Charmonium Spectroscopy

Diego Bettoni

Istituto Nazionale di Fisica Nucleare, Ferrara

Observables in $\bar{p}p$ interactions
and their relevance to QCD
ECT*, Trento
July 3-7, 2006

Outline

- Introduction
  - Why Charmonium
  - Experimental methods for the study of charmonium
- Highlights on the spectrum
  - A new measurement of the $\psi(2S)$ width
  - Singlet S states: $\eta_c(1S)$ and $\eta_c(2S)$
  - The $h_c(1^1P_1)$
- The New States
- The Observables
- Summary

Why is Charmonium Interesting ?

Charmonium is a powerful tool for the understanding of the strong interaction. The high mass of the c quark ($m_c \sim 1.5$ GeV/c^2) makes it plausible to attempt a description of the dynamical properties of the ($c\bar{c}$) system in terms of non-relativistic potential models, in which the functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction. The free parameters in these models are determined from a comparison with experimental data.

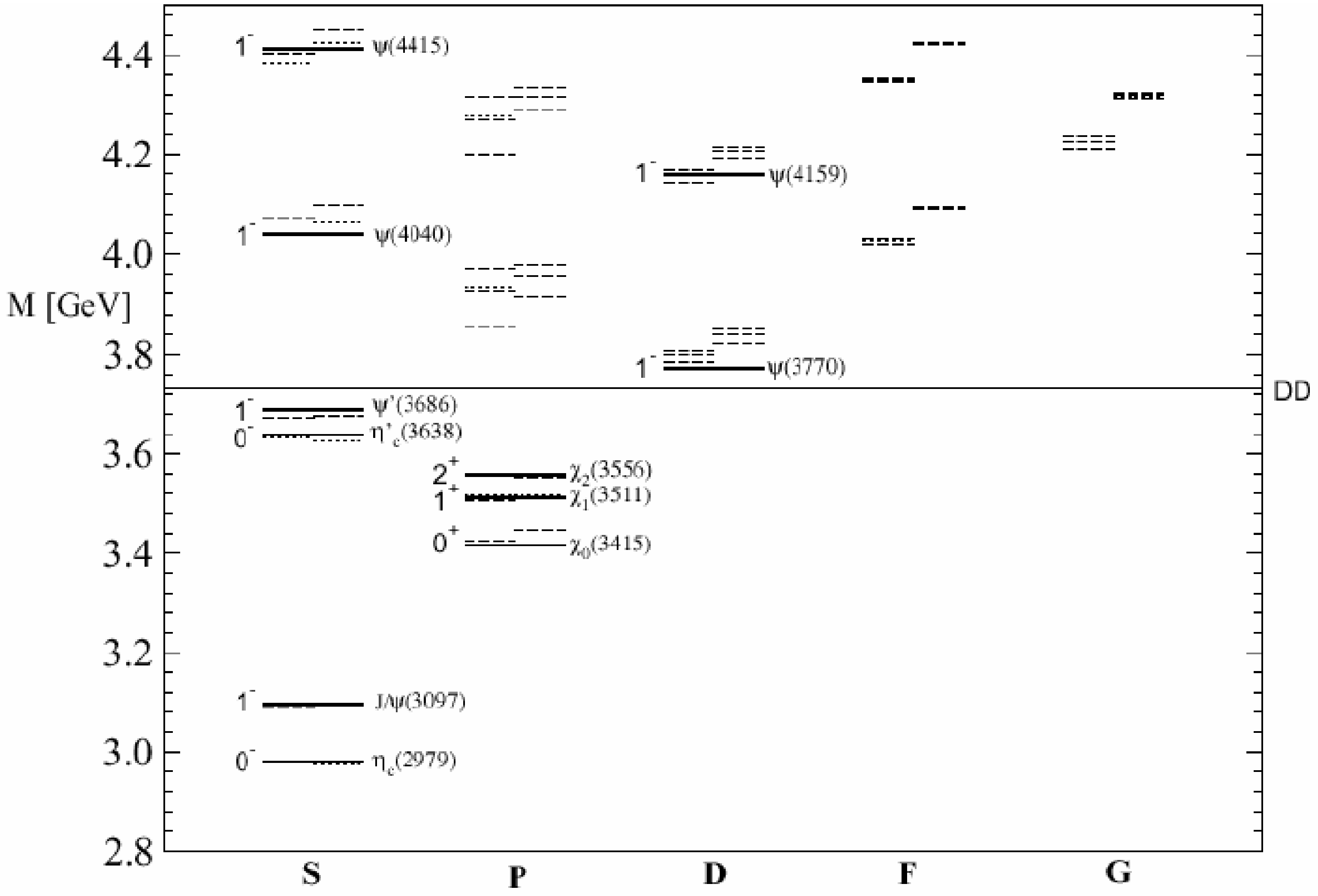
$$\beta^2 \approx 0.2 \quad \alpha_s \approx 0.3$$

Non-relativistic potential models + Relativistic corrections + PQCD

LQCD predicts spectrum.

LQCD needs spectroscopy.

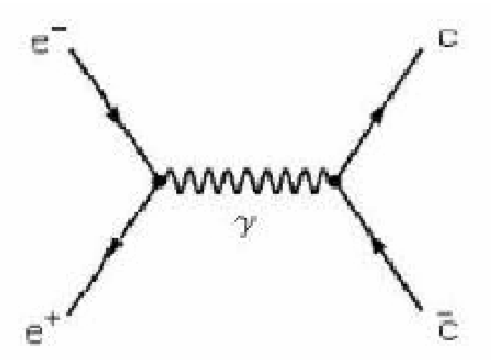
The Charmonium Spectrum



Experimental Methods for the Study of Charmonium

- e^+e^- collisions (SLAC: Mark I, II, III, TPC, Crystall Ball; DESY: DASP and PLUTO; LEP; CESR: CLEO, CLEO-c; BEPC BES; B-factories: BaBar and Belle).
  - direct formation
  - two-photon production
  - initial state radiation
  - B meson decay
  - double charmonium
- $p\bar{p}$ annihilations (CERN R704, FNAL E760 E835, GSI $\bar{\text{P}}$ANDA)
- hadroproduction (CDF, D0, LHC)
- electroproduction (HERA)

Direct Formation $e^+e^- \to c\bar{c}$

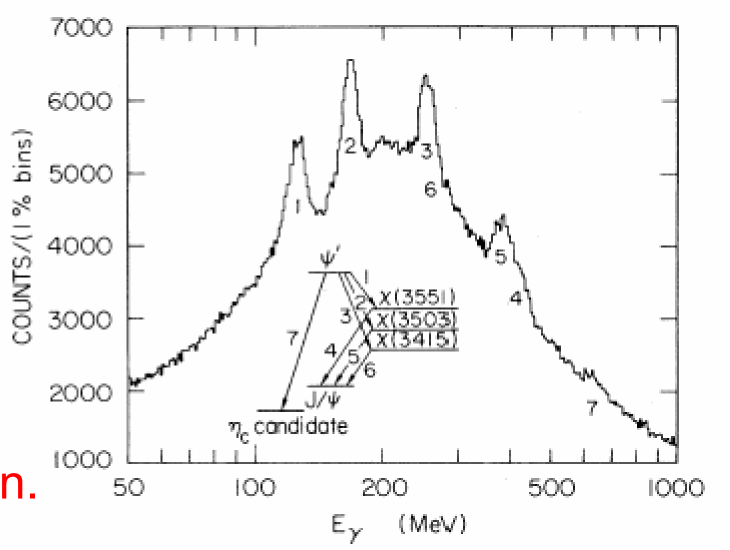


In e^+e^- annihilations direct formation is possible only for states with the quantum numbers of the photon $J^{PC}=1^{--}$: J/ψ, ψ′ and ψ(3770).

All other states can be produced in the radiative decays of the vector states. For example:

$$e^+ + e^- \to \psi'(2S) \to \gamma + X$$

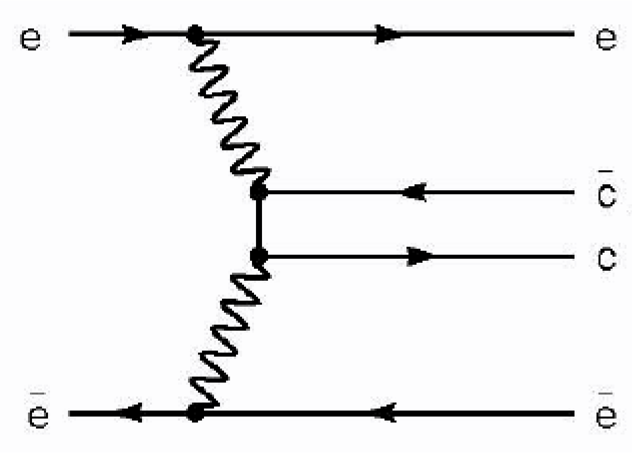
The precision in the measurement of masses and widths is limited by the detector resolution.



Crystal Ball inclusive photon spectrum

Two-photon Production $e^+e^-\rightarrow e^+e^-+(c\bar{c})$

J-even charmonium states can be produced in e^+e^- annihilations at higher energies through $\gamma\gamma$ collisions. The $(c\bar{c})$ state is usually identified by its hadronic decays. The cross section for this process scales linearly with the $\gamma\gamma$ partial width of the $(c\bar{c})$ state.



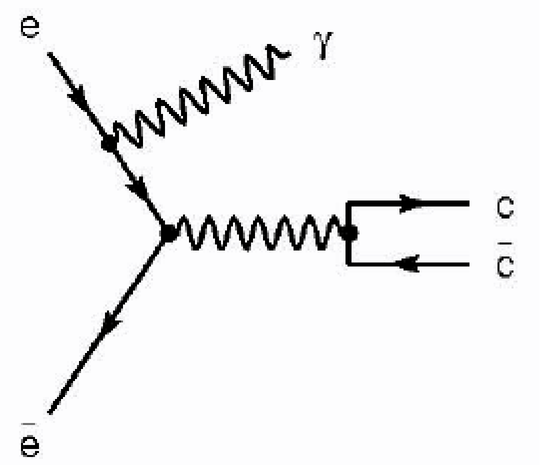
$$\sigma\left(e^+e^- \rightarrow e^+e^-(c\bar{c})\right) = \int d^5 L_{\gamma\gamma}(\alpha_i)\,\sigma\left(\gamma\gamma \rightarrow (c\bar{c})\right)$$

$$\sigma\left(\gamma\gamma \rightarrow (c\bar{c})\right) = 8\pi \frac{2J+1}{M}\Gamma_{\gamma\gamma}\frac{M\Gamma}{\left(s-M^2\right)^2+M^2\Gamma^2}F\left(q_1^2, q_2^2\right)$$

L = Luminosity function
α= e.g. 4-momenta of out going leptons.
J,M,Γ = spin, mass ,total width of $c\bar{c}$ state.
s = cm energy of $\gamma\gamma$ system
$\Gamma_{\gamma\gamma}$ two-photon partial width
q_1,q_2 photon 4-momenta
F = Form Factor describing evolution of cross section.

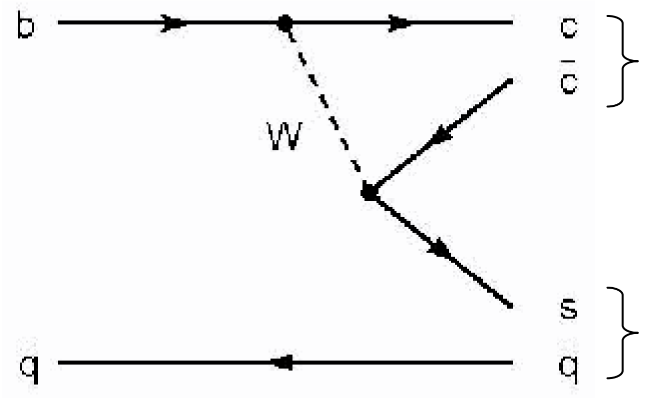
Limititations: knowledge of hadronic branching ratios and form factors used to extract the $\gamma\gamma$ partial width.

Initial State Radiation (ISR)



- Like in direct formation, only $J^{PC}=1^{--}$ states can be formed in ISR.
- This process allows a large mass range to be explored.
- Useful for the measurement of $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$.
- Can be used to search for new vector states.

B-Meson Decay

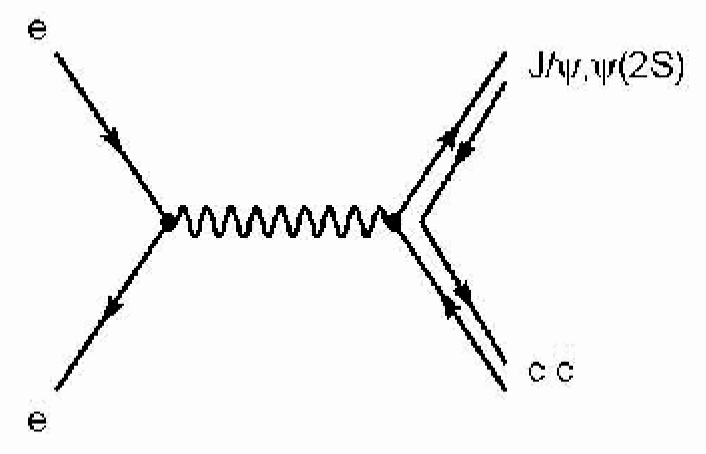


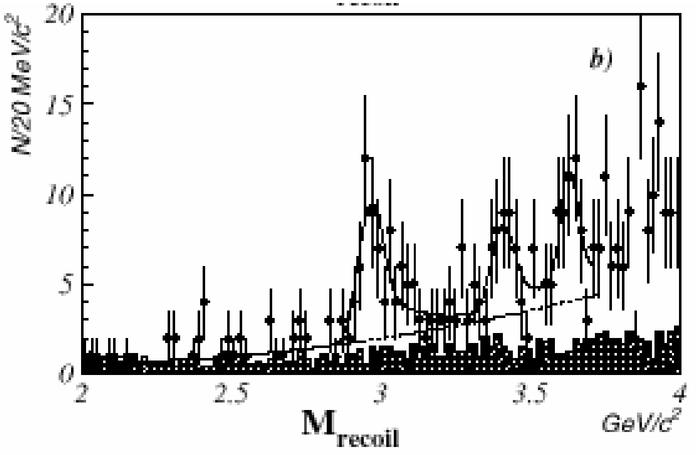
$J/\psi,\psi',\psi(3770),\ \eta_c,\eta'_c,\chi_{c0},\chi_{c1},D^{(*)},\ \bar{D}^{(*)},X(3872)$

$K^{\pm},K_S,K_L,K^*(890),K(1270)\ldots$

Charmonium states can be produced at the B-factories in the decays of the B-meson.
The large data samples available make this a promising approach.
States of any quantum numbers can be produced.
η'_c and X(3872) discoveries illustrate the capabilities of the B-factories for charmonium studies.

Double Charmonium





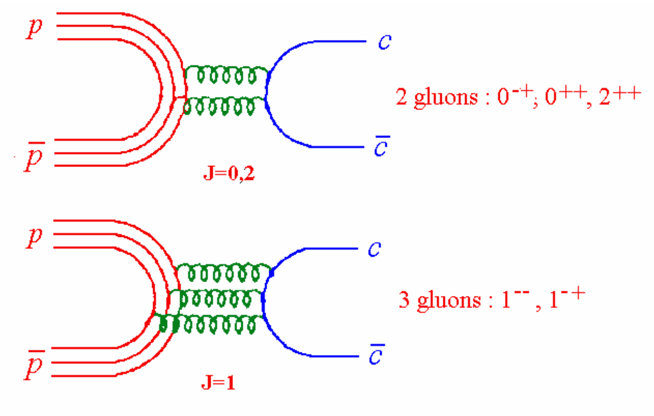
Discovered by Belle in $e^+e^- \rightarrow J/\psi + X$
The measured cross section for this process is about one order of magnitude larger than predicted by NRQCD.

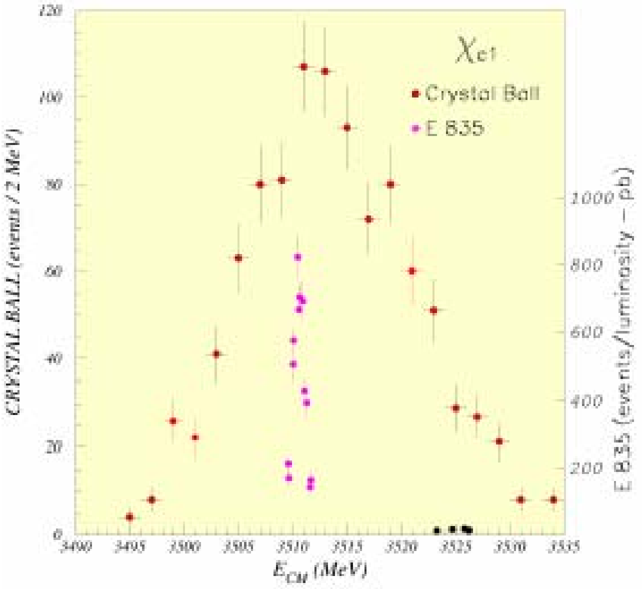
$$\sigma\left(e^+e^- \rightarrow J/\psi + \eta_c\right) \times B(\geq 4) = \left(0.033^{+0.007}_{-0.006} \pm 0.009\right) pb$$

Enhances discovery potential of B-factories: states which so far are unobserved might be discovered in the recoil spectra of J/ψ and η_c.

$\bar{p}p$ Annihilation

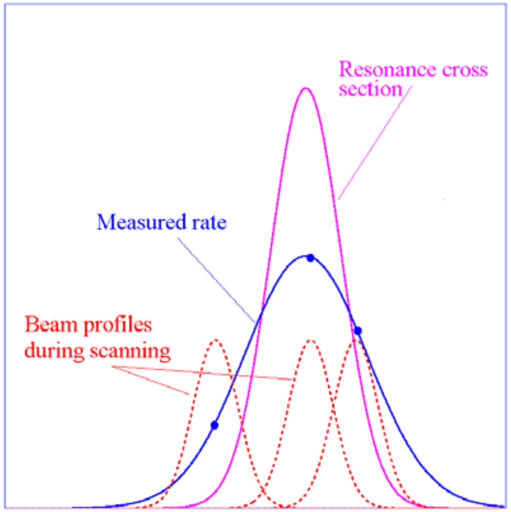
In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all quantum numbers.





The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

Experimental Method



The cross section for the process:

$$\bar{p}p \rightarrow \bar{c}c \rightarrow \text{final state}$$

is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

The production rate ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0\left\{\varepsilon\int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

Beam Energy and Width Measurement

In $\bar{p}p$ annihilation the precision in the measurement of mass and width is determined by the precision in the measurement of the beam energy and beam energy width, respectively.

$$E_{cm} = \sqrt{2} m_p (1+\gamma)^2$$

$$\gamma = \frac{E_{beam}}{m_p} = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = f \cdot L$$

$$\frac{\delta E_{cm}}{E_{cm}} = \frac{\beta^2 \gamma^3}{2(1+\gamma)} \sqrt{\left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta L}{L}\right)^2}$$

The beam revolution frequency *f* can be measured to 1 part in 10^7 from the beam current Schottky noise. In order to measure the orbit length L to the required precision (better than 1 mm) it is necessary to calibrate using the known mass of a resonance, e.g. the ψ' for which ΔM = 34 keV.

