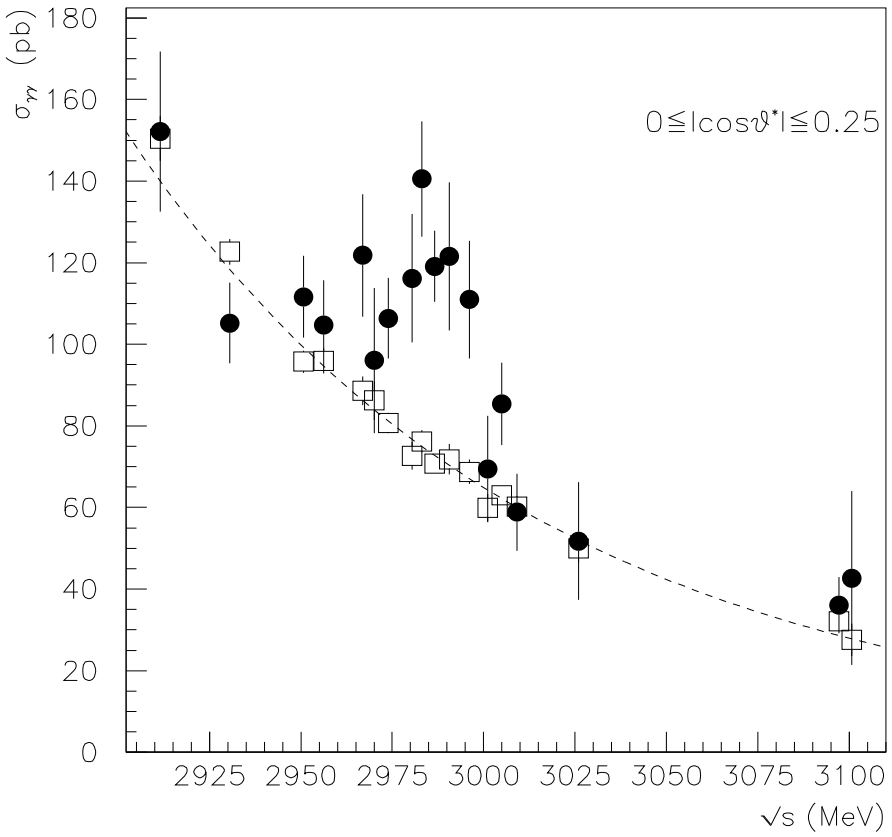
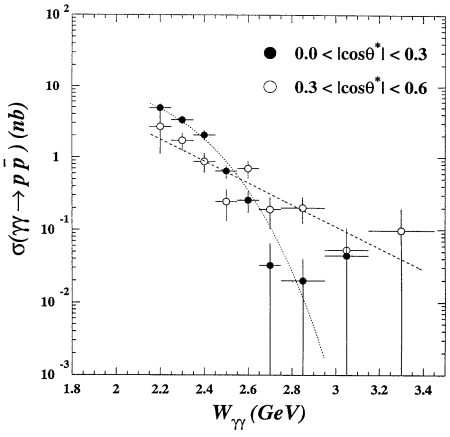
- Summary
  - Improved measurement of the η_c resonance parameters
  - Improved meaurement of the $\chi_2 \to \gamma\gamma$ partial width
  - Extended search for the η_c'
  - Hints of $\bar{p}p \to \chi_0 \to \gamma\gamma$
- Second E835 running period
  - Improve measurements of the χ_0 resonance parameters
  - Confirm $^1P_1$ discovery by E760

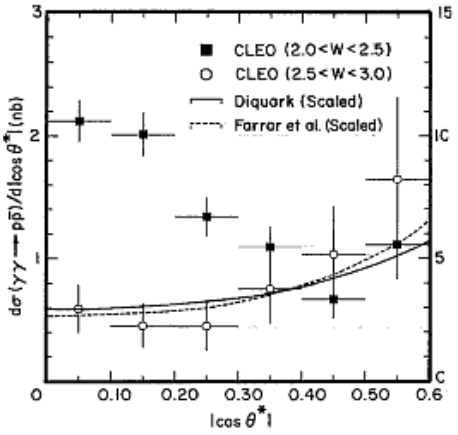
$\bar{p}p \to \gamma\gamma$



VENUS: Phys. Lett. **B407** 185 (1997)

