An Interference Measurement of the $\chi_{c0}(1^3P_0)$ in Proton-Antiproton Annihilation into Two Neutral Pseudoscalar Mesons

Fermilab Experiment E835:
Fermilab, Ferrara, Genova, Northwestern, Minnesota, Irvine, Torino

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Outline

- Charmonium Spectroscopy / Physics motivation

- Fermilab E835:
  Detector and Technique (the channel $\bar{p}p \to \chi_{c0} \to J/\psi\,\gamma\,,\, J/\psi \to e^+e^-$)

- Interference Measurement of the $\chi_{c0}(1^3P_0)$:
  - The channel $\bar{p}p \to \pi^0\pi^0$: Data selection / Background / Cross Section
    Interference Enhancement of the Resonance
    Fit to the Cross Section / Results
  - The channel $\bar{p}p \to \pi^0\eta$: Fit to the Cross Section / Results (upper limit)
  - The channel $\bar{p}p \to \eta\eta$: Fit to the Cross Section / Results

- The $h_c(1^1P_1)$ State of Charmonium:
  - The channel $\bar{p}p \to J/\psi\pi^0\,,\, J/\psi \to e^+e^-$
  - The channel $\bar{p}p \to \eta_c\gamma\,,\, \eta_c \to \gamma\gamma$

- Conclusions

Physics Motivations

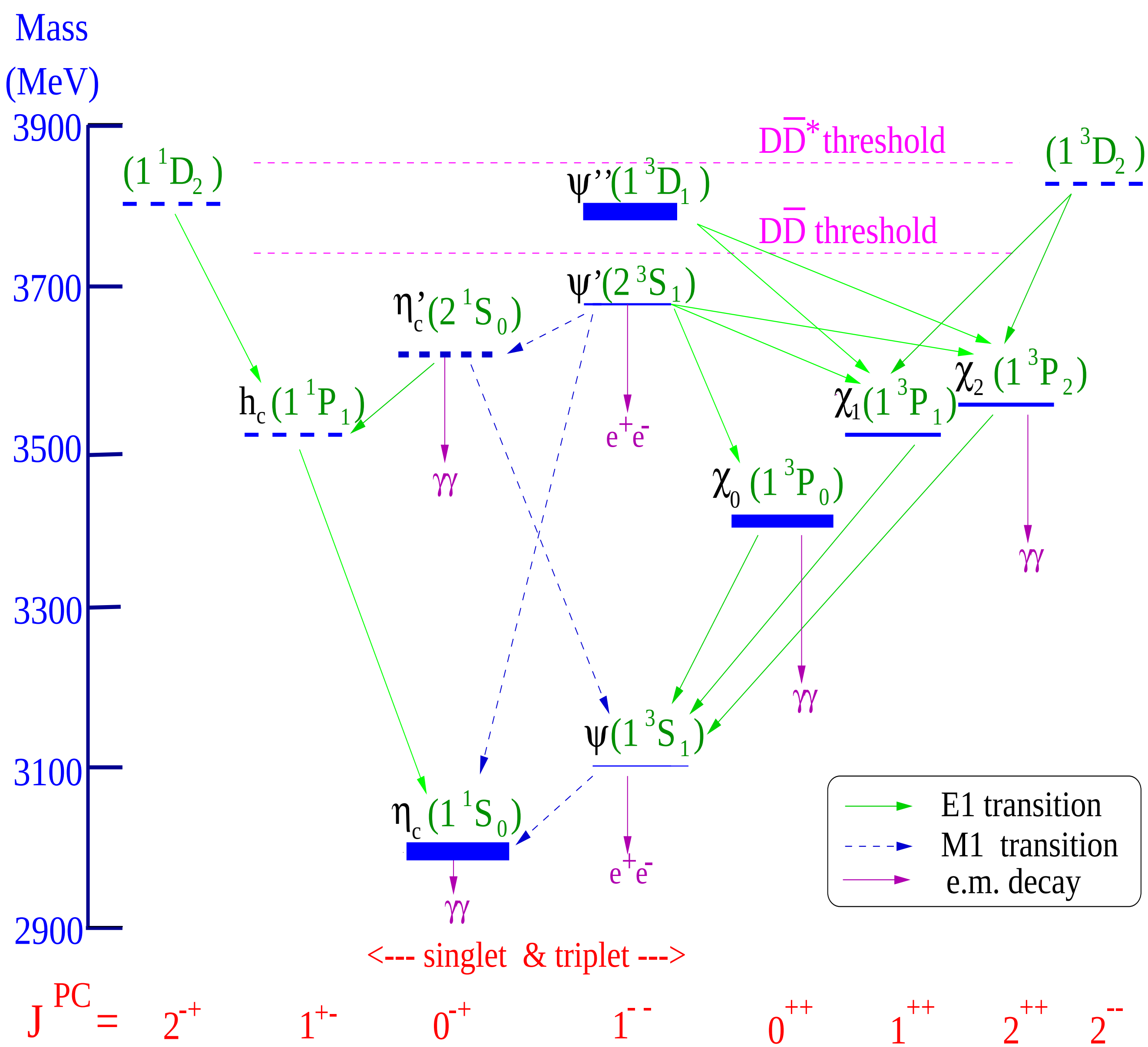
Charmonium spectroscopy provides a test for any theory of the strong interaction:

- Heavy quarks $\Rightarrow$ narrow resonances well separated in energy.
  (Light quark meson excited states are by contrast quite confusing.)
- States are self-conjugate $\Rightarrow$ high symmetry (a useful simplification)
- v^2/c^2 small enough to allow a non-relativistic approach
- in the framework of QCD, α_s is not so large to invalidate the employment of Perturbative QCD

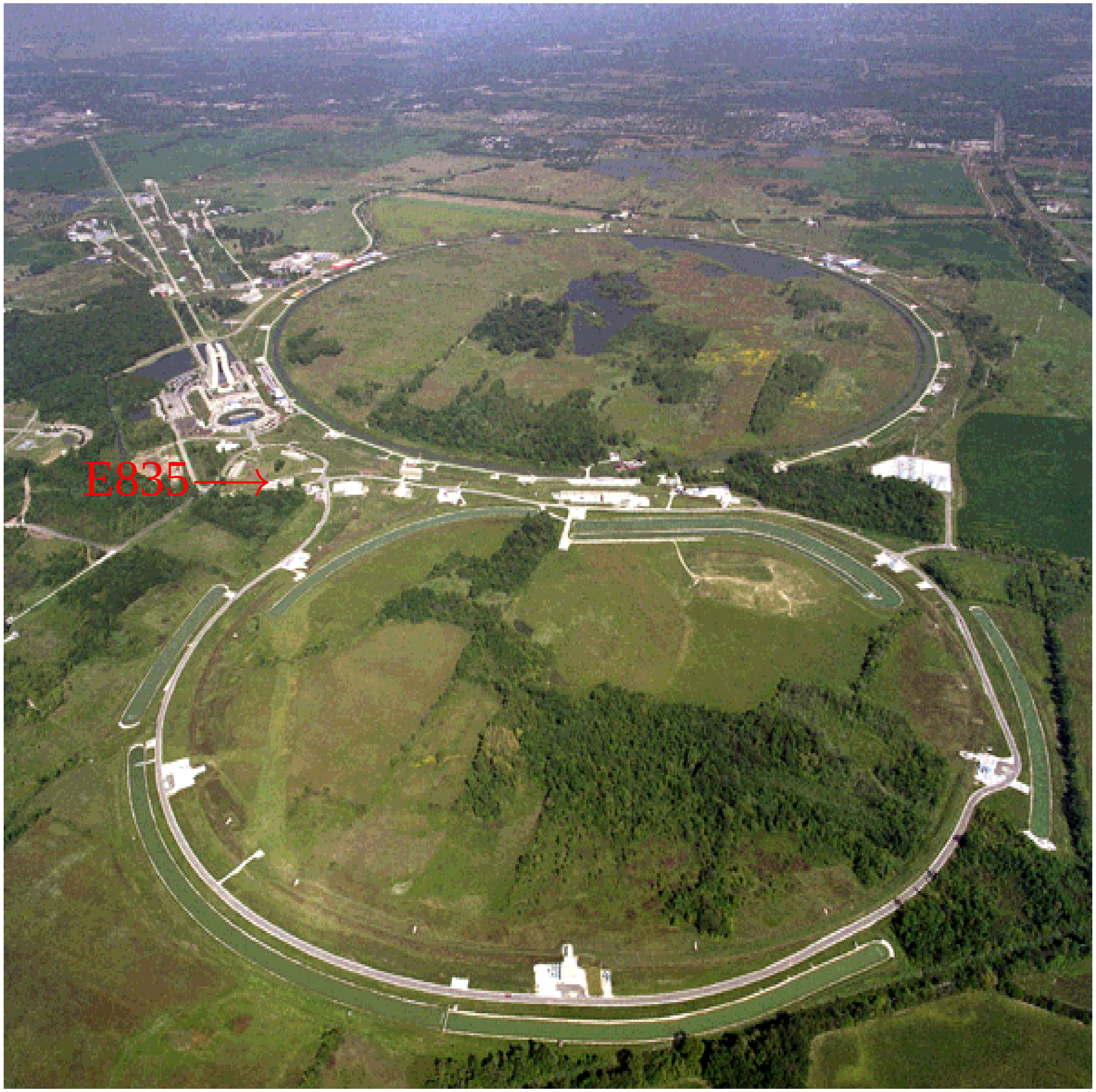
Outstanding problems:

- Weak knowledge of singlet states: η_c , η_c' , and h_c .
- The unique opportunity to decisively identify hadro-molecular states ($c\bar{c}q\bar{q}$) has not been adequately pursued.

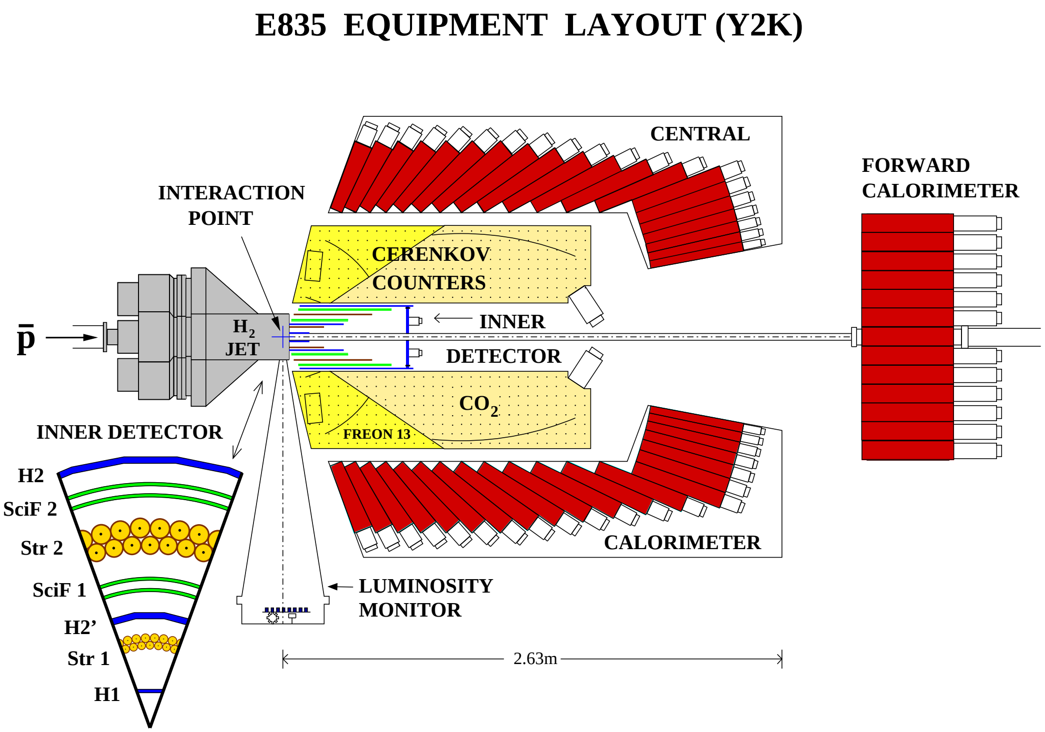
Charmonium Spectrum



E835 at Fermilab Antiproton Accumulator



Detector



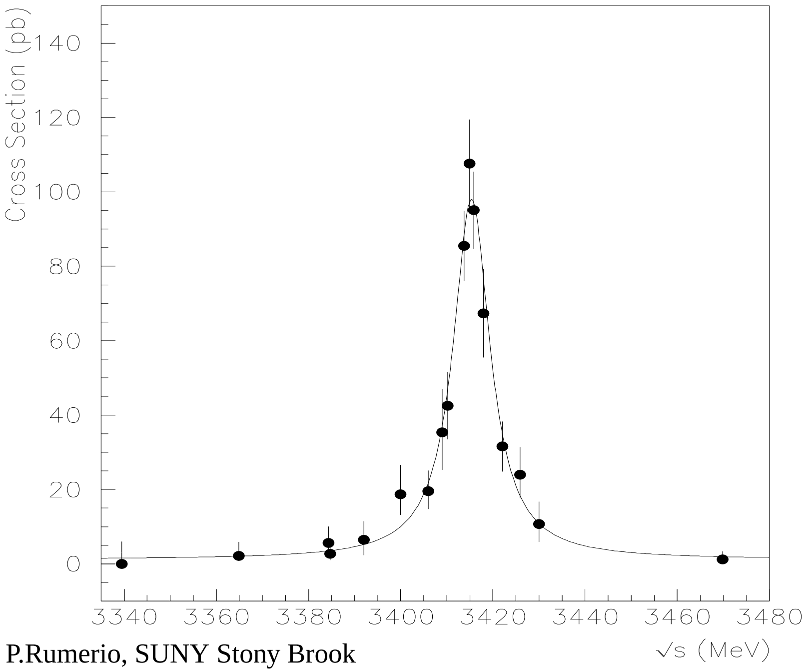
Most relevant detectors for multi-photon analyses:

- The **Central Calorimeter** measures energy and position of e.m. showers.
  1280 lead glass Čerenkov counters.
  Full azimuthal (ϕ) coverage. From 10° to 70° in polar (θ) angle of lab. frame.
- Systems of **scintillation counters** to veto on charged particles.
- The **Luminosity Monitor** determines the luminosity by measuring flux of elastically recoiling protons at $\sim\ 90^\circ$.

Scanning Technique

- The resonance is scanned by varying the energy of the $\bar{p}$-beam.
- At each energy point, the number of events and the integrated luminosity are measured.
- Thus the resonance parameters are determined without relying on the detector resolution $\Rightarrow$ energy resolution of $1/4$ MeV.

E835(2000): $p\bar{p} \to \chi_0 \to J/\psi\,\gamma \to e^+e^-\,\gamma$ [Physics Letter B 533 (2002) 237-242]



$$M_{\chi_0} = (3415.4 \pm 0.4 \pm 0.2)\ MeV/c^2$$
$$\Gamma_{\chi_0} = (9.8 \pm 1.0 \pm 0.1)\ MeV/c^2$$

$$B(\chi_0 \to p\bar{p}) \times B(\chi_0 \to J/\psi\,\gamma)$$

$$\times B(J/\psi \to e^+e^-) =$$
$$(1.61 \pm 0.11 \pm 0.08)\ 10^{-7}$$

These values for M_{χ_0} and Γ_{χ_0} will be used in the $\pi^0\pi^0$ and $\eta\eta$ analyses.

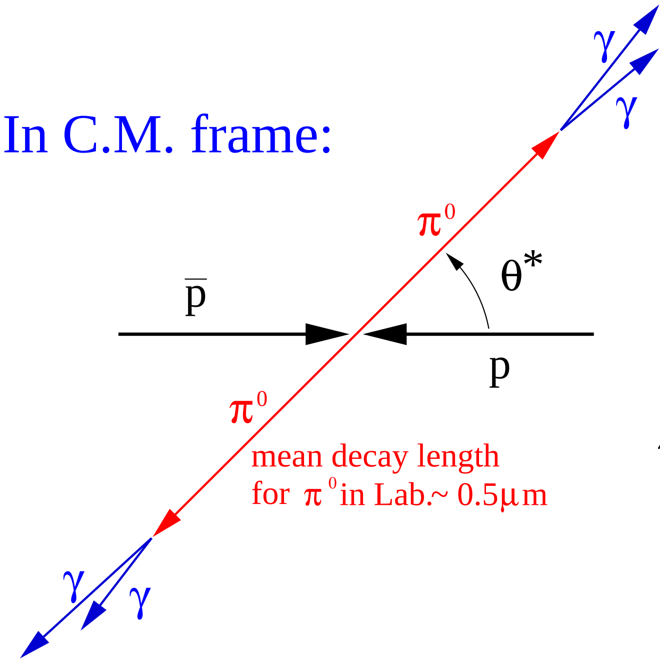
Data Sample

In year 2000, E835 collected 113 pb^{-1} of Integrated Luminosity at Charmonium energies. In particular, 32.8 pb^{-1} at χ_{c0} (17 energy points in the range $Ecm = 3340 - 3370$ MeV), from which we selected:

- $\sim 477,000\ \pi^0\ \pi^0$ events
- $\sim 23,000\ \eta\ \eta$ events
- $\sim 101,000\ \pi^0\ \eta$ events

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

In C.M. frame:

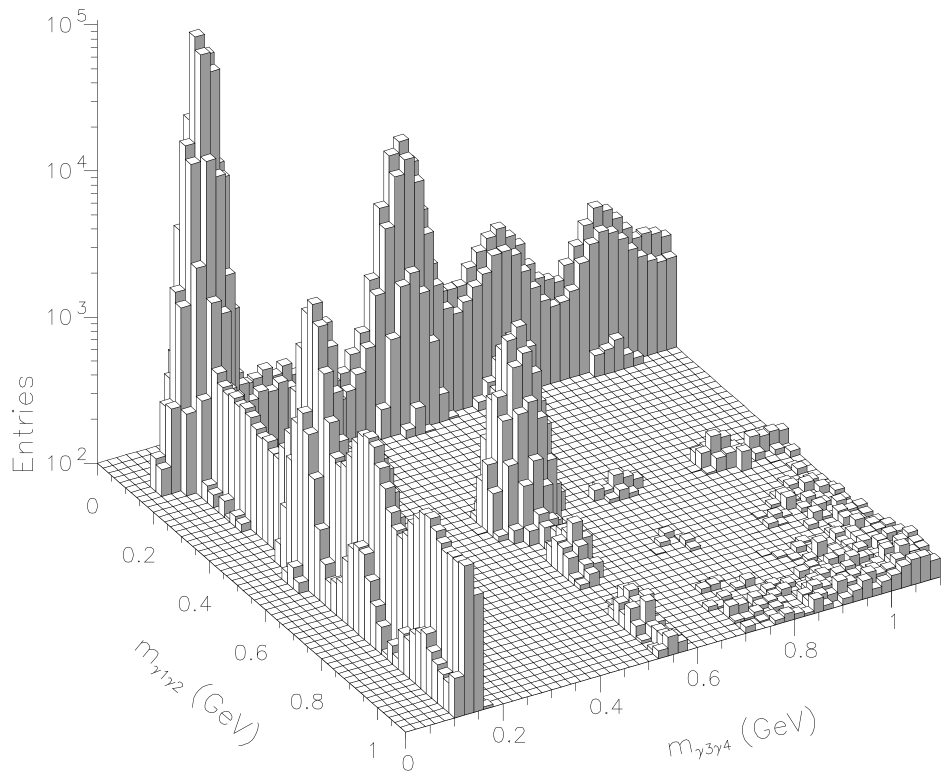


$z \equiv |\cos\theta^*|$

Data Selection

Four photon events are selected.

In particular, a four constraint fit to the hypothesis $\bar{p}p \to \gamma\gamma\,\gamma\gamma$ is performed ($C.L. > 5\%$).



$m_{\gamma_3\gamma_4}$ versus $m_{\gamma_1\gamma_2}$

Although all 3 possible ways to pair the four photons are considered, it is extremely rare ($< 0.01\%$ of the events) that more than one combination falls within the region of the $\pi^0\pi^0$, $\pi^0\eta$ and $\eta\eta$ peaks.

$\pi^0\pi^0$ Data Selection

The $\pi^0\pi^0$ topology is determined by a six constraint fit to the hypothesis
$\bar{p}p \to \pi^0\pi^0 \to \gamma\gamma\,\gamma\gamma$

Then, the $\pi^0\pi^0$ selection is applied:

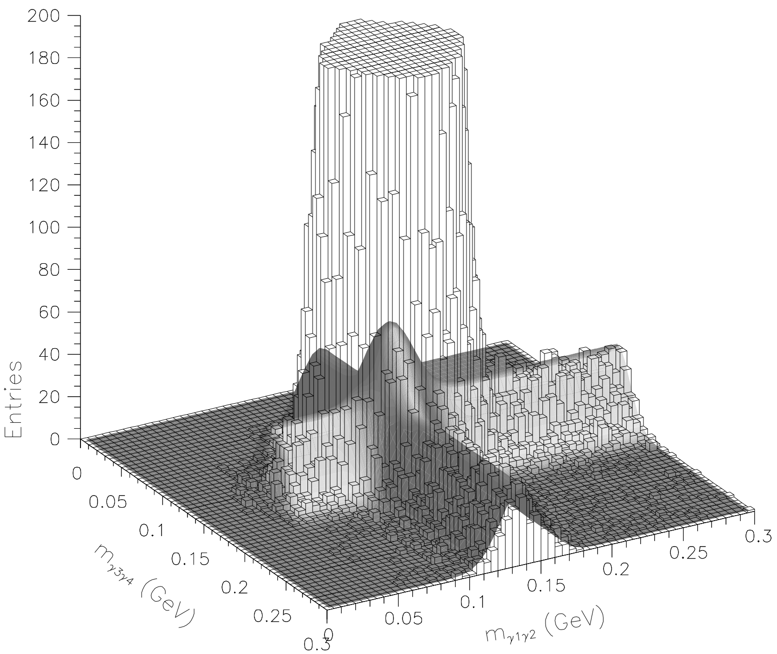
- 100 MeV$< m_{\gamma\gamma}^{fw} < 185$ MeV,
- 100 MeV$< m_{\gamma\gamma}^{bw} < 185$ MeV,
- Akinematics $(\Delta\theta) < 12$ mrad,
- Acoplanarity $(\Delta\phi) < 30$ mrad,
- No invariant masses for which $|m_{\gamma\gamma} - m_{\pi^0}| < 45$ MeV in the two combinations not chosen as the event topology,
- No successful fit (C.L.$< 10^{-5}$) to $\pi^0\eta \to \gamma\gamma\,\gamma\gamma$ or $\eta\eta \to \gamma\gamma\,\gamma\gamma$ in any of the 3 combinations.

