

$\gamma\gamma$ Physics and Transition Form Factors with KLOE/KLOE2

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Abstract. The KLOE results on the measurement of the transition form factors of the η and π^0 mesons in ϕ Dalitz decays are presented. Also we report in the determination of the $\Gamma(\eta \rightarrow \gamma\gamma)$ in $\gamma\gamma$ collisions, for which KLOE has delivered the most precise measurement up to the date. The prospects for $\gamma\gamma$ physics of the upgraded detector KLOE-2, which is taking data aiming to collect more than 5 fb^{-1} by March 2018, are reviewed.

1 Introduction

The measurement of the Transition Form Factors (TFFs) of pseudo-scalar mesons both in time-like and space-like regions of momentum transfer has been of interest in KLOE-2 and also a main item in the KLOE-2 physics program [1]. The TFFs describe the coupling of the mesons to photon thus providing information about the nature and structure of mesons. More recently the interest on TFFs has grown since they have an essential contribution to the calculation of the hadronic Light-by-Light (LbL)scattering contribution to the anomalous momentum of the muon [2]. Any experimental results both in time-like and space-like q^2 will help to constrain the models used in the calculations. In the case of time-like q^2 TFFs is interesting to measure them in Dalitz decays, for which KLOE has already provided very precise measurements in $\phi \rightarrow \eta e^+ e^-$ and $\phi \rightarrow \pi^0 e^+ e^-$. KLOE-2 program is also focused in another interesting item, this is $\gamma\gamma$ physics, by studying reactions such as $e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- X$, where X is a final state with even charge conjugation. The expected number of events is given as a function of the $\gamma\gamma$ energy in:

$$\frac{dN}{dW_{\gamma\gamma}} = L_{int} \frac{dF}{dW_{\gamma\gamma}} \sigma_{\gamma\gamma \rightarrow X} \quad (1)$$

where L_{int} is the integrated luminosity, $\sigma_{\gamma\gamma \rightarrow X}$ the $\gamma\gamma$ cross section and $\frac{dF}{dW_{\gamma\gamma}}$ corresponds to the luminosity function in Fig. 1. In DAΦNE, which is operated at the ϕ center of mass, $\sqrt{s} \sim M_\phi$, the final states accessible are either single pseudo-scalar $X = \eta, \pi^0$, or double pion production, $X = \pi\pi$. Via the cross section, $\sigma_{\gamma\gamma \rightarrow X}$, we can access the radiative width $\Gamma(X \rightarrow \gamma\gamma)$ of the pseudo-scalar meson and the TFF, $F(q_1^2, q_2^2)$, for space-like q^2 .

2 The KLOE detector

From 2001 to 2006 the KLOE detector at the DAΦNE ϕ -factory, located at the INFN-LNF in Frascati. It acquired about 2.5 fb^{-1} at the peak of the $\phi(1020)$, and about 250 pb^{-1} off-peak, most of it at

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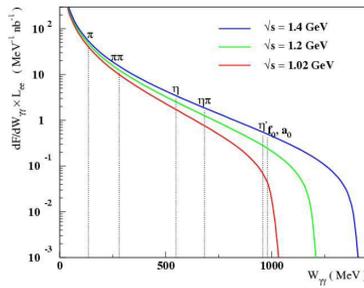


Figure 1: Effective luminosity for $\gamma\gamma$ processes at three different energies.

$\sqrt{s} = 1$ GeV. The new upgraded KLOE-2 detector started to take data in November of 2014, with the aim of collecting more than 5 fb^{-1} at the end of March 2018. In the meanwhile it has collected about 3.9 pb^{-1} . During this period DAΦNE peak luminosity has been of $2.2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, and the integrated daily luminosity has been of about 10 pb^{-1} .

3 KLOE-2 Detector Upgrade

After the installation of a new interaction scheme in DAΦNE in 2008, aiming for higher luminosity, the KLOE detector was prepared for a new data-taking campaign, known now as KLOE-2. Following the start of the DAΦNE commissioning for the KLOE-2 data taking in 2010, the first detector upgrade was the installation of a tagger system for scattered electrons and $\gamma\gamma$ physics. The tagger system [3] of KLOE-2 consists of two different devices: (1) the Low Energy Tagger (LET) and (2) the High Energy Tagger (HET), referring to the energy of the detected electrons or positron. In 2013 an Inner Tracker [4] made of four layers of cylindrical triple GEM detectors was installed between the interaction point (IP) and the Drift Chamber, to improve the vertex reconstruction for decay vertices close to the IP. Moreover, two crystal calorimeters (CCALT) have been added to cover the acceptance for photons and e^\pm from the IP down to 10° [5]. Finally, the DAΦNE focusing quadrupoles, placed inside the KLOE-2 detector, have been instrumented with tungsten and scintillating tile calorimeters (QCALT) [6].

