The charmonium mass spectrum

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Outline

- A little bit of history: the November revolution.
- Main experimental techniques for the study of charmonium:
  - $e^+e^- \to (c\bar{c})$
  - $p\bar{p} \to (c\bar{c})$
  - $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$
- The charmonium spectrum: present status

The November revolution

From ”The Rise of the Standard Model:”

"*As I look back to the first three years at SPEAR, I consider this one of the most revolutionary, or perhaps the most revolutionary, experiment in the history of particle physics.....*"

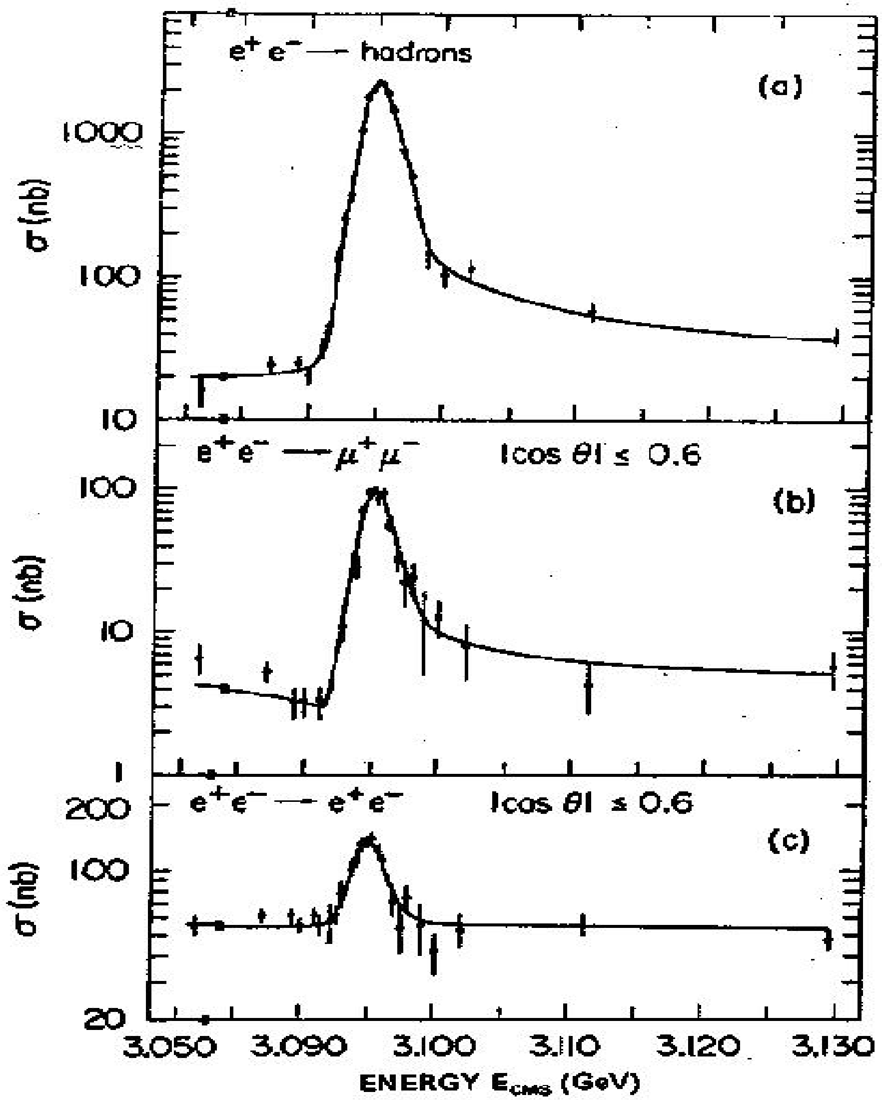
G.Goldhaber

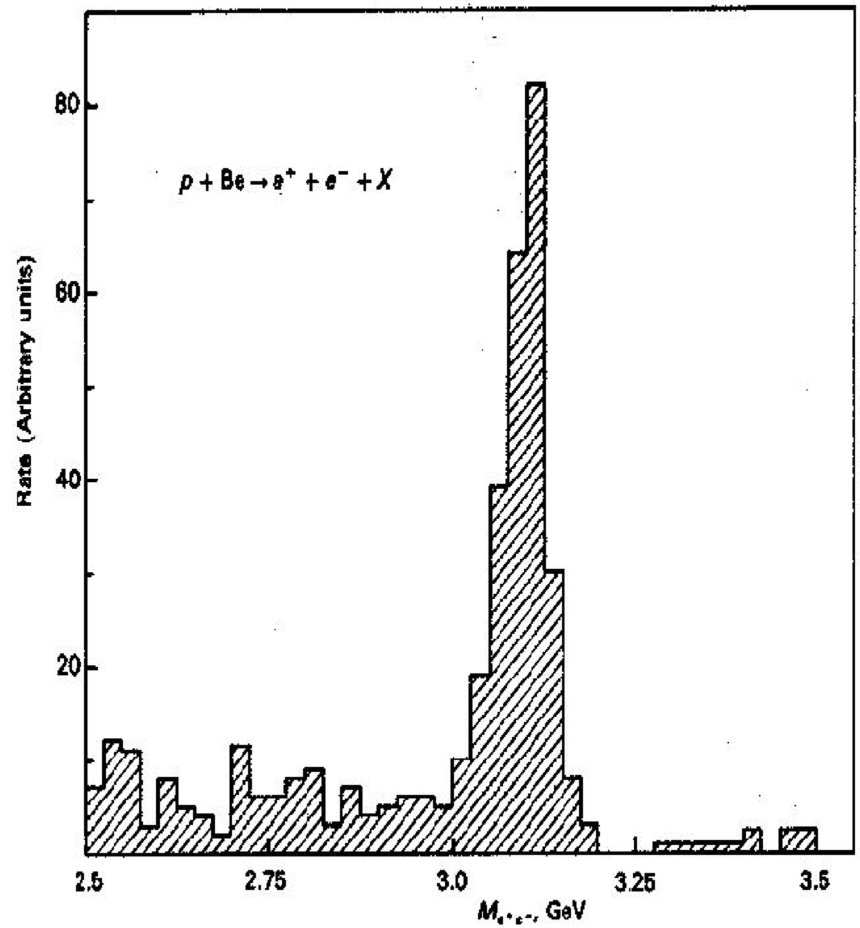
The discovery of the J/ψ

- On November 10-th 1974, at SLAC and BNL an extremely narrow resonance was discovered at an energy of about 3100 MeV
- The resonance was immediately confirmed at Frascati
- Its small width couldn't be explained in terms of the known quarks u,d or s
- This resonance was called J at BNL and ψ at SLAC (for a reason that I will explain soon)

The discovery of the J/ψ

The discovery of the J/ψ
at SLAC…





…and at the Brookhaven
National Laboratory

What is this resonance made of?

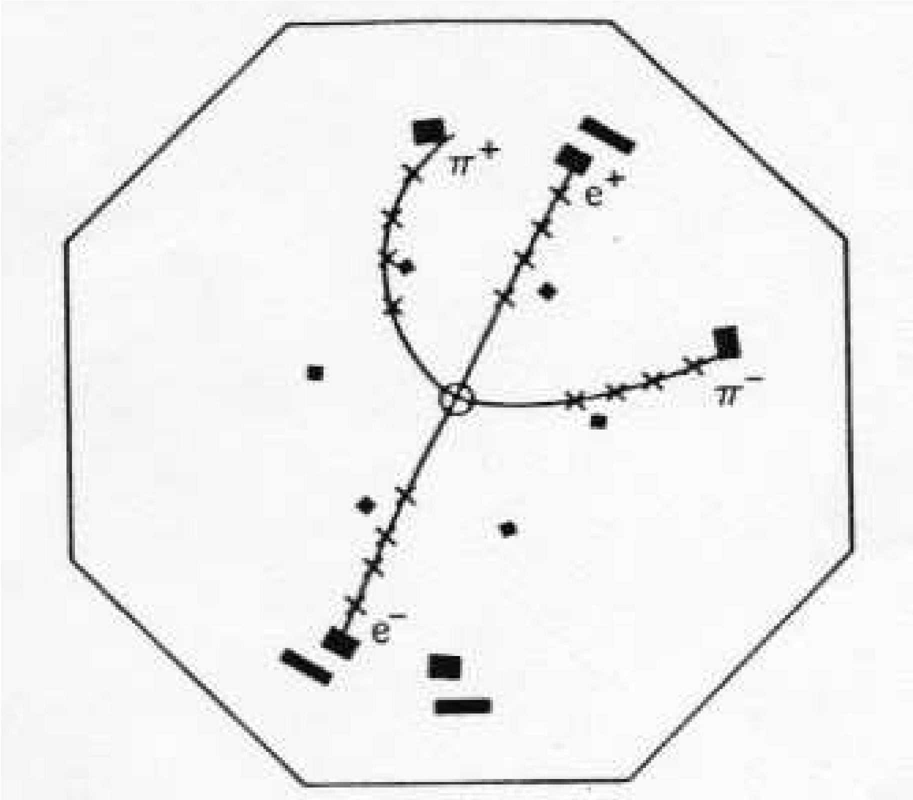
- A few years before, Glashow, Iliopoulos and Maiani proposed a model to explain the absence of the $\Delta S=1$ neutral weak currents:

$$\frac{K^+ \to \pi^+ \bar{\nu}\nu}{K^+ \to \pi^0 \mu^+ \nu_\mu} \leq 10^{-5}$$

- This model predicted the existence of a new quark *"charm"* with charge +2/3
- The discovery of the J/ψ confirmed this prediction and was actually the definitive confirmation of the existence of quarks

Why ψ?

You may wonder why this resonance was called ψ...... look at the picture of this $(\psi' \rightarrow J/\psi\pi^+\pi^-)$ event….



The name was clearly right!

Experimental techniques

- Three main methods are used to study the charmonium resonances:
  - electron-positron annihilations:

$$e^+e^- \to (c\bar{c})$$

  - proton- antiproton annihilations:

$$p\bar{p} \to (c\bar{c})$$

  - two-photon collisions:

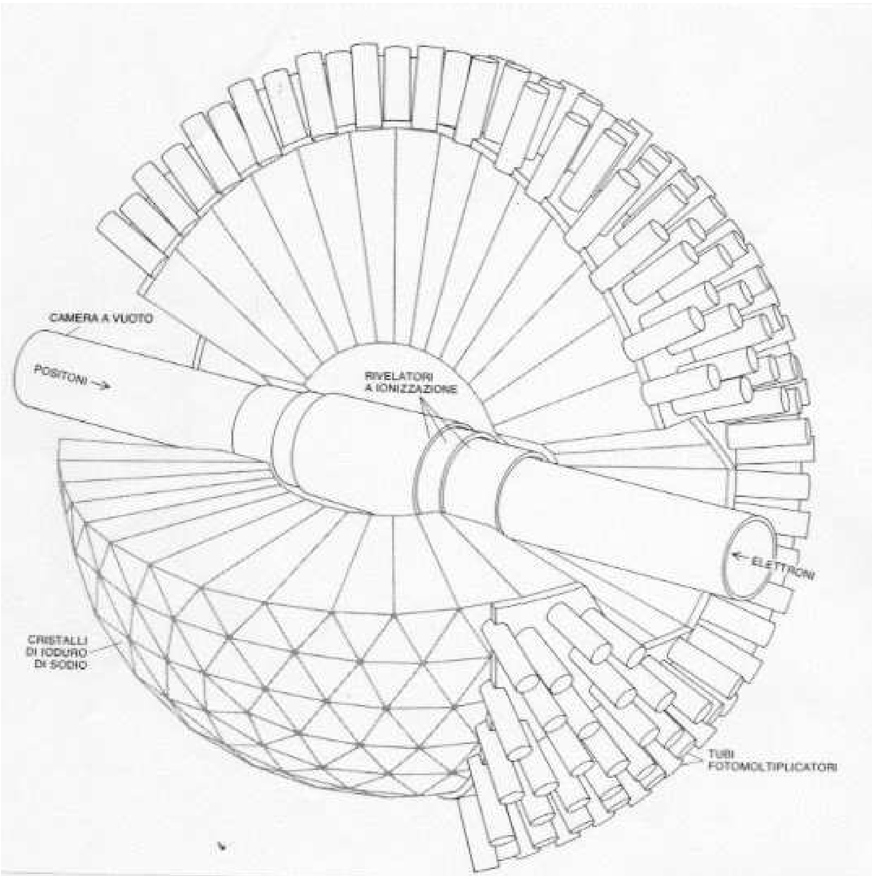
$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$$

Electron-Positron annihilations

- This method is one of the first exploited
- It allows the direct formation of the charmonium states with the same quantum number of the photon $(J^{PC} = 1^{--})$
- All the other states are studied through radiative decay of ψ' and J/ψ
- It provides a low background method for the identification of charmonium states
- MarkI,II,III and Crystal Ball at SLAC are some

  of the experiments that exploited this technique.

