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REVIEW OF RECENT DATA ON CHARMONIUM

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ABSTRACT

Recent results on charmonium resonances from experiments studying $\bar{p}p$, e^+e^- and $\gamma\gamma$ collisions are reviewed.
FNAL-E835 reports new measurements of parameters of the ground state $\eta_c(1^1\mathrm{S}_0)$, $\gamma\gamma$ partial width of η_c and $\chi_{c2}(1^3\mathrm{P}_2)$ and the first evidence of $\chi_{c0}(1^3\mathrm{P}_0)$ direct formation in $\bar{p}p$ annihilations.
New measurements of η_c and χ_{c2} $\gamma\gamma$ partial widths obtained in two-photon collisions at high energy e^+e^- colliders are reported by CESR and more recently LEP.
A new measurement of the χ_{c0} parameters studied in $\psi(2S)$ decays by the Beijing Spectrometer (BES) at BEPC is presented.
The results of these and older experiments are compared.

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1 Introduction

Since the J/ψ was discovered 25 years ago, the charmonium spectrum (fig.1) has been studied as the "hydrogen atom of strong interaction physics" [1].

The most successful and simplest theoretical predictions are based on non-relativistic, QCD inspired potential models. Precision measurements of this heavy bound ($c\bar{c}$) system (masses, widths, energy splittings, decay rates and their ratios) are important inputs to test the limit of perturbative QCD and the order of magnitude of relativistic and radiative corrections.

Charmonium states have been studied in many experiments, which basically use three different techniques: formation and subsequent cascade decays from e^+e^- colliders, two virtual photon interactions at e^+e^- high energy colliders and formation from $\bar{p}p$ collisions.

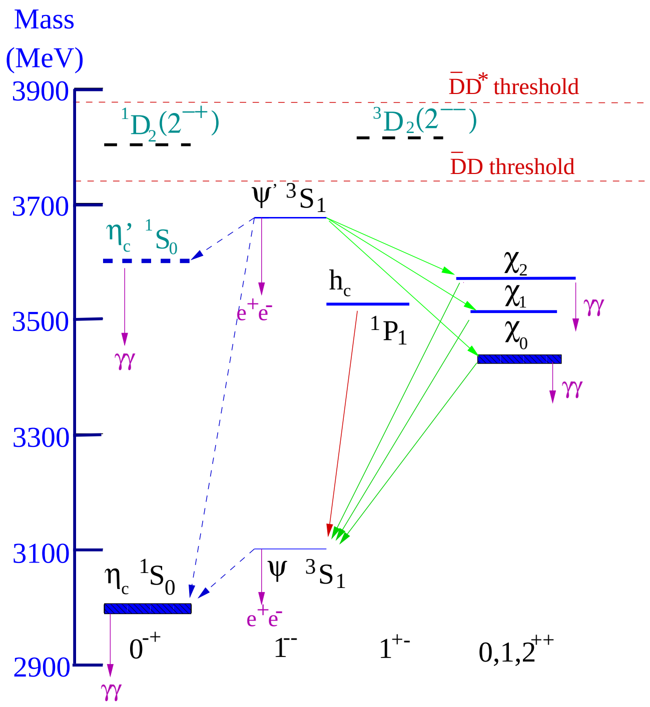

Figure 1: *Charmonium spectrum.*

Only $J^{PC} = 1^{--}$ states are directly formed, at first order, in e^+e^- annihilations while $J^{PC} \neq 1^{--}$ states can be obtained from radiative transitions of higher mass states (e.g. $e^+e^- \rightarrow \psi' \rightarrow \chi_{cJ}\,\gamma$), but their measurement depends on detector resolution. At second order, two-photon collisions are α^2 suppressed and only C = + 1 states can be formed.

After the historical discoveries of J/ψ and ψ' states, the Crystal Ball [2] experiment was the most successful experiment to study charmonium in e^+e^- annihilations. From the study of the radiative photon spectrum in $\psi(2S)$ decays, the masses and widths of most of the $c\bar{c}$ states with $J^{PC} \neq 1^{--}$ were determined.
This experiment provided the only existing evidence of the $\eta_c^{'}$ resonance [3], that, however, still awaits confirmation.

In the same line, at present the Beijing Spectrometer (BES) at BEPC measures charmonium states' parameters in $\psi(2S)$ decays, identifying the final cascade $c\bar{c}$ state under study with a conventional solenoidal magnet detector.

