Recent results from FNAL E835 on the study of charmonium states in proton-antiproton annihilation

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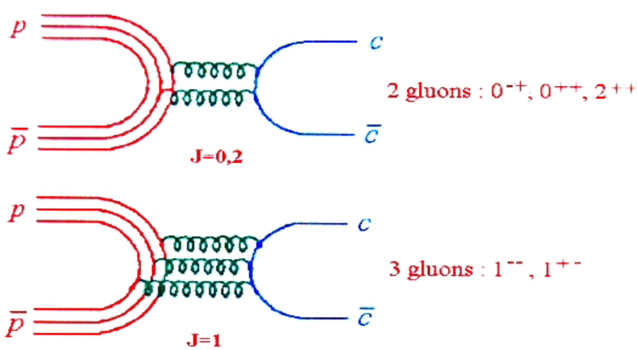
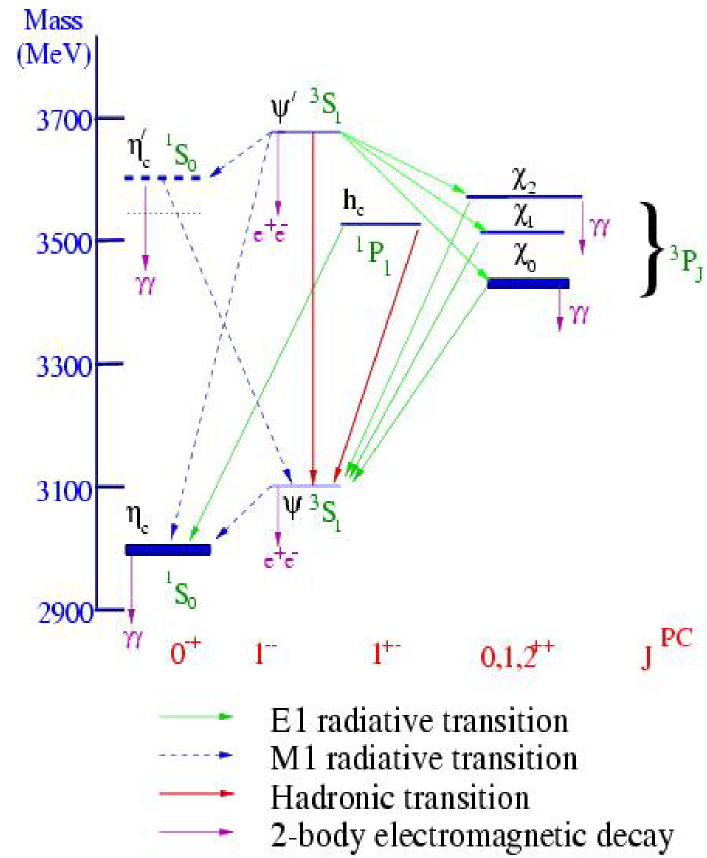
Charmonium spectroscopy in $\bar{p}p$ annihilation

- e^+e^- annihilation ⇒ only $J^{PC}=1^{--}$ states directly formed (J/ψ and ψ')
- γγ fusion ⇒ all C=+ (J≠1) states directly accessible
- B factory
- $\bar{p}p$ annihilation ⇒ all the states directly formed through 2 or 3 gluons intermediate states





$$\sigma(\bar{p}p \to had) \approx 70mb$$
$$\sigma(\bar{p}p \to J/\psi \to e^+e^-) \approx 25nb$$

- Large hadronic background
- Detection of electromagnetic final states

Antiproton beam and target

TARGET:

- Hydrogen gas-jet target
- Hydrogen clusters density:

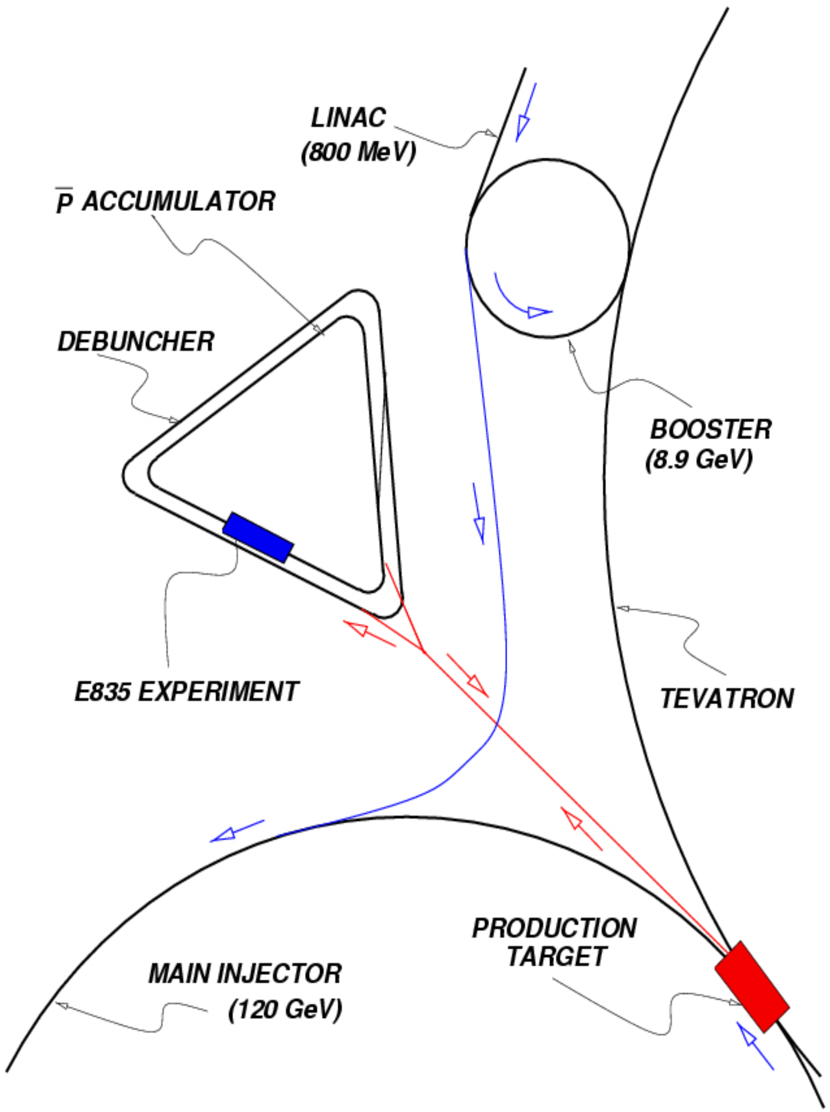
  $1 – 4 \cdot 10^{14}$ atoms/cm^3
- The H_2 target density can be tuned to obtain constant luminosity:

