New Results from E835 at Fermilab Antiproton Accumulator: Study of ($c\bar{c}$) States Formed in Antiproton-Proton Annihilations

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Abstract

Experiment E835 studies $c\bar{c}$ states directly formed in high luminosity antiproton-proton annihilations at Fermilab. Preliminary results are presented while most of the analyses are still ongoing. A new period of data taking is foreseen in 1999.

Introduction

Antiproton-proton annihilations allow the direct formation of all the states in the charmonium spectrum independently of their quantum numbers.
Charmonium physics resides in the domain intermediate between perturbative and non-perturbative regimes of QCD, but experimental results for masses and widths can only be compared to predictions based on PQCD, in particular, those based on potential models and analogies with QED with only first order radiative corrections.
Coupled-channels effects, as the $\bar{c}c$ mass approaches the open charm threshold, may affect the form of the interquark potential. Relativistic and higher order corrections to annihilation rates can be relevant in this energy regime.
The experimental method[1], already used by previous experiments at CERN-ISR (R704 in '84) and Fermilab-Accumulator (E760 in '90-91), exploits the high luminosity, quasi pointlike, source obtained by a "cool" coasting antiproton beam traversing an internal hydrogen jet target ($\rho \sim 10^{13} \div 10^{14}$ atoms/cc). Stochastic cooling compensates for multiple scattering and energy losses. Optimal running conditions were obtained keeping the instantaneous luminosity constant, by adjusting the gas jet target density through almost the whole duration of an antiproton stack. Typically, a stack of 5×10^{11} antiprotons is obtained in 18 h of antiproton accumulation, followed by 48 h of data taking.
The maximum integrated luminosity per stack was 4 pb^{-1}. Experiment 835 ran at the

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Fermilab Antiproton Accumulator for almost one year ('96-'97) with average instantaneous luminosity of $2 \times 10^{31} cm^{-2}s^{-1}$ collecting a total of about 150 pb^{-1} (a data sample almost a factor 5 larger than E760 and a factor 200 larger than R704).
The detector is composed of a leadglass calorimeter arranged to form a barrel and a forward system. A threshold gas Cherenkov counter, a charged particles tracking system and triggering hodoscopes are located inside the barrel section. Integrated luminosity is monitored using the yield of recoil protons from forward $\bar{p}p$ elastic scattering.
The whole apparatus is the upgrade of experiment E760, with a new tracking system and faster electronics built to withstand the increased instantaneous luminosity.
A fast data acquisition system allows a large number of triggers to be written to tape (total of about 5×10^9 events).
Precise measurements of the resonance parameters (mass,width) are obtained from the knowledge of the Accumulator parameters. The $\bar{p}$ beam absolute energy scale is determined[2] by measuring the revolution frequency ($\sim$ 1 part in 10^7) and calibrating the length of a reference orbit ($\sim$ 1 part in 10^6) via the ψ' mass which is known to $\pm$ 100 keV, from previous e$^+$e$^-$ experiments. A system of 48 Beam Position Monitors(BPM) measures the difference between the reference orbit and the current one, during data taking. The beam momentum spread ($\Delta p/p$) is very small, of the order of 2×10^{-4}.
The procedure is to scan across the resonance changing the value of the antiproton beam momentum. Analysis of the excitation curve gives mass and widths of the states; these quantities are derived from the precise measurements of the antiproton beam energy and are independent of the final state detector resolution.
Scans in the energy region of the η_c', χ_2, χ_1, χ_0, $^1P_1$, η_c were performed in the present run. E835 data taking ended in September 1997. An additional running period during 1999 will give us an opportunity to complete the physics program[3].

