Study of the Charmonium states in proton-antiproton annihilations from E835

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Fermilab E835 Collaboration

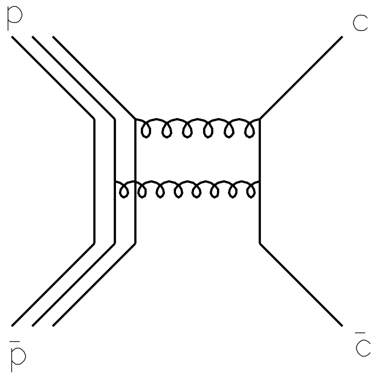
Fermilab, University of California (Irvine), University of Ferrara, University of Genova, University of Minnesota, Northwestern University, University of Torino and INFN

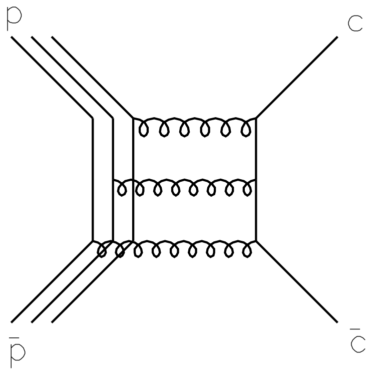
Outline

- Physics motivation
- Technique of the experiment
- $\bar{p}p \rightarrow J/\psi\gamma \rightarrow e^+e^-\gamma$ and $\bar{p}p \rightarrow \gamma\gamma$ event selection
- Results:
  - χ_{c0} mass and width
  - η_c mass and width
  - $\chi_{c0,2} \rightarrow \gamma\gamma$ partial width
  - η_c' search
- $\chi_{c1,2} \rightarrow J/\psi\gamma$ angular distributions
- Conclusions

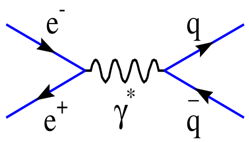
Physics Motivation

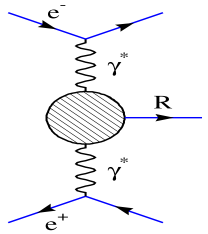
- Precision measurements of masses, widths, decay rates in $\bar{c}c$ systems are ingredients to test:
  - the limits of perturbative QCD
  - magnitude of relativistic and radiative corrections
- In $\bar{p}p$ annihilations all the states can be directly formed via 2 and 3 gluons





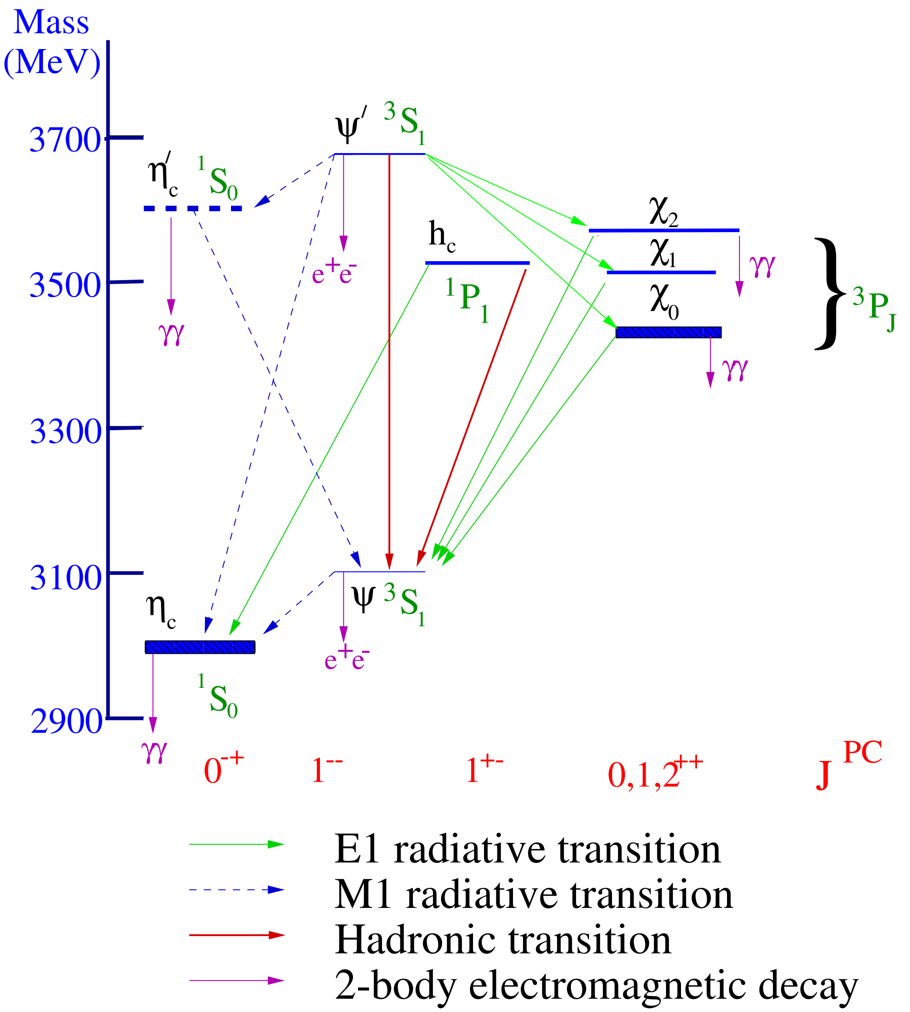
- on the contrary in e^+e^- annihilations only the states with the photon quantum numbers $(J^{PC} = 1^{--})$ can be formed.





C^+

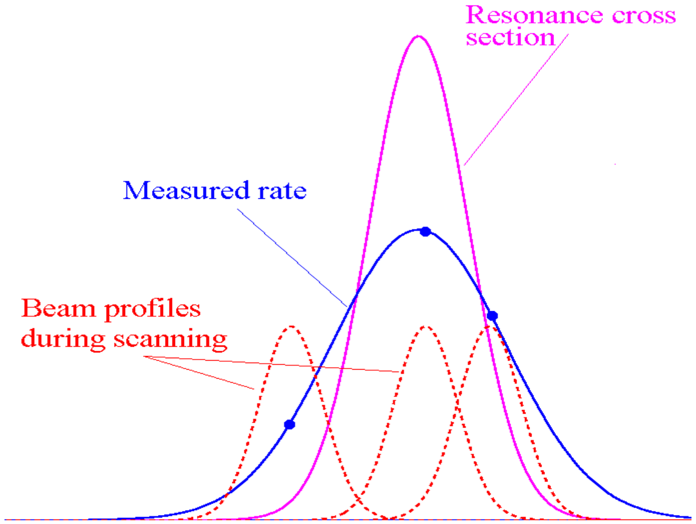
Physics Motivation: Charmonium spectrum



η_c' and ${}^1P_1$ observed only in a single experiment (Crystal Ball and E760 respectively)

Technique of the experiment: resonance scanning

The beam energy is swept across the resonance to measure the distribution of Number of events / Luminosity (measured rate) vs Beam energy: (Excitation curve)



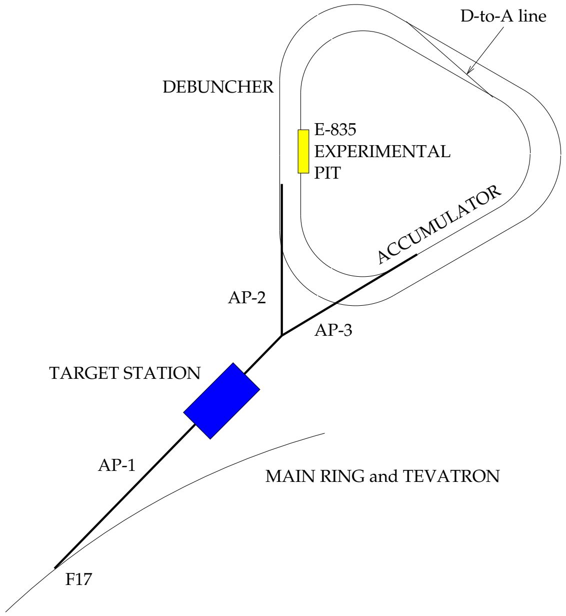
The Number of events, N_{ev}, is proportional to the convolution of the beam energy spectrum $I_{beam}(E)$ and the resonance Breit-Wigner cross-section, $\sigma_{BW}(E)$

$$\frac{N_{ev}}{Luminosity} \propto \int I_{beam}(E)\sigma_{BW}(E)dE$$

where:

$$\sigma_{BW}(E) = \frac{(2J+1)\pi}{k_{cm}^2} \frac{BR(\bar{p}p \to R) \times BR(R \to f)}{1+4(E-M_R)^2/\Gamma_R^2}$$

