Present status of charmonium spectroscopy in $p\bar{p}$ annihilations

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Fermilab E835 Collaboration is committed to complete the study of the charmonium spectrum by means of $p\bar{p}$ annihilations, obtained by intersecting the Fermilab Antiprotn Accumulator with an internal hydrogen jet target. In this paper we report the preliminary results from the 1996/1997 fixed target run, particularly about η_c mass and width, search for η_c' and first observation of the χ_0 state in $p\bar{p}$ annihilations.

1. Introduction

Despite the facts that charmonium has been discovered 25 years ago and that a significant experimental effort has been already devoted to its study, many important features of its spectrum are still unknown or poorly measured.

The first experiments were made in the 70s at e^+e^- colliders or at fixed target spectrometers but both techniques suffered from severe limitations.

The e^+e^- colliders can form directly only states with the same quantum numbers as the photon[2], namely $J^{PC} = 1^{--}$, i.e. J/ψ, ψ', ψ'' etc. Other states can be produced through electromagnetic decays of the ψ' but in this case the measurement of both mass and width depend on calorimeter resolution. Furthermore C conservation forbids the decay of a vector state to a C-odd state like, for example, the $^1P_1$.

At fixed target spectrometers all states can be produced directly but in this case as well the mass and width resolution depends on the momentum resolution of the spectrometer, which cannot allow to measure widths of the order of 1 MeV/c.

A major achievment in charmonium spectroscopy was possible in the early '80s thorugh the use $p\bar{p}$ annihilations, first at the CERN Intersecting Storage Ring with experiment R704[1] and then at the Fermilab Antiproton Accumulator with experiment E760[2].

With this technique *all* states can be formed directly via the diagrams in fig. 1. Furthermore, mass and width measurements depend on beam parameters only, which are known with high precision.

Experiment E835 at Fermilab is the continuation of E760 with an improved experimental setup and a new DAQ system.

In this paper we present some preliminary results obtained in the last fixed target run period at Fermilab in 1996/1997.

It is structured as follows: section 2 is a brief description of experiment E835, its detector and the experimental technique; section 3 reports the main results achieved in 1996/1997 fixed target run and, finally, section 4 is devoted to a brief discussion of the new results and the future perspectives.

2. The E835 Experiment

The E835 detector is schematically shown in Figure 2. It is a non magnetic spectrometer with cylindrical simmetry around the beam axis (z axis), optimized for the detection of electromag-

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[2]Neglecting next-to-leading QED contributions

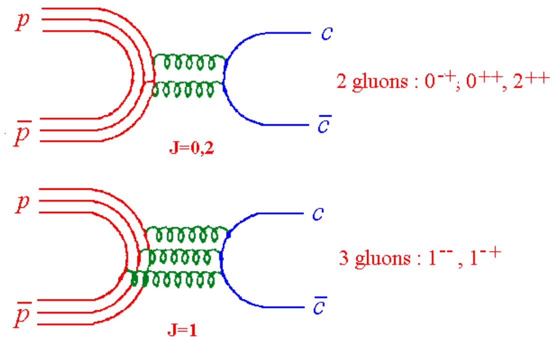

Figure 1. Feynman diagrams at lowest order in QCD for charmonium formation in $p\bar{p}$ annihilations.

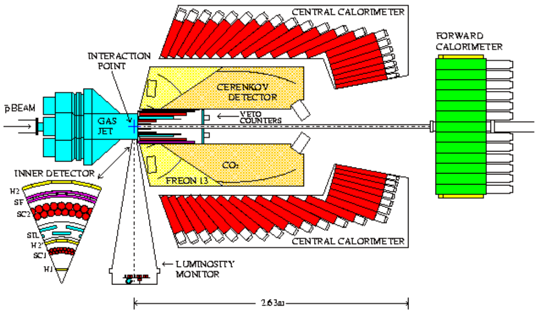

Figure 2. Schematic view of E835 detector layout.

netic final states.

It is composed of six main sub-systems: the hydrogen internal jet target, the three scintillating counters, the threshold Cherenkov counter, the tracking system, the electromagnetic calorimeters and the luminosity monitor.

The cooled antiproton beam circulating in the Fermilab Antiproton Accumulator (AA) intersects (with a crossing angle of 90°) a variable density internal jet target [8], capable to provide a cluster density up to 3.2 10^{14} $atoms \times s^{-1} cm^{-3}$ allowing instantaneuos luminosity greater than 2.0 $10^{31} cm^{-2} s^{-1}$.

