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

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$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$

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

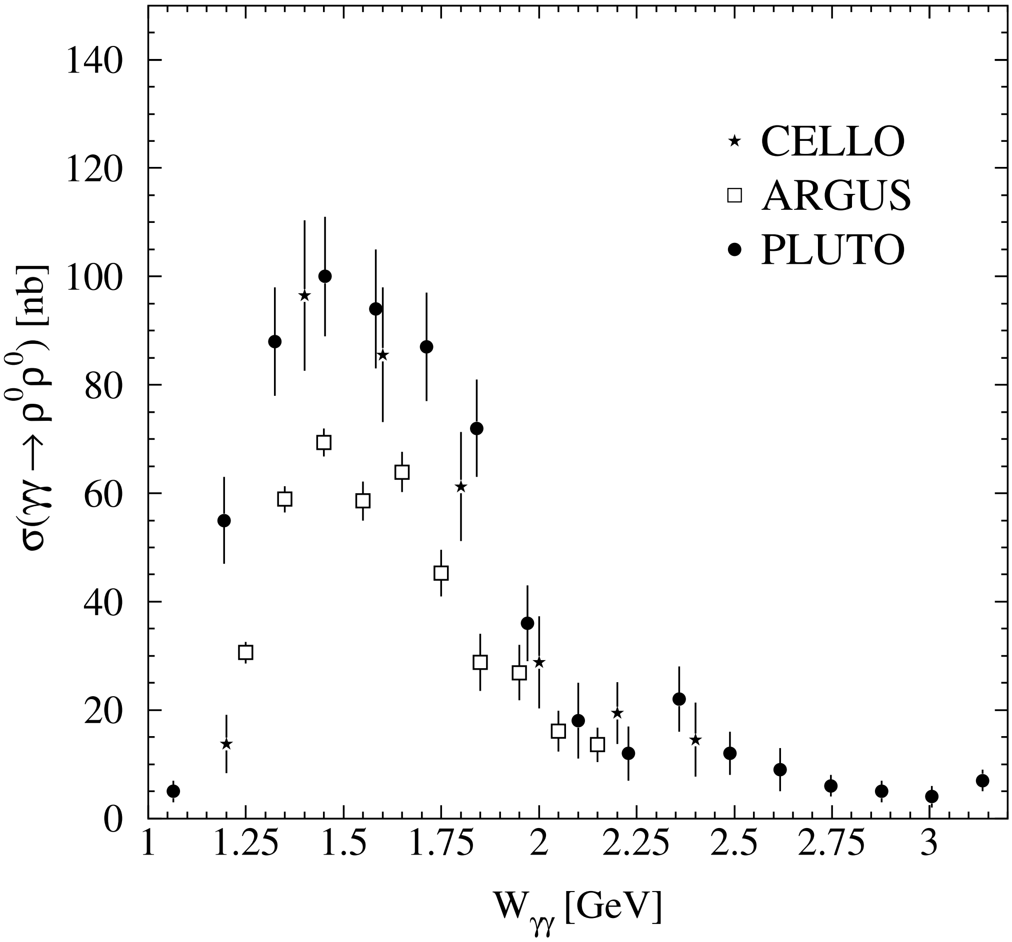
$e^+e^- \rightarrow e^+e^-\mathrm{K^0_S}\,\mathrm{K}^\pm\pi^\mp$ and $\eta\,\pi^+\pi^-$

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

Conclusions

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

- ❑ 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 $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$ Events in L3

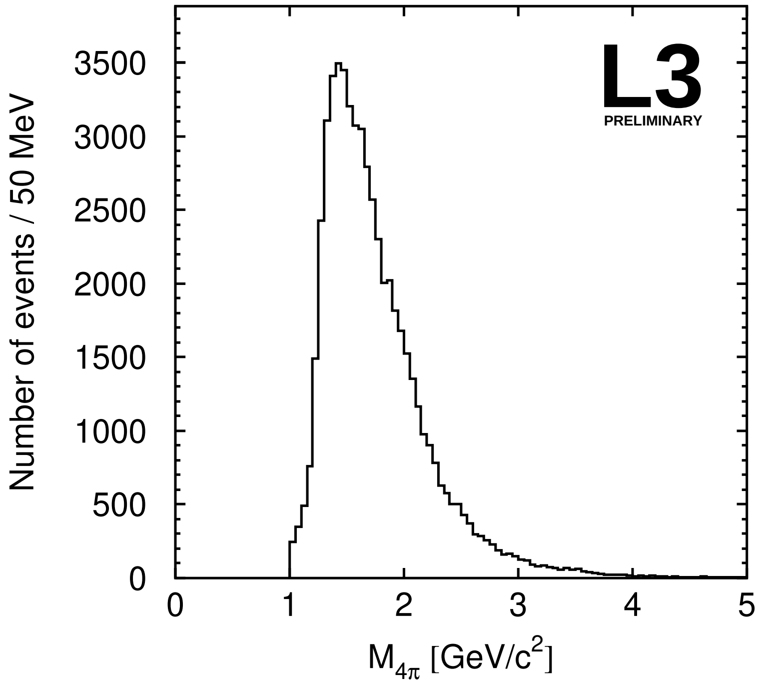
1996 - 1999 data at $\sqrt{s} = 160 \div 200\ \mathrm{GeV}$

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

Event selection:

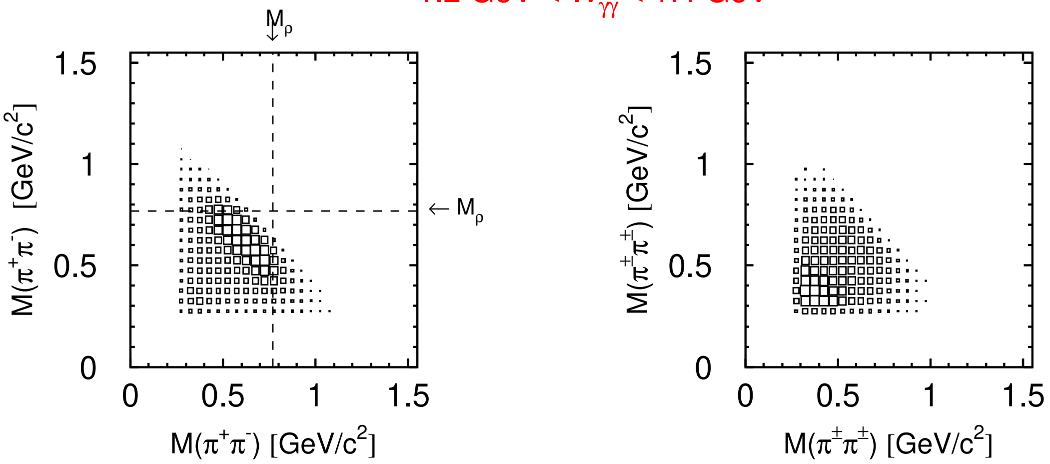
- four charged particles, with net charge zero
- tracks from the interaction vertex
- no photon candidates
- $(\Sigma\vec{p_t})^2 \leqslant 0.02\ \mathrm{GeV}^2/c^2$