$\pi^0\pi^0$ Background Subtraction

The scatter plot is fitted to

$$f(x,y) = \underbrace{\frac{A}{\sigma^2}\, exp\Big[-\frac{(x-m_{\pi^0})^2}{2\sigma^2}\Big]\, exp\Big[-\frac{(y-m_{\pi^0})^2}{2\sigma^2}\Big]}_{2\pi^0 signal}$$

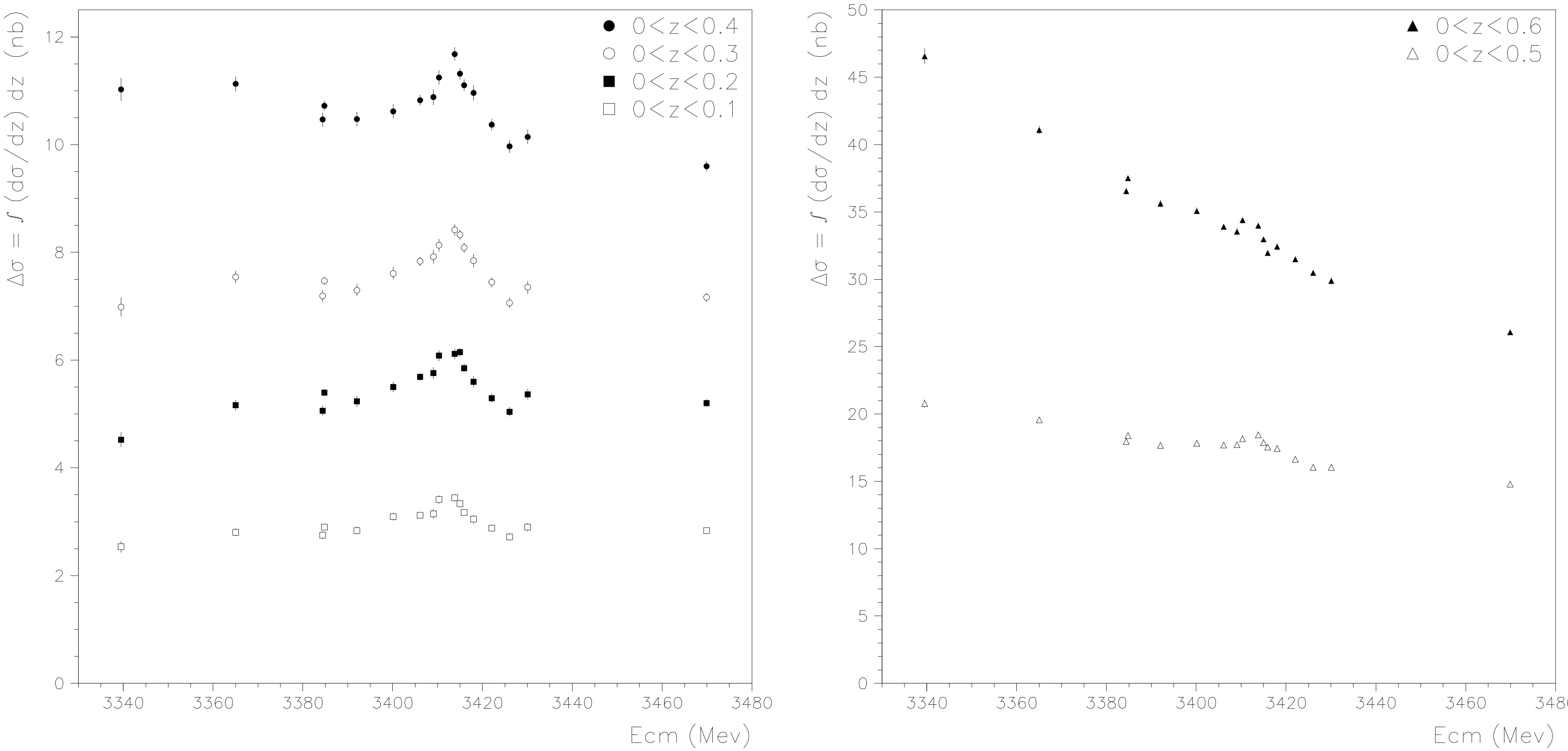
$$\underbrace{+\frac{B}{\sigma}\, exp\Big[-\frac{(x-m_{\pi^0})^2}{2\sigma^2}\Big] + \frac{C}{\sigma}\, exp\Big[-\frac{(y-m_{\pi^0})^2}{2\sigma^2}\Big] + D + E\,(x+y)}_{background}$$



by minimizing a negative-log-likelihood.
A, B, C, D, E, σ are free parameters.

The ratio $\dfrac{\text{bkg}}{\text{signal} + \text{bkg}}$ is $\sim 2\%$ at all energies.

$\pi^0\pi^0$ Integrated Cross-Section



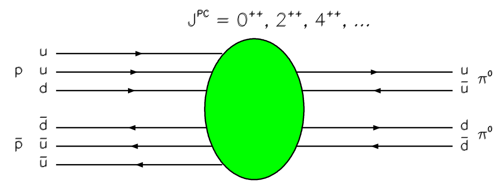
Quantum Numbers

S	L	$\bar{p}p$ J^{PC}	$^{2S+1}L_J$	$\bar{c}c$ resonance	$n^{2S+1}L_J$	$\pi^0\pi^0$, $\pi^0\eta$, or $\eta\eta$
0	0	0^{-+}	$^1S_0$	η_c (η_c')	1^1S_0 (2^1S_0)	
1	0	1^{--}	$^3S_1$	J/ψ (ψ')	1^3S_1 (2^3S_1)	
0	1	1^{+-}	$^1P_1$	h_c	1^1P_1	
1	1	0^{++}	$^3P_0$	χ_{c0}	1^3P_0	✓
1	1	1^{++}	$^3P_1$	χ_{c1}	1^3P_1	
1	1	2^{++}	$^3P_2$	χ_{c2}	1^3P_2	✓
0	2	2^{-+}	$^1D_2$			
1	2	1^{--}	$^3D_1$	J/ψ (ψ')	1^3S_1 (2^3S_1)	
1	2	2^{--}	$^3D_2$			
1	2	3^{--}	$^3D_3$			
0	3	3^{+-}	$^1F_3$			
1	3	2^{++}	$^3F_2$	χ_{c2}	1^3P_2	✓
1	3	3^{++}	$^3F_3$			
1	3	4^{++}	$^3F_4$			✓
0	4	4^{-+}	$^1G_4$			
1	4	3^{--}	$^3G_3$			
1	4	4^{--}	$^3G_4$			
1	4	5^{--}	$^3G_5$			

Phenomenology of the Process

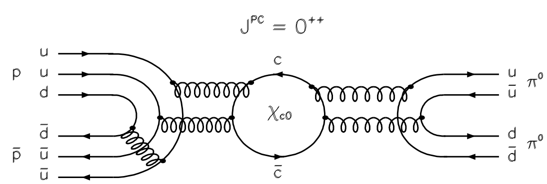
Two Competing Processes:

1) The non-resonant reaction $\bar{p}p \rightarrow \pi^0\pi^0$:



which may occur through the annihilation of 3, 2 and 1 valence $\bar{q}q$ pairs of the $\bar{p}p$ initial state;

2) The resonant reaction $\bar{p}p \rightarrow \chi_{c0} \rightarrow \pi^0\pi^0$:



which certainly requires the annihilation of all 3 valence $\bar{q}q$ pairs.

Angular Distribution

Defining $x = \frac{E_{CM} - M_{\chi 0}}{\Gamma_{\chi 0}/2}$ and $z \equiv |\cos\theta^*|$:

$$\frac{d\sigma}{dz}(x,z) = \sum_{|\lambda|=0,1} \left| \sum_{J=even} C_J^{|\lambda|} \, e^{i\delta_J^{|\lambda|}} \, P_J^{|\lambda|}(z) \right|^2 ,$$

where $\lambda = \lambda_{\bar{p}} - \lambda_p$ is the helicity of the initial $\bar{p}p$ state.
Writing explicitly the sums (defining $C_J \equiv C_J^0$) and considering that at $E_{CM} \simeq M_{\chi 0}$ the coefficient C_0 is made of a resonant and a non-resonant part, then:

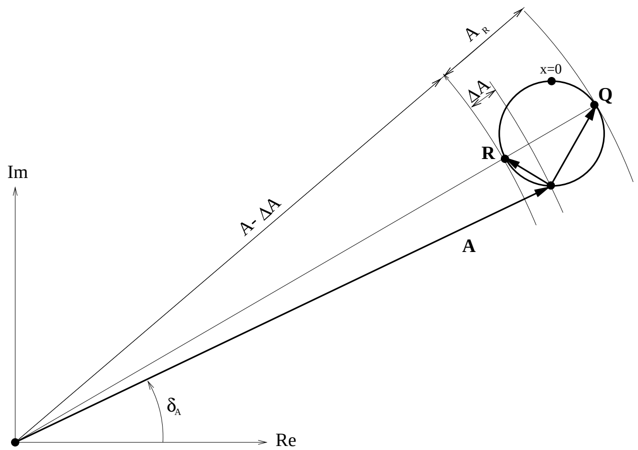
$$\frac{d\sigma}{dz}(x,z) = \left| \frac{-A_R}{x+i} + A \, e^{i\delta_A} \right|^2 + \left| B \, e^{i\delta_B} \right|^2 ,$$

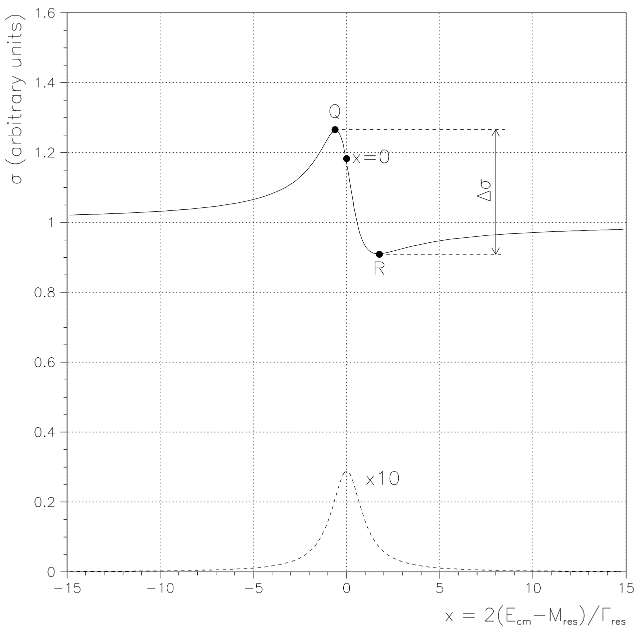
$$A \, e^{i\delta_A} \equiv \sum_{J=0,2,\ldots}^{J_{max}} (2J+1) \, C_J(x) \, e^{i\delta_J(x)} \, P_J(z),$$

$$B \, e^{i\delta_B} \equiv \sum_{J=2,4,\ldots}^{J_{max}} \frac{(2J+1)}{\sqrt{J(J+1)}} \, C_J^1(x) \, e^{i\delta_J^1(x)} \, P_J^1(z).$$

$A_R \rightarrow$ Resonant Amplitude,
$A \rightarrow$ Interfering part of the Non-Resonant Amplitude,
$B \rightarrow$ Non-Interfering part of the Non-Resonant Amplitude.

Interference Enhancement of a Resonance





The angular distribution can be rewritten as:

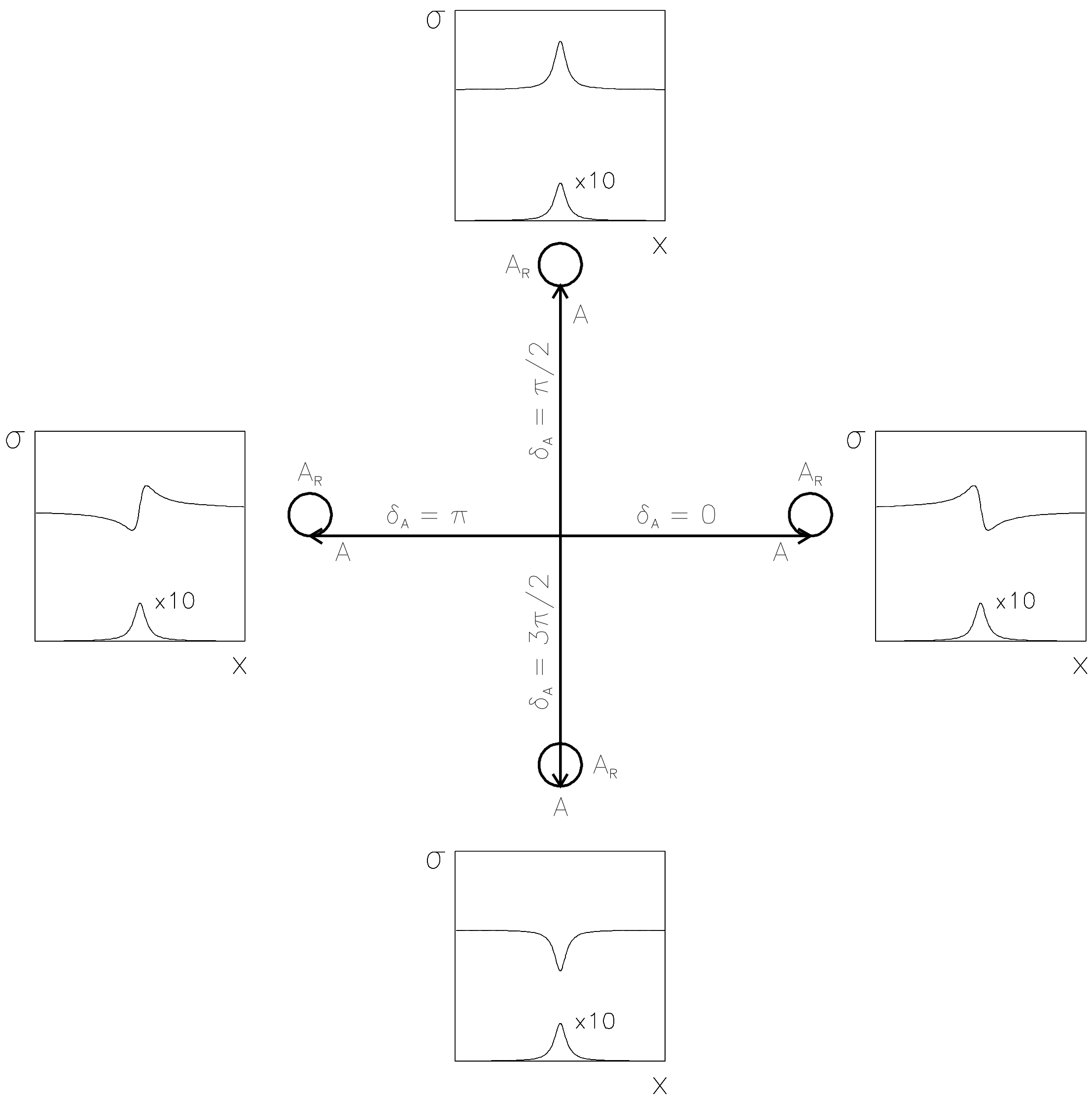
$$\frac{d\sigma}{dz} = \frac{A_R^2}{x^2+1} + A^2 + \underbrace{2A_R A\,\frac{\sin\delta_A - x\cos\delta_A}{x^2+1}}_{interference-term} + B^2.$$

$\longleftarrow$ The magnitude of the interference pattern is

$$\Delta\sigma = 2A_R A$$

and is independent from the phase δ_A.

