

Electromagnetic Transition Form Factors of Light Mesons

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Electromagnetic transition form factors provide basic knowledge of the structure of hadrons and address the validity of vector meson dominance. Transition form factors are of renewed interest due to the impact on the interpretation of the $g-2$ measurements.

1. Introduction

Reactions of hadrons with virtual photons can be studied with conversion decays of mesons which involve virtual photons in the final state, resulting in dilepton pairs. Decays like $A \rightarrow Bl^+l^-$ are also referred to as Dalitz decays. The study of conversion decays provides information on the intrinsic structure of hadrons via the form factor of the transition $A \rightarrow B$. The electromagnetic transition form factor is time-like and determined from the momentum transfer which is the squared momentum of the dilepton pair. In particular, the assumption of vector meson dominance (VMD), a virtual photon coupling to an intermediate vector meson due to having the same quantum numbers, can be tested. In the present studies, the decaying meson can be a pseudoscalar meson decaying into two photons, $P \rightarrow \gamma^{(*)}\gamma^*$, or a vector meson decaying into a pseudoscalar meson and a virtual photon $V \rightarrow P\gamma^*$ [1].

For a good overview of the interactions of light mesons with photons, see S. Leupold in [2]. Apart from being part of the fundamental properties of hadrons, transition form factors of pseudoscalar mesons also play a role as background in the search for physics beyond the standard model, e.g. the rare decay $\pi^0 \rightarrow e^+e^-$ [3]. Transition form factors of the light pseudoscalar mesons (P) are important in improving the theoretical uncertainty of the hadronic contribution from light-by-light scattering to the anomalous magnetic moment of the muon [4, 5]. Here, the light mesons and, formidably, the process $\pi \rightarrow \gamma^*\gamma^*$ is of particular significance in light-by-light scattering [6]. The desired information has to be deduced from data on decays $P \rightarrow \gamma l^+l^-$ as long as precise data on the double Dalitz decays, $P \rightarrow l^+l^-l^+l^-$, are unavailable.

A puzzle is presented by the ω meson decay where a discrepancy between the available predictions for the form factor of the ω meson and the experimental data close to the kinematic limit has been claimed [7]. However, this conclusion is contradicted by the $\omega - \pi$ form factor extracted from the cross section of $e^+ + e^- \rightarrow \omega\pi^0$ which can be described by vector meson dominance models [8]. This situation has not yet been experimentally resolved [9].

1.1 From Conversion Decays to Transition Form Factors

The decay of the virtual photon into a dilepton pair is merely determined by Quantum Electrodynamics. The decay rate of the Dalitz decay depends on the emission of the virtual photon and is affected by the form factor $F(q)$. The two processes factorize and the decay rate is

$$\frac{d\Gamma(A \rightarrow Bl^+l^-)}{dq \Gamma(A \rightarrow B\gamma)} = |F_{A \rightarrow B}(q)|^2 \cdot \left[\frac{d\Gamma(A \rightarrow Bl^+l^-)}{dq} \right]_{|QED|}$$

with the momentum transfer $q = m_{l^+l^-}$. The form factor can be fitted by a single pole approximation

$$F_{AB}(q) = [1 - q^2/\Lambda^2]^{-1}$$

where Λ would be the $\rho(770)$ meson mass for the model called standard vector meson dominance. In the case of a vector meson, the form factor relates to the size of the transition region, influenced by the coupling of the decaying vector meson to the outgoing pseudoscalar meson. In the case of a pseudoscalar meson decay, the form factor reveals the size of the decaying meson itself [1].

Experimentally, the form factor is accessed by dividing the experimental invariant mass distribution by the basic distribution according to Quantum Electrodynamics, assuming a point-like object.

$$|F(q)|^2 = \frac{d\Gamma}{dq} / \left[\frac{d\Gamma}{dq} \right]_{QED}$$

2. Experimental Approach

The preliminary experimental results presented here stem from the two concluded experiments WASA at COSY, Juelich, and CLAS6 at Jefferson Lab. The WASA (Wide Angle Shower Apparatus) detector was an internal fixed target experiment at the COSY (Cooler Synchrotron) accelerator, consisting a forward and a central detector system. The experiment described here used a 1.4 GeV proton beam and a hydrogen pellet target to produce η mesons. A detailed description of the experiment can be found in [10]. At Jefferson Lab, an energy-tagged photon beam, produced in Bremsstrahlung with 5.7 GeV electrons from the Continuous Electron Beam Accelerator Facility (CEBAF), was used for the CLAS6 (CEBAF Large Acceptance Spectrometer) experimental run called g12. The g12 run was a photoproduction experiment employing a 40cm long LH₂ target and covered the reactions $\gamma + p \rightarrow p + X$ with mesons ranging from π^0 to ϕ . The operation of the Cerenkov detector enabled an efficient suppression of charged pion background to dilepton measurement. A detailed description of the experiment can be found in [11].