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

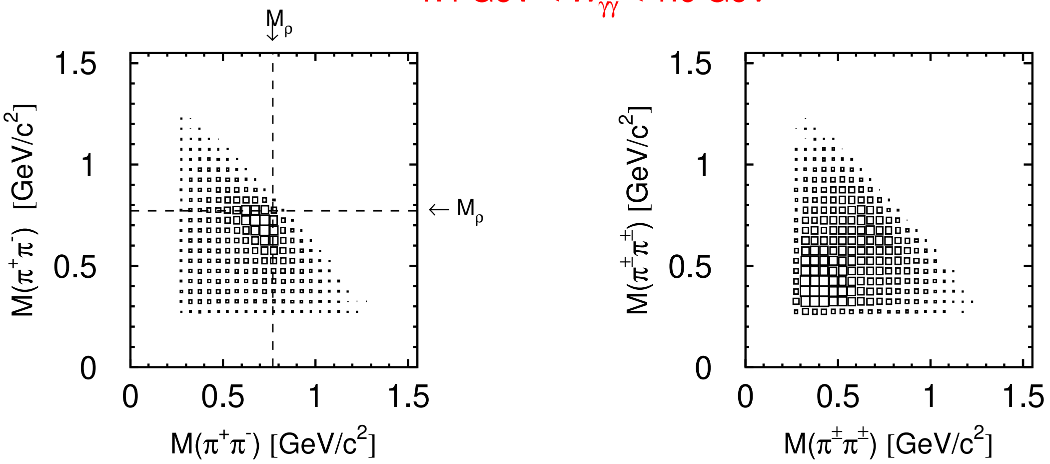


Pion pair spectra

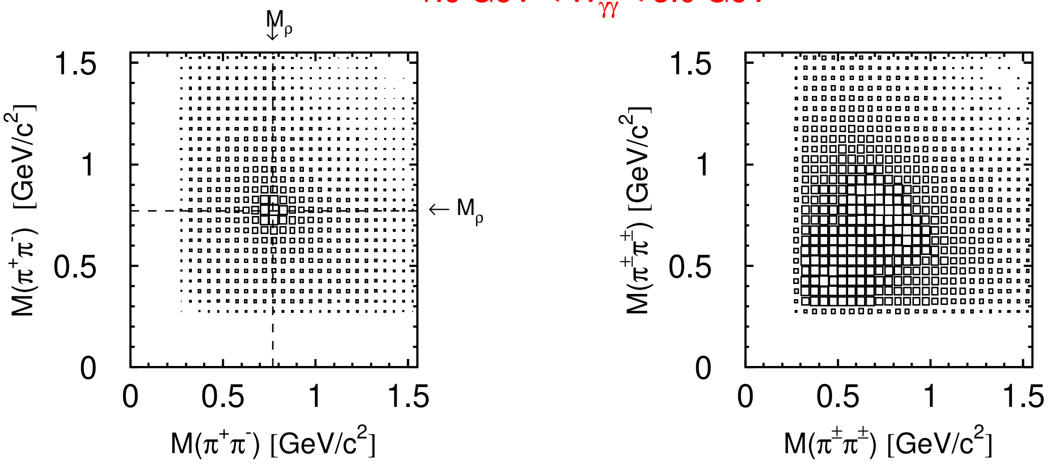
1.2 GeV < $W_{\gamma\gamma}$ < 1.4 GeV



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



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



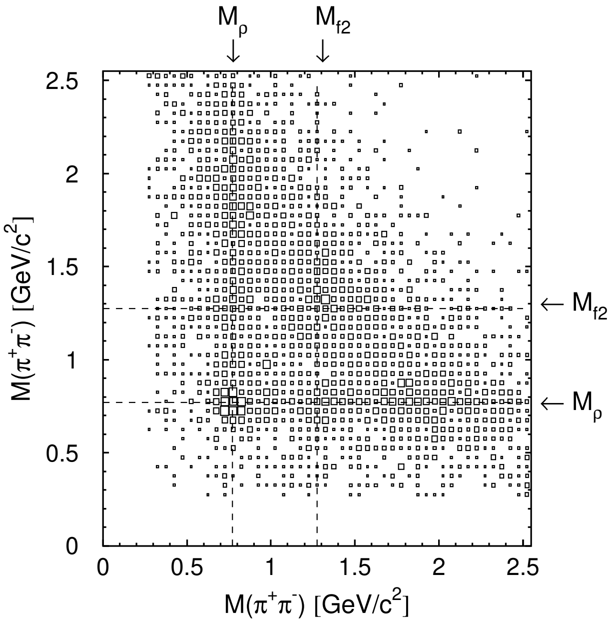
unlike−sign

like−sign

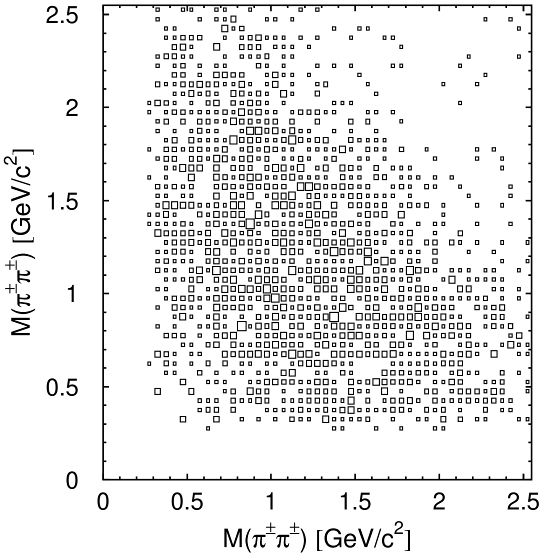
High mass data $W_{\gamma\gamma} > 3$ GeV

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.

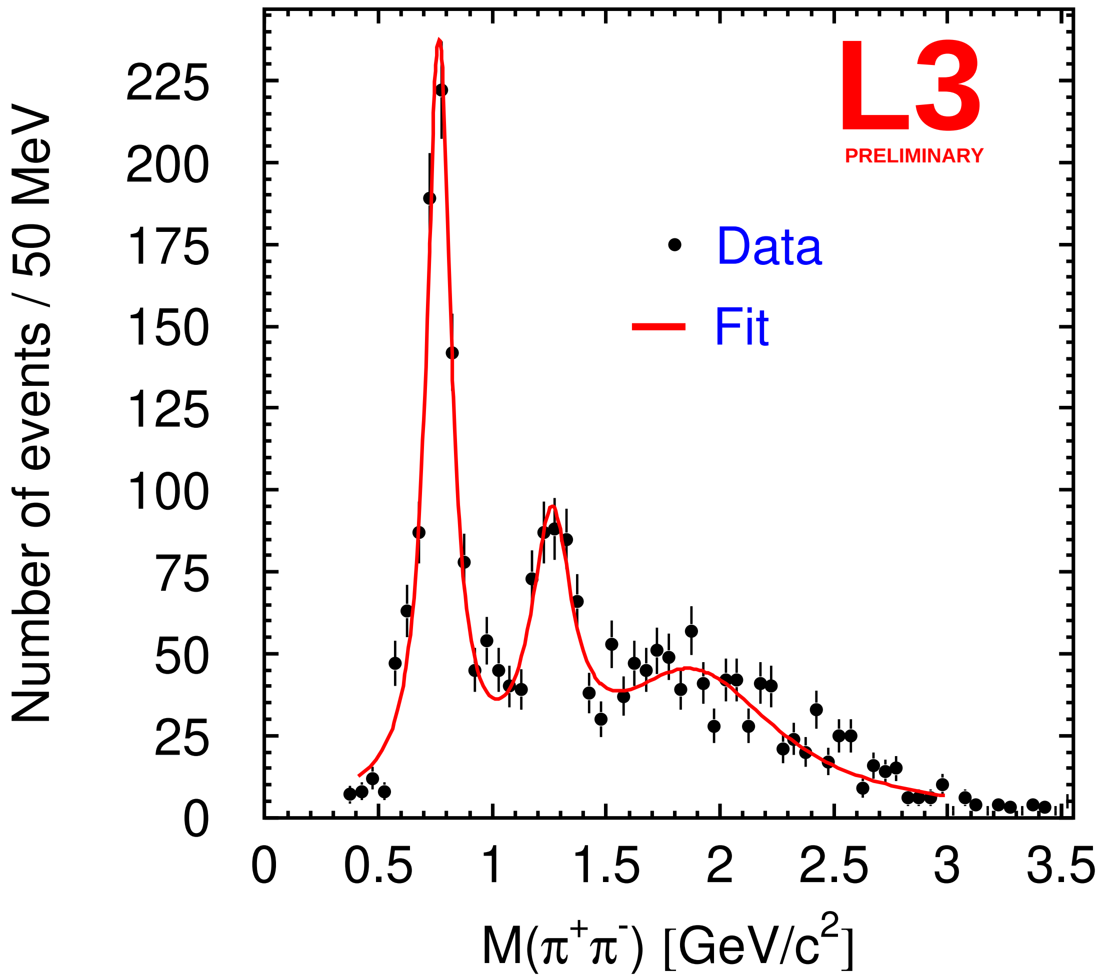
Unlike-sign charge two-pion mass combinations



