III International Conference
Hyperons, Charm and Beauty Hadrons
JUNE 30th - JULY 3rd, 1998 - PALAZZINA SAN LORENZO, PORTO ANTICO - GENOVA (ITALY)

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

Marco Pallavicini
University and I.N.F.N. Genova

on behalf of Fermilab E835 Collaboration:

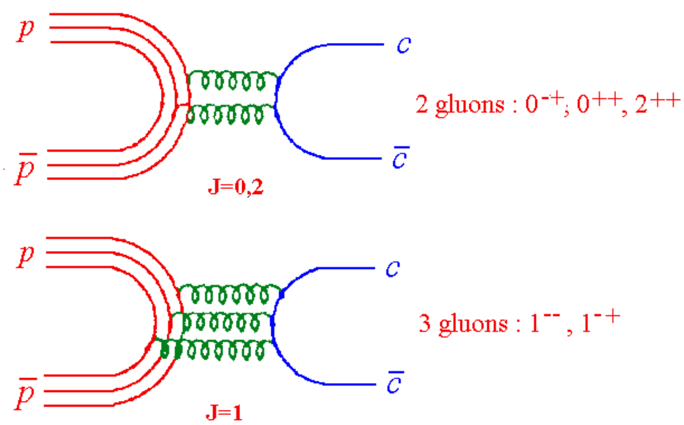
Fermilab
University and I.N.F.N. Ferrara
University and I.N.F.N. Genova
University of California at Irvine
Northwestern University
University and I.N.F.N. Torino

Talk overview

- Physical motivations for $\bar{p}p$ annihilations in charmonium spectroscopy and open problems
- Experimental technique
- Antiproton Accumulator and E835 Detector Layout
- Results from 1996/1997 fixed target run
- Comparison with previous measurements
- Future perspectives and conclusions

Physics motivations

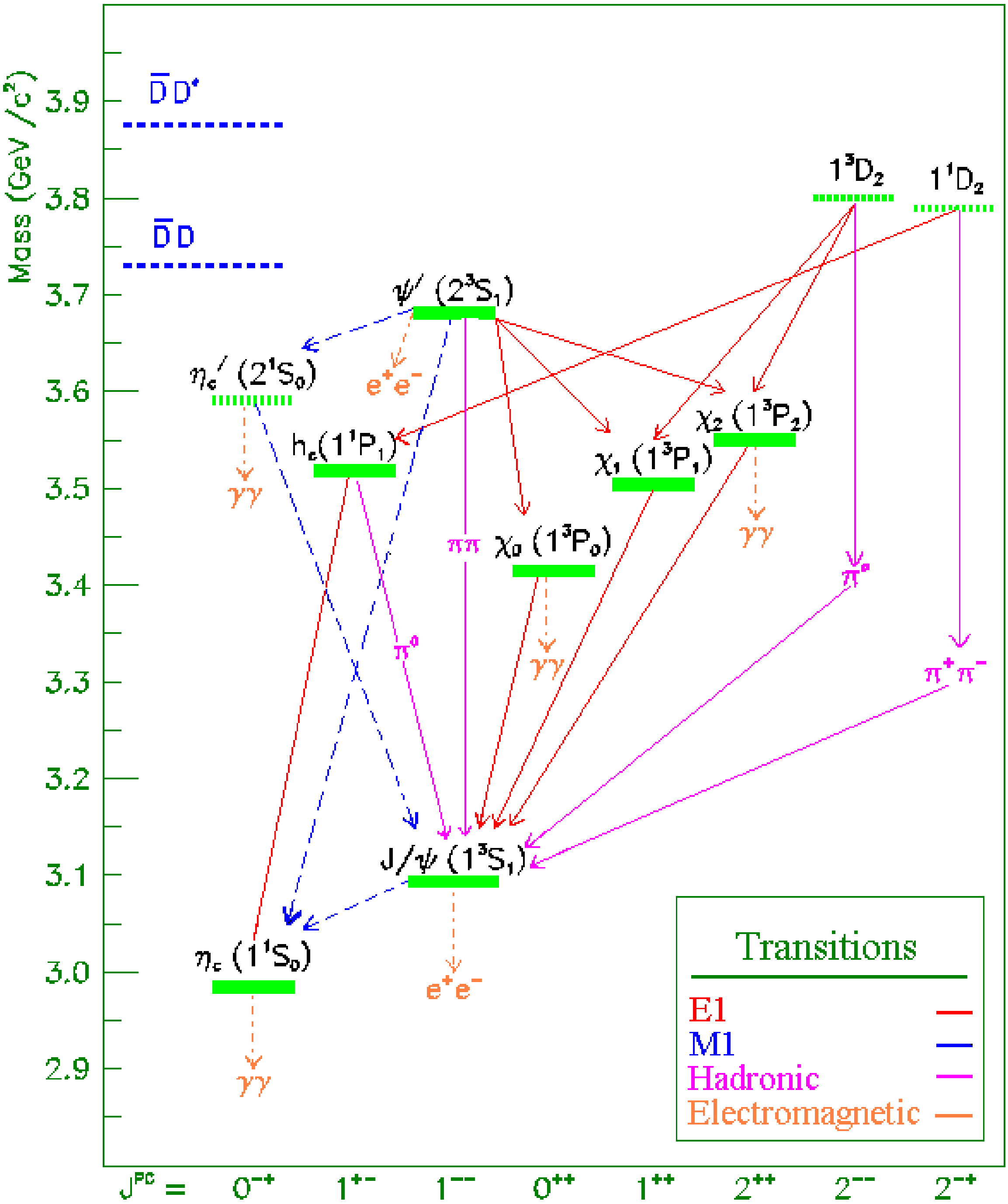
- Charmonium states have been studied for 25 years at e^+e^- colliders, in production at fixed target spectrometers and using $\bar{p}p$ annihilations.
- **Why $\bar{p}p$?**
  - All charmonium states can be formed.



    - **$e^+ e^-$:** Only 1^{--} states are directly accessible. χ_c and η_c only from cascade decays of ψ'; η'_c and $^1P_1$ unobserved or very poorly studied
    - Production at fixed target: all states are produced but mass and width resolution depends on detetector
  - Resonance mass and width are determined from beam parameters and do not depend on detector energy-momentum resolution.
    - The $\bar{p}$ beam quality is crucial
  - There is a clean electromagnetic signal over the large hadronic background even if $\bar{p}p$ coupling to $\bar{c}c$ is small.

$$\sigma\left(p\bar{p} \to hadrons\right) \approx 70\ mb$$
$$\sigma\left(p\bar{p} \to \bar{c}c\right) \approx 5\ \mu b$$
$$\sigma_{eff}\left(p\bar{p} \to J/\psi \to e^+e^-\right) \approx 25\ nb$$

