Resonance Production in Two-Photon Collisions at LEP with the L3 detector.

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$e^+e^- \to e^+e^-\pi^+\pi^-\pi^+\pi^-$

- ⇨ Present status
- ⇨ L3 data
- ⇨ Results for $W_{\gamma\gamma} > 3$ GeV
- ⇨ Spin-Parity-Helicity for $W_{\gamma\gamma} < 3$ GeV

$e^+e^- \to e^+e^-\mathrm{K}^0_\mathrm{S}\,\mathrm{K}^\pm\pi^\mp$ and $\eta\,\pi^+\pi^-$

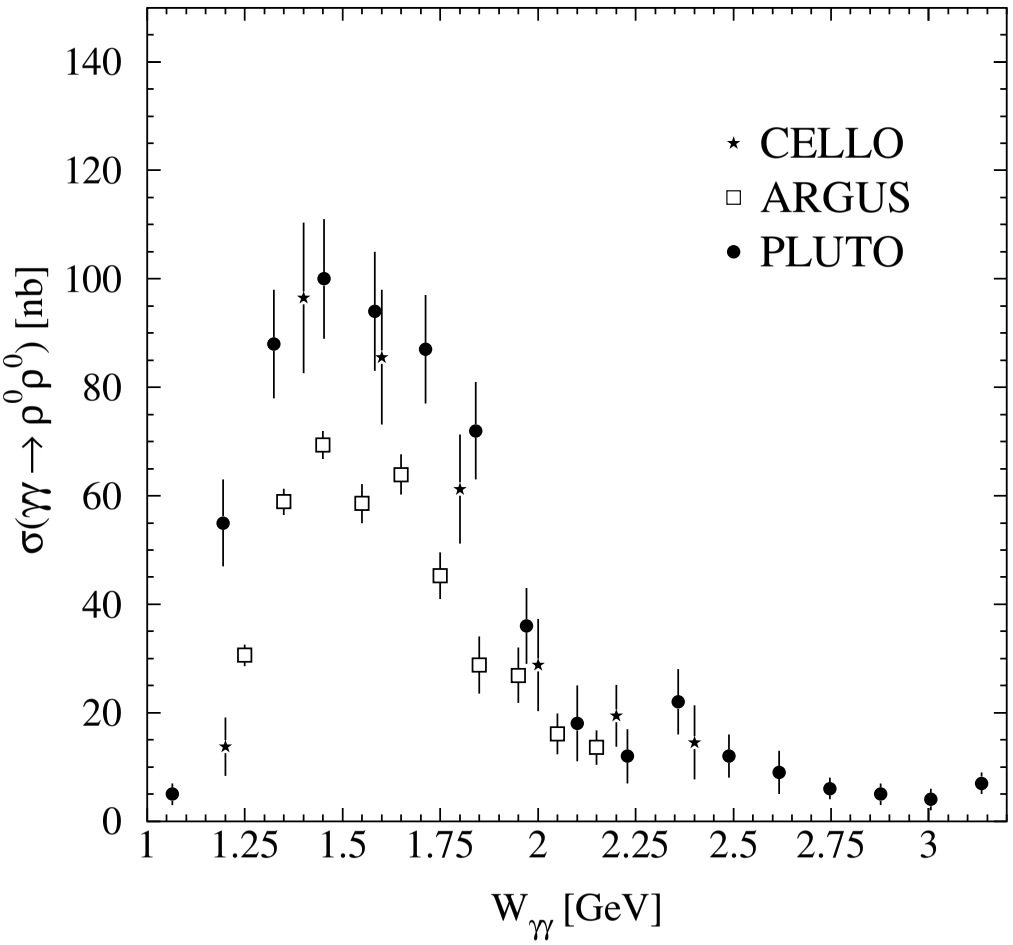
- ⇨ Present status of η and f_1 states
- ⇨ L3 data
- ⇨ Evidence for $\eta\,(1440)$, $\mathrm{f}_1(1285)$ and $\mathrm{f}_1(1420)$ in $\mathrm{K}^0_\mathrm{S}\,\mathrm{K}^\pm\pi^\mp$
- ⇨ Evidence for $\mathrm{f}_1(1285)$ in $\eta\,\pi^+\pi^-$
- ⇨ Two-photon width of $\eta\,(1440)$ and tests of gluonium.

Conclusions

Many thanks to O. Fedin, I. Vodopianov and M. Kienzle

$$e^+e^- \longrightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$$

- A large cross section for the quasi-real two-photon reaction $\gamma\gamma \longrightarrow \rho^0\rho^0$ near threshold has been observed by TASSO, MARK II, CELLO, PLUTO, TPC/2γ and ARGUS Collaboration.
- The highest statistics was collected by ARGUS : 5181 events for $1.1 < W_{\gamma\gamma} < 2.3$ GeV



Comparisons with $\gamma\gamma \longrightarrow \rho^+\rho^-$ cross sections indicate that this is not a single resonance.

Selection of $\gamma\gamma \to \pi^+\pi^-\pi^+\pi^-$ Events in L3

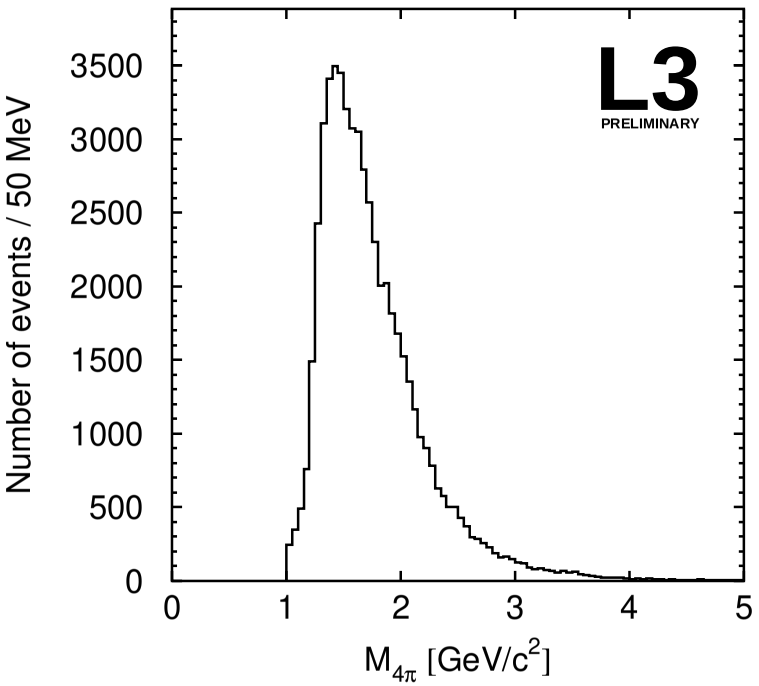
1996 - 1999 data at $\sqrt{s} = 160 \div 200$ GeV

Total integrated luminosity $\mathcal{L}_{e}^{+}e^{-} = 466.2$ pb^{-1}

Event selection:

- four charged particles, with net charge zero
- tracks from the interaction vertex
- no photon candidates
- $(\Sigma \vec{p_t})^2 \leqslant 0.02$ GeV$^2/c^2$

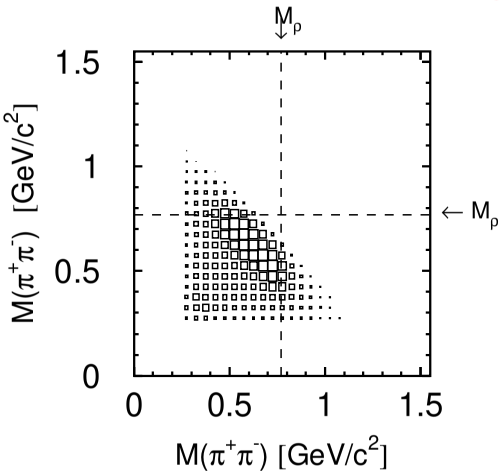
A sample of 51477 events is obtained,
49519 events with $1.1 < W_{\gamma\gamma} < 3.$ GeV
1146 events with $W_{\gamma\gamma} > 3.$ GeV.

