Charmonium Spectroscopy: Present Status and Prospects for PANDA

Diego Bettoni

Istituto Nazionale di Fisica Nucleare, Ferrara

Physics of Compressed Baryonic Matter, Symposium
Forschungszentrum Dresden Rossendorf
25 September 2007

Outline

- Charmonium
  - Why Charmonium
  - Experimental methods for the study of charmonium
  - Highlights on the spectrum below threshold
    - Triplet S states: J/ψ and ψ'
    - Singlet S states: $\eta_c(1S)$ and $\eta_c(2S)$
    - Triplet P states
    - The $h_c(1^1P_1)$
  - The spectrum above threshold
    - Missing states
    - New states
  - Charmonium at $\overline{\mathrm{P}}$ANDA.
- Charmonium Hybrids
- Charm and Charmonium in Nuclear Matter
- Open charm
- The PANDA detector
- 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

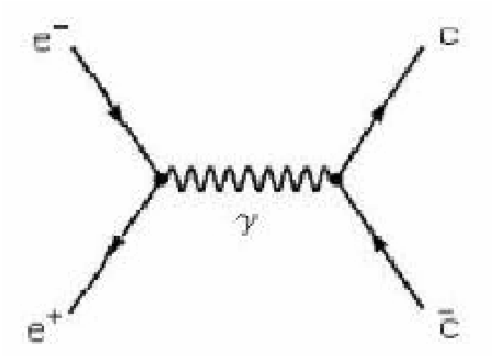
LQCD predicts spectrum.

LQCD needs spectroscopy.

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)

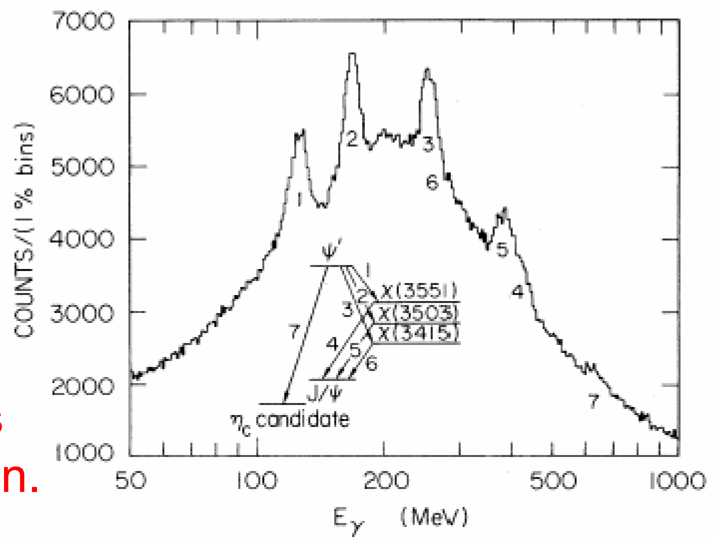
Direct Formation $e^+e^- \to c\bar{c}$



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 $\psi(3770)$.

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

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

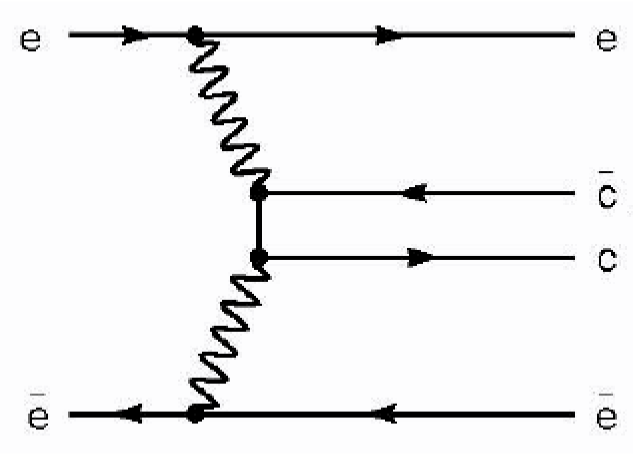


Crystal Ball inclusive photon spectrum

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

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

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.



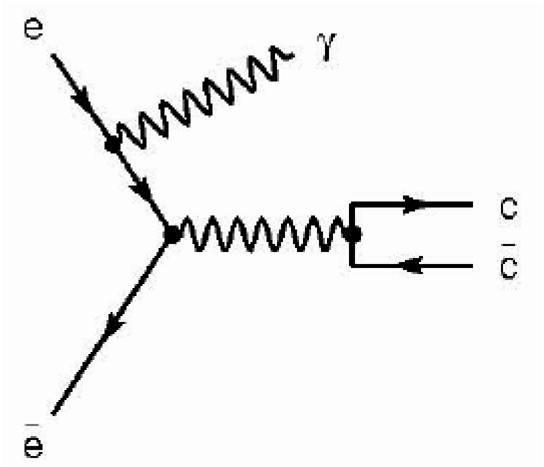
$$\sigma\left(e^+e^- \to e^+e^-(c\bar{c})\right) = \int d^5 L_{\gamma\gamma}(\alpha_i)\,\sigma\left(\gamma\gamma \to (c\bar{c})\right)$$

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

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.

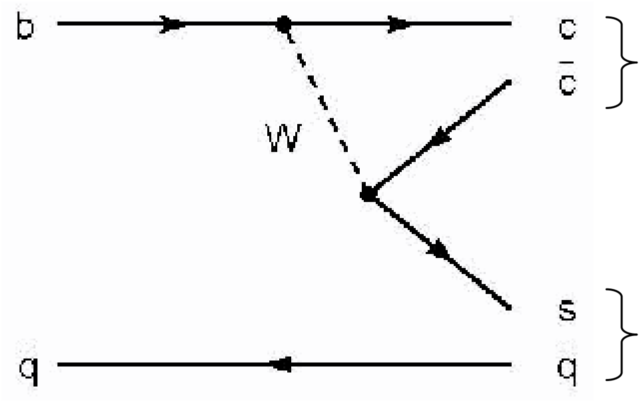
Limititations: knowledge of hadronic branching ratios and form factors used to extract the $\gamma\gamma$ partial width.

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 $R = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.
- Can be used to search for new vector states.

B-Meson Decay

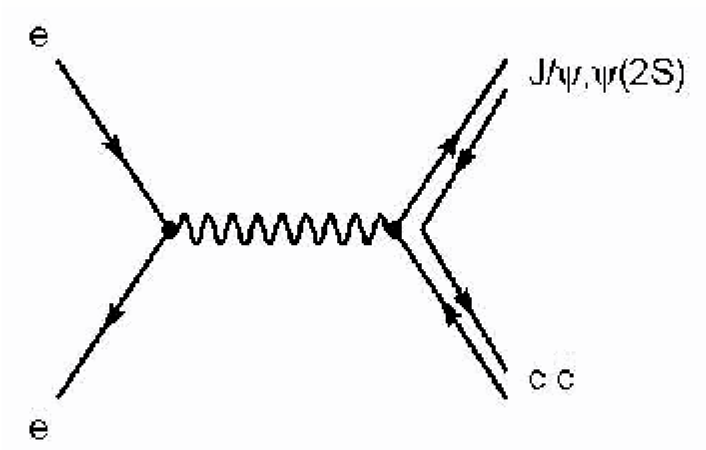


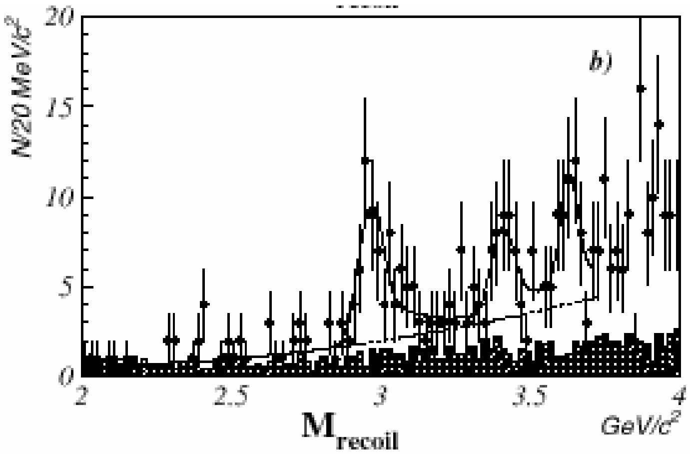
$J/\psi, \psi', \psi(3770), \eta_c, \eta'_c, \chi_{c0}, \chi_{c1}, D^{(*)}, \bar{D}^{(*)}, X(3872)$

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

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

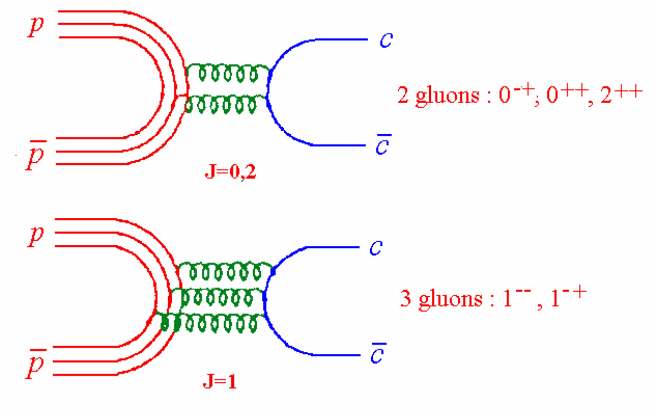
The measured cross section for this process is about one order of magnitude larger than predicted by NRQCD.

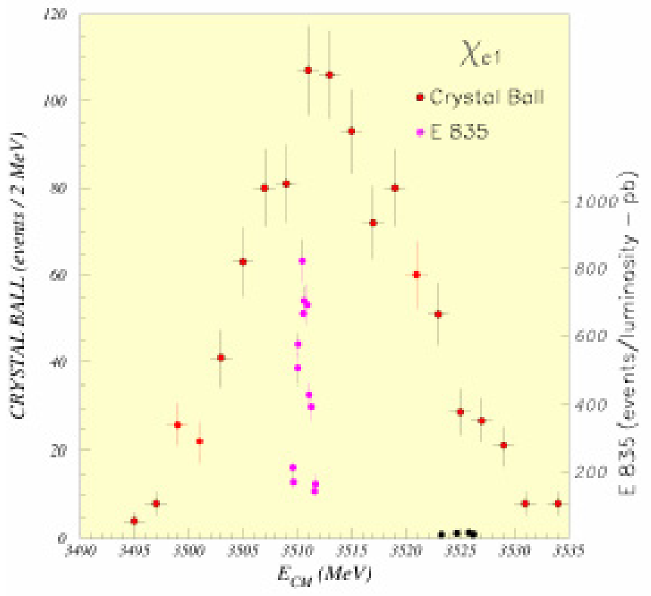
$$\sigma\left(e^+e^- \rightarrow J/\psi + \eta_c\right) \times B(\geq 4) = \left(0.033^{+0.007}_{-0.006} \pm 0.009\right) pb$$

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.

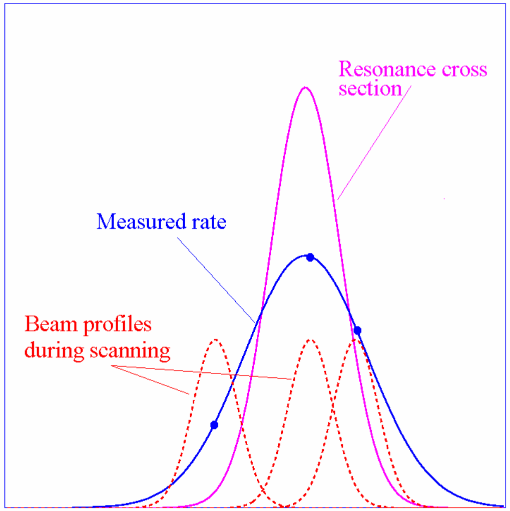
Experimental Method

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 $f(E,\Delta E)$:

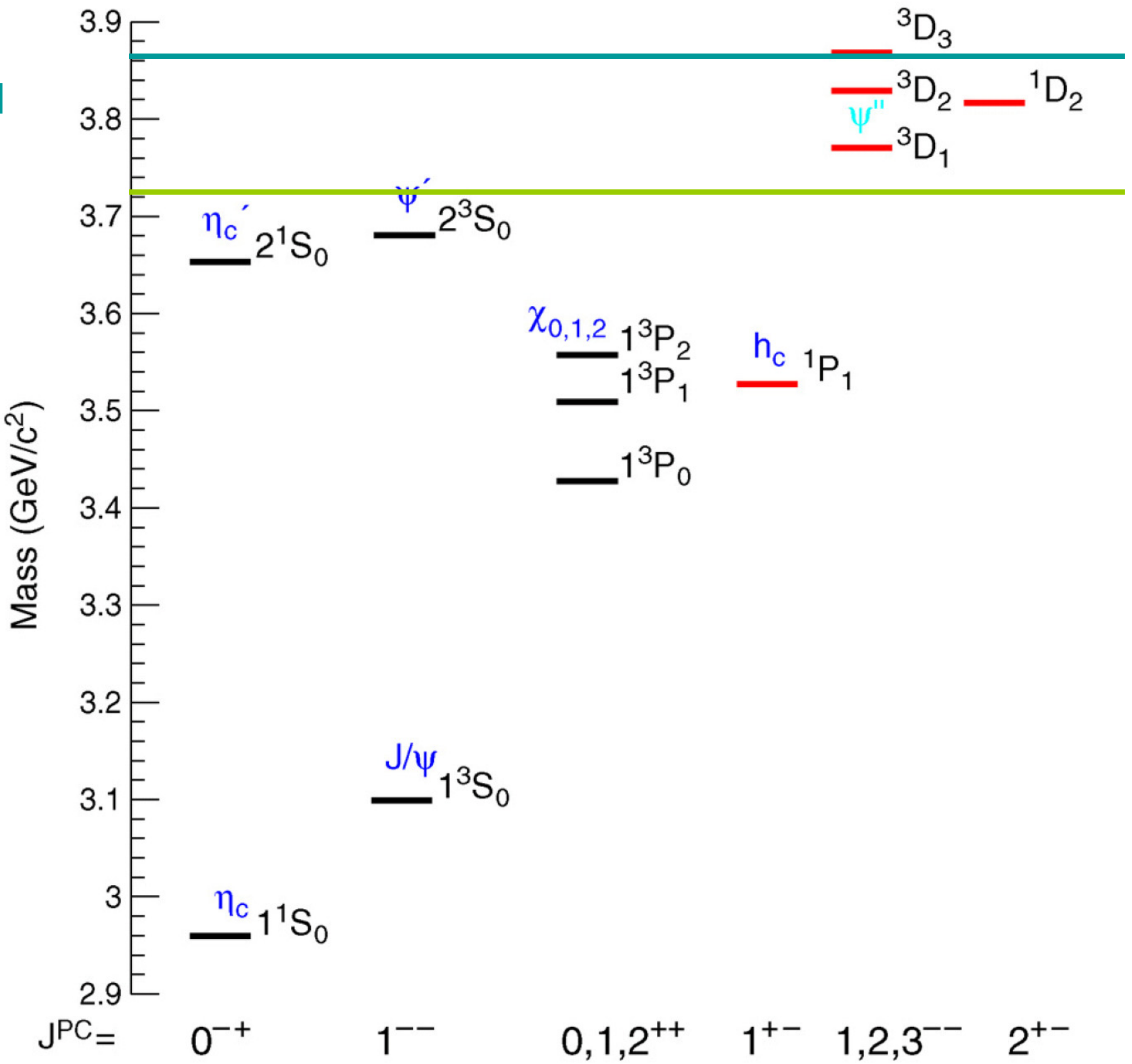
$$\nu = L_0\left\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E) + \sigma_b\right\}$$

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.

The Charmonium Spectrum

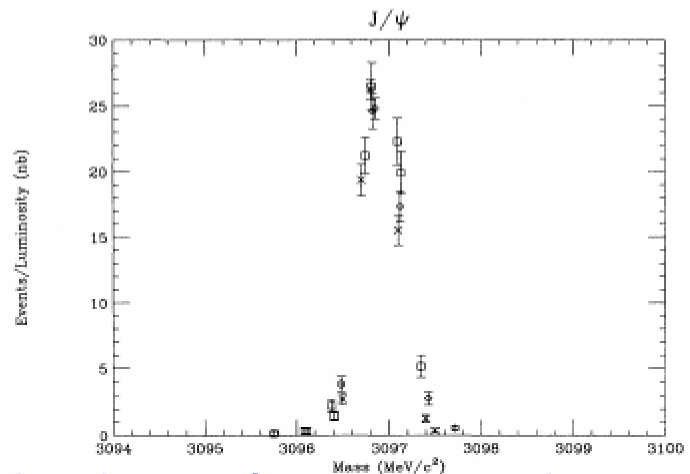
3.87 GeV/c^2
DD* threshold

3.73 GeV/c^2
DD threshold



The J/ψ(1^3S_0) and the ψ′(2^3S_0)

•The masses of the triplet S states have been measured very precisely in e^+e^- collision (using resonant depolarization) and in $p\bar{p}$ 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.

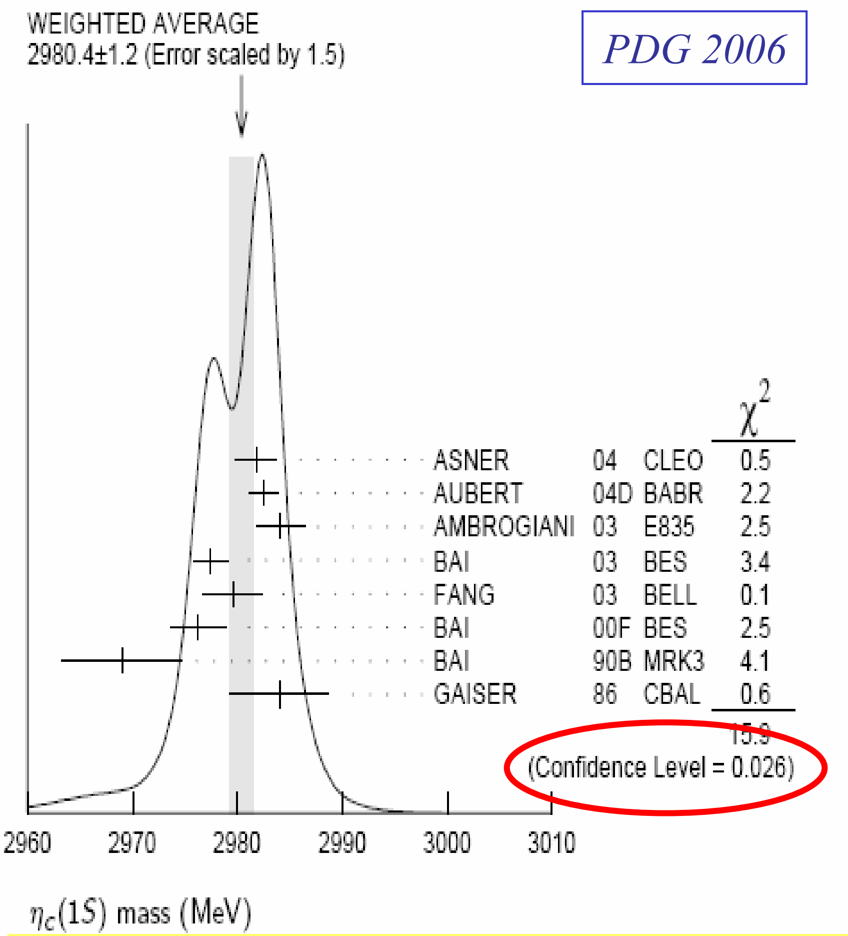
Triplet S states total widths (keV)

