Scalar meson exchange in $\phi \to P^0 P^0 \gamma$ decays

Rafel Escribano
Grup de Física Teòrica and IFAE (UAB)

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Motivation:

- excellent laboratory for investigating the light scalar meson resonances
- complements other analyses based on central production, D and J/ψ decays...

- Experimental data
- Theory review: scalar models market
- *Golden processes*:

$$\phi \to \pi^0\pi^0\gamma \quad \longleftrightarrow \quad f_0(980)$$
$$\phi \to \pi^0\eta\gamma \quad \longleftrightarrow \quad a_0(980)$$

- Other proc.: $\phi \to K^0\bar{K}^0\gamma$
- Conclusions

Experimental data

$\phi \to \pi^0\pi^0\gamma$

SND PL B485 (00) 349

$$B(\phi \to \pi^0\pi^0\gamma) = (1.221 \pm 0.098 \pm 0.061) \times 10^{-4}$$

CMD-2 PL B462 (99) 380

$$B(\phi \to \pi^0\pi^0\gamma) = (1.08 \pm 0.17 \pm 0.09) \times 10^{-4}$$

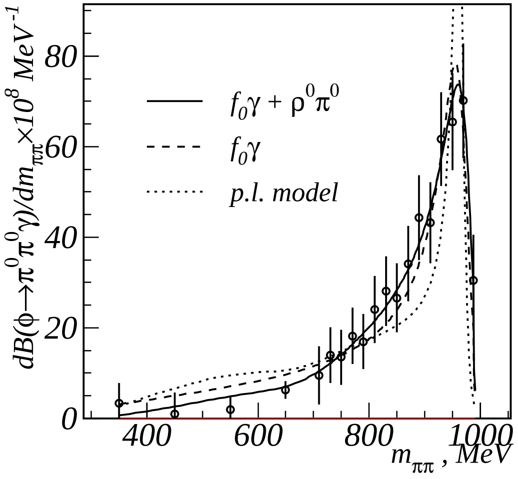
KLOE PL B537 (02) 21

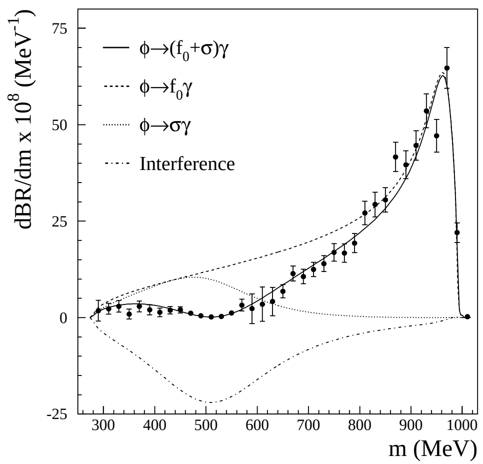
$$B(\phi \to \pi^0\pi^0\gamma) = (1.09 \pm 0.03 \pm 0.05) \times 10^{-4}$$

significant enhancement at large $\pi^0\pi^0$ invariant mass

$\Longrightarrow$

manifestation of a sizable contribution of the $f_0(980)\gamma$ intermediate state





Experimental data

$\phi \to \pi^0 \eta \gamma$

SND PL B479 (00) 53

$$B(\phi \to \pi^0 \eta \gamma) = (0.88 \pm 0.14 \pm 0.09) \times 10^{-4}$$

CMD-2 PL B462 (99) 380

$$B(\phi \to \pi^0 \eta \gamma) = (0.90 \pm 0.24 \pm 0.10) \times 10^{-4}$$

KLOE PL B536 (02) 209

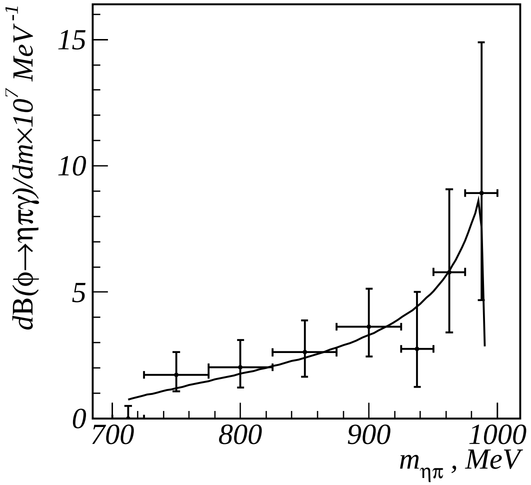
$$B(\phi \to \pi^0 \eta \gamma) = (0.851 \pm 0.051 \pm 0.057) \times 10^{-4} \quad (\eta \to \gamma\gamma)$$

