THE REACTION $e^+e^- \to \pi^+\,\pi^-$ AND ITS RELATION TO THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

W. Kluge[1]
Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 3640, 76021 Karlsruhe, Germany

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The hadronic contribution to the vacuum polarization in the nonperturbative regime of QCD is a crucial issue for the interpretation of the recent measurements of the anomalous magnetic moment of positive and negative muons in Brookhaven to allow for a precision test of the standard model. The present status of the hadronic contribution is reviewed with particular emphasis on recent results with the general purpose detector KLOE at the electron positron collider DAΦNE in Frascati.

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1 Introduction

In recent years the Muon (g-2) Collaboration at Brookhaven National Laboratory has measured the anomalous magnetic moment a_μ of positive and negative muons with an unprecedented precision of 0.7 ppm [1, 2]. The measurement of a_μ has a long and extremely successful history starting with experiments at CERN in the sixties, continuing at CERN in the seventies and culminating in the Brookhaven experiment E821 [3] (Table 1). Major findings have been precision tests of QED to higher and higher orders, the evidence for the contribution of hadronic vacuum polarization (Fig. 1) and finally for the weak contribution (Fig. 2, left). Recently also a sign error in the calculation of light-by-light scattering (Fig. 2, right) has been revealed triggered by the Brookhaven experiment [4].

The result of January 2004 representing also the present world average is

$$a_\mu = \frac{1}{2}(g_\mu - 2) = (11\,659\,208 \pm 6) \times 10^{-10}. \quad (1)$$

The Standard model predicts (in units of 10^{-10}) (using either e^+e^- data or τ decay data according to $\tau^\pm \to W^\pm\nu_\tau \to q_1\bar{q}_2\nu_\tau \to \pi^+\pi^o\nu_\tau$) (Fig. 3):

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had} + a_\mu^{LBL} + a_\mu^{weak}$$

[1]E-mail address: wolfgang.kluge@phys.uni-karlsruhe.de

Tab. 1. History of g-2 measurements of the muon.

Experiment	year ref.	value a_μ (error)	ppm	theory
Dirac particle $\mu^\pm$		0.000 000		Dirac
CERN cyclotron μ^+	1961 [12]	0.001 145 (22)		QED test
CERN cyclotron μ^+	1962 [13]	0.001 165 (5)	4300	heavy electron
1st CERN μ^- storage ring	1966 [14]	0.001 165 (3)		point like particle
1st CERN $\mu^\pm$ storage ring	1968 [15, 16]	0.001 166 16 (31)	270	$(\frac{\alpha}{\pi})^3$, lept. LBL
2nd CERN $\mu^\pm$ storage ring	1977 [17]	0.001 166 923 (8)	7.0	hadr. vac. pol., QED test
BNL E821 μ^+	2000 [18]	0.001 166 919 1 (59)	5.0	
BNL E821 μ^+	2001 [19]	0.001 165 920 2 (15)	1.3	
BNL E821 μ^+	2002 [1]	0.001 165 920 4 (9)	0.7	weak interact.
BNL E821 μ^-	2004 [2]	0.001 165 921 4 (9)	0.7	
combined weighted average $\mu^\pm$	2004	0.001 165 920 8 (6)	0.5	standard model

$a_\mu^{e^+e^-} = 11\,659\,180.9 \pm 7.2_{had} \pm 3.5_{LBL} \pm 0.4_{ew}$ [5, 6]
$a_\mu^{e^+e^-} = 11\,659\,179.4 \pm 8.6_{had} \pm 3.5_{LBL} \pm 0.4_{ew}$ [7]
$a_\mu^{e^+e^-} = 11\,659\,176.3 \pm 7.4_{had} \pm 3.5_{LBL} \pm 0.4_{ew}$ [8]
$a_\mu^{\tau} = 11\,659\,195.6 \pm 5.8_{had} \pm 3.5_{LBL} \pm 0.4_{ew}$ [5, 9].

The errors account for the hadronic contribution to lowest and higher orders (had), hadronic light by light scattering (LBL) and electroweak (ew) contributions.

The hadronic contribution to the vacuum polarization in the nonperturbative regime of QCD is *the* crucial number for the interpretation of the recent Brookhaven measurements to allow for a

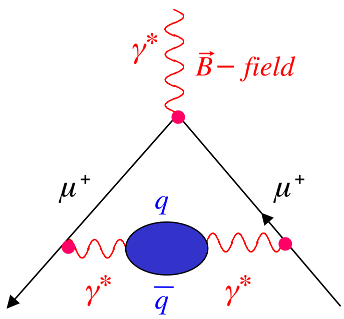

Fig. 1. Hadronic vacuum polarization due to $q\bar{q}$ pairs.

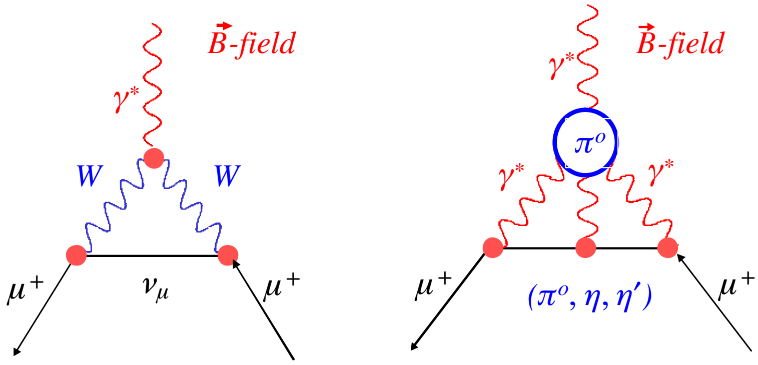

Fig. 2. Example of weak interaction contribution (left) and of light by light scattering (right) to the vacuum polarization.

