MEASUREMENT OF THE HADRONIC CROSS SECTION AT DAΦNE WITH THE KLOE DETECTOR

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Abstract. We have measured the cross section \( \sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma) \) as a function of the \( \pi^+\pi^- \) invariant mass, \( M_{\pi\pi} \), with the KLOE detector at DAΦNE (\( W = m_\mu = 1.02 \text{ GeV} \)). The photon in the above process is due to Initial State Radiation. Dividing by a theoretical radiator function, we obtain the cross section \( \sigma(e^+e^- \rightarrow \pi^+\pi^-) \) for the mass range \( 0.37 < M_{\pi\pi}^2 < 0.93 \text{ GeV}^2 \). We extract the pion form factor and the hadronic contribution to the muon anomaly, \( a_\mu \).

HADRONIC CROSS SECTION AT DAΦNE

Motivation
Accurate measurements of the cross section for \( e^+e^- \) annihilation into hadrons are of importance for an interpretation of the recent new precision measurement of the anomalous magnetic moment of the muon [1]. Hadronic contributions to the photon spectral functions due to quark loops are not calculable in the framework of perturbative QCD. It is well known, however, that the hadronic piece of the spectral function is connected by unitarity to the cross section for \( e^+e^- \rightarrow \) hadrons. A dispersion relation can thus be derived, giving the contribution to \( a_\mu \) as an integral over the hadronic cross section, multiplied by an appropriate kernel. The process \( e^+e^- \rightarrow \pi^+\pi^- \) below 1GeV is of special importance since it contributes to \( \sim 60\% \) to the total integral. The most recent evaluation of the dispersion integral [4] [5] gives the following values for the muon

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anomaly, compared to the experimental value of the E821 collaboration:

| Theory using $\tau$ data | $d_{\mu}^{\text{theo}} = (11 659 195.6 \pm 6.8) \times 10^{-10}$ |
|---------------------------|--------------------------------------------------|
| Theory using $e^+e^-$ data | $d_{\mu}^{\text{theo}} = (11 659 180.9 \pm 8.0) \times 10^{-10}$ |
| Experiment BNL-E821       | $d_{\mu}^{\text{exp}} = (11 659 203 \pm 8) \times 10^{-10}$ |

The first value is obtained including hadronic $\tau$ decay data, assuming conservation of the vector current (CVC) and correcting for isospin breaking effects. The second value uses $e^+e^-$ data only (see also [6]), in particular the recent reanalysis [3] of the CMD-2 measurement [2] of the $\pi^+\pi^-$ channel (0.6% systematic error) in the energy range below 1 GeV. The $e^+e^-\rightarrow\pi^+\pi^-$ based result disagrees by $\sim 2\sigma$ with the BNL measurement, while the value using $\tau$ decay data is in agreement with the experimental value. Further independent hadronic cross section measurements are needed to clarify the situation.

**Initial State Radiation**

Particle factories such as DAΦNE or the B-factories typically operate at fixed centre-of-mass energies: $W = m_\phi$ in the case of DAΦNE. Initial state radiation, ISR, is a complementary approach at particle factories which allows studying $e^+e^-\rightarrow$ hadrons over the entire energy range (from $2m_\pi$ to $W$). For a photon (energy $E_\gamma$) radiated before annihilation of the $e^+e^-$ pair, the invariant mass of the $\pi^+\pi^-$ system is given by: $M_{\pi\pi}^2 = s_\pi = W^2 - 2WE_\gamma$. In general the $\pi^+\pi^-\gamma$ and $\pi^+\pi^-$ cross section are related through:

$$s_\pi \frac{d\sigma(\pi^+\pi^-\gamma)}{ds_\pi} = \sigma(\pi^+\pi^-, s_\pi) \times H(s_\pi)$$

Eq. 1 defines the radiator function $H(s_\pi)$ which we obtain from the Monte Carlo program PHOKHARA, a NLO generator for the $\pi^+\pi^-\gamma$ exclusive final state [7] [8] [9] [10] [11].

Our present analysis is based on the observation of ref.[7], that for small polar angles of the radiated photon, the ISR process dominates over the FSR process, which is an indistinguishable background to our ISR approach. In the following we present the cross section measurement of the reaction $e^+e^-\rightarrow\pi^+\pi^-\gamma$ with $\theta_\gamma < 15^\circ$ or $\theta_\gamma > 165^\circ$. No explicit photon detection is done since the KLOE electromagnetic calorimeter (EmC) does not cover angles smaller than $20^\circ$. We cut on the di-pion production angle, $\theta_{\pi\pi}$, which is calculated from the momenta of the two charged tracks. If only one photon is emitted, the following relation holds exactly: $\theta_\gamma = 180^\circ - \theta_{\pi\pi}$. As we will show in the following, an efficient and almost background free signal selection can be obtained without photon tagging.

