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Studies of Light Meson Decays at KLOE

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The KLOE experiment at the DAΦNE e^+e^- collider in Frascati has collected 2.5 fb^{-1} of data at the ϕ meson peak in the recent years. The data contain high statistics samples of light meson decays, which are used to study the dynamics of η, ω, and η' meson decays with highest precision.

Recent results cover the first observation of the very rare decay $\eta \to e^+e^-e^+e^-$ and the branching ratio the anomalous decay $\eta \to \pi^+\pi^-\gamma$. In the latter decay also kinematical distribution have been studied in order to shed further light on the box anomaly, which governs the decay at the chiral limit.

Further, ongoing studies cover the isospin violating decay of the η meson into three pions and the decay $\eta' \to \pi^+\pi^-\eta$. The latter is of interest due to the possible contributions of scalar resonances in the final state interactions.

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1. KLOE detector at DAΦNE

The KLOE experiment is operated at the DAΦNE accelerator, which is located in the Frascati national laboratories of the INFN. DAΦNE is an e^+e^- collider running at a center-of-mass energy of 1020 MeV. It acts as a ϕ meson factory. The mesons are produced with a momentum of $p_x \approx 15$ MeV in the orbital plane due to the crossing angle of the beams in the interaction region.

The KLOE detector consists of a large cylindrical drift chamber which is surrounded by a barrel shaped sampling calorimeter, made of lead and scintillating fibers. Both detector components operate in the 0.52 T magnetic field produced by a superconducting solenoid.

The drift chamber [1] has a diameter of 4 m and is 3.3 m long. The combination of 12582 tungsten sense wires in an all-stereo configuration and a gas mixture composed of 90% helium and 10% isobutane results in a momentum resolution of $\sigma p_T/p_T \leq 0.4\%$ for polar angles larger than 45°. The position resolution is $\sigma_{R,\phi} \sim 150\mu$m in the transverse plane and $\sigma_z \sim 2$mm along the beam line, which results in a decay vertex position resolution of ~ 3 mm.

The electromagnetic calorimeter [2] covers 98% of the solid angle. Energies are measured with a resolution of $\sigma_E/E = 5.7/\sqrt{E[\text{GeV}]}$ and times with a resolution of $\sigma_t = (57/\sqrt{E[\text{GeV}]} \oplus 100)$ ps. The excellent time resolution allows charged particles to be identified by their time of flight, using the measured arrival time in the calorimeter.

During the past data taking campaigns a total amount of 2.5 pb^{-1} has been collected at the ϕ meson peak as well as 250 pb^{-1} off peak data ($\sqrt{s} \approx 1$ GeV). The physics case covered in the analysis of the data is manifold and covers kaon decay physics, the measurement of hadronic cross section as well as hadron spectroscopy, tests of symmetries and physics beyond the Standard Model. In the following, recent results and some of the ongoing investigations in the field of light meson decays are discussed. A more general overview of the recent KLOE results is given in the contribution of F. Bossi to these proceedings [3].

2. $\eta \to e^+e^-e^+e^-$

The decay of the η meson into four leptons proceeds through an intermediate state with two virtual photons and internal conversion of the photons into e^+e^- pairs. The matrix element is directly sensitive to the electromagnetic transition form factor of the η meson. Precise knowledge of the coupling of pseudoscalar mesons to photons is an important input to the evaluation of the anomalous magnetic moment of the muon $(g-2)_\mu$, where hadronic light-by-light scattering is currently still one of the largest uncertainties. Previously, only theory predictions of the branching ratio of $\eta \to e^+e^-e^+e^-$ [4] as well as experimental upper limits [5] were known.

A 1.7 fb^{-1} data set has been analyzed at KLOE with respect to $\eta \to e^+e^-e^+e^-$. Events with a high energetic photon that can be identified with the monochromatic photon of the radiative decay $\phi \to \gamma\eta$ and four charged tracks are selected. The time-of-flight measurement is used to identify the charged particles as electrons and a kinematic fit is used to reject wrongly reconstructed event candidates.

Background stems from ϕ meson decays with similar topologies and the e^+e^- continuum. Events in which photons converted to lepton pairs in the detector material, e.g. the beam pipe or the drift chamber walls, were suppressed using a condition based on the invariant mass and

the relative distance of track pairs calculated at the possible points of conversion. To determine the content of signal events the spectrum shown in Fig. 1 was fit with Monte Carlo distributions of signal and background, with the signal sample generated according to the matrix element of Bijnens and Perrsson [4].