3.1 The High Energy Tagger

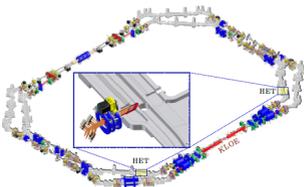


Figure 2. Schematic view of the DAΦNE ring with the HET stations.

Scattered e^\pm with $E > 400$ MeV escape the beam-pipe after the first bending dipole of DAΦNE. In this case the trajectories of the scattered particles are strongly correlated with their energies. The HET was conceived to detect these e^\pm . Thus, it can be also used as spectrometer, giving a fast feedback on the machine operation. The HET is made of two scintillator hodoscopes readout by PMTs and symmetrically placed at 11 m from the interaction point, see Fig. 2.

4 $\gamma\gamma$ physics without taggers

The two-photon width of the η meson has been measured by using KLOE data. For this measurement events from $e^+e^- \rightarrow e^+e^-\eta$ where $\eta \rightarrow \pi^+\pi^-\pi^0$ and $\eta \rightarrow \pi^0\pi^0\pi^0$. In the absence of taggers the scatter leptons are not detected. To avoid the large background from ϕ decays, the data collected off-peak at $\sqrt{s} \sim 1$ GeV was used for the analysis, corresponding to an integrated luminosity of about 240 pb^{-1} . In Fig. 3, the transverse momentum of the $\pi^+\pi^-\gamma\gamma$ and the squared missing mass is presented. For the 6γ system the squared missing mass and the longitudinal momentum are shown in Fig. 4. From the two dimensional fits of these distributions we obtain the cross sections $\sigma(e^+e^- \rightarrow e^+e^-\eta) = (34.5 \pm 2.5 \pm 1.3) \text{ pb}$ and $\sigma(e^+e^- \rightarrow e^+e^-\eta) = (32.0 \pm 1.5 \pm 0.9) \text{ pb}$ for charged and neutral decays of η , respectively. Combining both results, we obtained the cross section $\sigma(e^+e^- \rightarrow e^+e^-\eta) = (32.7 \pm 1.3 \pm 0.7) \text{ pb}$, from which we can extract the most precise measurement of the two-photon width: $\Gamma(\eta \rightarrow \gamma\gamma) = (520 \pm 20 \pm 13) \text{ eV}$, up to date.

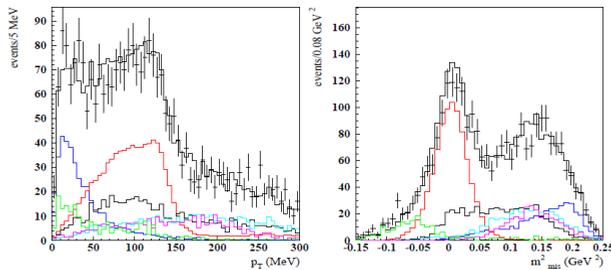


Figure 3: **Left:** distribution of the transverse momentum of the $\pi^+\pi^-$ system. **Right:** distribution of the squared missing mass. The contribution of the signal is blue, $e^+e^- \rightarrow \eta\gamma$ is red, $e^+e^- \rightarrow \omega\pi^0$ is black, $e^+e^- \rightarrow e^+e^-\gamma$ is green, $e^+e^- \rightarrow K^+K^-$ is blue and $e^+e^- \rightarrow K_S K_L$ is purple.

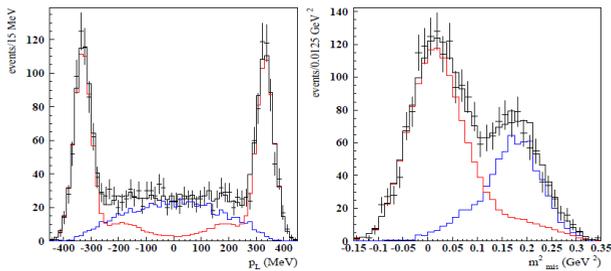


Figure 4: **Left:** distribution of the 6γ longitudinal momentum. **Right:** distribution of the squared missing mass. The blue line corresponds to the signal, the red line to $e^+e^- \rightarrow \eta\gamma$.

