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Charmonium and Bottomonium in $\bar{p}p$ Interactions

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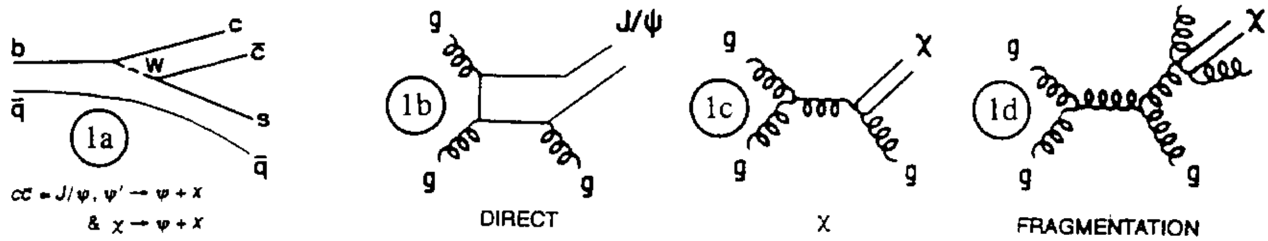
In this talk, I presented some examples of data from the CDF collaboration on $J/\psi, \chi, \psi'$ and Υ production. Such data are used to test models of production dynamics and for the understanding of rates for b quark production. I am not a member of the CDF experiment and showed their data with permission as an interested and impressed spectator. Data from D0 may be found in the talk of D. Denisov. As a complement to this data from the highest energy accelerator experiment, operating at $\sqrt{s} = 1.8$ TeV, I also showed data from Fermilab experiment E760 on masses, widths, states and branching ratios in the Charmonium system, obtained by studying resonant formation of $c\bar{c}$ states in $p\bar{p}$ annihilation at $\sqrt{s} = \mathrm{m}(c\bar{c})$.

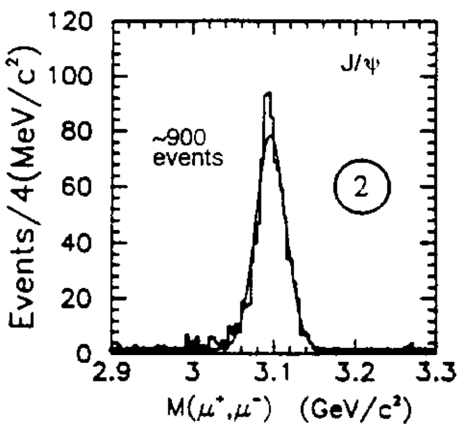
[1]Work supported under contract no. DE-AC02-76CHO3000 with the U.S. Department of Energy

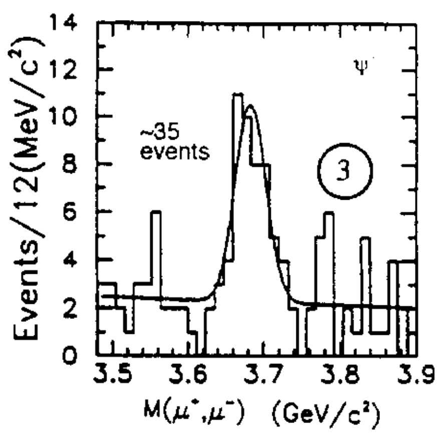
Data from CDF at $\sqrt{s} = 1.8$ TeV

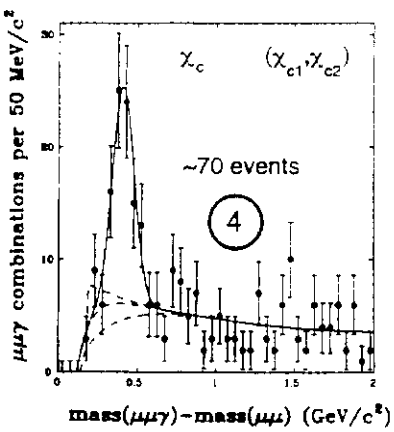
There are four processes which lead to production of charmonium states at non-zero p_t in high energy hadron collisions. These are shown schematically in Figure 1. In the words of Glover, Martin and Stirling[1], measuring and distinguishing processes 1(a) and 1(b,c and d) gives powerful information for b physics and for the Q.C.D. of heavy flavor production, including the gluon distribution at small 'x'. Progress in the calculation of diagram 1(d) was reported in the talk of A. Falk.



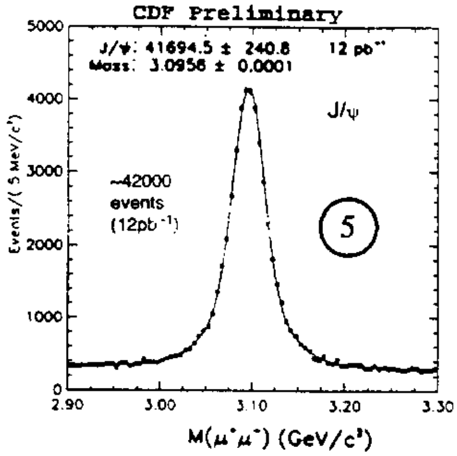
Figures 2, 3, and 4 show respectively CDF data on $J/\psi, \psi'$ and χ_c production from $\approx$ 2.5 pb^{-1} taken in the 1988-1989 run. These have been used to derive the rates of b quark production[2,3,4] under certain assumptions on the sources of production *viz* that all ψ' come from b decay, while the majority of χ_c production is from Q.C.D. processes. While the data allow the consistency of these assumptions to be checked, it was not possible to identify events as from b decay or from Q.C.D. production.