Two-photon interactions at higher energy e^+e^- colliders (CESR and LEP) can form a resonance (R) in the process $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-R$, where R is a neutral C = +1 meson. The cross section for two-photon resonance production [4] is: $\sigma(e^+e^- \rightarrow e^+e^-R) = \int \sigma_{\gamma\gamma\rightarrow R}\, dL_{\gamma\gamma}(W^2)$, where $\sigma_{\gamma\gamma\rightarrow R}(W^2)$ is the Breit-Wigner cross section with W and $L_{\gamma\gamma}(W^2)$ the two-photon center of mass energy and luminosity function respectively. The two-photon width $\Gamma_{\gamma\gamma}$ is proportional to the total cross section: $\sigma(e^+e^- \rightarrow e^+e^-R) = \mathcal{K}\ \Gamma_{\gamma\gamma}$, if the two photons are assumed to be quasi-real. The charmonium J^{PC} states accessible are 0^{-+}, 0^{++} and 2^{++}.

Charmonium states can be formed in $\bar{p}p$ annihilations, with the advantage that any set of quantum numbers J^{PC} is directly accessible. High precision measurements of the resonance parameters (M, Γ_{TOT} and BR$_{in}\times$ BR$_{out}$) can thus be achieved thanks to the precise knowledge of the initial state. The main disadvantage is the large non-resonant hadronic background $\dfrac{\sigma(\bar{p}p \rightarrow (c\bar{c})_R)}{\sigma(\bar{p}p \rightarrow X)} \leq \dfrac{1\mu b}{70mb} \approx 10^{-5}$.
This experimental method is optimally exploited using a high quality $\bar{p}$ beam and a high luminosity interaction source, as was demonstrated by a pioneering experiment at CERN and then by Fermilab E760 [5], which measured with high precision the parameters of the $^3S_1$, 1^1S_0, $^3P_{1,2}$ and $^1P_1$ (first and only existing evidence) states.

Fermilab experiment 835 [6] studies the direct formation of $c\bar{c}$ states in $\bar{p}p$ annihilations at the Fermilab Antiproton Accumulator ring.
A non-magnetic spectrometer detects the electromagnetic decays from a high luminosity interaction region where the stochastically cooled ($\Delta p/p \sim 5 \times 10^{-4}$) antiprotons (up to 50 mA) collide with the protons of an internal hydrogen gas jet target ($\rho_{max} \sim 3.0 \times 10^{14}\ at/cm^3$). A precise measurement of the $c\bar{c}$ resonance (R) parameters (mass, width, BR$_{R\rightarrow\bar{p}p}\times$ BR$_{R\rightarrow final\ state}$) can be performed by studying the excitation curve obtained by stepping the antiproton energy across the resonance. Selecting electromagnetic final states as a tag of charmonium formation makes it possible to extract a clean signal despite the huge hadronic background.

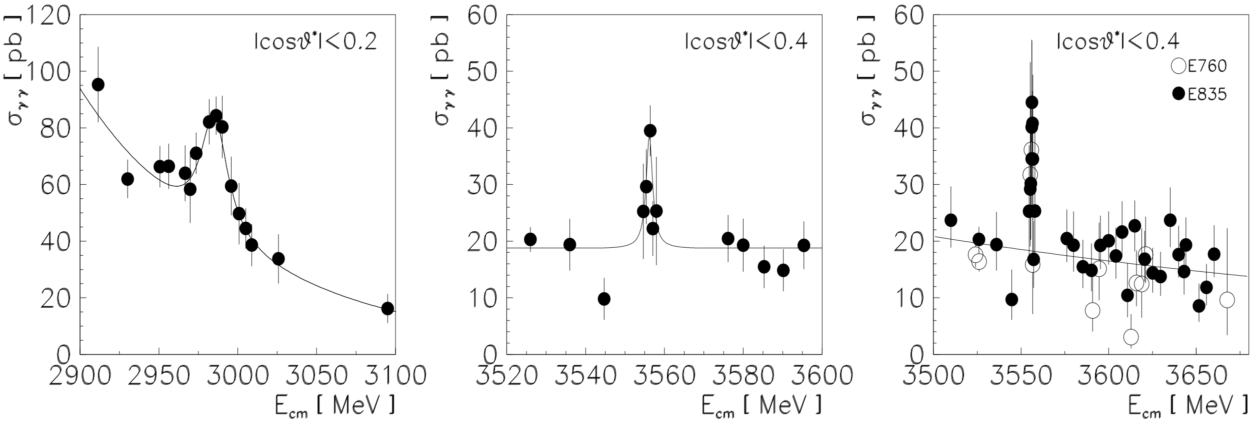

Figure 2: *FNAL-E835 cross section for $\eta_c \to \gamma\gamma$, $\chi_{c2} \to \gamma\gamma$ and $\eta'_c \to \gamma\gamma$ search*

