PROCEEDINGS OF SCIENCE

# Study of $e^+e^- \to \pi^+\pi^-\pi^0$ process using initial state radiation at KLOE

**Bo Cao**[†]
*on behalf of the KLOE/KLOE2 Collaboration.*
[†]*Department of Physics and Astronomy-Uppsala University, Sweden*
*E-mail:* bo.cao@physics.uu.se

In this project, we study the initial state radiation (ISR) process $e^+e^- \to \pi^+\pi^-\pi^0(\gamma)$ at center-of-mass (c.m.) energy $\sqrt{s} = 1019$ MeV corresponding to the $\phi$-meson mass. An integrated luminosity $\sim 1.62$ fb$^{-1}$ data sample collected during period 2004-2005 at KLOE is used in this analysis. The ISR technique is applied for the first time to provide the data set below 1 GeV. Studying the measured $3\pi$ invariant mass spectrum, the analysis aims to obtain the total cross section of the process $e^+e^- \to \pi^+\pi^-\pi^0$ in the energy range $[720, 820]$ MeV. Further goals of this study is to extract the peak cross section of the process $e^+e^- \to V \to 3\pi$, involving vector resonances $V = \omega, \phi$ and to measure cross section of non-resonant process $e^+e^- \to \gamma^* \to 3\pi$. Products of branching fractions $\mathscr{B}(\omega \to e^+e^-)\mathscr{B}(\omega \to 3\pi)$ will also be determined.

*European Physical Society Conference on High Energy Physics - EPS-HEP2019 -*
*10-17 July, 2019*
*Ghent, Belgium*





PoS(EPS-HEP2019)522

## 1. Introduction

Spin one-half fermions carry a magnetic moment associated to their intrinsic spin by a gyromagnetic factor $g$. The Dirac part of the $g$-factor is known to be exactly 2. For the muon, due to its mass, the value of the anomalous magnetic moment $a_\mu \equiv (g_\mu - 2)/2$ is particularly sensitive to physics beyond the standard model (SM) [1]. The world average value $a_\mu^{\rm exp} = (1165920.91 \pm 0.63) \times 10^{-9}$ [2] is presently dominated by the measurement performed at Brookhaven National Laboratory (BNL) [3]. The experimental value is $\sim 3.2$-$3.6\sigma$ above the SM prediction currently, this provides one of the strongest indication of new physics. In order to test this discrepancy, an ongoing new $g$-2 experiment at Fermilab [4] aims at achieving a fourfold improvement in statistical uncertainty. By assuming the same mean value for $a_\mu^{\rm exp}$ as the BNL measurement, the forthcoming result should reach a $7\sigma$ sensitivity that will allow any new physics effects to be firmly established. In the SM, $a_\mu^{\rm SM}$ includes QED, electroweak and hadronic contributions. The hadronic part $a_\mu^{\rm had}$ can be separated further in two contributions: hadronic vacuum polarization $a_\mu^{\rm had,VP}$, dominated by its leading-order (LO) contribution $a_\mu^{\rm had,LO,VP}$, and hadronic Light-by-Light contribution $a_\mu^{\rm had,LbL}$. The uncertainty of the $a_\mu^{\rm SM}$ is entirely dominated by the hadronic contribution in the

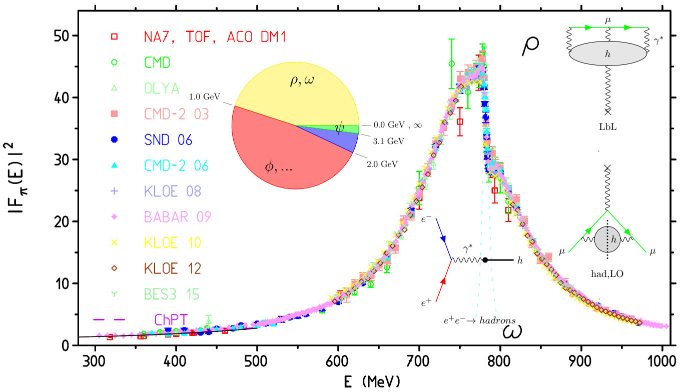


**Figure 1:** Pion form factor energy dependence, figure adapted from [5]. Interactions involved in the hadronic contributions to the $g$-2 evaluations and corresponding error-squared pie chart are shown. The $2\pi$ channel has been measured at Babar, KLOE and BESII using initial state radiation (ISR) technique [6, 7, 8]. The experiments have provided comprehensive and substantial data sets for the pion form factor measurements associated to the total cross section of the process $e^+e^- \to \pi^+\pi^-$.