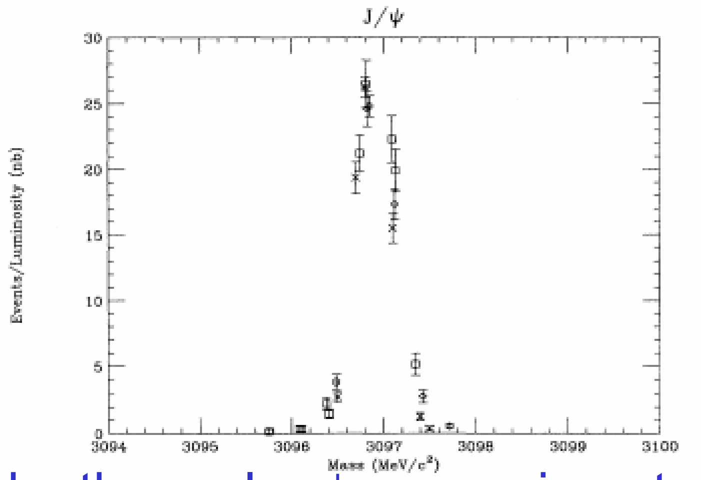
η is a machine parameter which can be measured to ~ 10 %

$$\frac{\delta p}{p} = -\frac{1}{\eta} \frac{\delta f}{f}$$

η machine slip factor

The $J/\psi(1^3S_0)$ and the $\psi'(2^3S_0)$

- The masses of the triplet S states have been measured very precisely in e^+e^- collision (using resonant depolarization) and in $\bar{p}p$ annihilation at Fermilab (E760) Accuracy of 11 keV/c^2 for the J/ψ and of 34 keV/c^2 for the ψ'.



- The widths of these states were determined by the early e^+e^- experiments by measuring the areas under the resonance curves. Direct measurement by E760 at Fermilab, which found larger values.

Triplet S states
total widths (keV)

	PDG92	PDG04
J/ψ	68 ± 10	91.0 ± 3.2
ψ'	243 ± 43	277 ± 22

New Measurement of the $\psi(2S)$ Width

From a presentation by G. Stancari – QWG4

$\psi(2S)$ Scan at Constant Orbit

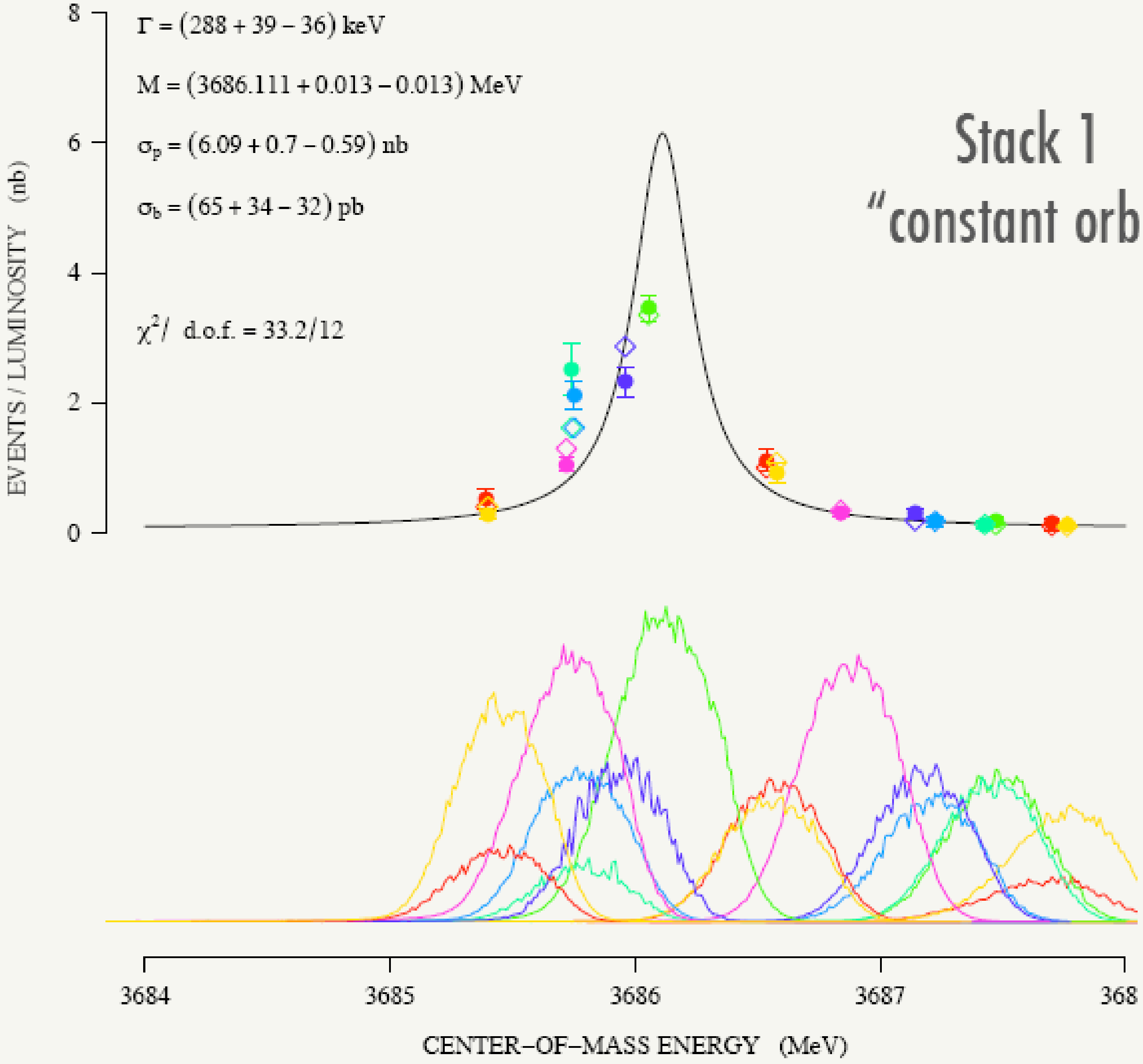
- Beam width is inversely proportional to slip factor η.

- Positive correlation between slip factor and resonance width.

- Slip factor can be measured from synchrotron frequency with 10 % accuracy.

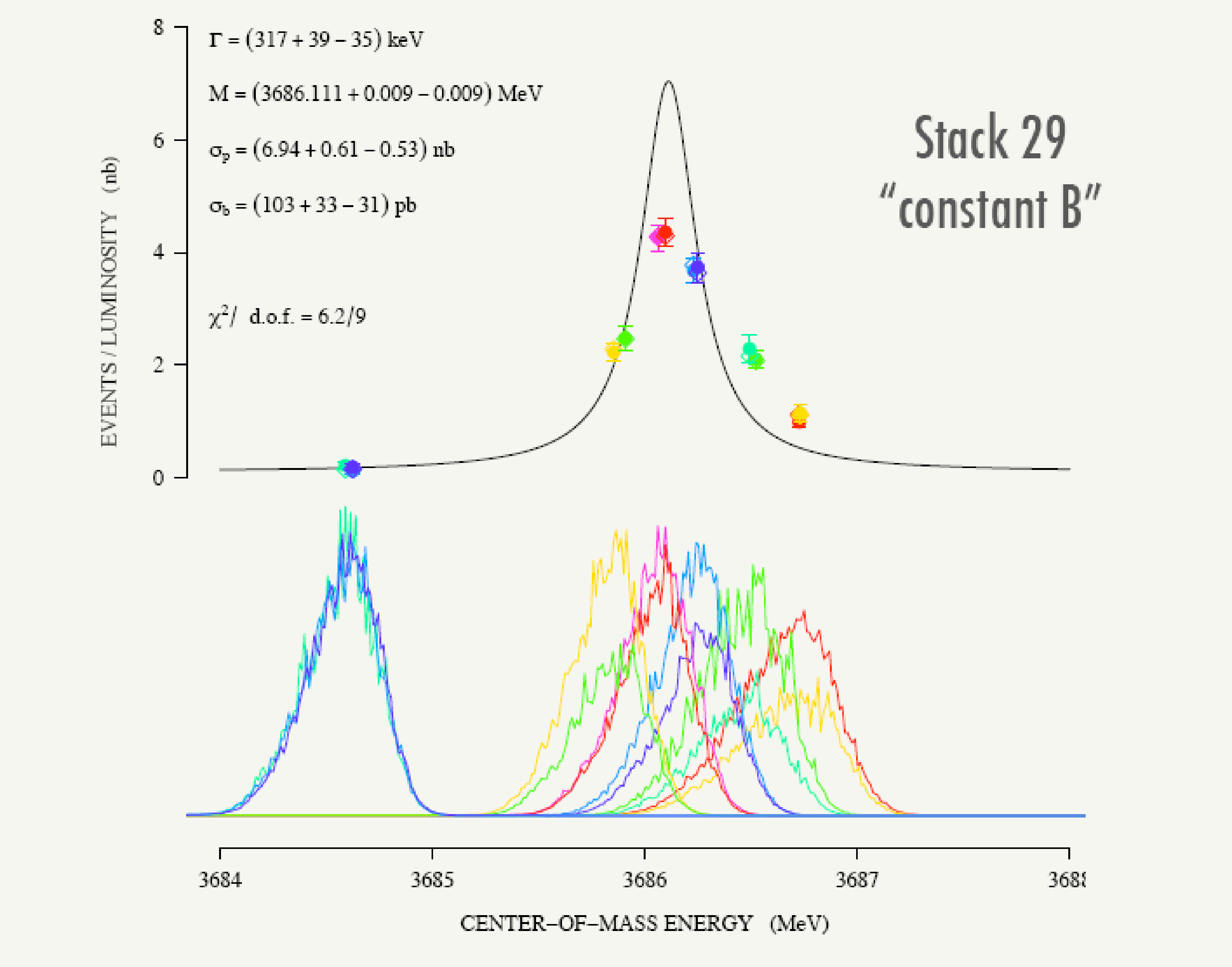
- Corresponding systematic uncertainty on resonance width is 16 %.

Stack 1
“constant orbit”



$\psi(2S)$ Scan at Constant B

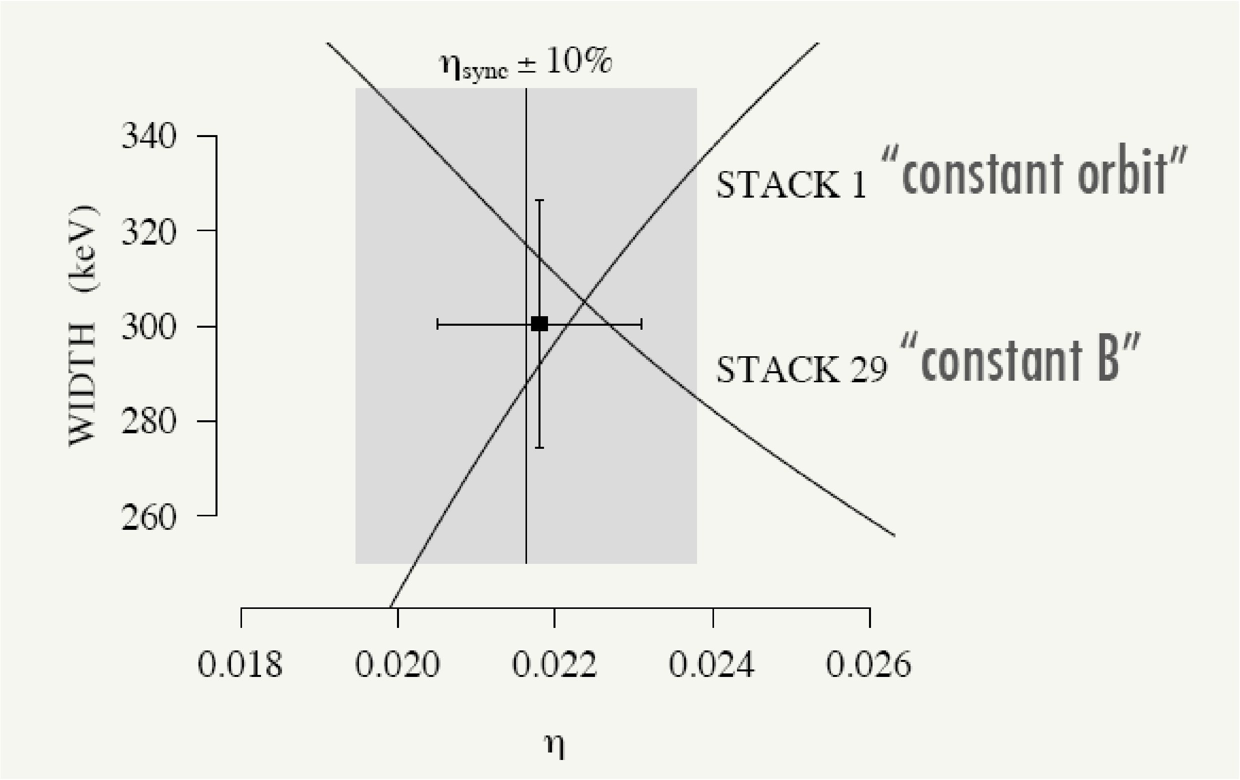
- Need better accuracy on η.
- E760 achieved 6 % accuracy with double-scan technique (Armstrong et al., PRD 47(1993)772.)
- In E835/2000.
  - Combine scan at constant orbit with scan at constant B.
  - higher luminosity.
  - accurate beam spectra.
- For measurement at constant B negative correlation between slip factor and resonance width.

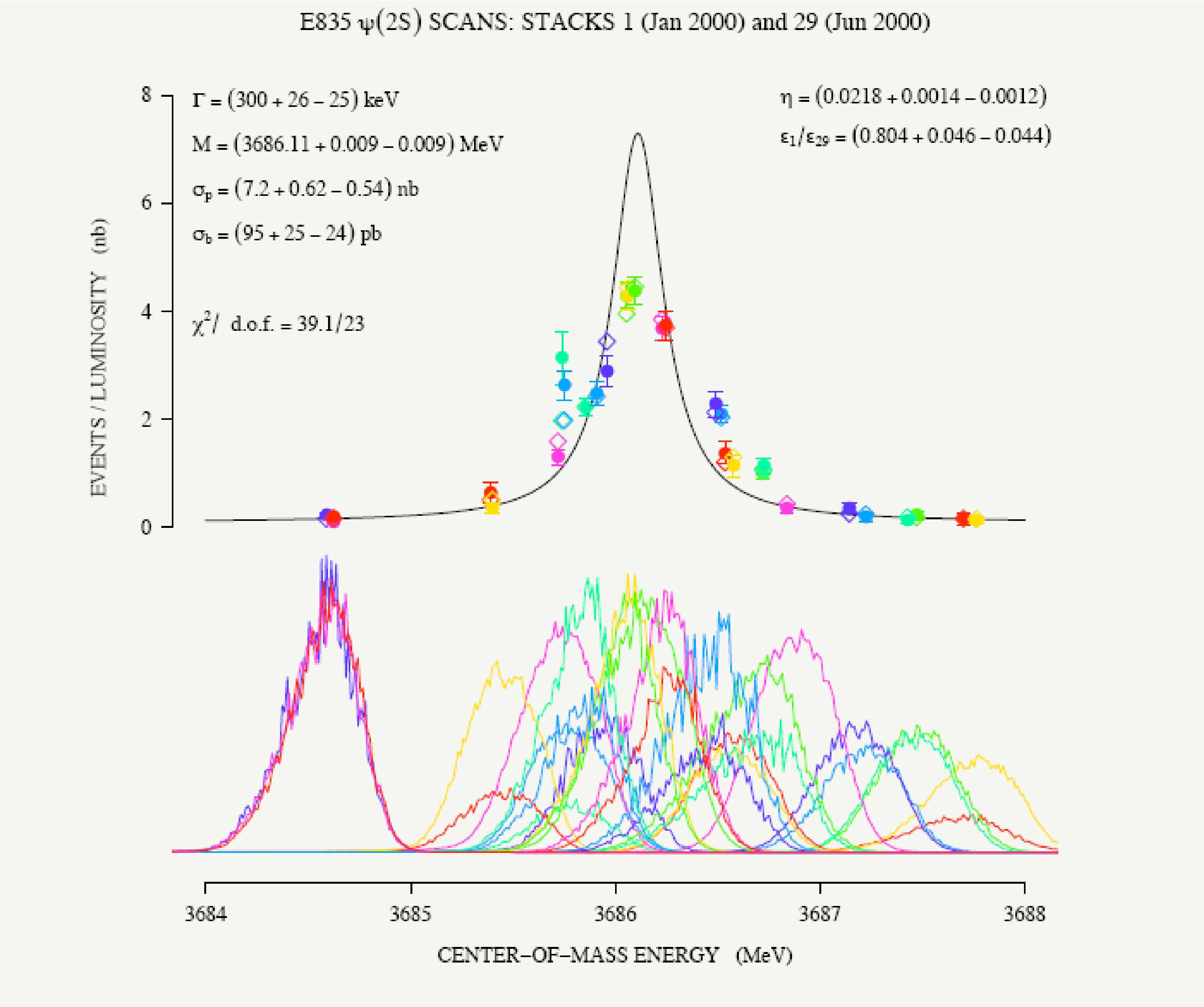


Stack 29

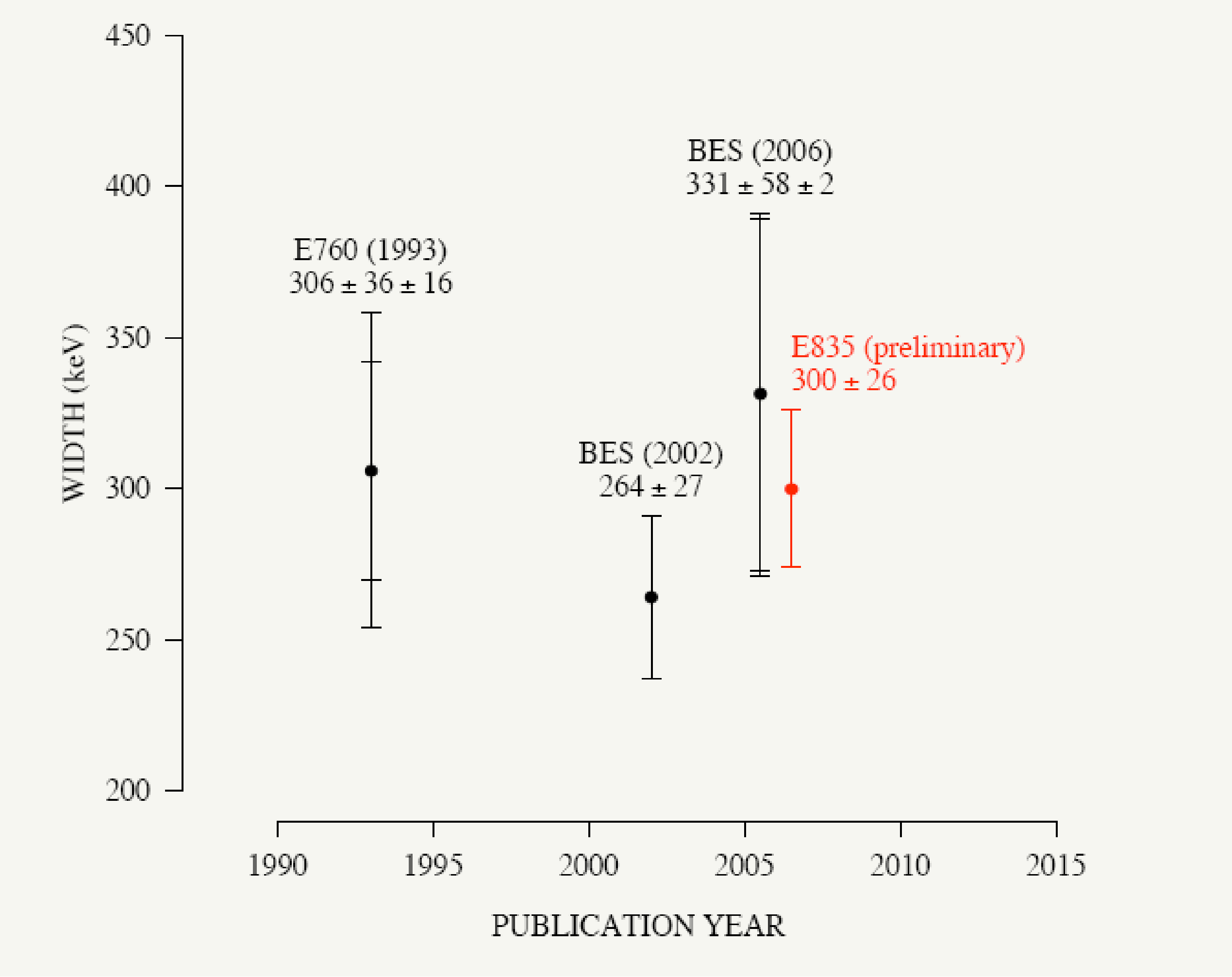
"constant B"

By combining the two stacks resonance width and slip factor can be determined simultaneously.