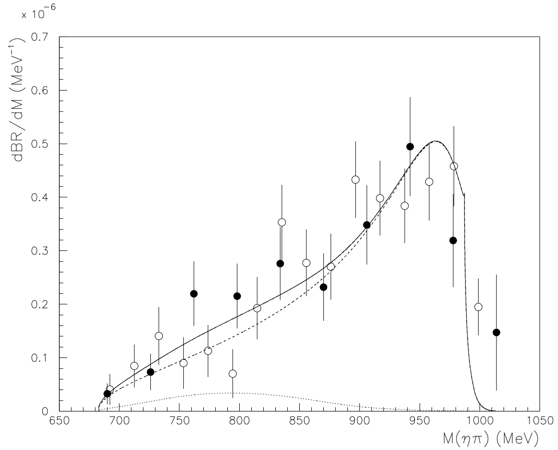
$$B(\phi \to \pi^0 \eta \gamma) = (0.796 \pm 0.060 \pm 0.040) \times 10^{-4} \quad (\eta \to \pi^+\pi^-\pi^0)$$

significant enhancement at large $\pi^0\eta$ invariant mass

$\Longrightarrow$

manifestation of a sizable contribution of the $a_0(980)\gamma$ intermediate state



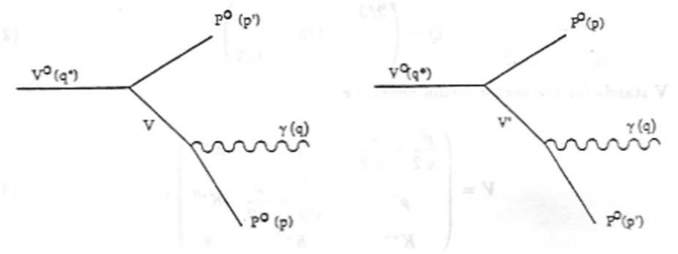


Theory Review

VMD

A. Bramon, A. Grau & G. Pancheri, PL B283 (92) 416

$$\mathcal{L}_{\mathrm{VVP}} = \frac{G}{\sqrt{2}}\epsilon^{\mu\nu\alpha\beta}\langle\partial_\mu V_\nu \partial_\alpha V_\beta P\rangle$$
$$\mathcal{L}_{\mathrm{V}\gamma} = -4f^2 eg A_\mu \langle Q V^\mu\rangle$$

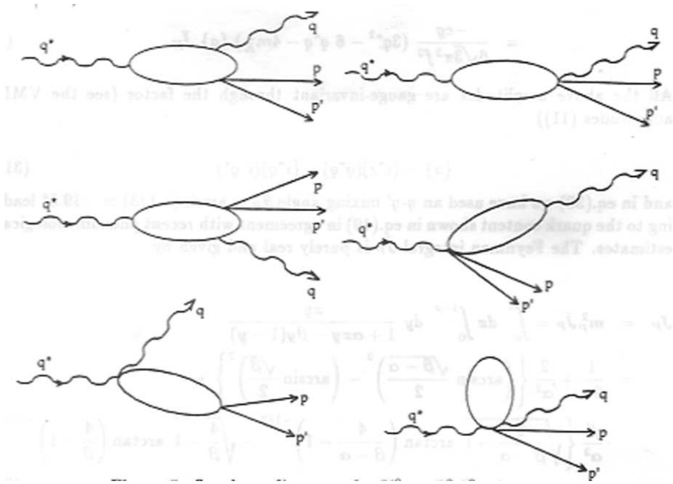


$$B^{\mathrm{VMD}}_{\phi\to\pi^0\pi^0\gamma} = 1.2\times 10^{-5} \qquad V = V' = \rho$$
$$B^{\mathrm{VMD}}_{\phi\to\pi^0\eta\gamma} = 5.4\times 10^{-6} \qquad V = \rho, V' = \omega$$
$$B^{\mathrm{VMD}}_{\rho\to\pi^0\pi^0\gamma} = 1.3\times 10^{-5} \qquad V = V' = \omega$$

