New Results on the Total Cross Section and on Charmonium Formation in Two-Photon Collisions at LEP

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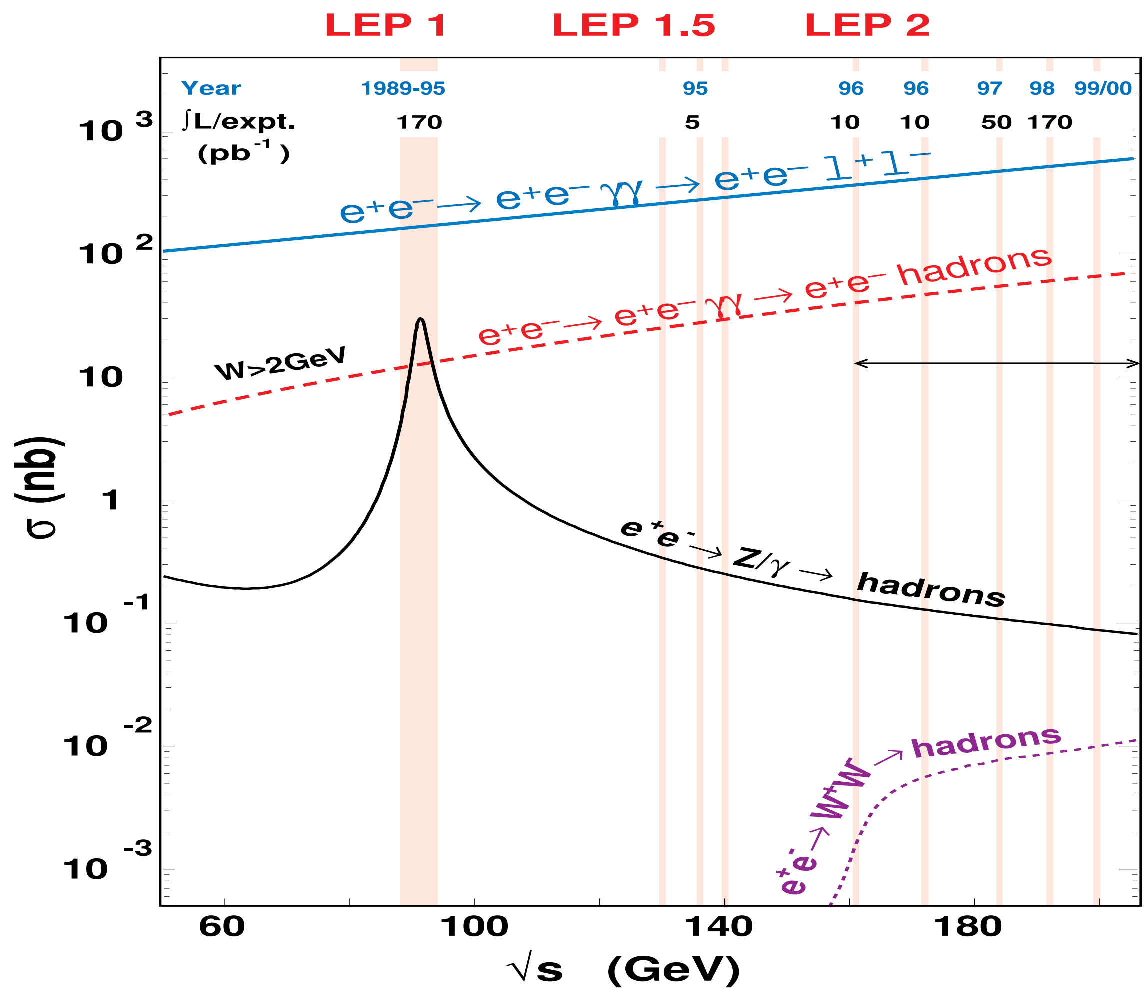
L3 Collaboration

- **Two-photon total cross section**
- η_c **Formation**
- χ_{c2} **Formation**

Abstracts n. 267, 268, 270, 20, 24

Two-Photon Collisions

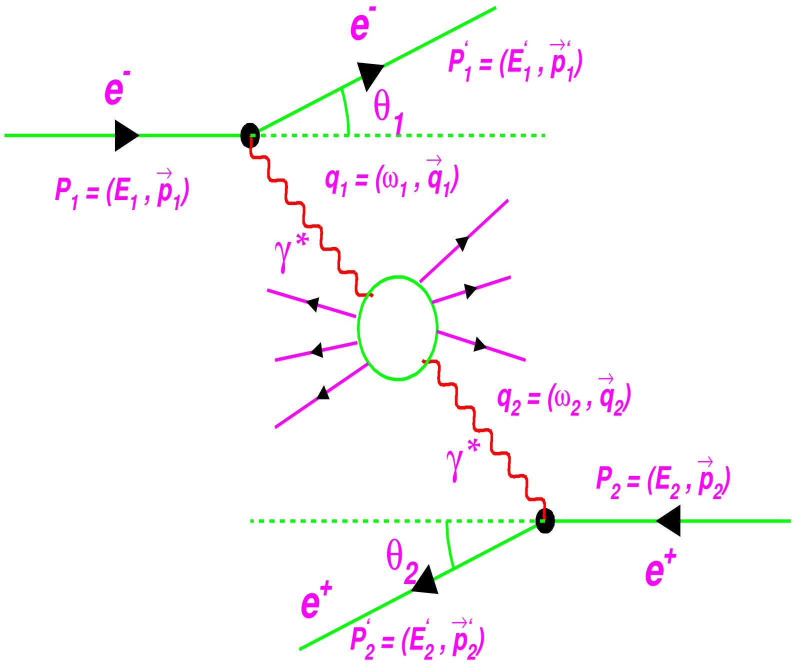
Two-photon interactions are the dominant process at LEP2, with high cross section and low background



$e^+e^- \to e^+e^-$ hadrons:
largest hadron source at LEP2

Important background for searches for New Physics: a good understanding of these processes is needed

Two-Photon Collisions



$$\mathbf{Q}^2 = -\mathbf{q}_1^2 = 2\mathrm{E}_1\mathrm{E}_1^{'}(1 - \mathbf{cos}\theta_1)$$
$$\mathbf{P}^2 = -\mathbf{q}_2^2$$
$$\mathbf{W}_{\mathbf{vis}}^2 = (\textstyle\sum_\mathbf{i} \mathbf{E_i})^2 - (\sum_\mathbf{i} \vec{\mathbf{p}}_\mathbf{i})^2$$

1. **Double-tagged events** $(\mathbf{Q}^2 \simeq \mathbf{P}^2 > 0)$ **both $e^\pm$ detected**
2. **Single-tagged events** $(\mathbf{Q}^2 > \mathbf{P}^2 \simeq 0)$ **one electron detected**
3. **Non-tagged events** $(\mathbf{Q}^2 \simeq \mathbf{P}^2 \simeq 0)$ **both $e^\pm$ in the beam pipe, quasi-real photons**

Non-tagged events:
Study of the total $\gamma\gamma$ cross section and Resonances