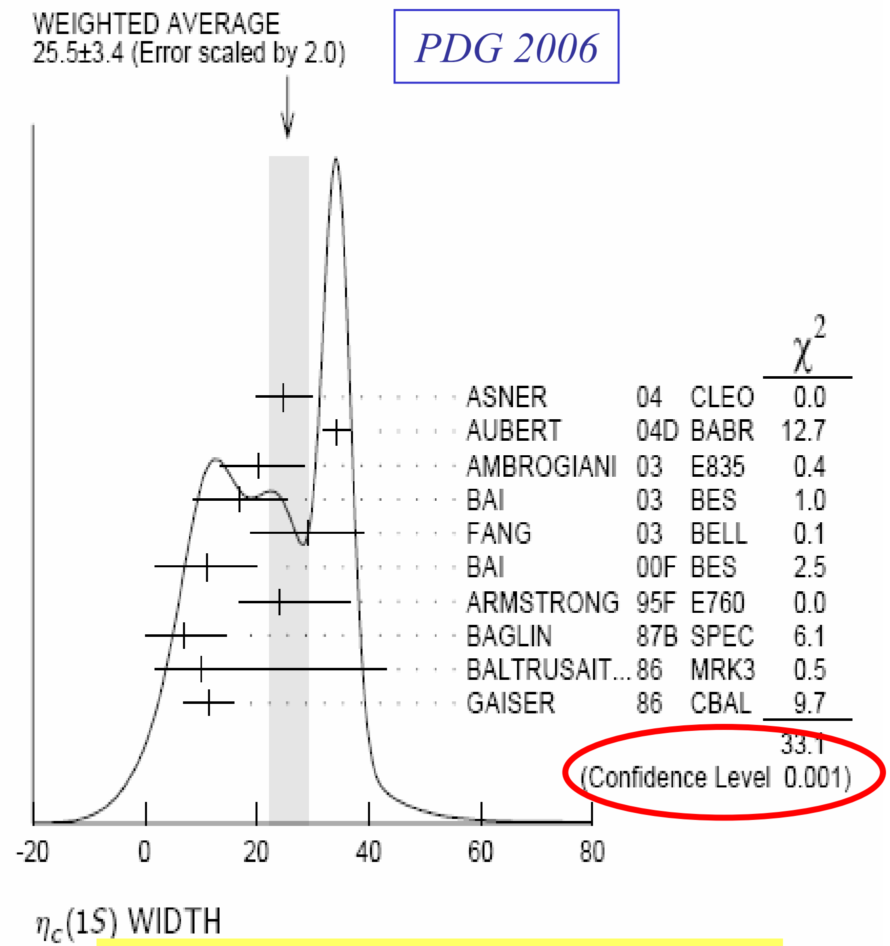
	PDG92	PDG06
J/ψ	68±10	93.4 ± 2.1
ψ′	243 ± 43	277 ± 22

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 and Total Width





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

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

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

Experiment	Width (KeV)
Belle	$5.5 \pm 1.2 \pm 1.8$
CLEO	$7.4 \pm 0.4 \pm 2.3$
Delphi	$13.9 \pm 2.0 \pm 3.0$
E835	$3.8\,^{+1.1}_{-1.0}\,^{1.9}_{-1.0}$
L3	$6.9 \pm 1.7 \pm 2.1$
E760	$6.7\,^{2.4}_{-1.7} \pm 2.3$
ARGUS	11.3 ± 4.2
CLEO	$5.9^{2.1}_{-1.8} \pm 1.9$
TPC	$6.4\,^{5.0}_{-3.4}$
BaBar	5.2 ± 1.2
CLEO2	$7.6 \pm 0.8 \pm 2.3$

$$\Gamma_{\gamma\gamma}(\eta_c) = 6.7^{+0.9}_{-0.8}$$

The $\eta_c(2^1S_0)$ Searches

- The first η'_c candidate was observed by Crystal Ball with a mass of

$$3594 \pm 5\ \mathrm{MeV/c^2}.$$

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

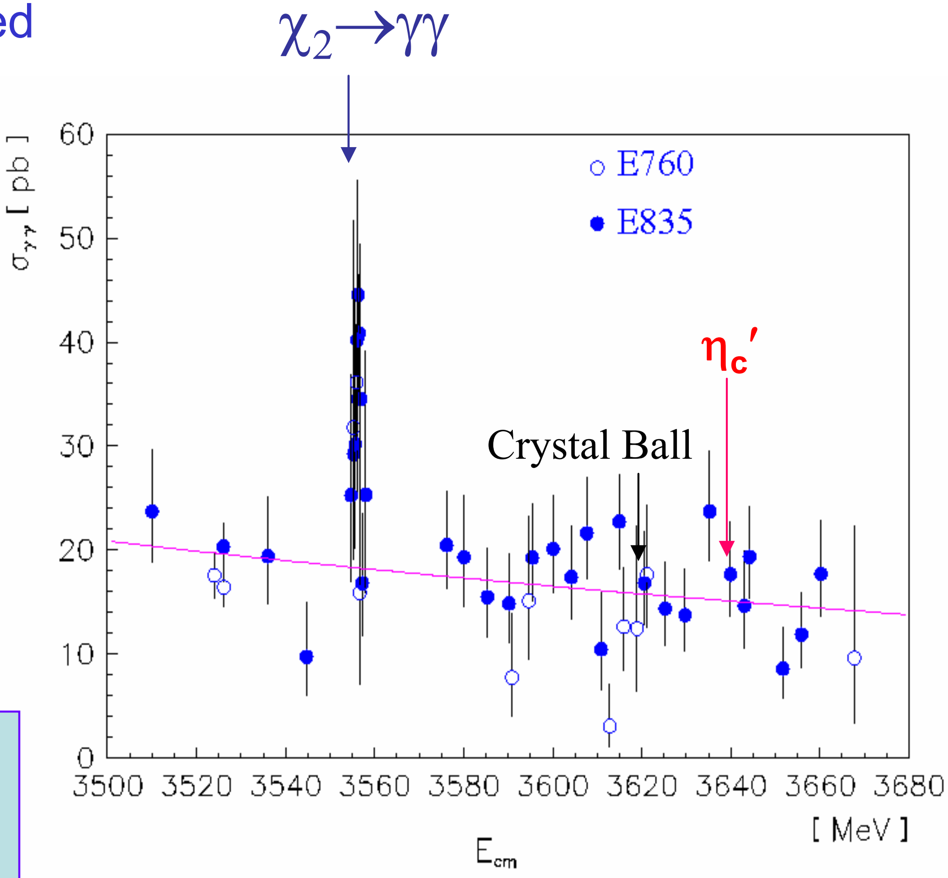
$$E_{cm} = (3570 \div 3660)\ \mathrm{MeV}$$

using the process:

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

but no evidence of a signal was found.

- η'_c not seen at LEP.



- 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

In 2002 the Belle collaboration has discovered the η'_c in the process:

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

with:

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

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

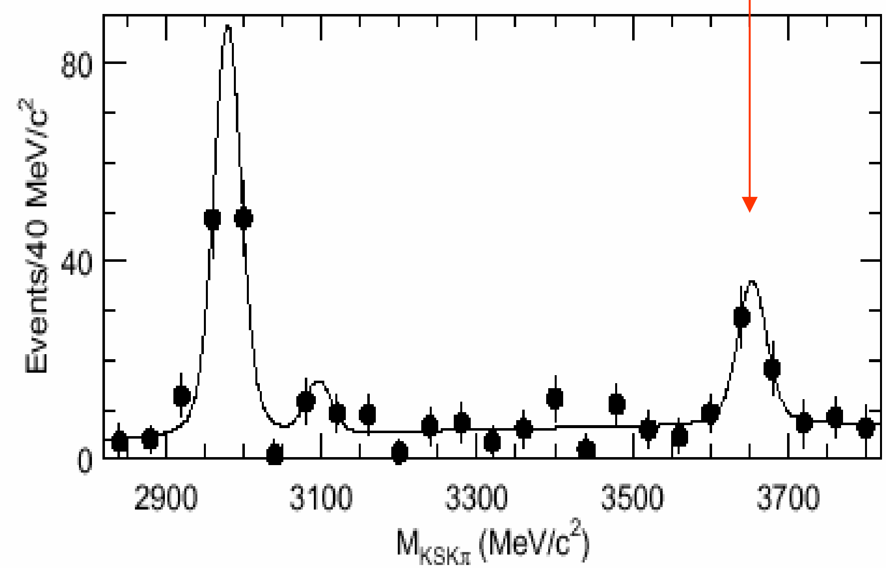
in disagreement with the Crystal Ball result.

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

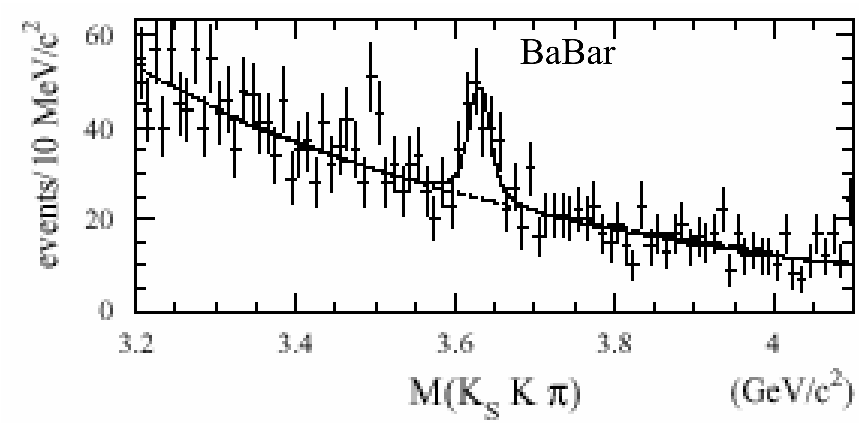
$\Gamma = 22 \pm 20(\mathrm{stat})\ \mathrm{MeV}$

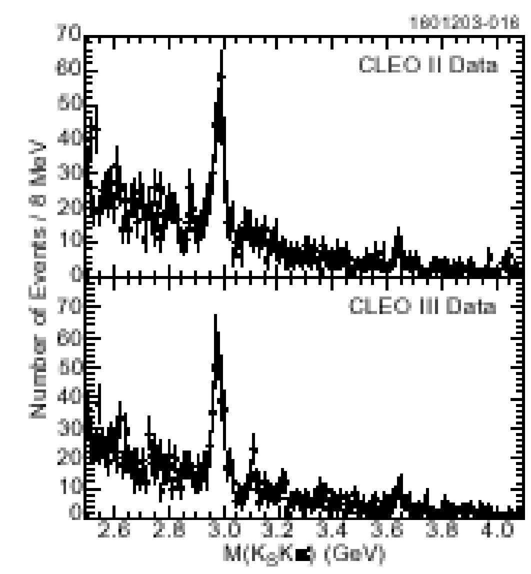
$M = 3654 \pm 6(stat)\ MeV/c^2$

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



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





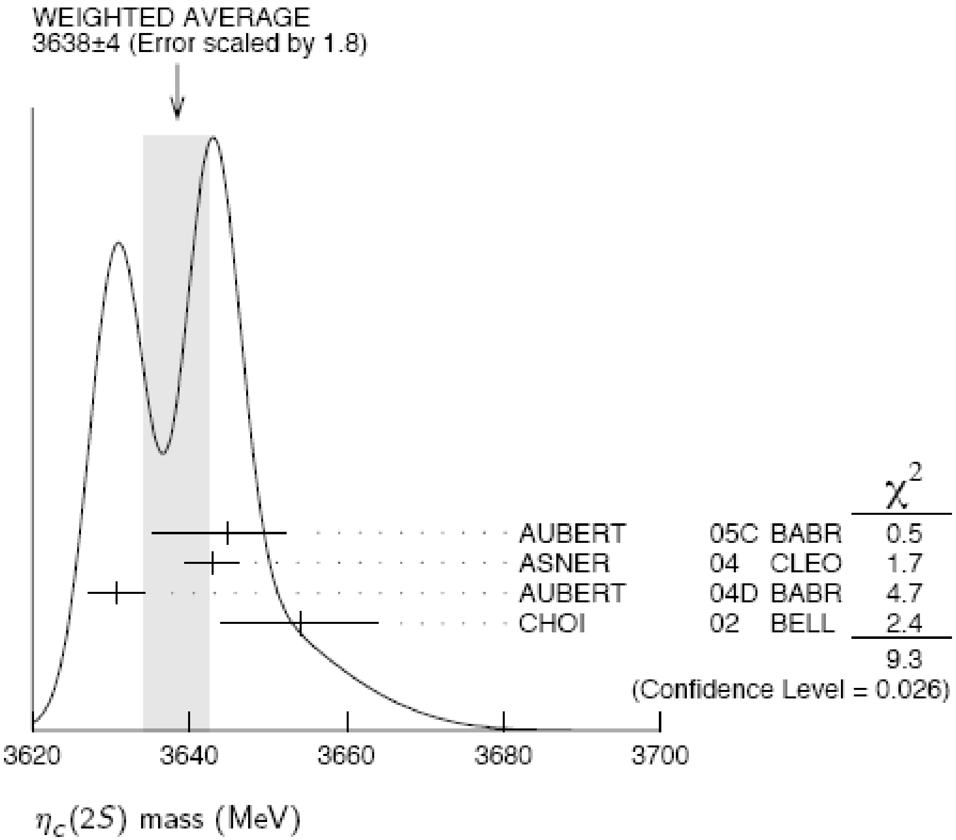
BaBar: $\Gamma(\eta'_c)$ = 17.0 ± 8.3 ± 2.5 MeV
CLEO: $\Gamma(\eta'_c)$ = 6.3 ± 12.4 ± 4.0 MeV

PDG 2006: $\Gamma(\eta'_c)$ = 14 ± 7 MeV

The $\eta_c(2^1S_0)$ Mass

PDG 2006

Experiment	Mass (MeV/c^2)
BaBar	$3645.0 \pm 5.5\ ^{+4.9}_{-7.8}$
CLEO	$3642.9 \pm 3.1 \pm 1.5$
BaBar	$3630.8 \pm 3.4 \pm 1.0$
Belle	$3654 \pm 6 \pm 8$
BaBar	3639 ± 7
Belle	3630 ± 8
Belle	3622 ± 12
Crystal Ball	3594 ± 5



$M(\eta_c') = 3638 \pm 4$ MeV/c^2

Is the 2S hyperfine splitting too small ?

$M(\eta_c') = 3638 \pm 4$ MeV/c^2

hyperfine splitting

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

$M(J/\psi) - M(\eta_c) = 117$ MeV/c^2

→ $M(\psi') - M(\eta_c') = 67$ MeV/c^2

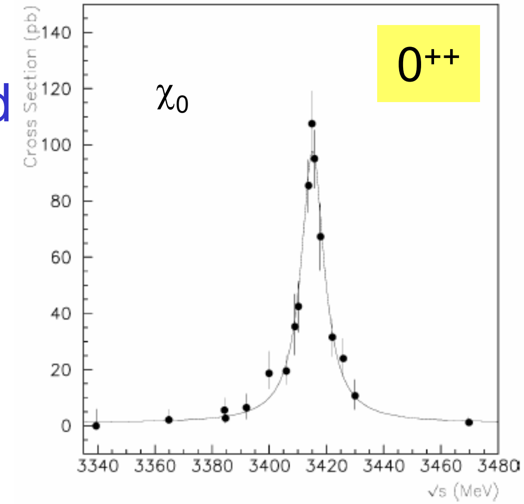
48 ± 4 MeV/c^2 observed

One possible explanation: coupled channel effects induce a mass shift of 20.9 MeV/c^2.

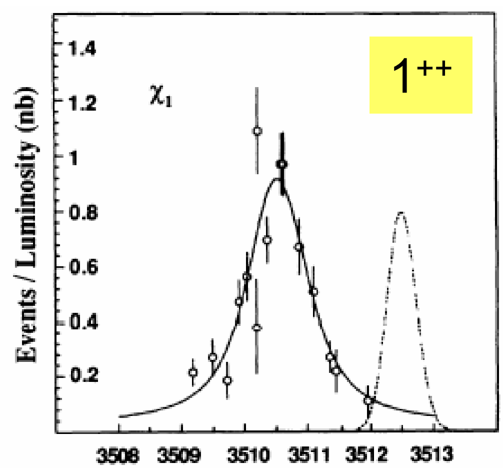
Estia Eichten – BaBar workshop on heavy quark and exotic spectroscopy

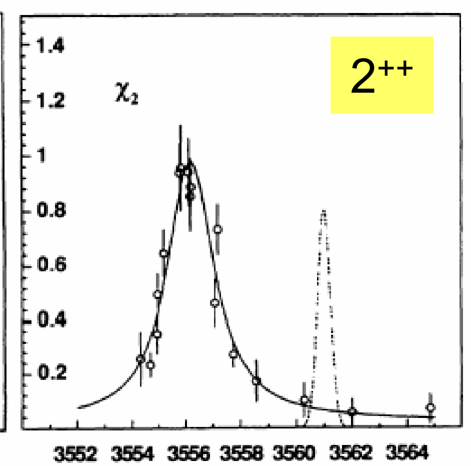
The $\chi_{cJ}(1^3P_J)$ States

- First observed by the early e^+e^- experiments, which measured radiative decay widths, directly for χ_1 and χ_2, indirectly for χ_0. Radiative decay important for relativistic corrections and coupled channel effects.
- Precision measurements of masses and widths in $p\bar{p}$ experiments (R704, E760, E835).
- χ_1 width measured only by E760, most precise measurement of χ_0 width by E835.

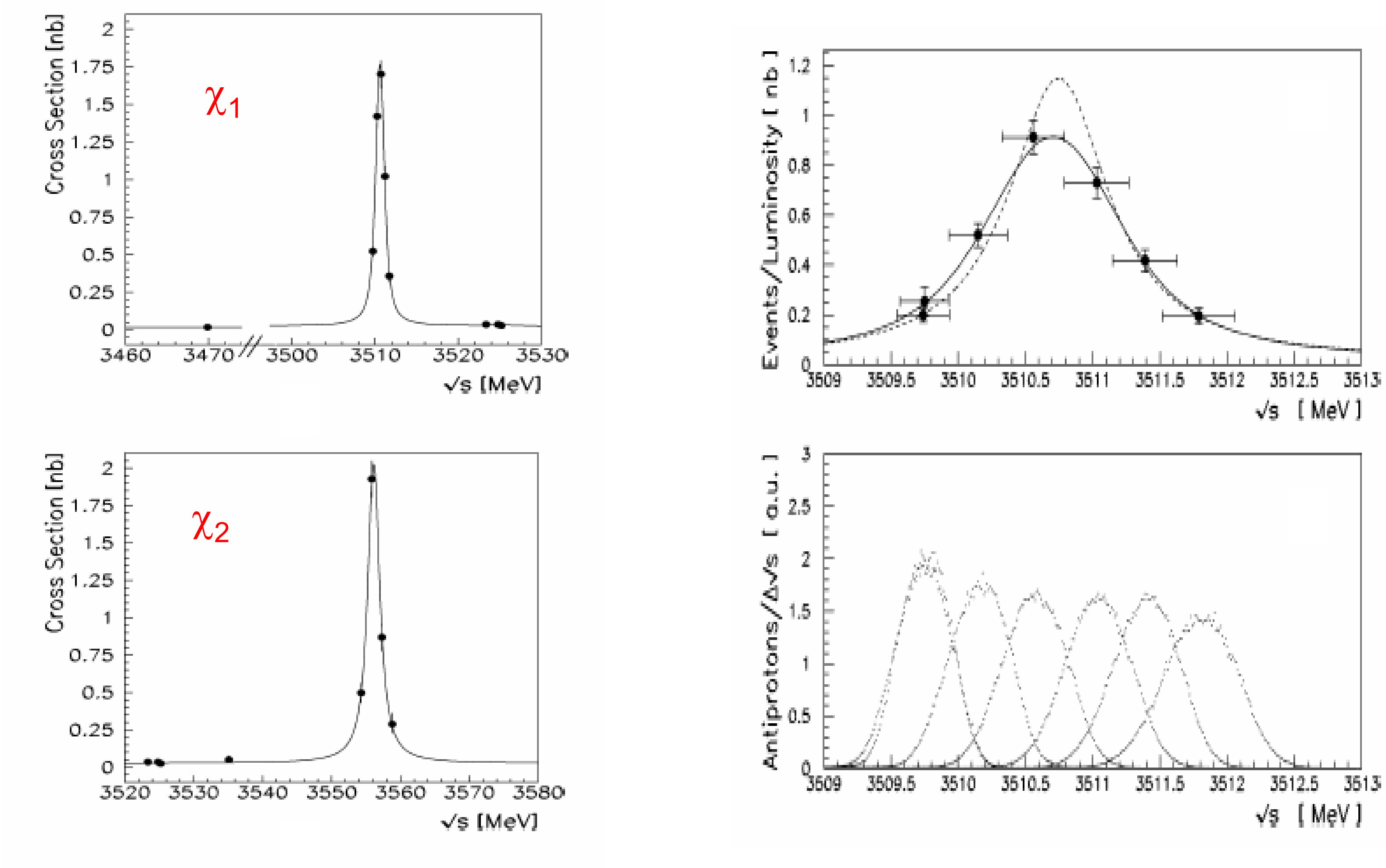


	Mass (MeV/c²)	Width (MeV)
χ_0	3415.16 ± 0.35	10.2 ± 0.9
χ_1	3510.59 ± 0.10	0.88 ± 0.14
χ_2	3556.26 ± 0.11	2.00 ± 0.18



