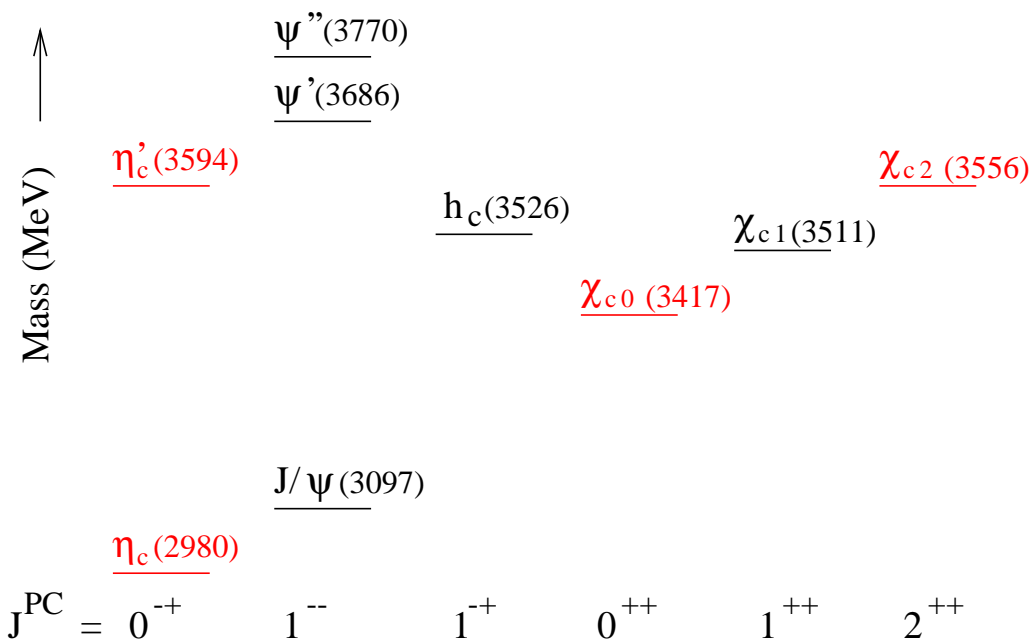


Gamma-gamma partial widths of charmonium states

Adriaan Buijs
Utrecht University



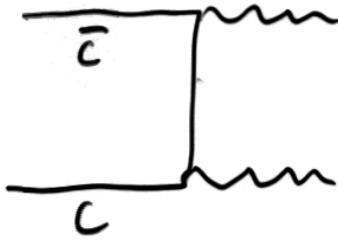
Issues:

- $p\bar{p}$ vs e^+e^- .
- η_c formation
- χ_c formation
- η'_c limits and η_c formfactor.

Informal workshop on charmonium spectroscopy,
Genoa, June 7-8 2001.

Introduction

Decay:

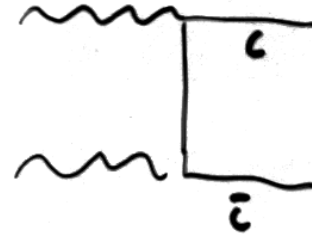


$$p\bar{p} \rightarrow c\bar{c} \rightarrow \gamma\gamma,$$

E760

E835

Formation:



$$\gamma\gamma \rightarrow c\bar{c} \rightarrow \text{hadrons},$$

CLEO

LEP

also

$$\psi' \rightarrow c\bar{c}\gamma \rightarrow \gamma\gamma\gamma.$$

Cristal Ball

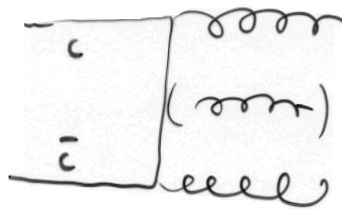
BES

also

$$\gamma^*\gamma \rightarrow c\bar{c} \rightarrow \text{hadrons},$$

L3

Compare with



Old measurements

SPEAR

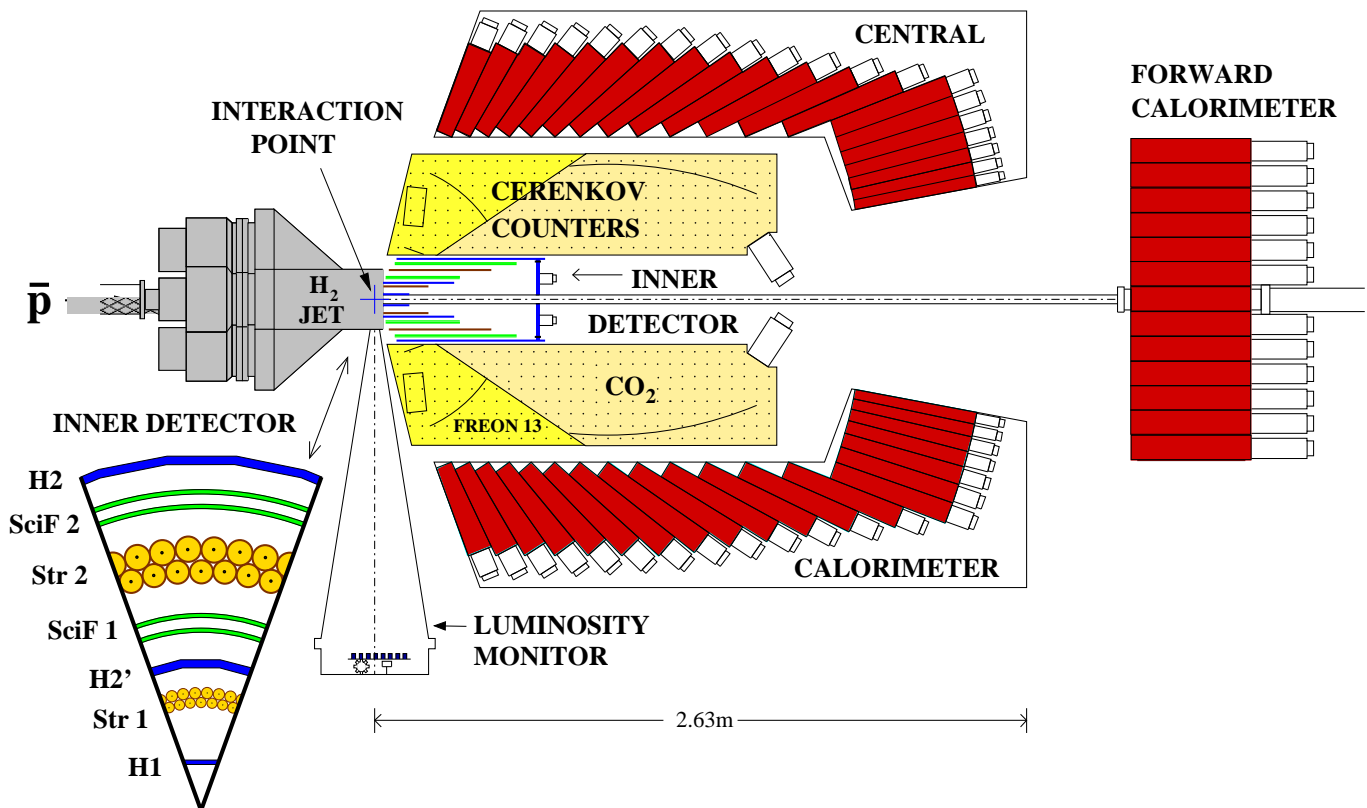
BES?

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

Experiments:

- R704, CERN ISR, 1986.
- E760 and E835, Fermilab, nunc.

E835 EQUIPMENT LAYOUT (Y2K)



Antiproton accumulator:

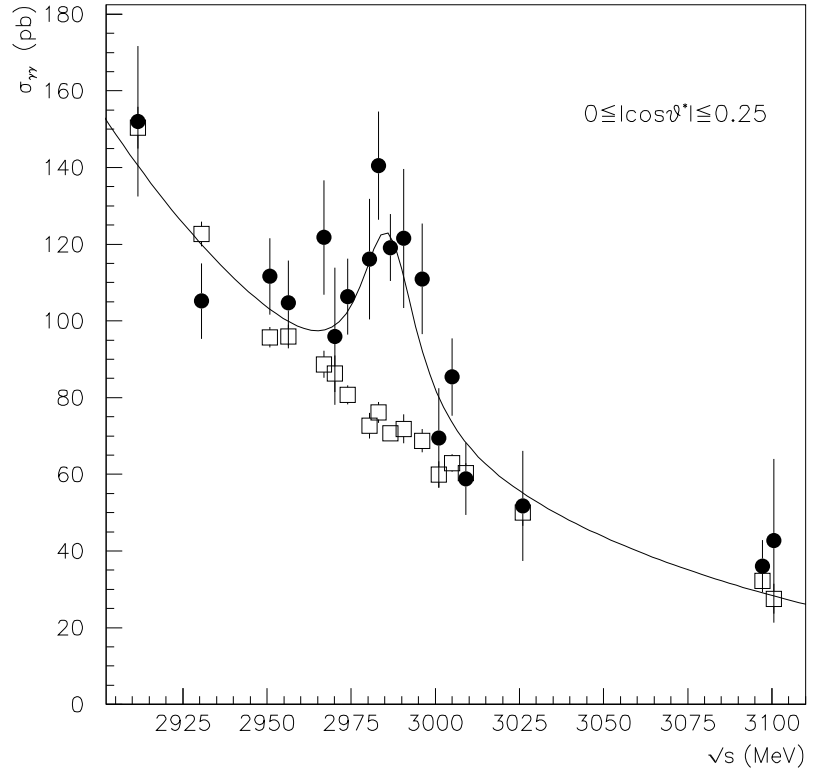
$$\sigma(\langle\sqrt{s}\rangle) \simeq 0.2 \text{ MeV!}$$

Perform cm scan. (In e^+e^- , nature does that for you.)

