Abstract. Two-photon physics from $e^+e^-$ collision is studied at DAΦNE. The processes $e^+e^- \rightarrow e^+e^-X$, with $X$ being either the $\eta$ meson or $\pi^0\pi^0$ have been studied with beams colliding at $\sqrt{s} \simeq 1$ GeV, below the $\phi$ resonance peak and without tagging of the outgoing $e^+e^-$. Preliminary results are presented on the observation of the $\gamma\gamma \rightarrow \eta$ process, with both $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\eta \rightarrow \pi^0\pi^0\pi^0$ channels, and the evidence for $\gamma\gamma \rightarrow \pi^0\pi^0$ production at low $\pi^0\pi^0$ invariant mass. The process $e^+e^- \rightarrow e^+e^-\pi^0$ will be studied at KLOE-2 running the machine at $\sqrt{s} = 1.02$ GeV thanks to new lepton tagger detectors. In particular, the possibility to measure the width $\Gamma_{\gamma\gamma \rightarrow \pi^0}$ and the $\pi^0\gamma\gamma^*$ form factor, $F(Q^2)$, at low invariant masses of the virtual photon (in the space-like region) is considered. The feasibility of these measurements is estimated on the basis of a Monte Carlo simulation, whose results are presented here.

1. Introduction

1.1. Two-photon physics at DAΦNE

The term ”$\gamma\gamma$ physics” stands for the study of the reaction (of order $\alpha^4$) $e^+e^- \rightarrow e^+e^-\gamma\gamma^* \rightarrow e^+e^-X$, where $X$ is some arbitrary final state allowed by conservations laws. Since the two photons are in a $C = +1$ state and the value $J = +1$ is excluded by the Landau-Yang theorem [1] if they can be considered quasi-real, $\gamma\gamma$ scattering at $e^+e^-$ colliders give access to states with $J_{PC} = 0^{\pm}, 2^{\pm}$, not directly coupled to one photon $J_{PC} = 1^{--}$. The number of produced events, $N_{eeX}$, can be estimated from the expression:

$$N_{eeX} = L_{ee} \int dW_{\gamma\gamma} \frac{dL}{dW_{\gamma\gamma}} \sigma(\gamma\gamma \rightarrow X)$$

where $L_{ee}$ is the $e^+e^-$ integrated luminosity, $W_{\gamma\gamma}$ the center of mass energy ($W_{\gamma\gamma} = M_X$), $\frac{dL}{dW_{\gamma\gamma}}$ the $\gamma\gamma$ flux and $\sigma(\gamma\gamma \rightarrow X)$ the cross section to a given final state, $X$.

The photon flux at DAΦNE ($\sqrt{s} = 1.02$ GeV) is shown in Fig. 1, where accessible final states are also indicated.

1.2. $\gamma\gamma$ collisions with KLOE at DAΦNE

The cross section $\sigma(\gamma\gamma \rightarrow X)$ for light mesons production (namely $X = \pi^0, \eta, \eta'$) has been studied over the years by many $e^+e^-$ colliders, from PETRA to CESR to LEP, mostly at a center of mass energy $7 < \sqrt{s} < 90$ GeV. However, in the low energy region ($m_\pi < W_{\gamma\gamma} < 700$
Figure 1. Photon-photon flux at DAΦNE as a function of $W_{\gamma\gamma}$ for a machine integrated luminosity, $L_{ee}$, of 1 fb$^{-1}$ and a center of mass energy of $\sqrt{s} = 1.02$ GeV.

MeV) the experimental situation is unsatisfactory because of large statistical and systematic uncertainties due to small data samples, large background contributions, very small detection efficiency and particle identification ambiguities for low-mass hadronic systems.

DAΦNE is a $e^+e^-$ collider designed to operate at the center of mass energy of $\sqrt{s} \approx 1.02$ GeV, namely the $\phi$ meson mass. It has provided to the KLOE experiment an integrated luminosity of about 2.5 fb$^{-1}$ on peak of the $\phi$ meson from year 1999 up to 2005 and also 250 pb$^{-1}$ at the off-peak center of mass energy of $\sqrt{s} = 1$ GeV in 2006.