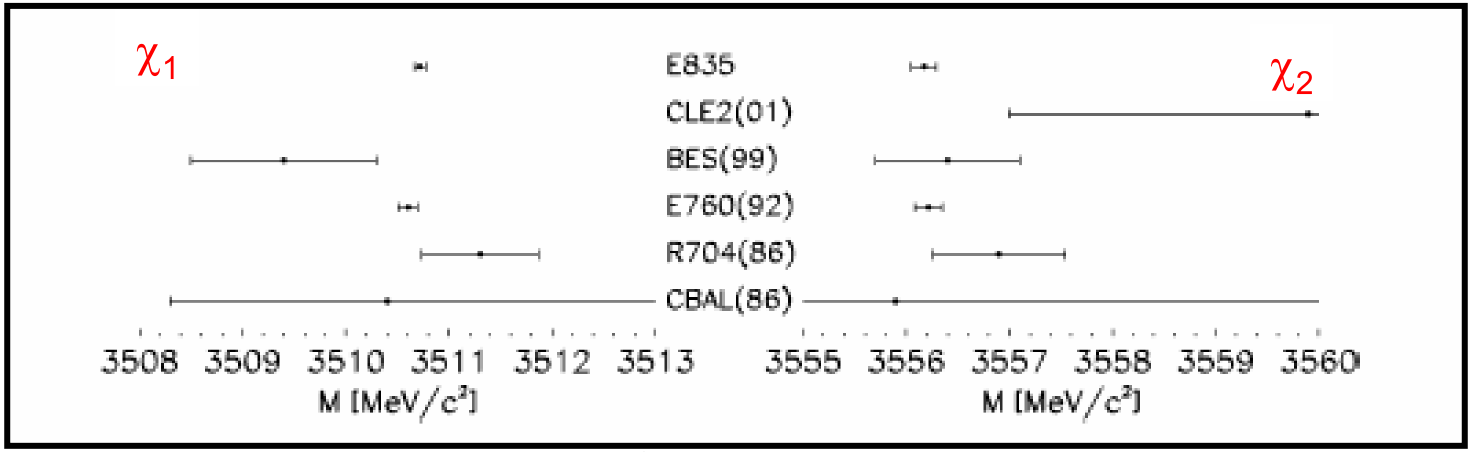


New Measurements of χ_{c1} and χ_{c2} in E835



χ_{c1} and χ_{c2} masses and widths

χ_{c1}	E835	E760
M(MeV/c^2)	3510.719 ± 0.051 ± 0.019	3510.60 ± 0.09 ± 0.02
Γ(MeV)	0.876 ± 0.045 ± 0.026	0.87 ± 0.11 ± 0.08
B($p\bar{p}$)Γ(J/ψγ)(eV)	21.5 ± 0.5 ± 0.6 ± 0.6	21.4 ± 1.5 ± 2.2
χ_{c2}	E835	E760
M(MeV/c^2)	3556.173 ± 0.123 ± 0.020	3556.22 ± 0.13 ± 0.02
Γ(MeV)	1.915 ± 0.188 ± 0.013	1.96 ± 0.17 ± 0.07
B($p\bar{p}$)Γ(J/ψγ)(eV)	27.0 ± 1.5 ± 0.8 ± 0.7	27.7 ± 1.5 ± 2.0



Fine Structure Splittings

$$\Delta M_{21} = M(\chi_{c2}) - M(\chi_{c1}) = 45.45 \pm 0.15 \; MeV/c^2$$

$$\Delta M_{10} = M(\chi_{c1}) - M(\chi_{c0}) = 95.2 \pm 0.6 \; MeV/c^2$$

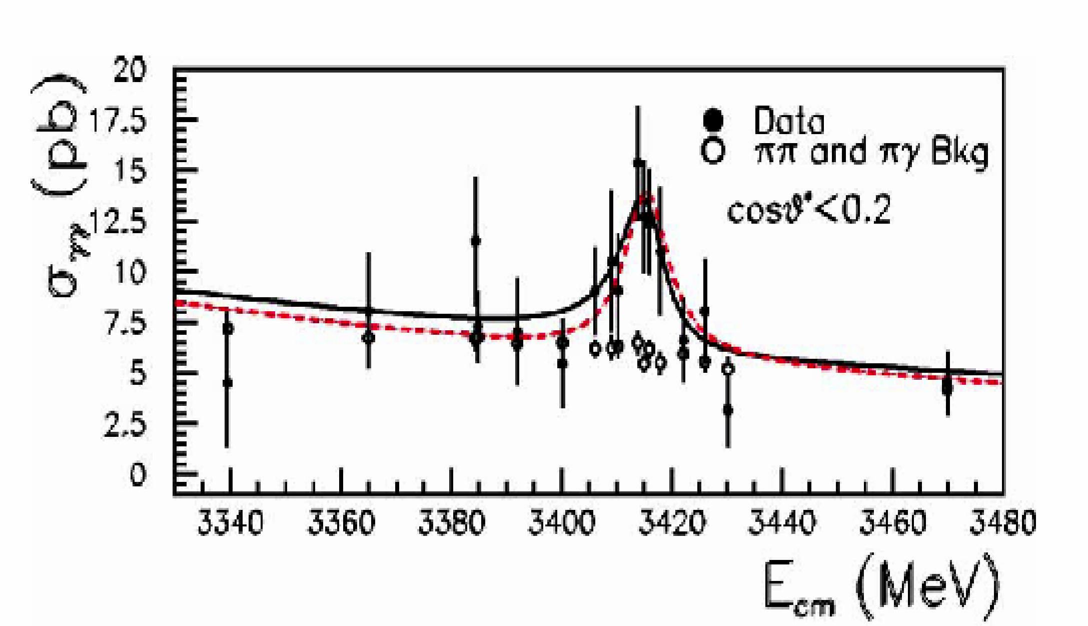
$$\rho = \frac{\Delta M_{21}}{\Delta M_{10}} = 0.477 \pm 0.002$$

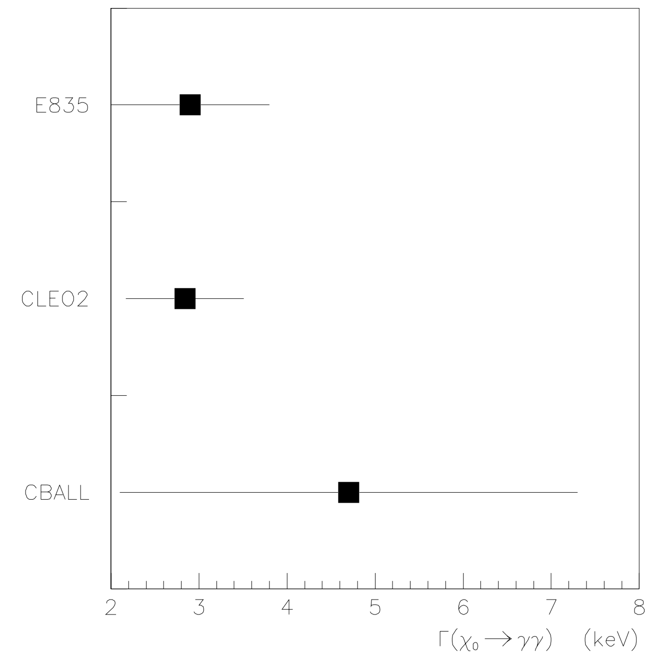
$$M_{cog} = 3525.39 \pm 0.10 \; MeV/c^2$$

$$\langle h_{LS} \rangle = \frac{2\Delta M_{10} + 5\Delta M_{21}}{12} = 34.80 \pm 0.09 \; MeV/c^2$$

$$\langle h_T \rangle = \frac{10\Delta M_{10} - 5\Delta M_{21}}{72} = 10.06 \pm 0.06 \; MeV/c^2$$

$\chi_{c0} \rightarrow \gamma\gamma$



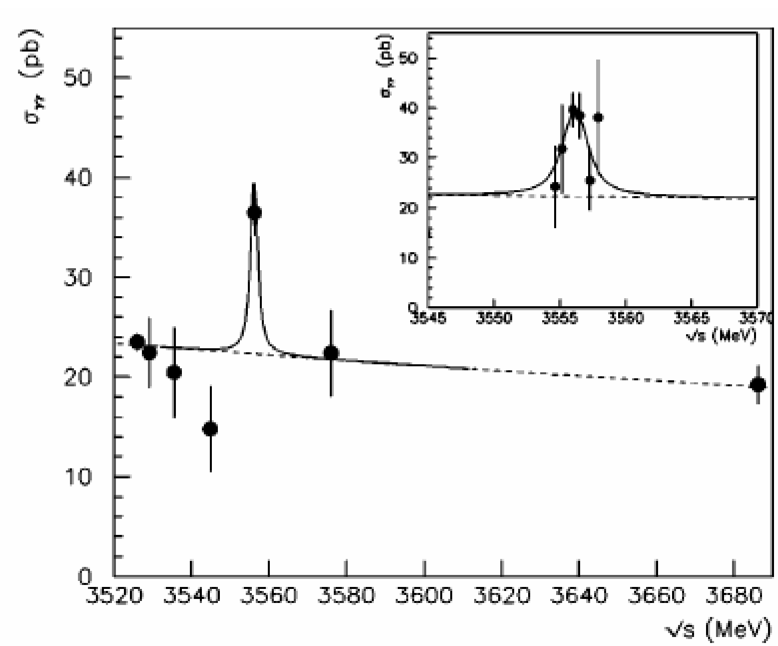


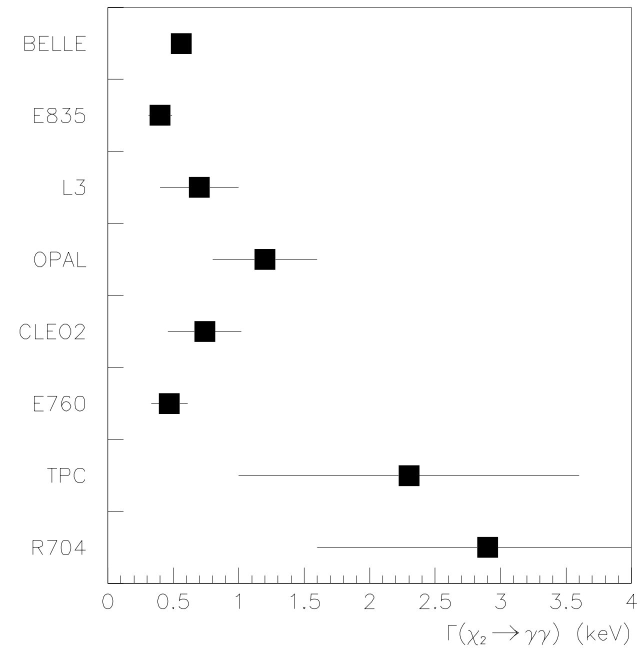
$$BR(\chi_{c0} \rightarrow p\bar{p}) \times BR(\chi_{c0} \rightarrow \gamma\gamma) = \left(6.52 \pm 1.18^{+0.48}_{-0.72}\right) \times 10^{-8}$$

$\Gamma_{\gamma\gamma}(\chi_{c0})$ = 2.9 ± 0.9 keV

$\Gamma_{\gamma\gamma}(\chi_{c0})$ = 2.6 ± 0.5 keV

$\chi_{c2} \to \gamma\gamma$





$$BR(\chi_{c2} \to \gamma\gamma) = (1.35 \pm 0.25 \pm 0.12) \times 10^{-4}$$

$\Gamma_{\gamma\gamma}(\chi_{c2})$ = 270 ± 49 ± 33 eV

$\Gamma_{\gamma\gamma}(\chi_{c2})$ = 0.49 ± 0.05 keV

E835

Interference Measurement of the χ_{c0} Parameters

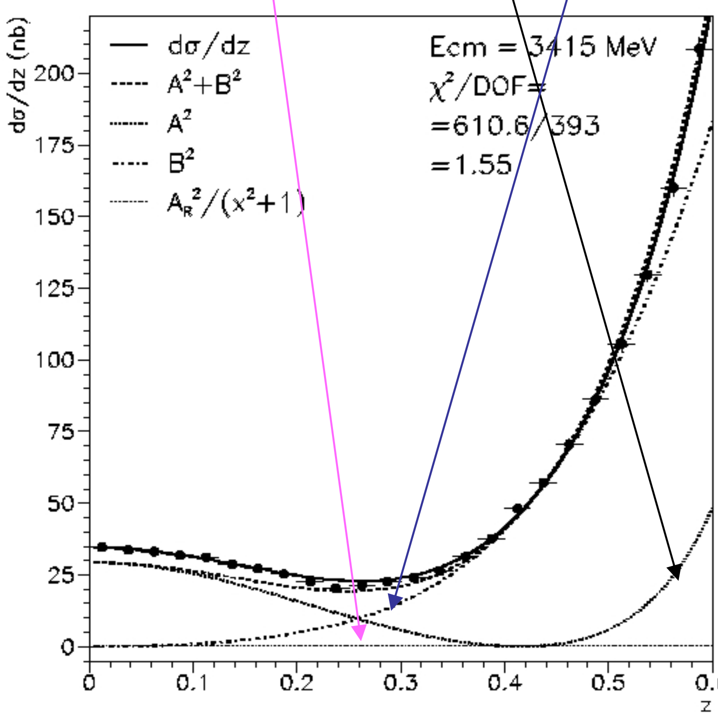
PRL 91, 091801 (2003)

$$p\bar{p} \rightarrow \pi^0\pi^0$$

$$\frac{d\sigma}{dz}(x,z) = \left|\frac{-A_R}{x+i} + Ae^{i\delta_A}\right|^2 + \left|Be^{i\delta_B}\right|^2$$

Resonant | Interfering (helicity 0) | Non-Interfering (helicity 1)

$$\begin{cases} x = \dfrac{E_{CM} - M_{\chi_0}}{\Gamma_{\chi_0}/2} \\ z = \cos\vartheta^* \end{cases}$$



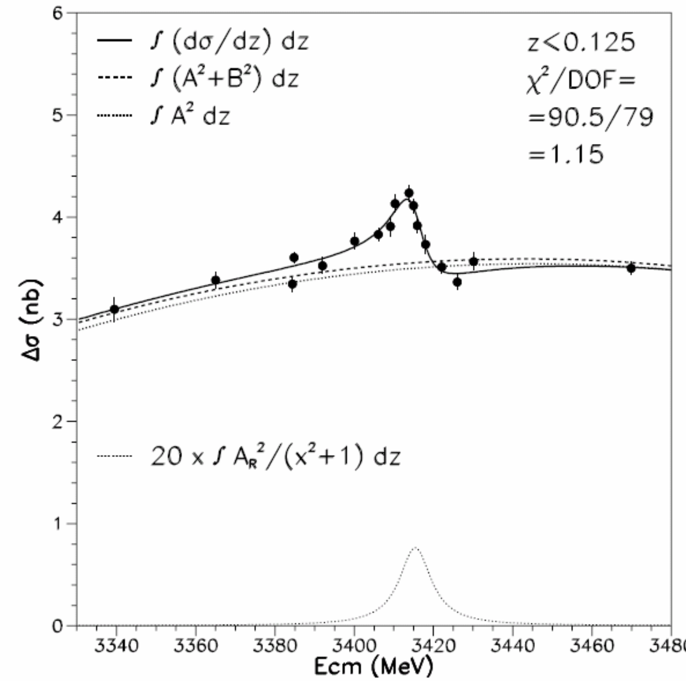


TABLE I. E835 results (errors are statistical and systematic, respectively).

$B_{in} \equiv$ $B_{out} \equiv$	Common channel $B(\chi_{c0} \to \bar{p}p)$ $B(\chi_{c0} \to J/\psi\,\gamma)$[a]	$B(\chi_{c0} \to \pi^0\pi^0)$
$M_{\chi_{c0}}$ (MeV/c^2)	$3415.4 \pm 0.4 \pm 0.2$[b]	$3414.7^{+0.7}_{-0.6} \pm 0.2$[c]
$\Gamma_{\chi_{c0}}$ (MeV)	$9.8 \pm 1.0 \pm 0.1$[b]	$8.6^{+1.7}_{-1.3} \pm 0.1$[c]
$B_{in} \times B_{out}$ (10^{-7})	$27.2 \pm 1.9 \pm 1.3$[b]	$5.42^{+0.91}_{-0.96} \pm 0.22$[c]
Final result for $B_{in} \times B_{out}$ (10^{-7}) and phase δ_A (degree)		$5.09 \pm 0.81 \pm 0.25$[d] $39 \pm 5 \pm 6$[d]

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 ≈ 30 % 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

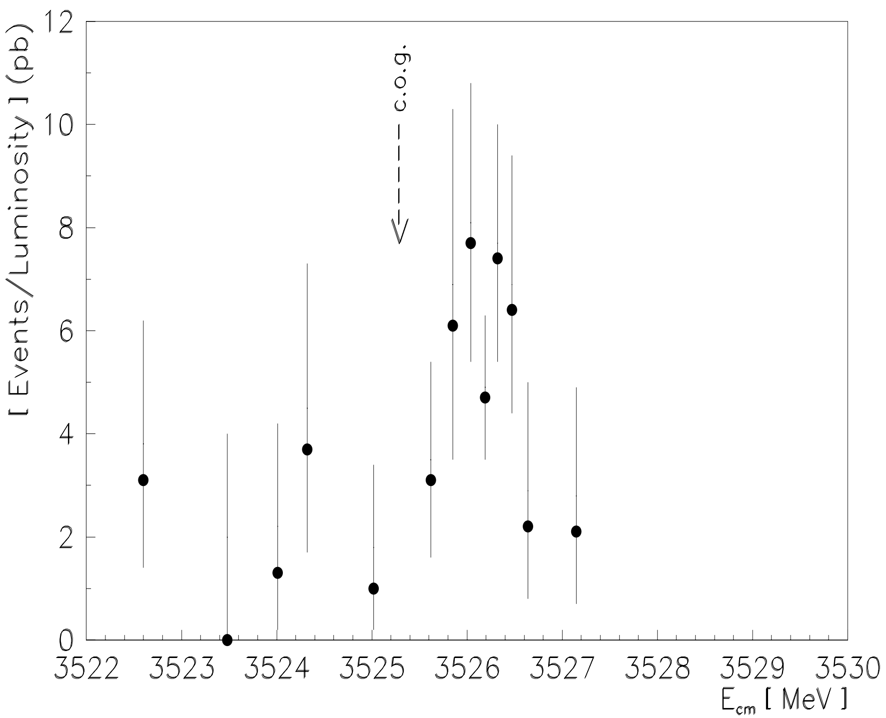
The $h_c(^1P_1)$ E760 observation

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

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

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:

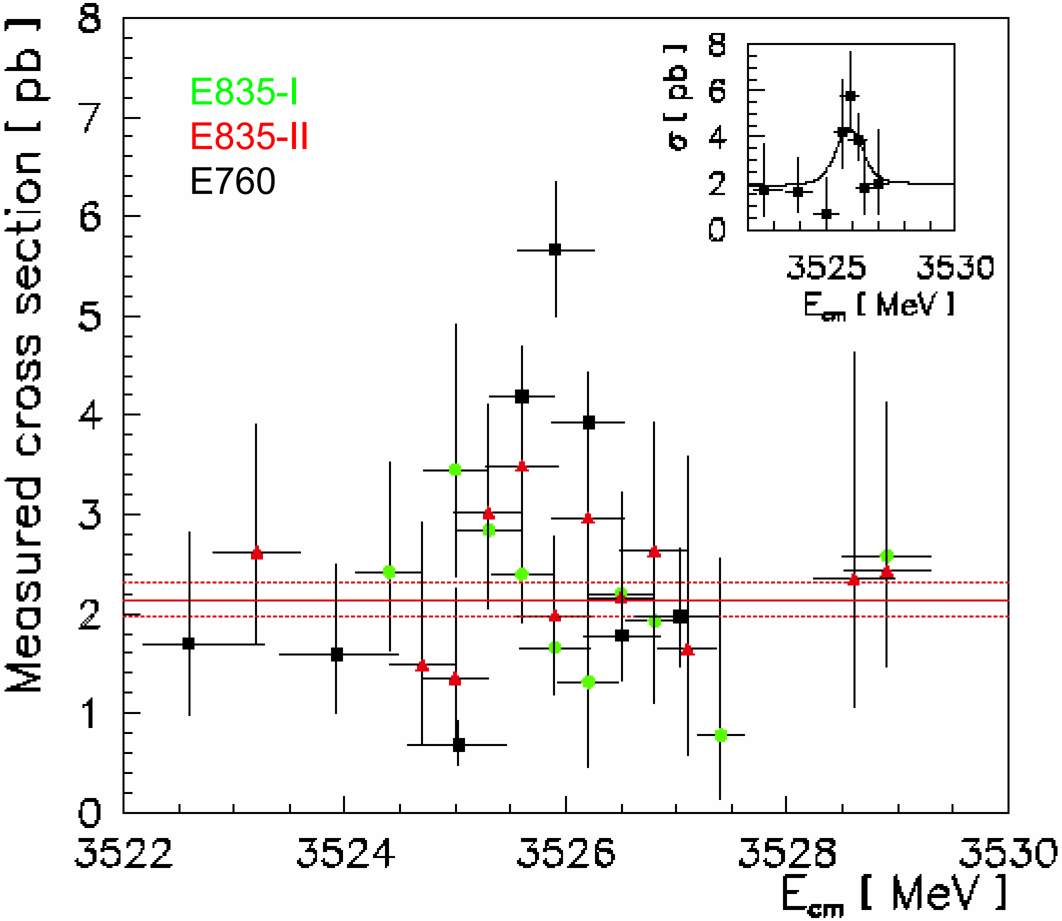
$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$
$$\Gamma(h_c) < 1.1\ MeV\ (90\%CL)$$



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

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

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.

