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Hadrons and broken symmetries with WASA-at-COSY

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Abstract. The WASA Detector Facility is an internal experiment at the cooler synchrotron (COSY) in Jülich, Germany. The COSY accelerator provides proton and deuteron beams with momenta up to 3.7 GeV/c giving access to hadron physics including the strange quark sector. The physics program with the WASA detector involves hadron dynamics and hadron structure. Key experiments address fundamental symmetries and symmetry violations via the study of rare and not-so-rare meson decays. From the very first production run, results on the Dalitz plot slope parameter in the isospin violating $\eta \to 3\pi^0$ decay have been obtained. The $3\pi^0$ final state is also used to study meson production mechanisms. Investigations of other decay modes of the η-meson address C, P, and T symmetries and combinations. Higher orders in chiral perturbation theory are probed with the $\eta \to \pi^0\gamma\gamma$ decay. The status and plans for studying hadron structure with Dalitz decays of mesons are presented.

Keywords. Leptonic, semileptonic, and radiative decays of mesons; hadronic decays of mesons; electromagnetic form factors.

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1. Introduction

The physics program of the WASA-at-COSY Collaboration [1] addresses three general topics of hadron physics:

- Symmetries and symmetry breaking
  - rare decays of light mesons (η, η', ω)
  - dynamical isospin breaking ($dd \to \alpha\pi^0$)
  - isospin violating mixing of scalar mesons (a_0/f_0)
- Hadron structure
  - transition form factors (Dalitz decays)
  - spectroscopy (hyperons)
- Hadron dynamics
  - reaction dynamics ($\pi\pi$, η production)
  - few-body reactions (ABC effect revisited).

Table 1. η decays currently investigated with WASA-at-COSY.

Decay mode	Fraction $\Gamma_i/\Gamma_{\rm tot}$	Physics issue
$\eta \to \pi^0\pi^0\pi^0$	$(32.56 \pm 0.23) \times 10^{-2}$	Dalitz plot parameter
$\eta \to \pi^+\pi^-\pi^0$	$(22.73 \pm 0.28) \times 10^{-2}$	Dalitz plot parameter
$\eta \to \pi^+\pi^-\gamma$	$(4.60 \pm 0.16) \times 10^{-2}$	QCD box anomaly
$\eta \to e^+e^-\gamma$	$(7.0 \pm 0.7) \times 10^{-3}$	Transition form factor
$\eta \to \pi^0\gamma\gamma$	$< 1.2 \times 10^{-3}$	Higher order ChPT
$\eta \to \pi^+\pi^-e^+e-$	$(4.2^{+1.5}_{-1.3}) \times 10^{-4}$	CP violation
$\eta \to e^+e^-e^+e^-$	$< 6.9 \times 10^{-5}$	Transition form factors
$\eta \to \pi^0e^+e^-$	$< 4 \times 10^{-5}$	C violation
$\eta \to e^+e^-$	$< 2.7 \times 10^{-5}$	New physics?

The studies aiming at symmetries and symmetry breaking investigate C, P, T symmetry violations and combinations thereof. Here, hadronic, radiative and (semi)leptonic meson decays are used. The topics include the $\pi^0 \to e^+e^-$ decay, and rare and not-so-rare decays of η and η'.

One of the key experiments is the measurement of $\vec{d}d \to {}^4\text{He}\,\pi^0$ to extract the p-wave contribution to the charge symmetry breaking amplitude. In the preparation of data taking with a polarized deuteron beam, the reaction has been measured with an unpolarized beam at a momentum of $p_d = 1.2$ GeV/c ($T_d = 351$ MeV) to establish the yet unknown cross-section and to demonstrate the separation of the helium isotopes.

The structure of hadrons includes investigations of the nature of hyperons, especially, the $\Lambda(1405)$. In this presentation, special attention is given to the electromagnetic transition form factor, studied in meson Dalitz decays.