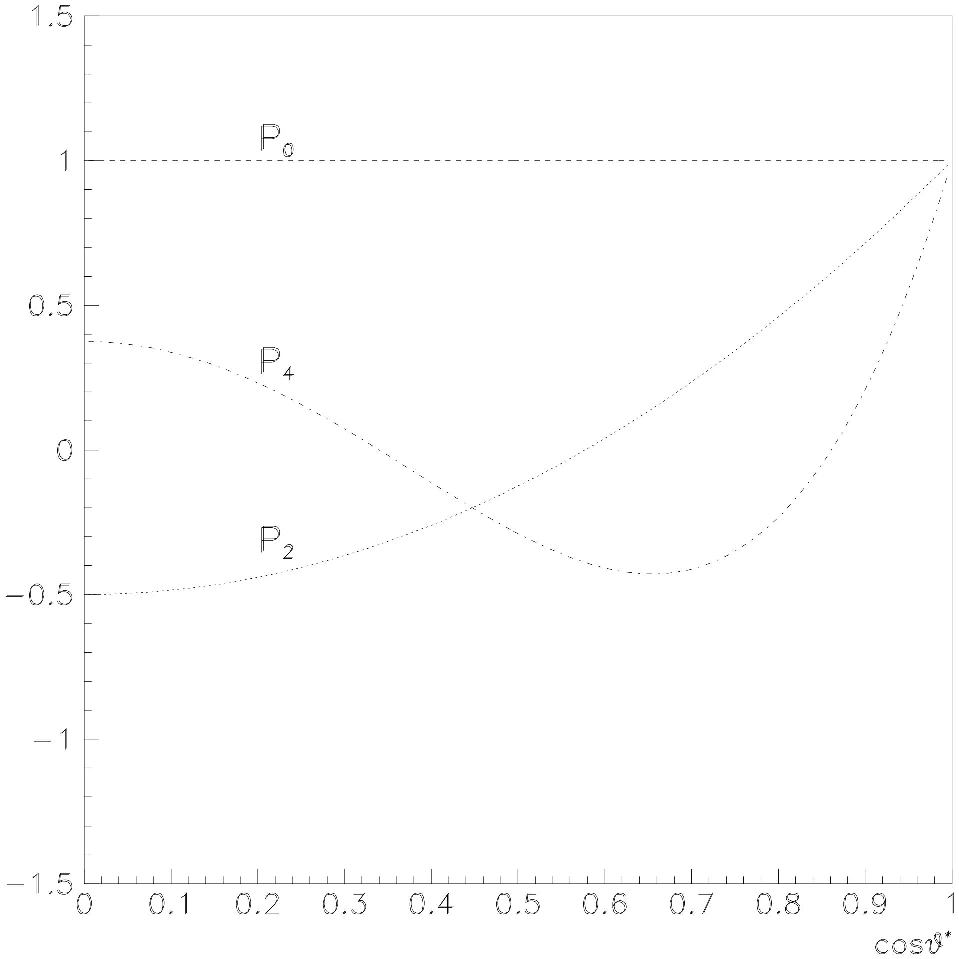
Interference Patterns

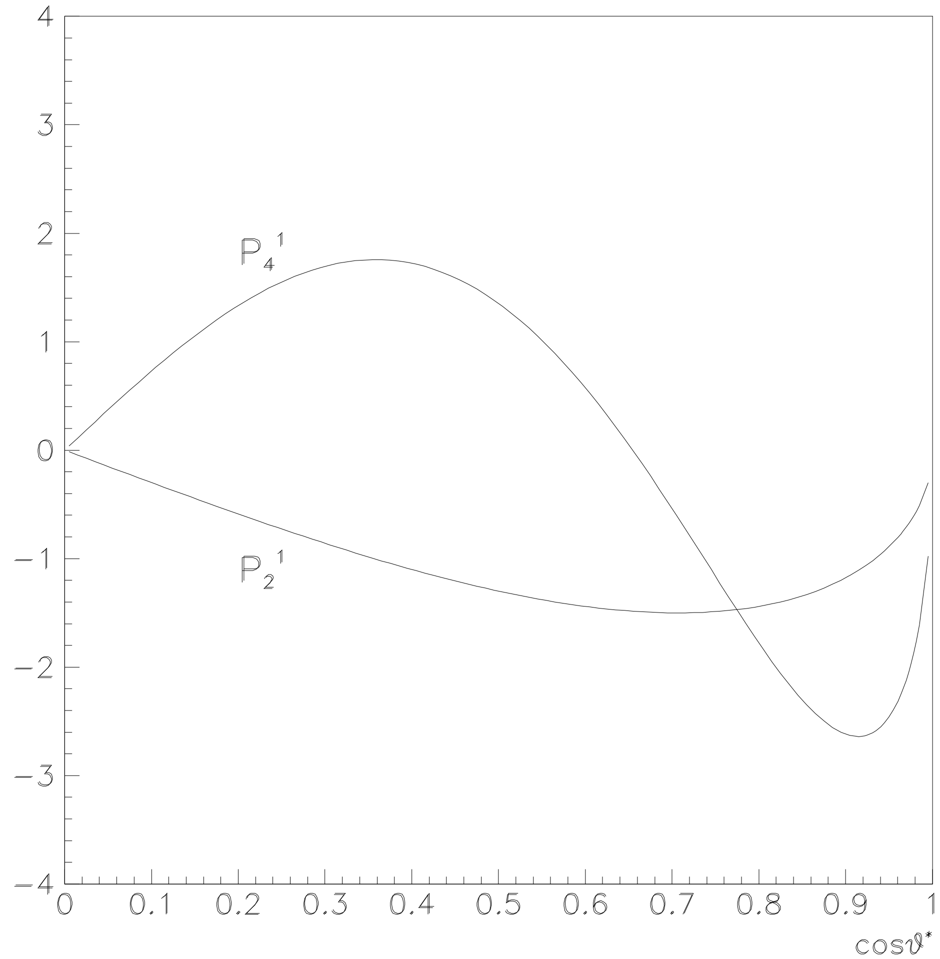


Legendre Polynomials and Associate Functions

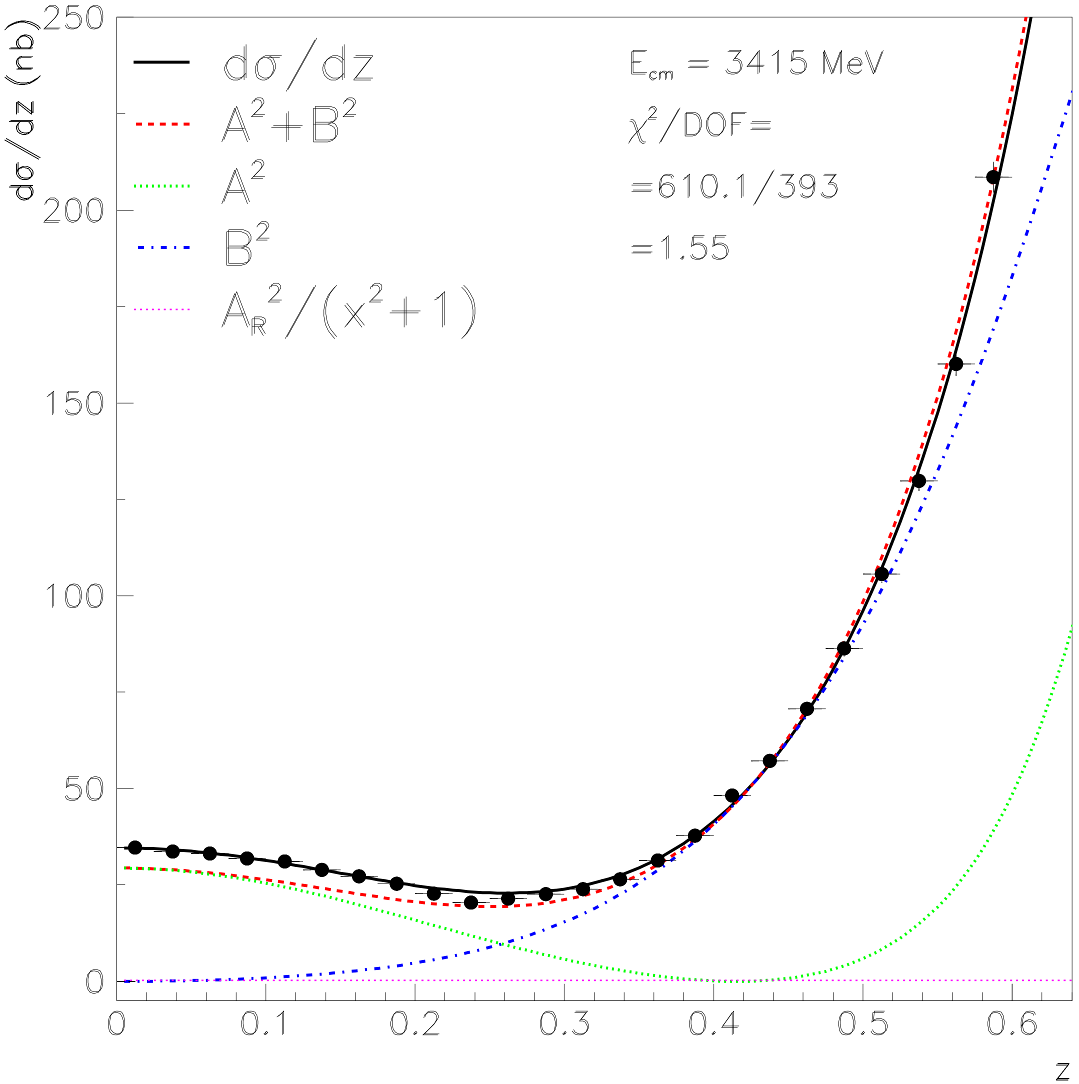
$$P_0 = 1$$
$$P_2 = \frac{1}{2}(3z^2 - 1)$$
$$P_4 = \frac{1}{8}(35z^4 - 30z^2 + 3)$$

