Resonance Formation in Two-Photon Collisions

L3 Collaboration

presented by

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Outline

Light Quark Resonances :

- $\eta' \to \pi^+\pi^-\gamma$
- $a_2 \to \pi^+\pi^-\pi^0$
- $f_2 \to \pi^+\pi^-$
- $f_2' \to K^+K^-, K_sK_s$

Radial excitation states :

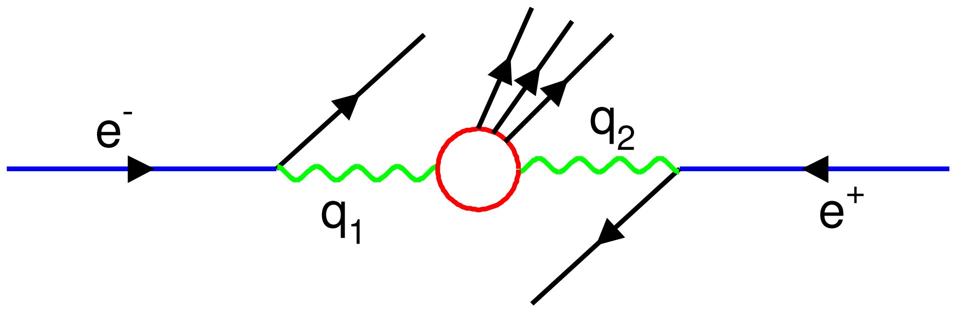
- $\pi^+\pi^-\pi^0$ at 1750 MeV
- K_sK_s at 1750 MeV

Charmonium states :

- η_c
- $\chi_{c2} \to \gamma J/\psi$

Cross section

Kinematics :



- Colliding photons are quasi-real, along beam direction (z-axis).
- $|p_T|^2 \simeq Q^2 \simeq \max(-q_1^2, -q_2^2)$
- Exclusive event selection : $|p_T|^2 \to 0$

Differential cross secton :

$$d\sigma = 2\pi(2J+1)\frac{m_A}{W_{\gamma\gamma}^2}\frac{\Gamma_{\gamma\gamma}}{(m_A^2 - W_{\gamma\gamma}^2)^2 + m_A^2\Gamma_A^2} \times \mathcal{T} \times d(\mathrm{LIPS})$$

Prominent Resonances :

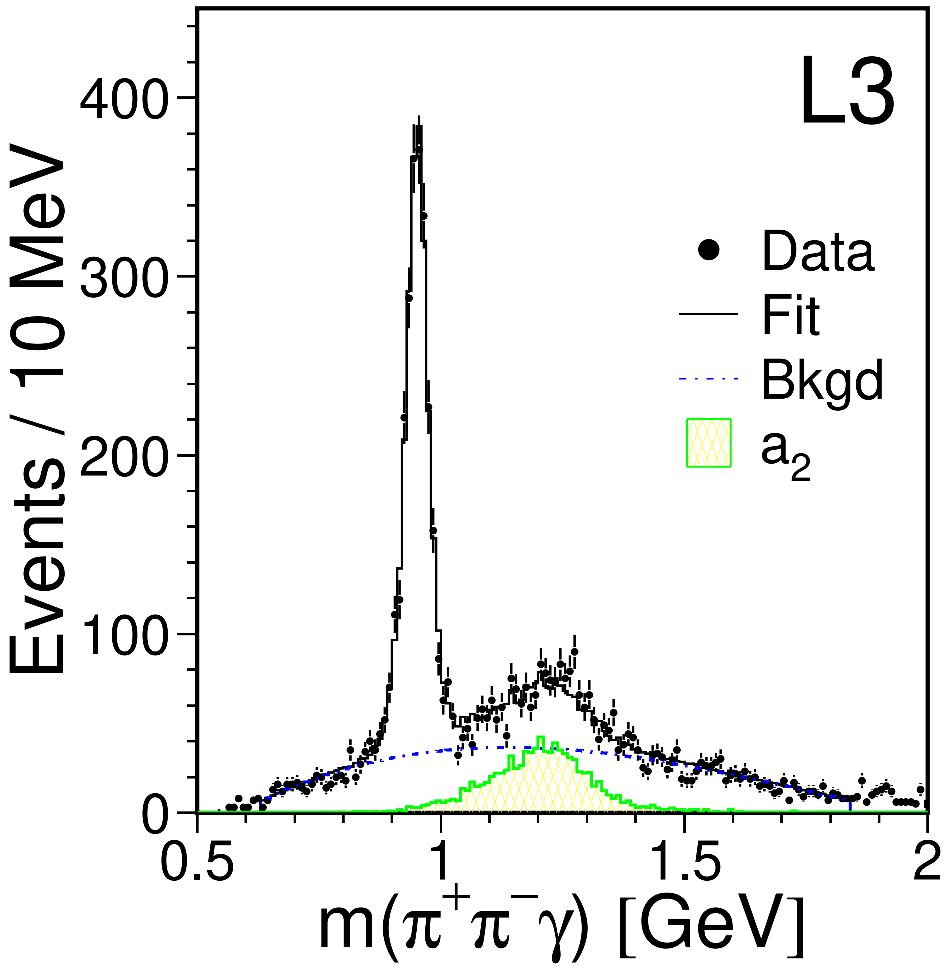
Landau-Yang theorem

J^{PC}	$I=1$	$I=0$	
0^{-+}	π	η	$\eta'(958)$
2^{++}	$a_2(1320)$	$f_2(1270)$	$f_2'(1525)$