Hadron dynamics is studied by meson production and few-body effects. A possible η-mesic helium state is pursued with high statistics and high acceptance. The feasibility has been demonstrated in a pilot measurement of the excitation function for the $dd \to {}^3\text{He}\ p\pi^-$ reaction. Details about the search for η-mesic helium are given in [2]. The ABC effect is an enhancement at low $\pi\pi$ invariant masses, only observed in isoscalar channels such as $pn \to d\pi^0\pi^0$ leading to a bound nuclear system in the final state. The effect has been interpreted by double-Δ excitation, but conventional calculations giving a good description of inclusive data fail to reproduce the strength of the effect seen in recent exclusive data obtained at the CELSIUS/WASA Facility [3].

The meson decay program currently focusses on decays of the η-meson which is a particularly favourable case for the investigation of rare decays. Strong decays are forbidden in the lowest order and first-order electromagnetic decays are also forbidden. Thus, rare and very rare decays test fundamental symmetries. Decays that are currently being investigated are listed in table 1 together with the corresponding physics issues and the branching ratios which are partly experimental upper limits [4].

The $\eta \to 3\pi^0$ decay has been studied with the $pp \to pp\eta$ reaction. The extracted data with more than 10^5 events result in a slope parameter $\alpha =$

-0.027 ± 0.008(stat.) $\pm$ 0.005(syst.) of the efficiency-corrected radial density distribution of the Dalitz plot [5]. The result compares well with results from other groups [6]. The measurement of the slope parameter enables a sensitive test of QCD predictions. The experimental findings show a strong discrepancy in the central value of current χPT calculations (up to NNLO). However, the large uncertainty does not allow to decide the sign of the slope. For the $\eta \rightarrow \pi^+\pi^-\pi^0$ decay channel, the Dalitz plot density will depend on both the x- and y-axis variables. There is one recent precise result from KLOE with $1.3 \cdot 10^6$ events [7] in the Dalitz plot. This is an improvement of more than two orders of magnitude in the event statistics compared to all the previous measurements. The KLOE results for the Dalitz plot density cannot be reproduced by chiral perturbation theory calculations.

The $\eta \rightarrow \pi^+\pi^-\gamma$ decay is studied with the goal to test chiral QCD anomalies handled by the Wess–Zumino–Witten (WZW) Lagrangian and to search for flavour-conserving CP violation. The $\eta \rightarrow \pi^+\pi^-\gamma$ decay is of great interest, because existing results [8–10] are low statistics, not corrected for efficiency, and ambiguous in their theoretical interpretation.

The rare $\eta \rightarrow \pi^0\gamma\gamma$ decay is relevant for higher-order calculations based on chiral perturbation theory [11]. The lowest-order Lagrangian ($O(p^2)$) and the tree contributions at $O(p^4)$ are zero as neither π^0 nor η can emit a single photon. The main contribution to the decay amplitude comes from the $O(p^6)$ counter terms.

Recently, investigations addressed the $\eta \rightarrow \pi^+\pi^-e^+e^-$ decay. The branching ratio of this decay has not been measured very precisely yet [12–14] and the decay allows a test of flavour-conserving CP violation. Theoretical studies indicated [15] that the asymmetry of the dihedral angle between the electron and pion production planes is an observable representing the degree to which CP violation contributes to the decay.

The $\eta \rightarrow e^+e^-e^+e^-$ decay has been investigated with the goal to establish the branching ratio and to determine the η-transition form factor $F(q_1^2, q_2^2)$. On the same event sample as mentioned above, 15–30 event candidates are identified being consistent with the current upper limit of $< 6.9 \times 10^{-5}$ [4].

C-parity conservation forbids the $\eta \rightarrow \pi^0e^+e^-$ decay to occur as a single photon process. Thus, the decay is allowed to proceed only via higher-order processes and is highly suppressed by the Standard Model.

The dominant mechanism in the leptonic decay $\eta \rightarrow e^+e^-$, forbidden to proceed via a single-photon intermediate state, is a fourth-order electromagnetic process with two virtual photons [16,17]. A very low branching ratio of 5×10^{-9} [18,19], predicted by the Standard Model, makes the decay sensitive to contributions from non-conventional effects that would significantly increase the branching ratio.