Like-sign charge two-pion mass combinations



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



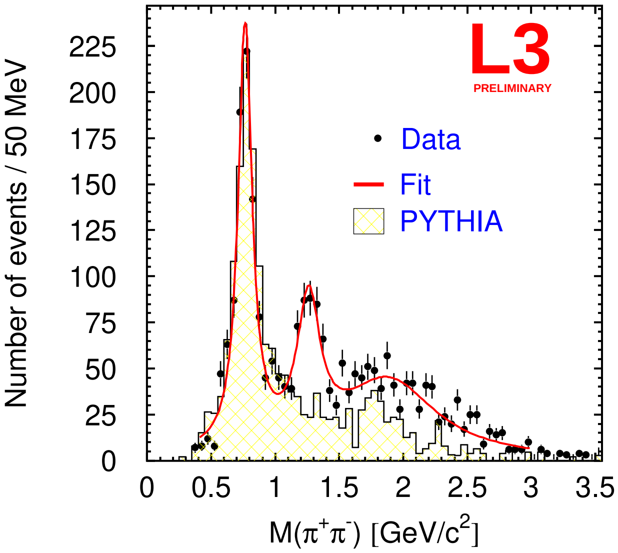
Events with $(\Sigma\vec{p_t})^2 \leqslant 0.02\ \mathrm{GeV}^2/c^2$. Fitted by three Breit-Wigner functions.

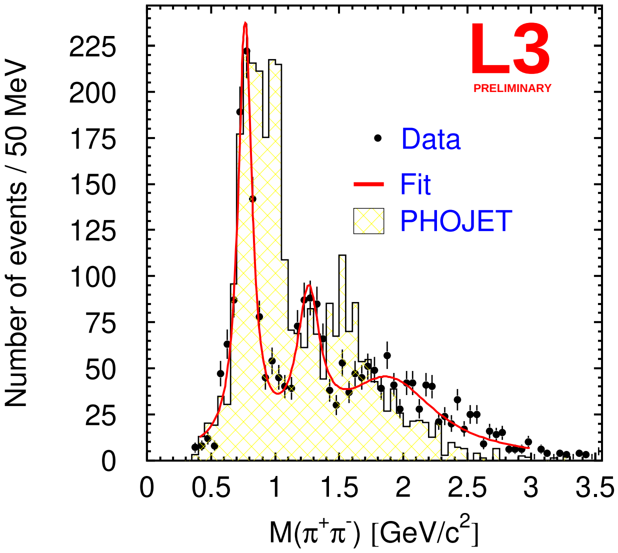
Fit result

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

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

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

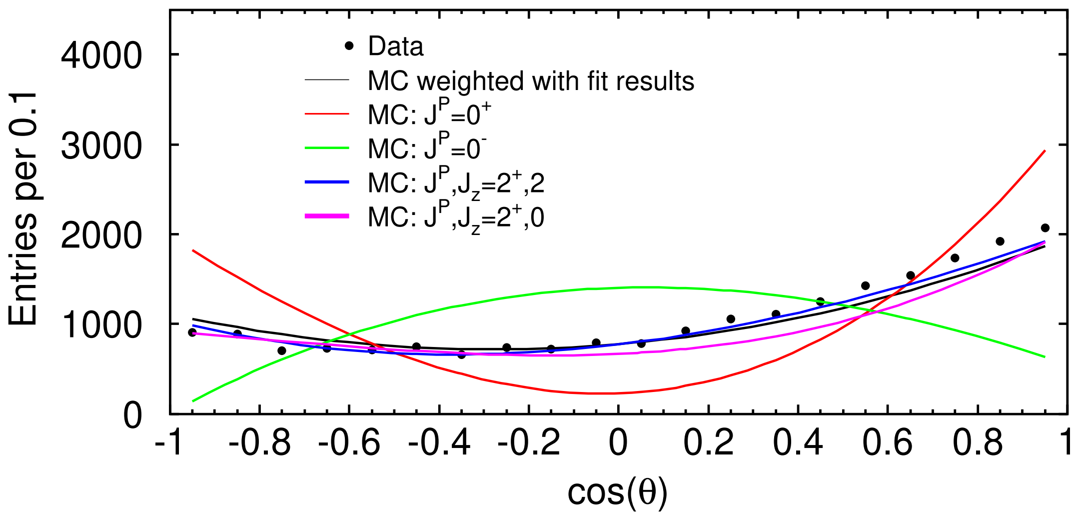
$$\log\Lambda = \sum_{i=1}^{N}\left[\log\left(\sum_j \lambda_j \frac{|g_j(\xi_i)|^2}{\overline{|g_j|^2}}\right) - \sum_j \lambda_j\right]$$

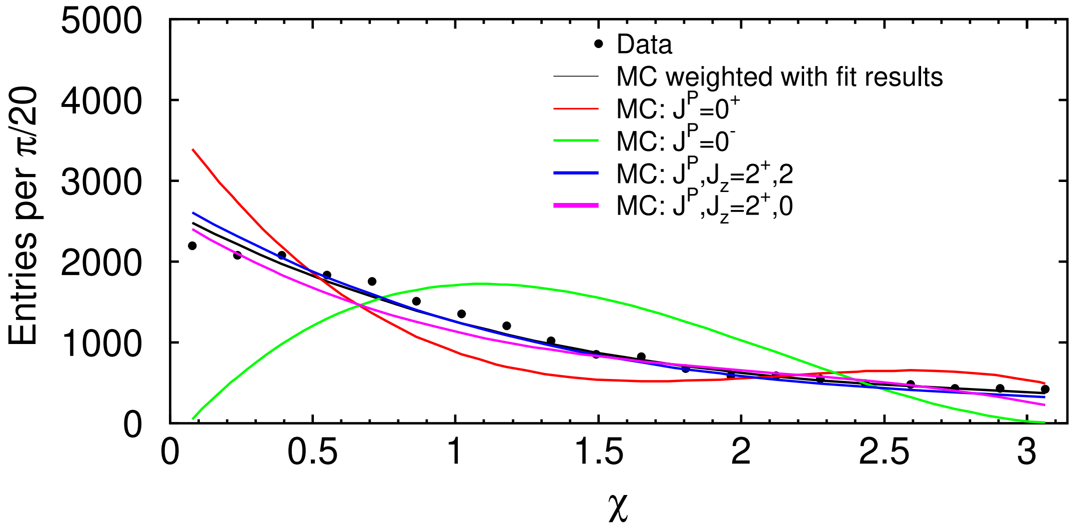
- $$\begin{aligned} g_{\pi^+\pi^-\pi^+\pi^-} &= 1 \\ g_{\rho^0\pi^+\pi^-} &= \tfrac{1}{2}\left\{BW(m_{12}) + BW(m_{34}) + BW(m_{14}) + BW(m_{32})\right\} \\ g^{J^p J_z}_{\rho^0\rho^0}(\xi) &= \tfrac{1}{\sqrt{2}}\Big\{BW(m_{12})BW(m_{34})\Psi^{J^p J_z LS}(\xi) \\ &\quad + BW(m_{14})BW(m_{32})\Psi^{J^p J_z LS}(\xi)\Big\} \end{aligned}$$
- $\xi = (m^2_{12}, m^2_{34}, \theta_\rho, \theta^{12}_\pi, \phi^{12}_\pi, \theta^{34}_\pi, \phi^{34}_\pi)$, 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 :