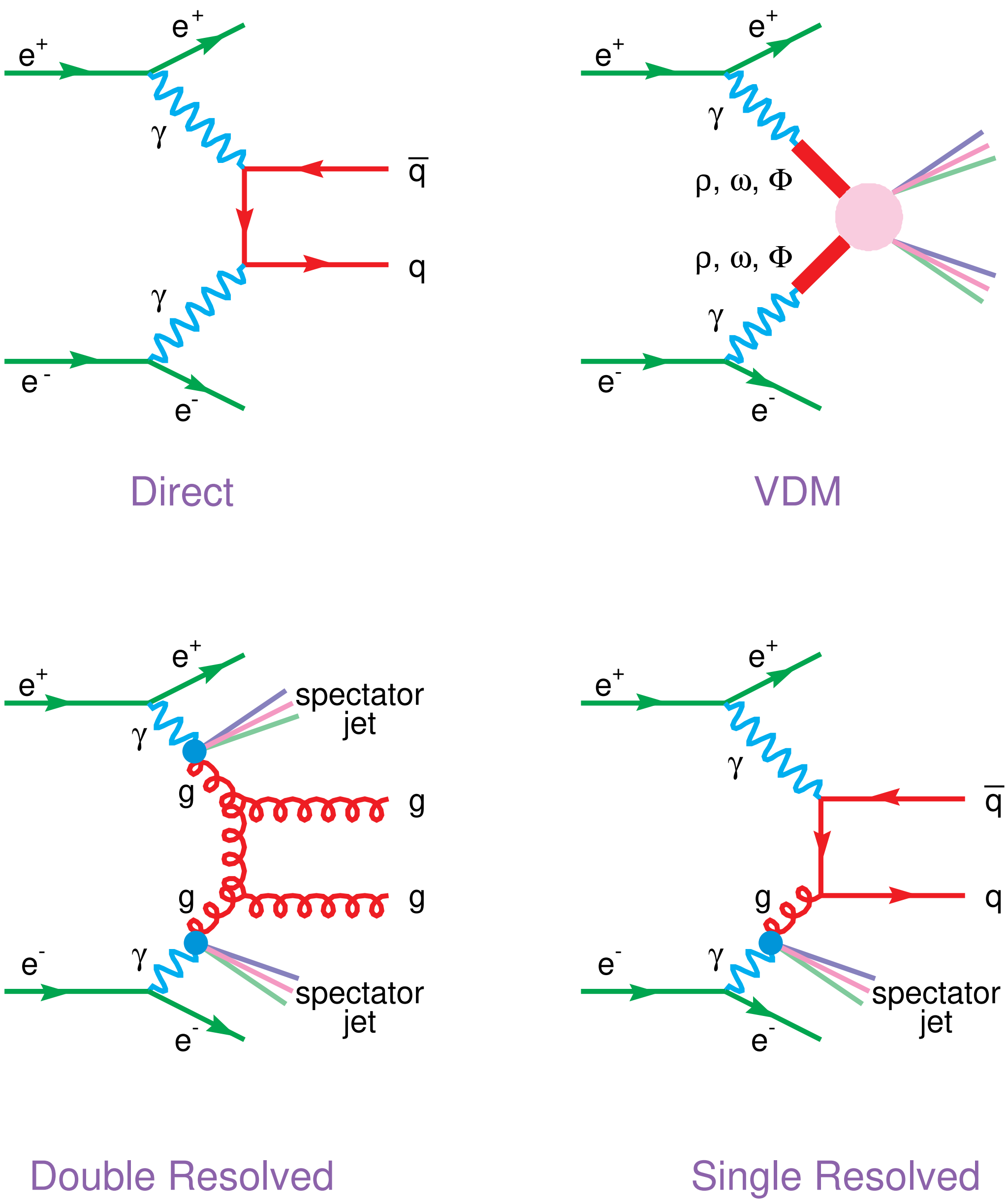
Single-tagged events:
Photon-meson transition form factor

Two-Photon Total Cross Section

$$|\gamma> = \sqrt{Z_3}\,|\gamma_{\mathbf{bare}}> + \frac{\mathbf{e}}{f_{\mathbf{q\bar{q}}}}|\mathbf{q\bar{q}}> + \frac{\mathbf{e}}{f_{\mathbf{q\bar{q}}^*}}|\mathbf{q\bar{q}}^*> \qquad \mathbf{Z}_3 = 1 - (\frac{\mathbf{e}}{f_{\mathbf{q\bar{q}}}})^2 - (\frac{\mathbf{e}}{f_{\mathbf{q\bar{q}}^*}})^2$$

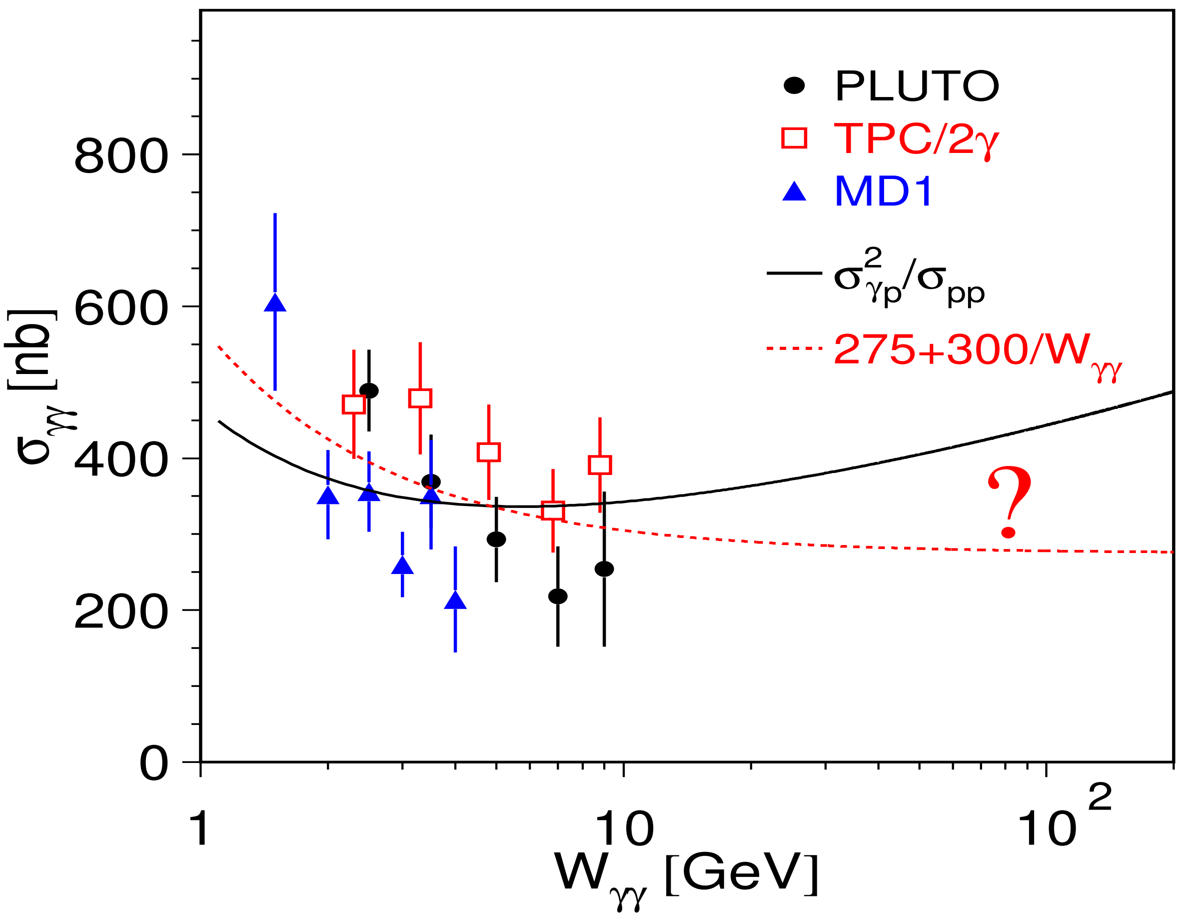
Diagrams contributing to:

$e^+e^- \rightarrow e^+e^-\gamma\gamma \rightarrow e^+e^-$ hadrons



$\sigma_{\gamma\gamma}$: Motivation

$\sigma_{\gamma\gamma}$ Measurements before LEP:



$W_{\gamma\gamma}$ below 10 GeV (limited by beam energy)

Wide spread in the measurements **because of difficult separation from annihilation processes**

How will $\sigma_{\gamma\gamma}$ behave at higher energies?

At LEP:

5 GeV < $W_{\gamma\gamma}$ < 145 GeV	**(L3)**	**has been measured**
10 GeV < $W_{\gamma\gamma}$ < 110 GeV	**(OPAL)**	

$\sigma_{\gamma\gamma}$

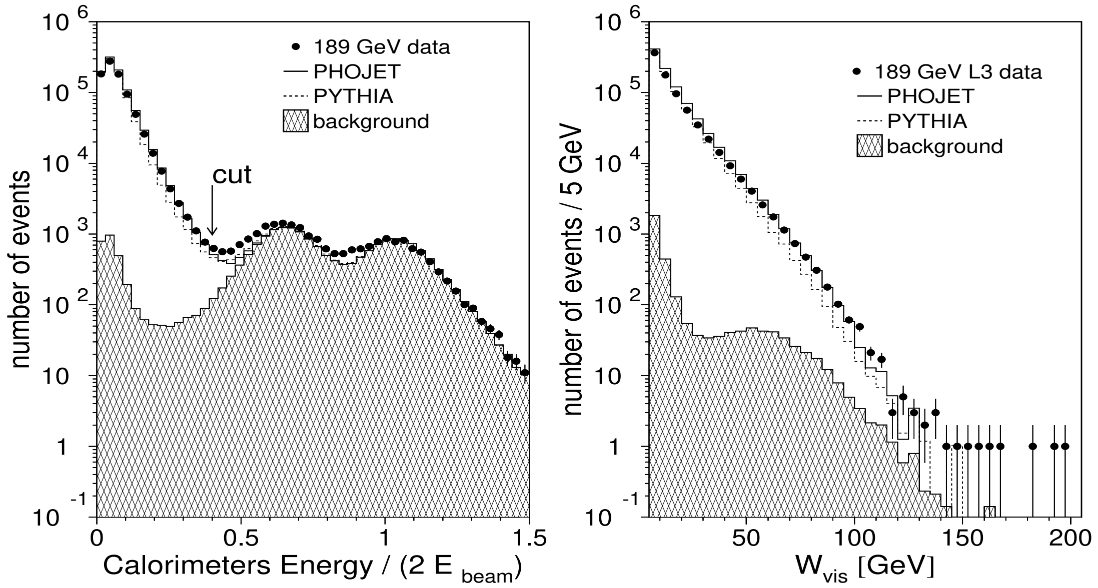
- **Data:**

L3 :	**91 GeV**	**140 pb^{-1}**	**publ.**
	130 –140 GeV	**5 pb^{-1}**	**publ.**
	161 GeV	**10 pb^{-1}**	**publ.**
	183 GeV	**52 pb^{-1}**	**prel.**
	189 GeV	**172 pb^{-1}**	**prel.**
OPAL:	**161 GeV**	**10 pb^{-1}**	**prel.**
	172 GeV	**10 pb^{-1}**	**prel.**
	183 GeV	**54 pb^{-1}**	**prel.**

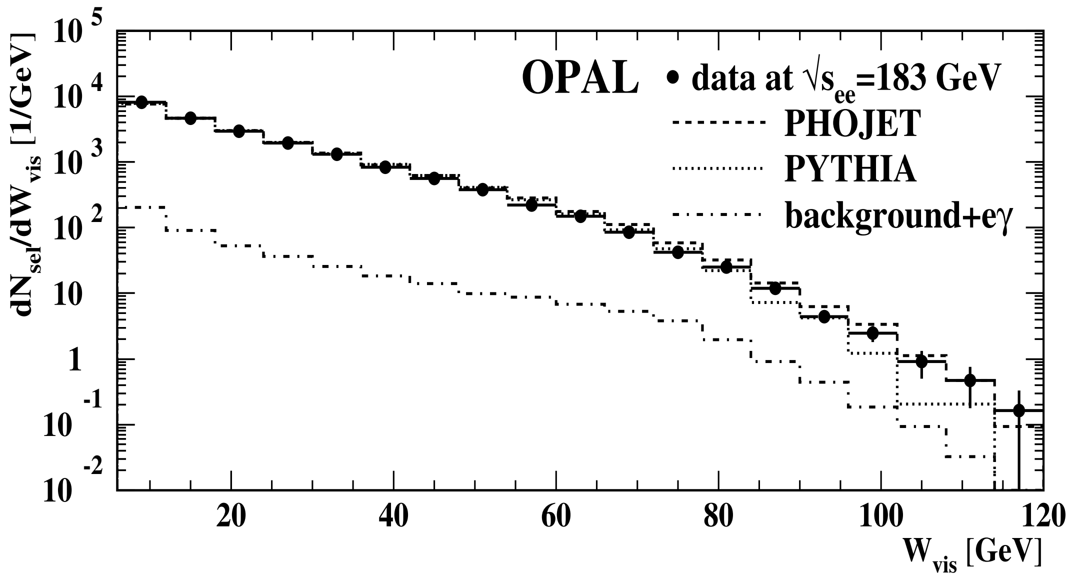
- **Signal Monte Carlo:**
  - **PHOJET: R. Engel and J. Ranft.**
    (Phys. Rev. D54, 4246, 1996)
  - **PYTHIA: T. Sjöstrand**
    (CPC 82, 74, 1994)
- **Need Monte Carlo generators which reproduce well the data**
- **Due to detector acceptance $< W_{vis} >$ is smaller than $W_{\gamma\gamma}$:**
  use unfolding procedures to extract $W_{\gamma\gamma}$ from W_{vis}

Non-tagged events

L3:



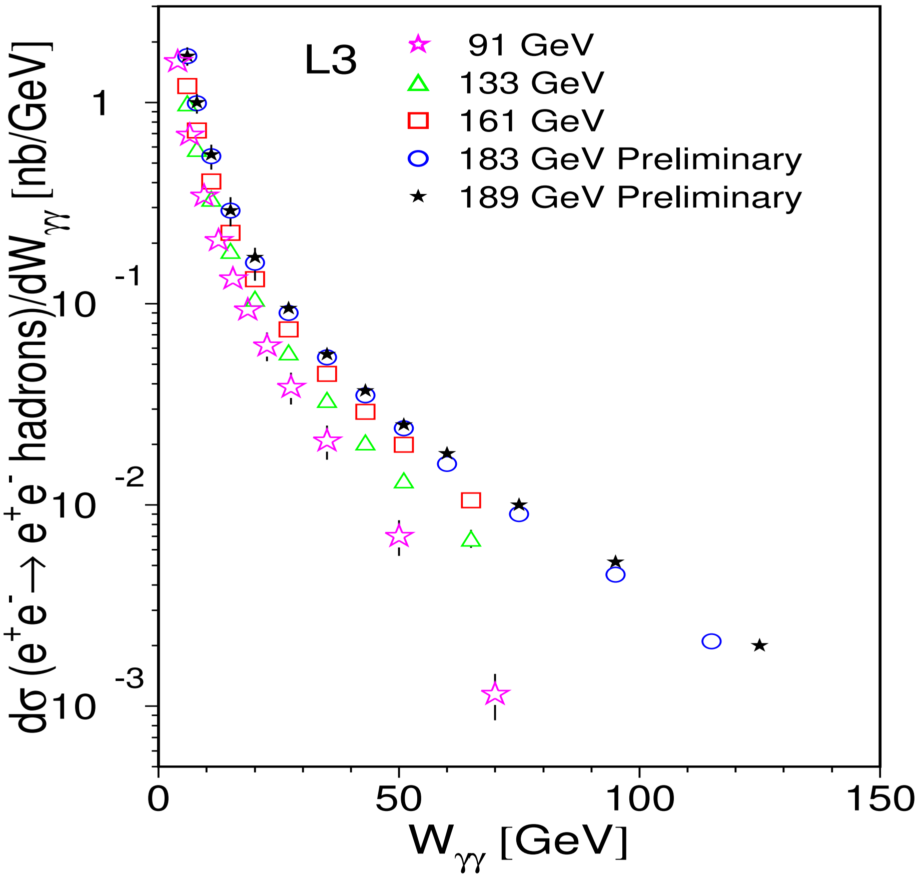
OPAL:



Low background level ($\simeq$ 1% at low W_{vis}, $\leq$ 10% at high W_{vis})

Satisfactory (not perfect, 20%–30%) agreement with both PYTHIA and PHOJET

$\sigma(e^+e^- \to e^+e^-\text{hadrons})$



Effect of the $\gamma\gamma$ luminosity function **which depends on $s/W^2_{\gamma\gamma}$**