$\eta' \to \pi^+\pi^-\gamma$

Select : 2 tracks + 1 photon

Normalize to MC of ρ-pole form factor

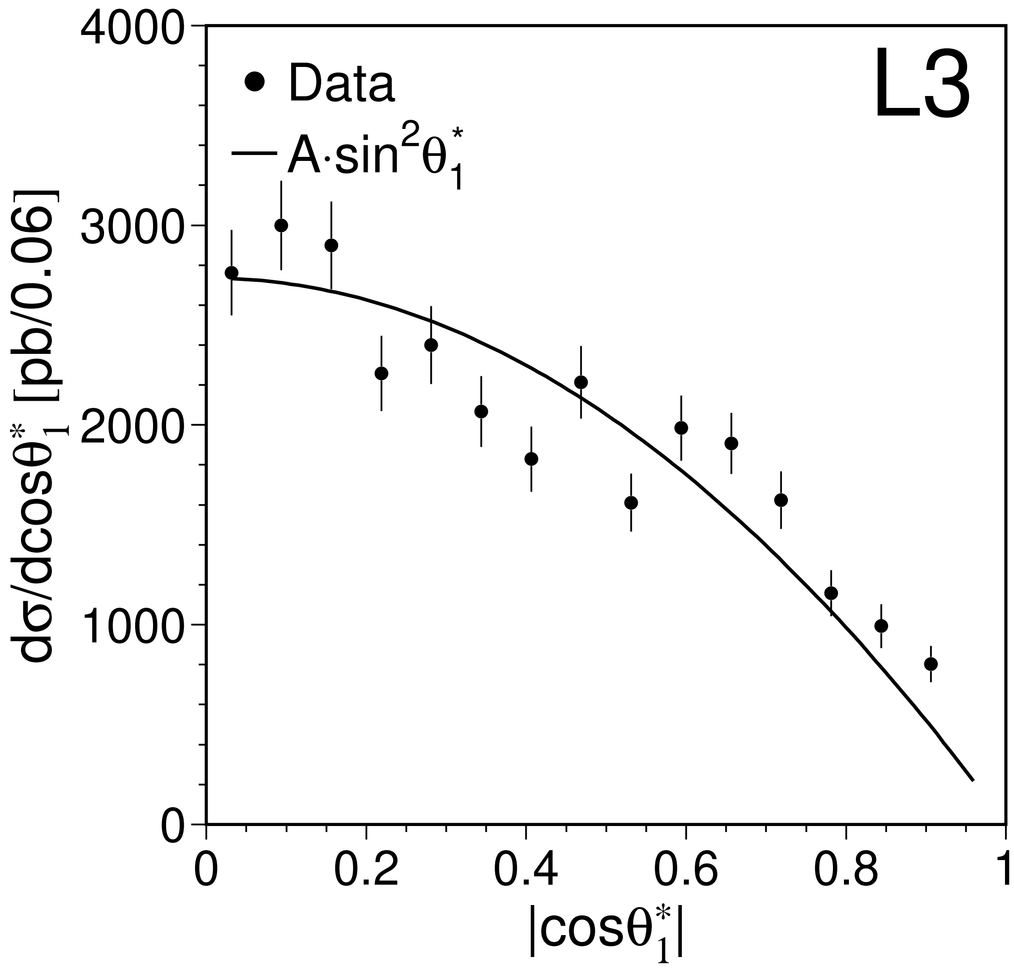


Fit : MC η', inclusive a_2, background

$$\Gamma_{\gamma\gamma} = 4.17 \pm 0.10 \pm 0.27 \text{ keV}$$

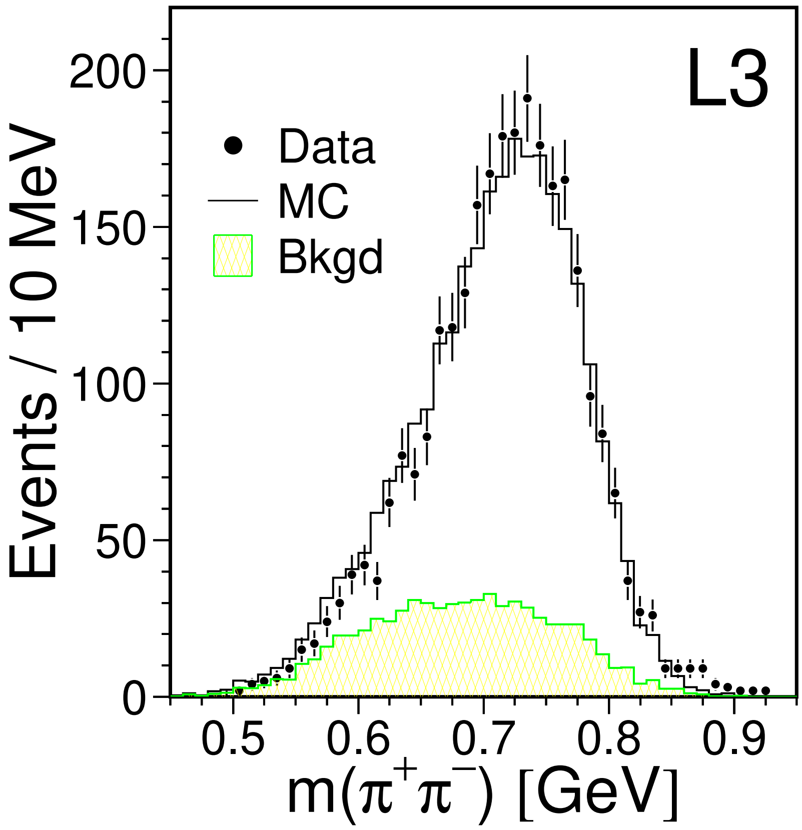
$\eta' \to \rho\gamma$

- $\eta' \to \rho\gamma$ **is dominant**
- **Select** η' **in**
  $0.85 < m(\pi^+\pi^-\gamma) < 1.05$ **GeV**
- ρ **spin=1 :**
  $|\mathcal{M}|^2 \propto \sin^2\theta_1^*$ **in** ρ **CMS**



- **Non-resonance contribution**
  $\eta' \to \pi^+\pi^-\gamma$

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



- **Mass dependent width** [Jackson]

$$\Gamma_\rho = \Gamma_0 \left(\frac{p}{p_0}\right)^3 \frac{m_\rho}{m_{\pi\pi}}$$

$m_\rho = 766 \pm 2$ MeV $\qquad \Gamma_\rho = 150 \pm 5$ MeV

Minimum χ^2 ($\chi^2/15df$=34/32) : $\xi = \phi = 0$

Significance level : 37%

η' cross section

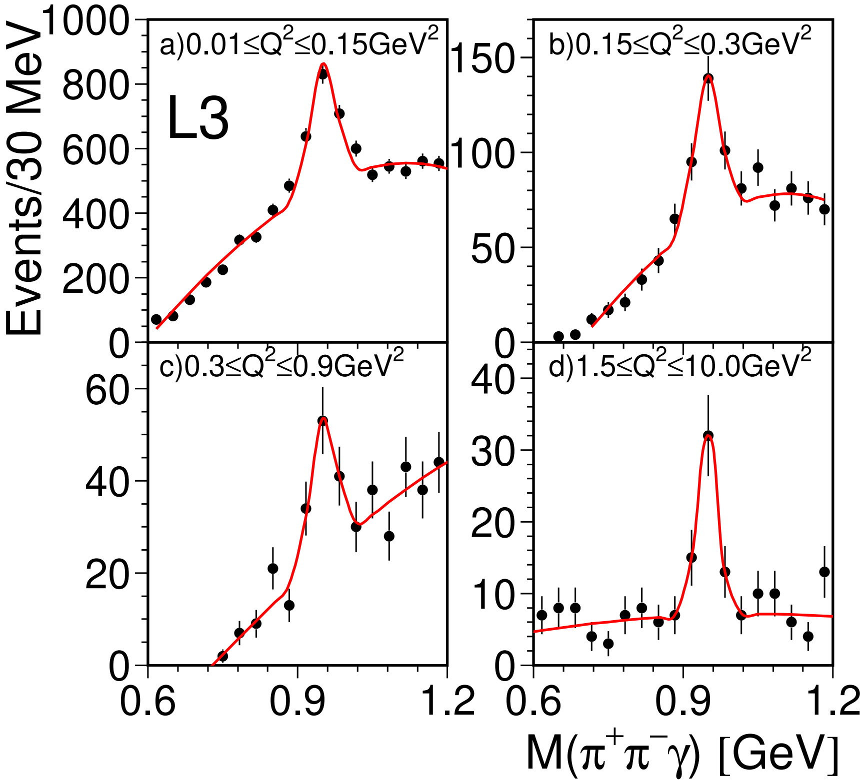
Transition form factor :

$$\sigma_{TT}(Q^2, P^2) = \frac{\pi}{4}\sqrt{X} \cdot F^2(Q^2, P^2) \cdot \sigma(0,0)$$

$$\frac{F^2(Q^2,P^2)}{F^2(0,0)} = \left(\frac{1}{1+Q^2/\Lambda^2}\right)^2 \cdot \left(\frac{1}{1+P^2/\Lambda^2}\right)^2$$

$$Q^2 \simeq \max(-q_1^2, -q_2^2),\ P^2 \simeq \min(-q_1^2, -q_2^2)$$

- **Untagged** : $0.01 < Q^2 < 0.9$ GeV^2
  $Q^2 \simeq |p_T|^2$
- **Single Tagged** : $1.5 < Q^2 < 10$ GeV^2
  $Q^2 \simeq 2E_{beam}E_{tag}(1 - \cos\theta_{tag})$