To fully exploit the information from meson decays, the WASA experiment with simultaneous detection of charged and neutral particles combined with high luminosities at the COSY accelerator is used.

2. Experimental approach

With a circumference of 184 m, the cooler synchrotron COSY-Jülich as shown in figure 1 stores and accelerates both unpolarized and polarized proton and deuteron beams injected from the injector cyclotron JULIC after pre-acceleration up to momenta of 0.3 GeV/c for protons and 0.55 GeV/c for deuterons [20]. COSY subsequently accelerates those particles up to momenta of 3.7 GeV/c with a typical momentum spread of $\Delta p/p \approx 10^{-4}$ and an emittance of better than $\epsilon = 1\pi$mm mrad. COSY can store 10^{11} protons or deuterons and exploits electron cooling with electron energies up to 75 keV and stochastic cooling for velocities $\beta \geq 0.85$. The cooling methods enable COSY to provide high precision beams for experiments for internal and external targets. COSY is a facility with more than 300 international users. The Jülich Center for Hadron Physics (JCHP) [21] operates several experimental facilities for in-beam and external beam experiments, in cooperation with large international collaborations.

The wide angle shower apparatus (WASA), an internal 4π spectrometer (see figure 2) with large solid angle acceptance, is operated in the internal COSY beam [1]. WASA comprises an electromagnetic calorimeter, a superconducting solenoid and high granularity central and forward tracking detectors. Angular and differential energy measurements are deduced from the reconstruction of charged and neutral decay particles. The target protons and deuterons are delivered by means of a frozen pellet target system providing hydrogen or deuterium pellets with diameters of $\sim$25 μm. The pellet target system provides high density combined with high purity necessary to measure rare meson decays at high luminosity. Since 2007, the internal experiment WASA-at-COSY has been routinely operating with luminosities up to a few times $L = 10^{31}$ cm^{-2} s^{-1}. The nearly 4π acceptance of WASA allows for the measurement of exclusive final states. With the operation of WASA-at-COSY, the high-statistics studies aiming at rare decays of η and η' are effectively turning COSY into a meson factory.

At WASA-at-COSY, the two complementary reactions $pp \to pp\eta$ and $pd \to ^3$He η have been investigated for hadronic η production. They differ considerably in production cross-section and in the contribution of multi-π background, which is roughly 20 times larger for the ratio $\sigma(2\pi^0)/\sigma(\eta)$ in the pp reactions.

3. η Meson production with WASA-at-COSY

During the last two years, data sets have been collected using pp and pd interactions at COSY. The very first production run in April 2007 yielded $8 \cdot 10^5$ events for the $pp \to pp(\eta \to 6\gamma)$ reaction. In the next four week run period in October 2008, η-decays were studied using the $pd \to ^3$He η reaction at a beam energy of 1 GeV. An unbiased data sample of 1.1×10^7 η-meson decays was collected. The data sample was increased to 3×10^7 η-meson decays in an eight-week continuation in August–September 2009. In addition, a few shorter runs aiming at the optimization of η-meson production in pp interactions were also carried out.

The cross-section of the $pd \to ^3$He η reaction rises quickly and reaches a plateau value of 400 nb at 2 MeV above the production threshold. The requirement for a ^{3}He ion in the final state selects only a small fraction of about 0.1% of the total pd cross-section. The discrimination of ^{3}He against protons and deuterons is reliable and can easily be implemented on the trigger level. Trigger rates at high luminosities are well within the data acquisition capabilities without imposing additional conditions