$d\sigma_{ee}$ increases with increasing beam energy

$d\sigma_{ee}$ decreases with increasing $W_{\gamma\gamma}$

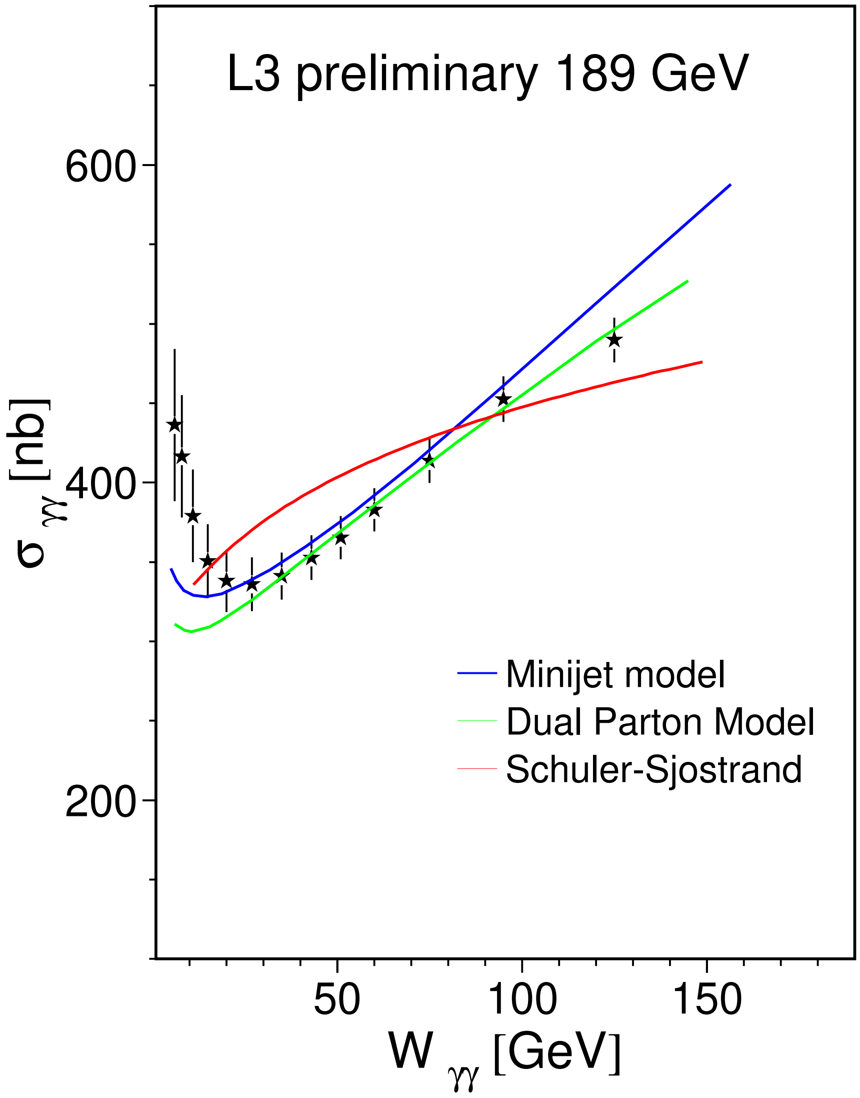
Extract $\sigma_{\gamma\gamma}$ from $d\sigma_{ee}$

$$\frac{d\sigma_{ee}}{d(W^2_{\gamma\gamma}/s)} = \int \frac{dQ^2}{Q^2}\frac{dP^2}{P^2} \sum_{a,b=T,S} \mathcal{L}_{ab}\,\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma}, P^2, Q^2)$$

$$\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma}, P^2, Q^2) = F_a(Q^2)F_b(P^2)\sigma^{\gamma\gamma}_{ab}(W_{\gamma\gamma})$$

***T and S are Transverse and Scalar photon helicity indices.**

$\sigma_{\gamma\gamma}$: Results



Data unfolded with Phojet

Minijet: Godbole and Pancheri (hep-ph/9903331)

DPM (Phojet): R. Engel private communication

SaS (Pythia): Z. Phys. C 73 (1997) 677

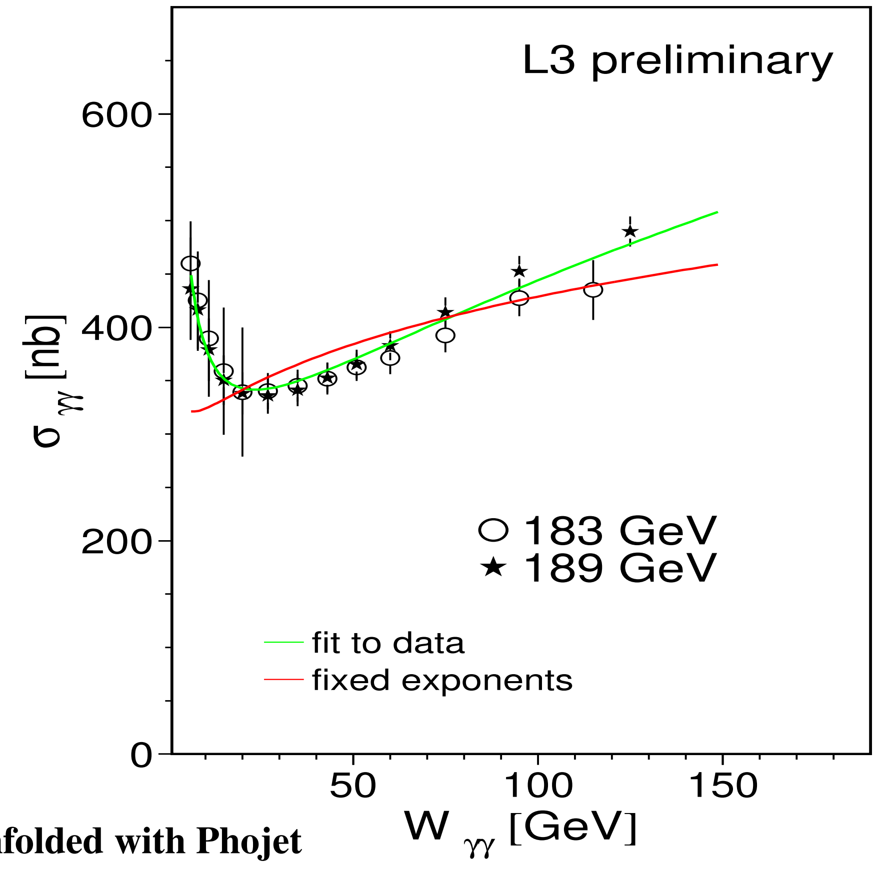
Predictions for $W_{\gamma\gamma} > 10 - 20$ GeV
The data are well reproduced by models which include QCD effects

$\sigma_{\gamma\gamma}$: Results

Fit with Donnachie and Landshoff parametrisation:

$$\sigma_{\gamma\gamma} = As^{\varepsilon} + Bs^{-\eta}\ ,\ s = W_{\gamma\gamma}^2$$

(Phys. Lett., B296 (1992) 227)



Data unfolded with Phojet

Universal fit (PDG 1998): $\varepsilon = 0.095 \pm 0.002$, $\eta = 0.34 \pm 0.02$, A, B **free**

Fit to 183–189 GeV data (26 points)

with correl. matrix, $\eta = 0.34$ **fixed, A,B free**

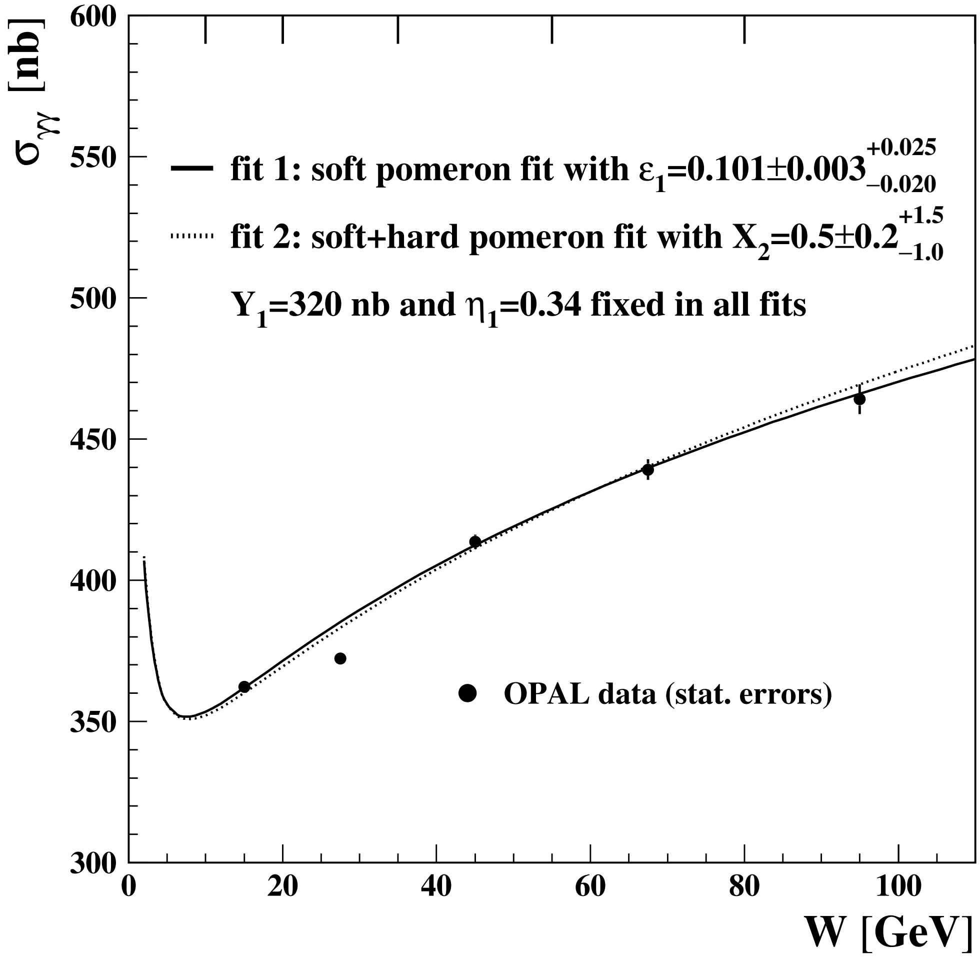
	ε	χ^2	CL
Universal ε	**0.095 fixed**	**62**	3.4×10^{-5}
Free ε	**0.222±0.019**	**9.3**	**99.5%**