4.1 $\gamma\gamma \rightarrow \pi^0$ with taggers at KLOE-2

The measurement of the radiative width of the π^0 is an important test of the strong interaction dynamics at low energies. It has been calculated in Chiral Perturbation Theory with an 1.4% uncertainty, $\Gamma(\pi^0 \rightarrow \gamma\gamma) = (8.09 \pm 0.11) \text{ eV}$ [7] and the most precise experiment measurement up to

now it is given by the PrimEx Collaboration, which is based in the Primakoff effect, $\Gamma(\pi^0 \rightarrow \gamma\gamma) = (7.82 \pm 0.14 \pm 0.17) \text{ eV}$ [8]. Nonetheless, the measurement using the Primakoff effect suffers from some model dependence owing to the conversions in the nucleus field. The π^0 width can be measured at KLOE-2 by using a different process selecting $e^+e^- \rightarrow e^+e^-\pi^0$ with quasi-real photons ($q^2 \simeq 0$). The event selection requires that the scattered leptons are detected in the HET stations and the two photons from π^0 decay are registered in the calorimeter. In agreement with Monte Carlo simulation, the double HET coincidence efficiency is 1.4%, hence with a cross section of $\sigma(\pi^0 \rightarrow \gamma\gamma) = 0.28 \text{ nb}$, we can expect $2000 \text{ events/fb}^{-1}$, which allows to reach 1% accuracy in $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ with the 5 fb^{-1} expected with KLOE-2. On top of this, the $\pi^0\gamma^*\gamma$ TFF, with a quasi-real photon and a virtual one, can be measured by selecting events where where one lepton is detected in the HET ($|q^2| \approx 0$) and the other one in the calorimeter, at large angle. This way we can investigate an unexplored q^2 region ($|q^2| < 0.1 \text{ GeV}^2$), which is important to constrain the TFF parameterizations, see Fig 5.

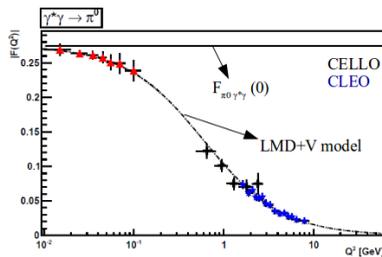


Figure 5: Simulation of KLOE-2 measurement of $F(Q^2)$ (red triangles) with statistical errors for 5 fb^{-1} ref. [9]

5 Transition Form Factors in Dalitz decays

In Dalitz decays, the measured TFFs are functions of the four-momentum squared, $q^2 = m_{l^+l^-}^2$, and are parametrized, according to Vector Meson Dominance (VMD) model, as $F(q^2) = 1/(1 - \frac{q^2}{\Lambda^2})$, where Λ is a characteristic mass identified with the nearest vector meson. The dilepton mass distributions of the reactions $\eta \rightarrow e^+e^-\gamma$ and $\eta \rightarrow \mu^+\mu^-\gamma$ were measured by NA60 [10] and the A2 Collaboration at MAMI [11, 12]. The mass distributions are described by $\Lambda_\eta^2 = 1.92 \div 1.95 \text{ GeV}^{-2}$, in agreement with the VMD prediction $\Lambda_\eta^2 = 1.88 \text{ GeV}^{-2}$. On the contrary, the TFF of $\omega \rightarrow \pi^0\mu^+\mu^-$, measured by NA60, with $\Lambda_\eta^2 = 2.24 \text{ GeV}^{-2}$ is not well reproduced by the VMD expectation, $\Lambda_\eta^2 = 1.68 \text{ GeV}^{-2}$. Other models [13–15] have been proposed, which predict deviations of the VMD model also in $\phi \rightarrow \eta(\pi^0)l^+l^-$.

5.1 $\phi \rightarrow \pi^0 e^+ e^-$

While the reaction $\phi \rightarrow \pi^0 e^+ e^-$ has been measured by the experiments CMD-2 and SND at Novosibirsk, reporting $\text{BR}(\phi \rightarrow \pi^0 e^+ e^-) = (1.22 \pm 0.34 \pm 0.21) \times 10^{-5}$ [16] and $(1.01 \pm 0.28 \pm 0.29) \times 10^{-5}$ [17], respectively, no measurement on the TFF has been published. Using a sample of 1.7 fb^{-1} of KLOE data, about 9000 events for this decay have been selected. In Fig. 6, the data/MC comparison for the e^+e^- and two photon invariant masses are shown.