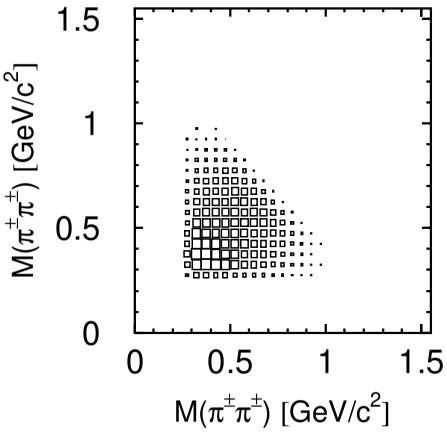


Pion pair spectra

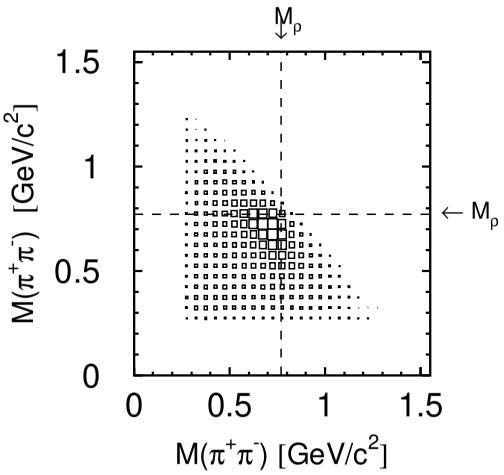
unlike−sign like−sign

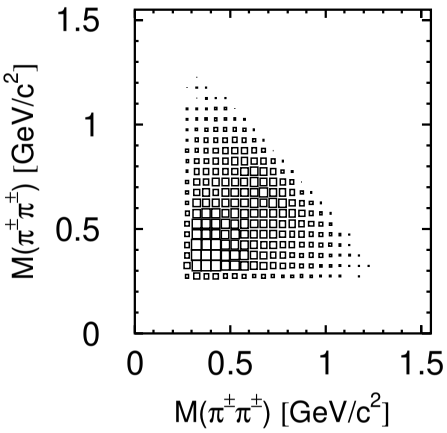
$1.2\ \mathrm{GeV} < W_{\gamma\gamma} < 1.4\ \mathrm{GeV}$



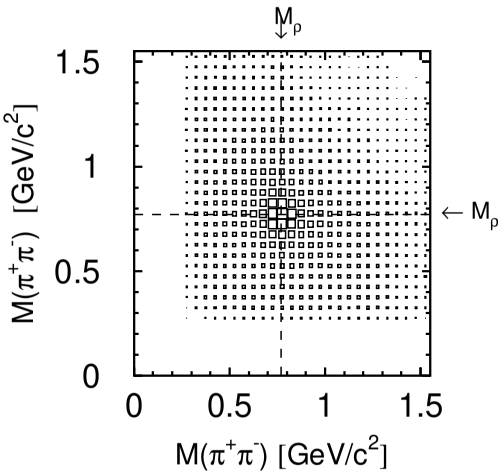


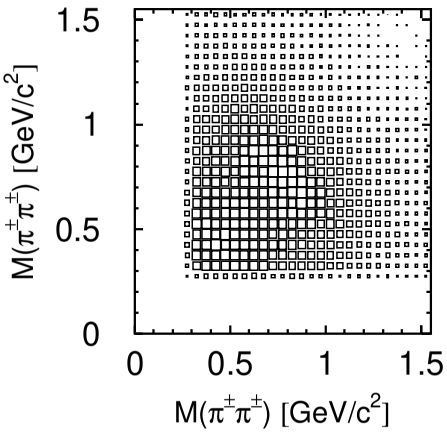
$1.4\ \mathrm{GeV} < W_{\gamma\gamma} < 1.6\ \mathrm{GeV}$





$1.6\ \mathrm{GeV} < W_{\gamma\gamma} < 3.0\ \mathrm{GeV}$

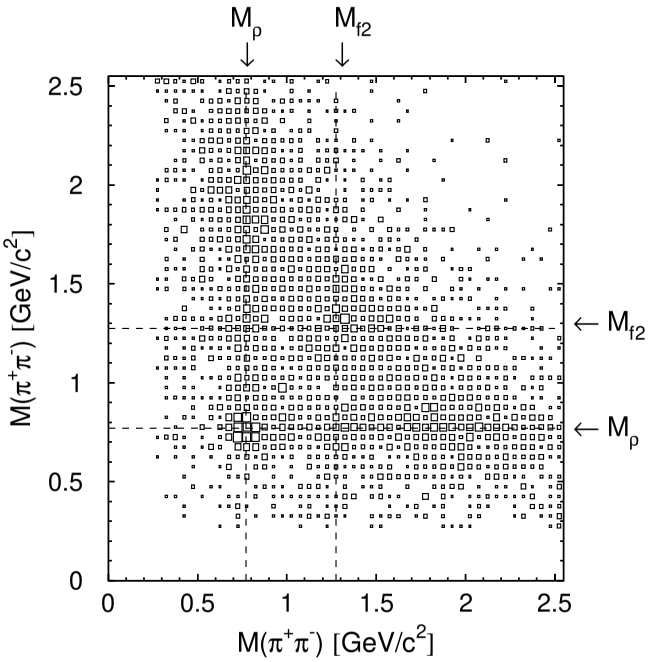




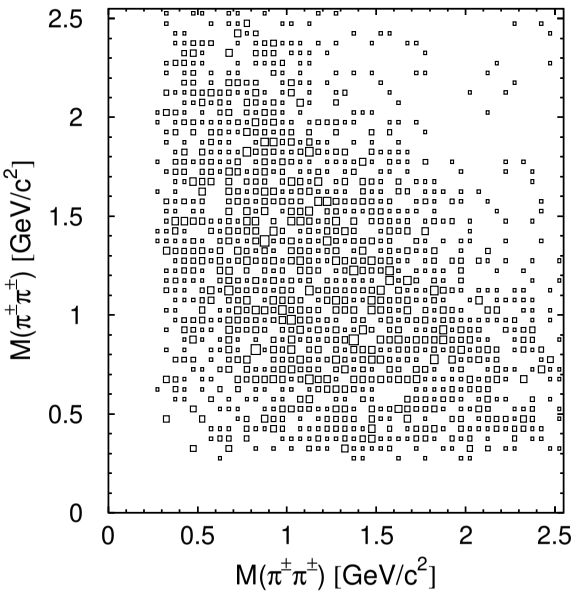
High mass data $W_{\gamma\gamma} > 3$ GeV

Two-pion mass distribution of the unlike-sign combinations for $W_{\gamma\gamma} > 3$ GeV show clear $\rho^0(770)$ and $f_2(1270)$ signals.

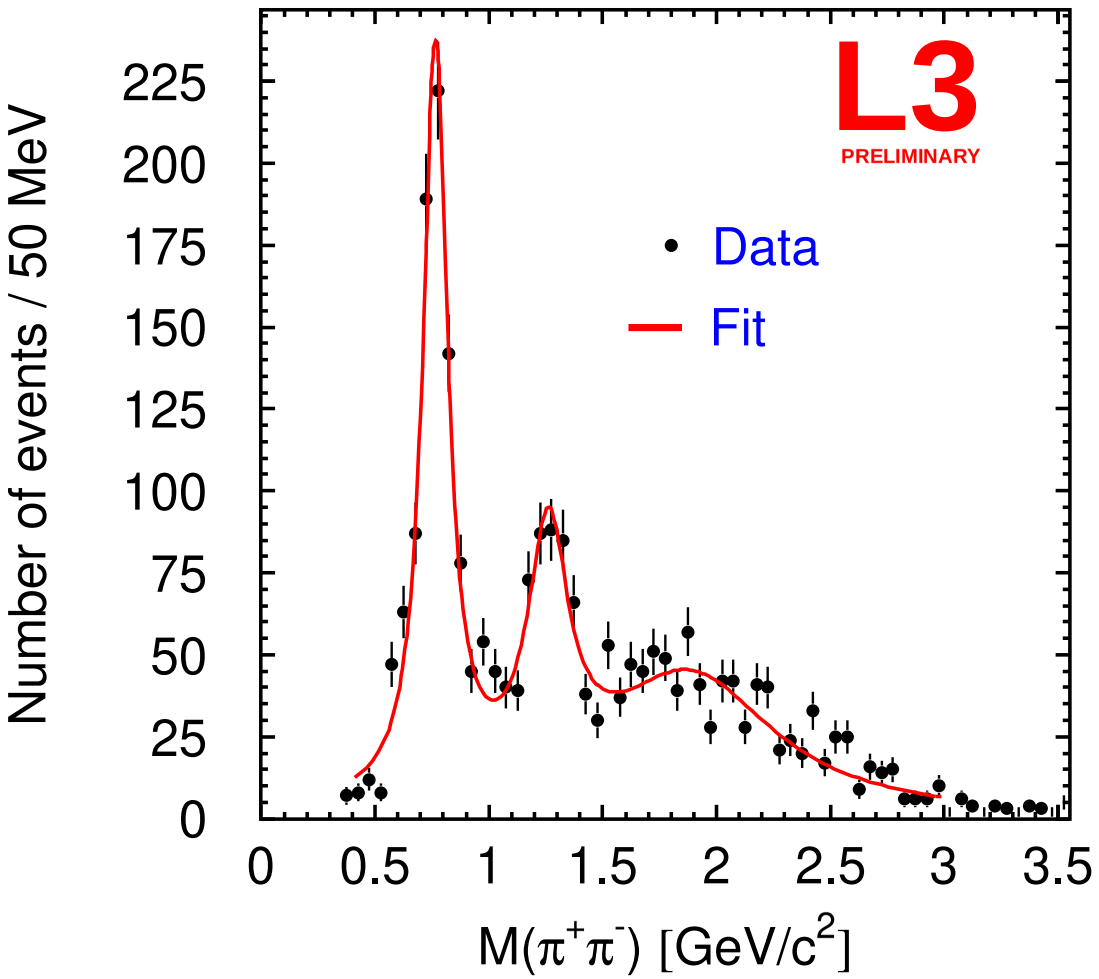
Unlike-sign charge two-pion mass combinations



Like-sign charge two-pion mass combinations



High mass data $W_{\gamma\gamma} \geq 3$ GeV



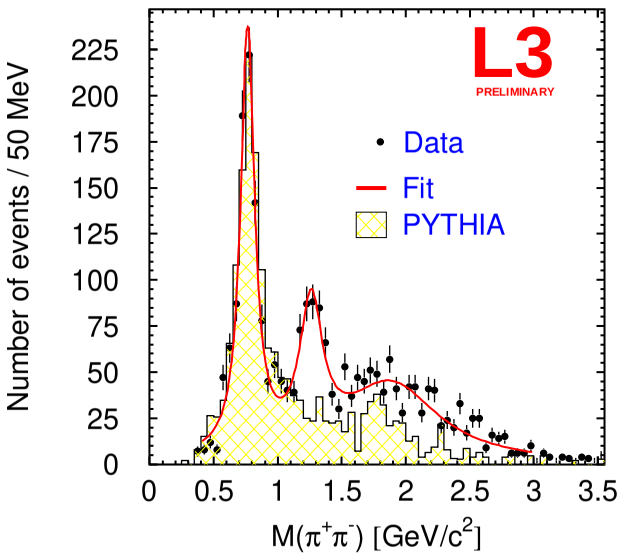
Events with $(\Sigma\vec{p}_t)^2 \leqslant 0.02$ GeV$^2/c^2$. Fitted by three Breit-Wigner functions.