Charmonium spectrum

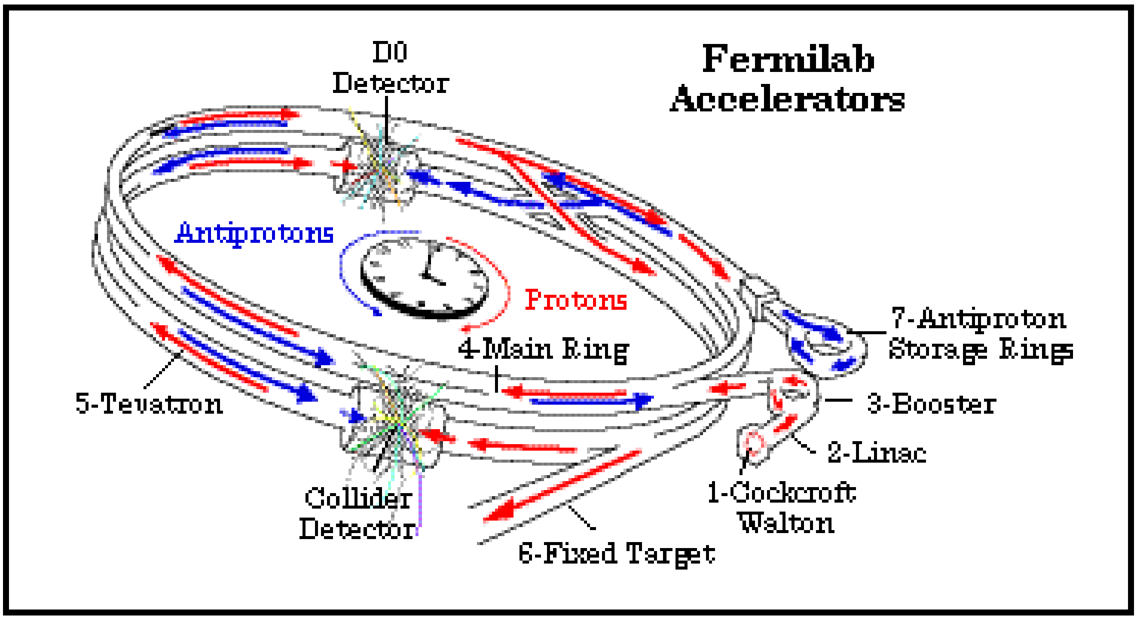


Previous experiments and E835

- Charmonium spectroscopy in $\bar{p}p$ annihilations was pioneered by CERN experiment R704 at ISR in mid-80s.
  - R704 proved that the experiment was feasible with an internal hydrogen jet target.
  - It produced the first measurements of χ_{c1} and χ_{c2}
- Fermilab experiment E760 has collected 35 pb^{-1} of integrated luminosity in 1990 and 1991.
  - First evidence of $^1P_1$ state.
  - Precise measurement of χ_{c1} and χ_{c2} masses and widths.
  - First direct observation of η_c in $\bar{p}p$ annihilations
- Experiment E835 has continued E760 program collecting 150 pb^{-1} and achieving:
  - The first observation of χ_{c0} in $\bar{p}p$ annihilations.
  - Precise measurement of η_c parameters
  - Extensive search for η'_c
  - Improved χ_{c1} and χ_{c2} angular distributions
  - Improved ψ' branching ratios measurement
  - Proton form factor in time like region
  - $\pi^0\pi^0$ cross section

Experimental Technique
The Source

- Proton anti-proton annihilations are obtained by intersecting the cooled $\bar{p}$ beam of the Fermilab Antiproton Accumulator with a molecular hydrogen jet target.
  - Small beam energy spread : $\Delta p/p \sim 2\ 10^{-4}$
  - Minimum center of mass energy step ~ 250 KeV, to be compared to charmonium widths ranging from ~100 KeV to ~ 10 MeV
  - High intensity. Beam current up to 60-80 *mA*, corresponding to $6\text{-}8\ 10^{11}$ $\bar{p}$ circulating
  - Good compensation for *dE/dx* in the target by stochastic cooling



Experimental technique
Beam energy measurement

- Beam energy is measured from beam revolution frequency and reference orbit length:

$$\beta c = L_{REF} f_{REV} \qquad E_{\bar{p}} = \frac{m_p c^2}{\sqrt{1-\left(f_{REV} L_{REF} / c \right)^2}}$$

$$\Delta E_{\bar{p}} = m_p c^2 \gamma_{\bar{p}}^3 \beta_{\bar{p}}^2 \left[\left(\frac{\Delta f}{f} \right)^2 + \left(\frac{\Delta L_{ORB}}{L_{ORB}} \right)^2 \right]^{1/2}$$

- Beam revolution frequency is well measured : $\Delta f/f \sim 10^{-7}$
- ΔL_{ORB} is the dominant source of error
- L_{REF} measured from ψ' peak position (known up to *100 KeV*).

BEAM ENERGY CALIBRATION

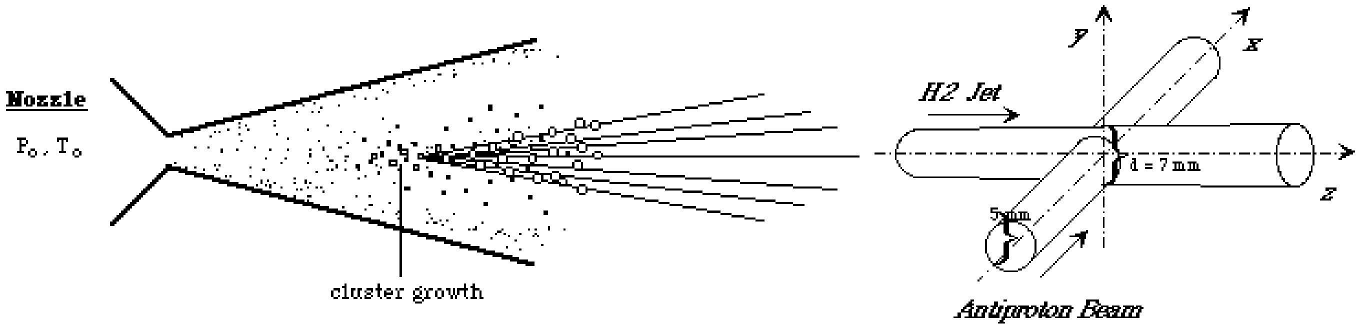
$$L_{REF} = \beta c / f_{REV} \qquad \Delta m_{\psi'} = \pm 100 KeV \Rightarrow \Delta L_{REF} = 0.67 mm$$

- At each energy point we measure: $\beta c = \left(L_{REF} + \Delta L \right) f$

48 Beam Position Monitors to measure the distance between reference orbit and real orbit

Experimental technique
The Target

- The proton target is done with a molecular hydrogen jet made up of microdroplets (clusters) formed inside a trumpet shaped nozzle at temperature (T~35°K) and pressure (P~1 bar) near saturation.



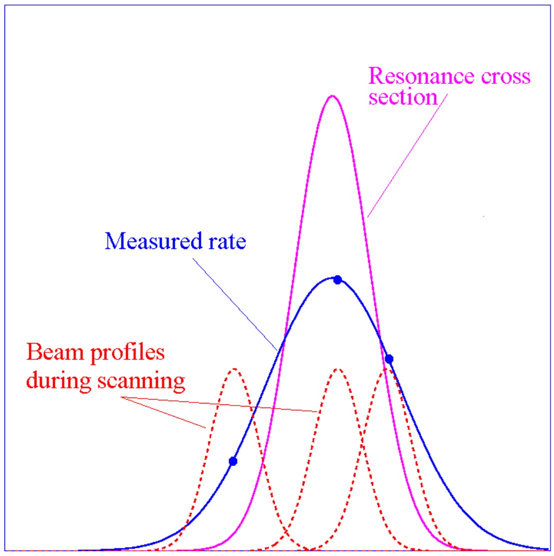
- Main features
  - Well localized target : ~ 0.5 x 0.5 x 0.5 cm^3
  - Large target density. Instantaneous luminosity has been limited by DAQ to 2.5 10^{31} cm^{-2} s^{-1}
  - Density control and beam current feedback to be able to run at constant luminosity
  - Motorized nozzle for allignment
  - Very efficient use of $\bar{p}$

Experimental technique
Resonance Scan

- Each charmonium state is studied by changing E_{beam} (E_{cm}) in small steps (~ 250 KeV in c.m.)
- Detection of charmonium formation through electromagnetic final states
- All beam parameters are known: orbit length and frequency spectrum is recorded

$$\frac{\#ev.}{\int L dt} = \varepsilon\alpha \int_0^\infty f_B\left(E-\sqrt{s}\right)\sigma_{BW}(E)dE + \sigma_B$$