The KLOE detector (Fig. 3) consists of a large volume drift chamber [2] ($\sim 3.3$ m length and $\sim 2$ m radius) surrounded by an electromagnetic lead-scintillating fibers calorimeter (EmC) [3] with excellent time ($\sigma_t = 57$ ps/$\sqrt{E(\text{GeV})} \oplus 100$ ps) and good energy ($\sigma_E/E = 5.7%$/\sqrt{E(\text{GeV})}$) resolution. The whole detector is surrounded by an iron yoke coupled to a superconducting coil providing an axial field of nearly $\sim 0.5$ T. This allows the reconstruction of charged particles momenta with resolution $\sigma_p/p \simeq 0.4%$ ($\sigma_p/p \simeq 1%$) for large (small) angle tracks coming from the collision point. The trigger system [4] requires at least two energy deposits above threshold in the calorimeter, not in the same end cap: the threshold is about 50 MeV for the barrel and 150 MeV for each end cap.

2. KLOE measurements

The $\gamma\gamma$ processes studied with KLOE are $e^+e^- \rightarrow e^+e^-\eta$ and $e^+e^- \rightarrow e^+e^-\pi^0\pi^0$ with $e^+e^-$ in the final state going undetected along the beam pipe. The sample used for the present analyses consists of 240 pb$^{-1}$ (integrated luminosity) data collected at $\sqrt{s} = 1$ GeV, which allows the reduction of the background coming from $\phi$ decays. Data are processed with a dedicated filter asking for at least two prompt photons, clusters not associated to tracks and propagating with $|r - ct| \sim 0$, with energy $E > 15$ MeV and polar angle $20^\circ < \theta < 160^\circ$, the most energetic one with $E > 50$ MeV, the fraction of energy carried by photons $R = (\sum_i E_i)/E_{\text{cal}} > 0.3$ and the total energy in the calorimeter $100 < E_{\text{cal}} < 900$ MeV. The latter requirement rejects low energy background and high rate processes like $e^+e^- \rightarrow e^+e^-, e^+e^- \rightarrow \gamma\gamma$. 

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2.1. Observation of $\gamma\gamma \rightarrow \eta$, with $\eta \rightarrow \pi^+\pi^-\pi^0$

The selection of these events asks for two photons constrained to originate from a $\pi^0$ decay and two tracks with opposite curvature coming from the collision point. The sum of the track momenta is constrained to be $|\vec{p}_1| + |\vec{p}_2| < 700$ MeV in order to suppress higher momentum values, typical of $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ or $e^+e^- \rightarrow \omega(\rightarrow \pi^+\pi^-\pi^0)\pi^0$. The charged pion mass is assigned to the two tracks and a least squares function based on Lagrange multipliers imposes that $\pi^+\pi^-\pi^0$ come from an $\eta$ decay. Therefore most background events are suppressed, except for the irreducible process $e^+e^- \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$, for which the requirement to have two and only two photons constrains the $3\pi$ system to be emitted with longitudinal momentum $p_L \simeq 350$ MeV and recoil missing mass $M_{\text{miss}} \simeq 0$; the monochromatic photon, $E_\gamma = 350$ MeV, is lost in the beam pipe. On the other hand, signal events are characterized by the following parabolic relation between $M_{\text{miss}}^2$ and $p_L$:

$$M_{\text{miss}}^2 \approx s + m_\eta^2 - 2E_T\sqrt{s} - \frac{p_L^2}{E_T}\sqrt{s} \quad E_T = \sqrt{p_L^2 + m_\eta^2} \approx m_\eta$$  \hspace{1cm} (1)

with negligible transverse momentum, a continuous spectrum in $p_L$, $-350 < p_L < 350$ MeV, and high $M_{\text{miss}}^2$ values. Fig. 4 (right) shows this difference in the correlation between the squared missing mass, $M_{\text{miss}}^2$, and the longitudinal momentum, $p_L$, for the signal (top) and for the irreducible $e^+e^- \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$ background (bottom).

Further criteria are applied for suppressing processes with photons and $e^+e^-$ as tracks in the final state, such as $\eta(\rightarrow 3\pi^0)\gamma$ with photon conversion or radiative Bhabha events, $e^+e^-\gamma(\gamma)$. Event distributions in $p_L$ and $M_{\text{miss}}^2$ from data are independently fitted with the superposition of MC shapes for signal and background (Fig. 4 (left)). A preliminary value for the cross section is $\sigma_{\gamma\gamma \rightarrow \eta \rightarrow \pi^+\pi^-\pi^0}(1 \text{ GeV}) = 41.7 \pm 4_{\text{stat}}$ pb. Systematics are under evaluation.

