Charmonium Spectroscopy From Fermilab E835

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Abstract. The Fermilab experiment E835 is dedicated to the study of charmonium spectroscopy via direct formation of charmonium resonances in proton-antiproton annihilations. The latest results from this experiment and their comparison to the world data are presented. The physics implications are discussed.

INTRODUCTION

Precision spectroscopy of the charmonium system can yield quantitative results concerning the nature of QCD in the non–perturbative regime, where it is not well understood. The mass of the charm quark is small enough that $c\bar{c}$ cross sections are reasonably large, yet it is large enough that its motion within charmonium is nearly non–relativistic. The spectrum of charmonium states is shown in Fig. 1.

From the discovery of J/ψ in 1974 until the mid–1980's, nearly all charmonium spectroscopy was studied via e^+e^- annihilations at facilities like SLAC and DESY. Because e^+e^- annihilations proceeds via a virtual photon, only $J^{PC} = 1^{--}$ states could be formed directly. The study of other states is possible only through the observation of radiative decays of $J/\psi, \psi' \rightarrow (c\bar{c})_R\ \gamma$. Thus mass and width measurements for these states were limited by the photon energy resolutions of the detector system. While most of the charmonium states were discovered in such experiments, their masses, and especially widths, were not well measured. In order to do precision spectroscopy of charmonium, a new technique was required. Such a technique, charmonium via $p\bar{p}$ annihilations, was pioneered by R704 at CERN [1]. Fermilab E760 and E835 have fully exploited this technique, and have obtained results which represent improvements in precision, in some cases by an order of magnitude.

The advantage of the technique of charmonium formation in $p\bar{p}$ annihilations is that all charmonium states can be formed directly; the $p\bar{p}$ annihilation process occurs

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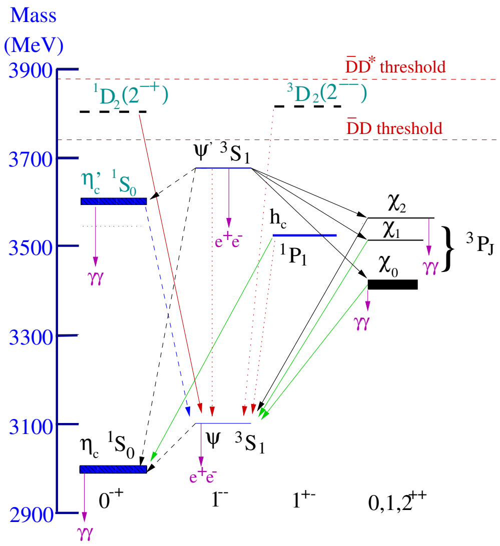

FIGURE 1. The spectrum of charmonium states.

through two or three gluons in the intermediate state, which may have any value of J^{PC}. Since every charmonium state can be formed directly, its resonance parameters may be determined with a precision dependent only on the knowledge of the beam energy and energy distribution, and event statistics.

FERMILAB EXPERIMENT E835

The E835 experiment is located in the Fermilab Antiproton Accumuliator (see Fig. 2). The circulating beam of antiprotons intersects a hydrogen jet target to produce $p\bar{p}$ interactions. During Fermilab fixed target operations, the Accumulator stores antiprotons at 8.9 GeV, and decelerates them to the momentum required for the resonant formation of the $c\bar{c}$ state under investigation.

The stochastically cooled $\bar{p}$ beam consists of $\sim 10^{12}$ $\bar{p}$ which orbit the 474.0454 m path length of the accumulator with frequency of $\sim$0.62 MHz. This frequency is measured using the Schotty noise spectrum of the beam to about 2 parts in 10^7. The beam intersects the gas jet target [2], whose density in the interaction region can be varied between 10^{12} and 10^{14} atoms/cm^3, in order to keep the instantaneous luminosity nearly constant (typically, 2×10^{31} cm^{-2}sec^{-1}).