Technique of the experiment: beam characteristics

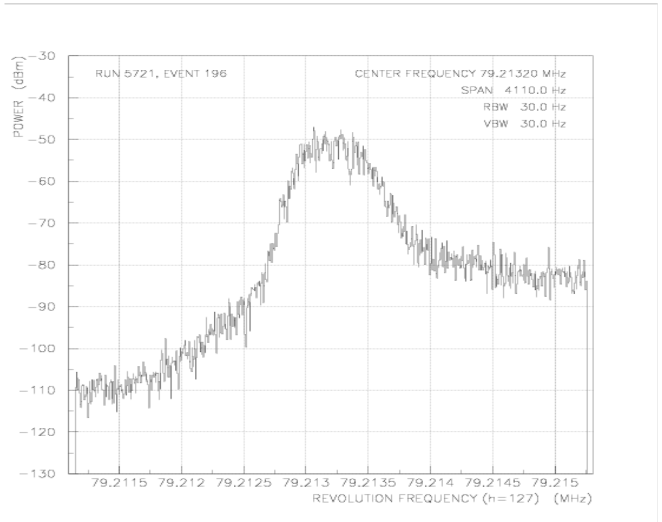


- continuous beam of up to $\simeq 8 \times 10^{11}\bar{p}$ (corresponds to 80 mA d.c. current)

➜ How is the beam energy measured ?

- $\bar{p}$ velocity $= c\beta =$ orbit length $\times$ revolution frequency
- orbit length $L =$ reference orbit length L_0 + correction ΔL
- L_0 has been computed by imposing the ψ' mass ($L_0 \simeq 474$ m)
- ΔL: calculated by measuring the deviation of the actual orbit from the reference beam orbit (ΔL is typically of a few mm).

- the error on the orbit length is ± 1 mm $\rightarrow \sigma_L/L \simeq 2.1 \times 10^{-6}$
- revolution frequency measured from the beam current Schottky noise $\sigma_f/f \simeq 10^{-7}$
- σ_L and σ_f values translate to $\sigma_{Ecm} \simeq 50$ to 150 keV depending on the E_{cm} value [here σ_{Ecm} is the beam energy central value uncertainty]
- $\Delta N_{\bar{p}}/\Delta E$ is measured from the beam current Schottky noise



- beam stochastically cooled: in the center of mass: $\sigma_E \simeq 400$ keV corresponding to $\sigma_E/E \simeq 10^{-4}$ [here σ_E is the beam energy spread]

Technique of the experiment: Jet target

- jet of clusterized hydrogen molecules crosses the beam at 90^0
- jet diameter $\simeq 7$ mm with a molecule density up to $\simeq 3 \times 10^{14} atoms/cm^3$ (controlled via P_0, T_0)

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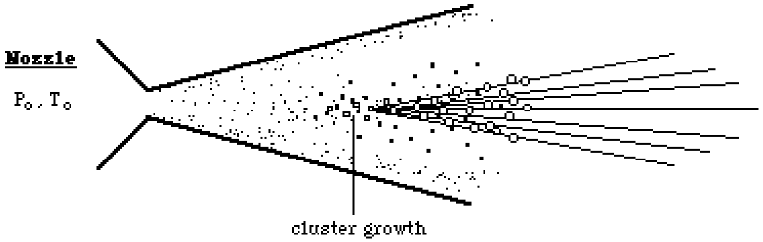
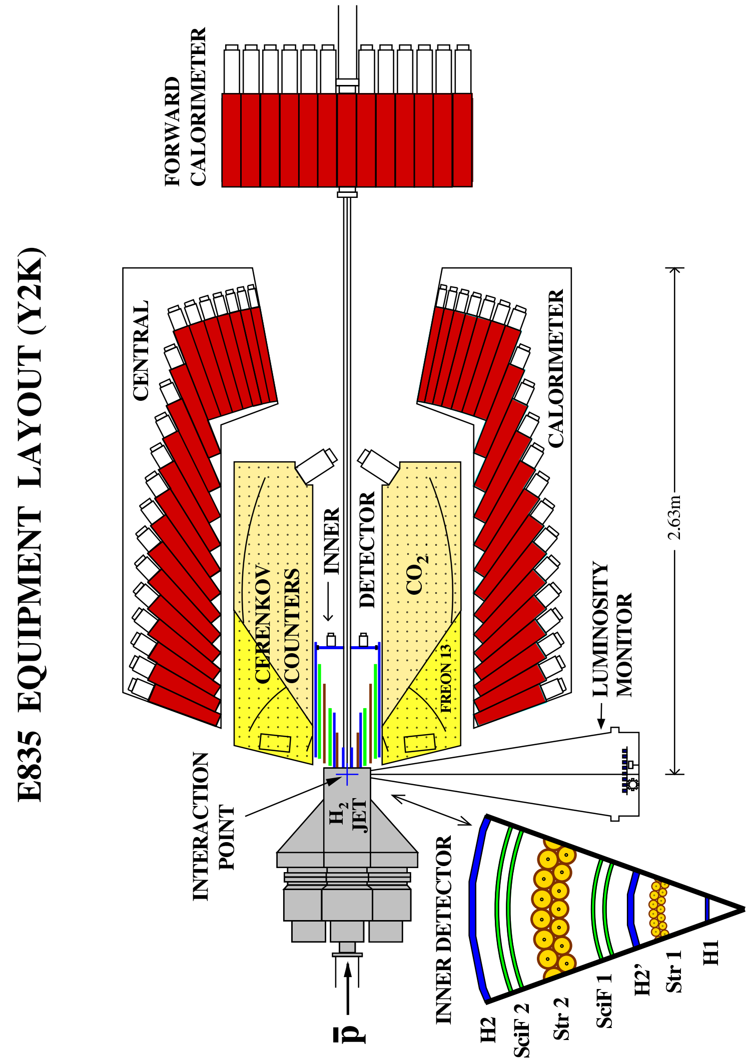


FIG. 1

- interaction region: $(5 \times 5 \times 7) mm^3$
- instantaneous luminosity up to $\simeq 2.5 \times 10^{31} cm^{-2} s^{-1}$ $\simeq 0.1$ events/pb/hour
- data taking procedure: as the beam current is decreasing the jet density is increased to keep an almost constant instantaneous luminosity
- luminosity measured from the $\bar{p}p$ elastic recoil at $\simeq 90^0$ with a 3 % precision.

Technique of the experiment: Detector



Technique of the experiment: Detector

- designed to study electromagnetic final states such as $J/\psi(\to e^+e^-) + X$ and $\gamma\gamma$
- hadronic final states as $\phi\phi$ and $\phi\phi\gamma$ and $\phi \to K^+K^-$ have been investigated
- $\pi^0\pi^0$, elastic $\bar{p}p$, ... have been used to calibrate the detector and check the data taking stability
- acceptance: 2π coverage in ϕ, polar angle coverage: $3^0 < \theta_{Lab} < 65^0$
- Threshold gas Cherenkov to tag electrons and three *barrels* of hodoscopes to trigger on event multiplicity and topology
- Central Calorimeter (lead glass) performances:
  - acceptance: $11^0 < \theta < 70^0$
  - energy resolution: $\sigma_E/E \simeq 0.06/\sqrt(E) + 0.014$
  - angular resolution: $\sigma_\theta \simeq 6$ mrad and $\sigma_\phi \simeq 11$ mrad
- Forward Calorimeter (lead glass) performances:
  - acceptance: $2^0 < \theta < 11^0$
  - energy resolution: similar to Central Calorimeter with a larger constant term

- Forward Calorimeter: continue
  - position resolution: 5. cm
- Tracking:
  - acceptance: $15^0 < \theta < 65^0$
  - azimuthal angle (ϕ) measured by 4 layers of Straws: $\sigma_\phi \simeq 8$ mrad
  - polar angle measured by 2 layers of Scintillating fibers: $\sigma_\theta \simeq 4$ mrad
- all the elements of the detector have precise timing information (1 nsec TDC resolution) to reject accidental pileup of close in time interactions