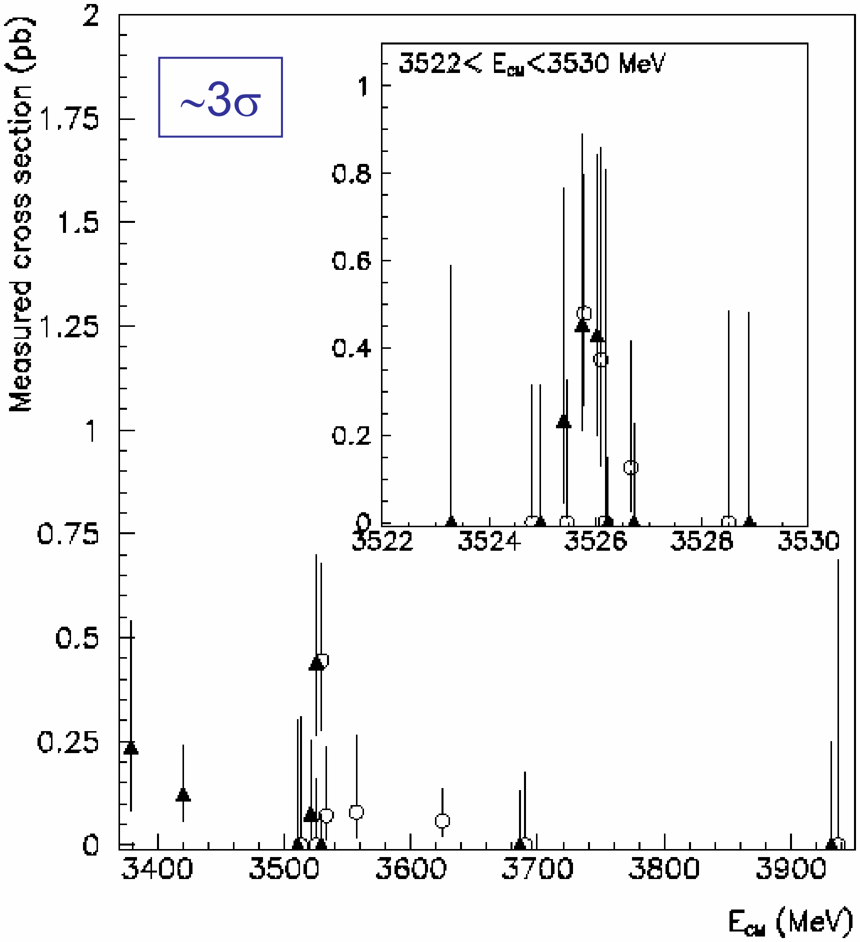
$$M(h_c) = 3525.8 \pm 0.2 \pm 0.2\ MeV/c^2$$

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

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

cfr E760 value:

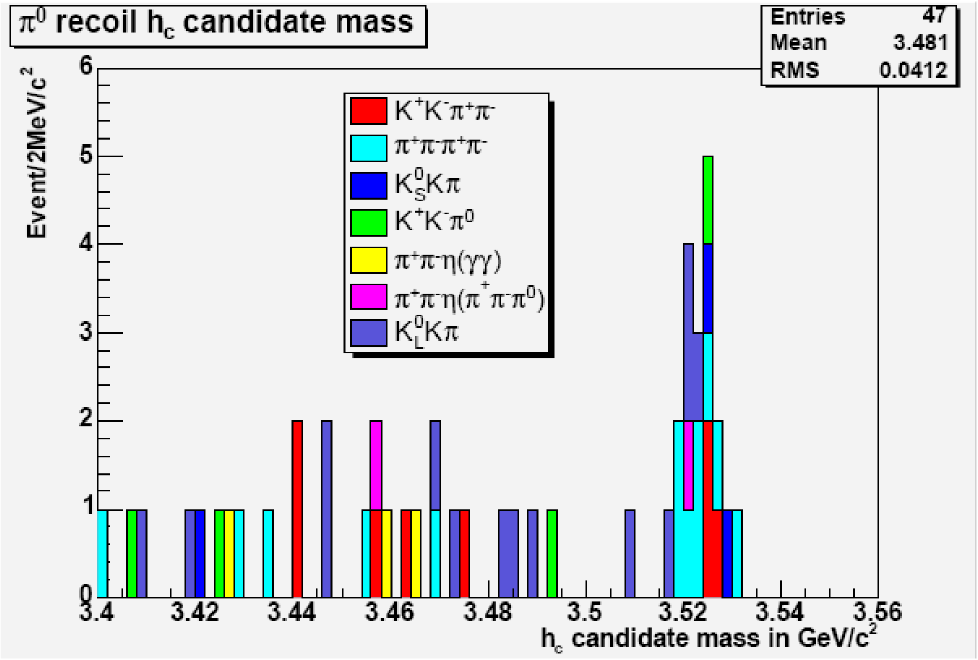
$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$



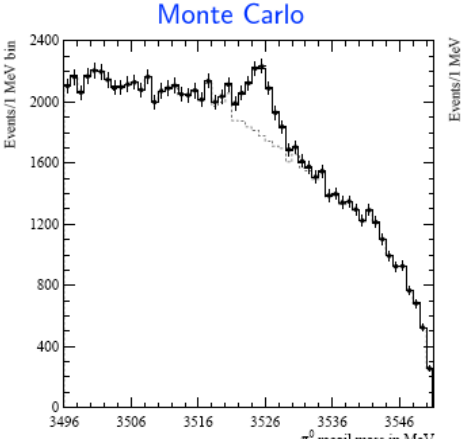
h_c Observation at CLEO

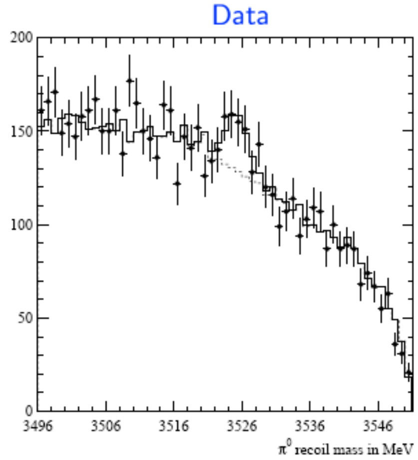
$e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c \qquad h_c \rightarrow \eta_c \gamma \quad \eta_c \rightarrow hadrons$

Inclusive analysis



exclusive analysis



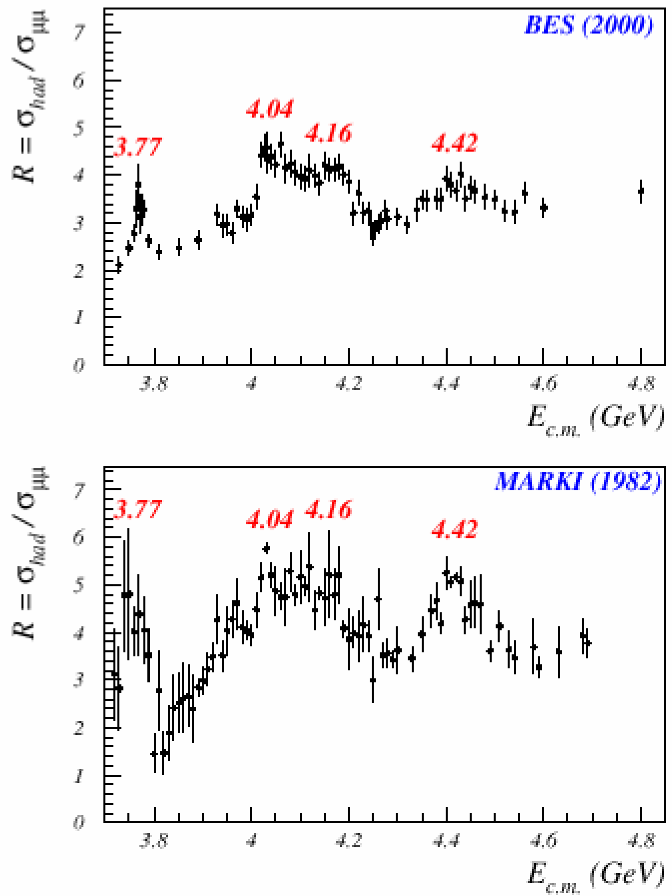


$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV/c^2$$

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 (ψ(3S), ψ(4S), ψ(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

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	

- 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:

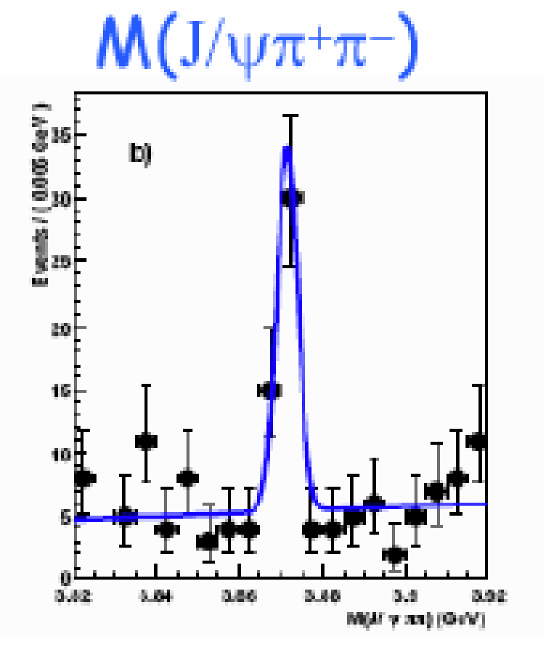
$^{1,3}D_2 \not\to \bar{D}D$ forbidden by parity conservation

$^{1,3}D_2 \not\to \bar{D}D^*$ 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 $\bar{D}$. The $J/\psi\pi^+\pi^-$ (BR = $(1.93 \pm 0.28) \times 10^{-3}$) and $J/\psi\pi^0\pi^0$ (BR = $(8.0 \pm 3.0) \times 10^{-4}$) decay modes have recently been observed by BES and CLEO.

X(3872)

The X(3872) Discovery



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

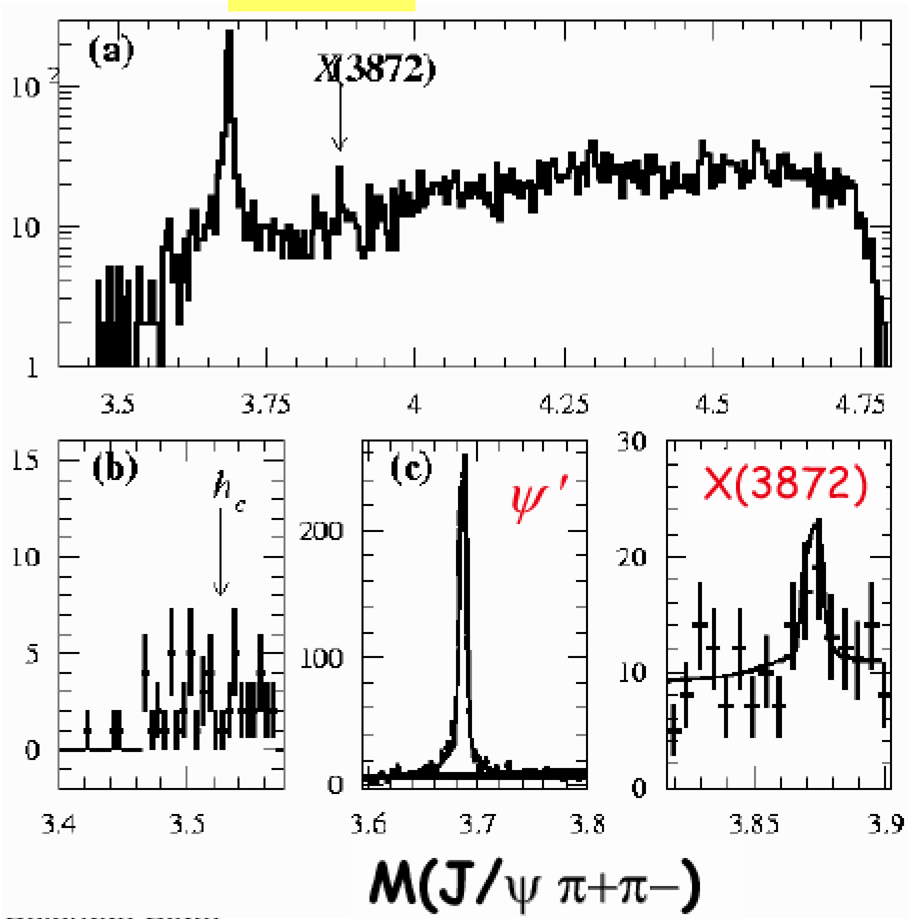
$B^{\pm} \to K^{\pm} (J/\psi \pi^{+}\pi^{-})$, $J/\psi \to \mu^{+}\mu^{-}$ or $e^{+}e^{-}$

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

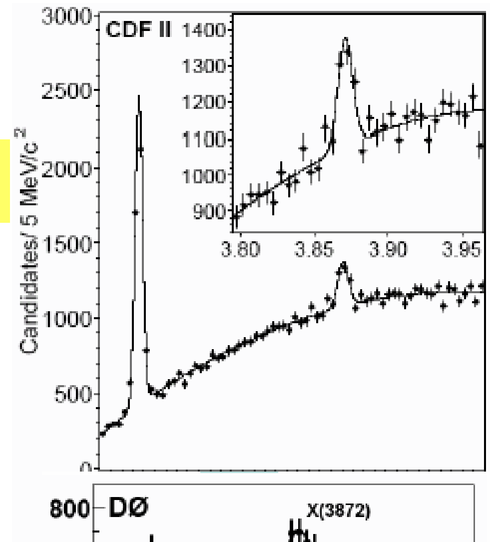
$$\frac{\Gamma\left(X(3872) \to \gamma \chi_{c1}\right)}{\Gamma\left(X(3872) \to \pi^{+}\pi^{-} J/\psi\right)} < 0.89 \quad (90\% \, C.L.)$$

The X(3872) Confirmation

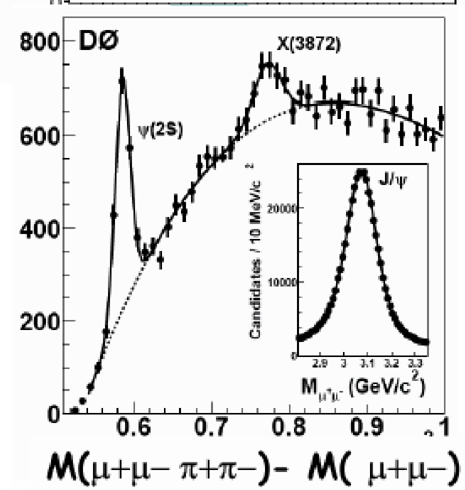
BaBar



CDF



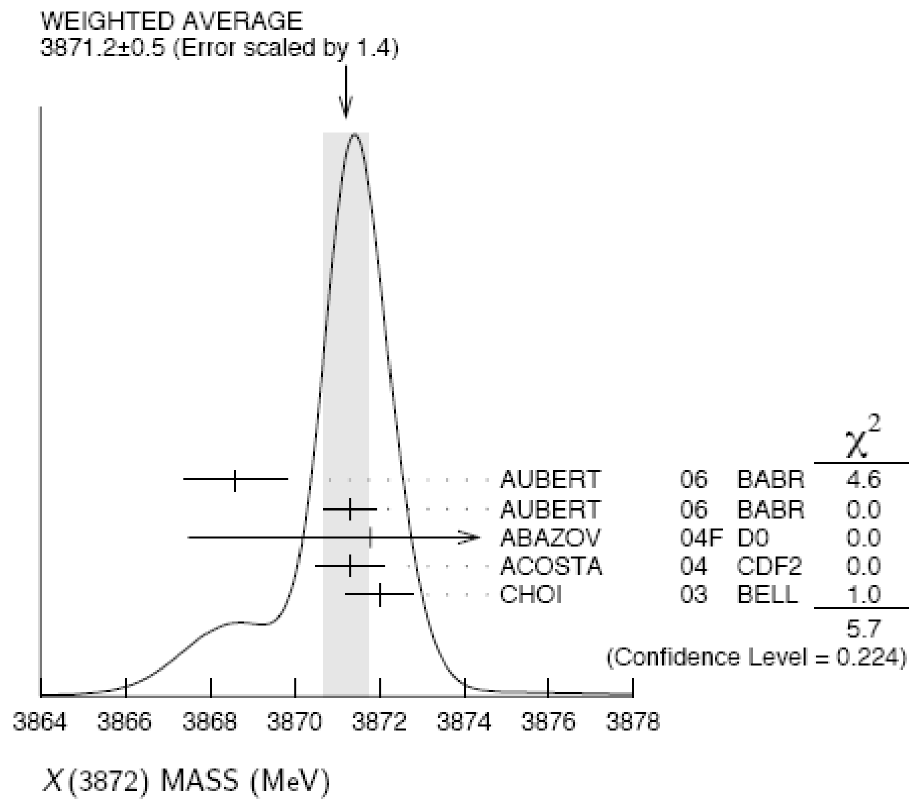
D0



Mass of the X(3872)

PDG 2006

Experiment	Mass (MeV/c^2)
BaBar	**3868.6 ± 1.2 ± 0.2**
BaBar	**3871.3 ± 0.6 ± 0.1**
D0	**3871.8 ± 3.1 ± 3.0**
CDF2	**3871.3 ± 0.7 ± 0.4**
Belle	**3872.0 ± 0.6 ± 0.5**
BaBar	**3873.4 ± 1.4**
E705	**3836 ±13**



M(X) = 3871.2 ± 0.5 MeV/c^2

Mass and Width of the X(3872)

- A new measurement of the D^0 mass by CLEO

$$M_{D^0} = 1864.847 \pm 0.150 \pm 0.095\, MeV/c^2$$

$$M_{D^0} + M_{D^{*0}} = 3871.81 \pm 0.36\, MeV/c^2$$

- The mass (3871.2 ± 0.5 MeV/c^2) is very close to the $D^0 \bar{D}^{*0}$ threshold.

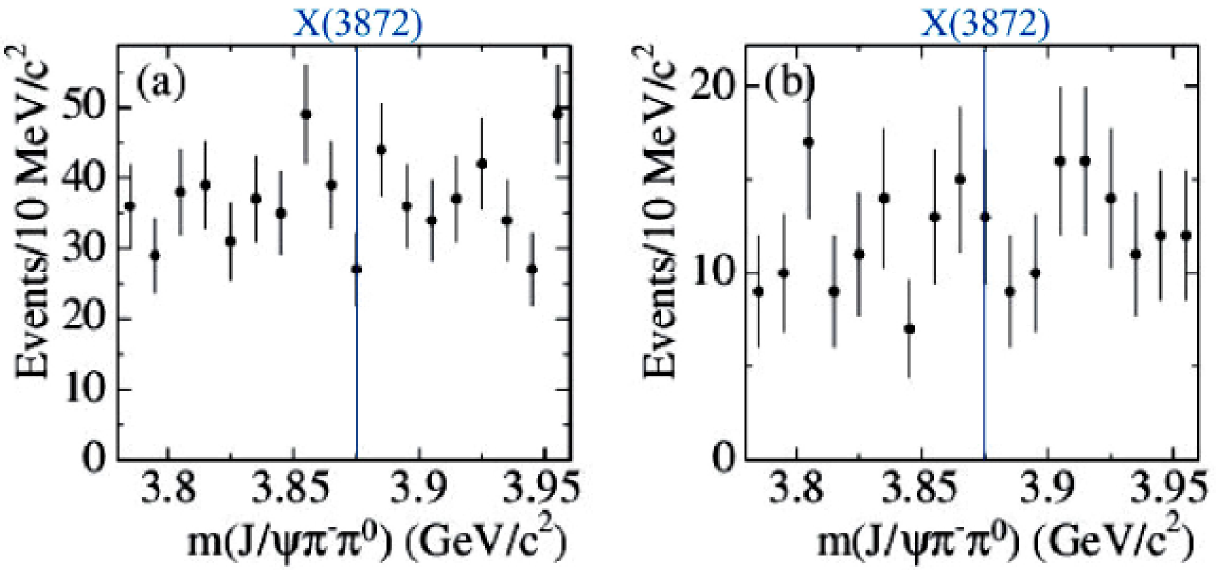
$$M_X - \left(M_{D^{*0}} + M_{D^0}\right) = -0.6 \pm 0.6\, MeV/c^2$$

no longer 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.