ChPT $+\rho\to\pi^+\pi^- + \phi\to K^+K^-$

A. Bramon, A. Grau & G. Pancheri, PL B289 (92) 97

$$\mathcal{L}_2 = \frac{f^2}{4}\langle D_\mu U^\dagger D^\mu U + M(U+U^\dagger)\rangle$$



$$\left.\begin{array}{l} B^\chi = 5.0\times 10^{-5} \\ B^\chi = 3.0\times 10^{-5} \\ B^\chi = 1.0\times 10^{-5}\end{array}\right\} \Rightarrow \left\{\begin{array}{l} B^{\mathrm{VMD}+\chi} = 6.1\times 10^{-5} \\ B^{\mathrm{VMD}+\chi} = 3.6\times 10^{-5} \\ B^{\mathrm{VMD}+\chi} = 2.9\times 10^{-5}\end{array}\right.$$

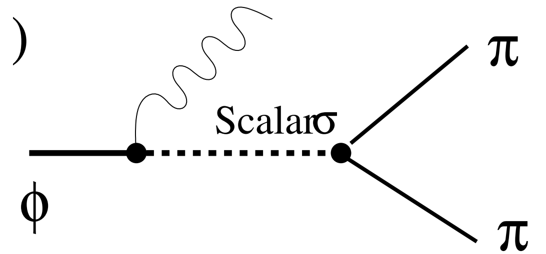
BUT both approaches do not contain the effect of scalar resonances

Scalar models market

All the following models contain the scalar resonances explicitly

No structure

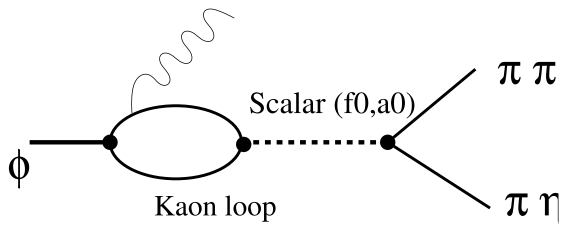
excluded by experimental data on $\phi \to \pi^0\pi^0\gamma$



Kaon loop

N. N. Achasov & V. V. Gubin, PR D63 (01) 094007

used in the experimental analyses of $\phi \to \pi^0\pi^0\gamma$ and $\phi \to \pi^0\eta\gamma$ decays

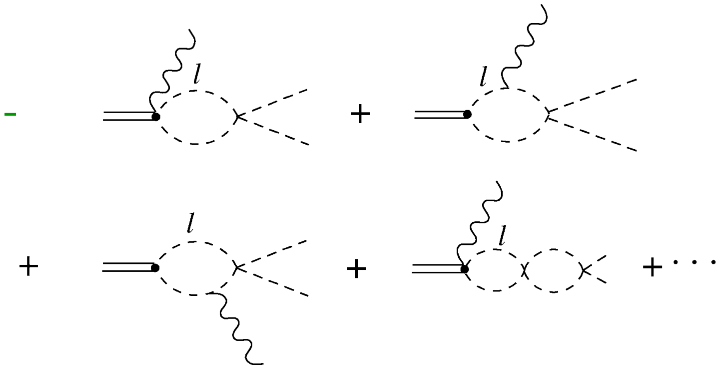


scalar resonances *ad hoc*

UχPT

E. Oset *et al.*, PL B470 (99) 20, NP A707 (02) 161

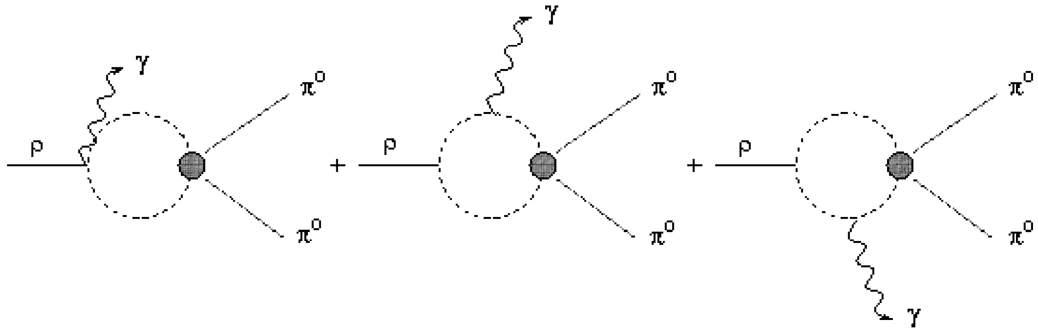
scalar resonances are generated dynamically by unitarizing the one-loop amplitudes