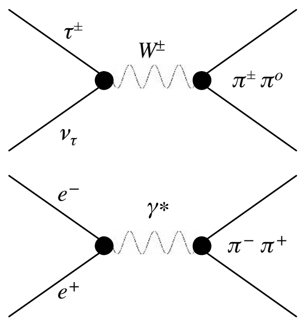

Fig. 3. Two pion final state arising from $\tau-$decay and from e^+e^-annihilation, CVC connects both processes.

precision test of the standard model because the lowest order (LO) hadronic vacuum polarization contribution has the largest error being of the order of the present experimental accuracy:

$$a_\mu^{had,LO,e^+e^-} = 696.3 \pm 6.2_{exp} \pm 3.6_{rad} \text{ [5,6]}$$
$$a_\mu^{had,LO,e^+e^-} = 694.8 \pm 8.6_{exp} \text{ [7]}$$
$$a_\mu^{had,LO,e^+e^-} = 692.4 \pm 5.9_{exp} \pm 2.4_{rad} \text{ [8]}$$
$$a_\mu^{had,LO,\tau} = 711.0 \pm 5.0_{exp} \pm 0.8_{rad} \pm 2.8_{SU(2)} \text{ [9]},$$

where the errors indicate those of the experiments, radiative corrections in the e^+e^- data and isospin breaking effects for τ decays. The deviations from the measurement of Brookhaven are found to be $(30.0 \pm 11.0) \times 10^{-10}$ $(2.7\,\sigma)$ and $(12.0 \pm 11.0) \times 10^{-10}$ $(1.0\,\sigma)$ for the e^+e^- and τ based estimates, respectively. The errors of the last numbers are those of the experimental data used for the hadronic contribution, the LBL contribution and from the Brookhaven experi-

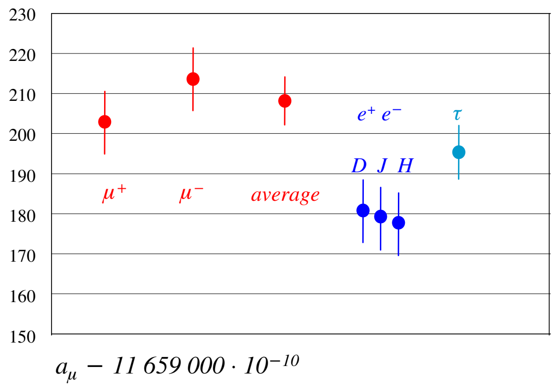

Fig. 4. The Brookhaven measurements for μ^+, μ^- and their average compared with calculations by the Standard model using $\tau-$decay and e^+e^-annihilation data. The characters *D, J, H* denote the analyses of Davier et al. [5,6], Jegerlehner [7], Hagiwara et al. [8], respectively and τ denotes the analysis of Davier et al. [9].

ment, taken in quadrature[2] (Fig. 4). The most recent results to determine the hadronic vacuum polarization can be found in the Proceedings of the Workshop on Hadronic Cross Section at Low Energy (October 2003), in the following quoted as SIGHAD03 [11].

The various final states contributing to the hadronic contribution to the vacuum polarization which result in the numbers given above are given in Table 2 and the available measurements of the ratio $R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$ are shown in Fig. 5 including the new measurements of BES [22].

The following figures show as examples recent data from ALEPH [9], CLEO [23] and BELLE [24] on $\tau-$decays for the low energy region (Figs. 6 and 7 (left)) and from BaBar for the reaction $e^+e^- \to \pi^+ \pi^- \pi^+ \pi^-$ in Fig. 7 (right) [25].

The measurement of the hadronic vacuum polarization has also an important impact onto the determination of the running coupling constant $\alpha(m_Z^2)$ (Fig. 8) in order to constrain the Higgs mass by means of quantum fluctuation calculations [26, 27].

2 The e^-e^- collider DAΦNE and the general purpose detector KLOE

The symmetric collider DAΦNE [28] accelerates and stores electrons and positrons of 510 MeV to produce ϕ-mesons with the mass 1020 MeV/c^2 and the quantum numbers $J^{PC} = 1^{--}$ via the reaction $e^+e^- \to \gamma^* \to \phi$.

The luminosity $\mathcal{L} \sim 0.5 \ldots 1.28 \times 10^{32}$ cm^{-2}s^{-1} so far achieved is below the design value of $\mathcal{L} \sim 5 \times 10^{32}$cm^{-2}s^{-1} $= 5 \times 10^2 \mu b^{-1}$s^{-1} but room for further improvements beyond the

[2]Recently Kinoshita and Nio [20] increased the QED contribution a_μ^{QED} by 1.3×10^{-10}, and Melnikov and Vainshtein [21] the contribution a_μ^{LBL} by 5×10^{-10} which would reduce the difference between measurements and the standard model accordingly.

Tab. 2. The various hadronic final states contributing to the hadronic vacuum polarization a_μ^{had} in units of 10^{-10} [6, 9, 10].