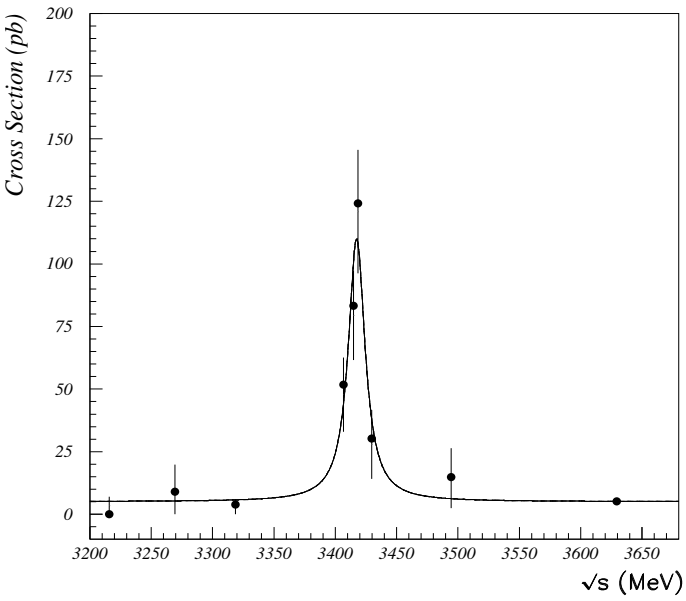


CLEO: Phys. Rev **D50** 5484 (1994)

