Charmonium Formation in Two-Photon Collisions at LEP

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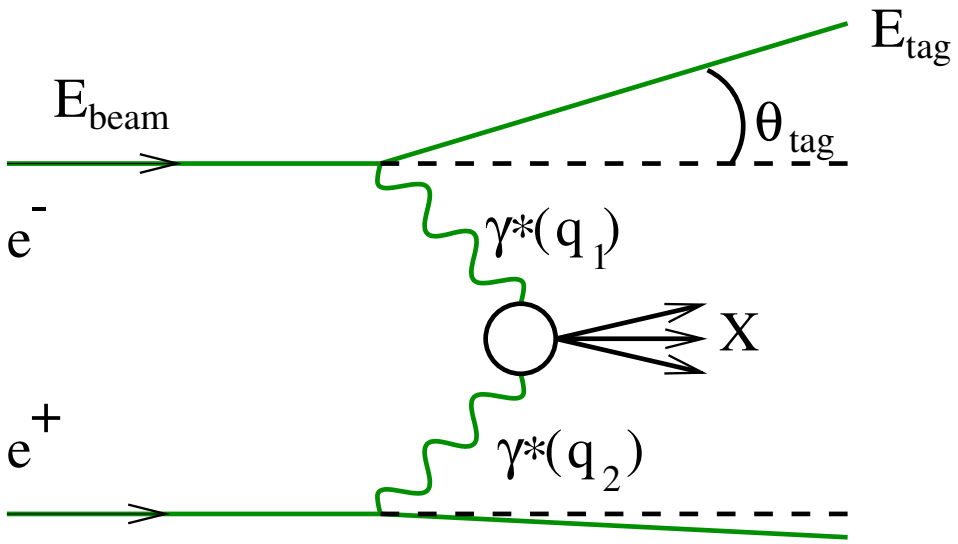
Issues:

- Introduction
- χ_{c2} formation
- η_c formation
- η_c' formation

PHOTON '99

Introduction



Two-photon collision:

$$e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$$

Photons radiated under small angle (quasi-real photons). Scattered electrons can be detected in a forward detector only if photon is very virtual.

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

- high and increasing integrated luminosity
- increasing beam energy

allow study of heavy quark production, both inclusive and resonant:

$$\begin{aligned} e^+e^- &\to e^+e^-\chi_{c2} \\ e^+e^- &\to e^+e^-\eta_c \\ e^+e^- &\to e^+e^-\eta_c' \end{aligned}$$

Resonance formation

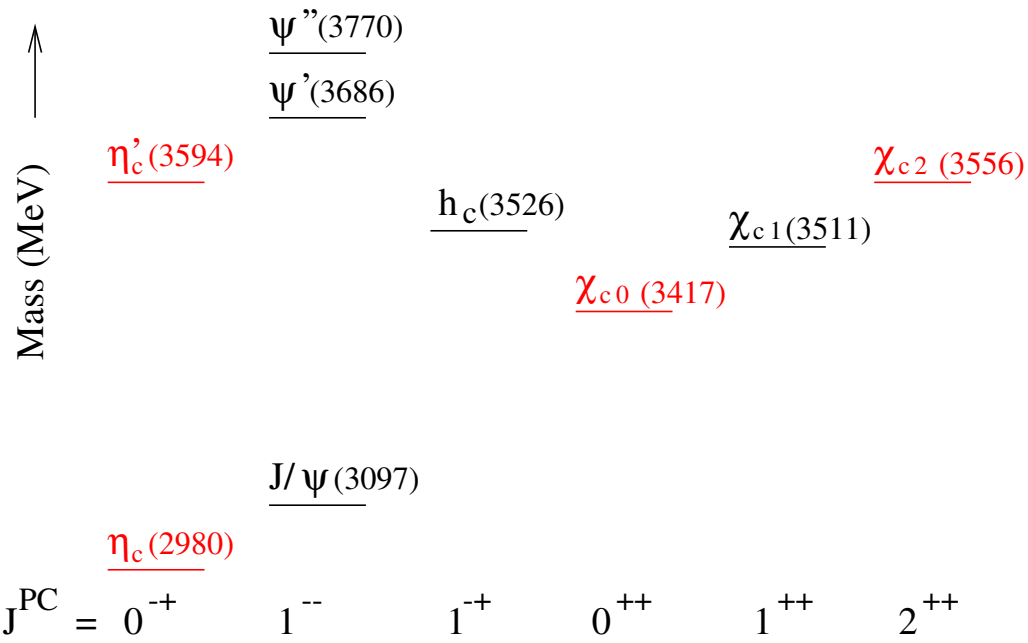
Total two-photon resonance cross section:

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

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

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

Charmonium (resonant $c\bar{c}$ states)



Theoretical predictions for two-photon charmonium formation:

- assume loosely bound state of two heavy quarks
- sensitive to assumptions and parameters of model

χ_{c2} formation

Status at photon '97: note:

Experiment	Production Mechanism	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
CLEO	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.08 \pm 0.30 \pm 0.26$
TPC/2γ	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$3.4 \pm 1.7 \pm 0.9$
L3 (prel.)	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.5 \pm 0.7 \pm 0.5$
R704	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.0\ ^{+0.9}_{-0.7} \pm 0.3$
E760	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.32 \pm 0.08 \pm 0.05$

- Most precise measurement is significantly lower.
- This is a $p\bar{p}$ measurement.