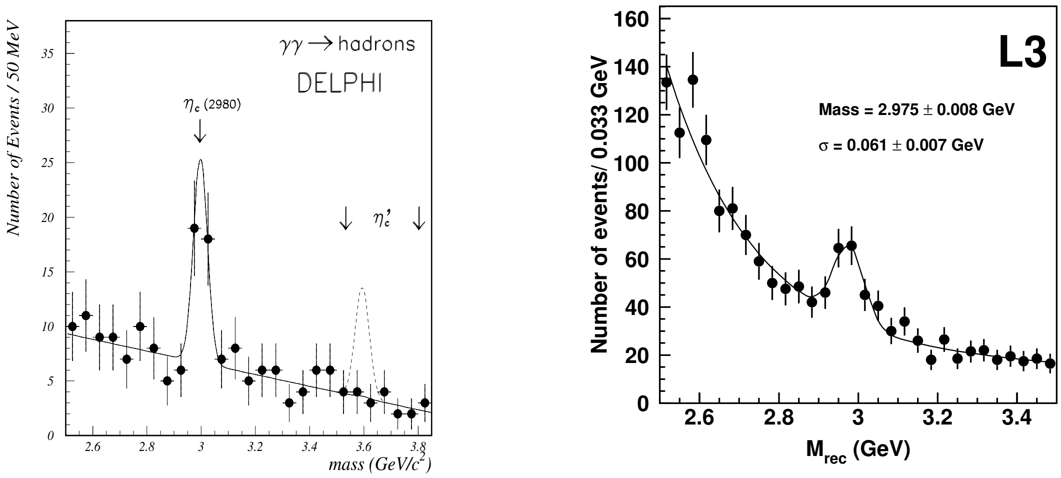

Figure 3: *η_c and η'_c search in DELPHI and η_c mass spectrum in L3. All selected decay channels added together.*

2 $\gamma\gamma$ partial widths

Results on $\gamma\gamma$ partial widths for η_c and χ_{c2} were recently obtained by FNAL-E835 (still preliminary) in $\bar{p}p$ annihilations and by DELPHI, L3 and OPAL experiments in two photon collisions at LEP (η_c still preliminary). Results from the CLEO experiment in two photon collisions at CESR include the most recent measurement of $\chi_{c0} \to \gamma\gamma$ and are shown for completeness.

E835's observed cross section in the study of the process $\bar{p}p \to (c\bar{c}) \to \gamma\gamma$ is shown in fig.2 for different regions in center of mass energy (E_{cm}).

The small signal (branching ratios of the order of 10^{-4}) must be extracted from a background mainly due to $\pi^0\pi^0$ and $\pi^0\gamma$ events, whose differential cross section is peaked at small θ^*. In order to optimize the signal-to-background ratio the events are selected in a limited angular region of $|\cos(\theta^*)|$ (<0.2 at the η_c energy and <0.4 at higher E_{cm}). The data are fitted using a maximum likelihood method with a Breit-Wigner plus background (where, at the η_c, $\sigma_{bckg} = A \times (M_{\eta_c}/E_{cm})^B$).

The preliminary results on the η_c parameters are: $M_{\eta_c} = 2985^{+1.7}_{-1.8}$ MeV, $\Gamma_{\eta_c} = 17.8^{+7.2}_{-6.9}$ MeV and, using the measured [7] $\mathcal{B}(\eta_c \to \bar{p}p)$, $\Gamma_{\gamma\gamma} = 3.7^{+1.5}_{-1.2} \pm 1.2$ keV (systematic error due to the uncertainty on the $\mathcal{B}_{\bar{p}p}$).