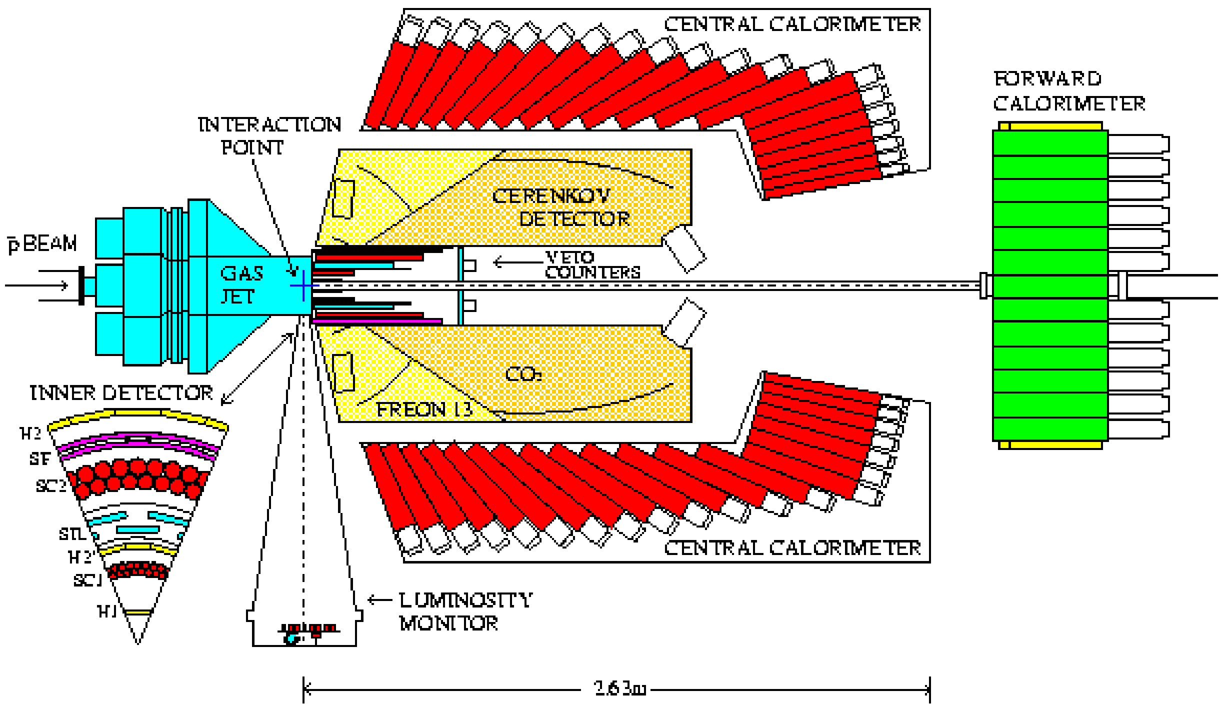
$$\sigma_{BW} = \frac{(2J+1)\pi}{4k^2}\frac{B\left(p\bar{p}\to R\right)B(R\to f)\Gamma_R^2}{\left(\sqrt{s}-M_R\right)^2+\frac{\Gamma_R^2}{4}}$$



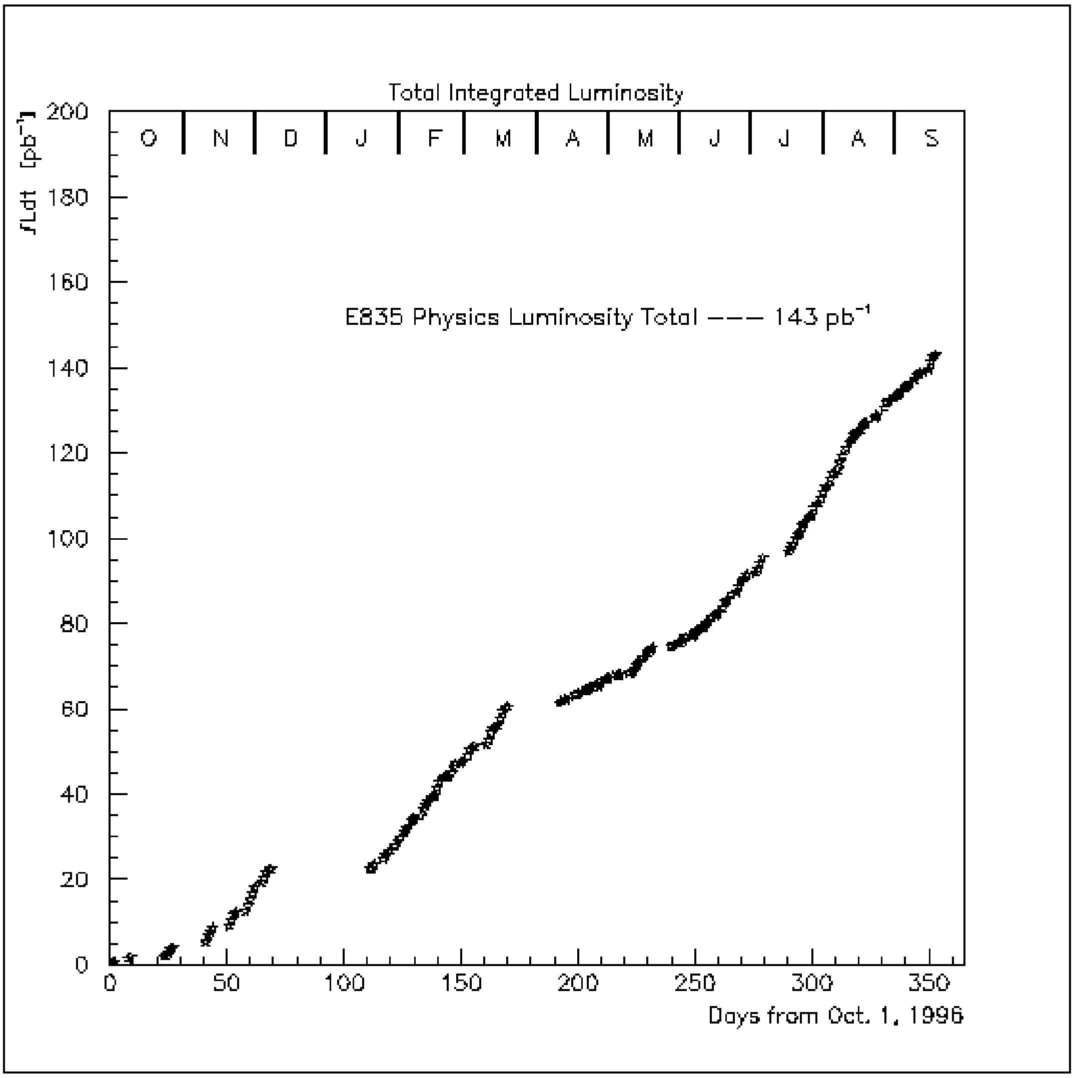
- *M_R, Γ_R and $BR_{in}xBR_{out}$* are extracted from the excitation curve using maximum likelihood fit. *M_R* depends on beam energy calibration only. *Γ_R* on energy spectrum width. *$BR_{in}xBR_{out}$* needs efficiency and acceptance estimate.

E835 detector

$$p\bar{p} \rightarrow c\bar{c} \rightarrow e^+e^-$$
$$p\bar{p} \rightarrow c\bar{c} \rightarrow J/\psi\ X \rightarrow e^+e^- X$$
$$p\bar{p} \rightarrow c\bar{c} \rightarrow \gamma\gamma$$
$$p\bar{p} \rightarrow multi \quad \gamma$$
$$p\bar{p} \rightarrow \phi\phi \rightarrow K^+K^-K^+K^-$$
$$p\bar{p} \rightarrow p\bar{p}$$