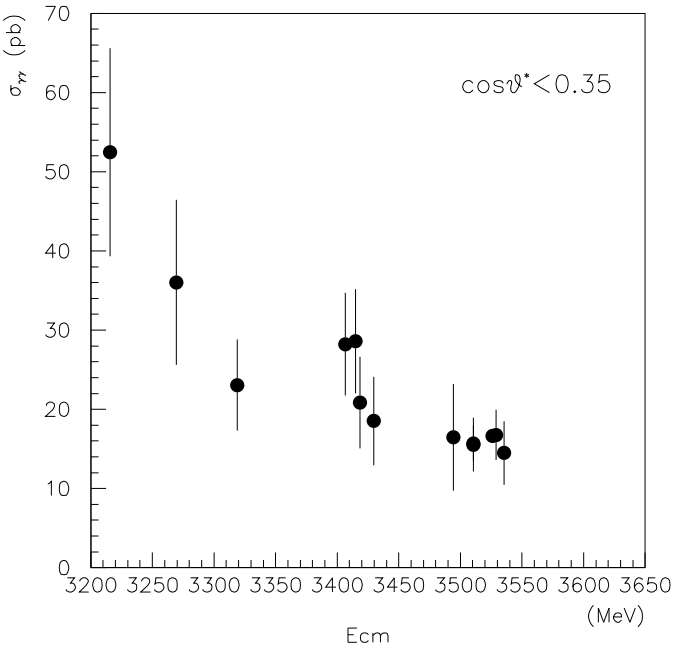


$\chi_0 (1^3P_0)$

PRELIMINARY



$\chi_0 \rightarrow \psi\gamma$

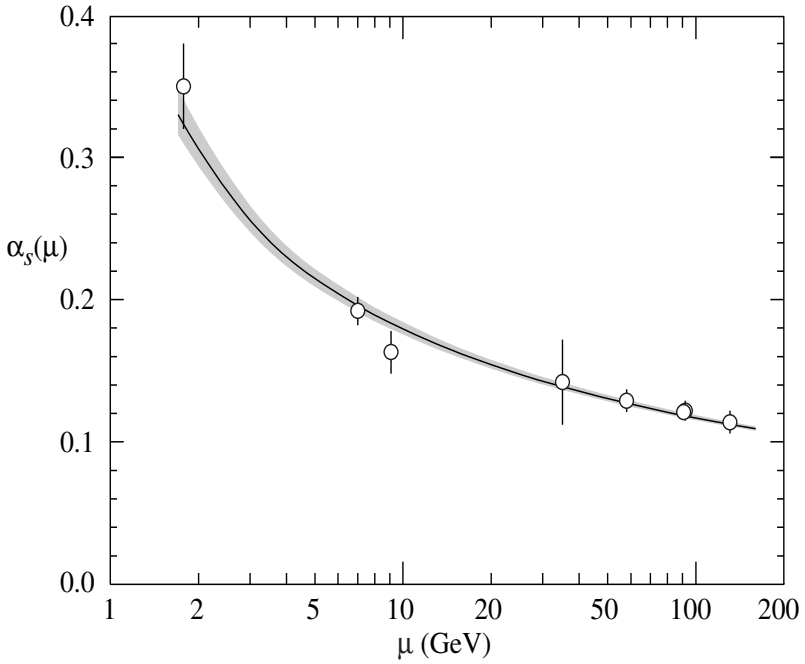


$\chi_0 \rightarrow \gamma\gamma$

Determination of $\alpha_s(m_c)$

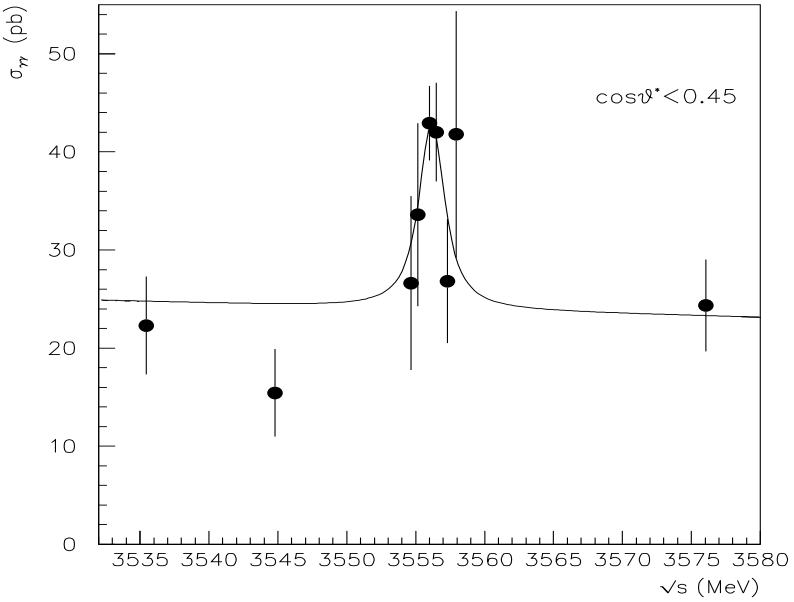
$$\frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\eta_c \to gg)} = \frac{8\alpha^2}{9\alpha_s^2} \cdot \frac{\left[1 - \frac{3.4}{\pi}\alpha_s\right]}{\left[1 + \frac{4.8}{\pi}\alpha_s\right]} \Rightarrow \alpha_s(m_c) = 0.32 \pm 0.04$$

$$\frac{\Gamma(\chi_2 \to \gamma\gamma)}{\Gamma(\chi_2 \to gg)} = \frac{8\alpha^2}{9\alpha_s^2} \cdot \frac{\left[1 - \frac{16}{3\pi}\alpha_s\right]}{\left[1 - \frac{2.2}{\pi}\alpha_s\right]} \Rightarrow \alpha_s(m_c) = 0.36 \pm 0.02$$