The cross section of the irreducible process $e^+e^- \rightarrow \eta\gamma \rightarrow \pi^+\pi^-\pi^0\gamma$ is evaluated using the same sample of data and asking for three photons in the final state. A kinematic fit is performed, requiring energy and momentum conservation, and the improved variables are used to fit the distribution of the recoil photon energy and the distribution of the invariant mass of the $\pi^+\pi^-\pi^0$ system. The preliminary result is $\sigma_{e^+e^-\rightarrow\eta\gamma}(1 \text{ GeV}) = 0.866 (9)_{\text{stat}} (93)_{\text{syst}}$ nb, where the systematic uncertainty is given by residual $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-\pi^0\pi^0$ background.
Figure 4. Left: fit in $dN/dM^2_{\text{\text{miss}}}$: signal (cyan), $\eta\gamma$ (red) and $e^+e^-\gamma(\gamma)$ (green) are well visible; Right: correlation between the squared missing mass, $M^2_{\text{\text{miss}}}$, and the longitudinal momentum, $p_L$, for the signal (top) and for the irreducible background $e^+e^-\rightarrow \eta\gamma\rightarrow \pi^+\pi^-\pi^0\gamma$ (bottom).

2.2. Observation of $\gamma\gamma\rightarrow \eta$, with $\eta\rightarrow \pi^0\pi^0\pi^0$

The main backgrounds for this analysis are annihilation processes with at least four prompt photons in the final state (i.e. $e^+e^-\rightarrow \eta\gamma$, $e^+e^-\rightarrow KSK_L$, $e^+e^-\rightarrow \omega\pi^0$, $e^+e^-\rightarrow f_0(980)(\rightarrow \pi^0\pi^0\pi^0)$), for which accidental or split calorimeter clusters increase the photon multiplicity. Events with six and only six prompt photons in the final state and with no tracks in the drift chamber are selected. The photons are paired choosing the combination which minimizes the $\chi^2$-like variable

$$\chi^2_{\text{\text{\text{miss}}}} = \frac{(m_{\pi^0} - m_{ij})^2}{\sigma_{ij}^2} + \frac{(m_{\pi^0} - m_{mn})^2}{\sigma_{mn}^2} + \frac{(m_{\pi^0} - m_{kl})^2}{\sigma_{kl}^2},$$

(2)

where $m_{ij}$ is the invariant mass of each pair of photons and $\sigma_{ij}$ the resolution. Then, a kinematic fit is performed asking for the six photons invariant mass to be equal to the mass of the $\eta$ meson. A cut is then applied on the energy of the most energetic photon, to reject $e^+e^-\rightarrow \eta\gamma$ events in which the monochromatic photon is detected. The squared missing mass, $M^2_{\text{\text{miss}}}$, distribution is well described by the $\gamma\gamma\rightarrow \eta\rightarrow \pi^0\pi^0\pi^0$ and $\eta(\rightarrow \pi^0\pi^0\pi^0)\gamma$ MC shapes. Fig. 5, left, shows the fit in $M^2_{\text{\text{\text{miss}}}}$.

The preliminary result obtained from the fit is $\sigma_{\gamma\gamma\rightarrow \eta\rightarrow 3\pi^0}(1\text{ GeV}) = 37.0 \pm 1.4_{\text{\text{\text{stat}}}} \pm 2.2_{\text{\text{\text{syst}}}}$ pb. We also quote a preliminary value for the cross section of the irreducible background $e^+e^-\rightarrow \eta\gamma$, $\sigma_{e^+e^-\rightarrow \eta\gamma}(1\text{ GeV}) = 0.875 (18)_{\text{\text{\text{stat}}}} (35)_{\text{\text{\text{syst}}}}$ nb, in agreement with that measured in the $e^+e^-\rightarrow \eta\gamma\rightarrow \pi^+\pi^-\pi^0\gamma$ analysis. This is shown in Fig. 5, right, among other experimental results [5] as a function of $\sqrt{s}$.

