STUDIES OF $\eta \to \pi^+\pi^-\gamma^{(*)}$*

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on behalf of the WASA-at-COSY Collaboration

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We describe experimental studies of the decays $\eta \to \pi^+\pi^-\gamma^{(*)}$, with the goal to test QCD anomalies and to search for flavor conserving CP violation.

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1. Introduction

The η meson is special among the pseudoscalar mesons. It is an eigenstate of the C, P and CP operations and it is relatively massive, so many decay modes are possible. However, it has a long life time of 5×10^{-19}s since all strong and electromagnetic decay modes are suppressed. In the first place the η meson is a low energy laboratory of Quantum Chromodynamics (QCD) described by the relevant effective field theory — Chiral Perturbation Theory (ChPT). The decays $\eta \to \pi^+\pi^-\gamma^{(*)}$ allow to study the chiral anomalies of QCD. These are handled by the Wess–Zumino–Witten (WZW) Lagrangian [1,2]. This term is needed to break the extra symmetry of the non-anomalous sector of ChPT, the conservation of the number of the Goldstone bosons modulo two. The WZW term describes interactions of a pseudoscalar and two vector mesons (triangle anomaly) or one vector meson and three pseudoscalars (box anomaly), or two kaons with three pions (pentangle anomaly). The predicted decay rate of the $\eta \to \pi^+\pi^-\gamma$ decay from the anomaly is nearly factor of two lower than the experimental value. A realistic description can be obtained by matching the result with a Vector Meson Dominance (VMD) model [3].

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Recent calculations are conducted in the framework of the Chiral Unitary Approach. Here a Bethe–Salpeter equation with coupled channels is used to generate resonances dynamically via infinite meson rescattering. The free parameters of this model are fixed by a fit to the experimental data [4].

Additional interest into the decay $\eta \to \pi^+\pi^-\gamma^{(*)}$ was raised by predictions of a mechanism for flavor conserving CP violation [5,6]. As illustrated in the left part of Fig. 1, one hypothetical CP-violating mechanism corresponds to a CP-violating $\eta \to \pi^+\pi^-$ process accompanied by the emission of bremsstrahlung radiation from one of the pions. However, this process is constrained by the current data on ε, ε' and the electric dipole moment of the neutron and estimated to be vanishingly small and thus undectable. Rather a direct photon emission process of E1 type (Fig. 1 (center)) is the prime candidate for a CP-violating process [5]. Due to its interference with the CP-conserving direct photon emission of M1 type (Fig. 1 (right)) one should observe emission of linearly polarized photons.

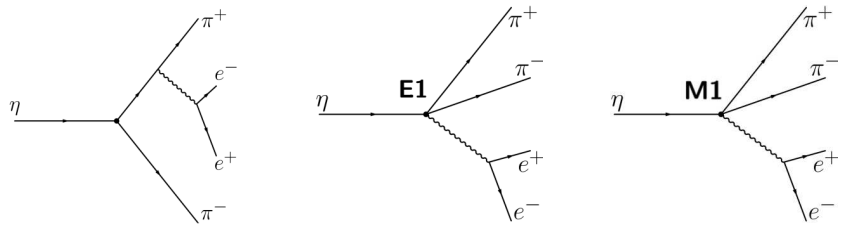


Fig. 1. Possible contributions to the decay amplitude of $\eta \to \pi^+\pi^-e^+e^-$: (left) internal bremsstrahlung radiation, center: direct emission of E1 type, (right) direct emission of M1 type.

The direct observation of the photon polarization in $\eta \to \pi^+\pi^-\gamma$ is experimentally difficult. However, in the case of the virtual photon converting to a lepton pair, the polarization affects the dihedral angle between the pion and the lepton systems. The contribution of the interference term would lead to an asymmetry in the angular distribution as described by Gao [6]. From an estimate of the upper bound of the direct CP-violating four-quark mechanism suggested in Ref. [5], Gao estimated the upper limit of this asymmetry to be 2%.

In a simple approximation the statistical error of measuring the asymmetry can be estimated as $\Delta A \approx 1/\sqrt{N}$, where N is the number of the events. This implies that to be sensitive to the estimated upper limit of the asymmetry a sample of about 10^5 events is needed.

Similar studies have been already performed, in the $K_L \to \pi^+\pi^-e^+e^-$ decay [7,8]. The observed asymmetry and CP violation in this flavor changing process is in accordance with the predictions given by CKM mechanism in the Standard Model.

