PROCEEDINGS OF SCIENCE

KLOE-2 results on hadron physics

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Two recent precision measurements of the Standard Model parameters using 1.7 fb^{-1} of e^+e^- data collected with the KLOE detector at DAΦNE are presented:

1. Dalitz plot distribution for the $\eta \to \pi^+\pi^-\pi^0$ decay is studied with the world's largest sample of $\sim 4.7 \cdot 10^6$ events from $e^+e^- \to \phi \to \eta\gamma$. The statistical uncertainty of all parameters is improved by a factor of two with respect to the earlier measurements. The data are used as input in dispersive calculations to determine ratio of the light quark masses.
2. Running of the effective QED coupling constant $\alpha(s)$ in the time-like region $0.600 < \sqrt{s} < 0.980$ GeV is studied using the Initial-State Radiation process $e^+e^- \to \mu^+\mu^-\gamma$. More than 5σ significance of the hadronic contribution to the running of $\alpha(s)$ is seen, which is the strongest direct evidence achieved in a single measurement. By using the $e^+e^- \to \pi^+\pi^-$ cross section measured by KLOE, the real and imaginary parts of $\alpha(s)$ have been extracted. From a fit of the real part the branching ratio $BR(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$ has been determined.

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Two recent precision measurements of the Standard Model (SM) parameters using 1.7 fb^{-1} of e^+e^- data collected 2004-2005 with the KLOE detector [1, 2] at DAΦNE [3] with center-of-mass energy of 1.0195 GeV are presented.

1. Precision measurement of the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution [4]

Isospin violating $\eta \to \pi^+\pi^-\pi^0$ decay constitute a benchmark for Chiral Perturbation Theory (ChPT), effective field theory of low-energy QCD, and at the same time is a sensitive probe of the difference between the masses of u and d quarks. The decay amplitude is proportional to light quark mass ratio, Q^{-2} [5]:

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \qquad \text{with } \hat{m} = \frac{1}{2}(m_d + m_u), \tag{1.1}$$

at up to NLO ChPT. Using a combination of kaon and pion masses to correct for the electromagnetic effects at the lowest order, $Q = 24.2$ is obtained.

The issue with $\eta \to \pi^+\pi^-\pi^0$ process is the slow convergence of the effective field theory. The ChPT results for the decay width are: at LO, $\Gamma_{LO} = 66$ eV, and at NLO, $\Gamma_{NLO} = 160 - 210$ eV [6]. The calculations should be compared to the experimental value of $\Gamma_{exp} = 300 \pm 12$ eV [7]. The experiment-theory discrepancy could originate from higher order contributions to the decay amplitude or from corrections to the Q value. The precision of the full NNLO calculations is affected by the uncertainties of the many involved coupling constants in the chiral lagrangian [8]. However, it is known that the $\pi\pi$ rescattering plays an important role in the decay. The rescattering can be accounted for to all orders using dispersive integrals and well known $\pi\pi$ phase shifts. In the dispersive calculations two approaches are possible. The first is to improve ChPT predictions starting from the NLO ChPT calculations. The second is to determine the proportionality factor for the Q^{-2} in the $\eta \to \pi^+\pi^-\pi^0$ decay amplitude from fits to the experimental Dalitz plot data and by matching the results to the LO amplitude in the region where it is considered accurate. Both approaches are pursued by three theory groups [9, 10, 11]. In the first approach the reliability of the calculations could be verified by a comparison with the experimental Dalitz plot data. Conversely, in the second approach precise experimental Dalitz plot distributions could be used to determine the quark ratio Q without relying on the higher order ChPT calculations. More new high statistics measurements are needed to clarify a tension among the experimental results [12, 13, 14, 15, 16, 17], and to provide input for the dispersive calculations.

For the $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot distribution, the normalized variables X and Y are commonly used:

$$X = \sqrt{3}\,\frac{T_+ - T_-}{Q_\eta}; \quad Y = \frac{3T_0}{Q_\eta} - 1 \tag{1.2}$$

with $Q_\eta = T_+ + T_- + T_0$ and $T_{+,-,0}$ kinetic energies of the pions in the η rest frame. The squared amplitude of the decay is parametrized by an expansion:

$$|A(X,Y)|^2 \propto 1 + aY + bY^2 + dX^2 + fY^3 + gX^2Y + \dots$$

The parameters $a, b, \dots$ could be extracted by the fit to the experimental Dalitz plot distribution. Note that the coefficients multiplying odd powers of X must be zero assuming charge conjugation, C, invariance.