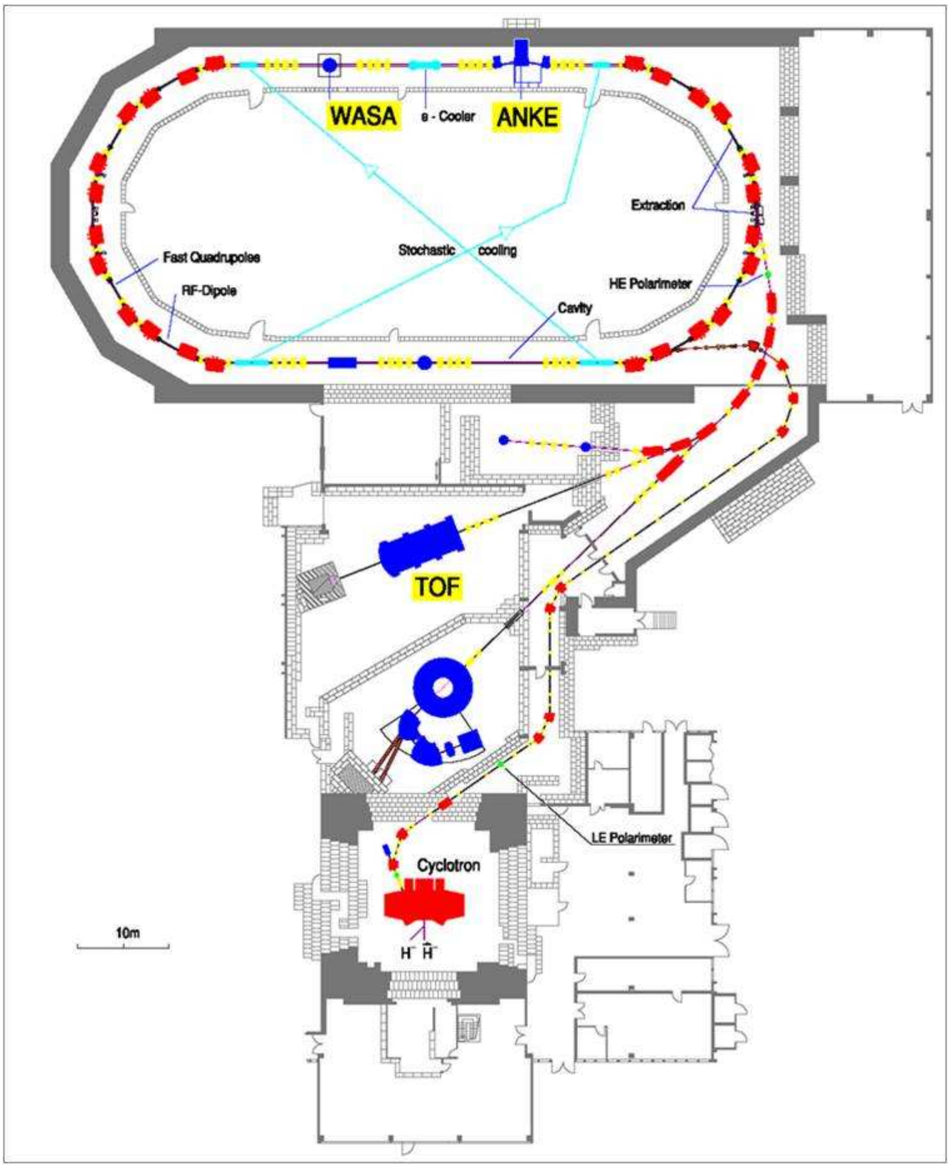

Figure 1. Floor plan of the cooler synchrotron.

on the η-decay system. The $pd \to {}^3\text{He}\ \eta$ reaction is used at a beam energy of 1.0 GeV where the ^{3}He ions can be measured in the forward detector which covers scattering angles from 3° to 18°. The left panels of figure 3 show the missing mass of the reconstructed ^{3}He for all data samples collected in the 2008 *pd* run period. In the right panel, only events correlated with a reconstructed $\eta \to \gamma\gamma$ decay are shown. Due to flux limitations from the calorimeter and mini-drift chambers, the