Crystal Ball

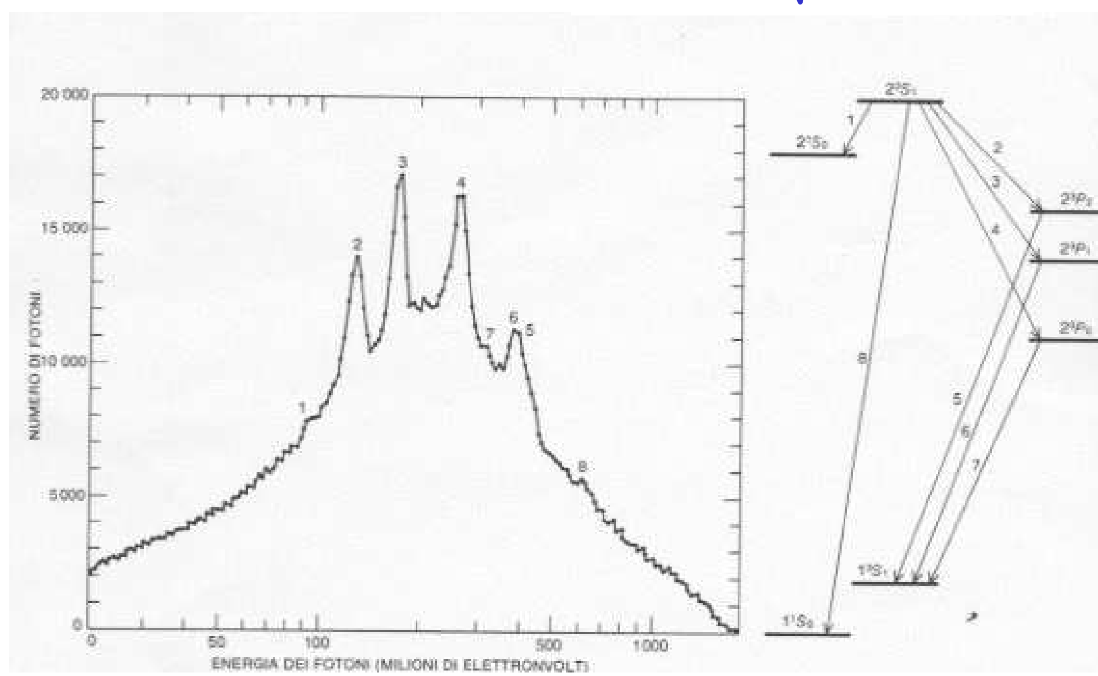


Crystal ball is a non magnetic detector designed to study the charmonium states mainly through the detection of photons emitted in radiative transitions:

$$\psi' \rightarrow \chi_c + \gamma \rightarrow J/\psi\gamma + \gamma \rightarrow l^+ l^- \gamma\gamma$$

$$\psi' \rightarrow \eta_c + \gamma \rightarrow \gamma\gamma + \gamma$$

- energy resolution: $\dfrac{\sigma(E)}{E} = \dfrac{2.8\%}{\sqrt[4]{E(GeV)}}$



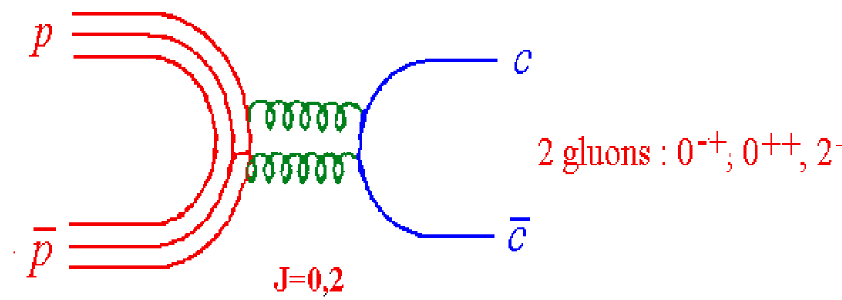
- Angular coverage: 98% 4π

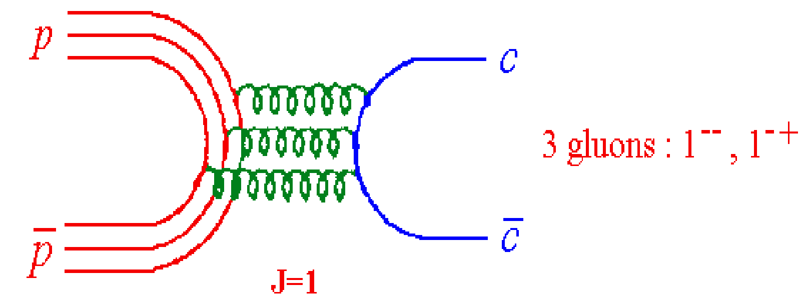
- Main detector made of 672 pyramidal NaI(Tl) blocks

- Each block is 15.7 radiation lengths thick

Proton-antiproton annihilations

- This method allows the direct formation of all the charmonium resonances
- The mass and width of the resonance are obtained from beam parameters and do not depend on the detector energy resolution

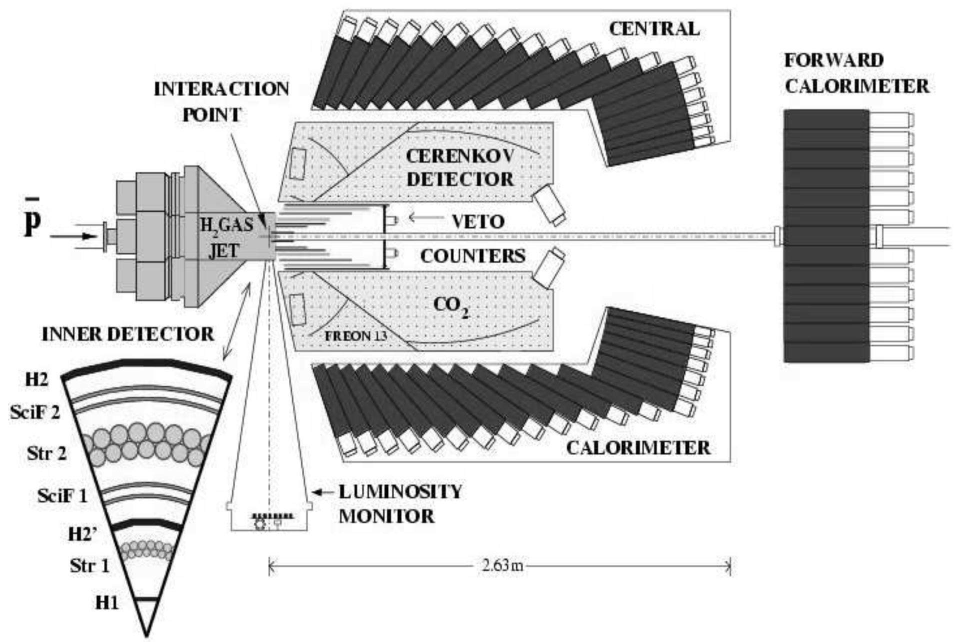




- The charmonium signal can be clearly selected over the large hadronic background by studying the electromagnetic decays

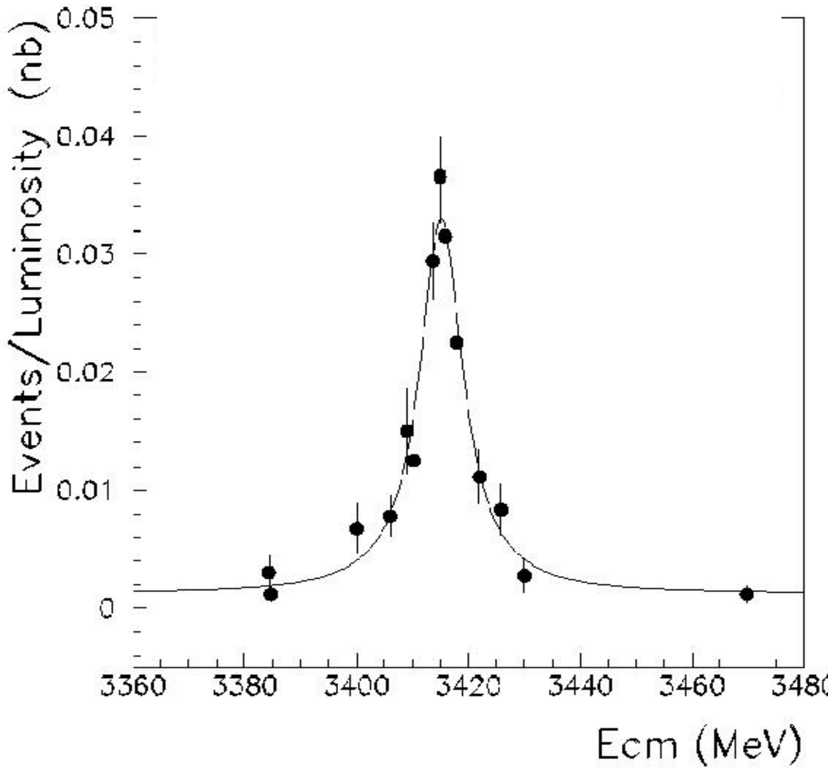
- This technique has been pioneered by R704 at the Intersecting Storage Ring at CERN and extensively used by E760/E835 at the Fermilab Antiproton Accumulator

E760/E835 at Fermilab



- Non magnetic spectrometer designed to study the charmonium resonances through their e.m. decays:

$$\bar{p}p \rightarrow \chi_c \rightarrow J/\psi\gamma \rightarrow e^+e^-\gamma$$
$$\bar{p}p \rightarrow \eta_c \rightarrow \gamma\gamma$$



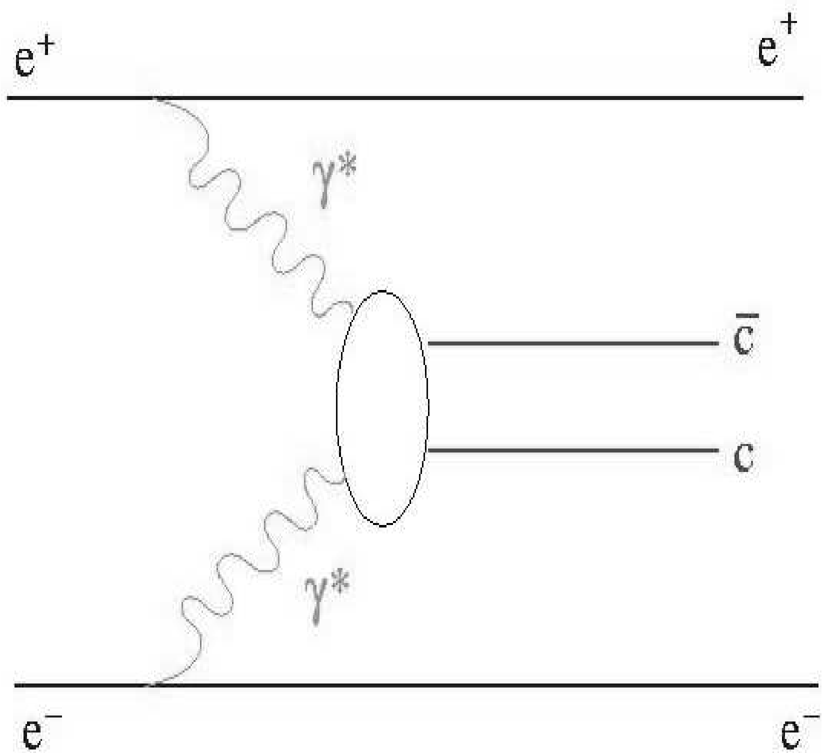
- Angular coverage: 33% 4π
- Angular and energy resolutions:

$$\sigma_\vartheta \quad \textit{from 1.5 to 5 mrad}$$

$$\sigma_\varphi \cong 10 mrad$$

$$\frac{\sigma(E)}{E} = \frac{6\%}{\sqrt{E(GeV)}} + 1.2\%$$

Two photon collisions



- With this technique C-even charmonium states can be produced through the fusion of two quasi-real photons emitted by e^+ and e^- :