Faster rise of $\sigma_{\gamma\gamma}$ with respect to pp or γ p interactions

$\sigma_{\gamma\gamma}$: Results

OPAL: different Regge parametrisation:

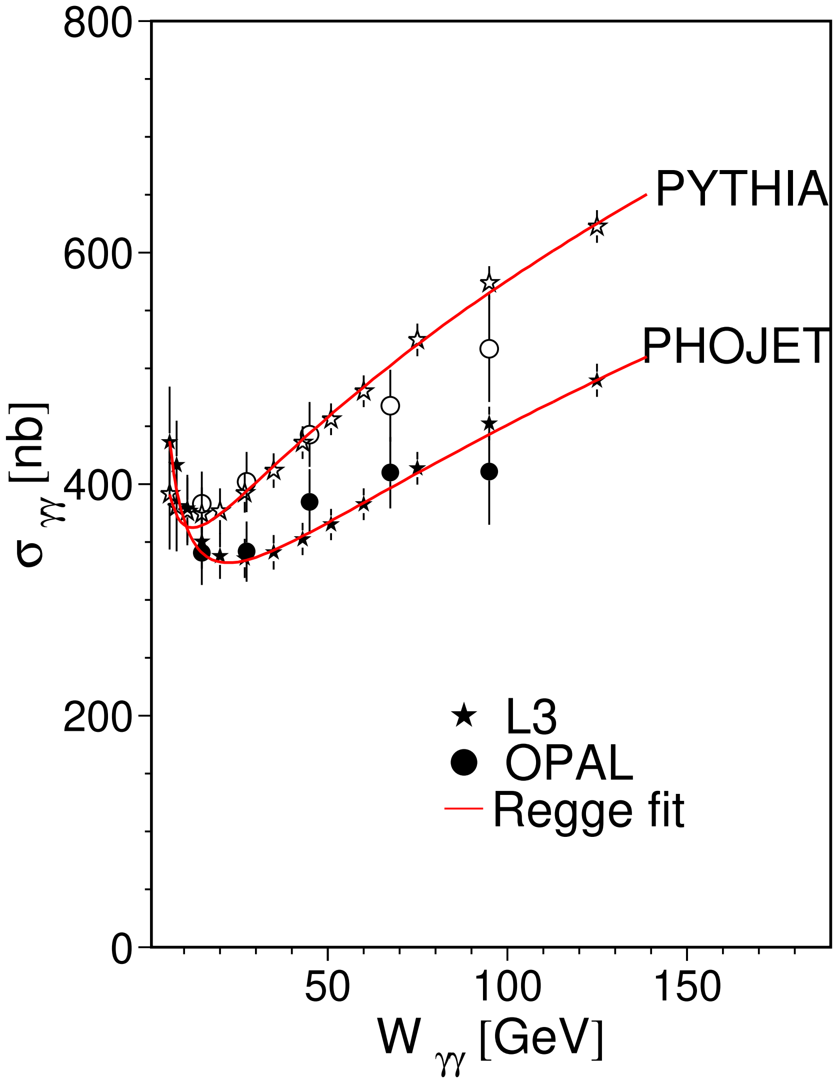
$$\sigma_{\gamma\gamma} = X_1 s^{\varepsilon_1} + X_2 s^{\varepsilon_2} + Y_1 s^{-\eta_1}$$



Unfolding with PYTHIA and PHOJET averaged

	ε_1	X_2 (nb)	χ^2/ndf
fit 1	$0.101 \pm 0.003^{+0.025}_{-0.020}$	0	137/3
fit 2	0.095 (fixed)	$0.5 \pm 0.2^{+1.5}_{-1.0}$	130/3

$\sigma_{\gamma\gamma}$: Results



Statistic and detector related systematic errors only

L3 and OPAL are compatible if the same generator is used.

Both experiments show clear rising behaviour with increasing energy, independent of MC

The uncertainty on absolute values is $\sim 20\%$
(MC model dependence)

Resonance Formation

$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-$ **R**, **R: C=+1 meson**

Total cross section:

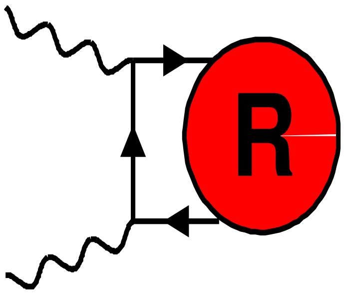
$$\sigma(e^+e^- \rightarrow e^+e^-R) = \int d\mathcal{L}_{\gamma\gamma}(W^2_{\gamma\gamma}) \;\; \sigma_{\gamma\gamma\rightarrow R}(W^2_{\gamma\gamma}, q_1^2, q_2^2)$$

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

The form factor can be parametrised as:

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

$\Lambda^2 = M_V^2, \quad V = \rho, \omega, \phi, J/\psi$ **in VDM**



$\eta_c(2980)$ Formation

L3: $\sqrt{s} = 91$ **GeV** $\mathcal{L} = 140$ **pb**$^{-1}$
$\sqrt{s} = 183$ **GeV** $\mathcal{L} = 52$ **pb**$^{-1}$

Individual decay BR small: 9 decay modes are studied (BR = $10.5 \pm 1.3\%$):

Decay mode	BR(%)(PDG)	Signature	ε_{183} (%)
$\eta_c \to \pi^+\pi^-\pi^+\pi^-$	1.2 ± 0.4	4 tracks	4.1
$\eta_c \to K^+K^-\pi^+\pi^-$	2.0 ± 0.7	4 tracks	4.5
$\eta_c \to K^0_s K^\pm \pi^\mp$	1.3 ± 0.4	2 tracks, sec. vertex	5.0
$\eta_c \to \pi^+\pi^-\eta\,(\eta \to \gamma\gamma)$	1.3 ± 0.5	2 tracks, 2 photons	3.9
$\eta_c \to K^+K^-\pi^0$	0.9 ± 0.3	2 tracks, 2 photons	3.3
$\eta_c \to \rho^+\rho^-,\ \rho^\pm \to \pi^\pm\pi^0$	1.7 ± 0.6	2 tracks, 4 photons	0.9
$\eta_c \to \pi^+\pi^-\eta\,(\eta \to \pi^+\pi^-\pi^0)$	0.8 ± 0.3	4 tracks, 2 photons	1.2
$\eta_c \to \pi^+\pi^-\eta'\,(\eta' \to \pi^+\pi^-\eta,\ \eta \to \gamma\gamma)$	0.5 ± 0.2	4 tracks, 2 photons	2.5
$\eta_c \to \pi^+\pi^-\eta'\,(\eta' \to \rho^0\gamma,\ \rho^0 \to \pi^+\pi^-)$	0.8 ± 0.3	4 tracks, 1 photon	2.5