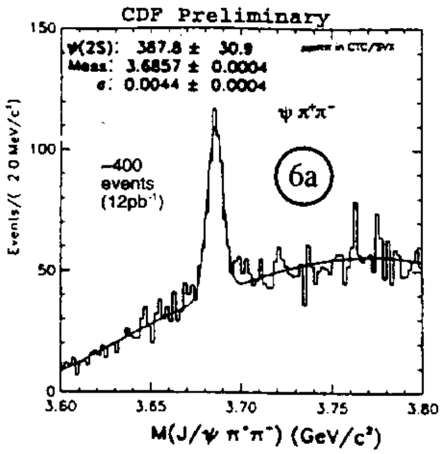


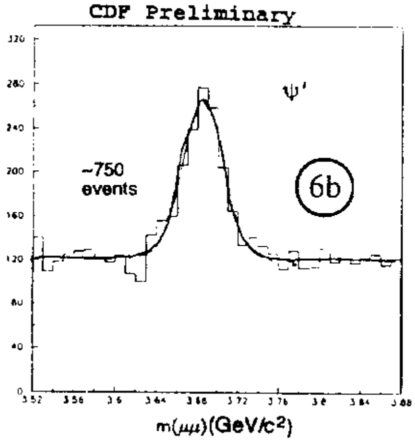


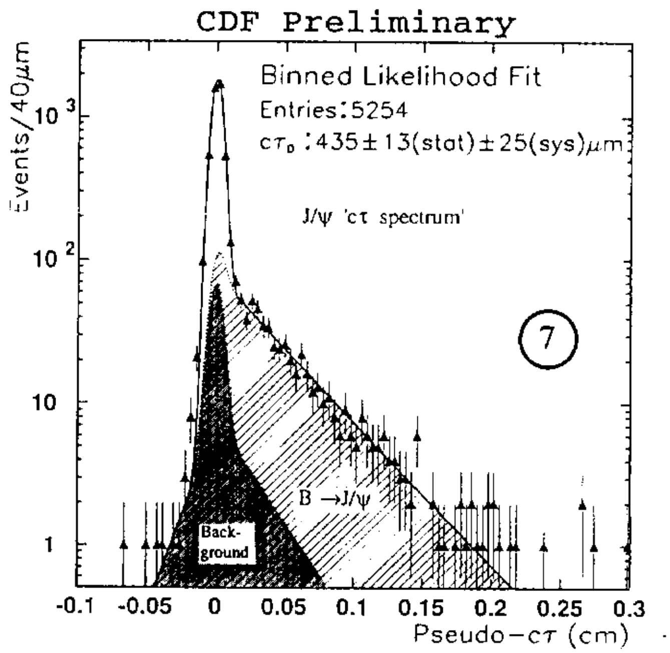


The situation has been much improved for the present run which started in 1992 and will continue till 1994. The new Silicon Vertex Detector (SVX) allows prompt and decay production to be distinguished and the integrated luminosity of the 92-93 data is already 10 times the previous data. As an example of the statistics of the new data, Figures 5 and 6 show plots of J/ψ and ψ' signals, the latter identified in both its direct $\mu\mu$ and $\psi\pi^+\pi^-$ decay modes. (The data on χ_c are equally improved but too preliminary to show.) As an example of the power of the SVX, figure 7 shows the flight-path distribution for a sample of J/ψ events. The solid line is a fit to the data which includes a prompt component (flight-path = 0), a background distribution derived from side-bands in the $\mu\mu$ mass distribution, and a component from decay of b quarks. This distribution has already been used to determine the average b hadron lifetime[5] but that is not my topic. One may anticipate similar distributions for ψ' and possibly for χ_c and thus explicit measurement of the amounts of direct and indirect production of charmonium.

