# Charmonium Resonance Formation in $\gamma\gamma$ Collisions at LEP with the L3 Detector

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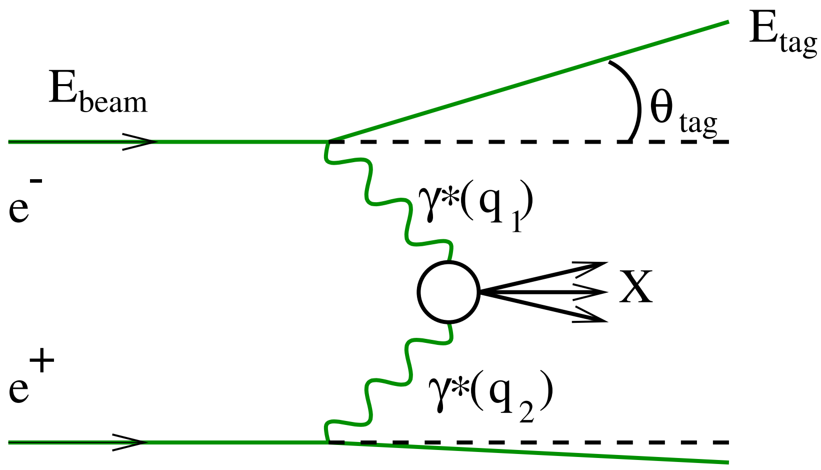
Issues:

- $\chi_{c2}$ two-photon width
- $\eta_c$ two-photon width and form factor

PANIC '99

# Resonance Formation in $\gamma\gamma$ Collisions




Total cross section for resonance formation in $\gamma\gamma$ collisions:

$$\sigma(e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-R) \;=\; \int d^5 L^{QED}_{\gamma\gamma} \cdot \sigma(\gamma\gamma \to R)$$

Two-photon cross section depends on resonance properties:

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

and transition form factor $F^2(q_1^2,q_2^2)$ ; of pole form:

$$F^2(q_1^2,q_2^2) \;=\; F^2(q_1^2)F^2(q_2^2) = \frac{1}{1-q_1^2/\Lambda^2}\cdot\frac{1}{1-q_2^2/\Lambda^2}$$

$$\Lambda = m_\rho, m_\omega, m_{J/\psi}, \ldots(\text{in VDM}).$$

Usually $q_1^2 \approx q_2^2 \approx 0$ (quasi-real photons) and the scattered electrons are untagged, $F^2(q_1^2,q_2^2) \to 1$ leading to the linear relationship:

$$\sigma(e^+e^- \to e^+e^-R) \;=\; \kappa\,\Gamma_{\gamma\gamma}(R)$$

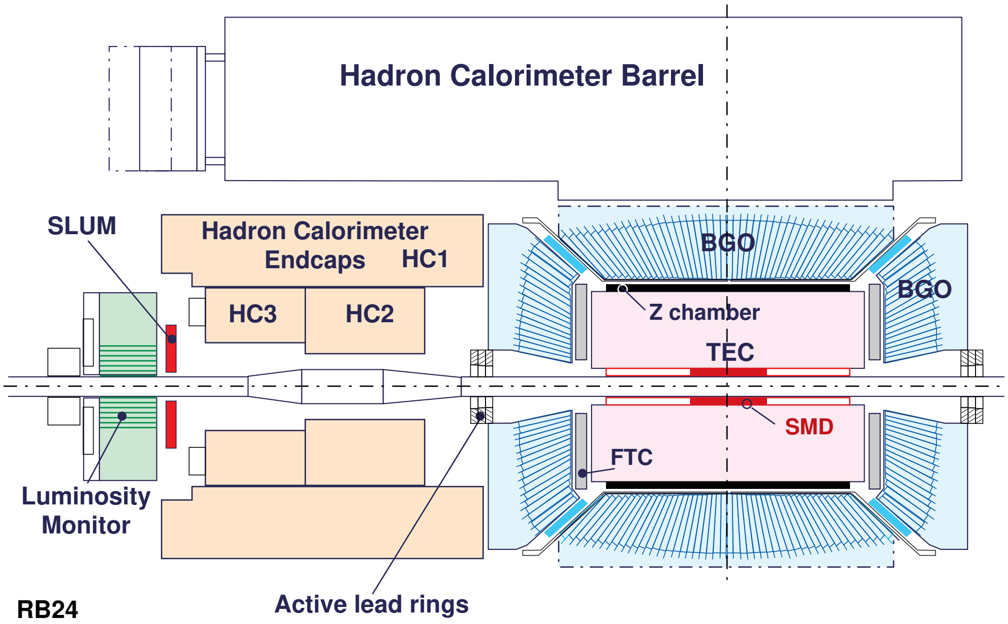
When a scattered $e^\pm$ is detected $Q^2 = -q_1^2$, $q_2^2 \approx 0$ the $\theta_{tag}$ and $E_{tag}$ allow the $Q^2$ dependence of the cross section to be measured.

# Tagging and the L3 detector

In L3, scattered $e^{\pm}$ are detected in 2 forward calorimeters:

| | $\theta_{\text{tag}}$ range (mrad) | $Q^2$ range GeV$^2$ LEP1 ($\sqrt{s} \approx 91$ GeV) | LEP2 ($\sqrt{s} \approx 183$ GeV) |
|---|---|---|---|
| VSAT | $5 \rightarrow 10$ | | $0.2 \rightarrow 0.8$ |
| LUMI | $30 \rightarrow 65$ | $1.3 \rightarrow 8.5$ | $5.2 \rightarrow 34.0$ |