3. KLOE measurement: $\gamma\gamma\rightarrow \pi^0\pi^0$

The major sources of background for this analysis is represented by annihilation processes with four or more prompt photons in the final state: $e^+e^-\rightarrow KSK_L$, $e^+e^-\rightarrow \eta\gamma$, $e^+e^-\rightarrow \omega\pi^0$, $e^+e^-\rightarrow f_0(980)(\rightarrow \pi^0\pi^0\pi^0)\gamma$. In addition, due to the possibility of cluster splitting, the $e^+e^-\rightarrow \gamma\gamma$ process is also considered as a source of background. Selected events have no tracks in the drift chamber and four prompt photons in the final state with polar angle $23^\circ < \vartheta < 157^\circ$ and energy $E_\gamma > 15$ MeV. The photons are paired choosing the combination which minimizes the $\chi^2$-like variable of Eq. (2) in the case of four photons coming from two neutral pions, $\chi^2_{4\gamma}$. Events with $\chi^2_{4\gamma} > 4$ are rejected: the effect of this selection is shown in Fig. 6, left. To reject
\[ \gamma \gamma \rightarrow \eta \rightarrow \pi^0 \pi^0 \pi^0 \] analysis. Left: squared missing mass distributions for data (points with error bars) and backgrounds (histograms) normalized according to the fit results. Colour code: red = \( e^+ e^- \rightarrow \eta \gamma \), light blue = signal, blue = \( e^+ e^- \rightarrow \omega \pi^0 \). Right: preliminary KLOE value for \( \sigma(e^+ e^- \rightarrow \eta \gamma) \) at \( \sqrt{s} = 1 \text{GeV} \) (red point), and SND results [5] for several values of \( \sqrt{s} \).

\( e^+ e^- \rightarrow K_S K_L \) events, where a large amount of non-prompt energy is released in the detector, a tighter cut on the energy fraction carried by photons, \( R = (\sum E_\gamma)/E_{\text{cal}} > 0.75 \), is applied. The four photon invariant mass spectrum for the selected data sample is shown in Fig. 6, right, together with the normalized background Monte Carlo simulations. The excess of events with respect to the expected annihilation processes, in the low invariant mass region, is an indication of the \( \gamma \gamma \rightarrow \pi^0 \pi^0 \pi^0 \) production.

The determination of the differential cross section \( d\sigma(\gamma \gamma \rightarrow \pi^0 \pi^0)/dM_{4\gamma} \) and of other possible residual backgrounds is in progress.

4. KLOE analyses: conclusions

From an integrated luminosity of 240 pb\(^{-1}\) of data collected at DAΦNE operating at \( \sqrt{s} \simeq 1 \) GeV, the following preliminary results in \( \gamma \gamma \) analyses are achieved:

- unambiguous signature of both \( \gamma \gamma \rightarrow \eta \) and \( \gamma \gamma \rightarrow \pi^0 \pi^0 \) events, without any \( e^\pm \) tagger;
- \( \gamma \gamma \rightarrow \eta \) events are observed through both \( \eta \rightarrow \pi^+ \pi^- \pi^0 \) and \( \eta \rightarrow \pi^0 \pi^0 \pi^0 \) channels, with independent systematics;
- from the same data sample, an exploratory research shows a structure at small values of the \( M_{4\gamma} \) spectrum, where the process \( e^+ e^- \rightarrow e^+ e^- \pi^0 \pi^0 \) is expected.

The cross section \( \sigma(e^+ e^- \rightarrow \eta \gamma) \) at \( \sqrt{s} = 1 \) GeV has been determined as well, with accuracy better than the closer data points.

These results are encouraging also in view of the forthcoming data taking campaign of the KLOE-2 project [6].
5. Two-photon physics at KLOE-2

After recent luminosity upgrade [7] performed on DAΦNE collider, a new data taking campaign has been approved for the KLOE experiment, together with several detector upgrades. One of the most significant features, characterising this new project called KLOE-2, is the presence of a small angle tagging system composed of two couples of new detectors (one couple for each accelerator’s arm) referred to as the Low Energy Tagger (LET) and High Energy Tagger (HET). These detectors will allow the study of \( \gamma\gamma \) physics running the collider at \( \phi \)-peak in the center of mass energy. A detailed description of all new detectors and of the KLOE-2 scientific program can be found in Ref. [8].

5.1. The taggers

The \( \gamma\gamma \) processes differ from the \( \phi \)-decay because of the presence of \( e^+e^- \) in the final state. The detection of these final leptons is absolutely mandatory to close the kinematics of the \( \gamma\gamma \) interactions, making them independent from backgrounds. Table 1 lists all interesting \( \gamma\gamma \) physics channels together with at least one \( \phi \)-decay which could produce an identical final state in the detector once outgoing \( e^+e^- \) from \( \gamma\gamma \) events go undetected along the beam pipe.