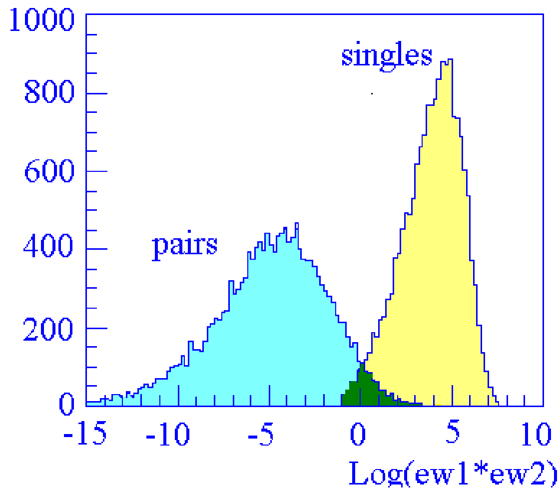


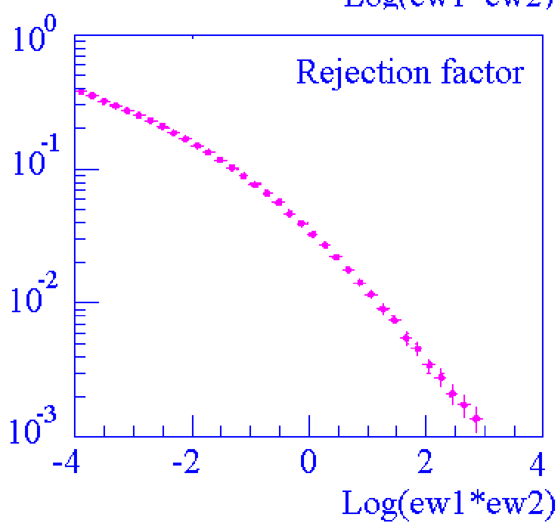
Total Integrated Luminosity



Event selection for e^+e^- exclusive and inclusive events

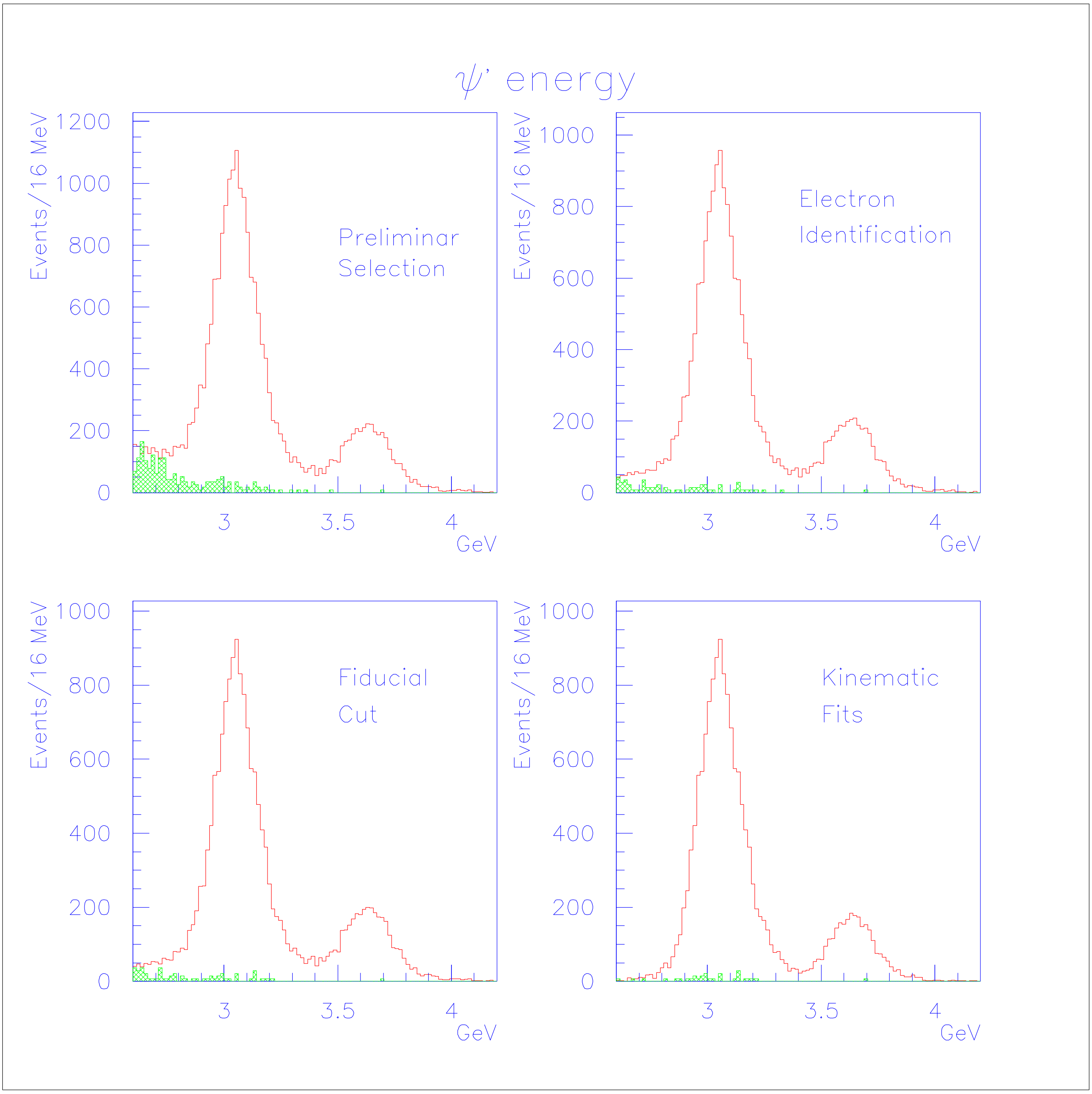
- Hardware 1st level trigger: candidate events are selected requiring two electrons (defined by scintillators and Cerenkov counter concidences) and two high invariant mass CCAL clusters (> 2 GeV).
- Online software filter selects “golden” candidates by requiring an inclusive invariant mass above 2.4 GeV
- Event selection is based on electron id, event topology, timing and kinematic fit.





- Electron i.d. is done using 8 variables from hodoscope counters dE/dx, Cerenkov photoelectrons, CCAL cluster shape variables. Background can be reduced to a few *pb* while keeping efficiency around 85%
- CCAL cluster timing (TDC) is used to reject pile-up clusters due to high intensity
- Event topology and kinematic fit are used to classify final states

Event selection at the ψ' energy



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

- We have gathered ~ 3.5 pb^{-1} on resonance (E_{cm} = 3406-3430 MeV) and ~ 1.8 pb^{-1} off resonance (E_{cm} = 3270, 3320 and 3495 MeV)
- We performed two different analysis to search evidence for the resonant process:

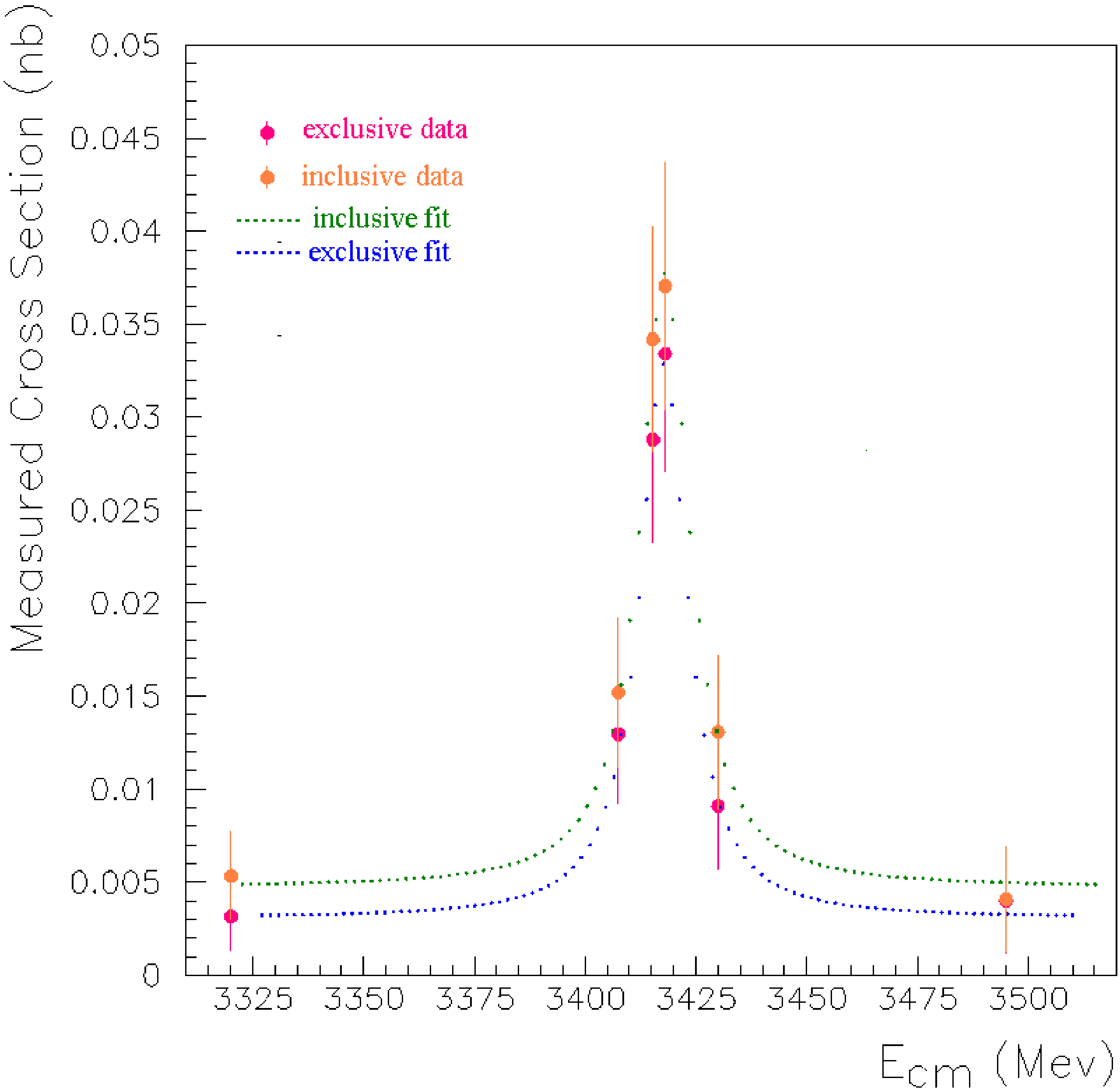
$$\boxed{p\bar{p} \to \chi_0 \to J/\psi\gamma \to e^+e^-\gamma}$$