\footnote{For small $s_\pi$, the di-pion system is recoiling against the small angle photon, resulting in small angle pion tracks which cannot be detected in the KLOE drift chamber. We are therefore limited to measuring $\sigma(\pi^+\pi^-)$ for $s_\pi > 0.3$ GeV$^2$. A complementary analysis in which photons are selected at large angles is in progress. In this case the photon can be tagged in the electromagnetic calorimeter and the kinematical acceptance allows us to measure events down to the $2\pi$ threshold.}
ANALYSIS OF $\pi^+\pi^-\gamma$ EVENTS

We have analyzed KLOE data taken in 2001 with an integrated luminosity of $140\text{pb}^{-1}$. After fiducial volume and selection cuts we collect $\sim 1.5 \times 10^6$ events. To obtain the cross section, we subtract the residual background from this spectrum and divide by the selection efficiency and the integrated luminosity.

We briefly comment in the following on the individual analysis items. Further details can be found in [12]. For a detailed description of the KLOE detector, which consists of a high resolution tracking detector ($\sigma_{p_T}/p_T \leq 0.4\%$) and an electromagnetic calorimeter ($\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$), we refer to ref. [13] [14].

- **Detection of two charged tracks**: with polar angle larger than $50^\circ$, coming from a vertex in the fiducial volume $R < 8 \text{ cm}$, $|z| < 7 \text{ cm}$. The cuts on the transverse momentum $p_T > 160 \text{ MeV}$ or on the longitudinal momentum $|p_z| > 90 \text{ MeV}$ reject tracks spiralizing along the beam line, ensuring good reconstruction conditions. The probability to reconstruct a vertex in the drift chamber is $\sim 98\%$ and has been studied with $\pi^+\pi^-\pi^0$ and $\pi^+\pi^-$ data.

- **Identification of pion tracks**: A Likelihood Method (calibrated on real data), using the time of flight of the particle and the shape of the energy deposit in the electromagnetic calorimeter, has been developed to reject $e^+e^- \rightarrow e^+e^-\gamma$ background. Background from $e^+e^-\gamma$ events is drastically reduced like that. A control sample of $\pi^+\pi^-\pi^0$ has been used to study the behaviour of pions in the electromagnetic calorimeter and to evaluate the selection efficiency ($> 98\%$) for signal events.

- **Background subtraction**: $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$ events are rejected by a cut in a kinematic variable called track mass, $m_{\text{trk}}$. This variable is calculated from the reconstructed pion momenta, $\vec{p}_+, \vec{p}_-$, applying 4-momentum conservation under the hypothesis that the final state consists of two particles with the same mass and one photon. For such $e^+e^- \rightarrow x^+x^-\gamma$ events, the value of $m_{\text{trk}}$ peaks at $m_\pi, m_\mu, m_e$ for $x = \pi, \mu, e$ respectively, thus allowing a selection of signal events. The density distribution of the two track events in the $[s_{\pi}, m_{\text{trk}}]$ plane is very effective for separating signal from background. The final event selection is defined by: $(m_{\text{trk}} > 120) \cap (m_{\text{trk}} < 250 - 105\sqrt{1 - (s_{\pi}/850000)^2}) \cap (m_{\text{trk}} < 220)$, all units in MeV.

- **Luminosity Measurement**: The integrated luminosity is measured with the KLOE detector using large angle Bhabha (LAB) events. The effective Bhabha cross section at large angles ($55^\circ < \theta^<_+< 125^\circ$) is about $430 \text{ nb}$. For the computation of the radiative corrections we use two independent Bhabha event generators: BHA-GENF [15] [16] and BABAYAGA ([17]). For each generator a systematic error of 0.5\% is quoted by the authors. The two generators agree to better than 0.2\% with each other. All selection efficiencies (trigger, EmC cluster, DC tracking) are $> 99\%$ and are well reproduced by the detector simulation program. We also obtain excellent agreement between the experimental distributions ($\theta^<_+, E^<_+$) and those obtained from Monte Carlo simulation. The experimental uncertainty in the acceptance due to all these effects is 0.4\%. We assign a total systematic error for the luminosity of $\delta \mathcal{L} = 0.5\%_{\text{th}} \oplus 0.4\%_{\text{exp}}$. 