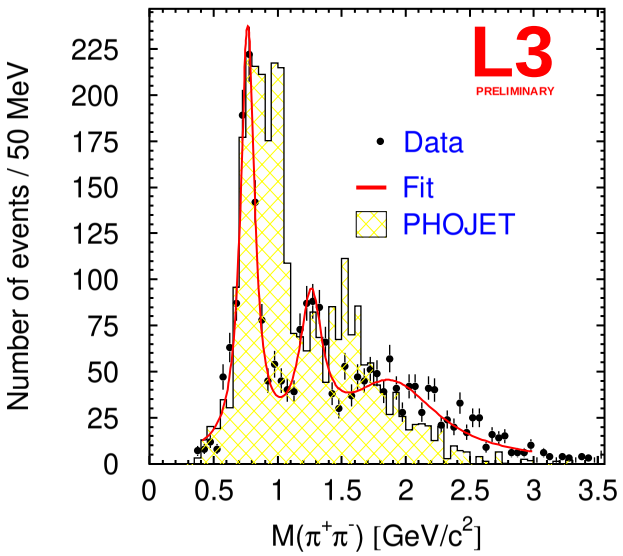
Fit result

$$m_\rho = 765 \pm 3 \text{ MeV} \quad \Gamma_\rho = 129 \pm 7 \text{ MeV}$$

$$m_{f2} = 1261 \pm 9 \text{ MeV} \quad \Gamma_{f2} = 217 \pm 28 \text{ MeV}$$

High mass data $W_{\gamma\gamma} \geq 3$ GeV





Neither PYTHIA nor PHOJET reproduce well the data

$W_{\gamma\gamma} < 3$ GeV Spin-Parity-Helicity Analysis

The possible final states in no-tag $\gamma\gamma$ reaction are :

even spins $J^P = 0^{\pm}, 2^{\pm}, 4^{\pm} \ldots$ with helicity $J_z = 0$

$J^P = 2^+, 3^+, 4^+ \ldots$ with helicity $J_z = \pm 2$

Formalism first used by TASSO :

- $2\pi^+2\pi^-$ non-resonant (PS)
- $\rho^0\pi^+\pi^-$ isotropic .
- $\rho^0\rho^0$ final states restricted to $L = 0$ and $L = 1$:
  $(J^p, J_z) = 0^+, 0^-, (2^+, \pm 2), (2^+, 0), (2^-, 0)$
  $(2^-, 0)$ can have a total spin S=1 or S=2.
- All final states are produced incoherently
- Fit for each mass bin, with N events, with parameters λ_j

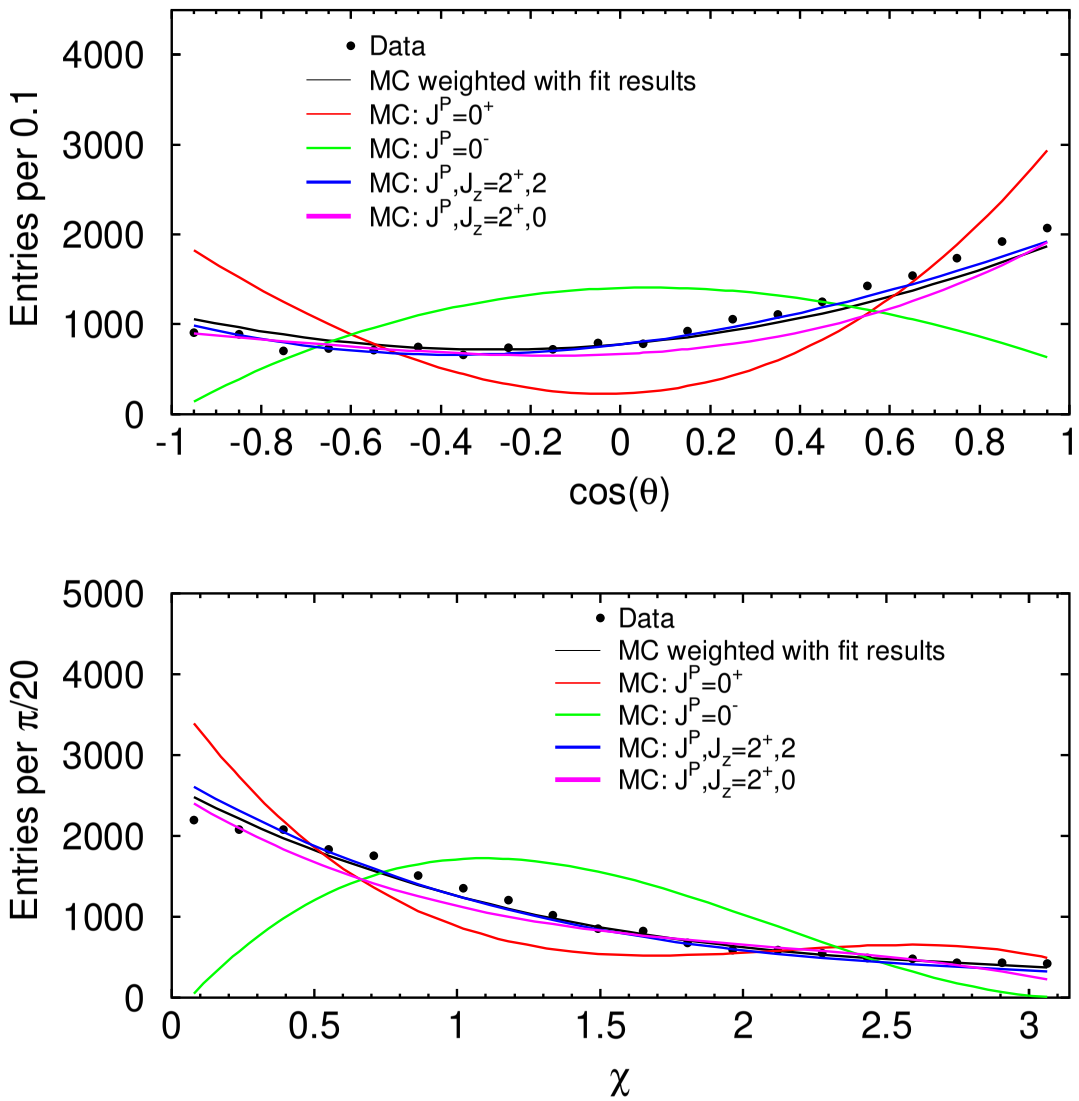
$$\log \Lambda = \sum_{i=1}^{N} \left[\log\left(\sum_j \lambda_j \frac{|g_j(\xi_i)|^2}{\overline{|g_j|^2}} \right) - \sum_j \lambda_j \right]$$

- $g_{\pi^+\pi^-\pi^+\pi^-} = 1$
  $g_{\rho^0\pi^+\pi^-} = \frac{1}{2}\Big\{ BW(m_{12}) + BW(m_{34}) + BW(m_{14}) + BW(m_{32}) \Big\}$
  $g^{J^p J_z}_{\rho^0\rho^0}(\xi) = \frac{1}{\sqrt{2}}\Big\{ BW(m_{12})BW(m_{34})\Psi^{J^p J_z LS}(\xi)$
  $+ BW(m_{14})BW(m_{32})\Psi^{J^p J_z LS}(\xi) \Big\}$
- $\xi = (m^2_{12}, m^2_{34}, \theta_\rho, \theta^{12}_\pi, \phi^{12}_\pi, \theta^{34}_\pi, \phi^{34}_\pi)$, set of seven variables to describe the four particles final state

Angular distributions, results of the fit

The data are well described by the model. Example :

$$1.6 < W_{\gamma\gamma} < 1.8 \text{ GeV}$$



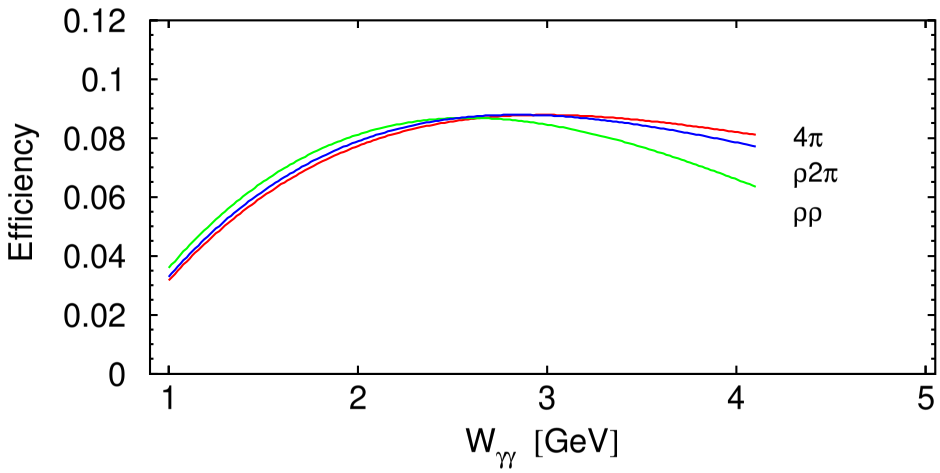
θ is the opening angle between two positive charged pions and the χ is the angle between the decay planes of the two ρ^0.