  - A inclusive J/ψ analysis ignoring γ
  - B exclusive $J/\psi\,\gamma$ analysis

Event Selection

- 2 good electrons $15° < \theta < 60°$ and $2.75 < M_{ee} < 3.35$ GeV
- at most one CCAL cluster "on time" E > 50 MeV and $3° < \theta < 68°$
- if $E_g < 100$ MeV, $\alpha_{OP}(e^{\pm}, \gamma) < 10°$ are discarded to remove background from bremmstrahlung
- inclusive or exclusive kinematic fit probability

First observation of χ_0 in $\bar{p}p$ annihilations (2)



<u>*Preliminary* Fit Results</u>

$$\textit{Mass} \quad 3417.9^{+1.7}_{-1.8} \ \textit{MeV} \qquad \textit{Width} \quad 15.0^{+4.9}_{-3.6} \ \textit{MeV}$$

Form factor

- We have performed the only measurement of the proton form factor in the time-like region above $6\ GeV^2$ by measuring the non-resonant cross section

$$p\bar{p} \to e^+ e^-$$

- First order QED predicts

$$\frac{d\sigma}{d(\cos\theta^*)} = \frac{\pi\alpha^2\hbar^2c^2}{2xs}\left[|G_M|^2\left(1+\cos^2\theta^*\right)+\frac{4m_p^2}{s}|G_E|^2\left(1-\cos^2\theta^*\right)\right]$$

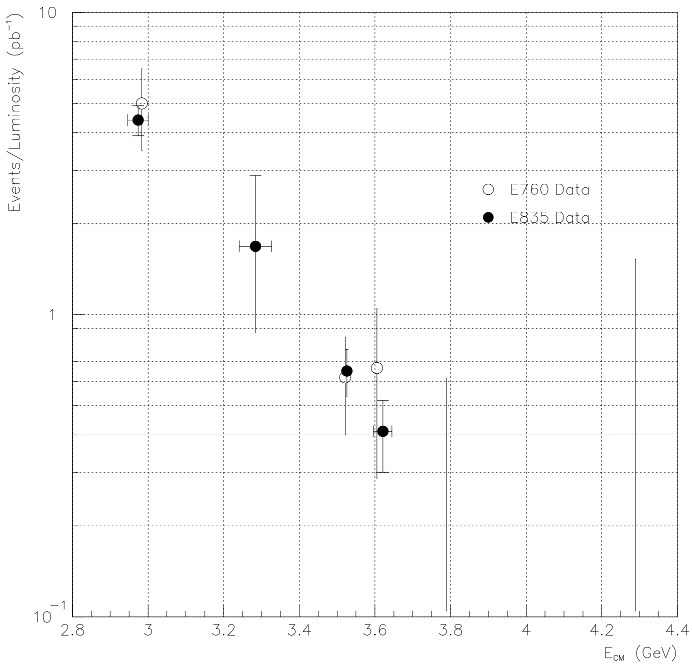
- Background from $\pi^0\pi^0$, $\pi^0\gamma$, $\gamma\gamma$ and $\pi^+\pi^-$ has been carefully evaluated and is negligible
- We could not measure the angular distribution beacuse of lack of statistics and geometrical acceptance. The form factors are extracted from the data assuming the following two different hypothesis:

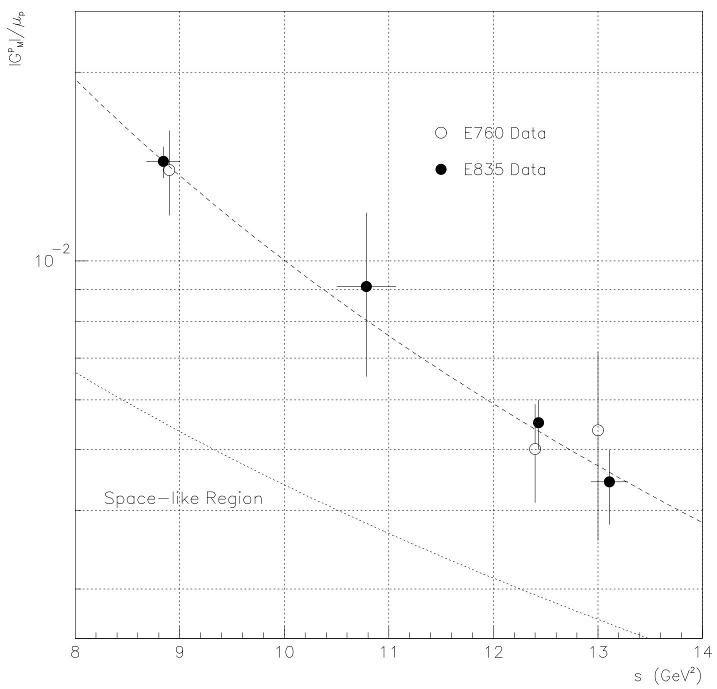
a) $|G_E|=|G_M|/\mu_p$
b) $|G_E|$ is assumed negligible

$$\frac{|G_M|}{\mu_p} = \frac{C}{s^2\ln\left(s^2/\Lambda^2\right)}$$

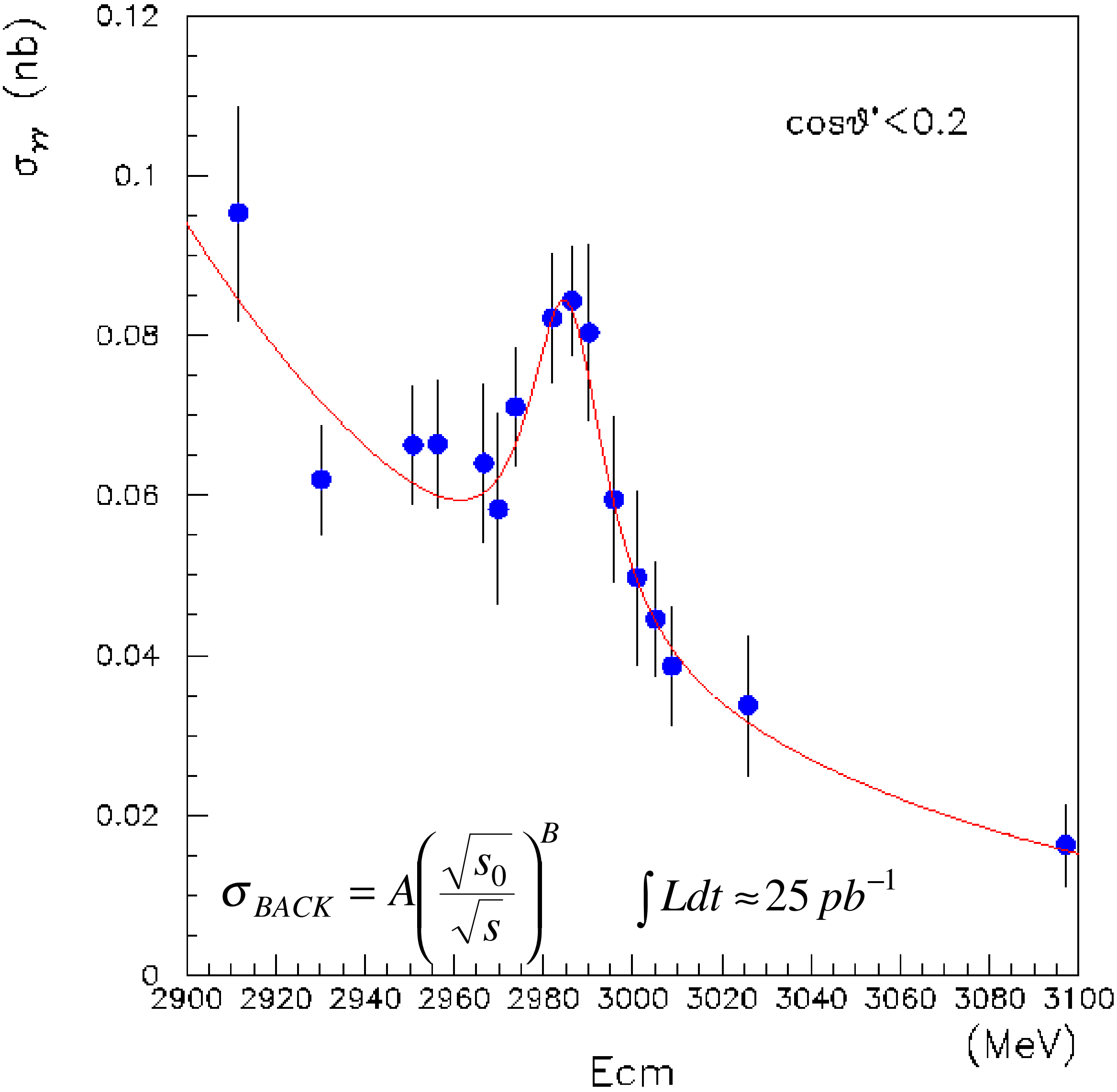
C and Λ free parameters

Form factor (*preliminary*)