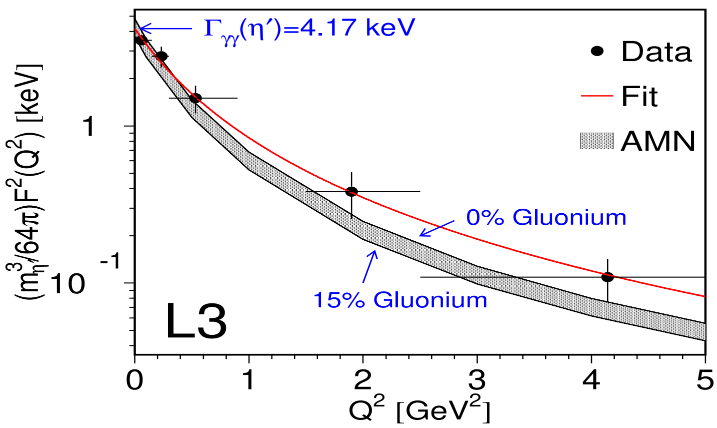


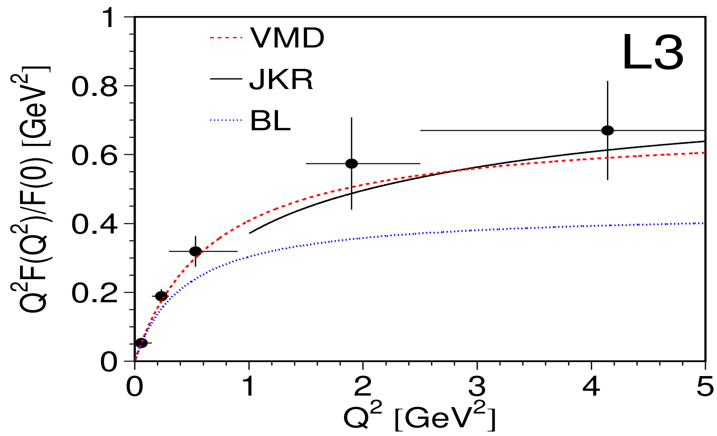
η' Form Factor

In each Q^2 interval :

Fit $F^2(\langle Q^2\rangle) = \left(\frac{1}{1+\langle Q^2\rangle/\Lambda^2}\right)^2$

$\langle Q^2\rangle$ **offset unfolded by MC**



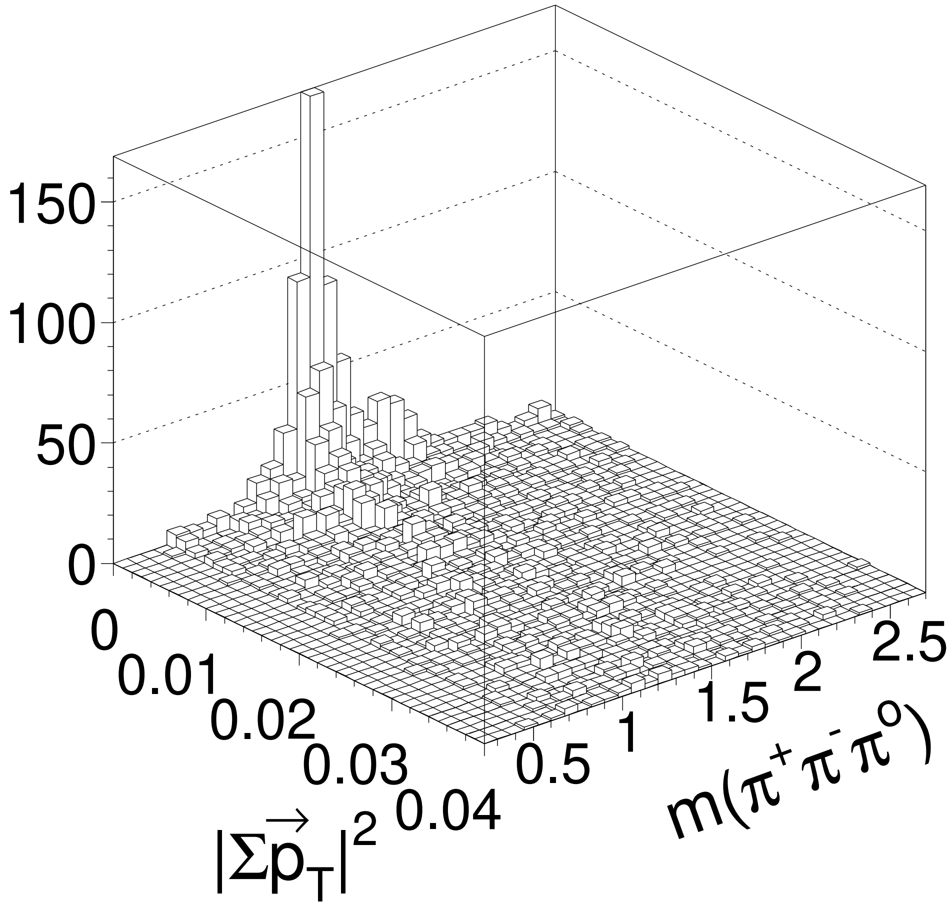


- **Shaded : QCD model with gluonium content [Anisovich et al.]**
- **VMD : Vector Dominant Model**
- **BL : QCD model [Brodsky,Lepage]**
- **JKR : QCD model [Jacob,Kroll,Raulfs]**