- tagging criteria: $E^{\text{LUMI}}(E^{\text{VSAT}})/E_{beam} > 0.7(0.5)$

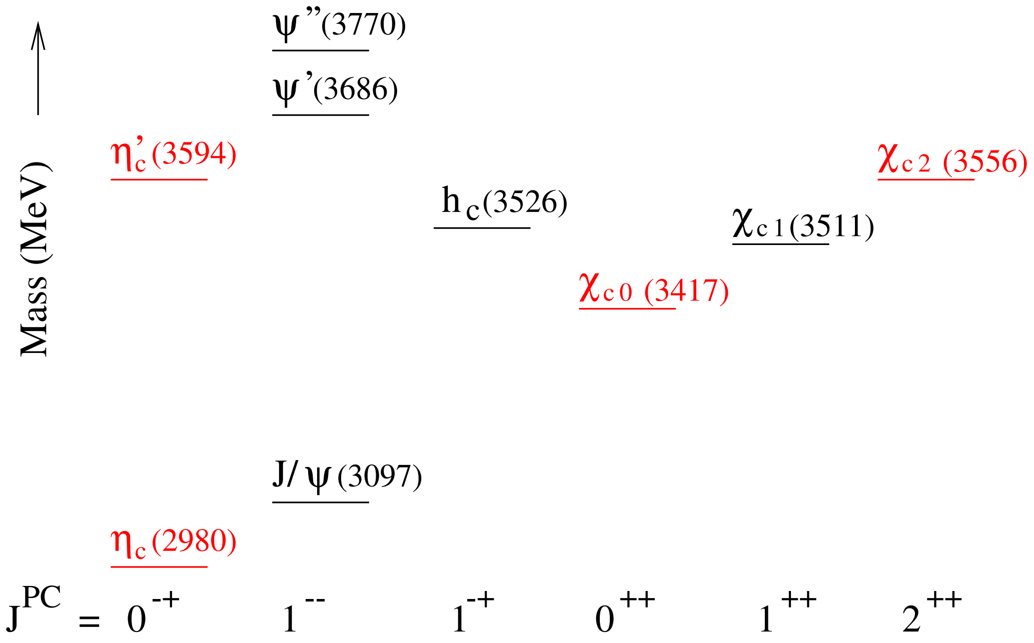



Also important for detection of resonance decay products:

- Precision tracking: Silicon Microvertex & Time Expansion Chamber
- High resolution BGO Calorimetry: (5% at 100 MeV, 1.4% $> 2$ GeV)
- Charged track trigger: low $p_t$ threshold $\approx 150$ MeV.

# Charmonium resonances

Charmonium mesons ($c\bar{c}$ states) accessible in quasi-real $\gamma\gamma$ collisons are: $\eta_c(2980), \chi_{c0}(3417), \chi_{c2}(3556)$ (with $C = +1$ & $J \neq 1$)




Potential decay modes to examine in $\gamma\gamma$ collisions:

$$
\begin{aligned}
\chi_{c2} &\longrightarrow \gamma J/\psi \text{ , } J/\psi \longrightarrow e^+e^- \text{or } \mu^+\mu^- & BR &= 0.016 \\
\eta_c &\longrightarrow (\text{hadronic final states}) & BR^1 &= 0.105 \\
\chi_{c0} &\longrightarrow \gamma J/\psi \text{ , } J/\psi \longrightarrow e^+e^- \text{or } \mu^+\mu^- & BR &= 0.0008 \\
\chi_{c0} &\longrightarrow (\text{hadronic final states}) & BR &= ???
\end{aligned}
$$

At $p\bar{p}$ machines E760,R704,... have studied $\eta_c$ and $\chi_{c2}$ by their $2\gamma$ decays.

$$p\bar{p} \longrightarrow \chi_{c2}(\eta_c) \longrightarrow \gamma\gamma$$

[1] Total BR for hadronic final states, analysed by L3.

# Motivation for study of Charmonium resonances

The $\gamma\gamma$ coupling $\Gamma_{\gamma\gamma}(R)$ and the form factor probe the quark substructure of the meson, testing:

- QCD predictions of quark-antiquark binding
- quark wave functions inside the meson
- value of $\alpha_s$ for heavy quark systems
- VDM prediction of $J/\psi$ pole for $\eta_c$ form factor

Example calculations[1] in QCD framework with lowest-order expressions and 1st order QCD corrections for the 2-photon widths of $\eta_c$ $({}^1S_0)$ and $\chi_{c2}$ $({}^3P_2)$ :

$$\Gamma(\eta_c \to \gamma\gamma) = \frac{12\,\pi\,e_c^2\,\alpha^2}{m_c^2}\ |\Psi_{\eta_c}(0)|^2\ \left[1 - \frac{3.4}{\pi}\,\alpha_s(m_c)\right]$$

$$\Gamma(\chi_{c2} \to \gamma\gamma) = \frac{36}{5}\ e_c^4\,\alpha^2\,\frac{\left|\Psi'_{\chi_{c2}}(0)\right|^2}{m_c^4}\ \left(1 - \frac{16}{3}\,\frac{\alpha_s}{\pi}\right)$$

Ratios between widths assuming equivalent wavefunctions, are known better than the widths themselves.