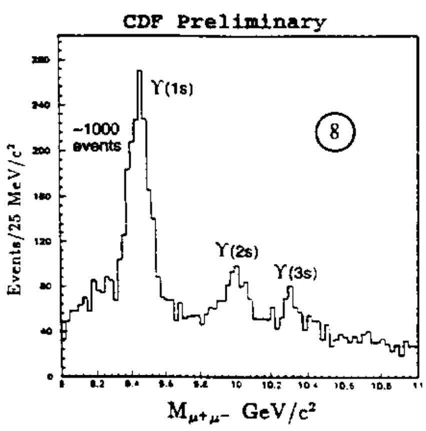


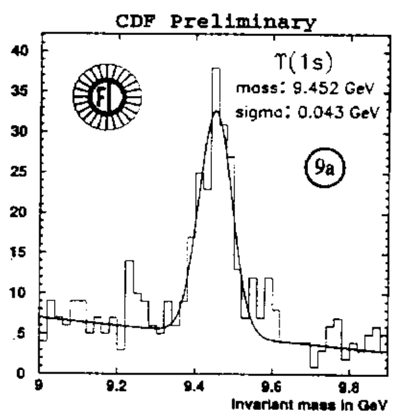


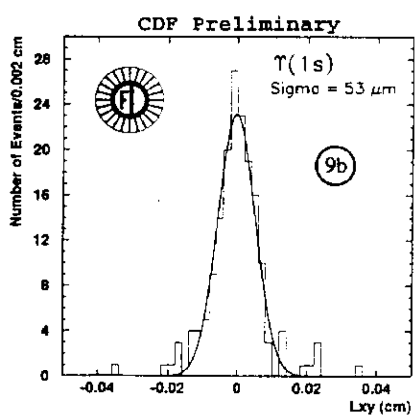




Finally from CDF, since the title of the talk mentions bottomonium, Figure 8 shows a sample of Υ's from the present run where 1S, 2S and 3S states are clearly visible. Figure 9a shows a sample of $\Upsilon(1S)$ and the flight path distribution (figure 9b), consistent as one might expect with the Υ production being all prompt.







Resonant Formation of Charmonium in $p\bar{p}$ annihilations

From interactions at $\sqrt{s} = 1.8$ TeV to interactions at $\sqrt{s}$ below 4 GeV, we turn now to a discussion and summary of charmonium results from Fermilab E760, a study of charmonium by resonant formation in $p\bar{p}$ annihilations.

Studying the resonant formation of charmonium in $\bar{p}$ annihilations has some technical and some physics advantages. From the physics point of view, $\bar{p}p$ annihilations allow the charmonium states to be formed either by two or three gluons. Unlike the case at electron-positron colliding machines where only states with $J^{PC} = 1^{--}$ are produced directly, $\bar{p}p$ annihilations can produce all J^{PC} states directly. This leads to the technical advantage that the precision in the mass and width measurements of all the charmonium states is set by the knowledge of the $\bar{p}$ beam parameters and not by the final state detector. There are, of course, some technical challenges to meet. The major one, the construction of an anti-proton source with sufficient luminosity and adequate beam control and diagnostics, has been accomplished by accelerator experts[6]. For the experimenter, the challenge is to construct a target and an apparatus to identify the small cross-sections (nanobarns to picobarns) in a total cross section of 60 millibarns. That all these challenges could be met was demonstrated by the pioneering experiment R-704 at CERN[7].

The physics motivation for studying the Charmonium system starts from the observation that the spin dependent splittings are much less than the energies of the states. As examples, the normalized hyperfine splitting of the ground state,

$$\frac{(M_{S=1}^{L=0}(J/\psi) - M_{S=0}^{L=0}(\eta_c))}{M(\eta_c)} \approx 0.03$$

and the normalized spin-orbit and tensor splitting as given by

$$\frac{M_{L=0}(\psi') - M_{L=1}(\chi)}{M(\chi)} \approx 0.07$$

This encourages one to treat charmonium as the positronium of Q.C.D., or pedagogically as the hydrogen atom. If one describes the $(c\bar{c})$ system in terms of a potential U(r) = V(r) + S(r) where V and S arise from the vector and scalar parts of the interaction respectively, then one can define three spin dependent terms in the Hamiltonian

the spin-orbit interaction, H_{LS} which splits states of given L and S but different J and has the form

$$= \frac{1}{2m^2}\left(\frac{3}{r}\frac{dV}{dr} - \frac{1}{r}\frac{dS}{dr}\right)\vec{L}\cdot\vec{S}$$

the spin-spin interaction, H_{ss}, which has the form

$$= \frac{2}{3m^2}\nabla^2 V\ \vec{s_1}\cdot\vec{s_2}$$

the tensor interaction H_T (reminiscent of the potential between two dipoles)

$$= \frac{1}{12m^2}\left(\frac{1}{r}\frac{dV}{dr} - \frac{d^2V}{dr^2}\right)\ S_{12}$$

where

$$S_{12} = \frac{(\vec{s_1} \cdot \vec{r})\,(\vec{s_2} \cdot \vec{r})}{r^2} - \frac{\vec{s_1} \cdot \vec{s_2}}{3}$$

and vanishes for $L = 0$.

The spin-spin interaction depends only on the vector part of the potential and is expected to vanish for states with $L \neq 0$. Table I gives the spin coefficients for the L=1 states.