$$\Lambda_{fit} = 0.900 \pm 0.046 \pm 0.022 \text{ GeV}$$

Exclusive $\pi^+\pi^-\pi^0$ Selection

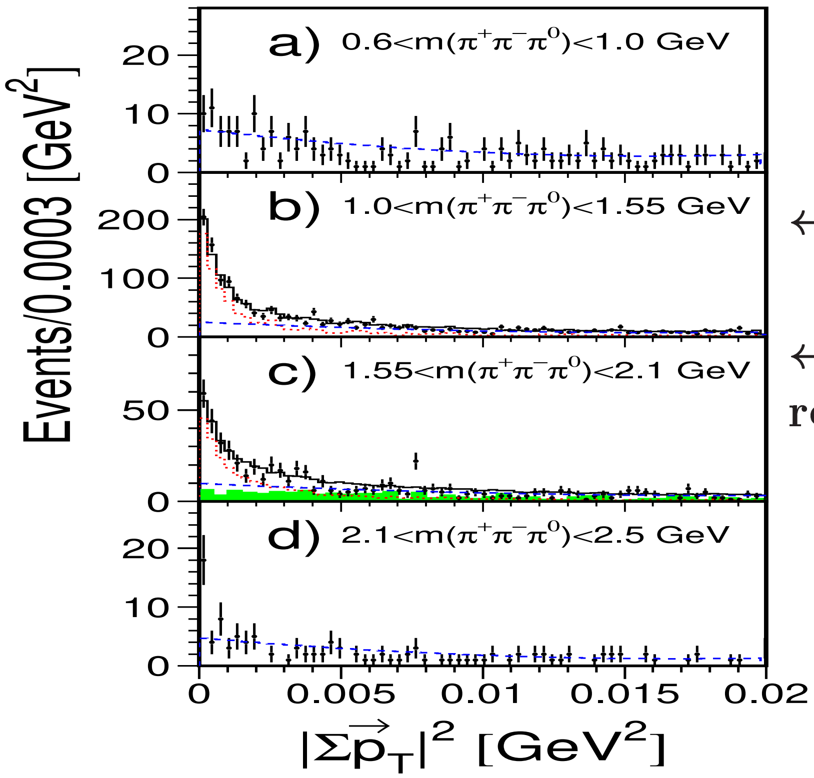
- Select $\pi^0 \to \gamma\gamma$:
  $105 < m(\gamma\gamma) < 165$ MeV
- Exclusive production :
  $|p_T|^2 < 0.0015$ GeV^2



Background in $|p_T|^2$

Fit $|p_T(\pi\pi\pi)|^2$ distributions to

- **Background : 2nd order polynomial (dashed)**
- **Resonance : Q^2 dependence MC (dotted);**



← $a_2(1320)$

← *high-mass region*
reported as $\pi_2(1670)$

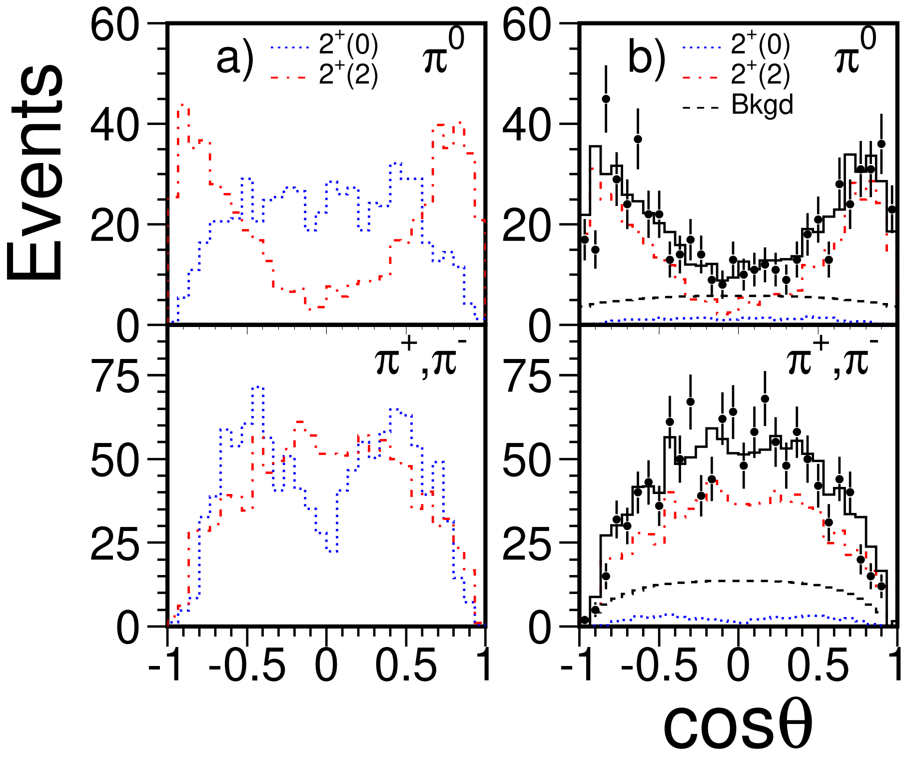
Inclusive background :
Estimated by $\pi^+\pi^-\pi^0(\pi^0)$ phase space (shaded)

Background fractions :

mass [GeV]	0.60 – 1.00	1.00 – 1.55	1.55 – 2.10	2.10 – 2.50
Total ev.	42	618	184	38
Bkgd [%]	–	19±0.5	25±3	–

$a_2(1320)$ Helicity

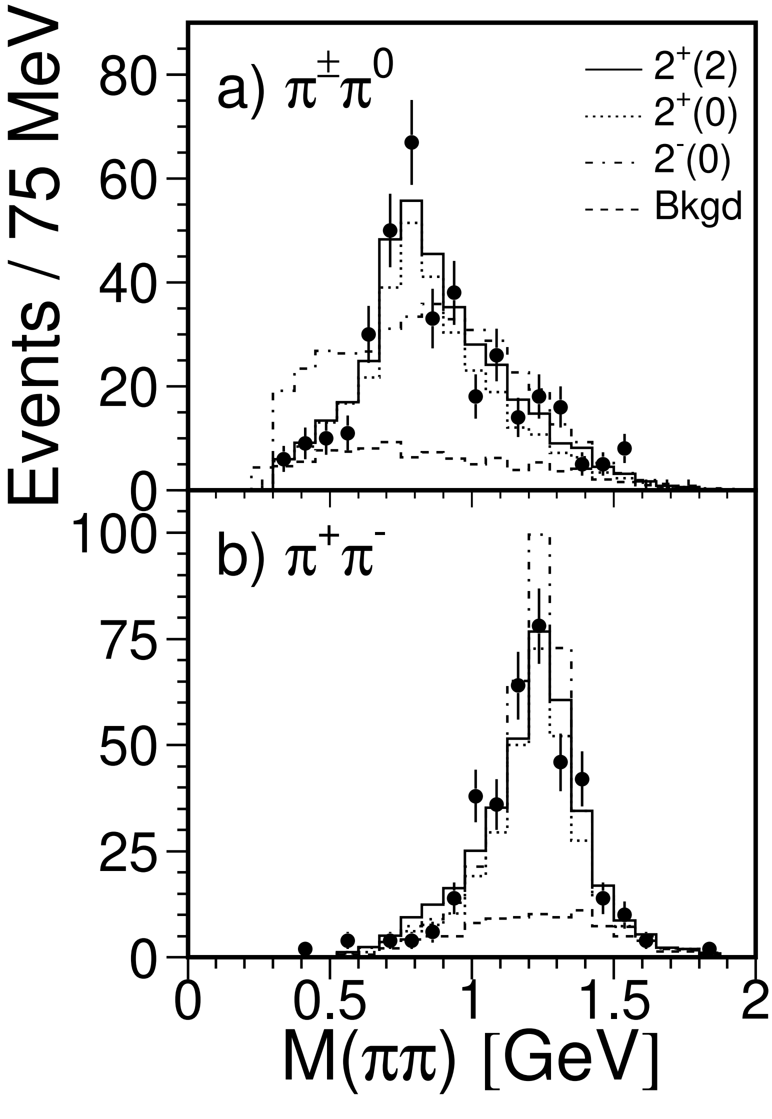
- $a_2(1320) \to \rho\pi$
- $J^P = 2^+$:
  helicity can be 0 or 2
  Fit $\cos\theta$ distributions in a_2 CMS



