

Studying η -Meson Decays with WASA-at-COSY

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Abstract. The η -meson is a unique tool in a way that it provides access to (rare) decay processes, which allow to probe symmetry breaking phenomena, determine transition form factors, or to explore the anomalous sector of QCD. Those decays have been studied with the WASA-at-COSY experiment. Two data sets with different η -production mechanisms have been acquired. The analysis of those data sets are restricted to: The investigation of the isospin violating decay $\eta \rightarrow \pi^+\pi^-\pi^0$; Exploring the box anomaly in $\eta \rightarrow \pi^+\pi^-\gamma$; The determination of the electromagnetic transition form factor via the reactions: $\eta \rightarrow e^+e^-\gamma$ and $\eta \rightarrow e^+e^-e^+e^-$; Testing the CP-violation in $\eta \rightarrow \pi^+\pi^-e^+e^-$. An overview of the analysis of those decays will be given in the following.

1 The WASA-at-COSY Facility

The different η -decays are measured and reconstructed within the 4π wide angle shower apparatus (WASA) (see Fig. 1), which is located at the cooler synchrotron (COSY) at the Jülich Research Center in Germany. A proton beam, provided by COSY, is impinged on a liquid deuterium / hydrogen target producing η -mesons via: $pd \rightarrow {}^3\text{He}\eta$ and $pp \rightarrow pp\eta$. The scattered projectiles are detected in the forward part of WASA, where the angular information is provided by tracking detectors and the kinetic energy is reconstructed by a range hodoscope (see Fig. 1). The decay products are detected in the central part of WASA. Charged particles are reconstructed within a drift chamber in combination with a ~ 1 T magnetic solenoid field. Additional plastic scintillators and an electromagnetic calorimeter allow for the distinction between pions and electrons. Neutral particles are reconstructed within the electromagnetic calorimeter.

2 The Data Sets

A first iteration of measurements was done using the $pd \rightarrow {}^3\text{He}\eta$ reaction ($\sim 3 \cdot 10^7$ η -mesons have been detected) for the study of the more abundant η -decay channels (such as $\eta \rightarrow \pi^+\pi^-\pi^0$) and to setup the framework for a common analysis. The rare η -decay modes (e.g. $\eta \rightarrow e^+e^-e^+e^-$) are studied by using the high-statistics $pp \rightarrow pp\eta$ data set ($\sim 10^9$ η -mesons have been produced). The η -mesons are reconstructed via their missing mass, which is defined as: $\text{Missing mass} = \sqrt{(P_{\text{in}} - P_{\text{out}})^2}$, where P_{in} is the four momentum of all incoming particles (i.e. beam and target) and P_{out} is the corresponding four momentum of all scattered projectiles. A plot of the missing mass distribution for the two data

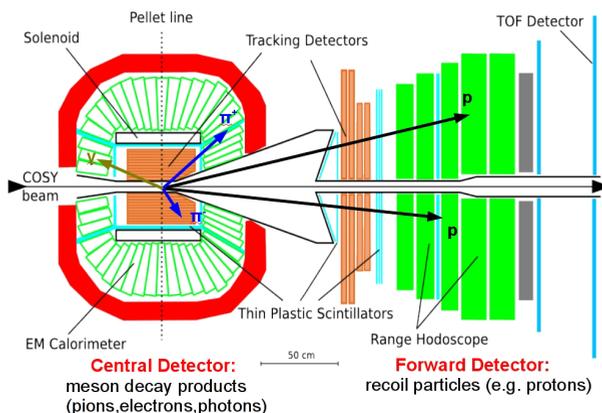


Figure 1. Schematic representation of the 4π WASA detector. The reaction $\eta \rightarrow \pi^+ \pi^- \gamma$ (see arrows) is shown as an example for the reconstruction of an η -decay.

