Meson Formation in Photon-Photon Collisions at LEP with the L3 Detector

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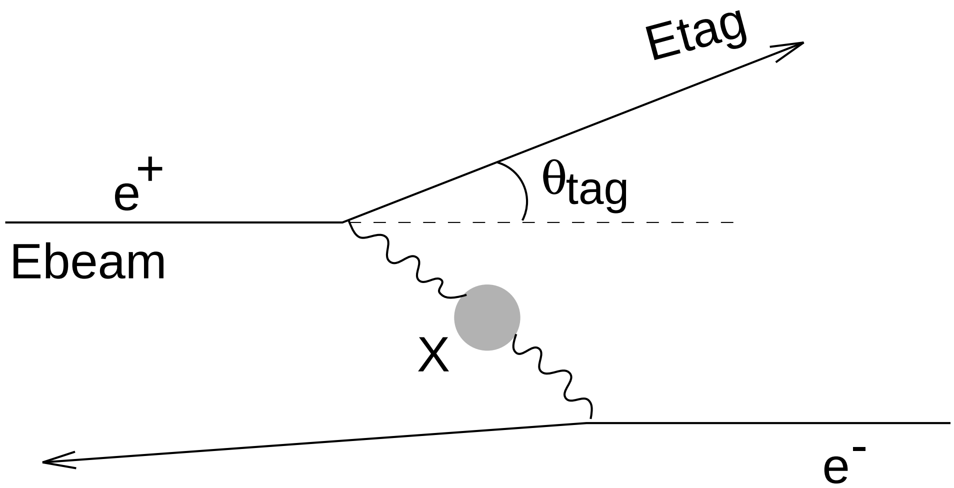
representing the L3 collaboration

- Introduction
- Study of the $\rho^0\rho^0$ final state (diffraction)
- Study of the $\pi^+\pi^-\pi^0$ final state (a_2)
- Study of the $\pi^+\pi^-\gamma$ final state (η')
- Study of the $K_s^0K_s^0$ final state (f_2')
- Study of the γJ/ψ final state (χ_{c2})
- Conclusions

Two-photon physics



Small scattering angle θ_{tag}; quasi-real photons: untagged events
Large scattering angle: tagged events

Total cross section:

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-\gamma\gamma \to \mathrm{e}^+\mathrm{e}^-\mathrm{X}) = \int \mathrm{d}^5\mathrm{L}_{\gamma\gamma}(\alpha_{\mathrm{i}})\sigma(\gamma\gamma \to \mathrm{X})$$

- Vector meson pair $\rho^0\rho^0$
- Resonance: neutral meson; C = +1; J=0, 2

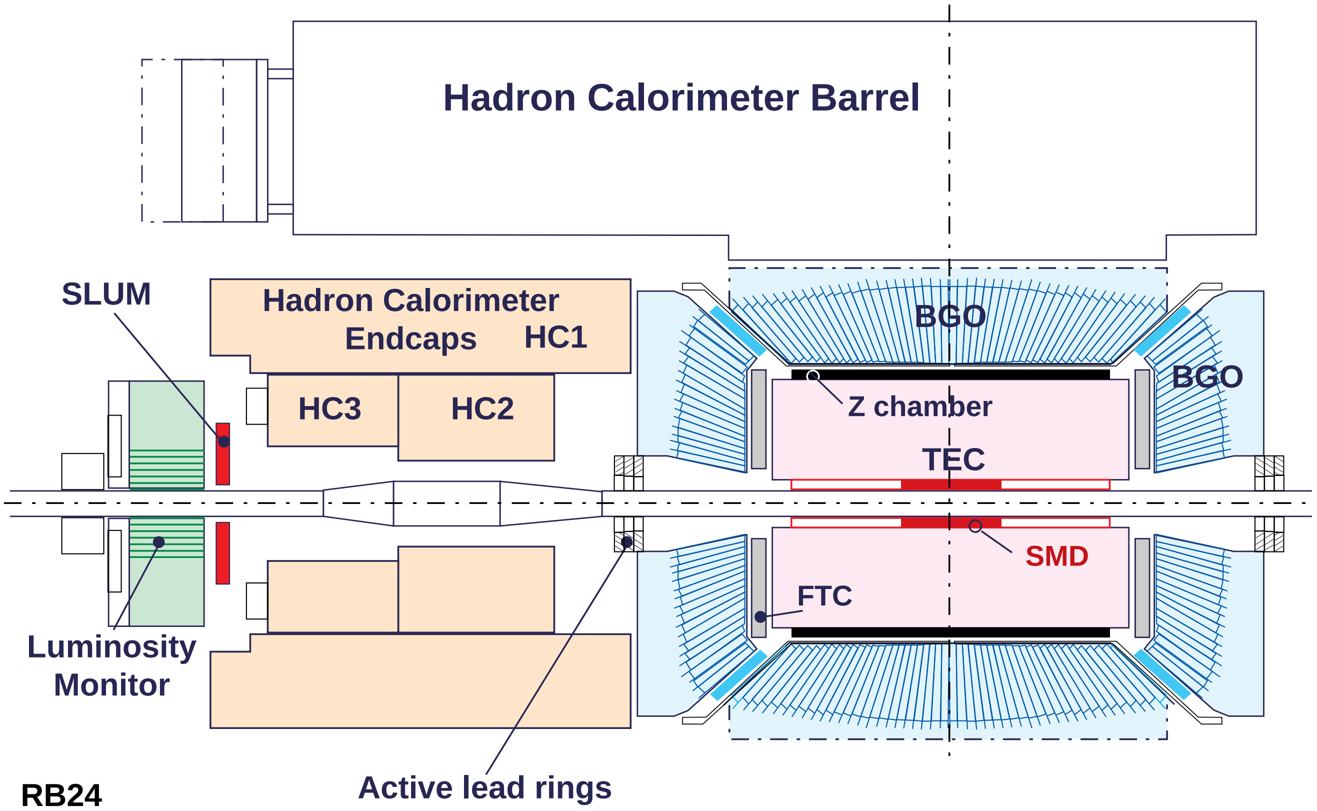
$$\sigma(\gamma\gamma \to R) = 8\pi\frac{(2J_R+1)}{M_R}\Gamma_{\gamma\gamma}(R)\frac{M_R\Gamma_R}{(M_X^2-M_R^2)^2+M_R^2\Gamma_R^2}\left(\frac{1}{1-q_1^2/\Lambda^2}\right)^2\left(\frac{1}{1-q_2^2/\Lambda^2}\right)^2$$