  $L_{INST} \sim 2 \cdot 10^{31}$ cm^{-2}s^{-1}
- Target dimension ≈ 7 mm

BEAM:

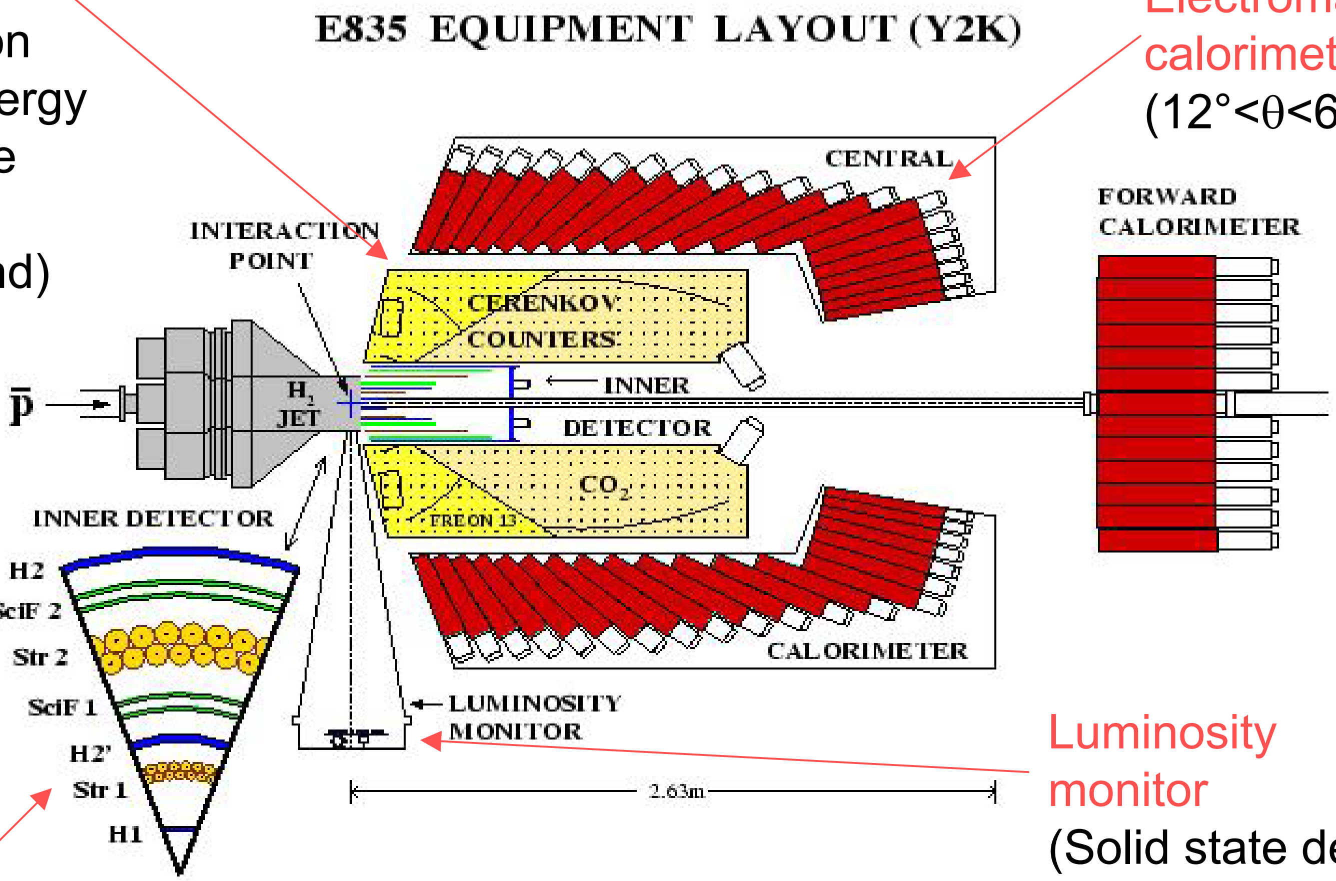
- Antiprotons are accumulated until the desired current is reach. Then they are stochastically cooled and decelerated to the desired energy (continuous beam)
- The total CM energy can be determined directly from the antiproton beam parameter

  $\sigma_E \approx 400$keV - $\sigma_E / E \approx 10^{-4}$
- Beam dimension ≈ 5 mm



Detector

Threshold Čerenkov counters (Separation of high energy $e^{\pm}$ from the hadronic background)



Electromagnetic calorimeter ($12° < \theta < 68°$)

Charged tracking system ($15° < \theta < 60°$)

Luminosity monitor (Solid state detector. Counter of elastic $\bar{p}p$ interactions at 90°)

Experimental technique

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

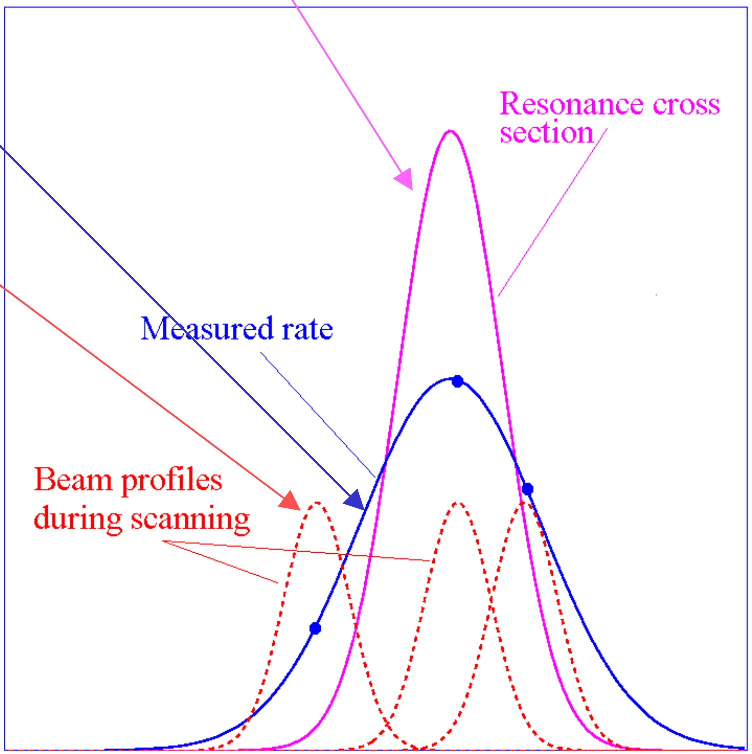
- The beam energy is moved to scan the resonance (precision $\sigma_E \approx 250$ keV)