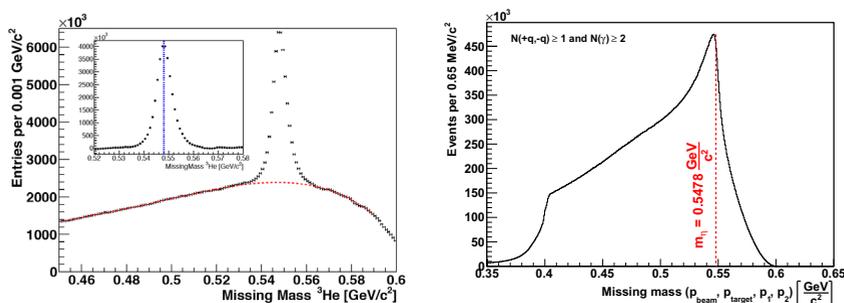


Figure 2. Missing mass distribution of the measured data for the reactions: $pd \rightarrow {}^3\text{He}\eta$ (left) and $pp \rightarrow pp\eta$ (right). The statistics shown on the right hand side correspond to $\sim 50\%$ of the total proton-proton data set.

sets is shown in Fig. 2. The missing mass distribution shown on the left of Fig. 2 is deduced from the $pd \rightarrow {}^3\text{He}\eta$ data set. A clear peak is pronounced at the η mass. The continuous background below the peak is related to direct pion production reactions such as: $pd \rightarrow {}^3\text{He}\pi^+\pi^-$, $pd \rightarrow {}^3\text{He}\pi^0\pi^0$ and $pd \rightarrow {}^3\text{He}\pi^+\pi^-\pi^0$. The corresponding distribution for the $pp \rightarrow pp\eta$ reaction is shown on the right hand side of Fig. 2. A peak at the η -mass is visible as well, however the non-resonant background is more dominating, compared to the left plot. This is related to the fact that, besides the η -production, the production cross sections for the multi-pion background is increased in the proton-proton case.

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3 Measurements and Results

3.1 $\eta \rightarrow \pi^+\pi^-\pi^0$ - The Dalitz Plot

This isospin violating decay allows to probe the quark mass ratio, as the decay amplitude Γ is proportional to Q^{-4} with [1]:

$$Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \text{ and } \hat{m} = \frac{1}{2}(m_u + m_d) \quad (1)$$

The decay amplitude is experimentally accessible via the Dalitz Plot analysis:

$$\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + dX^2 + fY^3 + \dots) \quad (2)$$

where a,b,d and f are fit-parameter and X and Y are the dimensionless Dalitz Plot variables. Table 1 summarizes theoretical approaches such as nonrelativistic effective field theory (NREFT) and chiral perturbation theory for the determination of the Dalitz Plot parameters a,b,d and f. The corresponding measured results are listed in the bottom half of Table 1. The results measured by WASA-at-COSY

Table 1. Comparison of the WASA-at-COSY results from the Dalitz Plot analysis with theory and recent results from the KLOE collaboration.

Parameter:		- a	b	d	f
Theor.	ChPT (NNLO) [2]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT [3]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA [4]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
Exp.	KLOE (08) [5]	1.090(5)($^{+8}_{-19}$)	0.124(6)(10)	0.057(6)($^{+7}_{-16}$)	0.14(1)(2)
	WASA [6]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16) [7]	1.104(3)(2)	0.142(3)($^{+2}_{-4}$)	0.073(3)($^{+4}_{-3}$)	0.154(6)($^{+4}_{-5}$)

are based on 120 k $\eta \rightarrow \pi^+\pi^-\pi^0$ events which have been reconstructed from the $pd \rightarrow {}^3\text{He}\eta$ data set. Table 1 shows that the current WASA-at-COSY results for the Dalitz Plot parameters are consistent with the KLOE results. A partial wave analysis (PWA) has been performed with the WASA data including the calculation of Q [4]: $Q = 21.4 \pm 0.4$. In a next step, the Dalitz Plot analysis will be redone using the $pp \rightarrow pp\eta$ data set.