E835 $\psi(2S)$ SCANS: STACKS 1 (Jan 2000) and 29 (Jun 2000)
$\Gamma = (300 + 26 - 25)$ keV
$M = (3686.11 + 0.009 - 0.009)$ MeV
$\sigma_p = (7.2 + 0.62 - 0.54)$ nb
$\sigma_b = (95 + 25 - 24)$ pb
$\chi^2/$ d.o.f. = 39.1/23
$\eta = (0.0218 + 0.0014 - 0.0012)$
$\varepsilon_1/\varepsilon_{29} = (0.804 + 0.046 - 0.044)$
EVENTS / LUMINOSITY (nb)
0
2
4
6
8
3684
3685
3686
3687
3688
CENTER–OF–MASS ENERGY (MeV)

Recent ψ(2S) width measurements

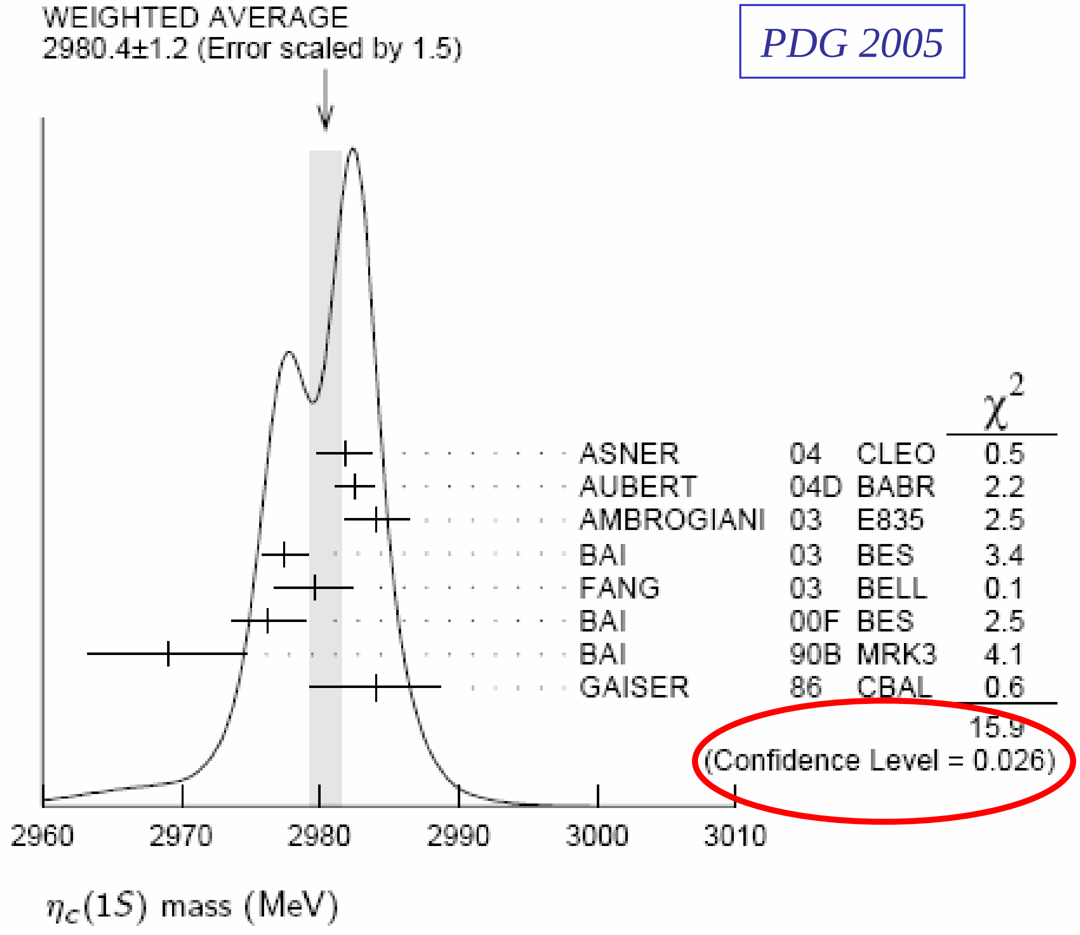


The $\eta_c(1^1S_0)$

- It is the ground state of charmonium, with quantum numbers $J^{PC}=0^{-+}$.
- Knowledge of its parameters is crucial. Potential models rely heavily on the mass difference $M(J/\psi)-M(\eta_c)$ to fit the charmonium spectrum.
- The η_c cannot be formed directly in e^+e^- annihilations:
  - Can be produced in M1 radiative decays from the J/ψ and ψ' (small BR).
  - Can be produced in photon-photon fusion.
  - Can be produced in B-meson decay.
- The η_c can be formed directly in $\bar{p}p$ annihilation.
- Many measurements of mass and η_c width (6 new measurements in the last 2 years). However errors are still relatively large and internal consistency of measurements is rather poor.
- Large value of η_c width difficult to explain in simple quark models.
- Decay to two photons provides estimate of α_s.

The $\eta_c(1^1S_0)$ Mass

Experiment	Mass (MeV/c^2)
CLEO	**2981.8 ± 1.3 ± 1.5**
BaBar	**2982.5 ± 1.1 ± 0.9**
E835	**2984.1 ± 2.1 ± 1.0**
BES	**2977.5 ± 1.0 ± 1.2**
Belle	**2979.6 ± 2.3 ± 1.6**
BES	**2976.3 ± 2.3 ± 1.2**
Mark III	**2969 ± 4 ± 4**
Crystal Ball	**2984± 2.3 ± 4**

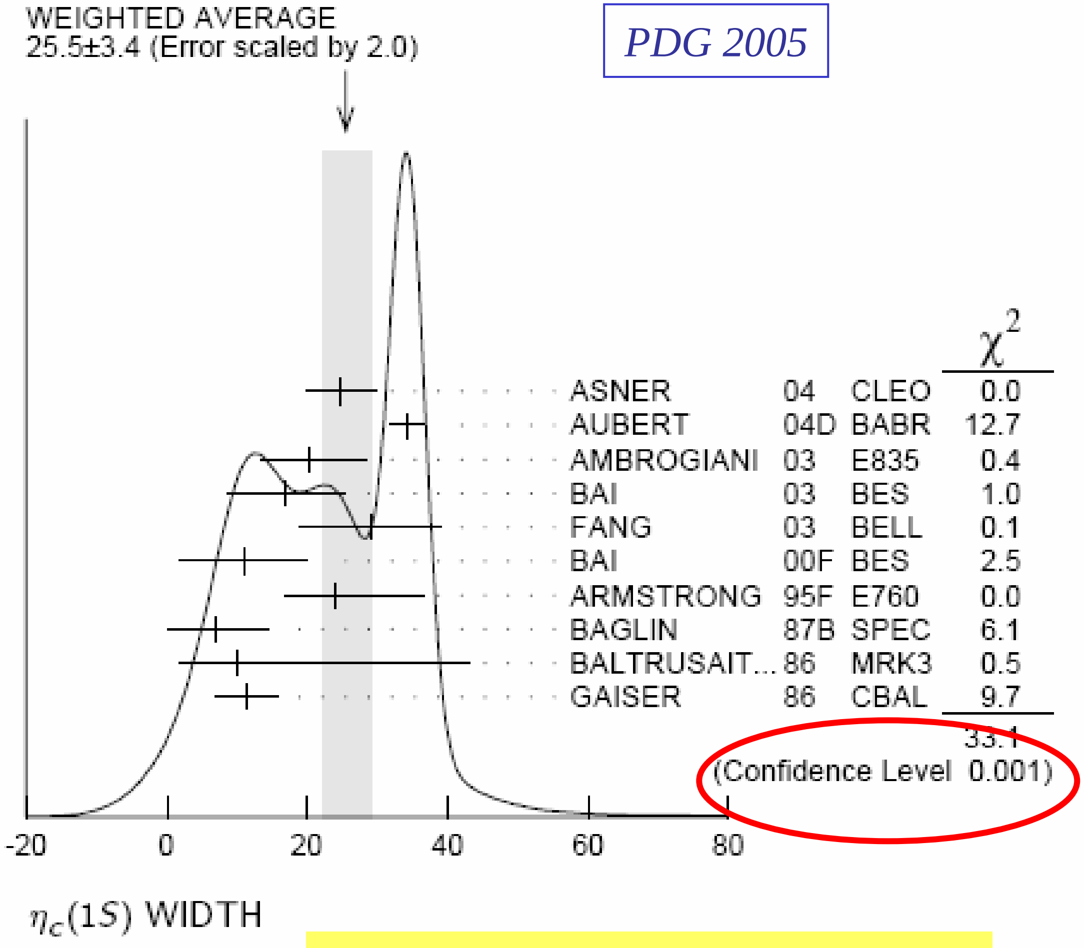


PDG 2005

$M(\eta_c) = 2980.4 \pm 1.2$ MeV/c^2

The $\eta_c(1^1S_0)$ Total Width

Experiment	Width (MeV)
CLEO	**$24.8 \pm 3.4 \pm 3.5$**
BaBar	**$34.3 \pm 2.3 \pm 0.9$**
E835	**$20.4^{+7.7}_{-6-7} \pm 2.0$**
BES	**$17.0 \pm 3.7 \pm 7.4$**
Belle	**$29 \pm 8 \pm 6$**
BES	**$11.0 \pm 8.1 \pm 4.1$**
E760	**$23.9^{+12.6}_{-7.1}$**
R704	**$7.0^{+7.5}_{-7.0}$**
Mark III	**$10.1^{+33.0}_{-8.2}$**
Crystal Ball	**11.5 ± 4.5**



PDG 2005

$\Gamma(\eta_c) = 25.5 \pm 3.4$ MeV

$\eta_c \to \gamma\gamma$

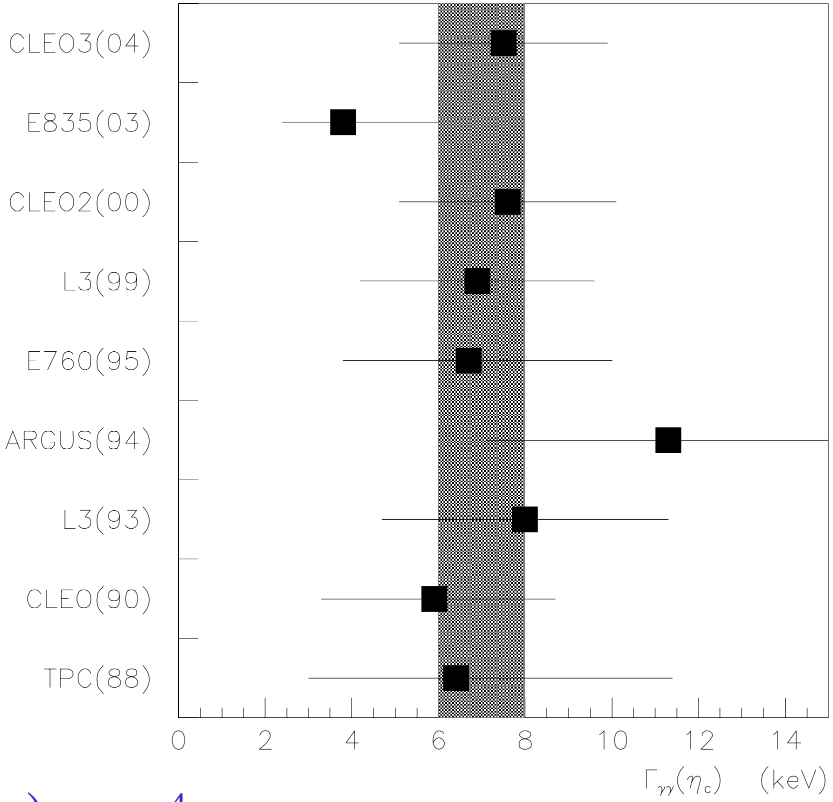
In PQCD the $\gamma\,\gamma$ BR can be used to calculate α_s:

$$B(\eta_c \to \gamma\gamma) = \frac{\Gamma_{\gamma\gamma}}{\Gamma(\eta_c)} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}} \approx \frac{8}{9}\frac{\alpha^2}{\alpha_s^2}\left(\frac{1-3.4\alpha_s/\pi}{1+4.8\alpha_s/\pi}\right)$$

Using α_s=0.32 (PDG) and the measured values for the widths:

$$\left.\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}\right|_{th} \approx 2.4\times10^{-4} \qquad \left.\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}\right|_{\exp} = (4.3\pm1.1)\times10^{-4}$$



$\Gamma_{\gamma\gamma}(\eta_c)$ = 7.0 ± 1.0 keV

The $\eta_c(2^1S_0)$ E760/E835 search

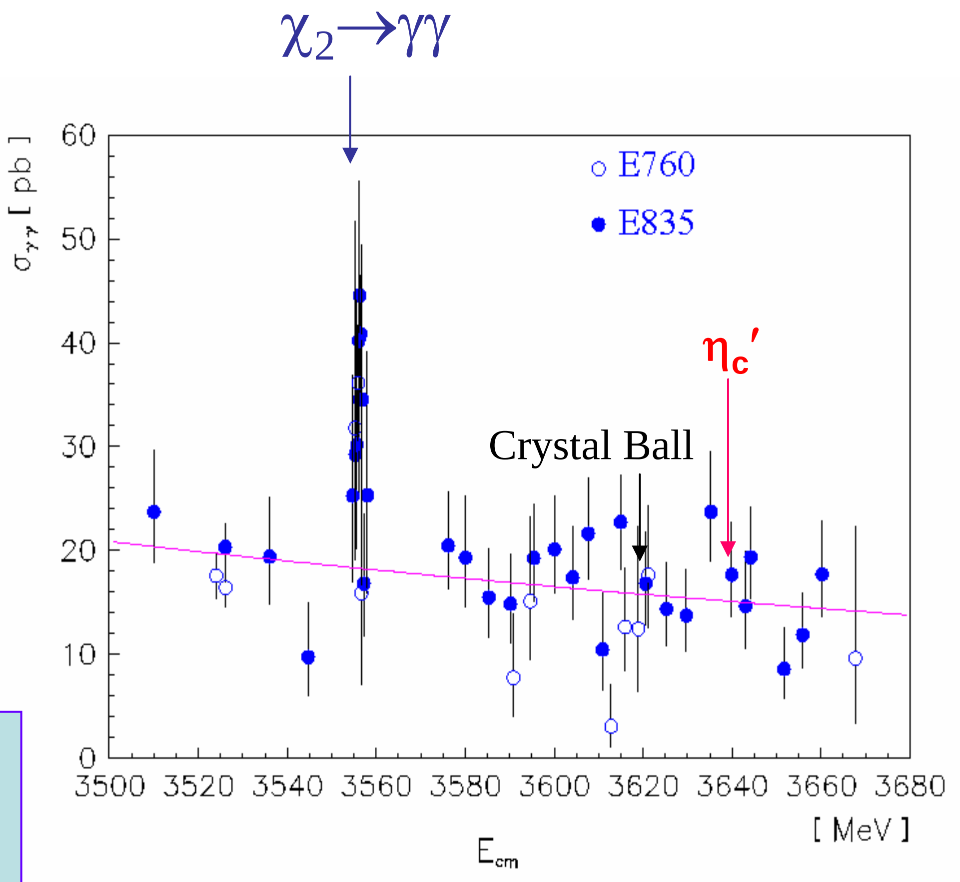
Both E760 and E835 searched for the η'_c in the energy region:

$$E_{cm} = (3570 \div 3660)\ \text{MeV}$$

using the process:

$$\bar{p} + p \to \eta'_c \to \gamma + \gamma$$

but no evidence of a signal was found.



- •Estimate/measure $\bar{p}p$ branching ratio
- •Low energy photon sensitivity for background rejection.
- •Add hadronic channels.

