$e^+e^- \to e^+e^- \pi^0\pi^0$ at DAΦNE

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Abstract. The production of the $\sigma(500)$ meson in $\gamma\gamma \to \pi^0\pi^0$ is studied. In particular, the KLOE data collected during the DAΦNE run at $\sqrt{s} = 1$ GeV are appropriate to this purpose because of the strong reduction of kaon backgrounds.

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1 Introduction

One of the first attempts to describe nucleon–pion interactions within a spontaneously broken $SU(2)_L \otimes SU(2)_R$ theory was the linear sigma model of Gell-Mann and Levy [1]. The idea is that of writing a Lagrangian of the $\psi = (p\ n)$ fields introducing chirally invariant terms of the form $\bar{\psi}_L \Sigma \psi_R$ with Σ transforming linearly under chiral transformations: $\Sigma \to L\Sigma R^\dagger$. Since the defining $SU(2)$ representation is pseudoreal, one can write Σ in terms of only four real parameters. The linear sigma model parameterization is indeed $\Sigma = \sigma 1 + i\tau^a \pi^a$, where π^a are the three isospin components of the pion and σ is a scalar field possibly associated to some particle in the spectrum. Upon spontaneous symmetry breaking the nucleon gets a mass $m_N = F_\pi g_{\pi NN}$ in agreement with the Goldberger–Treiman relation with g_A fixed to be 1 (whereas the physical value is 1.26). F_π is the constant, with dimension of a mass, appearing in the potential of the model, the well known Mexican hat potential $V = \lambda/4[(\sigma^2 + \pi^2) - F_\pi^2]^2$. One can show that F_π so defined coincides with the pion decay constant.

The drawback is that the artificial σ field appears to be coupled to pions and nucleons suggesting the existence of a new particle to be looked for. The natural process where a σ contribution is expected to be important is the $\pi\pi \to \pi\pi$ elastic channel. Unfortunately experimental studies have never provided over the years a clear signal for it and the assessment of σ has become more and more controversial. The indication coming from $\pi\pi$ collision studies is that if the σ can be considered as a resonance at all it ought to be an extremely broad (short lived) state. Very recently [2] it has been shown that the $\pi\pi$ scattering amplitude contains a pole with the quantum numbers of the vacuum, the σ, with a mass of $M_\sigma = 441^{+16}_{-8}$ MeV and a width $\Gamma_\sigma = 544^{+25}_{-18}$ MeV. The σ has been looked for also in D decays by the E791 Collaboration at Fermilab [4]. From the $D \to 3\pi$ Dalitz plot analysis, E791 finds that almost 46% of the width is due to $D \to \sigma\pi$ with a $M_\sigma = 478 \pm 23 \pm 17$ MeV and $\Gamma_\sigma = 324 \pm 40 \pm 21$ MeV. BES [5] has looked for σ in $J/\psi \to \omega\pi^+\pi^-$ giving a mass value of $M_\sigma = 541 \pm 39$ MeV and a width of $\Gamma_\sigma = 252 \pm 42$ MeV. For a summary of the experimental data see [3].

Trying to extend the linear sigma model from $SU(2)_L \otimes SU(2)_R$ to $SU(3)_L \otimes SU(3)_R$ in order to include the strange sector ($\psi = (u\ d\ s)$), one encounters the problem that the fundamental representation of $SU(3)$ is complex and a parameterization for the Σ field having the same form of the one given above requires 18 real parameters. One possibility is to construct a generalized sigma model with nine scalar and nine pseudoscalar fields [6]. Diverse solutions of this kind have been investigated in the literature, but none of them has proved to be effective in explaining the data.

The most successful approach to build a theory of pions at low energies is that of Callan–Coleman–Wess–Zumino (CCWZ) to define $\Sigma = \exp(2iT^a\pi^a/F_\pi)$ in terms of the eight Goldstone bosons arising from $SU(3)_L \otimes SU(3)_R \to SU(3)^{\text{diag}}$. With this definition of Σ, pions do not transform linearly under $\Sigma \to L\Sigma R^\dagger$. The non-linear realization (one of the infinite realizations, all equivalent at the level of physical results – the CCWZ theorem) of chiral symmetry has proven to be extremely successful in the building of chiral perturbation theory (ChPT) [7], the standard effective approach to describe pion interactions at low energies.