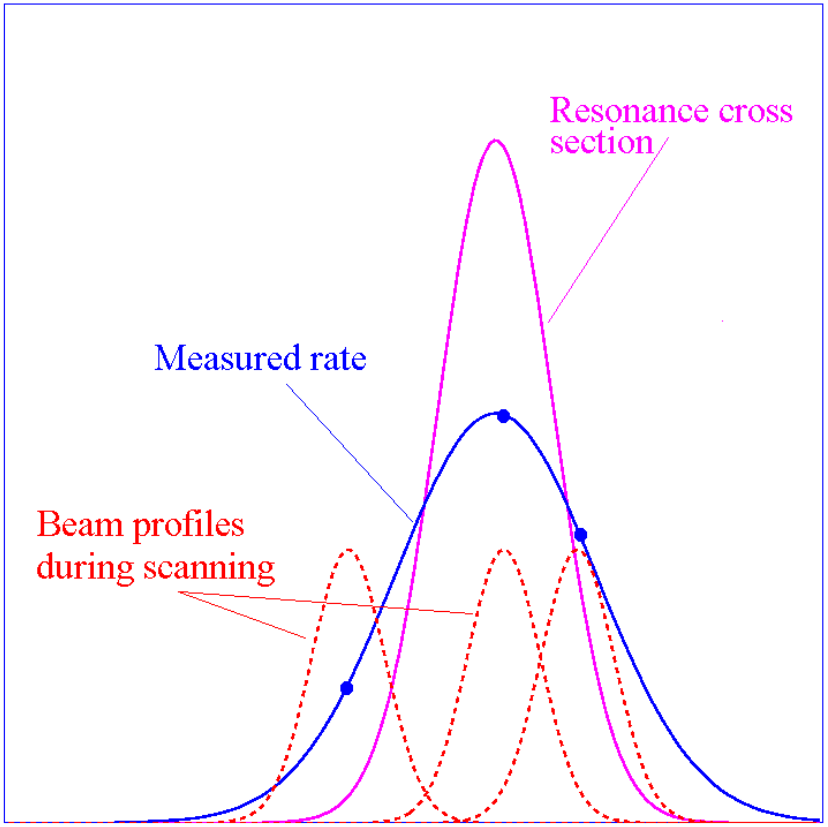
$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-(c\bar{c})$$

- The e^+ and e^- usually go undetected along the beam pipe (untagged events)

- CLEO-II and LEP experiments are presently using this technique

- The $\eta_c(0^{-+}), \chi_{c0}(0^{++})$ and $\chi_{c2}(2^{++})$ resonances can be produced, $\chi_{c1}(1^{++})$ forbidden by Young theorem

Resonance scan



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

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

- Each charmonium resonance is studied by changing the c.m. energy in small steps $(\cong 250 keV)$
- The charmonium is detected through its e.m. decays
- The measured excitation curve is the convolution of the resonance cross section (Breit-Wigner) and of the beam energy distribution
- The mass and the width of the resonance are extracted from the excitation curve with a maximum likelihood fit

Beam energy measurement

$$E_{\overline{p}} = \frac{m_p c^2}{\sqrt{1-\left(\frac{f\,L_{ORB}}{c}\right)^2}}$$

- The beam energy is calculated from the orbit length $(L_{orb.})$ and from the revolution frequency (f)

- The uncertainty on the energy measurement is dominated by ΔL_{orb} $(\Delta f / f \cong 10^{-7})$

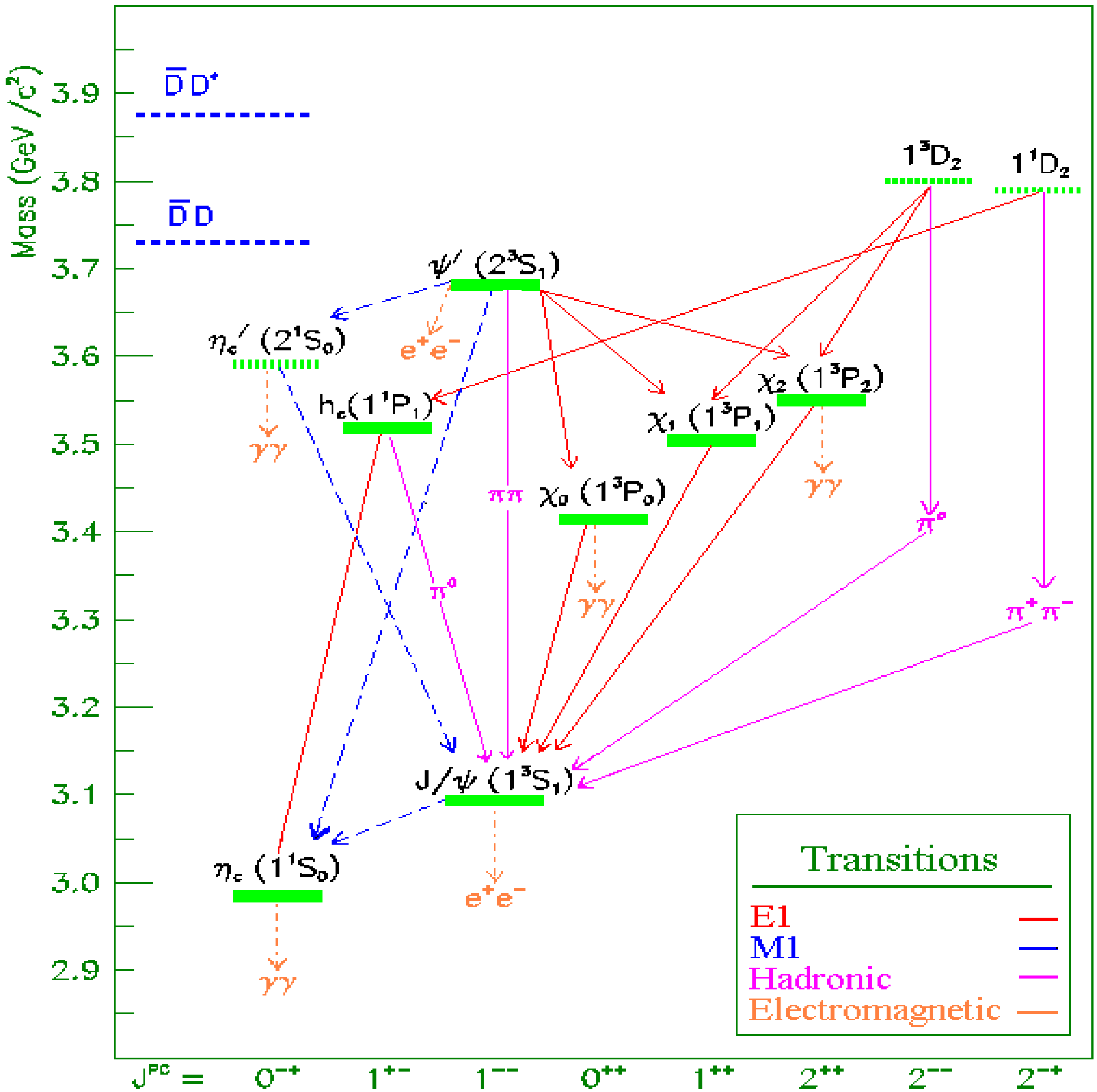
$$\Delta E_{\overline{p}} = m_p c^2 \gamma_{\overline{p}}^3 \beta_{\overline{p}}^2 \left[\left(\frac{\Delta f}{f}\right)^2 + \left(\frac{\Delta L_{ORB}}{L_{ORB}}\right)^2\right]^{1/2}$$

- The reference orbit length L_{ref} is calculated at the ψ' energy with a precision of $\cong 0.67mm$ $(\Delta m_{\psi'} \cong \pm 100keV)$

- The orbit length at all the other energies is calculated thanks to 48 Beam Position Monitors, which provide the orbit length difference ΔL:

$$L_{orb} = (L_{REF} + \Delta L)$$

The charmonium spectrum

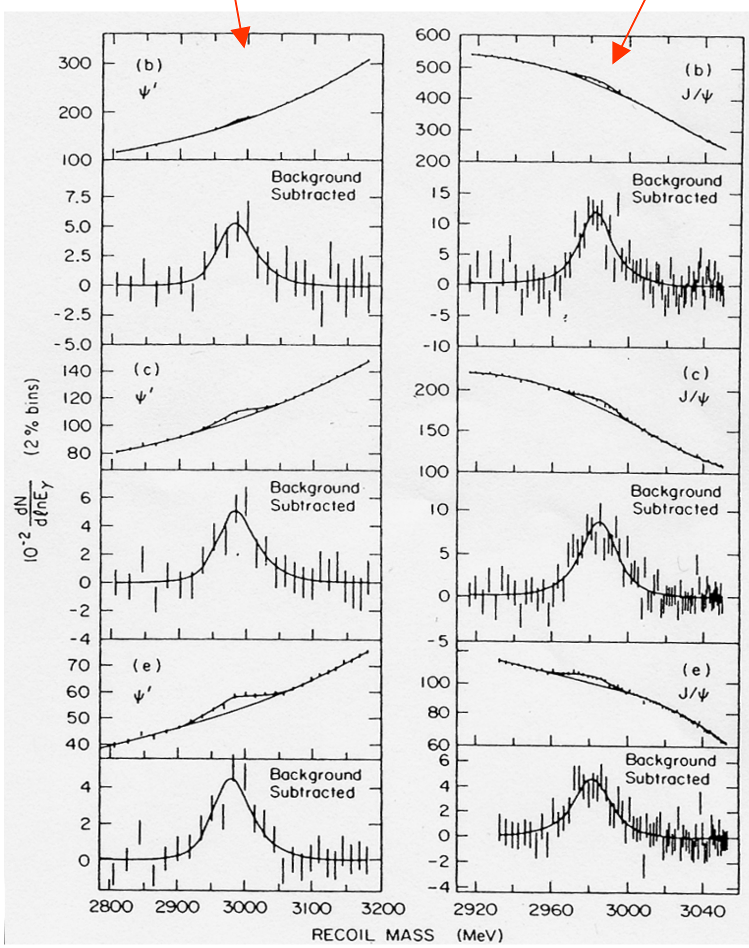


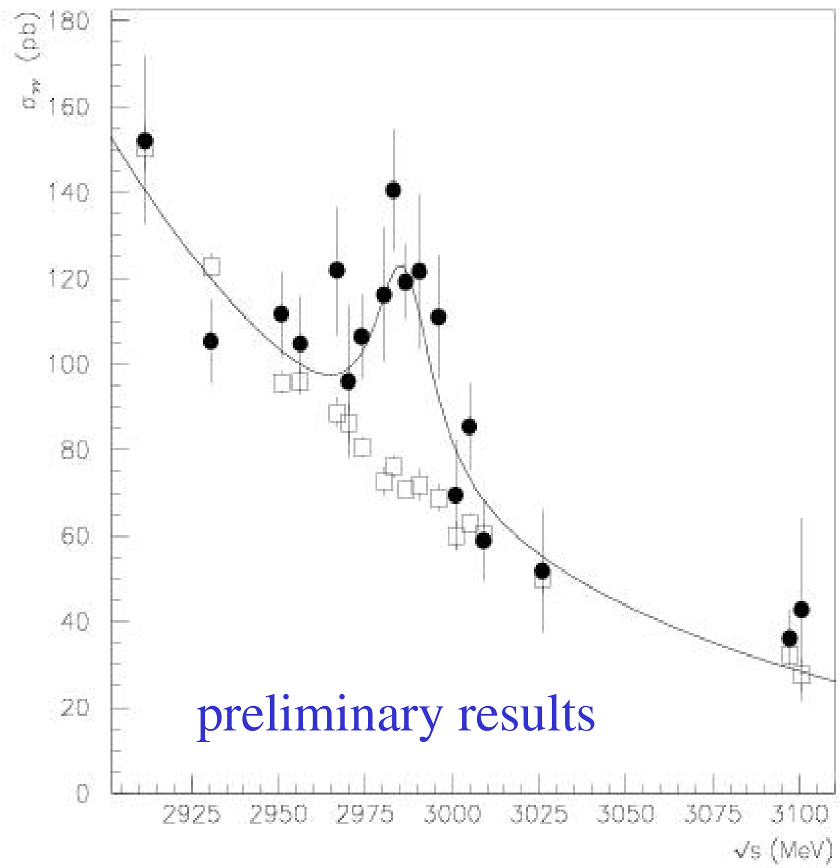
The fundamental state $\eta_c({}^1S_0)$

The η_c resonance observed by Crystal Ball…

$e^+e^- \rightarrow \psi' \rightarrow \eta_c\gamma$

$e^+e^- \rightarrow J/\psi \rightarrow \eta_c\gamma$





…and by E835 in the decay channel:

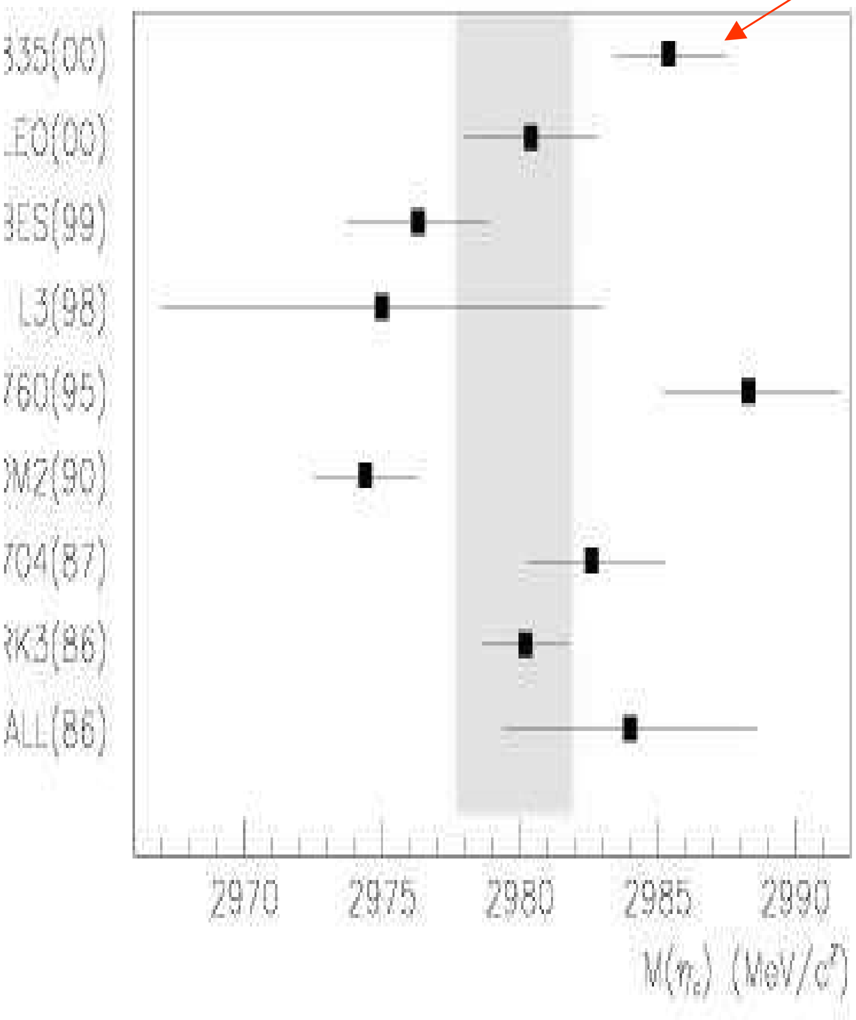
$$\bar{p}p \rightarrow \eta_c \rightarrow \gamma\gamma$$

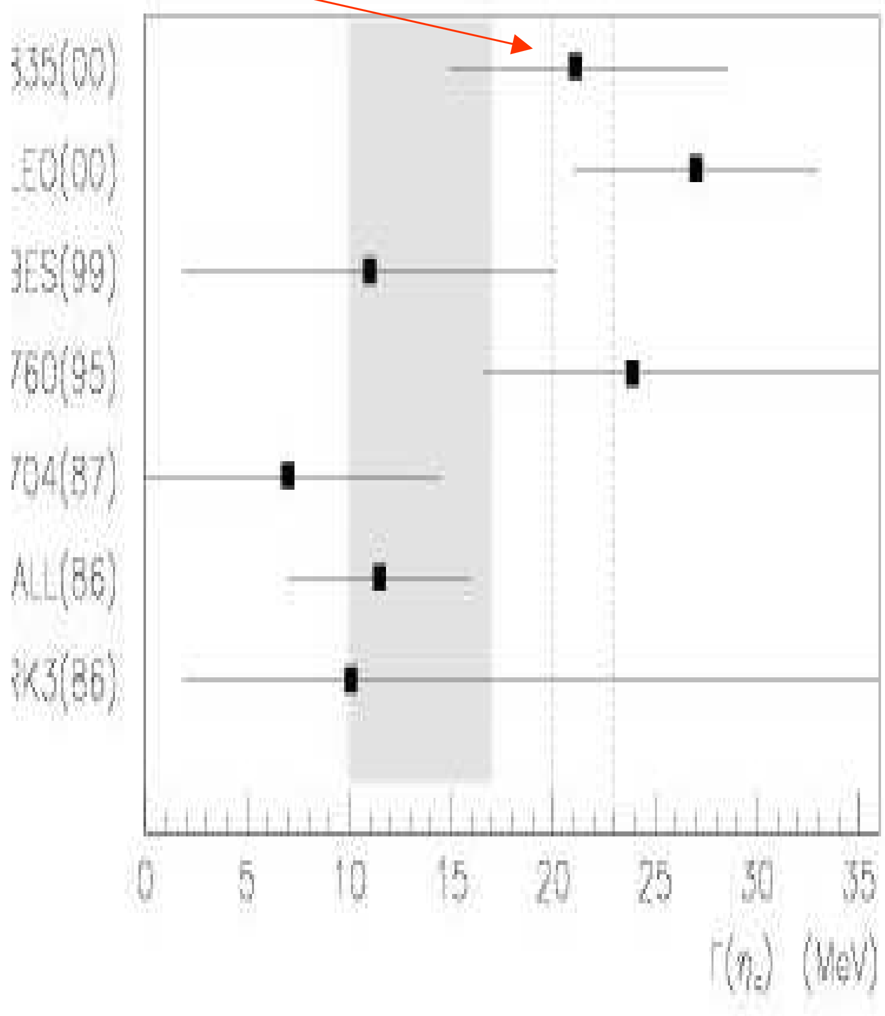
The fundamental state $\eta_c(^1S_0)$

Mass measurements

Total width measurements

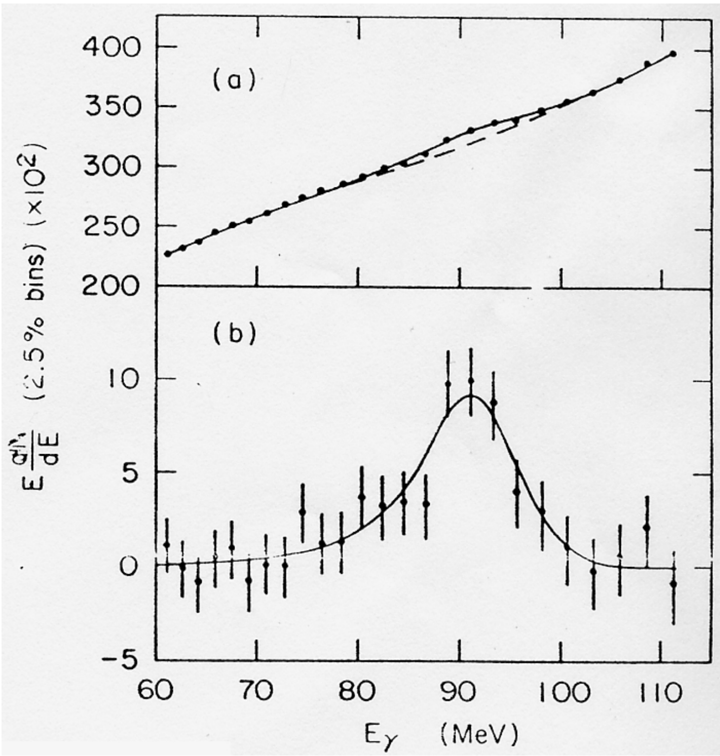
preliminary results





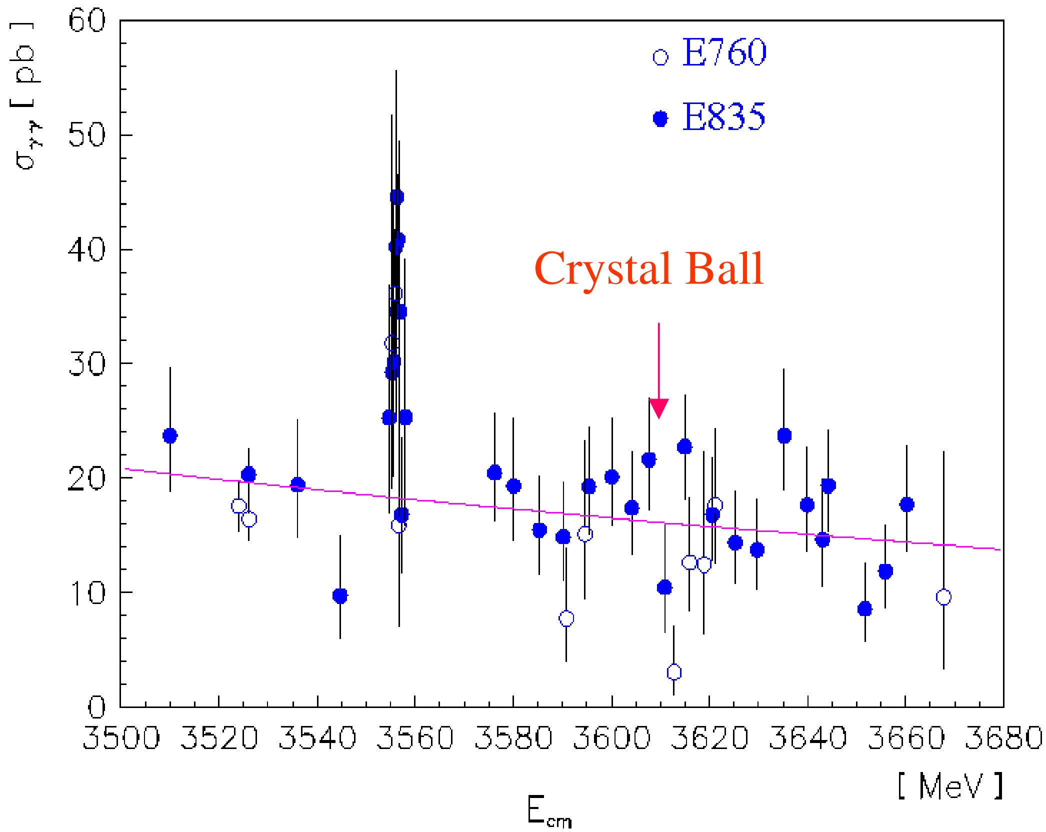
The $\eta_c(2^1S_0)$ state

- Crystal ball is the only experiment which saw an evidence of this resonance



- Mass: $(3594.0 \pm 5)MeV$
- Total width: $\leq 8MeV$

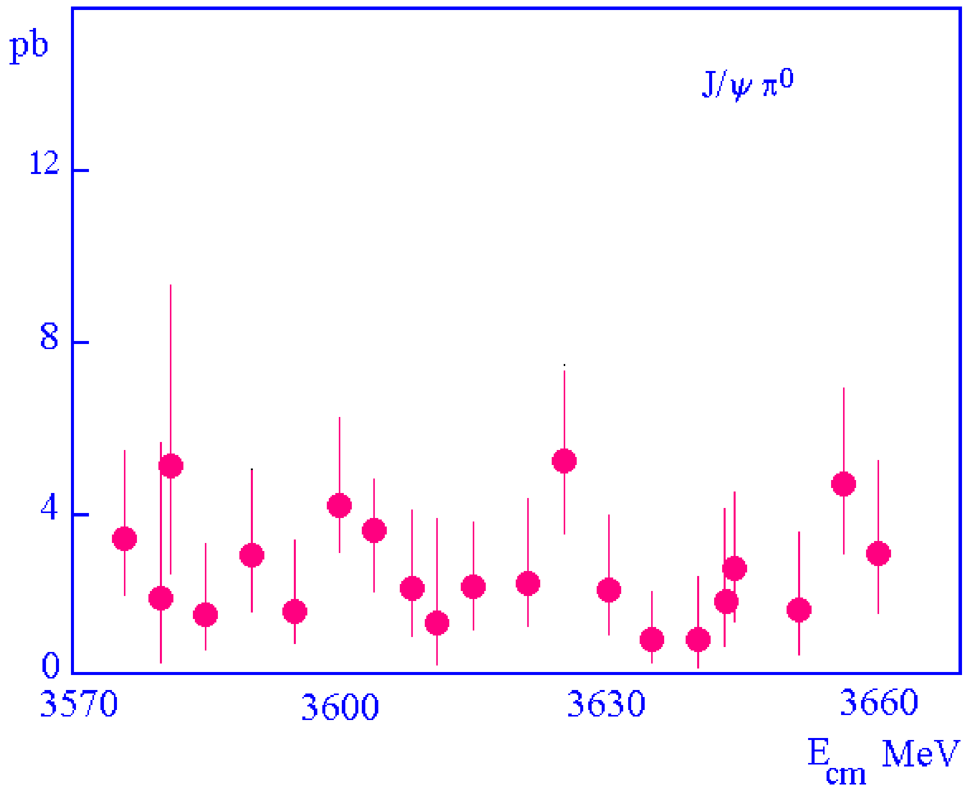
- E760/E835 searched for this resonance in the energy region: E_{cm}=(3570-3660) MeV, in the decay channel: $\eta_c' \rightarrow \gamma\gamma$ but no evidence of a signal was found