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





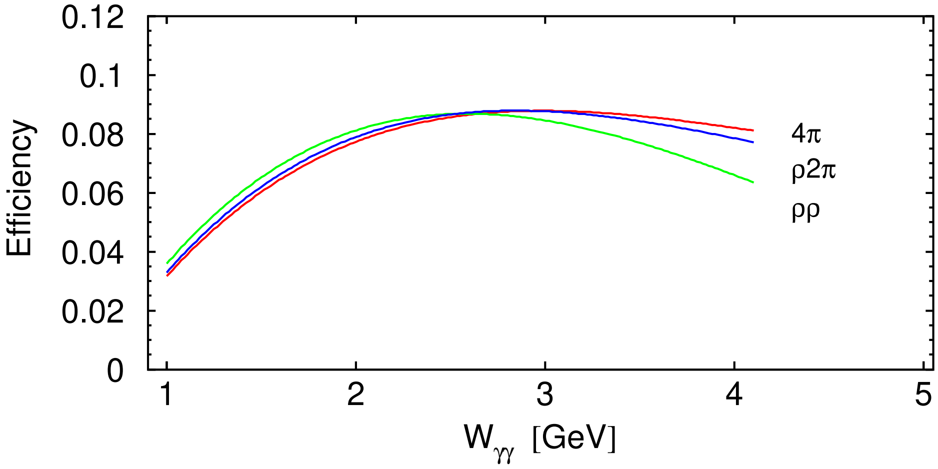
ϑ is the opening angle between two positive charged pions and the χ is the angle between the decay planes of the two ρ^0.

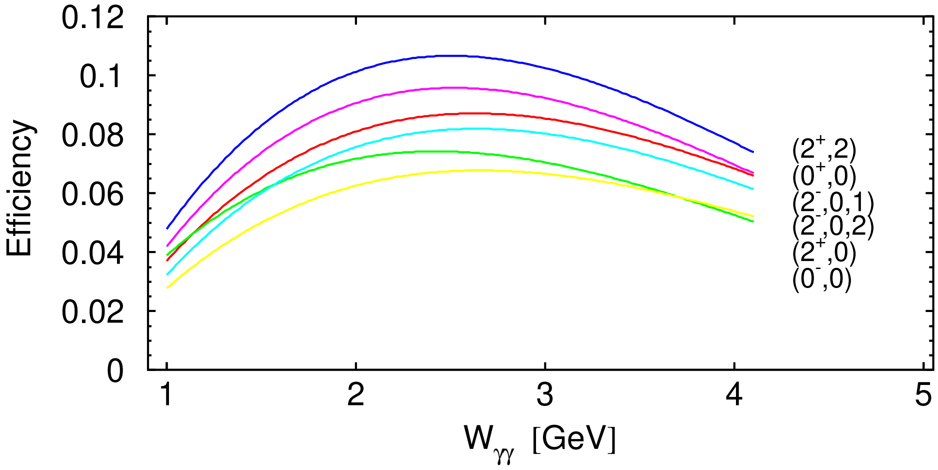
Spin-Parity-Helicity Analysis

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

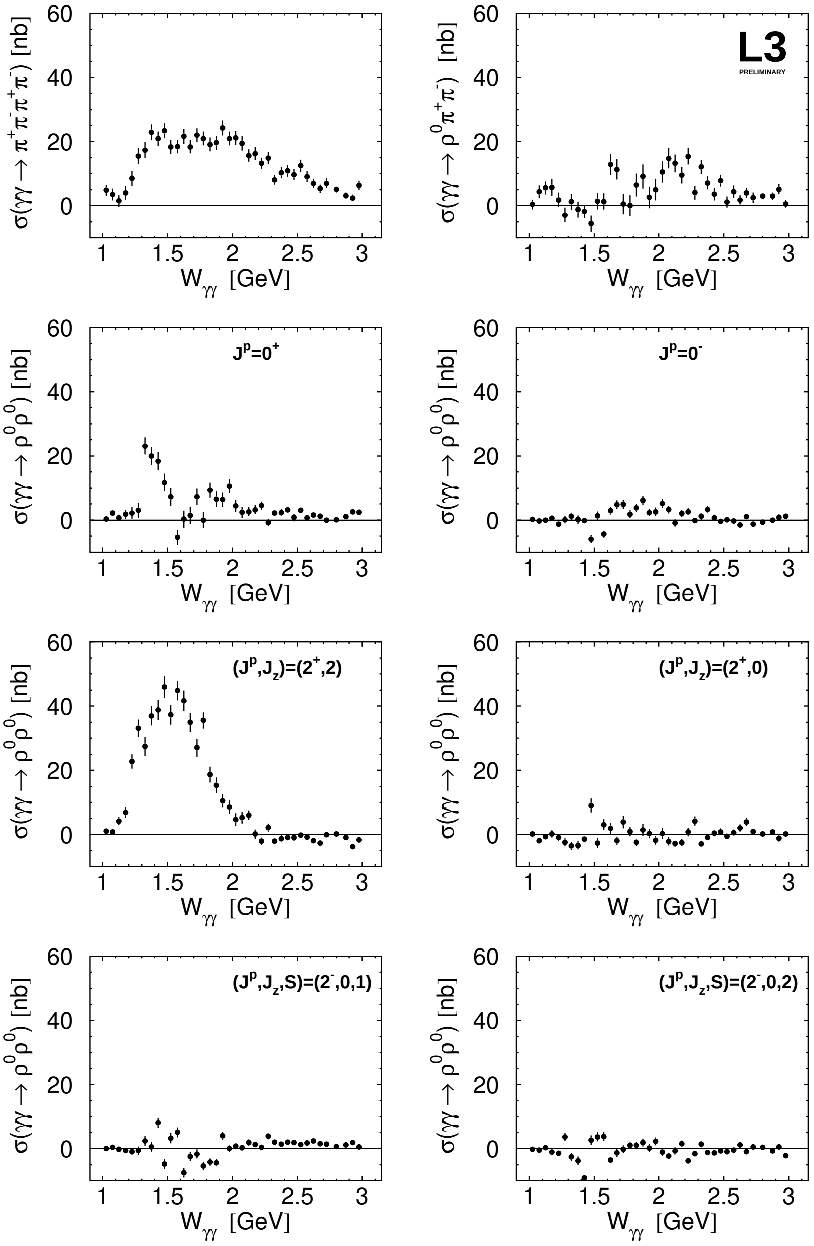
$$\sigma_{\gamma\gamma\to j} = \frac{N\lambda_j}{\mathcal{L}_{\mathrm{e^+e^-}}\,\varepsilon(W_{\gamma\gamma})\,\frac{\Delta\mathcal{L}_{\gamma\gamma}}{\Delta W_{\gamma\gamma}}\,\Delta W_{\gamma\gamma}}$$