X(3872) Search for a Charged Partner

If X(3872) has I=1 then $B(B \to KX^{\pm}) \sim 2\, B(B \to KX^0)$



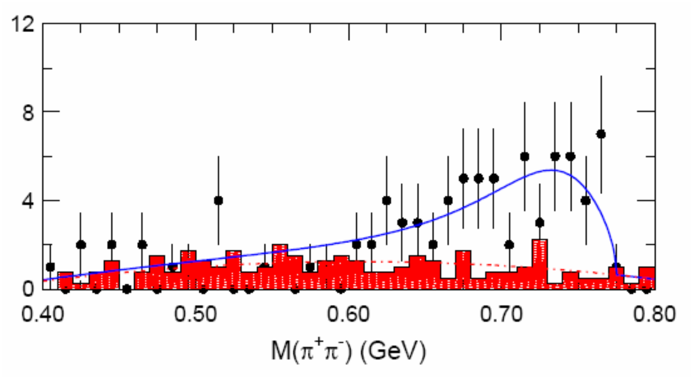
$B(B^0 \to X^- K^+,\ X^- \to J/\psi \pi^- \pi^0) < 5.4 \times 10^{-6}$ (90 % C.L.)
$B(B^- \to X^- \bar{K}^0,\ X^- \to J/\psi \pi^- \pi^0) < 22 \times 10^{-6}$ (90 % C.L.)

$I \neq 1$

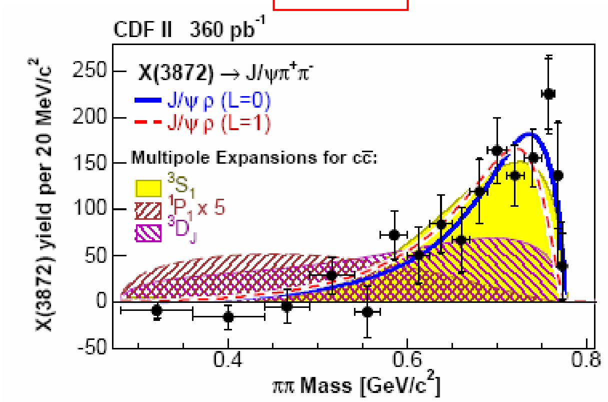
$\pi\pi$ Mass Distribution

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

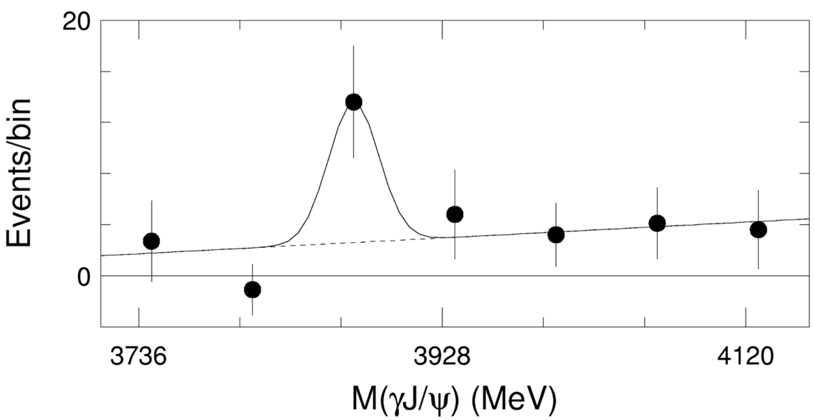


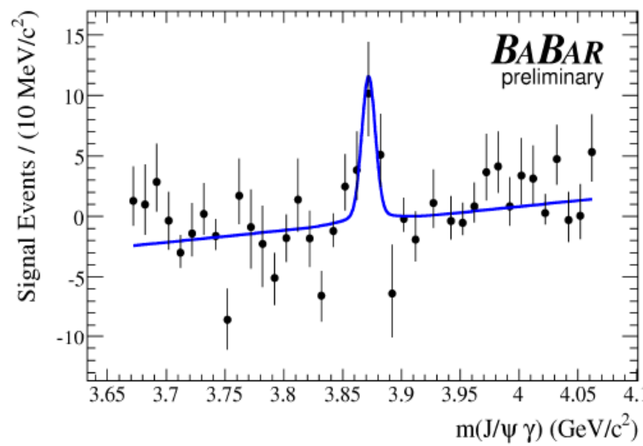
CDF



X(3872) Decays - I

Belle and BaBar detected the $\gamma J/\psi$ decay mode





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

Belle

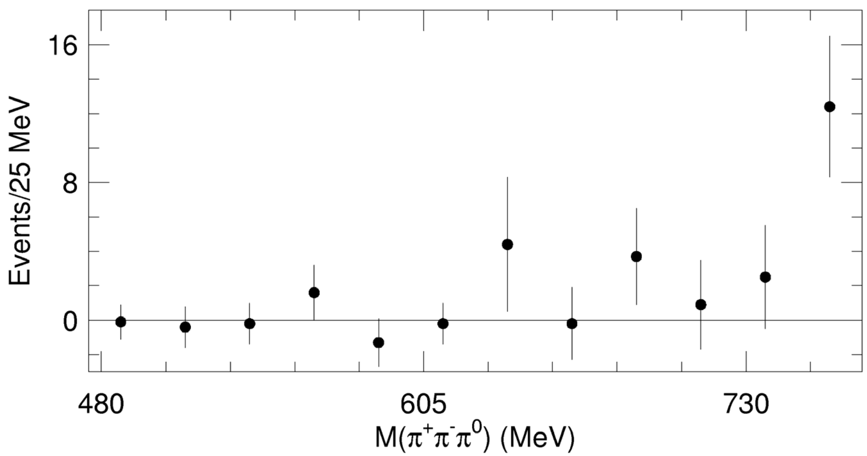
$$\frac{\Gamma(X \to J/\psi\gamma)}{\Gamma(X \to J/\psi\pi^+\pi^-)} = 0.34 \pm 0.14$$

BaBar

→ **C=+1**

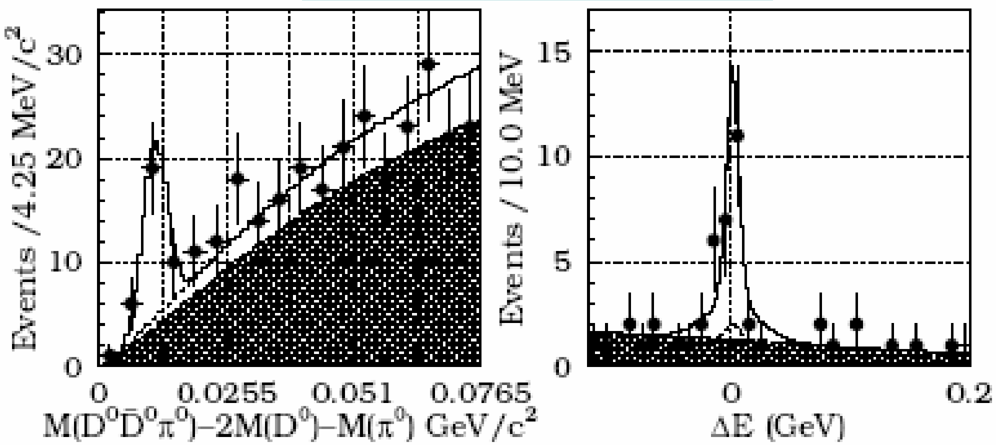
X(3872) Decays - II

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

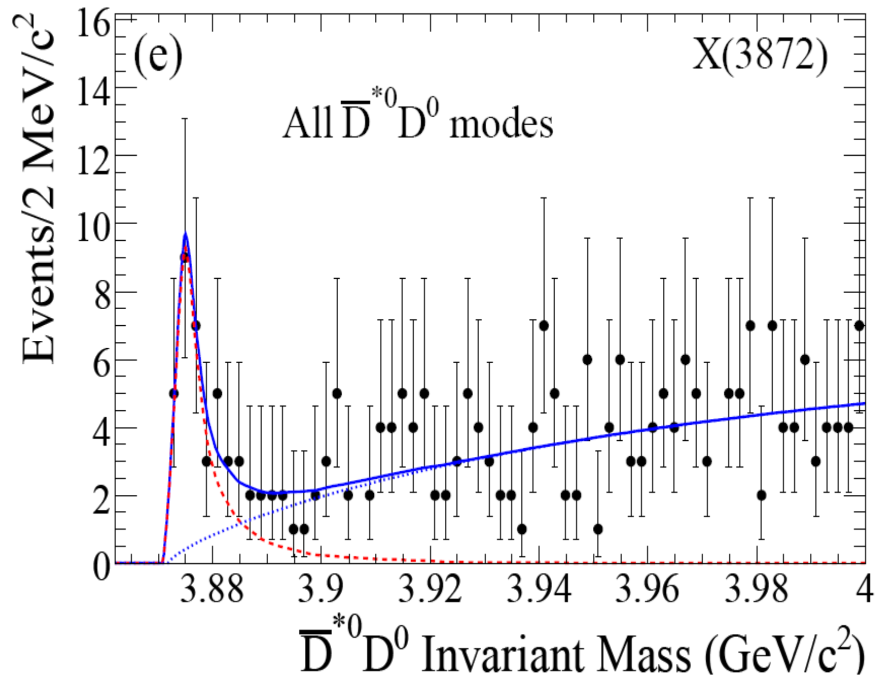


X(3872) Decays III: X(3872)→$D^0 \bar{D}^{0*}$

Belle hep-ex/0606055



BaBar arXiv:0708.1565



$M = 3875.2 \pm 0.7\,^{+0.3}_{-1.6} \pm 0.8$ MeV

$Br(B\to KX)Bf(X\to D^0\underline{D}^0\pi^0)$

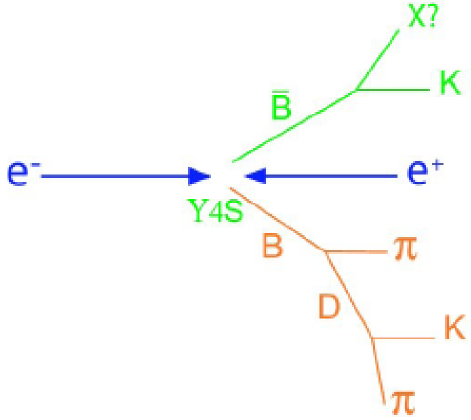
$= (1.27 \pm 0.31\,^{+0.22}_{-0.39})\times 10^{-4}$

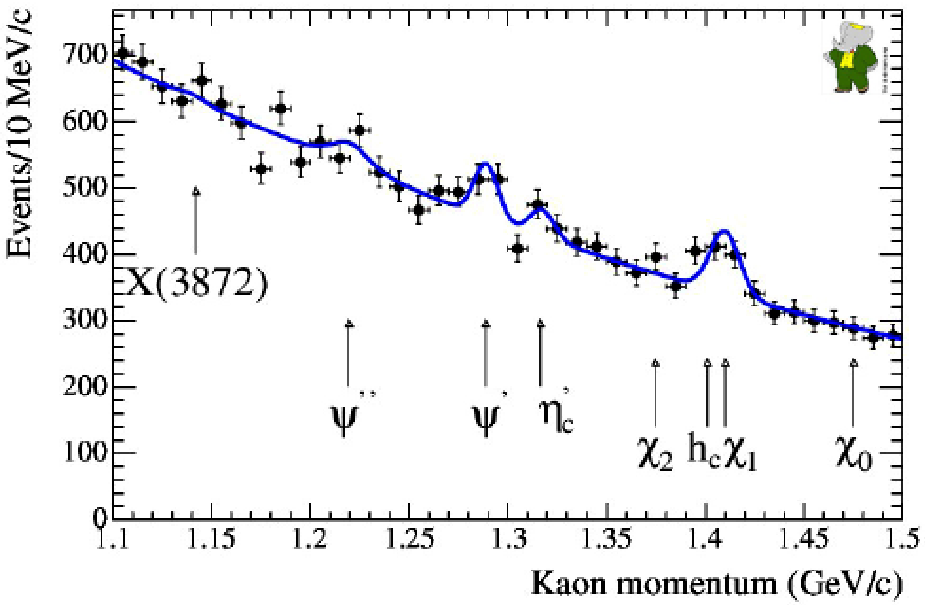
$$\frac{Br(X\to D^0\underline{D}^0\pi^0)}{Br(X\to \pi^+\pi^- J/\psi)} \sim 10$$

$M = 3875.1 \pm 1.1 \pm 0.5$ MeV

$\Gamma = 3.0 \pm 0.7\,^{+4.6}_{-2.3} \pm 0.9$ MeV

Inclusive Study of $B \to XK^+$ in BaBar





$B(B \to x(3872)K) = (0.5 \pm 1.4) \times 10^{-4} < 3.2 \times 10^{-4}$

$B(B \to J/\psi\ \pi^+\pi^-) > 4.3$ % at 90 % C.L. **too large for an isospin violating decay**

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 $J^{PC}=1^{++}$.

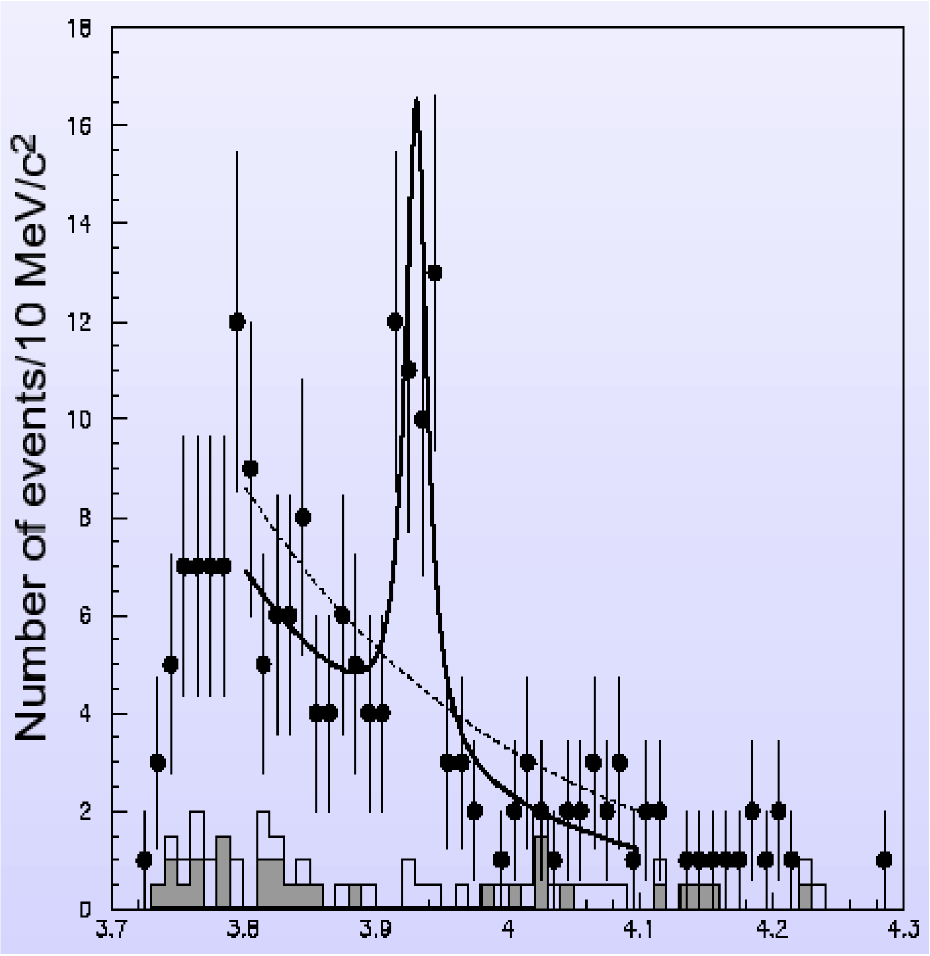
What is the X(3872) ?

- 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.
- Diquark-antidiquark ($cu - \bar{c}\bar{u}$).
- A threshold effect.
- 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 $\gamma\gamma \to$ Z(3931) $\to D\ \bar{D}$

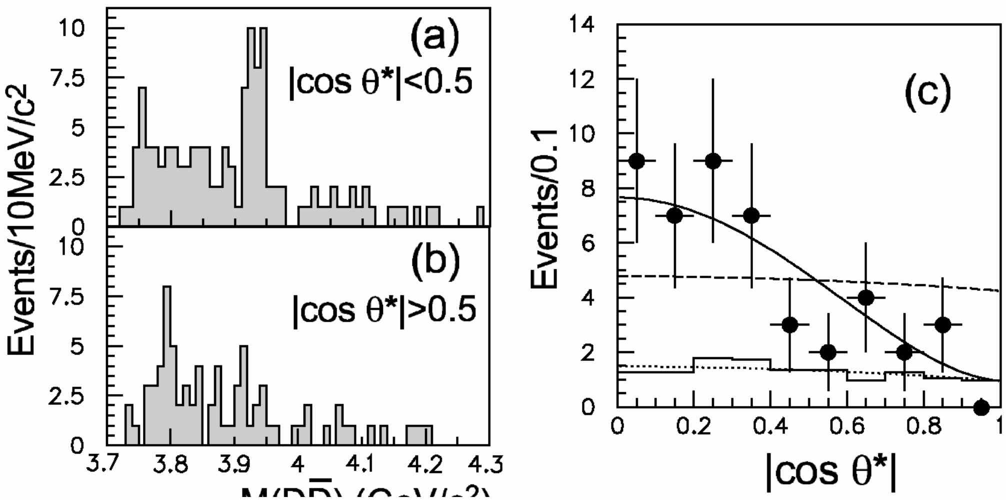


41± 11 evts (5.5σ)

M=3929 ± 5 ± 2 MeV/c²

Γ=29 ± 10 ± 2 MeV

What is the Z(3931) ?



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

J=2 favored

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

Issues:

- Z → DD* Crucial to observe this decay mode.
- χ_{c2}(2P) < χ_{c1}(2P) (if one of the 3940s).
- χ_{c2}(2P) → ψ(2S)γ.

X(3940)

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

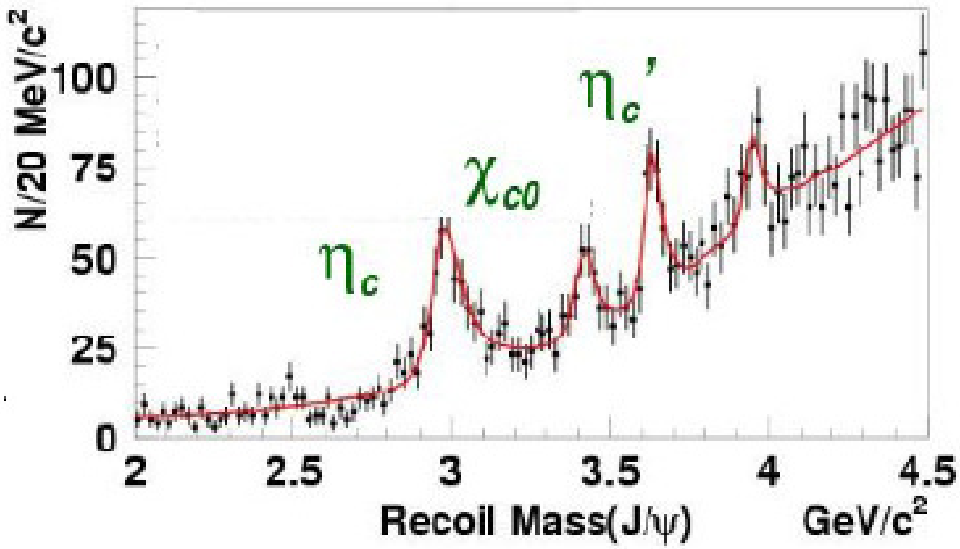
$M = 3943 \pm 6 \pm 6\ MeV/c^2$

$\Gamma = 15.4 \pm 10.1\ MeV$

$BR\left(X \rightarrow D\overline{D}^*\right) = 96^{+45}_{-32} \pm 22\ \%$

$BR\left(X \rightarrow D\overline{D}\right) < 41\ \%\ (90\ \%\ CL)$

$BR\left(X \rightarrow \omega J/\psi\right) < 26\ \%\ (90\ \%\ CL)$

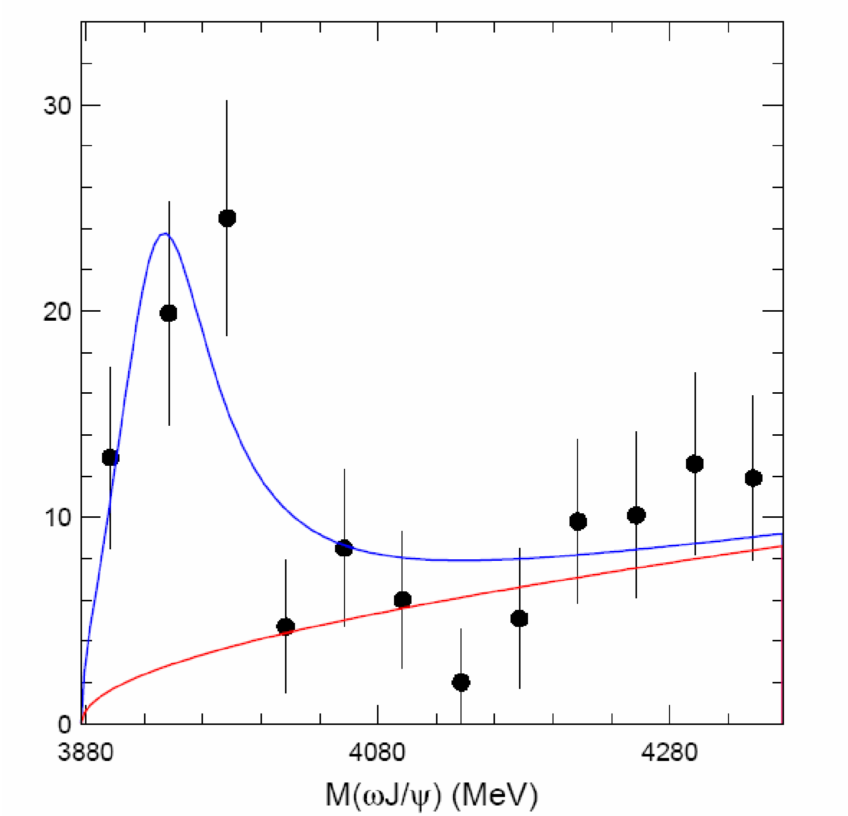


$\eta_c(3S)$ candidate. Check $\gamma\gamma \rightarrow D\overline{D}^*$

Width too large ?