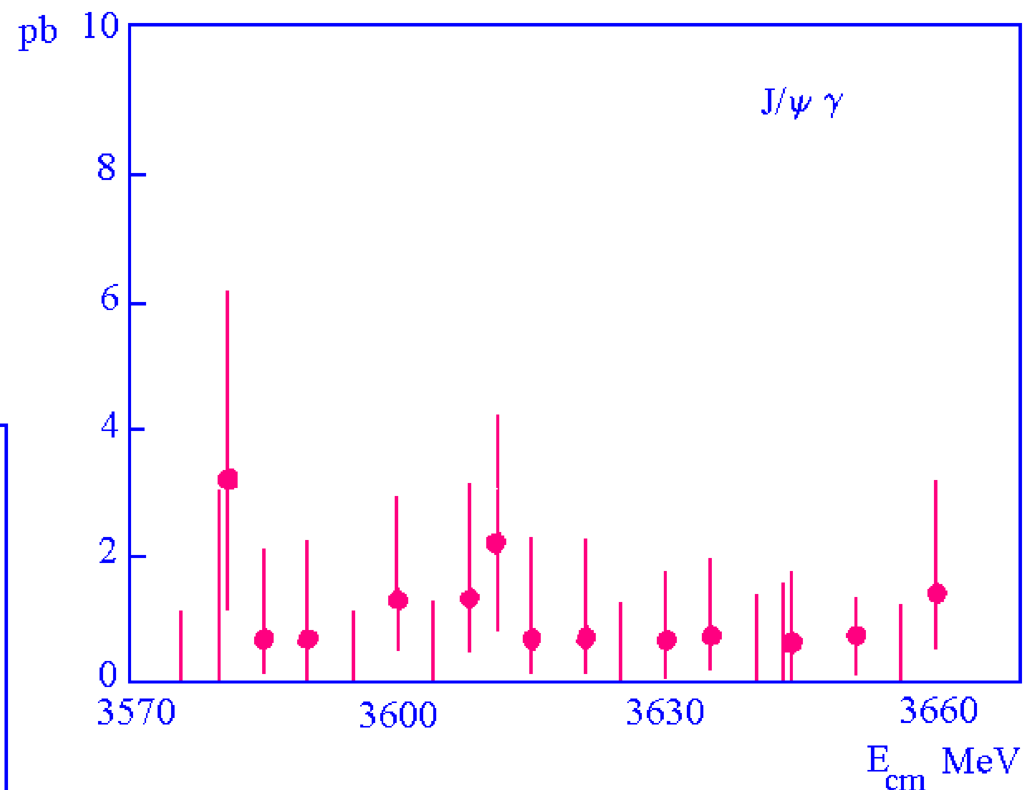


The $\eta_c(2^1S_0)$ state

Search of the η_c' resonance in the decay channel:

$$\eta_c' \to J/\psi\pi^0$$



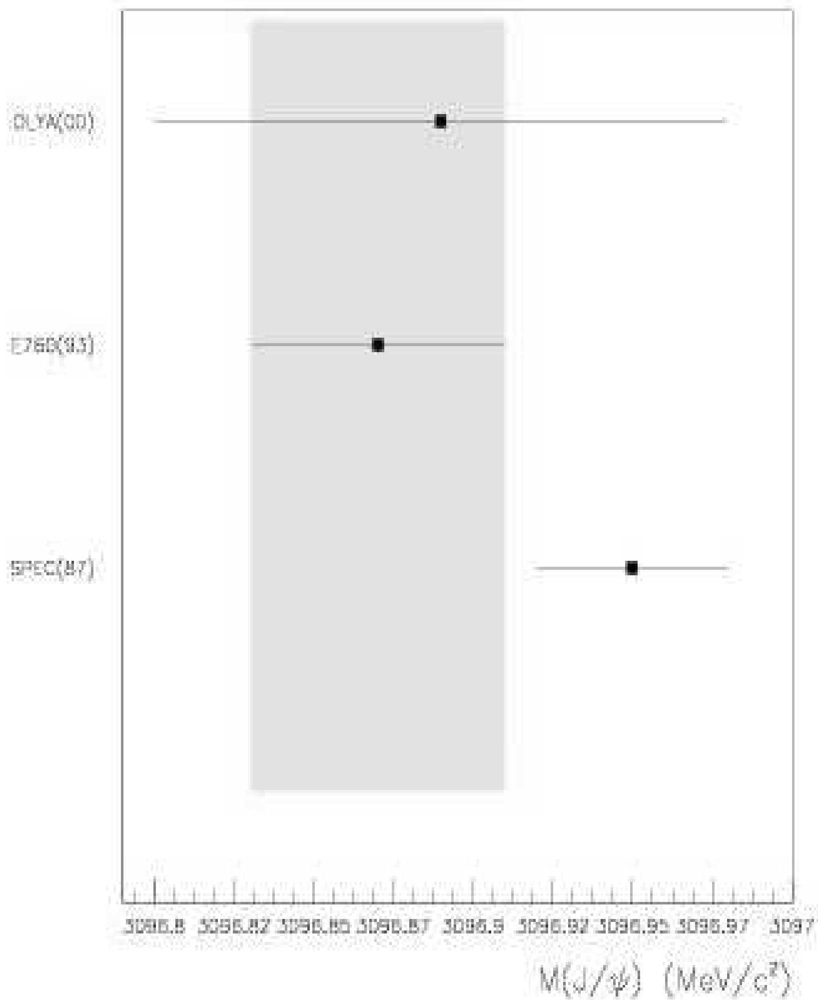


…and in the channel

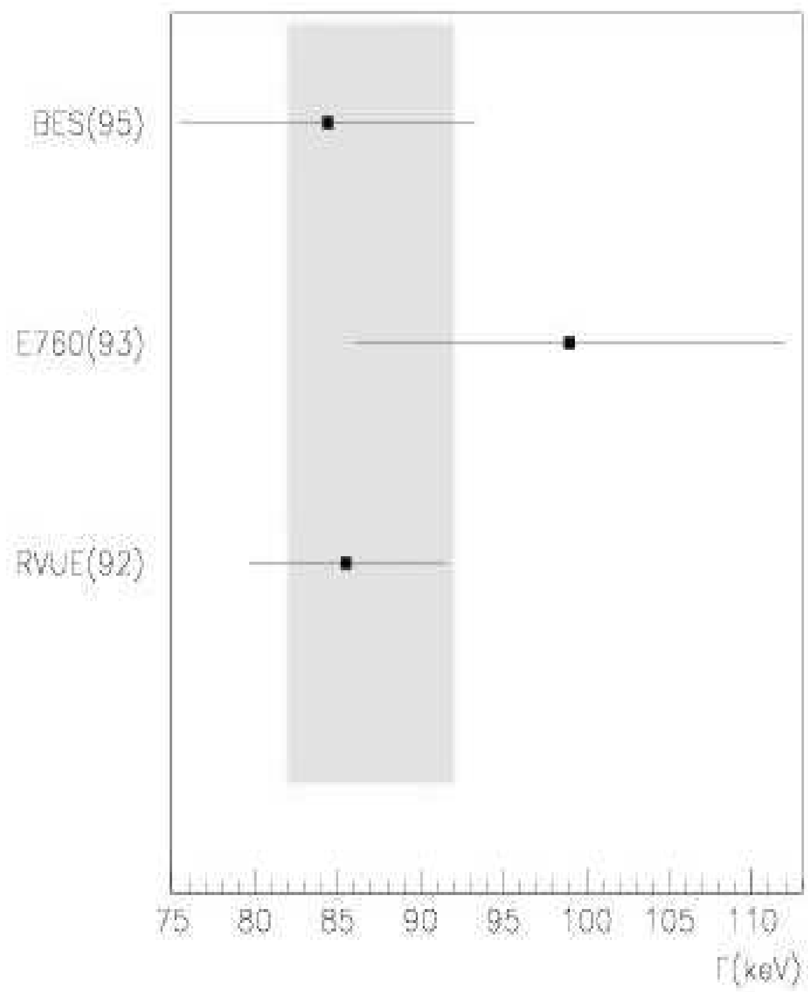
$$\eta_c' \to J/\psi\gamma$$

The $J/\psi(^3S_1)$ resonance

Mass measurements

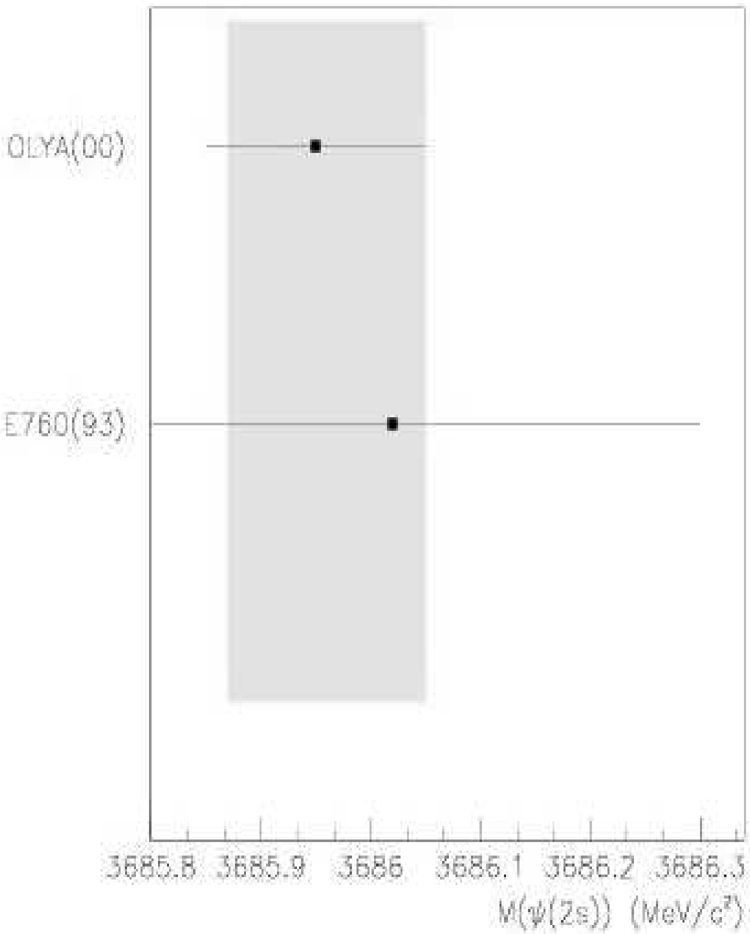


Total width measurements

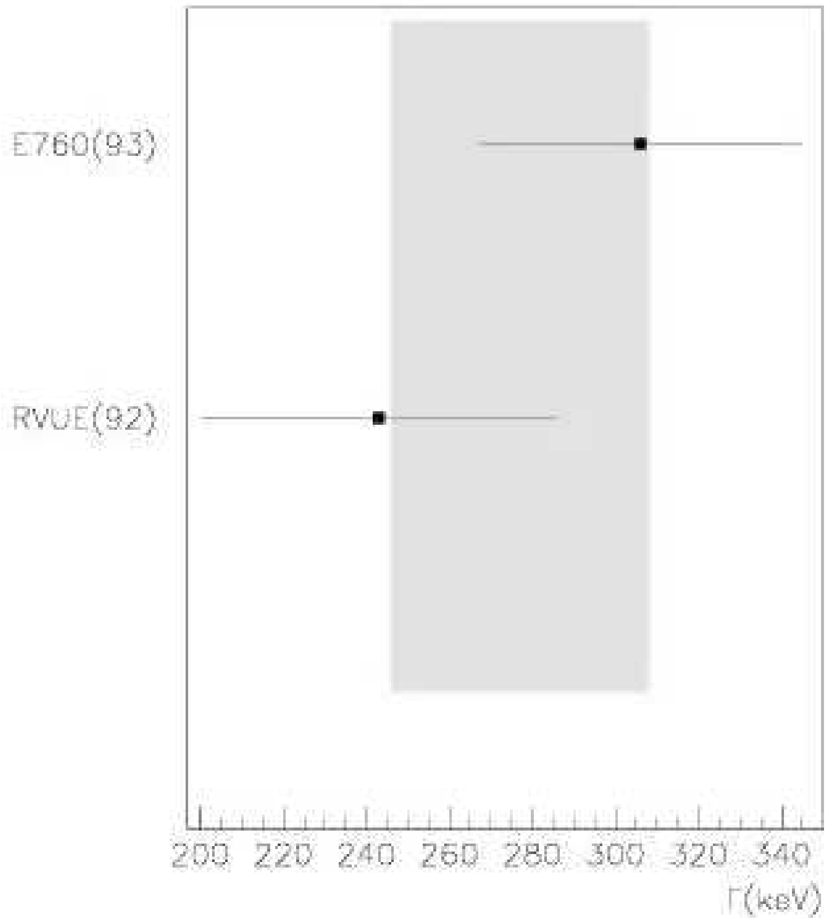


The $\psi'(2^3S_1)$ resonance

Mass measurements



Total Width measurements



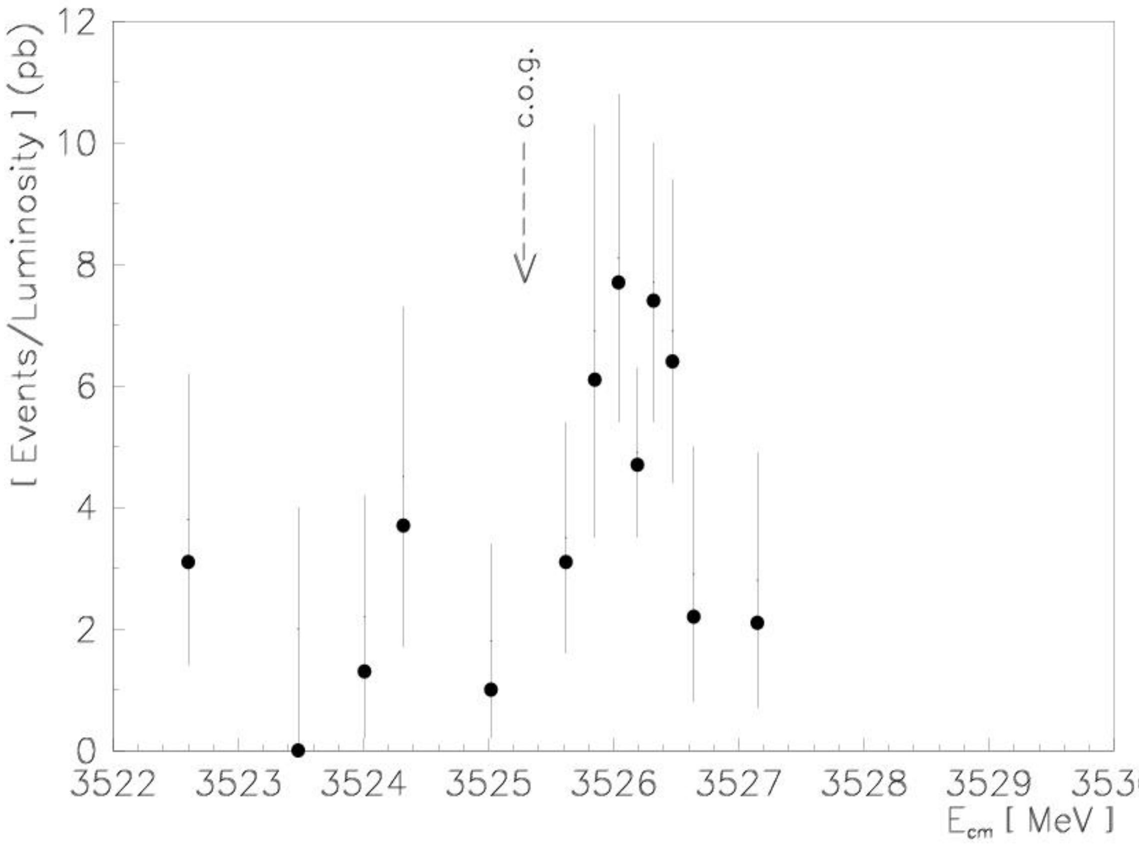
The P wave singlet state h_c $^1P_1$

- The only experiment which observed this resonance is E760, in the decay channel:

$$\bar{p}p \rightarrow {}^1P_1 \rightarrow J/\psi\pi^0 \rightarrow e^+e^-\gamma\gamma$$

- Mass: $(3526.2 \pm 0.15 \pm 0.2) MeV$

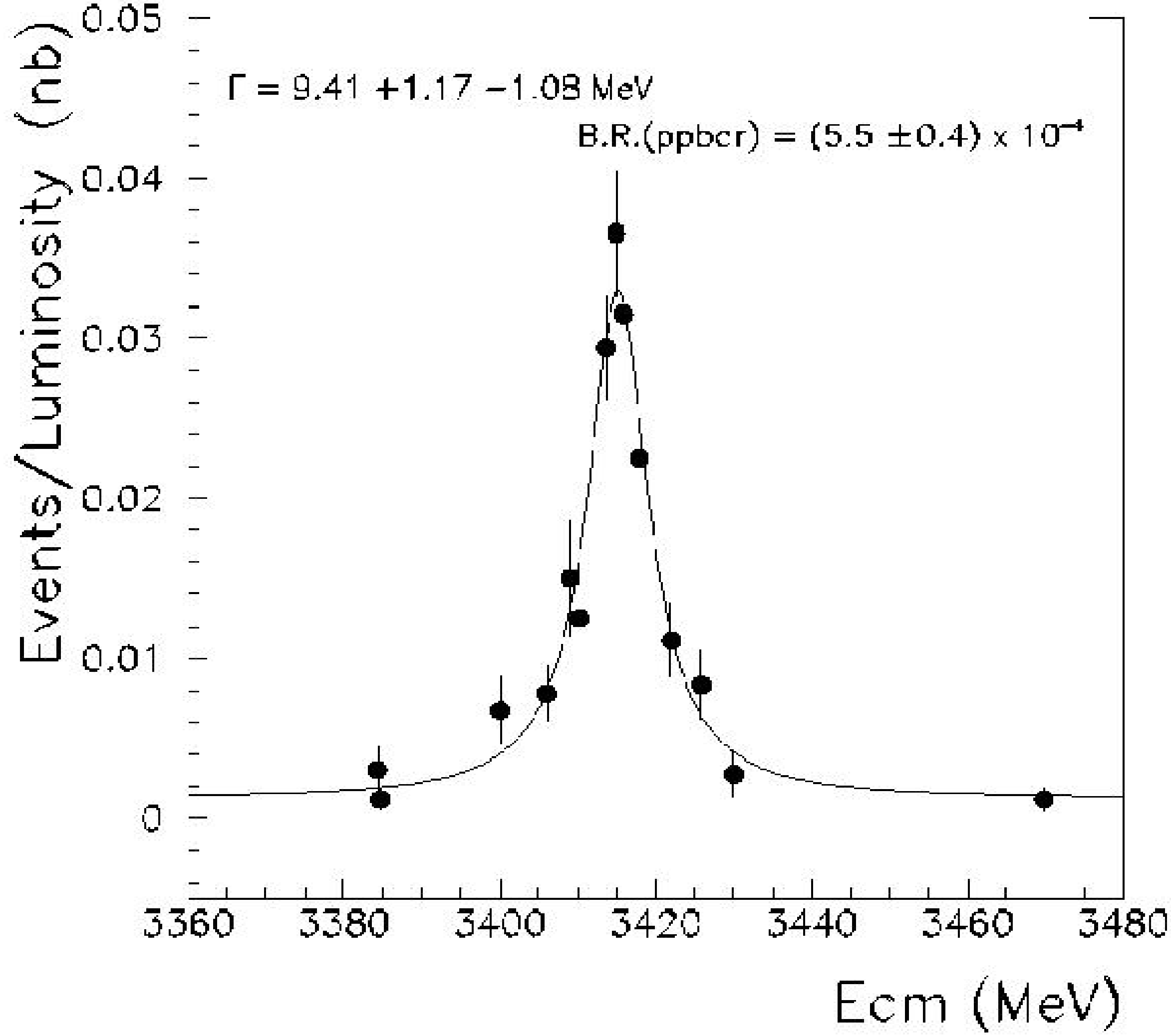
- Total width: < 1.1 MeV



The $\chi_0({}^3P_0)$ resonance

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

E835 is the first experiment which observed the χ_0 resonance in $\bar{p}p$ annihilations