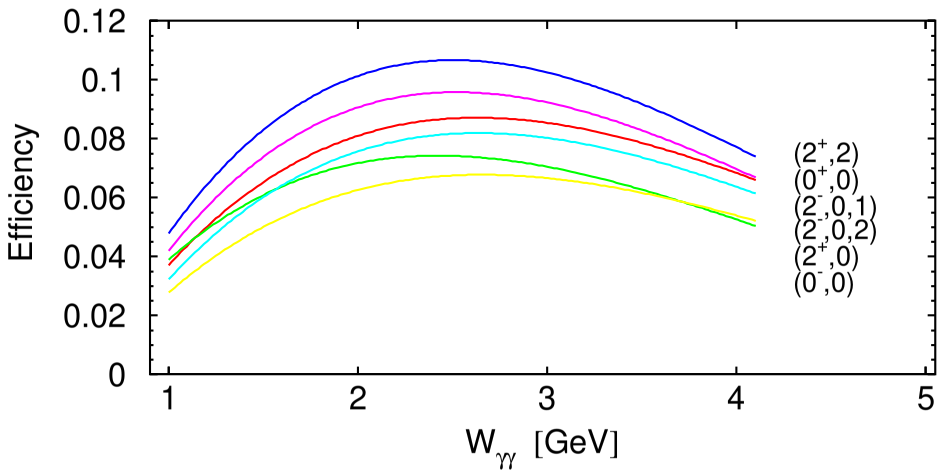
Spin-Parity-Helicity Analysis

The cross section for the formation of a partial wave j is:

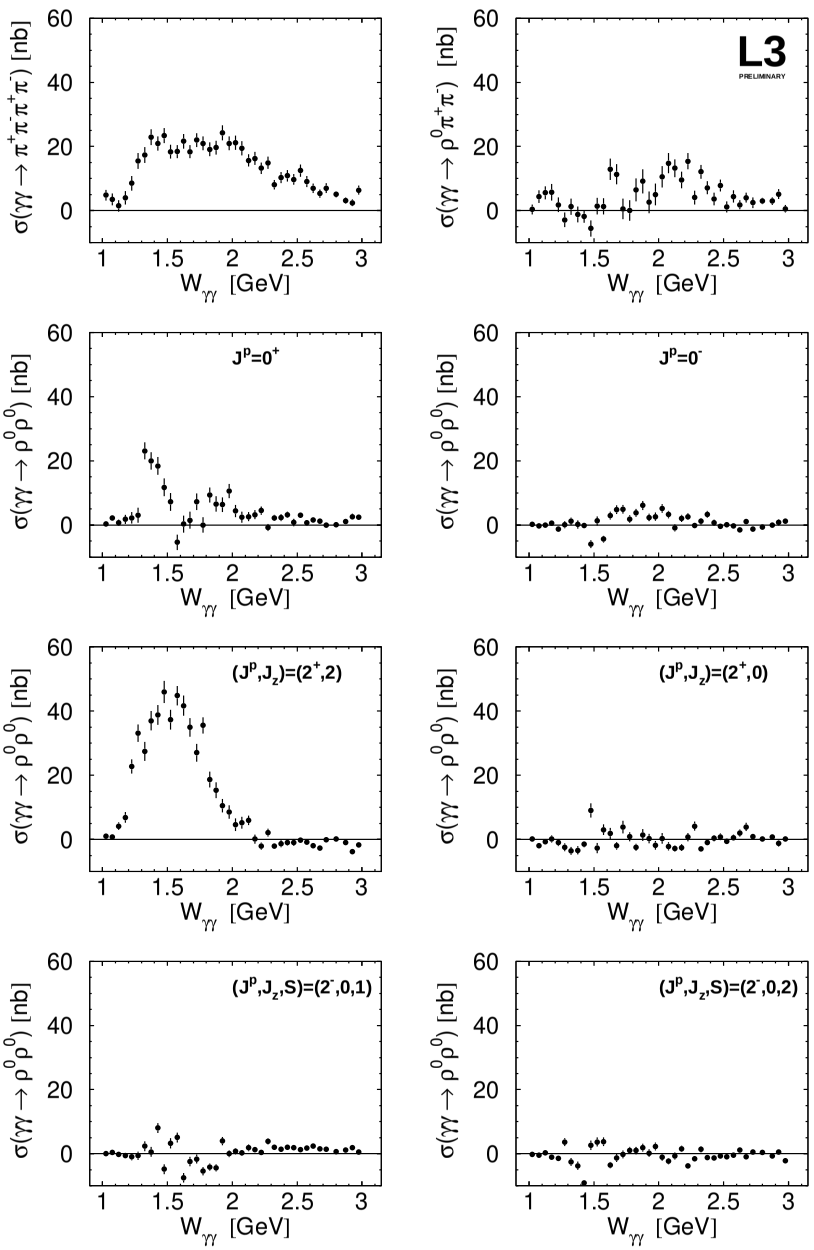
$$\sigma_{\gamma\gamma\to j} = \frac{N\lambda_j}{\mathcal{L}_{e^+e^-}\varepsilon(W_{\gamma\gamma})\frac{\Delta\mathcal{L}_{\gamma\gamma}}{\Delta W_{\gamma\gamma}}\Delta W_{\gamma\gamma}}$$

The efficiency ε includes detector acceptance, trigger efficiency and selection requirements.





Result of 8-parameter fit

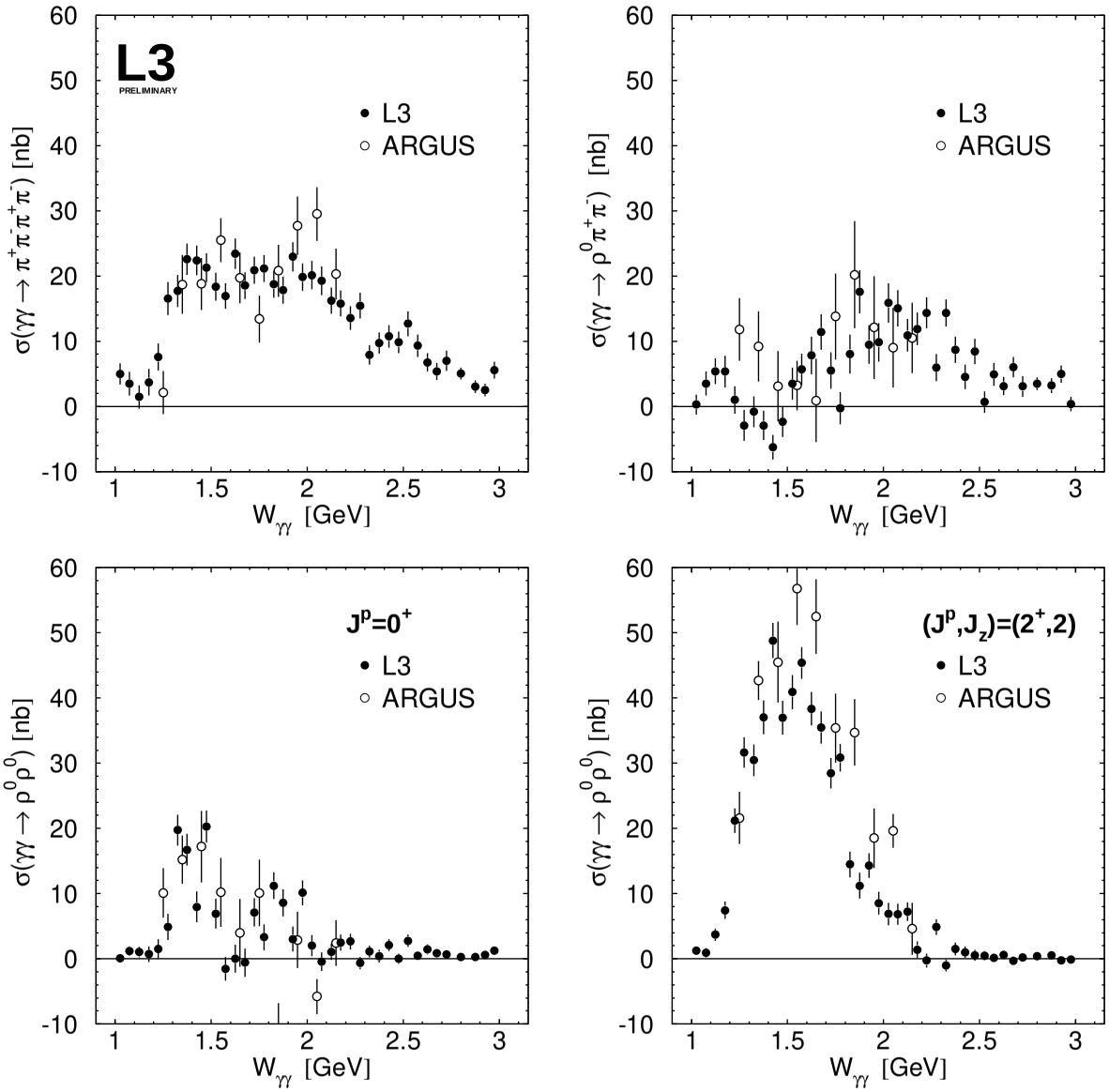


- Dominance of the partial wave $(J^p, J_z) = (2^+, 2)$
- Contribution of $J^p = 0^+$
- Negative parity and $(2^+, 0)$ states consistent with zero

Result of 4-parameter fit

The maximum likelihood fit repeated with the assumption that only four states are present in the data sample:

4π, $\rho^0 2\pi$ and $\rho^0\rho^0$ with $(J^p, J_z) = 0^+, (2^+, 2)$



❑ Cross sections are similar to the ones obtained by ARGUS.