Major background contributions to dilepton measurements come from other meson production channels as well as external conversion of photons in experiment materials. In-peak background stems from competing meson decays.

3. Conversion Decays of η Mesons

3.1 Conversion Decay $\eta \rightarrow \gamma e^+ e^-$

The Dalitz decay $\eta \rightarrow \gamma l^+ l^-$ has been studied in the decays into muons as well as electron-positron pairs [7, 9]. The values obtained for the slope parameter Λ^{-2} of the transition form factor of the η meson range are $1.934 \pm 0.067_{stat.} \pm 0.050_{syst.} \text{ GeV}^{-2}$ and $(1.97 \pm 0.11_{tot} \text{ GeV}^{-2}$, in good agreement with previous measurement and with recent theoretical calculations [12–15]. Further results are becoming available from WASA-at-COSY [16, 17]. A preliminary $\eta - \gamma$ transition form factor for the η meson from a WASA $p + p$ data set taken in 2012 presented in [16] is in good agreement with previous results. The missing mass distribution deduced by detecting the two outgoing protons for $\eta \rightarrow \gamma e^+ e^-$ event candidates from a WASA $p + p$ data set taken in 2010 is shown in [17]. The background subtracted η meson peak harbors 30000 $\eta \rightarrow \gamma e^+ e^-$ event candidates. The still inherent in-peak background stems from competing η decays and is estimated to be smaller than 20%.

3.2 Status Analysis $\eta \rightarrow e^+ e^- e^+ e^-$

Another analysis looks at the double Dalitz decay $\eta \rightarrow e^+ e^- e^+ e^-$, from the WASA $p + p$ data set taken in 2010. Fig.1 shows the missing mass distribution reconstructed from the two outgoing protons for $\eta \rightarrow e^+ e^- e^+ e^-$ event candidates. The legend indicates the data points as well as the signal

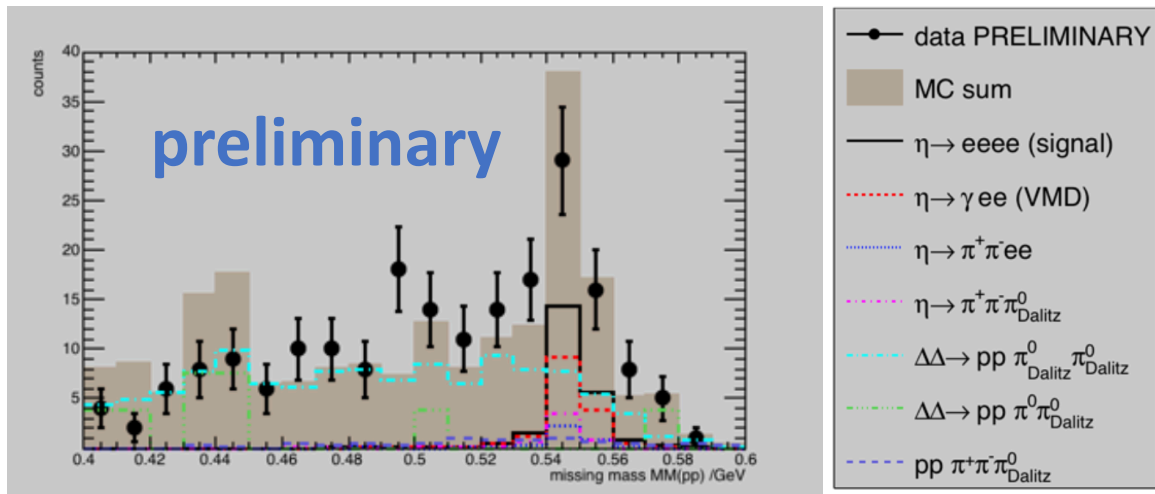


Fig. 1. The plot shows the missing mass distribution deduced by detecting the two outgoing protons from a WASA $p + p$ data set taken in 2010, see text.

and relevant background channels, simulated with Monte Carlo simulations, based on GEANT3 [18] and the event generator PLUTO [19]. The present statistics, based on circa half of the available data, is not sufficient to study two-dimensional momentum transfer distributions and to determine a doubly virtual form factor. The branching ratio has been determined by the KLOE collaboration to be $(2.4 \pm 0.2 \pm 0.1)$, based on 362 event [20].