In order to disentangle signal from background a dedicated lepton tagging system has been designed and built to catch those \( e^+e^- \) which are lost along the beam pipe. According to DAΦNE layout, only two possible positions were found to install new detectors: one next to the interaction point (where LET detector is placed) and the other one after the first bending dipole magnet of the machine (for the HET detector). The LET is placed inside the KLOE detector (\(~ 1 \text{ m} \) away from IP) to catch lower energy leptons, i.e. leptons which emitted a high energy photon. The HET is placed 11 m away from IP and detects higher energy leptons, that is those leptons which have lost such a tiny amount of energy that they manage to reach the exit of the
Table 1. Possible background processes for $\gamma\gamma$ physics coming from $\phi$ meson decay. Number of events are estimated for an integrated luminosity of 1 fb$^{-1}$.

| $\gamma\gamma$ channel | Missing | Signal Events | $\phi$-decay | Missing | BG events |
|-------------------------|---------|---------------|--------------|---------|-----------|
| $e^+e^- \rightarrow e^+e^-\pi^0\pi^0$ | $e^+e^-$ | $2 \times 10^4$ | $K_S(\pi^0\pi^0)K_L$ | $K_L$ | $\sim 10^9$ |
| $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ | $e^+e^-$ | $2 \times 10^6$ | $K_S(\pi^+\pi^-)K_L$ | $K_L$ | $\sim 2 \times 10^9$ |
| $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ | $e^+e^-$ | $2 \times 10^6$ | $\pi^+\pi^-\pi^0$ | $\pi^0$ | $\sim 1 \times 10^9$ |
| $e^+e^- \rightarrow e^+e^-\eta$ | $e^+e^-$ | $1 \times 10^9$ | $\eta(\gamma\gamma)\gamma$ | $\gamma$ | $\sim 10^9$ |
| $e^+e^- \rightarrow e^+e^-\pi^0$ | $e^+e^-$ | $4 \times 10^9$ | $\pi^0(\gamma\gamma)\gamma$ | $\gamma$ | $\sim 5 \times 10^9$ |

dipole.

In order to understand what kind of detector is needed in the region of interest the tracking of the off-energy particles along DAΦNE optics with BDSIM[9] (a GEANT4 extension toolkit capable of simulating nominal and off-energy particle transport in the accelerator beam line) is performed. Trajectories of particles coming from the IP with energies from 5 MeV to 510 MeV (which is the beam nominal energy of DAΦNE) are calculated in step of 0.5 MeV, in order to infer the energy distribution of leptons as a function of their position.

Energy distribution of leptons hitting the beam pipe wall in the LET region shows that there is essentially no correlation between their energy and $z$-coordinate (the beam line coordinate), hence a calorimetric choice for this detector is the most suitable one (for details see Ref. [10]).

Concerning HET detector instead, simulation shows that off-energy leptons do not hit the vacuum chamber wall in the corresponding region, being simply deviated from the nominal orbit in the $x$-coordinate direction (the one pointing to the collider center). In Fig. 7 (left) the distance between the tracked lepton and the nominal orbit is plotted as a function of the energy of the particle. The linear correlation between these quantities is striking. Moreover from the fit parameters, it is possible to see that in order to obtain an energy resolution of about 0.6 MeV, a spatial resolution of 1 mm is sufficient.

Another important feature of particles surviving the travel up to the exit of the dipole magnet is that they are the ones having a narrower angular distribution at IP (see Fig. 7 (right)). This will justify the fact that photons associated with tagged leptons have very low $q^2$ (see section 6.1).

Figure 7. Tracking to HET region. Left: lepton energy versus its trajectory distance (in $x$ direction) from nominal orbit in HET region. Right: Comparison between lepton angular distribution at IP for all leptons (black) and for the ones reaching the HET region (red).

The presence of a flange just after the dipole, together with the discussed favorable lepton
displacement in the HET region, suggest that the optimal choice for this second tagging station is to install a position detector here.

Physical requirements for the HET detector are the following: good time resolution to disentangle each bunch coming with a period of $\sim 2.7$ ns; capability to acquire data at a frequency of 368 MHz in order to allow event reconstruction with KLOE apparatus; radiation hardness to let the detector stand $\sim 30$ mm from the beam (a closer position would interfere with the proper functioning of the machine) for long term acquisition and tiny size in order to install it through the flange inside the DAΦNE vacuum chamber. The proposed tagger detector consists of a set of 28 plastic scintillators ($3 \text{ mm} \times 5 \text{ mm} \times 6 \text{ mm}$) plus one additional long scintillator ($3 \text{ mm} \times 5 \text{ mm} \times 6 \text{ mm}$) for coincidence purposes, coupled to properly shaped light guides which convey light signals out of the beam pipe to high quantum efficiency photomultipliers (PMT). A drawing of the detector inside the beam pipe is represented in Fig. 8 (left), together with a real picture of the detector itself in place (right).