$\chi_2\,(1^3P_2)$

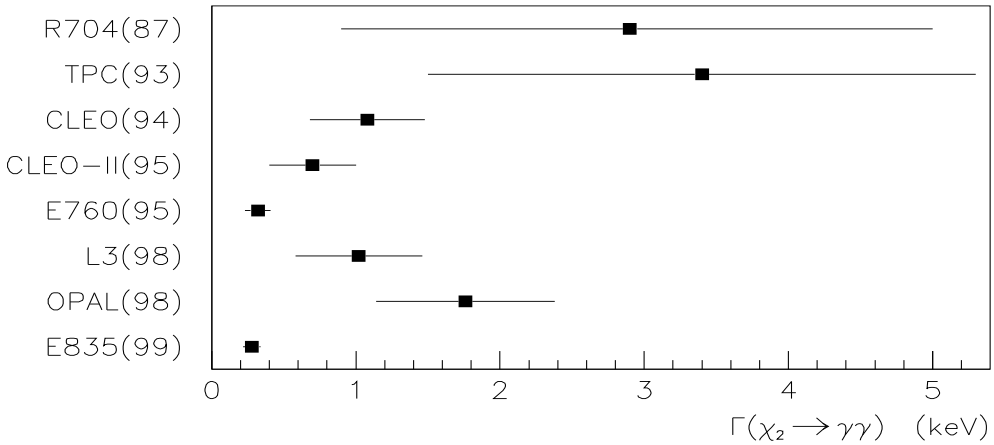
PRELIMINARY



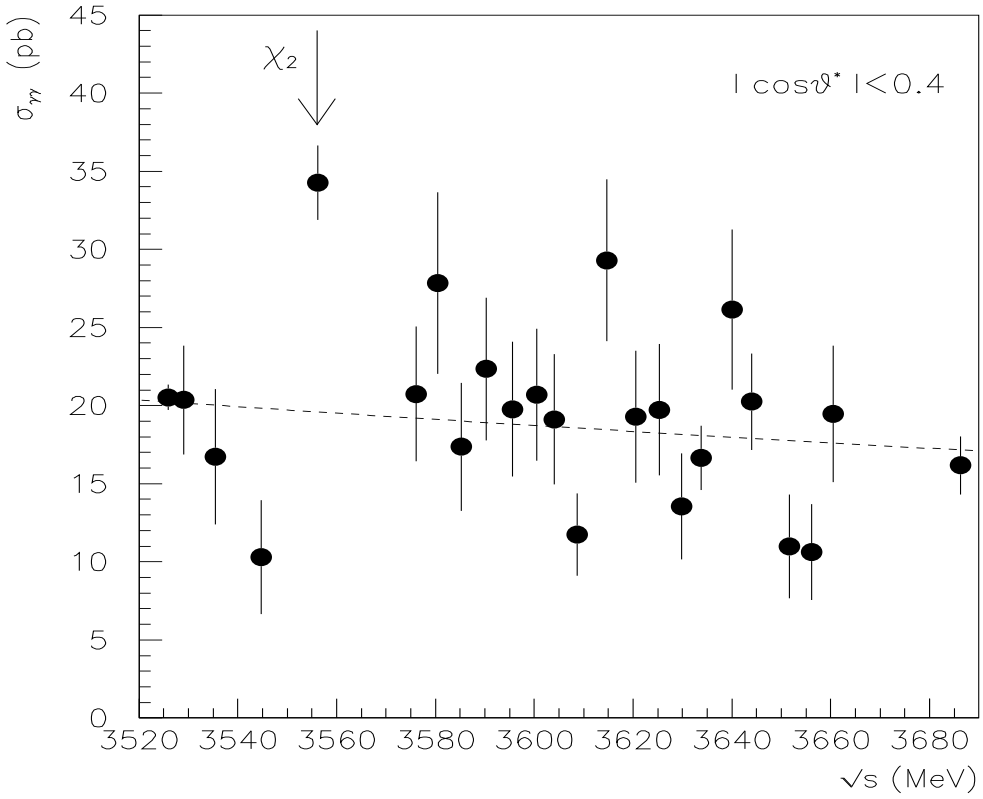
$M(\chi_2)=3556.17 \pm 0.13$ MeV, $\Gamma(\chi_2)=2.00 \pm 0.18$ MeV(PDG)

$$\Gamma(\chi_2 \rightarrow \gamma\gamma) = 0.31 \pm 0.05 \pm 0.04 \text{ keV}$$

$$\text{using } B(\chi_2 \rightarrow \bar{p}p) = (1.0 \pm 0.1) \times 10^{-3}$$



Search for $\eta_c'(2^1S_0)$



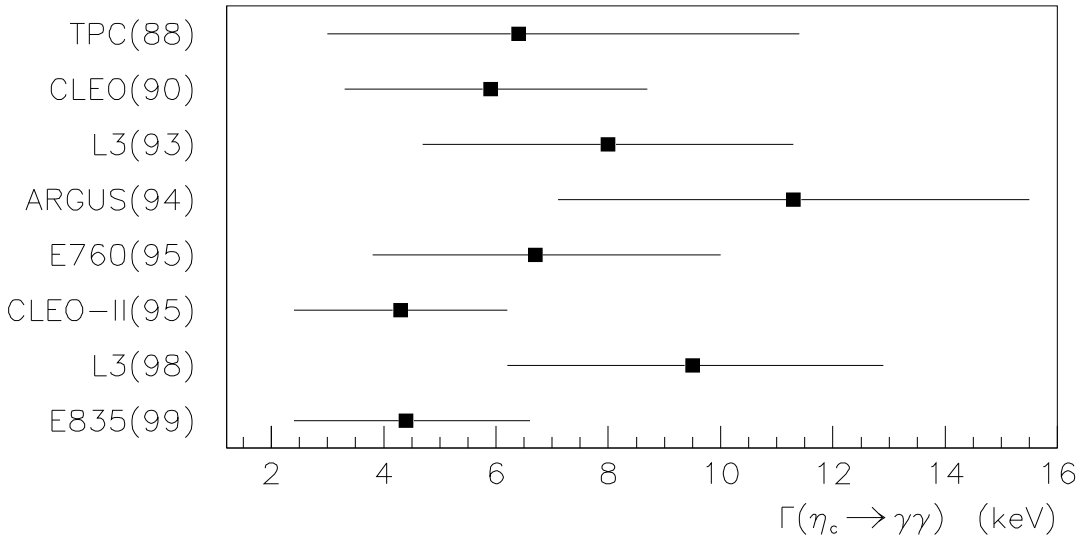
PRELIMINARY

$B(\eta_c' \to \bar{p}p) \times B(\eta_c' \to \gamma\gamma) < 11 \times 10^{-8}$ (90% CL) for Γ=5 MeV

$B(\eta_c' \to \bar{p}p) \times B(\eta_c' \to \gamma\gamma) < 6 \times 10^{-8}$ (90% CL) for Γ=10 MeV

➪ compare with value for the η_c of $(23.8 \pm 3.6) \times 10^{-8}$

$\Gamma(\eta_c \to \gamma\gamma)$



$$\frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\eta_c \to gg)} = \frac{8\alpha^2}{9\alpha_s^2} \cdot \frac{\left[1 - \frac{3.4}{\pi}\alpha_s\right]}{\left[1 + \frac{4.8}{\pi}\alpha_s\right]} \Rightarrow \alpha_s = 0.32 \pm 0.04$$

Assuming that $|\Psi(0)|^2$ is the identical for η_c and J/ψ gives the relation below. Differences in the wave functions may indicate the importance of hyperfine and/or coupled channel effects.