1. PDG: $K^0_S K^{\pm}\pi^{\mp}$ and $\eta\pi^+\pi^-$ states

Pseudoscalars: $I^G(J^{PC}) = 0^+(0^{-+})$

$\eta(1440)$:

M = 1400 – 1470 MeV Γ = 50 – 80 MeV

Seen in $\pi p,\ p\bar{p},\ J/\psi$ *radiative decay*

Has never been seen in $\gamma\gamma$ $\Rightarrow$ gluonium ???

1. $K^0_S K^{\pm}\pi^{\mp}$ decay :

$\eta_H \rightarrow K^*K$ M $= 1475 \pm 5$ MeV, $\Gamma = 81 \pm 11$ MeV

$\eta_L \rightarrow a_0\pi$ M $= 1418.4 \pm 1.4$ MeV, $\Gamma = 58 \pm 4$ MeV

2. $\eta\pi^+\pi^-$ decay :

η_L ? M $= 1405 \pm 5$ MeV $\Gamma = 56 \pm 7$ MeV

$\eta(1295)$:

M = 1297.0 $\pm$ 2.8 MeV Γ = 53 $\pm$ 6 MeV

Seen in $\pi p \rightarrow \eta\pi\pi$

Has never been seen in $\gamma\gamma$

2. PDG: $\mathrm{K}^0_{\mathrm{S}}\,\mathrm{K}^{\pm}\pi^{\mp}$ and $\eta\,\pi^+\pi^-$ states

Axial-Vectors: $I^G(J^{PC}) = 0^+(1^{++})$

$f_1(1285)$

M = 1281.9 ± 0.6 MeV Γ = 24.0 ± 1.2 MeV

Seen in

$\gamma\gamma^*,\ \pi p,\ pp,\ p\bar{p},\ Kp,\ J/\psi\ radiative\ decay$

1. $\mathrm{K}^0_{\mathrm{S}}\,\mathrm{K}^{\pm}\pi^{\mp}$ decay: (9.0 ± 0.4) %

2. $\eta\,\pi^+\pi^-$ decay: (52 ± 16) % ; $a_0(980)\pi$ (36 ± 7) %

$f_1(1420)$

M = 1426.3 ± 1.1 MeV Γ = 55.5 ± 2.9 MeV

Seen in

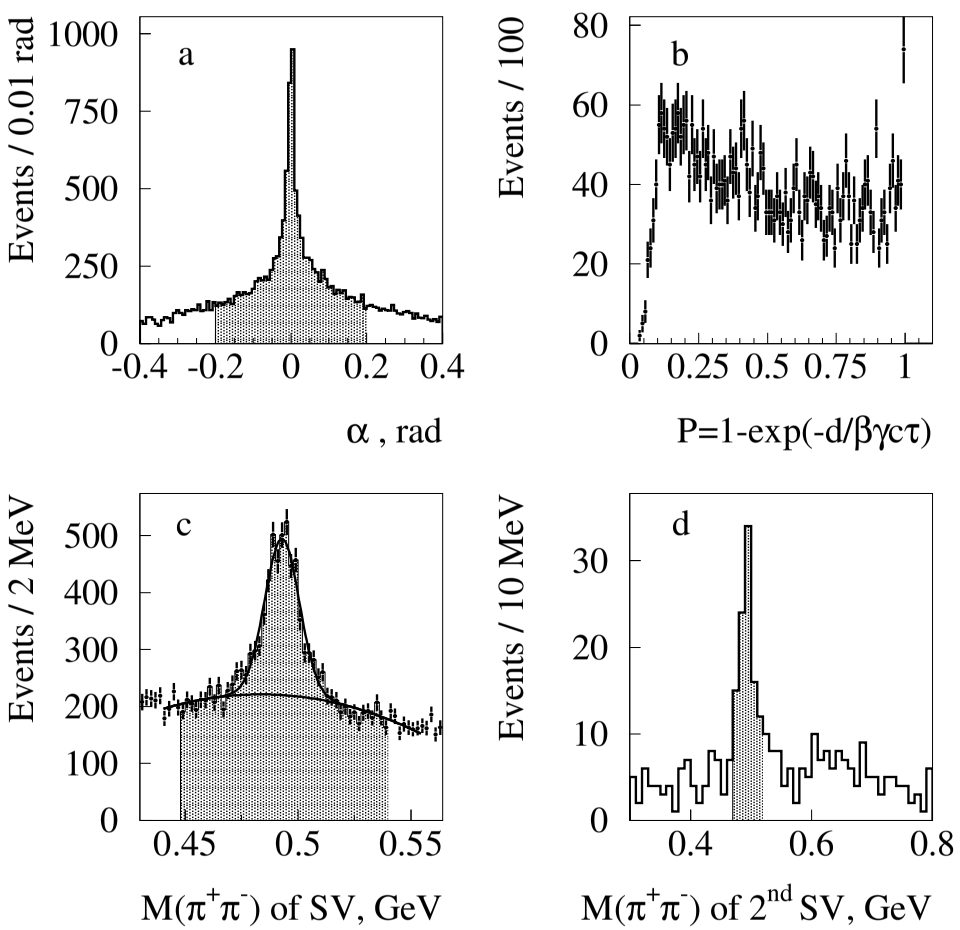
$\gamma\gamma^*,\ \gamma^*\gamma^*,\ \pi p,\ p\bar{p},\ Kp,\ J/\psi\ radiative\ decay$

1. $\mathrm{K}^0_{\mathrm{S}}\,\mathrm{K}^{\pm}\pi^{\mp}$ decay: K^*K dominant

2. $\eta\,\pi^+\pi^-$ decay: possibly seen

L3 : K^0_S selection

- Final K^0_S state: $\pi^+\pi^-$
- Secondary vertex (SV): 3 mm$\leq \mathrm{R}_{XY} \leq$200 mm
- Angle α between K^0_S momentum and K^0_S flight direction in transverse plane is within 0.2 rad
- Lifetime cut for K^0_S: $1 - exp(-d/\beta\gamma c\tau) \leq 0.99$
- Mass $K^0_S = 0.46$–0.53 GeV ; No 2^{nd} K^0_S
- dE/dx identification of pions

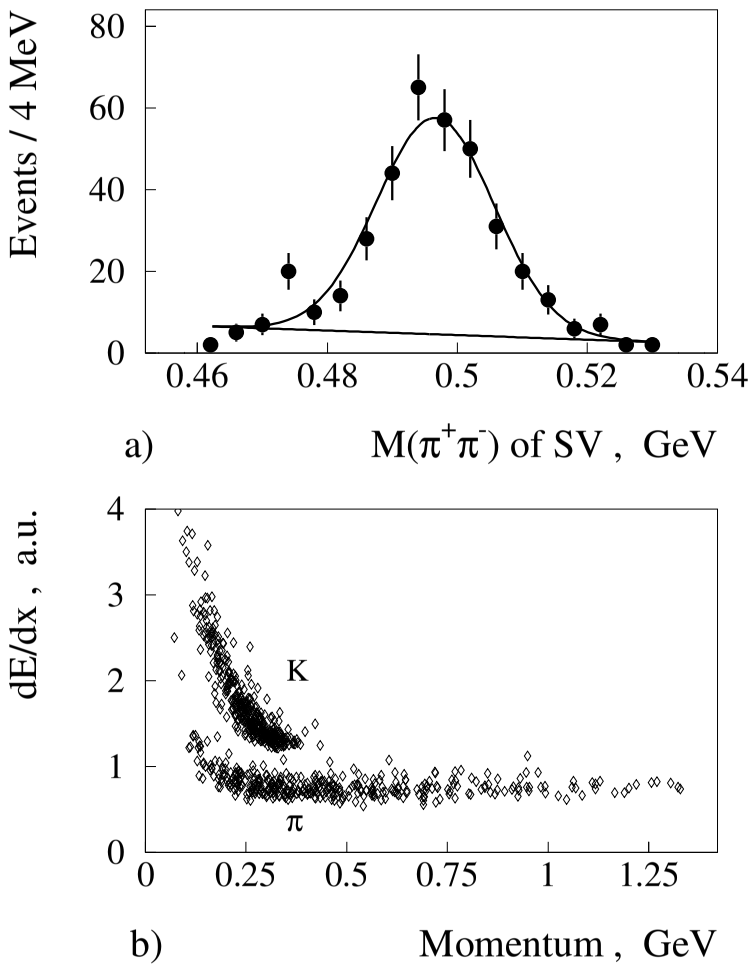


L3 data : $K^0_S\, K^{\pm}\pi^{\mp}$ selection

1997 - 1999 data at $\sqrt{s} = 183 \div 202$ GeV
Total integrated luminosity $\mathcal{L}_{e^+e^-} = 449$ pb^{-1}

- Events: 4 good tracks ; No photons
- $K^0_S \to \pi^+\pi^-$ at secondary vertex
- dE/dx identification of $\pi^{\pm}K^{\mp}$ at primary vertex:

CL(Kπ)>1%, CL($\pi\pi$)<10^{-3}



K^0_S : M=496 MeV, σ=9 MeV.