The non-linear sigma model excludes the σ field by construction; therefore the role of a σ particle in $\pi\pi$ interactions, as well as in heavy–light meson decays, calls for understanding. Above all, is this a real particle associated
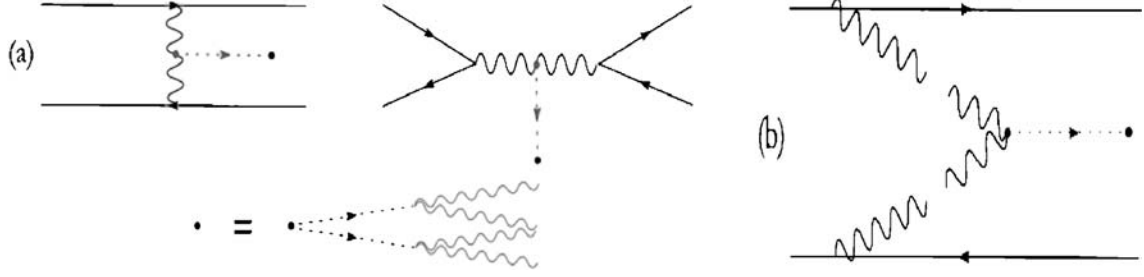
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Fig. 1. a The Feynman diagrams for $e^+e^- \to e^+e^-\pi^0\pi^0$. In the t-channel one photon is exchanged between electron and positron and a σ is coupled to it. The *black dot* indicates the decay of $\sigma \to \pi^0\pi^0$ where the two pions are allowed to decay via $\pi^0 \to \gamma\gamma$. The γ's are eventually measured in the detector. The final-particle phase space in our calculation is the four-body $e^+e^-\pi^0\pi^0$. In the s-channel a virtual photon emits a σ and another virtual photon, eventually decaying into e^+e^-. **b** The $\sigma(\gamma\gamma \to \pi^0\pi^0)$ cross section is factorized with the distribution functions of the photon in the electron. Such an approximation is strictly valid for collinear photons, being less and less applicable once one allows for a $p_\perp \neq 0$ of the electron

to some field in an effective Lagrangian (an exotic states Lagrangian for example) or is it just a pion rescattering effect?

The problem of assessing the existence and nature of this state is not confined to low energy phenomenology. Just to mention a possible relevant physical scenario in which σ could play a role, consider the contamination of $B \to \sigma\pi$ in $B \to \rho\pi$ decays (possible because of the large σ width). This could sensibly affect the isospin analysis for the CKM-α angle extraction [8]. Similarly recent studies of the γ angle through a Dalitz analysis of neutral D decays need the presence of a σ resonance in the fit [9].

In this paper we want to highlight the possibility that σ could be found in e^+e^- collisions at DAΦNE now running at a center of mass energy of 1 GeV, a region where the ϕ backgrounds are considerably diminished. In particular we examine the $e^+e^- \to e^+e^-\pi^0\pi^0$, γ-fusion channel. This could represent the cleanest technique available for an independent measure of the σ.

2 The $\gamma\gamma \to \pi^0\pi^0$ channel

Our aim is to suggest to extract a σ signal in $e^+e^- \to e^+e^-\pi^0\pi^0$ where also ChPT predictions are very solid: the $\gamma\gamma \to \pi^0\pi^0$ channel has been determined to two-loop accuracy in the region of photon–photon CM energy from about $2m_\pi$ up to 700 MeV [10]. In the same energy region the $\gamma\gamma \to \pi^+\pi^-$ process is affected by a large background of $\gamma\gamma \to \mu^+\mu^-$.