1. fit BW+BG to $p\bar{p} \rightarrow \gamma\gamma$. (χ_c , etac)
2. ratio $\gamma\gamma/J/\psi\gamma$. (χ_c)

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

η_c :



- integrated lumi 18 pb^{-1} .
- background obtained from $p\bar{p} \rightarrow \pi^0\gamma$ and $p\bar{p} \rightarrow \pi^0\pi^0 + \text{MC}$.

fit:

$$\sigma = \sigma_0 \times \frac{B(\eta_c \rightarrow p\bar{p}) \times B(\eta_c \rightarrow \gamma\gamma)}{(\sqrt{s} - m_{\eta_c})^2 / \Gamma_{\eta_c}^2 + 1} + A \times \left(\frac{2.99}{\sqrt{s}} \right)^B :$$

$$m_{\eta_c} = 2985 \pm 2 \text{ MeV},$$

$$\Gamma_{\eta_c} = 21 \pm 7 \text{ MeV},$$

$$B(\eta_c \rightarrow p\bar{p}) \times B(\eta_c \rightarrow \gamma\gamma) = 21.8 \pm 3.3 \times 10^{-8}.$$

With $B(\eta_c \rightarrow p\bar{p}) = 1.2 \pm 0.4 \times 10^{-3}$ (PDG):

$$\Gamma_{\gamma\gamma}(\eta_c) = 3.85_{-1.2}^{+1.5} \text{ keV.}$$

Note:

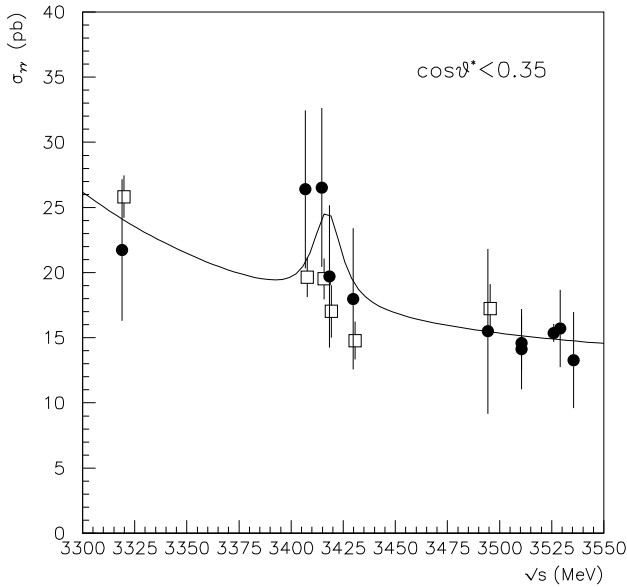
- With PDG-value of $\Gamma_{\eta_c} = 13.2 \text{ MeV}$:

$$\Gamma(\eta_c \rightarrow \gamma\gamma) \simeq 2.4 \text{ keV} \quad \text{Low!}$$

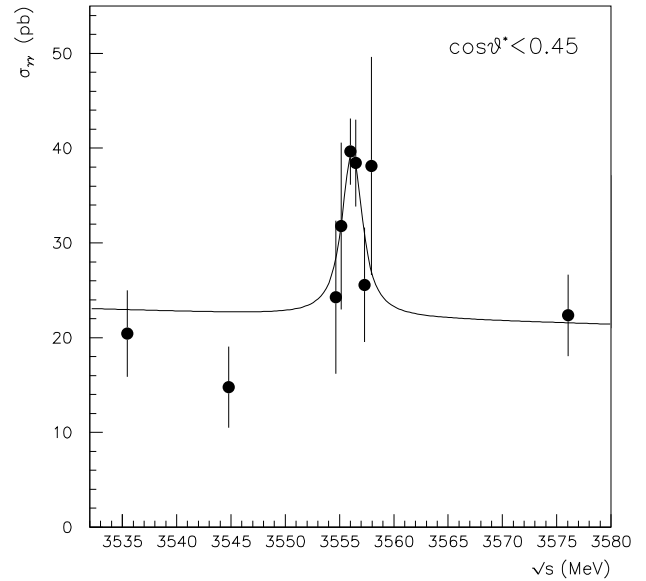
- Preliminary (W.Baldini, Photon '2000)

$p\bar{p} \rightarrow \gamma\gamma, \chi_c$

χ_{c0}



χ_{c2}



At each point, measure also:

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

Advantages:

- Systematic effects reduced;
- $\chi_c \rightarrow J/\psi \gamma$ BR relatively well known.

Ratio:

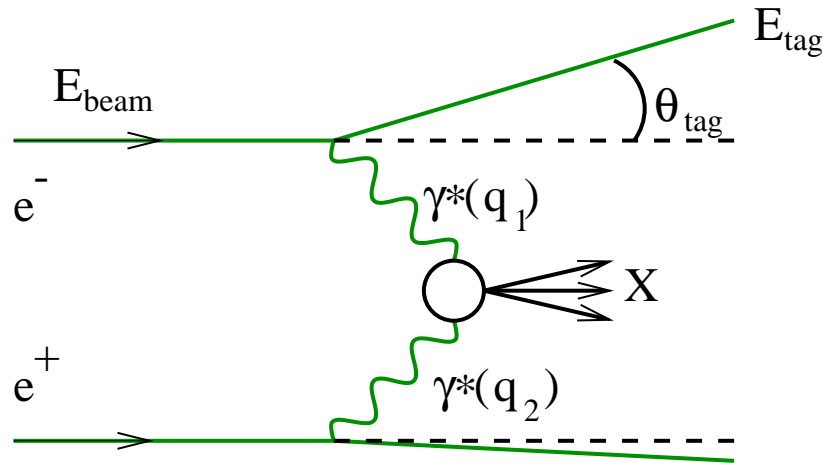
$$R \equiv \frac{B(\chi_c \rightarrow \gamma\gamma)}{B(\chi_c \rightarrow J/\psi \gamma \rightarrow e^+ e^- \gamma)} = \frac{\sigma(p\bar{p} \rightarrow \chi_c \rightarrow \gamma\gamma)}{\sigma(p\bar{p} \rightarrow \chi_c \rightarrow J/\psi \rightarrow e^+ e^- \gamma)}.$$

Need also Γ_{χ_c} : χ_{c2} from PDG, χ_{c0} from E835.

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.27 \pm 0.05 \text{ (stat)} \pm 0.03 \text{ (sys) keV,}$$

$$\Gamma_{\gamma\gamma}(\chi_{c0}) = 1.61 \pm 0.8 \text{ (stat)} \pm 0.65 \text{ (sys) keV.}$$

e^+e^- colliders



Two-photon collision:



- *Untagged*: (quasi-)real photons.
- *Tagged*: one photon virtual, need forward detector.

Total cross section behaves as $\sim M_X^{-3}$ and $\sim \log(E_{\text{beam}})$

- CESR/CLEO: high luminosity, low cm.
- LEP: high beam energy, low luminosity.