- The number of events N at energy E is obtained as:

$$N(E) = \int L dt \cdot \varepsilon \cdot \left[\sigma_{bkg}(E) + \int \sigma_{BW}(E') G(E' - E) dE' \right]$$

  - L = instantaneous luminosity
  - $G(E)$ = beam energy distribution (gaussian)
  - ε = detection efficiency

- The resonance cross section is obtained by deconvolution of the measured rate with the beam profile

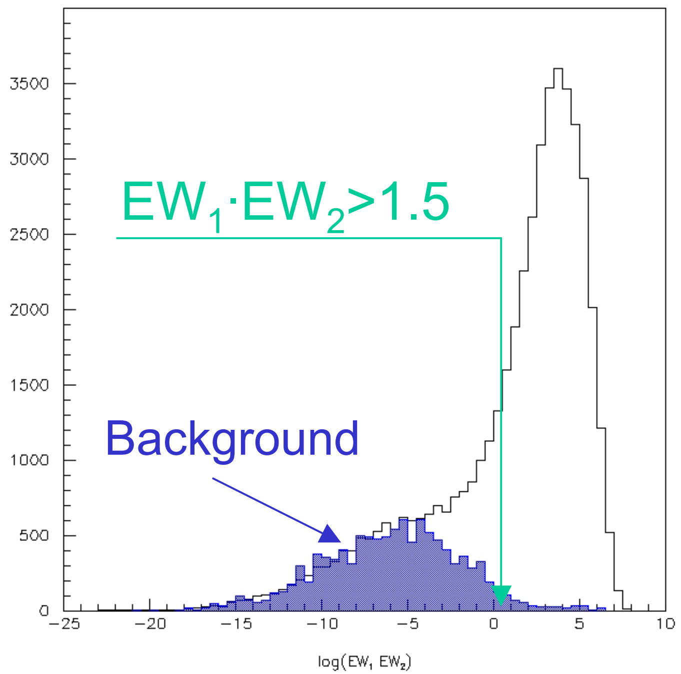


Event selection where final state includes e^+e^-

- Selection of electron / positron candidates:
  - high energy deposition in calorimeter
  - signal in the hodoscopes
  - signal in Čerenkov

- Electron Weight (EW):
  - Maximum likelihood method for the single electron selection based on calorimeter cluster shape and pulse height in Čerenkov and hodoscopes.