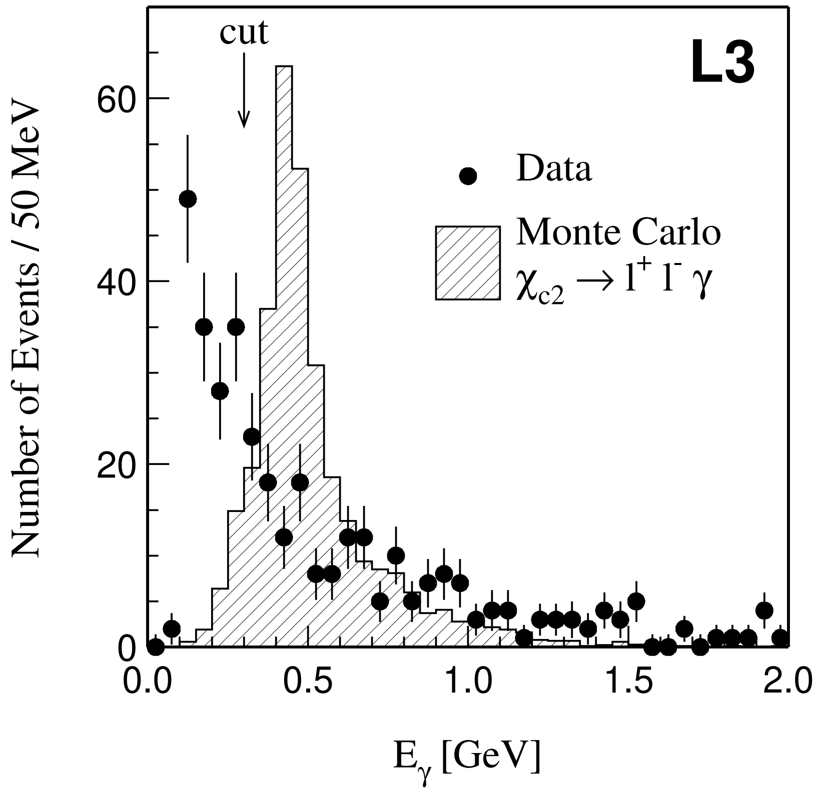
[1]W. Kwong, P.B. Mackenzie, *et al.*Phys. Rev. **D 37** (1988) 3210.

# L3 selection of $\chi_{c2} \to J/\psi\,\gamma \to \ell^+\ell^-\gamma$

LEP1 and LEP2 data samples:

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

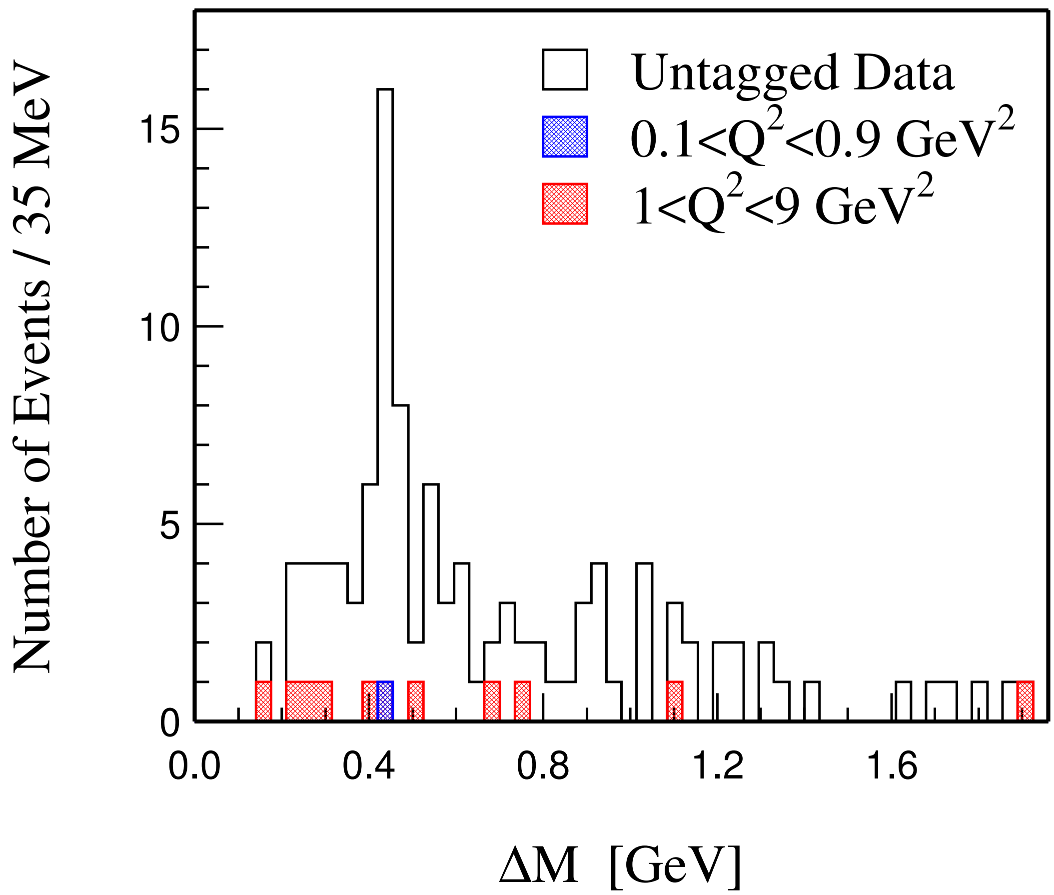
- 2 tracks of opposite charge with $\mu(e)$ signatures
- 1 photon, of energy $E_\gamma > 0.3$ GeV




- total transverse momentum imbalance $(\Sigma\vec{p_t})^2 < 0.08(0.10)\ \mathrm{GeV}^2$ for untagged(tagged) events.
- $|M(\ell^+\ell^-) - M(J/\psi\,)| < 0.25(0.30)$ GeV for LEP1(LEP2)

## L3 analysis of $\chi_{c2} \rightarrow J/\psi\,\gamma \rightarrow \ell^+\ell^-\gamma$

Within selection, $\Delta M = M(\ell^+\ell^-\gamma) - M(\ell^+\ell^-)$ , peaks at:




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

Number of signal events $S_i$ related to $\Gamma_{\gamma\gamma}$ by:

$$S_i \;=\; \epsilon_i \mathcal{L}_i BR(\chi_{c2} \rightarrow \gamma\ell^+\ell^-)\kappa_i \Gamma_{\gamma\gamma}$$