$$P_2^1 = -3z\sqrt{1 - z^2}$$
$$P_4^1 = -\frac{5}{2}z(7z^2 - 3)\sqrt{1 - z^2}$$



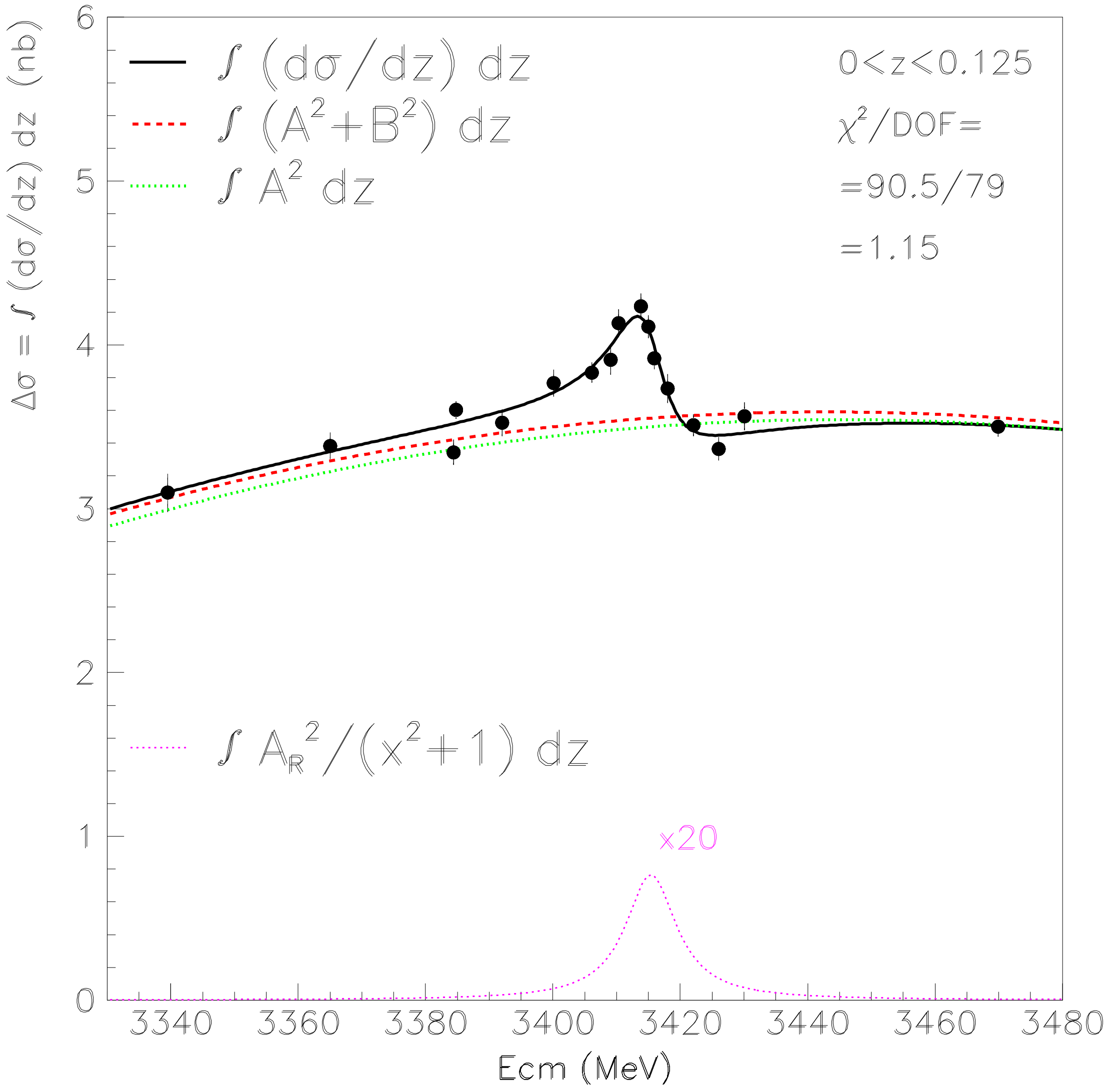


$\pi^0\pi^0$ Angular Distribution, Data and Fit



This fit is performed using the full available range in $z \equiv |\cos\theta^*|$ and $J_{max} = 4$. It is used to estimate B^2 at small values of z.

$\pi^0\pi^0$ Integrated Cross-Section VS Ecm



Fit performed in reduced range $0 < z < 0.125$ ($A^2 \equiv a_0 + a_1 x + a_2 x^2$ and B^2 from previous plot).

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

Results from the $\pi^0\pi^0$ Channel

[PRL 91, 091801 (2003)]

From the $\pi^0\pi^0$ analysis:

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

From E835(2000) $J/\psi\,\gamma$ channel:

$B(\chi_0 \to p\bar{p}) \times B(\chi_0 \to J/\psi\,\gamma) = (27.2 \pm 1.9 \pm 1.3)10^{-7}$

Then:

$B(\chi_0 \to J/\psi\,\gamma)/B(\chi_0 \to \pi^0\pi^0) = 5.34 \pm 0.93 \pm 0.34$ (**)

By using the PDG value

$B(\chi_0 \to \pi^0\pi^0) = B(\chi_0 \to \pi^+\pi^-)/2 = (2.50 \pm 0.35)10^{-3}$ (***),

and (*) it follows:

$B(\chi_0 \to p\bar{p}) = (2.04 \pm 0.32 \pm 0.10 \pm 0.28_{PDG})10^{-4}$.

By using (**) and (***), it follows:

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

Also, using the above and

$\Gamma_{\chi_0} = (9.8 \pm 1.0 \pm 0.1)$ MeV from E835(2000) - $J/\psi\,\gamma$ channel:

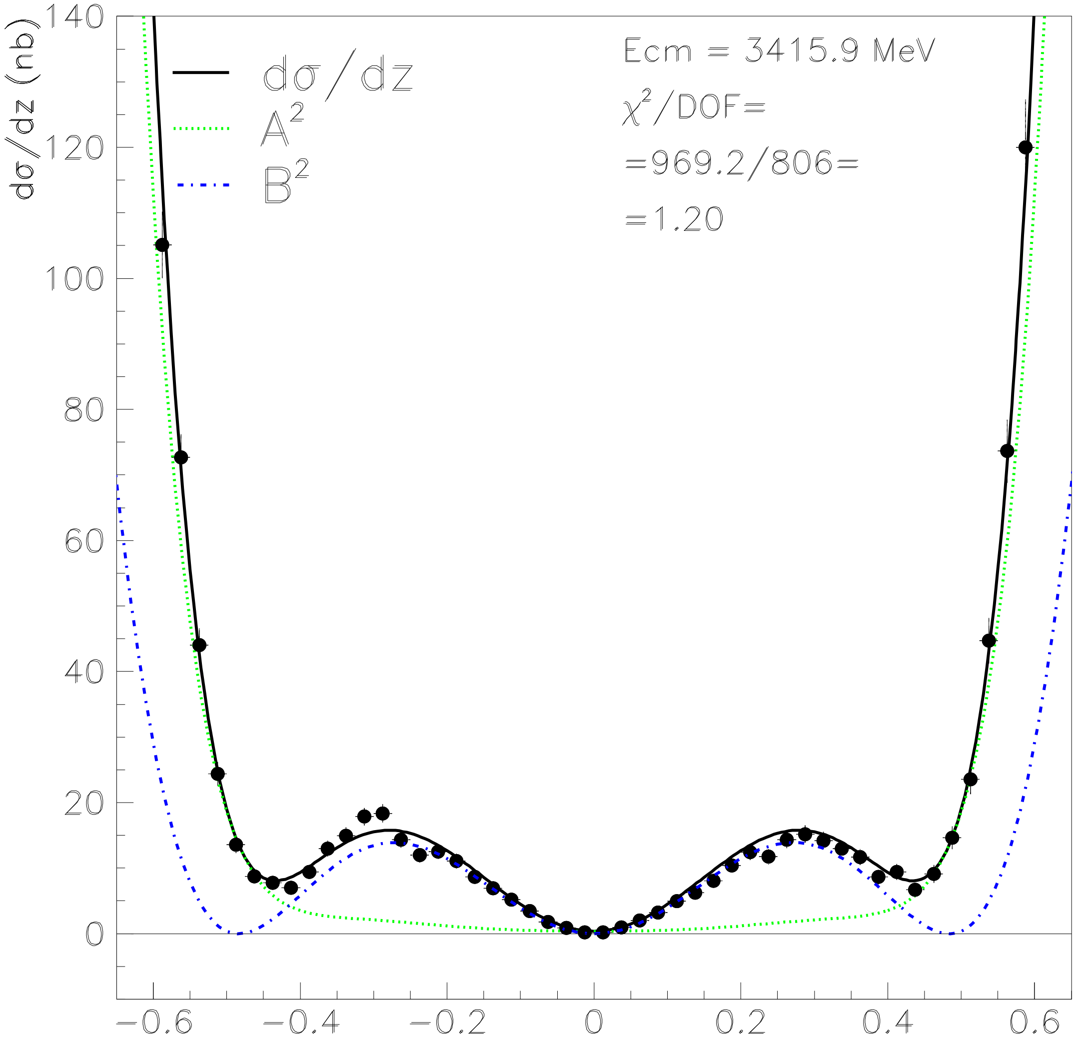
$\Gamma_{\chi_0 \to J/\psi\gamma} = (131 \pm 33)$ keV .

The Radiative Transitions of the χ_{cJ}'s

$c\bar{c}$ state	$B(J/\psi\,\gamma)$ $(\%)$	Γ (MeV)	$\Gamma_{J/\psi\gamma}$ (keV)	q (MeV)	$\frac{\Gamma_{J/\psi\gamma}}{(q/q_{\chi_0})^3}$ (keV)
$\chi_0(3415)$	$1.33 \pm 0.30 \pm 0.09$	$9.8 \pm 1.0 \pm 0.1$	131 ± 33	303	131 ± 33
$\chi_1(3511)$	31.6 ± 3.2	0.92 ± 0.13	290 ± 50	389	138 ± 24
$\chi_2(3556)$	18.7 ± 2.0	2.08 ± 0.17	389 ± 52	430	136 ± 18

There is now excellent agreement among the E1 radiative transitions.

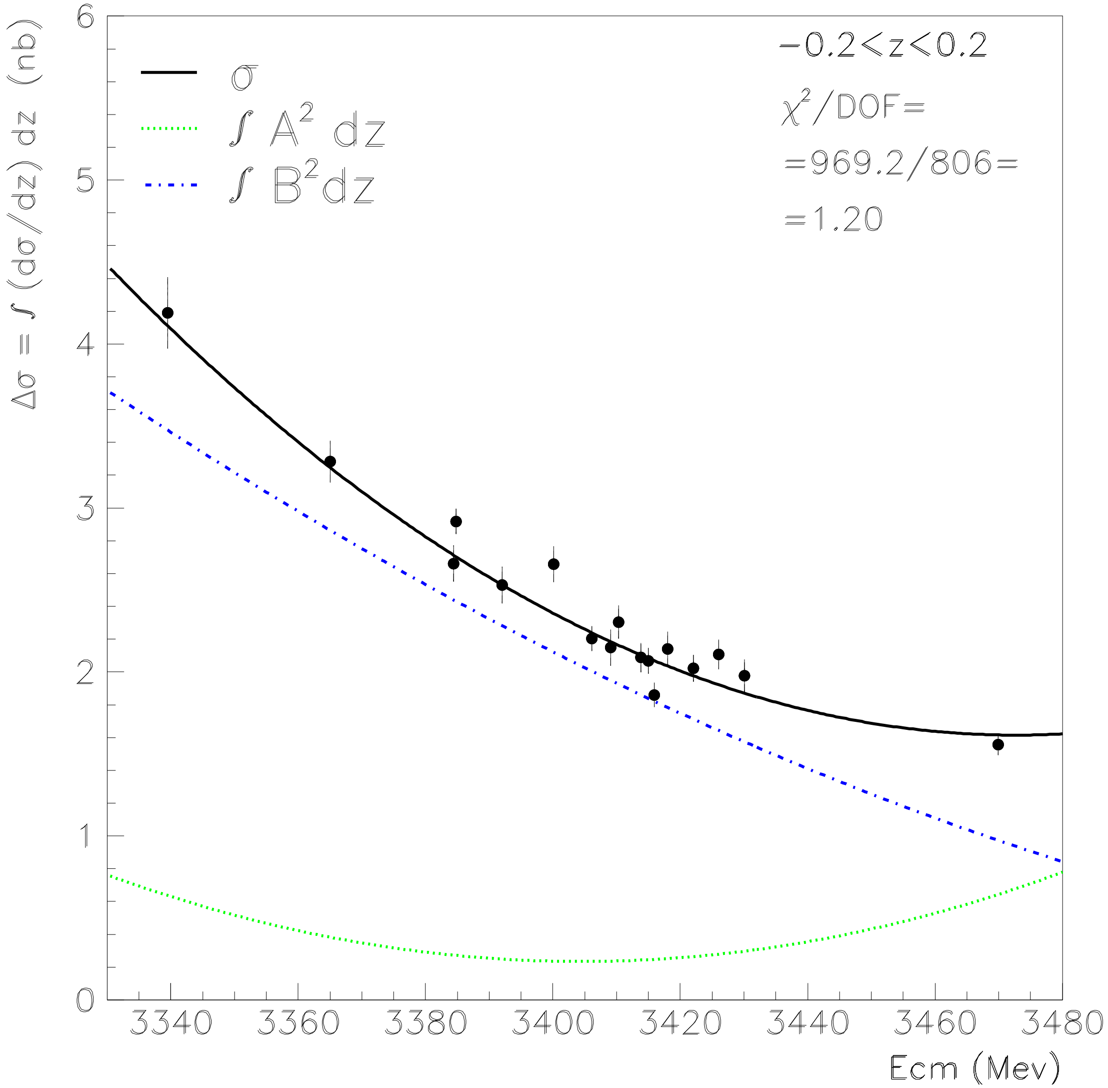
$\pi^0\eta$ Angular Distribution, Data and Fit



This partial wave expansion fit is performed using the full available range in $z \equiv |\cos\theta^*|$ and $J_{max} = 4$.