Results: historical review

❖ R704 at CERN-ISR (1984) proved the feasibility: clearly detected a sample of J/ψ, $\chi_{c1,2}$ ($\simeq 3$ pb^{-1})

❖ E760 at Fermilab (1990-91) ($\simeq 30$ pb^{-1})

Precise measurements of

- χ_{c1}, χ_{c2}, and J/ψ masses and widths

State	Mass(MeV/c^2)	Width (keV)
J/ψ	$3096.87 \pm 0.03 \pm 0.03$	$99 \pm 12 \pm 6$
χ_{c1}	$3510.53 \pm 0.04 \pm 0.012$	$880 \pm 110 \pm 80$
χ_{c2}	$3556.15 \pm 0.07 \pm 0.12$	$1980 \pm 170 \pm 70$

- ψ' width: $(306 \pm 36 \pm 16)$ keV
- coupling to $\bar{p}p$ of χ_{c1}, χ_{c2}, J/ψ, and ψ'
- measurement of the $\chi_{c2} \to \gamma\gamma$ partial width
- measurement of the η_c mass
- observation of a $h_c(^1P_1)$ candidate at 3526.2 MeV/c^2
- search for η_c'

❖ E835 at Fermilab '96 - '97 (143 pb^{-1})

- measurement of the χ_{c0} width and mass
- measurement of $\chi_{c0} \to \gamma\gamma$ and $\chi_{c2} \to \gamma\gamma$
- measurements of the η_c mass and width, and of the coupling $\eta_c \to \gamma\gamma$ (preliminary)

- η_c' search (preliminary)

❖ E835-2000 at Fermilab (2000) ($>$ 100 pb^{-1}, still taking data)

- accurate measurement of the χ_{c0} width and mass (preliminary)
- E835 and E835-2000 results are going to be presented

Event selection: inclusive J/ψ

Channels: $J/\psi + anything$ with J/ψ decaying to e^+e^-

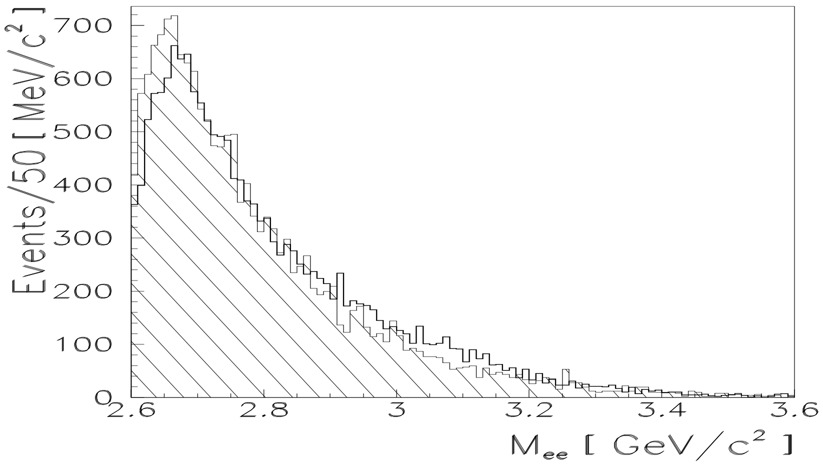
As an example, let's follow the selection for the decay chain :

$\bar{p}p \to \chi_{c0} \to J/\psi\gamma \to e^+e^-\gamma$

- Total $\bar{p}p$ cross section $\simeq 70$ mb
- Final state cross section from few pb to tens of nb $\to$ event reduction from 10^6 to 10^9

Hardware trigger:

- threshold Cherenkov to reject pions
- require two almost back to back large energy clusters in the Central Calorimeter or, in other words, a large e^+e^- invariant mass (≥ 2.2 GeV/c^2)



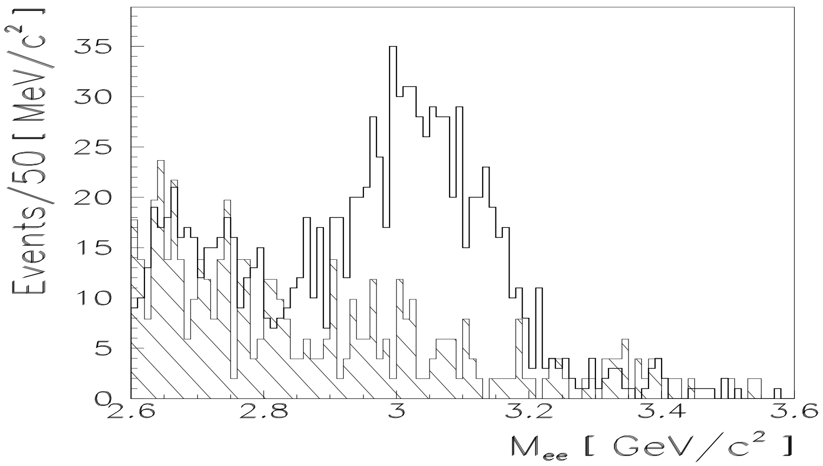
Distribution of the invariant mass between the two large energy clusters: no cut

Results: $J/\psi\gamma$ channel: Event selection

Software selection based upon:

➜ Electron identification (one against two electrons from γ conversion) based on:

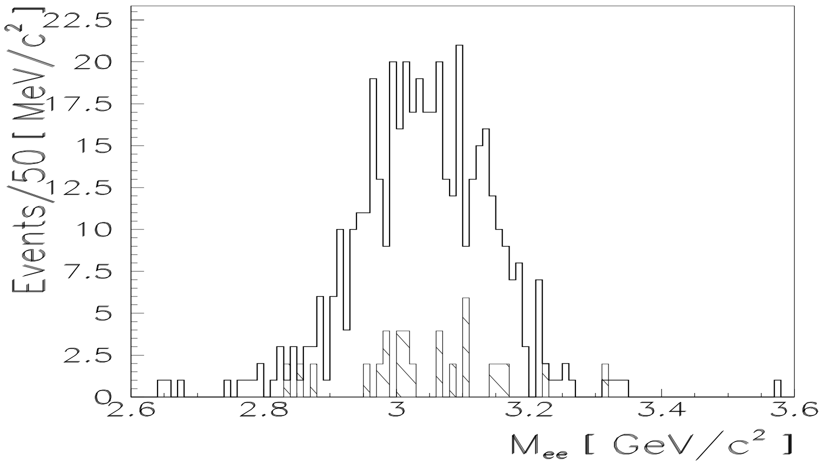
- ◇ dE/dx measured from the pulse heigths in the Hodoscopes
- ◇ Cherenkov pulse heigth
- ◇ the *transverse extension* of the shower shape in the Central Calorimeter



Distribution after Electron identification cut for events in the resonance region (unshaded area) and off-resonance (shaded area). Curves have been normalized to the same luminosity.

Results: $J/\psi\gamma$ channel: Event selection

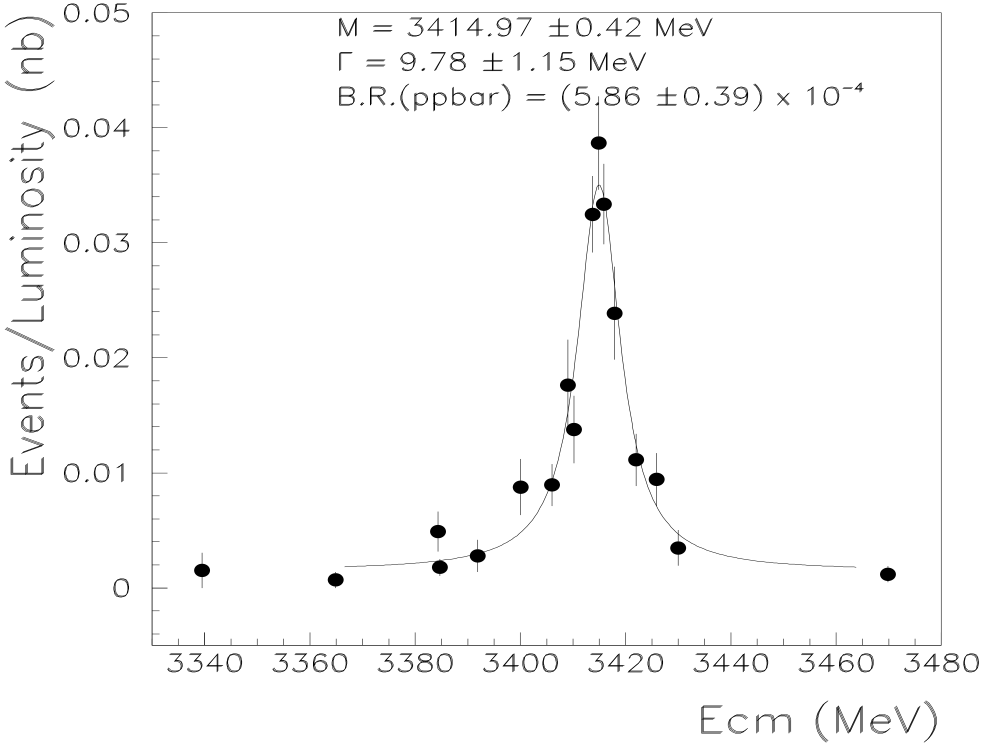
➜ Kinematical fit (5C): require a fit probability greater than 10^{-4}



Distribution after fit probability cut for events in the resonance region (unshaded area) and off-resonance (shaded area). Curves have been normalized to the same luminosity.