modes	energy range $[GeV]$	e^+e^- data	τ decays
low s expansion	$2m_\pi - 0.5$	$58.0 \pm 1.7 \pm 1.1_{rad}$	$56.0 \pm 1.6 \pm 0.3_{SU(2)}$
$\pi^+\pi^-$	$2m_\pi - 1.8$	$450.2 \pm 4.9 \pm 1.6_{rad}$	$464.0 \pm 3.2 \pm 2.3_{SU(2)}$
(incl. KLOE)		$448.3 \pm 4.1 \pm 1.6_{rad}$	
$\pi^+\pi^-\pi^o\pi^o$	$2m_\pi - 1.8$	$16.8 \pm 1.3 \pm 0.2_{rad}$	$21.4 \pm 1.4 \pm 0.6_{SU(2)}$
$\pi^+\pi^-\pi^+\pi^-$	$2m_\pi - 1.8$	$14.2 \pm 0.9 \pm 0.2_{rad}$	$12.3 \pm 1.0 \pm 0.4_{SU(2)}$
$\omega(782)$	$0.3 - 0.81$	$38.0 \pm 1.0 \pm 0.3_{rad}$	
$\phi(1020)$	$1.0 - 1.055$	$35.7 \pm 0.8 \pm 0.2_{rad}$	
other exclusive	$2m_\pi - 2.0$	$32.2 \pm 1.6 \pm 0.3_{rad}$	
$J/\psi, \psi(2S)$	$3.08 - 3.11$	$7.4 \pm 0.4 \pm 0.0_{rad}$	
$R[data]$	$2.0 - 5.0$	$33.9 \pm 1.7_{exp} \pm 0.0_{rad}$	
$R[QCD]$	$5.0 - \infty$	$9.9 \pm 0.2_{theor}$	
sum	$2m_\pi - \infty$	$696.3 \pm 6.2 \pm 3.6_{rad}$	$711.0 \pm 5.0 \pm 0.8_{rad}$ $\pm 2.8_{SU(2)}$

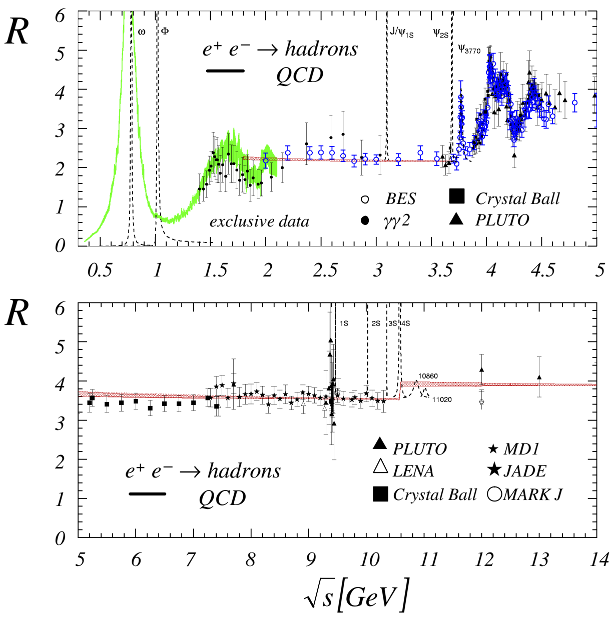

Fig. 5. R measurements.

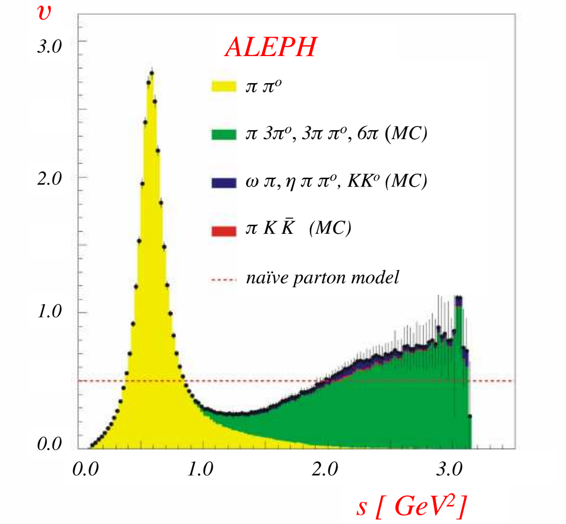

Fig. 6. Pion form factor (right) as measured by means of $\tau-$decays with ALEPH [9].

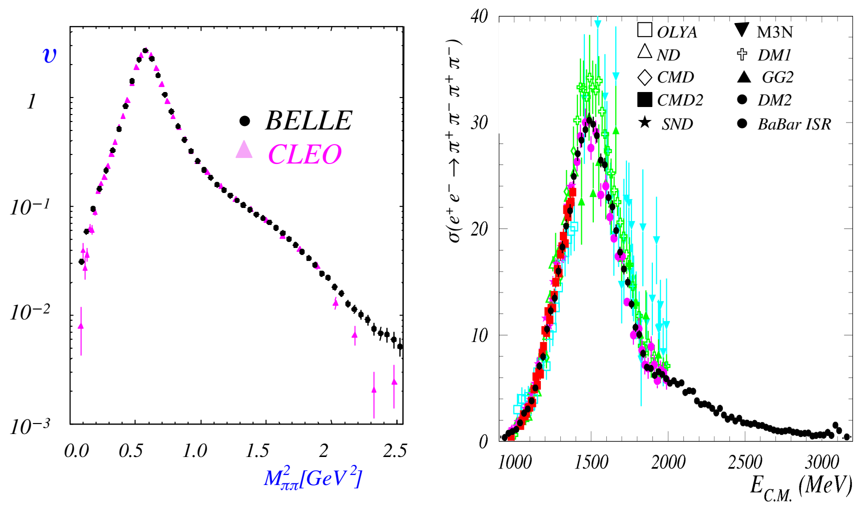

Fig. 7. Pion form factor as measured by means of $\tau-$decays with CLEO [23] and Belle [24] (left) and the cross section for the reaction $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ obtained from ISR at BaBar in comparison with all existing e^+e^- data [25] (right).

important progress made in 2002 and 2003 (with roughly 175 pb^{-1} in 2001 and 300 pb^{-1} in 2002) and 800 pb^{-1} until the end of December 2004 should still be possible.