$K^0_S\, K^{\pm}\pi^{\mp}$ mass spectrum

$$P_t^2 = (\sum \vec{p_t})^2 < 0.2\ \mathrm{GeV}^2 \quad \text{(290 events)}$$

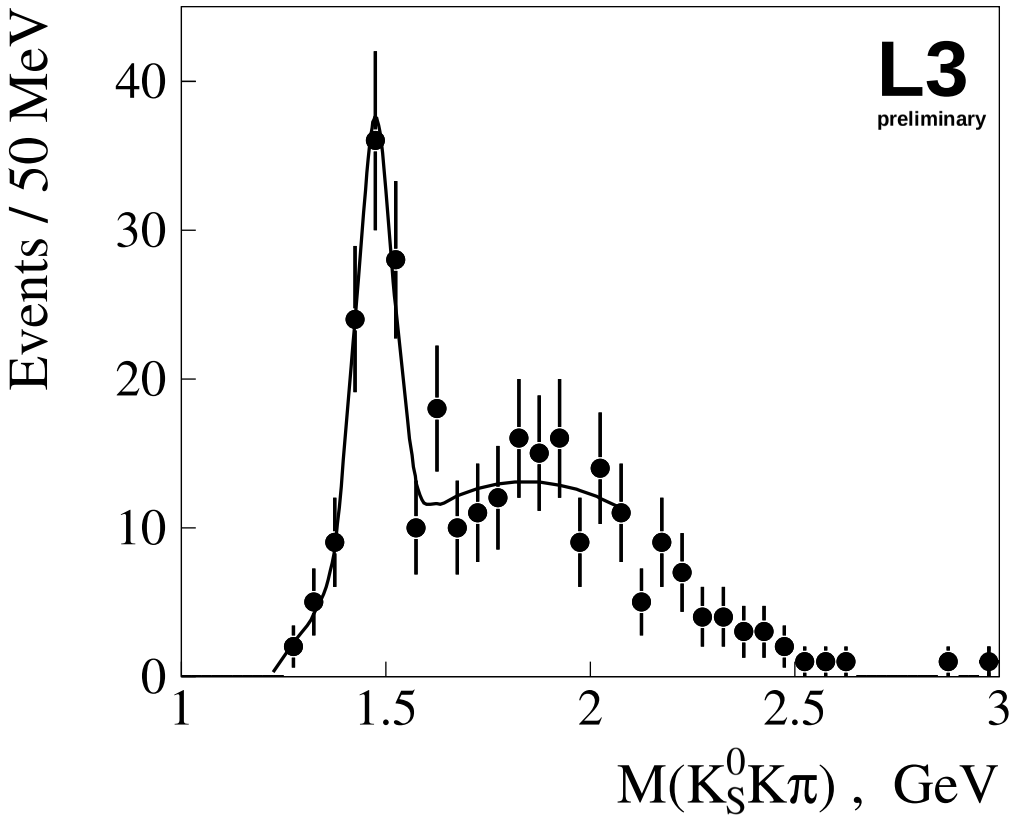
Fit :

Gaussian and second order polynomial background :

Number of events $= 66 \pm 11$

M $= 1473 \pm 8$ MeV

$\Gamma = \quad 97 \pm 16$ MeV (Experimental resolution 20 MeV)

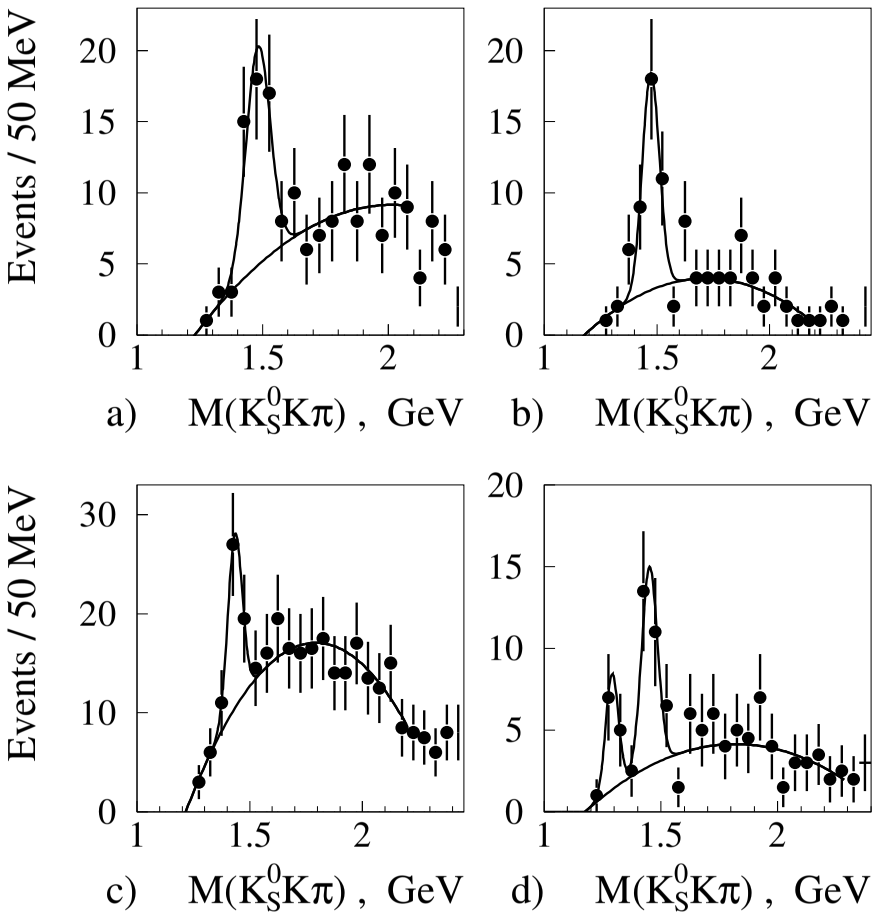


These parameters correspond to η_H

$K^0_S\,K^{\pm}\pi^{\mp}$: Q^2 bins

$$Q^2 \simeq P_t^2$$

$Q^2 \simeq 0 \Rightarrow$ spin 0 ; $Q^2 >> 0 \Rightarrow$ spin 1 (Landau-Yang)



	P_t^2(GeV^2)	N_{events}	M (MeV)
a	0–0.02	37 ± 9	1481 ± 12
b	0.02–0.2	28 ± 7	1473 ± 11
c	0.2–1	29 ± 9	1435 ± 10
d	1–7	21 ± 6	1452 ± 11
d	1–7	10 ± 4	1290 ± 12

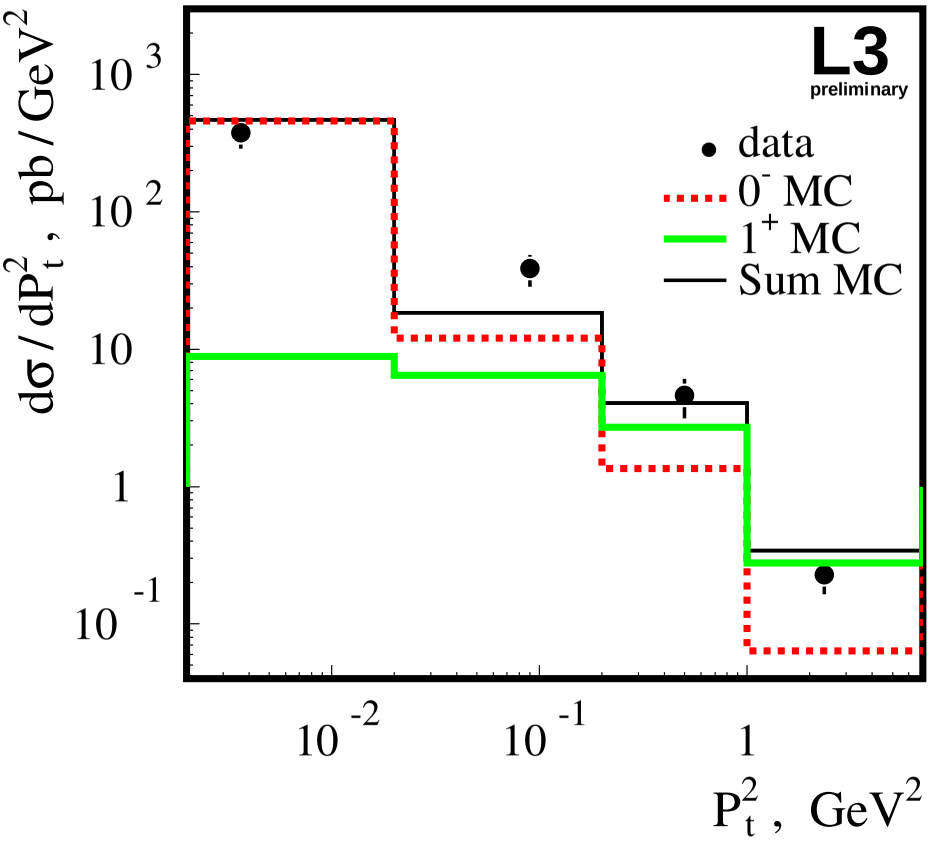
At high Q^2 both $f_1(1285)$ and $f_1(1420)$ are seen .