Results: χ_{c0} mass and width

Preliminary results: E835-2000

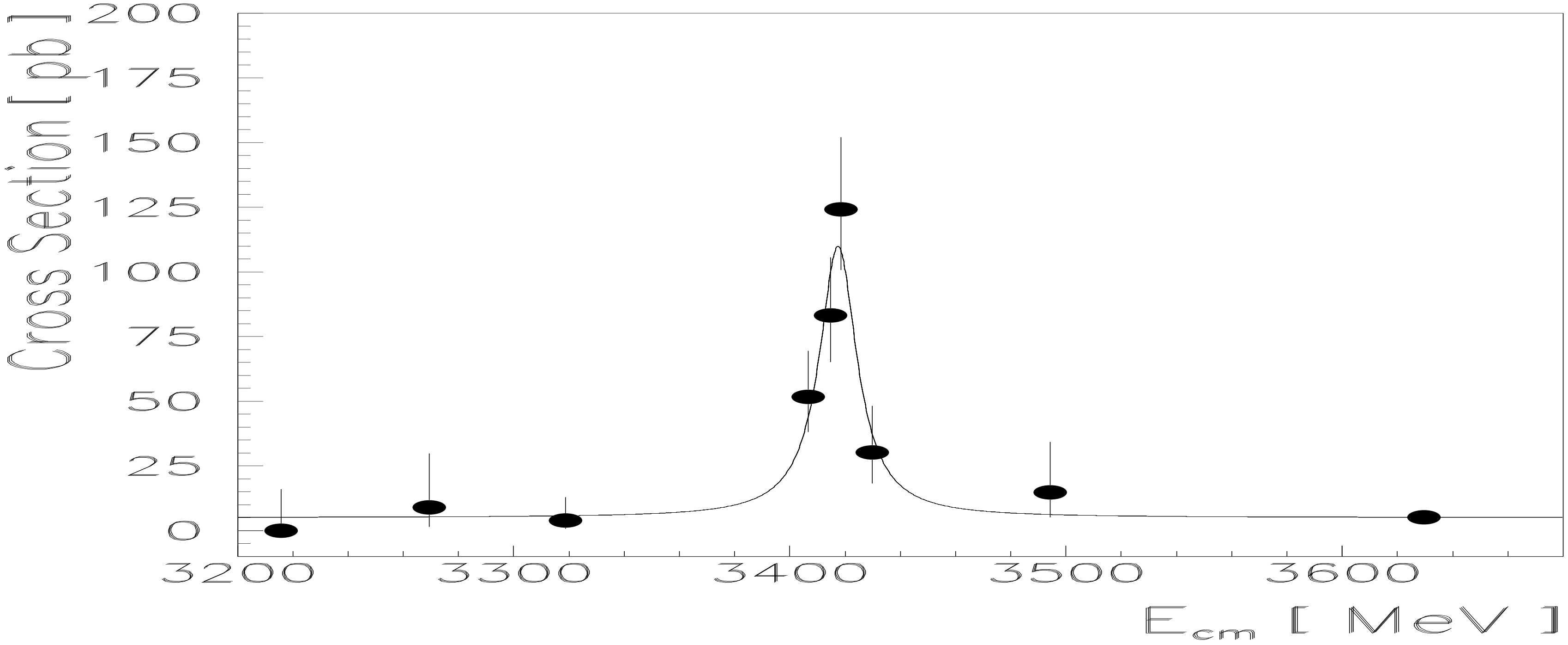


Fit of the measured cross section to a constant background plus a Breit-Wigner resonance using the Maximum Likelihood method to extract the resonance parameters: M, Γ, and $BR(\chi_{c0} \to \bar{p}p) \times BR(\chi_{c0} \to J/\psi\gamma)$

- geometrical acceptance $= 0.35 \pm 0.01$, trigger efficiency $= 0.90 \pm 0.02$, analysis efficiency $= 0.85 \pm 0.02$

Results: χ_{c0} mass and width

Results E835 '96 - '97



Results: χ_{c0} mass and width: Comparison

Preliminary results: E835-2000

Integrated luminosity:

- ◇ $\simeq 30pb^{-1}$ of which $\simeq 20pb^{-1}$ ($\simeq 400$ *events*) on the resonance (E835 - 2000)
- ◇ $\simeq 10pb^{-1}$ of which $\simeq 3.5pb^{-1}$ ($\simeq 70$ *events*) on the resonance (E835 - '96 - '97)

$M(\chi_{c0}) = 3414.97 \pm 0.42 \pm 0.2$ MeV/c^2 E835-2000

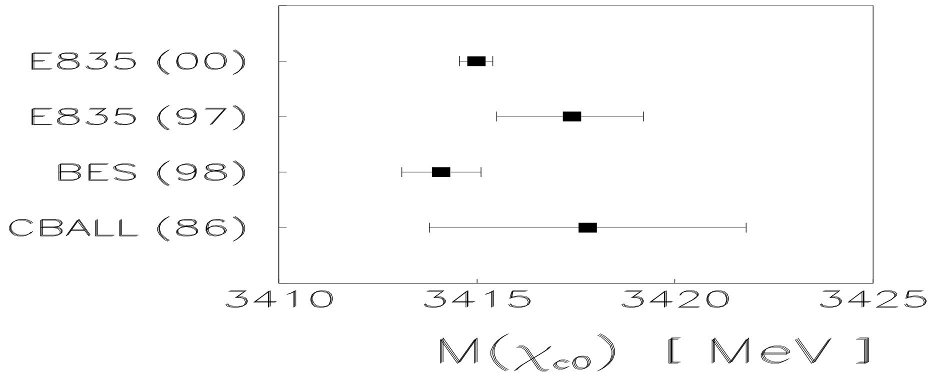
$M(\chi_{c0}) = 3417.4^{+1.8}_{-1.9} \pm 0.2$ MeV/c^2 E835 '96 - '97

$\Gamma(\chi_{c0}) = 9.78^{+1.22}_{-1.1} \pm 0.1$ MeV E835-2000

$\Gamma(\chi_{c0}) = 16.6^{+5.2}_{-3.7} \pm 0.1$ MeV E835 '96 - '97

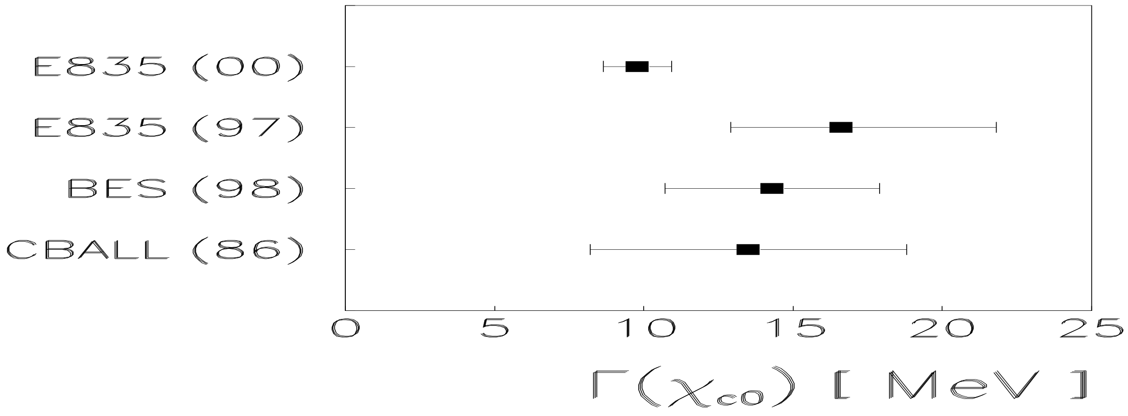
$BR(\bar{p}p \to \chi_{c0}) \times BR(\chi_{c0} \to J/\psi\gamma) \times BR(J/\psi \to e^+e^-\gamma) = 2.11^{+0.14}_{-0.13} \pm 0.11 \times 10^{-7}$
E835-2000