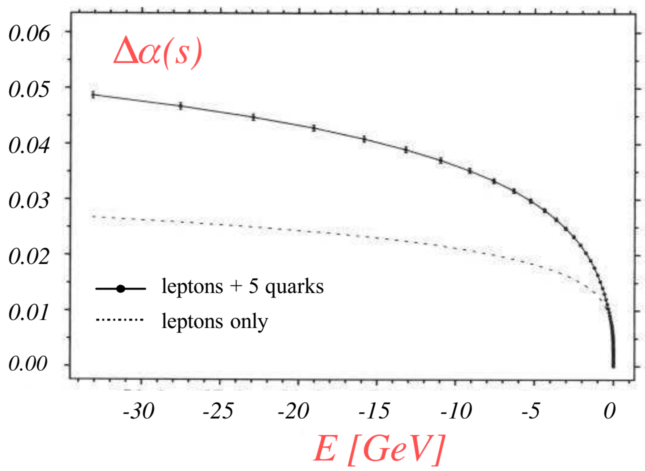

Fig. 8. The running electromagnetic coupling constant $\alpha_{e.m.}$ [26].

DAΦNE has two interaction regions. In one of them KLOE [29] has been installed in 1998. In the second one FINUDA [30] is located having replaced DEAR [31] in 2003. KLOE (K LOng Experiment) is a general purpose detector consisting of a large drift chamber and an electromagnetic calorimeter immersed in a $0.53\,T$ magnetic field [32, 33] to study $K, \phi, \rho, \eta, \eta'$ decays. In the original proposal for DAΦNE tests of discrete symmetries ($\mathcal{CP}-, \mathcal{CPT}-, \mathcal{T}-$ invariance) exploiting the unique possibility of quantum interferometry have been highlighted [34]. In the meantime it turned out that also the lower than anticipated luminosity allows to pursue interesting physics by measuring most of all rare but not too rare K_S decays (with branching ratios down to $\sim 10^{-7}$), radiative ϕ decays into the scalar mesons a_o, f_o [35] and the cross section $e^+e^- \to \gamma\,\gamma^\star \to \gamma\,\pi^+\,\pi^-$.

3 Cross section measurement of the reaction $e^+e^- \to \pi^+\pi^-$ with KLOE

The cross section $e^+e^- \to \pi^+\pi^-$ at energies between 0.3 and 1.0 GeV contributes almost 70 % of the hadronic vacuum polarization to the anomalous magnetic moment of the muon a_μ. How much this channel contributes to the accuracy of the running electromagnetic coupling constant at the Z^o resonance $\alpha(m_Z^2)$ is still being debated depending on the energy above which calculations of perturbative QCD can be regarded as reliable [36].

To measure this cross section with KLOE while DAΦNE is operated at the fixed energy of the $\phi(1020)$ the idea of the so called 'radiative return' is exploited [38–40]. Real photons emitted in the initial state (Initial State Radiation ISR, Fig. 9) by electrons or positrons reduce the centre-of-mass energy of the hadronic system $s = Q^2 = m_\phi^2 - 2\,E_\gamma\,m_\phi$ produced by virtual photons. Not only the ρ and ω resonances are excited $e^+e^- \to \gamma\,\gamma^\star \to \gamma\,\rho(\omega) \to \gamma\,\pi^+\pi^-$ but in fact the full energy range from the two pion threshold up to the ϕ-resonance is covered in this way.

KLOE does not only aim at an independent and complementary determination of the hadronic

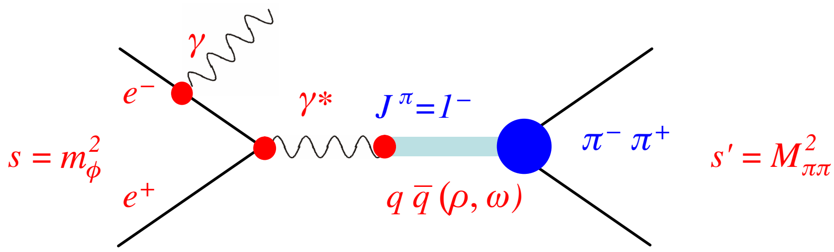

Fig. 9. Initial State Radiation ISR in the reaction $e^+e^- \to \pi^+\pi^-\gamma$.

vacuum polarization with systematic errors, different from those of the data of the Novosibirsk group [37] who pioneered those measurements at low energies, but also at an extension of the energy region to values significantly below the ρ resonance, eventually down to the two pion threshold.

Both methods to measure the energy dependence of the hadronic cross section (*radiative return*) as used by KLOE and the *beam energy scan* by the CMD-2 collaboration) are complementary due to different systematic errors. The ISR method has the advantage that the errors of the measured luminosity and of the energy of the electrons and positrons enter the photon spectrum and consequently the hadronic spectrum only once. As a consequence the overall normalization error is the same for all energies of the hadronic system.

In the present analysis the cross section has been measured between 0.6 and 1.0 GeV with a statistical error of less than 0.2 % and a systematical error of 1.3 % [41–48]. The analysis depends sensitively on the correct treatment of radiative corrections as well in the initial as in the final state. In the last years Monte Carlo generators (EVA and PHOKHARA) for radiative corrections have been developed by the theory group of Kühn and Czyż [38, 49–52]. The code PHOKHARA implements in its latest versions second order (real and virtual) ISR and lowest order FSR (modelled for point like pions). These codes have been included into the KLOE Monte Carlo software [39–48].

During the last two years $140\ pb^{-1}$ of the data taken in 2000 and 2001 have been analyzed requesting only the 2 pions detected in the drift chamber in the angular interval $50° < \theta_\pi < 130°$ with the additional condition of photon angles $\theta_\gamma = \theta_{(|\vec{p}(\pi^-)+\vec{p}(\pi^+)|)} < 15°$, $\theta_\gamma > 165°$, respectively [41–48]. As a consequence of this restricted phase space only the Q^2 region between 0.3 and 1.0 GeV^2 is populated. Fig. 10(left) shows the number of events per Q^2 interval. An excellent energy resolution of the photon spectrum is obtained due to the precise measurements of the momenta of the charged pions in the KLOE drift chamber: $E_\gamma = |\vec{p}(\pi^-) + \vec{p}(\pi^+)| \cdot c$.