Naïve model (Bodwin, Braaten, Lepage):

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

with

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

yields:

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

Other theoretical predictions are lower: 0.3-0.6 keV.
T. 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} formation

New measurements from OPAL and L3.

- Channel again: $\chi_{c2} \to J/\psi\,\gamma \to \ell^+\ell^-\gamma$.
- 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

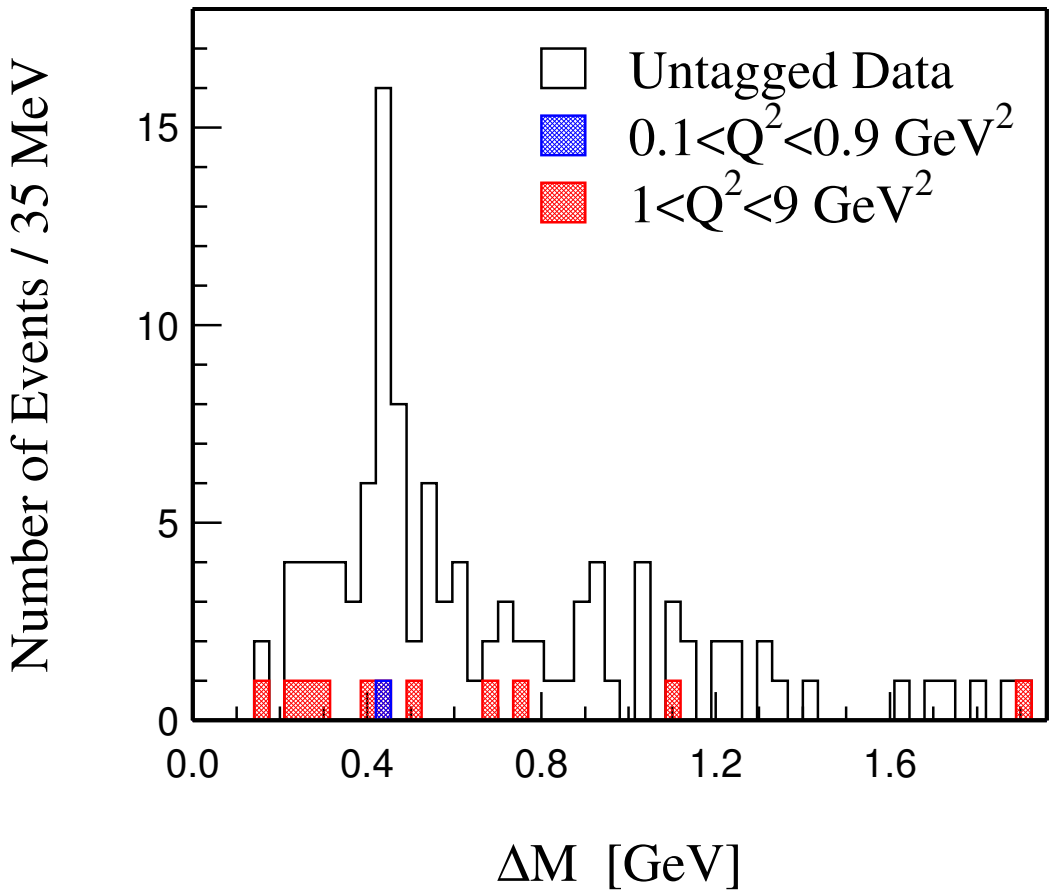
  $$M(\chi_{c2}) - M(J/\psi\,) = 0.459 \text{ GeV}.$$

- Resolution dominated by photon energy resolution.
- $E_\gamma > 0.3$ 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 $M(J/\psi\,)$
- L3 also measures tagged events.

χ_{c2} formation

L3:

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



$\Delta M = 0.445 \pm 0.010$ GeV, $\quad \sigma(\Delta M) = 0.023 \pm 0.007$ GeV.