Y(3940)

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



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

What can the X(3940) be ?

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

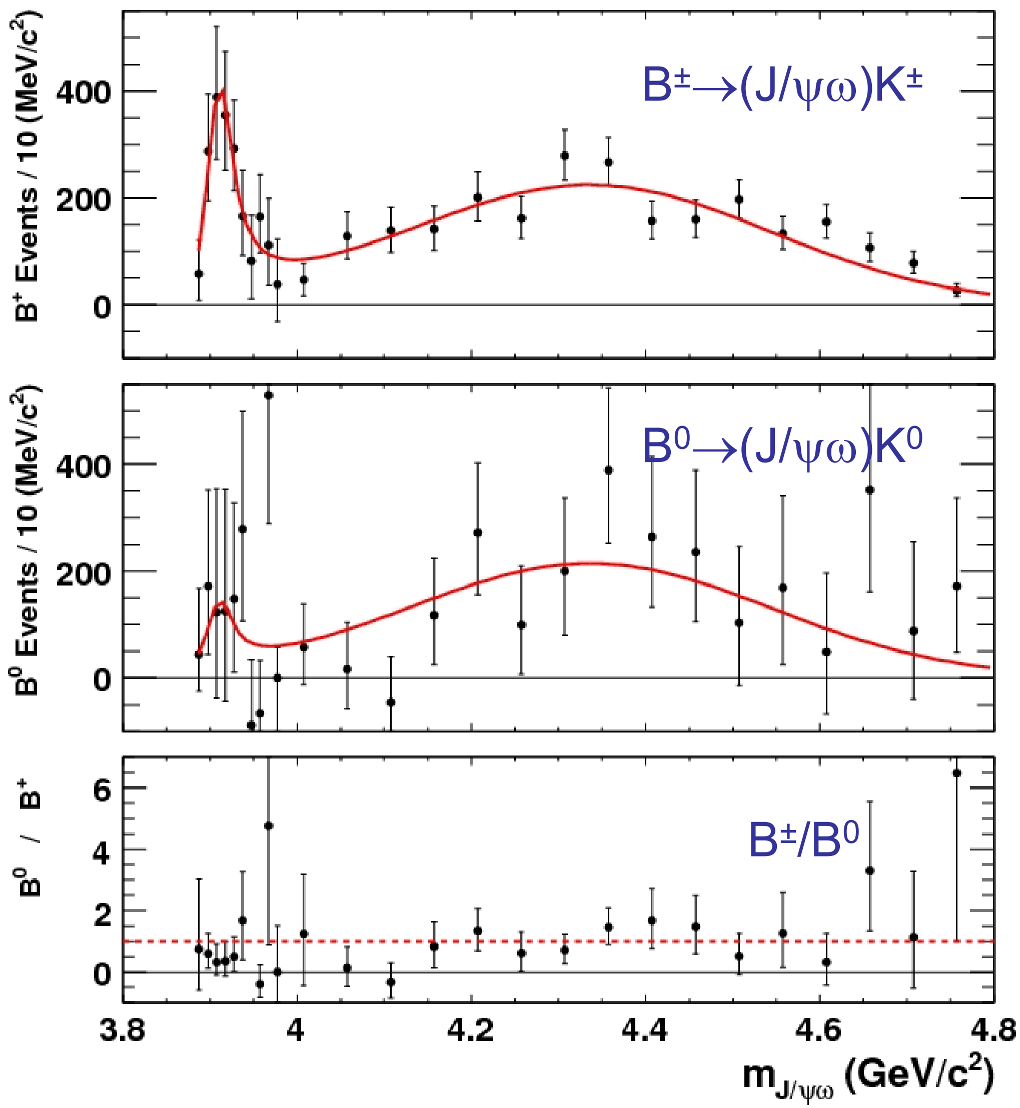
$M = 3943 \pm 11 \pm 13$ MeV/c^2
$\Gamma = 87 \pm 22$ MeV

Y(3940) confirmed by BaBar in $B \to K\omega\ J/\psi$

- Mass slightly lower than Belle
- Lower total width
- BR compatible with Belle
- $B^{\pm}$ e B^{0} compatible (but a higher statistics on the neutral channel is needed)

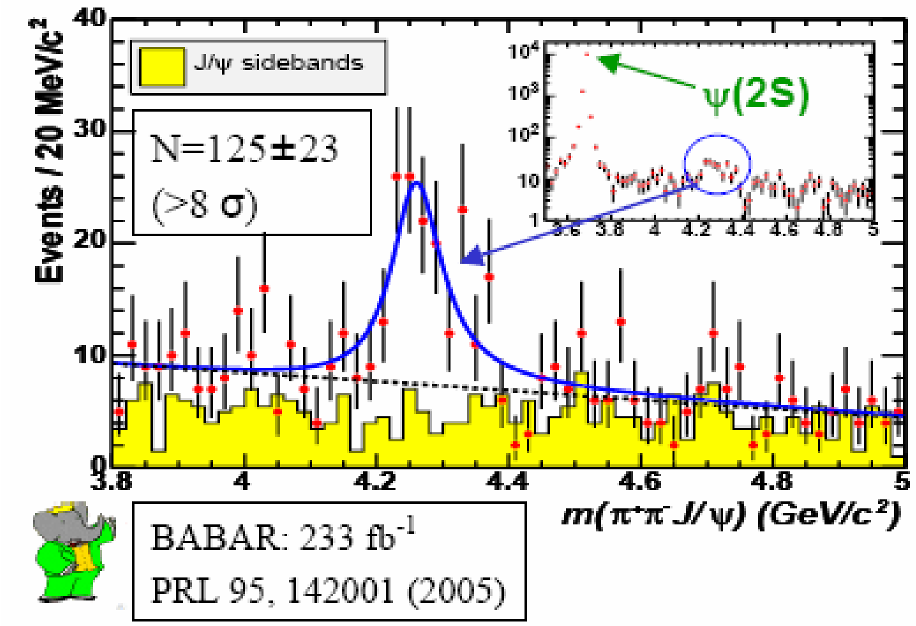
$M = 3914.3^{+3.8}_{-3.4} \pm 1.6$ MeV

$\Gamma = 33^{+12}_{-8} \pm 0.6$ MeV



Y(4260)

Y(4260) Discovery



New state discovered by BaBar in ISR events:

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

Assuming single resonance:

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

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

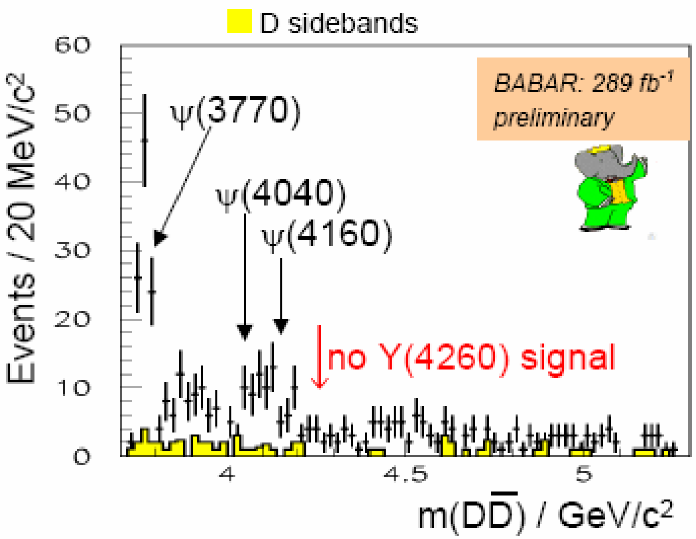
$$J^{PC} = 1^{--}$$

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

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

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 $\bar{p}p$

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

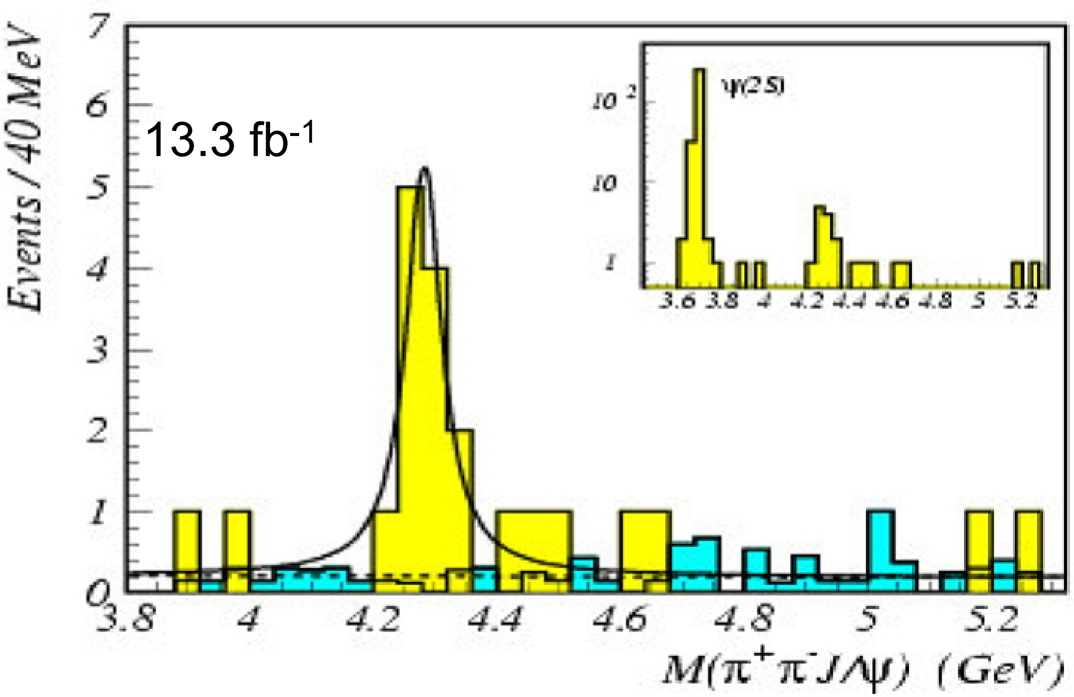
$$\frac{B(Y(4260)\to p\bar{p})}{B(Y(4260)\to J/\psi\pi^+\pi^-)} < 0.13\ (90\%\ \mathrm{CL})$$

Y(4260) confirmed by CLEO ...

ISR

$\Upsilon(1S)$-$\Upsilon(4S)$

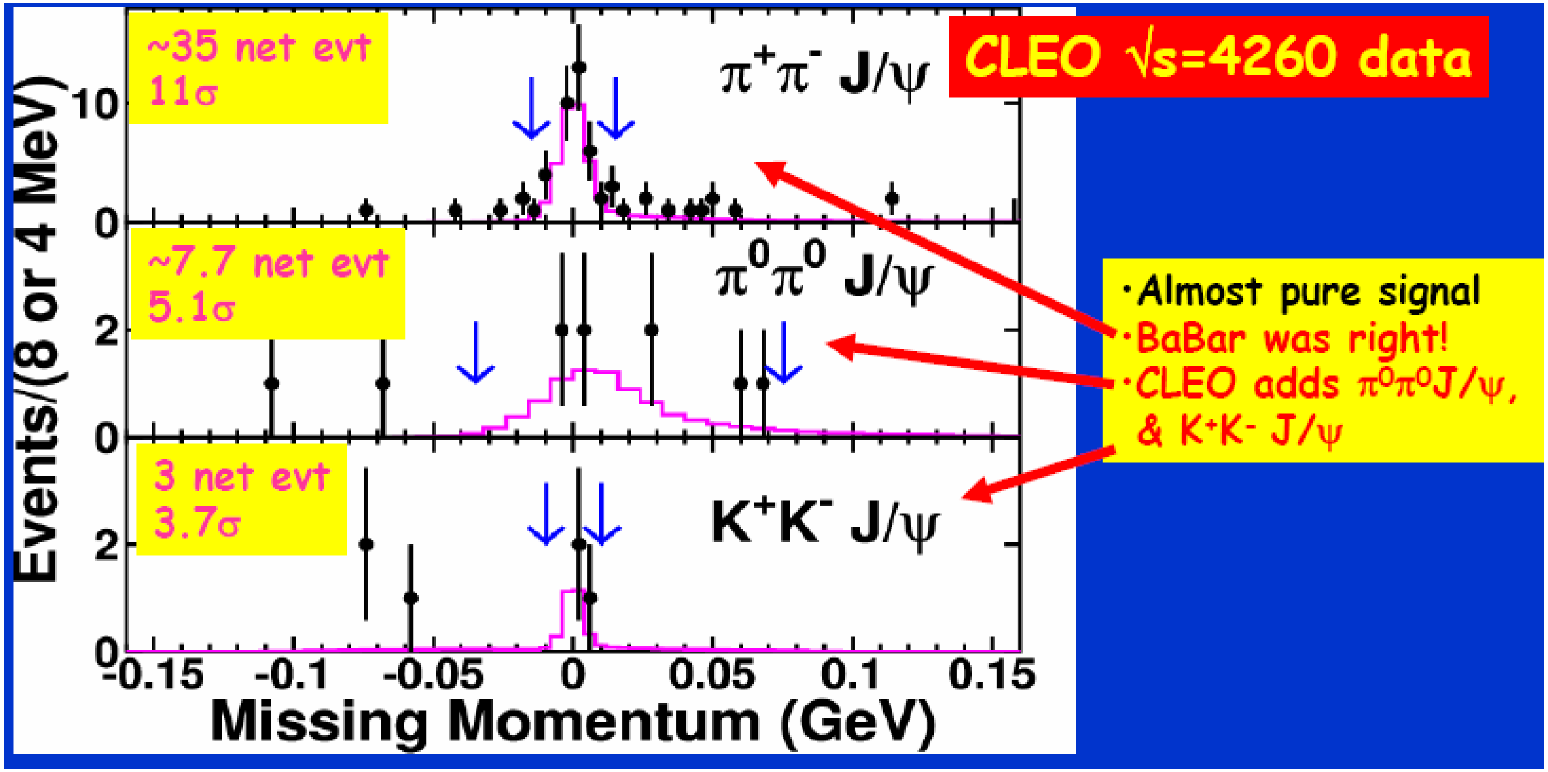
13.3 fb^{-1}



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

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

... and by CLEO III



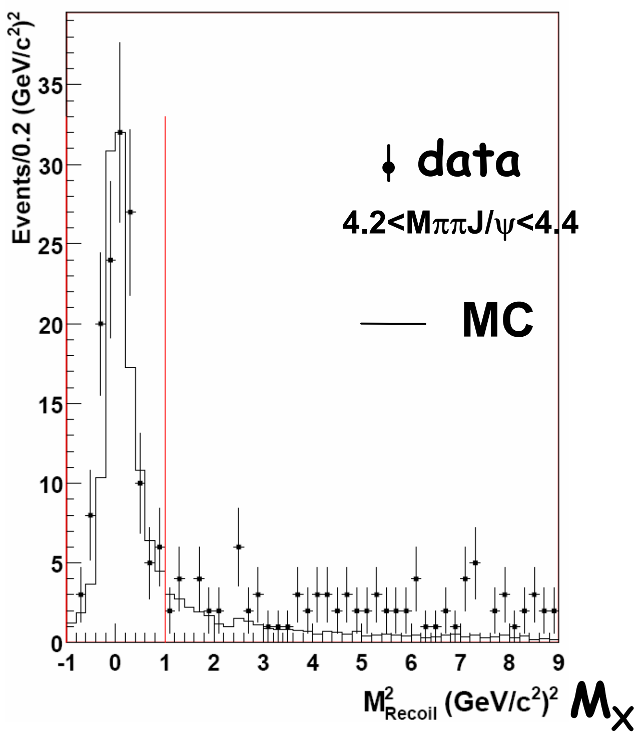
B. Heltsley – QWG4

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

Y(4260) at Belle

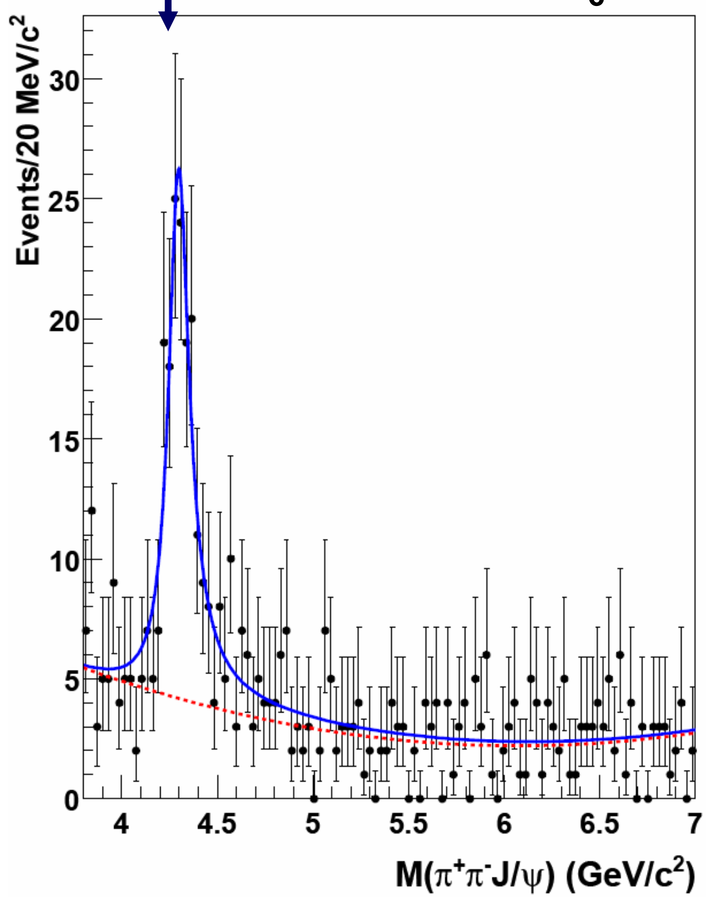
Select e+e-→ $\pi^+\pi^-$ $\ell^+\ell^-$ +X; N_{chg}=4

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



M=4295 ± 10 $^{+11}_{-5}$ MeV

Γ = 133 ± 26 $^{+13}_{-6}$ MeV



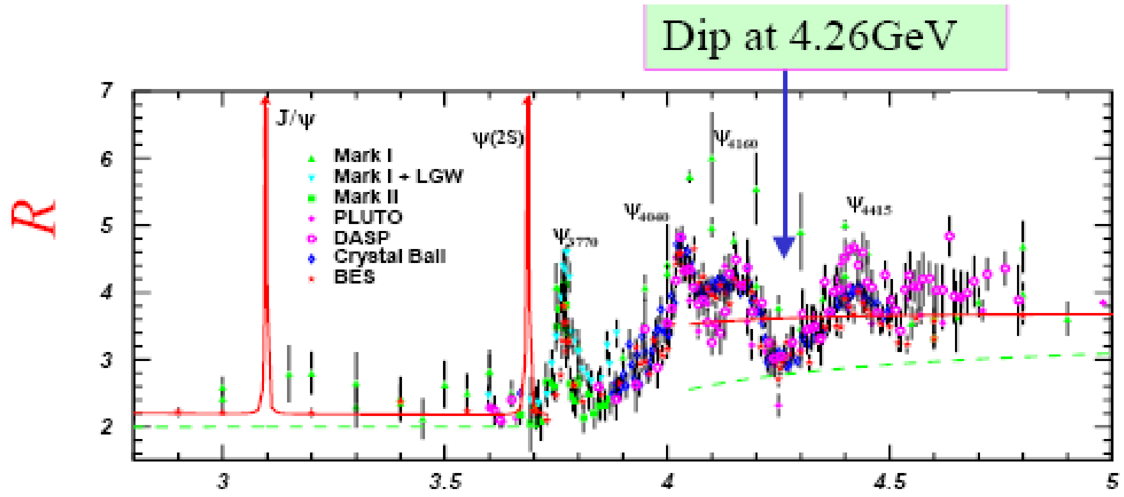
For $\psi'\to\pi^+\pi^-J/\psi$ in the same data:

$M(\psi')$ = 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.