low energy region, evaluation of the $a_\mu^{\rm had,VP}$ requires accurate knowledge of hadronic $R$-ratio $R_{\rm had}^{(0)}$ which is sensitive to measurement of processes involving exclusive haronic final states. The process $e^+e^- \to \pi^+\pi^-$ contributes approximately with 75% to the $a_\mu^{\rm had,VP}$ evaluation, Fig. 1. The three-pion channel $e^+e^- \to \pi^+\pi^-\pi^0$ accounts for the second largest contribution to the value of the $a_\mu^{\rm had,VP}$ and the corresponding uncertainty is $\sim 4.6\%$. The cross section $\sigma_{3\pi}$ of the process $e^+e^- \to \pi^+\pi^-\pi^0$ is dominated by the vector-meson resonances $\omega, \phi$ and $J/\psi$ in the low-energy region. Below the $\phi$-meson mass, $\sigma_{3\pi}$ is measured using conventional energy scan at fixed c.m. energies, *e.g.*, at CMD-2 [9], where $\omega$-meson parameters and corresponding line shape is measured accurately.

PoS(EPS-HEP2019)522

## 2. Experiment

The KLOE detector consists of a cylindrical drift chamber (DC) [10] surrounded by an electromagnetic calorimeter (EMC) [11], a superconducting coil provides a magnetic field of 0.52 T with direction along axial direction. The DC measures tracks with single hit spatial resolution $\sim 0.15$ mm in transverse plane $r$-$\phi$ and $\sim 2$ mm along the $z$-direction. The relative momentum resolution $\frac{\sigma_{p_\perp}}{p_\perp}$ is $\sim 0.4\%$ for tracks with polar angle in range $45^\circ < \theta_{\rm trk} < 135^\circ$. For clusters in EMC, the energy and time resolutions are $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(\rm GeV)}}$ and $\sigma_t = \frac{57\ \rm ps}{\sqrt{E(\rm GeV)}} \oplus 147$ ps, respectively.

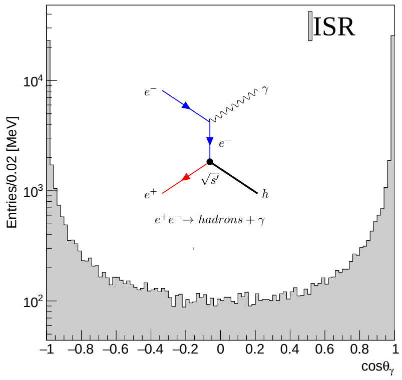


**Figure 2:** Angular distribution of the ISR photon.

In the low energy region, at a given c.m. energy $\sqrt{s}$, the use of ISR is an appealing method to probe the $R^{(0)}_{\rm had}$ and determine Born cross section $\sigma_0(e^+e^- \to hadrons)$. This technique requires a high luminosity that can be provided by the DAΦNE $\phi$-facotry [12], where the event statistic can compensate the small cross section of the radiative process $e^+e^- \to hardron + \gamma$ at effective c.m. energy $\sqrt{s'}$. The probability of ISR photon emission is governed by the radiator function $W_0(s,x,\theta)$ [13] approximated at leading-order when $\theta \gg m_e/\sqrt{s}$

$$W_0(s,x,\theta) = \frac{\alpha}{\pi x}\left(\frac{2-2x+x^2}{\sin^2\theta} - \frac{x^2}{2}\right), \tag{2.1}$$

where $x \equiv 2E_\gamma/\sqrt{s}$ is fraction of energy carried away by the ISR photon emission and $\sqrt{s'} = \sqrt{s(1-x)}$. $E_\gamma$ and $\theta$ are the ISR photon energy and polar angle, respectively, in the c.m. frame. The related angular distribution of the ISR photon is shown in Fig. 2.