Total two-photon resonance cross section:

$$\sigma(e^+e^- \rightarrow e^+e^-X) = \int d^5L_{\gamma\gamma}(\alpha_i)\sigma(\gamma\gamma \rightarrow X)$$

$$\sigma(\gamma\gamma \rightarrow R) = 8\pi \frac{(2J_R + 1)}{M_R} \Gamma_{\gamma\gamma}(R) \times \frac{M_R \Gamma_R}{(M_X^2 - M_R^2)^2 + M_R^2 \Gamma_R^2} F(q_1^2, q_2^2)$$

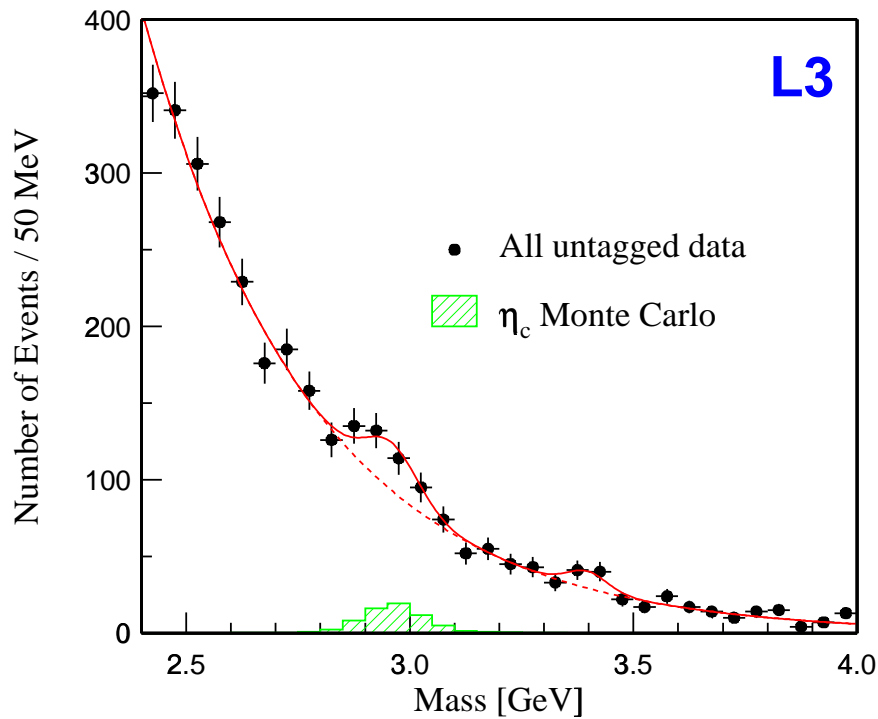
Transition Form Factor $F(q_1^2, q_2^2)$ contains explicit dependence on photon virtualities q_1^2, q_2^2 .

e^+e^- colliders, L3: η_c

(data up to 1997)

The η_c has been analysed in the decay modes:

| Decay mode | Branching ratio (%) | Signature |
|---|---------------------|-----------------------|
| $\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.) | 1.2 ± 0.4 | 4 tracks |
| $K^+K^-\pi^+\pi^-$ | 2.0 ± 0.7 | 4 tracks |
| $K_S K^\pm \pi^\mp, K_S \rightarrow \pi^+\pi^-$ | 1.3 ± 0.4 | 2 tracks, sec. vertex |
| $\pi^+\pi^-\eta, \eta \rightarrow \gamma\gamma$ | 1.3 ± 0.5 | 2 tracks, 2 photons |
| $\pi^+\pi^-\eta, \eta \rightarrow \pi^+\pi^-\pi^0$ | 0.8 ± 0.3 | 4 tracks, 2 photons |
| $\pi^+\pi^-\eta', \eta' \rightarrow \pi^+\pi^-\gamma$ | 0.8 ± 0.3 | 4 tracks, 1 photon |
| $\pi^+\pi^-\eta', \eta' \rightarrow \pi^+\pi^-\eta$ | 0.5 ± 0.2 | 4 tracks, 2 photons |
| $K^+K^-\pi^0$ | 0.9 ± 0.3 | 2 tracks, 2 photons |
| $\rho^+\rho^-, \rho^\pm \rightarrow \pi^\pm\pi^0$ | 1.7 ± 0.6 | 2 tracks, 4 photons |
| total | 10.5 | |

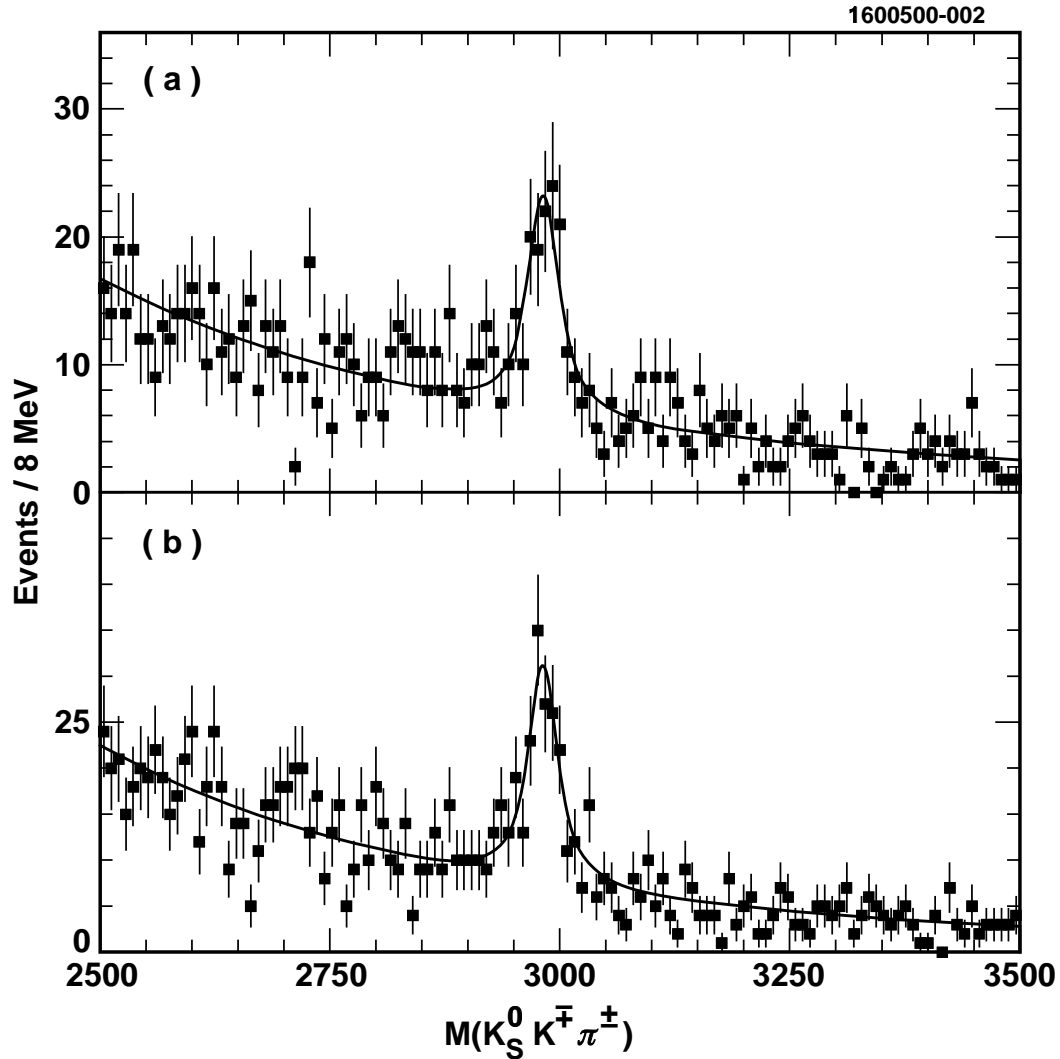


$\Gamma_{\gamma\gamma}$ from unbinned likelihood fit with different weight for each mass spectrum:

$$\Gamma_{\gamma\gamma}(\eta_c) = 6.9 \pm 1.7 \text{ (stat)} \pm 0.8 \text{ (sys)} \pm 2.0 \text{ (BR)} \text{ keV.}$$

e^+e^- colliders, CLEO: η_c

Only $\eta_c \rightarrow K_s K^\pm \pi^\pm$ decay mode (1.3%, PDG)



Fit: BW plus 2 Gaussians.

$$m_{\eta_c} = 2980.4 \pm 2.3 \text{ (stat)} \pm 0.6 \text{ (sys)} \text{ MeV,}$$

$$\Gamma_{\eta_c} = 27.0 \pm 5.8 \text{ (stat)} \pm 1.4 \text{ (sys)} \text{ MeV;}$$

$$\Gamma_{\gamma\gamma}(\eta_c) = 7.6 \pm 0.8 \text{ (stat)} \pm 0.4 \text{ (sys)} \pm 2.3 \text{ (BR)} \text{ keV.}$$

e^+e^- colliders, χ_{c0}

Old measurement: Xtal Ball, 1985 ($\psi' \rightarrow 3\gamma$)

$$\Gamma_{\gamma\gamma}(\chi_{c0}) = 4.0 \pm 2.8 \text{ keV.}$$

Unpublished: CLEO, photon '95 ($\chi_{c0} \rightarrow 4\pi$)

$$\Gamma_{\gamma\gamma}(\chi_{c0}) = 1.7 \pm 0.6 \pm 0.4 \pm 0.3 \text{ keV.}$$

Same proceedings: $\chi_{c2} \rightarrow 4\pi$

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.7 \pm 0.2 \pm 0.1 \pm 0.2 \text{ keV.}$$

e^+e^- colliders, χ_{c2}

measurements from OPAL and L3.