- Kinematic fit

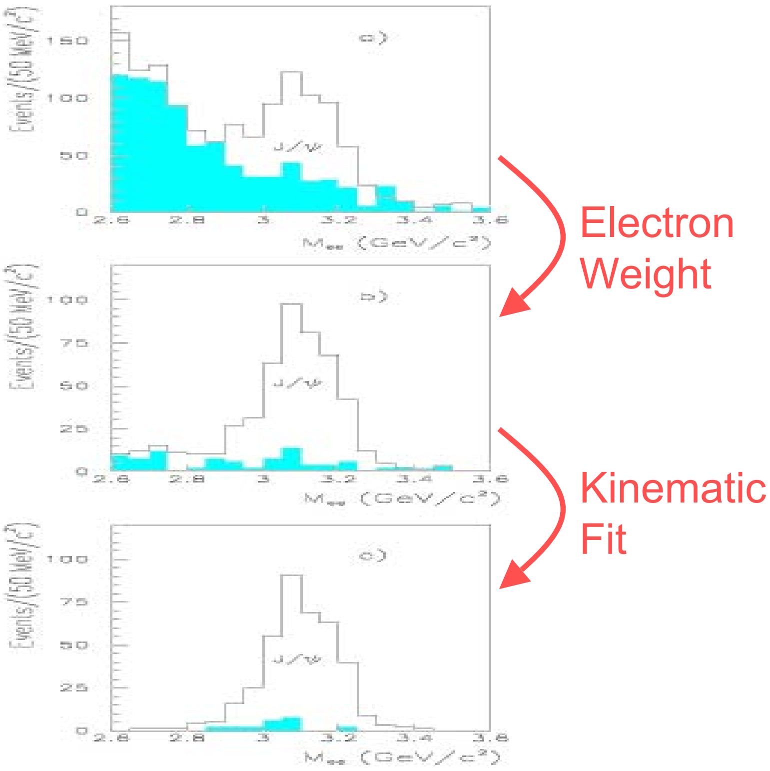


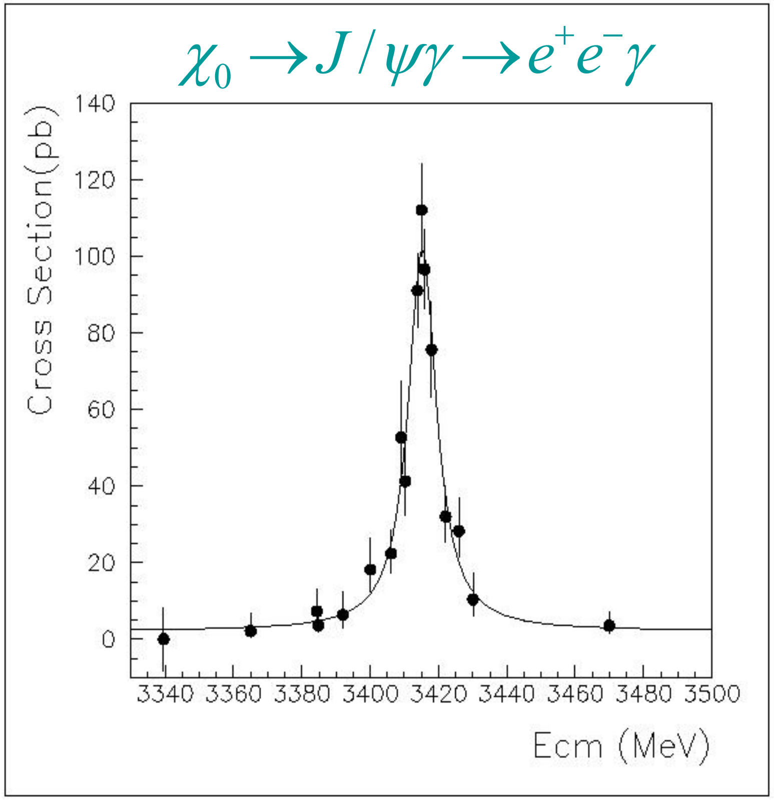
χ_0 mass and width

Luminosity: ~33 pb^{-1} (~20 pb^{-1} on resonance) on 17 energy points

Selected channel: radiative decay to J/ψ

N. Selected events: ~400



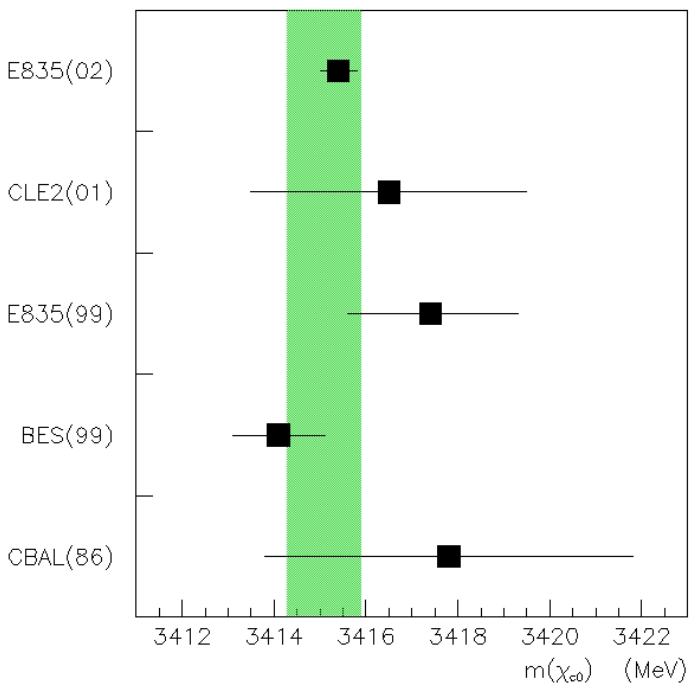


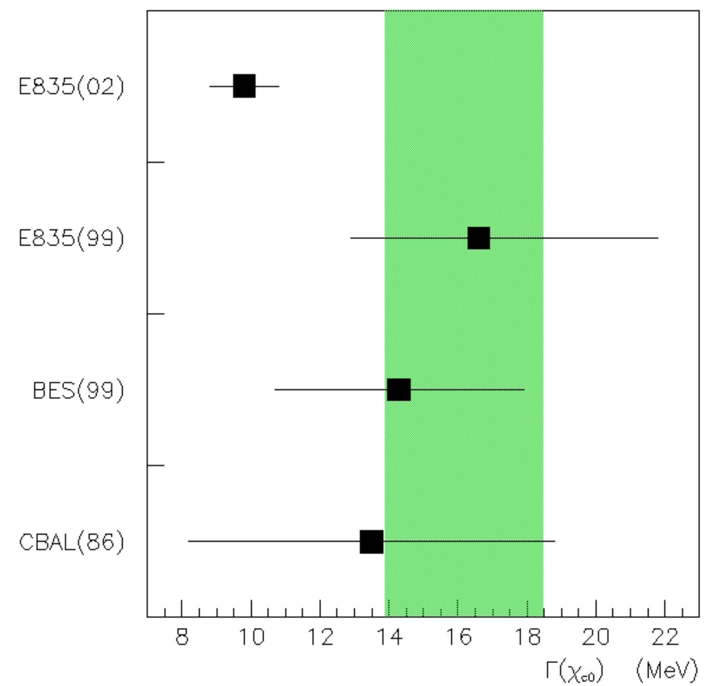
χ_0 mass and width

$$M = 3415.4 \pm 0.4 \pm 0.2 MeV / c^2$$

$$\Gamma = 9.8 \pm 1.0 \pm 0.1 MeV$$

$$BR(\chi_0 \rightarrow \bar{p}p) \times BR(\chi_0 \rightarrow J/\psi\gamma) \times BR(J/\psi \rightarrow e^+e^-) = (1.61 \pm 0.11 \pm 0.08) \times 10^{-7}$$





$\gamma\gamma$ final state selection

- Exactly 2 “on-time” clusters in the central calorimeter with high energy deposit and invariant mass within 20% of E_{CM}
- No “undetermined-time” extra clusters with invariant mass within 35 MeV of the π^0 mass
- 4C kinematic fit to $\gamma\gamma$
- $|\cos(\theta^*)|$ cut to improve signal to background ratio

$\gamma\gamma$ background (feeddown)

•Background mainly from:

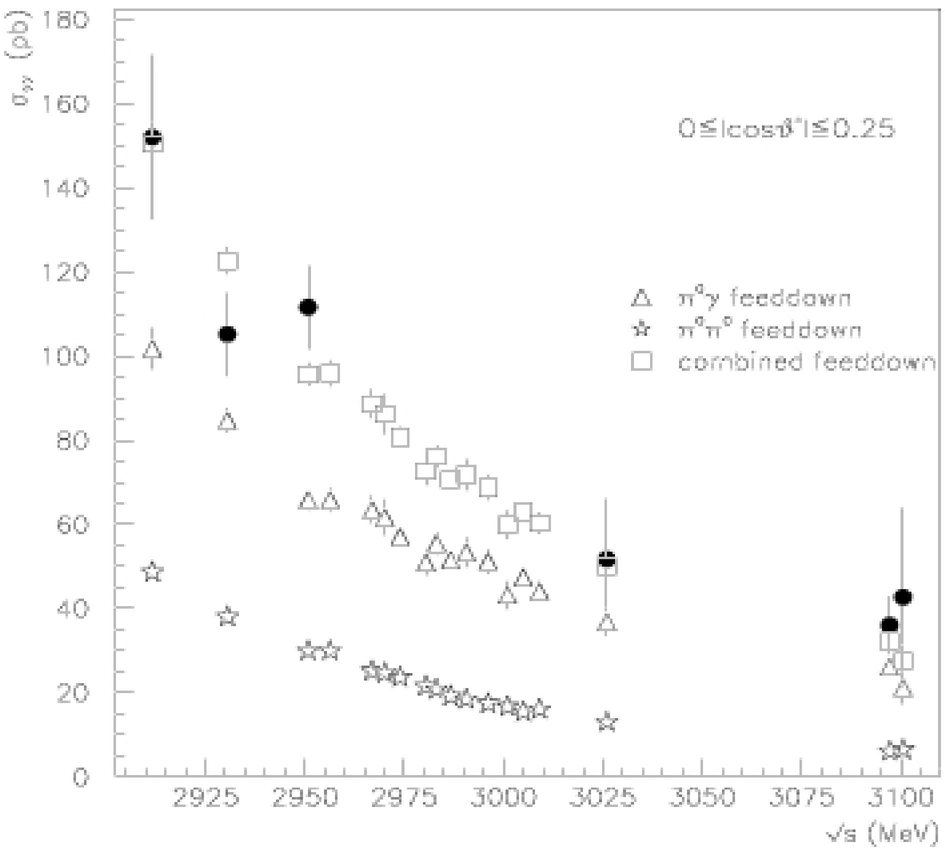
$$\bar{p}p \rightarrow \pi^0\gamma \rightarrow 3\gamma$$

$$\bar{p}p \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$$

where one or more photons are missing because of acceptance or calorimeter energy thresholds

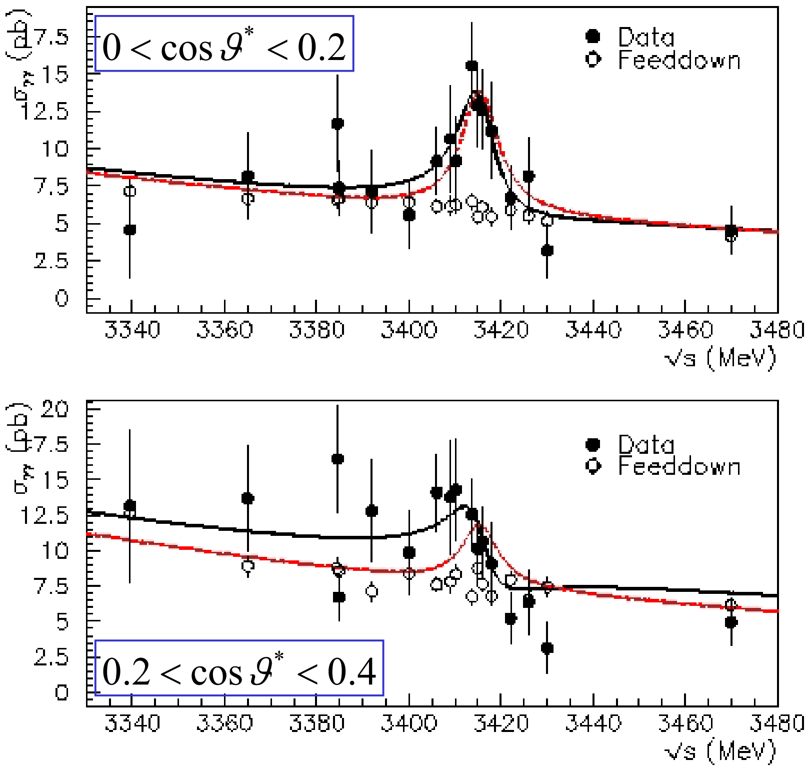
•Measurement of the cross section for the background processes and Monte Carlo determination of the background contribution

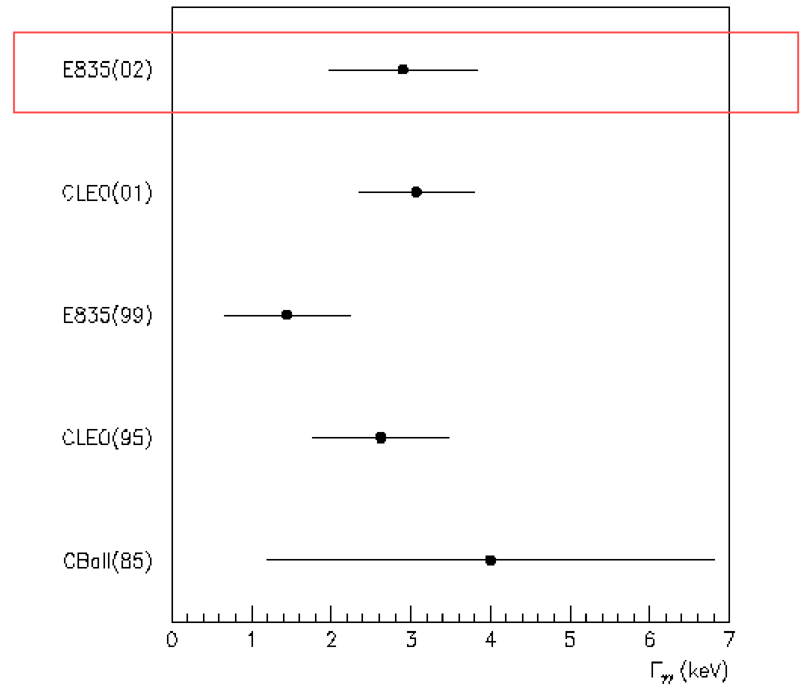
•Comparison with measured $\gamma\gamma$ cross section for off-resonance points



Preliminary

$\chi_0 \rightarrow \gamma\gamma$





$$BR(\chi_0 \rightarrow \bar{p}p) \times BR(\chi_0 \rightarrow \gamma\gamma) = (6.52 \pm 1.18 \pm 0.55) \times 10^{-8}$$