$BR(\bar{p}p \to \chi_{c0}) \times BR(\chi_{c0} \to J/\psi\gamma) \times BR(J/\psi \to e^+e^-\gamma) = 1.74^{+0.34}_{-0.28} \pm 0.09 \times 10^{-7}$
E835 '96 - '97



Results: χ_{c0} mass and width

Preliminary results: E835-2000



Taking from the literature:

$BR_{out} = BR(\chi_{c0} \to J/\psi\gamma) \times B(J/\psi \to e^+e^-) = 3.6 \pm 1.1 \times 10^{-4}$

leads to:

$B_{in} = BR(\chi_{c0} \to \bar{p}p) = 5.86^{+0.50+2.59}_{-0.49-1.36} \times 10^{-4}$

and: $\Gamma(\chi_{c0} \to \bar{p}p) = 5.72^{+0.88+2.52}_{-0.85-1.34} keV$

The $BR(\chi_{c0} \to \bar{p}p)$ (forbidden by massless QCD) is $\simeq 6$ times the $BR(\chi_{c1,2} \to \bar{p}p)$

[$BR(\chi_{c1} \to \bar{p}p) = (0.78 \pm 0.15) \times 10^{-4}$ and $BR(\chi_{c2} \to \bar{p}p) = (0.91 \pm 0.16 \times 10^{-4}$]

(continue) Results: χ_0

Preliminary results: E835-2000

$\frac{\Gamma(\chi_{c0} \to hadrons)}{\Gamma(\chi_{c2} \to hadrons)} = 5.65^{+0.70}_{-0.64}$

E835 '96 - '97 quoted $9.7^{+3.3}_{-2.5}$

Theoretical predictions give a results in the range from 8.1 to 9.7

assuming $\alpha_s = 0.33$

Results: $\gamma\gamma$ final state: Event selection

Process : $\bar{p}p \to \bar{c}c \to \gamma\gamma$ where $\bar{c}c$ stands for η_c, $\chi_{c0,2}$ or η'_c

Selection:

- two and only two clusters on time
- allow at most one time undetermined ⋆ cluster (< 40 MeV) if the invariant mass with any of the two above clusters is outside the π^0 region (100 - 170 MeV/c^2)
- kinematical fit (4C) with a probability larger than 5%

Background:

➤ $\pi^0\pi^0$ ($\pi^0\gamma$) final states where:

➜ 2 (1) γ from the π^0 decay is either undetected because:
➤out of acceptance/ below detection threshold in the calorimeters ($\simeq$ 20 MeV)
(main contribution to background)

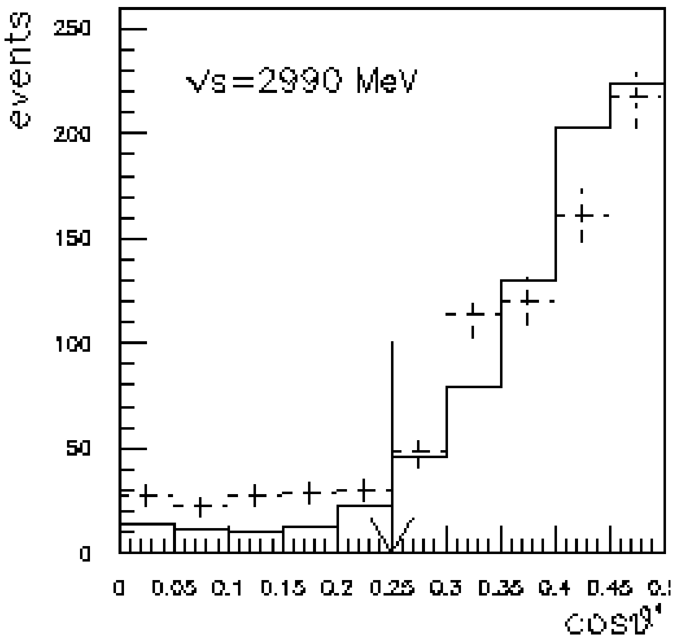
or:

➤ symmetric decay of the π^0 producing two overlapping photons (negligible contribution to background) ⋆ clusters are classified according to three categories: a)

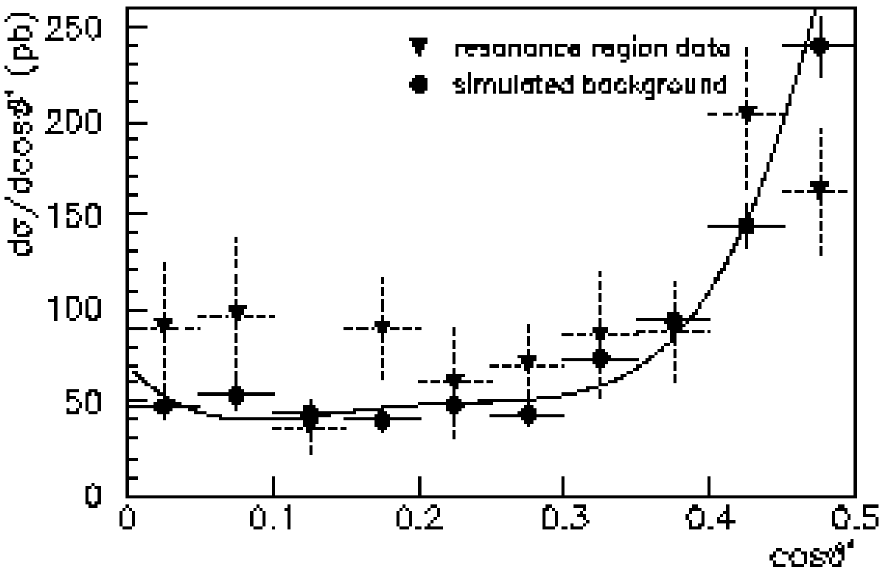
on-time : in a few nsec range from the event time; b) out-of-time; c) undetermined: no TDC information (below threshold)

Results $\gamma\gamma$ final states

Distribution of the center of mass decay angle of the $\gamma\gamma$ candidates



η_c region



χ region

Figure on the left: *crosses* are the experimental points and continuous line is the *feeddown* calculation results.

Figure on the right: full triangles are the experimental points and dots are the *feeddown* calculation results.

Results $\gamma\gamma$ final states: background comments

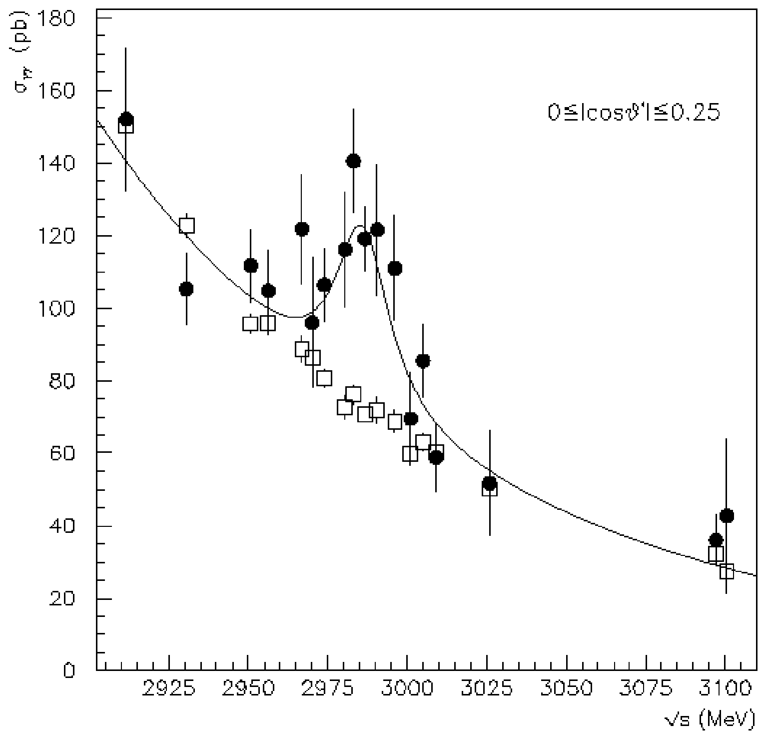
Background evaluation can be done in two ways:

- a) parametrization of the out of resonance points to the following formula (power law curve): $A(M_R/\sqrt{s})^B$
- b) 'feeddown calculation' : the shape of the background is evaluated starting from the $\pi^0\pi^0$ and $\pi^0\gamma$ cross-section and the actual overall level from data points out of the resonance

Results $\eta_c \to \gamma\gamma$

Preliminary results E835 '96 - '97

➤ cut at $\cos\theta_{cm} < 0.25$



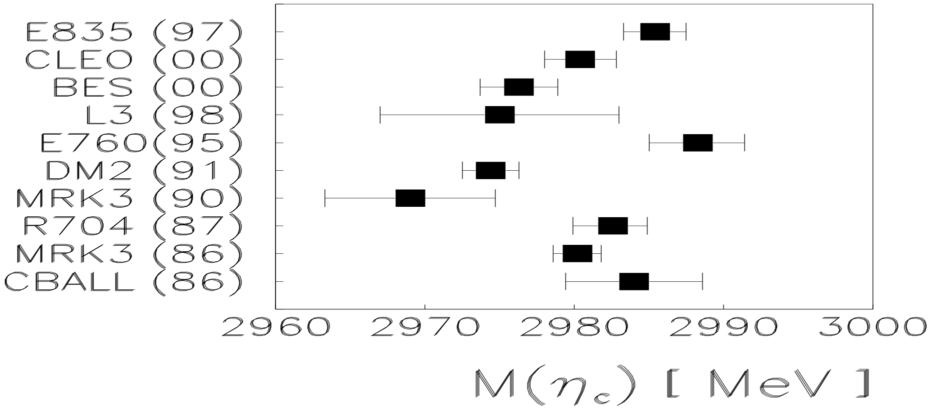
- fit to a resonance plus a continuum obtained from the 'feeddown' gives the following results:

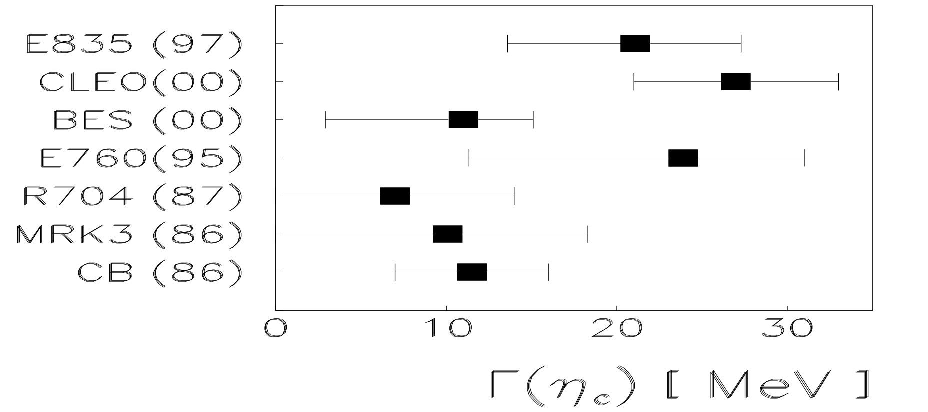
➤ Mass $= 2985.4 \pm 2.1$ MeV/c^2 ➤ Width $= 21.1^{+7.5}_{-6.2}$ MeV

➤ $\Gamma_{\gamma\gamma} = 3.9^{+1.5+1.8}_{-1.3-1.1}$ keV having taken $BR(\eta_c \to \bar{p}p) = (1.2 \pm 0.4) \times 10^{-3}$ from PDG

Results $\eta_c \to \gamma\gamma$: comments

Preliminary results E835 '96 - '97





Results $\eta_c \to \gamma\gamma$: comments

Preliminary results E835 '96 - '97

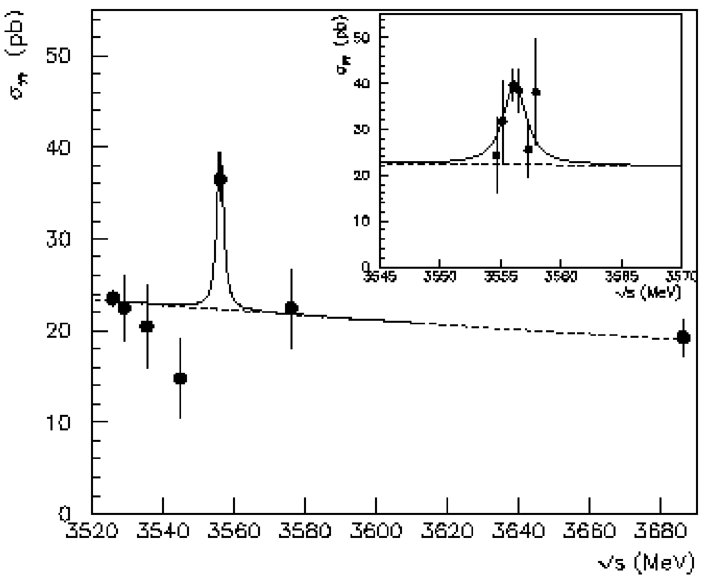
Using the perturbative QCD relations (first order approximation):

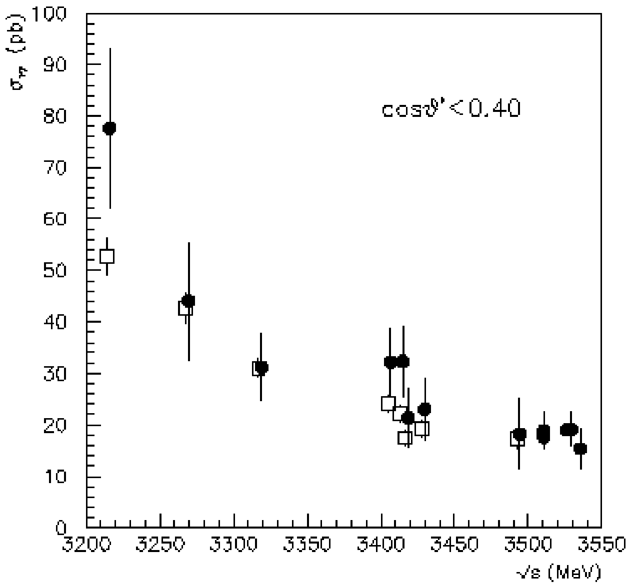
$$\frac{\Gamma(\eta_c \to gg)}{\Gamma(\eta_c \to \gamma\gamma)} \simeq \frac{\Gamma(\eta_c)}{\Gamma(\eta_c \to \gamma\gamma)} = \frac{9\alpha_s^2}{8\alpha^2} \times \frac{(1+4.8\alpha_s/\pi)}{(1-3.4\alpha_s/\pi)}$$

we derive $\alpha_s(m_c) = 0.33 \pm 0.02$

Results E835 '96 - '97

Measured $\gamma\gamma$ cross section for χ_2 and χ_0 with a cut at $\cos\theta^* < 0.4$