Since the decay $\eta \to \pi^+\pi^-\gamma^{(*)}$ is of electromagnetic nature, it can be used as a tool to study the η meson structure. Electromagnetic processes involving photons and mesons reflect the coupling of photons to the electric charges of the fundamental quark fields, *i.e.* these processes contain information about the charge distribution in mesonic matter. The electric structure of the meson is contained in the form factor, which is, in the non-relativistic case, related to the charge density distribution by a Fourier transformation.

For neutral pseudoscalar mesons, the scattering process with single photon exchange of Fig. 2 (left) is forbidden due to C-parity, which is conserved in strong and electromagnetic interactions. Consequently, the electromagnetic form factors of neutral mesons are always zero. But the internal structure of neutral mesons can manifest itself in radiative decays into a photon and a meson of opposite C-parity to the decaying particle, *i.e.* for pseudoscalar mesons in the decay $P \to V\gamma$ (see Fig. 2 (right)). The photon can be either real or virtual, in the latter case with a subsequent decay into a lepton pair l^+l^- (*internal conversion*)

$$P \;\to\; V\gamma^* \to Vl^+l^- \,, \tag{1}$$

where the square of the invariant mass $\mathrm{m}_{l^+l^-}$ of the lepton pair ($l = e, \mu$) is equal to the square of the four-momentum of the virtual photon.

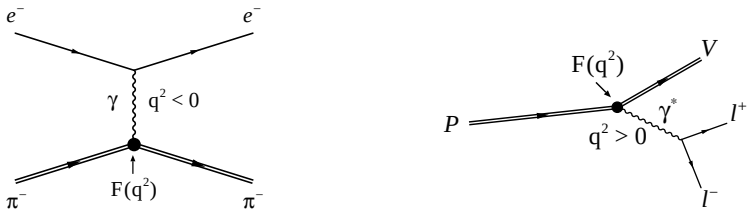


Fig. 2. Left: Space-like exchange in $e^-\pi^- \to e^-\pi^-$ scattering. Right: Diagram for decay of a pseudoscalar meson P into a vector meson V and an intermediate γ^* converting to a lepton–antilepton pair.

The lepton invariant mass distribution depends on the electromagnetic structure at the $P \to V$ transition vertex, which is due to a cloud of virtual states, *i.e.* the corresponding *transition form factor* describes the transition dynamics rather than static properties as in the case of the electromagnetic form factor for charged mesons. In the same way the process of $\eta \to \pi^+\pi^-\gamma^{(*)}$ can be used as the valuable source of knowledge about meson structure.

The studies require high statistic data samples never collected so far. Dedicated measurements of the decay $\eta \to \pi^+\pi^-\gamma$ have been performed in the 1970s, using pion beams impinging on hydrogen targets [9–12].

However, only data from references [9,10] were evaluated with respect to resonant/nonresonant contributions. The others measurements were devoted to studies of possible C violations. Data samples to extract the features of the box anomaly are of low statistics and not corrected for the efficiency. As stated by Borasoy [4] the sets seem to be inconsistent when trying to do a simultaneous fit. Thus an efficiency corrected sample of high statistics is needed to provide better input to the models. At the same time the limits on C violation tests can be improved. The $\pi^+\pi^-e^+e^-$ decay was measured recently by the CELSIUS/WASA (16 events) [13] and the KLOE (300 events) [14] collaborations. The statistics is sufficient enough to determine branching ratio, but still to little to evaluate the differential distributions and asymmetries. Thus, samples of about 10^5 $\eta \to \pi^+\pi^-\gamma^{(*)}$ decays are needed to have reasonable sensitivity. This is where WASA-at-COSY can contribute.

2. The WASA detector at COSY

WASA-at-COSY is a close to 4π detector, designed to measure decays of light mesons produced in hadronic interactions [15,16]. It is divided into a Forward Detector (FD) dedicated to the reconstruction of the recoil particles and a Central Detector (CD) for the reconstruction of decay particles of the mesons. A schematic side view of the setup is shown in Fig. 3. The highly segmented plastic scintillator detectors (FWC, FTH, FRH, FRI, FVH) in the FD provide energy and angular information already on the trigger level. Straw chambers (FPC) allow for superior angular resolution in the off–line analysis.