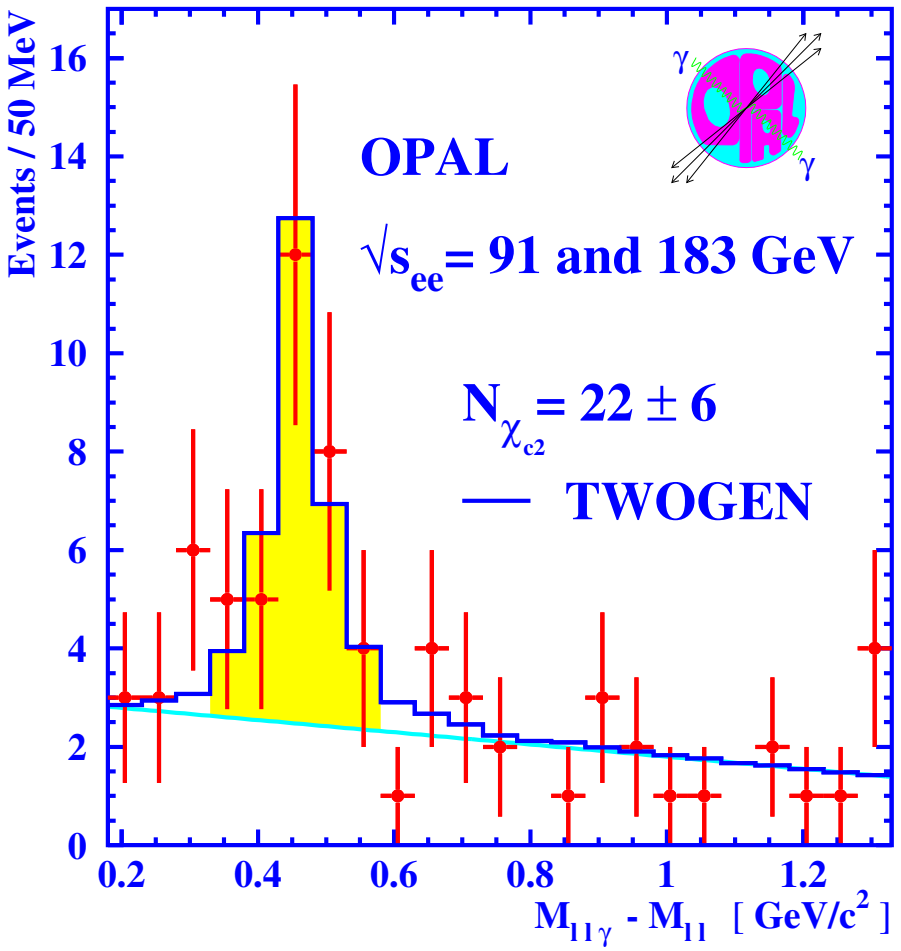
Unbinned likelihood fit to data and to J/ψ-sidebands spectrum

