Isospin breaking and $f_0(980) - a_0(980)$ mixing in the $\eta(1405) \to \pi^0 f_0(980)$ reaction

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Sep 30th, 2013

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Outline

F. A., W. H. Liang, E. Oset, J. J. Wu and B. S. Zou, Phys. Rev. D 86, 114007 (2012)

- introduction
- discussion assuming a contact $\eta' \to \pi^0 PP$ vertex
- study of a triangular mechanism first proposed by J. -J. Wu *et al.*
- Results
- Conclusion

- **BES experiment** $\longrightarrow$ [M. Ablikim *et al.* [BESIII Collaboration], Phys. Rev. Lett. 108, 182001 (2012)]
  - very narrow signal for the isospin violating channel $\longrightarrow$ in agreement with previous findings
  - very large isospin violation in $\eta(1405) \to \pi^0 f_0(980)$ compared to $\eta(1405) \to \pi^0 a_0(980)$

    (in comparison with other reactions such as $J/\psi \to \phi\pi^0\eta(\pi^+\pi^-)$)

$$\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} = 18\%$$

$\longrightarrow$ difficult to explain even assuming a large $I = 0$-$I = 1$ mixture

- **starting point $\longrightarrow$ $a_0(980)$ and $f_0(980)$ are dynamically generated by the meson-meson interaction provided by chiral Lagrangians**
  - building blocks: $\pi\pi$, $K\bar{K}$ for $f_0(980)$ and $\pi\eta$, $K\bar{K}$ for $a_0(980)$

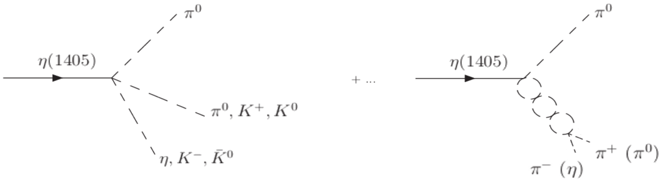
    [J. A. Oller and E. Oset, Nucl. Phys. A 620,438 (1997); A 652, 407 (1999)]
  - success in the study of $\Phi \to \pi^0\pi^0\gamma, \pi^0\eta$[1], $J/\psi \to \Phi(\omega)f_0$[2]... gives support to this assumption

    [1] J. E. Palomar, L. Roca, E. Oset and M. J. Vicente Vacas, Nucl. Phys. A 729, 743 (2003)
    [2] U. -G. Meissner and J. A. Oller, Nucl. Phys. A 679, 671 (2001)

Formalism assuming local primary $\eta(1405) \to \pi^0 PP$ vertices

Assumptions:

- $\eta(1405) \to \pi^0 PP \Longrightarrow$ **described by contact (or contactlike) vertices**



- $\eta(1405)$ **considered as an I = 0 state** $\longrightarrow$ **PP pair of interacting mesons: I = 1**

$I = 1$ combination $\longrightarrow \frac{1}{\sqrt{2}}(K^+K^- - K^0\bar{K}^0)$
$\Longrightarrow$ the physical masses of the kaons lead to an **isospin breaking effect**

- $\eta(1405)$ **considered as an SU(3) singlet** $\longrightarrow$ **since the π^0 is an octet, the pair PP must be octet**

using $8 \otimes 8 \to 1$ decomposition $\Longrightarrow \ M_{K^+K^-} = \sqrt{\frac{3}{5}}, \quad M_{K^0\bar{K}^0} = -\sqrt{\frac{3}{5}}, \quad M_{\pi^0\eta} = \sqrt{\frac{4}{5}}$

Formalism assuming local primary $\eta(1405) \to \pi^0 PP$ vertices

Scattering matrix for the production of the final state: $\mathbf{t_f = M_f + \sum_{i=1}^{3} M_i G_i T_{if}}$

