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Measurement of the running of the fine structure constant below 1 GeV with the KLOE detector

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Abstract. I will report on the recent measurement of the fine structure constant below 1 GeV with the KLOE detector. It represents the first measurement of the running of $\alpha(s)$ in this energy region. Our results show a more than 5σ significance of the hadronic contribution to the running of $\alpha(s)$, which is the strongest direct evidence both in time- and space-like regions achieved in a single measurement. From a fit of the real part of $\Delta\alpha(s)$ and assuming the lepton universality the branching ratio $BR(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$ has been determined

1 Introduction

Physics at non-zero momentum transfer requires an effective electromagnetic coupling $\alpha(s)$ [1]. The shift of the fine-structure constant from the Thomson limit to high energy involves low energy non-perturbative hadronic effects which affect the precision. These effects represent the largest uncertainty (and the main limitation) for the electroweak precision tests as the determination of $sin^2\theta_W$ at the Z pole or the SM prediction of the muon $g-2$ [1]. The QED coupling constant is predicted and observed [2, 3] to increase with rising momentum transfer (differently from the strong coupling constant α_S which decreases with rising momentum transfer), which can be understood as a result of the screening of the bare charge caused by the polarized cloud of virtual particles. The vacuum polarization (VP) effects can be absorbed in a redefinition of the fine-structure constant, making it s dependent:

$$\alpha(s) = \frac{\alpha(0)}{1 - \Delta\alpha(s)}. \tag{1}$$

The shift $\Delta\alpha$(s) in terms of the vacuum polarization function Π'_γ(s) is given by:

$$\Delta\alpha(s) = -4\pi\alpha(0)\,\mathrm{Re}\,[\Pi'_\gamma(\mathrm{s}) - \Pi'_\gamma(0)] \tag{2}$$

and it is the sum of the lepton (e, μ, τ) contributions, the contribution from the five quark flavours (u, d, s, c, b), and the contribution of the top quark (which can be neglected at low energies): $\Delta\alpha(\mathrm{s}){=}\Delta\alpha_{lep}(s) + \Delta\alpha^{(5)}_{had}(s) + \Delta\alpha_{top}(s)$.
The leptonic contributions can be calculated with very high precision in QED using the perturbation theory [4, 5]. However, due to the non-perturbative behaviour of the strong interaction at low energies,

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[1] In the following we will indicate with s the momentum transfer squared of the reaction.

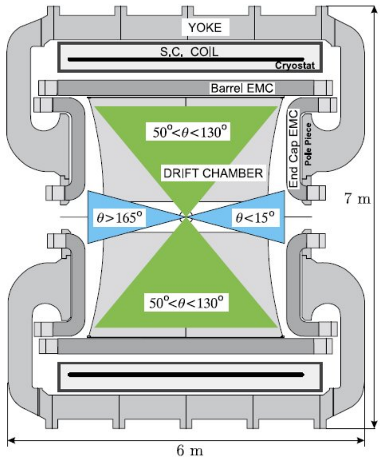

Figure 1. Detector section with the acceptance region for the charged tracks (wide cones) and for the photon (narrow cones).

perturbative QCD only allows us to calculate the high energy tail of the hadronic (quark) contributions. In the lower energy region the hadronic contribution can be evaluated through a dispersion integral over the measured $e^+e^- \to$ hadrons cross-section:

$$\Delta\alpha_{had}(s) = -(\frac{\alpha(0)s}{3\pi})\mathrm{Re}\int_{m_\pi^2}^{\infty} ds' \frac{R_{had}(s')}{s'(s'-s-i\epsilon)}, \quad (3)$$

where $R_{had}(s)$ is defined as the cross section ratio $R_{had}(s) = \frac{\sigma(e^+e^-\to\gamma*\to hadrons)}{\sigma(e^+e^-\to\gamma*\to\mu^+\mu^-)}$.

In this approach the dominant uncertainty in the evaluation of $\Delta\alpha$ is given by the experimental data accuracy.