The hodoscopes, named H1 (8 modules at $R \simeq 3$ cm, 2 mm thick) and H2 (32 modules at $R \simeq 17$ cm, 6 mm thick), provide first level trigger for charged events and their dE/dx measurements, plus that of the additional hodoscope H2' (24 modules at $R \simeq 7.0$ cm, 4 mm thick), are used to separate electrons from photon conversions in the beam pipe and in the inner detectors. Furthermore, all hodoscope signals are sent to a TDC to identify off-time hits.

The Cherenkov Counter provides first level trigger for electron events (combined with hodoscopes) and it is the main detector for offline electron identification.

The forward veto counter FCV reduces the trigger rate by rejecting events with tracks outside the detector acceptance.

The inner tracking system, fully contained within a radius of 16 cm from the beam axis, is composed of four different detectors sharing a common light mechanical structure: two Straw Tube Drift Chambers [4] (STR1 and STR2) for ϕ measurement [3], one Silicon Pad Detector [5] (SPD) and a Scintillating Fiber Detector with VLPC readout [6] (SF) for θ measurement.

The whole tracking system has full acceptance in ϕ and in the region $15° < \theta < 65°$ and provides a ϕ resolution of 15 $mrad$ and a θ resolution varying from 7 $mrad$ at small θ to 12 $mrad$ at large angle. Its total thickness at 90° is 0.07 % of radiation length X_0.

The Central Calorimeter (CCAL) [9] covers the full azimuth angle and $11° < \theta < 70°$ and is composed of 1280 lead glass detectors pointing to the interaction point, arranged in 20 rings in θ and 64 wedges in ϕ.

The signal from each block is read by a photomultiplier whose charge is first filtered with an active T-filter and then digitized with an 11 bit

[3]In the whole paper we denote with ϕ the azimuthal angle around the beam axis and θ the polar angle.

Channel	BR	PDG 96
e^+e^-	$7.8 \pm 0.2 \pm 0.8$	8.8 ± 1.3
$J/\psi\pi^+\pi^-$	$28.1 \pm 0.9 \pm 2.0$	32.4 ± 2.6
$J/\psi\pi^0\pi^0$	$19.8 \pm 1.1 \pm 1.4$	18.4 ± 2.7
$J/\psi\pi^0$	$1.0 \pm 0.3 \pm 0.1$	0.97 ± 0.21
$J/\psi\eta^0$	$3.0 \pm 0.2 \pm 0.4$	2.7 ± 0.4

Table 1
Preliminary results for the ψ' branching ratios measured by E835.

ADC. All individual signals are also split and sent to Time-to-Digital converters to cope with the piled up signals caused by the high instantaneous luminosity.

In addition, CCAL signals are summed in matrices of 5×8 blocks forming a coarse θ - ϕ mapping of the whole calorimeter and then sent to the first level trigger logic to identify high invariant mass events and events with energy deposited above 90 % of total energy.

At $\theta < 10°$ an additional Forward Calorimeter is used.

Finally, the luminosity monitor is done with a silicon detector mounted at θ 86.5°, right under the jet target. It detects recoil protons for scattering angles near 90° and the total luminosity is measured by comparing the proton rate to the well known elastic cross section.

3. Results

E835 has taken data for about one year during 1996/1997 Fermilab Fixed Target Run, collecting a total of 145 pb^{-1} near the center of mass energy of the ψ', J/ψ, η_c, η_c', h_c, χ_0, χ_1 and χ_2 resonances. More than 35 pb^{-1} have been used for η_c' search, about 20 pb^{-1} were taken to measure η_c parameters, 50 pb^-1 have been collected to try to confirm the observation of the $h_c(^1P_1)$, 7.3 pb^{-1} and 14.7 pb^{-1} were collected respectively at the χ_1 and χ_2 and finally 2.6 pb^{-1} have been taken at the χ_0 energy.

All analysis are still underway and the results presented here are preliminary.

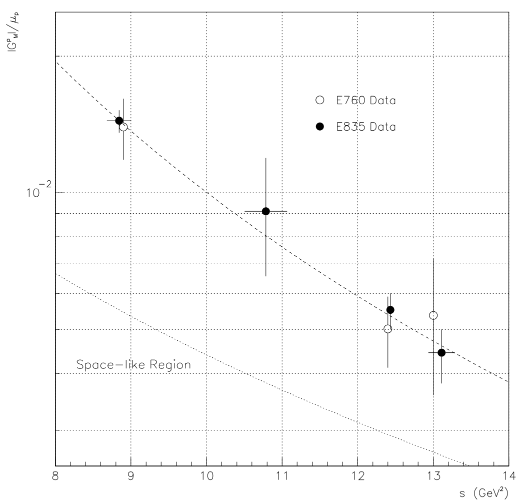

Figure 3. Proton magnetic form factor measured by E835 in the time-like region.

