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

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Overview

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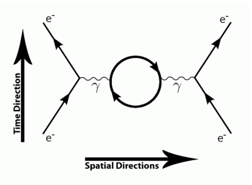
Physics Motivations

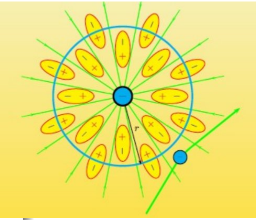
Knowledge of the QED coupling constant fundamental for testing the Standard Model

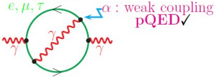


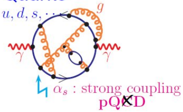
Modification of the QED coupling constant due to the Vacuum Polarization diagram:

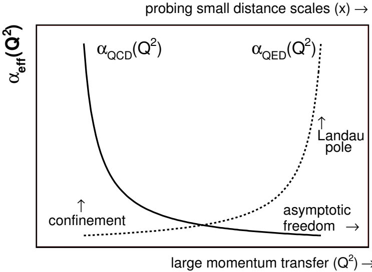
$$e^2 \rightarrow e^2(q^2) = \frac{e^2}{1+(\Pi'_\gamma(q^2)-\Pi'_\gamma(0))};$$

$$\alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha(q^2)}$$





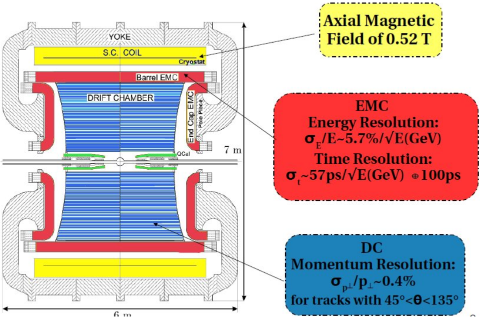


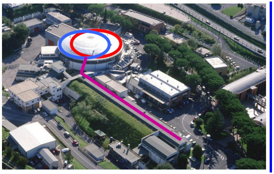


$$\Delta\alpha(q^2) = \Delta\alpha_{lep}(q^2) + \Delta\alpha_{had}(q^2)$$

No data in the low energy region

The Frascati Φ Factory and the KLOE detector





KLOE Data Set:

- On peak ($\sqrt{s} \sim 1.02 GeV$), $2.5 fb^{-1}$
- Off peak ($\sqrt{s} = 1.0 GeV$), $250 pb^{-1}$

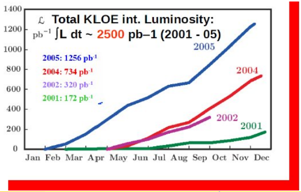
EMC:

♦ **lead/scintillating fibers**

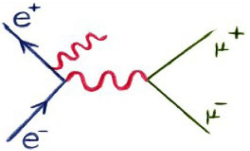
♦ **98% solid angle coverage**

DC:

♦ **Gas mixture:** $90\% He + 10\% C_4H_{10}$



Analysis Method



$$\left|\frac{\alpha_{QED}(s)}{\alpha_{QED}(0)}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

where:

$$\frac{d\sigma^{ISR}}{dM_{\mu\mu}} = \frac{N_{obs}-N_{bkg}}{dM_{\mu\mu}} \frac{1}{\epsilon(\sqrt{s_\mu})L}$$

- $\theta_\gamma < 15^\circ$ ($\theta_\gamma > 165^\circ$)
- $0 < \theta_\mu < 180^\circ$

with FSR effects removed

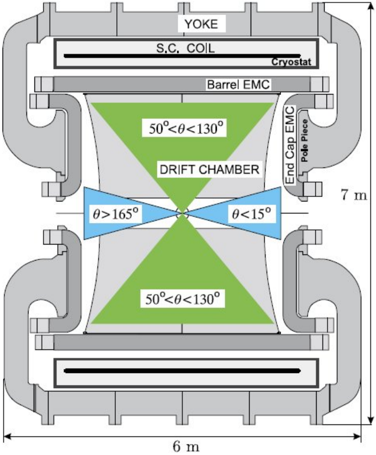
$\frac{d\sigma^{MC}}{dM_{\mu\mu}}$ obtained from PHOKARA gen.