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

$\chi_{c2} \to J/\psi\gamma \to \ell^+\ell^-\gamma$

$\mathcal{L} = 167$ pb^{-1} at $\sqrt{s}_{ee} = 91$ GeV

55 pb^{-1} at $\sqrt{s}_{ee} = 183$ GeV



Mean : 464 ± 14 MeV$/c^2$

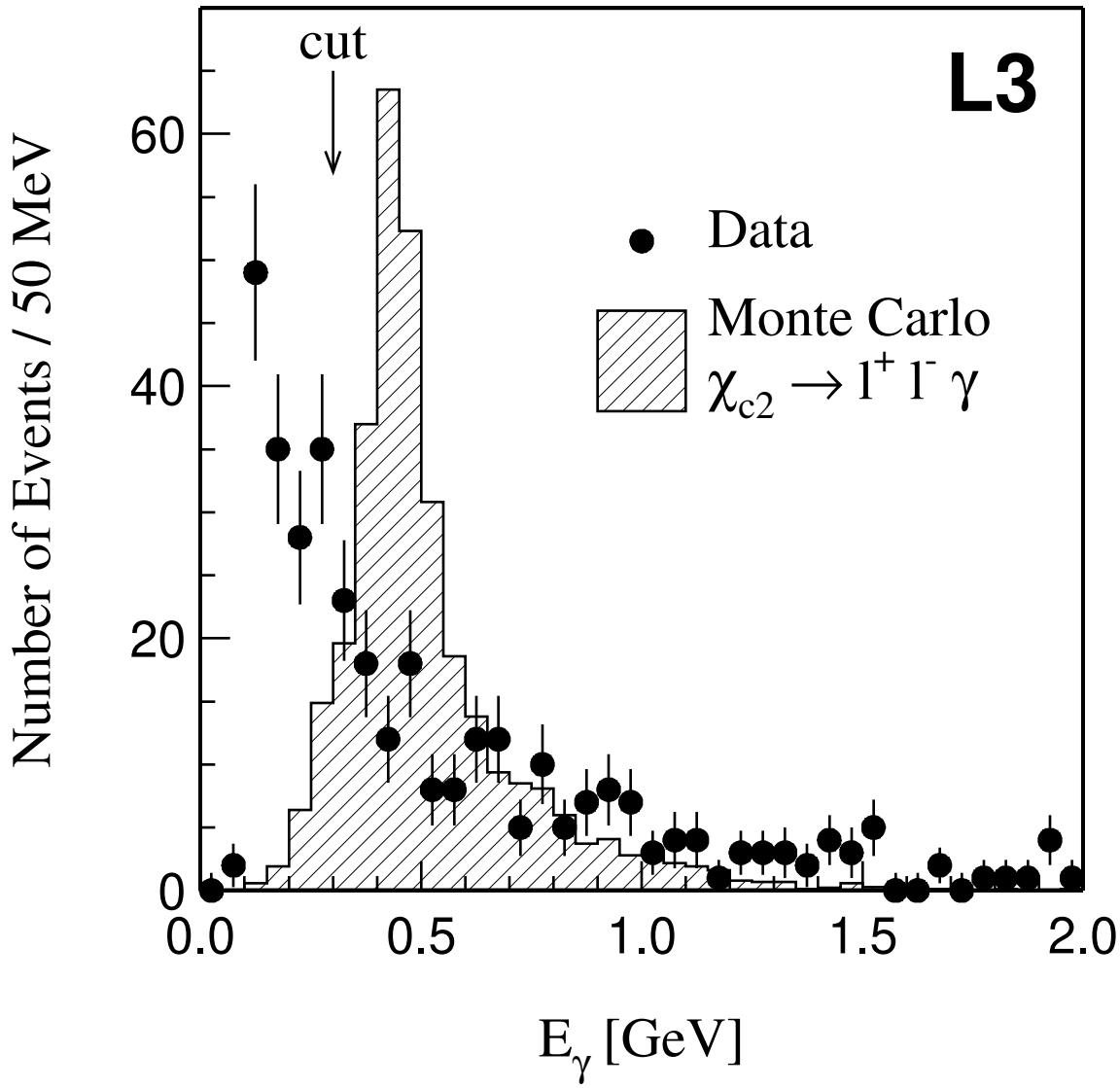
Width : 39 ± 16 MeV$/c^2$

$$\Gamma_{\gamma\gamma} = 1.76 \pm 0.47_{\text{stat}} \pm 0.37_{\text{sys}} \pm 0.15_{\text{BR}} \text{ keV}$$

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 $\chi_{c2} \to 4\pi$:

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

χ_{c2} formation

Summary:

Experiment	Production Mechanism	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
CLEO	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.08 \pm 0.30 \pm 0.26$
TPC/2γ	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$3.4 \pm 1.7 \pm 0.9$
L3	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.02 \pm 0.40 \pm 0.15$
OPAL	$\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$	$1.76 \pm 0.47 \pm 0.37$
Average	$\chi^2/Ndf = 0.8$	1.23 ± 0.26
E760	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.32 \pm 0.08 \pm 0.05$
CLEO	$\gamma\gamma \to \chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$	$0.7 \pm 0.2 \pm 0.1$
R704	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.0 \, ^{+0.9}_{-0.7} \pm 0.3$

Controversy still exists.

η_c formation

New contribution from L3

The η_c has been analysed in the decay modes:

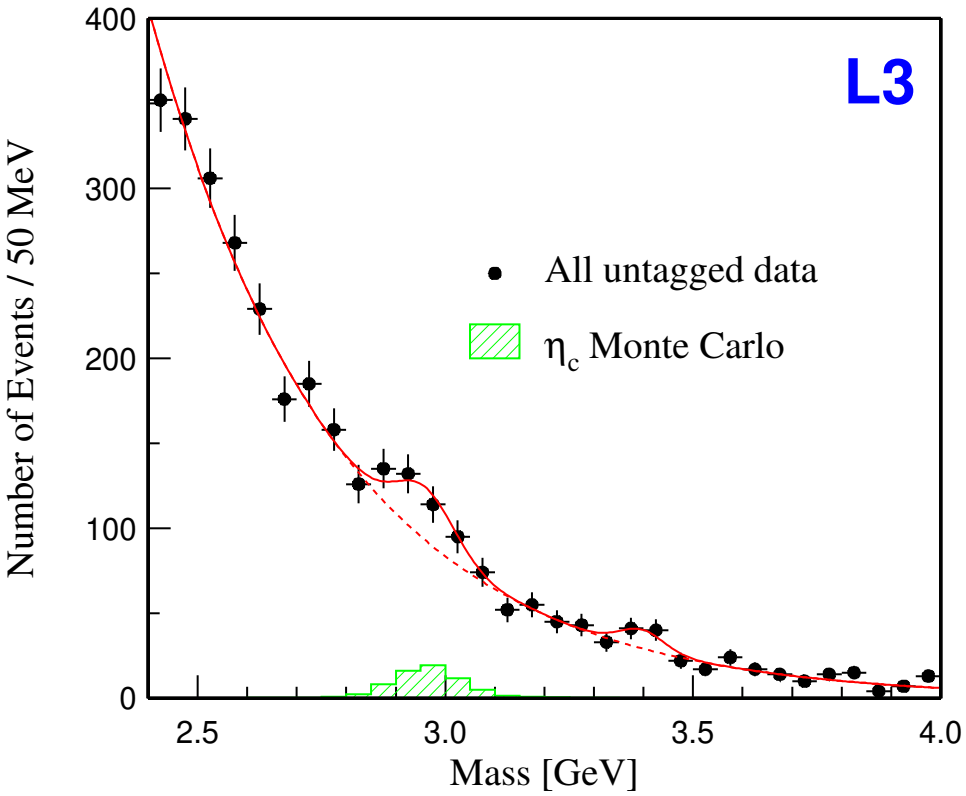
Decay mode	Branching ratio (%)	Signature
$\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.)	1.2 ± 0.4	4 tracks
$K^+K^-\pi^+\pi^-$	2.0 ± 0.7	4 tracks
$K_S K^\pm\pi^\mp$, $K_S \to \pi^+\pi^-$	1.3 ± 0.4	2 tracks, sec. vertex
$\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$	1.3 ± 0.5	2 tracks, 2 photons
$\pi^+\pi^-\eta$,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