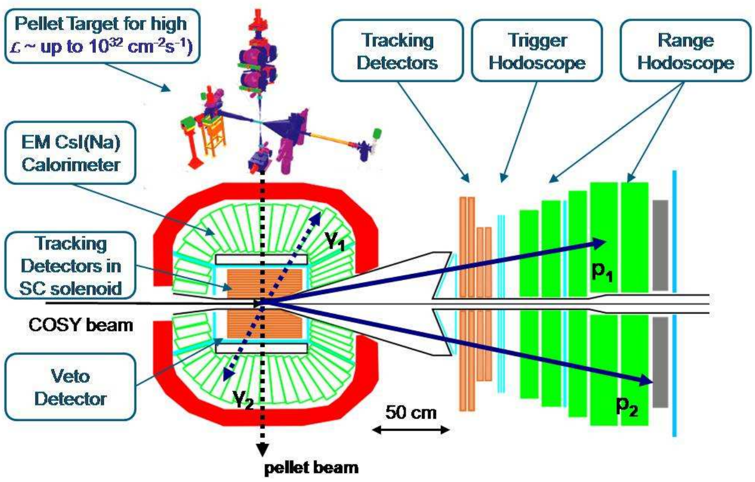

Figure 2. Schematic view of the WASA detector installed in the COSY ring.

acceptable rate of η-mesons from the $pd \to ^3$He η reaction is about 10 η events/s. This rate is sufficient for studies of not-so-rare η-decays. Further progress towards rare η decays is being made by focussing on the $pp \to pp\eta$ production reaction. The reaction has a 10–20 times larger cross-section (10 μb at 1.4 GeV) and the inclusive pp cross-section is two times lower than for pd interactions. The η-meson yield is higher for a given luminosity plus a higher luminosity of up to two times can be used. Meanwhile, the tagging of the $pp \to pp\eta$ reaction poses a challenge. This is illustrated in the right panels of figure 3 showing missing mass distributions for two reconstructed protons in the forward detector in a run at a beam energy of 1.4 GeV. The trigger condition in this case included the requirement for at least two tracks in the forward detector and at least two clusters from neutral particles in the calorimeter. The missing mass plot on the left-hand side was obtained based on the events selected by the trigger. The right figure shows the pp missing mass after the selection of the $\eta \to \gamma\gamma$ decay channel via the analysis. With the presently limited trigger selectivity, a production rate of about 100 η events/s has been achieved. Preparations for the improved trigger system are now underway.

The WASA detector has originally been optimized for the measurement of electron–positron pairs and photons from decays of π^0- and η-mesons. For studies involving dilepton production, the single Dalitz decays of mesons, like $\eta \to e^+e^-\gamma$ and $\pi^0 \to e^+e^-\gamma$, are important.

4. Dalitz decays of mesons

Dalitz decays of mesons access the electromagnetic transition form factor. In Dalitz decays, the meson decays into a photon or another meson and a lepton pair, formed by internal conversion of an intermediate virtual photon with invariant mass M. For point-like particles, the decay rate of this process as a function of M would

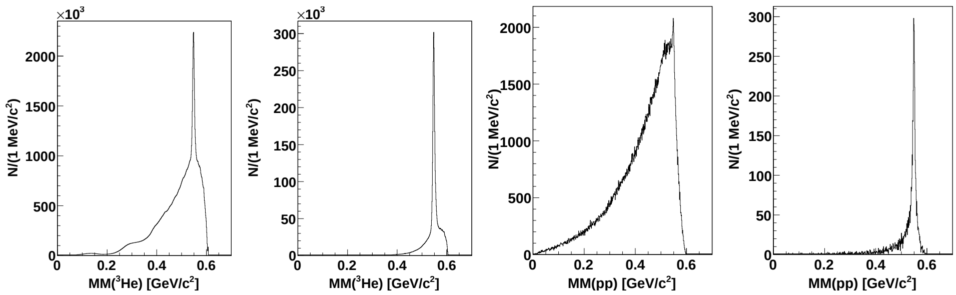

Figure 3. Left: ^{3}He missing mass distribution for the $pd \to ^3$He X reaction at 1.0 GeV. The trigger was based on a ^{3}He signature in the forward detector without bias on the meson decay system. The plot in the left panel shows all data collected in the 2008 run period with about 11×10^6 events in the peak. In the right panel, only events correlated with a reconstructed $\eta \to \gamma\gamma$ decay are shown. Right: Proton–proton missing mass distributions from the $pp \to ppX$ reaction at 1.4 GeV beam energy with a trigger requiring two tracks from charged particles in the forward detector and at least two clusters from neutral particles in the calorimeter. For the left panel, the data analysis is based on the forward detector tracks. For the right panel, events with an invariant mass of the two photons $\geq$300 MeV/c^2 are selected.