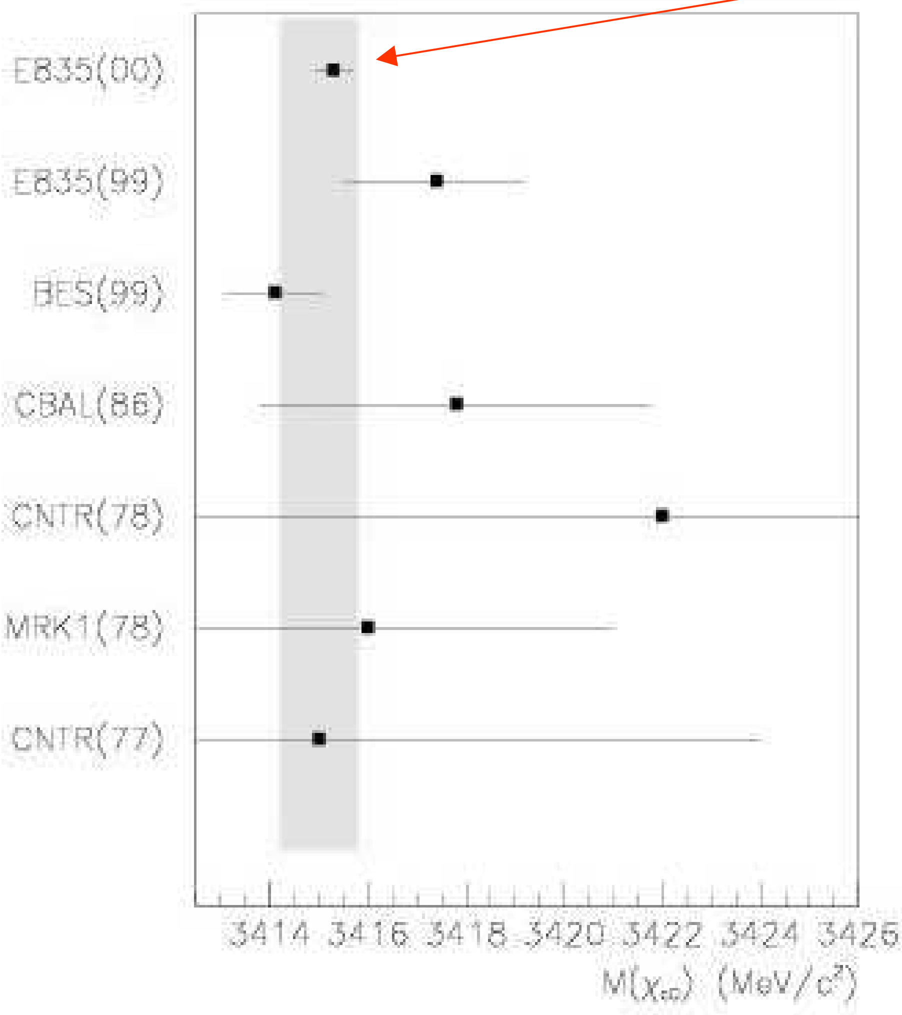


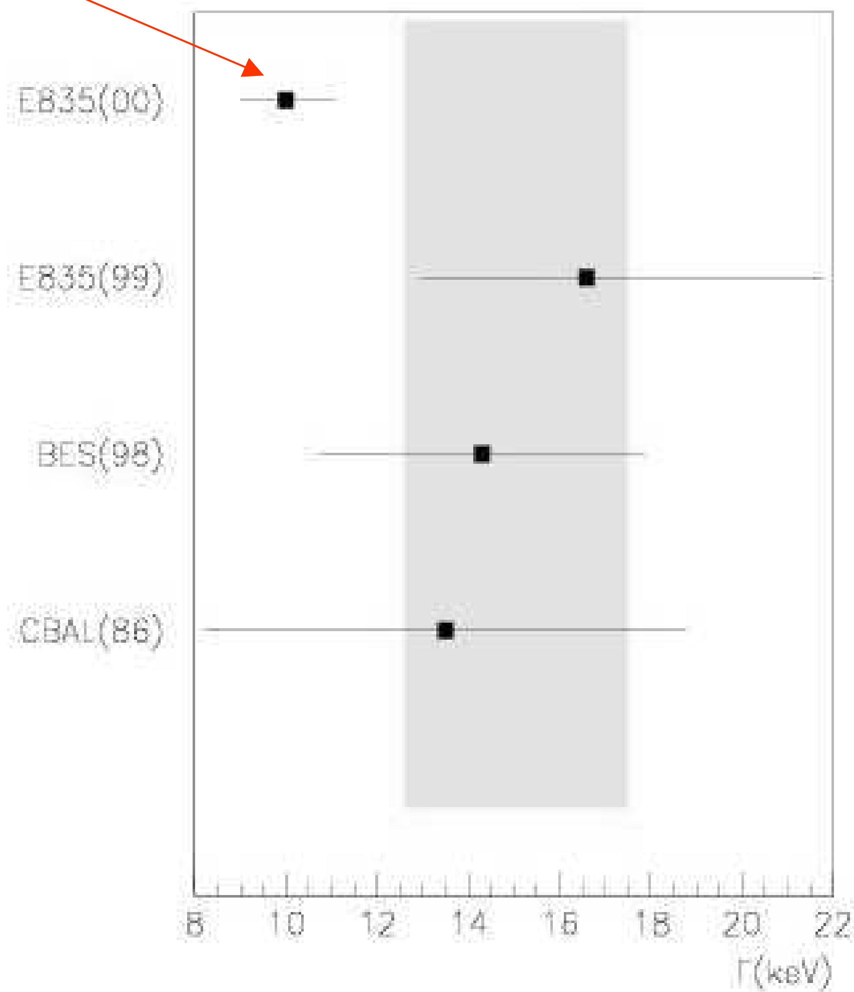
The $\chi_0(^3P_0)$ state

Mass measurements

Total width measurements

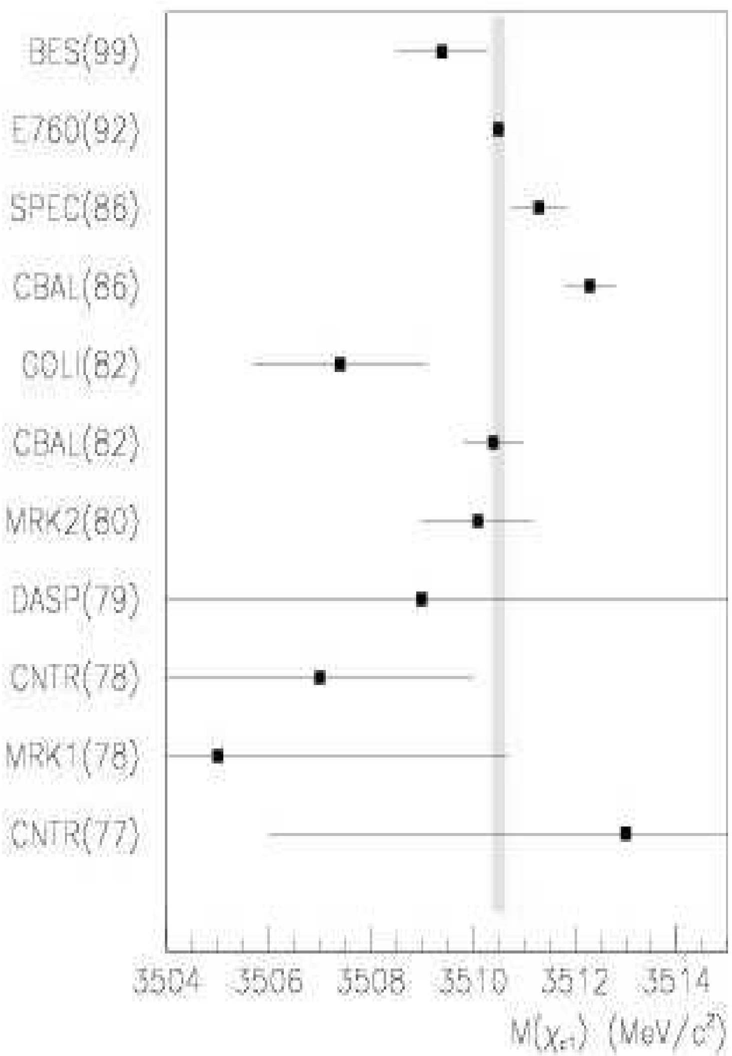
preliminary results, not yet in the PDG



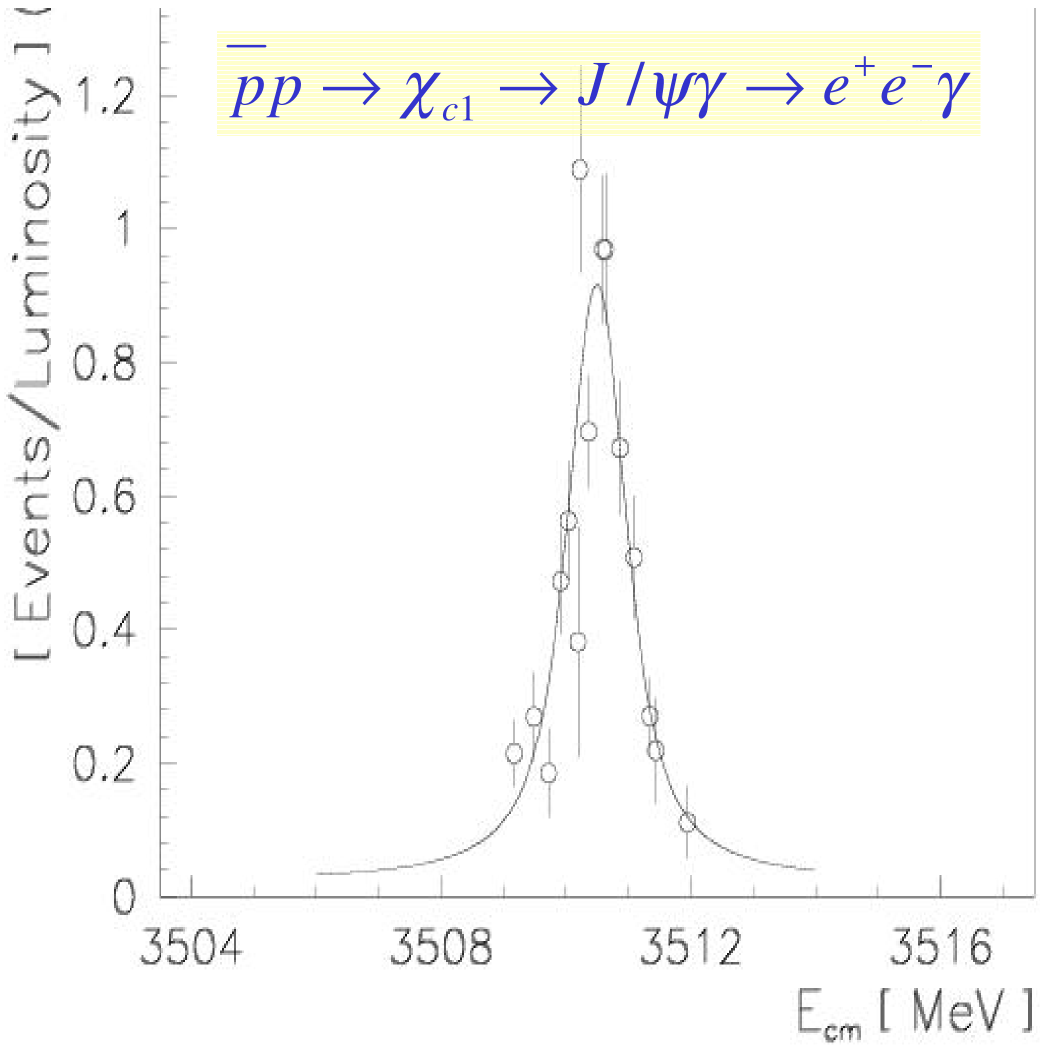


The $\chi_{c1}(^3P_1)$ state

mass measurements

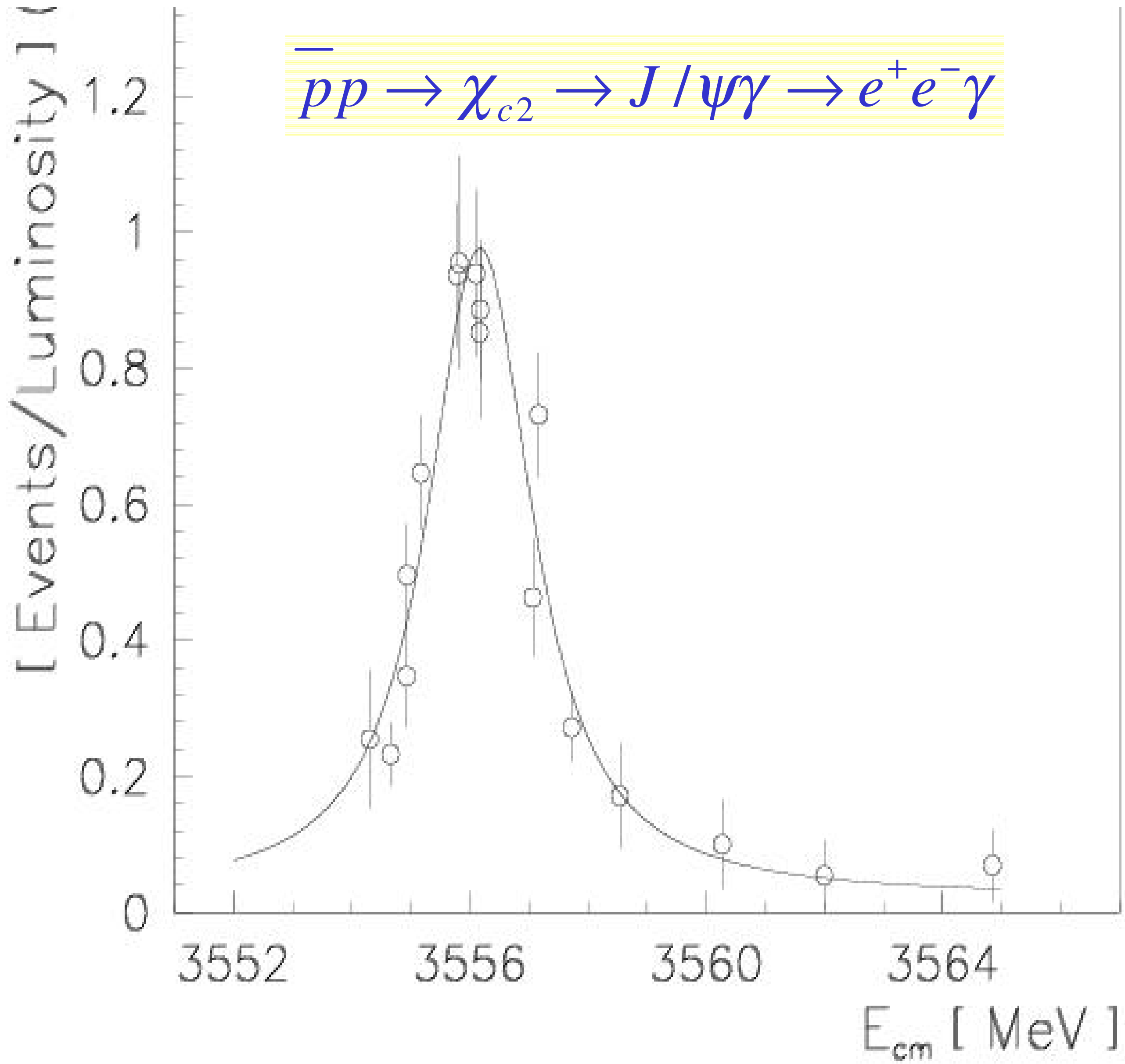


E760 is the only experiment which precisely measured the χ_{c1} total width: $\Gamma_{\chi_{c1}} = (0.88 \pm 0.11 \pm 0.08) MeV$