Taking $BR(\chi_0 \rightarrow \bar{p}p)$ from the PDG: $\Gamma(\chi_0 \rightarrow \gamma\gamma) = 2.9 \pm 0.9 keV$

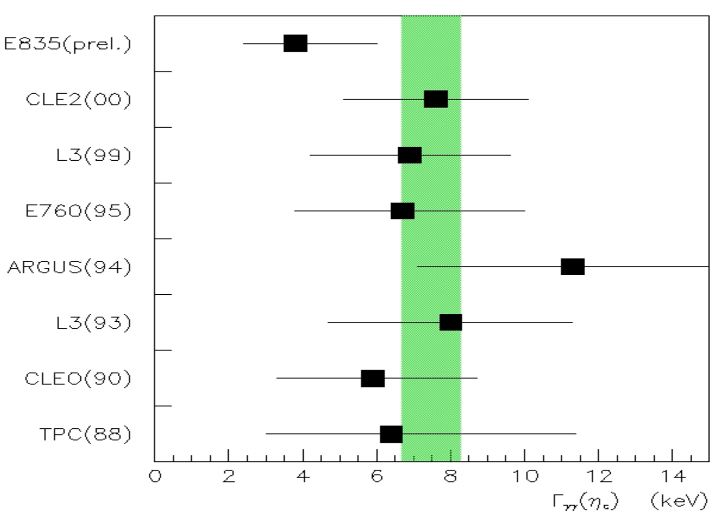
$\eta_c \rightarrow \gamma\gamma$

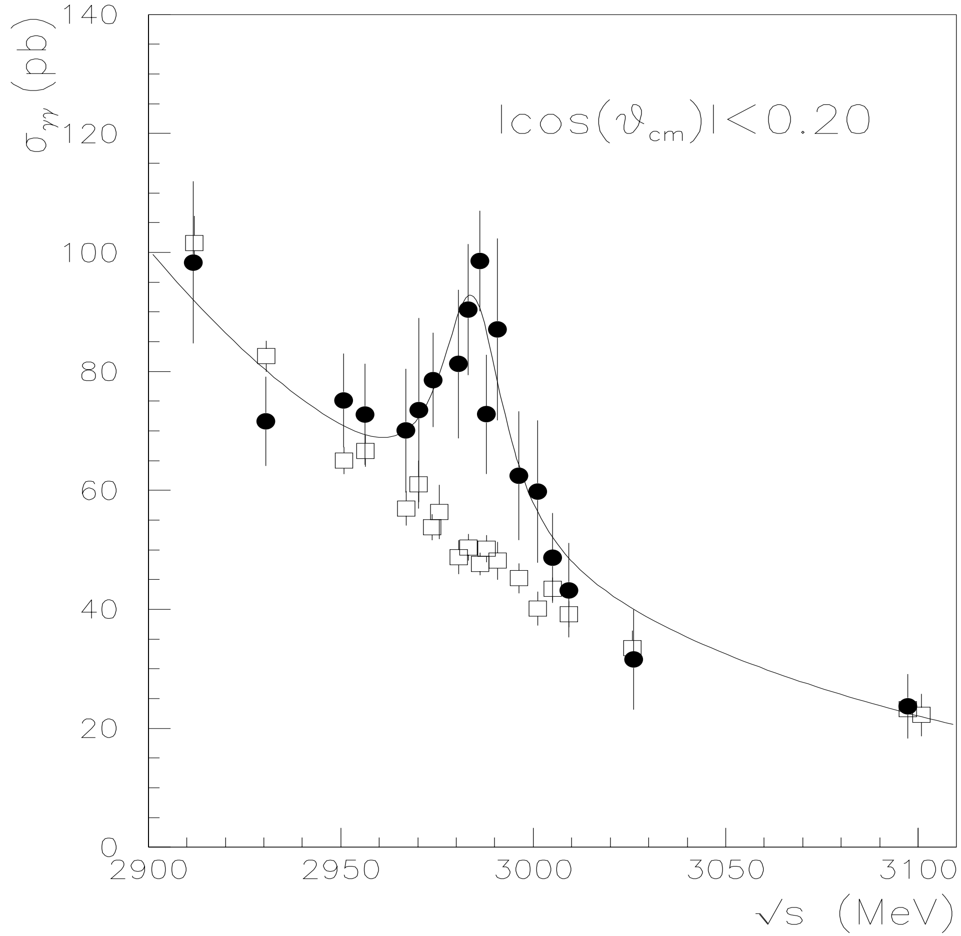
- 18.9 pb^{-1} of data
- All the resonance parameters are measured in the $\gamma\gamma$ channel:

$$M = 2984.1 \pm 2.1 \pm 1.0 MeV / c^2$$

$$\Gamma = 20.4^{+7.7}_{-6.7} \pm 2.0 MeV$$

$$\Gamma_{\gamma\gamma} = 3.8^{+1.1+1.9}_{-1.0-1.0} 1 keV$$





Interference between $\bar{p}p \rightarrow \chi_0 \rightarrow \pi^0\pi^0$ and the continuum

Preliminary

Measurement of the cross section for the process $\bar{p}p \rightarrow \pi^0\pi^0$ in the χ_0 energy region

~500000 $\pi^0\pi^0$ candidates

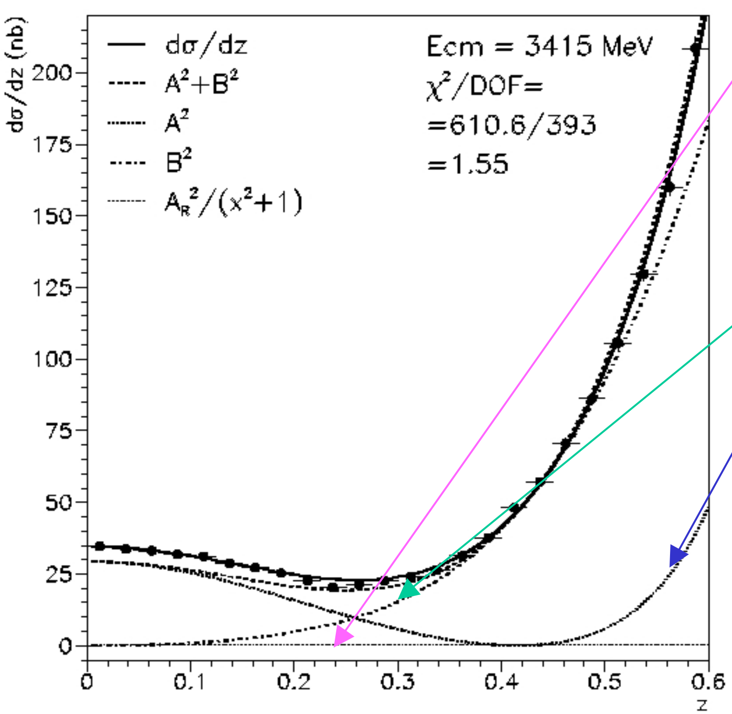
$$\frac{d\sigma}{dz}(x,z) = \left| \frac{-A_R}{x+i} + Ae^{i\delta_A} \right|^2 + \left| Be^{i\delta_B} \right|^2$$