The TFF as a function of the e^+e^- invariant mass is obtained after the background subtraction and in Fig. 7 is compared with the theoretical expectations. It shows a good agreement with the model

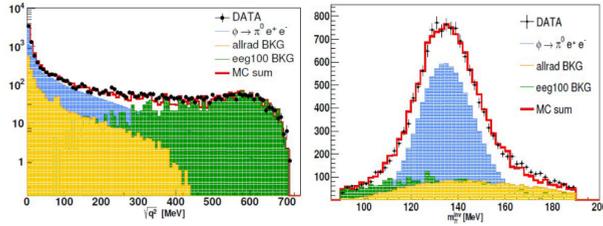


Figure 6: **Left:** e^+e^- invariant mass distribution for $\phi \rightarrow \pi^0 e^+ e^-$. **Right:** two photon invariant mass for $\phi \rightarrow \pi^0 e^+ e^-$

of ref. [14]. According to the model in ref [14], the branching ratio can be extrapolated for all the invariant mass range, giving $\text{BR}(\phi \rightarrow \pi^0 e^+ e^-) = (1.35 \pm 0.05^{+0.05}_{-0.10}) \times 10^{-5}$ [20].

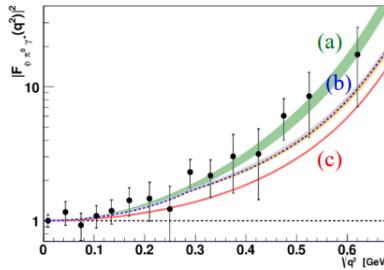


Figure 7: TFF as a function of e^+e^- invariant mass, compared with the theoretical predictions, (a)chiral theory approach: (green) ref. [14], (b)dispersive analysis: (orange and cyan) ref. [15] and (blue dashed line) ref. [18], (c)one-pole VMD model: (red)

5.2 $\phi \rightarrow \eta e^+ e^-$

A previous measurement of the TFF for $\phi \rightarrow \eta e^+ e^-$ was performed by the SND collaboration, resulting in $\Lambda_\phi^{-2} = (3.8 \pm 1.8) \text{ GeV}^{-2}$ [21]. This value, due to its large uncertainty, is compatible with the VMD prediction $\Lambda_\phi^{-2} \simeq 1 \text{ GeV}^{-2}$. At KLOE, the measurement was performed over a data sample of 1.7 fb^{-1} , looking for $\phi \rightarrow \eta e^+ e^-$ with $\eta \rightarrow \pi^0 \pi^0 \pi^0$. The invariant mass of the $e^+ e^-$ pair is presented in Fig. 8.

From the event counting the branching ratio $\text{BR}(\phi \rightarrow \eta e^+ e^-) = (1.075 \pm 0.007 \pm .038) \times 10^{-4}$ [22] is obtained. Fitting the invariant mass $e^+ e^-$ distribution to the parameterization of ref. [19], by using the one-pole formula for the TFF, we extract the slope $\Lambda_\phi^{-2} = (1.17 \pm 0.10^{0.07}_{-0.11}) \text{ GeV}^{-2}$ [22], a factor of 5 times more precise than previous result. This value is consistent with the VMD prediction. The TFF as a function of the $e^+ e^-$ invariant mass is shown in Fig. 9.

6 Conclusions

The large data sample of light mesons available at KLOE provides important results on decay dynamics and Transition Form Factors, together with limits on new physics, giving the most precise

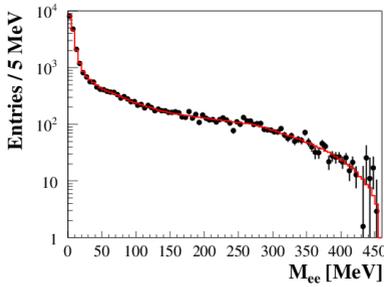


Figure 8: e^+e^- invariant mass of $\phi \rightarrow \eta e^+e^-$

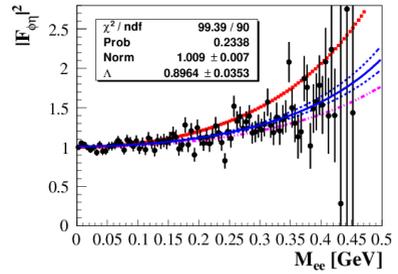


Figure 9: TFF as a function of the e^+e^- invariant mass of $\phi \rightarrow \eta e^+e^-$

measurements for TFF for the reactions $\phi \rightarrow \eta e^+e^-$ and $\phi \rightarrow \pi^0 e^+e^-$. The KLOE-2 data-taking, with the upgraded detector, is in progress, with the goal to collect 5 fb^{-1} by the end of March 2018. A rich program of measurements has been proposed [1]. Due to the new taggers, a special significance has the $\gamma\gamma$ production of pseudo-scalar mesons, that can help to shed light on some of the still puzzling questions.

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