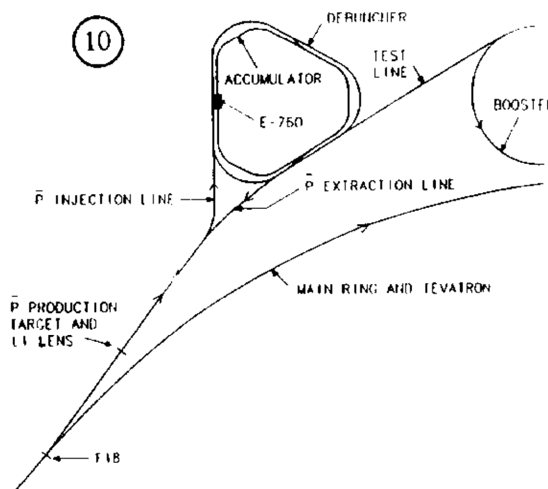
Table I: Spin-coefficients

Term	$^3P_0$	$^3P_1$	$^3P_2$	$^1P_1$
$\vec{L} \cdot \vec{S}$	-2	-1	$+1$	0
$\vec{s}_1 \cdot \vec{s}_2$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{-3}{4}$
S_{12}	-4	2	$\frac{-2}{5}$	0

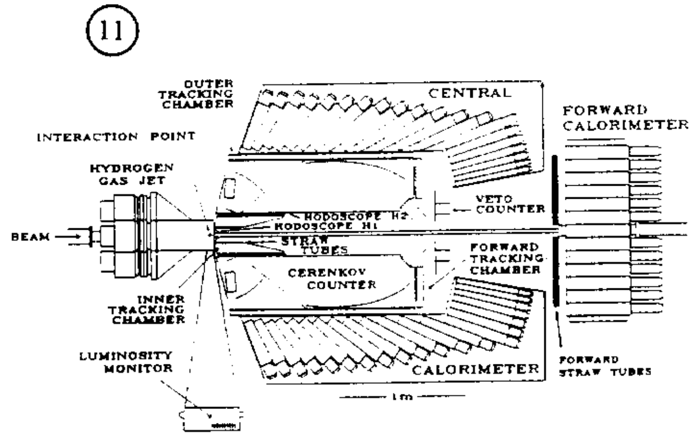
In general, measurements of the mass spectrum, total widths, radiative decays and two photon decays provide powerful tests for our understanding of Q.C.D. calculations both off and on the lattice. Part of the attraction to the experimenter is that the lowest order predictions of masses and widths are straightforward; part of the attraction to the theorist is that data are available to test the corrections to the lowest order theory. It is useful perhaps to realize that despite the superb work at e^+e^- machines, for example by the Crystal Ball collaboration[8], many important quantities of the Charmonium system remained to be measured. While the masses and widths of the ^3S states were well known, the widths of the ^3P states were essentially unknown; the ^1P state remained to be observed; the width of the ^1S state, the η_c, was poorly known, and the observation of the first excited ^1S state, the η'_c, reported at an unexpectedly low mass and not included in the Particle Data Tables, remained to be confirmed (or corrected). Fermilab E-760 was designed to address these issues. Proposed in 1985, the experiment[9] took its first data in 1990.

The experiment is located in the antiproton source at Fermilab[10], see figure 10, and uses an arrangement in which a hydrogen gas-jet intercepts the antiproton beam circulating in the antiproton accumulator. The average center of mass energy of the $\bar{p}p$ interactions is known to about 50 keV as evidenced by repeated scans at the J/ψ and ψ' resonances and the center of mass energy spread can be made as small as 250 keV. To identify charmonium in the presence of the large hadronic background, the states are detected through their electromagnetic decay modes e.g. $J/\psi \rightarrow e^+e^-, \chi \rightarrow J/\psi + \gamma, (J/\psi \rightarrow e^+e^-)$ and $\eta_c \rightarrow \gamma\gamma$ and the experiment apparatus is optimized for the detection and identification of photons and electrons.

The intersection of the gas-jet and the antiproton beam produces an interaction region about 0.5 cm on a side. The detector[11], shown in figure 11, covers the full azimuth and the laboratory polar angle from 2° to 70°; the fiducial acceptance in the center of mass is approximately $-0.5 < cos\theta^* < 0.5$. The resonances are scanned by *decelerating* the antiproton beam from the accumulation energy of 8.9 GeV to an energy just above the resonance and then decelerating through the resonance in steps of between 170 and 500 keV (center of mass energy) depending on the resonance. This is, of course, quite similar to the technique used at electron-positron machines with one obvious and one technical difference. The obvious difference is that the resonant charmonium cross section is only a tiny (1 part in 10^{-4}) of the total inelastic cross section. The other difference is that in our case the beam energy spread is small enough to allow the total width of the charmonium state to be determined directly from the shape of the excitation curve while in the case of electron-positron annihilation where synchrotron radiation broadens the beam energy spread, the total width is determined from the area under the excitation curve and the hadronic and leptonic branching ratios.



The Antiproton Source



E760 detector layout.

Figure 12 shows the excitation curves measured for the $J/\psi, \chi_1, \chi_2$ and ψ' states and table II shows the masses and widths derived therefrom compared with previous values.