$\eta_c \rightarrow \gamma\gamma$ (*preliminary*)

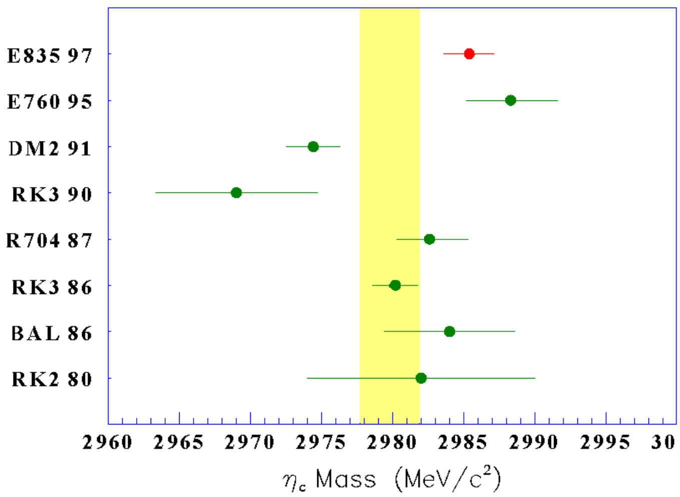


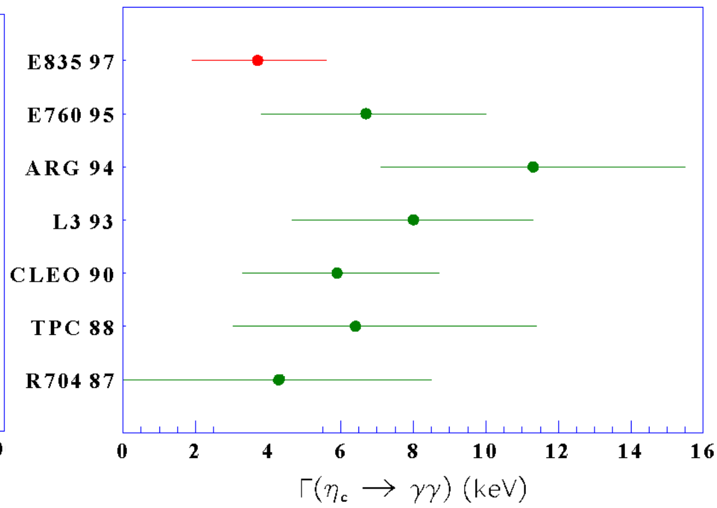
Event selection

- 2 On Time clusters. No on time extra clusters
- Reject events with internal π^0 and η
- Invariant mass > *3 GeV* and *cos(θ*)<0.2*
- Kinematic fit probability > 10 %

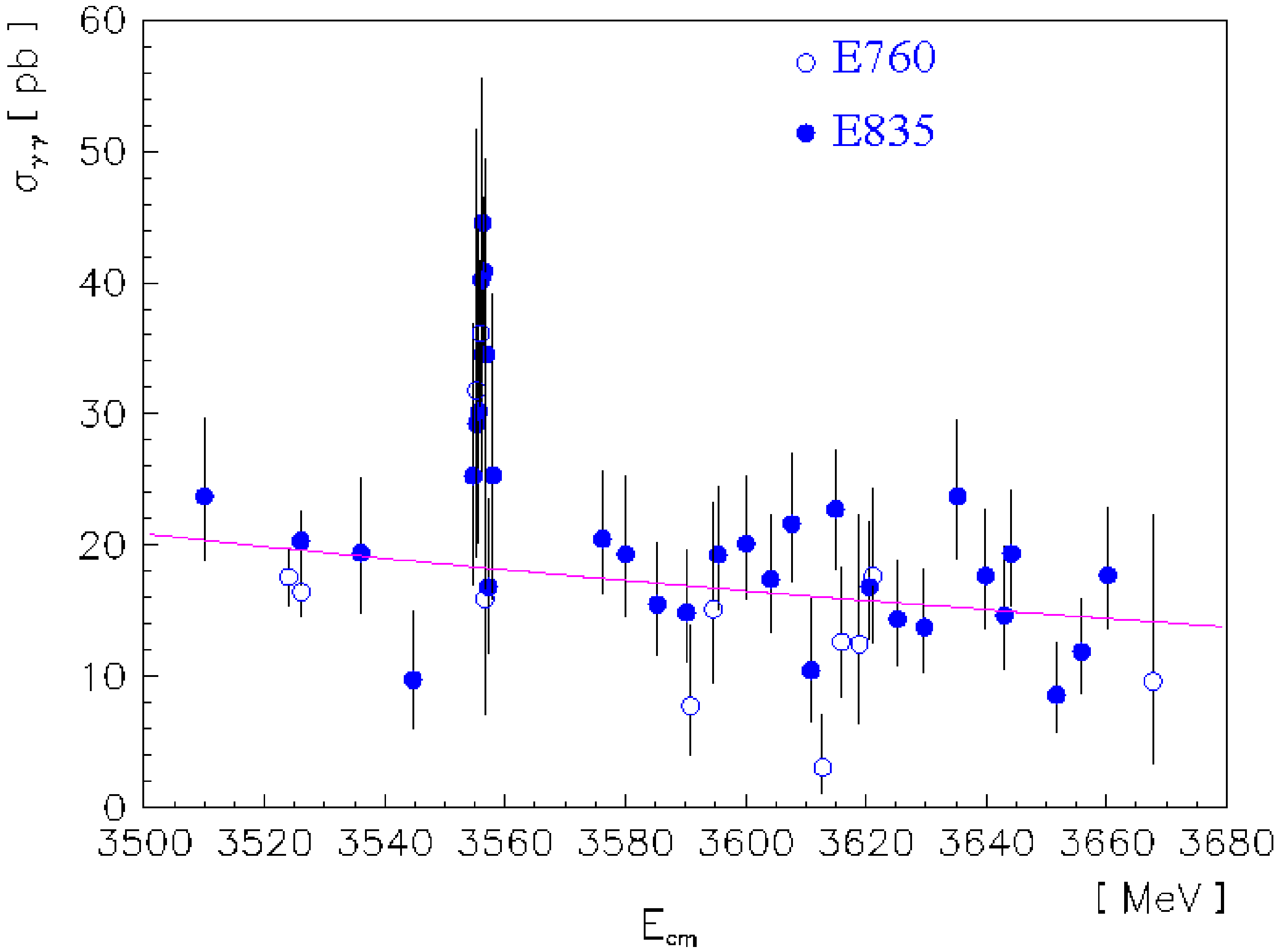
$\eta_c \longrightarrow \gamma\gamma$ results (*preliminary*)

- We have collected 18 pb^{-1} in the η_c region (from 2900 to 3100 MeV) and searched for $\gamma\gamma$ events in the angular region $\cos(\theta_{cm}) < 0.2$
- The preliminary results are:
  - Mass : $2985\,^{+1.7}_{-1.8}\ \ MeV/c^2$
  - Total width: $17.8\,^{+7.2}_{-5.9}\ \ MeV$
  - $\Gamma_{\gamma\gamma}$: $3.7^{+1.5}_{-1.3} \pm 1.2$ assuming $BR_{pp}=12\pm4\ 10^{-4}$
  - BR_{pp} x $BR_{\gamma\gamma}$: $24.6^{+3.9}_{-3.8}\ \ 10^{-8}$