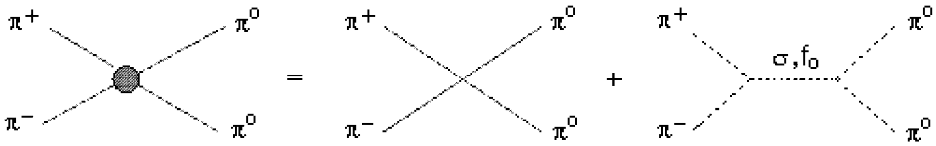


$$B^{\mathrm{U}\chi\mathrm{PT}}_{\phi\to\pi^0\pi^0\gamma} = 8 \times 10^{-5}$$
$$B^{\mathrm{U}\chi\mathrm{PT}}_{\phi\to\pi^0\eta\gamma} = 8.7 \times 10^{-5}$$
$$B^{\mathrm{U}\chi\mathrm{PT}}_{\rho\to\pi^0\pi^0\gamma} = 1.5 \times 10^{-5}$$

Linear Sigma Model

The LσM is a well defined $U(3) \times U(3)$ chiral model which incorporates *ab initio* both the pseudoscalar nonet together with its chiral partner the scalar nonet





$\phi \to \pi^0\pi^0\gamma$	$P^\pm = K^\pm$	$S = \sigma, f_0$	$\sigma \ll f_0$
$\phi \to \pi^0\eta\gamma$	$P^\pm = K^\pm$	$S = a_0$	
$\rho \to \pi^0\pi^0\gamma$	$P^\pm = \pi^\pm$	$S = \sigma, f_0$	$\sigma \gg f_0$
$\phi \to K^0\bar{K}^0\gamma$	$P^\pm = K^\pm$	$S = \sigma, f_0, a_0$	$f_0 \simeq a_0 \gg \sigma$

For the rest of the processes, the scalar contribution is not relevant

The complementarity between ChPT and the LσM will be used for including the scalar meson poles while keeping the correct behaviour at low dimeson invariant mass expected from ChPT

Golden Processes

$\phi \to \pi^0\pi^0\gamma$

A. Bramon, R. E., J. L. Lucio M., M. Napsuciale & G. Pancheri, EPJ C26 (02) 253

$\mathcal{A}(\phi\to\pi^0\pi^0\gamma)_{\mathrm{L}\sigma\mathrm{M}} \propto$ kaon loop $\times\,\mathcal{A}(K^+K^-\to\pi^0\pi^0)_{\mathrm{L}\sigma\mathrm{M}}$

with

$$\mathcal{A}(K^+K^-\to\pi^0\pi^0)_{\mathrm{L}\sigma\mathrm{M}} = g_{K^+K^-\pi^0\pi^0}$$

$$-\frac{g_{\sigma K^+K^-}g_{\sigma\pi^0\pi^0}}{s-m_\sigma^2} - \frac{g_{f_0K^+K^-}g_{f_0\pi^0\pi^0}}{s-m_{f_0}^2} - \frac{g^2_{\kappa^\mp K^\pm\pi^0}}{t-m_\kappa^2} - \frac{g^2_{\kappa^\mp K^\pm\pi^0}}{u-m_\kappa^2}$$

and

$$g_{\sigma K\bar K} = \frac{m_K^2-m_\sigma^2}{2f_K}(\mathrm{c}\phi_S - \sqrt{2}\mathrm{s}\phi_S) \qquad g_{\sigma\pi\pi} = \frac{m_\pi^2-m_\sigma^2}{f_\pi}\mathrm{c}\phi_S$$

$$g_{f_0 K\bar K} = \frac{m_K^2-m_{f_0}^2}{2f_K}(\mathrm{s}\phi_S + \sqrt{2}\mathrm{c}\phi_S) \qquad g_{f_0\pi\pi} = \frac{m_\pi^2-m_{f_0}^2}{f_\pi}\mathrm{s}\phi_S$$

Using the soft-pion limit:

$$\mathcal{A}(K^+K^-\to\pi^0\pi^0)_{\mathrm{L}\sigma\mathrm{M}} = \frac{s-m_\pi^2}{2f_\pi f_K}$$

$$\times\left[\frac{m_K^2-m_\sigma^2}{D_\sigma(s)}\mathrm{c}\phi_S(\mathrm{c}\phi_S-\sqrt{2}\mathrm{s}\phi_S) + \frac{m_K^2-m_{f_0}^2}{D_{f_0}(s)}\mathrm{s}\phi_S(\mathrm{s}\phi_S+\sqrt{2}\mathrm{c}\phi_S)\right]$$

$$+\frac{t-m_K^2}{4f_\pi f_K}\frac{m_\pi^2-m_\kappa^2}{D_\kappa(t)} + \frac{u-m_K^2}{4f_\pi f_K}\frac{m_\pi^2-m_\kappa^2}{D_\kappa(u)}$$

where

- $D_\sigma(s) = s - m_\sigma^2 + i m_\sigma\Gamma_\sigma$
- $D_{f_0}(s) = s - m_{f_0}^2 - \mathrm{Re}\Pi(m_{f_0}^2) + \Pi(s)$
  the complete one-loop propagator to take into account finite width corrections
- ϕ_S is the scalar mixing angle in the quark-flavour basis