The preliminary result: $\Gamma(\chi_{c2} \to \gamma\gamma) = 0.311 \pm 0.041 \pm 0.031$ keV is obtained by fitting the excitation curve with $M_{\chi_{c2}}$ and $\Gamma_{\chi_{c2}}$ fixed at the PDG values [7]. Perturbative QCD (with first order radiative corrections) [8], predicts the ratios:

$$\frac{\Gamma(\eta_c \to gg)}{\Gamma(\eta_c \to \gamma\gamma)} = \frac{9\alpha_S^2}{8\alpha^2} \times \frac{(1+4.8\alpha_S/\pi)}{(1-3.4\alpha_S/\pi)} \quad ; \quad \frac{\Gamma(\chi_{c2} \to gg)}{\Gamma(\chi_{c2} \to \gamma\gamma)} = \frac{9\alpha_S^2}{8\alpha^2} \times \frac{(1-2.2\alpha_S/\pi)}{(1-16\alpha_S/3\pi)}.$$

An average value of the strong coupling constant $\alpha_S(m_c = 1.5\ GeV) = 0.34 \pm 0.05$ can be derived from the E835 measurements of the total and partial widths of η_c and χ_{c2}, using $\Gamma(\eta_c \to gg) \simeq \Gamma_{TOT}(\eta_c)$ and $\Gamma(\chi_{c2} \to gg) \simeq \Gamma_{TOT}(\chi_{c2}) - \Gamma(\chi_{c2} \to \gamma J/\psi)$. This result is in good agreement with the measurement of $\alpha_S(m_\tau)$ from τ decays and with the world average $\alpha_S(M_Z)$ [7].

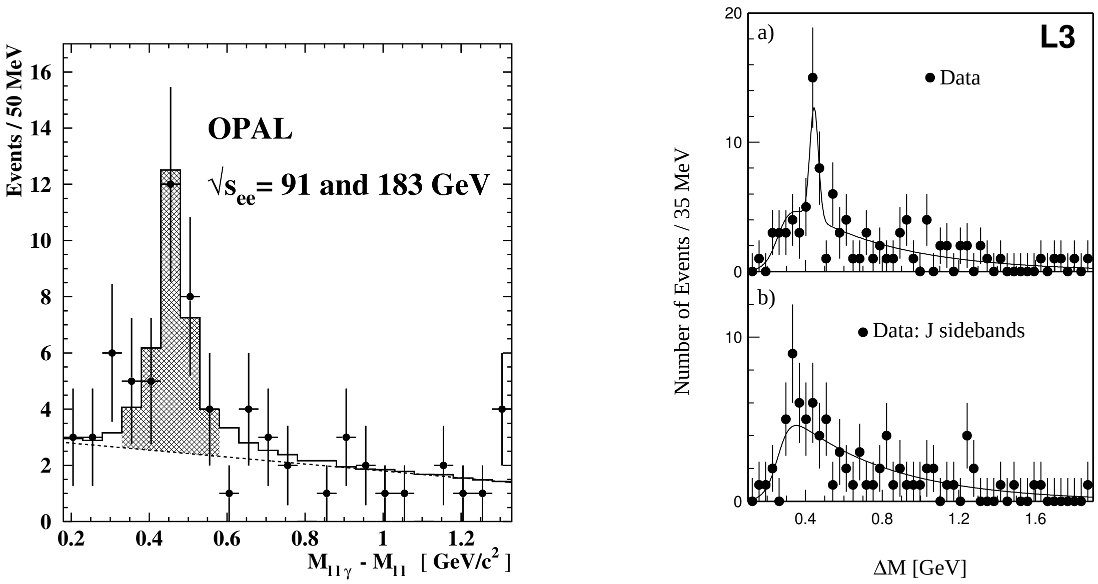

Figure 4: *Distribution of mass difference* $\Delta M = M(l^+l^-\gamma) - M(l^+l^-)$ *to identify* $\chi_{c2} \to J/\psi\gamma$ *with* $J/\psi \to e^+e^-, \mu^+\mu^-$ *with OPAL and L3 detector at LEP.*