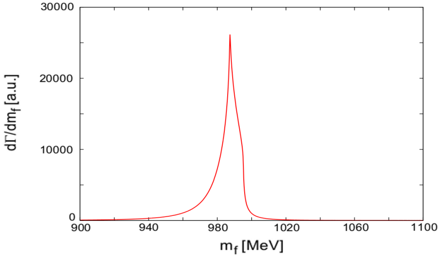
- T_{if}: 5×5 scattering matrix for the channels K^+K^-, $K^0\bar{K}^0$, $\pi^0\eta$, $\pi^+\pi^-$,$\pi^0\pi^0$
  [A. Oller and E. Oset, Nucl. Phys. A 620, 438 (1997) [Erratum-ibid. A 652, 407 (1999)]
- $M_i = A\left(\sqrt{\frac{3}{5}}, -\sqrt{\frac{3}{5}}, \sqrt{\frac{4}{5}}, 0, 0\right)$ $\quad A =$constant
- $G_i = \int_{|\vec{q}\,|<q_{max}} \frac{d^3q}{(2\pi)^3} \frac{\omega_1+\omega_2}{2\omega_1\omega_2} \frac{1}{P^{02}-(\omega_1+\omega_2)^2+i\epsilon}$ $\quad$ with $\quad q_{max} = 900\ MeV$

G_i and T_{if} $\Longrightarrow$ 2 sources of **isospin violation**

We compare $\mathbf{\frac{d\Gamma}{dm_f} = \beta p_1 \tilde{p}_2 |t_f|^2}$ **with the experiment**

- m_f = invariant mass of the final pair ($\pi^+\pi^-$ or $\pi^0\eta$)
- β = constant
- $p_1 = \frac{\lambda^{1/2}(m^2_{\eta'}, m^2_{\pi^0}, m^2_f)}{2m_{\eta'}}$ $\quad$ and $\quad \tilde{p}_2 = \frac{\lambda^{1/2}(m^2_f, m^2_2, m^2_1)}{2m_f}$

Results assuming local primary $\eta(1405) \to \pi^0 PP$ vertices

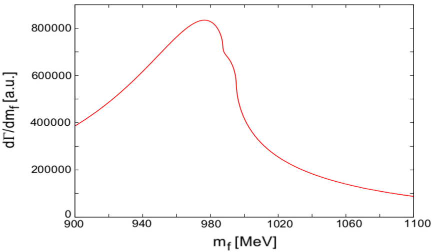


$\frac{d\Gamma}{dm_f}$ **for $\eta' \to \pi^0\pi^+\pi^-$ decay in the $f_0(980)$ region**

very narrow peak: width $\sim 10\ MeV$

in agreement with BES results

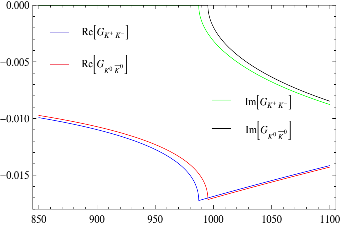
it's not the shape of the $f_0(980)$



$\frac{d\Gamma}{dm_f}$ **for $\eta' \to \pi^0\pi^0\eta$ decay in the $a_0(980)$ region**

- much larger width
- ratio of strengths at the peak $\sim 3\%$

Results assuming local primary $\eta(1405) \to \pi^0 PP$ vertices



shape of the peak for $\pi^+\pi^-$ production

$\Longrightarrow$ due to the fact that $G_{K^+K^-} - G_{K^0\bar{K}^0}$ is very small away from the two thresholds

$\Longrightarrow$ the $K\bar{K}$ thresholds show up as cusps in $\left(\frac{d\Gamma}{dm_f}\right)_{\pi^+\pi^-} / \left(\frac{d\Gamma}{dm_f}\right)_{\pi^0\eta}$