The $\eta_c(2^1S_0)$ discovery by BELLE

The Belle collaboration has recently presented a 6σ signal for $B \to KK_SK\pi$ which they interpret as evidence for η'_c production and decay via the process:

$$B \to K\eta'_c; \quad \eta'_c \to K_SK^+\pi^-$$

with:

$$M(\eta'_c) = 3654 \pm 6 \pm 8\ MeV/c^2$$

$$\Gamma(\eta'_c) < 55\ MeV$$

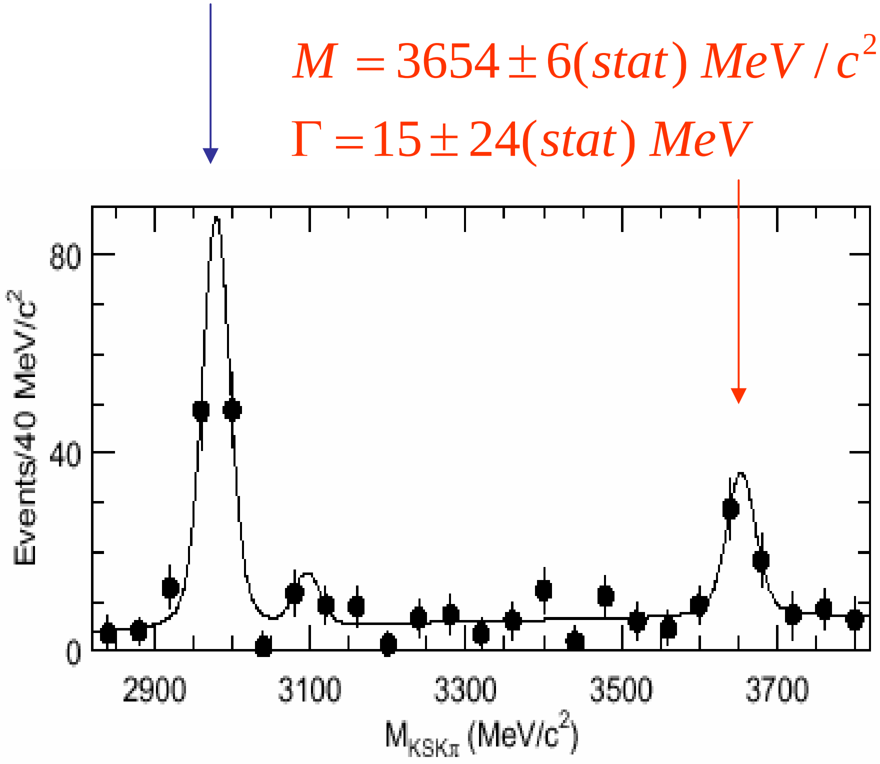
in disagreement with the Crystal Ball result.

$$M = 2978 \pm 2(\text{stat})\ \text{MeV}$$

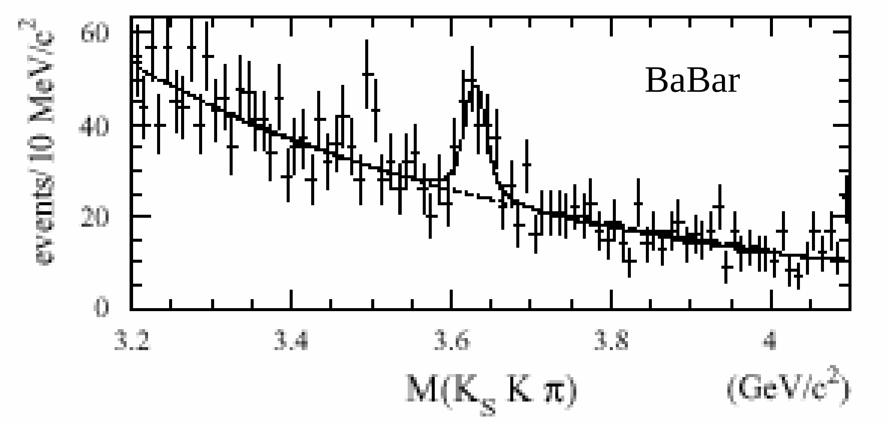
$$\Gamma = 22 \pm 20(\text{stat})\ \text{MeV}$$

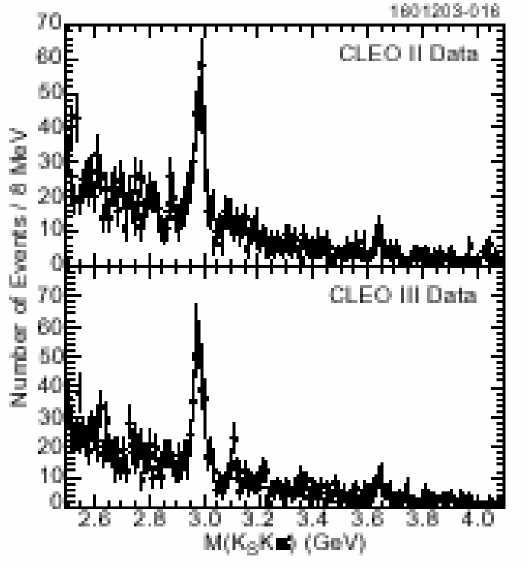
$$M = 3654 \pm 6(stat)\ MeV/c^2$$

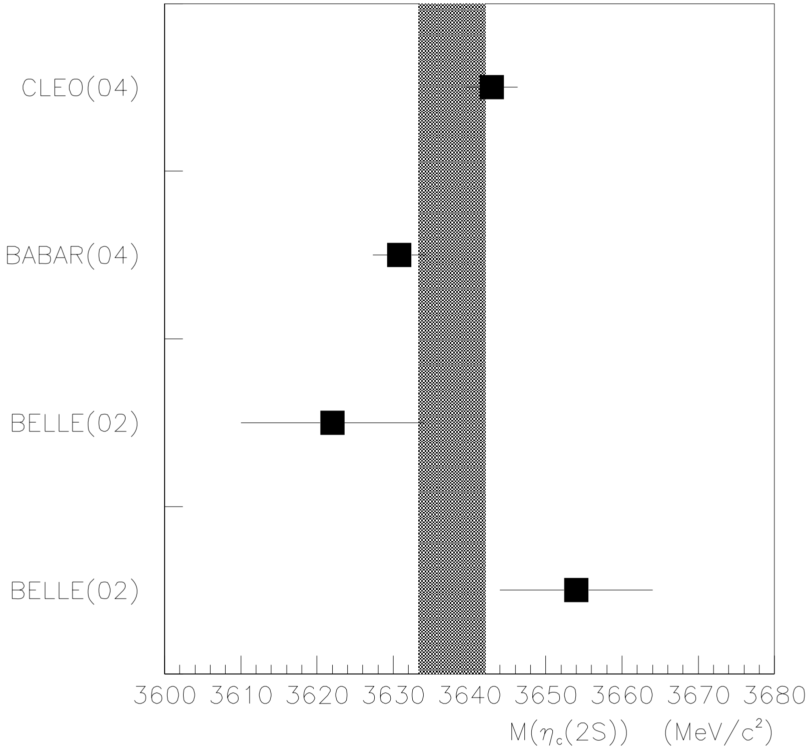
$$\Gamma = 15 \pm 24(stat)\ MeV$$



$\gamma\gamma \rightarrow \eta_c(2^1S_0)$



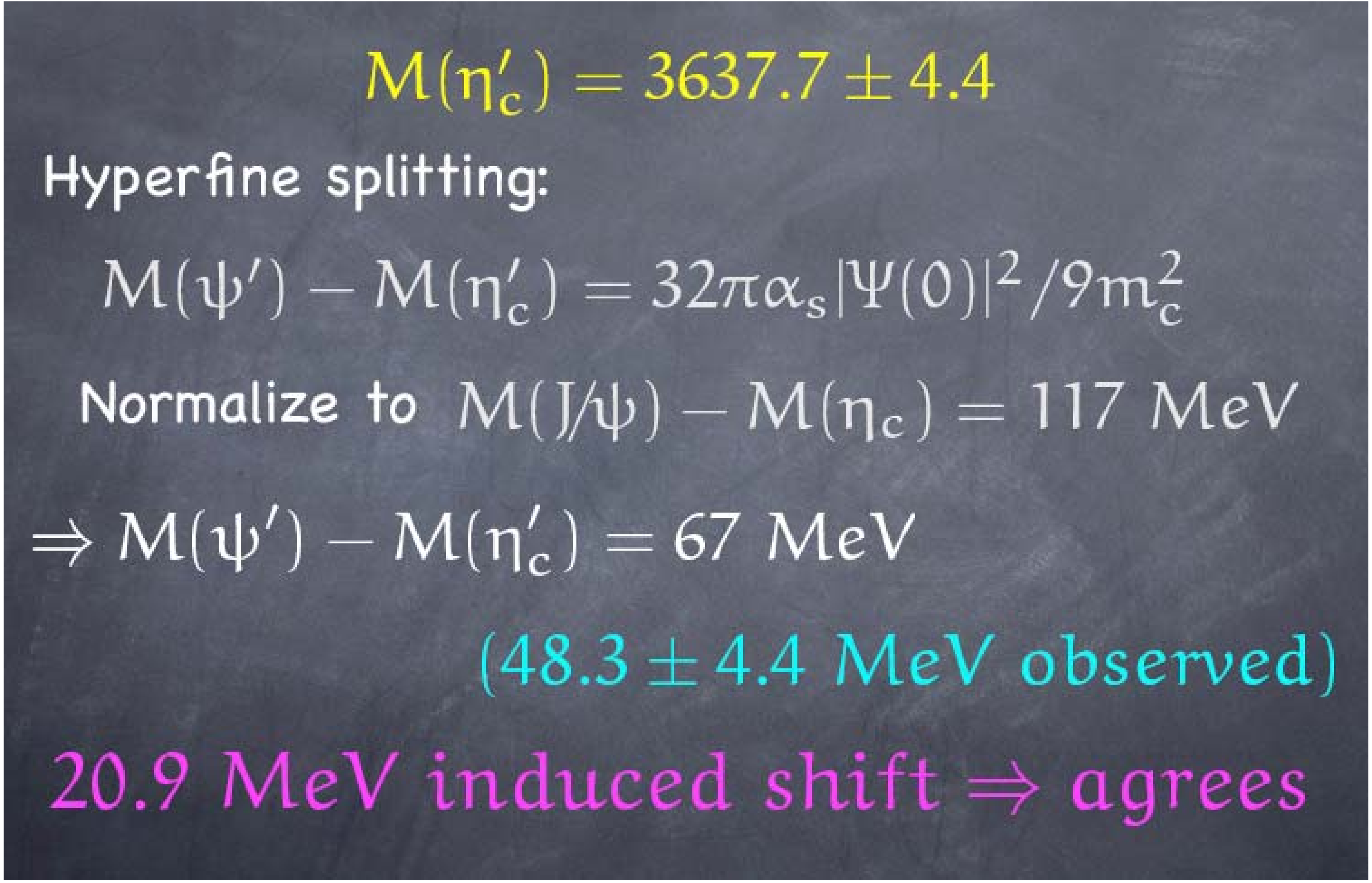




$M(\eta'_c) = 3637.7 \pm 4.4$ MeV/c^2

BaBar: $\Gamma(\eta'_c) = 17.0 \pm 8.3 \pm 2.5$ MeV

Effect of Coupled Channel on the Mass Spectrum



$$M(\eta_c') = 3637.7 \pm 4.4$$

Hyperfine splitting:

$$M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$$

Normalize to $M(J/\psi) - M(\eta_c) = 117\ \mathrm{MeV}$

$$\Rightarrow M(\psi') - M(\eta_c') = 67\ \mathrm{MeV}$$

(48.3 ± 4.4 MeV observed)

20.9 MeV induced shift ⇒ agrees

Estia Eichten – BaBar workshop on heavy quark and exotic spectroscopy

The $h_c(1^1P_1)$

Precise measurements of the parameters of the h_c give extremely important information on the spin-dependent component of the $q\bar{q}$ confinement potential. The splitting between triplet and singlet is given by the spin-spin interaction (hyperfine structure).

$$V_{SS} = \frac{2\left(\vec{S}_1 \cdot \vec{S}_2\right)}{3m_c^2} \nabla^2 V_V(r)$$

If the vector potential is 1/r (one gluon exchange) than the expectation value of the spin-spin interaction for P states (whose wave function vanishes at the origin) should be zero. In this case the h_c should be degenerate in mass with the center-of-gravity of the χ_{cJ} states. A comparison of the h_c mass with the masses of the triplet P states measures the deviation of the vector part of the $q\bar{q}$ interaction from pure one-gluon exchange.

Total width and partial width to $\eta_c+\gamma$ will provide an estimate of the partial width to gluons.

Expected properties of the $h_c(^1P_1)$

- Quantum numbers $J^{PC}=1^{+-}$.
- The mass is predicted to be within a few MeV of the center of gravity of the $\chi_c(^3P_{0,1,2})$ states

$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

- The width is expected to be small $\Gamma(h_c) \leq 1$ MeV.
- The dominant decay mode is expected to be $\eta_c+\gamma$, which should account for ≈ 50 % of the total width.
- It can also decay to J/ψ:

$J/\psi + \pi^0$	violates isospin
$J/\psi + \pi^+\pi^-$	suppressed by phase space and angular momentum barrier

The $h_c(^1P_1)$ E760 observation

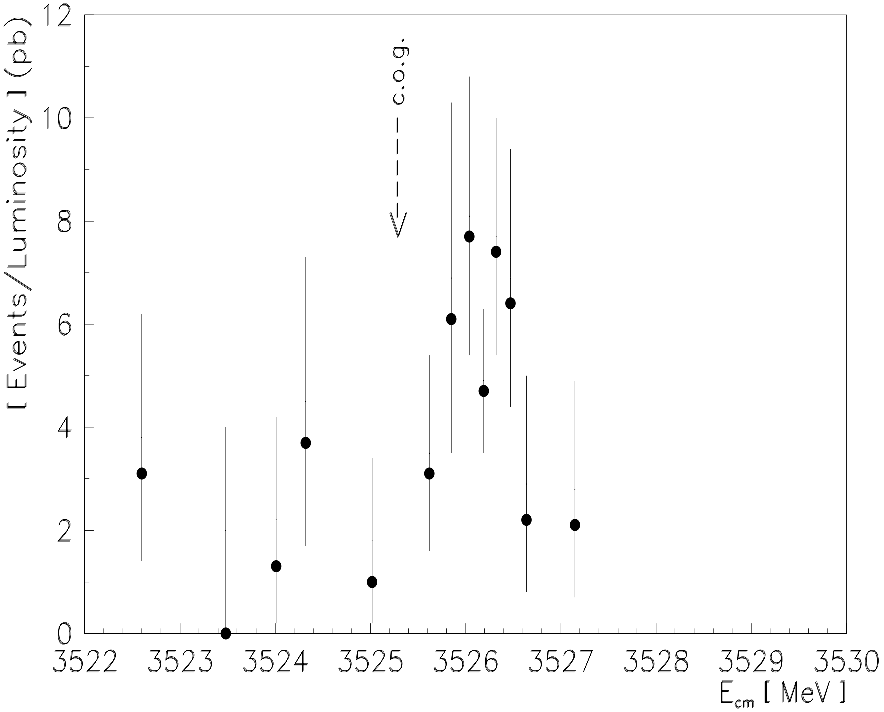
A signal in the h_c region was seen by E760 in the process:

$$\bar{p}p \to h_c \to J/\psi + \pi^0$$

Due to the limited statistics E760 was only able to determine the mass of this structure and to put an upper limit on the width:

$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$

$$\Gamma(h_c) < 1.1\ MeV\ (90\%CL)$$



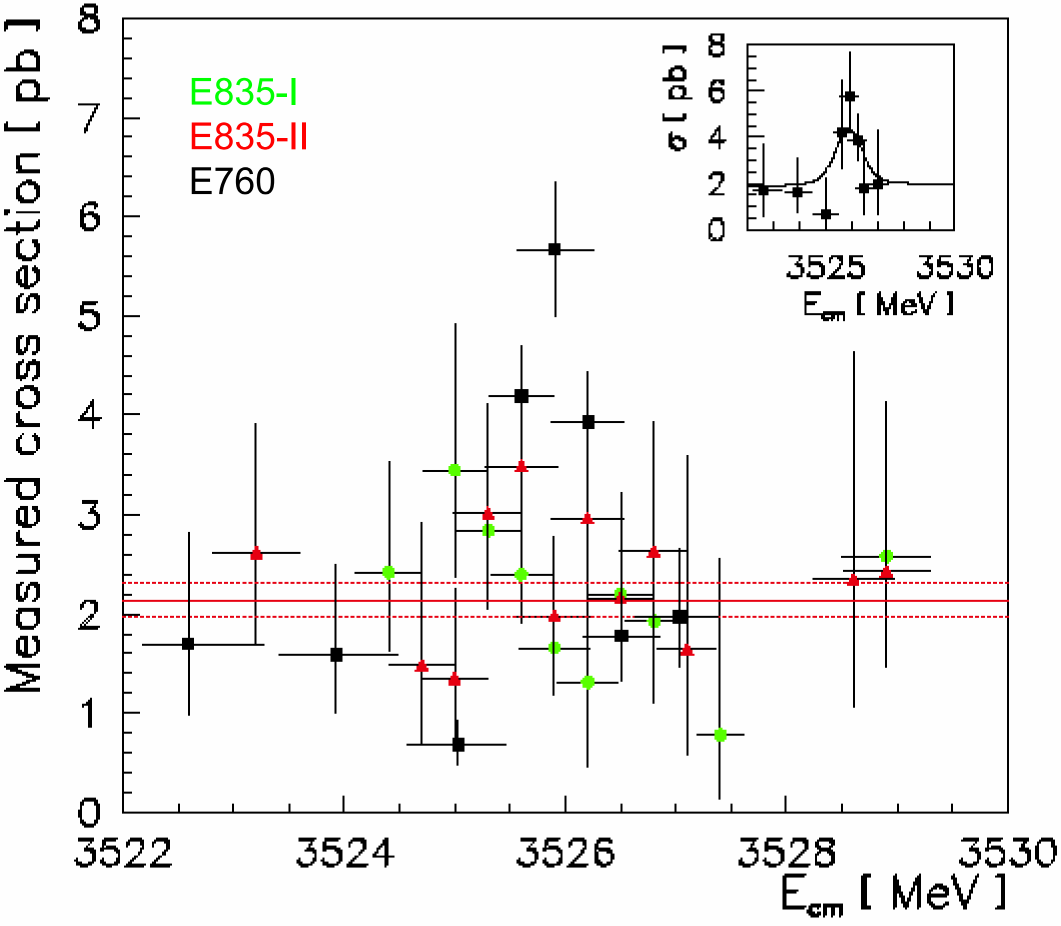
$$\frac{B(J/\psi\pi\pi)}{B(J/\psi\pi^0)} \leq 0.18 \quad (90\%C.L.)$$

$$(1.8 \pm 0.4) \times 10^{-7} < B(p\bar{p})B(J/\psi\pi^0) < (2.5 \pm 0.6) \times 10^{-7}$$

The $h_c(^1P_1)$ E835 search

- E835 took the following data in 2 running periods:
  - 90 pb^{-1} in the χ_{cJ} c.o.g. region.
  - data taken outside this energy region for background studies, providing 120 pb^{-1} for the $\eta_c\gamma$ mode and 80 pb^{-1} for the $J/\psi\pi^0$ mode.
- Very careful beam energy studies. All single χ_{c1} and χ_{c2} stacks taken in E835 have been preliminarly analyzed, to find $\sigma(E_{cm})_{run/run}$ better then 100 keV in both data taking periods.
- Not just a cross check: new measurements of the χ_{cJ} parameters.

E835 Results for $h_c \to J/\psi\pi^0$



no evidence for $h_c \to J/\psi\pi^0$.

$$B(p\bar{p})B\left(J/\psi\pi^0\right) \leq 0.6 \times 10^{-7}$$

E835 Results for $h_c \to \eta_c\gamma$

Observe excess of events in $\eta_c\gamma$ mode. Background hypothesis rejected with $\mathcal{P} = 0.001$.