In order to determine the cross section $\sigma_{\pi\pi}(s_\pi)$ for the reaction $e^+e^- \to \pi^+\pi^-$ the normalized data of Fig. 10 (left) have been divided by the radiation function $H(s_\pi)$ calculated with the code PHOKHARA (with higher order ISR and FSR for point like pions) using

$$s_\pi \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \cdot H(s_\pi)$$

and the detector acceptance has been obtained using Monte Carlo calculations to cover the full angular region from $0°$ to $180°$. The photon angular interval is still restricted to $\theta_\gamma < 15°$ and

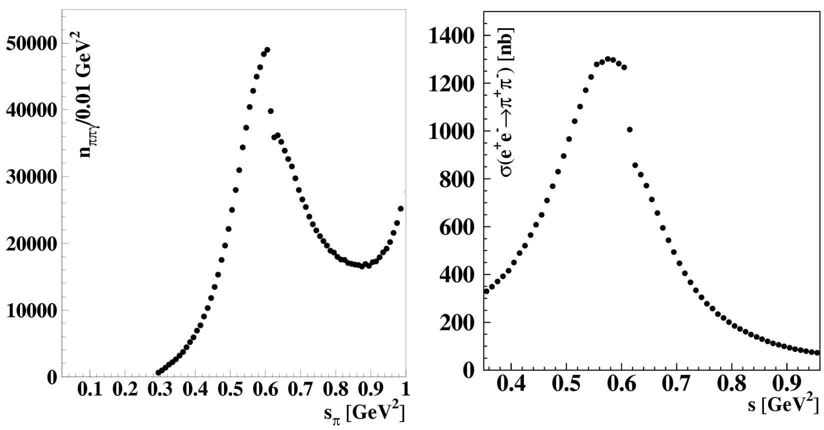

Fig. 10. The reaction $e^+e^- \to \pi^+\pi^-\gamma$. The number of events for an integrated luminosity of 170 pb^{-1} (left). The acceptance cuts are: $50^\circ < \theta_\pi < 130^\circ$ and $\theta_\gamma < 15^\circ, \theta_\gamma > 165^\circ$ and the cross section for the reaction $e^+e^- \to \pi^+\pi^-$ (right). The cross section has been obtained by dividing the normalised cross section by the radiator function $H(s_\pi)$ obtained with PHOKHARA [38, 49–52].

$\theta_\gamma > 165^\circ$. The result is shown in Fig. 10 (right). The results of Fig. 10 represent only $1/10$ of the data taken with KLOE, but correspond already to 20 times of the data taken by CMD-2 in its total operation time and hence to a correspondingly improved, eventually negligible statistical error.

The hadronic correction to the vacuum polarization for a_μ obtained in the interval $0.37 < Q^2_{\pi\pi} < 0.93\,\mathrm{GeV}^2$ is $a_\mu^{\pi\pi} = (375.6 \pm 0.8_{stat} \pm 4.8_{syst.+theor}) \times 10^{-10}$. Our total systematic error of $a_\mu^{\pi\pi}$ of $1.3\,\%$ includes an experimental systematic error of $0.9\,\%$ and a theoretical systematical error of also $0.9\ \%$ taken in quadrature. To arrive at this result the vacuum polarization for the virtual photon (Fig. 11) has been taken out according to $\sigma_{bare}(s) = \sigma_{dressed}(\frac{\alpha(0)}{\alpha(s)})^2$ with $\alpha(s) = \frac{\alpha_o}{1-\Delta\alpha_{lept}(s)-\Delta\alpha_{had}(s)}$ to obtain the bare cross section [5, 53] and a correction for FSR (Fig. 12) has been applied. Details of this procedure can be found in Refs. [47, 48]. A direct measurement of the ratio R to avoid the correction for the vacuum polarization of the virtual photons is an alternative which needs, however, better statistics and better identification of the muons. The higher luminosity of DAΦNE in 2004 will facilitate this possibility.

The pion form factor obtained is in good agreement with that of CMD-2 (Fig. 13). Correspondingly our value agrees with that of CMD-2 being $a_\mu^{\pi\pi} = (378.6 \pm 2.7_{stat} \pm 2.3_{syst.+theor}) \times 10^{-10}$ in the interval $0.37 < Q^2_{\pi\pi} < 0.93$ GeV^2 [37] and confirms the present discrepancy of the hadronic correction using data of electron-positron annihilation on the one hand and τ decay data on the other (Fig. 14).

The luminosity has been determined by the detection of large angle events of electron-positron (Bhabha) scattering (into an angular interval between 55° and 125°) and by comparison of the data with various Monte Carlo generators [54–56]. The theoretical and the experimental uncertainties are of the order of $0.5\ \%$. Details can be found in Refs. [47, 48].

For the future the measurement of the pion form factor will be extended down to the two pion

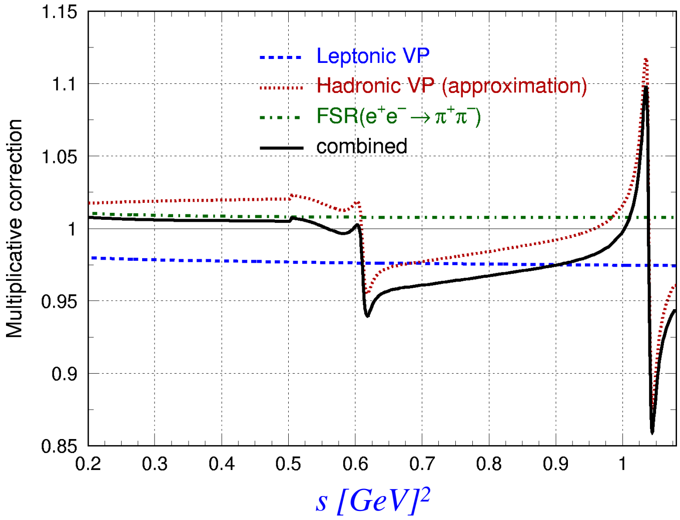

Fig. 11. Vacuum polarization corrections [5, 53].