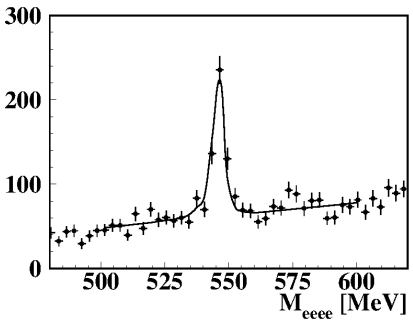

Figure 1: Invariant mass distribution of the four reconstructed leptons after background subtraction. The fitted peak contains 362 ± 29 events. This is the first observation of $\eta \to e^+e^-e^+e^-$

Based on the described procedure, $362 \pm 29\, \eta \to e^+e^-e^+e^-$ events are reconstructed, which results in a branching ratio $BR(\eta \to e^+e^-e^+e^-(\gamma)) = 2.4 \pm 0.2_{stat+bkg} \pm 0.1_{syst}$. This is the first observation of this decay mode. A detailed description of the analysis can be found in Ref. [6].

3. $\eta \to \pi^+\pi^-\gamma$

At the chiral limit, the decay $\eta \to \pi^+\pi^-\gamma$ is completely determined by the box anomaly. The physical process, however, is dominated by a resonant contribution of the triangle anomaly. Several attempts were made to describe the decay properly [7]. The observables to compare experiment and theory are the branching ratio of the decay mode as well as kinematic distributions, e.g. the invariant mass distribution of the charged pion pair.

A subset of 0.558 fb^{-1} of the KLOE data was used to determine the relative branching ratio $BR(\eta \to \pi^+\pi^-\gamma/\eta \to \pi^+\pi^-\pi^0)$, which recently had been determined by the CLEO collaboration with a significant deviation from the established value [8]. The event selection is based on kinematic conditions, which are chosen as similar as possible for $\eta \to \pi^+\pi^-\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ so that systematic effects cancel in the ratio. The final number of $\eta \to \pi^+\pi^-\gamma$ events is determined by fitting Monte Carlo distributions to the $E-p$ plot shown in the left panel of Fig. 2, with E and p being the energy and the absolute momentum of the single photon candidate from the η decay reconstructed exploiting energy and momentum conservation. A total of 204950 ± 450 signal events were reconstructed, with a background contamination of 10%. The number of $\eta \to \pi^+\pi^-\pi^0$ events is determined from a fit to the missing mass spectrum of the $\phi\gamma_\phi\pi^+\pi^-$ system, which is peaked at the π^0 meson mass, as shown in the central panel of Fig. 2. For this decay 1115805 ± 1056 events are reconstructed. The background contamination in the final selection is at the level of 0.65% only. In order to test the quality of this normalization sample, the absolute branching ratio for the η decay into three pions was calculated, based on the known cross section of the $\phi \to \gamma\eta$ decay at the given center of mass energy. The result is in good agreement with the value given by PDG [9].

Based on these findings, the relative branching ratio of the two η decay modes is determined as $BR(\eta \to \pi^+\pi^-\gamma/\eta \to \pi^+\pi^-\pi^0) = 0.1856 \pm 0.0005_{stat} \pm 0.0028_{syst}$. The value is in good agreement with the result of the CLEO collaboration [8].

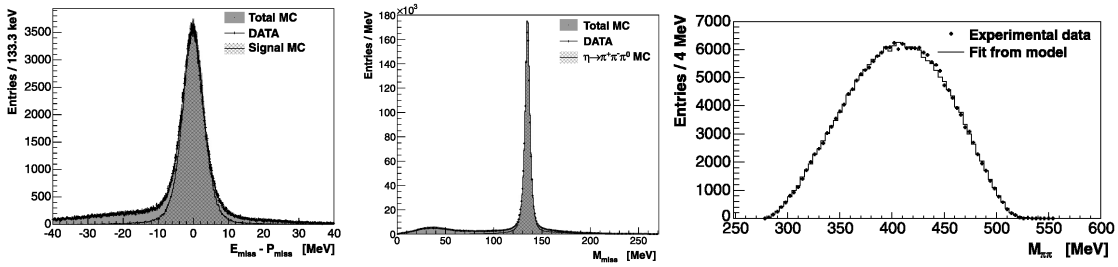

Figure 2: Left: Difference of missing energy and missing momentum of the $\pi^+\pi^-\gamma_\phi$ system after selecting $\eta \to \pi^+\pi^-\gamma$. Data are fit with MC distributions (shaded areas). **Center:** Missing mass distribution of the $\pi^+\pi^-\gamma_\phi$ after selecting $\eta \to \pi^+\pi^-\pi^0$. Data are fit with MC distributions (shaded areas). **Right:** The invariant mass spectrum of the di-pion system. The data points have been fit (black line) with the model independent ansatz of Ref. [10] to determine the shape parameter α.

The selected $\eta \to \pi^+\pi^-\gamma$ events were also used to study the shape of the invariant mass distribution of the two charged pions. The distribution is shown in the right panel of Fig. 2. To describe the shape, the model independent ansatz of Ref. [10] has been used. It applies a form factor, which is a product of the pion-vector form factor and a first order polynomial in $s_{\pi\pi}$, to parametrize the distribution with a single free parameter α, the coefficient of the polynomial.