Vector states and proton form factors

The vector states (J/ψ, ψ') are well known and are studied by E835 mainly for calibration purposes but the angular distributions in e^+e^- and the inclusive decays of the ψ' ($J/\psi\pi\pi$, $J/\psi\pi^0$ and $J/\psi\eta$) can be measured with precision better or equivalent to already existing measurements.

The preliminary results for ψ' branching ratios in electromagnetic final states are reported in table 1. Details on this analysis can be found in [3].

The selection of e^+e^- final states allows to measure the cross section outside the resonance regions, giving the best measurement of the proton electromagnetic form factors in the time-like region with q^2 between 8.5 GeV^2 and 13.5 GeV^2.

Figure 3 shows the e^+e^- cross section and the extracted electric form factor as a function of the center of mass energy.

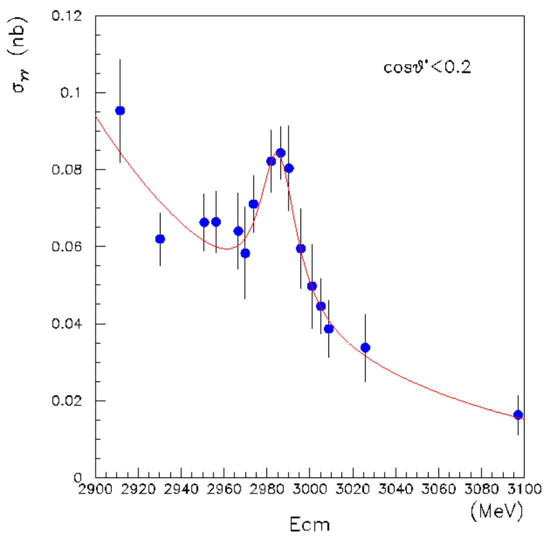

Figure 4. $\gamma\gamma$ cross section in the η_c region.

η_c parameters and η_c' search

The η_c parameters (mass, total width and the product of branching ratios in the initial and final state) have been measured by observing the reaction $p\bar{p} \rightarrow \eta_c \rightarrow \gamma\gamma$. The excitation curve as a function of the center of mass energy is shown in figure 4.

The main background to this channel (see E760 paper [12] for details) is due to $\pi^0\pi^0$ and $\pi^0\gamma$ events where two (one) photon(s) are below the CCAL energy threshold of 25 MeV or are outside geometrical acceptance.

In order to reduce the background coming from these channels, whose differential cross section is peaked at small θ^*, the final events have been selected in the angular region $cos(\theta^*) < 0.2$ to optimize signal-to-background ratio and the data are fitted using the maximum likelihood method with a Breit-Wigner plus a power law background of the form $\sigma_{back} = A \times (2988/E_{cm})^B$.

The preliminary values that result from the fit are: $M_{\eta_c} = 2985^{+1.7}_{-1.8}$, $\Gamma_{\eta_c} = 17.8^{+7.2}_{-6.9}$, $BR(\eta_c \rightarrow p\bar{p}) \times BR(\eta_c \rightarrow \gamma\gamma) = 24.6^{+3.9}_{-3.8} 10^{-8}$. If we use the PDG value for $BR(\eta_c \rightarrow p\bar{p})$ we can obtain $\Gamma_{\gamma\gamma} = 3.7^{+1.5}_{-1.2} \pm 1.2 KeV$.

The 2^1S_0 (η_c') state of charmonium was first observed by the Crystal Ball experiment [13] in 1982. They saw a structure in the inclusive photon spectrum from ψ' decays, corresponding to a mass of 3594 ± 5 MeV/c^2.

We have performed an extensive search of the η_c' state in the $\gamma\gamma$, $J/\psi\gamma$ and $J/\psi\pi^0$ final states.

No evidence was found in the energy region between 3580 and 3660 MeV which allows us to set a preliminary upper limit $BR(\eta_c' \rightarrow \gamma\gamma) \times BR(\eta_c' \rightarrow p\bar{p}) < 9\ 10^{-8}$ at 95% c.l. Figure 5 shows the $\gamma\gamma$ cross section between 3500 and 3680 MeV. A clear χ_2 peak is visible around 3555 MeV while no evidence for a resonance is visible above. Attempts to further reduce the $\gamma\gamma$ background are in progress.