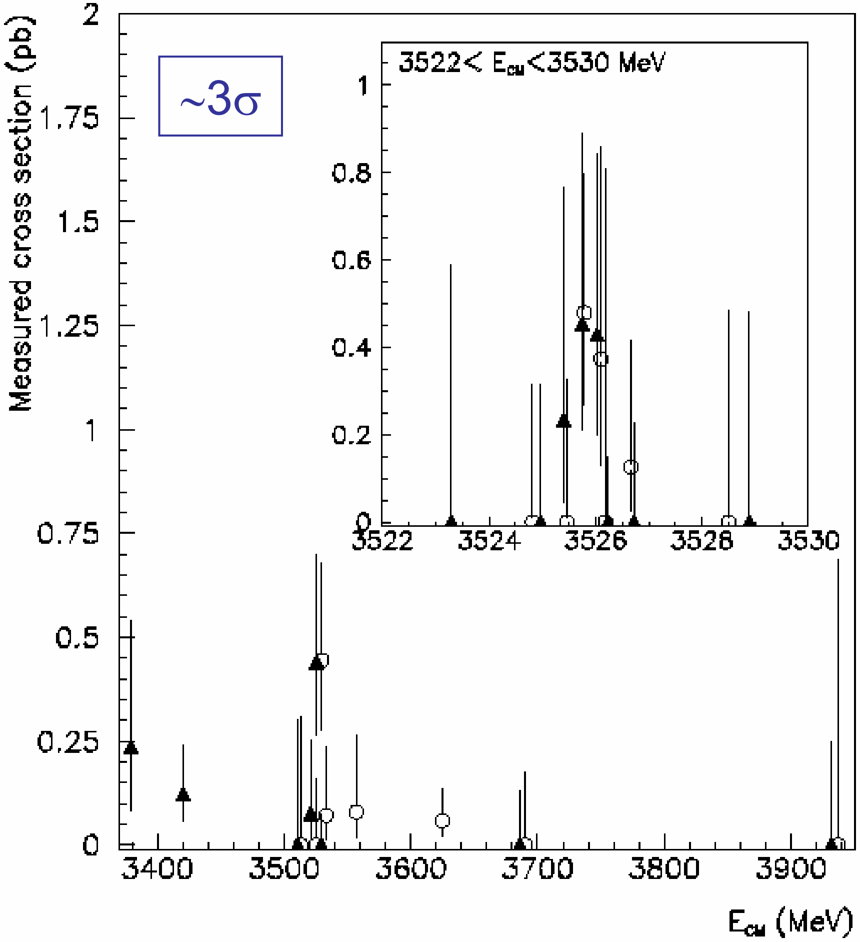
$$M(h_c) = 3525.8 \pm 0.2 \pm 0.2\ MeV/c^2$$

$$\Gamma(h_c) \leq 1\ MeV$$

$$\Gamma(p\bar{p})B(\eta_c\gamma) \leq 12.0 \pm 4.5\ eV$$

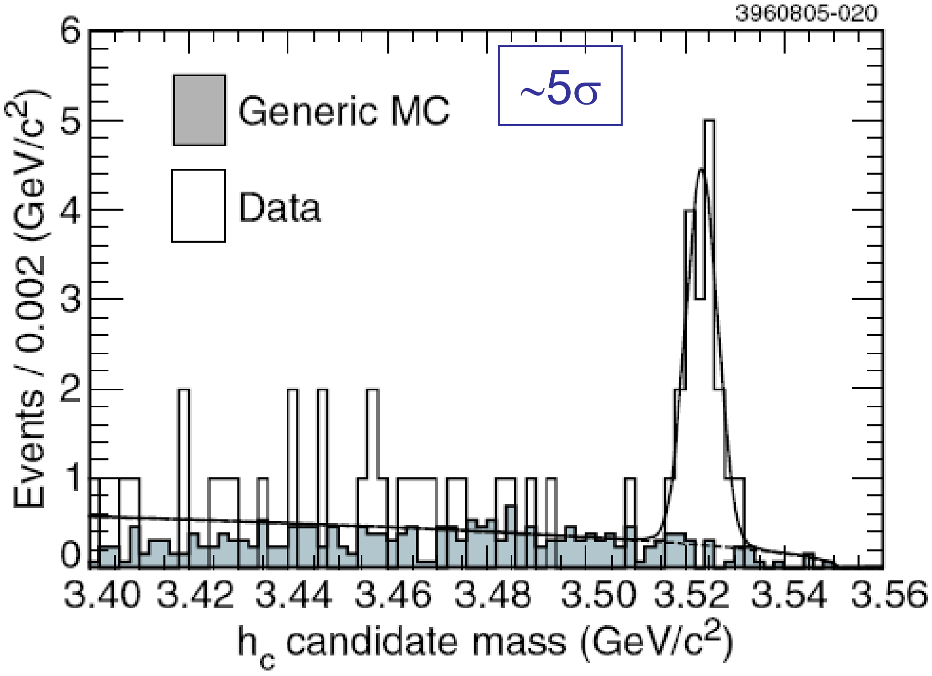
cfr E760 value:

$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$



h_c Observation at CLEO

$e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c$
$h_c \rightarrow \eta_c \gamma \quad \eta_c \rightarrow \text{hadrons}$



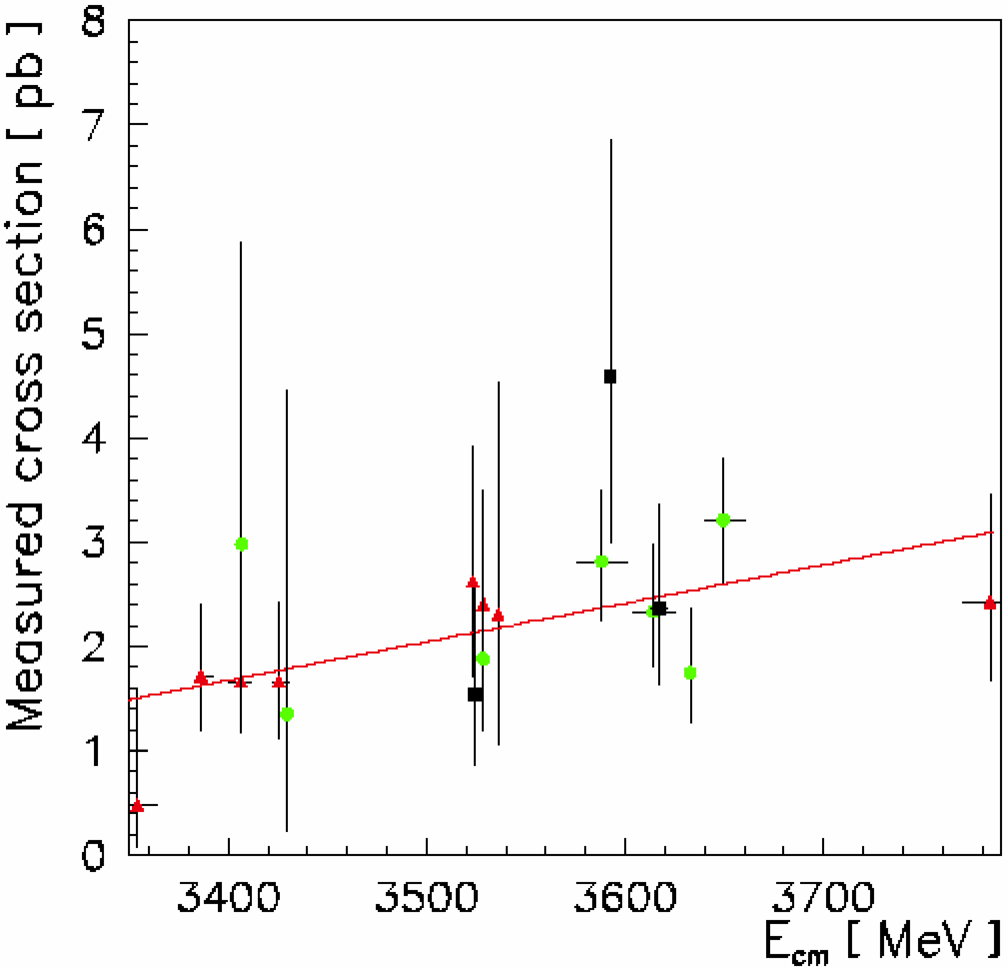
$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV/c^2$$

Other $h_c(^1P_1)$ Searches

- The E705 experiment at Fermilab observed an enhancement in the $J/\psi\pi^0$ mass spectrum at 3527 MeV/c^2 in $\pi^\pm$-Li interactions at 300 GeV/c incident momentum. The magnitude of this effect is 42±17 events above background, corresponding to a 2.5σ significance. Due to its vicinity to M_{cog} E705 interpreted this signal as due to the production of the h_c and its decay to $J/\psi\pi^0$.
- The BaBar collaboration has recently reported on a search for the h_c in the B decay process $B \rightarrow K+h_c \rightarrow K+J/\psi+\pi^++\pi^-$. The absence of a signal allowed the collaboration to set the following upper limit on the product of branching ratios (at 90 % C.L.):

$$B\left(B^- \rightarrow h_c + K\right) \times B(h_c \rightarrow J/\psi + \pi^+ + \pi^-) < 3.4 \times 10^{-6}$$

$\bar{p}p \to J/\psi + \pi^0$ from continuum

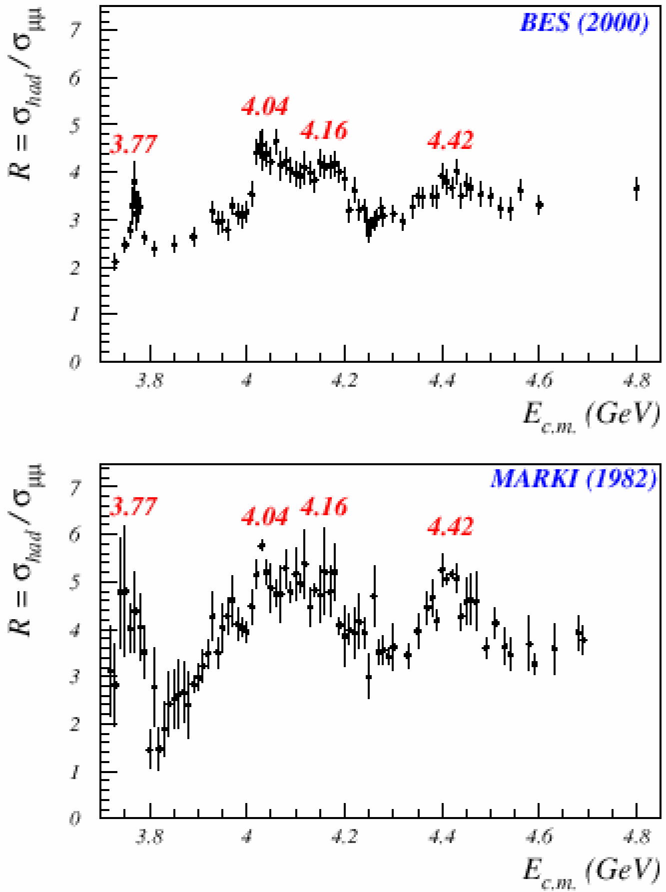


M. Andreotti et al., PRD 72, 032001(2005)

Charmonium States above the $D\bar{D}$ threshold

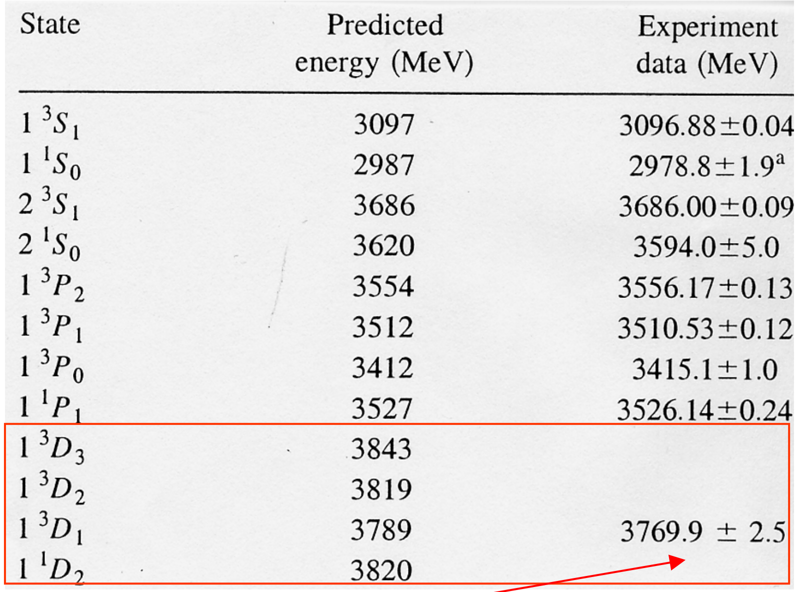
The energy region above the $D\bar{D}$ threshold at 3.73 GeV is very poorly known. Yet this region is rich in new physics.

- The structures and the higher vector states ($\psi(3S)$, $\psi(4S)$, $\psi(5S)$ ...) observed by the early e+e- experiments have not all been confirmed by the latest, much more accurate measurements by BES.
- This is the region where the first radial excitations of the singlet and triplet P states are expected to exist.
- It is in this region that the narrow D-states occur.



The D wave states

- The charmonium "D states" are above the open charm threshold (3730 MeV) but the widths of the J= 2 states $^3D_2$ and $^1D_2$ are expected to be small:



State	Predicted energy (MeV)	Experiment data (MeV)
$1\,^3S_1$	3097	3096.88±0.04
$1\,^1S_0$	2987	2978.8±1.9[a]
$2\,^3S_1$	3686	3686.00±0.09
$2\,^1S_0$	3620	3594.0±5.0
$1\,^3P_2$	3554	3556.17±0.13
$1\,^3P_1$	3512	3510.53±0.12
$1\,^3P_0$	3412	3415.1±1.0
$1\,^1P_1$	3527	3526.14±0.24
$1\,^3D_3$	3843	
$1\,^3D_2$	3819	
$1\,^3D_1$	3789	3769.9 ± 2.5
$1\,^1D_2$	3820	

$^{1,3}D_2 \not\to \overline{D}D$ forbidden by parity conservation

$^{1,3}D_2 \not\to \overline{D}D^*$ forbidden by energy conservation

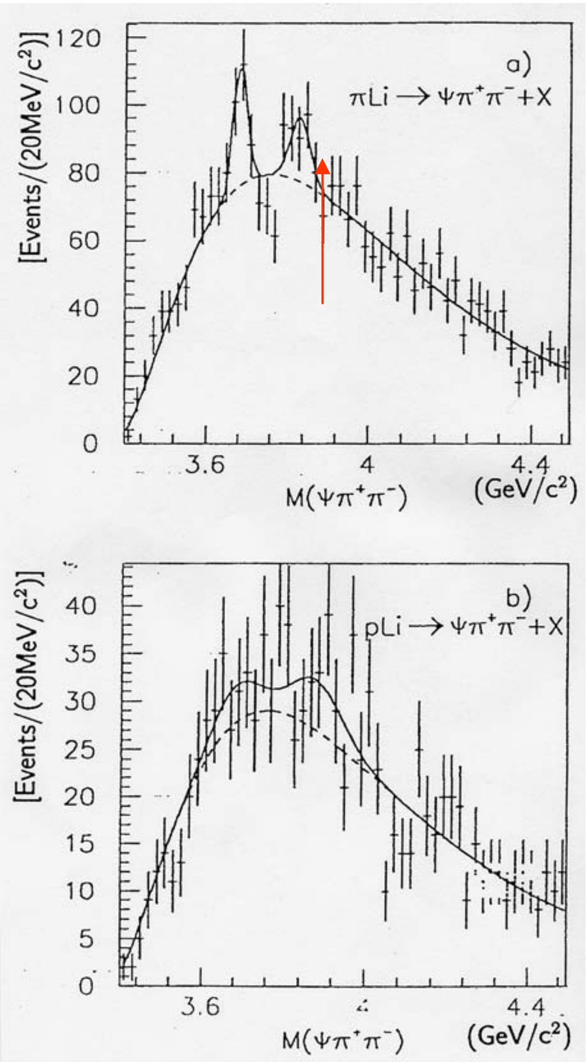
Only the $\psi(3770)$, considered to be largely $^3D_1$ state, has been clearly observed. It is a wide resonance ($\Gamma(\psi(3770)) = 25.3 \pm 2.9$ MeV) decaying predominantly to $D\bar{D}$. A recent observation by BES of the $J/\psi\pi^+\pi^-$ decay mode was not confirmed by CLEO-c.

The D wave states

- The only evidence of another D state has been observed at Fermilab by experiment E705 at an energy of 3836 MeV/c², in the reaction:

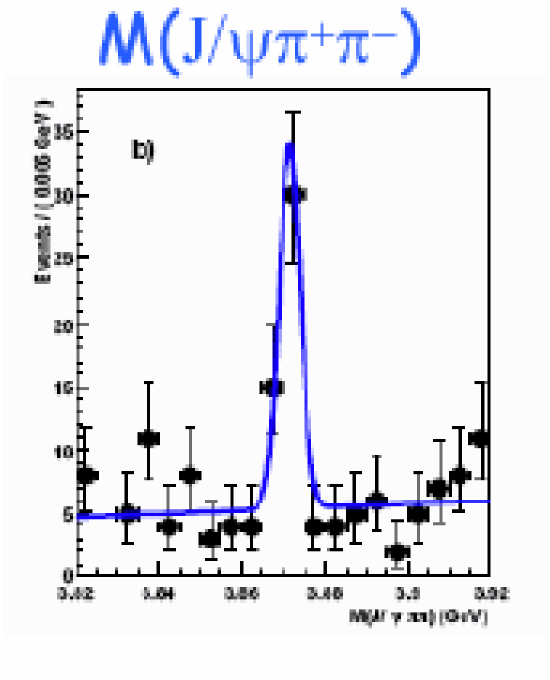
$$\pi Li \rightarrow J/\psi\pi^{+}\pi^{-} + X$$

- This evidence was not confirmed by the same experiment in the reaction $pLi \rightarrow J/\psi\pi^{+}\pi^{-} + X$ and more recently by BES



X(3872)

The X(3872) Discovery



New state discovered by Belle in the hadronic decays of the B-meson:

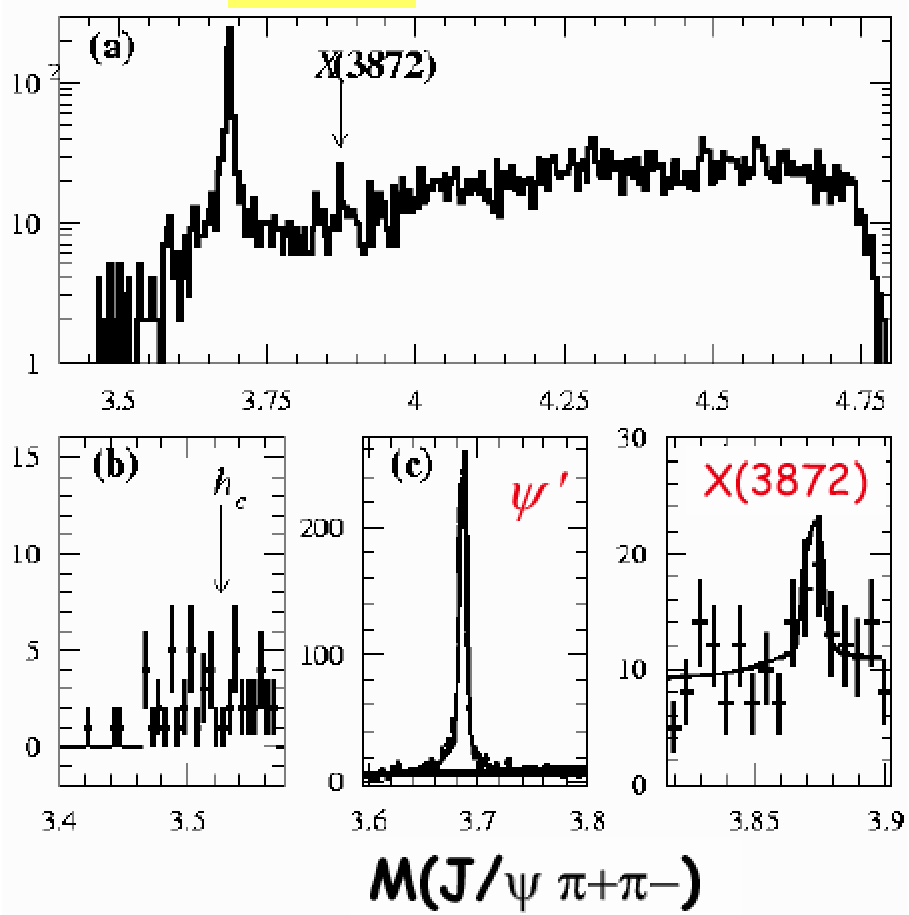
$B^\pm \to K^\pm (J/\psi\pi^+\pi^-)$, $J/\psi \to \mu^+\mu^-$ or e^+e^-

$M = 3872.0 \pm 0.6 \pm 0.5$ MeV
$\Gamma < 2.3$ MeV (90 % C.L.)