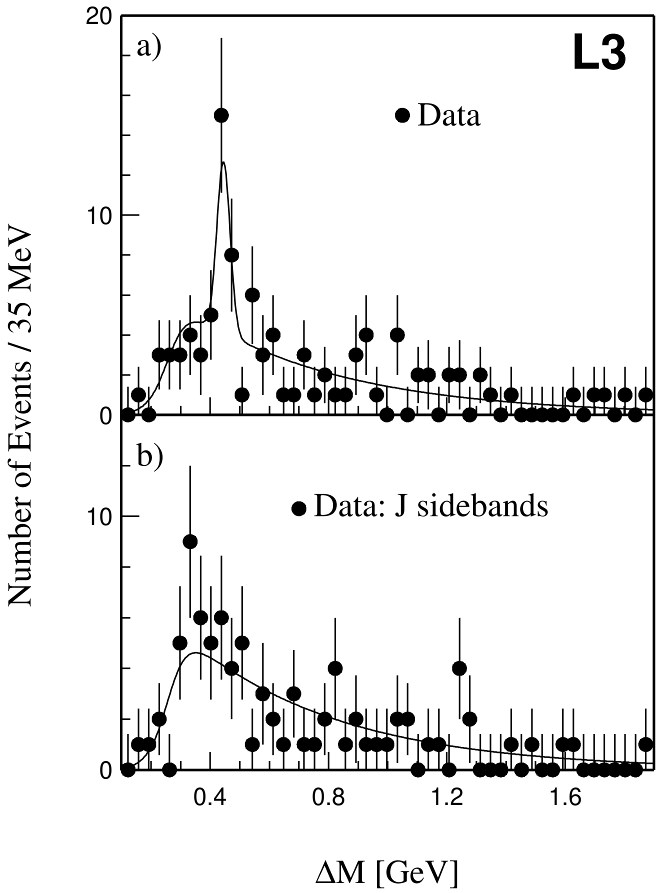
Efficiency $\epsilon_i$ and proportionality $\kappa_i$ determined from Monte Carlo[1]:

$$\epsilon_1(LEP1) \quad (10.4 \pm 0.5)\ \%$$
$$\epsilon_2(LEP2) \quad (8.6 \pm 0.5)\ \%$$

[1]PC MC, F.Linde.

# L3 Signal extraction, $\chi_{c2} \to J/\psi\,\gamma \to \ell^+\ell^-\gamma$

Model $\Delta M$ spectra with gaussian and threshold function: $a_1 \frac{e^{-x/a_2}}{1+e^{(a_3-x)/a_4}}$




$J/\psi$ sidebands: $M(\ell^+\ell^-) = [2.45, 2.75]$ & $[3.45, 3.75]$ GeV

Unbinned likelihood fit to $J/\psi$ sidebands and LEP1 & 2 spectra :

$$\Delta M = 0.445 \pm 0.010 \text{ GeV} \quad \sigma(\Delta \mathrm{M}) = 0.023 \pm 0.007 \text{ GeV}$$

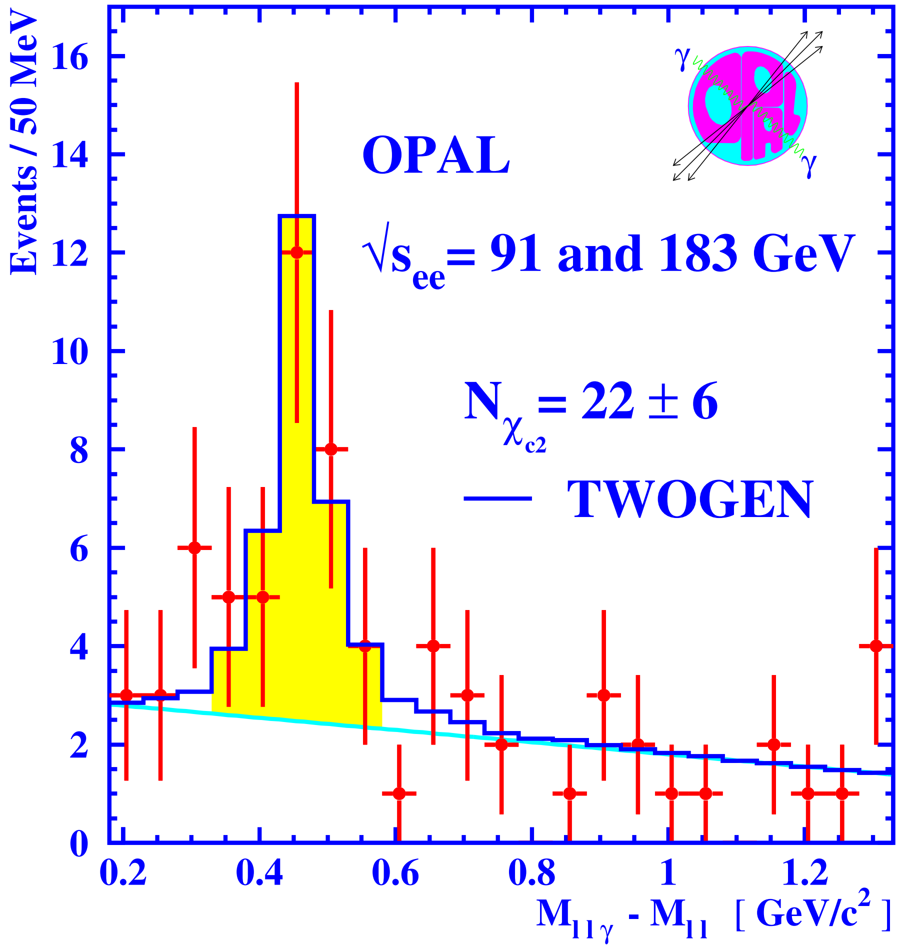
Yielding 13.6 signal events, corresponding to:

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

$\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$: 11% from $|M(\ell^+\ell^-) - M(J/\psi)| < 0.25 \pm 0.05$ GeV, 8% BR.