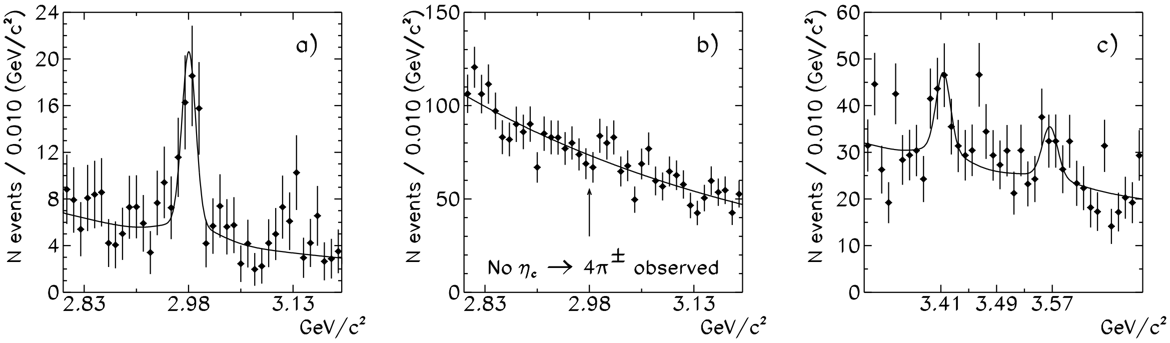

Figure 5: *Mass distributions for candidates: a) $K^0_s K^{\pm}\pi^{\pm}$, b) $\pi^+\pi^-\pi^+\pi^-$ in the η_c region, and c) $\pi^+\pi^-\pi^+\pi^-$ for χ_c mass range at CLEO II* [14].

An extensive search performed in the mass region (3575≤E$_{cm}$ ≤3660 MeV), with no evidence of a resonant signal, sets a preliminary upper limit on the product of branching fractions $\mathcal{B}(\eta_c^{'} \to \bar{p}p) \times \mathcal{B}(\eta_c^{'} \to \gamma\gamma) < 9 \times 10^{-8}$ 95% CL for $\Gamma = 5\ MeV$.

No evidence of $\eta_c^{'}$ production is found in the mass region 3520-3800 MeV by DELPHI [9] in the two-photon reaction at LEP, selecting five $\gamma\gamma \to hadrons$ channels. With the assumption $\dfrac{\mathcal{B}(\eta_c^{'} \to hadrons)}{\mathcal{B}(\eta_c \to hadrons)} \simeq 1$, the upper limit for the ratio of two-photon widths of $\eta_c^{'}$ and η_c is found to be $\dfrac{\Gamma_{\gamma\gamma}(\eta_c^{'})}{\Gamma_{\gamma\gamma}(\eta_c)} \leq 0.34$ $(90\%\ CL)$. The dashed curve in fig.3 shows the expected signal of $\eta_c^{'}$ production according to a recent theoretical prediction [10]. A peak corresponding to the η_c resonance appears in the same plot, this is the result of the sum of the invariant mass distributions of the final state particles in the five selected decay channels.

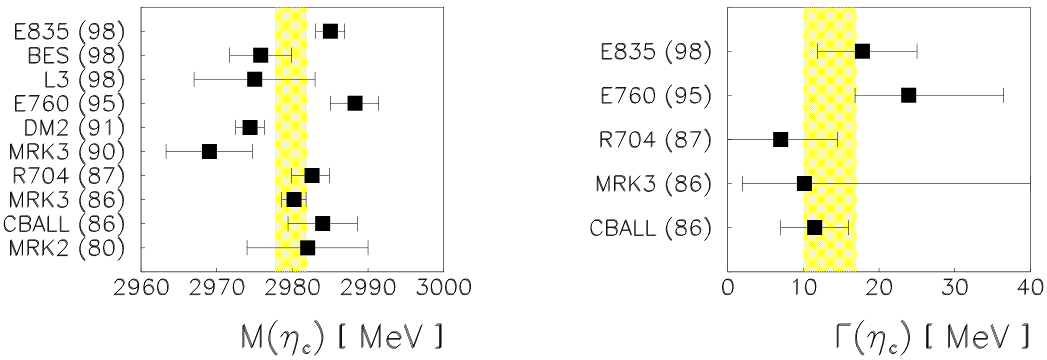

Figure 6: *Comparison of experimental results on M_{η_c} and Γ_{η_c}. The shadowed area is the PDG* [7] *average.*

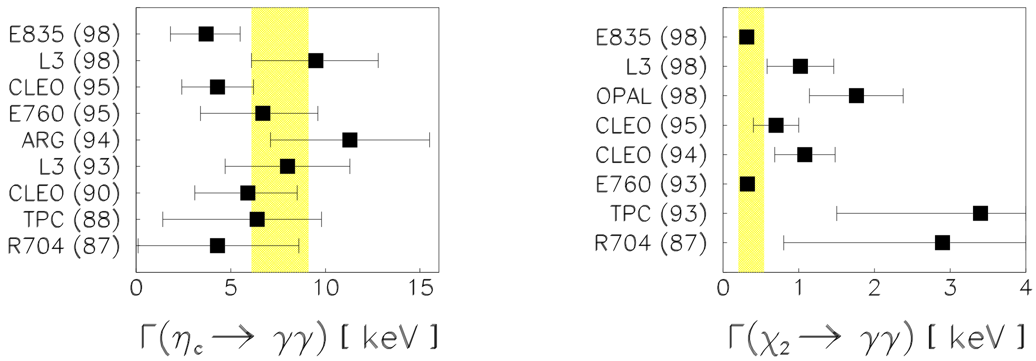

Figure 7: *Comparison of experimental results on $\Gamma_{\gamma\gamma}(\eta_c)$ and $\Gamma_{\gamma\gamma}(\chi_2)$. The shadowed area is the PDG* [7] *average.*