The CD is equipped with a straw chamber tracker (MDC), placed in a solenoid field. The chamber is surrounded by a plastic scintillator barrel (PSB), for charged particle identification. Neutral as well as charged particles can be reconstructed in a calorimeter made from CsI(Na) crystals (SE), which is the outermost subdetector of the CD.

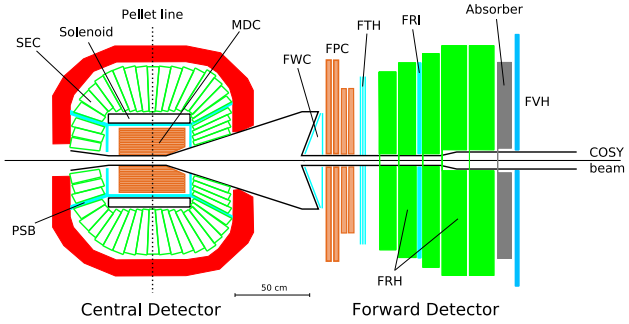


Fig. 3. Side view of the WASA detector at COSY.

The WASA detector is installed at the COoler SYnchrotron COSY in Jülich, Germany [17, 18]. This storage ring provides high intensity proton and deuteron beams in the momentum range of 0.6 to 3.7 GeV/c. Beams can be phase space cooled by means of electron cooling at injection as well as stochastic cooling at higher energies. Combined with the WASA pellet target system, luminosities of $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and beam life times of a few minutes are available.

This configuration enables WASA-at-COSY to perform high statistics measurements and to study rare decays of η mesons with branching ratios down to 10^{-5} in $pp \to pp\eta$ [19] and $pd \to {}^3\mathrm{He}\,\eta$ [20] reactions close to threshold.

3. Preliminary results

3.1. Tagging of meson production in the $pd \to {}^3HeX$ *and* $pp \to ppX$ *reactions*

The first step in the data analysis is the evaluation of the FD tracks. The recoil particles from the meson production have to be identified and selected. Due to the forward boost of fixed target experiments, it is necessary to distinguish the recoils from decay products emitted in the acceptance of the FD. The FD multilayer structure is designed for the use of the ΔE–E technique. As shown in Fig. 4, protons and ^{3}He ions can be distinguished from pions and deuterons on account of the characteristic energy deposits. For pp interactions the time correlation of the protons can be additionaly used. This helps to suppress time accidental signals. Cleanly identified signals in the FD are necessary to reconstruct the missing momentum of the decay system.

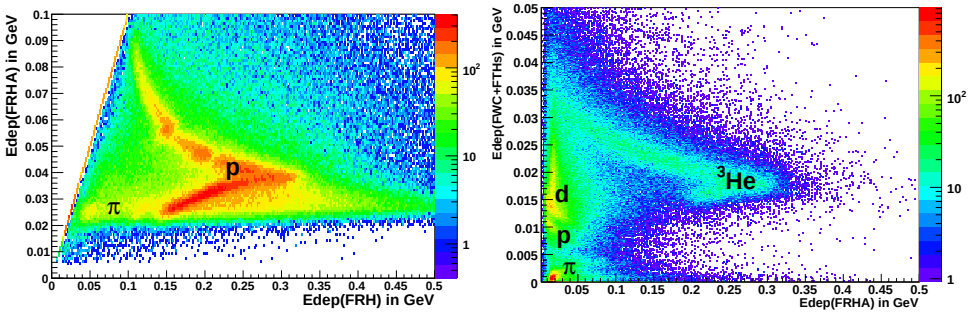


Fig. 4. ΔE–E technique for pp and for pd interactions.

3.2. Status of the analysis of $\eta \to \pi^+\pi^-\gamma$

For the reconstruction of the decay channel $\eta \to \pi^+\pi^-\gamma$ events with two tracks of opposite charge and one neutral track in correlation with the FD are accepted. As reference the time of the reconstructed protons (or ^{3}He) is used. This reduces the amount of the misidentified events where time accidental hits have the requested signature. Further suppression of the background is achieved by constraining the missing mass of the particles in forward direction and the neutral particle in the CD. For events originating from the decay of η mesons the mass of two pions is the lower limit for this observable. Additional cuts on the missing momentum and the missing energy allow to improve the quality of the reconstruction. In simulations based on Monte Carlo methods, the $\eta \to \pi^+\pi^-\pi^0$ decay and the direct multi pion production has been identified as the major source of background. Contributions of the $\eta \to \pi^+\pi^-\pi^0$ decay (blue line in Fig. 5) can be identified via a π^0 signal in the missing mass of the forward system and the charged pion candidates. However, the suppression of two pion production is more challenging (cyan line in Fig. 5). The goal is to provide background free and acceptance corrected invariant mass distributions of the pion system of the η decay.