Preliminary results

The direct formation of charmonium resonances (≤ 1 part in 10^6 of the total cross section of $\bar{p}p$ strong interactions) is detected through their electromagnetic final states, either "charged", selecting decay $J/\psi X$ with $J/\psi \rightarrow e^+e^-$, or "neutral", mostly $\gamma\gamma$.
Other neutral decay modes and exclusive decay channels are also recorded but have not been analyzed, yet.
A e$^+$e$^-$ signal, tagged by the Cherenkov counter, with a high invariant mass represents an almost background-free channel to study:
$\psi', J/\psi \rightarrow e^+e^-$ $\quad \psi' \rightarrow J/\psi X$ $\quad \eta_c' \rightarrow J/\psi\gamma$ $\quad \chi_{0,1,2} \rightarrow J/\psi\gamma$ $\quad {}^1P_1 \rightarrow J/\psi X$

^3S states and timelike form factor of the proton

J/ψ and ψ' are mainly studied for calibration purposes, but angular distribution in e$^+$ e$^-$ and exclusive branching ratio of $\psi' \rightarrow J/\psi X$ are also being measured.
Selecting exclusive e$^+$ e$^-$ events in the scan of resonances other than J/ψ and ψ', the measurement of the proton form factor in the time-like region will improve E760 result at 2920$\leq$E$_{cm}$ $\leq$ 3687 MeV.

P states

7.3 and 14.7 pb^{-1} of data were respectively collected at χ_1 and χ_2 formation energy to measure angular distribution of $J/\psi\gamma$ decay; total width measurements confirm E760 results. At the end of the run a preliminary measurement of $\chi_0 \rightarrow J/\psi\gamma$ line parameters was obtained with 2.6 pb^{-1}.

Almost 50 pb^{-1} of data were taken in the region of the χ center of gravity to study the enhancement in the $\psi\pi^0$ signal seen by E760 and attributed to formation of the $^1P_1$ state[4]. The analysis is in progress. The quality of the final results for this narrow and low cross-section state will depend on our ability of determining correctly the energy for each data point of the performed scan.

$\gamma\gamma$ final states: χ_2 and η_c

The annihilation process into two-photon final state is of great theoretical interest. The small signal (branching ratio of the order of 10^{-4}) must be extracted from a background mostly due to $\pi^0\pi^0$ and $\pi^0\gamma$. Final states containing a large mass object decaying into two photons are selected by a topological requirement on the electromagnetic showers in the central calorimeter, vetoing charged tracks. To be able to avoid pileup the associated timing information was recorded for each signal. A kinematical fit is applied to events with two high energy clusters with an invariant mass $M_{\gamma\gamma} \geq 85\% M_R$ and no extra cluster on time. A χ^2 probability $\geq 10\%$ is required.

Events in the χ_2 energy region were selected in the acceptance $\mid \cos\theta^* \mid \leq 0.4$ (fig. 1a) and fitted with a maximum likelihood method with fixed M_{χ_2}=M_{PDG} and Γ_{χ_2}=Γ_{PDG}. Preliminary results are: $BR_{\bar{p}p}\times BR_{\gamma\gamma}\times 10^8 = 2.19^{+0.34}_{-0.33}$ and $\Gamma_{\gamma\gamma} = 0.44 \pm 0.08$ keV, which is compared to previous results and theory in fig. 2a.

18 pb^{-1} of data were collected below transition to scan the η_c energy region. Fig. 1b shows the results of a maximum likelihood fit to data selected in the $\mid \cos\theta^* \mid \leq 0.2$ acceptance, where the background is parametrized as $\sigma_{back} = A(\sqrt{s_0}/\sqrt{s})^B$ with $\sqrt{s_0}$=2988 MeV. The preliminary results are: $M = 2985^{+1.7}_{-1.8}$MeV/c^2, $\Gamma_{TOT} = 17.8^{+7.2}_{-5.9}$MeV, $BR_{\bar{p}p}\times BR_{\gamma\gamma}\times 10^8 = 24.6^{+3.9}_{-3.8}$ and $\Gamma_{\gamma\gamma} = 3.7^{+1.5}_{-1.3} \pm 1.2$ keV (for $BR_{\bar{p}p} = 12 \pm 4 \times 10^{-4}$). The mass and $\Gamma_{\gamma\gamma}$ measurements are compared to previous results in fig. 2b and in fig. 2c, where two theoretical predictions are also shown.