- Helicity 2 fraction :
  $P_2 = 0.92 \pm 0.05 \pm 0.05$

- $1.55 < m(\pi^+\pi^-\pi^0) < 2.1$ GeV
- intermediate di-pion : ρ, f_2

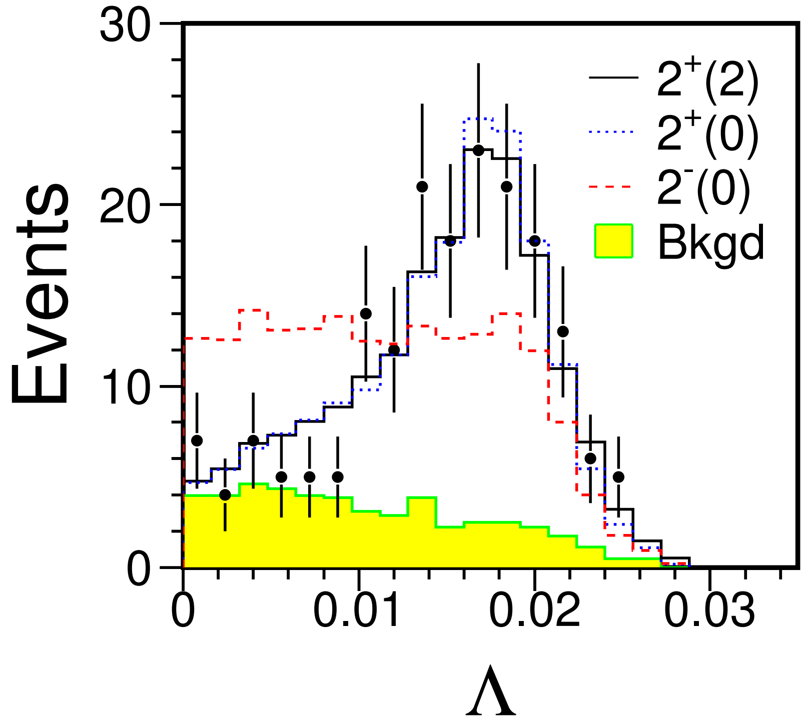
Di-pion mass spectra :



$\pi^+\pi^-\pi^0$ in High-mass region

- **Spin-Parity :**
  - Consider $J^P(\lambda) = 2^-(0), 2^+(0), 2^+(2)$
  - $d\sigma \propto |BW_\rho \cdot T(\rho\pi) + \alpha e^{i\phi} \cdot BW_{f_2} \cdot T(f_2\pi)|^2$

- **$J^P(\lambda)$ tests :** $\Lambda = \left|\frac{\vec{p}_{\pi+} \times \vec{p}_{\pi-}}{Q_K^2}\right|^2$



- **J^P in favor of 2^+**

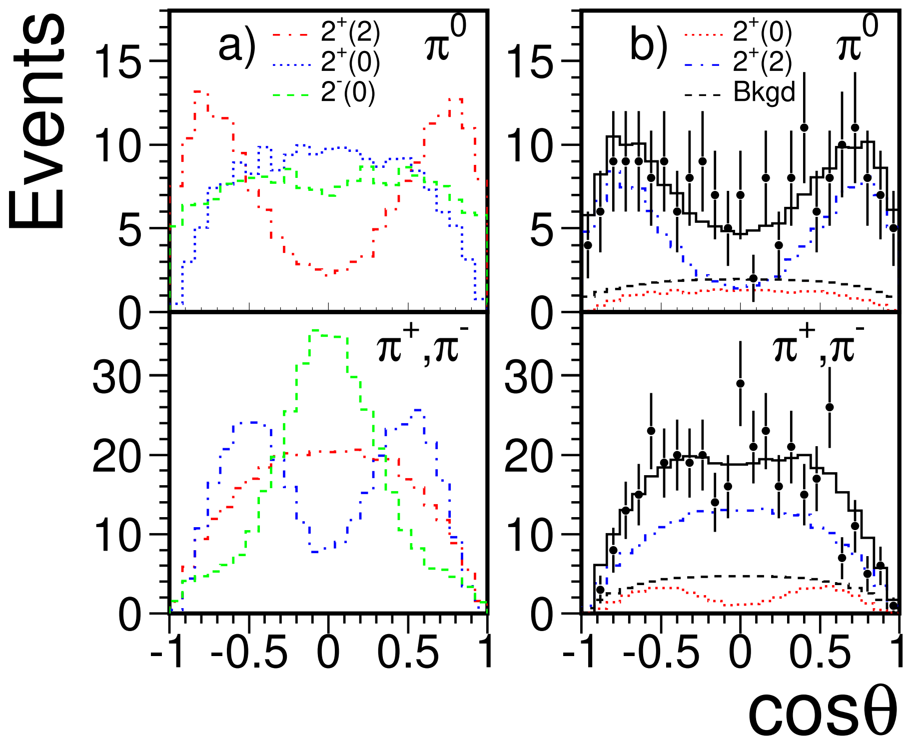
	$2^+(0)$	$2^+(2)$	$2^-(0)$
$\chi^2/15df$	0.61	0.83	3.94

- **For $J^P(\lambda) = 2^+(2)$**

$$\phi = 170^\circ \pm 17^\circ$$
$$\alpha = 0.97 \pm 0.17$$

Helicity, High-mass Sample

- $J^P = 2^+$:
  helicity can be 0 or 2
  Fit $\cos\theta$ distributions in $\pi^+\pi^-\pi^0$ CMS