Golden Processes

$$\phi \to \pi^0\pi^0\gamma$$

Remarks:

1.

$$\lim_{m_S\to\infty} \mathcal{A}(K^+K^- \to \pi^0\pi^0)_{\mathsf{L\sigma M}} = \frac{s-m_\pi^2}{2f_\pi f_K} + \frac{t+u-2m_K^2}{4f_\pi f_K}$$

$$= \frac{s}{4f_\pi f_K} = \mathcal{A}(K^+K^- \to \pi^0\pi^0)_{\mathsf{ChPT}} \quad ✔$$

2. non-resonant contributions are integrated out:

$$\lim_{m_R\to\infty} \mathcal{A}^{\text{non-resonant}}_{\phi\to\pi^0\pi^0\gamma} = \mathcal{A}^{\chi\text{-loops}}_{\phi\to\pi^0\pi^0\gamma} - \lim_{m_{\sigma,f_0}\to\infty} \mathcal{A}^{\mathsf{L\sigma M}}_{\phi\to\pi^0\pi^0\gamma}$$

$\Longrightarrow$

$$\mathcal{A}(\phi\to\pi^0\pi^0\gamma)_{\mathsf{L\sigma M}} = \frac{e g_s}{2\pi^2 m^2_{K^+}} \{a\}\, L(s) \times \mathcal{A}(K^+K^-\to\pi^0\pi^0)_{\mathsf{L\sigma M}}$$

with

$$\mathcal{A}(K^+K^- \to \pi^0\pi^0)_{\mathsf{L\sigma M}} = \frac{m_\pi^2 - s/2}{2f_\pi f_K} + \frac{s-m_\pi^2}{2f_\pi f_K}$$

$$\times \left[\frac{m_K^2 - m_\sigma^2}{D_\sigma(s)} c\phi_S(c\phi_S - \sqrt{2}s\phi_S) + \frac{m_K^2 - m_{f_0}^2}{D_{f_0}(s)} s\phi_S(s\phi_S + \sqrt{2}c\phi_S)\right]$$

where now only the σ and f_0 poles appear

$\Longrightarrow$

this amplitude should be able to reproduce the $\pi^0\pi^0$ invariant mass spectrum for all $s \equiv m^2_{\pi^0\pi^0}$ ✔

3. if $m_\sigma \simeq m_K$ and Γ_σ is large $\Longrightarrow \sigma \ll f_0$ ✔

4. $\mathcal{A}^{\mathsf{L\sigma M}}_{K^+K^-\to\pi^0\pi^0}$ and consequently $\mathcal{A}^{\mathsf{L\sigma M}}_{\phi\to\pi^0\pi^0\gamma}$ are very dependent on ϕ_S and m_{f_0} ✔

Golden Processes

$\phi \to \pi^0\pi^0\gamma$

Results:

For

$$\left.\begin{array}{l} m_\sigma = 478 \text{ MeV} \\ \Gamma_\sigma = 324 \text{ MeV} \\ \text{E791 Coll., PRL 86 (01) 770} \\ m_{f_0} = 985 \text{ MeV} \\ \phi_S = -9^\circ \end{array}\right\} \Longrightarrow B^{\text{L}\sigma\text{M+VMD}}_{\phi\to\pi^0\pi^0\gamma} = 1.16 \times 10^{-4}$$