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





Result of 8-parameter fit

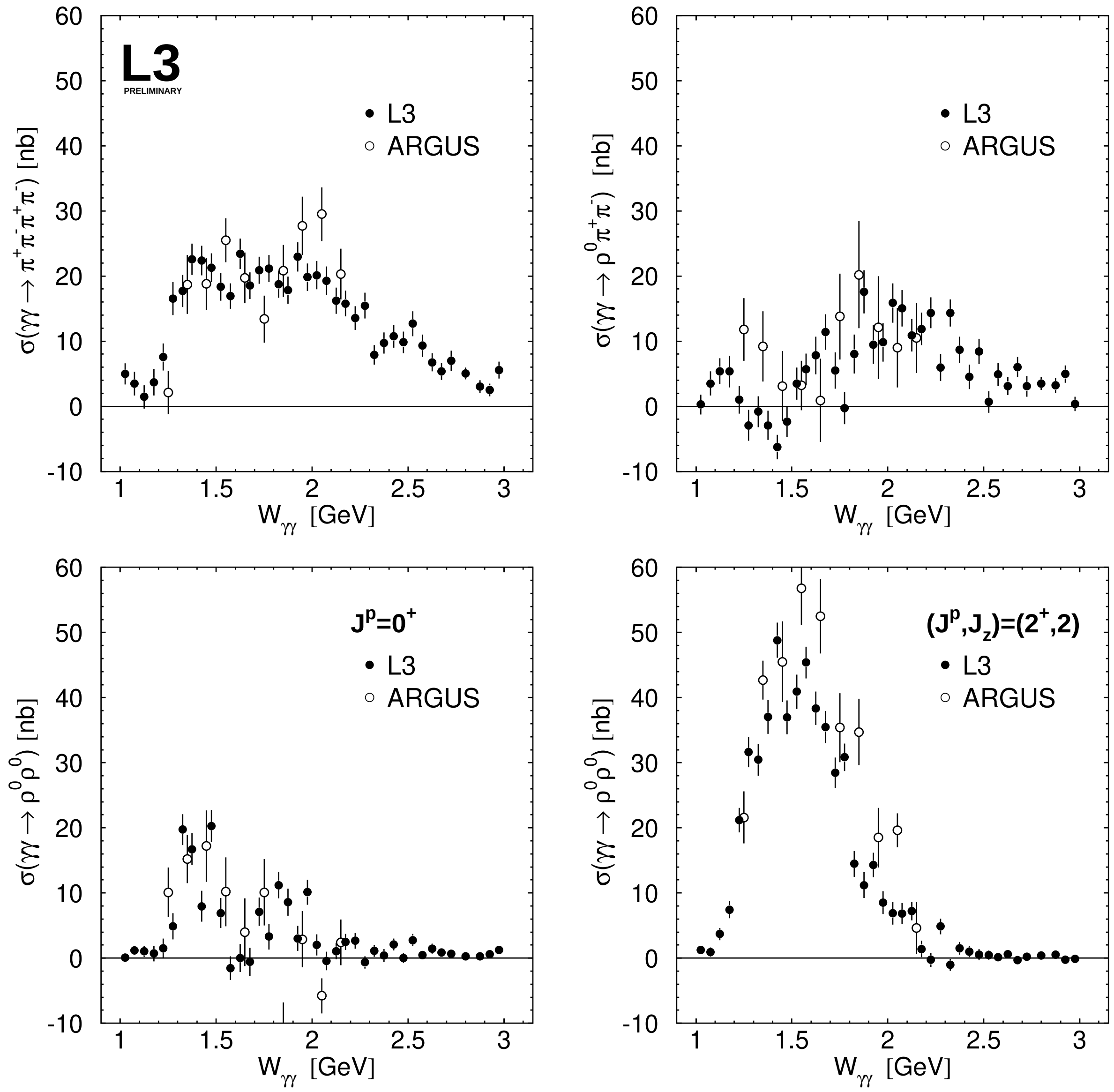


- Dominance of the partial wave $(J^p, J_z) = (2^+, 2)$
- Contribution of $J^p = 0^+$
- Negative parity and $(2^+, 0)$ states consistent with zero

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 $\Gamma =$ 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 $= 1473 \pm 4$ MeV
$\Gamma = 79 \pm 13$ MeV

$\eta_L \rightarrow a_0\pi$ M $= 1418.7 \pm 1.2$ MeV
$\Gamma = 59 \pm 5$ 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 $\Gamma =$ 53 $\pm$ 3 MeV

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

Has never been seen in $\gamma\gamma$

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

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

$f_1(1285)$

M $=$ 1281.9 ± 0.6 MeV $\quad \Gamma =$ 24.0 ± 1.2 MeV

Seen in

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

1. $\mathrm{K^0_S\,K^{\pm}\pi^{\mp}}$ decay: 9.6%
2. $\eta\,\pi^+\pi^-$ decay: 50% ; $a_0(980)\pi$ 34%

$f_1(1420)$

M $=$ 1426.2 ± 1.2 MeV $\quad \Gamma =$ 55.0 ± 3.0 MeV

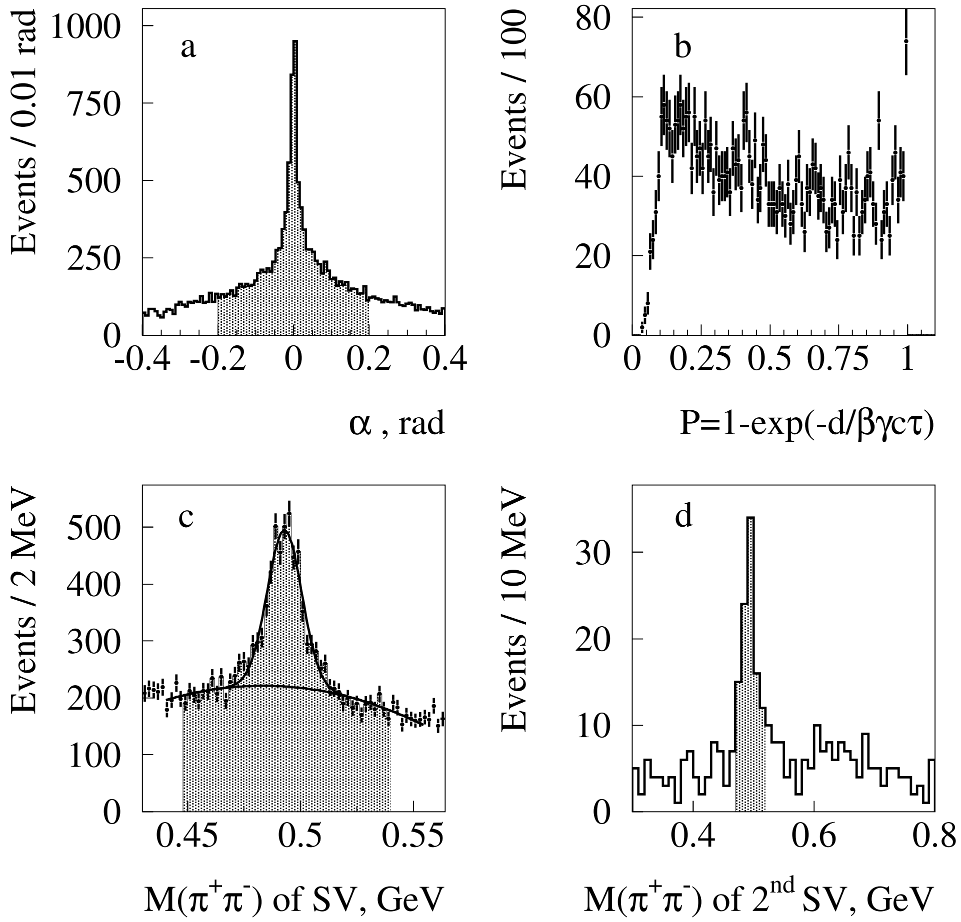
Seen in

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

1. $\mathrm{K^0_S\,K^{\pm}\pi^{\mp}}$ decay: K^*K dominant
2. $\eta\,\pi^+\pi^-$ decay: possibly seen