L3 [11] experiment presented preliminary results on $\Gamma_{\gamma\gamma}(\eta_c)$ (see fig.3), obtained as an average of ten different selected decay channels: $\Gamma_{\eta_c \to \gamma\gamma} = 9.5\ ^{+2.1}_{-1.9}$ $(stat.+sys.) \pm 2.7(\mathcal{B})$ keV [1].

Both OPAL [13] and L3 [12] experiments measured the two-photon partial width of the χ_{c2} reconstructing the resonance in the decay channel $\chi_{c2} \to J/\psi\gamma \to l^+l^-\gamma (l = e, \mu)$. In fig.4 the mass difference between the $ll\gamma$ and the ll invariant mass ($\mathrm{M}_{ll\gamma}$-M_{ll}) is shown for both experiments. OPAL measured $\Gamma_{\gamma\gamma}(\chi_{c2})$=1.76±0.47($stat.$) ±0.37($sys.$)±0.15($\mathcal{B}$) keV and L3, with a different background parametrization, measured $\Gamma_{\gamma\gamma}(\chi_{c2})$=1.02±0.40($stat.$) ±0.15($sys.$)±0.09($\mathcal{B}$) keV.

As a comparison, the most recent results from CLEO-II [14] are shown in fig.5 from which the following two photon partial widths are measured:
$\Gamma_{\gamma\gamma}(\eta_c \to K^0_S K^\pm \pi^\pm)$= 4.3±1.0($stat.$) ±0.7($sys.$)±1.4($\mathcal{B}$) keV;
$\Gamma_{\gamma\gamma}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$= 1.7±0.6($stat.$) ±0.4($sys.$)±0.3($\mathcal{B}$) keV;
$\Gamma_{\gamma\gamma}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$= 0.7±0.2($stat.$) ±0.1($sys.$)±0.2($\mathcal{B}$) keV.

Experimental results on M_{η_c} and Γ_{η_c} are compared in fig.6, while the results on the partial width $\Gamma_{\gamma\gamma}$ of η_c and χ_{c2} are shown in fig.7.

3 Study of P-wave (χ_{cJ}) charmonium states

P-wave charmonium states are directly accessible in $\bar{p}p$ annihilations.
E760 performed very precise measurements [15] of the masses and the total widths of the χ_{c1} and χ_{c2} resonances studying the process: $\bar{p}p \to \chi_c \to J/\psi\gamma \to e^+e^-\gamma$. Using known branching ratios $\mathcal{B}(\chi_{cJ} \to J/\psi\gamma) \times \mathcal{B}(J/\psi \to e^+e^-)$, the partial widths $\Gamma_{\bar{p}p}$ and the branching ratios $\mathcal{B}(\chi_{cJ} \to \bar{p}p)$ were also obtained.

[1] A recent abstract submitted for the next Int. Eur. Conf. EPS HEP 99 (July 1999), gives a new results $\Gamma_{\gamma\gamma}(\eta_c)$ = 6.9 ±1.7($stat.$)±0.8($sys.$)±2.0($\mathcal{B}$) keV.