The center of mass energy $\sqrt{s}$ is determined by the revolution frequency and the orbit length, which is measured accurate to ± 7 mm by a calibration scan at the ψ', whose mass is 3685.96$\pm$0.09 MeV [3]. Deviations of the beam from this reference orbit length are measured by beam position monitors to ± 1 mm, so that $\sqrt{s}$ may be known to $\sim\pm 50$ keV. The beam momentum spread, which is directly related to the width of the Schotty noice spectrum, is $\Delta p/p \sim 1$–2×10^{-4}. This Δp corresponds to the center of mass energy spread $\sigma(\sqrt{s}) \approx 200$ keV at the ψ'.

The E760 detector system, which is optimized for the detection and identification

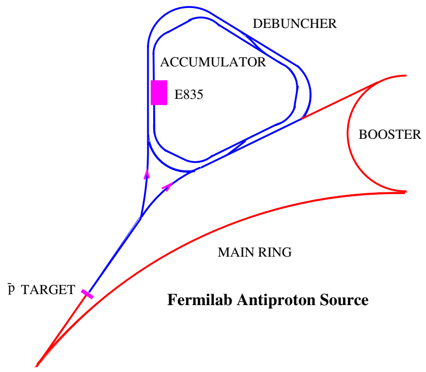

FIGURE 2.

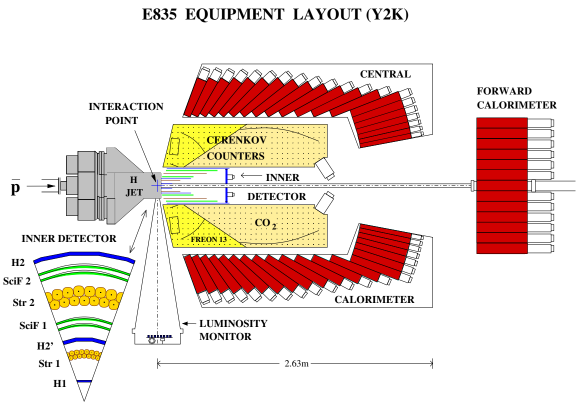

FIGURE 3. Schematic of the E835 detector system.

of photons and electrons, has been described before [4–6]. The E835 detector system (See Fig. 3) is an upgrate of the E760 detector [7]. The apparatus has full acceptance in azimuth (ϕ), with a cylindrical central system covering the polar angle $11^\circ < \theta < 70^\circ$, and a planar forward system covering $3^\circ < \theta < 12^\circ$. The central system contains three azimuthally segmented scintillator hodoscopes for triggering and measuring dE/dx, straw tubes for tracking in ϕ, scintillating-fiber trackers for tracking in θ, a 16 cell threshold gas Čerenkov counter for electron identification, and a 1280 element lead-glass calorimeter (CCAL) for measuring the direction and energy of photons and electrons. The forward system consists of a scintillator hodoscope and a 144 element lead-glass array (FCAL).

The luminosity monitor [8] counts proton recoils near 90° from elastic $p\bar{p}$ scatters and provids absolute luminosity with a statistical precision of 0.1% and systematic uncertainty of $\pm 2.5\%$.

In the E835 experiment, charmonium states are studied by decelerating the $\bar{p}$ beam so that $\sqrt{s}$ is varied in small steps across the resonance under study. At each step, the yield of the final state particles from the electromagnetic decays is measured. The number of events divided by luminosity taken at each point, plotted versus the center of mass energy, gives the resonance excitation curve. This is just the convolution of the measured

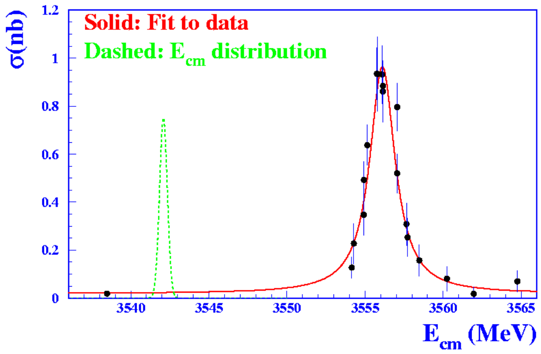

FIGURE 4. Example of the scan of χ_{c2} state. The solid curve is a fit to the acceptance and efficiency–corrected data, while the dotted curve shows the beam energy spread.

beam energy distribution function and the Breit–Wigner resonance cross section (which is proportional to the product of the branching ratios for the formation and the decay of the resonance, $B_{in} \times B_{out}$). Fig. 4 shows an example of such an excitation curve from the scan of χ_{c2} in E760 [4].

