Meson transition form factor measurements with A2

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Abstract. Meson transition form factors (TFF) describe the electromagnetic structure of mesons and hence provide an important tool for the understanding of the meson-photon interactions. The A2 experiment at MAMI provides a high yield of light mesons produced in photo-induced reactions on protons, which makes the experiment ideal for precision measurements of meson TFFs via studies of meson decays. The A2 collaboration has recently published results of TFFs obtained from measurements of Dalitz decays of the π^0 and η mesons as well as the $\omega \to \pi^0 e^+ e^-$ decay. For the study of the η' Dalitz decay, data has been collected and is being analysed. As a ongoing endeavour, A2 is performing a dedicated measurement of the π^0 TFF with statistics increased by several factors compared to the previous A2 result.

1 Introduction

In the low energy regime of QCD, perturbative approaches are not usable and one instead relies on models and effective field theories to describe the interactions and properties of hadrons. One such property is the meson transition form factor (TFF), which describes the dynamic of the transition between photons and mesons and hence provides an important probe of the intrinsic structure of mesons [1]. High statistics measurements of TFFs also play a role for the precision frontier of the Standard Model (SM). In the case of the anomalous magnetic moment of the muon, a_μ, there is currently a highly intriguing 3-4σ discrepancy between the direct measurement, a_μ^{exp}, [2] and SM calculations, a_μ^{SM}, [3]. With even more precise measurements of a_μ^{exp} underway and planned [4, 5] a huge effort has been made on the theory side to further increase the accuracy of a_μ^{SM}. The largest uncertainty comes from the strong sector, which consists of contributions from the hadronic vacuum polarisation (hVP), a_μ^{hVP}, and the hadronic light-by-light interaction (hLbL), a_μ^{hLbL}. The meson TFFs plays a vital role in the latter component, where the largest individual contribution to the uncertainty comes from the pseudoscalar pole term, in which a pseudoscalar meson couples to two photons.

The A2 experiment contributes to the measurements of the meson TFFs through studies of decays of mesons. Presented in this article are three pseudoscalar Dalitz decay studies, $P \to \gamma e^+ e^-$, where one of the photons coupling to the meson is on-shell and the other has a virtuality accessible by measuring m_{ee}. Additionally, also one vector to pseudoscalar transition, $V \to P e^+ e^-$, is presented, where the both photons are virtual, but one has a virtuality fixed to m_V. The TFF is accessed by studying the differential decay rate normalised to the

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on-shell decay rate

$$\frac{d\Gamma(A \to Be^+e^-)}{dm_{ee}\Gamma(A \to B\gamma)} = [\text{QED}] \left| \frac{\mathcal{F}_{AB}(m_{ee})}{\mathcal{F}_{AB}(0)} \right|^2 = [\text{QED}] \left| F_{AB}(m_{ee}) \right|^2 , \tag{1}$$

where A is the decaying meson and B is either a photon in case of Dalitz decay or the pseudoscalar meson in case of the $V - P$ decay. The left hand part of equation (1) can be provided by experimental measurements. By dividing with the QED calculation, which gives the point-like process, a distribution determined solely by the TFF, $|F_{AB}(m_{ee})|^2$, is accessed. A straight forward way of comparing different distributions is to use a Vector Meson Dominance inspired one-pole approximation,

$$F(m_{ee}) \overset{q^2<\Lambda}{\approx} 1 + \frac{m_{ee}}{\Lambda^2}, \tag{2}$$

where Λ, representing the pole mass, becomes the slope parameter, Λ^{-2}, which can be compared to results from different experimental and theoretical distributions.

2 The A2 experiment

A2 is a fixed target setup using a photon beam, which emanates from the brehmstrahlung process of a mono-energetic electron beam, delivered by the Mainzer Microtron (MAMI) [6, 7], impinging on a thin radiator. MAMI can deliver a beam energy up to 1604 MeV and the resulting energy distribution of the photon beam covers the production region of several of the lighter mesons. The scattered beam electrons are diverted and tagged for an energy measurement of the photon beam. Using the Glasgow photon tagger [8] the accessible energy range is $E_\gamma \in 5$ - 93 % of E_{MAMI}, which covers the photoproduction region of π^0, η and ω. By instead using the End Point Tagger [9] , even higher photon energies, $E_\gamma \in 89$ - 98 % of E_{MAMI}, are accessible allowing access to the photoproduction region of the η' meson as well.

The photon beam is collimated before reaching the target, situated in the middle of the Crystal Ball setup, see [10] and references therein. For the studies presented here, a 5 or 10 cm long liquid hydrogen target was used. The interaction point is surrounded by a particle identification detector (PID), consisting of 24 parallel thin scintillator bars, and two multi-wire proportional chambers (MWPC). Both can be used for charged particle detection and tracking. The surrounding Crystal Ball (CB) calorimeter consists of 672 NaI(Tl) crystals arranged into two hemispheres allowing for a 93% solid angle coverage. The TAPS calorimeter is installed 1.5 m downstream of the target and covers the forward angles of 2-20°. It is constructed as a wall consisting of 366 hexagonal BaF_2 crystals and the two inner rings closest to the beam line consists of 72 $PbWO_4$ crystals. Particle identification in TAPS is possible with either the time-of-flight method, a pulse shape analysis of the output of the BaF_2 crystals or the Veto wall, consisting of 384 thin plastic scintillators situated in front of TAPS.