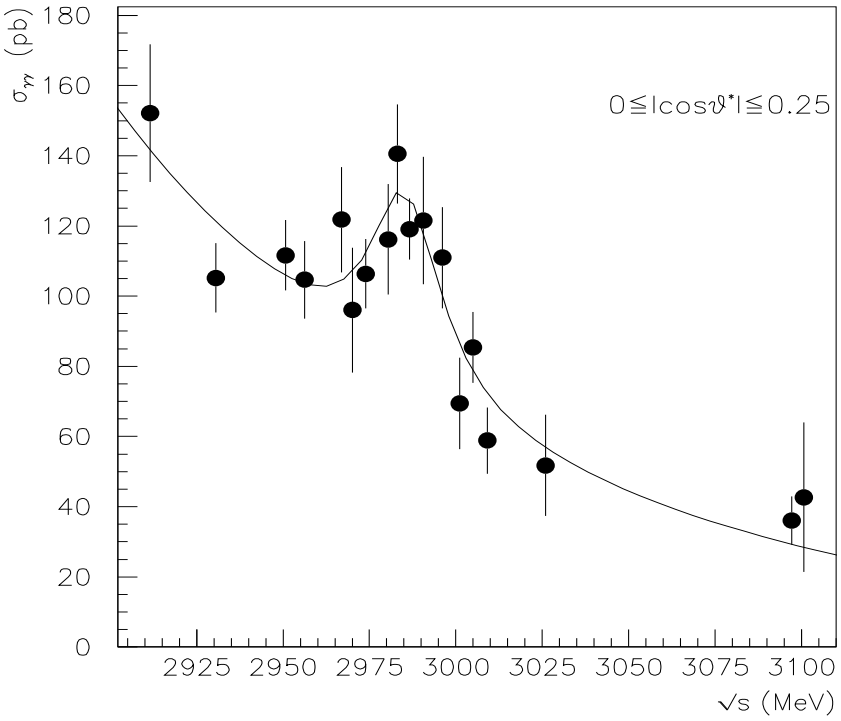
$$\frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(J/\psi \to e^+e^-)} = \frac{4}{3} \cdot \left[1 + \frac{1.96}{\pi}\alpha_s\right] \Rightarrow \Gamma(\eta_c \to \gamma\gamma) \approx 8.6 \text{ keV}$$

E835: $4.4 \pm {}^{1.7}_{1.4} \pm 1.5$ keV

Differences in the wavefunctions are also suggested by the radiative transition $J/\psi \to \eta_c\gamma$, which is weaker than expected by NRQCD.

$\eta_c(1^1S_0)$

PRELIMINARY



$$M(\eta_c) = 2985.1 \pm 2.1 \text{ MeV}$$

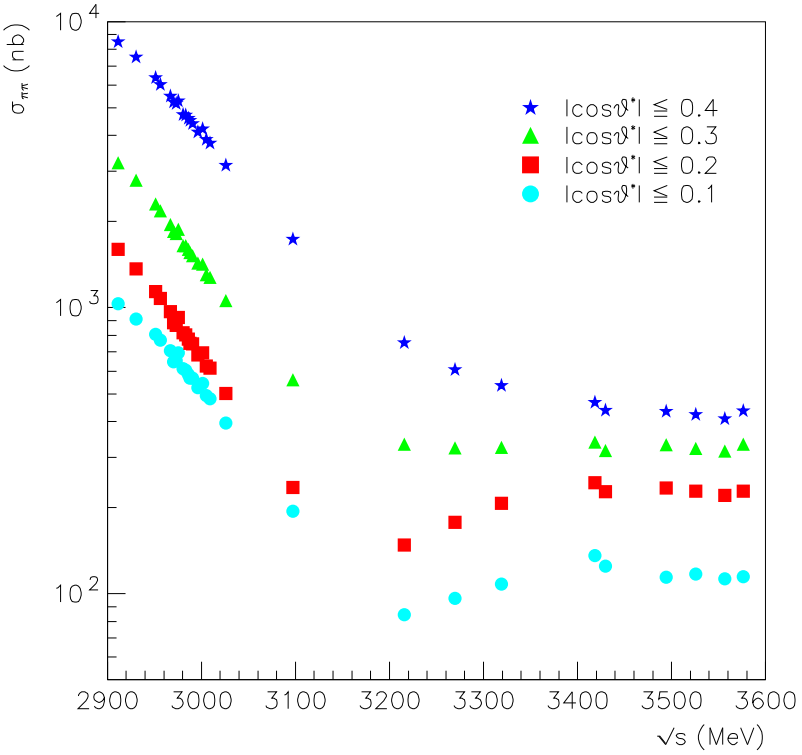
$$\Gamma(\eta_c) = 22.4 \pm {}^{7.8}_{6.4} \text{ MeV}$$

