Physics Letters B 677 (2009) 260–266

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Study of the electromagnetic transition form-factors in $\eta \to \mu^+\mu^-\gamma$ and $\omega \to \mu^+\mu^-\pi^0$ decays with NA60

NA60 Collaboration

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ARTICLE INFO

Article history:
Received 15 February 2009
Received in revised form 29 April 2009
Accepted 16 May 2009
Available online 20 May 2009
Editor: V. Metag

PACS:
13.85.Qk
13.40.Gp
13.20.-v

Keywords:
Lepton pairs
Transition form factor
Conversion decays

ABSTRACT

The NA60 experiment at the CERN SPS has studied low-mass muon pairs in 158*A* GeV In–In collisions. The mass and p_T spectra associated with peripheral collisions can quantitatively be described by the known neutral meson decays. The high data quality has allowed to remeasure the electromagnetic transition form factors of the Dalitz decays $\eta \to \mu^+\mu^-\gamma$ and $\omega \to \mu^+\mu^-\pi^0$. Using the usual pole approximation $F = (1 - M^2/\Lambda^2)^{-1}$ for the form factors, we find Λ^{-2} (in GeV^{-2}) to be $1.95 \pm 0.17(\text{stat.}) \pm 0.05(\text{syst.})$ for the η and $2.24 \pm 0.06(\text{stat.}) \pm 0.02(\text{syst.})$ for the ω. While the values agree with previous results from the Lepton-G experiment, the errors are greatly improved, confirming now on the level of 10σ the strong enhancement of the ω form factor beyond the expectation from vector meson dominance. An improved value of the branching ratio $\text{BR}(\omega \to \mu^+\mu^-\pi^0) = [1.73 \pm 0.25(\text{stat.}) \pm 0.14(\text{syst.})] \times 10^{-4}$ has been obtained as a byproduct.

1. Introduction

The standard electromagnetic decay modes of light unflavored mesons ($S = C = B = 0$) include the so-called Dalitz decays $A \to Bl^+l^-$. Here, the meson A decays into an object B (a photon or another meson) and a lepton pair, formed by internal conversion of an intermediate virtual photon with invariant mass M. Assuming

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2009.05.029

point-like particles, the decay rate of this process vs. M can exactly be described by QED [1]. However, the rate is strongly modified by the dynamic electromagnetic structure arising at the vertex of the transition $A \to B$. This modification is formally described by a (multiplicative) *transition form factor* $|F_{AB}(M)|^2$. A major element governing $|F_{AB}|^2$ is the resonance interaction between photons and hadrons in the time-like region, commonly referred to as vector meson dominance (VMD). Experimentally, $|F_{AB}(M)|^2$ is directly accessible by comparing the measured invariant mass spectrum of the lepton pairs from Dalitz decays with the point-like QED prediction. A comprehensive review of the topic is contained in [2].

The physics interest in studying Dalitz decays and the associated transition form factors is twofold. First, the electromagnetic interaction continues to be an extremely useful tool to gain deeper insight into meson structure, while the role of the resonance interaction in this context is far from being quantitatively settled. Because the experiments are very difficult, the quality of the existing data is generally poor. Second, and related to the last point, the study of *direct* production of dileptons in high-energy nuclear collisions in the context of thermal radiation requires a precise and complete knowledge of the characteristics and the relative weights for the existing decay channels, and this is universally true at all facilities where such studies are ongoing (SIS, SPS, RHIC, and FAIR in the future). Disregarding the case of the π^0, the major two Dalitz decays contributing to the mass range $M > 0.2$ GeV are those of the $\eta(548)$ and the $\omega(782)$. For the dielectron channel, the existing results on $|F|^2$ for the η [3] and ω [4] are not accurate enough for meaningful physics conclusions. For the dimuon channel, however, significant results on $|F|^2$ have been obtained by the Lepton-G experiment, both for $\eta \to \mu^+\mu^-\gamma$ [5] and for $\omega \to \mu^+\mu^-\pi^0$ [6]. Using the usual pole approximation [2]

$$|F|^2 = \left(1 - M^2/\Lambda^2\right)^{-2} \tag{1}$$

for the form factors, Λ^{-2} has been found to be 1.9 ± 0.4 GeV^{-2} for the η and 2.36 ± 0.21 GeV^{-2} for the ω. While the value for the η is compatible with VMD within its large error, the value for the ω exceeds that expected from VMD (1.69 GeV^{-2}) by 3 standard deviations. This discrepancy, statistically significant, has remained unexplained up to today. Numerically, the associated enhancement of the mass-differential decay rate relative to that for VMD amounts to about one order of magnitude at $M = 0.6$ GeV, i.e. close to the kinematic limit of $M_\omega - M_{\pi^0} = 0.648$ GeV, with corresponding consequences for values and systematic errors of the yield of excess dileptons observed in this mass region [7–11].