~2.5σ discrepancy between BaBar and Belle mass measurements.

No available vector state slot in charmonium spectrum

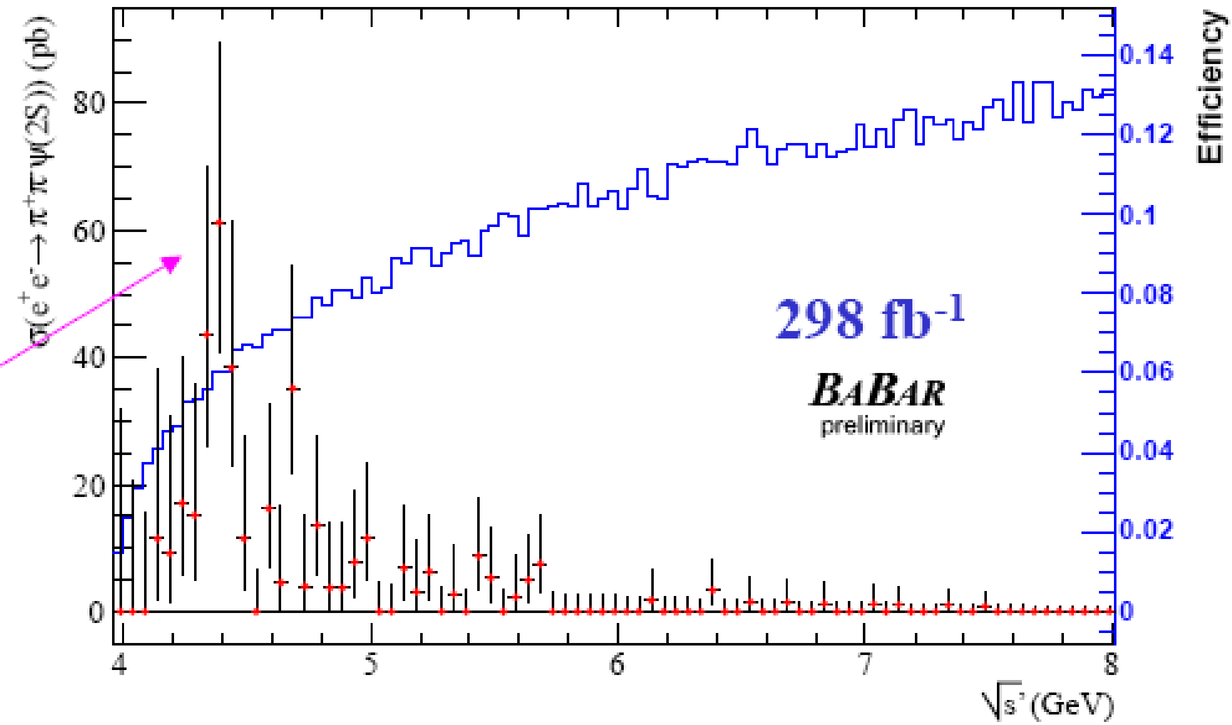
New Structure at 4320 in BaBar ISR data

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

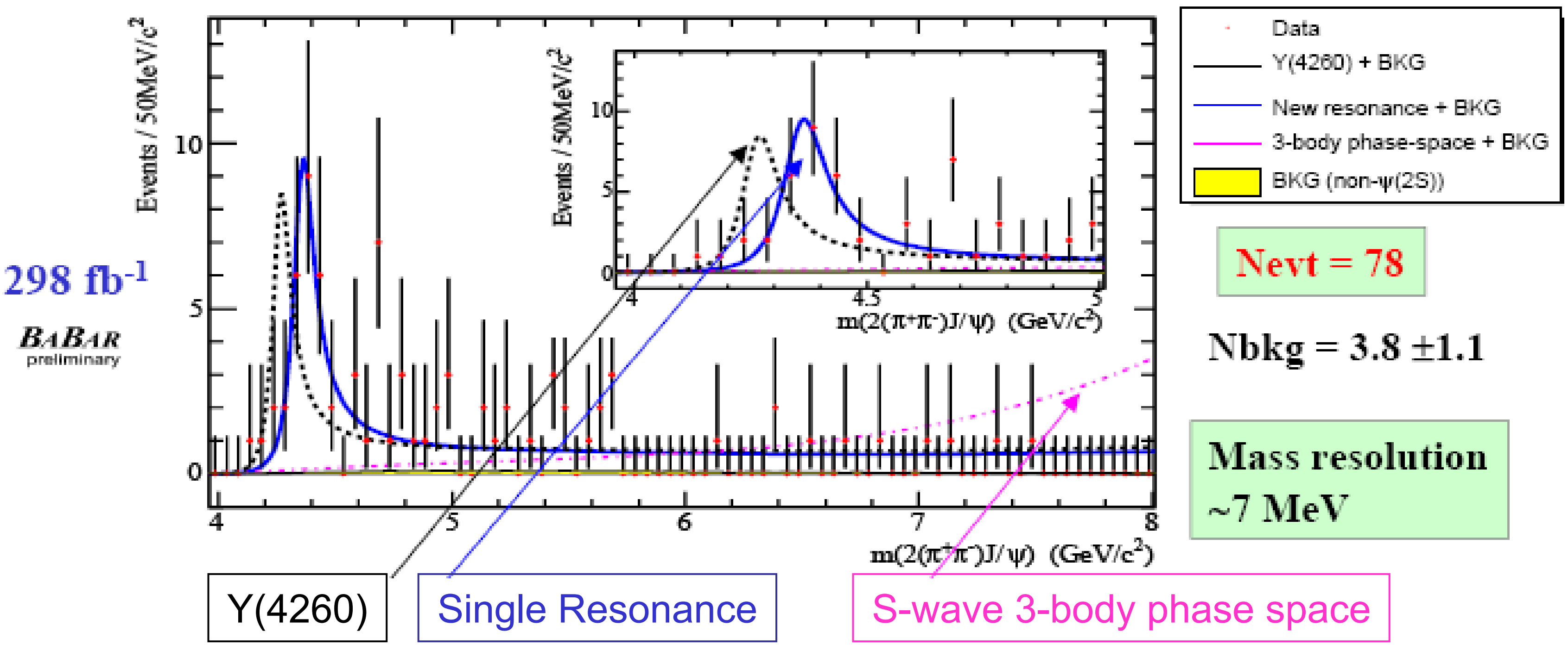
w/ bkg subtraction

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

A structure!



S. Ye – QWG4



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

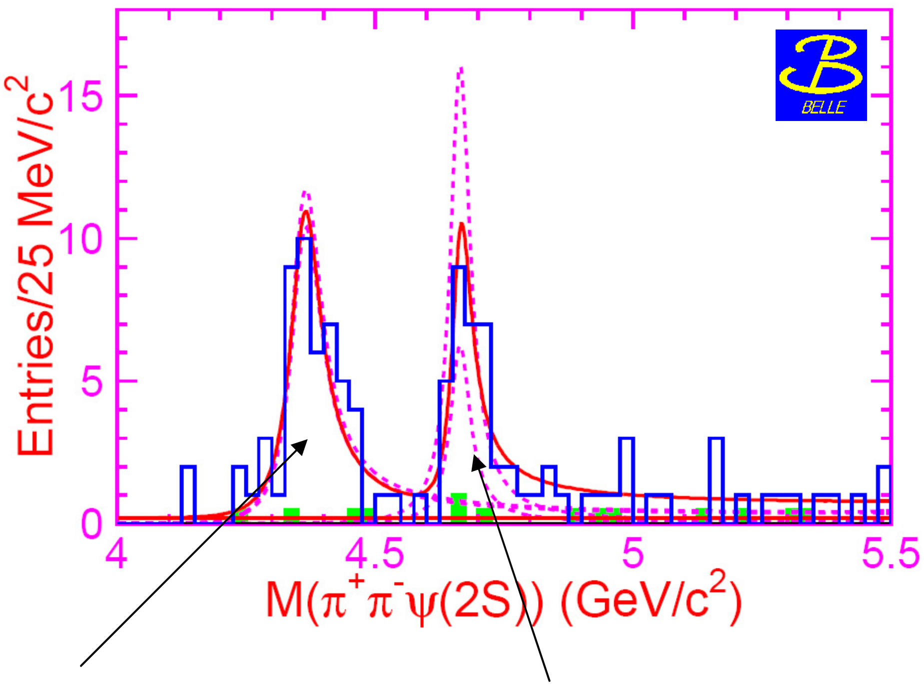
Assuming single resonance:

$$M = 4324 \pm 24\ MeV/c^2$$

$$\Gamma = 172 \pm 33\ MeV$$

PRL 98, 212001 (2007)

New Vector State Observed by Belle



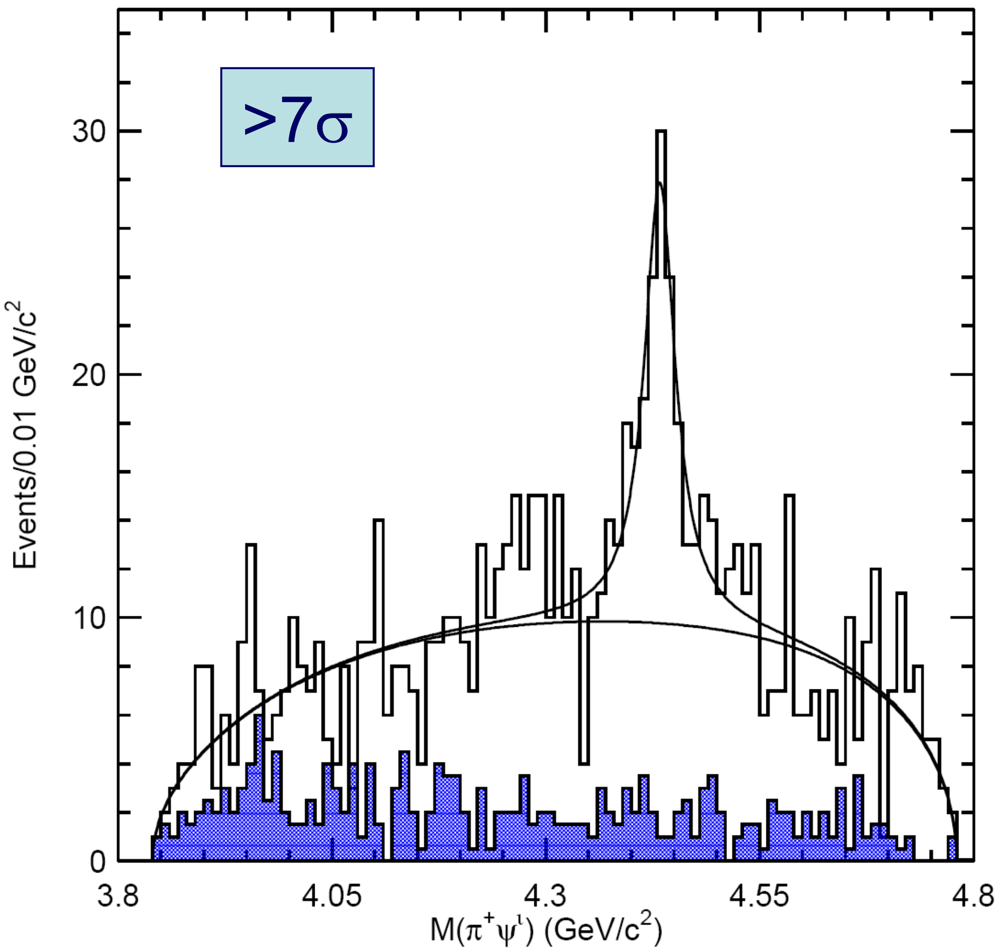
M = 4361±9±9 MeV
Γ = 74±15±10 MeV

M = 4664±11±5 MeV
Γ = 48±15±3 MeV

arXiv:0707.3699

A New Charged State from Belle

- Study of $B \to K\pi^{\pm}\psi'$ decay
- Structure in $\pi^{\pm}\psi'$ invariant mass
- $B^{\pm}$ e B^0 consistent
- Too narrow for a reflection
- First evidence of a charged state in charmonium mass region
- Work in progress in BaBar



$$M = 4433 \pm 4 \pm 1 \; MeV / c^2$$

$$\Gamma = 44^{+17+30}_{-13-11} \; MeV$$

$$BR(B \to ZK) \times BR(Z \to \psi'\pi) = (4.1 \pm 1.0 \pm 1.3) \times 10^{-5}$$

arXiv:0708.1790

The XYZ of Charmonium

- The Z(3931) is tentatively being identified with the $\chi_{c2}(2P)$
  - Width too small ?
- The X(3940) is tentatively being identified with the $\eta_c(3S)$
  - Width too large ?
- Many other states have been discovered whose interpretation is not at all clear: X(3872), Y(3940), Y(4260), Y(4320), Y(4660), Z(4430) ...
  - missing $c\bar{c}$ states
  - molecules
  - tetraquarks
  - hybrids

The situation above threshold needs to be fully understood.

The Physics Program of $\bar{P}$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 PANDA

- At $2\times10^{32}cm^{-2}s^{-1}$ accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) $\Rightarrow$ $10^4 \div 10^7$ ($c\bar{c}$) states/day.
- Total integrated luminosity 1.5 fb^{-1}/year (at $2\times10^{32}cm^{-2}s^{-1}$, 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).
- Fine scans to measure masses to $\approx$ 100 KeV, widths to $\approx$ 10 %.
- Explore entire region below and above open charm threshold.
- Decay channels
  - $J/\psi+X$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\bar{D}$

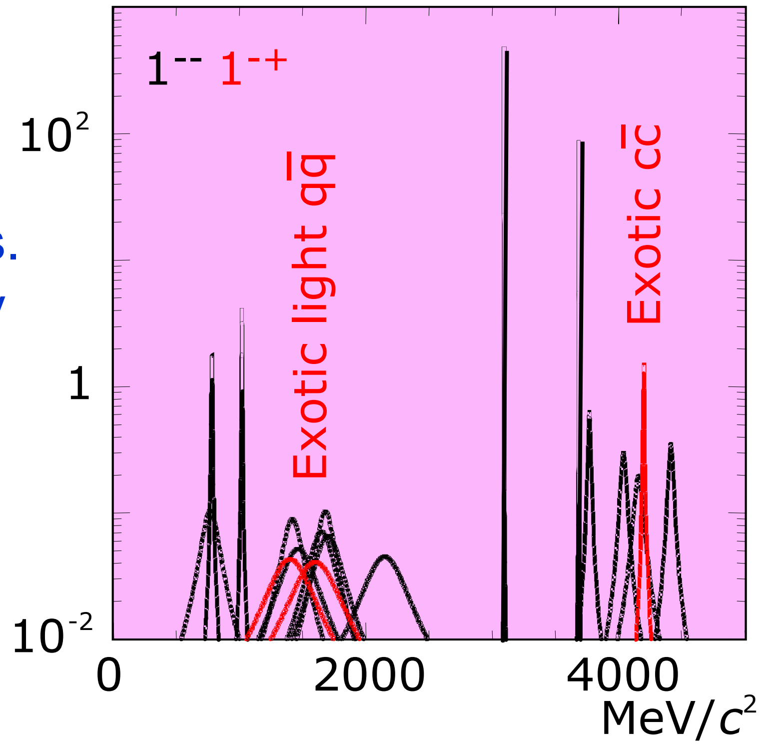
Hybrids and Glueballs

The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

Glueballs states of pure glue

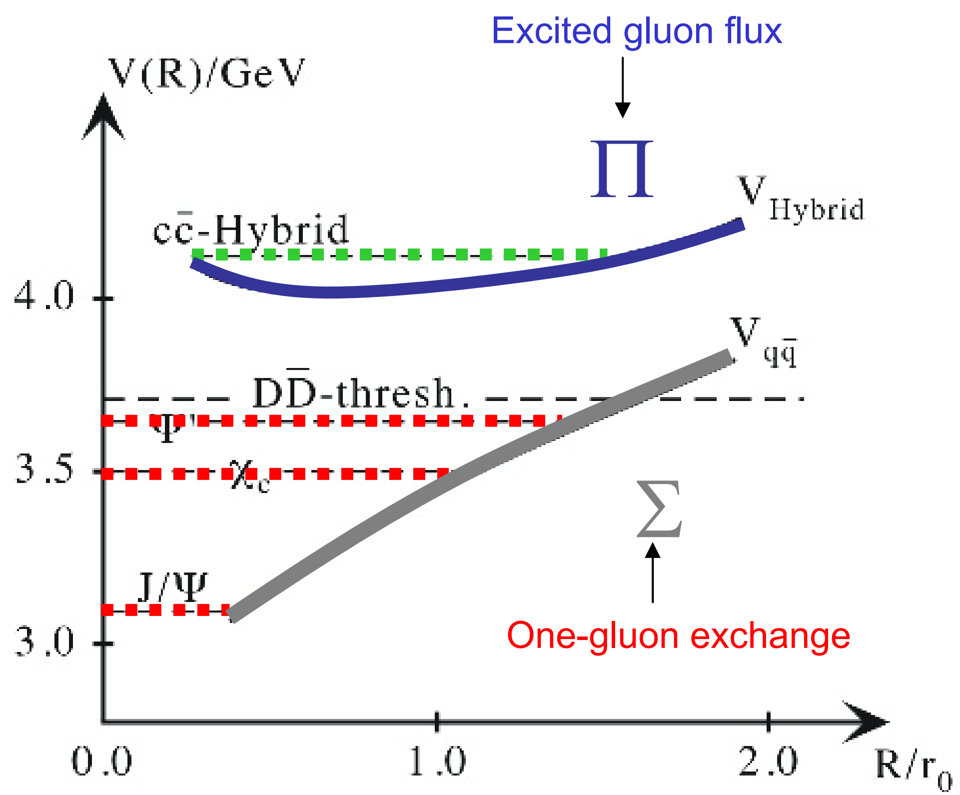
Hybrids $q\bar{q}g$

- Spin-exotic quantum numbers J^{PC} are powerful signature of gluonic hadrons.
- In the light meson spectrum exotic states overlap with conventional states.
- In the $c\bar{c}$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously.
- $\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC}=1^{-+}$.
- $\pi_1(2000)$ and $h_2(1950)$
- Narrow state at 1500 MeV/c^2 seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).



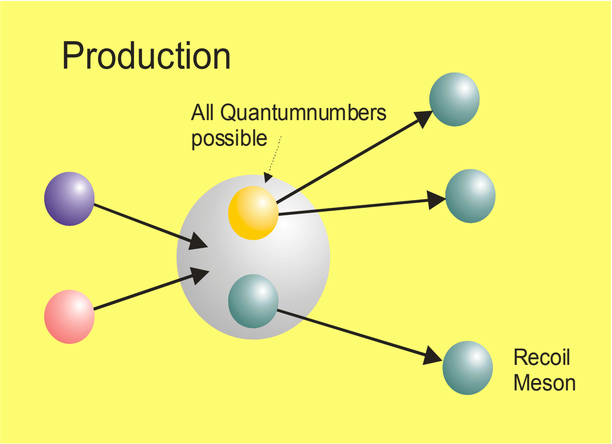
Charmonium Hybrids

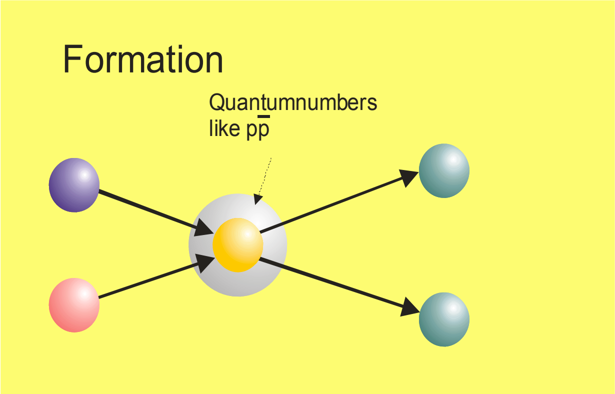
- Bag model, flux tube model constituent gluon model and LQCD.
- Three of the lowest lying $c\bar{c}$ hybrids have exotic J^{PC} (0^{+-}, 1^{-+}, 2^{+-})
  $\Rightarrow$ no mixing with nearby $c\bar{c}$ states
- Mass 4.2 – 4.5 GeV/c^2.
- Charmonium hybrids expected to be much narrower than light hybrids (open charm decays forbidden or suppressed below DD** threshold).
- Cross sections for formation and production of charmonium hybrids similar to normal $c\bar{c}$ states
  (~ 100 – 150 pb).