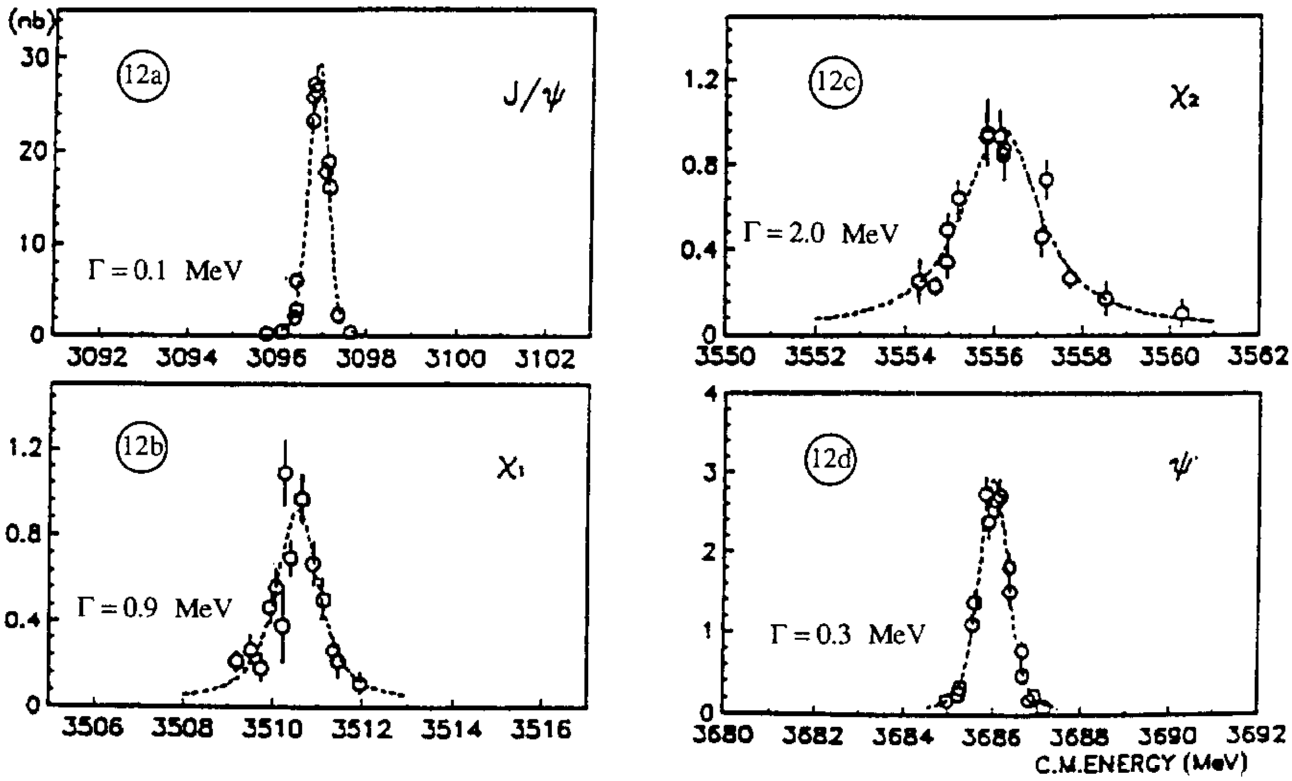
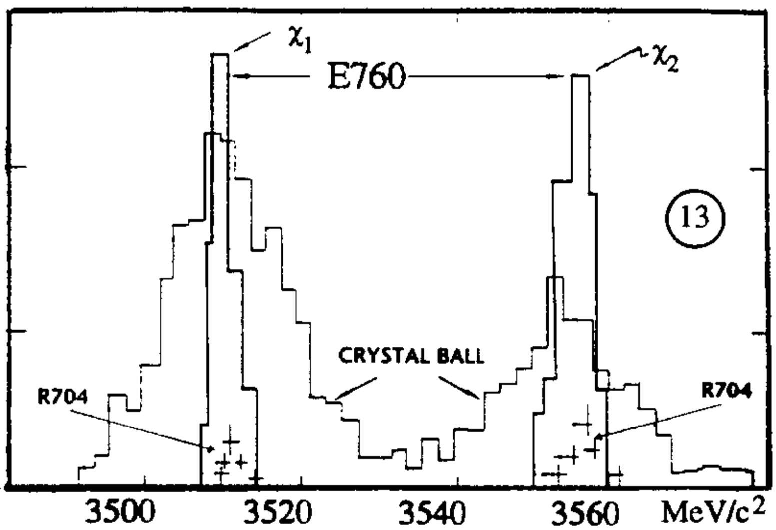