be exactly described by quantum electrodynamics (QED). The rate Γ is modified by the dynamic electromagnetic structure arising at the vertex of the transition. This modification is described by a transition form factor. Here, the interaction between photons and hadrons in the time-like region is dominant as in vector meson dominance (VMD). The form factor is experimentally accessible by comparing the dilepton invariant mass spectrum with the point-like QED prediction.

$$\frac{\mathrm{d}\Gamma_{e^+e^-\gamma}}{\mathrm{d}M^2} = \left[\frac{\mathrm{d}\Gamma_{e^+e^-\gamma}}{\mathrm{d}M^2}\right]_{\mathrm{QED}} \cdot \left|F(M^2)\right|^2 . \qquad (1)$$

The form factor can be parametrized with a pole approximation (Λ) (or with the mass of a vector meson (m_{V}))

$$\left|F(M^2)\right| = \frac{1}{1-(M^2/\Lambda^2)} \left(= \frac{1}{1-(M^2/m_V^2)}\right) . \qquad (2)$$

Until recently, the world data set could be found in Landsberg's 1985 report [16]. Λ^{-2} has been found to be (1.9 ± 0.4) GeV^{-2} for the η-meson decay. Within the large error, the value is compatible with VMD, i.e. a vector meson mass close to the mass of the ρ-meson (0.77 GeV/c^2). The value of $\Lambda^{-2} = (2.36 \pm 0.21)$ GeV^{-2} for the ω-meson exceeds the VMD expectation (1.69 GeV^{-2}) by three standard deviations. This discrepancy is statistically significant and has not been clarified yet. Recent results, coming from measuring dimuon pairs with the heavy ion experiment NA60 [22], confirm the older data. However, additional assumptions enter in the analysis in order to extract the information from 158 A GeV In–In collisions, exploiting the nearly pp-like peripheral rather than the more central interactions.

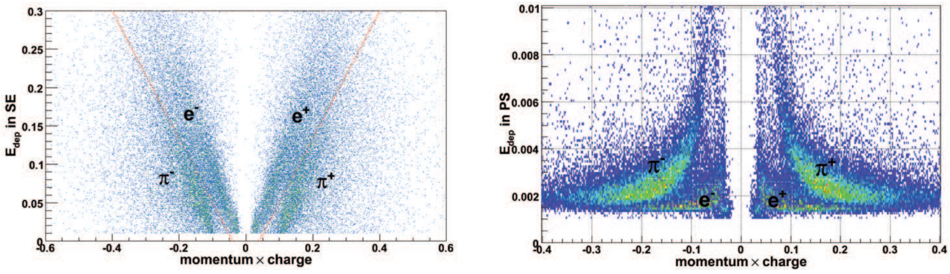

Figure 4. Charged particle identification with the WASA central detector (simulation).

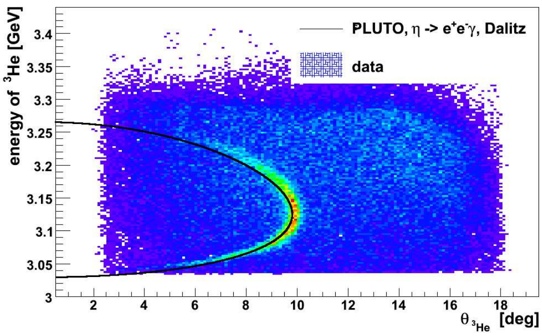

Figure 5. $pd \rightarrow {}^3$He $\eta \rightarrow {}^3$He $e^+e^-\gamma$ event candidates in the WASA forward detector (beam energy = 1 GeV).