in nice agreement with experimental results

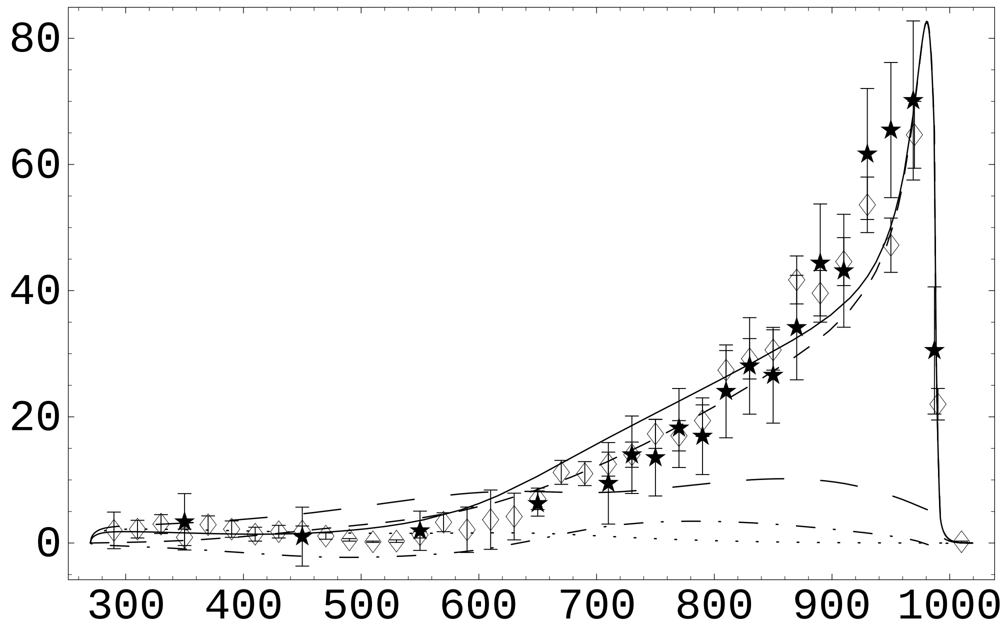


Figure 1: $dB(\phi \to \pi^0\pi^0\gamma)/dm_{\pi^0\pi^0} \times 10^8$ (in MeV^{-1}) *versus* $m_{\pi^0\pi^0}$ (in MeV). The dashed, dotted and dot-dashed lines correspond to the contributions from the LσM, VMD and their interference, respectively. The solid line is the total result. The long-dashed line is the chiral loop prediction. Experimental data are taken from SND (solid star) and KLOE (open diamond).

$\phi \to \pi^0\eta\gamma$

A. Bramon, R. E., J. L. Lucio M., M. Napsuciale & G. Pancheri, PL B494 (00) 221

$$\mathcal{A}(\phi\to\pi^0\eta\gamma)_{\mathrm{L}\sigma\mathrm{M}} = \frac{e g_s}{2\pi^2 m_{K^+}^2}\{a\}\, L(s)\times\mathcal{A}(K^+K^-\to\pi^0\eta)_{\mathrm{L}\sigma\mathrm{M}}$$

$$\mathcal{A}(K^+K^-\to\pi^0\eta)_{\mathrm{L}\sigma\mathrm{M}} = \frac{s-m_\eta^2}{2f_\pi f_K}\frac{m_K^2-m_{a_0}^2}{D_{a_0}(s)}\, c\phi_P + \frac{m_\eta^2+m_\pi^2-s}{4f_\pi f_K}(c\phi_P-\sqrt{2}\, s\phi_P)$$

where

- $D_{a_0}(s) = s - m_{a_0}^2 - \mathrm{Re}\Pi(m_{a_0}^2) + \Pi(s)$
- ϕ_P is the pseudoscalar mixing angle in the quark basis

Results:

$m_{a_0} = 984.7$ MeV PDG'02
$\phi_P = 41.8°$ PL B541 (02) 45

$$\Longrightarrow B_{\phi\to\pi^0\eta\gamma}^{\mathrm{L}\sigma\mathrm{M+VMD}} = 8.3\times 10^{-5}$$