![Figure 8. HET detector. Right: a drawing of the High Energy Tagger placed in the accelerator’s flange. Left: a picture taken during HET detector insertion. The green object on the right is the bending dipole magnet.](image)

6. The process $\gamma\gamma \rightarrow \pi^0$

Concerning the $\gamma\gamma$ physics program for the KLOE-2 experiment, the collaboration is planning to perform two interesting measurements in single $\pi^0$ production process (through $e^+e^- \rightarrow e^+e^-\pi^0$ process), that is:

- a precision determination of the $\gamma\gamma \rightarrow \pi^0$ decay width: $\Gamma_{\gamma\gamma \rightarrow \pi^0}$;
- a measurement of the $\gamma^*\gamma \rightarrow \pi^0$ transition form factor, $F(Q^2)$, in the unexplored region of low-momentum transfer.

A complete feasibility study of these two measurements has been performed and is available in Ref. [11].

6.1. The basics of width and form factor measurements

Since the original proposal of Low [12] to measure the width of the neutral pion decay into two photons through the $e^+e^- \rightarrow e^+e^-\pi^0$ process, only with the Crystal Ball detector at DESY this measurement has been done using this method, with the result $\Gamma_{\gamma\gamma \rightarrow \pi^0} = (7.7 \pm 0.5 \pm 0.5)$ eV [13]. It was stressed ([14] and [15]) that for a precision measurement of $\pi^0$ width via $\gamma\gamma$
fusion" ($\gamma \gamma \to \pi^0$) process, one needs to improve the original Low’s proposal. Namely, instead of a no-tag experiment (like [13]) one should perform a lepton double-tagging at small angles. Thanks to the lepton tagging system, and the HET in particular, it is now possible to perform that double tagging at KLOE-2.

One can extract the value of the partial decay width from data, using the formula

$$\Gamma_{\pi^0 \to \gamma \gamma} = \frac{N_{\pi^0}}{\epsilon \mathcal{L}} \frac{\hat{\Gamma}_{\pi^0 \to \gamma \gamma}}{\tilde{\sigma}_{e^+e^- \to e^+e^- \pi^0}}$$

(3)

where $N_{\pi^0}$ is the number of detected pions, $\epsilon$ accounts for the detection acceptance and efficiency, $\mathcal{L}$ is the integrated luminosity, $\hat{\Gamma}_{\pi^0 \to \gamma \gamma}$ is the $\pi^0$ width calculated from the theoretical model and $\tilde{\sigma}_{e^+e^- \to e^+e^- \pi^0}$ the cross section obtained with a high statistics Monte Carlo simulation using the same model as for the $\Gamma_{\gamma \gamma \to \pi^0}$ calculation.

The form factor $F(Q^2)$ can be evaluated through the relation:

$$\frac{F^2(Q^2)}{F^2(Q^2)_{MC}} = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{data}}{\left(\frac{d\sigma}{dQ^2}\right)_{MC}}$$

(4)

where $\left(\frac{d\sigma}{dQ^2}\right)_{data}$ is the experimental differential cross section, and $\left(\frac{d\sigma}{dQ^2}\right)_{MC}$ is the Monte Carlo one obtained with the from factor $F(Q^2)_{MC}$.

The $\pi^0$ production in the process $e^+e^- \to e^+e^- \pi^0$ is simulated with EKHARA [16] Monte Carlo generator. The simulated signal is given only by the $t$-channel amplitude ($\gamma^*\gamma^* \to \pi^0$). Since a stand-alone EKHARA version works in the center of mass frame of incident leptons and does not simulate the pion decays, it has been modified to take into account the DAΦNE crossing angle between the incoming beams ($\theta_{e^+e^-} \approx 51.3$ mrad) and the decay of the $\pi^0$ into two photons. Tracking simulation shows that only few of the emitted leptons ($\sim 2\%$) reach the HET detectors, providing a realistic estimate of the coincidence acceptance. In the following the coincidence of the HET detectors (briefly HET-HET coincidence) will be required, which selects the energy of the final leptons to be between 420 and 460 MeV (single HET acceptance is $420 < E < 490$ MeV).