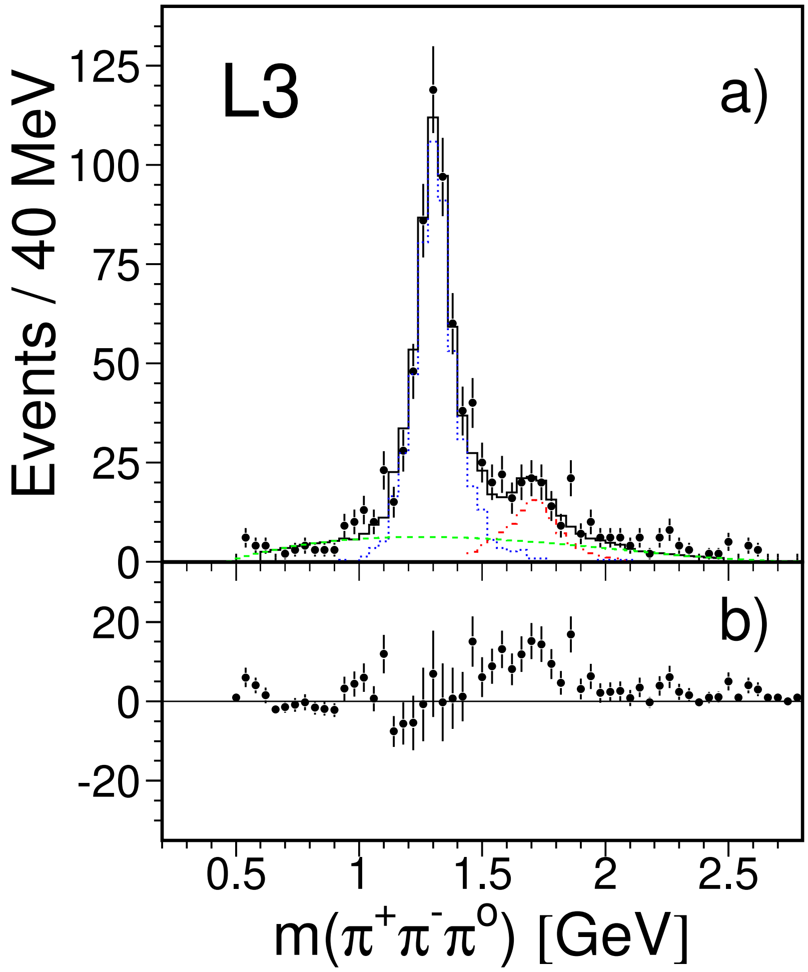


- Helicity 2 fraction :
  $P_2 = 0.77 \pm 12\ \%$

- Including $2^-(0)$ contribution :
  $\Gamma_{\gamma\gamma}(\pi_2) BR(\pi^+\pi^-\pi^0) < 0.072$ keV (90% CL)

$\pi^+\pi^-\pi^0$ Mass Spectrum

- **Fit mass spectrum :**
  MC $a_2(1320)$ + Breit-Wigner (1750)



- **Resonance Parameters :**

	$a_2(1320)$	high mass region
$\Gamma_{\gamma\gamma}$ [keV]	$0.98 \pm 0.05 \pm 0.09$	–
$\Gamma_{\gamma\gamma} \cdot BR$ [keV]	–	$0.29 \pm 0.04 \pm 0.02$
m [MeV]	$1323 \pm 4 \pm 3$	$1752 \pm 21 \pm 11$
Γ [MeV]	$105 \pm 10 \pm 11$	$150 \pm 110 \pm 34$

OGE-SRM[1] predicts radial excitation a_2' :
m=1740 MeV, $\Gamma_{\gamma\gamma}$ =0.33-0.38 keV

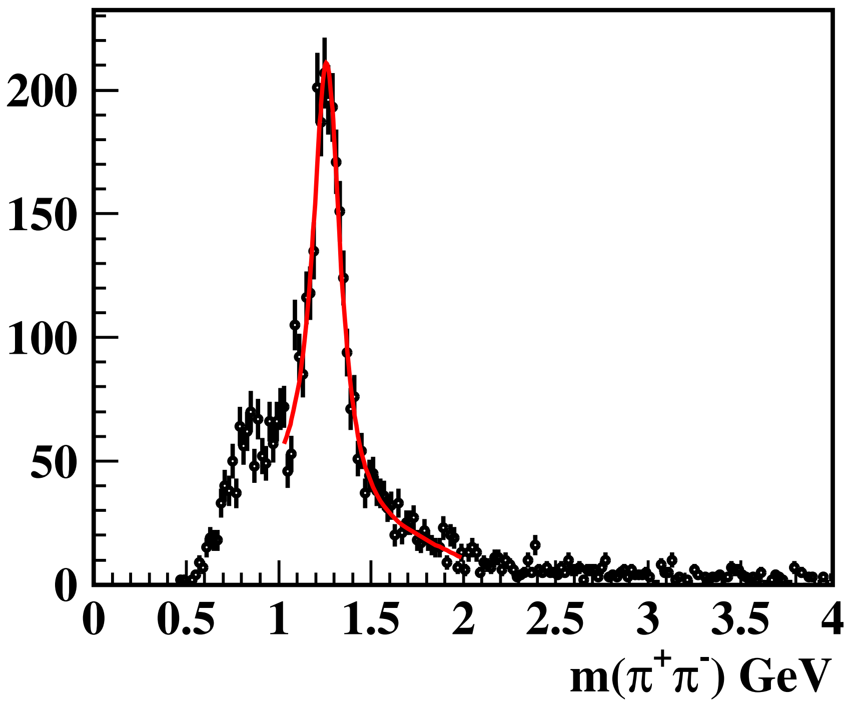
[1]C.R. Münz, Nucl.Phys. A609 (1996) 364

$\gamma\gamma \to \pi^+\pi^-$ sample

Hadronic track pairs :