Fitting the invariant mass distribution, taking into account the efficiency and the full smearing matrix, the parameter was determined as $\alpha = 1.32 \pm 0.08_{stat}\,{}^{+0.10}_{-0.09}{}_{syst} \pm 0.02_{theo}$. This is in agreement with the recent measurement by the WASA-at-COSY collaboration [11]. A detailed description of the analysis can be found in Ref. [12].

4. Further studies

Ongoing investigations of light meson decays at KLOE focus on the dynamics of the decays in order to test chiral perturbation theory and its predictions. The aim is to extract Dalitz plot parameters of $\eta, \omega \to \pi^+\pi^-\pi^0$ and $\eta' \to \eta\pi^+\pi^-$ with highest precision. The latter process is of interest due to the possibility of studying $\eta - \pi$ interaction at low energies, which also allows for possible contributions of scalar states [13]. At KLOE η' mesons are produced through the radiative decay $\phi \to \gamma\eta'$. In the analysis, the $\eta' \to \eta\pi^+\pi^-$ decay is reconstructed, tagging the η meson by its two photons decay mode. 1.7 fb^{-1} of the KLOE data set have been analyzed and 10160 ± 110 event candidates were reconstructed, as shown in the left panel of Fig. 3. The main background stems from $\eta \to \pi^+\pi^-\pi^0$, where the η meson was produced in the radiative ϕ decay and thus has an identical topology as the signal, and from $\phi \to \pi^+\pi^-\pi^0$. A kinematic fit is used to reject events which have a probability larger than 1% for the reaction hypothesis $\phi \to \gamma(\eta \to \pi^+\pi^-\pi^0)$. Background contamination of the final selection is 20%. The selected events can be used to study Dalitz plot distributions. The right panel of Fig. 3 shows the X distribution of the Dalitz plot, with X defined as $X = \frac{\sqrt{3}(T_{\pi^+} - T_{\pi^-})}{T_{\pi^+} + T_{\pi^-} + T_\eta}$, with T being the kinetic energies of the corresponding mesons in the rest frame of the η' meson. The distribution has been fit with Monte Carlo distributions of signal

and background processes. A fit of the full Dalitz plot in order to extract the parametrization is in progress. The resolution achieved in the Dalitz plot variables, $\sigma(x) \approx \sigma(y) = 0.02$, is competitive with the resolution achieved by the BES-3 Collaboration, which recently published a measurement with the currently highest statistical precision [14].

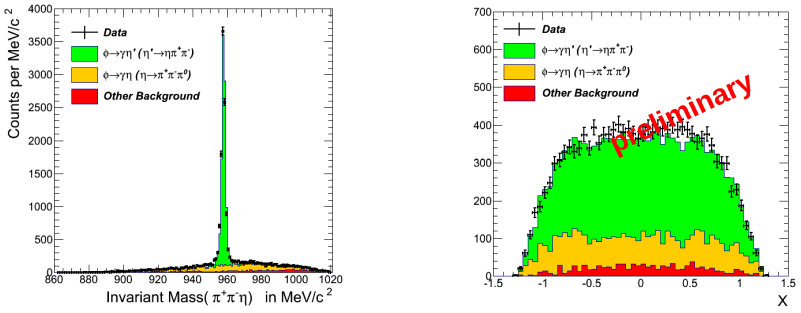

Figure 3: Left: Invariant mass spectrum of the $\pi^+\pi^-\gamma\gamma$ system after selecting $\eta' \to \eta\pi^+\pi^-$. Data have been fit with MC distributions. **Right:** Distribution of the Dalitz plot variable X of the selected events. Data are fit with MC distributions.

5. Outlook

The successful physics program of KLOE is continued by the KLOE-2 Collaboration [15]. A new and extensive data taking campaign with upgrades of the accelerator as well as of the detector systems allows for higher precision and sensitivity.

The upgrade of the DAΦNE collider will give rise to three times higher luminosities compared to the previous configuration. The increase will be achieved by a modification of the layout of the interaction region. The crabbed waist scheme and a larger crossing angle of the colliding electron and positron beams have been implemented.

The KLOE detector has been upgraded by a set of new subdetectors. Calorimeters [16], which cover the quadrupoles allow to increase the acceptance for photons with scattering angles below 20 degrees as well as photons emitted from decay vertices inside the KLOE-2 volume. The inner tracker [17] is made from four layers of cylindrical triple GEM detectors, located between the beam pipe and the inner wall of the drift chamber. It will improve the reconstruction of low momentum particles. Finally, tagging detectors are installed close to [18] and far away [19] from the interaction point. They will be used to measure electrons and positrons from the reaction $e^+e^- \to e^+e^-X$, which are scattered at very low angles. The taggers are essential to study $\gamma\gamma$-physics at the ϕ meson peak.

The commissioning of the upgraded machine started end of 2010 and the detector upgrades will be finalized in spring 2013. In the upcoming data taking it is planned to collect a new sample of at least 5 fb^{-1}. The light meson decay studies at KLOE-2 will benefit from the increase of precision. Rare processes, especially in η and η' decays, will be studied in detail.

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