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

$\mathcal{L} = 167$ pb$^{-1}$ at $\sqrt{s}_{ee} = \;\; 91$ GeV
55 pb$^{-1}$ at $\sqrt{s}_{ee} = 183$ GeV




**Mean :** $464 \pm 14$ MeV$/c^2$
**Width :** $39 \pm 16$ MeV$/c^2$

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

# $\Gamma_{\gamma\gamma}(\chi_{c2})$ measurements and predictions

| Measurements | | $\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV) |
|---|---|---|
| CLEO[1] | $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$ | $1.08 \pm 0.30 \pm 0.26$ |
| TPC/$2\gamma$[2] | $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$ | $3.4 \pm 1.7 \pm 0.9$ |
| L3[3] | $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$ | $1.02 \pm 0.40 \pm 0.15$ |
| OPAL[4] | $\gamma\gamma \to \chi_{c2} \to \gamma J/\psi$ | $1.76 \pm 0.47 \pm 0.37$ |
| $\Gamma_{\gamma\gamma}^{avg}$ | $\chi^2/Ndf = 0.8$ | $1.23 \pm 0.26$ |
| E760[5] | $p\bar{p} \to \chi_{c2} \to \gamma\gamma$ | $0.32 \pm 0.08 \pm 0.05$ |
| E835[6] | $p\bar{p} \to \chi_{c2} \to \gamma\gamma$ | $0.31 \pm 0.05 \pm 0.04$ |
| R704[7] | $p\bar{p} \to \chi_{c2} \to \gamma\gamma$ | $2.0\ ^{+0.9}_{-0.7} \pm 0.3$ |
| CLEO[8] | $\gamma\gamma \to \chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$ | $0.7 \pm 0.2 \pm 0.1$ |

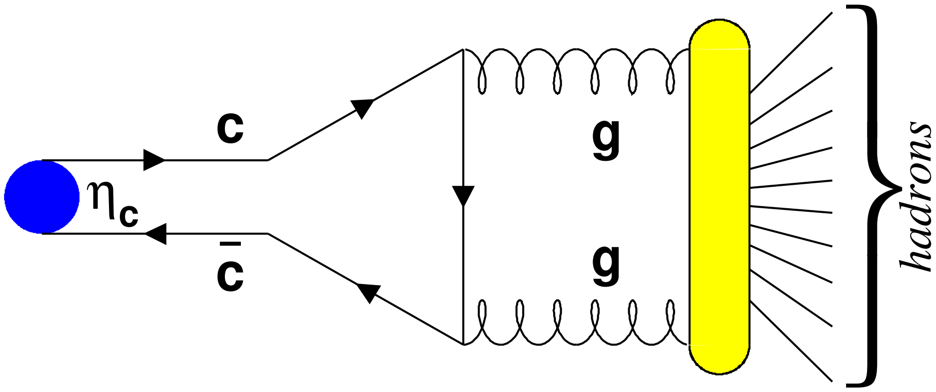
| Predictions | |
|---|---|
| T. Barnes, proc. IXth workshop on $\gamma\gamma$ collisions (1992) | $0.34 - 0.56$ |
| C.R. Münz, Nucl. Phys. A609 (1996) 364 | $0.44 \pm 0.14$ |
| H.-W. Huang *et al.*, Phys. Rev. D54 (1996) 2123 | $0.39 - 0.50$ |
| G.A. Schuler *et al.*, Nucl. Phys. B523 (1998) 423. | 0.28 |

- Results from $\gamma\gamma$ are consistent
- $\Gamma_{\gamma\gamma}^{avg}$ is $3\sigma$ higher than E760,E835 $p\bar{p}$ measurements
- $\Gamma_{\gamma\gamma}^{avg}$ is higher than the range of predictions $0.3 - 0.6$ keV

[1] CLEO Collab., J. Dominick *et al.*, Phys. Rev. **D 50** (1994) 4265.
[2] TPC/$2\gamma$ Collab., D.A. Bauer *et al.*, Phys. Lett. **B 302** (1993) 345.
[3] L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B 453** (1999) 73-82.
[4] OPAL Collab., K.Ackerstaff *et al.*, Phys. Lett. **B 439** (1998) 197.
[5] E760 Collab., T.A. Amstrong *et al.*, Phys. Rev. Lett. **70** (1993) 2988.
[6] E835 Collab., presentation of M. Stancari at PHOTON'99.
[7] R704 Collab., C. Baglin *et al.*, Phys. Lett, **B 187** (1987) 191.
[8] V.Savinov, R.Fulton, contribution to PHOTON'95, hep-ex/9507006.

# L3 selection of $\eta_c$ decays into hadronic states

Decays expected to proceed via 2 gluons:




No dominant decay mode $\longrightarrow$ separate analysis of 9 modes:

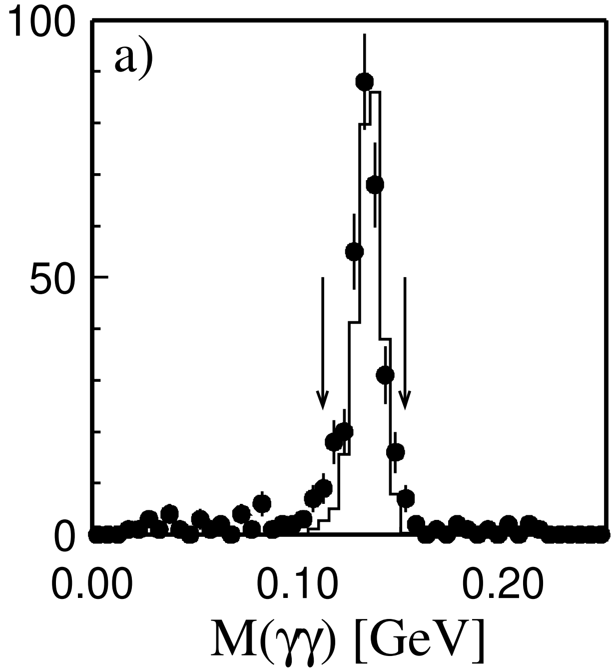
| Decay mode | Branching ratio (%) | Signature |
|---|---|---|
| $\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.) | $1.2 \pm 0.4$ | 4 tracks |
| $K^+K^-\pi^+\pi^-$ | $2.0 \pm 0.7$ | 4 tracks |
| $K^0_S K^\pm \pi^\mp$, $K_S \to \pi^+\pi^-$ | $1.3 \pm 0.4$ | 2 tracks, sec. vertex |
| $\pi^+\pi^-\eta$, $\eta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