$\eta'_c \longrightarrow \gamma\gamma$ and $\chi_2 \longrightarrow \gamma\gamma$

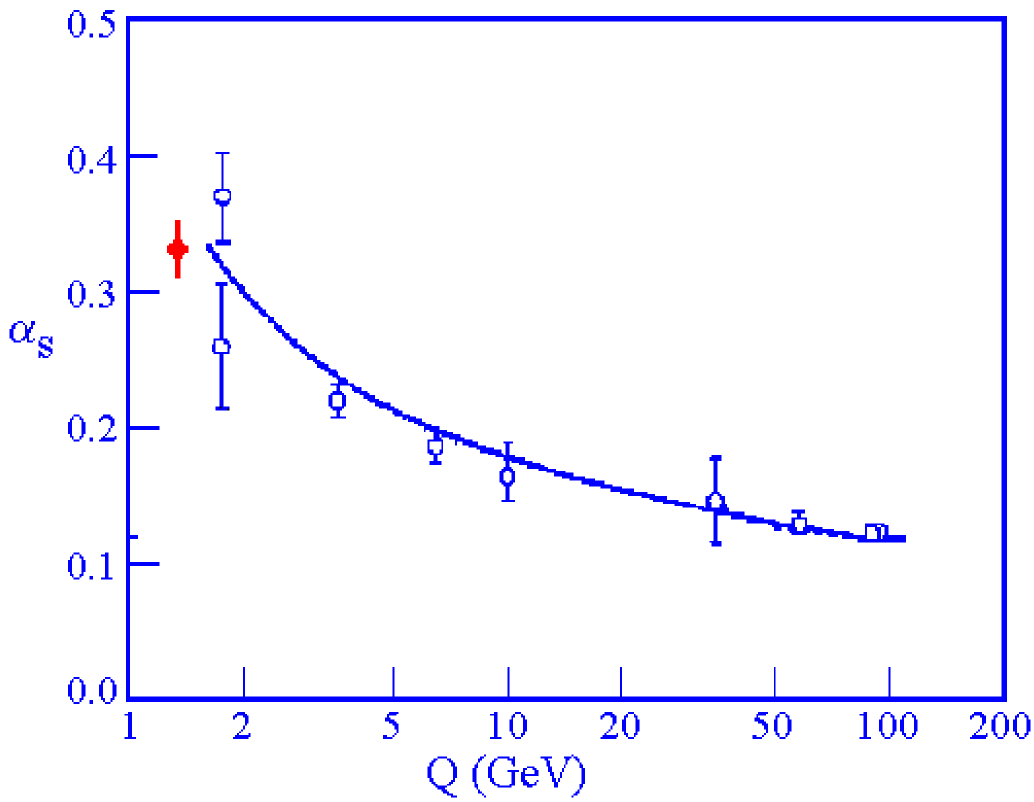


α_s calculation

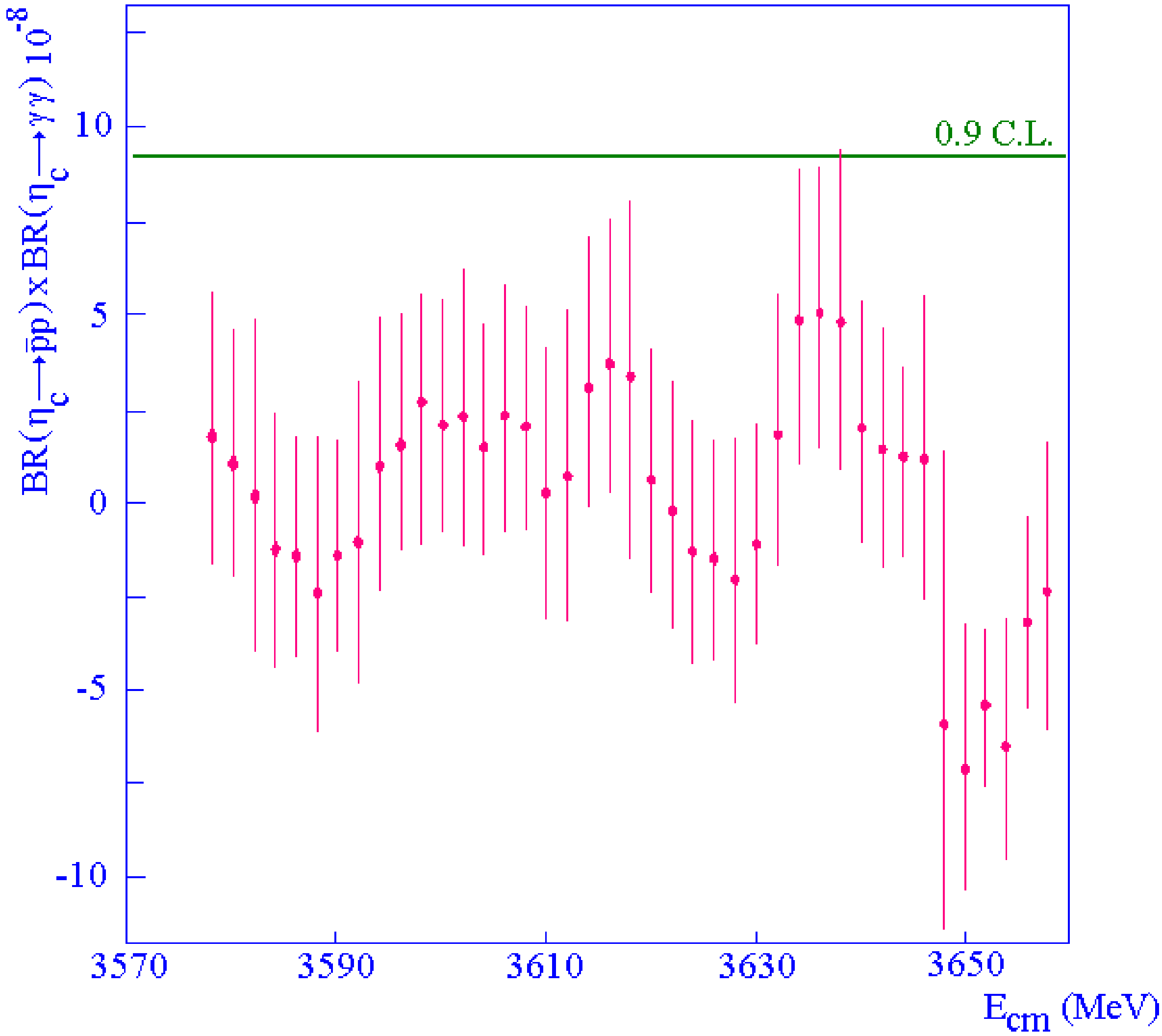
- Perturbative QCD with first order radiative corrections predicts:

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}(\eta_c) \cong \frac{8\alpha^2}{9\alpha_s^2}\left(\frac{1-3.4\,\alpha_s/\pi}{1+4.8\,\alpha_s/\pi}\right) \qquad \frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}(\chi_2) \cong \frac{8\alpha^2}{9\alpha_s^2}\left(\frac{1-16\,\alpha_s/3\pi}{1-2.2\,\alpha_s/\pi}\right)$$

- From our preliminary measurement we get:
  - η_c : $\alpha_s(m_c) = 0.32 \pm 0.05$ assuming $\Gamma_{gg} \sim \Gamma_{TOT}$
  - χ_2 : $\alpha_s(m_c) = 0.33 \pm 0.02$ assuming $\Gamma_{gg} \sim \Gamma_{TOT} - \Gamma_{J/\psi}$



η'_c search (*preliminary*)