In this Letter, we present new results on the transition form factors of the Dalitz decays $\eta \to \mu^+\mu^-\gamma$ and $\omega \to \mu^+\mu^-\pi^0$. They have been obtained as a byproduct of the ongoing analysis of low-mass dimuon production in 158A GeV In–In collisions, exploiting here the nearly *pp*-like peripheral rather than the more central interactions associated with excess dileptons [8–10]. The high data quality has enabled us to greatly improve the accuracy of the form factor measurements as compared to the Lepton-G experiment.

2. Experiment

The NA60 experiment at the CERN SPS is described in detail in [12]. In short, the apparatus complements the muon spectrometer previously used by NA50 with a high-granularity radiation-hard silicon pixel telescope, placed inside a 2.5 T dipole magnet. The telescope tracks all charged particles upstream of the hadron absorber and determines their momenta independently of the muon spectrometer. The matching of the muon tracks before and after the absorber, both in *coordinate and momentum space*, strongly improves the dimuon mass resolution in the low-mass region and reduces the combinatorial background due to π and K decays. The additional bend by the dipole field greatly improves the opposite-sign dimuon acceptance at low masses and low transverse momenta. The rapidity coverage is $0.3 < y_{cm} < 1.3$ in this region. The selective dimuon trigger and the radiation-hard vertex tracker with its high read-out speed allow the experiment to run at very high rates for extended periods, leading to an unprecedented level of statistics for low-mass lepton pairs.

3. Analysis procedure

The results reported in this Letter were obtained from the analysis of data taken in 2003 for 158A GeV In–In collisions. The analysis procedure is also described in detail in [12]. The essential steps of the data reconstruction concern the tracking in the two spectrometers, vertex finding, and matching of the tracks. Matching is done by selecting those associations between the muon- and pixel-spectrometer tracks which give the smallest weighted squared distance (*matching* χ^2) between the two tracks, in the space of angles and inverse momenta, taking into account their error matrix [12]. The combinatorial background of uncorrelated muon pairs originating from π and K decays is determined by a *mixed-event technique*. After subtraction of the combinatorial background, the remaining opposite-sign pairs still contain "signal" fake matches (associations of genuine muons to non-muon vertex tracks). These have a shape of the matching χ^2 distributions different from those of the true matches. They are determined either by an overlay Monte Carlo method (used here) or by event mixing [12], with identical results, and are then also statistically subtracted from the data. The collision centrality of the events is defined through the total charged-particle rapidity density as measured by the silicon pixel telescope.

For the purpose of this Letter, solely peripheral In–In collisions are considered. To keep sufficient events, they are selected through the cut in multiplicity density $4 < dN_{ch}/d\eta < 30$, with an average multiplicity density $\langle dN_{ch}/d\eta\rangle = 17$. The raw opposite-sign, background and signal dimuon mass spectra for this peripheral selection are shown in Fig. 1. After subtracting the relatively small contributions from combinatorial background and signal fake matches, the resulting net spectrum contains about 26 000 muon pairs in the mass range 0.2–1.4 GeV. The average signal-to-background ratio is $\sim$2.5 in the mass region $<$0.65 GeV. Although the relative uncertainties of the combinatorial background are $\sim$4% for the peripheral selection (larger than the 1% achieved for more central collisions [12]), the resulting systematic errors of the net data are still on the level of only about 1.5%. The vector mesons ω and ϕ are completely resolved; even the rare two-body decay $\eta \to \mu^+\mu^-$ is seen. The mass resolution of the ω is 20 MeV.

As shown in our previous analysis [13], the peripheral data can fully be described by the expected electromagnetic decays of the neutral mesons. In the procedure used then and updated now, muon pair production from the 2-body decays of the η, ρ, ω and ϕ resonances and the Dalitz decays of the η, η' and ω is simulated using the improved hadron decay generator GENESIS [14, 15], while GEANT is used for transport through the acceptance of the NA60 apparatus, including the effects of the dimuon trigger. The Monte Carlo data are overlaid onto real data and then reconstructed in the same way as the latter, to take account of the pair reconstruction efficiency. The data are fit with this "decay cocktail" of sources, using the production cross section ratios η/ω, ρ/ω, ϕ/ω and the level of dimuons from charm ($D\bar{D}$) decays as free parameters; the ratio η'/ω is kept fixed at 0.12 [15, 18]. The branching ratios of the different decays are taken from the PDG [19], and the transition form factors of the three Dalitz decays are those measured by Lepton-G [2,5,6] (which is also the