- Channel $\chi_{c2} \rightarrow J/\psi \gamma \rightarrow \ell^+ \ell^- \gamma$.
- Select events with lepton pairs: e^+e^- and $\mu^+\mu^-$ and a photon.
- Measure:

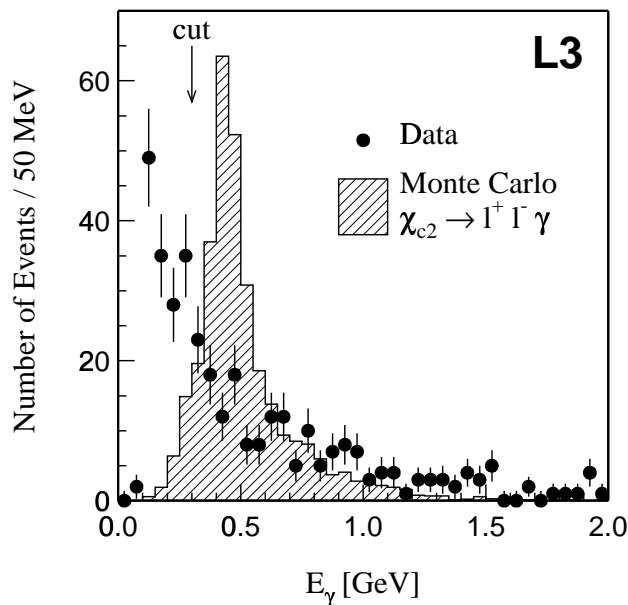
$$\Delta M = M(\ell^+ \ell^- \gamma) - M(\ell^+ \ell^-),$$

should peak at

$$M(\chi_{c2}) - M(J/\psi) = 0.459 \text{ GeV}.$$

- Resolution dominated by photon energy resolution.
- $E_\gamma > 0.3 \text{ GeV}$ for L3 and OPAL.
- OPAL has good $M(J/\psi)$ resolution (jetchamber), dominant error from E_γ -cut (background).
- L3 has good E_γ resolution (BGO), dominant error from $M(J/\psi)$

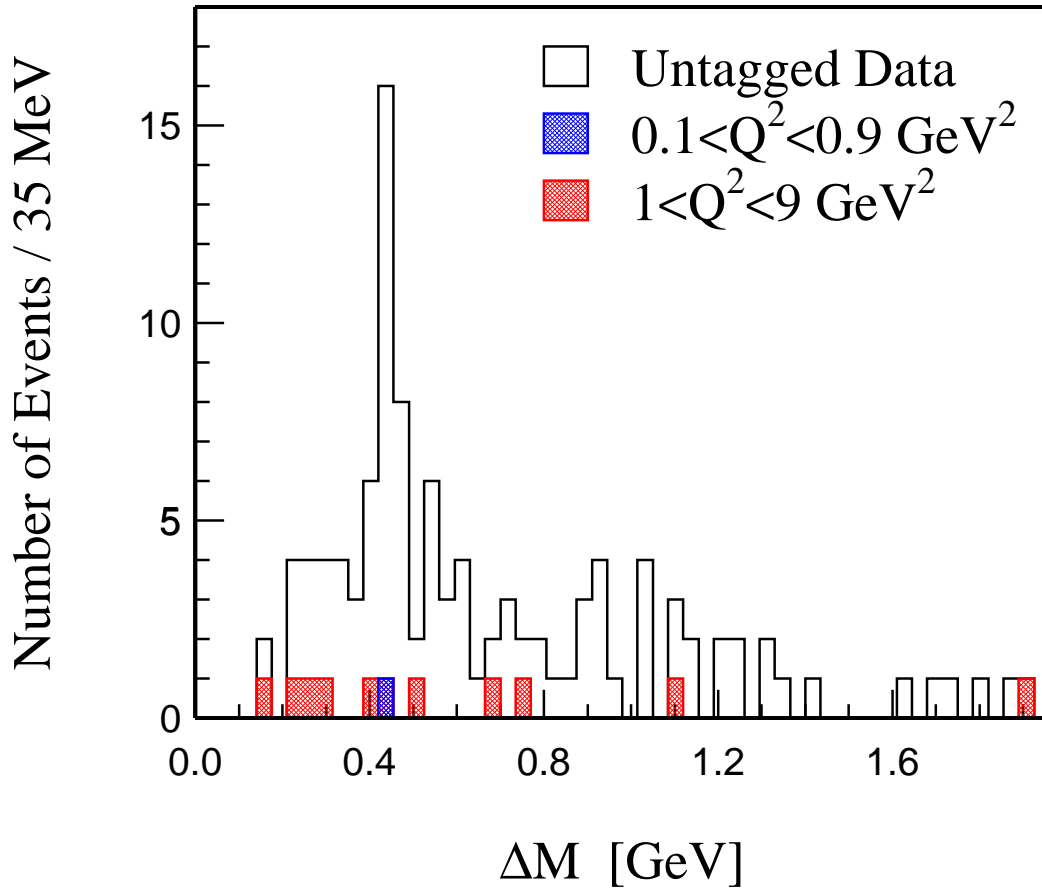
Common cut in all experiments:



χ_{c2} formation: L3

L3: up to 1997

$\mathcal{L} = 140 \text{ pb}^{-1}$ at $\sqrt{s} = 91 \text{ GeV}$ and
 52.4 pb^{-1} at $\sqrt{s} = 183 \text{ GeV}$



$$\Delta M = 445 \pm 10 \text{ MeV},$$
$$\sigma(\Delta M) = 23 \pm 7 \text{ MeV}.$$

Unbinned likelihood fit to data and to J/ψ -sidebands spectrum.

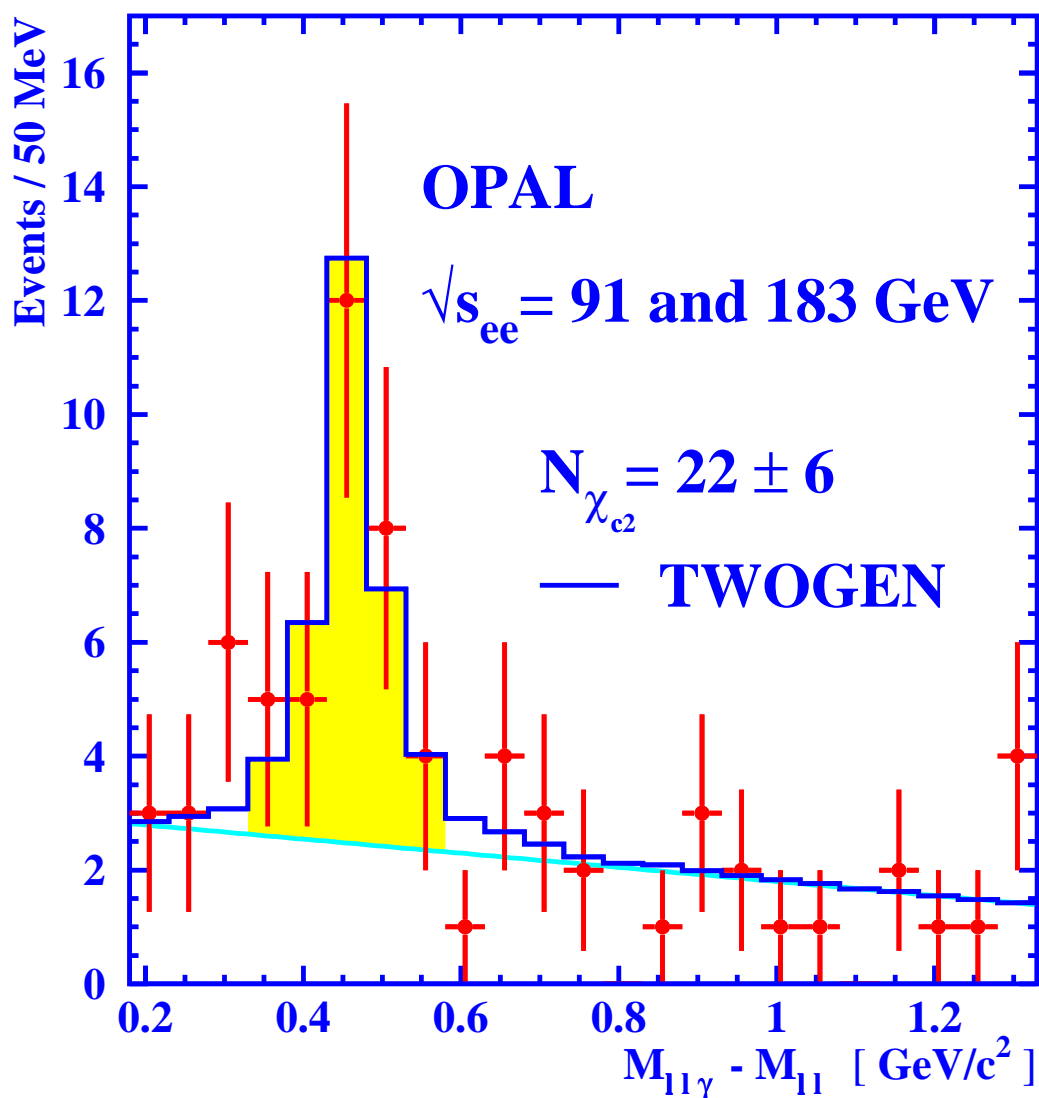
$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.02 \pm 0.40 \text{ (stat)} \pm 0.15 \text{ (sys)} \pm 0.09 \text{ (Br) keV}$$