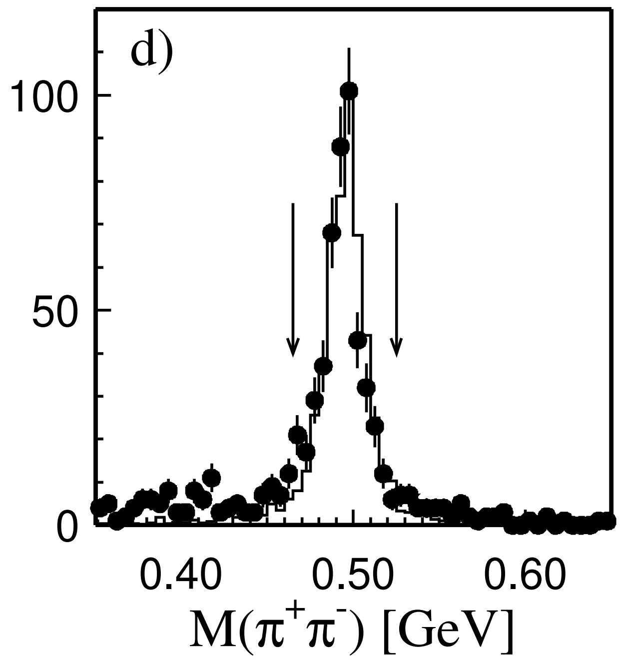
# Identification of $\eta_c$ decay modes

- Sum of transverse momenta $(\Sigma\vec{p_t})^2 < 0.1\,\mathrm{GeV}^2$
- 2 or 4 charge balanced charged tracks with 0,1,2,4 photons.

$\pi^0$ or $\eta \to \gamma\gamma$
with consistent $M(\gamma\gamma)$

$K_S^0 \to \pi^+\pi^-$
2nd vertex $>$ 3 mm from I.P.
consistent $M(\pi^+\pi^-)$



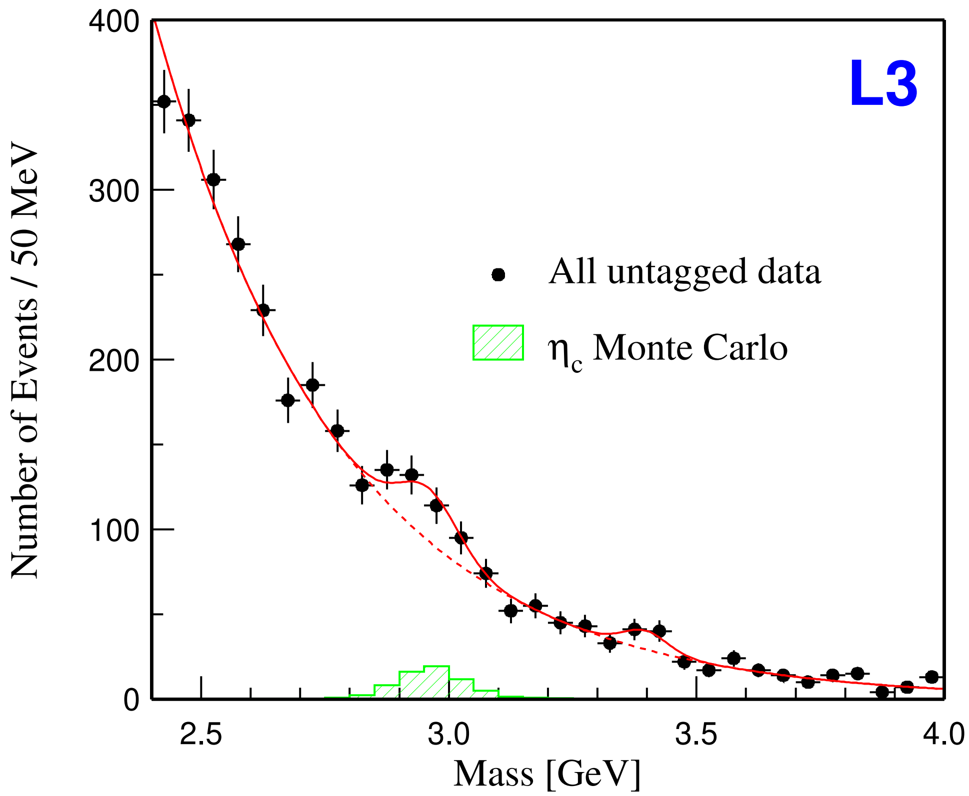

- $\pi/K$ separation with $dE/dx$ (good for $p < 0.5$ GeV)

| Decay mode | Branching ratio (%) | $\epsilon_{91}$ (%) | $\epsilon_{183}$ (%) |
|---|---|---|---|
| $\pi^+\pi^-\pi^+\pi^-$ ($\rho^0\rho^0$ incl.) | $1.2 \pm 0.4$ | 4.9 | 4.1 |
| $K^+K^-\pi^+\pi^-$ | $2.0 \pm 0.7$ | 5.2 | 4.5 |
| $K_S^0K^\pm\pi^\mp$, $K_S^0 \to \pi^+\pi^-$ | $1.3 \pm 0.4$ | 5.1 | 5.0 |
| $\pi^+\pi^-\eta$, $\eta \to \gamma\gamma$ | $1.3 \pm 0.5$ | 3.3 | 3.9 |
| $\pi^+\pi^-\eta$, $\eta \to \pi^+\pi^-\pi^0$ | $0.8 \pm 0.3$ | 2.6 | 3.3 |
| $\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\gamma$ | $0.8 \pm 0.3$ | 0.8 | 0.9 |
| $\pi^+\pi^-\eta'$, $\eta' \to \pi^+\pi^-\eta$ | $0.5 \pm 0.2$ | 1.6 | 1.2 |
| $K^+K^-\pi^0$ | $0.9 \pm 0.3$ | 2.8 | 2.5 |
| $\rho^+\rho^-$, $\rho^\pm \to \pi^\pm\pi^0$ | $1.7 \pm 0.6$ | 3.0 | 2.5 |