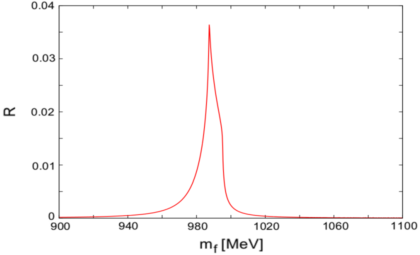
[J. -J. Wu, Q. Zhao and B. S. Zou, Phys. Rev. D 75, 114012 (2007)]
[C. Hanhart, B. Kubis and J. R. Pelaez, Phys. Rev. D 76, 074028 (2007)]
[L. Roca, Phys. Rev. D 88, 014045 (2013)]

Ratio $\left(\frac{d\Gamma}{dm_f}\right)_{\pi^+\pi^-} / \left(\frac{d\Gamma}{dm_f}\right)_{\pi^0\eta}$ as a function of m_f

$$\frac{\Gamma(\pi^0, \pi^+\pi^-)}{\Gamma(\pi^0, \pi^0\eta)} = 1.5\%$$

along the lines of 0.6% observed in $J/\psi \to \phi\pi^0\eta(\pi^+\pi^-)$ and $\chi_{c1} \to \pi^0(\pi^+\pi^-)(\pi^0\eta)$

[M. Ablikim *et al.* [BES III Collaboration], Phys. Rev. D 83, 032003 (2011)]



Is the $\eta(1405)$ an SU(3) singlet?

$\mathbf{R} = \frac{M(\pi^0\eta)}{M(K^+K^-)}$ $\Longrightarrow$ its order of magnitude can be determined from experiment

From

K. Nakamura *et al.* [Particle Data Group Collaboration], J. Phys. G G 37 (2010) 075021

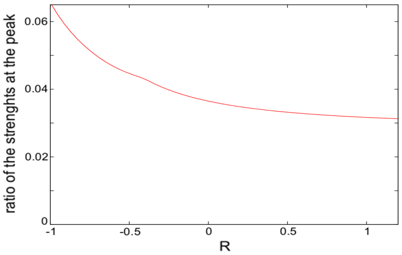
C. Amsler, A. V. Anisovich, C. A. Baker *et al.*, Eur. Phys. J. C 33, 23 (2004)

$\Longrightarrow$ $|\mathbf{R}| = \mathbf{0.75 \pm 0.17}$

with positive sign would be in agreement with the pure singlet assumption $R = \sqrt{4/3} = 1.15$ **(**$R = 0$ **for the decuplet and** $R = -\sqrt{3}$ **for the** 27**)**

in order to evaluate the uncertainties due to diversion from the SU(3) singlet assumption, we study the results for R $\in [-1, 1.2]$

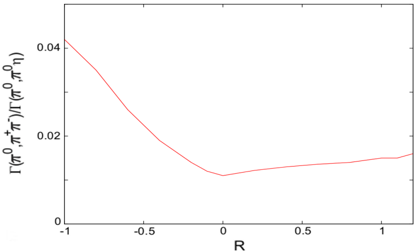
Is the $\eta(1405)$ an SU(3) singlet?



$\Longrightarrow$ it changes within a factor 2 in the range

$\Longrightarrow$ $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \in [1\% - 4\%]$

$\Longrightarrow$ **we cannot obtain the ratio of 18% found by BES** even considering the uncertainties



Is the $\eta(1405)$ an $\mathrm{I} = 0$ object?

If the $\eta(1405)$ were an $I = 1$ object:

- interacting pair: $I = 0$ (to magnify the $f_0(980)$ production)
- $K\bar{K}$ $I = 0$ combination $\longrightarrow \frac{1}{\sqrt{2}}(K^+K^- + K^0\bar{K}^0)$

Let us consider an **isospin mixture** $\Longrightarrow$ $$\tilde{\mathbf{M}}_{\mathbf{i}} = \mathbf{A}\left((1+\alpha)\sqrt{\tfrac{3}{5}}, (\alpha-1)\sqrt{\tfrac{3}{5}}, \sqrt{\tfrac{4}{5}}, 0, 0\right)$$

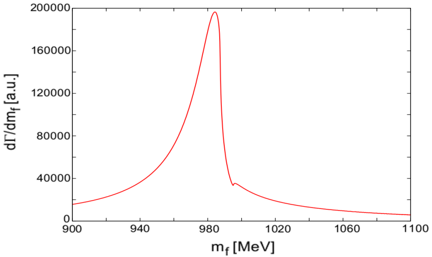
with α = measure of the mixture

to get the ratio $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} = 18\%$ found by BES we need $\alpha = \mathbf{0.54}$

$\Longrightarrow$ **massive isospin violation** difficult to justify

But there is a stronger reason to reject this value of α...