Table II: Charmonium Resonance parameters

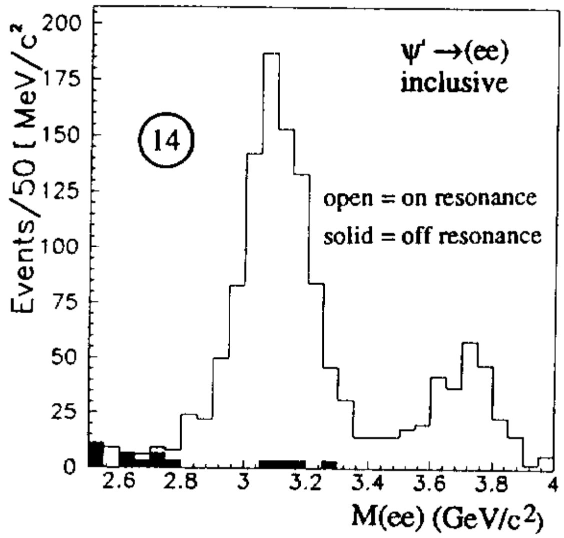
Resonance	Mass (MeV/c^2)	Width (keV)
J/ψ (E-760)	3096.88 $\pm 0.01 \pm 0.06$	99 $\pm 12 \pm 6$
J/ψ (Old Value)	3096.93 ± 0.09	86 ± 6
χ_1 (E-760)	3510.53 $\pm 0.04 \pm 0.12$	880 $\pm 110 \pm 80$
χ_1 (Old Value)	3510.6 ± 0.5	< 1300
χ_2 (E-760)	3556.15 $\pm 0.07 \pm 0.12$	1980 $\pm 170 \pm 70$
χ_2 (Old Value)	3556.3 ± 0.4	2600 $^{+1200}_{-900}$
ψ' (E-760)	3686.0 (input)	312 $\pm 36 \pm 12$
ψ' (Old Value)	3686.0 ± 0.1	243 ± 43

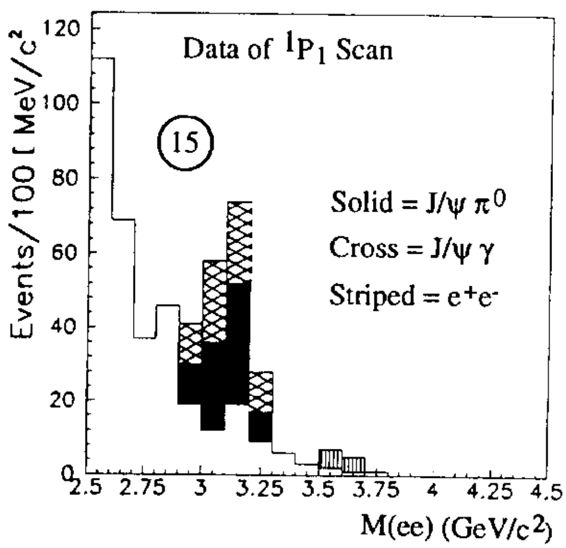
One may notice in particular the improvement in the precision of the measurements of the χ states. Figure 13 shows graphically the advantage of measuring the mass and width using direct formation where the resonance parameters are determined from the beam energy compared to indirect formation where one relies on the final state detector. The measurements of the χ_1 and χ_2 widths, and their ratio, can be compared to theoretical predictions assuming that the only significant decay modes are the radiative decays and the hadronic decays through 3 and 2 gluons respectively. The radiative decay widths, which can be inferred from the radiative branching ratio and the total width, can also be compared with the simple electric dipole predictions. The agreements are all quite satisfactory[11].

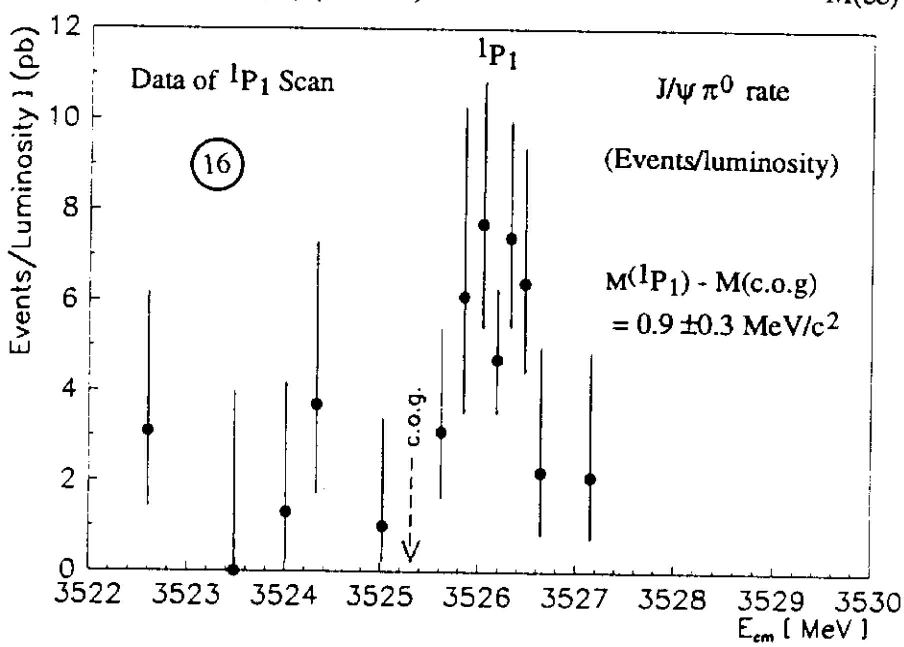


The precision in the measurement of the χ masses is important for interpreting the mass of the $^1P_1$ state. The difference between the J-weighted average mass of the ^3P states and the $^1P_1$ mass is a measure of the H_{ss} in the $P-$state. For a short-range interaction, this difference is expected to be small, typically a few MeV. Thus the interpretation of any measurement of the $^1P_1$ mass depends on good precision in the masses of the χ states, particularly the χ_1 and χ_2.