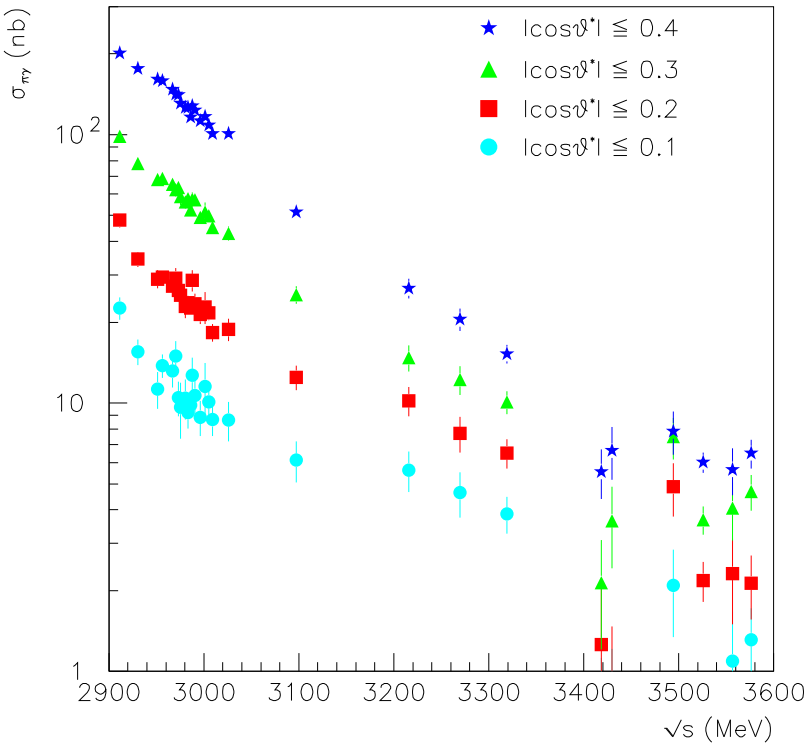
$$B(\eta_c \to \bar{p}p) \times B(\eta_c \to \gamma\gamma) = (23.6 \pm 3.5) \times 10^{-8}$$

$$\Gamma(\eta_c \to \gamma\gamma) = 4.4 \pm {}^{1.7}_{1.4} \pm 1.5 \text{ keV}$$

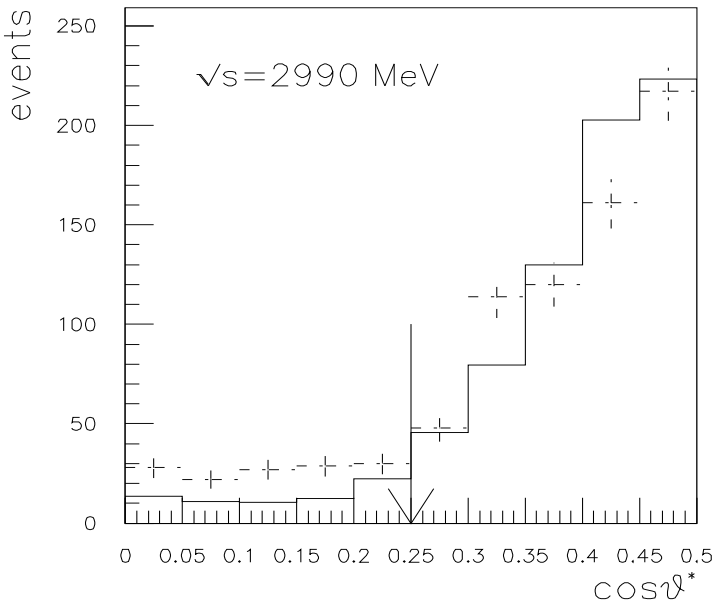
$$\left(\text{using } B(\eta_c \to \bar{p}p) = (12 \pm 4) \times 10^{-4} \right)$$