with the following conditions:

- $\theta_\gamma < 15^\circ$ ($\theta_\gamma > 165^\circ$)
- $0 < \theta_\mu < 180^\circ$

Inclusive of the ISR and with the VP contribution removed

Event selection: Small Angle (SA)



- Two tracks of opposite sign with

$$50^\circ < \theta < 130^\circ$$

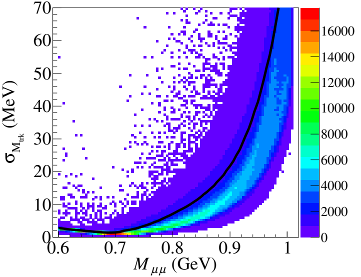
- Photons (not detected) at small angles :

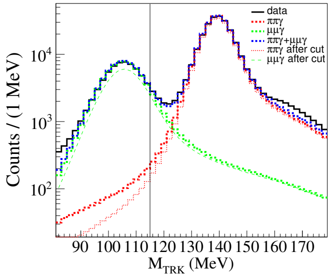
$$\theta < 15^\circ \, or \, \theta > 165^\circ$$

- Photon momentum from kinematics:
$\vec{p_\gamma} \simeq \vec{p_{miss}} = -(\vec{p_+} + \vec{p_-})$

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination

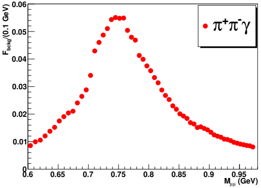
Event selection

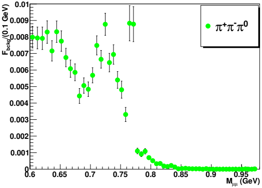


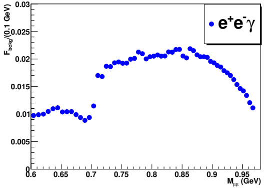


- $M_{TRK} < 115$ MeV for muons

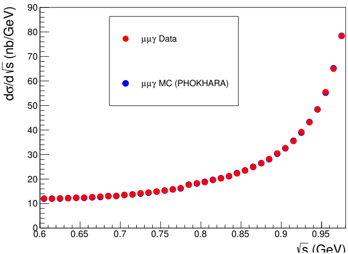
$$M_{TRK} = (\sqrt{s} - \sqrt{|\vec{p_+}|^2 + M_{TRK}^2} - +\sqrt{|\vec{p_-}|^2 + M_{TRK}^2})^2 - (\vec{p_+} + \vec{p_-})^2 = 0$$

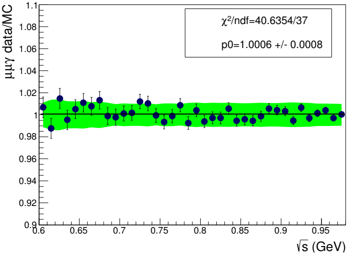






Measurement of the $\mu^+\mu^-\gamma$ cross section





$$\frac{d\sigma}{dM_{\mu\mu}} = \frac{N_{obs}-N_{bkg}}{dM_{\mu\mu}} \frac{(1-\delta_{FSR})}{\epsilon(\sqrt{s_\mu})L}$$

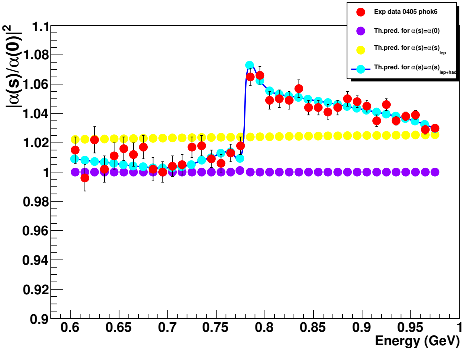
$$\frac{d\sigma^{DATA}_{\mu\mu\gamma}}{d\sigma^{MC}_{\mu\mu\gamma}} = 1.0006 \pm 0.0007$$

Excellent agreement with NLO theory (PHOKHARA MC) VP inside

H. Czyż, A. Grzelinska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 39 (2005) 411.

Total systematic error $\sim 1\%$.

