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KLOE Measurement of the $\sigma(\pi^+\pi^-(\gamma))$ cross section and the $\pi^+\pi^-$ contribution to the muon anomaly

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The KLOE Experiment at the ϕ factory DAΦNE has performed a precise measurement of the cross section $\sigma(e^+e^- \to \pi^+\pi^-\gamma)$ using Initial State Radiation (ISR) events, with photons emitted at small polar angle. Results based on an integrated luminosity of 240 pb^{-1} are discussed. The determination of the $\pi^+\pi^-$ contribution to a_μ in the mass range $0.35 < M^2_{\pi\pi} < 0.95$ GeV^2 yields $(387.2 \pm 0.5_{stat} \pm 3.3_{sys}) \times 10^{-10}$. This value is compared with the most recent measurements from energy scan e^+e^- experiments and found to confirm the current discrepancy between predicted and measured value for a_μ. An independent analysis, requiring the ISR photon detected at large polar angle, is sensitive to the $\pi^+\pi^-$ threshold and indicates an accurate control of same final state interfering backgrounds by using the forward–backward asymmetry.

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1. Introduction

Recent measurements of the muon magnetic anomaly, performed at the Brookhaven Laboratory, reached an accuracy of 0.54 ppm [1]. The main source of uncertainty in the value predicted [2] in the Standard Model is given by the hadronic contribution to the lowest order, a_μ^{hlo}. This quantity is obtained with a dispersion integral of the hadronic cross section measurements. In particular, the pion form factor, $|F_\pi|^2$, defined via $\sigma_{\pi\pi} \equiv \sigma_{e^+e^-\to\pi^+\pi^-} \propto s^{-1}\beta_\pi^3(s)|F_\pi(s)|^2$, accounts for $\sim 70\%$ of the value and for $\sim 60\%$ of the uncertainty of a_μ^{hlo}.

2. Measurement of the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section at DAΦNE

DAΦNE is an e^+e^- collider operating at $\sqrt{s} \simeq M_\phi$, the ϕ meson mass, which has provided an integrated luminosity of about 2.5 fb^{-1} to the KLOE experiment up to year 2005. In addition, about 250 pb^{-1} of data have been collected at $\sqrt{s} \simeq 1$ GeV, in 2006. The KLOE detector consists of a cylindrical drift chamber [3] with excellent momentum resolution ($\sigma_p/p \sim 0.4\%$ for tracks with polar angle larger than 45°) and a lead scintillating fibers calorimeter [4] with good energy ($\sigma_E/E \sim 5.7\%/\sqrt{E\ [\mathrm{GeV}]}$) and precise time ($\sigma_t \sim 57$ ps$/\sqrt{E\ [\mathrm{GeV}]} \oplus 100$ ps) resolution. At DAΦNE, we extract $\sigma_{\pi\pi}$ from the differential cross section of the $\pi^+\pi^-$ invariant mass, $M_{\pi\pi}$, measured from ISR events $e^+e^- \to \pi^+\pi^-\gamma$ [5]:

$$s\,\frac{\mathrm{d}\sigma_{\pi\pi\gamma}}{\mathrm{d}M_{\pi\pi}^2}\bigg|_{\mathrm{ISR}} = \sigma_{\pi\pi}(M_{\pi\pi}^2)\,H(M_{\pi\pi}^2, s) \tag{2.1}$$

where H is the radiator function and Final State Radiation (FSR) effects are properly taken into account in the analysis. In particular, the cross section for ISR events diverges as $1/\theta_\gamma^4$ such that it dominates over FSR photon production at small photon angle θ_γ. Present results [6] are based on an integrated luminosity of 240 pb^{-1} of data taken in 2002, which correspond to about 3 Million events included in the following fiducial volume for the charged pions and the undetected photon:

a) two tracks with opposite sign curvature within the polar angle range $50^\circ < \theta < 130^\circ$;

b) photon direction reconstructed from the tracks as $\mathbf{p}_\gamma = -(\mathbf{p}_+ + \mathbf{p}_-)$ with $\theta_\gamma < 15^\circ$.

The separation of pion and photon selection regions reduces the contamination from the resonant decay $\phi \to \pi^+\pi^-\pi^0$, where the π^0 mimics the missing momentum of the photon, to the 5% level and suppresses the process $e^+e^- \to \pi^+\pi^-\gamma_{\mathrm{FSR}}$ to the 0.3% level. On the other hand, requirements *a)* and *b)* together imply $\sim 100^\circ$ for the opening angle between the pions that results in the kinematic suppression of events with $M_{\pi\pi} < 0.35$ GeV^2, in particular the $\pi\pi$ threshold region cannot be studied. Discrimination of $\pi^+\pi^-\gamma$ from $e^+e^-\gamma$ events is done via particle identification based on the time of flight, on the shape and the energy of the clusters associated to the tracks. The event is selected if at least one of the two tracks has not been identified as an electron.