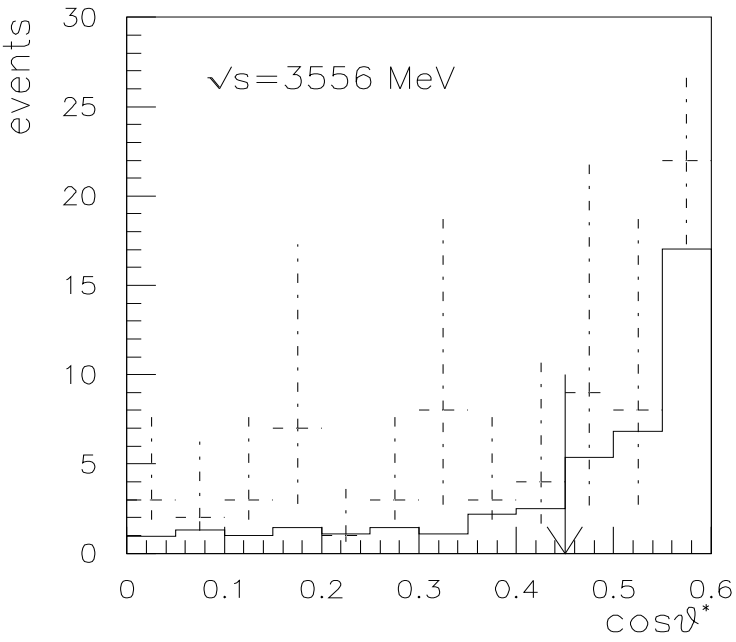
$\pi^0\pi^0$ (above) and $\pi^0\gamma$ (below) cross sections





Angular Distributions





solid = background calculation, dashed = data

$\gamma\gamma$ event selection

- Two high-energy deposits in the CCAL, kinematical fit to $\gamma\gamma$ hypothesis has >5% probability
- No "tracks" in the charged particle detectors
- $|\cos\theta^*| < \alpha(\sqrt{s})$ to improve signal to background ratio

Backgrounds

- $\bar{p}p \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$; two of the photons missing (~5×10^{-3} $\sigma_{\pi\pi}$)
- $\bar{p}p \rightarrow \pi^0\gamma \rightarrow 3\gamma$; one of the photons missing (~0.03 $\sigma_{\pi\gamma}$)

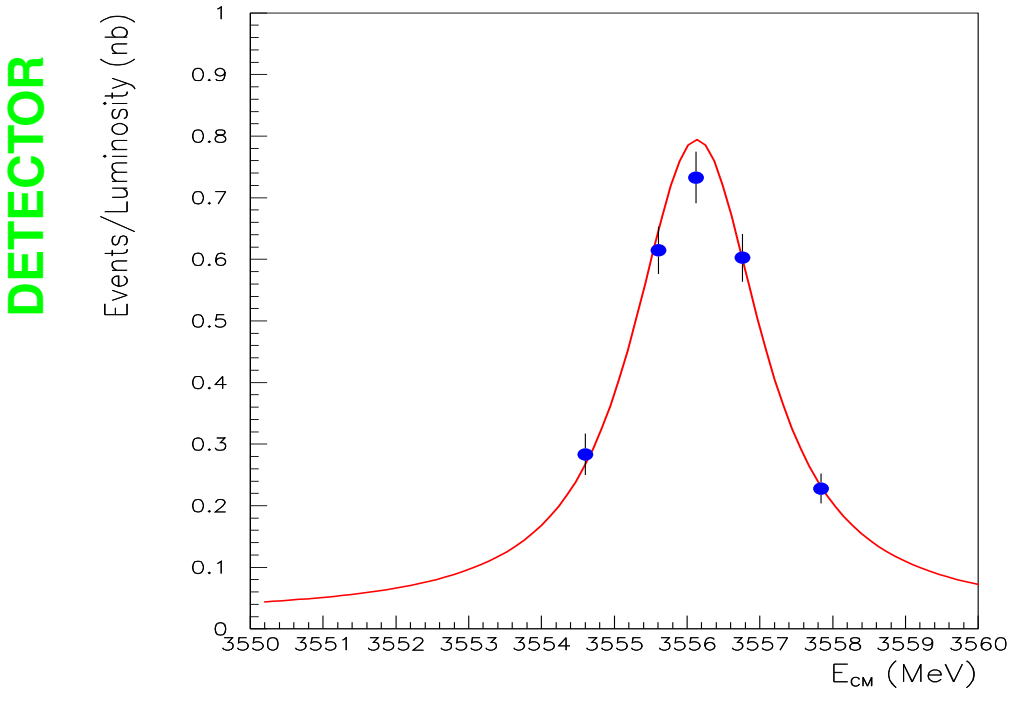
Photons are "lost" either below the CCAL energy threshold of 20 MeV or outside its acceptance, $10°<\theta<70°$. (Merged π^0s are identified by their shower shape.)

Background from above two sources can be studied by first measuring the $\pi^0\pi^0$ and $\pi^0\gamma$ cross sections, then using a "monte carlo" to predict their contribution to the background.

- $\bar{p}p \rightarrow \gamma\gamma$ continuum
  - Estimate ~20 pb at the η_c , based on measurement by VENUS : $\sigma(\gamma\gamma \rightarrow \bar{p}p) = 30 \pm 30$ pb for $|\cos\theta^*|<0.3$, and assumed neglible at higher values of $\sqrt{s}$.
  - E835 measurement of $\sigma(\bar{p}p \rightarrow e^+e^-) = 5 \pm 1$ pb for $|\cos\theta^*|< 0.3$ gives another order of magnitude estimate.