## 3. Analysis

In this analysis, a $\mathscr{L}_{\rm int} \sim 1.62$ fb$^{-1}$ data collected during 2004-2005 is used. Approximately 10% of the data sample is used to tune the analysis itself. Signal events $e^+e^- \to \pi^+\pi^-\pi^0\gamma$ are selected requiring two charged tracks with opposite curvatures and three clusters. For tracks which are assumed to be charged pions, the vertex is confined in a cylindrical volume with dimension $\rho_{\rm vtx} = \sqrt{x^2+y^2} < 4$ cm and $|z_{\rm vtx}| < 10$ cm. Prompt cluster is defined with Time-of-Flight (ToF) in time window $|T_{\rm clu} - R_{\rm clu}/c| < \min(2,\ 5\sigma_t)$ ns, where $R_{\rm clu}$ is distance from the position of the cluster to the interaction point (IP) and $c$ is the speed of light. Energy deposit of cluster in the calorimeters is required to be $E_{\rm clu} > 15$ MeV and angular acceptance is $|\cos\theta| < 0.92$. Due to unique event classification procedure at KLOE known as the "streaming" process, after event reconstruction, most of signal events pass selection criteria which are dedicated to the $K_L K_S$ "stream". In order to fully reconstruct $3\pi$ final states, we first perform a kinematical fit subjected to seven physical constraints: standard four constraints (4C) using energy-momentum conservation of all final state particles and additional three constraints on ToF of neutral clusters. The chi-square value $\chi^2$ are calculated accordingly. The neutral pion is reconstructed by the kinematical fit using the energies

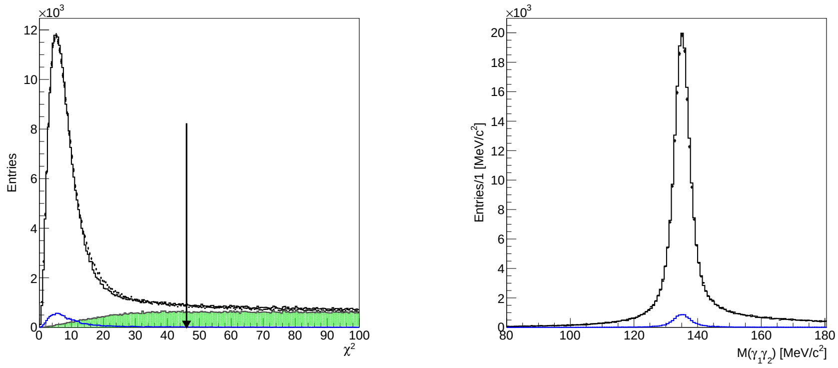


**Figure 3:** Figure to the left: Chi-square distributions. Figure to the right: Invariant mass distributions of best $\pi^0$ photon pair. Data (dots), MC sum (black histogram), ISR (blue) and background (shaded) events are shown.

and positions of calorimeter of neutral clusters. We construct pseudo chi-square function and calculate corresponding $\chi^2_{\gamma\gamma}$ values for all three combinations of $\pi^0$ photon pairs. The $\gamma_1$-$\gamma_2$ couple with the minimum chi-square value is chosen to be the best $\pi^0$ photon pair, whereas unpaired $\gamma_3$ is assumed to be the ISR photon candidate. $K_L K_S$ events are significantly rejected by requiring $\chi^2 < 46$ in the $\chi^2$ distribution shown in Fig. 3. In order to further improve signal to background ratio, we construct a mass variable $M$ which satisfies the following relation

$$\sqrt{s} - \sqrt{M^2 + p^2_{\pi^+}} - \sqrt{M^2 + p^2_{\pi^-}} - \left|\bar{p}_\phi - \bar{p}_{\pi^+} - \bar{p}_{\pi^-}\right| = 0, \tag{3.1}$$

where $\bar{p}_\phi$ is $\phi$-meson momentum, that has a transverse component $\sim 13$ MeV in the lab frame. Most of $\rho\pi$ events are strongly suppressed after applying cut $M > 300$ MeV/c$^2$. The background abundance and shapes are normalized and determined by fitting Monte Carlo (MC) simulated physics channels to the data, using Maximum Likelihood (ML) method, and using the fractions of MC channel contributions as free parameters.

## 4. Conclusion and outlook

After applying all selection and acceptance cuts, invariant mass spectrum of $3\pi$ is shown in Fig. 4. The main backgrounds $e^+e^-\gamma$, $K_L K_S$, $K^+K^-$ etc. are scaled according to luminosity scaling factors. It is remarkable that the contributions from processes in the continuum ($ee$, $\mu\mu$ and $\pi\pi$ scattering) are negligible. Above 650 MeV/c$^2$, combinatorial background consists of events from $\eta\gamma$ or $K^+K^-$ with different decay topologies. In the $\omega$ mass region, a good agreement between the data and simulations is achieved after the ML fit with minimum degrees of freedom. The ongoing analysis aims to evaluate the total cross section $\sigma_{3\pi}$, to perform extraction of the peak cross section of the process $e^+e^- \to V \to 3\pi$, where $V = \omega, \phi$ are vector resonances, and to measure cross section of non-resonant process $e^+e^- \to \gamma^* \to 3\pi$. Product of branching fractions $\mathscr{B}(V \to e^+e^-)\mathscr{B}(V \to 3\pi)$ will also be determined.