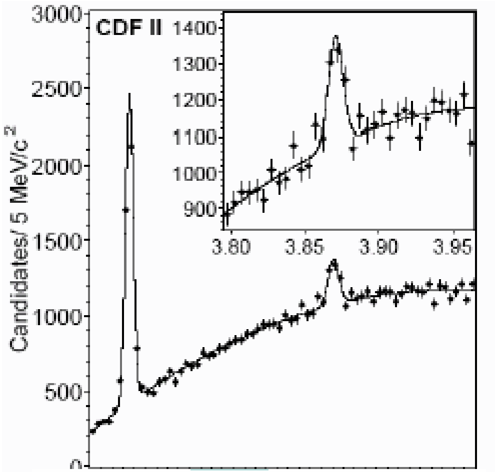
$$\frac{\Gamma\left(X(3872)\to\gamma\chi_{c1}\right)}{\Gamma\left(X(3872)\to\pi^+\pi^- J/\psi\right)} < 0.89 \quad (90\%\, C.L.)$$

The X(3872) Confirmation

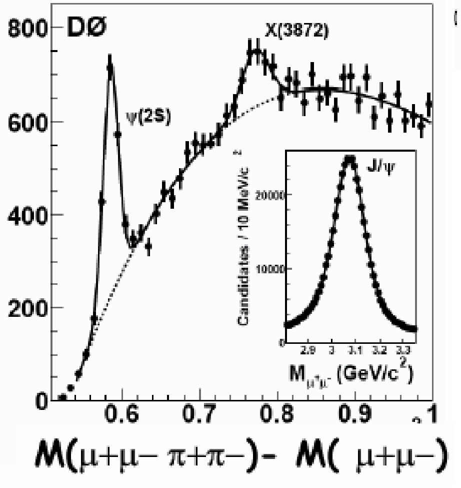
BaBar



CDF



D0



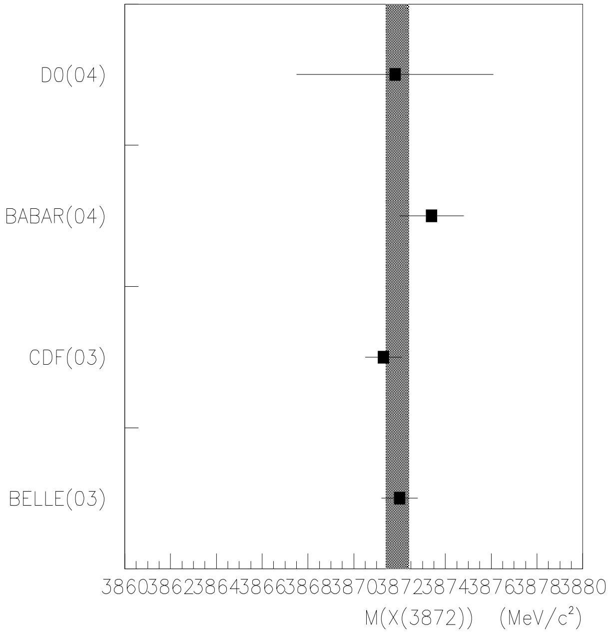
Mass and Width of the X(3872)

- The mass (3871.9 ± 0.5 MeV/c^2) is very close to the $D^0 \bar{D}^{*0}$ threshold.

$$M_X - \left(M_{D^{*0}} + M_{D^0}\right) = +0.6 \pm 1.1 MeV/c^2$$

dominated by error on D^0 mass.

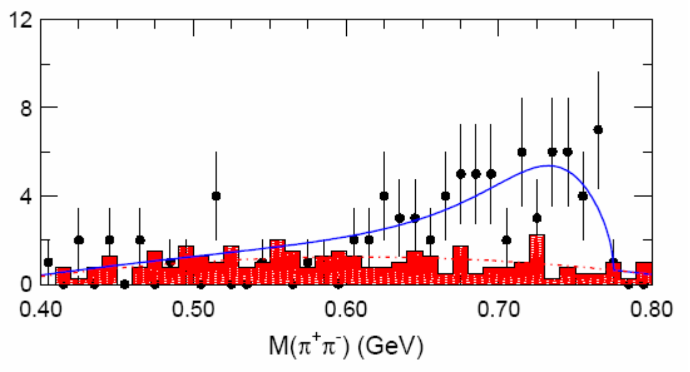
- The state is very narrow. The present limit by Belle is 2.3 MeV, compatible with a possible interpretation as $^3D_2$ or $^1D_2$.With a mass of 3872 MeV/c^2 both could decay to $D^0 \bar{D}^{*0}$, but the widths would still be very narrow. The $^3D_3$ could decay to $D \bar{D}$, but its f-wave decay would be strongly suppressed.



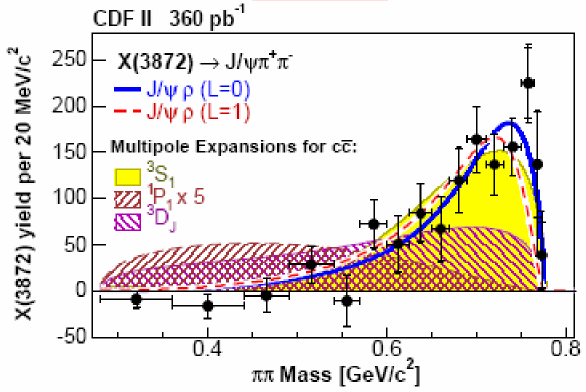
$\pi\pi$ Mass Distribution

In the $J/\psi\pi^+\pi^-$ decay the $\pi^+\pi^-$ mass distribution peaks at the kinematic limit, which corresponds to the ρ mass. The decay to $J/\psi\rho$ would violate isospin and should therefore be suppressed. Important to look for the $\pi^0\pi^0$ decay mode, since the ρ cannot decay in this mode.

Belle

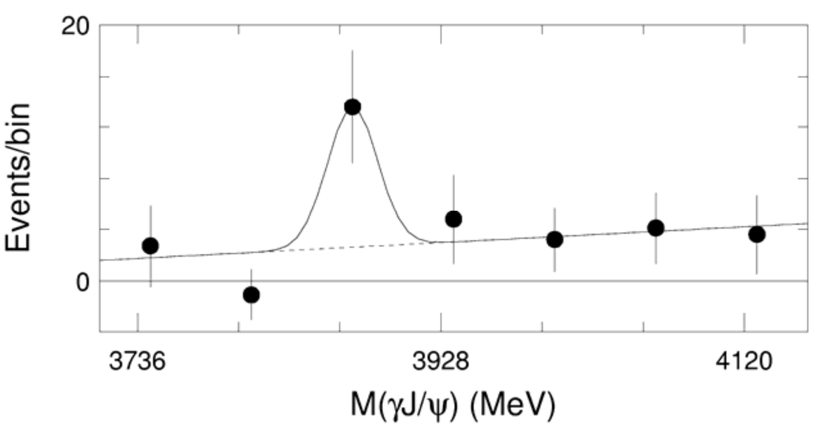


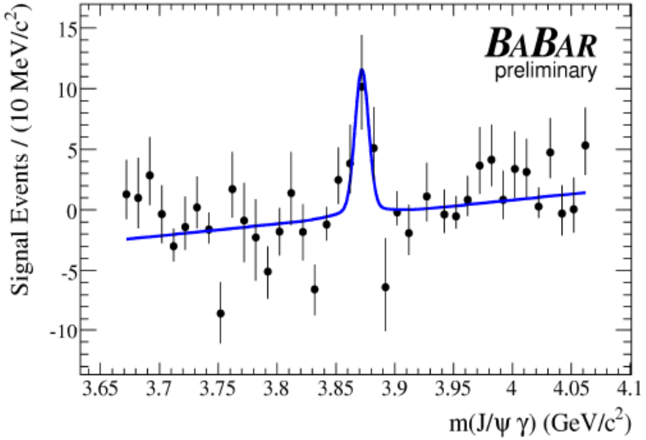
CDF



X(3872) Decays - I

Belle and BaBar detected the γJ/ψ decay mode





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

Belle

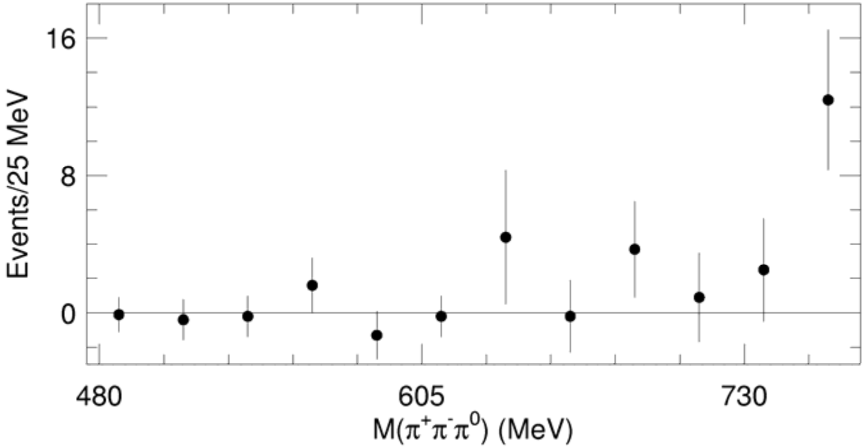
$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 0.34 \pm 0.14$$

BaBar

→ C=+1

X(3872) Decays - II

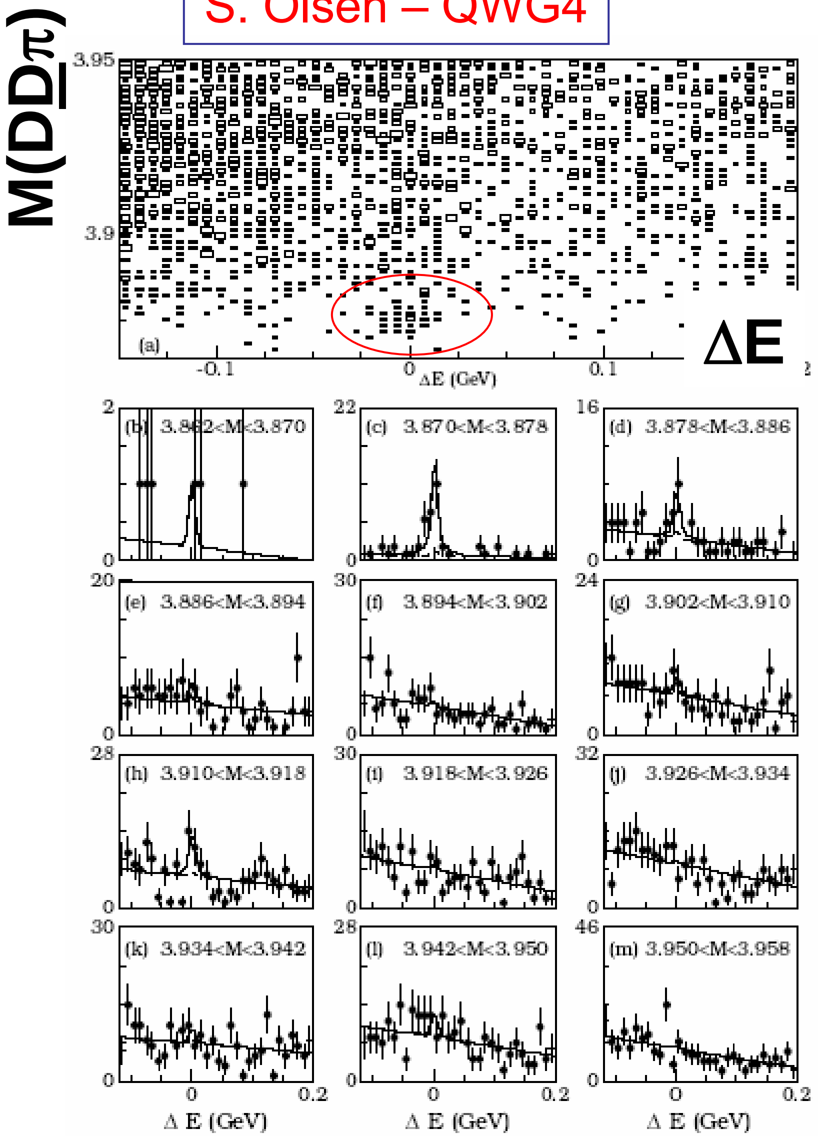
- The decays X(3872) → $\gamma\chi_{c1}$ and X(3872) → $\gamma\chi_{c2}$ have been unsuccessfully looked for by Belle. This makes the $^3D_2$ and $^3D_3$ interpretations problematic.
- The decay X(3872)→$J/\psi\eta$ has been unsuccessfully looked for by BaBar. This is a problem for the charmonium hybrid interpretation.
- The decay X(3872) → $\omega J/\psi \rightarrow \pi^+\pi^-\pi^0 J/\psi$ seen by Belle.

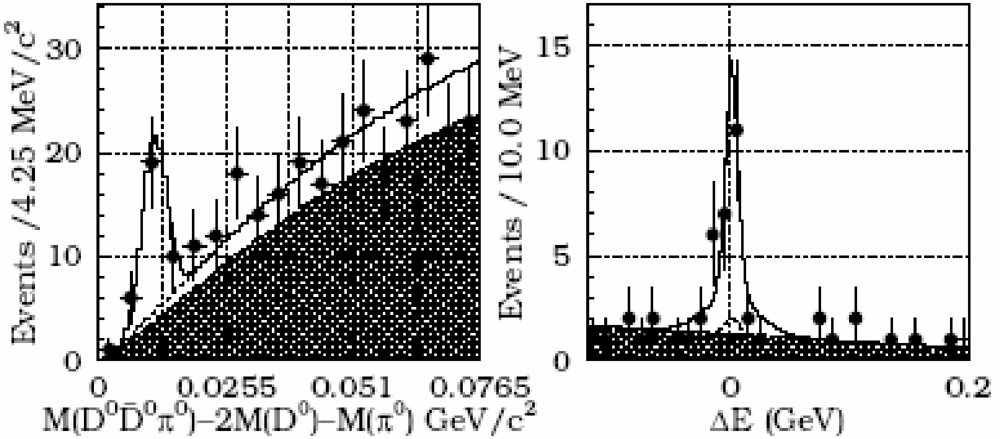


X(3872) Decays III:
Threshold peak in $B \rightarrow K D^0 \underline{D}^0 \pi^0$ observed by Belle

S. Olsen – QWG4

Belle hep-ex/0606055 ← today!





$$M = 3875.4 \pm 0.7\ {}^{+0.7}_{-1.7} \pm 0.8\ \text{MeV}$$

$$Br(B \rightarrow KX)Bf(X \rightarrow D^0\underline{D}^0\pi^0)$$
$$= (1.27 \pm 0.31{}^{+0.22}_{-0.39})\times 10^{-4}$$

$$\frac{Br(X \rightarrow D^0\underline{D}^0\pi^0)}{Br(X \rightarrow \pi^+\pi^- J/\psi)} \sim 10$$

X(3872) Quantum Numbers

- Non observation in ISR (BaBar, CLEO) rules out $J^{PC}=1^{--}$.
- $\gamma J/\psi$ decay implies C = +1.
- From $\pi\pi J/\psi$ decay:
  - Angular correlations (Belle and CDF) rule out 0^{++} and 0^{-+}.
  - Mass distribution rules out 1^{-+} and 2^{-+}.
- $D^0 \bar{D}^0 \pi^0$ decay mode rules out 2^{++}.

Most likely assignment is $J^{PC}=1^{++}$.

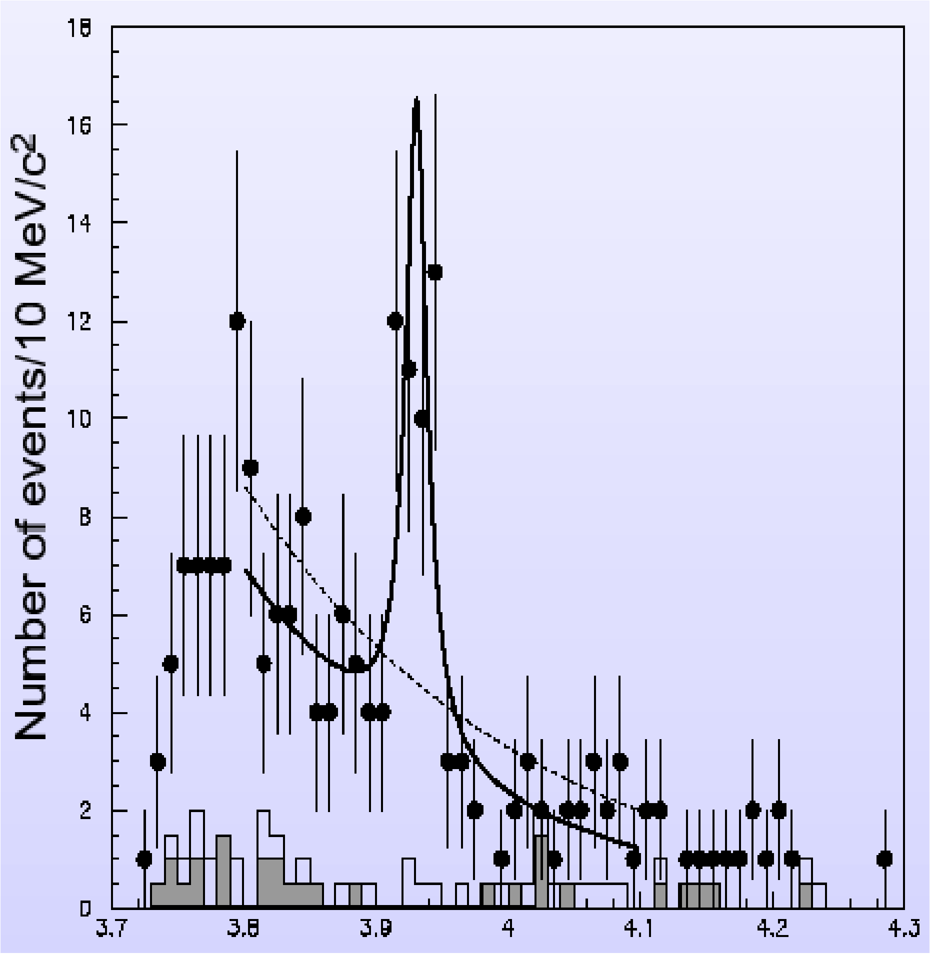
What is the X(3872) ?

- If X(3872) is a charmonium state, the most natural hypotheses are the 1^3D_2 and 1^3D_3 states. In this case the non-observation of the expected radiative transitions is a potential problem, but the present experimental limits are still compatible with these hypotheses.
- The charmonium hybrid ($c\bar{c}g$) interpretation has been proposed by Close and Godfrey. However present calculations indicate higher mass values (around 4100 MeV/c^2) for the ground state. Absence of $J/\psi\eta$ mode a potential problem.
- A tetraquark.
- A glueball.
- Due to its closeness to the $D^0 \bar{D}^{*0}$ threshold the X(3872) could be a $D^0 \bar{D}^{*0}$ molecule. In this case decay modes such as $D^0 \bar{D}^0 \pi^0$ might be enhanced. Most likely interpretation ?

Further experimental evidence needed: search for charged partners, search for further decay modes, in particular the radiative decay modes.