# Fit to $\eta_c$ mass spectra

Mass spectra of all untagged events yields $\eta_c$ & $\chi_{c0}$ signals:

$M(\eta_c) = 2.974 \pm 0.018\,\mathrm{GeV}$ $\qquad$ $M(\chi_{c0}) = 3.400 \pm 0.019\ \mathrm{GeV}$




Mass spectra $f_i$ of decay modes in the LEP1,2 samples modelled by normalised exponential backgrounds $b_i(x)$ and Gaussian signals $g_i(x)$:

$$f_i(x) = (1 - p_i)b_i(x) + p_i g_i(x) \quad (b_i(x) \text{ allowed to vary})$$

$$p_i = S_i/N_i^{tot} \qquad \text{(signal/total in sample i)}$$
$$S_i = \epsilon_i \mathcal{L} \mathrm{BR_i} \kappa \Gamma_{\gamma\gamma} \qquad (\epsilon_\mathrm{i} \ \& \ \kappa \text{ from MC})$$

Unbinned likelihood fit yields $76 \pm 19$ $\eta_c$ events, corresponding to:

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

Dominant $\Delta\Gamma_{\gamma\gamma}/\Gamma_{\gamma\gamma}$: BR(J/$\psi \rightarrow \eta_c\gamma$)=$(1.27 \pm 0.36)\%$ & $\mathrm{BR_i}$.

# $\Gamma_{\gamma\gamma}(\eta_c)$ measurements and predictions

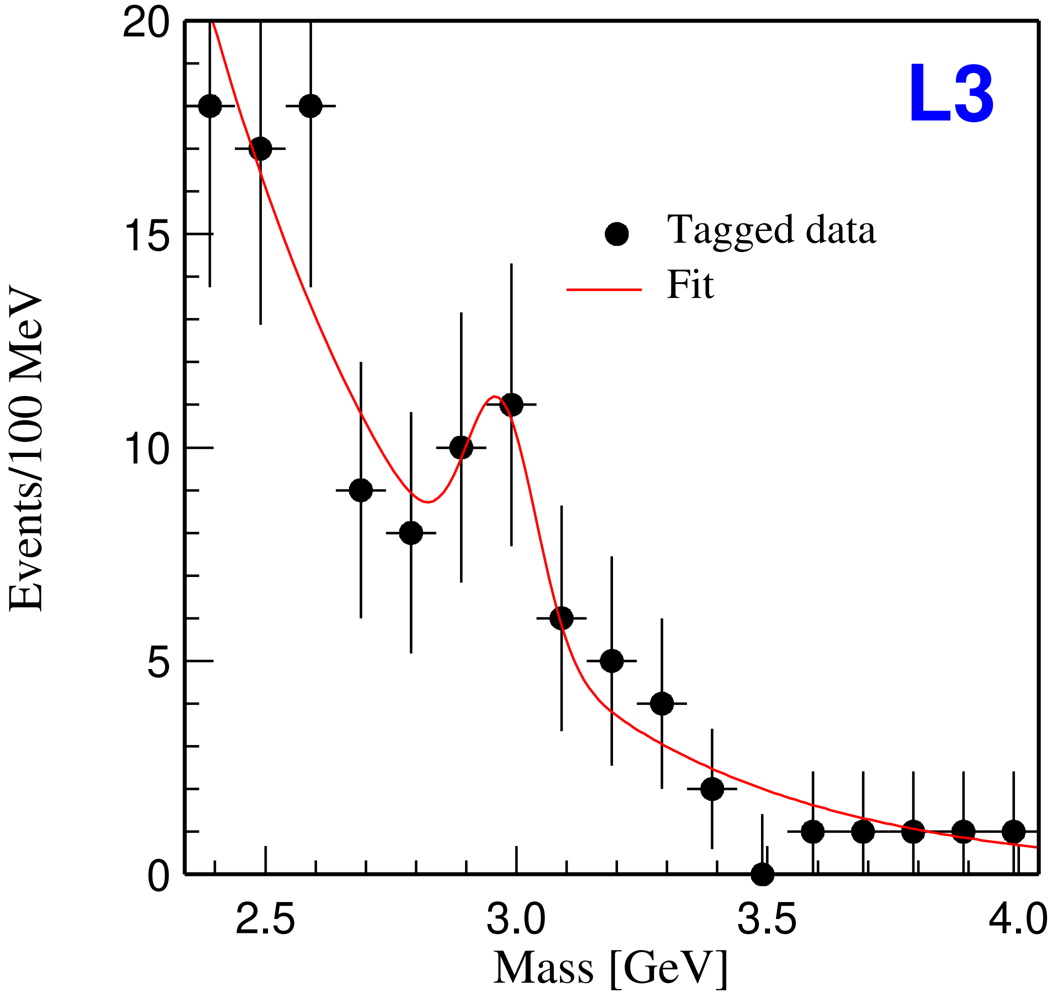
| Measurements | $\Gamma_{\gamma\gamma}(\eta_c)$ (keV) |
|---|---|
| PLUTO[1] | $28 \pm 15$ |
| E760[2] | $6.7\ ^{+2.4}_{-1.7} \pm 2.3$ |
| ARGUS[3] | $11.3 \pm 4.2$ |
| CLEO[4] | $5.9\ ^{+2.1}_{-1.8} \pm 1.9$ |
| TPC/$2\gamma$[5] | $6.4\ ^{+5.0}_{-3.4}$ |
| L3[6] | $6.9 \pm 1.7 \pm 0.8$ |
| Predictions[7] | 3 - 9 |

- Measurements and predictions are consistent .