3.2 $\eta \rightarrow \pi^+\pi^-\gamma$ - The Box Anomaly and $\pi^+\pi^-$ FSI

In the limit of vanishing quark masses the decay amplitude $A_{\eta \rightarrow \pi^+\pi^-\gamma}$ of $\eta \rightarrow \pi^+\pi^-\gamma$ is sensitive to the box anomaly term which is part of the Wess-Zumino-Witten lagrangian [8, 9]. However, this amplitude is dominated by pion-pion final state interactions (FSI) when going to physical quark masses. Therefore $A_{\eta \rightarrow \pi^+\pi^-\gamma}$ has to be modified in terms of the squared pion invariant mass $s_{\pi\pi}$: [10]

$$A_{\eta \rightarrow \pi^+\pi^-\gamma} \mapsto A_{\eta \rightarrow \pi^+\pi^-\gamma} \times [F_{PV}(s_{\pi\pi}) \times (1 + \alpha s_{\pi\pi})] \quad (3)$$

where F_{PV} is the pion vector form factor, which describes all resonant and non-resonant pion-pion interactions. This factor is independent of the underlying reaction mechanism. Reaction specific contributions are described by the linear term $(1 + \alpha s_{\pi\pi})$ with α being a fit parameter. Fig. 3 shows the single photon energy E_γ in the η -rest frame which is proportional to $s_{\pi\pi}$ [11]. The left hand side of Fig. 3 shows the result obtained from the reaction $pd \rightarrow {}^3\text{He}\eta$ [11] where 13 k $\eta \rightarrow \pi^+\pi^-\gamma$ events

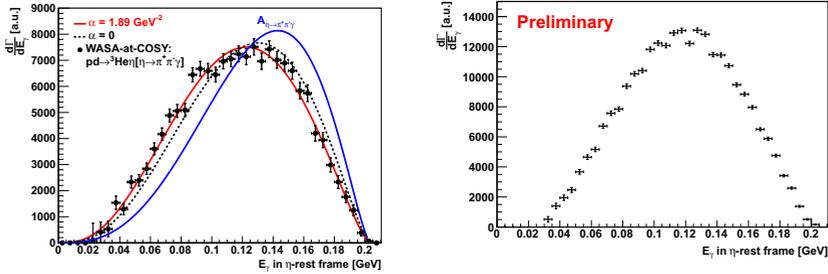


Figure 3. Single photon energy E_γ in the η -rest frame obtained from the $pd \rightarrow {}^3\text{He}\eta$ data set [11] (left) and $pp \rightarrow pp\eta$ data set (right). The black points represent the measured data. The solid / dashed lines correspond to a fit of Eq. 3.

have been reconstructed. The black data points are fitted by Eq. 3 with α fixed to zero (black dashed curve) and α left as a free parameter (red curve). The blue curve is a prediction of the E_γ -distribution without including final state interactions at all [14] (i.e. using $A_{\eta \rightarrow \pi^+\pi^-\gamma}$ solely). A fit of Eq. 3 to the $pd \rightarrow {}^3\text{He}\eta$ data with α left free (red curve in Fig. 3) leads to [11]:

$$\alpha = (1.89 \pm 0.25_{\text{stat}} \pm 0.59_{\text{sys}} \pm 0.02_{\text{theor.}}) \text{GeV}^{-2} \quad (4)$$