Charmonium Hybrids

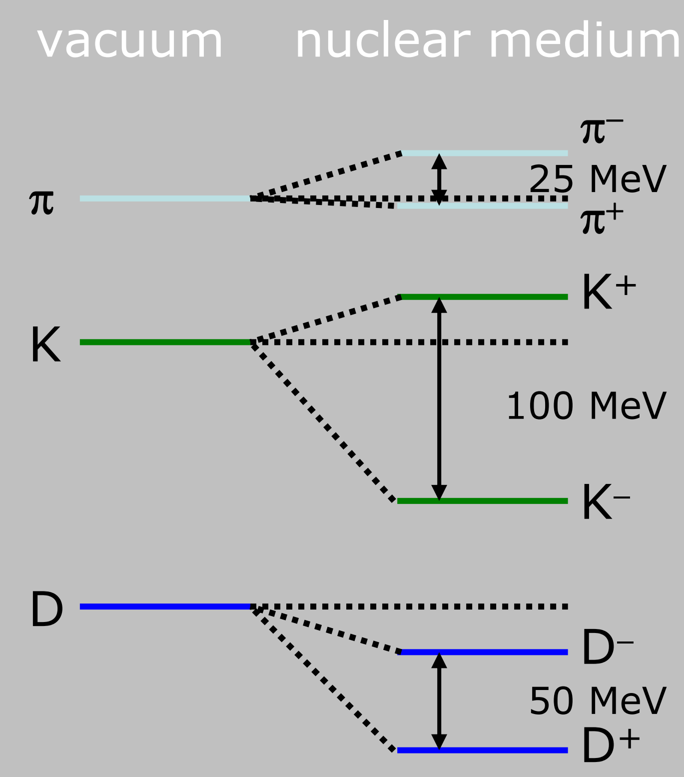
- Gluon rich process creates gluonic excitation in a direct way
  - ccbar requires the quarks to annihilate (no rearrangement)
  - yield comparable to charmonium production
- 2 complementary techniques
  - Production (Fixed-Momentum)
  - Formation (Broad- and Fine-Scans)
- Momentum range for a survey
  - p → ~15 GeV





Hadrons in Nuclear Matter

- Partial restoration of chiral symmetry in nuclear matter
  - Light quarks are sensitive to quark condensate
- Evidence for mass changes of pions and kaons has been deduced previously:
  - deeply bound pionic atoms
  - (anti)kaon yield and phase space distribution
- $(c\bar{c})$ states are sensitive to gluon condensate
  - small (5-10 MeV/c^2) in medium modifications for low-lying $(c\bar{c})$ (J/ψ, η_c)
  - significant mass shifts for excited states: 40, 100, 140 MeV/c^2 for χ_{cJ}, ψ', $\psi(3770)$ resp.
- D mesons are the QCD analog of the H-atom.
  - chiral symmetry to be studied on a single light quark
  - theoretical calculations disagree in size and sign of mass shift (50 MeV/c^2 attractive – 160 MeV/c^2 repulsive)



Hayaski, PLB 487 (2000) 96
Morath, Lee, Weise, priv. Comm.

Charmonium in Nuclei

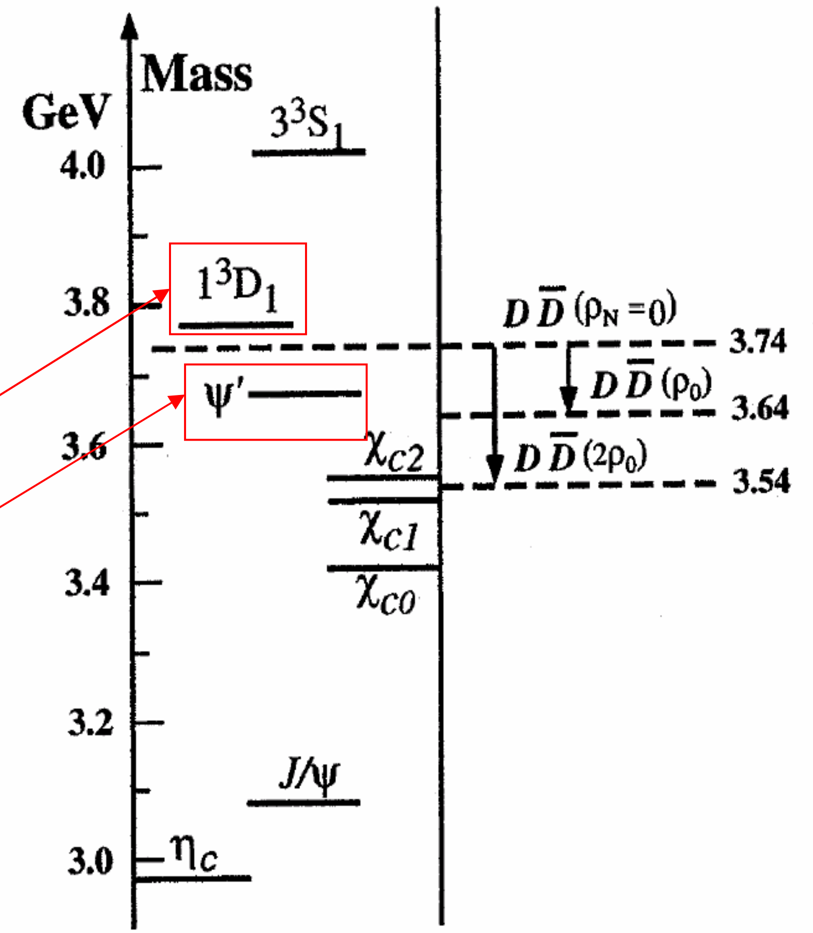
- Measure J/ψ and D production cross section in $\bar{p}p$ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

  ψ(1D) 20 MeV → 40 MeV

  ψ(2S) .28 MeV → 2.7 MeV

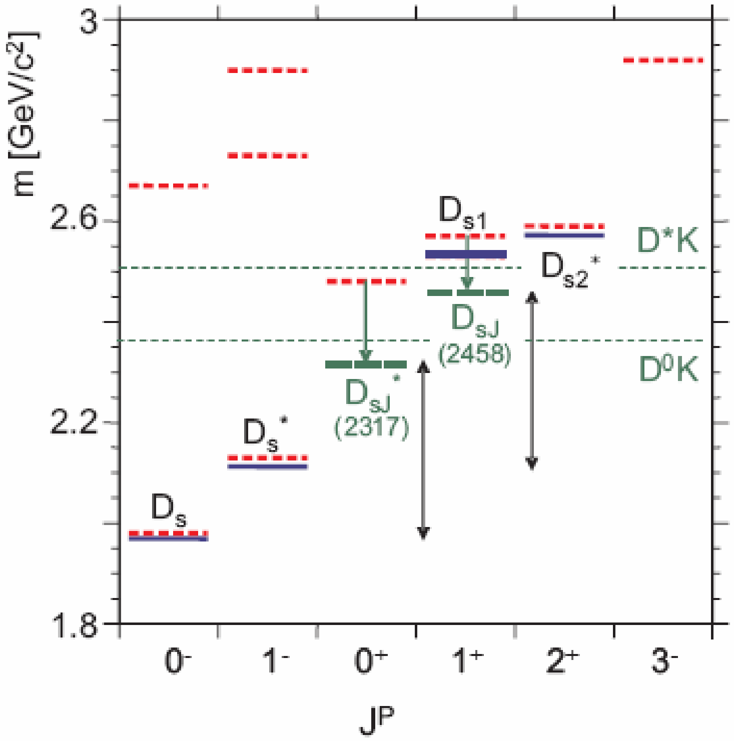
⇒Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton ($c\bar{c}$) or hadronic decays (D)



Open Charm Physics

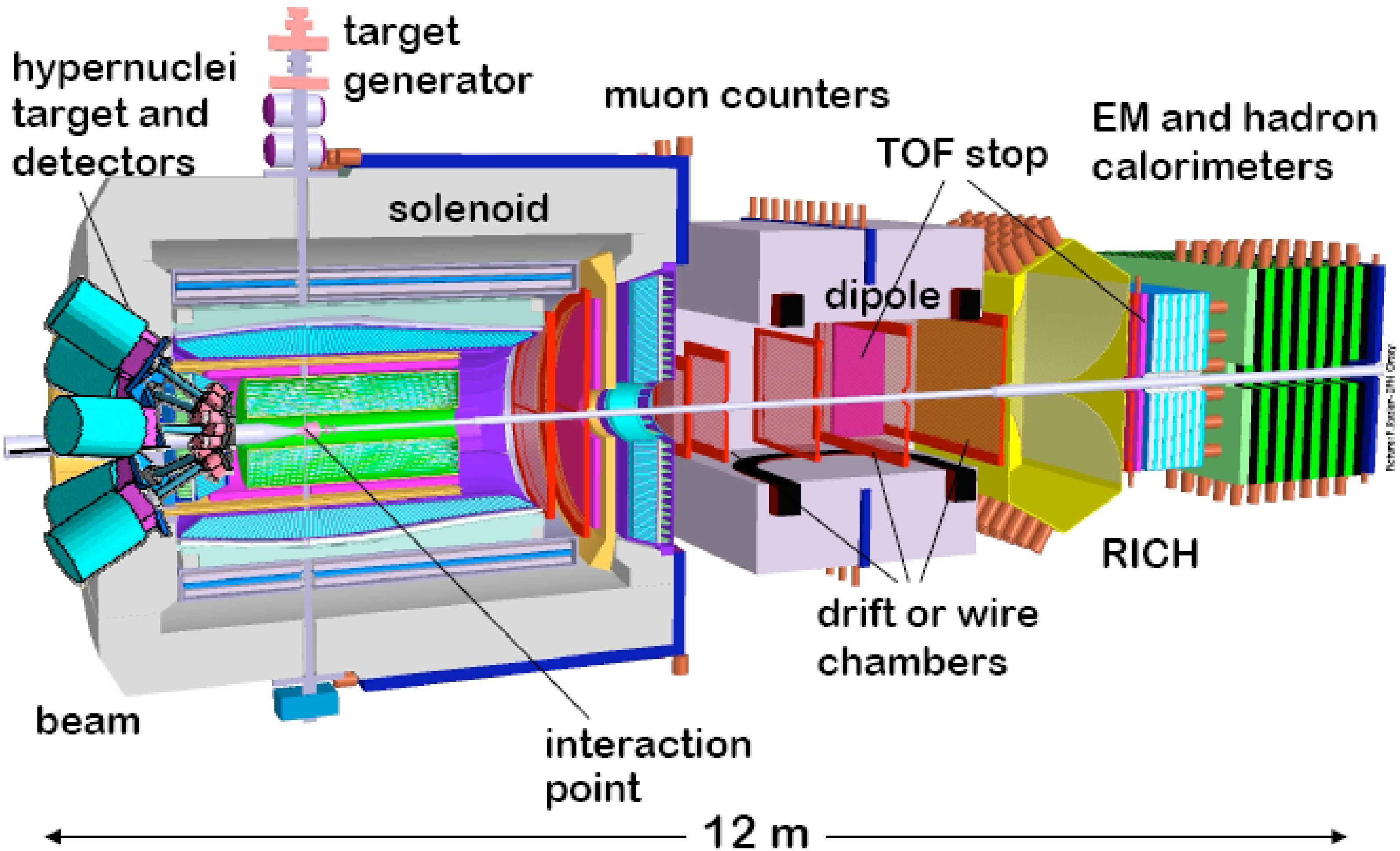
- New narrow states D_{sJ} recently discovered at B factories do not fit theoretical calculations.
- At full luminosity at $\bar{p}$ momenta larger than 6.4 GeV/c PANDA will produce large numbers of $D\bar{D}$ pairs.
- Despite small signal/background ratio (5×10^{-6}) background situation favourable because of limited phase space for additional hadrons in the same process.



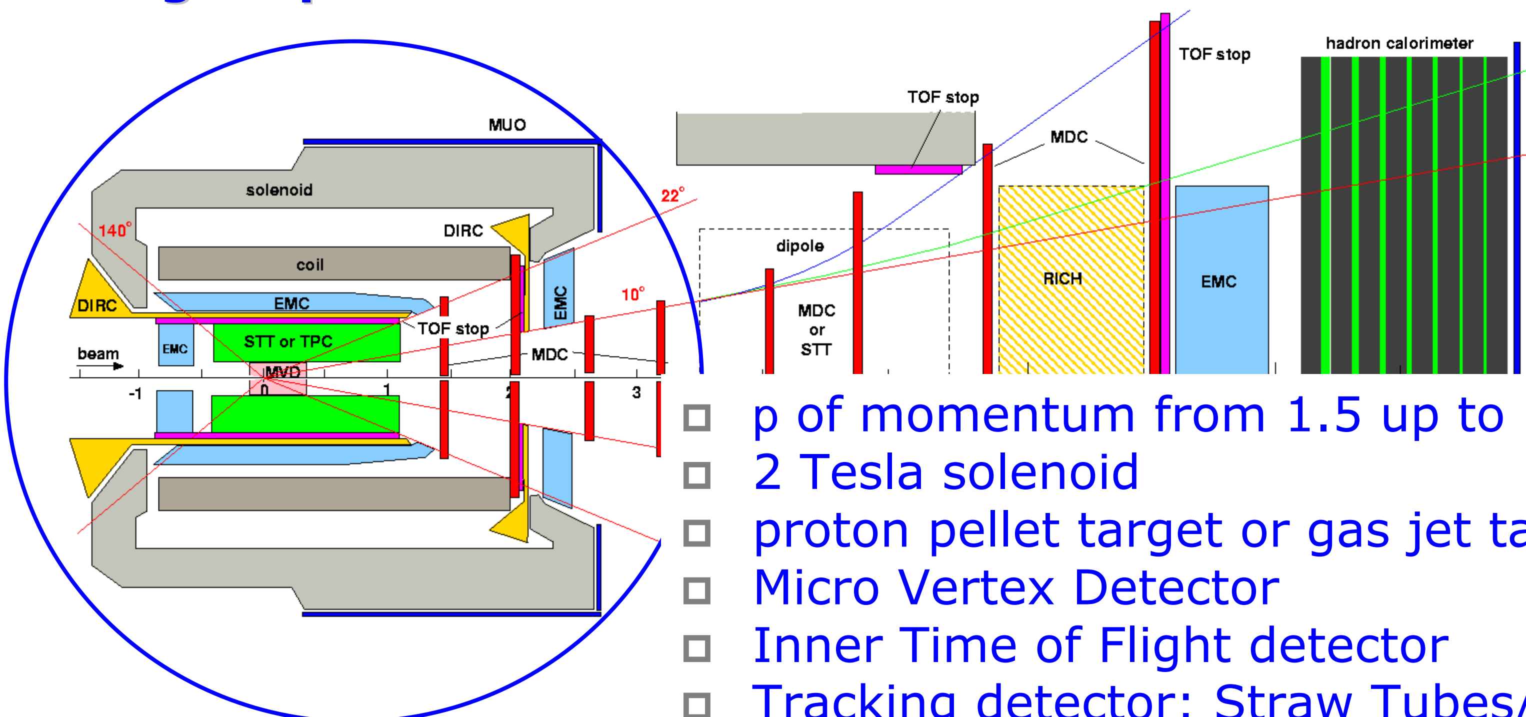
The Detector

- Detector Requirements:
  - (Nearly) 4π solid angle coverage (partial wave analysis)
  - High-rate capability (2×10^7 annihilations/s)
  - Good PID (γ, e, μ, π, K, p)
  - Momentum resolution ($\approx$ 1 %)
  - Vertex reconstruction for D, K^0_s, Λ
  - Efficient trigger
  - Modular design
- For Charmonium:
  - Pointlike interaction region
  - Lepton identification
  - Excellent calorimetry
    - Energy resolution
    - Sensitivity to low-energy photons

Panda Detector

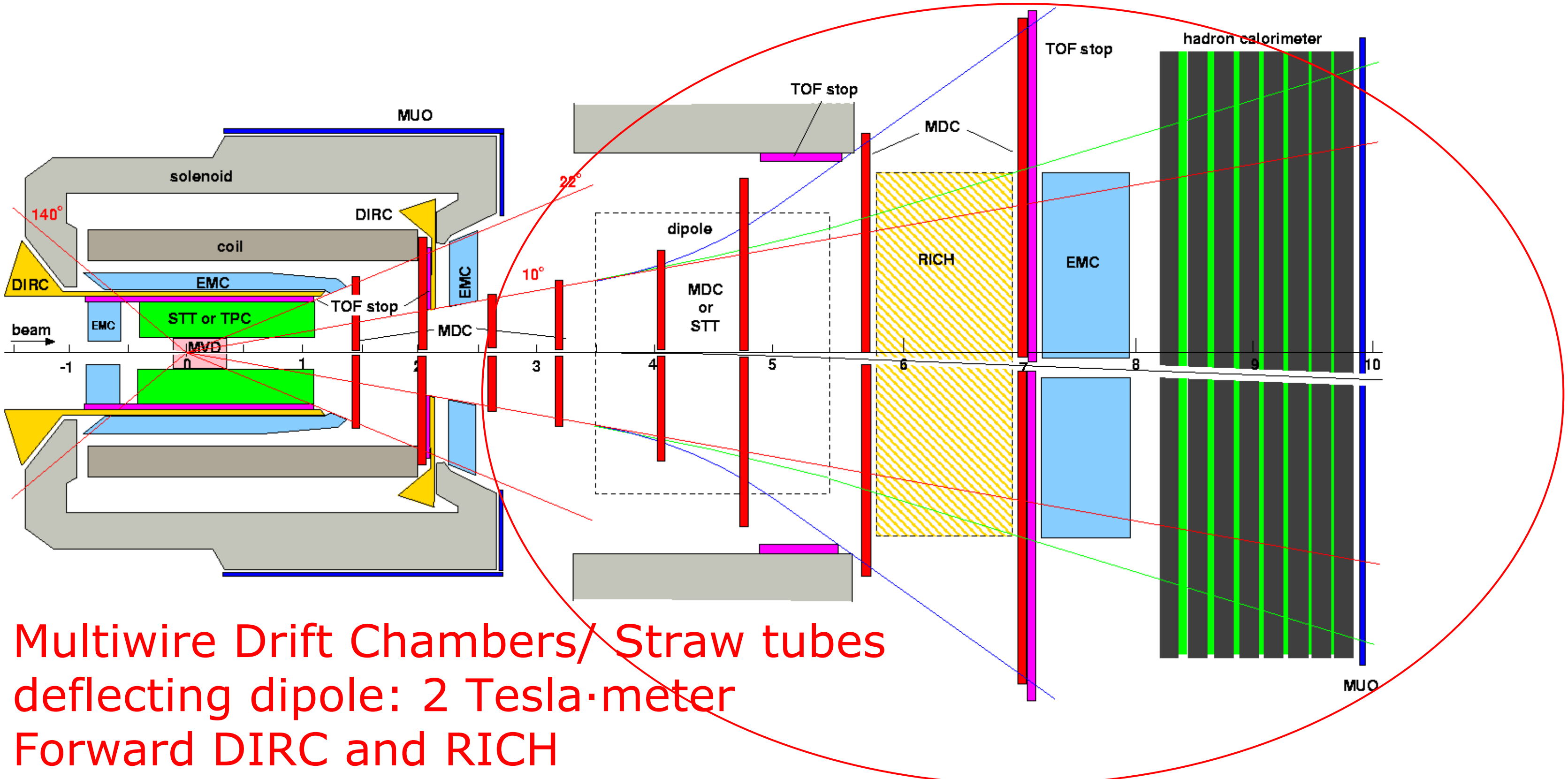


Target Spectrometer



- p of momentum from 1.5 up to 15 GeV/c
- 2 Tesla solenoid
- proton pellet target or gas jet target
- Micro Vertex Detector
- Inner Time of Flight detector
- Tracking detector: Straw Tubes/TPC
- DIRC
- Electromagnetic Calorimeter
- Muon counters
- Multiwire Drift Chambers

Forward Spectrometer



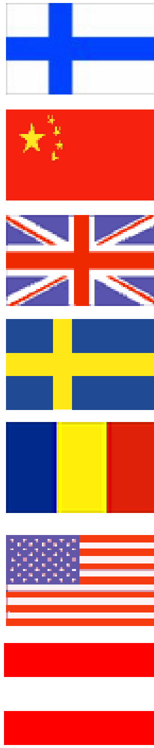
- Multiwire Drift Chambers/ Straw tubes
- deflecting dipole: 2 Tesla·meter
- Forward DIRC and RICH
- Forward Electromagnetic Calorimeters
- Time of Flight counters
- Hadron Calorimeter

PANDA Collaboration

- At present a group of **350 physicists** from 47 institutions of 15 countries

Austria – Belaruz - China - Finland - France - Germany – Italy – Poland – Romania - Russia – Spain - Sweden – Switzerland - U.K. – U.S.A..

Basel, Beijing, Bochum, Bonn, IFIN Bucharest, Catania, Cracow, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, Lanzhou, LNF, Mainz, Milano, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia, Piemonte Orientale, IPN Orsay, IHEP Protvino, PNPI St. Petersburg, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien



http://www.gsi.de/panda

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.