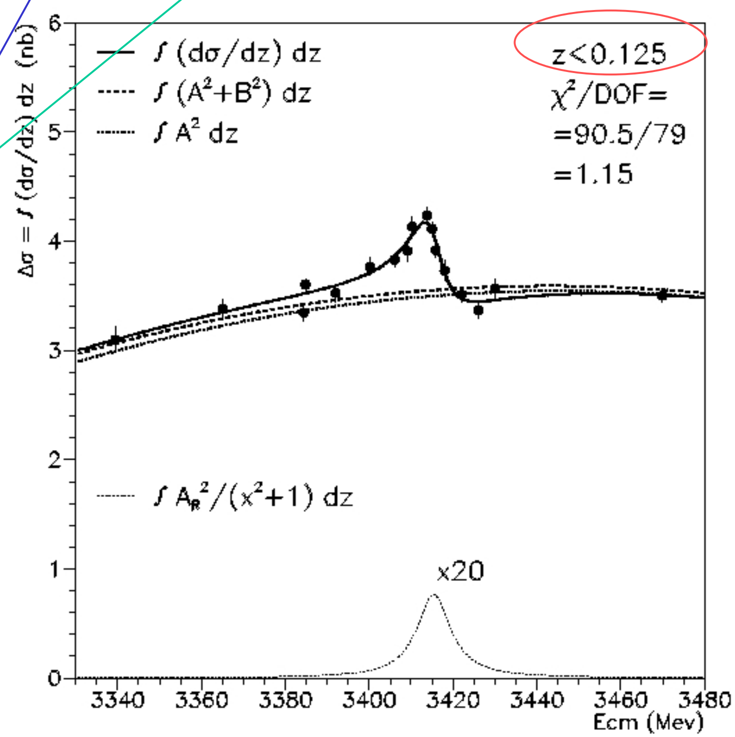
$$\begin{cases} x = \dfrac{E_{CM} - M_{\chi_0}}{\Gamma_{\chi_0}/2} \\ z = \cos\vartheta^* \end{cases}$$

Resonant

Interfering (helicity 0)

Non-Interfering (helicity 1)





χ_0 branching ratios

$$BR(\chi_0 \to \bar{p}p) \times BR(\chi_0 \to \pi^0\pi^0) = (5.09 \pm 0.81 \pm 0.25) \times 10^{-7}$$

Using the PDG value: $BR(\chi_0 \to \pi^0\pi^0) = BR(\chi_0 \to \pi^+\pi^-)/2 = (2.50 \pm 0.35) \times 10^{-3}$

$$BR(\chi_0 \to \bar{p}p) = (2.04 \pm 0.43 \pm 0.10) \times 10^{-4}$$

To be compared with the PDG: $BR(\chi_0 \to \bar{p}p) = (2.2 \pm 0.5) \times 10^{-4}$

Using the result: $BR(\chi_0 \to \bar{p}p) \times BR(\chi_0 \to J/\psi\gamma) \times BR(J/\psi \to e^+e^-) =$
$= (1.61 \pm 0.11 \pm 0.08) \times 10^{-7}$

$$\frac{BR(\chi_0 \to J/\psi\gamma)}{BR(\chi_0 \to \pi^0\pi^0)} = 5.34 \pm 0.93 \pm 0.34$$

$$BR(\chi_0 \to J/\psi\gamma) = (13.3 \pm 3.0 \pm 0.9) \times 10^{-3}$$

To be compared with the PDG: $BR(\chi_0 \to J/\psi\gamma) = (10.2 \pm 1.7) \times 10^{-3}$

Electric dipole trasition ($P \rightarrow S+\gamma$)

The value obtained for $\Gamma(\chi_0 \rightarrow J/\psi\gamma)$, using the new total width and the BR measurements, is consistent with the theory of electric dipole transition

$$\Gamma(P \rightarrow S+\gamma) = \frac{4}{9} e_Q^2 \alpha k^3 \, | E_{if} |^2 \qquad \begin{cases} k = \dfrac{M_i^2 - M_f^2}{2M_i} \\ | E_{if} | = \displaystyle\int_0^\infty dr R_i(r) \cdot r^2 \cdot R_f(r) \end{cases}$$

	$\Gamma(J/\psi\gamma)_{exp}$ (keV)	k (MeV)	Γ/k^3 (MeV^{-2})
χ_0	130±33	304	$(4.6\pm1.2)\times10^{-9}$
χ_1	290±50	390	$(4.9\pm0.8)\times10^{-9}$
χ_2	389±52	430	$(4.9\pm0.7)\times10^{-9}$

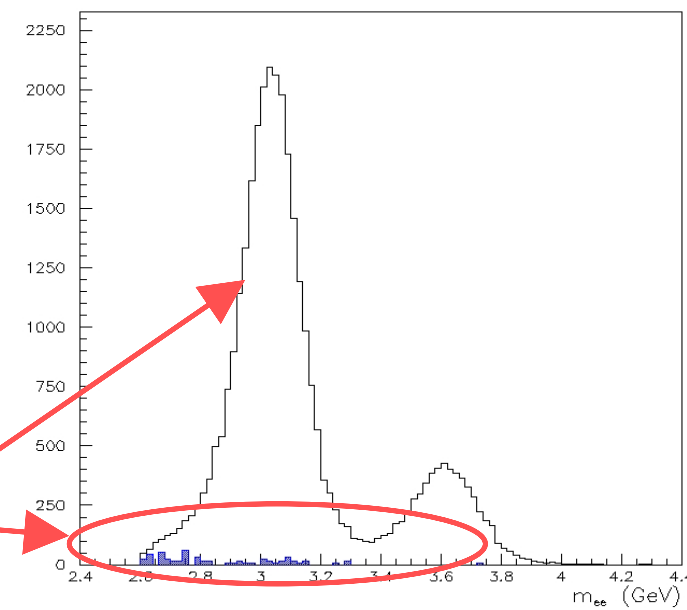
e^+e^- final states selection at the ψ'