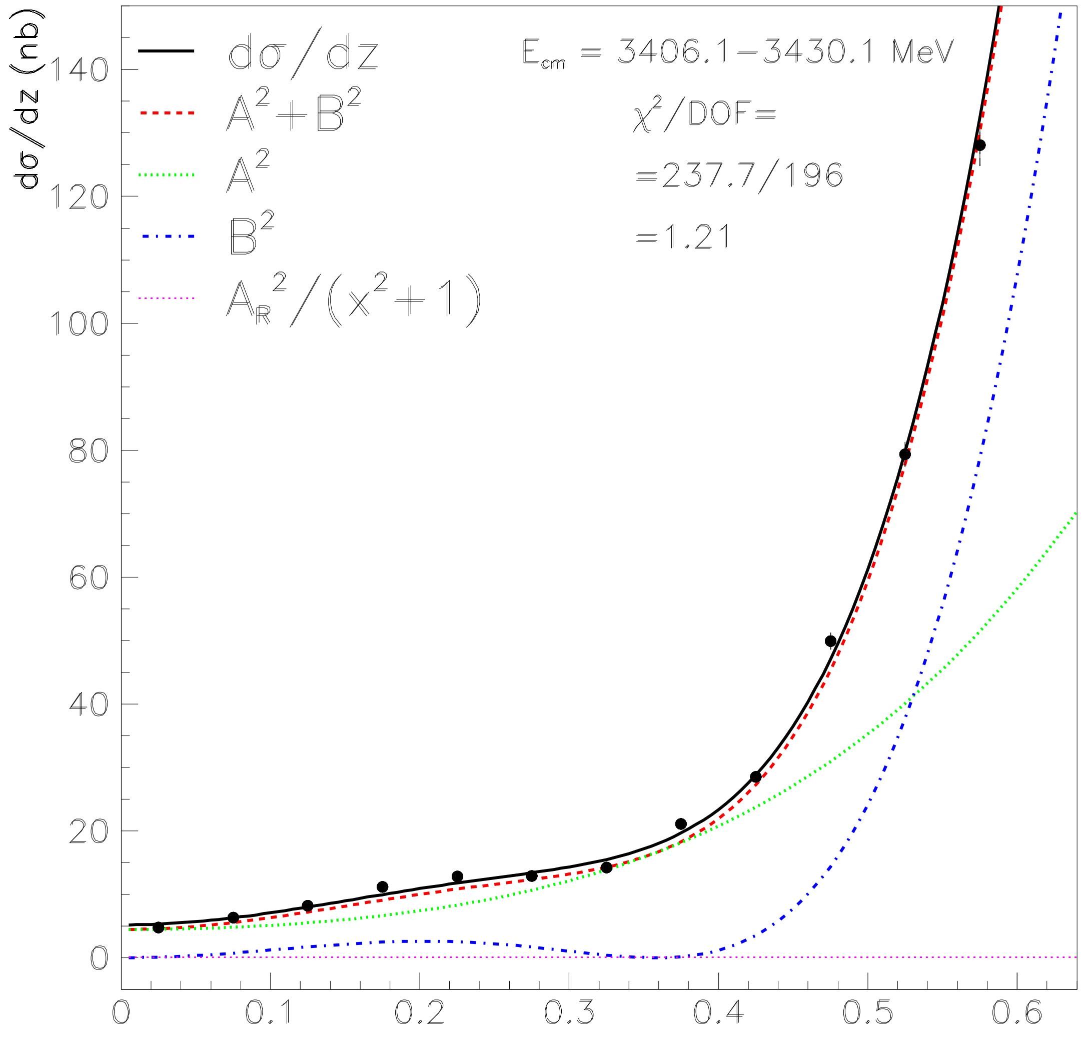
$c\bar{c} \rightarrow \pi^0\eta$ is Isospin-suppressed.

$\pi^0\eta$ Integrated Cross-Section VS Ecm



Result: $B(\chi_{c0} \to \bar{p}p) \times B(\chi_{c0} \to \pi^0\eta) < 4 \times 10^{-8}$

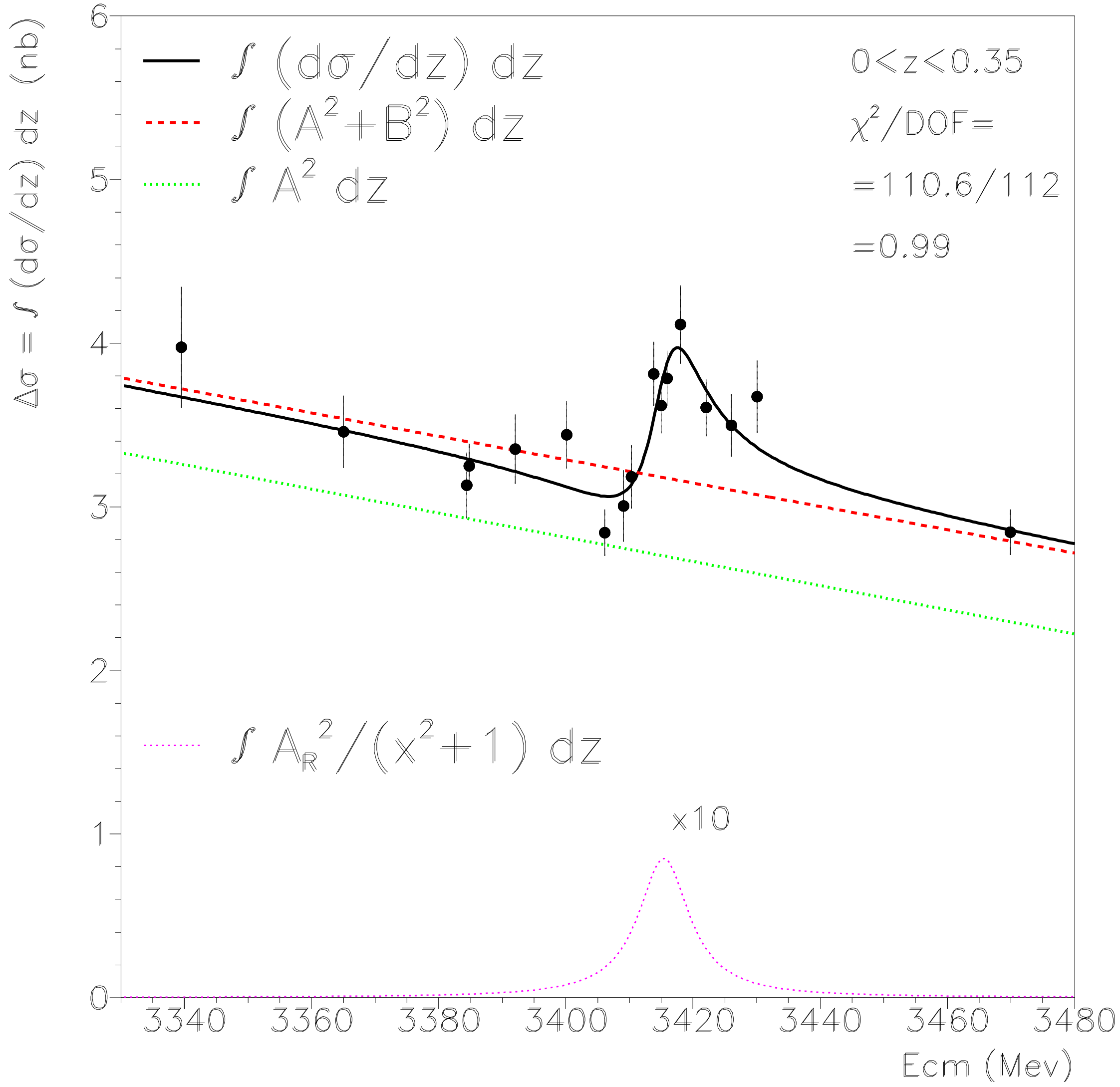
$\eta\eta$ Angular Distribution, Data and Fit



This partial wave expansion fit is performed using the full available range in $z \equiv |\cos\theta^*|$ and $J_{max} = 4$.

It is used to estimate B^2 at small values of z.

$\eta\eta$ Integrated Cross-Section VS Ecm



Fit performed in reduced range $0 < z < 0.35$, with $A^2 \equiv a_0 + a_1 x + a_2 z^2 + a_3 z^2 x + a_4 z^4$ and B^2 from previous plot.

Result: $B(\chi_0 \rightarrow p\bar{p})\ B(\chi_0 \rightarrow \eta\eta) = (4.0 \pm 1.2^{+0.5}_{-0.3})\ 10^{-7}$

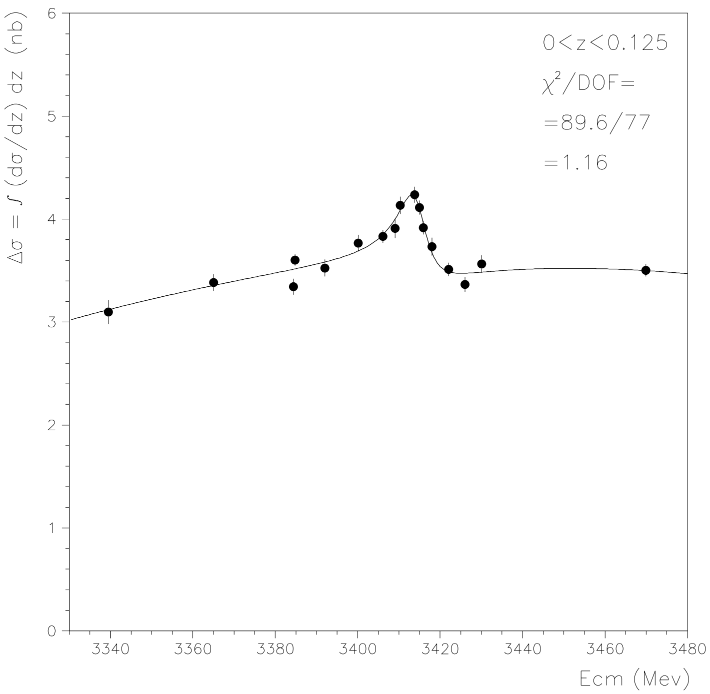
Results for M_{χ_0} and Γ_{χ_0} using $\pi^0\pi^0$ and $\eta\eta$ Samples Alone

Removing the constraints

$$M_{\chi_0} = (3415.4 \pm 0.4 \pm 0.2)\ \mathrm{MeV}$$
$$\Gamma_{\chi_0} = (9.8 \pm 1.0 \pm 0.1)\ \mathrm{MeV},$$

and fitting again, we obtain:

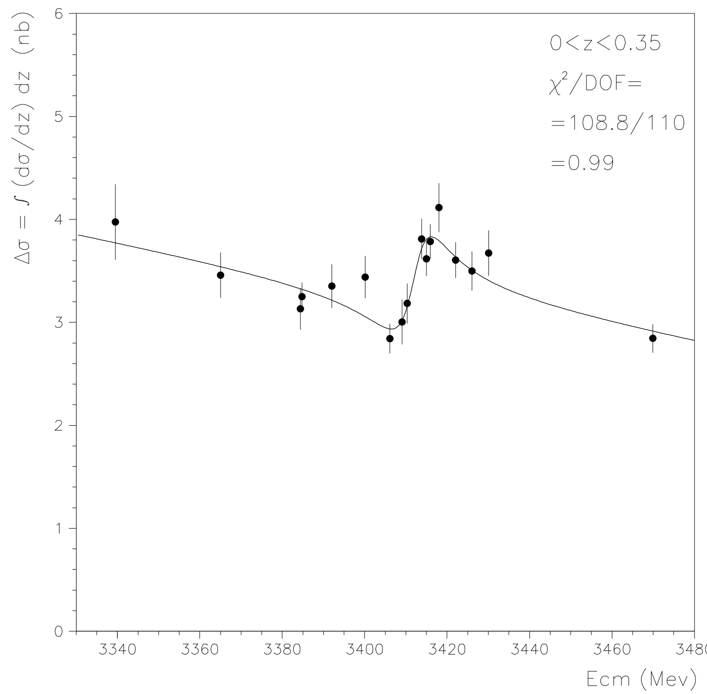
from $\pi^0\pi^0$



mm

$$M_{\chi_0} = (3414.7^{+0.7}_{-0.6} \pm 0.2)\ \mathrm{MeV}$$
$$\Gamma_{\chi_0} = (8.6^{+1.7}_{-1.3} \pm 0.1)\ \mathrm{MeV}$$

from $\eta\eta$



$$M_{\chi_0} = (3412.2^{+2.1}_{-1.8} \pm 0.2)\ \mathrm{MeV}$$
$$\Gamma_{\chi_0} = (10.3^{+3.0}_{-3.1} \pm 0.1)\ \mathrm{MeV}$$

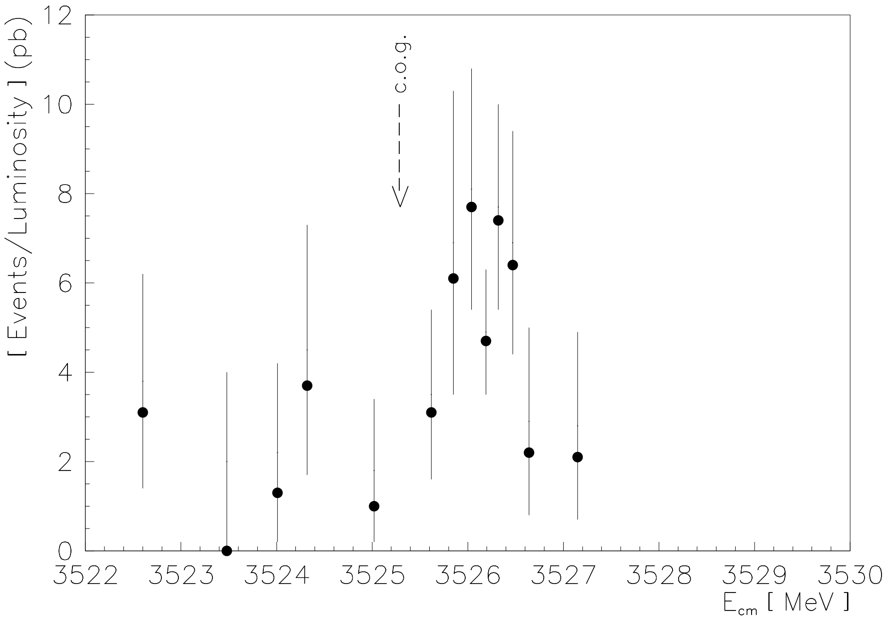
The h_c (1^1P_1) State of Charmonium

- It is the most elusive state below open-charm threshold
- $J^{PC} = 1^{+-}$
- M_{h_c} is expected to be close to the center of gravity (c.g.) of the χ_{cJ}'s:
  $M_{c.g.} = 3525.31 \pm 0.07$ MeV.
  A measurement of the splitting $M_{h_c} - M_{c.g.}$ would probe the nature of the strong interaction: in a single-gluon exchange interaction this splitting would be zero.
- The h_c is expected to be narrow, $\Gamma_{h_c} < 1$ MeV
- Given agreement between the E1 radiative transitions $\chi_{cJ} \to J/\psi\, \gamma$ and assuming
  1. h_c and χ_{cJ}'s have equal radial wave function
  2. $M_{h_c} \simeq M_{c.g.}$

  the E1 transition of the h_c into $\eta_c\,\gamma$ would be $\Gamma_{h_c \to \eta_c \gamma} \simeq (620 \pm 70)$ keV
- The annihilation into 3 gluons is predicted to be $\Gamma_{h_c \to 3g} \simeq 100$ keV
  [Kwang, Tuan and Yan, Phys. Rev. D 37, 1210 (1988)]

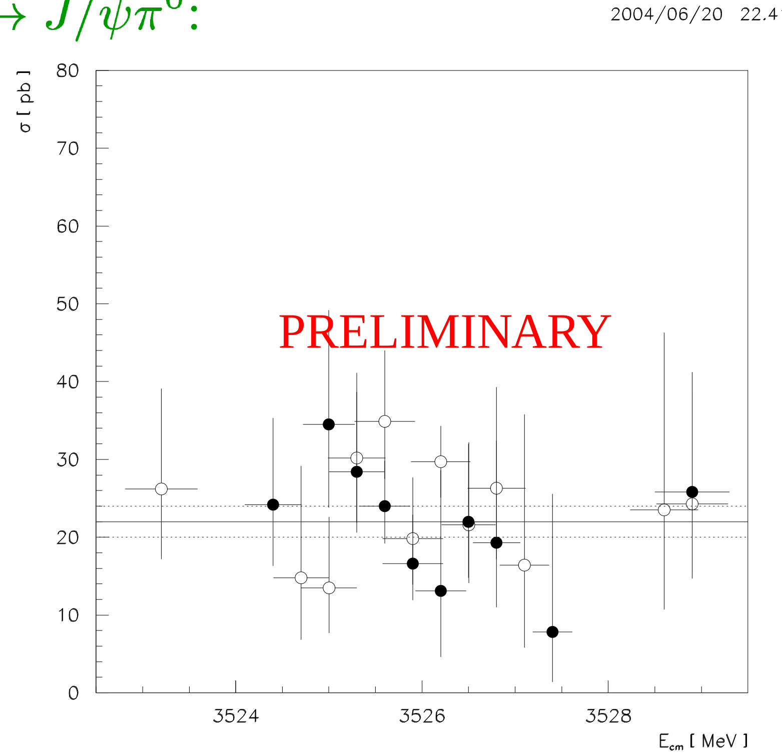
The h_c (1^1P_1) in $\bar{p}p \to J/\psi\,\pi^0$ $[J/\psi \to e^+e^-, BR = (5.93 \pm 0.10)\%]$

E760 (16 pb^{-1} at χ_{cJ} c.g. in 1990) observed a structure in $\bar{p}p \to J/\psi\pi^0$ (isospin violating) interpreted as the h_c:



$M_R = 3526.2 \pm 0.15 \pm 0.2$ MeV
$\Gamma_R < 1.1$ MeV (90%CL)
$(1.8 \pm 0.4) \cdot 10^{-7} < \mathcal{B}(p\bar{p})\mathcal{B}(J/\psi\pi^0)$
$< (2.5 \pm 0.6) \cdot 10^{-7}$
$\frac{\mathcal{B}(J/\psi\pi\pi)}{\mathcal{B}(J/\psi\pi^0)} \leq 0.18$ (90%CL)

E835 (90 pb^{-1} at χ_{cJ} c.g. in 1996/97 and 2000) preliminary analysis finds no evidence for $h_c \to J/\psi\pi^0$:



Assuming no interference and unpolarized J/ψ (as done in E760) we would set an upper limit (90%CL) on
$\mathcal{B}(h_c \to p\bar{p})\mathcal{B}(h_c \to J/\psi\pi^0) \approx 0.6 \cdot 10^{-7}$
for $M = 3526.2 \pm 0.3$ MeV/c^2 and
$\Gamma = 750 \pm 250$ keV

The h_c (1^1P_1) in $\bar{p}p \to \eta_c \gamma_3$ $[\eta_c \to \gamma_1\gamma_2, BR = (4.3 \pm 1.5)\cdot 10^{-4}]$

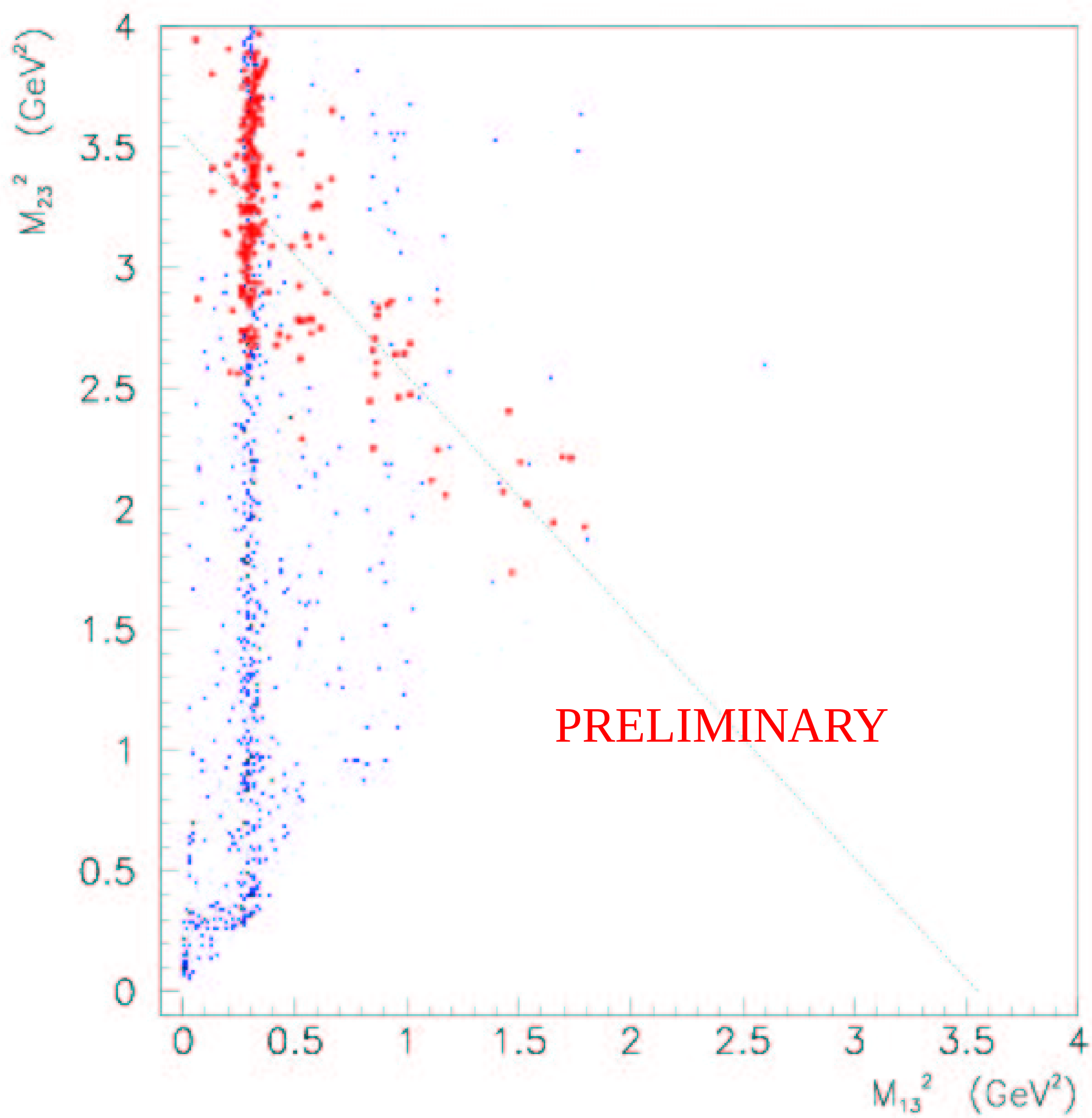
Daliz plot for 3γ candidates in χ_{cJ} c.g.