In this paper we present a direct measurement of the running of the effective QED coupling constant α in the time-like region 0.6< $\sqrt{s}$ <0.98 GeV by comparing the process $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ with the photon emitted in the Initial State (ISR) to the corresponding cross section obtained from Monte Carlo (MC) simulation with the coupling set to the constant value $\alpha(s) = \alpha(0)$. The analysis has been performed by using the data collected with the KLOE detector at DAΦNE [6], the e^+e^- collider running at the ϕ meson mass, with a total integrated luminosity of 1.7 fb^{-1}.

2 Event selection

The KLOE detector consists of a cylindrical drift chamber (DC) [7] and an electromagnetic calorimeter (EMC) [8]. The DC has a momentum resolution of $\sigma_{p_\perp}/p_\perp \sim 0.4\%$ for tracks with polar angle $\theta > 45^\circ$. Track points are measured in the DC with a resolution in $r-\phi$ of ~ 0.15 mm and ~ 2 mm in z. The EMC has an energy resolution of $\sigma_E/E \sim 5.7\%/\sqrt{E(GeV)}$ and an excellent time resolution of $\sigma_t \sim 54\,\mathrm{ps}/\sqrt{E}\,(\mathrm{GeV}) \oplus 100$ ps.

A photon and two tracks of opposite curvature are required to identify a $\mu\mu\gamma$ event. Events are selected with a (undetected) photon emitted at small angle (SA), *i.e.* within a cone of $\theta_\gamma < 15^\circ$ around the beamline (narrow cones in Fig. 1) and the two charged muons are emitted at large polar angle, $50^\circ < \theta_\mu < 130^\circ$. High statistics for the ISR signal and significant reduction of background events as $\phi \to \pi^+\pi^-\pi^0$ in which the π^0 mimics the missing momentum of the photon(s) and from the FSR radiation process, $e^+e^- \to \mu^+\mu^-\gamma_{FSR}$, are guaranteed by this selection.

3 Measurement of the running of α

The strength of the coupling constant is measured as a function of the momentum transfer of the exchanged photon $\sqrt{s} = M_{\mu\mu}$ where $M_{\mu\mu}$ is the $\mu^+\mu^-$ invariant mass. The value of $\alpha(s)$ is extracted from the ratio of the differential cross section for the process $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ with the photon emitted in the Initial State (ISR) to the corresponding cross section obtained from Monte Carlo (MC) simulation with the coupling set to the constant value $\alpha(s) = \alpha(0)$:

$$|\frac{\alpha(s)}{\alpha(0)}|^2 = \frac{d\sigma_{data}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}}{d\sigma^0_{MC}(e^+e^- \to \mu^+\mu^-\gamma(\gamma))|_{ISR}/d\sqrt{s}} \tag{4}$$

To obtain the ISR cross section, the observed cross section must be corrected for events with one or more photons in the final state (FSR). This has been done by using the PHOKHARA MC event generator, which includes next-to-leading-order ISR and FSR contributions [9]. Figure 2, left, shows the ratio of the $\mu^+\mu^-\gamma$ cross-section from data with the corresponding NLO QED calculation from PHOKHARA generator including the Vacuum Polarization effects. The agreement between the two cross sections is excellent.