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

Event selection:

- 2 or 4 charged tracks
- $M(\gamma\gamma)$ close to π^0 or η mass, K_S has secondary vertex
- Sum of transverse momenta $(\Sigma\vec{p}_t)^2$ of all final state particles should be small (< 0.1 GeV^2)

η_c formation



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

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

Experiment	$\Gamma_{\gamma\gamma}(\eta_c)$ (keV)
E760	$6.7\ ^{+2.4}_{-1.7} \pm 2.3$
ARGUS	11.3 ± 4.2
CLEO	$5.9\ ^{+2.1}_{-1.8} \pm 1.9$
TPC/2γ	$6.4\ ^{+5.0}_{-3.4}$
L3	$6.9 \pm 1.7 \pm 0.8$

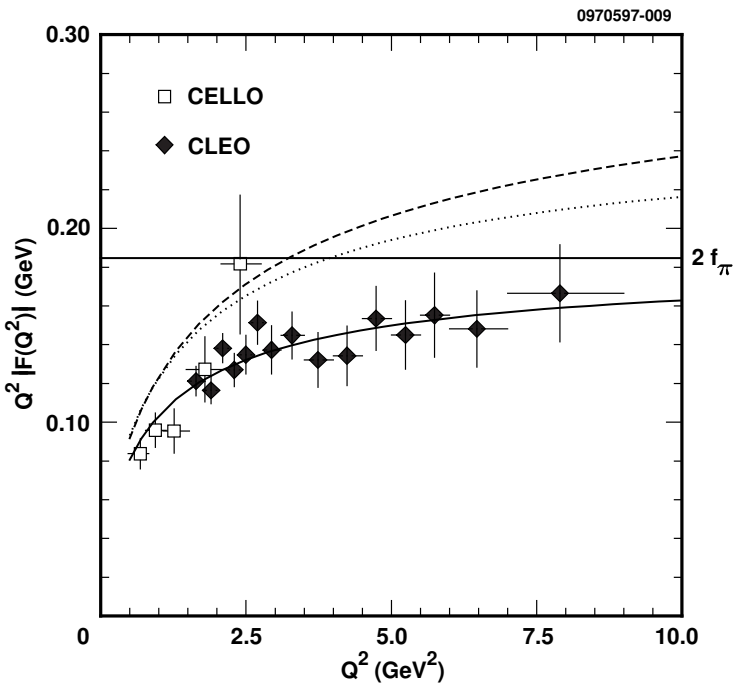
Theoretical predictions [1]: 3 - 11 keV

[1] E.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.

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:

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

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'	$859 \pm 9 \pm 18 \pm 20$

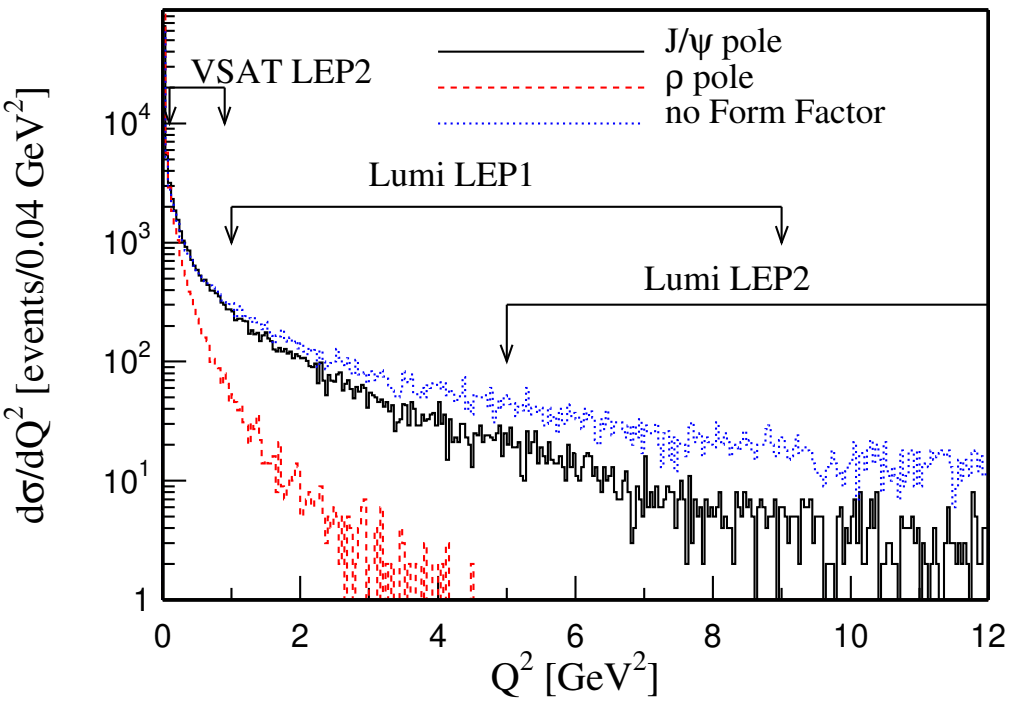
Virtual photon $\Rightarrow$ scattered beam particle is detected:

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

L3 has two BGO calorimeters for measuring tags:

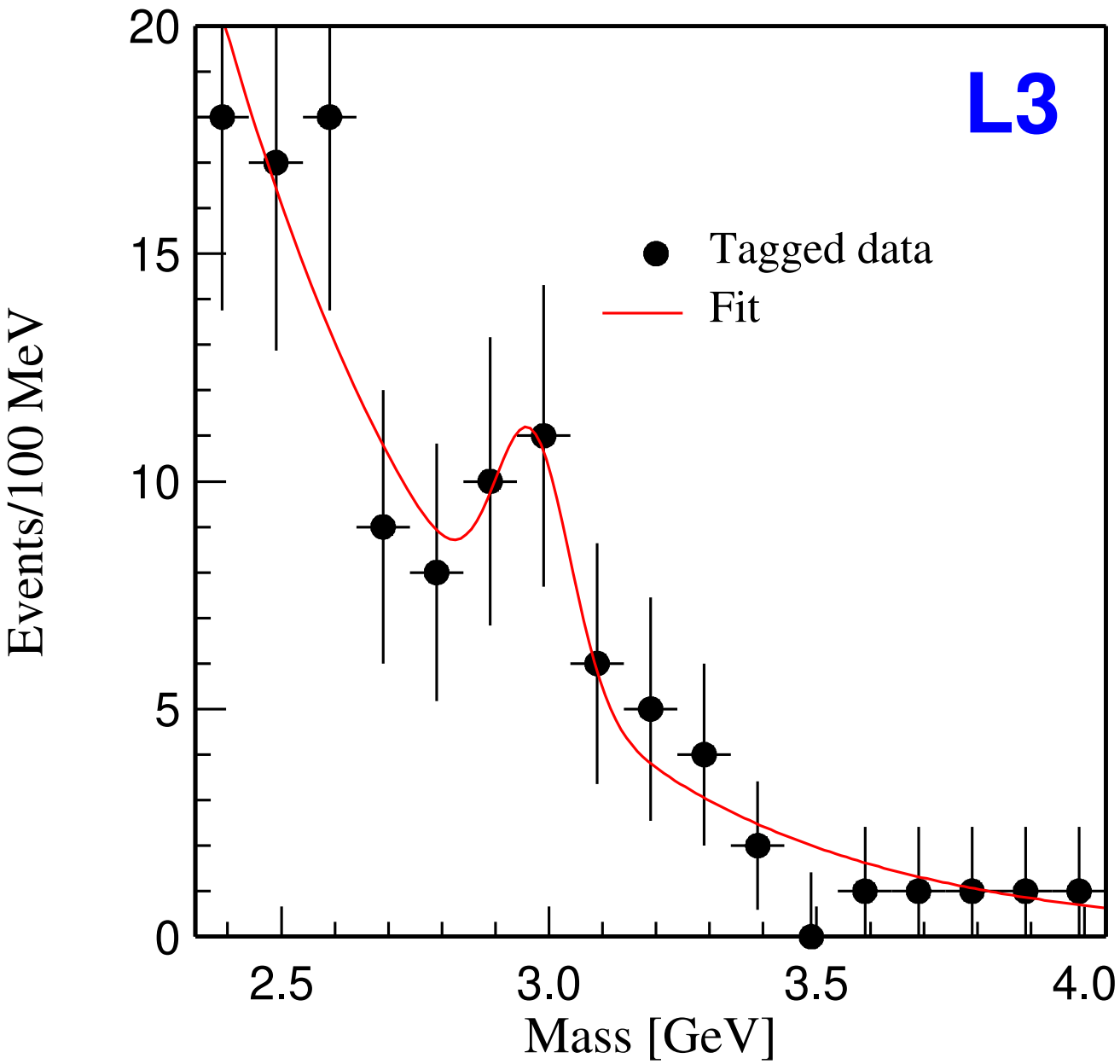
Very small angle tagger (VSAT) $5 < \theta_{\text{tag}} < 10$ mrad,

