Hadron physics with KLOE–2

Eryk Czerwiński¹ on behalf of KLOE–2 collaboration²
Laboratori Nazionali di Frascati – INFN, Via E. Fermi 40, I-00044 Frascati (Rome) Italy

Abstract
In the upcoming month the KLOE–2 data taking campaign will start at the upgraded DAΦNE φ-factory of INFN Laboratori Nazionali di Frascati. The main goal is to collect an integrated luminosity of about 20 fb⁻¹ in 3-4 years in order to refine and extend the KLOE program on both kaon physics and hadron spectroscopy. Here the expected improvements on the results of hadron spectroscopy are presented and briefly discussed.

Keywords: e⁺e⁻ collisions, meson transition form factors, π pair production, Φ meson
2010 MSC: 81-05, 81-06

1. KLOE–2 detector at upgraded DAΦNE collider
The KLOE detector setup consists of a large drift chamber (radius from 0.25 to 2.0 m and 3.3 m length) surrounded by an electromagnetic calorimeter. Both are immersed in 0.52 T axial field of superconducting solenoid [1]. From 2000 to 2006 the KLOE experiment has collected 2.5 fb⁻¹ at the peak of the Φ meson resonance at the e⁺e⁻ collider DAΦNE in Frascati plus additional 250 pb⁻¹ of off-peak data.

A new beam crossing scheme is operating at DAΦNE allowing to reduce beam size and increase luminosity (to reach a peak of about 5×10^{32} cm⁻² s⁻¹, a factor of 3 larger than the previously obtained). At the moment, the detector is being upgraded with small angle tagging devices, to detect both low (Low Energy Tagger - LET) and high (High Energy Tagger - HET) energy e⁺e⁻ originated from e⁺e⁻ → e⁺e⁻X reactions. It is planned to collect around 5 fb⁻¹ within one year with this setup.

2. γγ physics
The term γγ physics (or two photon physics) stands for the study of the reaction:

\[ e^+e^- \rightarrow γγ \rightarrow e^+e^-X, \] (1)

where X is an arbitrary hadronic state with quantum numbers J^{PC} = 0^{++}, 2^{++} ... and the two photons tend to be quasi-real [5]. If no cut is applied to the final-state leptons, the Weizsäcker-Williams approximation [6] can be used to understand the main qualitative features.
of process (1). Then the event yield, $N_{eeX}$, can be evaluated according to:

$$N_{eeX} = L_{ee} \int \frac{dF}{dW_{\gamma\gamma}} \sigma_{\gamma\gamma\rightarrow X}(W_{\gamma\gamma}) \, dW_{\gamma\gamma},$$

where $W_{\gamma\gamma}$ is the invariant mass of the two quasi–real photons, $L_{ee}$ is the integrated luminosity, and $dF/dW_{\gamma\gamma}$ is the $\gamma\gamma$ flux function:

$$\frac{dF}{dW_{\gamma\gamma}} = \frac{1}{W_{\gamma\gamma}} \left( \frac{2\alpha}{\pi} \right)^2 \left( \ln \frac{E_b}{m_e} \right)^2 f(z),$$

where $E_b$ is the beam energy and

$$f(z) = (z^2 + 2)^2 \ln \frac{1}{z} (1-z^2) (3+z^2), \quad z = \frac{W_{\gamma\gamma}}{2E_b}.$$

Figure 1 shows examples of the $\gamma\gamma$ flux functions multiplied by an integrated luminosity $L_{ee} = 1 \text{ fb}^{-1}$, as a function of the $\gamma\gamma$ invariant mass for different center-of-mass energies; threshold openings of different hadronic states are indicated. Previous experiments measured the $\gamma\gamma$ cross section for pseudoscalar meson production in the range $7 < \sqrt{s} < 35 \text{ GeV}$. A low energy $e^+e^-$ collider, such as DAΦNE, compensates the small cross section value with the high luminosity.

![Figure 1: Differential $\gamma\gamma$ flux function as a function of the center-of-mass energy.](image)

3. Meson transition form factors

The transition form factors $F_{P_{\gamma\gamma}}(m^2_\pi, Q^2, Q'^2)$ at spacelike momentum transfers can be measured with process (1). They are important to discriminate among different phenomenological models relevant for the hadronic light-by-light scattering contribution to the $g=2$ of the muon [21].

The form factor at negative $q^2$ appears in the production cross section of $\pi^0$, $\eta$ and $\eta'$ mesons in the reaction $e^+e^- \rightarrow e^+e^-P$. By detecting one electron at large angle with respect to the beams, the form factor $F_{P_{\gamma\gamma}}(m^2_\pi, Q^2, 0)$ with one quasi–real and one virtual space-like photon ($Q^2 = -q^2)$ can be measured for the on–shell pseudoscalar meson. For both $\pi^0$ and $\eta$ mesons the region below 1 GeV$^2$ is still poorly known but can be covered by KLOE–2. Furthermore, by selecting events in which both $e^+$ and $e^-$ are detected by the drift chamber (instead of the tagger devices) KLOE–2 can provide experimental information on form factors $F_{P_{\gamma\gamma}}(m^2_\pi, Q_1^2, Q_2^2)$, with two virtual photons.