6.2. $\gamma \gamma \to \pi^0$: feasibility of the $\pi^0$ width measurement

Fig. 9, left, shows the energy of the emitted $\pi^0$ in the $\gamma \gamma$ process: as can be seen, the request of HET-HET coincidence allows the selection of $\pi^0$ which are almost at rest (dark region), compared with the no-tag case (light-gray). Since the $\pi^0$ decays almost at rest, most of the photons from its decay are emitted with large polar angle (defined as the angle between the direction of the photon and the beam axis), as show in Fig. 9 (right).

In particular, about 95% of the decay photons are emitted above 25° and below 155°, resulting in a large acceptance for photons reaching the KLOE electromagnetic calorimeter.

By requiring both photons in the barrel of the EmC (i.e. between 50° and 130°) an the HET-HET coincidence, a value for the acceptance $\epsilon_{acc}$ of 1.2% is obtained with the detector 30 mm far away from nominal orbit (from this moment on $x_0$ will be the distance of closest plastic scintillator to nominal orbit from the nominal orbit itself). Since the total cross-section is $\sigma_{tot} \approx 0.28$ nb, a visible cross section of about 3.4 pb is obtained within the acceptance cuts. So the integrated luminosity $\mathcal{L}$ at DAΦNE required to reach a 1% statistical error (for $x_0 = 30$ mm) is:

$$\mathcal{L} = \frac{10000}{\sigma_{tot} \epsilon_{acc} \epsilon_{det}} \approx \frac{3}{\epsilon_{det}} \text{ fb}^{-1}$$

(5)
Figure 9. The $\pi^0$ energy (left) and the polar angle (right) distribution in the laboratory frame with (dark) and without (light-gray) HET-HET coincidence.

where the efficiency $\epsilon_{det}$ due to trigger, reconstruction and analysis criteria is estimated to be about 50%, by means of the KLOE Monte Carlo code ($\textsc{geanfi}$ [17]). Therefore, the required data sample can be obtained during the first phase (about one year) of data taking.

Extraction of the width $\Gamma_{\gamma\gamma\to\pi^0}$ with $\sim 1\%$ accuracy requires a very good control of the systematic errors. From the experimental point of view, the clean signature of the process (the photons from $\pi^0$ decay are emitted in back-to-back configuration because of pion momentum, see Fig.9 (left)), the use of the KLOE detector and the HET-HET coincidence should allow to keep systematic effects under control at the required level of precision. A possible background to this measurement, in particular, comes from radiative Bhabha scattering, which could have the same signature of our signal. An extensive simulation of this background (based on $\sim 10^8$ events generated with Babayaga MC generator [18], [19]) shows that no events survive the coincidence of HET detectors for $e^+$ and $e^-$ and the KLOE acceptance for photon, and therefore the expected contribution is negligible.

Fig. 10(a) and Fig. 10(b) clarify the Bhabha background issue. In particular, the former shows how the reconstructed invariant mass of leptons hitting the two HET stations from background events produces a wide distribution which crosses the corresponding invariant mass distribution peak (around $m_{\pi^0} \simeq 135$ MeV) from signal.

The distributions in Fig. 10(a) are obviously not on scale. Due to the huge difference in the total cross section, the signal-to-background ratio is extremely unfavorable (about $6 \times 10^{-7}$) preventing the disentanglement of the two processes to be performed only with the information coming from the HET detector alone (note that since the HET is unable to measure leptons momenta, the invariant mass evaluation is performed assuming a zero angular deviation from the nominal orbit at IP).

If the requirement of at least one photon in the final state (to be detected by KLOE EmC) is added, the disentanglement becomes very simple. In Fig. 10(b), the angular distribution of photons emitted within a Bhabha scattering process is shown in blue. Asking for both positron and electron to be detected by HET the red angular distribution in the same figure is obtained. It’s clearly visible that the HET-HET coincidence selects photons which are almost collinear with the beam (i.e. $0^\circ < \theta < 175^\circ$ and $175^\circ < \theta < 180^\circ$) which cannot be detected by the KLOE EmC, whose angular acceptance is $25^\circ < \theta < 155^\circ$. In the case of $\gamma\gamma$ processes on the contrary, the photons coming from the decay of the pion, produced at rest, are emitted back-to-back almost uniformly in the solid angle (cfr Fig.9 (right)). Signal and background are distinguished with very high efficiency (almost 100%) simply requiring at least a photon in the EmC.