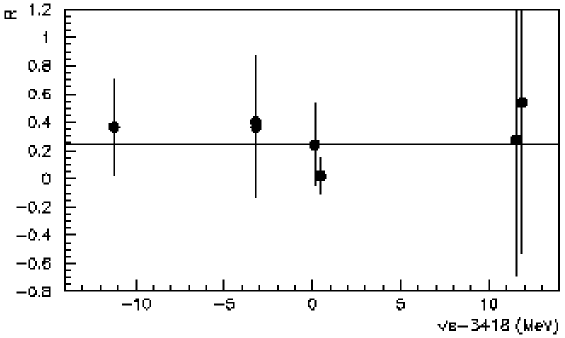
Results $\chi_{c0,2} \to \gamma\gamma$

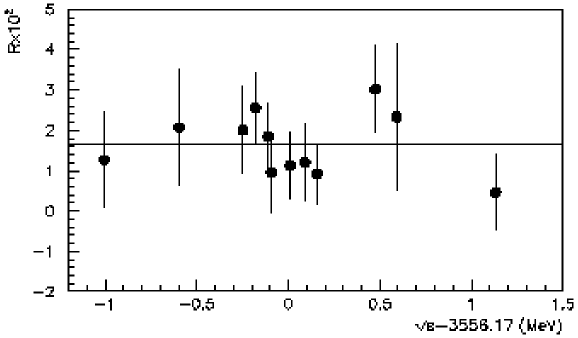
Results E835 '96 - '97

➤ $J/\psi\gamma$ and $\gamma\gamma$ decays are collected at the same time, thus some of the systematics can be cancelled out by considering:

$$R = \frac{(N^{res}_{\gamma\gamma} - N^{bckgd}_{\gamma\gamma})/\epsilon_{\gamma\gamma}}{(N^{res}_{J/\psi\gamma} - N^{bckgd}_{J/\psi\gamma})/\epsilon_{J/\psi\gamma}} = \frac{BR(\gamma\gamma)}{BR(J/\psi\gamma)}$$

where ϵ is the product of acceptance times efficiency for each channel



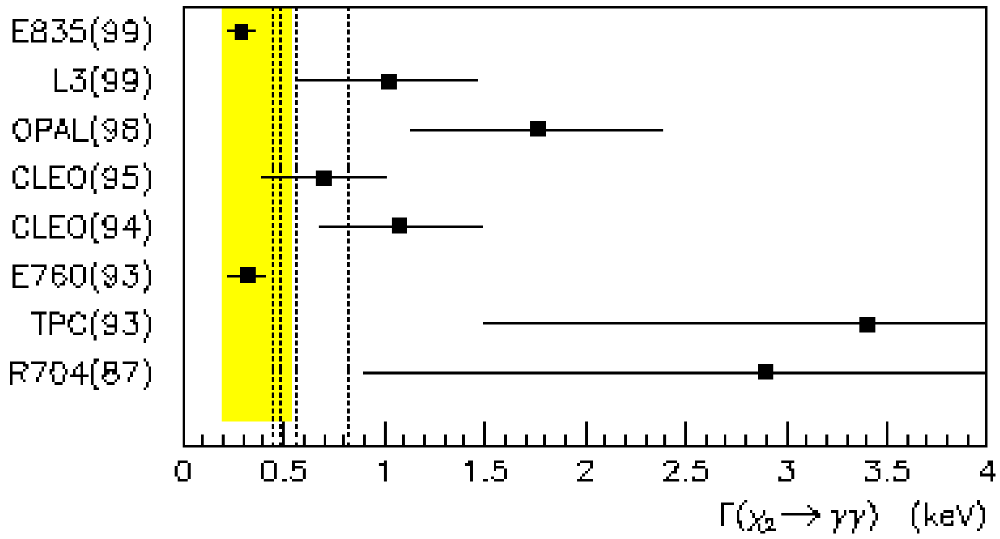


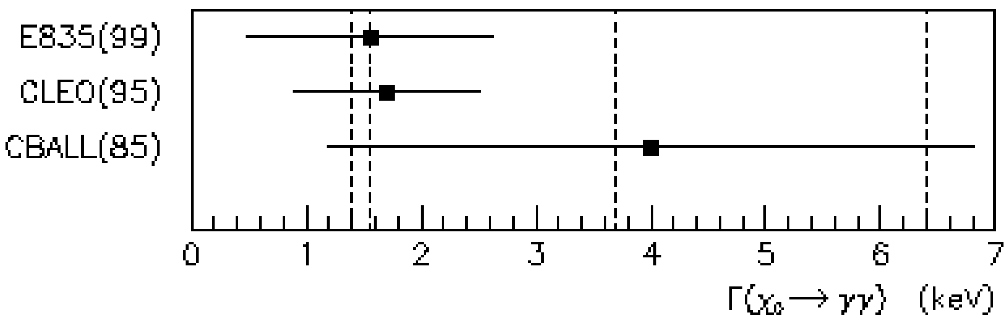
	χ_{c0}	χ_{c2}
$< R >$	$(0.244 \pm 0.125) \times 10^{-4}$	$(1.67 \pm 0.30) \times 10^{-4}$
$BR(\gamma\gamma)$	$(0.97 \pm 0.50 \pm 0.28) \times 10^{-4}$	$(1.35 \pm 0.25 \pm 0.12) \times 10^{-4}$
$\Gamma_{\gamma\gamma}$	$(1.61 \pm 0.83 \pm 0.65)$ keV	$(270 \pm 49 \pm 33)$ eV

For the χ_{c0} the corresponding upper limits are $< 2.09 \times 10^{-4}$ (95% C.L.) for the branching ratio and < 3.47 keV (95% C.L.) for the partial width.

Results $\chi_{c0,2} \rightarrow \gamma\gamma$: comparison

Results E835 '96 - '97





Results $\chi_{co,2} \rightarrow \gamma\gamma$

Results E835 '96 - '97

From the results here presented:

➤ $\alpha_s(m_c)$ can be derived from the first order radiative correction formulas:

$$\frac{\Gamma(\chi_{c2}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to gg)} = \frac{(36/5)e_c^4\alpha^2|R'_{nP(0)}|^2/m_Q^2}{(8/5)\alpha_s^2|R'_{nP(0)}|^2/m_Q^2)\times(1+8.4\alpha_s/\pi}$$

which gives $\alpha_s(m_c) = 0.38 \pm 0.02$

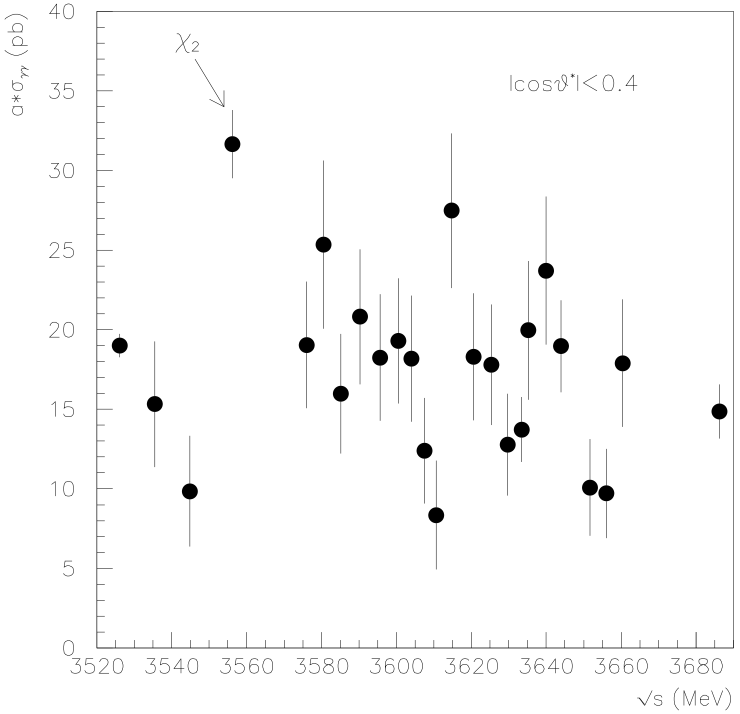
Concerning $\chi_{c0} \rightarrow \gamma\gamma$: E835-2000 has collected 6 times more statistics and analysis is underway

Results $\eta_c' \to \gamma\gamma$

Preliminary results E835 '96 - '97

E835 performed a search of the η_c' through the process: $\bar{p}p \to \eta_c' \to \gamma\gamma$

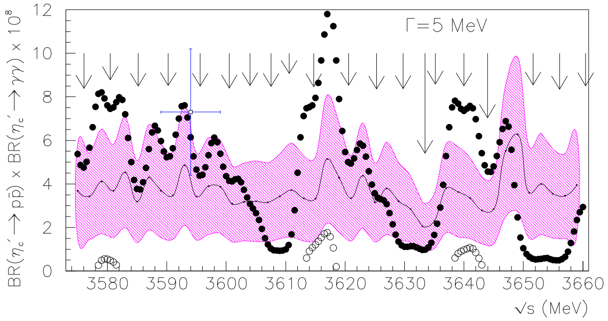
- ➜ data taken in the center of mass energy region between 3576 and 3660 MeV
- ➜ 20 points almost equally spaced (5 MeV) with an average luminosity of 1.5 pb^{-1} per point
- ➜ cut at $\cos\theta^* < 0.4$

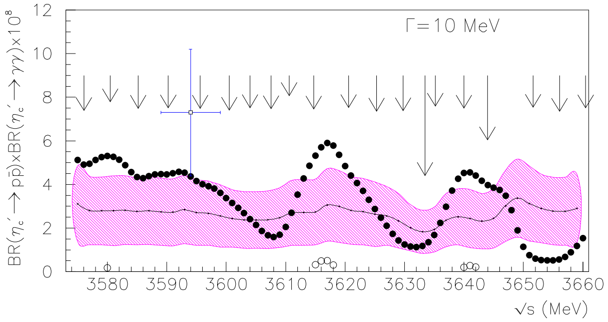


Results $\eta_c' \to \gamma\gamma$

Preliminary results E835 '96 - '97

The upper limit of $BR(\bar{p}p \to \eta_c') \times BR(\eta_c' \to \gamma\gamma)$ at 90 % CL is shown for $\Gamma = 5$ and 10 MeV as a function of the resonance mass (dots).