To perform our calculation of this process we will assume that the σ is not a standard meson, but a crypto-exotic state [11]. In particular we assume that σ is $[qq][\bar{q}\bar{q}]$ where the parentheses indicate a diquark bound in the $\bar{3}_c$ attractive color channel [12]. Assuming a common spatial configuration and spin 0 for the diquark we have a $\bar{3}_f$ configuration for the diquark and $\bar{3}_f$ for the antidiquark because of Fermi statistics. We can therefore expect to have a full nonet of states $3_f \otimes \bar{3}_f = 1_f \oplus 8_f$ whose exotic content is "crypted" (we would equally have such a nonet with a standard $q\bar{q}$ assignation). Such a hypothesis about the σ structure is particularly appealing for two reasons.

1. It allows one to obtain a mass spectrum for the scalar mesons ($\sigma, f_0(980), a_0(980), \kappa(900)$) which shows an inverted pattern with respect to the $q\bar{q}$ one. The experimental spectrum for these states, provided the κ is confirmed, resembles the inverted pattern.

2. Considering the σ to be a meson with a different body plan, qualitatively different from pions, allows one to formulate an independent effective theory for scalar meson dynamics [11] escaping the problem of the emergence of σ in ChPT.

Our calculation will be performed using the full matrix element derived by the Feynman amplitudes in Fig. 1a. To further test our results, we also adopt the double equivalent photon approximation, see Fig. 1b, largely used in the past for studying this kind of processes [13, 14].

The double equivalent photon approximation is strictly valid when the photons emitted by the electrons (see Fig. 1b) are collinear. On the other hand the results of our straightforward calculation are formally valid also for final state electrons selected with a certain $p_\perp$. In such a way one should be able, at least in principle, to perform the experimental analysis also in absence of forward electron detectors (electron tagging).

The model dependent part of the calculation is in the $\gamma\gamma\sigma$ vertex. In Fig. 2 we show how we do parameterize such an interaction. Because of gauge invariance, the vertex has the form $a/M_\sigma^2 \phi F^{\mu\nu} F_{\mu\nu}$, ϕ representing the σ field. In a previous paper [11] the method for the computation of the coupling of a crypto-exotic σ to ρ mesons is traced. The coupling a used here does not need to be equivalent to the $\mathcal{A} = 2.6$ GeV coupling fitted in [11]. $\mathcal{A}$ defines the decay vertex $\sigma \to \pi\pi$. Since we cannot fit a from the data we treat it as a free parameter. This does not affect our analysis since we will only discuss normalized distributions. In other words the four-quark hypothesis does not alter quantitatively the nature of our conclusions though it is intimately connected to the qualitative picture of the microscopic dynamics of the $\sigma \to \rho\rho$ decay. The ρ mesons are coupled to photons using a VMD Ansatz; see Fig. 2.

The σ propagation is described by a simple Breit–Wigner function with mass and width taken from E791 data. The cross section can be plotted as a function of sev-
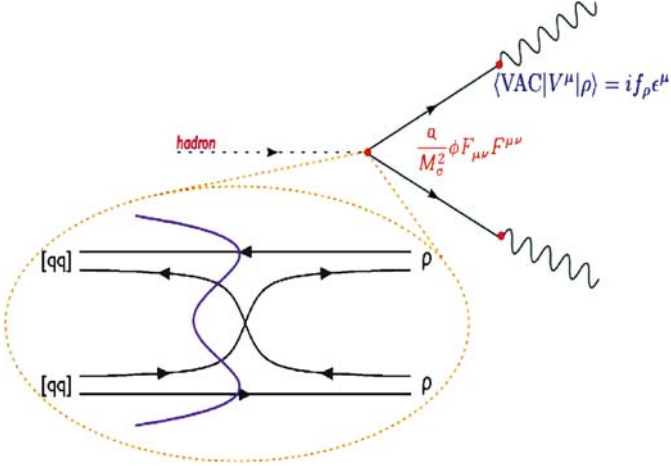
Fig. 2. The vertex $\sigma\gamma\gamma$ is obtained assuming vector-meson dominance (VMD): the σ decays to $\rho\rho$ and each ρ converts to γ according to its f_ρ decay constant. Our microscopic picture of the decay process of a σ to $\rho\rho$ is a kind of tunneling of a quark which escapes its diquark shell to meet an antiquark from the antidiquark forming a standard color singlet $q\bar{q}$ meson. The higher the barrier to be crossed the stronger is the diquark energy binding. The interaction strength a is expressed as the coupling of a gauge-invariant term $a/M_\sigma^2\phi F^{\mu\nu}F_{\mu\nu}$, ϕ being the field associated to the σ [11]