*We warmly thank our former KLOE colleagues for the access to the data collected during the KLOE data taking campaign. We thank the DAΦNE team for their efforts in maintaining*

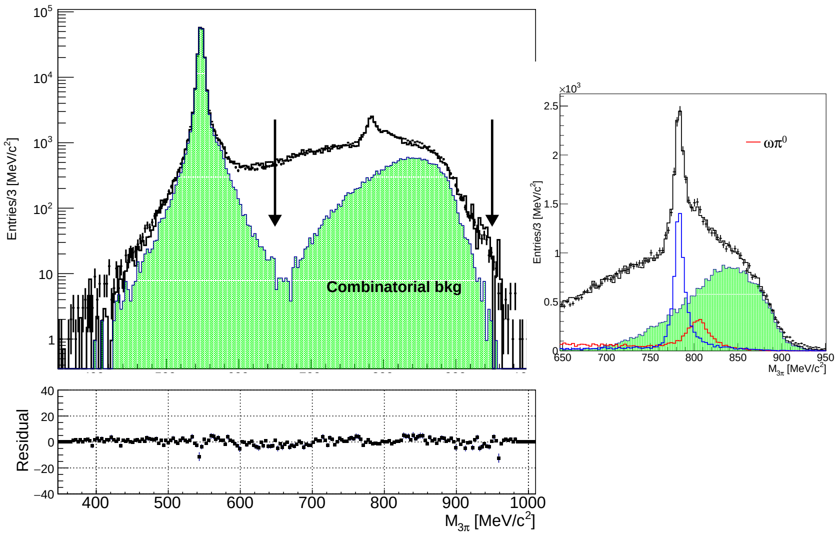


**Figure 4:** Distributions of $3\pi$ invariant mass: data (dots), $\eta\gamma$ (shaded histogram), $\omega\pi^0$ (red) and ISR (blue) events.

*low background running conditions and their collaboration during all data taking. We want to thank our technical staff: G.F. Fortugno and F. Sborzacchi for their dedication in ensuring efficient operation of the KLOE computing facilities; M. Anelli for his continuous attention to the gas system and detector safety; A. Balla,M. Gatta, G. Corradi and G. Papalino for electronics maintenance; M. San-toni, G. Paoluzzi and R. Rosellini for general detector support; C. Piscitelli for his help during major maintenance periods.*

## References

[1] A. Czarnecki and M. J. William., Phys. Rev. **D64**, 013014 (2001).

[2] M. Tanabashi *et al*. Review of Particle Physics. Phys. Rev. **D98**, 030001 (2018).

[3] G. W. Bennett *et al*. (Muon *g*-2 Collaboration), Phys. Rev. **D73**, 072003 (2006).

[4] J. Grange *et al*. *The New Muon g-2 Experiment at Fermilab*, arXiv:1501.06858 (2015).

[5] F. Jegerlehner. *Muon g-2 theory: The hadronic part*, EPJ Web of Conferences **166**, 00022 (2018).

[6] M. Ablikim *et al*. (BESIII Collaboration), Phys. Lett. **B753**, 629 (2016).

[7] B. Aubert. *et al*. (BABAR Collaboration), Phys. Rev. Lett. **103**, 231801 (2009).

[8] F. Ambrosino *et al*. (KLOE Collaboration), Phys. Lett. **B700**, 102 (2011).

[9] R. R. Akhmetshin *et al*. (CMD-2 Collaboration), Phys. Lett. **B476**, 33 (2000).

[10] M. Adinolfi *et al*. (KLOE Collaboration), **A488**, 51 (2002).

[11] M. Adinolfi *et al*. (KLOE Collaboration), Nucl. Instrum. Meth. **A482**, 364 (2002).

[12] J. Lee-Franzini and P. Franzini. *A Flavor of KLOE*, Acta Physica Polonica **B38**, 2703 (2007).

[13] G. Bonneau, and F. Martin, *Hard-photon emission in* $e^+e^-$ *reactions*, Nucl. Phys. **B27**, 381 (1971).