**1.** PLUTO Collab., Ch. Berger *et al.*, Phys. Lett. **B 167** (1986) 120.
**2.** E760 Collab,, T.A. Armstrong *et al.*, Phys. Rev. **D 52** (1995) 4839.
**3.** ARGUS Collab., H. Albrecht *et al.*, Phys. Lett. **B 338** (1994) 390.
**4.** CLEO Collab., W.-Y. Chen *et al.*, Phys. Lett. **B 243** (1990) 169.
**5.** TPC/$2\gamma$ Collab., H. Aihara *et al.*, Phys. Rev. Lett. **60** (1988) 2355.
**6.** L3 Collab., M. Acciarri *et al.*, submitted to Phys. Lett. B. CERN-EP/99-072, 21 May 1999.
**7.** E.S. Ackleh and T. Barnes, Phys. Rev **D 45** (1992)232;
M.R. Ahmady and R.R. Mendel, Phys. Rev **D 51** (1995)141;
C.R. Münz, Nucl. Phys. **A 609** (1996) 364;
H.-W. Huang *et al.*, Phys. Rev **D 56** (1997)368.

# $\eta_c$ form factor

Tagged event spectrum, with $e^{\pm}$ in LUMI at $\sqrt{s} \approx 91$ GeV or in VSAT at $\sqrt{s} \approx 183$ GeV:




| | $\theta_{\text{tag}}$ range (mrad) | $Q^2$ range $\text{GeV}^2$ LEP1 ($\sqrt{s} \approx 91$ GeV) | LEP2 ($\sqrt{s} \approx 183$ GeV) |
|---|---|---|---|
| VSAT | $5 \to 10$ | | $0.2 \to 0.8$ |
| LUMI | $30 \to 65$ | $1.3 \to 8.5$ | $5.2 \to 34.0$ |

Exponential background & gaussian signal fit[1] yields $8.3^{+5.5}_{-4.9}$ events.

[1] Gaussian width and position fixed to Monte Carlo values.

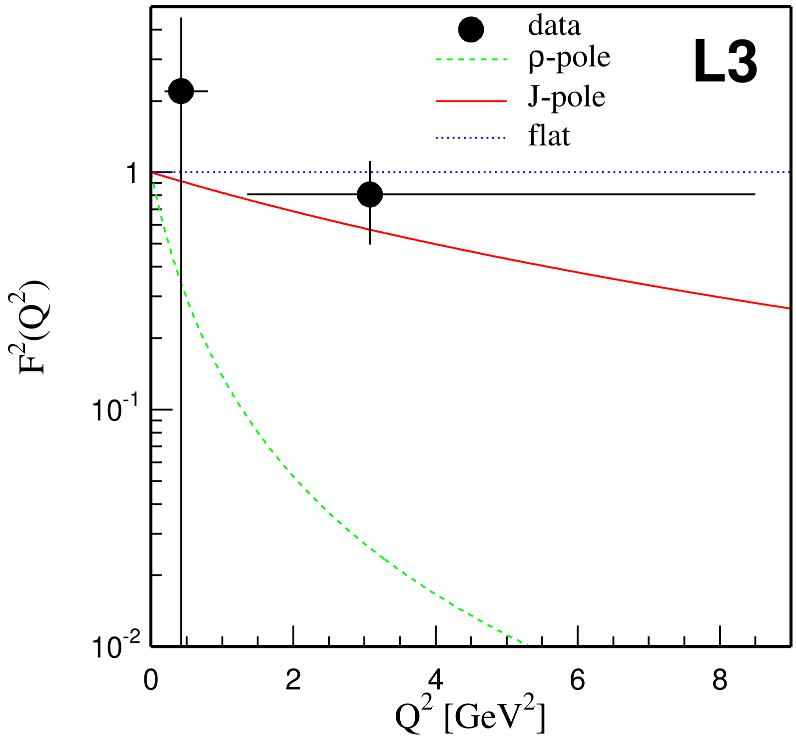
# $\eta_c$ Transition Form factor

Form factor $F^2(q_1^2, q_2^2)$ with tagged $e^\pm$, $Q^2 = -q_1^2$, $q_2^2 \approx 0$:

$$\longrightarrow \quad F^2(Q^2) = \frac{1}{1 + Q^2/\Lambda^2} \quad \Lambda = M_\rho, M_{J/\psi}, \infty \quad \text{(in VDM)}$$

$$\sigma(e^+e^- \to e^+e^-\eta_c; \Delta Q^2) = \kappa\Gamma_{\gamma\gamma}(\eta_c)F^2(Q^2; \Delta Q^2) \quad \text{(NB cancellation)}$$

| | | | $\text{LUMI}_{91}$ | $\text{VSAT}_{183}$ | |
|---|---|---|---|---|---|
| tagged events | | : | $7.7 \pm 3.0$ | $2.3 \pm 2.3$ | |
| $\frac{\sigma(\Delta Q^2)}{\Gamma_{\gamma\gamma}}$ (pb/keV) | data | | $1.3 \pm 0.5$ | $5 \pm 5$ | $\Pr(\chi^2)$ (%) |
| | $\text{MC}_\rho$ | | 0.051 | 0.81 | 4.3 |
| | $\text{MC}_{J/\psi}$ | | 0.85 | 2.1 | 58 |
| | $\text{MC}_\infty$ | | 1.6 | 2.3 | 70 |




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

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

# Conclusions on $\gamma\gamma$ Charmonium Formation

L3 has measured:

- $\mathbf{\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.02 \pm 0.40 \pm 0.15}$ keV

  Consistent with other $\gamma\gamma$ measurements but $3\sigma$ higher than the most precise ($p\bar{p}$) measurement, and somewhat higher than the theoretical predictions.

- $\mathbf{\Gamma_{\gamma\gamma}(\eta_c) = 6.9 \pm 1.7 \pm 0.8}$ keV

  Consistent with other measurements and with theoretical predictions.

- The $Q^2$ dependence of $\sigma(e^+e^- \rightarrow e^+e^-\eta_c)$ (first measurement)

  A $J/\psi$ -mass pole in the VMD model is favoured.