Z(3931)

New state observed by Belle in $\gamma\gamma \rightarrow Z(3931) \rightarrow D\ \bar{D}$

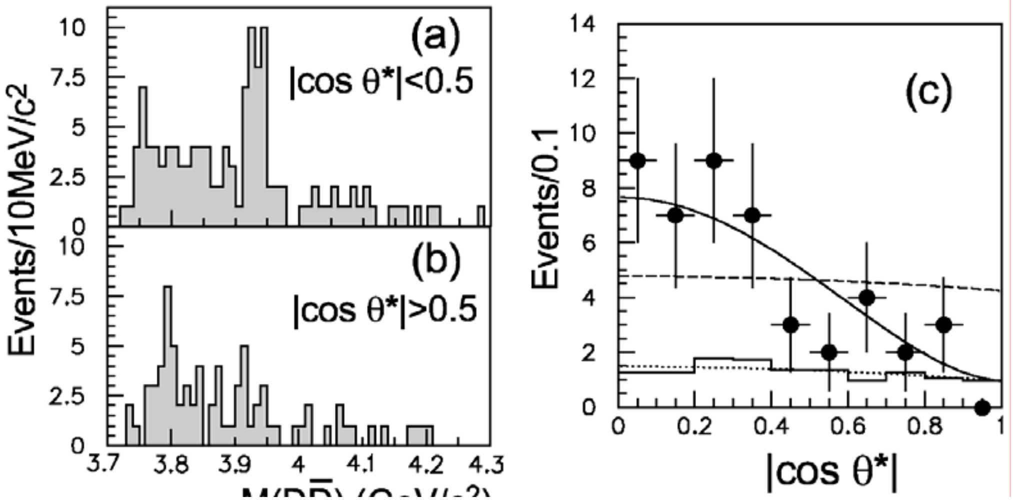


41± 11 evts (5.5σ)

M=3931 ± 4 ± 2 MeV

Γ=20±8 ±3 MeV

What is the Z(3931) ?



$\sin^4\theta$ (J=2)

J=2 favored

Matches well expectations for χ_{c2}(2P).

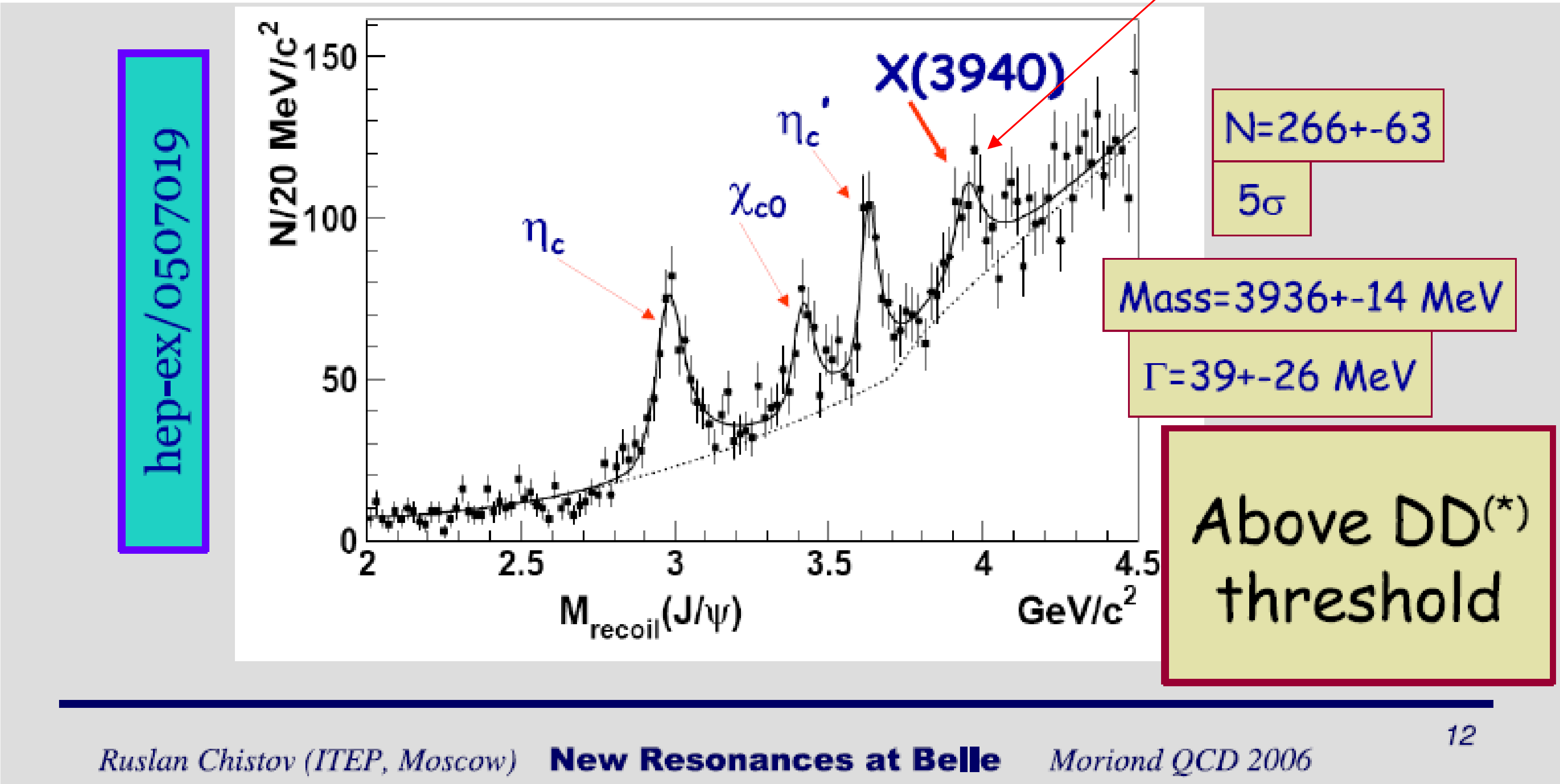
Issues:

- Z → DD^*.
- χ_{c2}(2P) < χ_{c1}(2P) (if one of the 3940s).
- χ_{c2}(2P) → ψ(2S)γ.

X(3940)

$e^+ e^- \to J/\psi + X$ (double $c\bar{c}$)

η_c'' ?



hep-ex/0507019

N=266+-63

5σ

Mass=3936+-14 MeV

Γ=39+-26 MeV

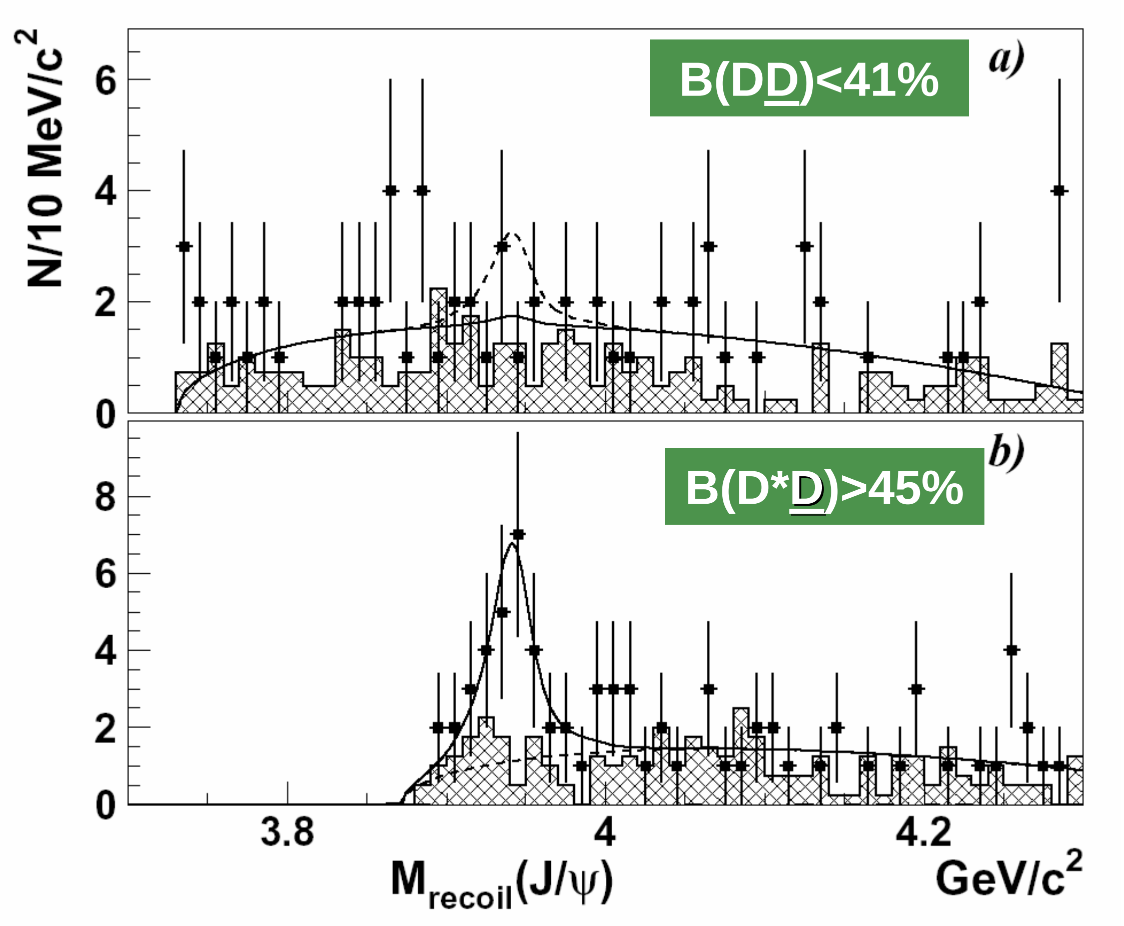
Above $DD^{(*)}$ threshold

Ruslan Chistov (ITEP, Moscow) **New Resonances at Belle** *Moriond QCD 2006* 12

What is the X(3940) ?

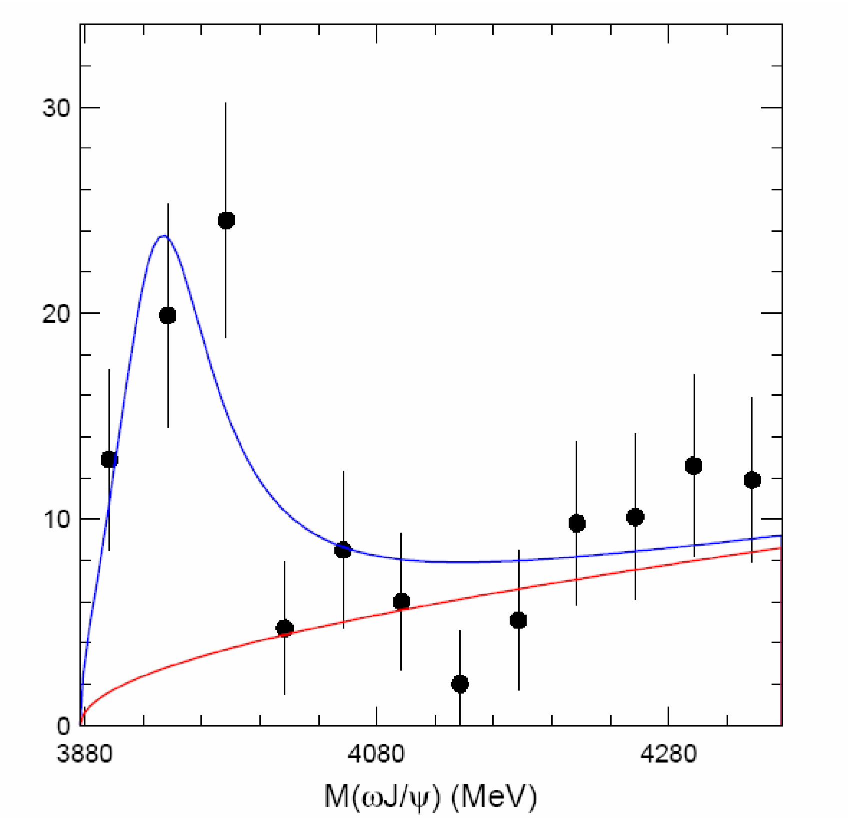
- Observed in double charmonium production.
- Observed decay in DD^*.
- Decays to $\omega J/\psi$ and $\bar{D}D$ not seen by Belle (but limits are still high).

$\eta_c(3S)$ candidate



Y(3940)

New state observed by Belle in $B \to K\omega\, J/\psi$



$M \approx 3940 \pm 11$ MeV
$\Gamma \approx 92 \pm 24$ MeV

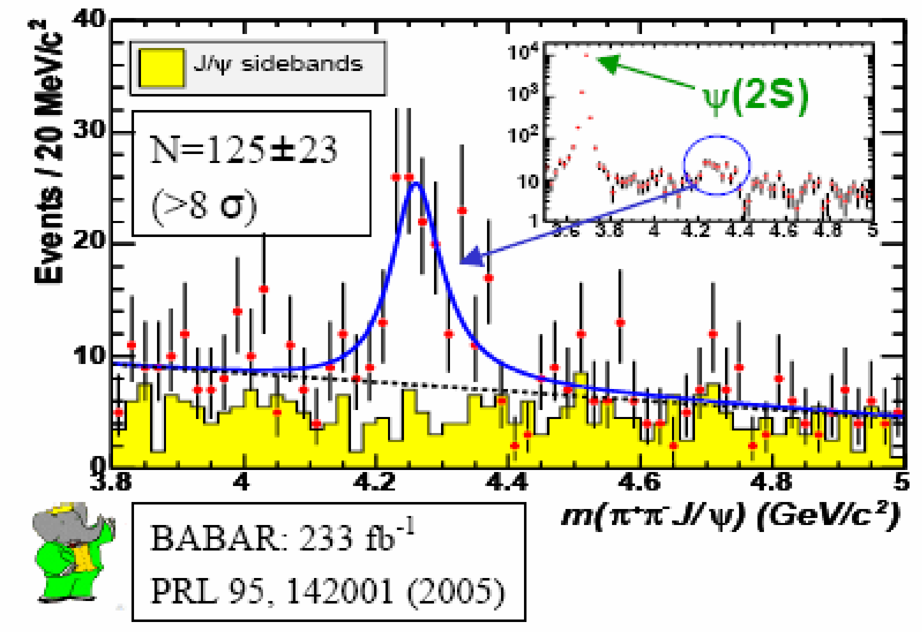
- Different production and decay modes from X(3940).
- Not seen in $D\bar{D}$ or DD*.
- $\mathcal{B}(\omega J/\psi) > 17\%$.
- $\mathcal{B}(B \to KY)\,\mathcal{B}(Y \to \omega J/\psi) = 5(9)(16) \times 10^{-5}$, converts into a partial width > 7 MeV !!!

What can the X(3940) be ?

- charmonium (χ_{c1}(2P)).
- threshold enhancement.
- charmonium hybrid.
- ...

Y(4260)

Y(4260) Discovery



N=125±23
(>8 σ)

BABAR: 233 fb^{-1}
PRL 95, 142001 (2005)

New state discovered by BaBar in ISR events:

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

Assuming single resonance:

$$M = 4259 \pm 8^{+2}_{-6}\ MeV/c^2$$

$$\Gamma = 88 \pm 23^{+6}_{-4}\ MeV$$

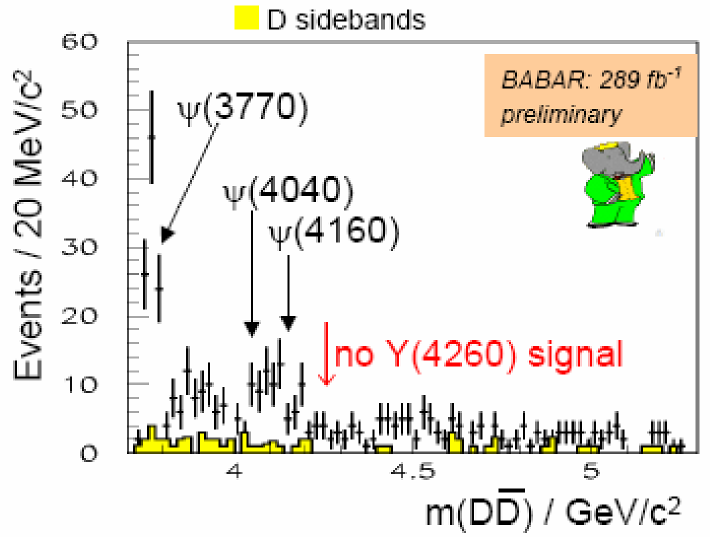
$J^{PC} = 1^{--}$

$$\sigma\left(e^+e^- \rightarrow Y, Y \rightarrow \pi^+\pi^- J/\psi\right) = (51 \pm 12)\,pb$$

$$\Gamma_{ee}^{Y} \times B(Y \rightarrow \pi^+\pi^- J/\psi) = \left(5.5 \pm 1.0^{+0.8}_{-0.7}\right) eV$$

Search for other decay modes in BaBar

$D\ \bar{D}$



No evidence found

$$\frac{B(Y(4260)\to D\bar{D})}{B(Y(4260)\to J/\psi\pi^+\pi^-)} < 7.6\ \ (95\%\ \mathrm{CL})$$

This ratio is ~500 for ψ(3770)
where $D\bar{D}$ is dominant

No signal observed in $\Phi\pi^+\pi^-$ or in $p\bar{p}$

$$\Gamma^{Y}_{ee} \times B(Y(4260)\to \phi\pi^+\pi^-) < 0.4\ \mathrm{eV}\ (90\%\ \mathrm{CL})$$

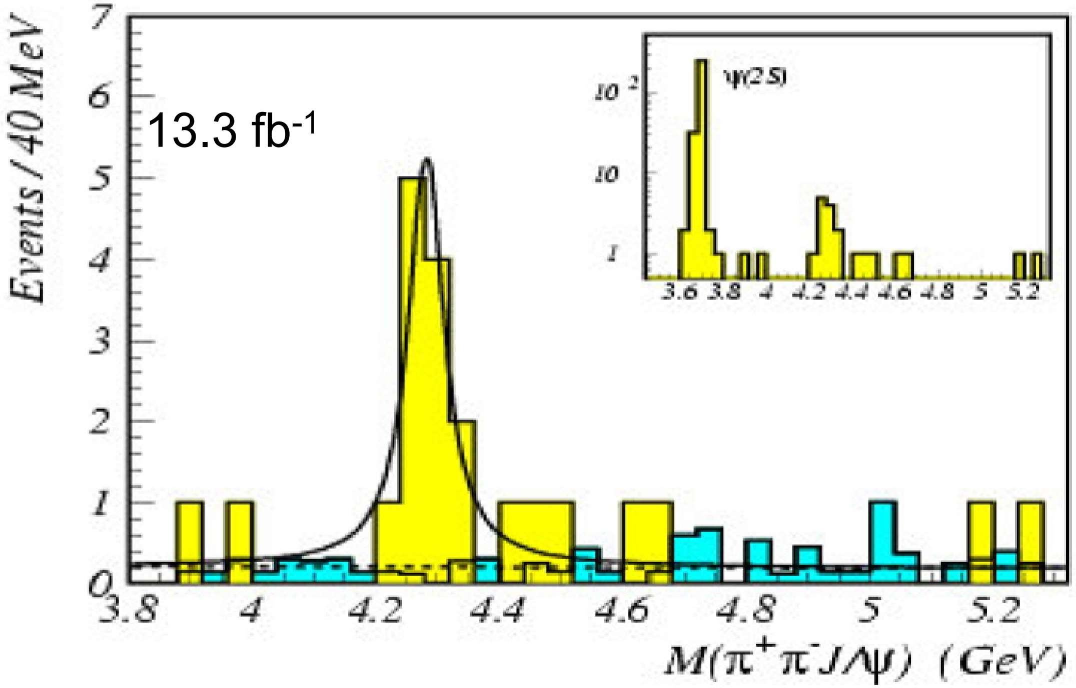
$$\frac{B(Y(4260)\to p\bar{p})}{B(Y(4260)\to J/\psi\pi^+\pi^-)} < 0.13\ (90\%\ \mathrm{CL})$$

Y(4260) confirmed by CLEO ...