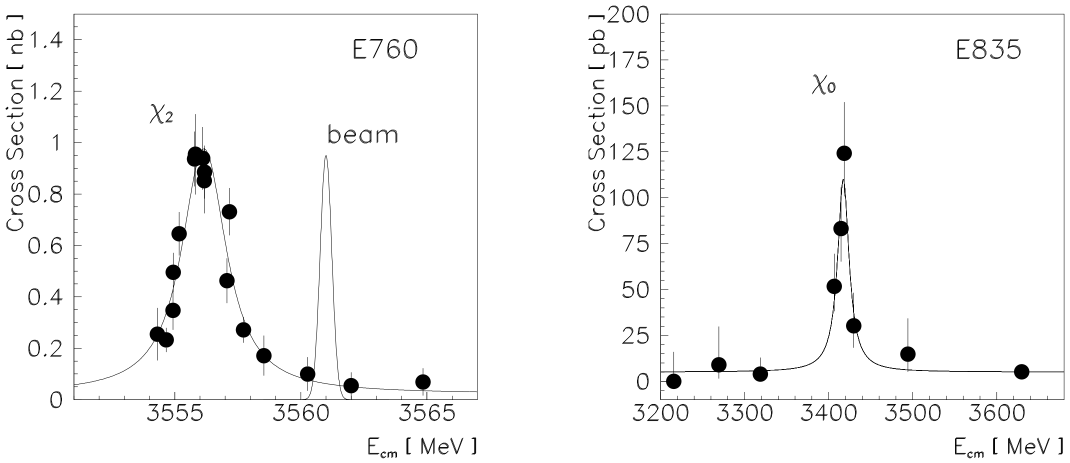

Figure 8: *FNAL-E760 $\chi_2 \to J/\psi\gamma$ and FNAL-E835 $\chi_0 \to J/\psi\gamma$*

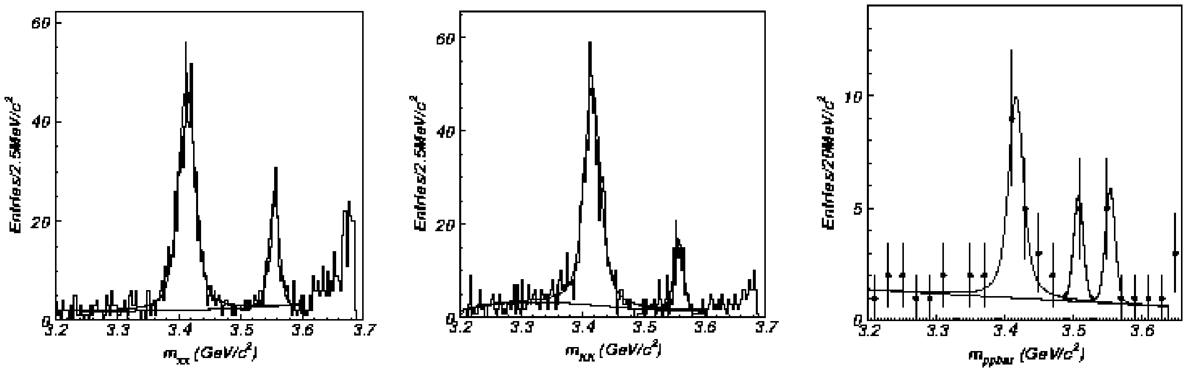

Figure 9: *BES mass distributions for selected $\psi(2S) \to \gamma X$ (X=$\pi^+\pi^-$, K^+K^-, $\bar{p}p$) events.*

E835 measured the χ_{c0} resonance for the first time in $\bar{p}p$ annihilations, selecting the radiative decays $\chi_{c0} \to J/\psi\gamma \to e^+e^-\gamma$. Fig.8 shows the χ_{c2} scan of E760 compared to the χ_{c0} scan performed by E835. χ_{c0} parameters were directly measured by fitting the experimental points with a Breit-Wigner resonant cross section and a flat background cross section: $\mathrm{M}(\chi_{c0}) = 3417.44^{+1.8}_{-1.9} \pm 0.2$ MeV and $\Gamma_{TOT} = 16.6^{+5.2}_{-3.7}$ MeV. The branching ratio and the partial width to $\bar{p}p$ are derived from known branching ratios $\mathcal{B}(\chi_{cJ} \to J/\psi\gamma) \times \mathcal{B}(J/\psi \to e^+e^-)$ of the final state. The large uncertainty in the $\mathcal{B}(\chi_{c0} \to J/\psi\gamma)$ = (6.0 $\pm$1.8) $\times 10^{-3}$ as measured by Crystal Ball [2] dominates the systematic errors on these quantities.

Recently BES [16, 17] published a study of P-wave charmonium states using a sample of $(3.79\pm0.31)\times10^6$ $\psi(2S)$ decays. Many hadronic decays were studied, as reported in [17], and their branching fractions determined using the measured $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$ [7]. The $\mathrm{M}(\chi_{c0})$ = 3414.1$\pm$0.6$\pm$ 0.8 MeV is determined by fitting the combined invariant mass distribution of all the selected channels with three resolution-broadened Breit-Wigner functions, corresponding to the three ${}^3P_J$ states. The resolution was determined from fits to the χ_{c1} and χ_{c2} and the total width of χ_{c1} and χ_{c2} fixed at the PDG values [7]. The $\Gamma_{TOT}(\chi_{c0})$ = 14.3 $\pm$2.0$\pm$3.0 MeV was measured selecting a $\pi^+\pi^-$ event sample (shown in fig.9), using the precisely measured χ_{c2} total width [7] ($\Gamma_{TOT}(\chi_{c2})$ = 2.00$\pm$0.18 MeV) to determine the detector resolution and a MC simulation to determine how the resolution changes between $M_{\chi_{c2}}$ and $M_{\chi_{c0}}$. Fig.9 also shows the $\bar{p}p$ mass distribution for selected $\psi(2S) \to \gamma\bar{p}p$ events at BES.