| Acceptance                      | 0.3% |
|--------------------------------|------|
| Trigger + Offline Reconstruction Filter | 0.6% |
| Tracking                        | 0.3% |
| Vertex                          | 0.7% |
| Particle ID Estimator (Likelihood) | 0.1% |
| Track Mass                      | 0.2% |
| Background subtraction          | 0.5% |
| Total experimental systematics  | 1.2% |

The contribution of the several analysis items to the total systematic error is shown in table 1. The value for the total systematic error of 1.2% is preliminary and expected to be reduced to $\sim$1.0% soon. We have not unfolded data for mass resolution effects. MC studies have shown that the effect of detector smearing is small.

RESULTS

The result of our cross section measurement for $e^+e^- \to \pi^+\pi^- \gamma$ is shown in fig. 1. According to eq. 1 the radiator function $H(s_{\pi})$ is needed in order to extract $\sigma(e^+e^- \to \pi^+\pi^-)$. We obtain $H(s_{\pi})$ from PHOKHARA, setting $F_{\pi}(s_{\pi}) = 1$ and switching off the vacuum polarization of the intermediate photon in the generator. The radiator $H(s_{\pi})$ is also shown in fig. 1, left. The H-function is theoretically known with a precision of $\sim$0.5%. We take this value (together with the error on luminosity) as the theory error.

FSR and Vacuum Polarization Corrections

Two further radiative corrections have to be applied to our data before evaluating the hadronic contribution to the muon anomaly (see ref. [4] for details). The cross section has to be the bare cross section, i.e. vacuum polarization corrections must be subtracted. This can be done by correcting the cross section for the running of $\alpha$.

The second correction deals with the treatment of FSR events. In our $\pi^+\pi^-\gamma$ cross section measurement a part of multiphoton events (more than 1 hard photon) are removed by the $m_{trk}$ cut. The efficiency of this cut is evaluated by Monte Carlo using a recently published new version of PHOKHARA [11], in which simultaneously photons from ISR and FSR are simulated. A preliminary study shows, that the cross section is changed by less than 2% due to this next-to-leading-order FSR effect. We are working out the final corrections to be applied to data. For now, we apply an error of 1% as a conservative estimate of the uncertainty due to FSR corrections.

Hadronic contribution to the muon anomaly

We have evaluated the hadronic two-pion contribution to the muon anomaly, $a^\pi\pi_{\mu}$, by inserting our measured bare cross section $e^+e^- \to \pi^+\pi^-$ into the dispersion integral. In order to compare our result with the CMD-2 result we cover the same energy interval as CMD-2. The preliminary KLOE result (in $10^{-10}$ units) is in good agreement with the
FIGURE 1. Left: Cross section for $e^+e^- \rightarrow \pi^+\pi^-\gamma$. The radiator $H(s_\pi)$, is also shown. Right: Bare cross section for $e^+e^- \rightarrow \pi^+\pi^-$. 

CMD-2 value as can be seen in the following table:

| $s_\pi$ / GeV$^2$ | $a_{\mu}^{\pi\pi}$ [KLOE] | $a_{\mu}^{\pi\pi}$ [CMD-2] |
|------------------|-----------------|-----------------|
| 0.37 – 0.65      | 309.4 ± 6.0     | 308.5 ± 2.8     |
| 0.65 – 0.93      | 68.8 ± 1.2      | 72.2 ± 0.7      |

Our data are in good agreement with CMD-2 below the $\rho$ peak. For the energy range $0.65 < s_\pi < 0.93$ GeV$^2$ our data are lower than CMD-2. Final corrections for FSR are still missing. We conclude that our data confirm the results from $e^+e^- \rightarrow \pi^+\pi^-$ and the discrepancy with respect to $\tau$ data.

3 These numbers are the outcome of an updated analysis, presented at SIGHAD03 (October 8-10,2003) and supersede the result presented at HADRON2003: $a_{\mu}^{\pi\pi} = 374.1 \pm 1.1_{\text{stat}} \pm 5.2_{\text{syst}} \pm 2.6_{\text{theo}}^{+7.5}_{-0.01}$ FSR

4 This is our evaluation of $a_{\mu}^{\pi\pi}$ [CMD-2], based on the values tabulated in ref. [3]
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