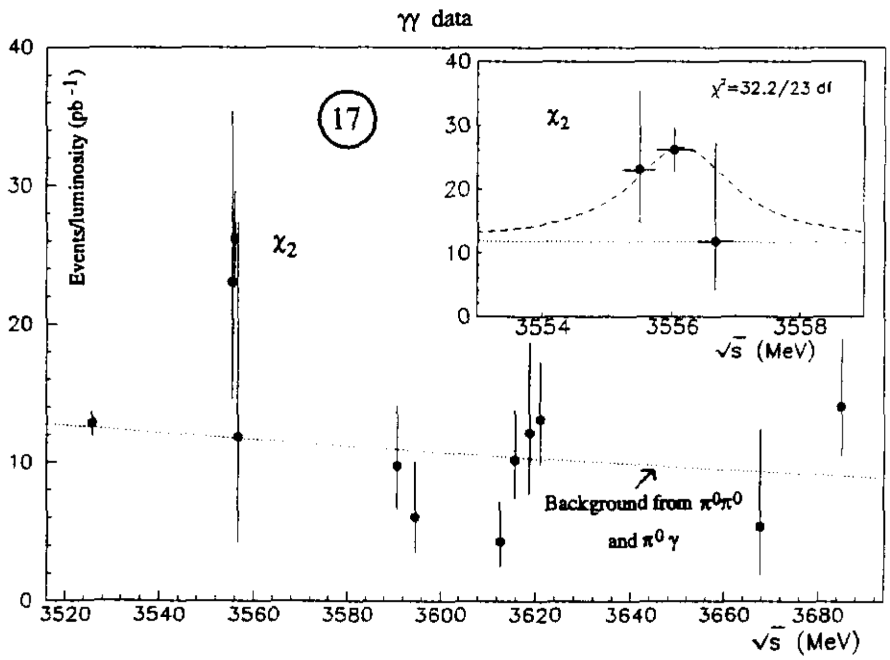
Details of the $^1P_1$ search and observation are given in [12] so I only give some salient points here. The search concentrated on the major decay modes $^1P_1 \rightarrow \eta_c\gamma, \eta_c \rightarrow \gamma\gamma$ and the isospin violating mode $^1P_1 \rightarrow J/\psi + \pi^0$; the decay to $J/\psi + \gamma$ would violate C parity conservation. The search region was set a priori between 3520 and 3530 GeV around 3525 GeV, the center of "gravity" of the χ states. An inevitable corollary of the narrow beam energy spread is that the search had to be performed in small energy steps, typically of 0.6 MeV. At each step we took about 1 pb^{-1} of data and there was a certain amount of tension as the scheduled end of the run was approaching, forcing hard choices between searching for the ${}^1P_1$, searching for the η_c' and measuring the η_c. Our first observation was a continuum production of J/ψ at a level of about 100 pb. As an example of the mass distribution reconstructed in the electromagnetic calorimeter, figure 14 shows the inclusive electron-positron mass distribution recorded at the ψ' resonance, the two peaks correspond to $\psi' \rightarrow J/\psi$ inclusive and $\psi' \rightarrow e^+e^-$. Figure 15 shows the mass distribution of the ${}^1P_1$ scan; most of the peak at the J/ψ mass is accounted for by $J/\psi\ \pi^0$ and $J/\psi\ \gamma$. The rate of $J/\psi\ \gamma$ production is consistent with being from the tails of the χ_1 and χ_2 and its energy dependence shows no resonant behavior. The rate of $J/\psi\ \pi^0$, figure 16, however, shows a significant (3.6 sigma) peak at a mass of 3526.2±0.3 MeV/c^2 which we interpret as the ${}^1P_1$ state. This is about 0.9 MeV/c^2 above the center of gravity of the χ states, consistent with the calculation of reference 13.