Trend: ↘

χ_{c2} formation: OPAL

OPAL: up to 1997

$\mathcal{L} = 167 \text{ pb}^{-1}$ at $\sqrt{s} = 91 \text{ GeV}$ and
 55 pb^{-1} at $\sqrt{s} = 183 \text{ GeV}$



$$\Delta M = 464 \pm 14 \text{ MeV},$$
$$\sigma(\Delta M) = 39 \pm 16 \text{ MeV}.$$

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.76 \pm 0.47 \text{ (stat)} \pm 0.37 \text{ (sys)} \pm 0.15 \text{ (Br)} \text{ keV}$$

χ_{c2} formation

Personal observations:

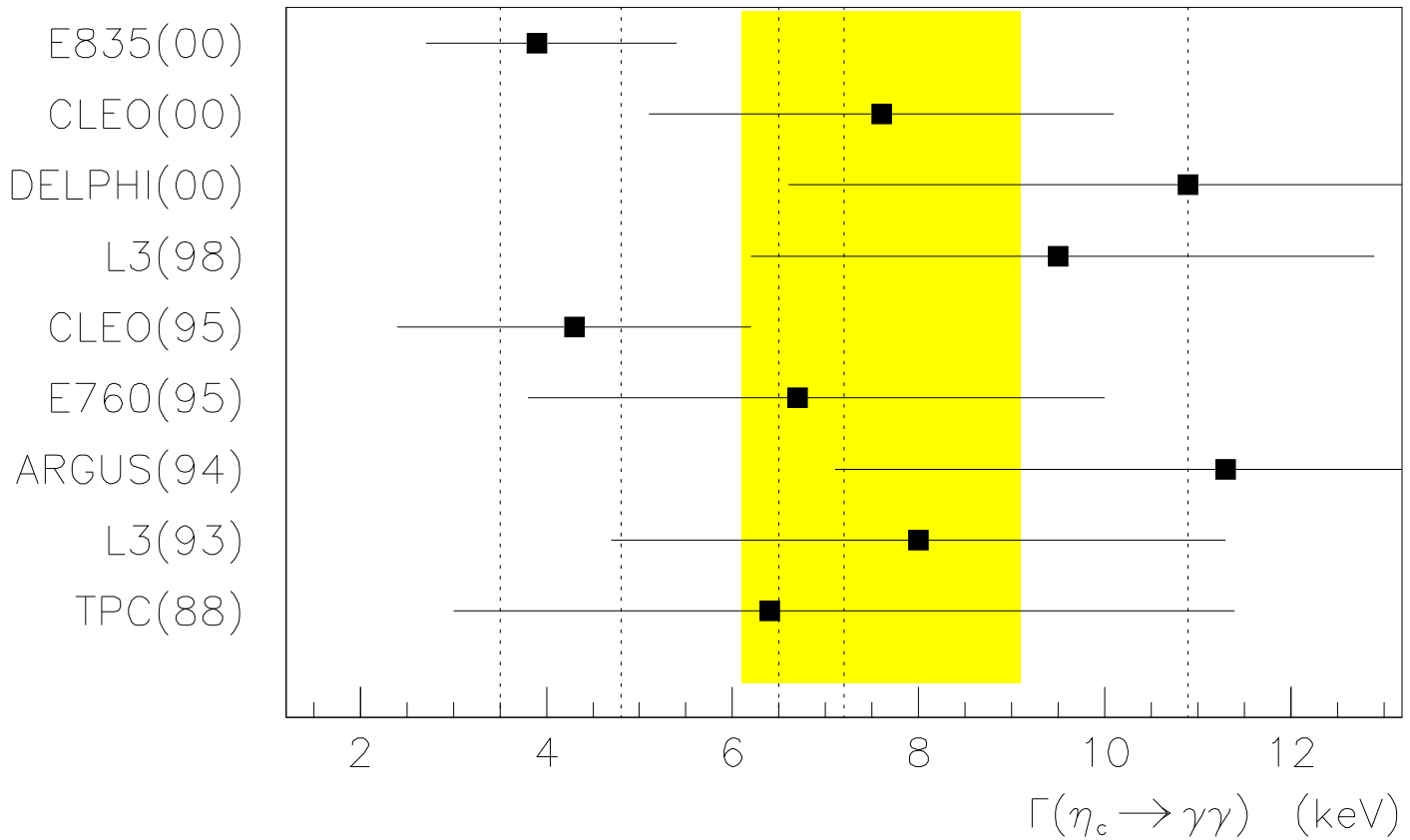
- Background line of OPAL perhaps a bit low.
- Result depends critically on E_γ -cut.
- This is common to all e^+e^- experiments, except CLEO (photon '95) measuring $\chi_{c2} \rightarrow 4\pi$:

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.7 \pm 0.2 \text{ (stat)} \pm 0.1 \text{ (sys)} \pm 0.2 \text{ (BR) keV.}$$

η_c summary

Theoretical predictions ¹: 3 - 11 keV

Figures taken from Wander Baldini, Photon 2000:



- Errors remain large
- Common 30% BR error!
- E835(00) lowest of the pack (Same BR!).

¹E.S. Ackleh and T. Barnes, Phys. Rev D45(1992)232; M.R. Ahmady and R.R. Mendel, Phys. Rev D51(1995)141; C.R. Münz, Nucl. Phys. A609(1996)364; H.-W. Huang *et al.*, Phys. Rev D56(1997)368.

χ_{c2} , summary

Naïve model (Bodwin, Braaten, Lepage):

$$\Gamma(\chi_{c2} \rightarrow \gamma\gamma) = \frac{8}{9} \left(\frac{\alpha}{\alpha_s} \right)^2 \times \Gamma(\chi_{c2} \rightarrow gg),$$

with

$$\Gamma(\chi_{c2} \rightarrow gg) \simeq \Gamma(\chi_{c2} \rightarrow \text{hadrons}) - \Gamma(\chi_{c1} \rightarrow \text{hadrons}).$$

yields:

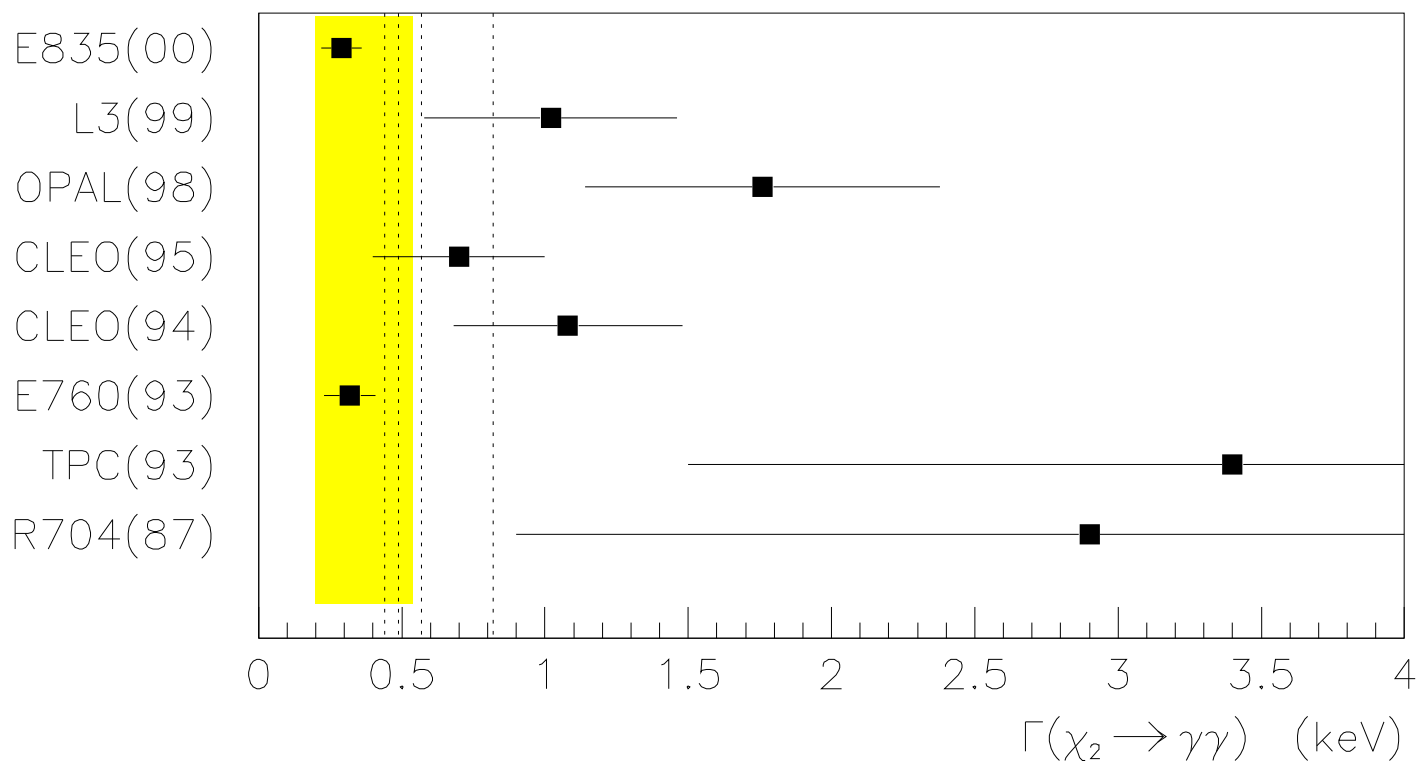
$$\Gamma(\chi_{c2} \rightarrow \gamma\gamma) = 0.82 \pm 0.30 \text{ keV}.$$