L3 : $\mathrm{K^0_S}$ *selection*

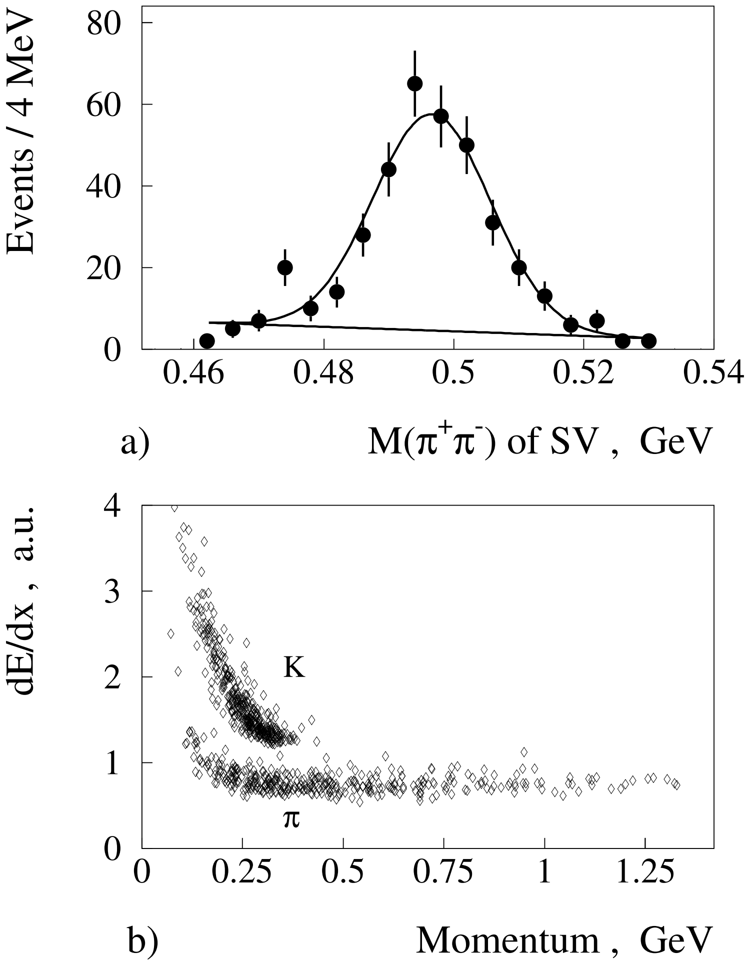
- Final $\mathrm{K^0_S}$ state: $\pi^+\pi^-$
- Secondary vertex (SV): 3 mm$\leq \mathrm{R}_{XY} \leq$200 mm
- Angle α between $\mathrm{K^0_S}$ momentum and $\mathrm{K^0_S}$ flight direction
  in transverse plane is within 0.2 rad
- Lifetime cut for K^0_S: $1 - exp(-d/\beta\gamma c\tau) \leq 0.99$
- Mass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



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

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

- ❐ Events: 4 good tracks ; No photons
- ❐ $\mathrm{K_S^0} \rightarrow \pi^+\pi^-$ at secondary vertex
- ❐ dE/dx identification of $\pi^{\pm}K^{\mp}$ at primary vertex: CL(Kπ)>1%, CL($\pi\pi$)<10^{-3}



$\mathrm{K_S^0}$: M=496 MeV, σ=9 MeV.

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

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

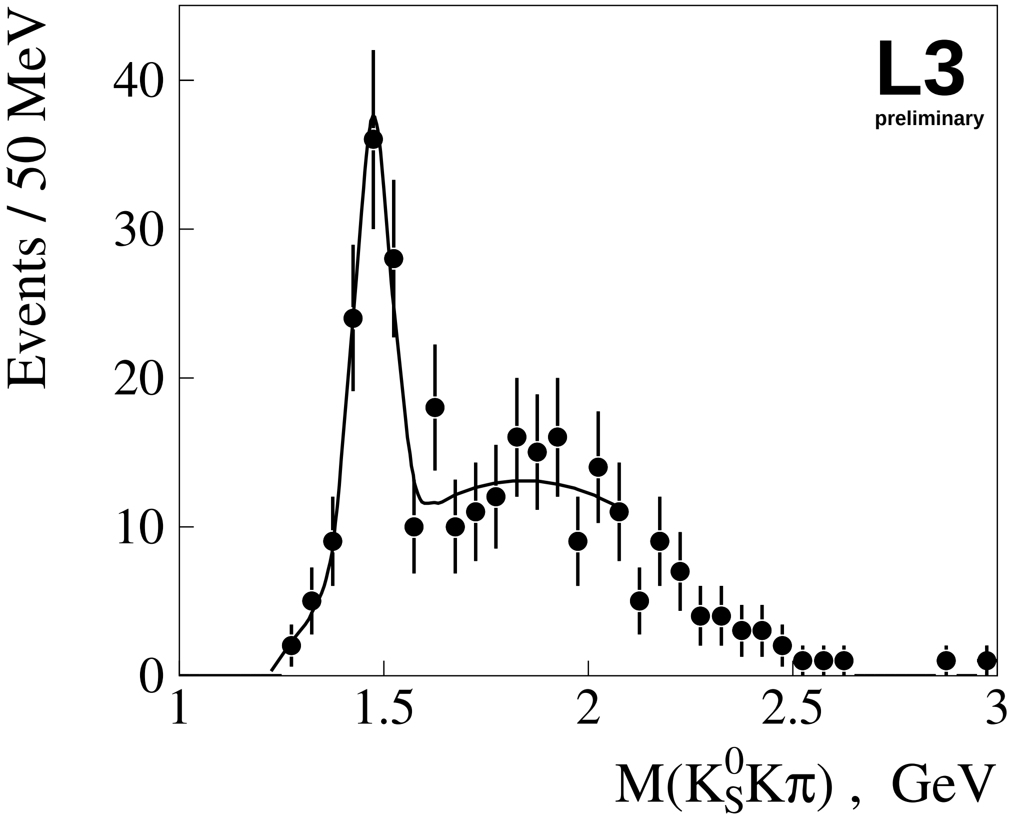
Fit :

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)