$\varepsilon_{91}\,(\%) \simeq \varepsilon_{183}\,(\%)$

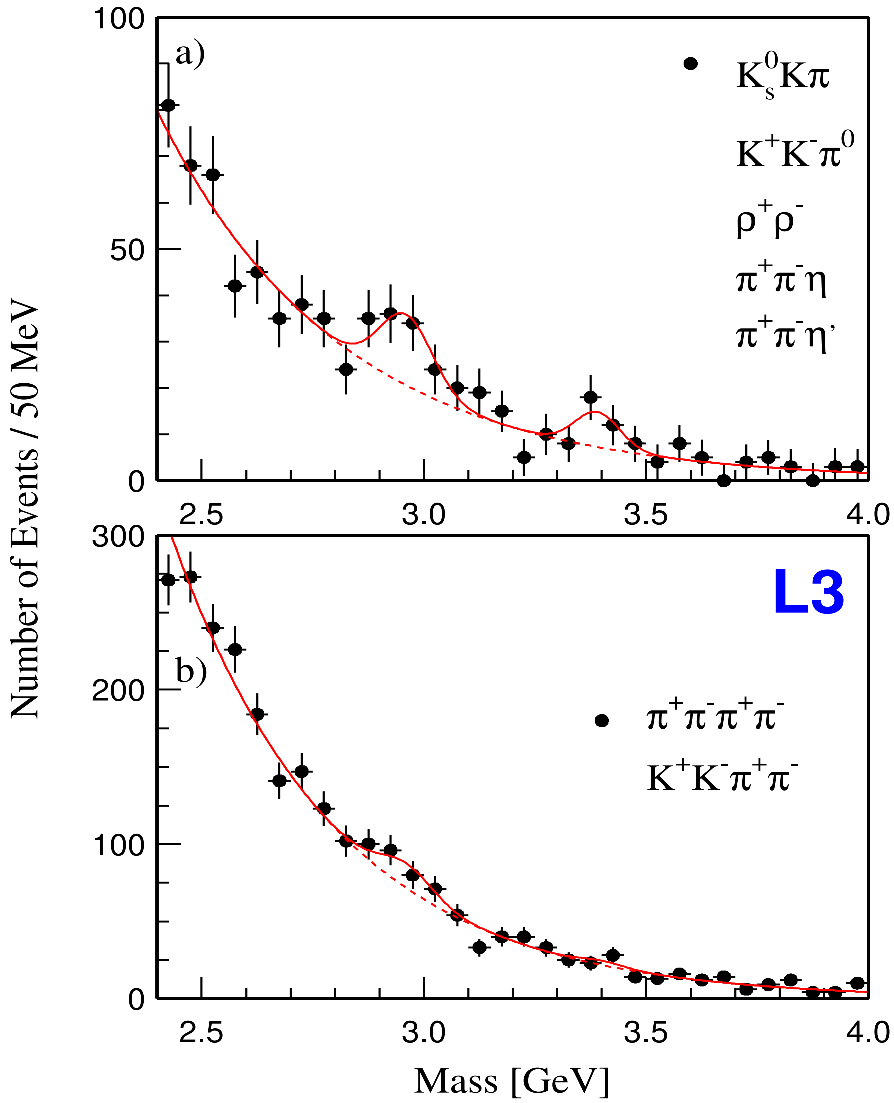
All BR affected by $\sim 28\%$ error due to uncertainty on BR ($J/\psi \to \eta_c\gamma$)

World average (PDG98): $\Gamma_{\gamma\gamma}(\eta_c) = 7.5\,^{+1.6}_{-1.4}$ **keV**

From theoretical[1] predictions: $\Gamma_{\gamma\gamma}(\eta_c) \sim$ **3-11 keV**

[1] E.S. Ackleh *et al.*., Phys. Rev. D 45 (1992) 232, M.R. Ahmady *et al.*, 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

$\eta_c(2980)$ Formation



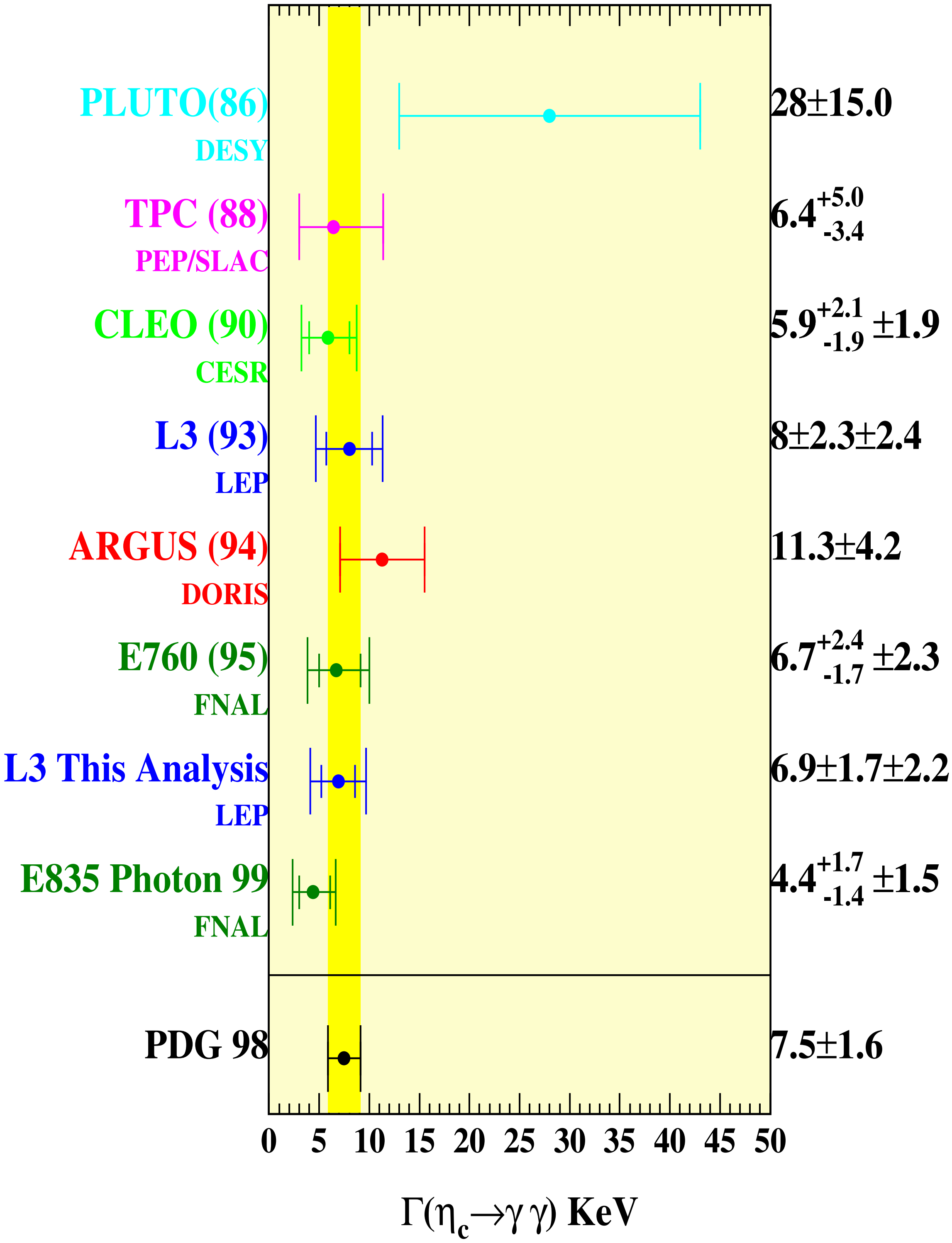
Unbinned likelihood fit

Signal of 76 ± 14 events at $M_{\eta_c} = 2.974 \pm 0.018$ GeV

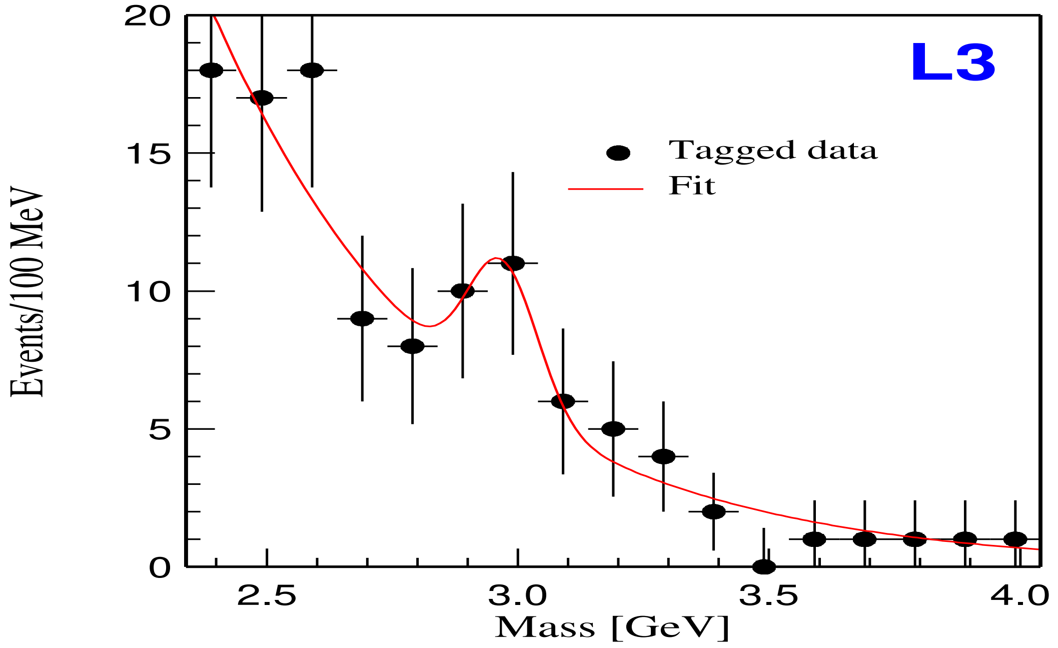
$$\Gamma_{\gamma\gamma}(\eta_c) = \mathbf{6.9 \pm 1.7\ (stat.) \pm 0.8\ (syst.) \pm 2.0\ (BR)\ \ keV}$$