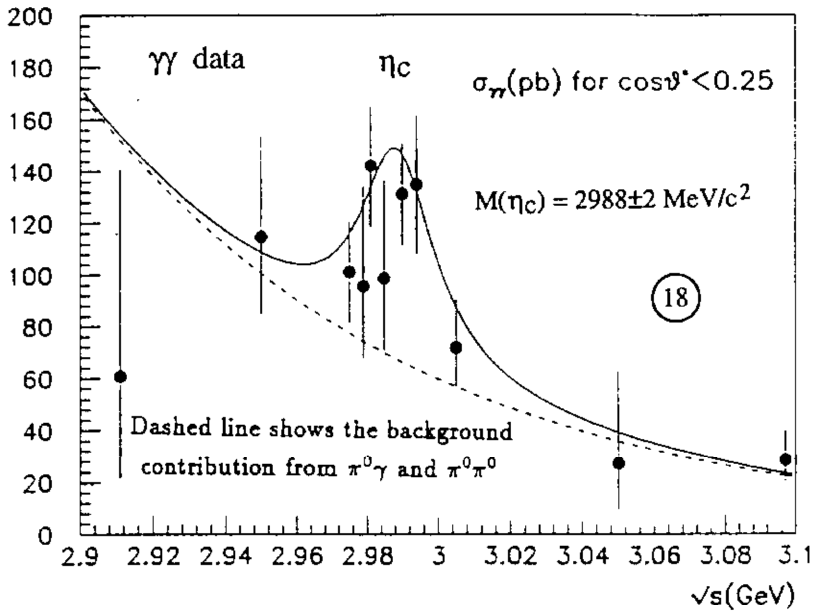




While the previous data all included a J/ψ in the final state, the experiment also has the ability to study $\gamma\gamma$ final states, or what may be called $C = +1$ physics. As an example, figure 17 shows the rate for candidate $\gamma\gamma$ events in the mass region from the ${}^1P_1$ to the ψ'. The major background in this channel comes from $\pi^0\gamma$ and $\pi^0\pi^0$ final states where photon(s) either fell outside the geomtric acceptance or were too low in energy (<20 MeV) to be detected. The excess at the χ_2 implies a branching ratio of $B(\chi_2 \to \gamma\gamma)$ of $(1.6 \pm 0.5) \times 10^{-4}$ or equivalently a partial width $\Gamma_{\gamma\gamma} = 320 \pm 100eV$. The branching ratio can be calculated from the ratio of the electromagnetic and hadronic widths to be given by $\frac{\alpha^2}{\alpha_s^2} \times \frac{(1-16\alpha_s/3\pi)}{(1-2.2\alpha_s/2.2\pi)}$ from which, for example, one can extract a value of $\alpha_s \approx 0.35$. The experiment searched for the η_c' in its two photon decay mode both in the region where it was reported by the Crystal Ball and near the region preferred by theory. The data run ended before we could reach any definitive conclusions in the sense of confirming or absolutely excluding the Crystal Ball value or finding the η_c' at some other mass.



The experiment has also taken data in the region of the η_c. Time limitations affected the quality of the measurement but even here the power of the direct production technique can be seen. Figure 18 shows the $\gamma\gamma$ yield from the η_c scan. There is a clear peak above a background which is well accounted for by $\pi^0\pi^0$ and $\pi^0\gamma$ events with missing photon(s). Since this background is strongly peaked at large values of $cos\theta^*$ and the η_c decay is isotropic, the acceptance is restricted to $cos\theta^* < 0.25$. Though the amount of data taken was limited, an immediate result of the measurement is that the mass we observe is 2988±2 MeV/c^2, compared to the previous world average of 2980±2. A paper on this and the η_c total width and partial width to $\gamma\gamma$ is in preparation.



The Future

For the future, a continuation proposal by the E760 collaboration has been accepted as E835 for the next fixed-target run at Fermilab. The goal is to complete the charmonium table as much as possible and we should clearly like to

- observe and measure the mass and total width of the η_c' and its decay to $\gamma\gamma$;
- observe and measure the masses of the ${}^{3,1}D_2$ states;
- observe the $\eta_c\gamma$ decay of the ${}^1P_1$;
- measure the width of the ${}^1P_1$;
- improve the measurement of the η_c parameters;
- measure the χ_0 total width and its $\gamma\gamma$ decay.

Based on our experience, this will require an integrated luminosity of 200 pb^{-1} compared to the 30 pb^{-1} we took in E760. Upgrades to the antiproton source make this feasible and we are modifying our detector to take the higher rates needed.

Acknowledgements

I thank Dr. Vaia Papadimitriou and Professor Paris Sphicas for discussing the CDF data with me. I thank my colleagues on E760 for making this experiment such a pleasure - and doing the work I am reporting here. Any presentation of E760 must acknowledge the Fermilab Antiproton Source department whose outstanding performance makes our experiment possible.

Finally, I wish to state here the appreciation we feel towards our hosts for their warm and generous hospitality which made this conference so enjoyable and stimulating. Professor Bellini explained in his welcome that "Humilitas" is the ancient motto of the Borromei; its meaning for our conference could be taken as

Heard Unusually Many Interesting Lectures
Italian Treatment Absolutely Superb

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13. FIG. 13 Comparison of E-760 and previous experiments at the χ states

14. FIG. 14 The reconstructed mass spectrum of electron pairs from the ψ'

15. FIG. 15 The reconstructed mass spectrum of electron pairs from the ${}^1P_1$ scan.

16. FIG. 16 The rate of $J/\psi + \pi^0$ events over the ${}^1P_1$ scan.

17. FIG. 17 The rate of $\gamma\gamma$ candidates from the energy of the ${}^1P_1$ to the ψ'.

18. FIG. 18 The $\gamma\gamma$ yield from the η_c scan.