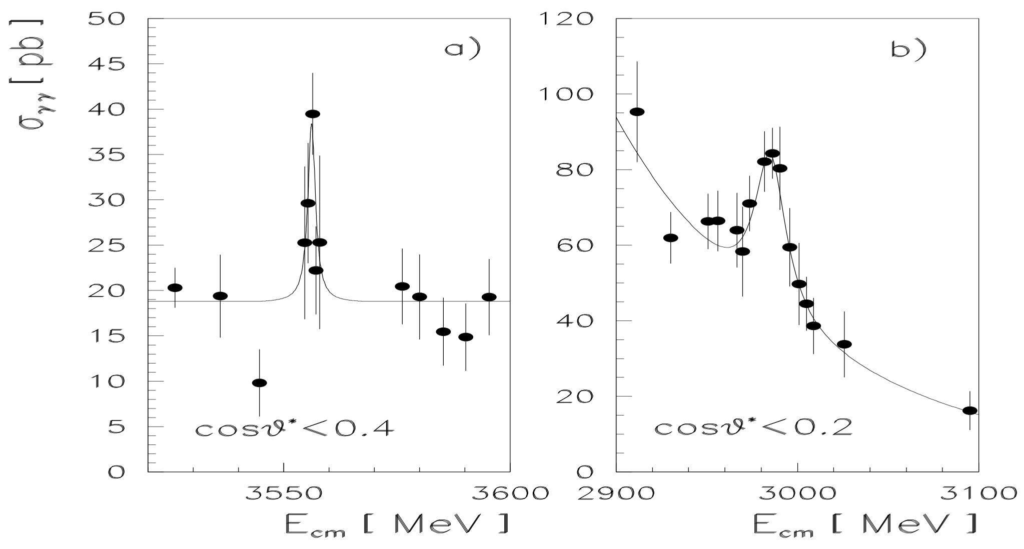

Fig. 1. Measured cross section $\bar{p}p \to \gamma\gamma$ in the χ_2 (a) and η_c (b) energy region. The line represents the best fit to the data.

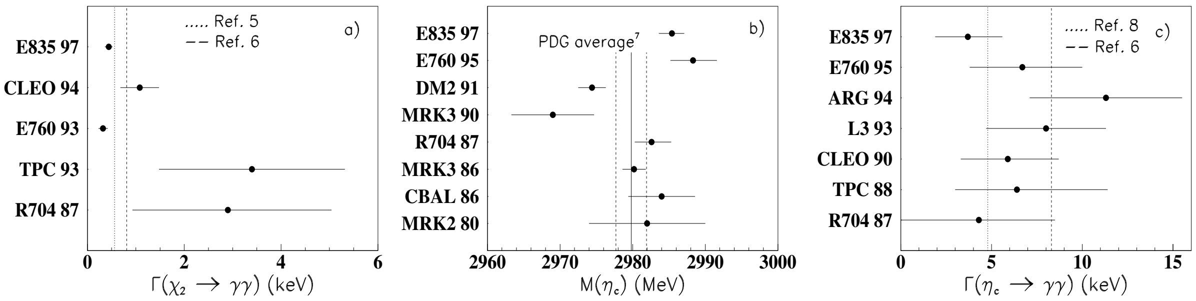

Fig. 2. Comparison of E835 preliminary measurements of $\Gamma(\chi_2 \to \gamma\gamma)$ (a), M_{η_c} (b) and $\Gamma(\eta_c \to \gamma\gamma)$ (c) to previous results.

α_S determination

PQCD with first order radiative corrections[6] (m_c= 1.5 GeV) predicts that:

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}(\eta_c) \approx \frac{8\alpha^2}{9\alpha_S^2}(\frac{1-3.4\alpha_S/\pi}{1+4.8\alpha_S/\pi}) \quad ; \quad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}(\chi_2) \approx \frac{8\alpha^2}{9\alpha_s^2}(\frac{1-16\alpha_S/3\pi}{1-2.2\alpha_S/\pi}).$$

From our preliminary results we obtain:
$\alpha_s(m_c) = 0.32^{+0.05}_{-0.04}$, assuming $\Gamma_{gg} \sim \Gamma_{TOT}$ at the η_c
$\alpha_s(m_c) = 0.33 \pm 0.02$ with $\Gamma_{gg} \sim \Gamma_{TOT} - \Gamma_{J/\psi\gamma}$ at χ_2.
Our result is shown as the first point on the left in fig. 3, in comparison to previous measurements.