The KLOE trigger itself requires two energy releases in the EmC in order to assert the first level trigger. Since the energy distribution of the decay photons is peaked around 70 MeV and
the energy threshold levels of the EmC are comparable with this value, a significant percentage of $\gamma\gamma$ events are lost (especially when the photon is hitting the End Cap region, where threshold is higher). An alternative to increase the trigger efficiency would be to acquire $\gamma\gamma$ events by means of HET-HET coincidence plus a single barrel energy release in KLOE. This kind of trigger logic would not interfere with KLOE data taking and would be, above all, free from radiative Bhabha scattering.

From the theoretical point of view, the systematic errors can arise from the uncertainty in the modeled $\pi^0\gamma^*\gamma^*$ transition form factor. For this kind of effect, numerical simulation with different formulae for the form factor are performed, showing that the imposition of the HET-HET coincidence leads to a significant restriction on the photon virtuality in $\gamma^*\gamma^* \rightarrow \pi^0$: for most of the events one has $|q^2| < 10^{-4}$ GeV$^2$ has shown in Fig. 11.

Thus for the KLOE-2 case the possible effect of the photon virtualities which can influence the accuracy of Eq. (3) is negligible. In particular, the uncertainty in the measurement of $\Gamma_{\gamma\gamma \rightarrow \pi^0}$ due to the form factor parametrization in the generator is expected to be less than 0.1%.
6.3. \( F(m_{\pi^0}^2, 0, q^2) \): Monte Carlo simulation

By requiring one lepton inside the KLOE drift chamber \((20^\circ < \theta < 160^\circ\) corresponding to \(|q_1^2| < 0.1\text{ GeV}^2\) and the other one in the HET detector \((\text{corresponding to } |q_2^2| < 10^{-4}\text{ GeV}^2\text{ for most of the events, see Fig. 11)}\) one can measure the differential cross section \((d\sigma/dQ^2)_{\text{data}}\) where \(Q^2 = -q^2\). Using Eq. (4), the form factor \(|F(Q^2)|\) can be extracted from this cross section.

\[
F_{\pi^0,\gamma^*\gamma^*}(0,0) = \frac{4\pi\alpha^2 m_{\pi^0}^2}{\Gamma_{\gamma\gamma\rightarrow\pi^0}} \left(\frac{d\sigma}{dq^2}\right)_{q^2=0}
\]

\[
F_{\pi^0,\gamma^*\gamma^*}(q_1 = 0, q_2 = 0) = \frac{4\pi\alpha^2 m_{\pi^0}^2}{\Gamma_{\gamma\gamma\rightarrow\pi^0}}
\]

Slope calculations suffer from model dependence (not accounted for in the error estimation) due to form factor parametrization. The validity of these parametrizations has never been verified, because there are no data at low momenta \((Q^2 < 0.5\text{ GeV}^2)\). Therefore, filling of this experimental gap in \(Q^2\) by the KLOE-2 experiment \((\text{at } Q^2 < 0.1\text{ GeV}^2)\) would help to verify the consistency of the form factor parametrizations.

The impact of these measurement on the model parameters \(e.g.,\) the normalization of the form factor and hence on the value and the precision of the contribution of the pion pseudoscalar exchange to the hadronic light-by-light scattering \([23]\) has also been evaluated. According to simulations the proposed measurements can improve the uncertainty on the value \(a_{\mu}^{\text{LbyL;\pi^0}}\) of \(\sim 2\) (see Ref. \([11]\) for details).
7. KLOE-2 perspectives: conclusions

A simulation of the KLOE-2 experiment with 1 year of data taking was performed. Numerical results indicate the feasibility of a $\sim 1\%$ statistical error in the measurement of $\Gamma_{\gamma\gamma \rightarrow \pi^0}$. Such a precision is better than the current experimental world average and theoretical accuracy. The $\pi^0$ electromagnetic transition form factor, $F(Q^2)$, can be measured in the region $0.01 < Q^2 < 0.1 \text{ GeV}^2$ with a statistical error of $\lesssim 6\%$ in each bin. This low $Q^2$ measurement can test the consistency of the models which have been fitted so far to the data from CELLO, CLEO and BaBar [24] at higher $Q^2$. The proposed measurement with the KLOE-2 experiment can also reduce the error on the hadronic light-by-light contribution to $\mu g-2$ by a factor $\sim 2$.

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