The branching fraction and the partial width to $\bar{p}p$ determined from the measured $\mathcal{B}(\psi(2S) \to \gamma\chi_{cJ})$ [7] are compared in table 1 with E760 and E835 measurements.

It is a puzzling feature that BES results for all $\chi_{cJ} \to \bar{p}p$ branching ratios are

Table 1: *Comparison of E760/E835 and BES results for $\chi_{cJ} \to \bar{p}p$. First error is statistical, second is systematic.*

	E760/E835		**BES**	
	$BR_{\bar{p}p} \times 10^4$	$\Gamma_{\bar{p}p}(keV)$	$BR_{\bar{p}p} \times 10^4$	$\Gamma_{\bar{p}p}(keV)$
χ_0	$4.82^{+0.97+2.08}_{-0.81-1.12}$	$8.0^{+1.9+3.5}_{-1.6-1.9}$	1.59$\pm$0.43$\pm$0.53	2.3$\pm$1.1
χ_1	0.78$\pm$0.10$\pm$0.11	0.069$\pm$0.009$\pm$0.010	0.42$\pm$0.22$\pm$0.28	0.037$\pm$0.032
χ_2	0.91$\pm$0.08$\pm$0.14	0.180$\pm$0.016$\pm$0.026	0.58$\pm$0.31$\pm$0.32	0.116$\pm$0.090

systematically lower with respect to E760/E835 results. In both experiments, BES and E835, the $\mathcal{B}_{\bar{p}p}$ and the $\Gamma_{\bar{p}p}$ are derived from the product of branching fractions $\mathcal{B}_{in} \times \mathcal{B}_{out}$ and from $\mathcal{B}_{\psi(2S)\to\gamma\chi_{cJ}}$ and $\mathcal{B}_{\chi_{cJ}\to J/\psi\gamma}$ respectively.

New measurements of $\mathcal{B}_{\psi(2S)\to\gamma\chi_{cJ}}$ and $\mathcal{B}_{\chi_{cJ}\to J/\psi\gamma}$ would be desirable to exclude one possible origin of such inconsistency.

Fig.10 shows a comparison of the experimental results on $M(\chi_{c0})$ and $\Gamma_{TOT}(\chi_{c0})$ including Crystal Ball results.

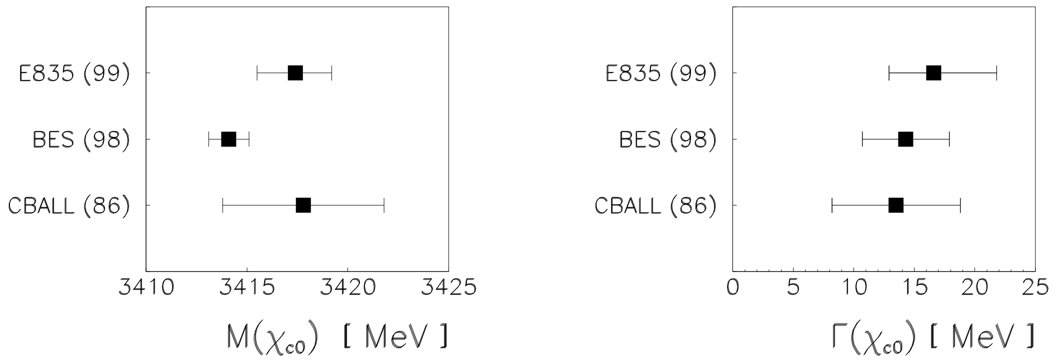

Figure 10: *Comparison of experimental results on $M_{\chi_{c0}}$ and $\Gamma_{\chi_{c0}}$*

4 Conclusions

All the experiments, whose recent results are discussed in this paper, are still taking data and finalizing their analyses. New experimental measurements can still improve our knowledge of charmonium spectrum and complement theoretical developments.

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