- e, μ **rejected by Neural Network**
- **dominated by** $\pi^+\pi^-$ **pair**

Effective mass of $\pi^+\pi^-$ **pair**

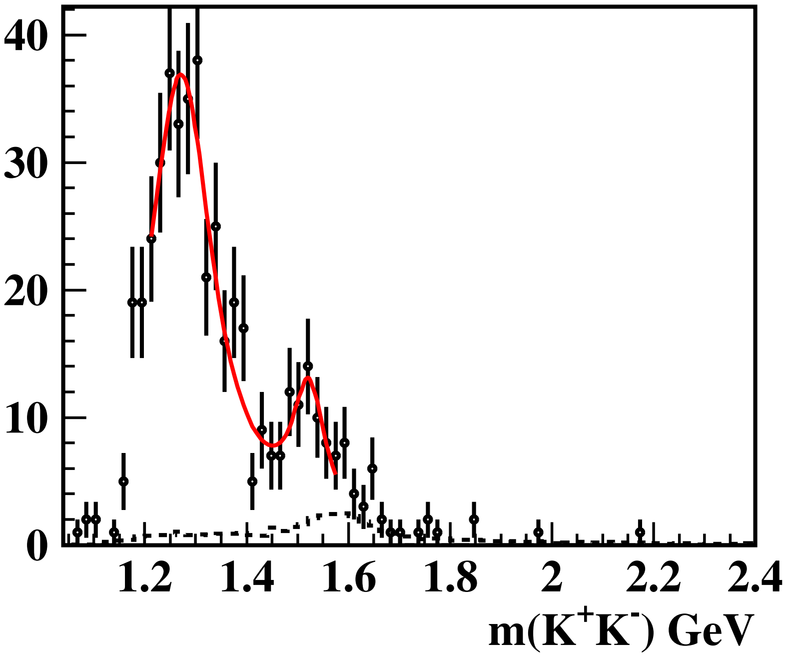


Breit-Wigner fit for f_2 **:**

- $m = 1260 \pm 3$ **MeV**
- $\Gamma = 184 \pm 12$ **MeV**

$\gamma\gamma \to K^+K^-$ sample

Effective K^+K^- mass

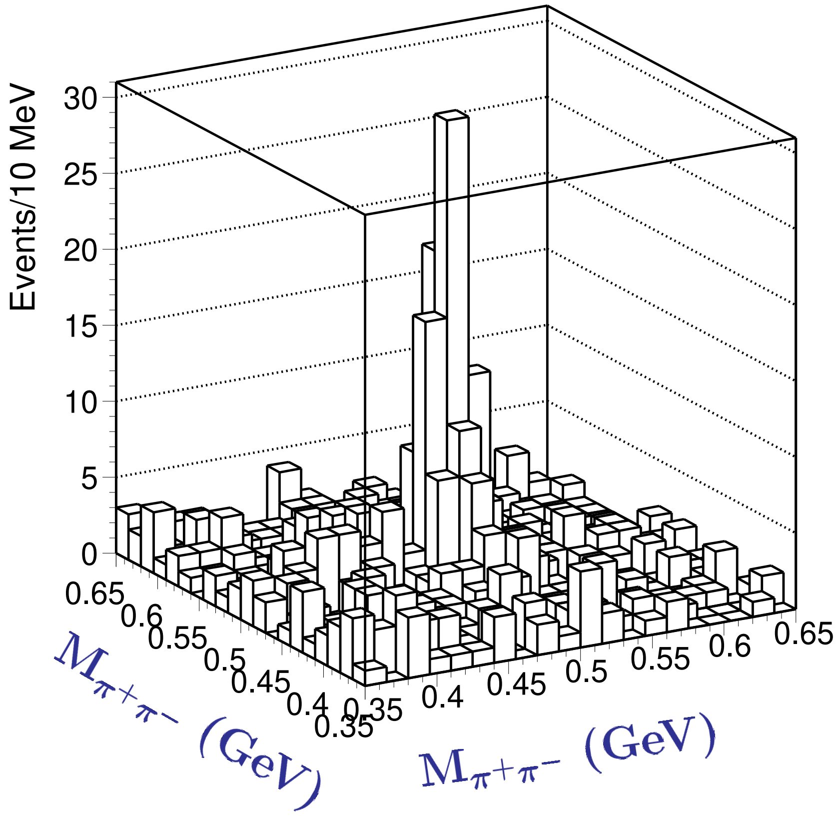


Fit to two Breit-Wigner terms, background

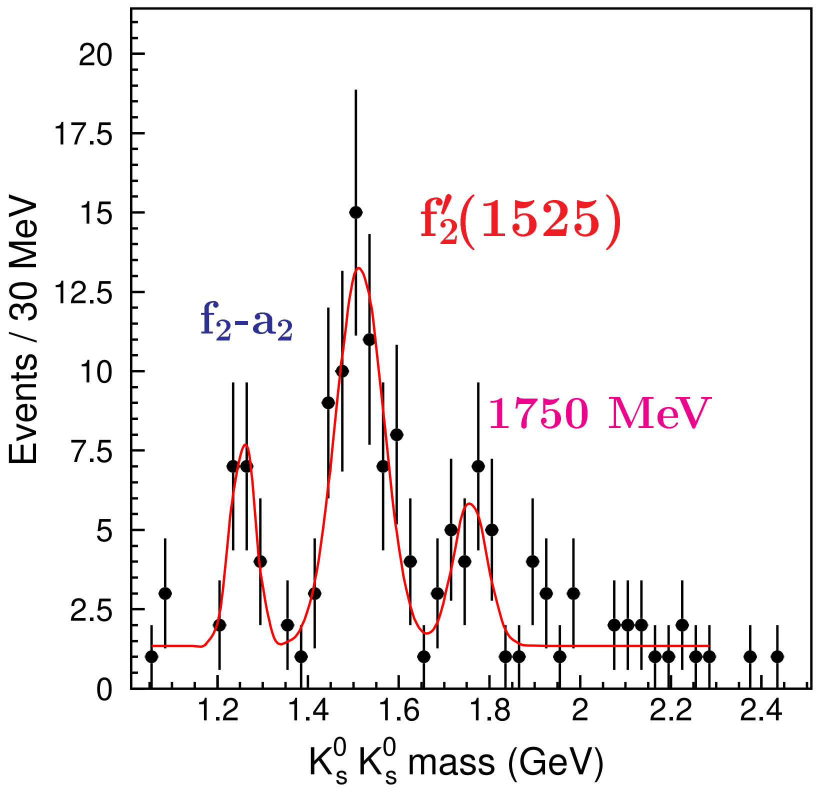
- f_2, a_2 Constructive interference [Lipkin]
  $m = 1271 \pm 8$ MeV
  $\Gamma = 158 \pm 23$ MeV
- $f_2'(1525)$
  $m = 1522 \pm 9$ MeV
  $\Gamma = 79 \pm 32$ MeV

$K_s^0 K_s^0$ Final State

- $K_s^0 \to \pi^+\pi^-$
  selected using secondary vertex
- Two pairs of $m(\pi^+\pi^-)$
  within $m_{K_s} \pm 30$ MeV
- 148 events are selected.



$K_s^0 K_s^0$ Mass Spectrum

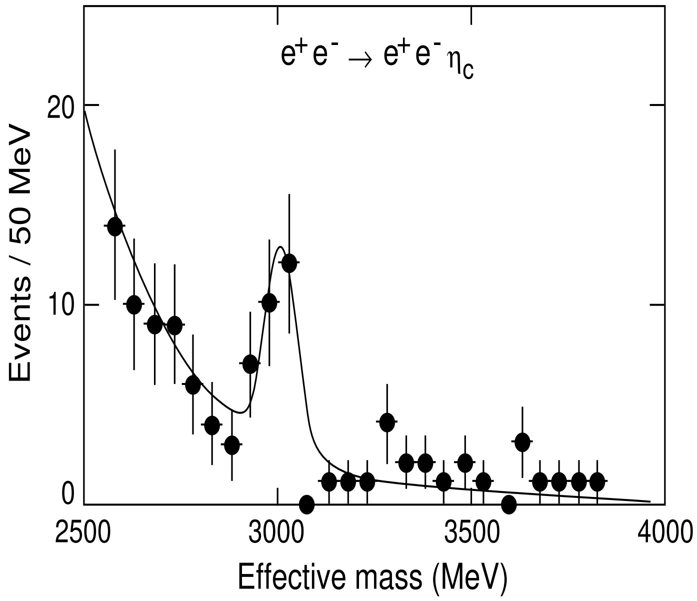


Maximum Likelihood fit:

	Mass (MeV)	Width (MeV)	Events
$f_2'(1525)$	1515 ± 10	112 ± 19	57.4 ± 9.2
1750 MeVRegion	1760 ± 14	119 ± 26	17.4 ± 5.6

- f_2-a_2 **destructive interference** [Lipkin]
- $\Gamma_{\gamma\gamma}(f_2')\ \times \mathrm{BR}(f_2' \to K\bar{K})$
  $=0.09 \pm 0.02 \pm 0.02$ **keV for pure helilicity-2**
- **Enhancement at 1750 MeV (3 σ effect)**
- **OGE-SRM prediction :**
  f_2'', M=1740 MeV, $\Gamma_{\gamma\gamma}=$ 1.040 keV

Combined η_c mass spectrum :