4. Preliminary Look at the $\omega - \pi^0$ Transition Form Factor

The left panel of Fig. 2 shows the preliminary dilepton mass distribution of the $\omega \rightarrow \pi^0 e^+ e^-$

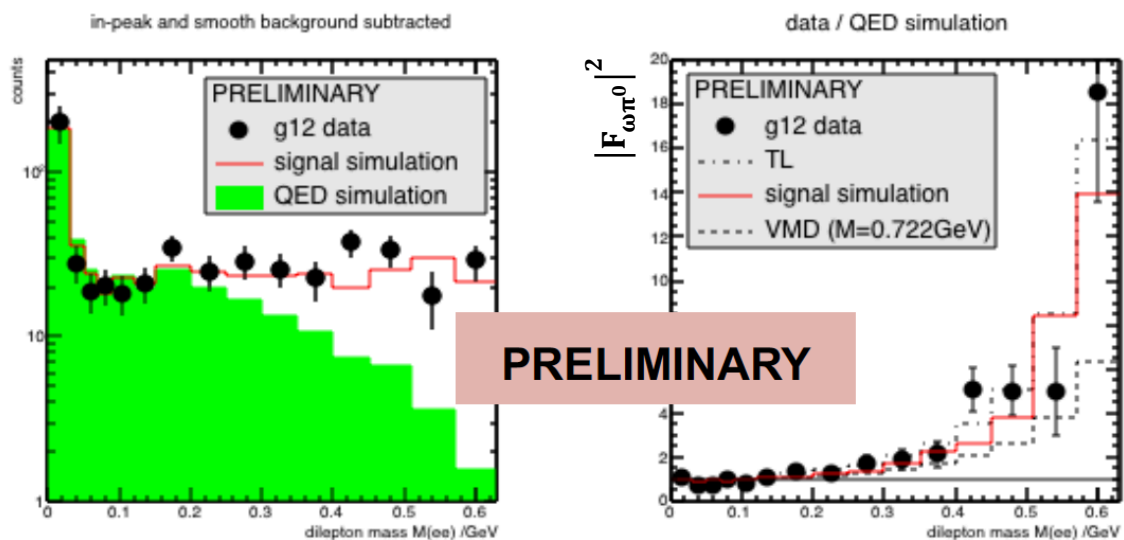


Fig. 2. Preliminary results for the $\omega - \pi^0$ transition form factor, see text.

event candidates, from the CLAS g12 experimental run along with a signal simulation (red solid line) and the simulated distribution from Quantum Electrodynamics (green shaded histogram). The background from other meson production channels and the simulated in-peak background have been subtracted from the data. A Monte Carlo signal simulation, based on GEANT3 [18] and a vector meson dominance model implemented as default in the event generator PLUTO [19] is shown as red solid line. The right panel presents the preliminary $\omega - \pi^0$ transition form factor

$$|F(q^2)|^2 = \frac{d\Gamma}{dq^2} / \left[\frac{d\Gamma}{dq^2} \right]_{|QED|}$$

as a function of the dilepton mass. As an example of modern calculations, the dashed-dotted line represents the extended VMD approach from [21]. The present analysis is in agreement with the findings of [9] and the result appears to fall between the two VMD models. Similarly, this preliminary result does not provide sufficient precision at the large masses to solve the puzzle of the $\omega - \pi$ transition form factor exceeding the VMD expectations when extracted from the ω decay.

5. Summary and Outlook

The preliminary results coming up from the experiments CLAS g12 and WASA-at-COSY show interesting results albeit with small statistics. The analyses have been based on cuts and performed under the condition that the exact event topology is found. A re-analysis of the data sets is focused on improving the significance by allowing higher particle multiplicities and employing a kinematic fit, in avoidance of the restrictions of a cut-based analysis. The investigations of higher particle multiplicities is independently necessary to gauge possible combinatoric background. Next generation measurements are ongoing with the upgraded CLAS12 experiment at Jefferson Lab and will include the η' decays. Exploitation of a further WASA-at-COSY data set, kinematically tuned to the exclusive production π^0 mesons, is underway. The hope is to get good statistics for the doubly virtual decay $\pi^0 \rightarrow \gamma^* \gamma^*$.

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