4. $\gamma\gamma \rightarrow \pi\pi$

The two photon production of hadronic resonances is often advertised as one of the clearest ways of revealing their composition [8–18]. KLOE–2 with the study of $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ decays can improve the experimental precision in the following energy ranges contributing to the solution of the open questions on low–energy hadron physics:

- 280–450 MeV: The Mark II experiment [19] is the only one that has made a special measurement of the normalized cross-section for the $\pi^+\pi^-$ channel near threshold, however, their data have very large error-bars;
- 450–850 MeV: Measure $\pi\pi$ production in this region in both charge modes for our understanding of strong QCD coupling and the nature of the vacuum [20];
- 850–1100 MeV: Accurate measurement of the $\pi^+\pi^-$ and $\pi^0\eta^0$ cross-sections (integrated and differential).

The $e^+e^- \rightarrow e^+e^-\pi^+\pi^-$ process is a clean electromagnetic probe to investigate the nature of the $\sigma$ meson through the analysis of the $\pi\pi$ invariant mass which is expected to be plainly affected by the presence of this scalar meson. A precision measurement of the cross-section of $\gamma\gamma \rightarrow \pi^+\pi^-$ and $\gamma\gamma \rightarrow \pi^0\eta^0$ would also complete the information from previous experiments allowing the determination of the $\gamma\gamma$ couplings of the scalar mesons.

4.1. $\gamma\gamma \rightarrow \pi^0\eta^0$

The interest in this process is given by the $\sigma \rightarrow \pi\pi$ contribution [21]. The determination of the $\sigma\gamma\gamma$ coupling can be compared with that of pseudoscalars or other scalar states to clarify their quark structure. From Figure 2, an excess of about 4000 events with respect to the expected background is evident at low 4 photons invariant mass ($M_{00}$) values, consistent in shape with
expectations \[^{22}\] from \(e^+e^- \rightarrow e^+e^-\pi^0\pi^0\) events. The precise yield estimate depends on assumptions for the background processes. Systematic study of the differential cross section and understanding of the \(\sigma \rightarrow \pi\pi\) contribution are in progress.

The studies point out that KLOE-2 with an integrated luminosity at the \(\phi\) peak of \(L = 5 \text{ fb}^{-1}\) can measure the \(\gamma\gamma \rightarrow \pi^0\eta^0\) cross-section with the same energy binning obtained from Crystal Ball \[^{23}\], reducing the statistical uncertainty in each bin to 2%.

5. \(\eta \rightarrow \pi^0\gamma\gamma\)

Using the KLOE preliminary result on the branching fraction and the analysis efficiency obtained of \(\sim 5\%\), 1300 \(\eta \rightarrow \pi^0\gamma\gamma\) events are expected from the first year of data-taking at KLOE-2, thus allowing an accuracy of 3% to be reached on the BR(\(\eta \rightarrow \pi^0\gamma\gamma\)). Moreover, KLOE-2 can provide the \(m_{\gamma\gamma}\) distribution with sufficient precision to solve the ambiguity connected to the sign of the interference between VMD and scalar terms as shown in Figure 3.

6. \(\eta' \rightarrow \eta\pi\pi\)

In the \(\eta' \rightarrow \eta\pi^+\pi^-\) and \(\eta' \rightarrow \eta\pi^0\pi^0\), the \(\pi\pi\) system is produced mostly with scalar quantum numbers. Indeed, the available kinetic energy of the \(\pi^+\pi^-\) pair is \([0, 137]\) MeV, suppressing high angular momentum contribution. Furthermore, the exchange of vector mesons is forbidden by G-parity conservation. For these reasons, only scalar mesons can participate to the scattering amplitude. The decay can be mediated by the \(\sigma\), \(a_0(980)\) and \(f_0(980)\) exchange and by a direct contact term due to the chiral anomaly \[^{24}\]. The scalar contribution can be determined by fitting the Dalitz plot of the \(\eta' \rightarrow \eta\pi\pi\) system. The golden channel for KLOE-2 is the decay chain \(\eta' \rightarrow \eta\pi^+\pi^-\), with \(\eta \rightarrow \gamma\gamma\). The signal can be easily identified from the \(\eta\) and \(\eta'\) invariant masses. Such final state was already studied at KLOE to measure the branching fraction of the \(\phi \rightarrow \eta'\gamma\) decay \[^{25}\]. The analysis efficiency was 22.8\%, with 10\% residual background contamination. With \(O(10)\) fb\(^{-1}\), we expect 80,000 fully reconstructed events. In Figure 4 the \(m_{\pi^+\pi^-}\) invariant mass distribution is shown with and without the \(\sigma\) contribution with the expected KLOE-2 statistics.