Contamination from the processes $\phi \to \pi^+\pi^-\pi^0$ and $e^+e^- \to \mu^+\mu^-\gamma$ is rejected by cuts in the track mass variable, $\mathrm{M_{trk}}$, defined under the hypothesis that the final state consists of two charged particles with equal mass $\mathrm{M_{trk}}$ and one photon. The residual background is estimated fitting the $\mathrm{M_{trk}}$ spectrum of the selected data sample with a superposition of Monte Carlo (MC) distributions

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describing the signal and background sources, with free parameters being the fractional weights of signal and backgrounds, computed in bins of $M^2_{\pi\pi}$. Both trigger and tracking efficiencies are checked with two indepdendent control samples from data. Efficiencies for $\mathrm{M_{trk}}$ cuts and acceptance are evaluated from MC, corrected to reproduce data distributions.

Background subtraction	0.3 %
$\mathrm{M_{trk}}$ cuts	0.2 %
Tracking	0.3 %
Hardware Trigger	0.1 %
Acceptance on θ_γ	0.2 %
Software Trigger	0.1 %
Luminosity $(0.1_{th} \oplus 0.3_{exp})$%	0.3 %
$\sqrt{s}$ dependence of H	0.2 %
Experimental systematics	0.6 %
Vacuum Polarization	0.1 %
FSR resummation	0.3 %
Radiator function H	0.5 %
Theory systematics	0.6 %

Table 1: Systematic fractional errors on the $a_\mu^{\pi\pi}$ determination in the mass range $0.35 < M^2_{\pi\pi} < 0.95$ GeV^2.

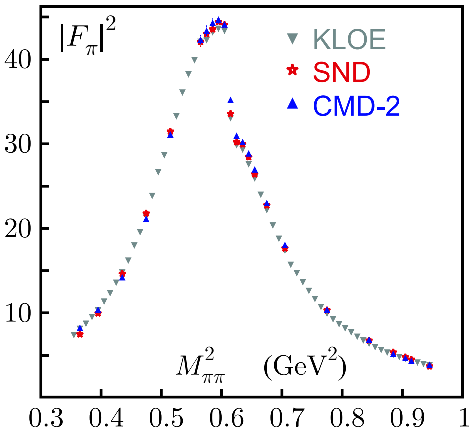

Figure 1: Comparison on the pion form factor measured by CMD-2, SND and KLOE (with only statistical errors for this latter).

3. Evaluation of $|F_\pi|^2$ and $a_\mu^{\pi\pi}$: comparison with present e^+e^- results

The $\pi\pi\gamma$ differential cross section is obtained from the observed spectrum, N_{obs}, after subtracting the background events, N_{bkg}, and correcting for the selection efficiency, $\varepsilon_{sel}(M^2_{\pi\pi})$:

$$\frac{d\sigma_{\pi\pi\gamma}}{dM^2_{\pi\pi}} = \frac{N_{obs} - N_{bkg}}{\Delta M^2_{\pi\pi}} \frac{1}{\varepsilon_{sel}(M^2_{\pi\pi})\,\mathscr{L}} \tag{3.1}$$

where the integrated luminosity, $\mathscr{L}$, is obtained [7] from the number of Bhabha events divided by the cross section evaluated with the MC generator `Babayaga@NLO` [8]. Then, $\sigma_{\pi\pi}$ is determined dividing Eq.(3.1) by the radiator function H, evaluated with the MC code `Phokhara` [9, 10], and corrected for the running of the fine structure constant [11] (Vacuum Polarization) and for the difference between $M_{\pi\pi}$ and the virtual photon mass, for those events with both an initial and a final photon. Table 1 shows the different contributions to the systematic error of the dispersive integral for $a_\mu^{\pi\pi}$ in the mass range [0.35,0.95] GeV^2. Figure 1 shows the comparison on $|F_\pi|^2$ with the results from the energy scan experiments at Novosibirsk CMD-2 [12] and SND[13]. For those experiments, whenever there are several data points falling in one 0.01 GeV^2 bin, we average the values. The present $a_\mu^{\pi\pi}$ result – denoted as KLOE08 – is compared with the published measurement [14, 15] – denoted as KLOE05 – from 140 pb^{-1} of data taken in 2001, and also with SND and CMD-2. Table 2 shows the good agreement amongst KLOE results, and also with the published CMD-2 and SND values. The KLOE08 result has a systematic error 30% smaller than KLOE05, and confirms the current disagreement between the Standard Model prediction based on e^+e^- experiments and the measured value of a_μ, as shown in Figure 2. Furthermore, the absolute difference

$a_\mu^{\pi\pi}(M^2_{\pi\pi} \in [0.35, 0.95]\ \text{GeV}^2) \times 10^{10}$	
KLOE05	$384.4 \pm 0.8_{stat} \pm 4.6_{sys}$
KLOE08	$387.2 \pm 0.5_{stat} \pm 3.3_{sys}$
$a_\mu^{\pi\pi}(M_{\pi\pi} \in [630, 958]\ \text{MeV}) \times 10^{10}$	
CMD-2	$361.5 \pm 1.7_{stat} \pm 2.9_{sys}$
SND	$361.0 \pm 2.0_{stat} \pm 4.7_{sys}$
KLOE08	$356.7 \pm 0.4_{stat} \pm 3.1_{sys}$

Table 2: Comparison among $a_\mu^{\pi\pi}$ values.