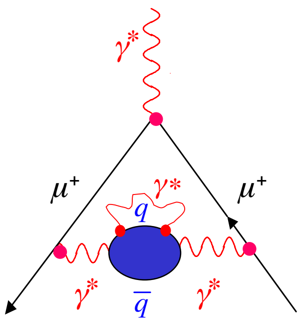

Fig. 12. Correction of Final State Radiation FSR.

threshold [57]. The energy interval below the $\rho-$resonance covers the important contribution of roughly 100×10^{-10} to the hadronic vacuum polarization of a_μ. This requires not only the detection of the charged pions but also of photons emitted at angles larger than $15°$, where the contribution of FSR and the background from the decay $\phi \to \pi^+\pi^-\pi^o$ will be significant. Consequently a more realistic treatment of FSR [58] as well as experimental tests of the used scalar model of FSR will turn out to be of great importance. A first preliminary large angle spectrum is shown in Fig. 15 (left) where pions as well as photons have been detected in the angular interval $50° < \theta_{\pi,\gamma} < 130°$. The spectrum extends clearly down to the $2-$pion threshold with some background still to be identified and subtracted.

The model dependence of the FSR (point like pions) can be checked by observing the charge

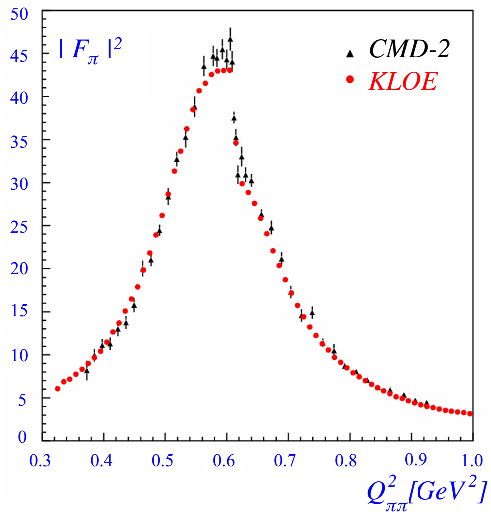

Fig. 13. Comparison of the pion form factor as determined by CMD-2 and KLOE. The data points of KLOE have negligible statistical errors. Both data sets are in fair agreement.

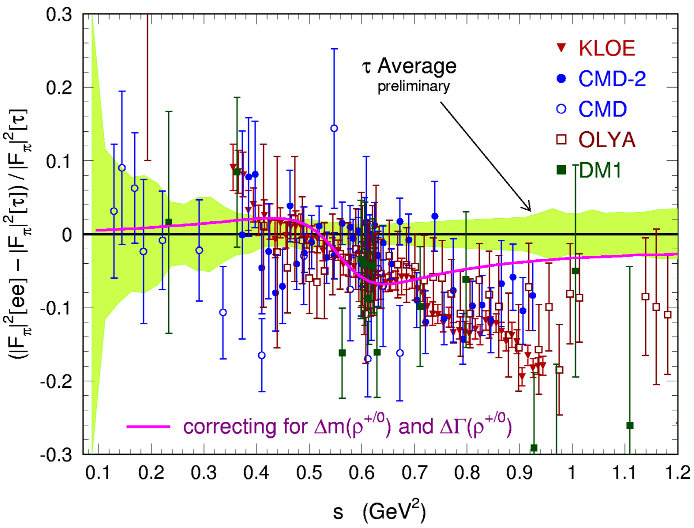

Fig. 14. Comparison of $\tau-$decay data and of data of the reaction $e^+e^- \to \pi^+\pi^-$. The $\tau-$decay data are higher above the $\rho-$resonance ($s = 0.6$ GeV^2) [5, 10]. According to Höcker [10] mass and width corrections for charged and neutral $\rho-$mesons $\Delta m_{\rho^{\pm,o}}$ and $\Delta\Gamma_{\rho^{\pm,o}}$ do not reduce the differences between the e^+e^- and from τ data significantly, in particular not above 0.7 GeV^2 (full curve).