- ψ' and J/ψ detected through their e^+e^- decay

$$\psi' \to e^+e^-$$
$$\left.\begin{array}{l} \psi' \to J/\psi\pi^+\pi^- \to e^+e^-\pi^+\pi^- \\ \psi' \to J/\psi\pi^0\pi^0 \to e^+e^-4\gamma \\ \psi' \to J/\psi\eta \to e^+e^-2\gamma \end{array}\right\} \quad \psi' \to J/\psi X \to e^+e^- X$$

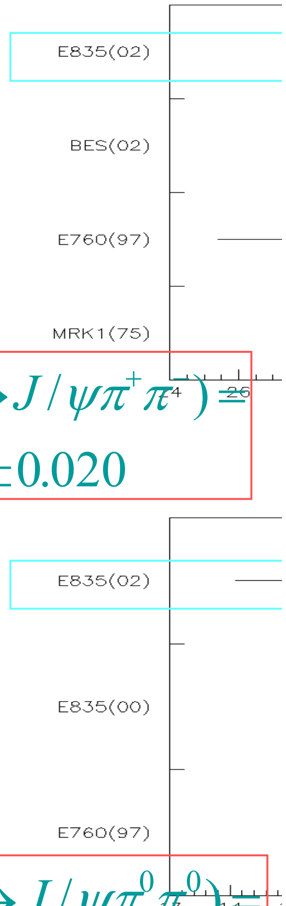
- All the exclusive channels are selected with kinematic fits

- 14.3 pb^{-1} of data in the ψ' energy region collected in year 2000
  - 12.4 pb^{-1} on resonance ⇒ 32862 events
  - 1.9 pb^{-1} off resonance ⇒ 66 events



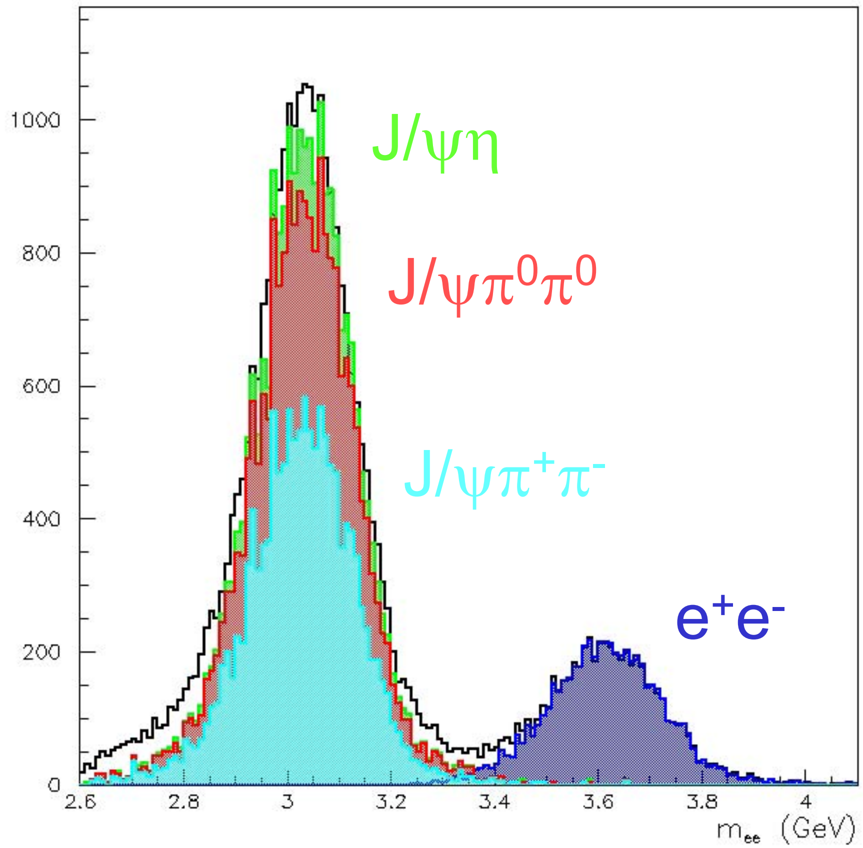
ψ' branching ratios

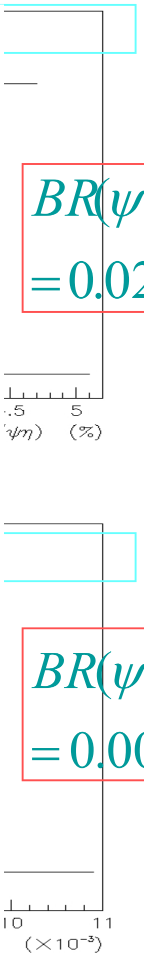
Preliminary



$$BR(\psi' \to J/\psi\pi^+\pi^-) = 0.294 \pm 0.020$$

$$BR(\psi' \to J/\psi\pi^0\pi^0) = 0.164 \pm 0.019$$





$$BR(\psi' \to J/\psi\eta) = 0.028 \pm 0.004$$

$$BR(\psi' \to e^+e^-) = 0.0063 \pm 0.0004$$

Conclusions

- Charmonium states are studied in proton – antiproton annihilation detecting electromagnetic final states
- Extensive study of the χ_{c0} ...
  - Mass and total width
  - $\gamma\gamma$ width
  - Interference in $\pi^0\pi^0$ decay
- ... and of the η_c
  - Mass and total width
  - $\gamma\gamma$ width
- New measurement of $BR(\psi' \to J/\psi\, X)$ and $BR(\psi' \to e^+e^-)$