$\mathrm{K}^0_\mathrm{S}\,\mathrm{K}^\pm\pi^\mp$: $d\sigma/d\mathrm{P}_t^2$

Fit of the $d\sigma/d\mathrm{P}_t^2$ dependence :

Resonance(s)	Kolmogorov test CL
pseudoscalar $\eta\,(1440)$ only	$< 10^{-5}$
vector meson $\mathrm{f}_1(1420)$ only	$< 10^{-5}$
sum: $\eta\,(1440)$+$\mathrm{f}_1(1420)$	30%

The result of $\eta\,(1440)$+$\mathrm{f}_1(1420)$ fit is shown:



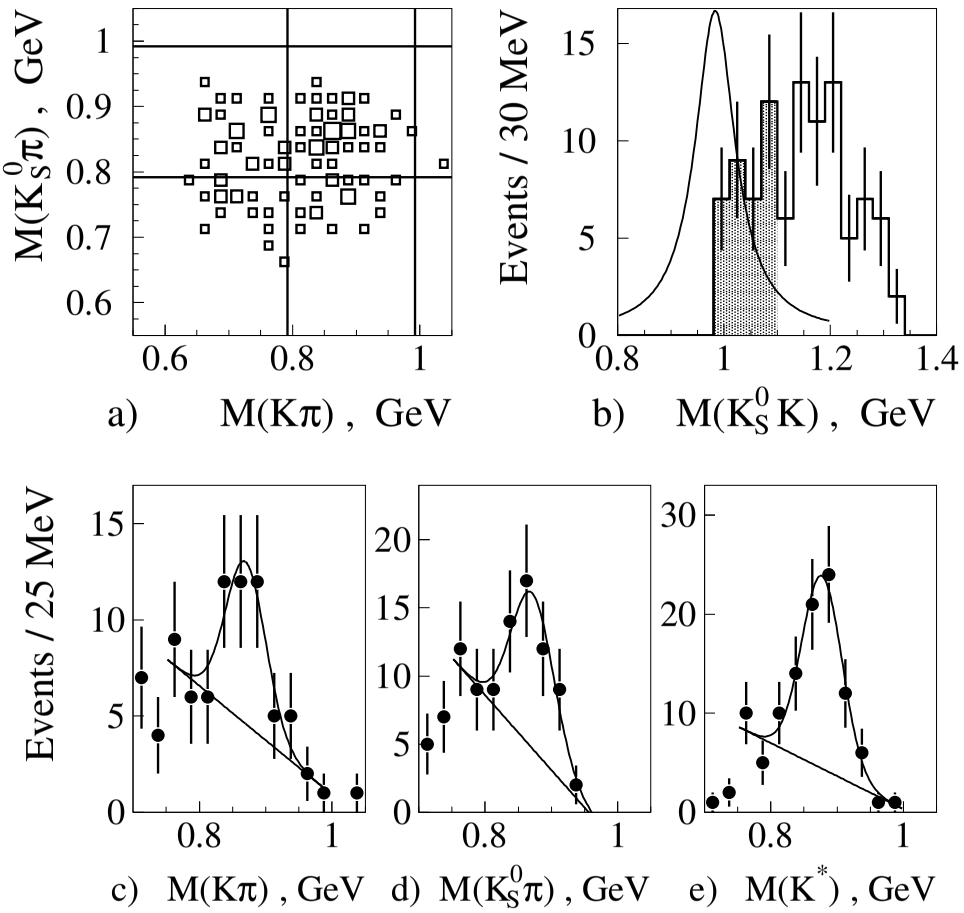
$\Rightarrow$ Presence of both 0^- and 1^+ in the peak

$\eta\,(1440) \Rightarrow 72 \pm 9$ events,

$\mathrm{f}_1(1420) \Rightarrow 43 \pm 9$ events.

Two-body decay : $K^*(892)K$ and $a_0(980)\pi$

$P_t^2 < 0.2$ GeV^2 and
1370 GeV $< M(K_S^0 K^{\pm}\pi^{\mp}) < 1560$ GeV



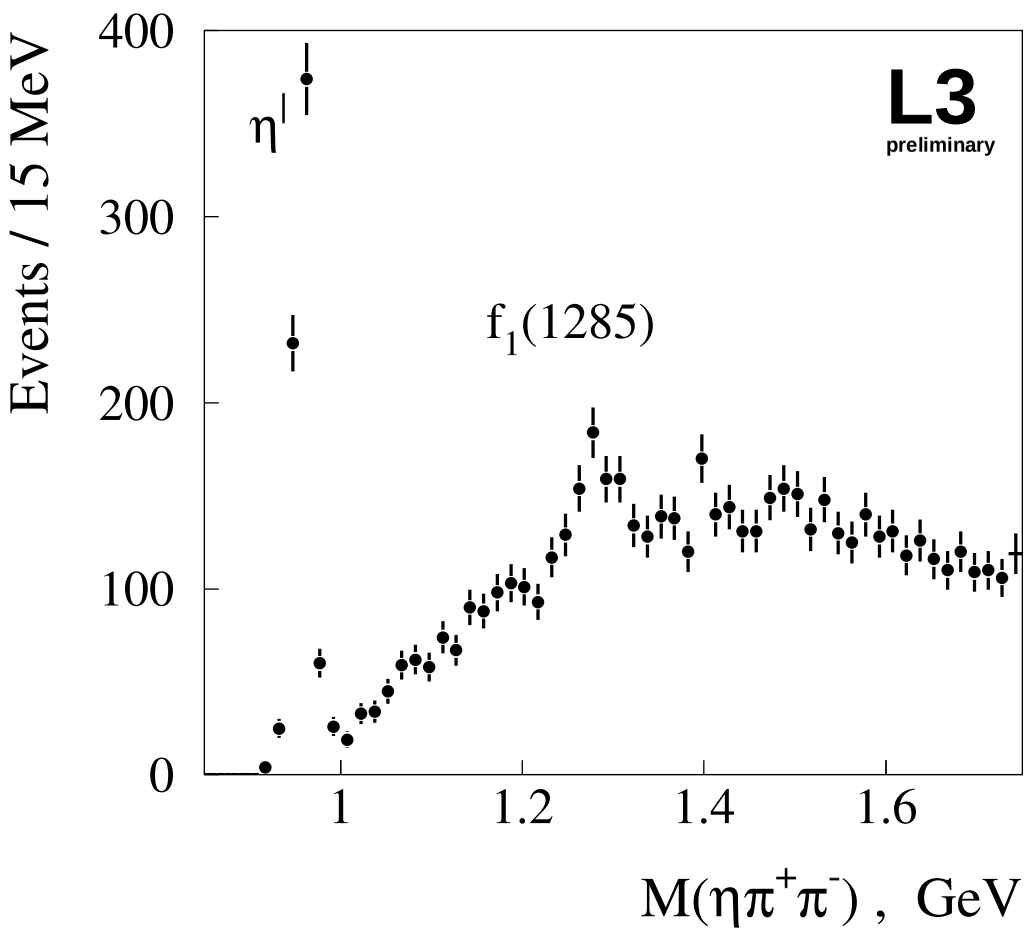
$K^*(892)K$ dominant $\Rightarrow \eta_H$

Too small statistics to establish $\eta_L \rightarrow a_0(980)\pi$

$\eta\,\pi^+\pi^-$: selection

- Events: 2 tracks and 2 photons
- Photon: isolated cluster in ECAL, $E > 0.1$ GeV
- $\eta \Rightarrow 0.47 < M_{\gamma\gamma} < 0.62$ GeV
- Kinematical fit with η mass constraint