$\Gamma_{\gamma\gamma}(R) = \Gamma_R \cdot \mathrm{Br}(R \to \gamma\gamma)$ measures strength of interaction $\gamma\gamma \to R$
Transition Form Factor F^2 contains dependence on (q_1^2, q_2^2)

Vector Dominance model $F^2 \sim \left(\frac{1}{1-q_1^2/\Lambda^2}\right)^2\left(\frac{1}{1-q_2^2/\Lambda^2}\right)^2 \to \left(\frac{1}{1+Q_2^2/\Lambda^2}\right)^2$ with $\Lambda \sim M_\rho, M_\omega, M_\phi, \ldots$

L3 detector

The inner part of the L3 detector:



- Central track detector: measure charged tracks
- Electromagnetic calorimeter: measure electromagnetic clusters
- Luminosity monitor: measure scattered beam particles

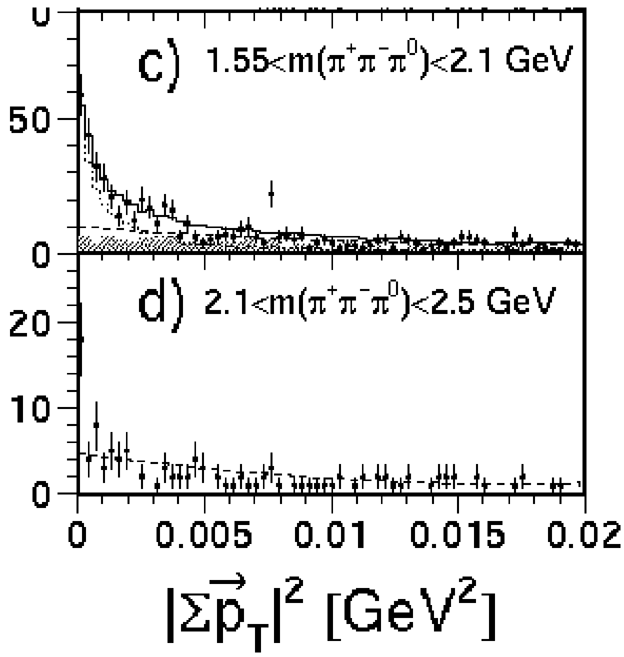
Data selection

Data samples:
1991-1995, $\sqrt{s} \simeq 91$ GeV, $\mathcal{L} = 140\ \mathrm{pb}^{-1}$
1996, $\sqrt{s} \simeq 161$ and 172 GeV, $\mathcal{L} = 20\ \mathrm{pb}^{-1}$
1997, $\sqrt{s} \simeq 183$ GeV, $\mathcal{L} = 50\ \mathrm{pb}^{-1}$

Select exclusive final states:

- $\rho^0\rho^0$, $\rho^0 \rightarrow \pi^+\pi^-$ (1997 data)
- $\pi^+\pi^-\pi^0$ (1991-1995 data)
- $\pi^+\pi^-\gamma$ (1992-1995 data)
- $K_s^0 K_s^0$, $K_s^0 \rightarrow \pi^+\pi^-$ (1991-1997)
- $\gamma J/\psi$, $J/\psi \rightarrow l^+l^-$ (1991-1995 and 1997)

Need exact number of tracks and photons in final state.
Conservation of transverse momentum suppresses inclusive final states:

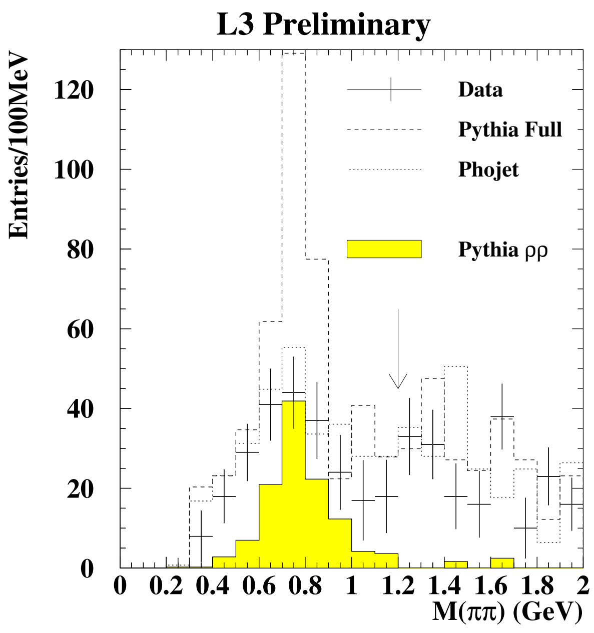


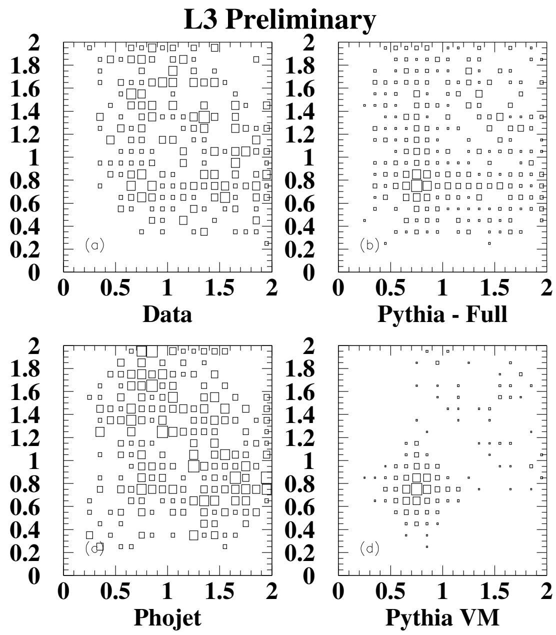
$\rho^0\rho^0$ final state

Study $\rho^0\rho^0$ formation with $W_{\gamma\gamma} > 3$ GeV:

- Study Vector Dominance Model validity
- Check contribution of elastic and diffractive events in $\gamma\gamma \rightarrow$ *hadrons* event generators used for total cross section measurement: Phojet R. Engel, Phys. Rev. D 54 (1996)4244 and Pythia G.A. Shuler and T. Sjöstrand, Z. Phys. C 73 (1997)677

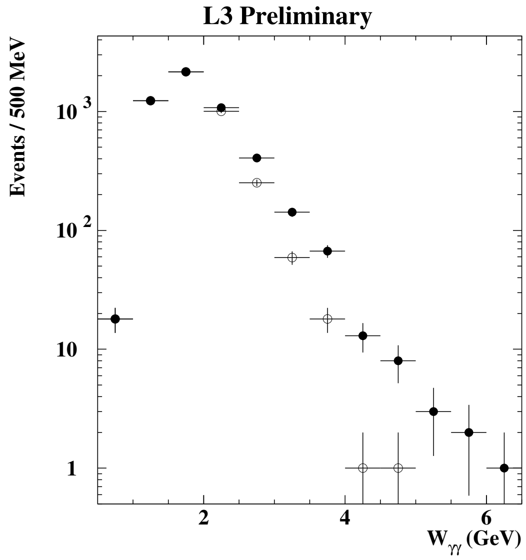
Select $\pi^+\pi^-\pi^+\pi^-$ events. Invariant mass of two pions:

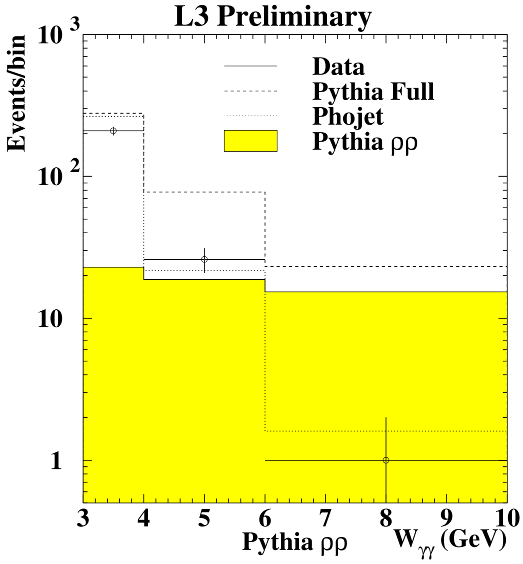




$\rho^0\rho^0$ final state

- $|\cos\theta^*| < 0.8$ cuts out forward region
- Calculate $W_{\gamma\gamma} = M(\pi^+\pi^-\pi^+\pi^-)$



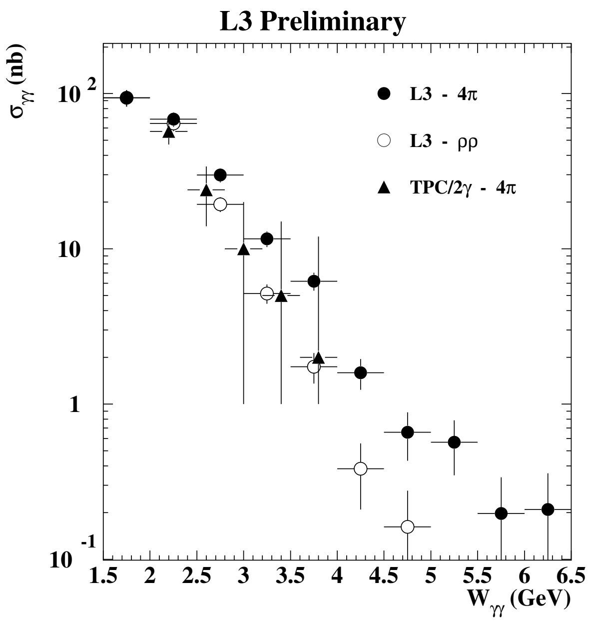


Phojet agrees better with data than Pythia

Cross section for $\pi^+\pi^-\pi^+\pi^-$ and $\rho^0\rho^0$ (**Very Preliminary**)

Monte Carlo efficiency from $\rho^0\rho^0$ continuum with flat phase space

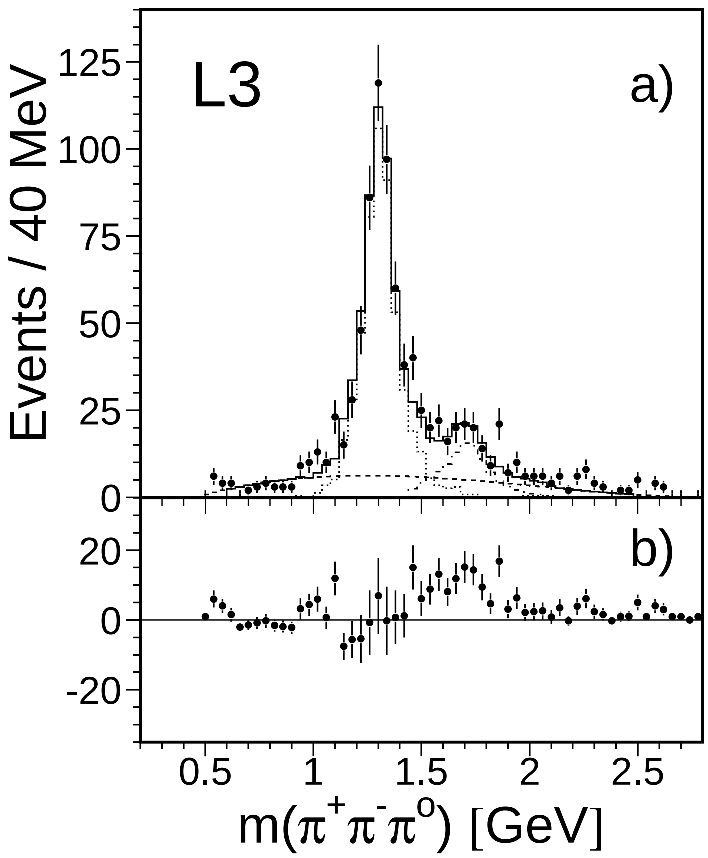
(PC event generator,F.L.Linde, PhD thesis, Leiden University (1988))



$\pi^+\pi^-\pi^0$ final state Phys. Lett. B 413 (1997) 147.