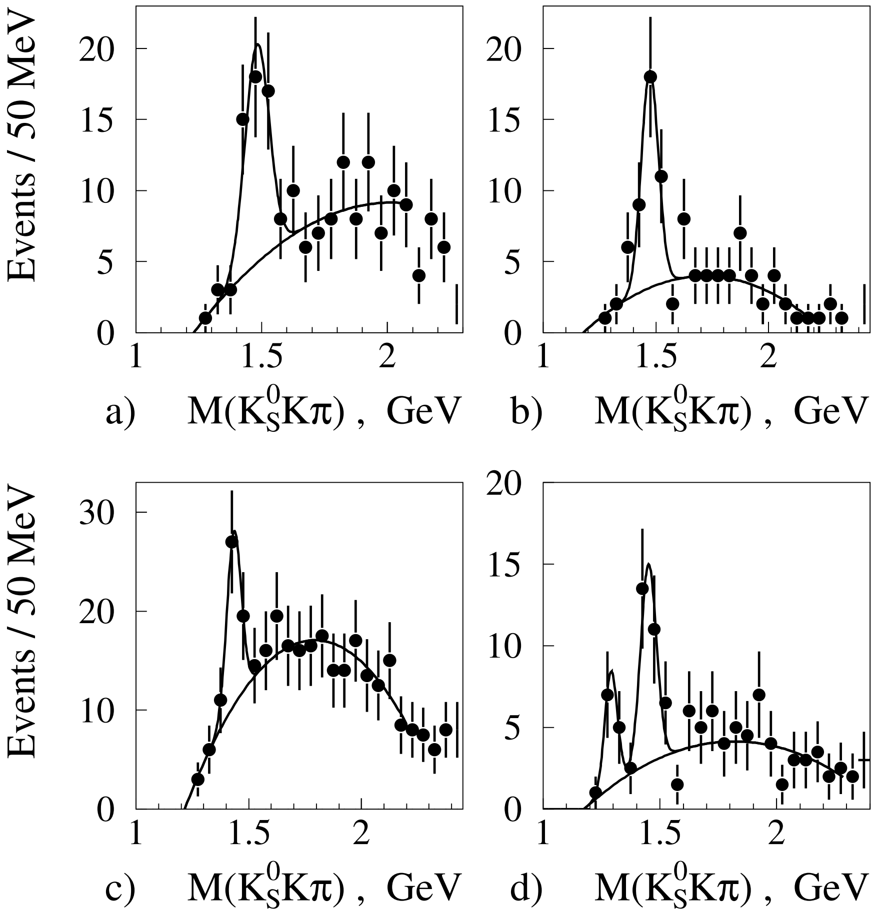


These parameters correspond to η_H

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

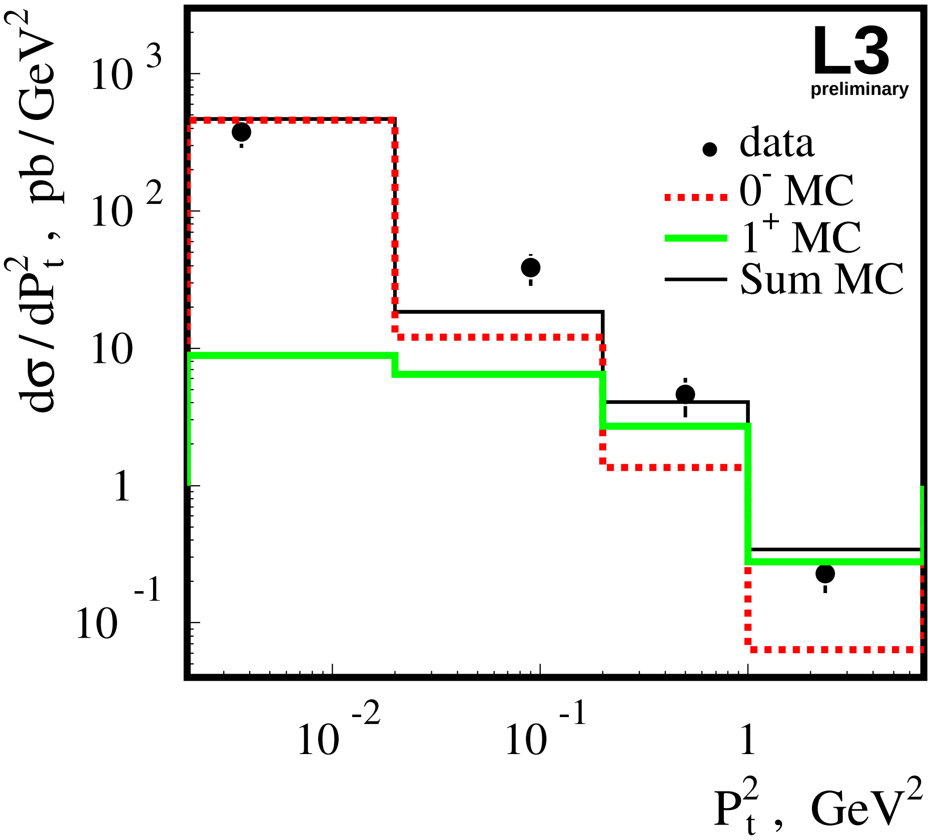
At high Q^2 both $f_1(1285)$ and $f_1(1420)$ are seen .

$K^0_S K^{\pm}\pi^{\mp}$: $d\sigma/dP_t^2$

Fit of the $d\sigma/dP_t^2$ dependence :

Resonance(s)	Kolmogorov test CL
pseudoscalar $\eta(1440)$ only	$< 10^{-5}$
vector meson $f_1(1420)$ only	$< 10^{-5}$
sum: $\eta(1440)+f_1(1420)$	30%

The result of $\eta(1440)+f_1(1420)$ fit is shown:



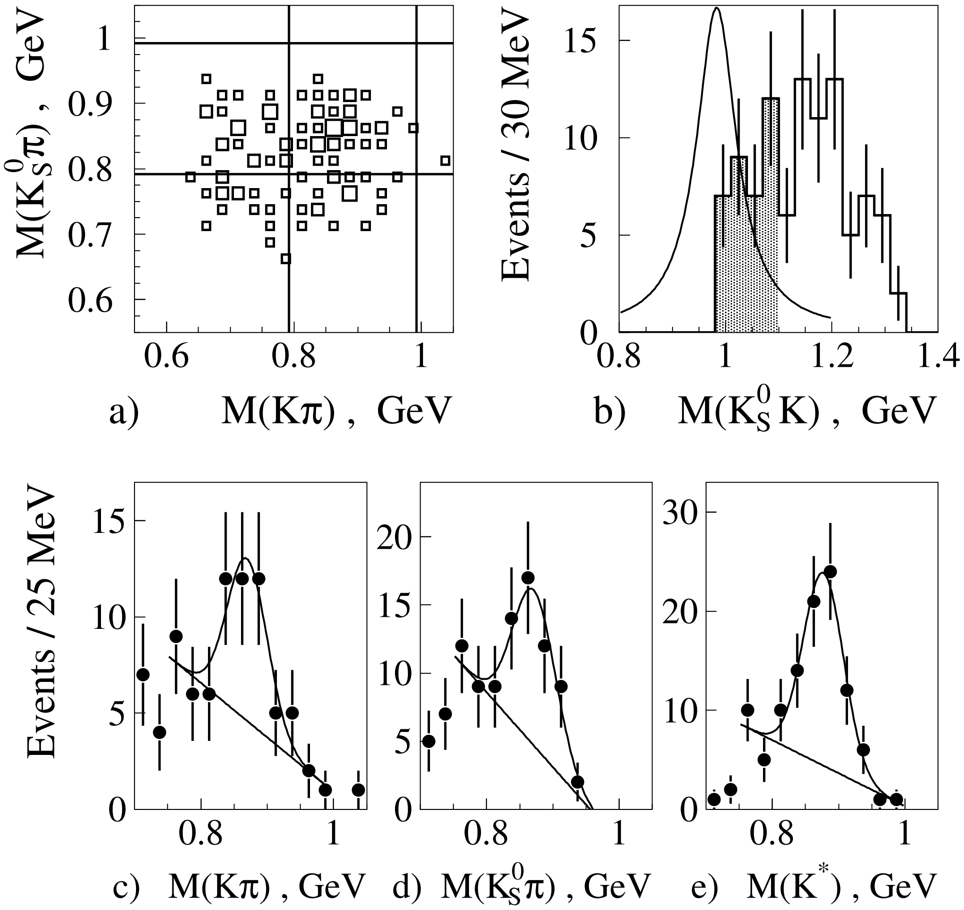
⇒ Presence of both 0^- and 1^+ in the peak

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

$f_1(1420) \Rightarrow 43 \pm 9$ events.

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

$\mathrm{P}_t^2 < 0.2\ \mathrm{GeV}^2$ and
$1370\ \mathrm{GeV} < M(\mathrm{K}_\mathrm{S}^0\mathrm{K}^\pm\pi^\mp) < 1560\ \mathrm{GeV}$