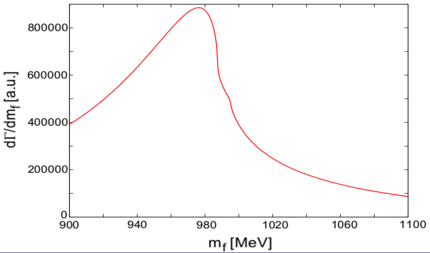
Is the $\eta(1405)$ an I = 0 object?



$\frac{d\Gamma}{dm_f}$ for $\eta' \rightarrow \pi^0\pi^+\pi^-$ decay in the $f_0(980)$ region

$f_0(980)$ produced with its natural width $\sim$ 20 MeV

in disagreement with BES results

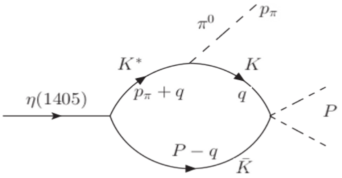


$\frac{d\Gamma}{dm_f}$ for $\eta' \rightarrow \pi^0\pi^0\eta$ decay in the $a_0(980)$ region

ordinary shape

Primary production vertex with the $K^*\bar{K}$ singularity

different production mechanism proposed by J. -J. Wu *et al.*, Phys. Rev. Lett. **108**, 081803 (2012)



novelty: 2 singularity cuts in the loop function G ($K^*\bar{K}$ and $K\bar{K}$)

$$G = i\int \frac{d^4q}{(2\pi)^4}\frac{NUM}{(p_\pi - q)^2 - m_{K^*}^2 + i\epsilon}\frac{1}{q^2 - m_K^2 + i\epsilon}\frac{1}{(P-q)^2 - m_K^2 + i\epsilon}$$

$\longrightarrow$ superficially divergent

problem: the ratio $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)}$ depends on an unknown form factor

$\longrightarrow$ naturally solved in our approach

Primary production vertex with the $K^*\bar{K}$ singularity

regularized by a 3-momentum cutoff from meson-meson scattering data

$\longrightarrow$ necessary choice in the background of chiral unitary approach

$\longrightarrow$ the cutoff appears automatically in the loop function from the $K\bar{K} \rightarrow PP$ potential

$$V(\vec{q},\vec{q}\,') = v\theta(q_{max} - |\vec{q}|)\theta(q_{max} - |\vec{q}\,'|) \text{ (for } s\text{-waves)}$$

it can be shown that, after the integration in q^0

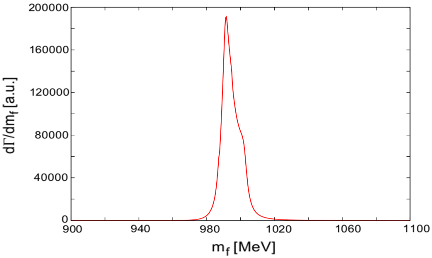
$$G = \int_{|\vec{q}|<q_{max}} \frac{d^3q}{(2\pi)^3} \frac{1}{2\omega} \frac{1}{P^0} \frac{1}{2\omega_{K^*}} \left[\frac{NUM(q^0=-\omega)}{P^0+2\omega} \frac{1}{p^0_\pi - \omega - \omega_{K^*}} + \frac{NUM(q^0=P^0-\omega)}{P^0-2\omega+i\epsilon} \frac{1}{P^0+p^0_\pi-\omega-\omega_{K^*}+i\epsilon} \right]$$