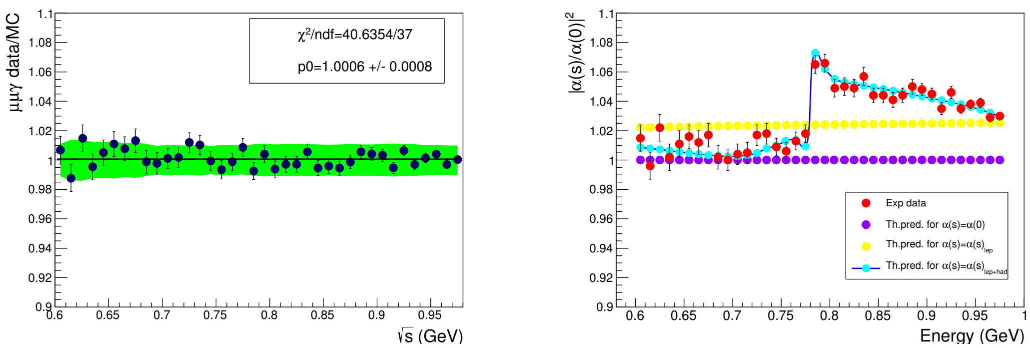

Figure 2. Left: Ratio between the measured differential $\mu^+\mu^-\gamma$ cross section and the MC prediction from PHOKHARA. The green band shows the systematic error. Right: The square of the modulus of the running $\alpha(s)$ in units of $\alpha(0)$ compared with the prediction (provided by the `alphaQED` package [10]) as a function of the dimuon invariant mass. The red points are the KLOE data with statistical errors; the violet points are the theoretical prediction for a fixed coupling ($\alpha(s) = \alpha(0)$); the yellow points are the prediction with only virtual lepton pairs contributing to the shift $\Delta\alpha(s) = \Delta\alpha(s)_{lep}$, and finally the points with the solid line are the full QED prediction with both lepton and quark pairs contributing to the shift $\Delta\alpha(s) = \Delta\alpha(s)_{lep+had}$.

We use Eq. (4) to extract the running of the effective QED coupling constant $\alpha(s)$. By setting in the MC the electromagnetic coupling to the constant value $\alpha(s) = \alpha(0)$, the hadronic contribution to the photon propagator, with its characteristic $\rho-\omega$ interference structure, is clearly visible, see Fig. 2, right. The prediction from Ref.[10] is also shown. While the leptonic part is obtained by perturbation theory, the hadronic contribution to $\alpha(s)$ is obtained via an evaluation in terms of a weighted average compilation of $R_{had}(s)$, based on the available experimental $e^+e^- \to$ hadrons annihilation data (for an up to date compilation see [11] and references therein).

For comparison, the prediction with constant coupling (*no running*) and with only lepton pairs contributing to the running of $\alpha(s)$ is given.

By including statistical and systematics errors, we exclude the only-leptonic hypothesis at $6\,\sigma$ which is the strongest direct evidence ever achieved by a collider experiment [2].

3.1 Extraction of Real and Imaginary part of $\Delta\alpha(s)$

By using the definition of the running of α the real part of the shift $\Delta\alpha(s)$ can be expressed in terms of its imaginary part and $|\alpha(s)/\alpha(0)|^2$:

$$\mathrm{Re}\,\Delta\alpha = 1 - \sqrt{|\alpha(0)/\alpha(s)|^2 - (\mathrm{Im}\,\Delta\alpha)^2}. \tag{5}$$

The imaginary part of $\Delta\alpha(s)$ can be related to the total cross section $\sigma(e^+e^- \rightarrow \gamma^* \rightarrow \mathit{anything})$, where the precise relation reads [1, 15, 16]: $\mathrm{Im}\,\Delta\alpha = -\frac{\alpha}{3}R(s)$, with $R(s) = \sigma_{tot}/\frac{4\pi|\alpha(s)|^2}{3s}$. $R(s)$ takes

into account leptonic and hadronic contribution $R(s) = R_{lep}(s) + R_{had}(s)$, where the leptonic part corresponds to the production of a lepton pair at lowest order taking into account mass effects:

$$R_{lep}(s) = \sqrt{1 - \frac{4m_l^2}{s}}\left(1 + \frac{2m_l^2}{s}\right), \quad (l = e, \mu, \tau). \tag{6}$$

In the energy region around the ρ-meson we can approximate the hadronic cross section by the 2π dominant contribution:

$$R_{had}(s) = \frac{1}{4}\left(1 - \frac{4m_\pi^2}{s}\right)^{\frac{3}{2}} |F_\pi^0(s)|^2, \tag{7}$$

where F_π^0 is the pion form factor deconvolved: $|F_\pi^0(s)|^2 = |F_\pi(s)|^2 \left|\frac{\alpha(0)}{\alpha(s)}\right|^2$.

The results obtained for the 2π contribution to the imaginary part of $\Delta\alpha(s)$ by using the KLOE pion form factor measurement [17], are shown in Fig. 3 and compared with the values given by the $R_{had}(s)$ compilation of Ref. [10] using only the 2π channel, with the KLOE data removed (to avoid correlations).