DETECTION of $(c\bar{c})_R$ via $p\bar{p} \to (c\bar{c})_R \to e^+e^-X$

The almost background free channels for the investigation of $(c\bar{c})$ states in E835 are those which include a single high–mass e^+e^- pair. These events are triggered by a high mass pair of clusters in CCAL, assocoated with two tracks in the inner charged tracking detectors and at least one associated signal in the Čerenkov detector.

Measurement of χ_{c0} resonance parameters via $p\bar{p} \to \chi_{c0} \to J/\psi\gamma \to (e^+e^-)\gamma$ detection

Our new measurements of the χ_{c0} from the year 2000 run [9] are based on a total luminosity of 32.8 pb^{-1}. Three cluster events consisting of an e^+e^- pair and a photon, and having a fit probability meeting the $J/\psi\gamma$ hypothesis ≥0.1%, lead to a very clean signal of χ_{c0}, as shown in Fig. 5 (left). The resonance parameters are determined to be
$M(\chi_{c0}) = 3415.4 \pm 0.4 \pm 0.2$ MeV,
$\Gamma_{tot}(\chi_{c0}) = 9.8 \pm 1.0 \pm 0.1$ MeV, and
$B_{p\bar{p}}(\chi_{c0}) = (4.1 \pm 0.3^{+1.5}_{-0.9}) \times 10^{-4}$.

Althought the hadron helicity conservation rule for massless quarks forbids the formation of zero spin states in $p\bar{p}$ annihilations, our value of $B_{p\bar{p}}(\chi_{c0})$ is actually about four times larger than $B_{p\bar{p}}(\chi_{c1})$ and $B_{p\bar{p}}(\chi_{c2})$. The values for the mass and width of the χ_{c0} from this and previous experiments are shown in Fig. 5 (right). The present results represent a significant improvement in precision for both mass and width.

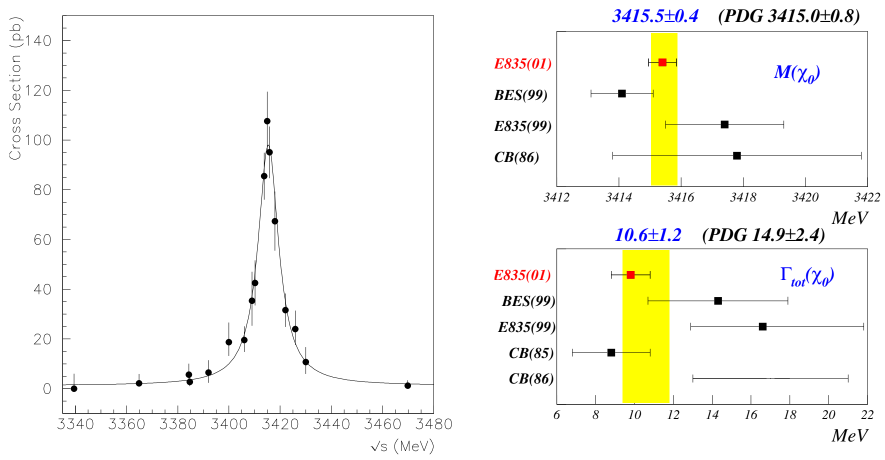

FIGURE 5. (left) $J/\psi\ \gamma$ cross section in the χ_{c0} mass region; (right) the mass and width of the χ_{c0} from the present and other experiments; the new world average values are shown as shaded bands and are compared with the value in PDG–2000 [3].

