THE PROCESS $e^+e^- \to e^+e^-\pi^0\pi^0$ AT DAΦNE*

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After a brief review of the present knowledge on the σ scalar state, the process $\gamma\gamma \to \pi^0\pi^0$ is emphasized as a crucial test for its comprehension. The feasibility of the measurement at the DAΦNE collider is discussed.

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1. Introduction

Experimental and phenomenological studies have never provided a clear and convincing signal of the lightest hadron resonance, the $f_0(600)$ or σ, having the vacuum quantum numbers [1]: $I^G(J^{\rm PC}) = 0^+(0^{++})$. Furthermore, it is crucial to extract its couplings (with photons, for instance) to infer the quark structure, in view of comparing different σ hypotheses: the lowest state of the scalar $qq\bar{q}\bar{q}$ nonet [2,3], a $K\bar{K}$ molecule [4] or a $q\bar{q}$ state [5]. Table I shows recent measurements and phenomenological estimates for mass and width of the σ. Phenomenological analyses quoted here are based either on the analyticity properties of the $\pi\pi$ scattering amplitude [9], or on simultaneous fits of $\pi\pi$ scattering and BES data [10].

1.1. Experimental hints

Three recent measurements are mentioned as the most discussed — among many studies carried over the years — for a direct evidence of the σ meson.

The E791 experiment [6] has measured the Dalitz plot of the two $\pi\pi$ invariant masses in the decay $D^+ \to \pi^+\pi^+\pi^-$. Their conclusion is that the $D^+ \to \pi^+\sigma \to \pi^+\pi^+\pi^-$ contribution accounts for the 46% of the event yield, that is explained in terms of 7 interfering amplitudes. The goodness of fit gets worse from $\chi^2/\text{dof} = 138/162$ to $254/162$ omitting the σ amplitude.

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TABLE I

Recent estimates and measurements of the σ parameters.

	Breit–Wigner parameters	
	mass (MeV)	width (MeV)
E791 exp. [6]	$478^{+24}_{-23}{}_{\rm stat} \pm 17_{\rm sys}$	$324^{+42}_{-40}{}_{\rm stat} \pm 21_{\rm sys}$
CLEO exp. [7]	513 ± 32	335 ± 67
	pole-position (MeV)	
BES exp. [8]	$(541 \pm 39) - i\,(252 \pm 42)$	
I. Caprini *et al.* [9]	$(441^{+16}_{-8}) - i\,(272^{+9}_{-12.5})$	
D. Bugg [10]	$(472 \pm 30) - i\,(271 \pm 30)$	

An independent result is obtained by the BES experiment [8], measuring the Dalitz plot of the $\omega\pi^-$ *versus* $\omega\pi^+$ invariant masses in the decay $J/\psi \to \omega\pi^+\pi^-$. The band along the upper right-hand edge is related to a broad low mass enhancement in the $\pi\pi$ invariant. They performed a partial wave analysis to disentangle among different spin resonances — 7 interfering amplitudes also in this case — and tried several parametrizations for the σ meson, each leading to consistent results for the σ pole position.

The third case regards the description of the $\pi^+\pi^-$ invariant mass in the $D^0 \to K_{\rm S}\,\pi^+\pi^-$ decay, performed by the CLEO experiment [7]. They claim not to be sensitive enough to definitely confirm a $D^0 \to K_{\rm S}\,\sigma$ contribution, but their values of σ mass and width are quoted by the Particle Data Group.

The issue of assessing the existence and features of this state is also important for the analyses measuring angles of the CKM matrix. For instance, the extraction of the γ angle through $B^\pm \to DK^\pm$ decays [11] relies on the knowledge of the Dalitz plot of the aforementioned $D^0 \to K_{\rm S}\,\pi^+\pi^-$ decay.

In summary, most of the present experimental knowledge of the σ meson relies on measurements of difficult interpretation: there is still room for other and hopefully cleaner processes.

2. The process $\gamma\gamma \to \pi\pi$

The reaction $e^+e^- \to e^+e^-\sigma \to e^+e^-\pi\pi$, via $\gamma\gamma$ fusion channel, is a clean electromagnetic probe to study the σ meson properties because an eventual structure would just show up in the $\pi\pi$ invariant mass, with no need to perform a Dalitz plot study. Moreover the extraction of the $\sigma\gamma\gamma$ coupling can be compared with that of pseudoscalar or other scalar states to clarify the σ quark structure.