Fig. 3. The *solid line* represents the so called double equivalent photon approximation; see Fig. 1b [14]. *Dashed* and *dot-dashed curves* represent the t and $s+t$ channel respectively in the Feynman diagram computation of Fig. 1a. By m^* we denote the invariant mass of the e^+e^- final state pair (missing mass). With a moderate statistics simulation, the four-body phase space of the matrix element calculation converges with more difficulty with respect to the two-body phase space of the double equivalent photon approximation

3 Results

The reason for plotting the cross section distribution as a function of the missing mass m^* of the final e^+e^- pair, see Fig. 3, is that using this variable we can get rid of the most relevant background we have, namely $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$. This is peaked around zero in the m^* variable and the distribution smearing could still allow for the signal from background extraction.

$\gamma\gamma \to \pi^0\pi^0$ has been computed in ChPT to two-loop level accuracy [10]. We can as well plot the normalized distribution $1/\sigma * d\sigma/dW_{\gamma\gamma}$, $W_{\gamma\gamma}$ being the photon–photon CM energy; see Fig. 4. The two-loop ChPT cross section $\sigma(\gamma\gamma \to \pi^0\pi^0)$ is convoluted with photon distribution functions as prescribed by the double equivalent photon approximation.

It is not surprising that the effect of a Breit–Wigner resonance makes this distribution different from what is expected in ChPT where the σ can only be simulated by an effect of the strong interaction in the $\pi\pi$ channel. Assuming that σ is a propagating particle, with either four-quark or two-quark structure, qualitatively changes $d\sigma/dW_{\gamma\gamma}$ with respect to ChPT predictions. Anyway, the $W_{\gamma\gamma}$ region where our calculation differs more sensibly from ChPT could be affected by interference effects with
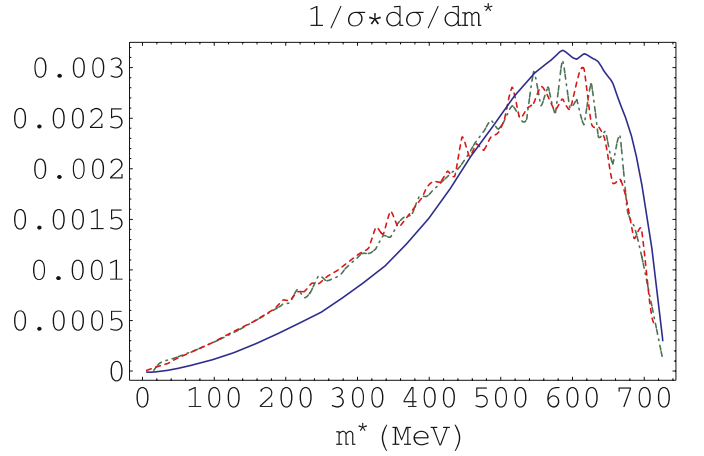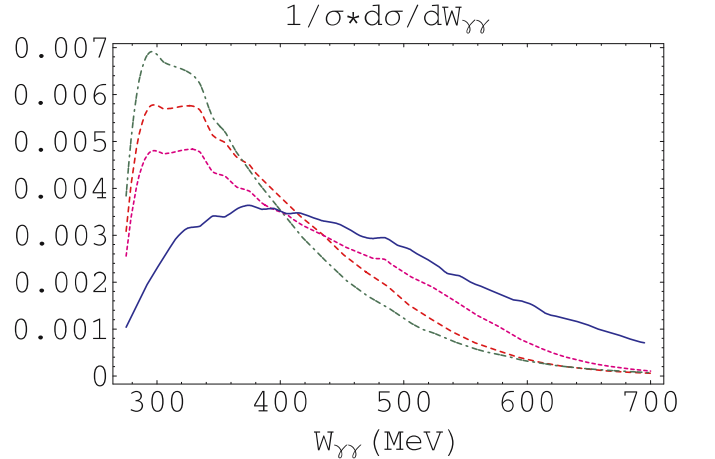