This value is significantly different from zero and indicates, that reaction dependent contributions from the production mechanisms of the two pions have to be included. The result in Eq. 4 is inconsistent with the theoretical predictions [14–16]. However, this value is supported by the latest KLOE result [12] with: $\alpha = (1.32 \pm 0.08_{\text{stat}} \pm 0.1_{0.09_{\text{sys}}} \pm 0.02_{\text{theor.}}) \text{GeV}^{-2}$. Another observable to investigate the box anomaly and final state interactions is the relative branching ratio $\Gamma(\eta \rightarrow \pi^+\pi^-\gamma)/\Gamma(\eta \rightarrow \pi^+\pi^-\pi^0)$. The value found for the WASA proton-deuteron data set [13] shows a slight mismatch with the current PDG value [17]. The right hand side of Fig. 3 shows the E_γ -distribution obtained from analyzing $\sim 50\%$ of the $pp \rightarrow pp\eta$ data set, resulting in 209 k reconstructed $\eta \rightarrow \pi^+\pi^-\gamma$ events. This distribution has already been corrected for multi-pion background. Currently ongoing steps include a correction for misidentified $\eta \rightarrow \pi^+\pi^-\pi^0$ events as well as an efficiency correction. The α -parameter as well as the relative branching ratio will be determined for the high statistics proton-proton data set, in order to decrease the statistical uncertainties and to recheck the existing results. Theoretically, the decay $\eta \rightarrow \pi^+\pi^-\gamma$ would be suitable to investigate CP-violation via measuring E_1 transitions of the single photon. However, this would require information about the photon polarisation, which is not possible with the WASA setup. An other elegant way to probe the CP-violation is to look at this decay with the photon being virtual and decaying into a dilepton-pair: $\eta \rightarrow \pi^+\pi^-\gamma^*[\gamma^* \rightarrow e^+e^-]$. This leads to four charged particles in the final state which can be reconstructed with WASA.

3.3 $\eta \rightarrow \pi^+\pi^-e^+e^-$ - CP-Violation

The information about a possible CP-Violation is embedded in the asymmetry A_Φ [18]:

$$A_\Phi = \frac{N(\sin[\Phi] \cos[\Phi] > 0) - N(\sin[\Phi] \cos[\Phi] < 0)}{N(\sin[\Phi] \cos[\Phi] > 0) + N(\sin[\Phi] \cos[\Phi] < 0)} \quad (5)$$

where Φ is the angle between the decay planes of the dileptons and the charged pions. The upper limit for Eq. 5 predicted by theory is $\sim 1\%$ [18]. The current measured result for A_Φ has been found

by KLOE [19]: $A_\Phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \cdot 10^{-2}$. The branching ratio BR for this decay has been measured by KLOE as well and is given by [19]: $BR(\eta \rightarrow \pi^+\pi^-e^+e^-) = (2.68 \pm 0.09_{stat} \pm 0.07_{sys}) \cdot 10^{-4}$. Fig. 4 shows the missing mass as well as the $\sin \Phi \cos \Phi$ -distribution after reconstructing 251 ± 17

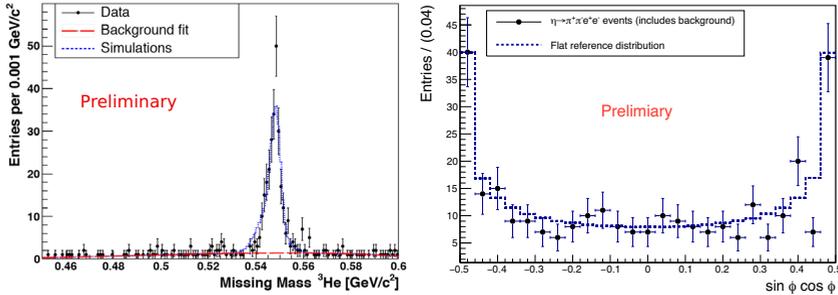


Figure 4. Left: Missing mass after reconstructing $\eta \rightarrow \pi^+\pi^-e^+e^-$ from the proton-deuteron data set [13]. The horizontal red line represents a fit of the background. Right: $\sin \Phi \cos \Phi$ -distribution for data [13] (black points) and Monte Carlo simulations of $\eta \rightarrow \pi^+\pi^-e^+e^-$ (blue dashed line).

$\eta \rightarrow \pi^+\pi^-e^+e^-$ events from the proton-deuteron data set. The preliminary results deduced from Fig. 4 are [13]:

$$A_\Phi = (-1.1 \pm 6.6_{stat} \pm 0.2_{sys}) \cdot 10^{-2} \quad (6)$$

$$BR(\eta \rightarrow \pi^+\pi^-e^+e^-) = (2.7 \pm 0.2_{stat} \pm 0.2_{sys}) \cdot 10^{-4} \quad (7)$$

Both values are in agreement with the current KLOE results. However, Fig. 4 already indicates a need for more statistics in order to decrease the statistical uncertainties. Therefore, this measurement will be redone with the proton-proton data set. A first estimation shows that about ~ 1 k $\eta \rightarrow \pi^+\pi^-e^+e^-$ events are expected for the full $pp \rightarrow pp\eta$ data set, which is comparable with the statistics from the KLOE experiment.