From the experimental point of view, the process with the least contamination is indeed $e^+e^- \to e^+e^-\pi^0\pi^0$, where the main issues against the charged channel are:

- the $\gamma\gamma \to \mu^+\mu^-$ reaction is almost an order of magnitude larger, such that the discrimination between pion and muon tracks can be the limiting factor;
- the sizeable continuum of $\gamma\gamma \to \pi^+\pi^-$ at tree level in QED may overlap with the σ shape;
- the background from initial state radiation $e^+e^- \to \rho(\omega)\gamma^*$, with $\rho(\omega) \to \pi^+\pi^-$ and $\gamma^* \to e^+e^-$ conversion.

Finally, the selection rules for $\gamma\gamma \to \pi^0\pi^0$ veto the interference with many states with mass close to the σ, with the $f_0(980)$ being the nearest resonance.

3. Simulation of $e^+e^- \to e^+e^-\pi^0\pi^0$

The full matrix element calculation of this process is performed [13] and compared with the double equivalent photon method [12], also known as the Weizsäcker–Williams approximation, valid at small polar angles of the scattered electrons. Fig. 1 shows the four-momentum of the virtual photons (left panel) and the difference between azimuthal angles of the two pions (right panel) in the two approaches. The relative difference in the integrated photon spectrum is about 5%, and, as expected, the pions tend to be less collinear in the transverse plane, once the full 4 body final state is simulated.

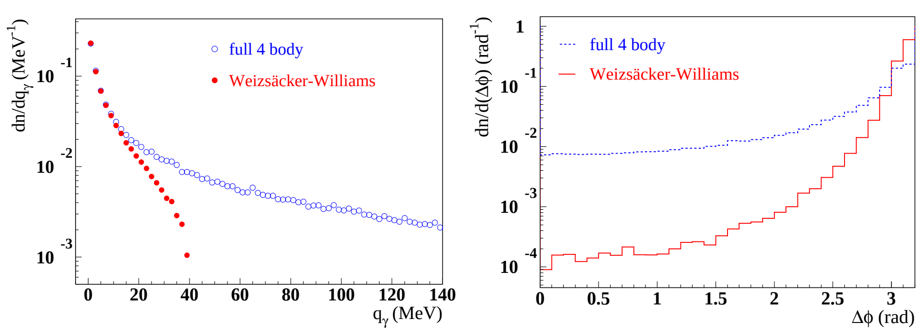

Fig. 1. Comparison between the full 4 body and the Weizsäcker–Williams evaluations for $e^+e^- \to e^+e^-\pi^0\pi^0$, in the virtual photon momentum (left) and in the azimuth difference of the two pions (right).

The model dependence of the calculation is in the $\sigma\gamma\gamma$ vertex. This is obtained assuming vector meson dominance (VMD): the σ decays to $\rho\rho$ with transitions ρ-γ, whose strength is described by VMD. The underlying dynamics of $\sigma \to \rho\rho$ is similar to that of $\sigma \to \pi\pi$, assuming [2] the σ as a bound state of two diquarks: the process is described by the tunneling probability for a q to escape its diquark shell and bind with a $\bar{q}$ of the anti-diquark to form a standard $q\bar{q}$ meson. The left panel in Fig. 2 shows a schematic description of this dynamics.

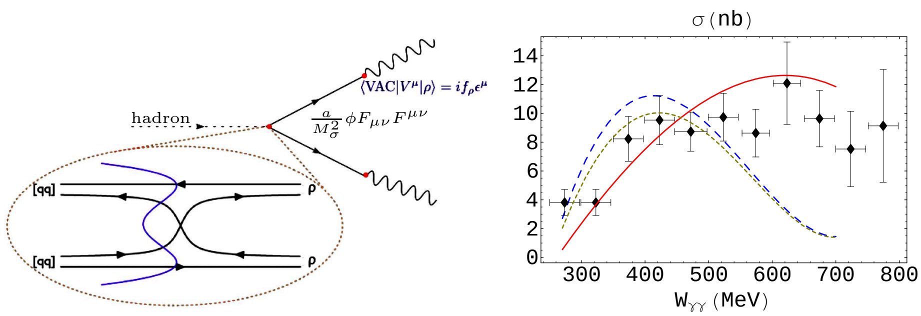

Fig. 2. A schematic view of the $\gamma\gamma \to \sigma$ transition (left). Comparison of the Crystal Ball $\sigma_{\gamma\gamma\to\pi^0\pi^0}$ data points with predictions from ChPT (solid), Breit–Wigner with (dotted) and without (dashed) the Adler zero (right).

The σ propagation is described by a standard Breit–Wigner function with mass and width taken from the pole position evaluated in [9].

The right panel in Fig. 2 shows the comparison between this estimate and the prediction performed in Chiral Perturbation Theory [14] (ChPT) for the cross section $\sigma(\gamma\gamma \to \pi^0\pi^0)$. Both calculations are superimposed on data from the Crystal Ball experiment [15], *the only one to provide a normalized cross section* [16]. These data are not able to discriminate between the two approaches at low energies, where the ChPT evaluation is more reliable.