Fig. 4. $W_{\gamma\gamma}$ is the photon–photon center of mass energy. The *solid line* is the $e^+e^- \to e^+e^-\pi^0\pi^0$ cross section distribution calculated convoluting the two-loop $\sigma(\gamma\gamma \to \pi^0\pi^0)$ cross section with the photon distribution functions according to the double equivalent photon approximation. *Dashed, dot-dashed* and *dotted lines* represent the same quantity where the two pions come from the decay of a σ produced in photon–photon fusion. In particular the *dashed curve* is computed using the σ parameters found by E791 ($M_\sigma = 478$ MeV and $\Gamma_\sigma = 324$ MeV) [4], the *dot-dashed* one corresponds to an $M_\sigma = 441$ MeV and $\Gamma_\sigma = 544$ MeV (from the $\pi\pi$ scattering amplitude analysis [2]) while the *dotted curve* is computed according to BES results ($M_\sigma = 541$ MeV and $\Gamma_\sigma = 252$ MeV) [5]

$\gamma\gamma \to f_0(980) \to \pi^0\pi^0$. However, to address this issue will require precise data at much higher $\sqrt{s}$ values.

In Fig. 5 we compare our results to the only existing data set for the $\sigma(\gamma\gamma \to \pi^0\pi^0)$, namely the 1993 Crystal
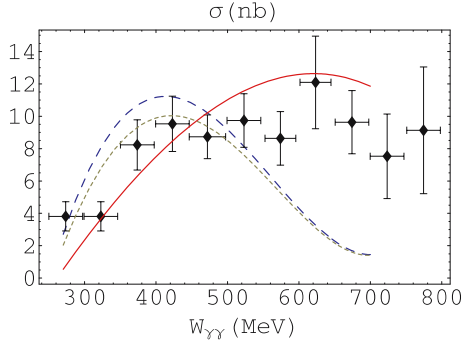
Fig. 5. *Data points* are cross section values for $\gamma\gamma \to \pi^0\pi^0$ obtained by Crystal Ball (1993). The *solid curve* represent the two-loop ChPT result . The *dashed line* is $\sigma(\gamma\gamma \to \sigma \to \pi^0\pi^0)_{\text{B.W.}}$. The *dotted line* is the same as the *dashed* re-weighting the amplitude by an Adler zero factor [15] $(s - s_A)$ where $s_A = 0.5\,\text{m}_\pi^2$. Data uncertainties certainly call for a more precise measurement of this channel

Ball data points. The solid line represents the two-loop ChPT result . The dashed line is $\sigma(\gamma\gamma \to \sigma \to \pi^0\pi^0)_{\text{B.W.}}$ where the a parameter has been fitted to the cross section value of the lowest $W_{\gamma\gamma}$ experimental point. The dotted line is the same as the dashed re-weighting the amplitude by an Adler zero factor [15] $(s - s_A)$ where $s_A = 0.5m_\pi^2$. The resonant contribution should be properly combined with the chiral loop amplitudes to show a more realistic result: the two contributions do not exclude each other.

Our results are certainly dependent on the Breit–Wigner (BW) parameterization of the σ contribution (we have also analyzed the possibility of implementing the BW Ansatz with a σ comoving width). However, given the poor resolution expected for low energy photons and the actual absence of an electron tagging device, we believe that our simple approach is appropriate enough to motivate an experimental analysis in this channel: Fig. 5 certainly enforces the case to require more precise data. The use of a Breit–Wigner parameterization of σ at E791 and BES is probably more challenged by the fact that charged pions momenta are more precisely measured in these experiments, allowing for a quite good resolution on the invariant masses. Moreover the recent experience at BaBar [16], where the $D(D_s) \to 3\pi$ Dalitz plots are currently under study, has shown preliminarily that the use of more sophisticated approaches to the parameterization of the isoscalars (e.g. K-matrix) are not providing more stringent and convincing results in the extraction of the $D \to \sigma\pi$ channel with respect to what obtainable via a simple BW Ansatz.