3.4 $\eta \rightarrow e^+e^-\gamma$ and $\eta \rightarrow e^+e^-e^+e^-$ - Dalitz Decays

The Dalitz decay $\eta \rightarrow e^+e^-\gamma$ allows to investigate the single off-shell transition form factor $F(q^2)$, by measuring the dilepton invariant mass distribution q as well as the relative branching ratio $\frac{\Gamma(\eta \rightarrow e^+e^-\gamma)}{\Gamma_\eta}$. If the photon becomes virtual, the Dalitz decay turns into the double Dalitz decay: $\eta \rightarrow e^+e^-e^+e^-$ which gives access to the double off-shell transition form factor $F(q_1^2, q_2^2)$. The observable to check theoretical predictions for $F(q_1^2, q_2^2)$ [20] is the branching ratio $BR(\eta \rightarrow e^+e^-e^+e^-)$. Fig. 5 shows the missing masses after reconstructing $\eta \rightarrow e^+e^-\gamma$ and $\eta \rightarrow e^+e^-e^+e^-$ events. The corresponding preliminary values for the relative branching ratios are given by [13]:

$$BR(\eta \rightarrow e^+e^-\gamma) = (6.72 \pm 0.07_{stat} \pm 0.31_{sys}) \cdot 10^{-3} \quad (8)$$

$$BR(\eta \rightarrow e^+e^-e^+e^-) = (3.2 \pm 0.9_{stat} \pm 0.5_{sys}) \cdot 10^{-5} \quad (9)$$

Both results are in agreement with current measurements [17] and based on: $14,040 \pm 120$ reconstructed $\eta \rightarrow e^+e^-\gamma$ events and 18 ± 5 reconstructed $\eta \rightarrow e^+e^-e^+e^-$ events. Each reaction is reanalyzed in the proton-proton data set, in order to improve statistics. Additionally the dilepton invariant mass for the single Dalitz decay will be determined. The large invariant mass region will profit from the high statistics and allow for a precise determination of $F(q^2)$ at large q -values.

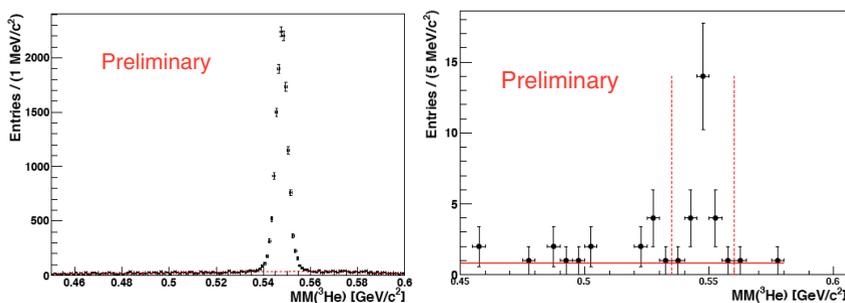


Figure 5. Missing mass after reconstructing $\eta \rightarrow e^+e^-\gamma$ (left) and $\eta \rightarrow e^+e^-e^+e^-$ (right) from the proton-deuteron data set [13]. The red horizontal lines in each plot represent the fitted background. The vertical lines in the right diagram correspond to the integration window.

4 Summary and Outlook

The η -decays discussed in the previous section have been measured in the $pd \rightarrow {}^3\text{He}\eta$ and $pp \rightarrow pp\eta$ reaction. The analysis for the proton-deuteron data set is finished and results have been published or are on the way of publishing [6, 11, 13]. The analysis of the proton-proton data set is still ongoing and will profit from the analysis that has been set up for the proton-deuteron data. New results with improved statistics and a more detailed insight into the nature of η -decays are expected in the near future.

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