In our analysis tracks of opposite curvature and three neutral clusters are required in the final state. The highest–energy photon, from the radiative $\phi \to \eta\gamma$ decay, is selected with energy above 250 MeV. Discrimination against electron contamination from Bhabha scattering is achieved by means of time-of-flight measurements in the calorimeter. Additional cuts have been applied to reduce background: i) on the angle between $\pi^+(\pi^-)$ and the closest photon from π^0 decay; ii) on the angle between clusters in the π^0 rest frame and iii) on the the reconstructed π^0 mass squared. Signal selection efficiency is 37.6% and signal to background ratio is $S/N = 133$ in the final data sample. The Dalitz plot distribution is constructed using 31 and 20 bins for X and Y respectively. The bin widths were determined both, by the resolution and the minimal bin content. The acceptance corrected data are presented in Fig. 1.

The final results for the Dalitz plot parameters, including influence of systematic effects, are: $a = -1.095 \pm 0.003^{+0.003}_{-0.002}$, $b = 0.145 \pm 0.003 \pm 0.005$, $d = +0.081 \pm 0.003^{+0.006}_{-0.005}$, $f = +0.141 \pm 0.007^{+0.007}_{-0.008}$, $g = -0.044 \pm 0.009^{+0.012}_{-0.013}$. They are a factor of 2-3 more precise than previous measurements and for the first time statistically significant contribution of the X^2Y term is found. In addition tests of C conservation in the decay were performed by studying asymmetries for the unbinned data. All the results are consistent with zero. For example asymmetry between $T_+ > 0$ and $T_- < 0$ events, A_{LR}, is $(-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$. The new KLOE-2 data are being used for the dispersive analyses, as the most precise input, *e.g.* in determination of the quark mass ratio $Q = 22.0 \pm 0.7$ by the Bern group [18].

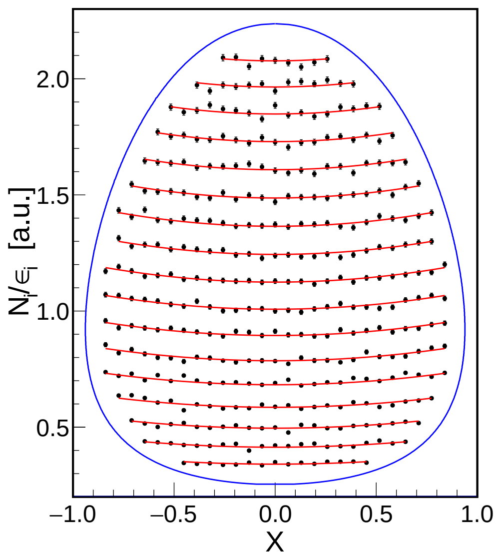

Figure 1: Acceptance corrected $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot data together with the result of the fit. Only statistical uncertainties are shown.

2. Measurement of the running of the fine structure constant below 1 GeV [19]

One of the SM basic input parameters is the effective QED coupling constant α, determined from the anomalous magnetic moment of the electron with the impressive accuracy of 0.37 parts per billion [20]. However, physics at non-zero momentum transfer squared, s, requires an effective electromagnetic coupling $\alpha(s)$. The shift of the effective coupling involves low energy non-perturbative hadronic effects which affect the precision. These effects represent the largest uncertainty for the electroweak precision tests as the determination of $\sin^2\theta_W$ at the Z pole or the SM prediction of the muon $g-2$ [21].

We have measured hadronic contribution to the running $\alpha(s)$ using the differential cross section for the process $e^+e^- \to \mu^+\mu^-\gamma(\gamma)$ in the region $0.600 < \sqrt{s} < 0.980$ GeV, with the photon emitted in the Initial State (ISR). The value of $|\alpha(s)/\alpha(0)|^2$ is extracted from the ratio of the experimental differential cross section to the corresponding cross section obtained from Monte Carlo simulation with $\alpha(s)$ set to the constant value of $\alpha(s) = \alpha(0)$.

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, *i.e.* within a cone of $\theta_\gamma < 15^\circ$ around the beamline and the two charged muons are emitted at large polar angle, $50^\circ < \theta_\mu < 130^\circ$. The ISR $\mu^+\mu^-\gamma$ cross section is obtained from the observed number of events (N_{obs}) and the background estimate (N_{bckg}) as:

$$\left.\frac{d\sigma(e^+e^- \to \mu^+\mu^-\gamma(\gamma))}{d\sqrt{s}}\right|_{ISR} = \frac{N_{obs} - N_{bkg}}{\Delta} \cdot \frac{1-\delta_{FSR}}{\varepsilon(\sqrt{s}) \cdot L}, \tag{2.1}$$

where $\Delta = 10$ MeV is the $\sqrt{s}$ bin width, ε is the efficiency, L is the integrated luminosity and $1-\delta_{FSR}$ is the correction applied to remove the final state radiation contribution. The extracted $|\alpha(s)/\alpha(0)|^2$ is shown in Fig. 2(a) and compared to the leptonic part from perturbative calculations and to the full hadronic and leptonic contribution where the hadronic part of $\alpha(s)$ is obtained by a dispersive integral using a compilation of the $e^+e^- \to hadrons$ data[1] [22, 23].