7. \(\eta/\eta'\) mixing

The \(\eta'\) meson, being almost a pure SU(3)\(^{\text{Flavor}}\) singlet, is considered a good candidate to host a gluon condensate. KLOE has extracted the \(\eta'\) gluonium content and the \(\eta/\eta'\) mixing angle \[^{26}\] according to the model of Ref. \[^{27}\]. The \(\eta\) and \(\eta'\) wave functions can be decomposed in three terms: the \(u,d\) quark wave function \(|q\bar{q}\rangle = \frac{1}{\sqrt{2}}(|u\bar{u}| + |d\bar{d}|)\), the \(|s\bar{s}\rangle\) component and the gluonium \(|GG\rangle\). The wave functions are written as: \(|\eta'\rangle = \cos\theta_G \sin\psi_P |q\bar{q}\rangle + \cos\psi_P \cos\theta_P |s\bar{s}\rangle + \)
The $m_{\pi^+\pi^-}$ distribution in the $\eta' \rightarrow \eta \pi^+\pi^-$ decay with the $\sigma$ meson (right–centered distribution) and without (left–centered distribution) contribution.

$$\sin \psi_G (gg) \text{ and } |\eta\rangle = \cos \psi_P (q\bar{q}) - \sin \psi_P (s\bar{s})$$

where $\psi_P$ is the $\eta$-$\eta'$ mixing angle and $Z_G^\eta = \sin^2 \psi_G$ is the gluonium fraction in the $\eta'$ meson. The $Z_G^\eta$ parameter can be interpreted as the mixing with a pseudoscalar glueball.

With the KLOE–2 data-taking above the $\phi$ peak, e.g., at $\sqrt{s} \sim 1.2$ GeV, it will be possible to measure the $\eta'$ decay width $\Gamma(\eta' \rightarrow \gamma\gamma)$ through the measurement of the reaction $\sigma(e^+e^- \rightarrow e^+e^- (\gamma'\gamma') \rightarrow e^+e^- \eta')$. The measurement to 1% level of both the cross section and the branching ratio will bring the fractional error on the $\eta'$ total width, $\Gamma_{\eta'} = \Gamma(\eta' \rightarrow \gamma\gamma)/BR(\eta' \rightarrow \gamma\gamma)$, to $\sim 1.4\%$.

Figure 5 shows the 68% C.L. region in the $\psi_P, Z_G^\eta$ plane obtained with the improvements discussed in this section. The comparison of the top to bottom panels makes evident how the fit accuracy increases with the precision measurement of the $\eta'$ total width.

References

1. M. Adinolfi et al., Nucl. Phys. A663 1103 (2000).
2. F. Archilli et al., arXiv:1002.2572 (2010).
3. D. Babusci et al., LNF note 10/17(P), arXiv:1007.5219 (2010).
4. G. Amelino-Camelia et al., Eur. Phys. J. C68 619 (2010).
5. C.N. Yang, Phys. Rev. 77 242 (1950).
6. S.J. Brodsky, T. Kinoshita, H. Terazawa, Phys. Rev. D4 1532 (1971).
7. F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 1 (2009).
8. E. van Beveren, F. Kleefeld, G. Rupp, M.D. Scadron, Phys. Rev. D79 095010 (2009).
9. C. Hanhart, Y.S. Kalashnikova, A.E. Kudryavtsev, A.V. Nefediev, Phys. Rev. D75 074015 (2007).
10. T. Branz, T. Gutsche, V.E. Lyubovitskij, Phys. Rev. D78 114004 (2008).
11. M.K. Volkov, E.A. Kuraev, Y.M. Bystritskiy, 0904.2484 (2009).
12. G. Mennessier, S. Narison, W. Ochs, Phys. Lett. B665 205 (2008).
13. N.N. Achasov, G.N. Shestakov, Phys. Rev. D77 074020 (2008).
14. F. Giacosa, AIP Conf. Proc. 1030 153 (2008).
15. F. Giacosa, T. Gutsche, V.E. Lyubovitskij, Phys. Rev. D77 034007 (2008).
16. E. Klempt, A. Zaitsev, Phys. Rept. 454 1 (2007).
17. M.R. Pennington, 0711.1435 (2007).
18. T. Barnes, Phys. Lett. B165 434 (1985).
19. J. Boyer et al., Phys. Rev. D42 1350 (1990).
20. M.R. Pennington, Mod. Phys. Lett. A22 1439 (2007).
21. C. Amsler et al., Phys. Lett. B667 1 (2008).
22. F. Nguyen, Chin. Phys. (HEP & NP) C34 1 (2010).
23. H. Marsiske et al., Phys. Rev. D41 3324 (1990).
24. A.H. Fariborz, J. Schechter, Phys. Rev. D60 034002 (1999).
25. A. Aloeiso et al., Phys. Lett. B541 45 (2002).
26. F. Ambrosino et al., JHEP 07 105 (2009).
27. J.L. Rosner, Phys. Rev. D27 1101 (1983).