Event selected in 2900-3100 MeV

Channel	$\mathcal{BR}$ [3] %	Acceptance %	N_{obs}	N_{back}
$\eta\pi^+\pi^-$ ($\eta \Rightarrow \gamma\gamma$)	1.27 ± 0.47	2.4 ± 0.1	1	0.
$\eta\pi^+\pi^-$ ($\eta \Rightarrow \pi^+\pi^-\pi^0$)	0.77 ± 0.28	0.53 ± 0.07	2	0.8 ± 0.6
$\eta'\pi^+\pi^-$ ($\eta' \Rightarrow \rho^0\gamma$)	0.82 ± 0.34	5.2± 0.2	2	0.5 ± 0.3
$\eta'\pi^+\pi^-$ ($\eta' \Rightarrow \pi^+\pi^-\eta$)	0.47 ± 0.19	1.3 ± 0.2	0	0.5 ±0.6
$\eta'\pi^+\pi^-$ ($\eta' \Rightarrow \gamma\gamma$)	0.06 ± 0.02	3.0 ± 0.2	1	0.
$\pi^+\pi^-\pi^+\pi^-$	1.2 ± 0.4	3.7 ± 0.1	8	1.7±0.3
$K^+K^-\pi^+\pi^-$	2.0 ± 0.7	3.6 ± 0.2	4	3.2±0.4
$K^{\star 0}K^\pm\pi^\mp$ ($K^{\star 0} \Rightarrow K^\mp\pi^\pm$)	1.33 ± 0.46	6.6 ± 0.2	5	2.9±0.3
$K^{\star 0}K^{\star 0}$ ($K^{\star 0} \Rightarrow K^\pm\pi^\mp$)	0.19 ± 0.06	5.8 ± 0.3	1	0.5±0.2
$\phi\phi$ ($\phi \Rightarrow K^-K^+$)	0.17 ± 0.07	5.6 ± 0.2	0	0.
$K_s^0K^\pm\pi^\mp$ ($K_s^0 \Rightarrow \pi^-\pi^+$)	1.51 ± 0.41	6.9 ± 0.3	3	0.5±0.2
$K^+K^-\pi^0$	1.10 ± 0.30	3.8 ± 0.2	1	0.2±0.1

Maximizing likelihood function

$$L(\Gamma_{\gamma\gamma}(\eta_c)) = \Pi_i^{Ch} P(N^i_{obs}|N^i_{exp})$$

$$\Gamma_{\gamma\gamma}(\eta_c) = 8.0 \pm 2.3 \pm 2.4 \text{ keV}$$

$\chi_{c2}(3556)$:

2^{++} P-wave charmonium state

Decay modes considered for χ_{c2} :

- $\chi_{c2} \to \gamma J/\psi$

  $J/\psi \to \mu^+\mu^-$

  $J/\psi \to e^+e^-$

- BR($\chi_{c2} \to l^+l^-\gamma$) = 1.61 ± 0.14 %
- Background ~ $\mathcal{O}(\alpha^5)$ QED processes

QCD prediction :

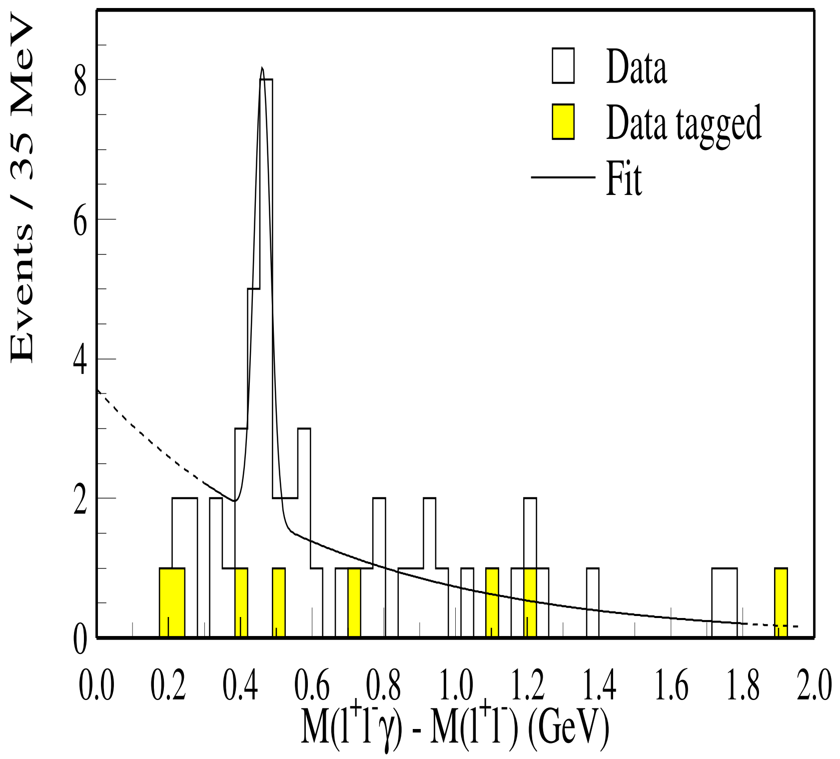
$$\frac{\Gamma(\chi_{c2}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to gg)} = \frac{8}{9}\left(\frac{\alpha}{\alpha_s}\right)^2 \simeq \frac{\Gamma(\chi_{c2}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to hadrons)} \qquad \Gamma_{\gamma\gamma} = 1.5 \text{ keV} \quad [1]$$

$$\frac{\Gamma(\chi_{c2}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to gg)} = \frac{8}{9}\left(\frac{\alpha}{\alpha_s}\right)^2 \simeq \frac{\Gamma(\chi_{c2}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to hadrons)-\Gamma(\chi_{c1}\to hadrons)}$$

$$\Gamma_{\gamma\gamma} = 0.8 \text{ keV} \quad [2]$$

[1] V.A. Novikov et al. Phys. Rep. 41 (1978) 1.
[2] G.T. Bodwin et al. Phys. Rev. D46 (1992) R1914.

- **Mass spectrum of $m(\chi_{c2}) - m(J/\psi)$ peak at 459 MeV**



- **Events observed:**
  $N_{\chi_{c2}} = 10.6 \pm 4.0$

- **Normalize to MC J/ψ-pole form factor :**
  $\Gamma_{\gamma\gamma} = 1.5 \pm 0.6 \pm 0.3$ keV

Conclusion

- $\eta' \to \rho\gamma$
  $\Gamma_{\gamma\gamma} = 4.17 \pm 0.10 \pm 0.27$ keV
  Form factor $\Lambda = 0.900 \pm 0.046 \pm 0.022$ GeV
- Radial excitation a_2'
  $m = 1752 \pm 21 \pm 11$ MeV
  $\Gamma = 150 \pm 110 \pm 34$ MeV
- $K_s K_s$ enhancement at 1750
  $m = 1760 \pm 14$ MeV
  $\Gamma = 119 \pm 26$ MeV
- η_c, χ_{c2} observed
  $\Gamma_{\gamma\gamma}(\chi_{c2}) = 1.5 \pm 0.6 \pm 0.3$ keV
- $\Gamma_{\gamma\gamma}$ of Tensor states
  agree with Relativistic Quark Model