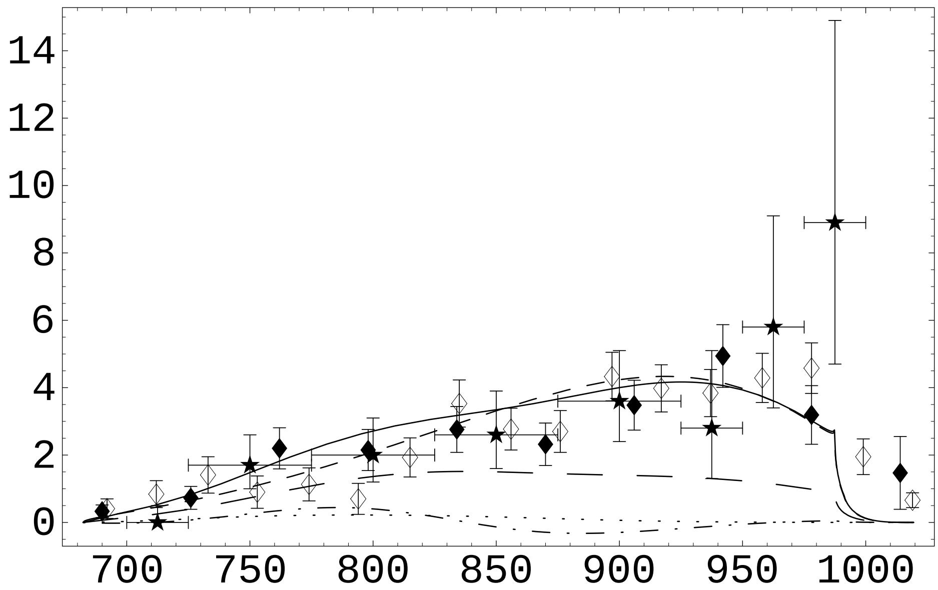


Figure 2: $dB(\phi\to\pi^0\eta\gamma)/dm_{\pi^0\eta}\times 10^7$ (in MeV^{-1}) *versus* $m_{\pi^0\eta}$ (in MeV). Experimental data are taken from SND (solid star) and KLOE: (open diamond) from $\eta\to\gamma\gamma$ and (solid diamond) from $\eta\to\pi^+\pi^-\pi^0$.

Other Processes

$$\phi \to K^0 \bar{K}^0 \gamma$$

$$\mathcal{A}(\phi \to K^0 \bar{K}^0 \gamma)_{\mathrm{L}\sigma\mathrm{M}} = \frac{e g_s}{\sqrt{2}\pi^2 m_{K^+}^2} \{a\}\, L(s) \times \mathcal{A}(K^+K^- \to K^0 \bar{K}^0)_{\mathrm{L}\sigma\mathrm{M}}$$

$$\mathcal{A}(K^+K^- \to K^0 \bar{K}^0)_{\mathrm{L}\sigma\mathrm{M}} = \frac{m_K^2 - s/2}{2 f_K^2} + \frac{s - m_K^2}{4 f_K^2} \times$$

$$\left[\frac{m_K^2 - m_\sigma^2}{D_\sigma(s)} (\mathrm{c}\phi_S - \sqrt{2}\mathrm{s}\phi_S)^2 + \frac{m_K^2 - m_{f_0}^2}{D_{f_0}(s)} (\mathrm{s}\phi_S + \sqrt{2}\mathrm{c}\phi_S)^2 - \frac{m_K^2 - m_{a_0}^2}{D_{a_0}(s)} \right]$$

Results:

$$\left. \begin{array}{l} m_{f_0} = 985 \text{ MeV}, \ \phi_S = -9^\circ \\ m_{a_0} = 984.7 \text{ MeV PDG'02} \end{array} \right\} \Longrightarrow B^{\mathrm{L}\sigma\mathrm{M}}_{\phi \to K^0 \bar{K}^0 \gamma} = 4 \times 10^{-8}$$