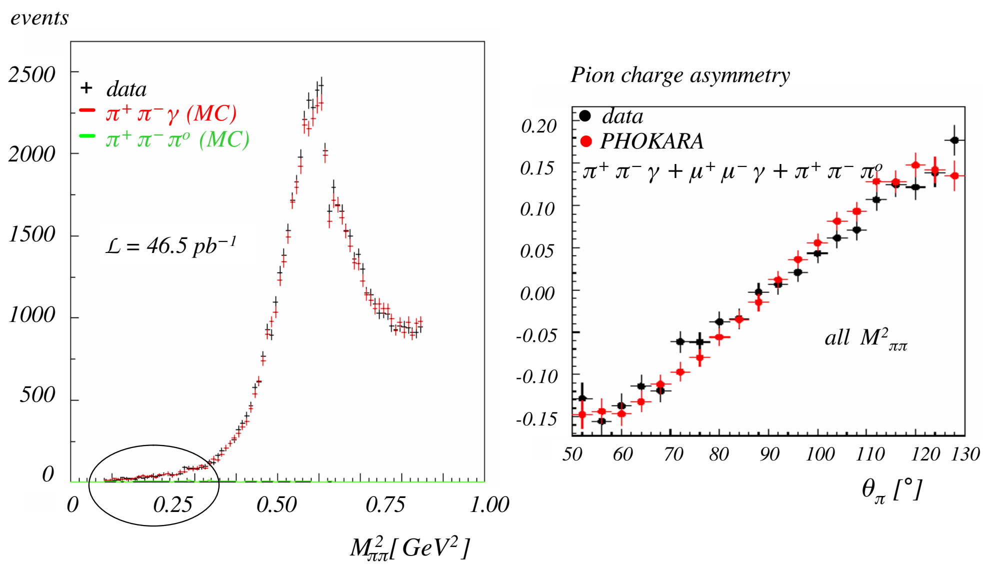

Fig. 15. Large angle spectrum (left). Pions as well as photons have been detected in the angular interval $50^\circ < \theta_{\pi,\gamma} < 130^\circ$. The spectrum extends down to the 2−pion threshold (indicated by the oval) and asymmetry (right) $\mathcal{A}(\theta_\pi) = \frac{N_i^{\pi^+}(\theta_\pi) - N_i^{\pi^-}(\theta_\pi)}{N_i^{\pi^+}(\theta_\pi) + N_i^{\pi^-}(\theta_\pi)}$ of charged pions as a function of their polar angle. The asymmetry arises from the interference of FSR and ISR and depends almost linearly on the polar angle.

asymmetry as a function of the polar angle of the charged pions emitted in the final state: $\mathcal{A}(\theta_\pi) = \frac{N_i^{\pi^+}(\theta_\pi) - N_i^{\pi^-}(\theta_\pi)}{N_i^{\pi^+}(\theta_\pi) + N_i^{\pi^-}(\theta_\pi)}$. The charge asymmetry arises from the interference of ISR and FSR and depends linearly on the polar angle θ_π [38]. First results (Fig. 15 (right)) show deviations from the point like model of less than 7 % depending on $Q^2_{\pi\pi}$. The contribution of FSR in the phase space region analyzed so far is of maximal 1 % such that the error of the FSR contribution is smaller than 0.1 %.

4 Conclusion

The difference between the hadronic vacuum polarization obtained from e^+e^- and from τ data persists with the new data from KLOE. Davier [6] and Jegerlehner et al. [59] see a possible explanation in different masses for charged and neutral ρ−mesons. According to Höcker [10] mass and width corrections for charged and neutral ρ−mesons $\Delta m_{\rho^{\pm,o}}$ and $\Delta\Gamma_{\rho^{\pm,o}}$ do, however, not reduce significantly the differences between the e^+e^- and from τ data, in particular not above 0.7 GeV^2 (full curve in Fig. 14).

5 DAΦNE-2

An upgrade of $DA\Phi NE$ to reach a luminosity of up to 5×10^{34} cm^{-2}s^{-1} (and lower machine background) corresponding to $5\times10^{11} K_S\,[y^{-1}]$ or an increase of the energy up to 2 GeV [60–62] would allow to pursue a very sound physics program [63,64]. The measurement of hadronic cross sections could be extended up to 2 GeV yielding in particular the important contribution from the $4\,\pi$ final state $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ and $e^+e^- \to \pi^+\pi^-\pi^o\pi^o$ realized by an energy scan as well as via the radiative return method.

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References

[1] Brookhaven E 821: G. W. Benett et al.: *Phys. Rev. Lett.* **89** (2002) 101804

[2] Brookhaven E 821: G. W. Benett et al.: *Phys. Rev. Lett.* **92** (2004) 161802

[3] F. J. M. Farley, Y. K. Semertzidis: *Prog. Part. Nucl. Phys.* **52** (2004) 1; SIGHAD03 [11], p. 235

[4] A. Nyffeler: SIGHAD03 [11], p. 162

[5] M. Davier, S. Eidelman, A. Höcker, Z. Zhang: *Eur. Phys. J. C* **27** (2003) 497; Eur. Phys. J. C **31** (2003) 503; hep-ph/0308213

[6] M. Davier, SIGHAD03 [11], p. 192; hep-ex/0312065

[7] F. Jegerlehner, hep-ph/0312372

[8] K. Hagiwara, A. D. Martin, D. N. Nomura, T. Teubner, hep-ph/0312250

[9] M. Davier, SIGHAD03 [11], p. 123; hep-ex/0312064

[10] A. Höcker, ICHEP2004, 32$^{\rm nd}$ ICHEP, Aug. 16-22, 2004 Beijing

[11] SIGHAD03: *Nucl. Phys. B (Proc. Suppl.)* **131** (2004)

[12] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, V. L. Telegdi, A. Zichichi: *Phys. Rev. Lett.* **6** (1961) 128; G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, A. Zichichi: *Nuovo Cimento* **22** (1961) 1043; G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens. A. Zichichi: *Phys. Lett.* **1** (1962) 16

[13] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, A. Zichichi: *Nuovo Cimento* **37** (1965) 1241

[14] F. J. M. Farley, J. Bailey, R. C. A. Brown, M. Giesch, H. Jöstlein, S. van der Meer, E. Picasso, M. Tannenbaum: *Nuovo Cimento* **45** (1966) 281

[15] J. Bailey, G. v. Bochmann, R. C. A. Brown; F. J. M. Farley, H. Jöstlein, E. Picasso, R. W. Williams: *Phys. Lett. B* **28** (1968) 287

[16] J. Bailey, W. Bartl, G. v. Bochmann, R. C. A. Brown; F. J. M. Farley, M. Giesch, H. Jöstlein, S. van der Meer, E. Picasso, R. W. Williams: *Nuovo Cimento A* **9** (1972) 369