Select exclusive $\pi^+\pi^-\gamma\gamma$ final states, with $0.105 < M(\gamma\gamma) < 0.165$ GeV, and calculate $M(\pi^+\pi^-\pi^0)$.
Divide sample:

- Low-mass region 1.0-1.55 GeV with $\left|M_\rho - M(\pi^\pm\pi^0)\right| < 0.25$: expect $a_2(1320) \to \rho^\pm\pi^\mp$, $\rho^\pm \to \pi^\pm\pi^0$
- High-mass region 1.55-2.1 GeV: Look for $J^P = 2^-$ $\pi_2(1670)$ seen by Crystal Ball and CELLO, but not by ARGUS; check $\rho\pi$ and $f_2\pi$ final states.



- First peak: mass 1323±4±3 MeV, width 105±10±11 MeV
- Second peak: mass 1752±21±4, width 150±110±34, significance 6 standard deviations

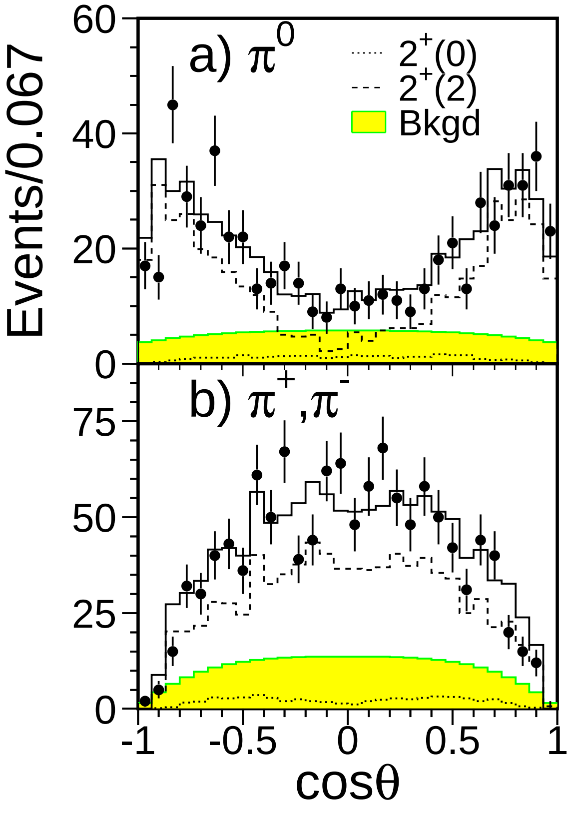
$\pi^+\pi^-\pi^0$ final state

Angular distribution

$$T = \sum_\lambda R_\lambda \left| \left(\frac{T_\lambda(X \to \rho^+\pi^- \to 3\pi)}{m_\rho^2 - m_{2\pi}^2 - im_\rho\Gamma_\rho} + \frac{T_\lambda(X \to \rho^-\pi^+ \to 3\pi)}{m_\rho^2 - m_{2\pi}^2 - im_\rho\Gamma_\rho} \right) + \alpha \exp(i\phi) \left(\frac{T_\lambda(X \to f_2\pi^0 \to 3\pi)}{m_{f_2}^2 - m_{2\pi}^2 - im_{f_2}\Gamma_{f_2}} \right) \right|^2 .$$

R_λ probability for total helicity state λ
T_λ transition amplitude, function of angles of decay products
α, ϕ relative contribution and relative phase of $f_2\pi$

Helicity study for $a_2 \to \rho^\pm\pi^\mp$, $\rho^\pm \to \pi^\pm\pi^0$: λ=0 or λ=2.



Helicity-2 fraction $R_2 = 0.92 \pm 0.05 \pm 0.05$
$\Gamma_{\gamma\gamma}(a_2) = 0.98 \pm 0.05 \pm 0.09$ keV in agreement with recent relativistic potential model calculation C.R. Münz, Nucl. Phys. A 609 (1996) 364.

$\pi^+\pi^-\pi^0$ high mass sample

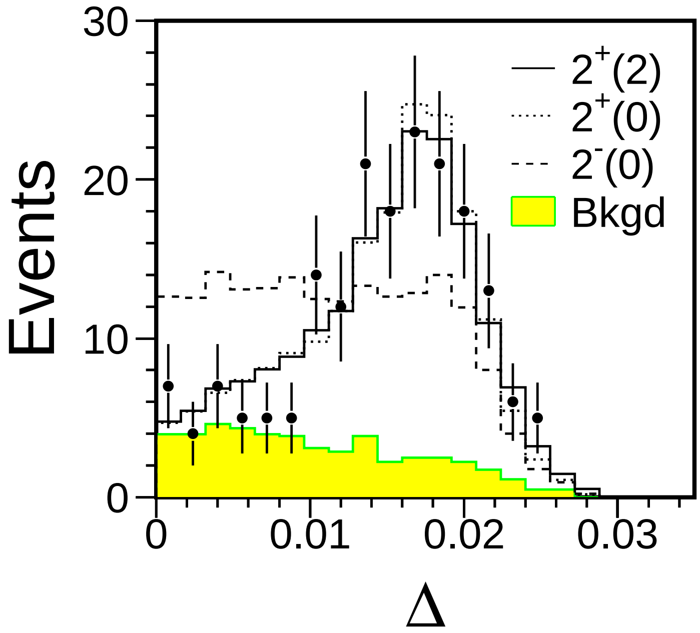
Spin/parity study for high mass sample

$1.55 < M(\pi^+\pi^-\pi^0) < 2.1$ GeV, possibilities $J^P(\lambda) = 2^-(0), 2^+(0), 2^+(2)$.