Angular distribution analysis for $\chi_{c1,c2} \to J/\psi\gamma \to (e^+e^-)\gamma$

The electron gamma angular correlation for the reaction $\chi_{c1,c2} \to J/\psi\gamma \to (e^+e^-)\gamma$ was measured using the data collected in 1996-97 run. The radiative transitions are dominantly $E1$ nature, with small $M2$ components allowed. The fractional magnetic quadrupole amplitudes $a_2 = M2/E1$ are found to be [10]:

$a_2(\chi_{c1})$=0.002±0.032, $a_2(\chi_{c2})$=–0.093±0.040.

While the $a_2(\chi_{c2})$ is in agreement with what is expected, the near zero value of $a_2(\chi_{c1})$ is surprising.

Branching ratios from the Reactions $p\bar{p} \to \psi' \to J/\psi\gamma\gamma$

During both 1996–97 and 2000 runs of E835 the ψ' resonance was scanned. The nearly 24 pb^{-1} of ψ' data have been analyzed for the reaction $\psi' \to J/\psi\gamma\gamma$ to determine $B_{J/\psi\eta}(\psi')$, $B_{J/\psi\pi^0}(\psi')$ and $B_{J/\psi\gamma}(\chi_{c0,c1,c2})$. In Fig. 6 (left) the Dalitz plot for M($\gamma\gamma$) versus M($J/\psi\gamma$) is shown. Appropriate cuts in this plot determine the desired branching ratios. As an example, the projection for $M(J/\psi\gamma_{high})$ is shown in Fig. 6 (right). The χ_{c1} and χ_{c2} resonances are well resolved, while χ_{c0} is barely visible.

The data are still being analyzed.

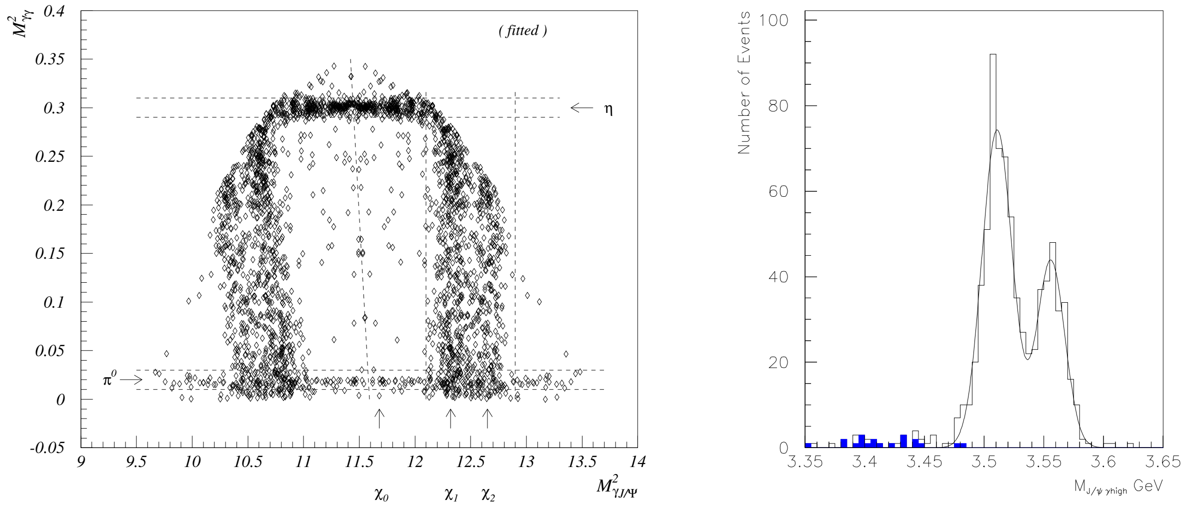

FIGURE 6. (left) the Dalitz plot, $\mathrm{M}^2(\gamma\gamma)$ versus $\mathrm{M}^2(J/\psi\gamma)$, in reaction $\psi' \to J/\psi\gamma\gamma$; (right) the invariant mass of J/ψ and fast γ, the $\chi_{c1}(3510)$ and $\chi_{c2}(3556)$ resonances are well resolved.