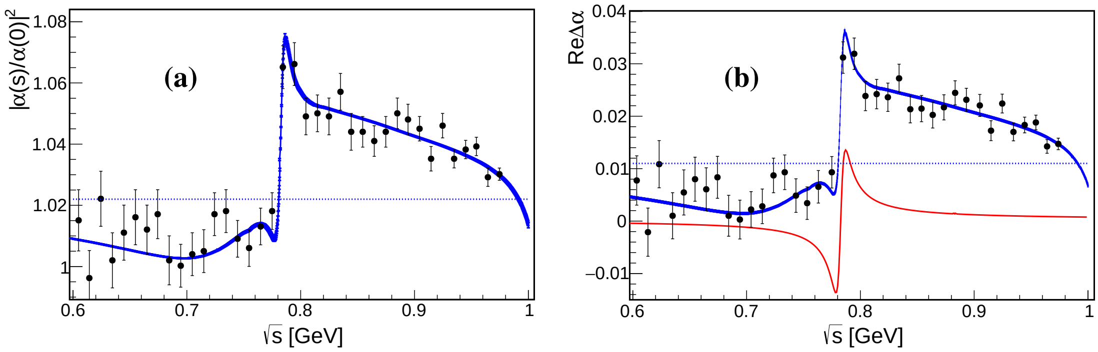

Figure 2: (a) $|\alpha(s)/\alpha(0)|^2$ and (b) Re$\Delta\alpha$ determined directly from the KLOE-2 data (points with statistical uncertainties only), result of the disperisive calculations (blue band), leptonic part (dotted line). In the panel (b) also the extracted contribution from the ω meson is shown (red solid line).

The imaginary part of $\alpha(s)$ could be usually neglected [24]. However, it should be taken into account in the presence of resonances like the ρ meson, where the cross section is measured with an accuracy better than 1%. The imaginary part of $\Delta\alpha \equiv 1 - \alpha(0)/\alpha(s)$ can be related to the total cross section $\sigma(e^+e^- \to \gamma^* \to anything)$: $\mathrm{Im}\Delta\alpha = -\frac{\alpha}{3}R(s)$, with $R(s) = \sigma_{tot}/\frac{4\pi|\alpha(s)|^2}{3s}$. $R(s)$ includes leptonic and hadronic contribution $R(s) = R_{lep}(s) + R_{had}(s)$. In the energy region around the ρ-meson the hadronic cross section could be approximated by the 2π dominant contribution:

$$R_{had}(s) = \frac{1}{4}\left(1 - \frac{4m_\pi^2}{s}\right)^{\frac{3}{2}} |F_\pi(s)|^2 \left|\frac{\alpha(0)}{\alpha(s)}\right|^2, \tag{2.2}$$

where $F_\pi(s)$ is the pion form factor obtained from KLOE measurement [25]. This information allows to extract the real part experimentally for first time. The data for Re$\Delta\alpha$ are shown in Fig. 2(b).

[1] `alphaQED` package [December 2016] `http://www-com.physik.hu-berlin.de/~fjeger/alphaQED.tar.gz`

Our Re$\Delta\alpha$ data could be used to determine $\omega \to \mu^+\mu^-$ branching ratio. For this purpose we parametrize the hadronic contributions as a sum of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ and a non-resonant term [24]. We use a Breit-Wigner description for the ω and ϕ resonances and for the ρ a Gounaris-Sakurai parametrization [26] of the pion form factor, where the interference with the ω and the higher ρ states could be neglected due to statistical precision of the data. The dispersion integral for $\Delta\alpha_{had}$ reads:

$$\Delta\alpha_{had} = -\frac{\alpha(0)s}{3\pi}\,\mathrm{P.V.}\int_{4m_\pi^2}^{\infty} ds'\,\frac{R_{had}(s')}{s'(s'-s-i\varepsilon)}, \tag{2.3}$$

where P.V. indicates Cauchy principal value. The fit of Re$\Delta\alpha$ with fixed leptonic and ϕ parts shows a clear contribution of the ρ and ω resonances to the photon propagator, which results in a more than 5σ significance of the hadronic contribution to $\alpha(s)$. This is the strongest direct evidence achieved by a single experiment. The ω contribution to Re$\Delta\alpha$ obtained from the fit could be translated, assuming lepton universality, to the branching ratio value $BR(\omega \to \mu^+\mu^-) = (6.6 \pm 1.4_{stat} \pm 1.7_{syst}) \cdot 10^{-5}$ to be compared with the only one previous measurement of $(9.0 \pm 2.9_{stat} \pm 1.1_{syst}) \cdot 10^{-5}$ from ALEPH [27].

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