4. Feasibility studies with the present KLOE set-up

At the beginning of 2006, the KLOE experiment [17] collected $\sim$200 pb^{-1} of data operating at $\sqrt{s} = 1$ GeV. Assuming the Breit–Wigner function, a partial width $\Gamma_{\sigma\to\gamma\gamma} = 4$ keV [18] and a detection efficiency of 20%, the expected yield for $e^+e^- \to e^+e^-\pi^0\pi^0$ is 4000 events ($\sigma \simeq 0.1$ nb).

In absence of any $e^\pm$ tagging device, final states consisting of $\pi^0\pi^0$ plus missing momentum have the same signal signature. The major source of background is the $\omega\pi^0$ production: $\sigma_{e^+e^-\to\omega\pi^0\to\pi^0\pi^0\gamma} \simeq 0.6$ nb. In this case the missing mass, $m_{\text{miss}} = m_X$ in the reaction $e^+e^- \to X\pi^0\pi^0$, is expected to peak at 0, compared to a smooth function for the signal process. Fig. 3

shows the comparison between this background and the signal, in the $\pi\pi$ invariant mass (left panel) and in $m_{\rm miss}$ (right panel). All histograms are obtained folding the energy distribution of each photon coming from the π^0 with the energy resolution of the KLOE Electromagnetic Calorimeter [19]:

$$\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E\ [\mathrm{GeV}]}}\ .$$

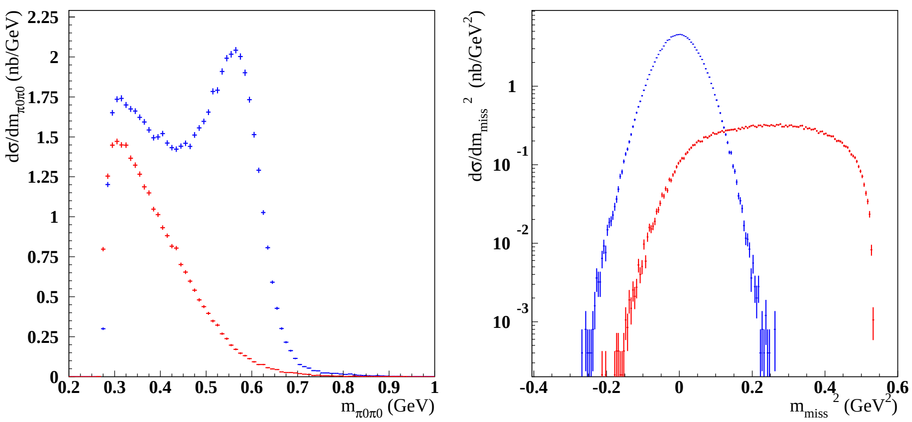

Fig. 3. Comparison between $e^+e^- \to e^+e^-\pi^0\pi^0$ (lighter histogram) and $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ (darker histogram) in the $\pi\pi$ invariant mass (left) and in the missing mass (right).

This smearing procedure does not change the signal variables, while the δ function in $m_{\rm miss}$ is broadened for the background: $m_{\rm miss}$ allows for a better discrimination of the signal, even accounting for the experimental resolution. While the ϕ decays are strongly reduced below the peak:

$$\begin{aligned} \sigma_{\phi\to\eta\gamma\to 3\pi^0\gamma} &\simeq 0.2\,\mathrm{nb}\,, \\ \sigma_{e^+e^-\to\phi\to K_{\rm S}K_{\rm L}\to\pi^0\pi^0K_{\rm L}}(K_{\rm L}\ \text{undetected}) &\simeq 0.2\,\mathrm{nb}\,, \end{aligned}$$

other reactions[1] have cross section $\simeq 10\,\mathrm{pb}$.

5. Future developments and conclusions

The σ meson deserves more and more attention, because it could be the missing piece of the 4 quark scalar nonet and it enters in some precision CKM studies. Our suggestion is to study the σ signal in $e^+e^- \to e^+e^-\pi^0\pi^0$ events at low $\pi\pi$ mass for at least two reasons:

[1] Such as $e^+e^- \to \eta e^+e^- \to 3\pi^0e^+e^-$ or $\phi \to f_0(980)\gamma \to \pi^0\pi^0\gamma$.

- It is the least known region in the measurements claiming the clear evidence, such as E791 and BES;
- ChPT predictions are more precise in the mass range from $2m_\pi$ to about 700 MeV, so that the σ may show up as a deviation.

We may benefit from the KLOE data run at $\sqrt{s} = 1$ GeV, where ϕ decays are suppressed. However, precision studies call for higher $\sqrt{s}$ to cover the whole σ shape and for $e^{\pm}$ taggers to win background [20].

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