χ_{c0} peak at 3.400 ± 0.019 GeV, with 29 ± 11 events
$\Gamma_{\gamma\gamma}(\chi_{c0})$ not measured because BR's are unknown

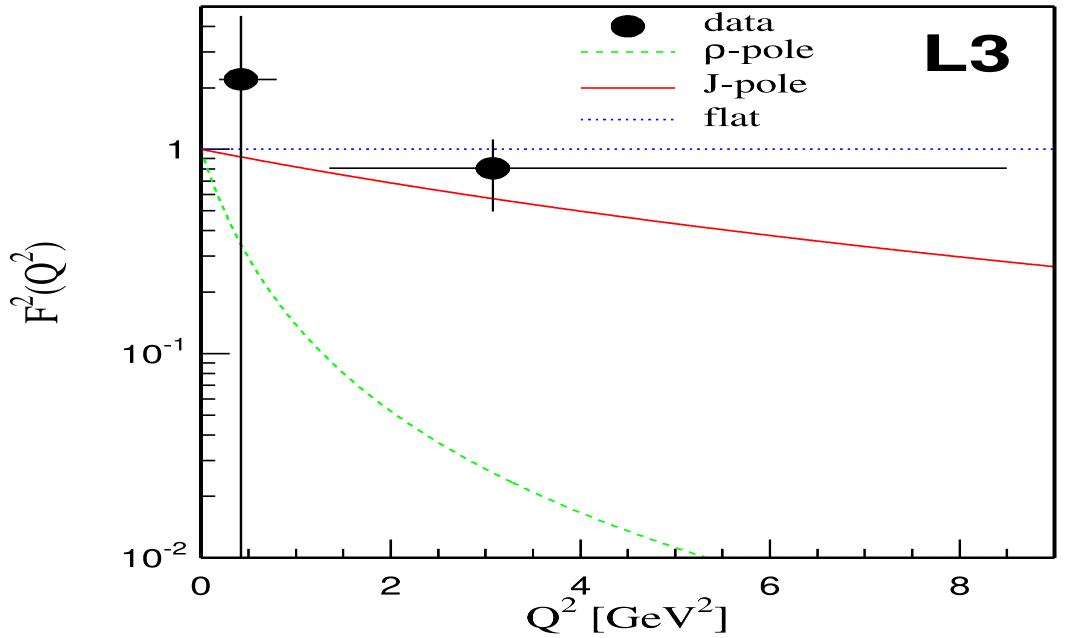
$\eta_c(2980)$: Comparison



$\eta_c(2980)$ Form Factor



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



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

$\chi_{c2}(3555)$ Formation

$$\chi_{c2} \to \mathrm{J}/\psi\,\gamma \to \ell^+\ell^-\gamma \qquad \ell = \mathrm{e},\ \mu$$

Total BR = 1.6%

From theoretical[2] predictions: $\Gamma_{\gamma\gamma}(\chi_{c2}) \sim$ **0.3-0.8 keV**

$$\frac{\Gamma_{gg}(\chi_{c2})}{\Gamma_{\gamma\gamma}(\chi_{c2})} = \frac{9\alpha_s^2(m_c)}{8\alpha^2}\left(\frac{1-2.2\alpha_s/\pi}{1-16\alpha_s/3\pi}\right)$$

Experiment	Production mechanism	$\Gamma_{\gamma\gamma}(\chi_{c2})$ (keV)
R704	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$2.0^{+0.9}_{-0.7} \pm 0.3$
TPC/2γ	$\gamma\gamma \to \chi_{c2} \to \gamma \mathrm{J}/\psi$	$3.4 \pm 1.7 \pm 0.9$
E760	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.32 \pm 0.08 \pm 0.05$
E835 (Photon 99)	$p\bar{p} \to \chi_{c2} \to \gamma\gamma$	$0.31 \pm 0.05 \pm 0.04$
CLEO	$\gamma\gamma \to \chi_{c2} \to \gamma \mathrm{J}/\psi$	$1.08 \pm 0.30 \pm 0.26$

L3: $\sqrt{s} = 91$ GeV $\quad \mathcal{L} = 140\ \mathrm{pb}^{-1}$
$\sqrt{s} = 183$ GeV $\quad \mathcal{L} = 52\ \mathrm{pb}^{-1}$

OPAL: $\sqrt{s} = 91$ GeV $\quad \mathcal{L} = 167\ \mathrm{pb}^{-1}$
$\sqrt{s} = 183$ GeV $\quad \mathcal{L} = 55\ \mathrm{pb}^{-1}$

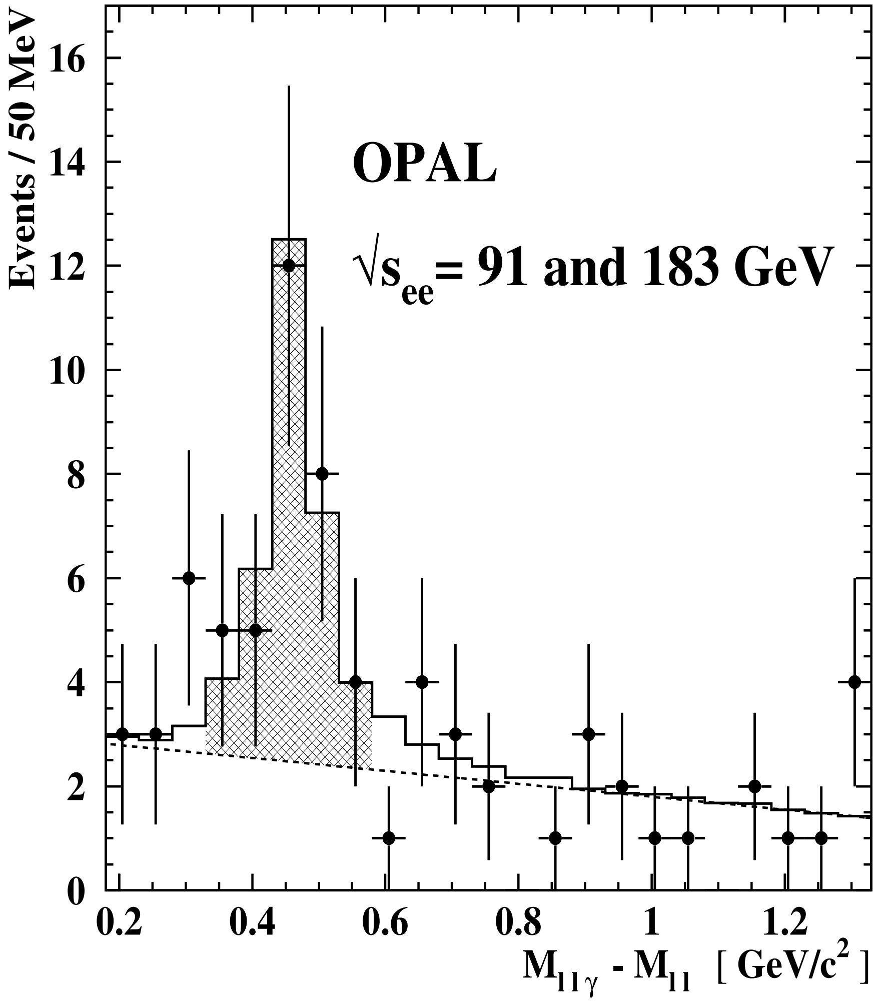
Signal Monte Carlo events are weighted according to the angular distribution of a spin-two resonance

Q^2 dependence with a J/ψ pole transition form factor

[2] G.T. Bodwin *et al.*, Phys. Rev. D 46 (1992) 1914, Schuler *et al.*, hep-ph/9710462

$\chi_{c2}(3555)$ Formation

OPAL:

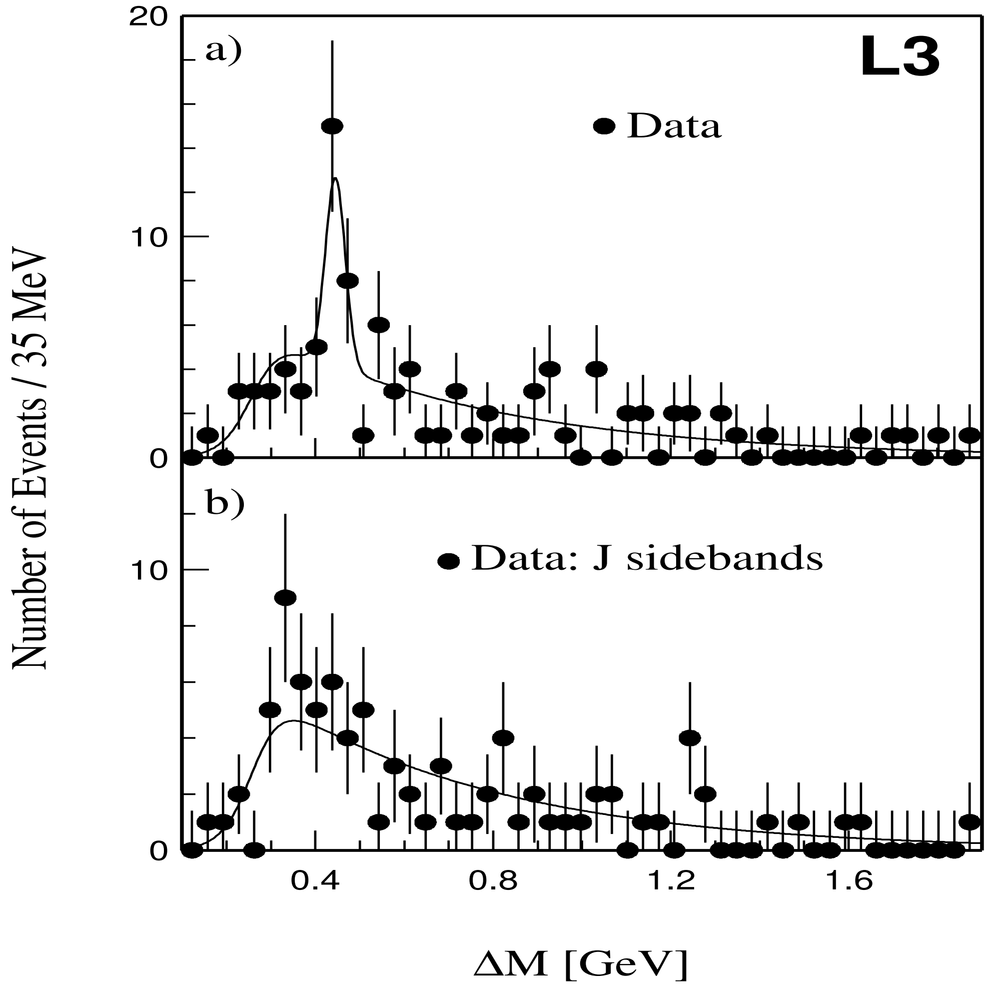


34 signal events

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = \mathbf{1.76 \pm 0.47\ (stat.) \pm 0.37\ (syst.) \pm 0.15\ (BR)\ keV}$$

$\chi_{c2}(3555)$ Formation

L3:



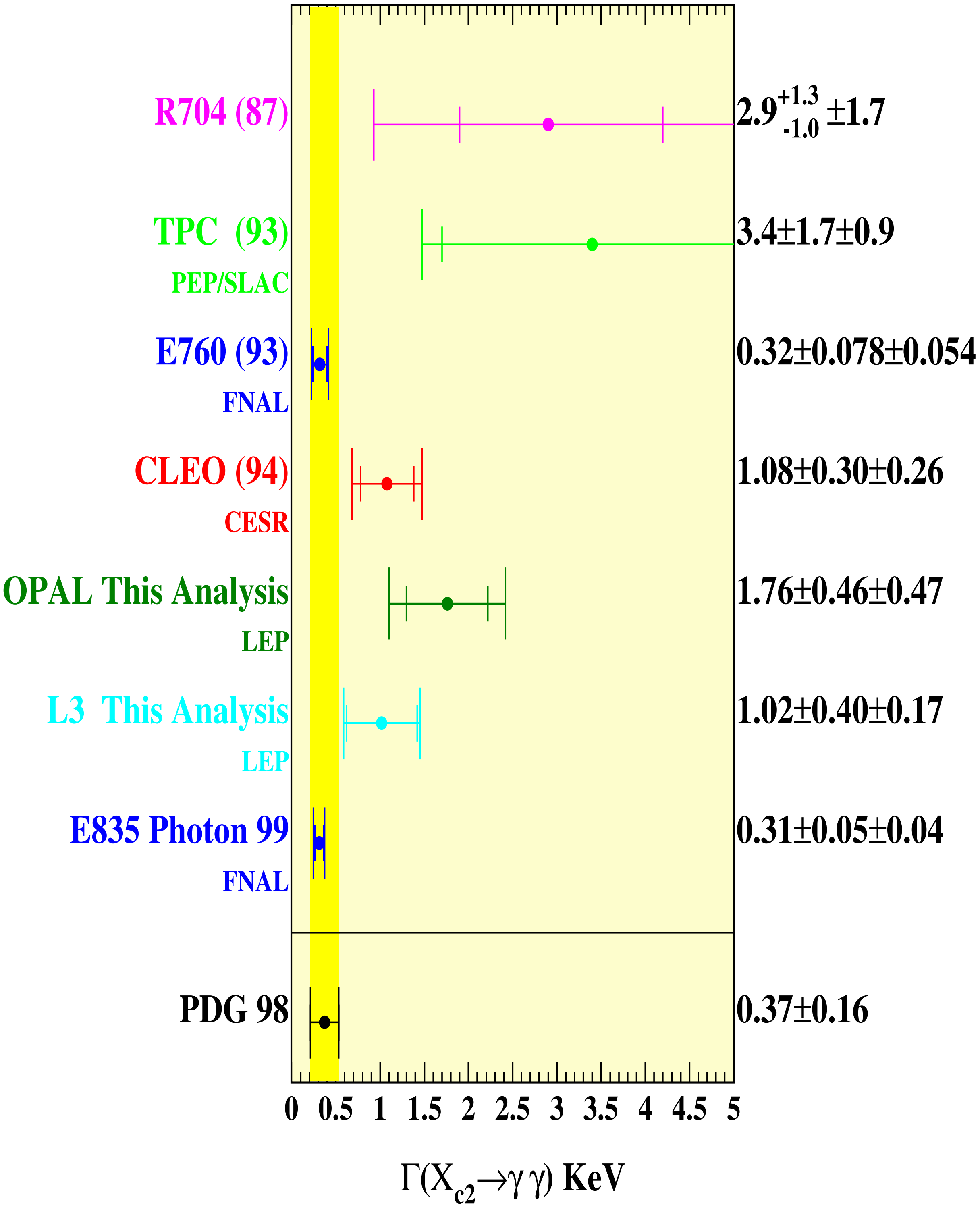
14 signal events

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = \mathbf{1.02 \pm 0.40\ (stat.) \pm 0.15\ (syst.) \pm 0.09\ (BR)\ keV}$$

$$\alpha_s(m_c) = 0.21 \pm 0.05$$

$\alpha_s(m_c)$ **lower than the measurements obtained at the** τ **mass**

$\chi_{c2}(3555)$: Comparison



Conclusions

- The total cross section $\sigma(e^+e^- \rightarrow e^+e^-\text{hadrons})$ is measured at LEP for 5 GeV < $W_{\gamma\gamma}$ < 145 GeV
- The total cross section $\sigma(\gamma\gamma \rightarrow \text{hadrons})$ for real photons increases with increasing $W_{\gamma\gamma}$, as QCD predicts
- The two-photon width of the η_c has been measured. It is in good agreement with previous measurement and theoretical predictions
- The Q^2 dependence of the η_c cross section has been measured for $Q^2 \leq 9\ \text{GeV}^2$. It is better described by a J/ψ mass pole than by a ρ mass pole
- The two-photon width of the χ_{c2} has been measured. It is somewhat higher than the theoretical predictions. The combined value of all two-photon measurements: $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.23 \pm 0.23\ (\text{stat.} + \text{syst.}) \pm 0.11\ (\text{BR})$ keV, is three standard deviations higher than the $p\bar{p}$ measurement of E760 and E835