Define Dalitz parameter $\Delta = \left|\frac{p_{\pi^+} \times p_{\pi^-}}{Q_k^2}\right|^2$, with

p_{π^+}, p_{π^-} pion momenta in $\pi^+\pi^-\pi^0$ frame,

Q_k maximum possible kinetic energy for a pion in the event.



$J^P(\lambda)$	$2^-(0)$	$2^+(0)$	$2^+(2)$
Phase angle ϕ	100	130±18	170±17
Amplitude α	1.0	0.99±0.10	0.97±0.17
Confidence level (%)	$3.6 \cdot 10^{-5}$	64	78

$J^P(\lambda)=2^-(0)$ (π_2): $\Gamma_{\gamma\gamma} Br(\pi^+\pi^-\pi^0) \leq 0.072$ keV.

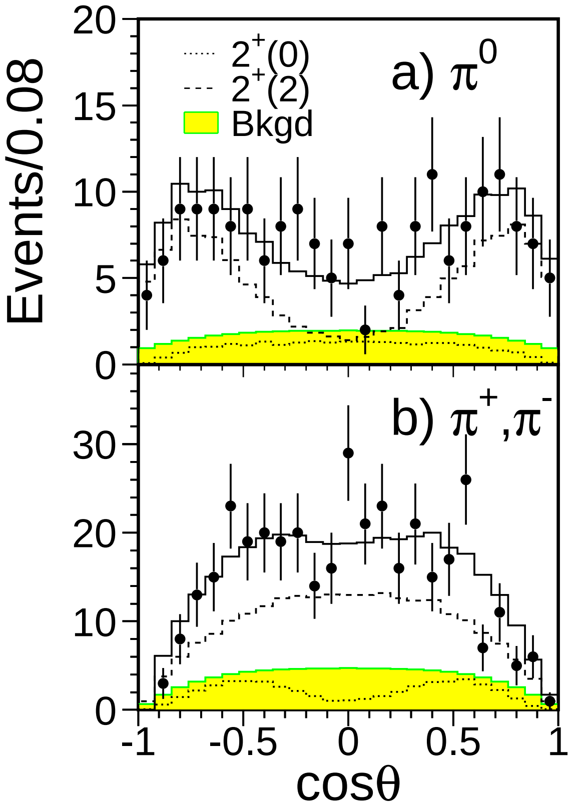
CELLO $\Gamma_{\gamma\gamma}(\pi_2) = 1.3 \pm 0.3 \pm 0.2$ keV

Crystal Ball $\Gamma_{\gamma\gamma} Br(\pi^0\pi^0\pi^0) = 0.251 \pm 0.040 \pm 0.035$ keV;

ARGUS $\Gamma_{\gamma\gamma}(\pi_2) < 0.19$ keV

$\pi^+\pi^-\pi^0$ high mass sample

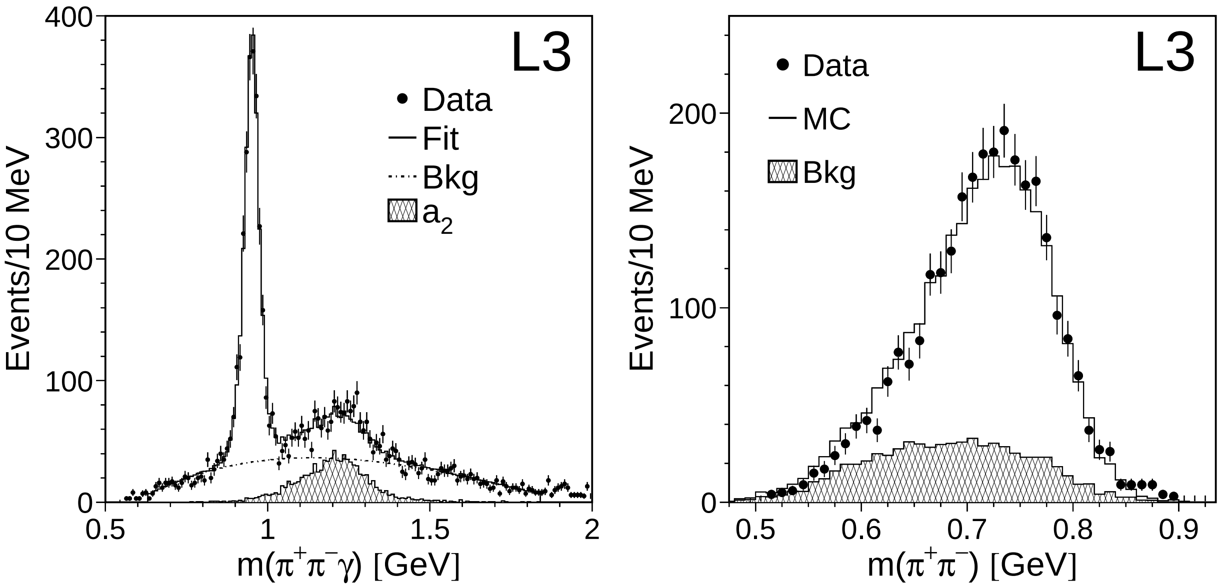
Use $\cos\theta$ distributions again to estimate λ=0,2 contributions



- helicity-2 fraction 0.77±0.12
- High mass peak $\Gamma_{\gamma\gamma}\mathrm{Br}(\rho\pi + f_2\pi)$ = 0.29±0.04±0.02 keV
- Interpret as radial recurrence of a_2:
  OGE-SRM model $M(a_2') = 1740$ MeV C.R. Münz, Nucl. Phys. A 609 (1996) 364.