E835 maps out a resonance by decelerating the antiproton beam in small energy steps, and measuring the event rate at each energy.

$\bar{p}p \rightarrow \chi_2 \rightarrow J/\psi + X$



Resolution: $\sigma E_{cm} \cong 0.4$ MeV (FWHM)

Parameters of a resonance curve:

- Mass $\mathbf{M_R = E_{CM}/c^2}$ - Center of mass energy at the peak of a resonance curve.
- Total Width $\Gamma_{\mathbf{tot}}$ - the sum of partial widths for all decay channels. $\Gamma_{tot} = 1/\tau$ where τ is the lifetime of the particle.
- The product $\mathbf{B_{in}B_{out}}$ - B_{in} and B_{out} are the branching ratios ($B = \Gamma_{partial}/\Gamma_{tot}$) in the resonance formation channel ($R \rightarrow \bar{p}p$) and in the decay channel respectively. ($\propto \sigma_{peak}$)

Source and Target

- **Antiproton Accumulator** - Provides a stochastically cooled $\bar{p}$ beam with a momentum range 3.4 to 8.9 GeV/c (E_{cm} 2.9 to 4.3 GeV)
- **Hydrogen Gas Jet** - Target with diameter~7mm and density $(0.5 - 2.5)*10^{14}$ atoms/cm^2
- **Luminosity** - Measured with $\bar{p}p$ elastic scattering rate.

Detector Components

- **Hodoscopes** - The four hodoscopes identify charged particles, covering 2° to 65° in θ
- **Charged Tracking** - Two straw chambers measure ϕ of the charged particles and scintillating fibers measure θ
- **Gas Threshold Cherenkov Counter** - identifies e^+, e^- from heavier charged particles.
- **Central Calorimeter** - Array of 1280 lead glass counters, segmented in θ and ϕ that measures the energy and position of e^+, e^-, γ covering 10° to 70° in θ
- **Forward Calorimeter** - Array of lead glass counters covering from 2° to 10° in θ

Why $\bar{p}p$ annihilations?

Early experiments observed charmonium states through the radiative decays of the ψ and ψ', the resolution of the detector limiting the precision of the measurement.

All of the charmonium states can be formed directly with $\bar{p}p$ annihilation, for the price of a large hadronic background. (~mb compared to $\bar{c}c$ signals ~nb). The solution of R704, E760 and its successor E835 is to look only for the electromagnetic decays of the charmonium states.

E835 technique

Stochastically cooled circulating $\bar{p}$ beam intersecting a hydrogen gas-jet target

- Beam momentum spread : $\Delta p/p \sim 10^{-4}$
- Beam orbital frequency: ~0.63 MHz, measured to ±0.2 Hz
- Beam lifetime ~2-3 days, $\int Ldt$ ~4 pb^{-1}
- Variable density of jet: 0.5-2.5 $x10^{14}$ atoms/cm^3
- Interaction volume ~ 5 mm x 5 mm x 7mm
- Lumonisity ~2 x 10^{31} $cm^{-2}s^{-1}$
- Orbit length = 474.045 ± 0.007 m, calibrated at the ψ' mass
  Deviations from calibration orbit measured to ±1 mm

$\langle E_{cm} \rangle$ to ±100 keV, σE_{cm} ~ 400 keV (FWHM)

Why study charmonium ($\bar{c}c$)?

Called the "hydrogen atom of QCD", it is an excellent system for studying the QCD potential.

- Simple and highly symmetric
- Spectrum of discrete levels
- Heavy quarks can be treated non-relativistically
- Higher cross sections than corresponding $\bar{b}b$ states

Why $\bar{c}c \rightarrow \gamma\gamma$?

Theoretical predictions for the annihilation rates of ($\bar{c}c$) states into gluons or electromagnetic particles are easily started from the analagous positronium calculations.

$$\Gamma(^1S_0 \rightarrow \gamma\gamma) = \frac{12\pi\alpha^2 e_q^4}{m_q^2}|\Psi(0)|^2\left[1 - \frac{3.4}{\pi}\alpha_s\right]$$

$$\Gamma(^1S_0 \rightarrow gg) = \frac{8\pi\alpha_s^2}{3m_q^2}|\Psi(0)|^2\left[1 + \frac{4.8}{\pi}\alpha_s\right]$$

Two Photon Decay Widths of Charmonium Resonances

Michelle Stancari

University of California, Irvine

- Why study charmonium?
- E835 technique
- Measurements of $\bar{c}c \rightarrow \gamma\gamma$ decays
- Measurement of $\bar{p}p \rightarrow \gamma\gamma$ continuum

E835 Collaboration:

Fermi National Accelerator Laboratory
Northwestern University
Univerity of California, Irvine
University of Ferrara , INFN
University of Genoa, INFN
University of Torino, INFN