The extraction of the $\mathrm{Re}\,\Delta\alpha$ has been performed using the Eq. (5) and it is shown in Fig. 3, right. The experimental data with only the statistical error included have been compared with the `alphaQED` prediction when $\mathrm{Re}\,\Delta\alpha = \mathrm{Re}\,\Delta\alpha_{\mathrm{lep}}$ (yellow points in the colour Figure) and $\mathrm{Re}\,\Delta\alpha = \mathrm{Re}\,\Delta\alpha_{\mathrm{lep+had}}$ (dots with solid line). As can be seen, an excellent agreement for $\mathrm{Re}\,\Delta\alpha$(s) has been obtained with the data-based compilation.

Finally $\mathrm{Re}\,\Delta\alpha$ has been fitted by a sum of the leptonic and hadronic contributions, where the hadronic contribution is parametrized as a sum of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ resonance components and a non-resonant term.

The product of the branching fractions has been extracted [18]:

$$BR(\omega \rightarrow \mu^+\mu^-)BR(\omega \rightarrow e^+e^-) = (4.3 \pm 1.8_{stat} \pm 2.2_{syst}) \cdot 10^{-9}, \tag{8}$$

[2]The first evidence for the hadronic VP came from the ACO experiment which found an evidence at 3σ of the ϕ contribution to the process $e^+e^- \rightarrow \mu^+\mu^-$ in the region ±6 MeV around the ϕ peak (at 1019.4 MeV) [12]. The strongest evidence for hadronic VP effect comes from the muon g-2 experiment; at CERN it was determined at more than 7σ level [13, 14].

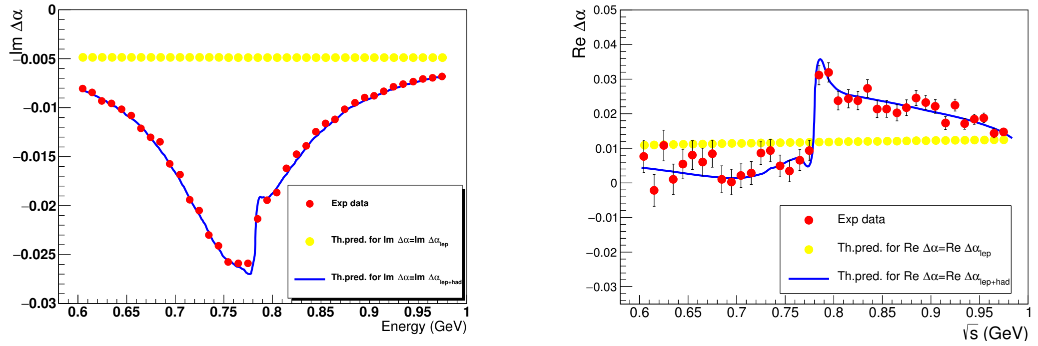

Figure 3. Left: $\mathrm{Im}\,\Delta\alpha$ extracted from the KLOE data compared with the values provided by `alphaQED` routine (without the KLOE data) for $\mathrm{Im}\,\Delta\alpha = \mathrm{Im}\,\Delta\alpha_{\mathrm{lep}}$ (yellow points) and $\mathrm{Im}\,\Delta\alpha = \mathrm{Im}\,\Delta\alpha_{\mathrm{lep+had}}$ only for $\pi\pi$ channels (blue solid line). Right: $\mathrm{Re}\,\Delta\alpha$ extracted from the experimental data with only the statistical error included compared with the `alphaQED` prediction (without the KLOE data) when $\mathrm{Re}\,\Delta\alpha = \mathrm{Re}\,\Delta\alpha_{\mathrm{lep}}$ (yellow points) and $\mathrm{Re}\,\Delta\alpha = \mathrm{Re}\,\Delta\alpha_{\mathrm{lep+had}}$ (blue solid line).

where the first error is statistical and the second systematic. By multiplying by the phase space factor $\xi = \left(1 + 2\frac{m_\mu^2}{m_\omega^2}\right)\left(1 - 4\frac{m_\mu^2}{m_\omega^2}\right)^{1/2}$ and assuming lepton universality, $BR(\omega \to \mu^+\mu^-)$ can be extracted:

$$BR(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5} \tag{9}$$

compared to $BR(\omega \to \mu^+\mu^-) = (9.0 \pm 3.1) \cdot 10^{-5}$ from PDG [19].

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