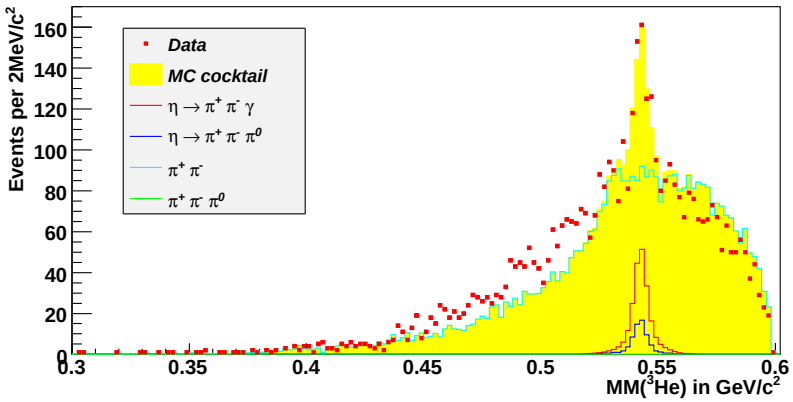


Fig. 5. Missing mass distribution of ^{3}He for the selected $\eta \to \pi^+\pi^-\gamma$ candidates, fitted with distributions obtained from simulations.

3.3. Status of the analysis of $\eta \to \pi^+\pi^-e^+e^-$ in the $pd \to {}^3He\,\eta$ reaction

The signature of this final state is four tracks from the charged particles in the CD. Fig. 6 shows the missing mass distribution of ^{3}He for the four track events.

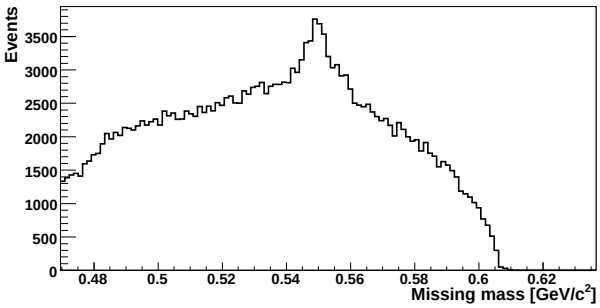


Fig. 6. Missing mass distribution of ^{3}He for the four track events.

The identification of the electrons and the pions will be accomplished by employing a correlation plot of the deposited energy in the PSB (ΔE) (see Fig 7) or in the electromagnetic calorimeter (E) as a function of the momentum of the reconstructed tracks (P).

The purity of identification is demonstrated in Fig. 7. In addition, the invariant mass of the e^+e^- pairs is peaked at the lowest possible value, the mass of two electrons, for the $\eta \to \pi^+\pi^-e^+e^-$ decay. The invariant mass is also strongly correlated with the opening angle between the leptons. Therefore, among the pairs of tracks with the opposite curvature the one with smallest opening angle is mostly likely (in more than 90% cases) due to the electron–positron pair.

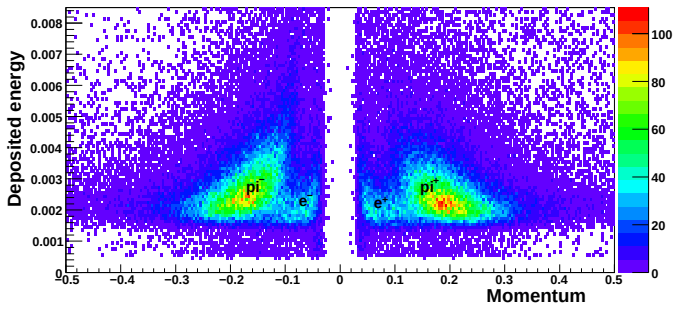


Fig. 7. Experimental spectra of the correlation between energy deposited in PS and the momentum reconstructed in the MDC.

4. Outlook

Recent data taken with WASA-at-COSY in 2007 and 2008 are under evaluation and show first promising signals. For the upcoming year a high statistics production run for proton–deuteron interactions is planned.

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