On the theoretical side, a new counting scheme for the theory of pseudoscalar and vector mesons has recently been introduced to go beyond VMD in a systematic way [23]. Next-to-leading order calculations for the ω-transition form factor are expected.

Before investigating the ω-decays, it is relevant to study the η-Dalitz decay by measuring electron–positron pairs in elementary reactions. With WASA-at-COSY, the decays have been observed both in *pp* and *pd* interactions. The combined *pd* and *pp* data runs should contain a few thousand $\eta \rightarrow e^+e^-\gamma$ events. The difficulty in selecting decay candidates is the identification of electrons and positrons and the discrimination against the dominant pion background. e^+e^- candidates are selected by using the reconstructed momentum and charge state of the particle from the tracking information. Figure 4 shows the principle with simulated events. Figure 5 demonstrates the quality of the data for events coming from the reaction 1 GeV $pd \rightarrow {}^3$He η where $e^+e^-\gamma$ candidates have been selected. The plot compares the energy of the ^{3}He candidates vs. the scattering angle with the kinematic expectation (solid line). The signature of the two-body reaction ^{3}He + η is clearly visible.

Using the information of the detected ^{3}He particle, the missing meson mass is reconstructed. Figure 6 shows simulations of the situation for *pd* (top) and *pp* (bottom) reactions. The signal and background contributions are shown individually

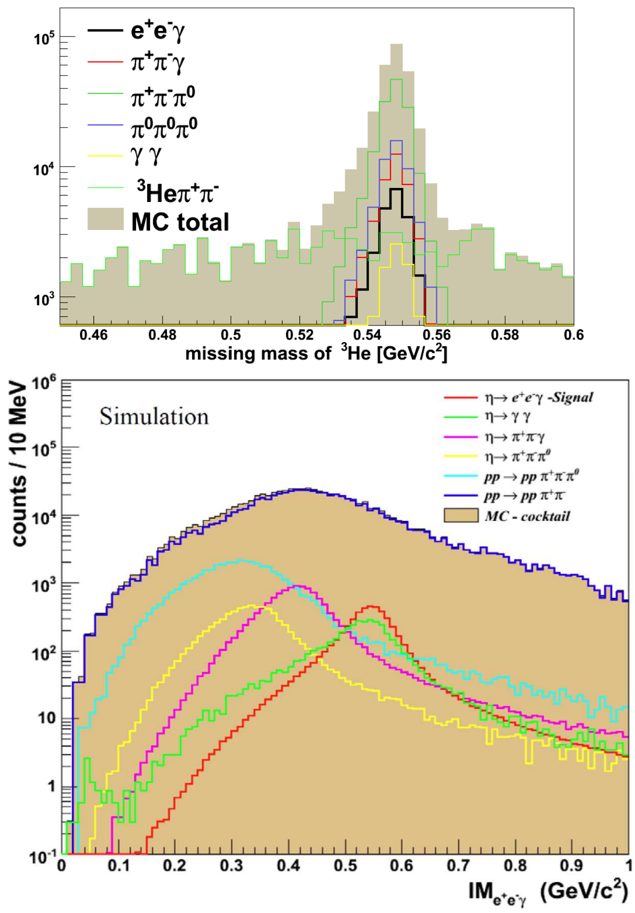

Figure 6. Simulated cocktail plots for the missing meson mass for *pd* (top) and *pp* (bottom) reactions. The signal and background contributions are shown individually and summed up to the total.

and summed up to the total. Background contributions stem from other decays of the η-meson as well as from direct multi-pion production. The figure demonstrates that the background situation is predicted to be more severe for the *pp* case.

5. Summary

The WASA-at-COSY Facility has taken valuable data on several key aspects of the physics program. Here, η decays offer the opportunity to study the effects of chiral dynamics and symmetry breaking patterns in the low-energy regime of QCD. A combined sample of 3×10^7 η-mesons (unbiased) has been produced in $pd \rightarrow {}^3\text{He}\ X$

reactions. A large sample of η decays in $pp \to pp\eta$ at limited luminosity has been collected. Further beam times as well as corresponding publications are underway.

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