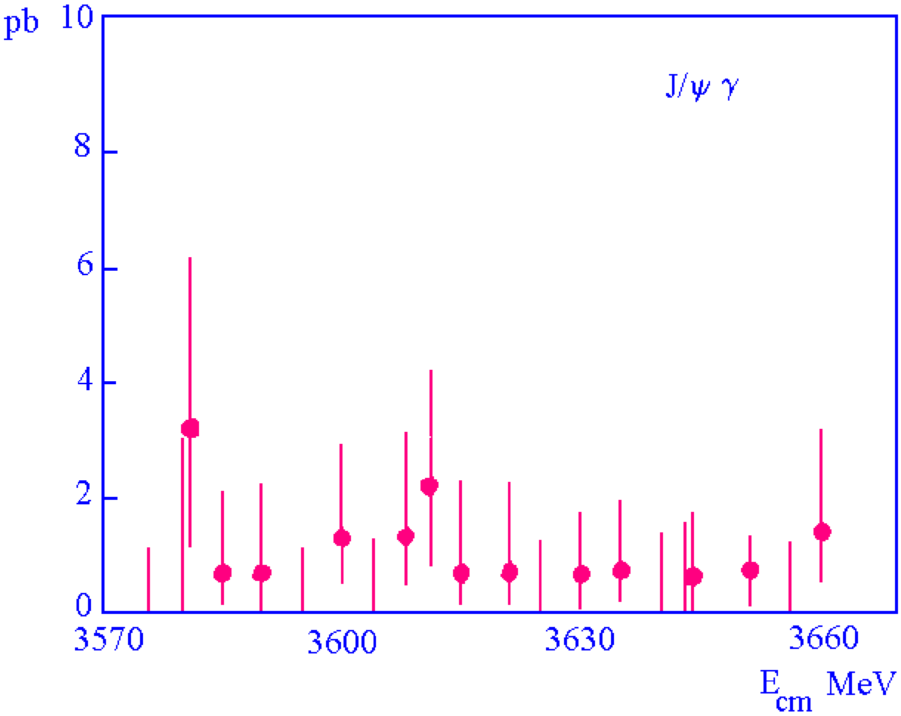


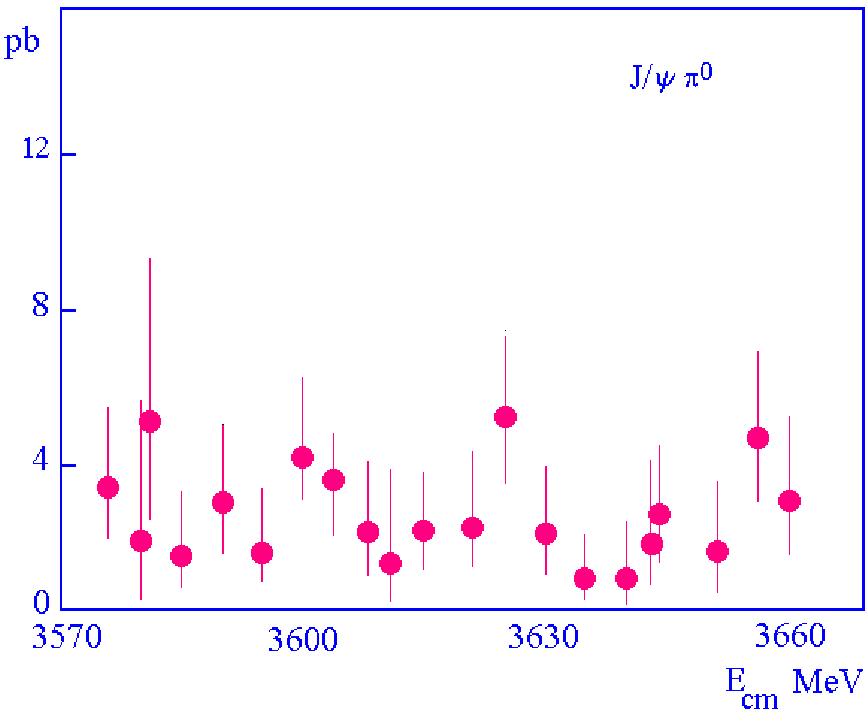
♣ We fit the data (maximum likelihood) with hypothesis of a spin 0 resonance plus a power law background

♣ We find with Γ=5 *Mev and* $3576 < E_{cm} < 3660$ *MeV* :

$$BR(R \to \bar{p}p)BR(R \to \gamma\gamma) < 9\ 10^{-8} \quad 95\%\ c.l.$$

η_c' search in other channels



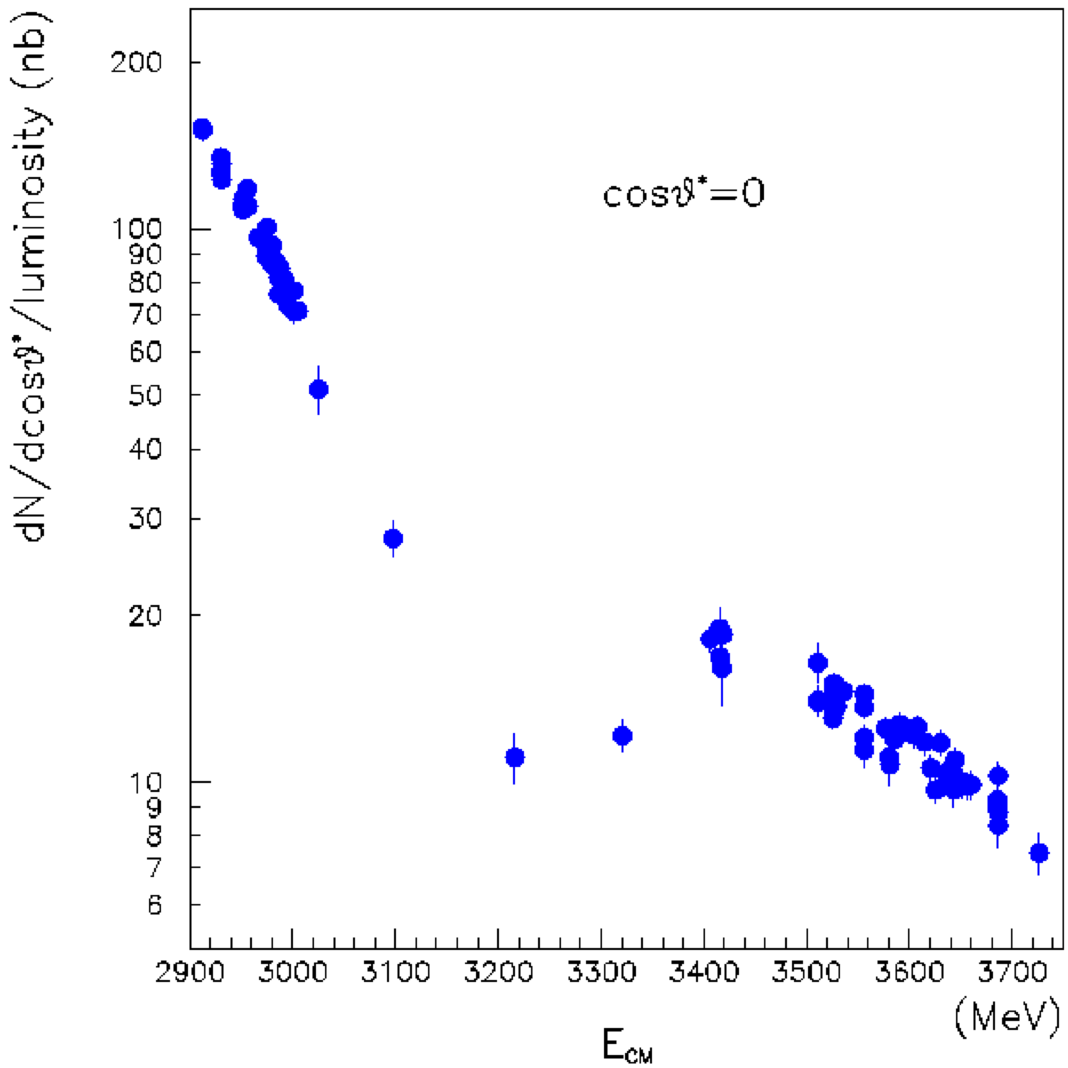


$\pi^0\ \pi^0$ at 90°

♣ We have measured the cross section:

$$\bar{p}p \longrightarrow \pi^0\pi^0 \longrightarrow \gamma\gamma\gamma\gamma$$

with π^0s scattered at 90° in the c.m. frame



CONCLUSIONS

- ♣ We have gathered 145 pb^{-1} integrated luminosity with ~5 10^9 events to be processed and analized.
- ♣ e^+e^- and $\gamma\gamma$ events are already on disk and preliminary analysis are completed in many channels
- ♣ I have shown preliminary results on η_c (<u>mass, width and branching ratios</u>), χ_0, η_c' search (negative, so far), ψ' branching ratios, $\pi^0\pi^0$ cross section, proton form factor
- ♣ We are working on:
  - Multi γ analysis (2-3 neutral mesons)
  - $\bar{p}p$ elastic at 90º
  - ΦΦ-->4K

FUTURE PROGRAMS

- ♣ Run extension in 1999 has been approved by Fermilab and INFN
- ♣ New antiproton accumulator!
- ♣ <u>To be done</u>:
  - ♦ Complete η_c' search
  - ♦ Confirm $^1P_1$ measured by E-760
  - ♦ Search for $^3D_2$, improve χ_0 measurement