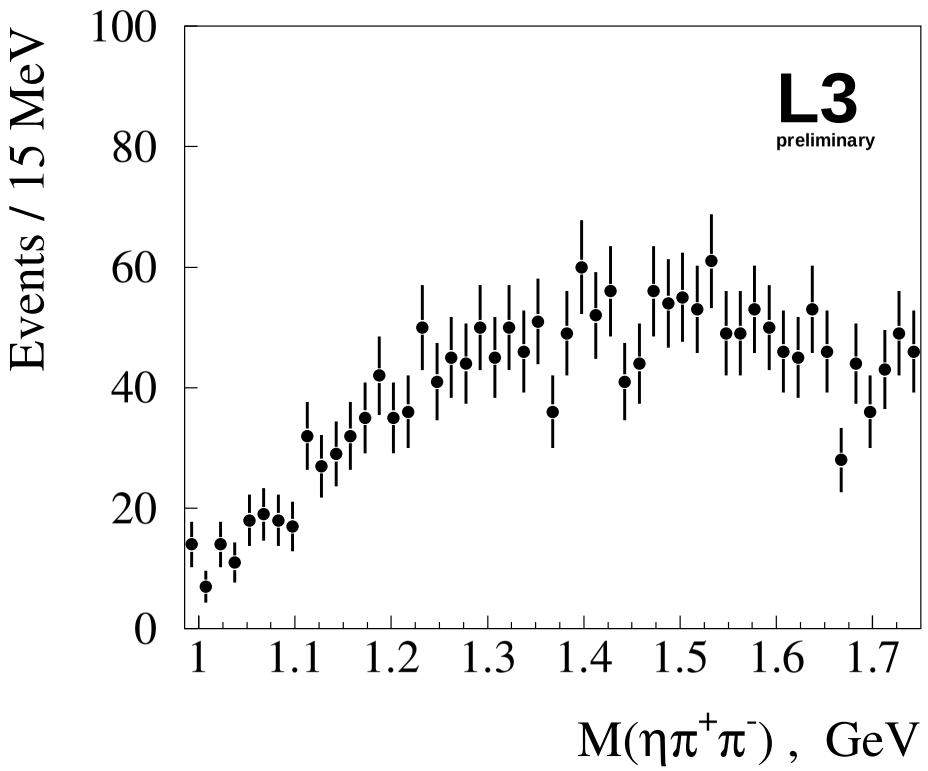
No P_t^2 cut (6444 events)



$\eta'(958)$ and $f_1(1285)$

$\eta\,\pi^+\pi^-$

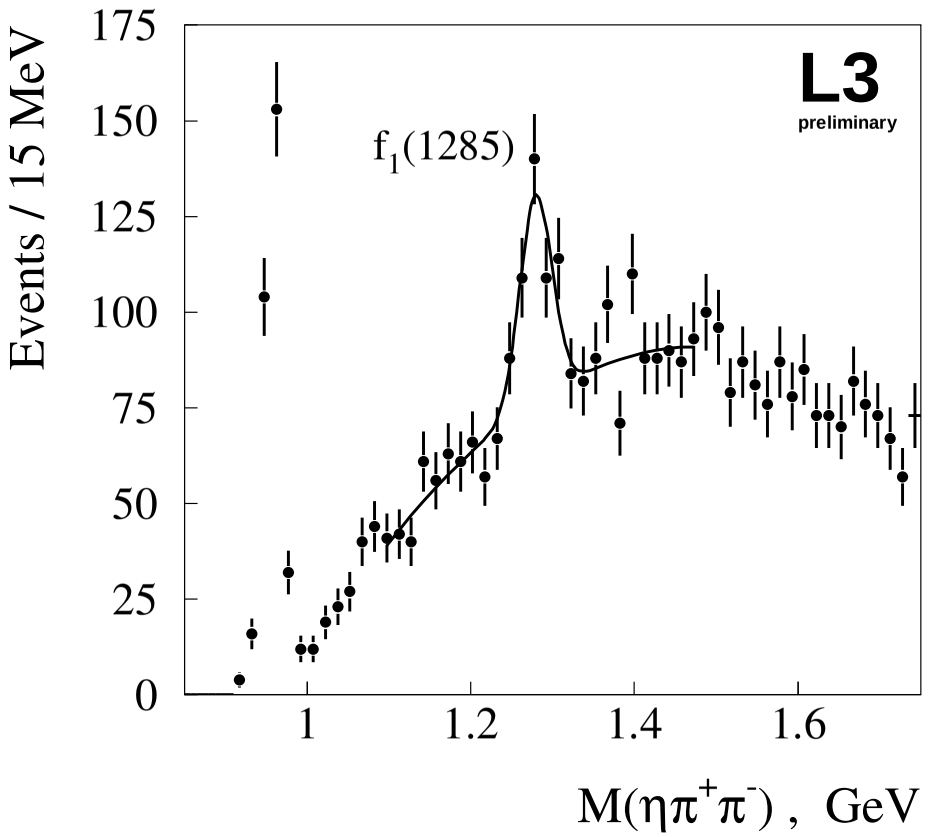
Mass spectrum for $\mathrm{P}_t^2 < 0.02\ \mathrm{GeV}^2$



No $\eta\,(1295)$ nor $\eta\,(1440)$

$\eta\,\pi^+\pi^-$

Mass spectrum for $\mathrm{P}_t^2 > 0.02\ \mathrm{GeV}^2$



Fit of a gaussian over a polynomial background :

Number of events = 176±29

M = 1280±4 MeV, $\sigma = 20 \pm 3$ MeV

$\Rightarrow f_1(1285)$

$\Gamma_{\gamma\gamma}$ of $\eta\,(1440)$ and $\eta\,(1295)$

Use $\mathrm{P}_t^2 < 0.02\ \mathrm{GeV}^2$ (only 2% of 1^+)

$$\Gamma_{\gamma\gamma} \cdot BR = \frac{N}{\mathcal{K}\,\epsilon\,\mathcal{L}_{ee}}$$

$\mathcal{L}_{ee} = 449\ \mathrm{pb}^{-1}$

$\mathcal{K}$ from MC

1) $\mathrm{K}^0_\mathrm{S}\,\mathrm{K}^\pm\pi^\mp$ decay :

$\epsilon = 1.03 \pm 0.04\%$

$\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1440) \to \mathrm{K}\bar{\mathrm{K}}\pi) = 212 \pm 50\ (\mathrm{stat.}) \pm 23\ (\mathrm{sys.})\ \mathrm{eV}$

$\Gamma_{\gamma\gamma} \cdot BR < 1.2$ keV CELLO Coll., Z.Phys. C42(1989)367

This value is consistent with pseudoscalar radial recurrence, $u\bar{u} + d\bar{d}$, as calculated by A.V. Anisovich *et al.*, Eur. Phys. J. A 6 (1999) 247.

$\Rightarrow$ Consistent with η_H, no proof of η_L

2) $\eta\,\pi^+\pi^-$ decay :

$\epsilon = 2.0\%$

$\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1440) \to \eta\pi\pi) < 80\ \mathrm{eV}$ at CL=90%

$\Gamma_{\gamma\gamma} \cdot BR < 300$ eV Crystal Ball Coll., Phys.Rev. D36(1988)2633

$\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1295) \to \eta\pi\pi) < 55\ \mathrm{eV}$ at CL=90%

$\Gamma_{\gamma\gamma} \cdot BR < 300$ eV Crystal Ball Coll.

Tests for Gluonium

❒ Stickiness (M. Chanowitz (1984))

$$\frac{|\langle \mathrm{R}|\mathrm{gg}\rangle|^2}{|\langle \mathrm{R}|\gamma\gamma\rangle|^2} \sim S_X = N_l \left(\frac{m_X}{\mathcal{K}_{J/\psi\to\gamma R}}\right)^{2l+1} \frac{\Gamma(J/\psi \to \gamma \mathrm{R})}{\Gamma(\mathrm{R} \to \gamma\gamma)}$$

$$\Gamma(J/\psi \to \gamma\eta\,(1440) \to \mathrm{K^0_S\,K^{\pm}\pi^{\mp}}) = (79 \pm 16)\ \mathrm{eV}$$
$$\Gamma(J/\psi \to \gamma\eta\,(1440) \to \eta\,\pi^+\pi^-) = (29 \pm 6)\ \mathrm{eV}$$

$S_{\eta\,(1440)} = 79 \pm 26$ from $\mathrm{K^0_S\,K^{\pm}\pi^{\mp}}$

$S_{\eta\,(1440)} > 87$ at 95% CL, from $\eta\,\pi^+\pi^-$

❒ Gluiness (Close, Farrar and Li (1997))

$$G = \frac{9\,e_Q^4}{2}\left(\frac{\alpha}{\alpha_s}\right)^2 \frac{\Gamma(\mathrm{R} \to gg)}{\Gamma(\mathrm{R} \to \gamma\gamma)}$$

$G_{\eta\,(1440)} = 41 \pm 14$ from $\mathrm{K^0_S\,K^{\pm}\pi^{\mp}}$

$G_{\eta\,(1440)} > 45$ at 95% CL, from $\eta\,\pi^+\pi^-$

(For the η', S $= 3.5 \pm 0.3$, G $= 5.2 \pm 0.8$)

$\Rightarrow$ Strong gluon admixture

Lattice QCD calculations predict pseudoscalar gluonium only at ~ 2 GeV!

Conclusions and Outlook

Two-photon interactions, with the high statistics obtained at LEP, can help to clarify the complex region of low mass resonances.

$e^+e^- \longrightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$

- ⇨ 2^{++} and 0^{++} waves in the $\rho^0\rho^0$ channel.
  More detailed spin-parity-helicity analysis and the study of the $\rho^+\rho^-$ channel will identify the f_2 and f_0 resonances
- ⇨ For $W_{\gamma\gamma} > 3$ GeV the production mechanism of the ρ^0 and f_2 must be studied.

$e^+e^- \longrightarrow e^+e^-\mathrm{K^0_S\,K^\pm\pi^\mp}$ and $\eta\,\pi^+\pi^-$

- ⇨ Consistent with η_H
- ⇨ $\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1440) \rightarrow \mathrm{K\bar{K}}\pi) =$
  212 ± 50 (stat.) ± 23 (sys.) eV
  Which is the nature of this state?
  Gluonium or radial recurrence?
- ⇨ Measure the $\Gamma_{\gamma\gamma}$ of $\mathrm{f_1}(1285)$ and $\mathrm{f_1}(1420)$