[17] J. Bailey et al.: *Nucl. Phys. B* **150** (1979) 1

[18] Brookhaven E 821: H. N. Brown et al.: *Phys. Rev. D* **62** (2000) 091101

[19] Brookhaven E 821: H. N. Brown et al.: *Phys. Rev. Lett.* **86** (2001) 2227
[20] T. Kinoshita, M. Nio: hep-ph/040220
[21] K. Melnikov, A. I. Vainshtein: hep-ph/0312226
[22] BES: *Phys. Rev. Lett.* **84** (2000) 594; *Phys. Rev. Lett* **88** (2002) 101802; Z. Zhao: SIGHAD03 [11], p. 25, 223
[23] S. A. Dytman: SIGHAD03 [11], p. 32
[24] H. Hayashii: SIGHAD03 [11], p. 134
[25] M. Davier: SIGHAD03 [11], p. 82
[26] F. Jegerlehner, DESY report 01-128, SIGHAD03 [11], p. 213
[27] B. Pietrzyk: SIGHAD03 [11], p. 97
[28] DAΦNE: *www.lnf.infn.it/acceleratori/*
[29] KLOE: *www.lnf.infn.it/kloe/*
[30] FINUDA: *www.lnf.infn.it/esperimenti/finuda/finuda.html*
[31] DEAR: *www.lnf.infn.it/esperimenti/dear/*
[32] M. Adinolfi et al.: *Nucl. Instr. Meth. Phys. Res. A* **488** (2002) 51
[33] M. Adinolfi et al.: *Nucl. Instr. Meth. Phys. Res. A* **482** (2002) 363
[34] Second DAΦNE Handbook Vol. I & II. Eds. L. Maiani, G. Pancheri, N. Paver, LNF, *www.lnf.infn.it/theory/dafne.html*
[35] P. de Simone: *Acta Phys. Slov.* **55** (2005) 15
[36] S. Eidelman, F. Jegerlehner, A. L. Kataev, O. Veretin: *Phys. Lett. B* **454** (1999) 369
[37] CMD-2: *Phys. Lett. B* **527** (2002) 161; *Phys. Lett. B* **578** (2004) 285
[38] S. Binner, J. H. Kühn, K. Melnikov: *Phys. Lett. B* **459** (1999) 279
[39] A. Denig for KLOE: DAΦNE99, Nov. 16-99, 1999, Frascati Physics Series XVI (2002) 569
[40] A. Denig for KLOE: hep-ex/0106100
[41] S. Müller for KLOE: *Nucl. Phys. B (Proc. Suppl.)* **126** (2004) 335
[42] S. Müller for KLOE: hep-ex/0312056
[43] A. Denig for KLOE: hep-ex/0311012
[44] J. Lee-Franzini for KLOE: hep-ex/0403006
[45] B. Valeriani for KLOE: SIGHAD03 [11], p. 75
[46] W. Kluge for KLOE: 7^{th} DESY Workshop on Loops and Legs in QFT, April 25-30, 2004; Zinnowitz: *Nucl. Phys. B (Proc. Suppl.)* **135** (2004) 357
[47] KLOE: hep-ex/0407048, accepted by *Phys. Lett. B*
[48] A. Denig, S. Di Falco, M. Incagli, W. Kluge, D. Leone, S. Müller, F. Nguyen, B. Valeriani, G. Venanzoni, KLOE Note # 192 (2004), *www.lnf.infn.it/kloe/pub/knote/kn192.ps*
[49] G. Rodrigo, A. Gehrmann-De Ridder, M. Guilleaume, J. H. Kühn: *Eur. Phys. J. C* **22** (2001) 81
[50] G. Rodrigo, H. Czyż, J. H. Kühn, M. Szopa: *Eur. Phys. J. C* **24** (2002) 71
[51] H. Czyż, A. Grzelińska, J. H. Kühn, G. Rodrigo: *Eur. Phys. J. C* **27** (2003) 563
[52] H. Czyż, A. Grzelińska, J. H. Kühn, G. Rodrigo: *Eur. Phys. J. C* **33** (2004) 333
[53] F. Jegerlehner, priv. comm.
[54] F. A. Behrens, R. Kleiss: *Nucl. Phys. B* **228** (1983) 537; E. Drago, G. Venanzoni, report INFN-AE-97-48
[55] BABAYAGA by C. M. Carloni Calame e al.: *Nucl. Phys. B* **584** (2000) 459, hep-ph/0312014

[56] KKMC: S. Jadach et al.: *Comp. Phys. Commun.* **130** (2000) 260

[57] D. Leone for KLOE: *Int. Workshop on Tau Lepton Physics Tau04*, Sept. 14-17, 2004, Nara (Japan), to be published in the Proc.

[58] J. Gluza, A. Höfer, S. Jadach, F. Jegerlehner: *Eur. Phys. J. C* **28** (2003) 261

[59] S. Ghozzi, F. Jegerlehner: *Phys. Lett. B* **583** (2004) 222

[60] C. Biscari: :*Future Plans for* e^+e^- *Factories*, 2003 Particle Accelerator Conference, Portland, May 12-16, 2003, LNF-03/012(P)

[61] G. Benedetti: *Feasibility Study of a 2* GeV *Lepton Collider at DAΦNE*, 2003 Particle Accelerator Conference, Portland, May 12-16, 2003, LNF-03/012(P)

[62] A. Gallo, DAΦNE 2004: *Physics at meson factories*, 7-11 June 2004, LNF Frascati (Roma), to be published in the Proceedings

[63] A. Denig, Alghero DAΦNE-2 Workshop, 10-13 Sept 2003, hep-ex/0403005 and SIGHAD03 [11], p. 88

[64] P. Franzini, Alghero DAΦNE-2 Workshop, 10-13 Sept 2003, hep-ex/0401031