Other theoretical predictions² are lower: **0.3-0.6 keV**.

| Author | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV) |
|-----------------------|--|
| Barnes | 0.34 – 0.56 |
| Münz | 0.44 ± 0.14 |
| Huang <i>et al.</i> | 0.39 – 0.50 |
| Schuler <i>et al.</i> | 0.28 |

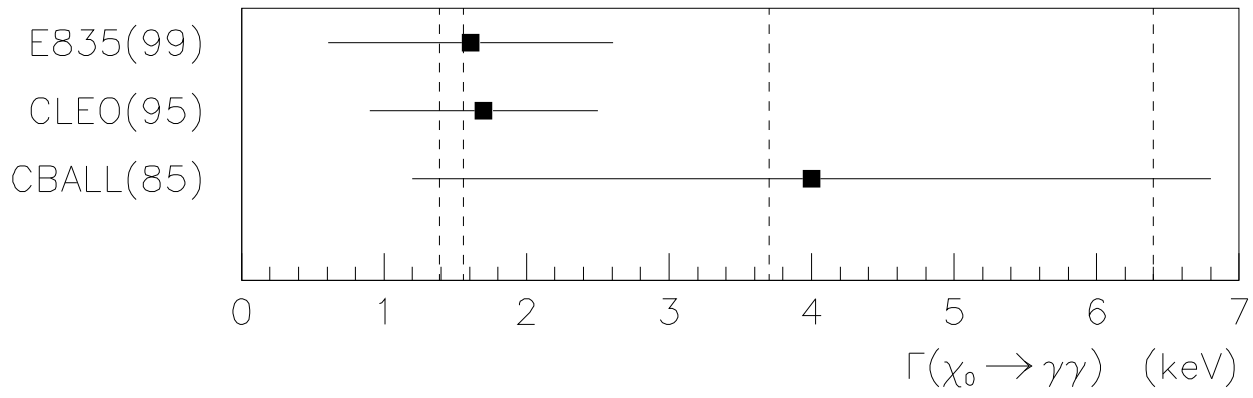
²T. Barnes, proceedings IXth workshop on $\gamma\gamma$ collisions (1992);
C.R. Münz, Nucl. Phys. A609 (1996) 364;
H.-W. Huang *et al.*, Phys. Rev. D54 (1996) 2123;
G.A. Schuler *et al.*, Nucl. Phys. B523 (1998) 423.

χ_{c2} , summary cont'd



- $p\bar{p}$ measurements lower
- 'optimizing' cuts?
- Branching ratios.
- New CLEO analysis desired.

χ_{c0} , summary



- Different branching ratios.
- New CLEO analysis desired.

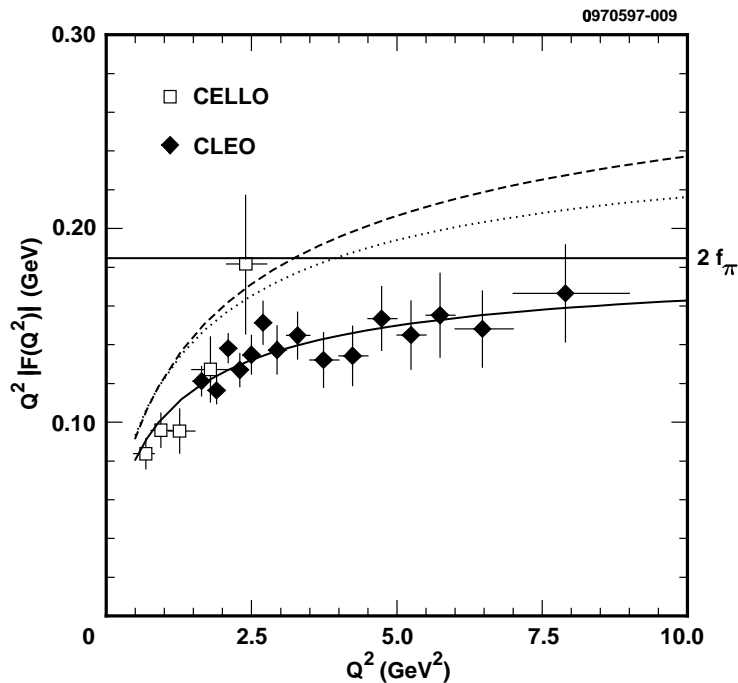
$$\alpha_s$$

Extraction of α_s :

η_c Form factor

Meson-Photon transition form factor $F_{R\gamma}(Q^2)$.

- Measurement of internal structure of mesons.
- Good measurements of low-mass meson FF's exist:
 - Asymptotic wave function $\phi_A S(x_1) = 6x_1x_2$ gives a good description of the measured pion form factor in the Hard Scattering Approach. (Kroll, CLEO, Photon '95)
 - π^0 and η have the same internal structure (CLEO, photon '97), η' is different.



Commonly used parameterisation:

$$|F_{R\gamma}(Q^2)|^2 = \frac{4}{\pi\alpha^2} \frac{\Gamma(R \rightarrow \gamma\gamma)}{M_R^3} \frac{1}{(1 + Q^2/\Lambda_R^2)^2}.$$

η_c Form factor

| Meson | Λ_R (MeV) |
|---------|----------------------------|
| π^0 | $776 \pm 10 \pm 12 \pm 16$ |
| η | $774 \pm 11 \pm 16 \pm 22$ |
| η' | $859 \pm 9 \pm 18 \pm 20$ |

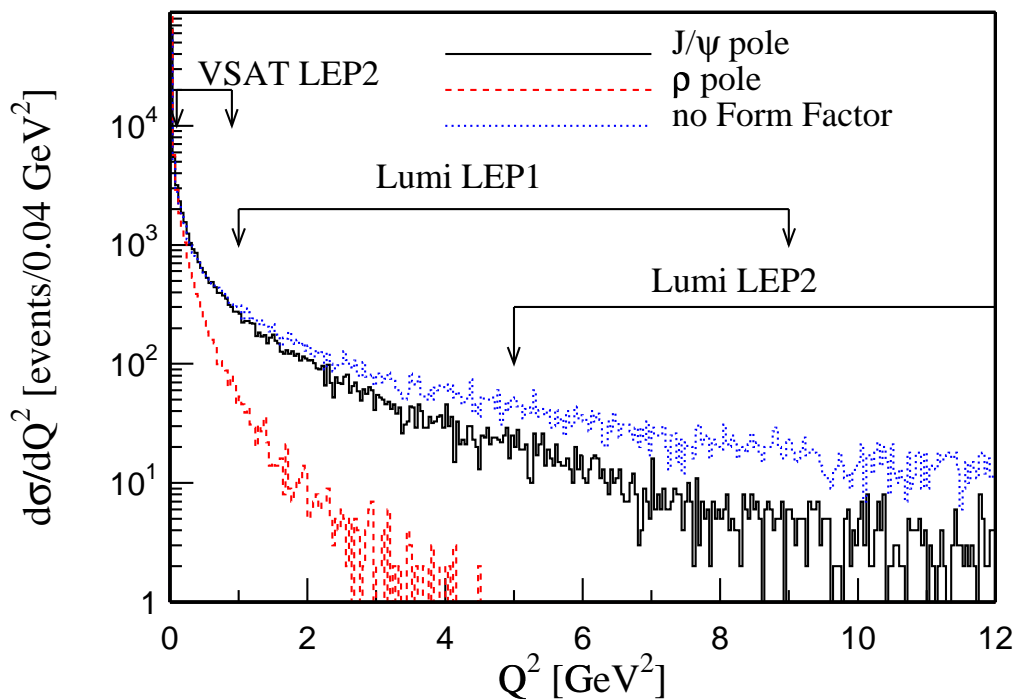
Virtual photon \Rightarrow scattered beam particle is detected:

$$Q^2 = 2E_{\text{beam}}E_{\text{tag}}(1 - \cos \theta_{\text{tag}}).$$

L3 has two BGO calorimeters for measuring tags:

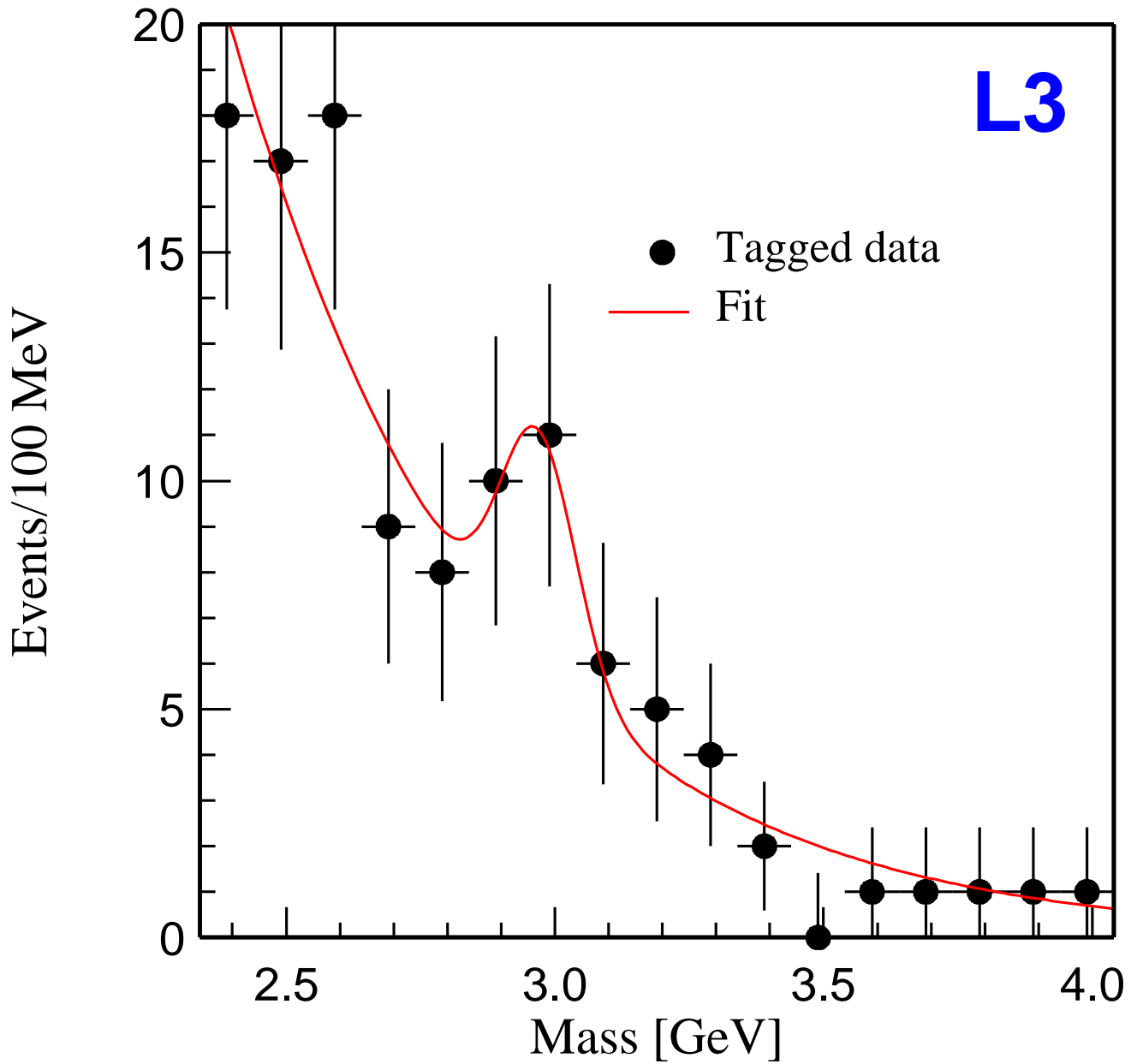
Very small angle tagger (VSAT) $5 < \theta_{\text{tag}} < 10$ mrad,

Luminosity Monitor $30 < \theta_{\text{tag}} < 65$ mrad



η_c Form factor

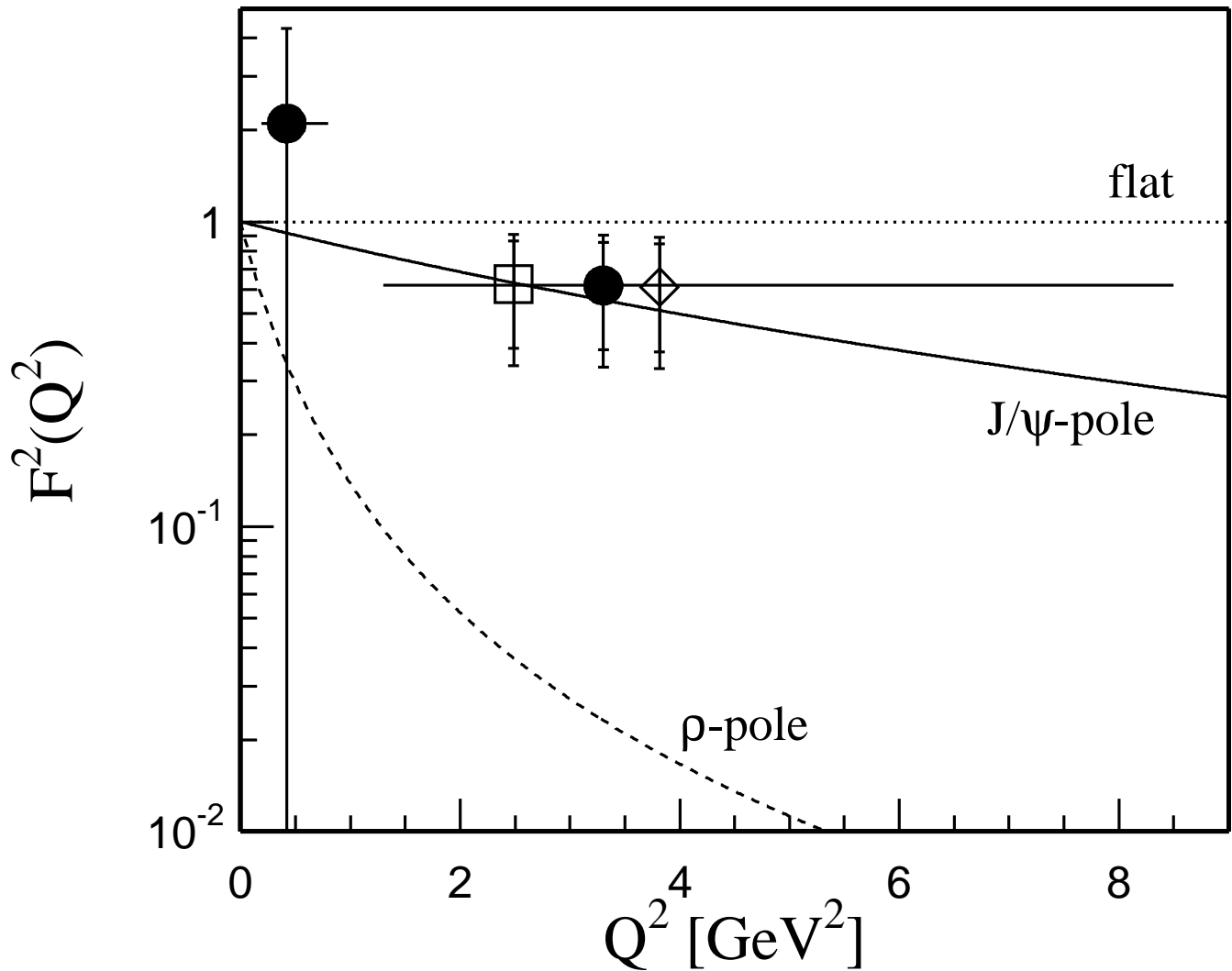
Mass spectrum tagged events:



signal: $8.3^{+5.5}_{-4.9}$ events.