DETECTION of $(c\bar{c})_R$ via $p\bar{p} \to (c\bar{c})_R \to \gamma\gamma$

The two photon event selection used in our measurements has been described in detail in two recent publications [11,12].

Measurement of two–photon width of χ_{c2} and χ_{c0}

In 1993 E760 reported a measurement of $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.321 \pm 0.078 \pm 0.054$ [13] which was smaller than all previous measurements and upper limits by factors 5 to 30. Most of the previous determinations of the $\gamma\gamma$ partial width of χ_{c2} came from $\gamma\gamma$-fusion experiments and all such measurements appeared to be consistent with each other. It was therefore considered important to measure $\Gamma_{\gamma\gamma}(\chi_{c2})$ again.

A measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ was made in E835 with approximately $8.4pb^{-1}$ of integrated luminosity near the χ_{c2} peak [12], compared to $\sim 2.6pb^{-1}$ in E760. The cross sections for $p\bar{p} \to \gamma\gamma$ in this region are shown in Fig. 7 (left). Since the total width $\Gamma_{tot}(\chi_{c2}) = 1.98 \pm 0.18$ MeV, the $p\bar{p}$ branching fraction $B_{p\bar{p}}(\chi_{c2}) = 1.0 \pm 0.1 \times 10^{-4}$ and the mass $M(\chi_{c2}) = 3556.16 \pm 0.14$ MeV were each well measured in E760, the data were analyzed using these values as constants. The new result obtained is

$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.270 \pm 0.049 \pm 0.033$ keV.

Thus the present measurement confirms the E760 result, and has nearly factor two smaller errors. Our measurement of $\Gamma_{\gamma\gamma}(\chi_{c2})$ is shown for comparison with other experimental results in Fig. 7 (right). It is encouraging to note that the CLEO results appear to be converging to our results, although their errors remain much larger.

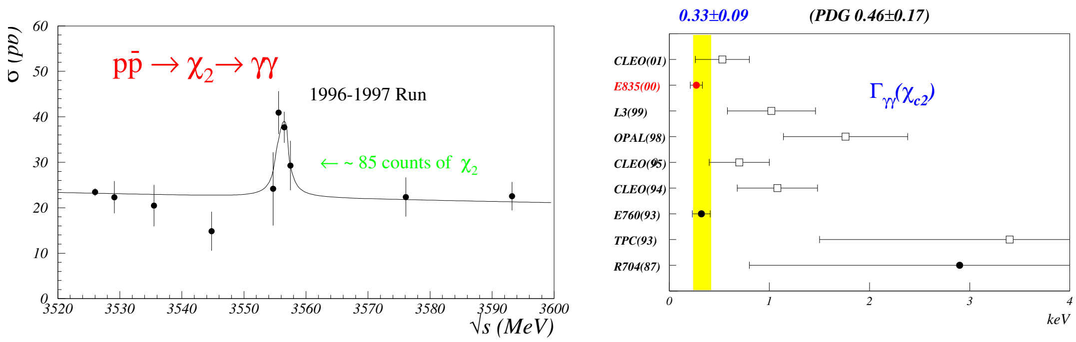

FIGURE 7. (left) $\gamma\gamma$ cross section in the χ_{c2} mass region; (right) the two photon partial width of the χ_{c2} from the present and other experiments. The new world average value is shown as shaded band and is compared with the value in PDG–2000 [3].

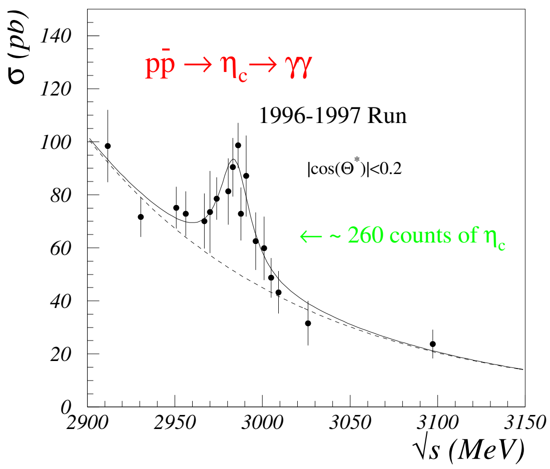

FIGURE 8. $\gamma\gamma$ cross section in the η_c mass region.