$\pi^+\pi^-\gamma$ final state Phys. Lett. B 418 (1997) 191.

Untagged $\pi^+\pi^-\gamma$ events:



$\Gamma_{\gamma\gamma}(\eta')\mathrm{Br}(\eta' \to \pi^+\pi^-\gamma) = 1.26 \pm 0.03 \pm 0.06$ keV,
$\Gamma_{\gamma\gamma}(\eta') = 4.17 \pm 0.10 \pm 0.27$ keV

Test possible deviation from Breit-Wigner for ρ due to box anomaly

$$BW(\rho) = \frac{1}{(m_{12}^2 - m_\rho^2) - i m_{12}\Gamma_\rho} + \frac{\xi}{m_{\eta'}^2}\exp(i\phi)$$

Data agrees with (C.L.=37%)

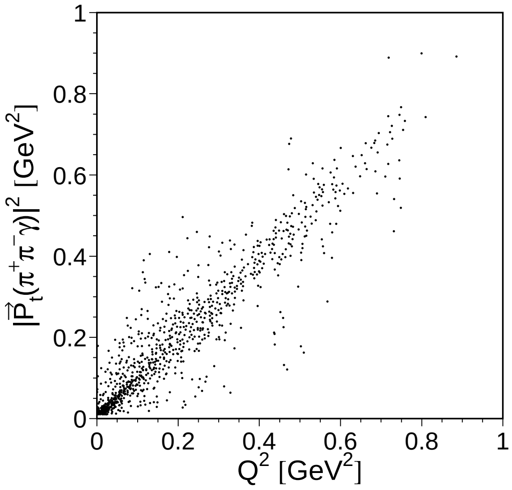
$$\xi = 0$$
$$m_\rho = 766 \pm 2 \text{ MeV}$$
$$\Gamma_\rho = 150 \pm 5 \text{ MeV}$$

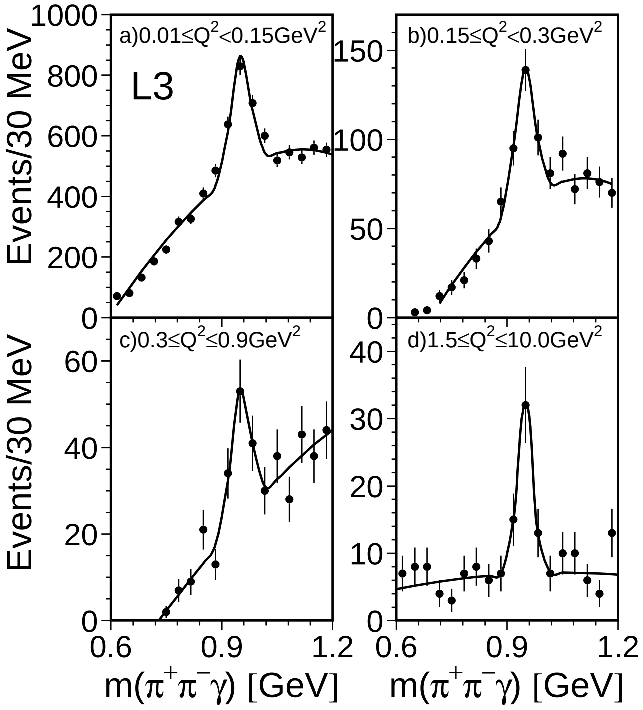
and excludes
S.I. Bityukov *et al.* $\xi = 2.78$ and $\phi = -1.07$: C.L. $\sim 10^{-4}$
M. Benayoun *et al.* $\xi = 0.4$ and $\phi = 3.14$: C.L.=3%

$\pi^+\pi^-\gamma$ final state

Select $\pi^+\pi^-\gamma$ events with non-zero Q^2=max$(-q_1^2, -q_2^2)$

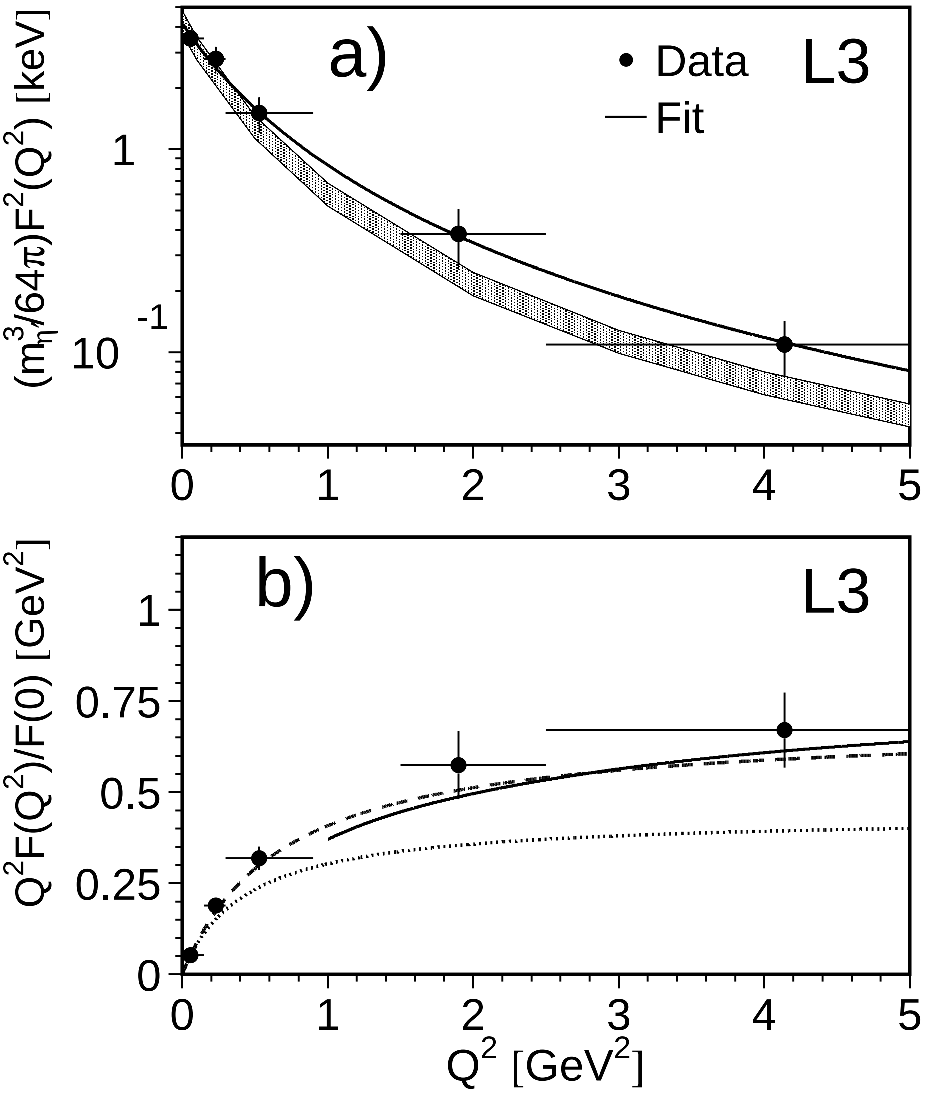
- Single tagged events $1.5 < Q^2 < 10.0$ GeV^2
- Use that $P_t^2(\pi^+\pi^-\gamma) \simeq Q^2$: $0.01 < Q^2 < 0.9$ GeV^2