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



η_c Form factor

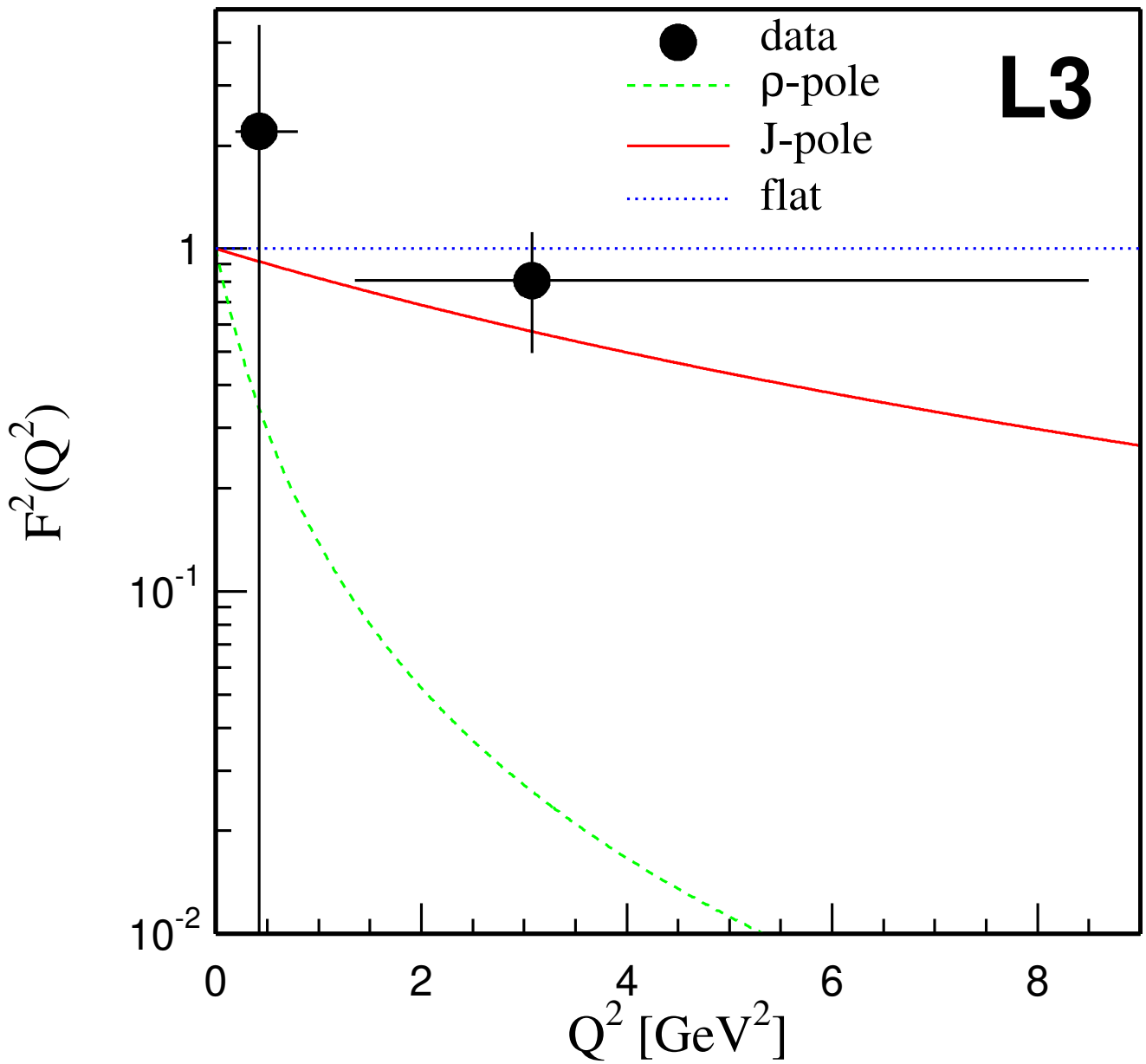
Mass spectrum tagged events:



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

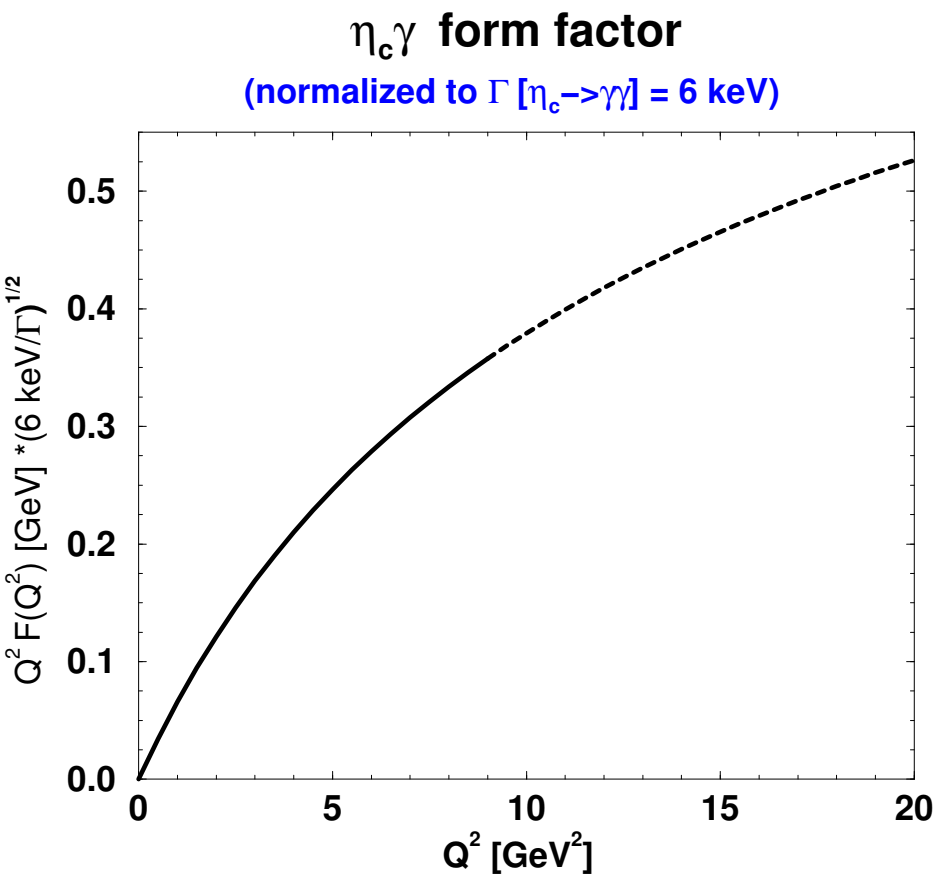
Quantitatively:

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

Or:

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

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

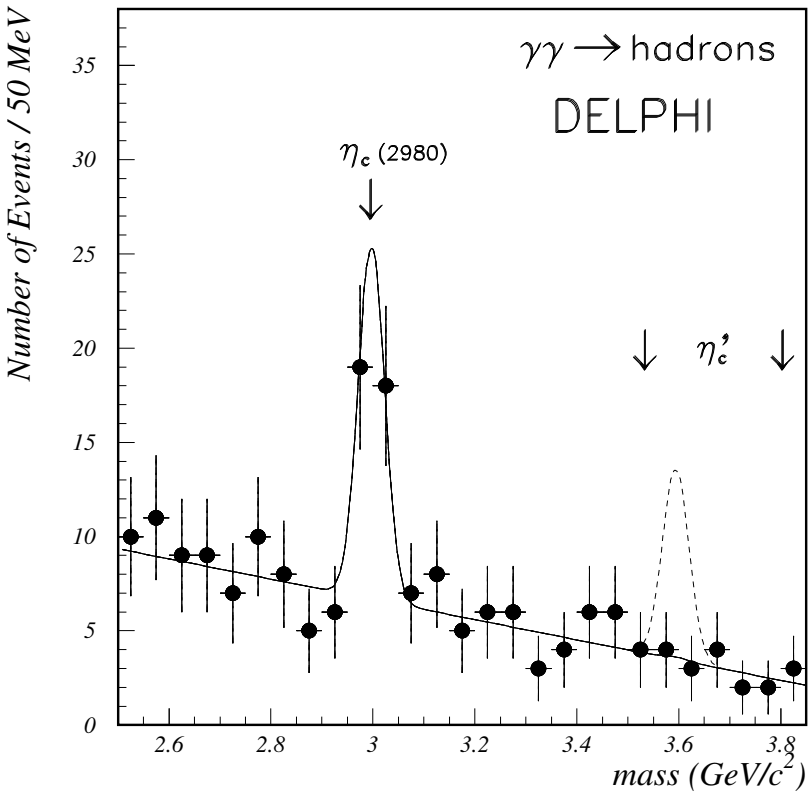


η_c'

- 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:

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

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



DELPHI measures ratio:

$$\frac{\Gamma(\eta_c' \to \gamma\gamma)}{\Gamma(\eta_c \to \gamma\gamma)} < 0.34 \qquad \text{at } 90\% \text{ c.l.}$$

L3 absolute measurement:

$$\Gamma(\eta_c' \to \gamma\gamma) < 2.0 \text{ keV} \qquad \text{at } 95\% \text{ c.l.}$$

L3 ratio:

$$\frac{\Gamma(\eta_c' \to \gamma\gamma)}{\Gamma(\eta_c \to \gamma\gamma)} < 0.29 \qquad \text{at } 95\% \text{ c.l.}$$

Compare with Ted:

$$\frac{\Gamma(\eta_c' \to \gamma\gamma)}{\Gamma(\eta_c \to \gamma\gamma)} \simeq 0.75.$$

$$\Rightarrow \textbf{discrepancy}$$

Conclusions

Conclusions:

- The two-photon widths of the χ_{c2} as measured in e^+e^- machines converge towards a value around 1 keV. Theory prefers lower values, so does a rather precise measurement in $p\bar{p}$ annihilation.
- The two-photon width of the η_c converges to values around 7 keV. No real problem with theory.
- First direct measurement of the form factor of the η_c: Large pole-mass clearly preferred! As predicted!
- η_c' remains elusive.