Summary of selection:

- Neutral trigger
- Select 3 (and only 3) in-time e.m. showers
- π^0 suppression
- Cuts to suppress forward/backward-peaked background
- 4C-fit: C.L.($\bar{p}p \to 3\gamma$)> 10^{-4}
- Dalitz plot cut: $M_{13}, M_{23} > 1$ GeV

Dashed line $\longrightarrow$ shows the expected η_c band

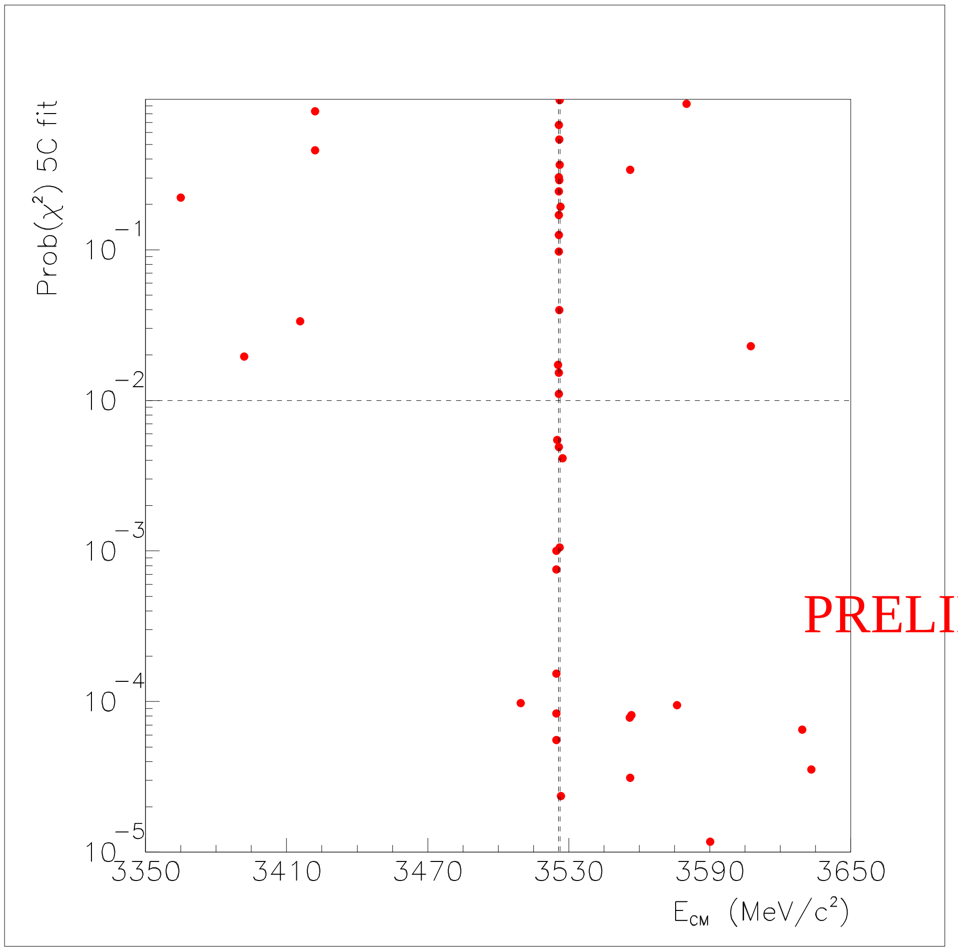
Red dots $\longrightarrow$ indicate events fitting $\eta_c\gamma$



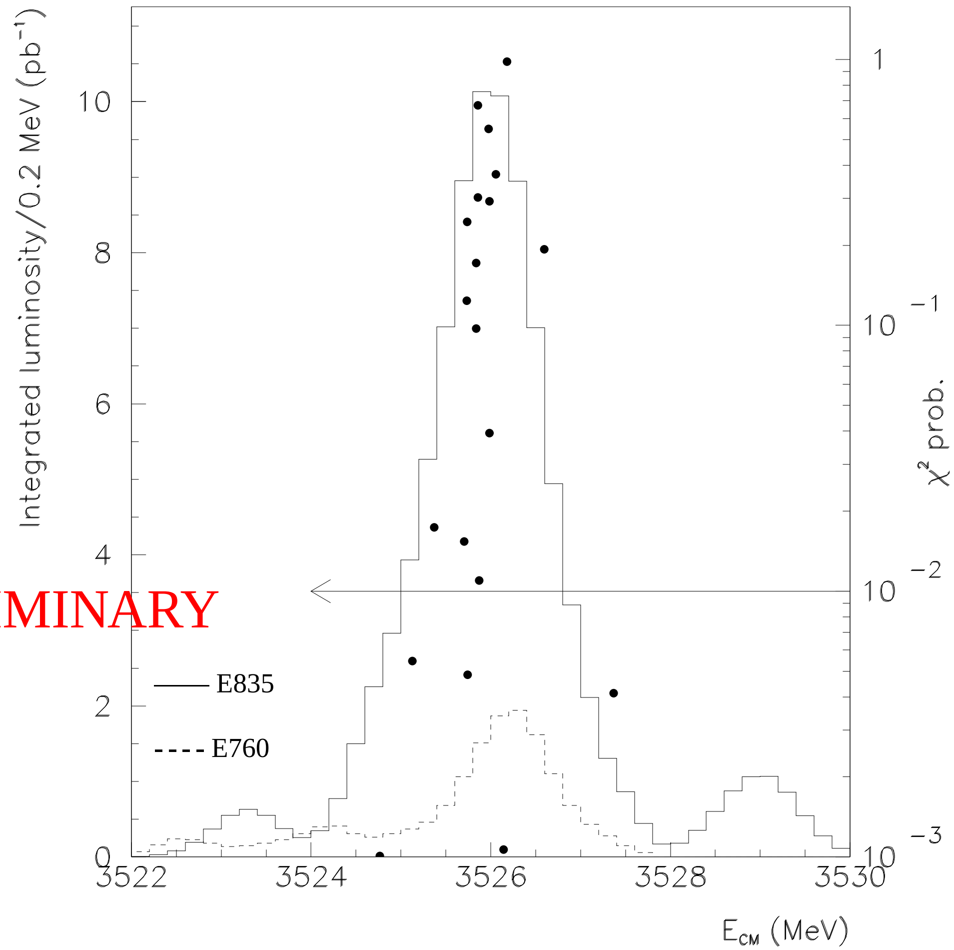
The $h_c\ (1^1P_1)$ in $\bar{p}p \to \eta_c\gamma$

- 5-C kinematic fit probability to $p\bar{p} \to \eta_c\gamma \to 3\gamma > 10^{-2}$

Wide Energy Range:

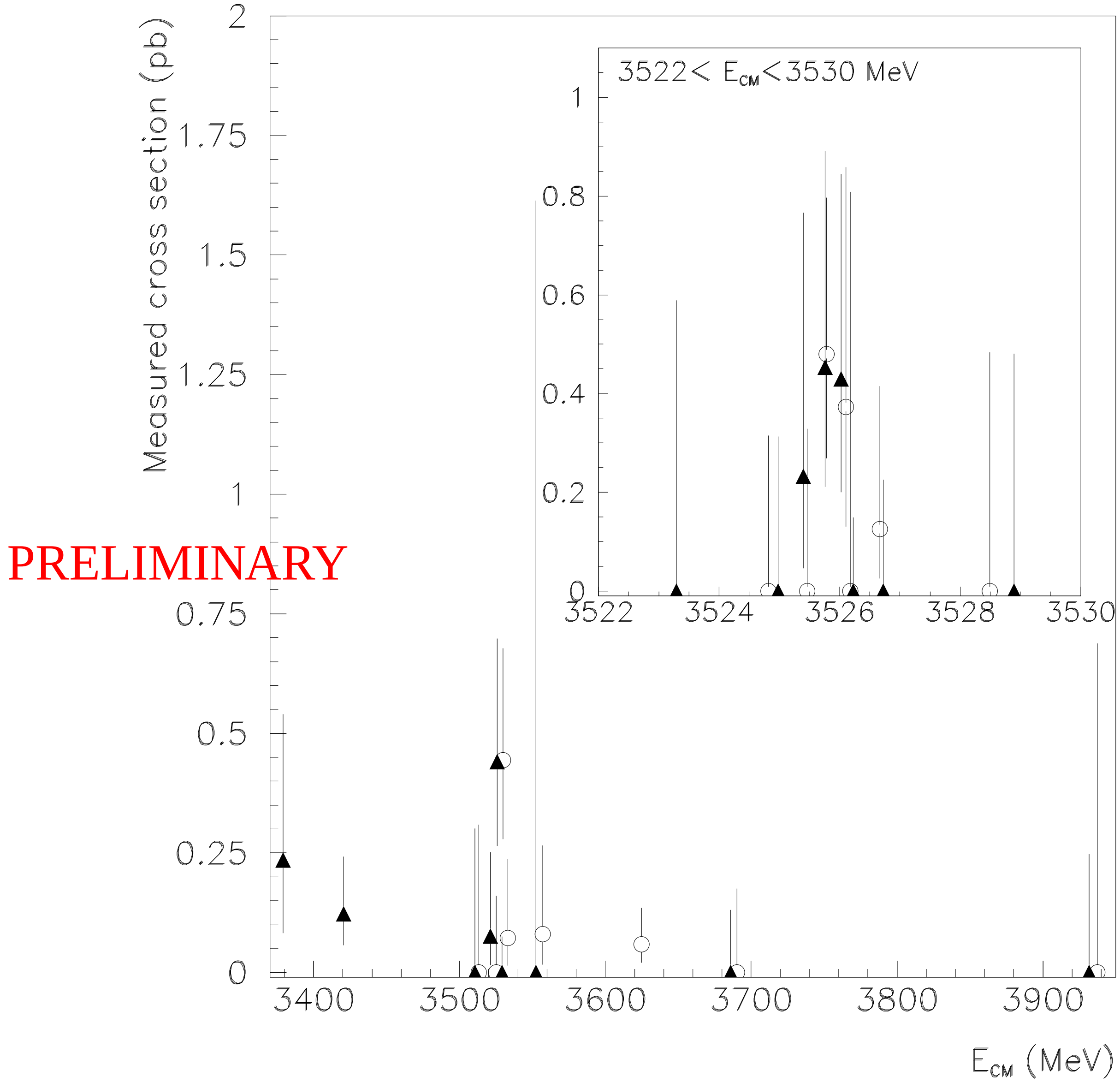


Energy Region of the χ_{cJ} c.g. :



PRELIMINARY

The h_c (1^1P_1) in $\eta_c\gamma$: Cross Section



E835 1996/97 (open circles) and 2000 (triangles) data plotted separately

The h_c (1^1P_1) in $\eta_c\gamma$: Significance and Results (PRELIMINARY)

In the Region of the χ_{cJ} c.g. :

– in the 1-MeV energy band 3526.2 ± 0.5 MeV $\rightarrow$ 14 events / 52 pb^{-1}

– outside that band $\rightarrow$ 1 event / 41 pb^{-1}

Note A: there are 9 events / 165 pb^{-1} in the full energy range outside the 1-MeV band

Note B: 13 of the 14 events are localized in the 0.5-MeV band < 3526.2 MeV (29 pb^{-1})

Significance tests say P(background fluctuation) $\lesssim 10^{-3}$

Preliminary Results:

$M \simeq (3525.8 \pm 0.2 \pm 0.2)$ MeV

$\Gamma < 1$ MeV

$\Gamma(h_c \rightarrow p\bar{p}) \times B(h_c \rightarrow \eta_c\gamma) \simeq (12 \pm 4 \pm 4)$ eV

in agreement with "reasonable" expectations.

Summary

- These studies have improved our knowledge of the χ_{c0} state:
  - M, Γ, $\Gamma_{p\bar{p}}$ and $\Gamma_{J/\psi\gamma}$ (E1 radiative transition)
  - $B(p\bar{p}) \times B(\pi^0\pi^0)$ and $B(p\bar{p}) \times B(\eta\eta)$
- Demonstrated the feasibility of measurements of resonances in processes dominated by non-resonant continuum
  - Developed a technique for managing interfering / non-interfering continuum and extract resonance parameters.
- Improved the understanding of the $p\bar{p}$ annihilation process
- Gained some insights into possible future strategies for:
  - studying singlet states ($\phi\phi$ final states seem a powerful tool)
  - searching for hadromolecular states by
    $c\bar{c}q\bar{q} \to \pi^0\pi^0,\ \eta\eta \ \ (I = 0)$
    $c\bar{c}q\bar{q} \to \pi^0\eta \ \ (I = 1)$.
- Study of the $h_c(1^1P_1)$ state (preliminary):
  - E835 does not find evidence of the h_c in $\bar{p}p \to J/\psi\,\pi^0$
  - it finds a significant excess of $\eta_c\gamma$ candidates at
    $M \simeq (3525.8 \pm 0.2 \pm 0.2)$ MeV $\quad$ ($\Gamma < 1$ MeV)