4 Backgrounds

Here we proceed to a list of the relevant backgrounds which have to be taken under control in the data analysis. In fact, even if KLOE is collecting data at $\sqrt{s} = 1$ GeV, some of the ϕ decays with at least four photons in the final state have

a rate comparable to the signal one (we require at least four γ's in the final state).

- $\phi \to \eta\gamma \to 3\pi^0\gamma$. At a center of mass energy of 1 GeV the ϕ is strongly reduced. The cross section for $e^+e^- \to \phi \to \eta\gamma$ drops by about a factor of 30 [17] from 20 nb at $\sqrt{s} = M_\phi$ down to 0.67 nb at $\sqrt{s} \simeq 1$ GeV; since the branching ratio $\text{BR}(\eta \to 3\pi^0) \simeq 32.5\%$, we have $\sigma(e^+e^- \to \phi \to \eta\gamma \to 3\pi^0\gamma) \sim 0.2$ nb, at $\sqrt{s} \simeq 1$ GeV.
- $\phi \to K_S K_L$. The cross section in this case drops from 1350 nb to 11 nb according to the indications of CMD-2 [18]. This background is particularly dangerous when K_S decays into two π^0's $(\text{BR}(K_S \to 2\pi^0) \simeq 31\%)$ and K_L escapes detection. Considering that in KLOE, at $\sqrt{s} = 1$ GeV, about 75% of the K_L's decay inside the detector, and that about 70% of the surviving ones interact in the Electromagnetic Calorimeter, we get a further reduction of $\sigma(e^+e^- \to \phi \to K_S K_L \to \pi^0\pi^0 K_L)$ (with K_L undetected) which amounts to 0.2 nb.
- $\phi \to \pi^0\pi^0\gamma$. Starting from the KLOE result [19] $\text{BR}(\phi \to f_0(980)\gamma) \simeq 10^{-4}$ at $\sqrt{s} = M_\phi$, and assuming that $\sigma(e^+e^- \to \phi \to f_0(980)\gamma)$ gets reduced by a factor 30 at $\sqrt{s} = 1$ GeV, we estimate a cross section of about ~ 10 pb for this channel.
- $\phi \to \pi^0\eta\gamma$. Given the KLOE result [20] $\text{BR}(\phi \to a_0(980)\gamma) \simeq 7 \times 10^{-5}$ at $\sqrt{s} = M_\phi$, and taking into account $\text{BR}(\eta \to \gamma\gamma) \simeq 39.4\%$ and the reduction by a factor of 30, we estimate a cross section of about ~ 4 pb for this channel.
- $e^+e^- \to \eta e^+e^- \to \pi^0\pi^0\pi^0 e^+e^-$. We estimate a cross section for this process amounting to $\sigma \simeq 13$ pb. Such a background should be removable imposing that the four reconstructed photons belong to two pions going back-to-back in the transverse plane.

4.1 The $e^+e^- \to \omega\pi^0$ channel

Contrary to ϕ decays, the cross section for this process tends to increase from $\sigma = (0.51 \pm 0.07)$ nb at $\sqrt{s} = 1.02$ GeV to $\sigma = (0.56 \pm 0.14)$ nb at $\sqrt{s} = 1.005$ GeV, as measured by the SND [21] experiment. Moreover the peak at 0.6 GeV in the $\pi\pi$ invariant mass, as shown in the right panel of Fig. 6, corresponds to events with two pions emerging back-to-back in the transverse plane.

Since the fraction of background events in which the fifth photon is lost has the same experimental signature of the signal, namely two π^0's collinear in the transverse plane plus missing energy, we performed a dedicated study of this channel. We consider $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ to proceed via VMD $e^+e^- \to \gamma^* \to \rho \to \omega\pi^0$. This channel has a missing mass peaked at zero. However, the energy resolution of the photons coming from the two π^0's modifies this simple pattern.