Measurement of the effective α_{QED} coupling constant between 600 and 975 MeV



$$\left|\frac{\alpha_{QED}(s)}{\alpha_{QED(0)}}\right|^2 = \frac{\frac{d\sigma^{ISR}}{dM_{\mu\mu}}}{\frac{d\sigma^{MC}}{dM_{\mu\mu}}}$$

$\frac{d\sigma^{MC}}{dM_{\mu\mu}}$ with the VP contribution removed.

$$\left|\frac{\alpha(s)}{\alpha(0)}\right|^2 = |1/(1-\Delta\alpha(s))|^2$$

$$\Delta\alpha(s) = \Delta\alpha_{lep}(s) + \Delta\alpha_{had}(s)$$

(we neglect the top contribution)

♦ **"Theoretical prediction" (provided by the `alphaQED` package of F. Jergerlehner)** $\Delta\alpha_{lep}$ **computed in QED with negligible error;** $\Delta\alpha_{had}$ **obtained by a compilation of data in time-like region (with 0.1% accuracy).** $\rightarrow \Delta\alpha_{had}(s) = -(\frac{\alpha s}{3\pi}) Re \int_{m_\pi^2}^{\infty} ds' \frac{R(s')}{s'(s'-s-i\epsilon)}$

♦ **The red points show the KLOE data with statistical error bars.**

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

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

The Imaginary part of $\Delta\alpha(s)$ can be related to the total cross section $\sigma(e^+e^- \rightarrow \gamma^* \rightarrow anything)$ ("anything" means any possible state).

$$Im\Delta\alpha = -\frac{\alpha}{3} R(s).$$

where:

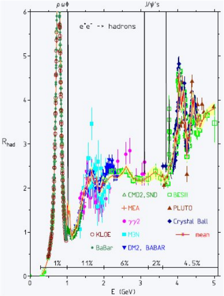
$$R(s) = \sigma_{tot} / \frac{4\pi\alpha(s)^2}{3s}$$

- $R(s)$ take into account leptonic and hadronic contribution
- $R(s) = R_{lep}(s) + R_{had}(s)$, where the leptonic part reads:

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

Calculation of R_{had}

In the energy region around the $\rho - meson$ we approximate the hadronic cross section to be given by the 2π dominant contribution



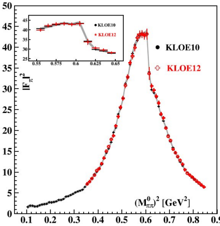
KLOE12 measurement of the pion form factor $|F_\pi(s)|^2$ was used:

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

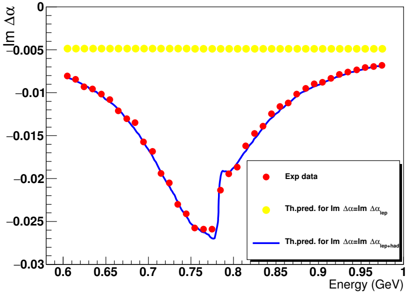
where:

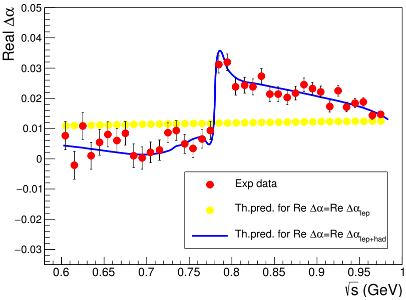
$$|F_\pi^0(s)|^2 = |F_\pi(s)|^2 |\frac{\alpha(0)}{\alpha(s)}|^2.$$

Physics Letters B 720 (2013) 336–343



Imaginary part of $\Delta\alpha$ only 2π and Real part of $\Delta\alpha$



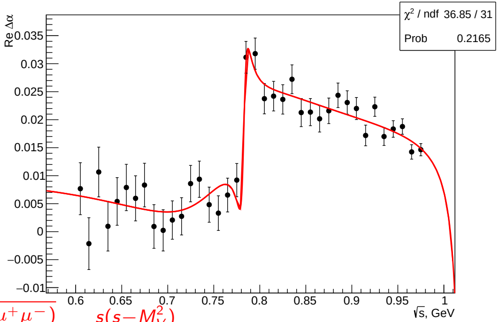


$$Re\,\Delta\alpha = 1 - \sqrt{|\alpha/\alpha(s)|^2 - (Im\,\Delta\alpha)^2}$$

Excellent agreement with the "theoretical prediction" (data compilation)