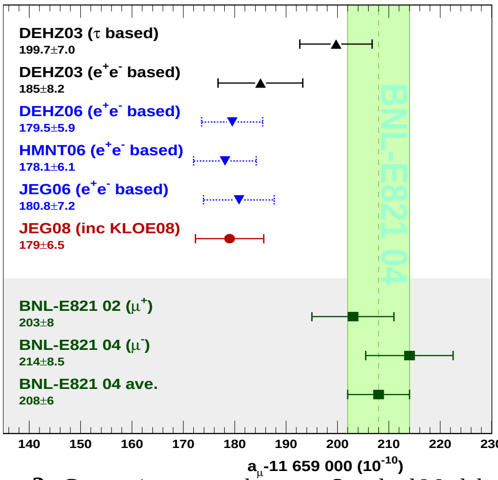

Figure 2: Comparison on a_μ between Standard Model predictions and measurements.

between KLOE08 and the Novosibirsk results (see Figure 3, left) in the $a_\mu^{\pi\pi}$ contributions from each $M^2_{\pi\pi}$ bin, confirms the consistency among recent e^+e^- measurements.

4. Outlook: the case of the $\pi^+\pi^-$ threshold region

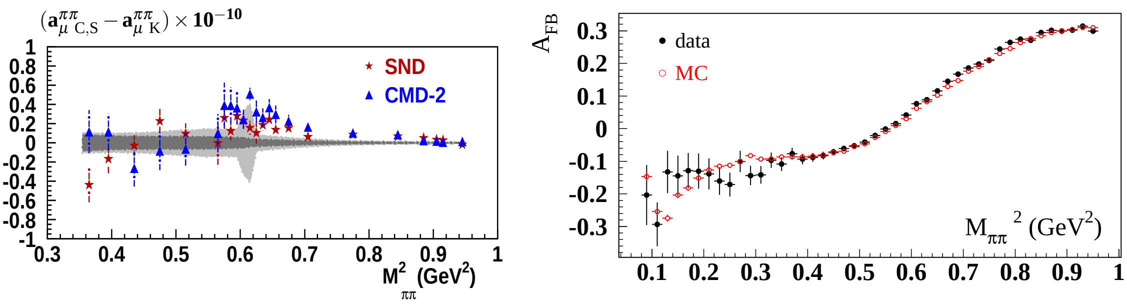

Figure 3: Left: difference in the dispersive integral value from each mass bin evaluated from CMD-2 or SND data with respect to KLOE; the dark (light) band describes statistical (statistical $\oplus$ systematic) errors. Right: preliminary data–MC comparison on A_{FB}, from data taken at $\sqrt{s} = 1$ GeV.

The $\pi^+\pi^-$ threshold region becomes accessible when the ISR photon is emitted into the same solid angle of the pion tracks. Thus, an indepdendent KLOE analysis is done requiring the detection of at least one photon of energy larger than 20 MeV and with $50^\circ < \theta_\gamma < 130^\circ$ in the calorimeter. This selection is sensitive to larger FSR effects, including interference from the resonant [16, 17] decays $\phi \to f_0(980)\gamma$, with $f_0(980) \to \pi^+\pi^-$ and $\phi \to \rho^\pm\pi^\mp$, with $\rho^\pm \to \pi^\pm\gamma$. These processes are included in Monte Carlo using phenomenological models [18, 19]. This interference pattern can be tested with the forward–backward asymmetry in the $\pi^\pm$ direction:

$$\mathrm{A}_{FB}(M^2_{\pi\pi}) = \frac{N(\theta_{\pi^+} > 90^\circ) - N(\theta_{\pi^+} < 90^\circ)}{N(\theta_{\pi^+} > 90^\circ) + N(\theta_{\pi^+} < 90^\circ)} \tag{4.1}$$

The analysis based on photons detected at large angle using data taken at $\sqrt{s} = 1$ GeV allows the study of the $\pi^+\pi^-$ threshold region without appreciable background from ϕ decays.

Figure 3, right, shows a reasonable agreement in the preliminary comparison between data and MC on A_{FB}, from an integrated luminosity of 230 pb^{-1}.

5. Conclusions

KLOE has measured the $\pi^+\pi^-$ contribution to the muon anomaly, $a_\mu^{\pi\pi}$, in the interval $0.592 < M_{\pi\pi} < 0.975$ GeV, with negligible statistical error and a 0.6% experimental systematic uncertainty. Theoretical uncertainties in the estimate of radiative corrections increase the systematic error to 0.9%. This result is consistent with recent measurements from energy scan experiments and together they confirm the difference between the a_μ measurement and the Standard Model prediction. Present efforts are focused on:

- finalizing the $\sigma_{\pi\pi}$ measurement from data taken at $\sqrt{s} = 1$ GeV, using large angle photons;
- measuring $|F_\pi|^2$ directly from the ratio, bin-by-bin, of $\pi^+\pi^-\gamma$ to $\mu^+\mu^-\gamma$ spectra [20].

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