Every photon energy distribution is convoluted with a Gaussian function, where the standard deviation is the energy resolution function of the KLOE Electromagnetic Calorimeter [22]:

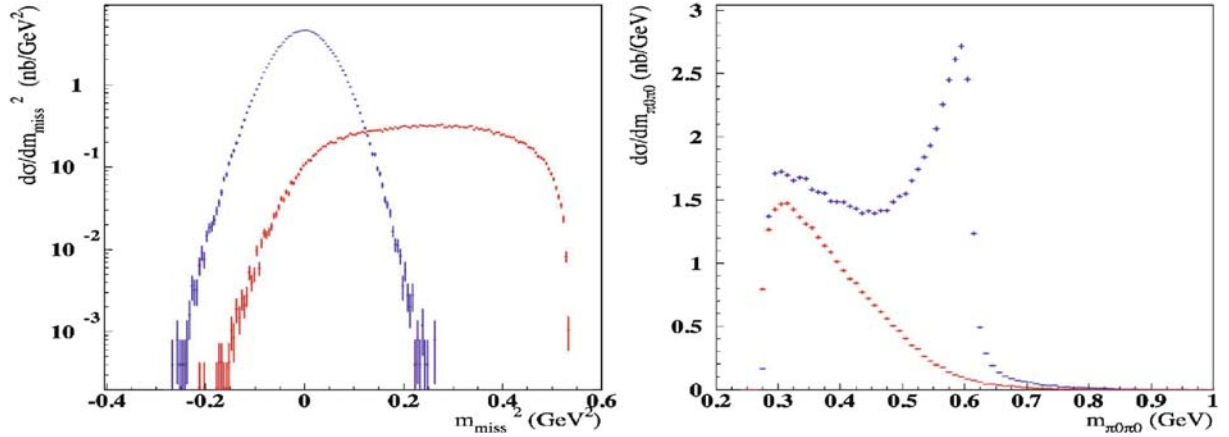$$\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{[\text{GeV}]}}. \tag{1}$$

Fig. 6. In the *left panel* we compare the background $e^+e^- \to \omega\pi^0$ distribution (the one centered around zero) to the signal (the broader distribution) as functions of the missing mass $m_{\text{miss}} \equiv m^*$. In the background we have five photons in the final state. We pick up four of them reconstructing $\pi^0\pi^0 \to 4\gamma$ and perform the smearing, as explained in the text. Even after smearing the signal and the $\omega\pi^0$ background appear to have different shapes in m^*. In the *right panel* we perform the same comparison using another variable, namely, the invariant mass of the $\pi^0\pi^0$ system. The peak is in correspondence of two back-to-back π^0's; the shape at ~ 280 MeV is the $2m_\pi$ invariant mass

The same procedure is applied to the four photons generated by the signal $e^+e^- \to \pi^0\pi^0 e^+e^-$.

Upon such a smearing procedure, no significant change is introduced in the signal distribution, while the δ-function in the missing mass gets broadened but still does not superimpose to the signal region, see Figs. 3 and 6, where the cross section value $\sigma(e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma) = 0.6$ nb is used.

It is also clear that the experimental analysis is going to deal not only with the photon energy resolution, but also with the photon efficiency as a function of the energy and of the polar angle given the correct pairing of the final photons to the parent π^0's. A full simulation of the detector would be in order for a detailed discussion of these issues. Nevertheless, it is reasonable to guess that the same sources of inefficiency are shared by the signal and the background processes.

5 Conclusions

We believe that KLOE in the low energy DAΦNE run has a concrete opportunity to find (or disprove) the σ in a clean experimental channel, $\gamma\gamma \to \pi^0\pi^0$. The scope of our feasibility study is to underscore this possibility and to suggest some data analysis strategies. The crucial interest should be that of investigating the nature of the σ: is it a particle or an effect of chiral dynamics? The comparison with ChPT predictions for $\gamma\gamma \to \pi^0\pi^0$ illustrates that if a broad resonance is indeed produced in $\gamma\gamma$ it could be detectable in the low energy $\gamma\gamma$ region, see Fig. 4, from the distribution slopes. As soon as smearing is introduced the two curves (resonance-type versus ChPT) will tend to superimpose. This certainly calls for a more selective analysis of the data, making use of forward detectors to tag electrons. Such devices, which at the moment are not part of

the experimental apparatus, could be integrated in view of possible future luminosity upgrades.

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