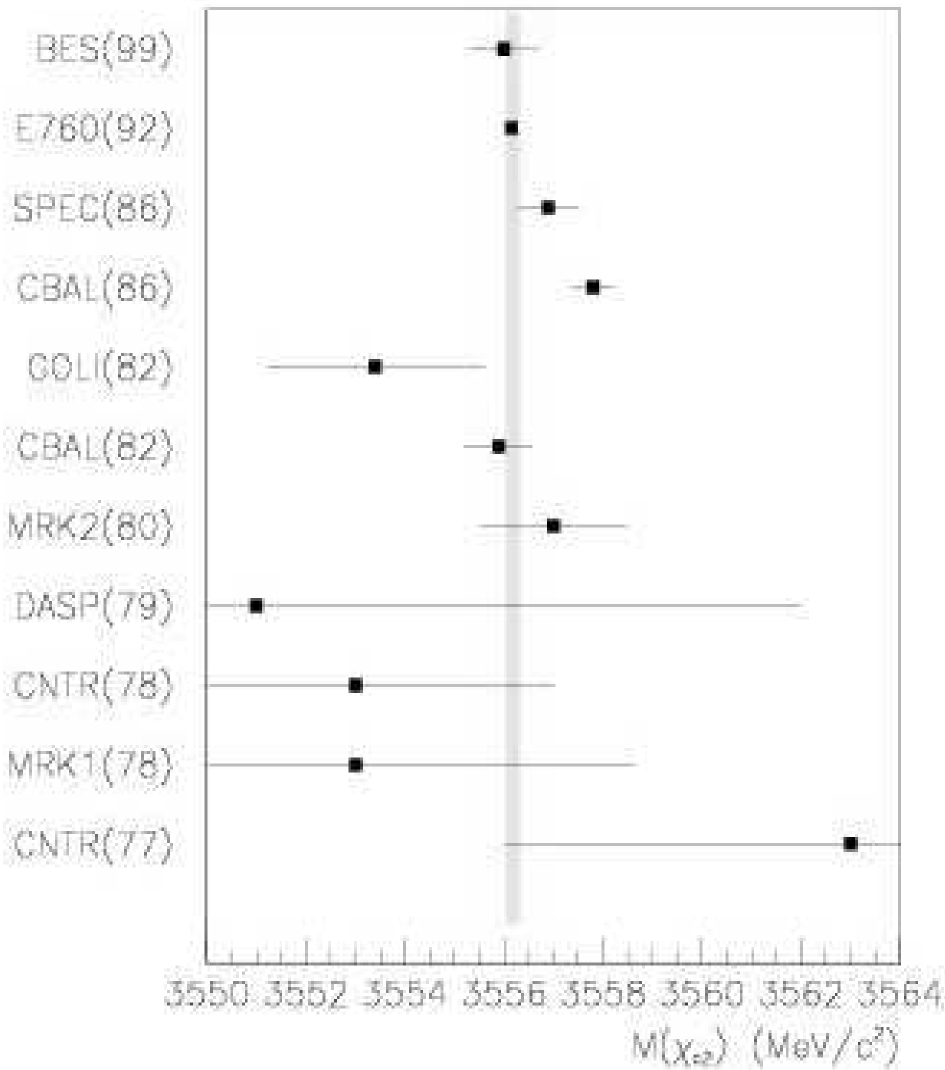
The $\chi_{c2}(^3P_2)$ state

The χ_{c2} resonance excitation curve observed by E760

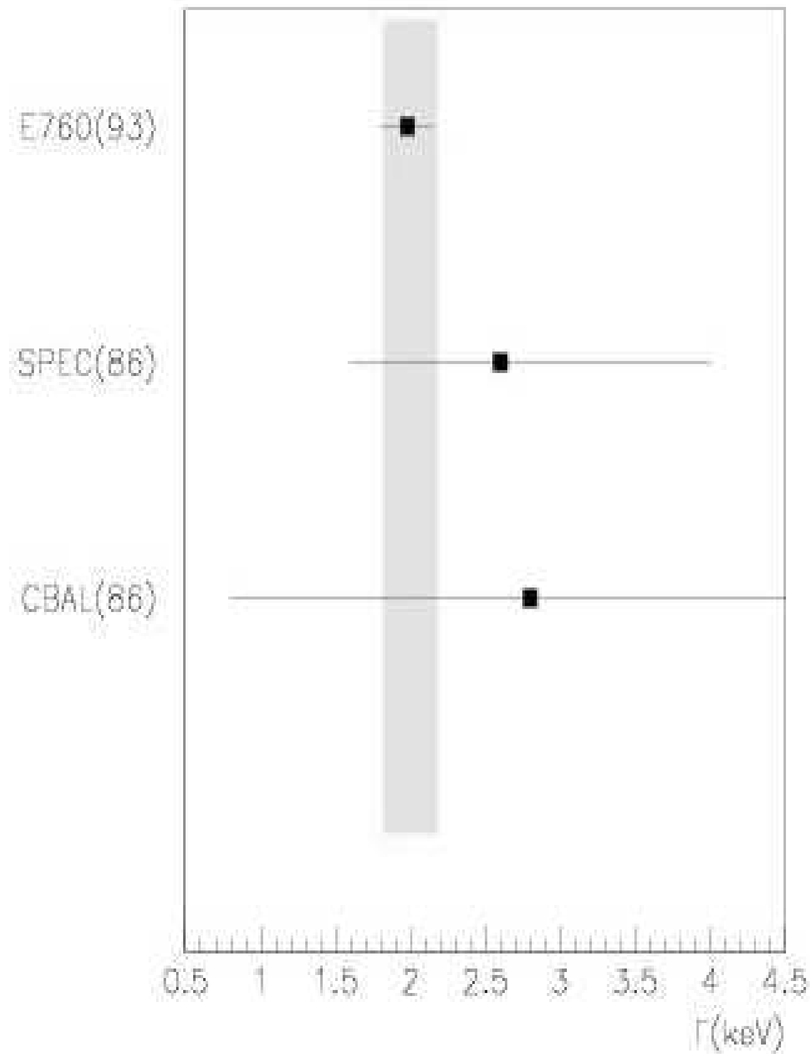


The $\chi_{c2}(^3P_2)$ state

mass measurements



total width measurements



The D wave states

- The charmonium "D states" are above the open charm threshold (3730 MeV) but the widths of the J= 2 states ${}^3D_2$ and ${}^1D_2$ are expected to be small:

State	Predicted energy (MeV)	Experiment data (MeV)
$1\,{}^3S_1$	3097	3096.88 ± 0.04
$1\,{}^1S_0$	2987	2978.8 ± 1.9^a
$2\,{}^3S_1$	3686	3686.00 ± 0.09
$2\,{}^1S_0$	3620	3594.0 ± 5.0
$1\,{}^3P_2$	3554	3556.17 ± 0.13
$1\,{}^3P_1$	3512	3510.53 ± 0.12
$1\,{}^3P_0$	3412	3415.1 ± 1.0
$1\,{}^1P_1$	3527	3526.14 ± 0.24
$1\,{}^3D_3$	3843	
$1\,{}^3D_2$	3819	
$1\,{}^3D_1$	3789	3769.9 ± 2.5
$1\,{}^1D_2$	3820	

${}^{1,3}D_2 \not\to \overline{D}D$ forbidden by parity conservation

${}^{1,3}D_2 \not\to \overline{D}D^*$ forbidden by energy conservation

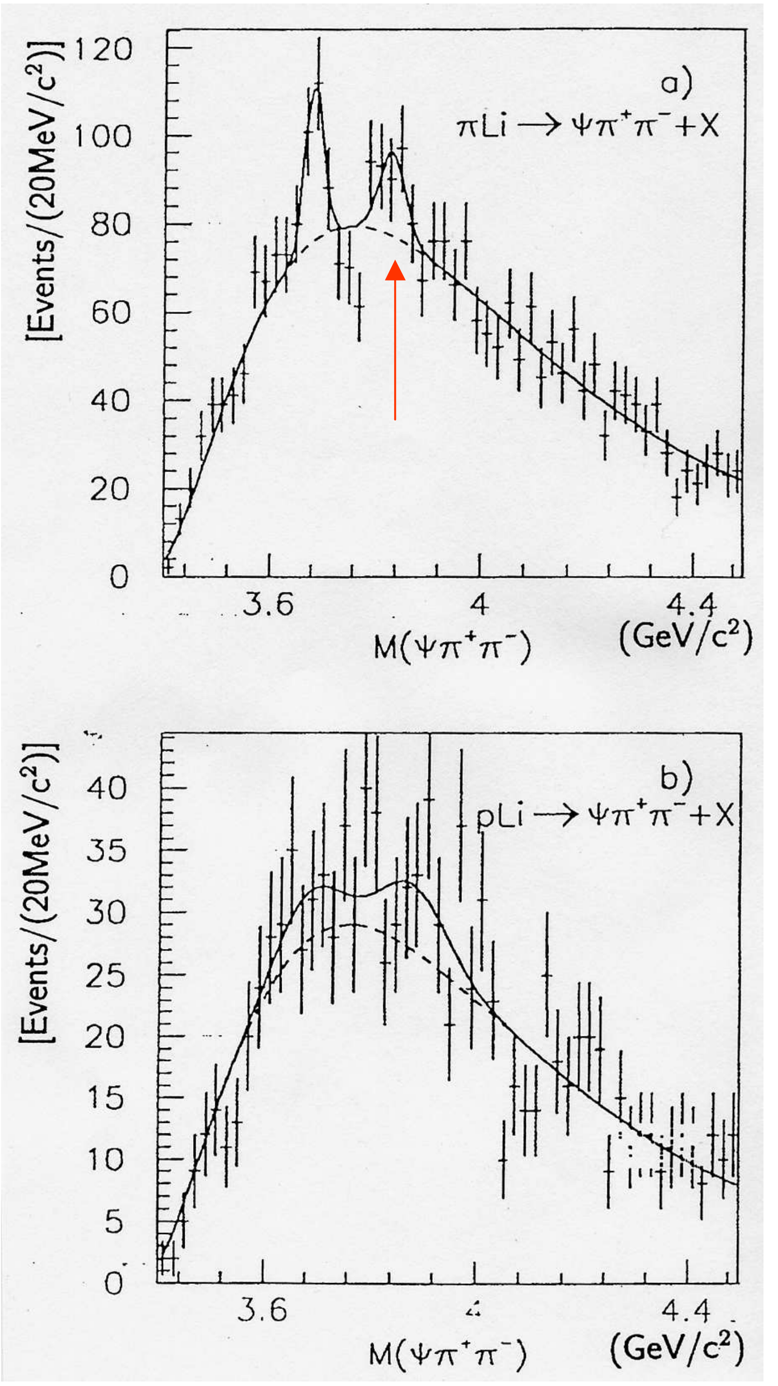
- Only the $\psi(3770)$, considered to be largely ${}^3D_1$ state, has been clearly observed

The D wave states

- The only evidence of another D state has been observed at Fermilab by experiment E705 at an energy of 3836 MeV, in the reaction:

$$\pi Li \rightarrow J/\psi \pi^+ \pi^- + X$$

- This evidence was not confirmed by the same experiment in the reaction $pLi \rightarrow J/\psi \pi^+ \pi^- + X$ and more recently by BES



Conclusions

After almost 30 years since its discovery we have learned a lot about charmonium. But, still, many questions, like the non observation of the η_c' , the confirmation of the ${}^1P_1$ resonance and the poor knowledge of the D states are still open questions and efforts should be put to solve them.