No statistically significant signal for χ_{c0} was found in the reaction $p\bar{p} \to \chi_{c0} \to \gamma\gamma$ in the E835 data collected in the 1996–97 run. We set a 95% upper limit of $\Gamma_{\gamma\gamma}(\chi_{c0}) \leq 3.47$ keV. We have collected $\sim$10 times more data at χ_{c0} peak in the year 2000 run, which should lead to more definite results on $\Gamma_{\gamma\gamma}(\chi_{c0})$. We note, in the meantime, that CLEO has reported $\Gamma_{\gamma\gamma}(\chi_{c0}) = 3.8 \pm 0.7 \pm 0.4 \pm 1.7$ keV [14].

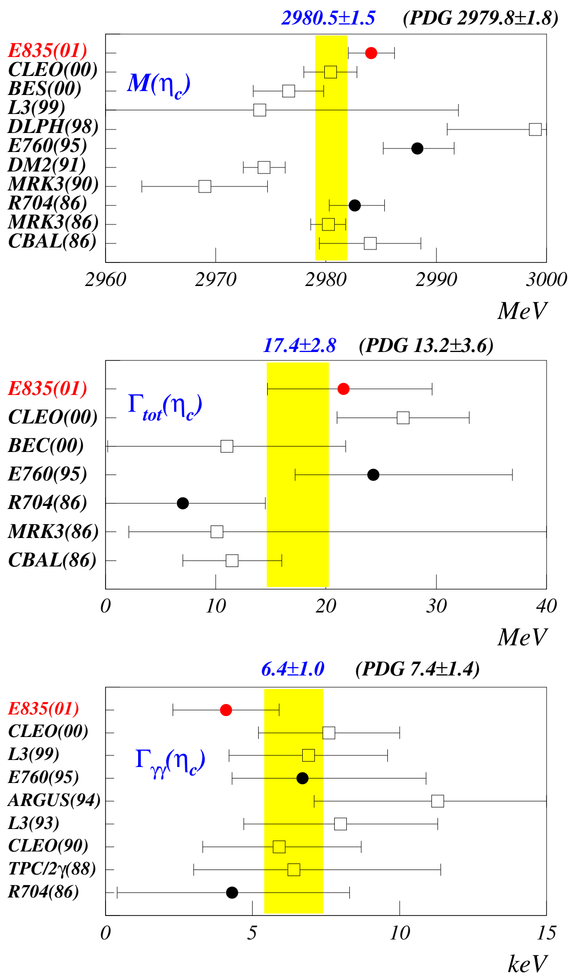

FIGURE 9. The mass, width, and two photon partial width of the η_c from the present and other experiments. The new world average values are shown as shaded bands and are compared with the values in PDG–2000 [3].

Measurement of η_c resonance parameters

The E760 experiment reported on the reaction $p\bar{p} \to \eta_c \to \gamma\gamma$ in 1995 [15]. The most significant results of these measurements, in which a total luminocity of 3.5 pb^{-1} was invested, were that the width of η_c was nearly twice as large ($\Gamma_{tot}(\eta_c) = 23.9^{+12.6}_{-7.1}$ MeV) as the average of previous measurements ($\Gamma_{tot}(\eta_c) = 10.3^{+3.8}_{-3.4}$ MeV [16]), and that $\Gamma_{\gamma\gamma}(\eta_c) = 6.7^{+2.4}_{-1.7} \pm 2.4$ keV.

The E835 experiment has made a new study of the $p\bar{p} \to \eta_c \to \gamma\gamma$ reaction with a much larger integrated luminosity of 24.4 pb^{-1}. The measured cross section are shown in Fig. 8.