η_c Form factor

Form Factor $F_{\eta_c\gamma}(Q^2)^2$:



Prob(J/ψ -pole) $\simeq 10 \times$ Prob(ρ -pole)

η_c Form factor

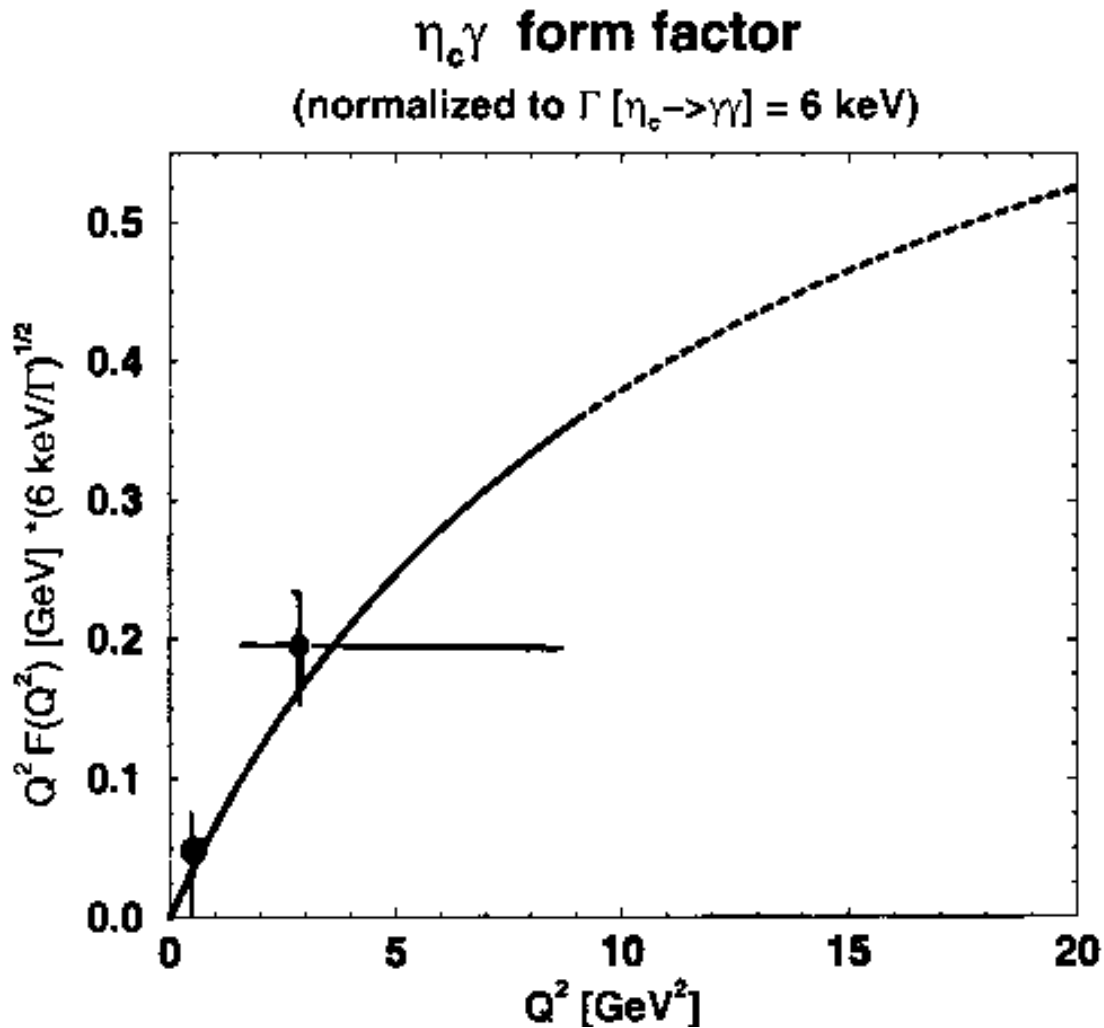
Quantitatively:

$$\Lambda_{\eta_c} = 5.3_{-2.5}^{+\infty} \text{ GeV.}$$

Or:

$$\Lambda_{\eta_c} > 1.6 \text{ GeV at 95\% c.l.}$$

Comparison with **prediction** by Feldmann and Kroll
(Photon '97):

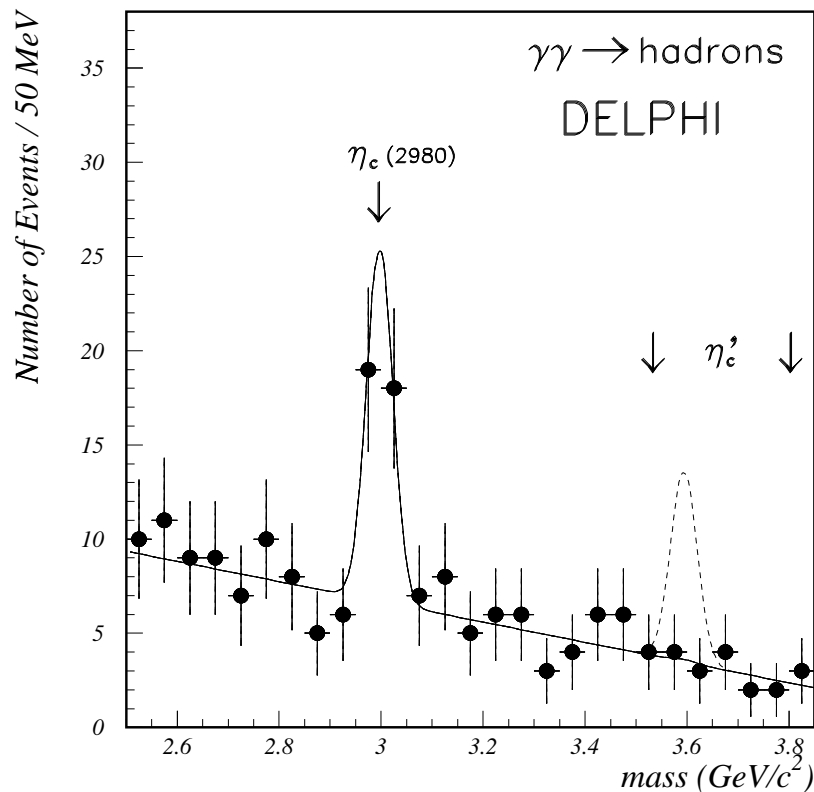


η'_c

- η'_c , the first radial excitation of $\eta_c(2980)$ was observed by Crystal Ball with $m_{\eta'_c} = 3594 \pm 5$ MeV.
- Not observed since.
- Barnes, Browder and Tuan (PL B385 (1996) 391) calculate:

$$\Gamma(\eta_c \rightarrow \gamma\gamma) = 4.8 \text{ keV, and}$$
$$\Gamma(\eta'_c(3590) \rightarrow \gamma\gamma) = 3.7 \text{ keV}$$

- Suppose decay branching ratios of η'_c and η_c the same.
- Detection properties (efficiencies, luminosities) are similar.



DELPHI measures ratio:

$$\frac{\Gamma(\eta'_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \gamma\gamma)} < 0.34 \quad \text{at 90\% c.l.}$$

L3 absolute measurement:

$$\Gamma(\eta'_c \rightarrow \gamma\gamma) < 2.0 \text{ keV} \quad \text{at 95\% c.l.}$$

L3 ratio:

$$\frac{\Gamma(\eta'_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \gamma\gamma)} < 0.29 \quad \text{at 95\% c.l.}$$

Compare with Ted:

$$\frac{\Gamma(\eta'_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \gamma\gamma)} \simeq 0.75.$$

\Rightarrow **discrepancy**

Discussion and Conclusions

- Charmonium formation in $\gamma\gamma$ **difficult** to measure:
 - Luminosity;
 - Trigger;
 - Selection cuts;
 - MC; needed for trigger and selection cuts, use control channels also.
 - External branching ratios. **Common systematic error!**

Needed:

- CLEO/BaBar/Belle (people!).
- $Br \psi'$.
- Charmonium formation in $\bar{p}p$ **difficult** to measure:
 - Background,
 - External branching ratios.
- Discrepancy:
 - $\gamma\gamma$ widths of $\bar{p}p$ always lower.
- C. Patrignani: look at χ_{c2} measurement,
 - $\gamma\gamma$: measure $\Gamma_{\gamma\gamma} \times Br(\chi_{c2} \rightarrow \gamma J/\psi)$;
 - $\bar{p}p$: measure $\Gamma_{\gamma\gamma} / Br(\chi_{c2} \rightarrow \gamma J/\psi)$;
- However: for η_c both measure

$$\Gamma_{\gamma\gamma} \times Br(\eta_c \rightarrow \text{hadrons}).$$

Discussion and Conclusions

- Other effect: "tuning of cuts"

Suggest:

- Fit of all measurables (à la LEP);
- Working group with (a) member(s) of each (active) experiment.
- Leads to better contact with theorists.
- Extract α_s and m_c .