no background problem for testing CP violation at DaΦne

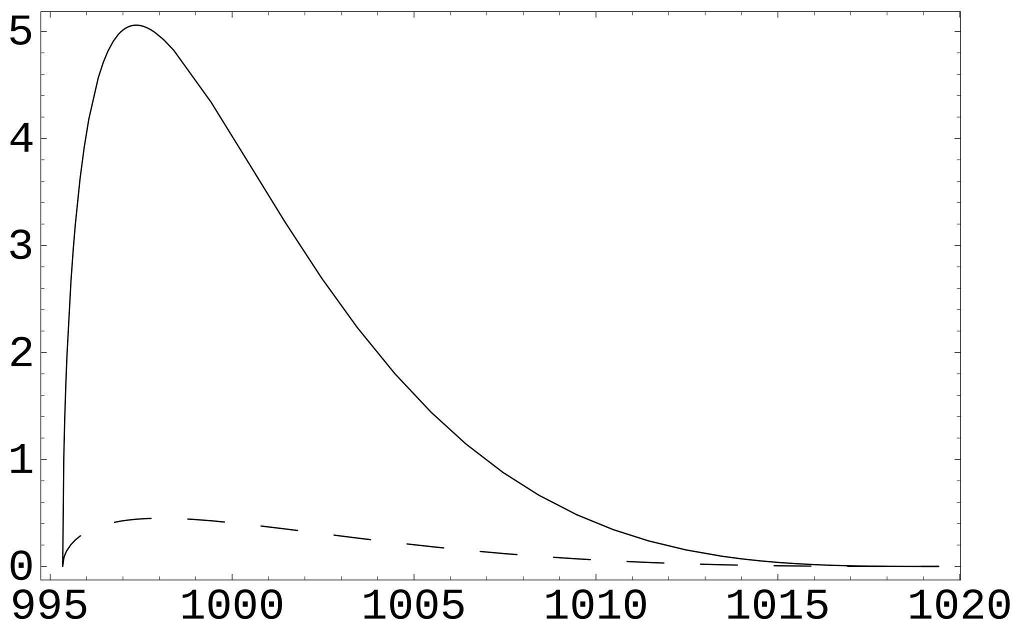


Figure 3: $dB(\phi \to K^0 \bar{K}^0 \gamma)/dm_{K^0 \bar{K}^0} \times 10^9$ (in MeV^{-1}) *versus* $m_{K^0 \bar{K}^0}$ (in MeV). Total result (solid line); the chiral loop prediction (long-dashed line).

Preliminary

$$\phi \to f_0\gamma / a_0\gamma$$

$$\mathcal{A}(\phi \to f_0\gamma)_{\mathrm{L}\sigma\mathrm{M}} = \frac{e g_s}{2\pi^2 m_{K^+}^2}\{a\}\, L(m_{f_0}^2) \times g_{f_0 K^+ K^-}$$

$$\mathcal{A}(\phi \to a_0\gamma)_{\mathrm{L}\sigma\mathrm{M}} = \frac{e g_s}{2\pi^2 m_{K^+}^2}\{a\}\, L(m_{a_0}^2) \times g_{a_0 K^+ K^-}$$

where

$$g_{f_0 K^+ K^-} = \frac{m_K^2 - m_{f_0}^2}{2 f_K}(\mathrm{s}\phi_S + \sqrt{2}\mathrm{c}\phi_S) \qquad g_{a_0 K^+ K^-} = \frac{m_K^2 - m_{a_0}^2}{2 f_K}$$

$\Longrightarrow$

$$R(\phi \to f_0\gamma / a_0\gamma)_{\mathrm{L}\sigma\mathrm{M}} = \frac{|L(m_{f_0}^2)|^2}{|L(m_{a_0}^2)|^2} \frac{\left(1 - m_{f_0}^2/m_\phi^2\right)^3}{\left(1 - m_{a_0}^2/m_\phi^2\right)^3} \times \frac{g_{f_0 K^+ K^-}^2}{g_{a_0 K^+ K^-}^2}$$

$$\simeq \frac{g_{f_0 K^+ K^-}^2}{g_{a_0 K^+ K^-}^2} \simeq (\mathrm{s}\phi_S + \sqrt{2}\mathrm{c}\phi_S)^2$$

Results:

For

$$\phi_S = -9^\circ \quad \Longrightarrow \quad R(\phi \to f_0\gamma / a_0\gamma)_{\mathrm{L}\sigma\mathrm{M}} \simeq 1.5$$

to be compared with the KLOE measurement
[PL B537 (02) 21, PL B536 (02) 209]

$$R(\phi \to f_0\gamma / a_0\gamma)_{\mathrm{KLOE}} = 6.1 \pm 0.6$$

However, this value is obtained from a large destructive interference between the $f_0\gamma$ and $\sigma\gamma$ contributions, in disagreement with other experiments

Conclusions

- $\phi \to \pi^0\pi^0\gamma$, $\phi \to \pi^0\eta\gamma$ and $\phi \to K^0\bar{K}^0\gamma$ can be used to extract relevant information on the properties of the $f_0(980)$ and $a_0(980)$ scalar resonances
- The complementarity between ChPT and the LσM can be used to parametrize the needed amplitudes
- The LσM predictions for these processes are compatible with experimental data
- $\phi \to \pi^0\pi^0\gamma$

  Dependent on m_{f_0} and ϕ_S
  Explanation for the suppression of the σ contribution
- $\phi \to \pi^0\eta\gamma$

  Dependent on m_{a_0} and ϕ_P
- $\phi \to K^0\bar{K}^0\gamma$

  Confirmation that is not a problem for testing CP violation at DaΦne
- $\phi \to f_0\gamma/a_0\gamma$

  can be used to extract relevant information on the scalar mixing angle and on the nature of the $f_0(980)$ and $a_0(980)$
- Higher accuracy data and more refined theoretical analyses would contribute decisively to clarify the sector of the lowest lying scalar states