Fit of the Real part of $\Delta\alpha$

We fit Re$\Delta\alpha$ by a sum of the leptonic and hadronic contributions, where the hadronic contribution is parametrized as a sum of $\rho(770)$, $\omega(782)$ and $\phi(1020)$ resonances components and a non resonant term (param. with a pol1).



$$Re\ \Delta\alpha_{V=\omega,\phi} = \frac{3\sqrt{BR(V\to e^+e^-)\cdot BR(V\to\mu^+\mu^-)}}{\alpha M_V}\frac{s(s-M_V^2)}{(s-M_V^2)^2+M^2\Gamma_V^2}$$

Gounaris-Sakurai parametrization for the ρ:

$$F_\pi(s) = BW^{GS}_{\rho(s)} = \frac{M_\rho^2(1+d\Gamma_\rho/M_\rho)}{M_\rho^2-s+f(s)-iM_\rho\Gamma_\rho(s)}$$

(interference with the ω and the higher excited states of the ρ neglected).

Γ_ω , M_ϕ, Γ_ϕ, and $BR(\phi\to e^+e^-)BR(\phi\to\mu^+\mu^-)$ fixed to PDG values
K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update.

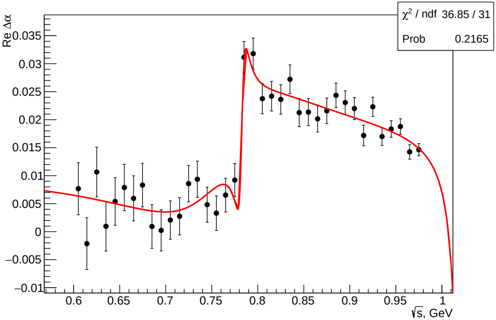
Fit of the Real part of $\Delta\alpha$

Assuming lepton universality and multiplying for the phase space correction:

$$\xi = \left(1 + 2\frac{m_\mu^2}{m_\omega^2}\right)\left(1 - 4\frac{m_\mu^2}{m_\omega^2}\right)^{1/2}$$

$$\Downarrow$$

the $BR(\omega \to \mu^+\mu^-)$results:
$(6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$ compared to $(9.0 \pm 3.1) \cdot 10^{-5}$ from PDG.



Parameter	Result from the fit	Result from the fit with $\rho - \omega$ interf.	PDG
M_ρ, MeV	775 ± 6	778 ± 7	775.26 ± 0.25
Γ_ρ, MeV	146 ± 9	147 ± 10	147 ± 0.9
M_ω§, MeV	782.7 ± 1.0	783.4 ± 0.8	782.65 ± 0.12
$BR(\omega \to \mu^+\mu^-)BR(\omega \to e^+e^-)$	$(4.3 \pm 1.8) \cdot 10^{-9}$	$(4.4 \pm 1.8) \cdot 10^{-9}$	$(6.5 \pm 2.3) \cdot 10^{-9}$
χ^2/ndf	1.19	1.15	

Conclusions

- The measurement of α_{QED} running has been performed in the time-like region $0.6 < \sqrt{s} < 0.975$GeV.
- It represents the first measurement of the running of α_{QED} in this region by a single experiment.It shows a significance of more than 5σ of the hadronic contribution to the running of α_{QED} with a spectacular evidence of $\rho - \omega$ resonances contribution to the photon Vacuum Polarization
- For the first time also the real and imaginary part of $\Delta\alpha$ have been extracted using the experimental data.
- The fit Re$\Delta\alpha$ allows also to measure the the $BR(\omega \to \mu^+\mu^-)$: $(6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$
- Paper published in Phys.Lett.B (https://dx.doi.org/10.1016/j.physletb.2016.12.016).

THANK YOU!!!