$\pi^+\pi^-\gamma$ final state

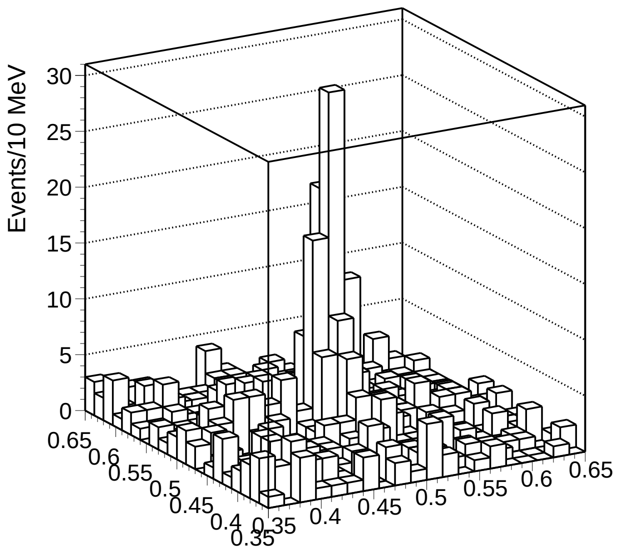
Form factor $F^2 = \Delta\sigma(\text{data}) / \Delta\sigma(\text{MC} : F^2 = 1)$

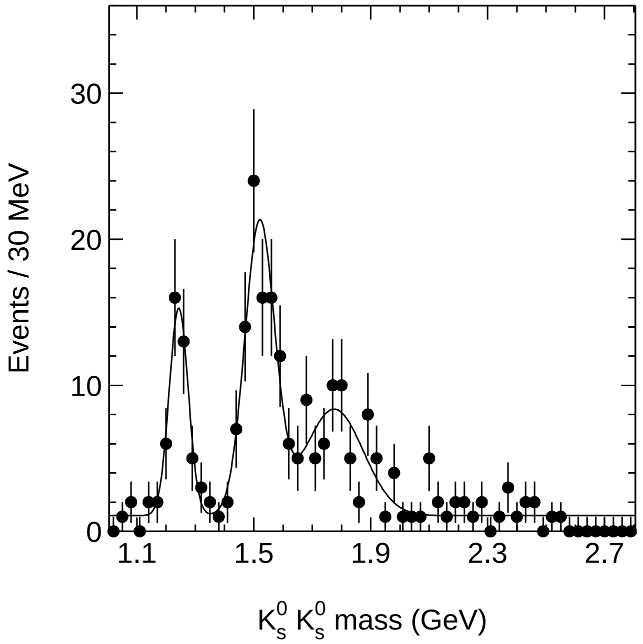


- Fit to VDM model: $F^2 \sim \Gamma_{\gamma\gamma} \cdot 1/(1 + Q^2/\Lambda^2)^2$
  pole $\Lambda = 0.900 \pm 0.046 \pm 0.022$ GeV,
  Meson interaction size $< r^2 >= 6/\Lambda^2 = 0.29 \pm 0.03\ fm^2$
- Better agreement with R. Jacob *et al.* than with Brodsky & Lepage
- Agreement with V. Anisovich *et al.*

$K_s^0 K_s^0$ final state **update of Phys. Lett. B 363 (1995) 118.**

$K_s^0 \to \pi^+\pi^-$: cτ=2.68 cm: secondary vertex.



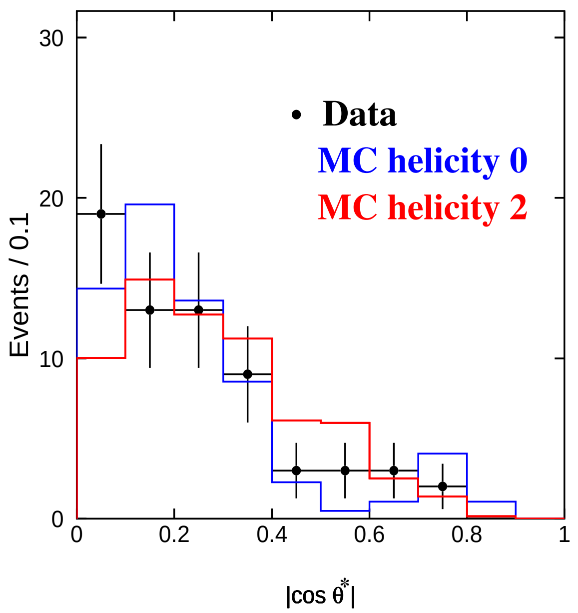


Select exclusive $K_s^0 K_s^0$ final states.
Three peaks:

- $a_2(1320)$ - $f_2(1270)$ destructive interference for $K_s^0 K_s^0$, constructive for K^+K^- H.J. Lipkin, Nucl. Phys. B 7 (1968) 321
- $f_2'(1525)$ peak: Mass 1515±10 MeV, width 112±19 MeV
- 3rd peak with mass 1760±14 MeV, width 119±26 MeV, statistical significance 3 standard deviations

$K^0_s K^0_s$ final state

Study helicity of f_2': λ=0 or λ=2.
$\Gamma_{\gamma\gamma}(f_2') \cdot \mathrm{Br}(f_2' \to K\bar{K}) = 0.198 \pm 0.040 \pm 0.050$ keV if λ=0
$\Gamma_{\gamma\gamma}(f_2') \cdot \mathrm{Br}(f_2' \to K\bar{K}) = 0.093 \pm 0.018 \pm 0.022$ keV if λ=2



λ=2 is favored with C.L.=0.15 against C.L.=$2 \cdot 10^{-4}$

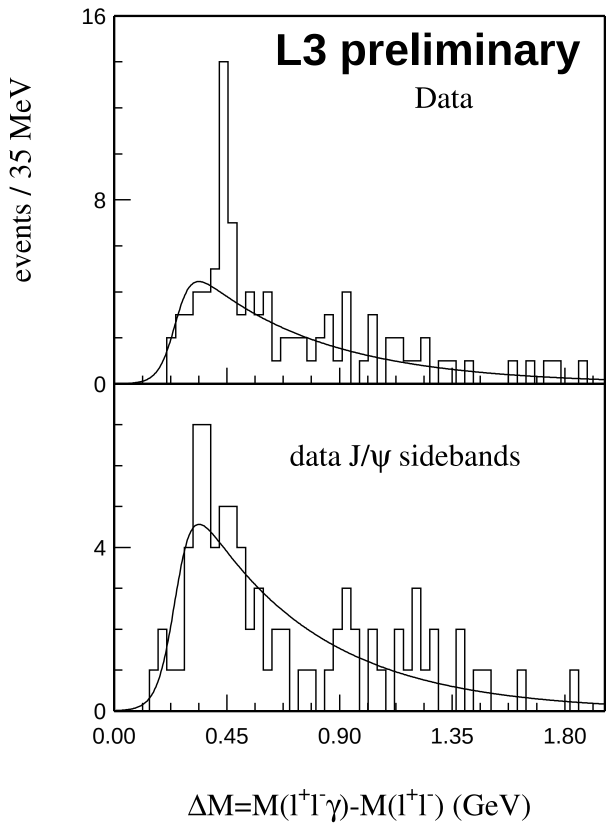
Mixing angle θ between singlet and octet members of tensor meson nonet:

$$\frac{\Gamma_{\gamma\gamma}(f_2')}{\Gamma_{\gamma\gamma}(f_2)} = \frac{m^3_{f_2'}}{m^3_{f_2}} \cdot \frac{(\cos\theta - 2\sqrt{2}\sin\theta)^2}{(\sin\theta + 2\sqrt{2}\cos\theta)^2} \tag{1}$$

Data $\theta = (29.4^{+1.4}_{-1.6})^\circ$
Ideal mixing $\theta = 35.3^\circ$
Gell-Mann - Okubo mass formula $\theta = (28 \pm 3)^\circ$

γ J/ψ final state

Look for the $J^{PC} = 2^{++}$ charmonium resonance χ_{c2}:
Select γ J/ψ events, J/$\psi \to e^+e^-$ or $\mu^+\mu^-$ with mass cut
$2.85 < M(l^+l^-) < 3.35$ GeV.
Plot $\Delta M = M(l^+l^-\gamma) - M(l^+l^-)$: $M(\chi_{c2}) - M(\mathrm{J}/\psi)$= 0.459 GeV
Use J/ψ sidebands for background shape



12 signal events above a background of 11

$$\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.99^{+0.43}_{-0.37} \pm 0.36 \text{ keV}$$

Better agreement with CLEO $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.08 \pm 0.30 \pm 0.26$ keV,
than with E760 $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.32 \pm 0.08 \pm 0.05$ keV measurement.

Conclusions

- Less $\pi^+\pi^-\pi^+\pi^-$ and $\rho^0\rho^0$ formation above $W_{\gamma\gamma} = 3$ GeV than expected from Phojet or Pythia event generators
- $a_2(1320) \rightarrow \pi^+\pi^-\pi^0$ dominated by $J^{PC} = 2^{++}$ helicity 2 wave, $\Gamma_{\gamma\gamma}(a_2) = 0.98 \pm 0.05 \pm 0.09$ keV.
  Resonance with $M \simeq 1750$ MeV and dominated by $J^{PC} = 2^{++}$ helicity 2 wave observed with $\Gamma_{\gamma\gamma}\mathrm{Br}(\rho\pi + f_2\pi) = 0.29 \pm 0.04 \pm 0.02$ keV,
  no evidence for $J^P = 2^-$ resonance formation
- η' observed in $\pi^+\pi^-\gamma$ final state with
  $\Gamma_{\gamma\gamma}(\eta') = 4.17 \pm 0.10 \pm 0.27$ keV,
  η' transition form factor measured for $0.01 < Q^2 < 10.0$ GeV^2,
  VDM pole mass $\Lambda = 0.900 \pm 0.046 \pm 0.022$ GeV
- In $K_s^0 K_s^0$ final state we measure
  $\Gamma_{\gamma\gamma}(f_2') \cdot \mathrm{Br}(f_2' \rightarrow K\bar{K}) = 0.093 \pm 0.018 \pm 0.022$ keV
  for a helicity 2 wave,
  and we observe a 3 standard deviation peak
  at $M(K_s^0 K_s^0) \simeq 1750$ MeV.
- $\Gamma_{\gamma\gamma}(\chi_{c2}) = 0.99^{+0.43}_{-0.37} \pm 0.36$ keV