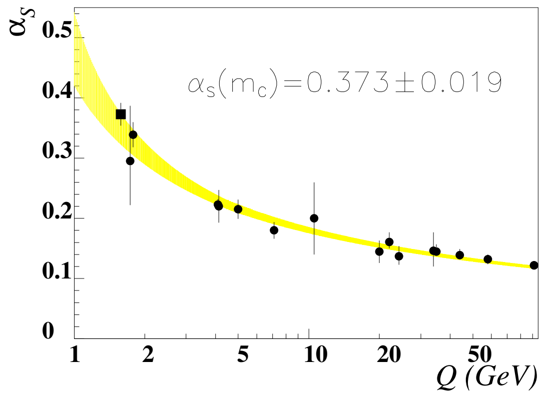

FIGURE 10. Measurements of $\alpha_s(Q)$ from various experiments. The shaded band indicates the evaluation of the PDG average value of $\alpha_s(m_Z)$ down to Q=1 GeV.

The resonance was parametrized by the Breit–Wigner formula with M, Γ_{tot} and $B_{in} \times B_{out}$ (or $B_{in} \times \Gamma_{out}$) as fit parameters. The background evaluation was done in a two ways:

- parametrized to a power law curve $A(\sqrt{s})^B$.
- using 'feeddown calculation': the shape of background was evaluated starting from $p\bar{p} \to \pi^0\gamma$ and $p\bar{p} \to \pi^0\pi^0$ cross sections, and taking account of one and two missing photons. The two methods give consistent results:

$M(\eta_c) = 2984.1 \pm 2.1$ MeV,
$\Gamma_{tot}(\eta_c) = 21.6 \pm 7.5$ MeV, and
$\Gamma_{\gamma\gamma}(\eta_c) = 4.1 \pm 1.3 \pm 1.4$ keV.

These results are preliminary. The value of mass, width and two photon partial width of the η_c from this and the other experiments are shown in Fig. 9. It should be noted that except for the BES result, all recent measurements give $\Gamma_{tot}(\eta_c)\approx$20–25 MeV, which is significantly different from the current PDG average of 13.2±3.6 MeV [3].

Determination of α_s

We can determine the strong coupling constant $\alpha_s(m_c)$ by our measurements of the total and partial widths of η_c and χ_{c2}. The pQCD formulas with first order radiative corrections give:

$$\frac{\Gamma_{gg}(\eta_c)}{\Gamma_{\gamma\gamma}(\eta_c)} = \frac{9\alpha_s^2}{8\alpha^2} \times \frac{(1+4.8\alpha_s/\pi)}{(1-3.4\alpha_s/\pi)}$$

since $\Gamma_{gg}(\eta_c) \approx \Gamma_{tot}(\eta_c)$, we obtain $\alpha_s = 0.33 \pm 0.05$.

$$\frac{\Gamma_{gg}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c2})} = \frac{9\alpha_s^2}{8\alpha^2} \times \frac{(1-2.2\alpha_s/\pi)}{(1-5.3\alpha_s\pi)}$$

since $\Gamma_{gg}(\chi_{c2}) \approx \Gamma_{tot}(\chi_{c2}) - \Gamma_{J/\psi\gamma}(\chi_{c2})$, we get $\alpha_s = 0.38 \pm 0.02$.

We note, however, that both determination are strongly affected by the first order radiative corrections, the determination at η_c much more so than determination at χ_{c2}.

In Fig. 10 we show the average value of $\alpha_s(m_c)$ determined from our data with the other experimental results.

SUMMARY

E760 made precision measurements of the resonance parameters of several charmonium resonances. E835 has continued the program, with

• First observation of χ_{c0} in $p\bar{p}$ annihilations and precision measurements of mass, total width and $p\bar{p}$ partial width of χ_{c0}.

• Branching ratios from the analysis of ψ' decay into $J/\psi\gamma\gamma$ final states.

• Angular correlation analysis for the $\chi_{c1} \to J/\psi\gamma$ and $\chi_{c2} \to J/\psi\gamma$ decays.

• Branching ratios and two photon partial widths for χ_{c0} and χ_{c2}.

• Precision measurements of mass, total width and two photon partial width of η_c.

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