$\chi_{1,2}$ angular distributions: introduction

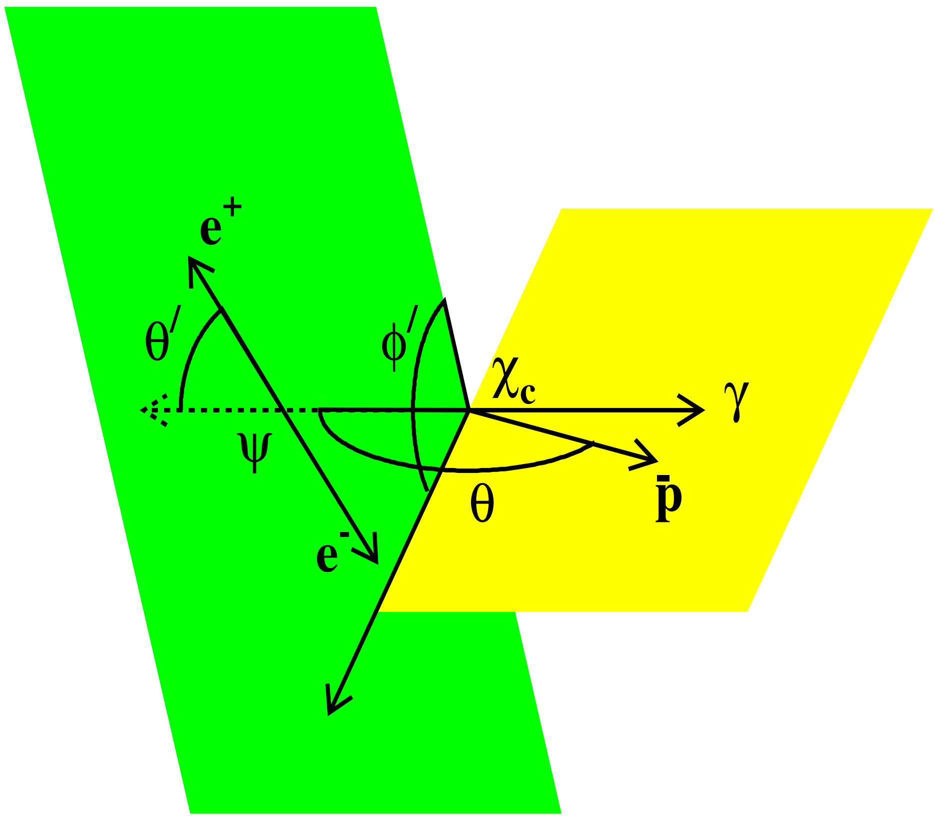
Preliminary results E835 '96 - '97

Angular distribution analysis allows:

- from the production channel ($\bar{p}p \to \chi_{1,2}$) one can probe the helicity selection rules
  Parameters to describe the formation process:
  $B_{|\lambda\bar{p}-\lambda p|}$ where $\lambda\bar{p} - \lambda p$ is the helicity component ($\chi_{1,2}$ spin) along the $\bar{p}$ direction
- ◇ $B_0^2 + 2B_1^2 = 1$
- from the decay channel ($\chi_{1,2} \to J/\psi\gamma \to e^+e^-$) one can measure the multipole relative contributions (electric dipole E1, magnetic quadrupole M2, electric octupole E3)
  Parameters to describe the decay process:
  $A_{|\lambda\psi-\lambda\gamma|}$ where $\lambda\psi - \lambda\gamma$ is the $\chi_{1,2}$ spin projection along the ψ direction :
  A_0, A_1, A_2
- ◇ A_0, A_1, A_2 can be expressed in terms of the multipole expansion parameters:
  a_1, a_2, a_3
- ◇ $a_1^2 + a_2^2 + a_3^2 = 1$

$\chi_{1,2}$ angular distributions: introduction

Angle definitions:

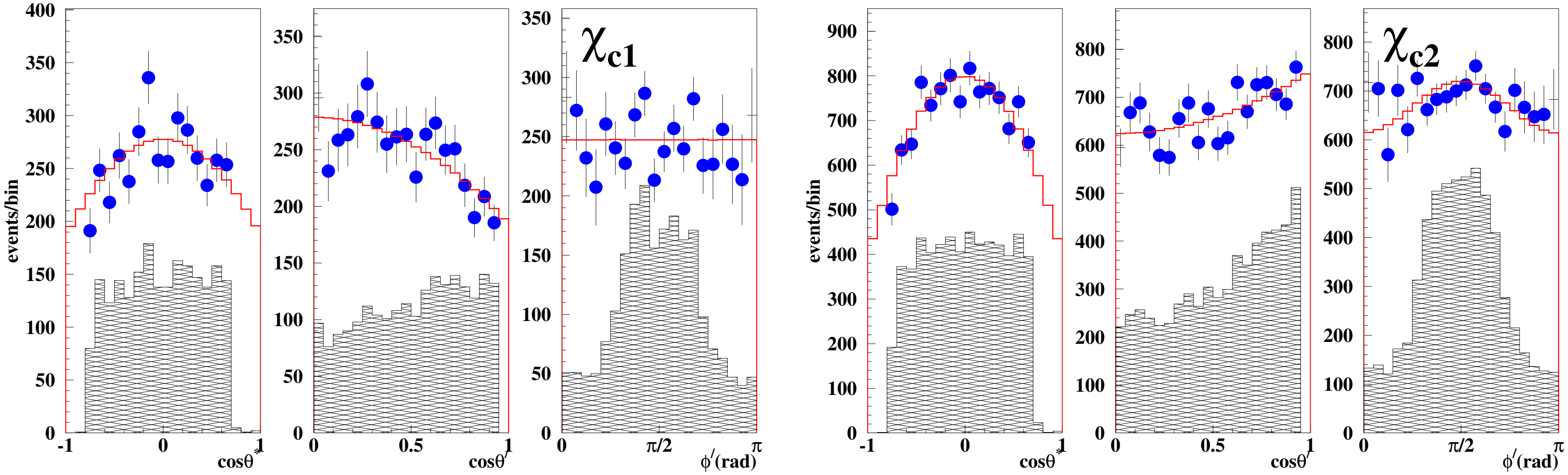


$\chi_{1,2}$ angular distributions: results

Preliminary results E835 '96 - '97

From a sample of 2144 χ_1 and 6028 χ_2 with a unbinned Maximum Likelihood analysis we obtained:

- χ_1 : $a_2 = 0.011^{+0.032}_{-0.031}$
- χ_2 : $a_2 = -0.107^{+0.049}_{-0.047}$, $a_3 = 0.014^{+0.046}_{-0.038}$, and $B_0^2 = 0.097^{+0.090}_{-0.093}$



a_2 value depends on the anomalous magnetic moment κ_c of the $c-$quark

As usual the ratio $a_2(\chi_1)/a_2(\chi_2)$ should be less affected from the calculation approximations: the predicted theoretical value is $+0.67$ where we derived -0.10 ± 0.31.

Conclusions

The experiment (E835 at Fermilab) to study the charmonium states in $\bar{p}p$ formation process has measured several parameters.

A preliminary list includes:

- mass and width of the χ_{c0} and η_c precisely measured
- ◇ better constraints for the $\bar{c}c$ potential models
- Branching ratios and $\gamma\gamma$ partial widths of χ_{c0}, χ_{c2}, and η_c
- ◇ verify some of the PQCD predictions
- ➜ Future analyses on several possible final states [we took data with a suitable hardware/software trigger]:
- $\phi\phi \rightarrow K^+K^-K^+K^-$ and $\phi\phi\gamma \rightarrow K^+K^-K^+K^-\gamma$
- multi-gamma as $\eta\eta$, $\eta\pi^0$, etc..