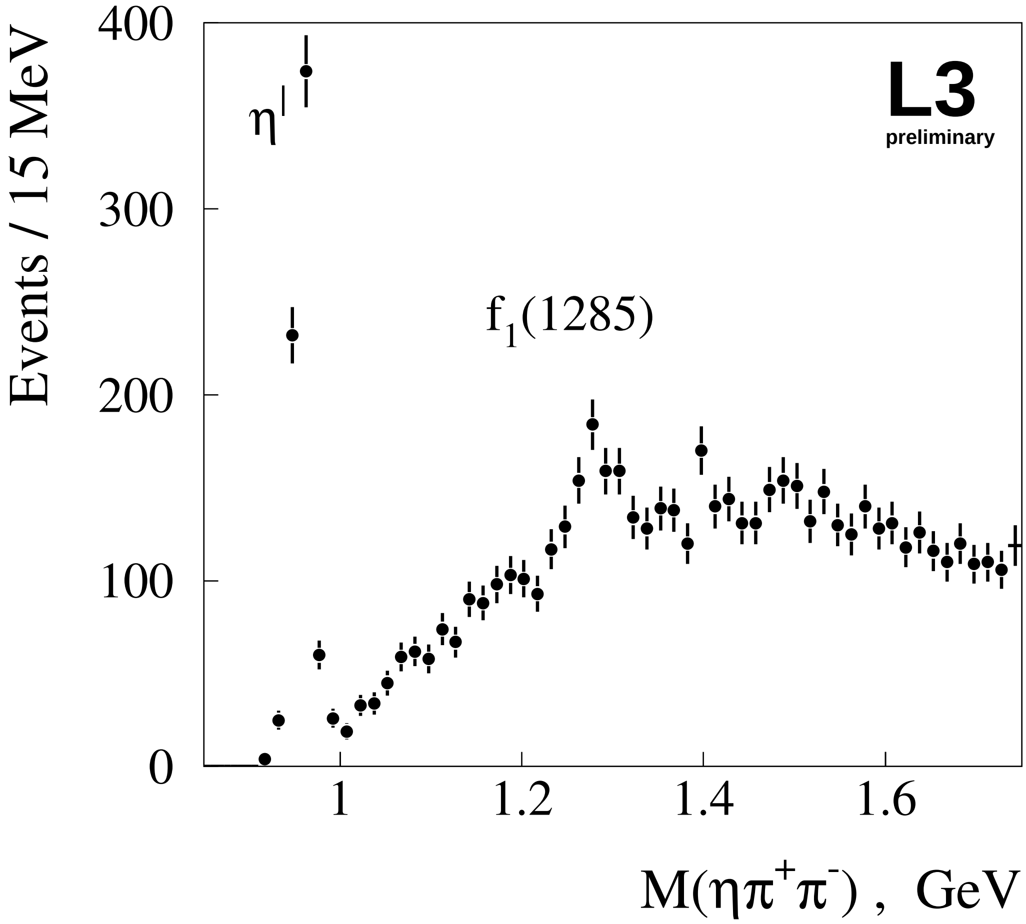
$K^*(892)K$ dominant $\Rightarrow \eta_H$

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

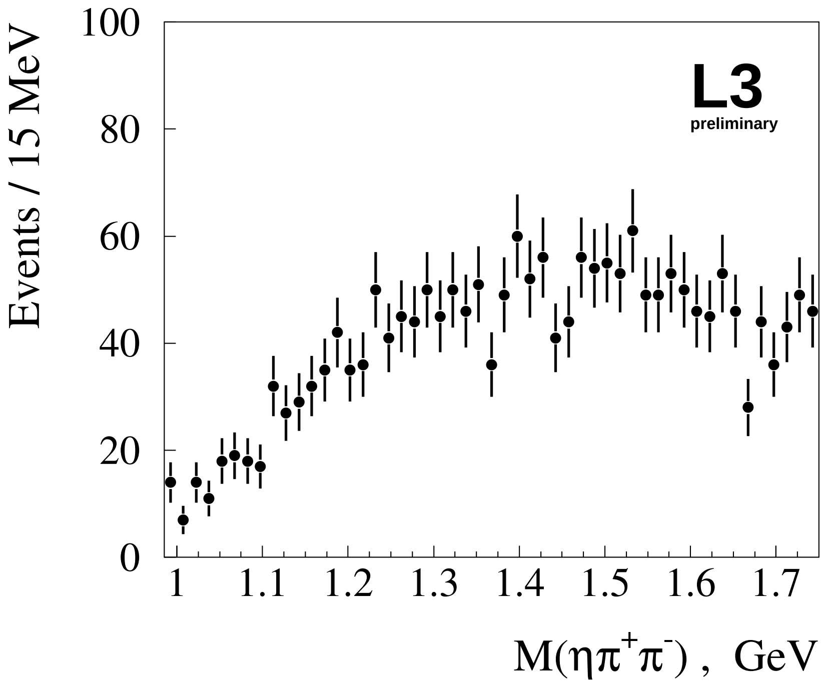
No P_t^2 cut (6444 events)



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

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

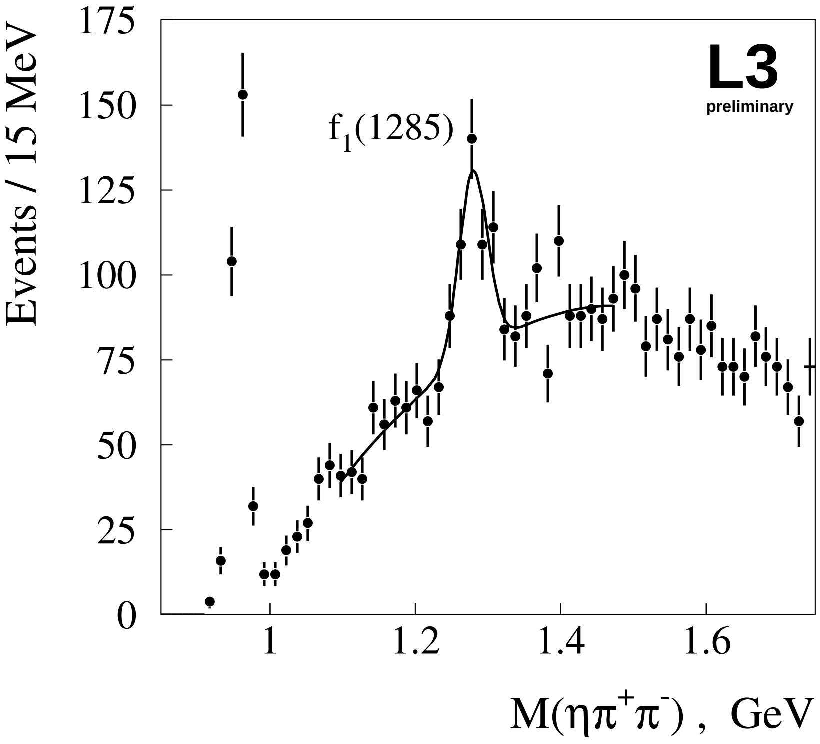
Mass spectrum for $P_t^2 < 0.02\ \mathrm{GeV}^2$



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

$\Rightarrow \mathrm{f}_1(1285)$

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

Use $P_t^2 < 0.02\ \mathrm{GeV}^2$ (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) $K^0_S\,K^\pm\pi^\mp$ decay :

$\epsilon = 1.03 \pm 0.04\%$

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

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

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

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

$\epsilon = 2.0\%$

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

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

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

$\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1295) \rightarrow \eta\pi\pi) < 55$ 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 $\mathrm{K^0_S\,K^\pm}\pi^\mp$

$S_{\eta\,(1440)} > 98$ at 95% CL, from $\eta\,\pi^+\pi^-$

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

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

$G_{\eta\,(1440)} = 35 \pm 12$ from $\mathrm{K^0_S\,K^\pm}\pi^\mp$

$G_{\eta\,(1440)} > 44$ at 95% CL, from $\eta\,\pi^+\pi^-$

(For the η', S $= 3.5 \pm 0.3$, G $= 6.5 \pm 0.8$)

⇒ Strong gluon admixture

Lattice QCD calculations predict pseudo-scaler 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.

$e^+e^- \rightarrow e^+e^-\pi^+\pi^-\pi^+\pi^-$

- 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.

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

- $\Gamma_{\gamma\gamma} \cdot BR(\eta\,(1440) \rightarrow \mathrm{K}\bar{\mathrm{K}}\pi) =$
  212 ± 50 (stat.) $\pm\, 17$ (sys.) eV
  Which is the nature of this state?
  Gluonium or radial recurrence?
- Measure the $\Gamma_{\gamma\gamma}$ of $\mathrm{f}_1(1285)$ and $\mathrm{f}_1(1420)$