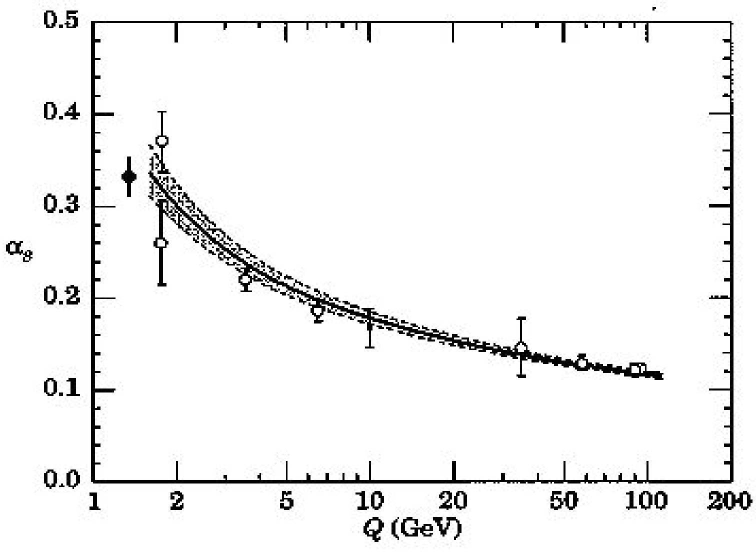

Fig. 3. The variation of α_S with mass scale.

η_c' search

A scan (5 MeV step) was performed in the mass interval $3575 \leq E_{cm} \leq 3660$ MeV to search for the $\eta_c' \to \gamma\gamma$ with an integrated luminosity of 35 pb^{-1}.
The analysis of these data is ongoing.

$\pi^0\pi^0$ cross section

The study of the $\gamma\gamma$ background requires the careful study of $\pi^0\pi^0$ events, which are also used for calibration purposes. The differential cross section dn/dcos(θ) at $\theta^* = 90^0$ as a function of $\sqrt{s}$, is shown in fig. 4.

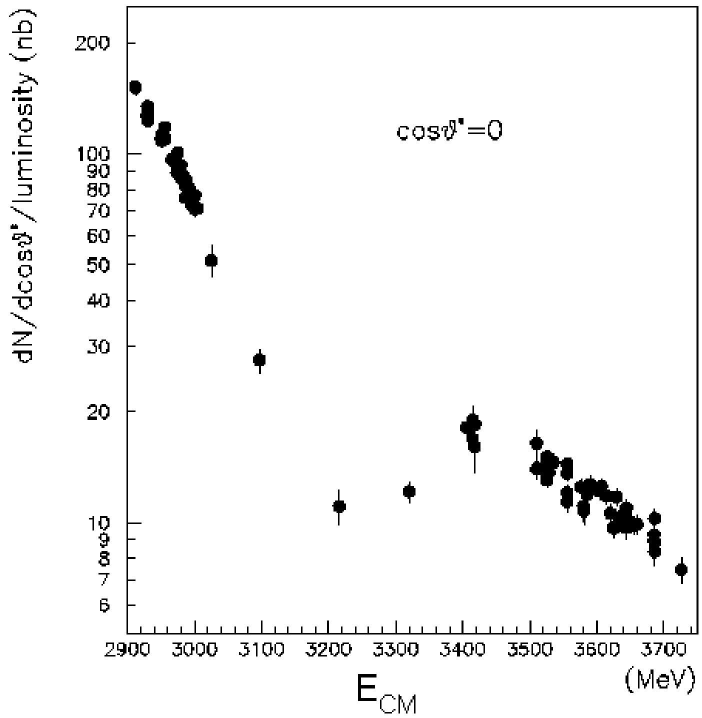

Fig. 4. Measured differential cross section $\bar{p}p \rightarrow \pi^0\pi^0$ at $cos\theta^* = 0$.

Conclusions

The collaboration is now carefully analyzing data. The η_c parameters have been measured with a preliminary error on the mass of 2 MeV and a relative error on the width of 33%. Data were taken at the χ_1 and χ_2 region which confirm the widths as measured in E760 and a clean signal of $\chi_0 \rightarrow J/\psi\gamma$ has been seen. The determination of $\alpha_S(m_c)$, extrapolated up to Q = M_Z is fully in agreement with the world average[7].

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