ISR

Υ(1S)-Υ(4S)

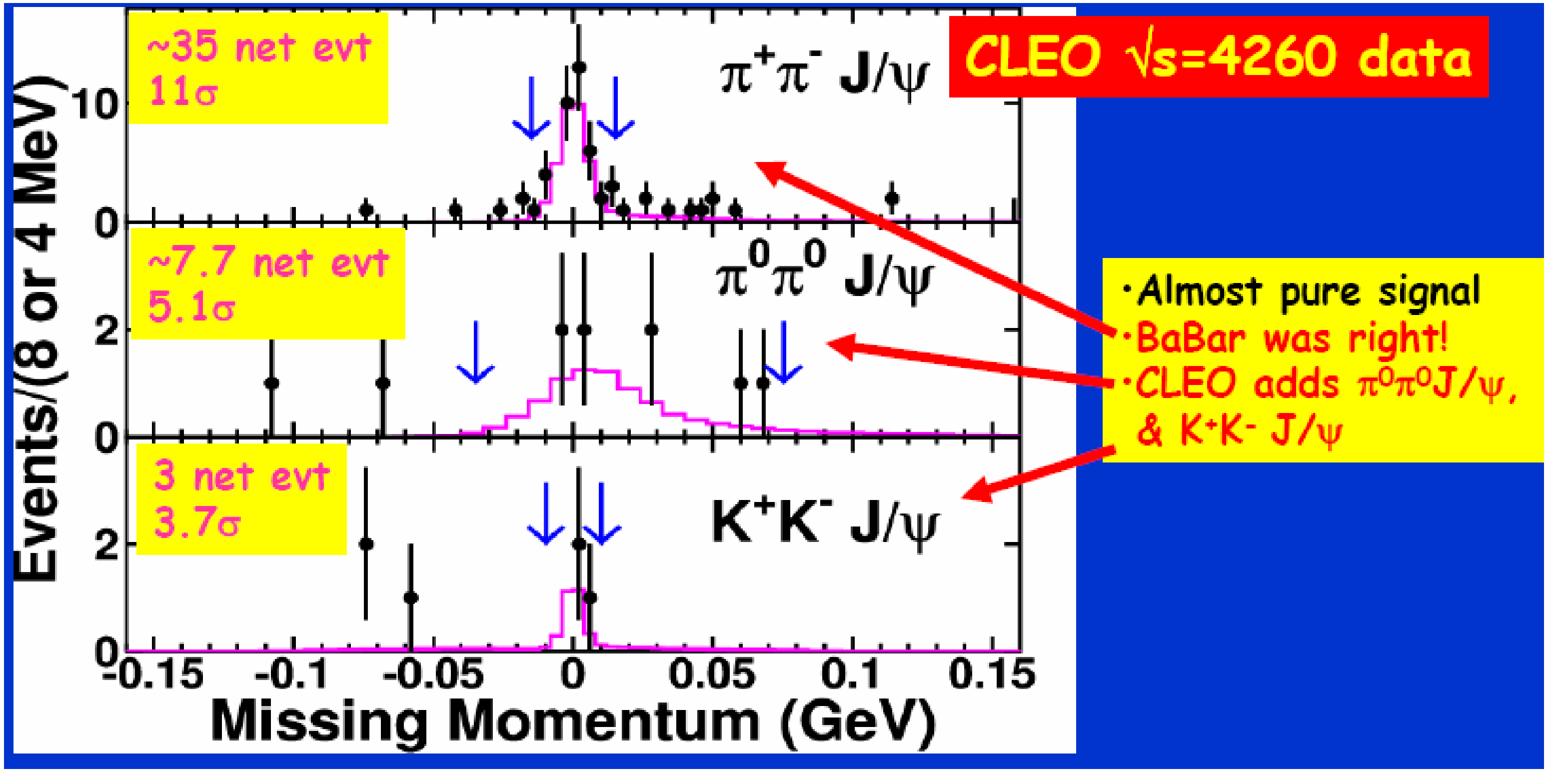
13.3 fb^{-1}



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

$$\Gamma = 70^{+40}_{-25} \pm 5\ MeV$$

... and by CLEO III



CLEO √s=4260 data

- Almost pure signal
- BaBar was right!
- CLEO adds $\pi^0\pi^0 J/\psi$, & $K^+K^- J/\psi$

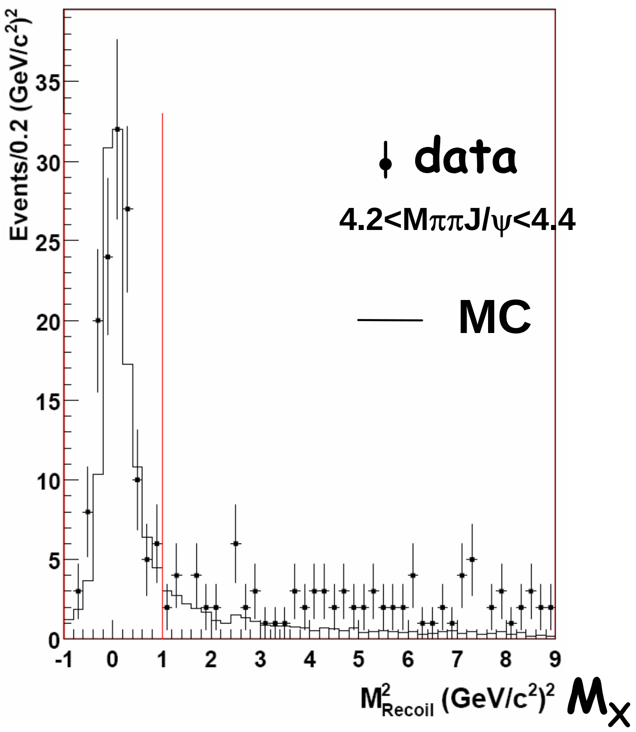
B. Heltsley – QWG4

Also observed in $\pi^+\pi^-\psi$ (0.39) and K^+K^-J/ψ (0.15).

Y(4260) at Belle

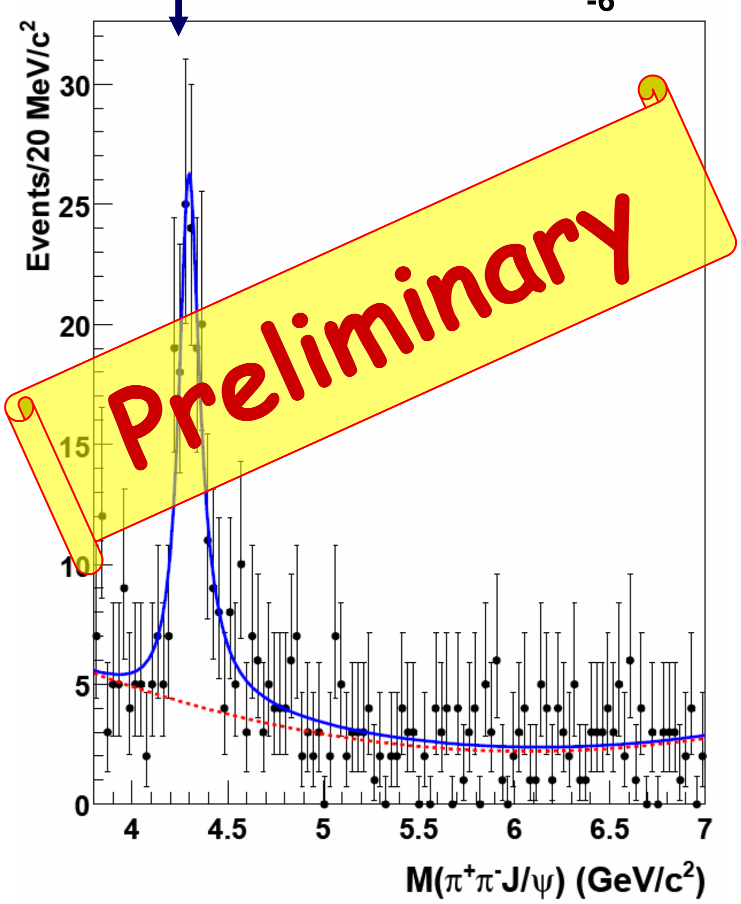
Select e+e-→ $\pi^+\pi^-\ \ell^+\ell^-$ +X; N_{chg}=4

$M_{\ell+\ell-}=M_{J/\psi}\pm30$MeV; $p_{J/y}>2$ GeV; $M_{\pi\pi}>0.4$GeV



$M=4295 \pm 10\ ^{+11}_{-5}$ MeV

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



For $\psi'\rightarrow\pi^+\pi^- J/\psi$ in the same data:

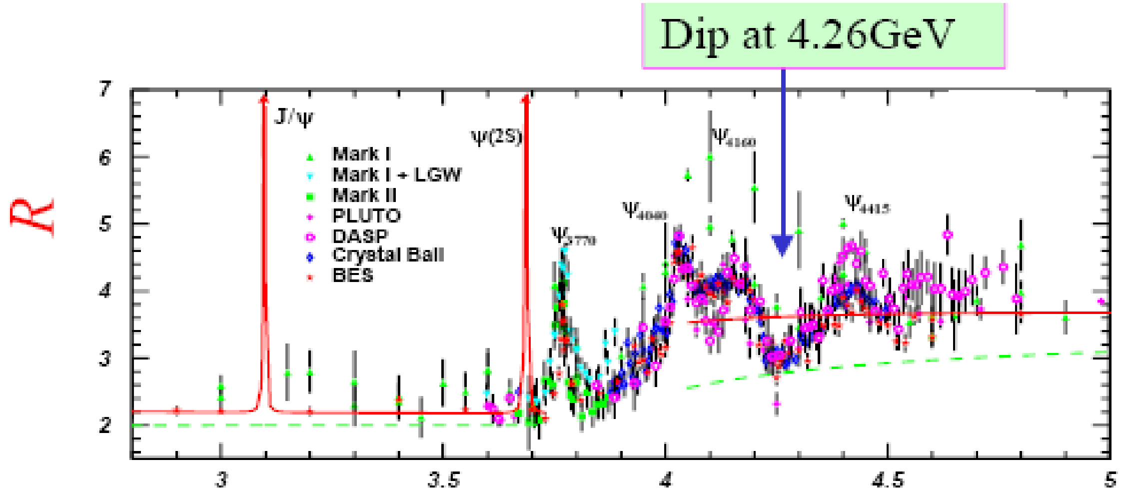
$M(\psi')$ = 3685.3 ± 0.1 MeV

(PDG: $M(\psi')$=3686.09 ± 0.04)

S. Olsen – QWG4

Properties of Y(4260)

Local minimum in $e^+e^- \to$ hadrons cross section.



Dip at 4.26GeV

~2.5σ discrepancy between BaBar and Belle mass measurements.

No available vector state slot in charmonium spectrum

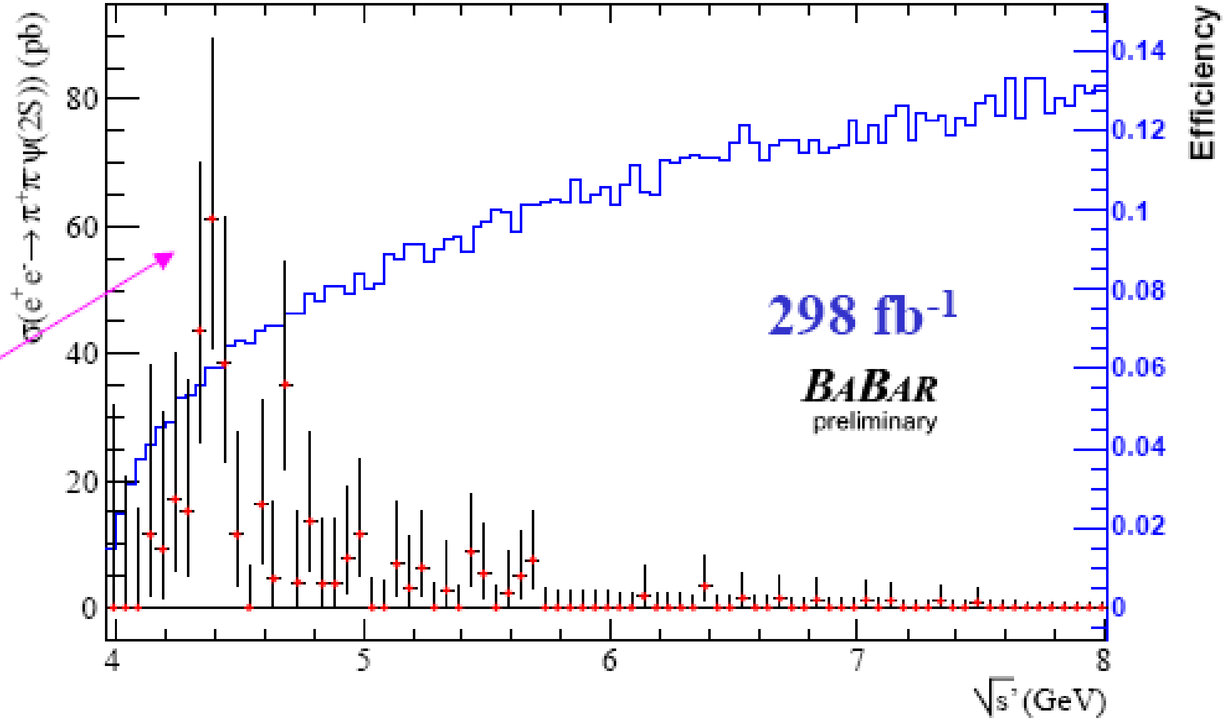
New Structure at 4350
in BaBar ISR data

Cross Section of $e^+e^- \to \psi(2S)\pi^+\pi^-$

w/ bkg subtraction

The maximum cross section is about **60 pb around 4.35 GeV**

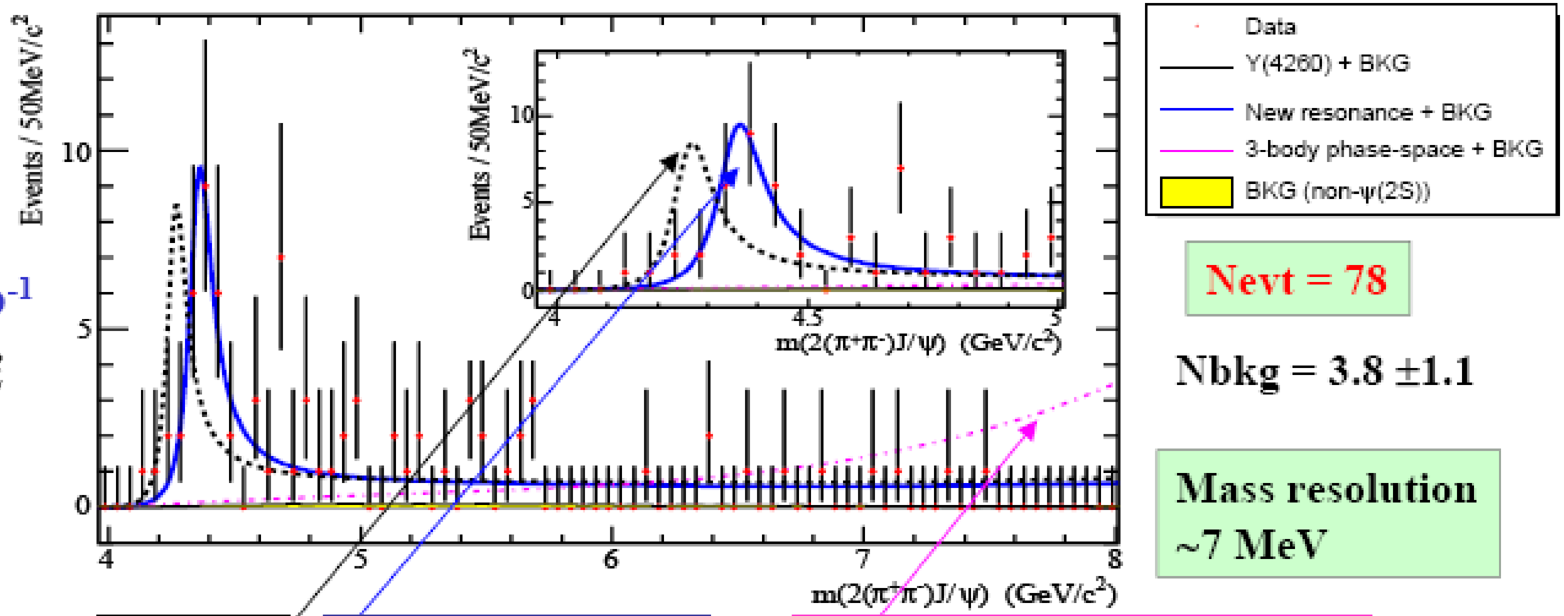
A structure!



S. Ye – QWG4

$298\ \mathrm{fb}^{-1}$

BABAR preliminary



Nevt = 78

Nbkg = 3.8 ±1.1

Mass resolution ~7 MeV

Y(4260)

Single Resonance

S-wave 3-body phase space

Incompatible with Y(4260), ψ(4415) or phase space.

Assuming single resonance:

$$M = 4354 \pm 16\ MeV / c^2$$
$$\Gamma = 106 \pm 19\ MeV$$

The Observables

The Physics Program of $\bar{\text{P}}$ANDA

- $\bar{p}p$ annihilation is unbeatable for the systematic, precise spectroscopy of known states:
  - Mass measurements with < 100 KeV accuracy
  - Total width determination, even for very narrow states
- $\eta_c(1S)$ mass, total width, decays.
- $\eta_c(2S)$ mass, total width, decays.
- h_c mass, total width, decays.
- angular distributions in the radiative decays of the χ_{cJ} states.
- J^{PC} of newly discovered states $\Rightarrow$ measure angular distributions.
- Systematic scan of region above $\bar{D}D$ threshold.
- Radiative and strong decays, e.g. $\psi(4040) \rightarrow D^* \bar{D}^*$ and $\psi(4160) \rightarrow D^* \bar{D}^*$, multi amplitude modes which can test the mechanisms of the open-charm decay.

Charmonium at $\bar{\text{P}}$ANDA

- At 2×10^{32}cm^{-2}s^{-1} accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) ⇒ $10^4\div10^7$ ($c\bar{c}$) states/day.
- Total integrated luminosity 1.5 fb^{-1}/year (at 2×10^{32}cm^{-2}s^{-1}, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs 2×10^{-4} (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).

The detector

- Detector Requirements:
  - (Nearly) 4π solid angle coverage (partial wave analysis)
  - High-rate capability (2×10^7 annihilations/s) Event pile-up.
  - Good PID (γ, e, μ, π, K, p)
  - Momentum resolution ($\approx$ 1 %)
  - Vertex reconstruction for D, K^0_s, Λ
  - Efficient trigger
  - Minimize multiple scattering Material budget.
- For Charmonium:
  - Pointlike interaction region
  - Lepton identification
  - Excellent calorimetry
    - Granularity
    - Energy resolution
    - sensitivity to low-energy photons ($\gamma\gamma$, $\pi^0\gamma$ etc.) Material budget.

Summary

More than 30 years after the discovery of the J/ψ, charmonium physics continues to be an exciting and active field of research.

- Advances in experiment: discovery of expected and unexpected states (mostly at the B-factories)
- Advances in theory: LQCD, EFT, models ...

Still, the knowledge of the spectrum is far from complete.

A systematic high-precision study of all known states and the search for missing states will be carried out in $\bar{p}p$ annihilations by $\overline{\text{P}}$ANDA at GSI.