$\Longrightarrow$ **logarithmically divergent**

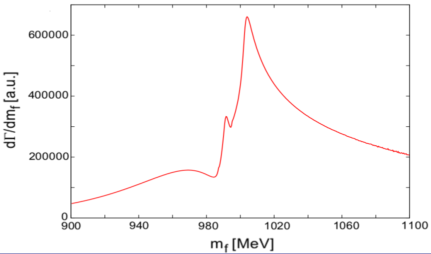
- $\eta(1405)$ considered as an $I = 0$ object
- K^+K^- and $K^0\bar{K}^0$ channels appear with opposite sign

$$\Longrightarrow \mathbf{t_f = G_{K^+K^{*+}}\ T_{K^+K^-,f} - G_{K^0K^{*0}}\ T_{K^0\bar{K}^0,f}}$$

Results with the triangular diagram



$\frac{d\Gamma}{dm_f}$ for $\eta' \to \pi^0\pi^+\pi^-$ decay in the $f_0(980)$ region



$\frac{d\Gamma}{dm_f}$ for $\eta' \to \pi^0\pi^0\eta$ decay in the $a_0(980)$ region

the shapes are similar to the previous case but...

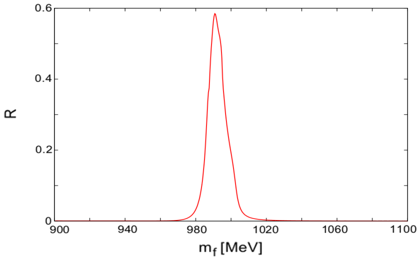
their ratio is much bigger!

Results with the triangular diagram

Ratio $\left(\frac{d\Gamma}{dm_f}\right)_{\pi^+\pi^-} / \left(\frac{d\Gamma}{dm_f}\right)_{\pi^0\eta}$ as a function of m_f

$\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \simeq$ **16%** [including corrections]

closer to the experimental value of $\mathbf{(17.9 \pm 4.2)\%}$



increase of one order of magnitude

$\Longrightarrow$ consequence of the two singularities in the triangle diagram

(peculiar to the $\eta(1405)$ case)

The $\eta(1475)$ and $\eta(1295)$

- in BES experiment [M. Ablikim *et al.* [BES III Collaboration], Phys. Rev. D **83**, 032003 (2011)]

  $\Longrightarrow$ $\eta(1405)$ and $\eta(1475)$ indistinguishable

  $\Longrightarrow$ we evaluate the same ratio for the $\boldsymbol{\eta}$**(1475)** : $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \simeq 16\%$

  $\Longrightarrow$ **same result as before**

- for the $\boldsymbol{\eta}$**(1295)** we get:

  - in the case of CPV $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \simeq 1.7\%$

  - in the case of $K^*\bar{K}$ production $\frac{\Gamma(\pi^0,\pi^+\pi^-)}{\Gamma(\pi^0,\pi^0\eta)} \simeq 12\%$
    (due to the fact that the $K^*\bar{K}$ channel is not open but close by)

    $\Longrightarrow$ **the comparison with the experiment can give us informations about the $s\bar{s}$ component in the $\eta(1295)$**

Conclusions

- the isospin violation is tied to the difference of masses between charged and neutral kaons $\Longrightarrow f_0$ produced with $\Gamma = 9\ MeV$

- assuming the primary $\pi^0 PP$ production given by a contact term the value of $\frac{\Gamma(\pi^0, \pi^+\pi^-)}{\Gamma(\pi^0, \pi^0\eta)}$ is too small compared to the one found by experiment

- following the approach of Wu *et al.* the ratio is increased of one order of magnitude
  - relating the cutoff in the new loop with the one from meson-meson scattering we can make a precise determination of the ratio
  - we get results very close to the one found by BES

- the present results strengthen the support for the $a_0(980)$ and $f_0(980)$ as dynamically generated

Isospin breaking and $f_0(980) - a_0(980)$ mixing in the $\eta(1405) \to \pi^0 f_0(980)$ reaction

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