3 Meson TFF studies at A2

3.1 $\pi^0 \to e^+e^-\gamma$

With π^0 being the lightest of the pseudoscalar mesons, this form factor is the most important contribution to the calculation of a_μ^{hLbL}, since the pole terms mentioned in Sect. 1 scales inversely with mass. Additionally, this form factor is also needed for precise calculations of the rare decay $\pi^0 \to e^+e^-$ [11]. The precision of the form factor slope given by the PDG [12] is dominantly relying on a model dependent extrapolation from a space like measurement done by CELLO [13]. However, two high statistics results on direct time-like measurements from A2 [14] and NA62 [15] were recently published. Additionally, A2 has collected data to further increase the statistics compared to previously published results.

The published A2 result consists of $4 \cdot 10^5$ $\pi^0 \to e^+e^-\gamma$ events from two separate data sets. The photon beam energy used for producing the π^0 lies in the $\Delta^+(1230)$ region. Only a small amount background channels must be suppressed in the analysis. The kinematic fit procedure is used to select the signal events and to improve the final state kinematics. The resulting form factor slopes are extracted using a QED calculation that includes radiative corrections [16]. The error in each m_{ee} data point is dominated by statistics. The resulting slope parameter is $a_\pi = m^2_{\pi^0}\Lambda^{-2} = 0.030 \pm 0.010_{tot}$, which is in agreement with other experimental results and predictions made from theoretical calculations.

With the considerable increase in statistics of the π^0 Dalitz decay compared to the previous data, the new A2 data set will significantly improve the precision of direct time-like measurements of the $|F_{\pi^0}(m_{ee})|^2$.

3.2 $\eta \to e^+e^-\gamma$

The time-like TFF from η Dalitz decays, $F_\eta(m_{ee})$, is the most investigated one among the light mesons. A2 alone has produced several experimental results [17–19] in addition to the results by NA60 [20, 21].

The latest A2 result is based on two separate data sets, collected in 2007 and 2009. The kinematic fit procedure is used to select signal events and improve the final state kinematics. A cut based analysis of the cluster shapes in the calorimeter allows for a reduction of background containing charged pions, e.g. $\eta \to \gamma\pi^+\pi^-$ and $\eta \to \pi^+\pi^-\pi^0$. The analysis yields $5.4 \cdot 10^4$ $\eta \to e^+e^-\gamma$ events, which is used to produce the resulting form factor distribution. The slope parameter, extracted by fitting Eq. (2) to the combined data points, is $\Lambda_\eta^{-2} = (1.97 \pm 0.11_{tot})\,\mathrm{GeV}^2$. In Ref. [19], the data points are available with their respective total errors.

3.3 $\eta' \to e^+e^-\gamma$

The phase space available in the η' decay allows access to the pole region of the ω and ρ resonances and can therefore provide a clearer picture of the role of the vector mesons in the process of radiative decays of pseudoscalar mesons.

A2 performed an η'-campaign in 2014 after the installation of the EPT. 10 weeks of beamtime resulted in a data set containing more than 6 million η' events [22]. One of the goals of this campaign is the dedicated study of $\eta' \to e^+e^-\gamma$ aiming at the extraction of the $|F_{\eta'}(m_{ee})|^2$. Only two previous measurements are published, one by Lepton-G [23, 24] and one more recent from BESIII [25]. The analysis of the A2 data is still ongoing, but the projected statistics suggests an improved coverage of the vector meson pole region compared to previous measurements.

3.4 $\omega \to e^+e^-\pi^0$

Previous measurements of $|F_{\omega\pi^0}(m_{ee})|^2$ from Lepton-G [26] and NA60 [20, 21] revealed an interesting deviation from theory in the higher region of $m_{\ell\ell}$. Not only the well established Vector Meson Dominance model failed to describe the data, but also more recent theoretical predictions are unable to correctly predict the high $m_{\ell\ell}$-region, see Ref. [19] and references therein.

The A2 result is based on the same data sets used for the η analysis and the final event selection contains $1.1 \cdot 10^3$ $\omega \to e^+e^-\pi^0$ [19]. The data points for $|F_{\omega\pi^0}(m_{ee})|^2$, extracted from the combined result of both data sets, are provided with their total uncertainties. The slope parameter, given by a fit of Eq. (2) to these data points, is $\Lambda^{-2}_{\omega\pi^0} = (1.99 \pm 0.21_{tot})$ GeV^2. The A2 result agrees within the uncertainties with both the previous measurements and the theoretical predictions. However, the A2 data points are systematically closer to the theoretical predictions of the slope.

4 Summary and outlook

With the high production yield of light mesons, the A2 experimental setup is ideal for precision studies of meson decays. Measurements of the Dalitz decays of π^0, η and η' as well as the $\omega \to \pi^0e^+e^-$ process allow access to the pseudoscalar meson transition form factors. The A2 collaboration has published results on measurements of $|F_{\pi^0}(m_{ee})|^2$, $|F_\eta(m_{ee})|^2$ and $|F_{\omega\pi^0}(m_{ee})|^2$. A large data set has been collected and is currently analysed to provide a measurement of $|F_{\eta'}(m_{ee})|^2$, which is expected to cover the pole region of the ρ and ω mesons. Additionally, a new and larger data set of π^0 mesons has been collected, where the $\pi^0 \to e^+e^-\gamma$ process will be used to extract a $|F_{\pi^0}(m_{ee})|^2$ with world leading accuracy.

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