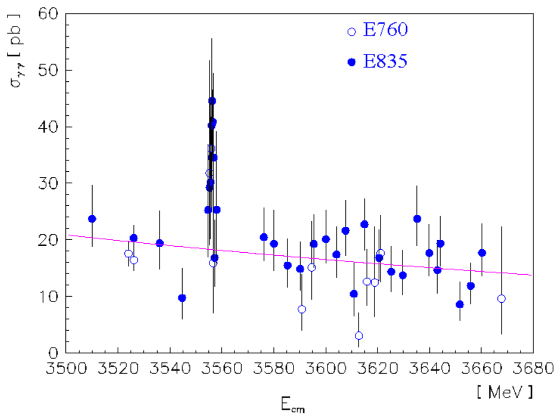

Figure 5. Cross section of the process $p\bar{p} \rightarrow \gamma\gamma$ in the center-of-mass energy region between 3500 and 3680 MeV. A clear peak corresponding to the χ_2 resonance can be seen on the left. There is no evidence for the η_c', yielding the upper limit given in the text.

χ_0 observation in $p\bar{p}$ annihilations

We have taken 2.6 pb^{-1} in the χ_0 region, between 3300 and 3500 MeV, performing the first observation of this resonance in $p\bar{p}$ annihilations by looking at the radiative decay of the χ_0 in $J/\psi\gamma$. Figure 6 shows the excitation curve with two different analysis (see figure caption). The preliminary results for the mass and the width are: $M_{\chi_0} = 3417.9^{+1.7}_{-1.8}$, $\Gamma_{\chi_0} = 15.0^{+4.9}_{-3.6}$.

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

We have seen that the background to $\gamma\gamma$ channels is mainly due to $\pi^0\pi^0$ and $\pi^0\gamma$ events. Therefore the precise knowledge of these cross section is crucial to understand this background.

The uncorrected differential cross section of the $\pi^0\pi^0$ channel near 90° in the center-of-mass as a function of energy is shown in figure 7. Analysis is in progress to measure the $\pi^0\gamma$ cross section as well and the induced $\gamma\gamma$ feed-down.

4. Conclusions and future perspectives

The Collaboration is now completing the analysis of the data. The η_c parameters have been preliminary measured with error below 2 MeV on the mass and 33% error on the total width.

A clean signal of the χ_0 resonance has been seen with preliminary measurement of the mass and width comparable with existing ones.

An extensive search of the η_c' has been performed with no evidence of the resonance.

A further period of data taking in 1999 has been approved by Fermilab and funding agencies and is now in preparation. The main goal of this new run is to confirm the h_c state discovered by E760, complete the search of the η_c' and possibly to conclude the study of the spectrum below threshold by looking at the D states.

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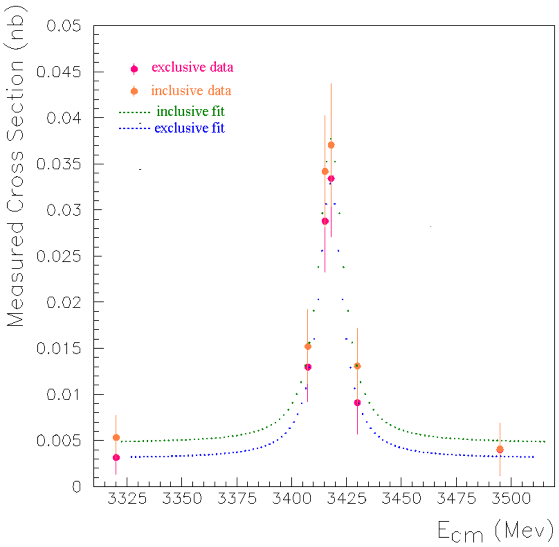

Figure 6. Cross section of the process $p\bar{p} \to J/\psi\gamma$ in the center-of-mass energy region between 3300 and 3500 MeV, corresponding to the χ_0 resonance. The two curves are the same data analyzed in two different ways. The upper one is purely J/ψ inclusive, ignoring the photon. The lower one requires the photon to be detected and to fit the kinematic hypothesis. Both analysis give fully compatible results for both mass and total width.

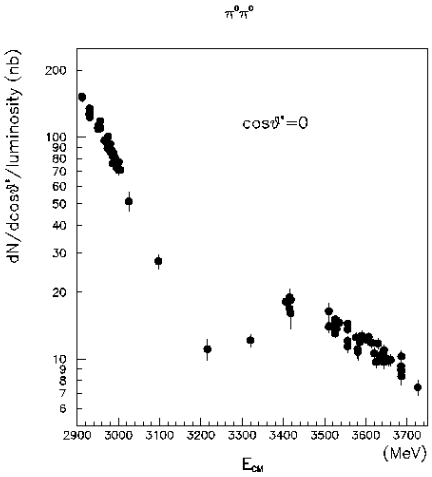

Figure 7. Differential cross section of the process $p\bar{p} \to \pi^0\pi^0$ measured near 90° in the center-of-mass ($cos(\theta^*) \simeq 1.$).