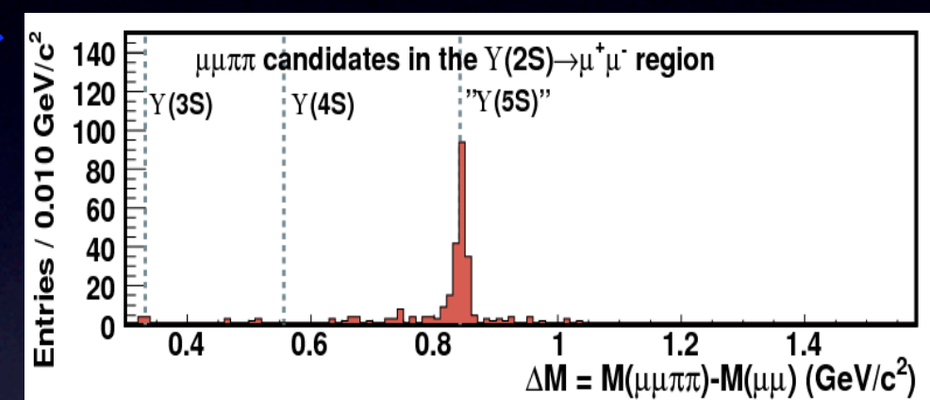
⇒ gaining insight in (as yet poorly known) Υ hadronic decays

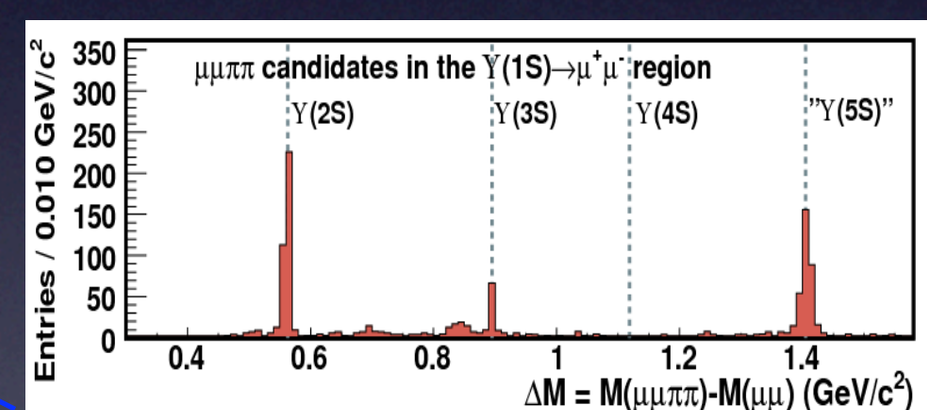
Anomalous Υ(5S) decay rates at Belle

Similar analysis on Belle sample at Υ(5S) c.m. energy:

- look for $l^+ l^- \pi^+ \pi^-$ final state and plot $m(l^+ l^-)$ vs. $m(l^+ l^- \pi^+ \pi^-) - m(l^+ l^-)$







Assuming published values for Υ(5S) parameters, rates are ~100 × similar rates for bottomonium:

- equivalent states of charmonium *Y*?

Conclusions

In recent years, *B*-factories have been playing a starring role in the study of charmonium and bottomonium systems

A partially unexpected wealth of results in this field:

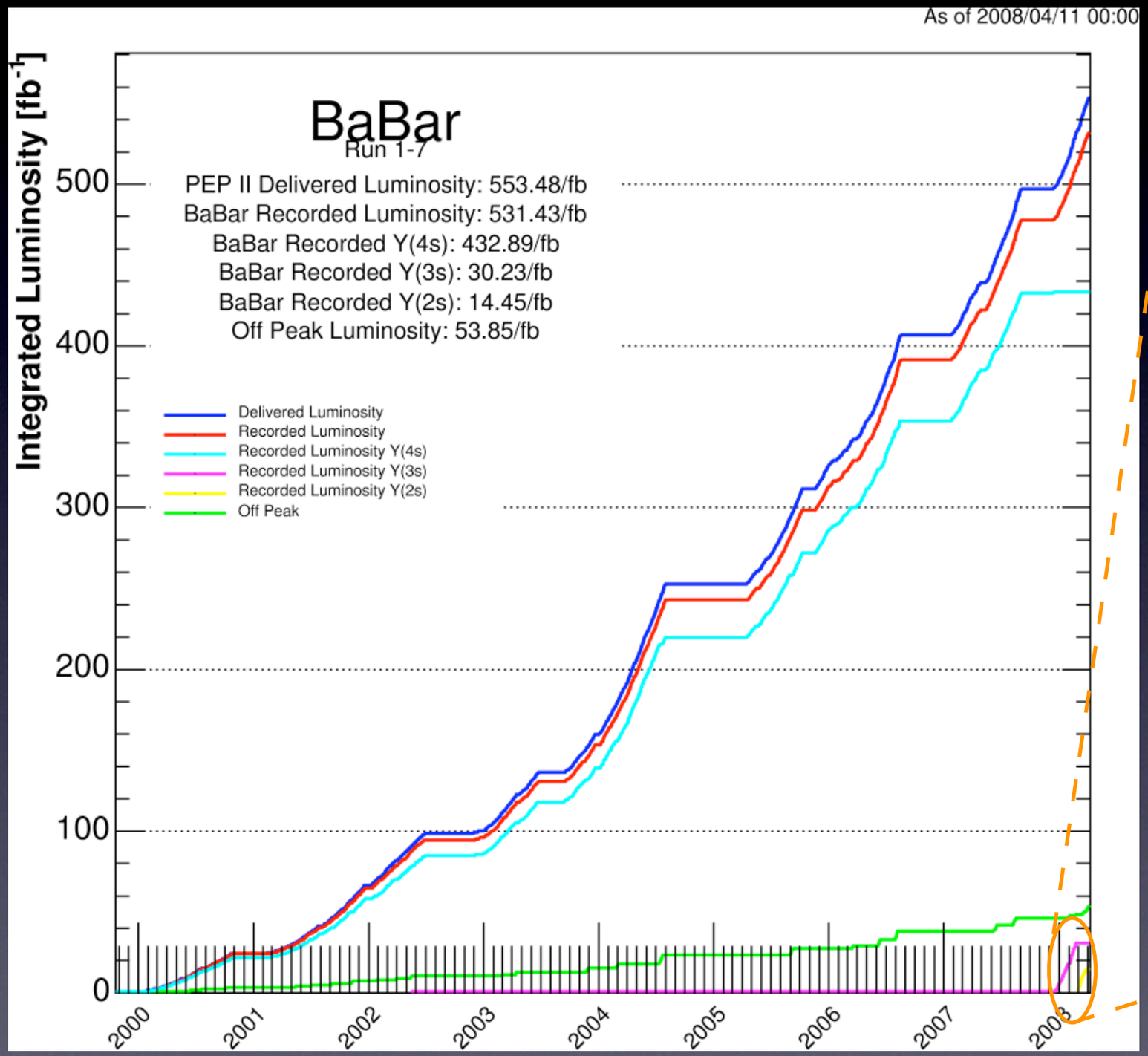
- significant contribution to the knowledge of quarkonium spectroscopy and production/decay mechanisms;
- discovery of many quarkonium-like states of uncertain interpretation, possibly disclosing a door on a new spectroscopy of non-conventional structures (exotics)

Despite (some) data taking coming to an end, important results can still come from several analyses on the complete data sets

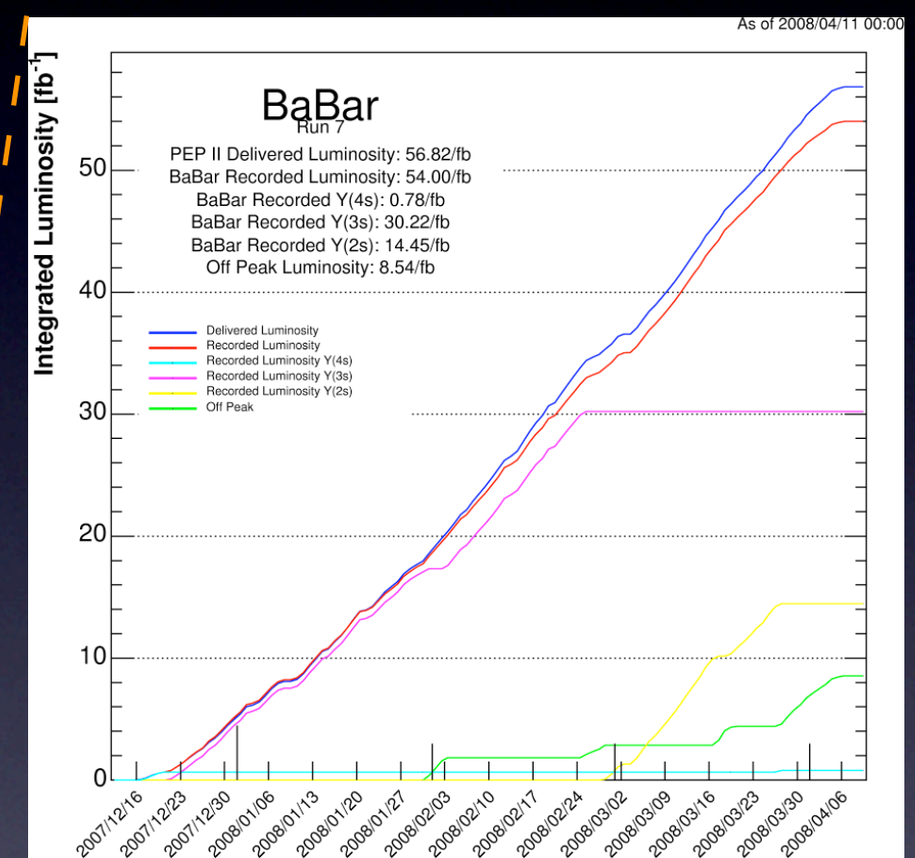
- in particular, recent 'ad-hoc' data sets taken in the bottomonium region

Back-up

BABAR data sample



Run 7



Belle data sample