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EFFECTIVE LAGRANGIAN MODEL CALCULATION OF DILEPTON PRODUCTION IN $\pi + N$ COLLISIONS*

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We present an effective Lagrangian model calculation of the process $\pi N \to N e^+ e^-$. We discuss in some detail the description of electromagnetic interaction of hadrons using a variant of the vector meson dominance model, and the problem of gauge-invariance preserving form factors for Born contributions.

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1. Introduction

Dileptons are electron–positron (or muon–antimuon) pairs. In hadronic and nuclear collisions, dileptons usually originate from the decay of a virtual photon. Neutral vector mesons (ρ^0, ω, and ϕ) have the same quantum numbers as the photon, therefore, they can directly decay to a dilepton. According to the vector meson dominance model, this decay proceeds through a conversion to a virtual photon.

Dileptons receive special attention in the study of heavy ion collisions. This is because leptons do not participate in the strong interaction, therefore, they leave the interaction volume undisturbed, carrying information from the dense phase of the collision. In particular, the invariant mass of dileptons gives the mass of the decaying virtual photon or vector meson. Thus, the in-medium spectral function of vector mesons can be studied via the dilepton invariant mass spectrum.

Many different channels contribute to the dilepton spectrum of hadronic or heavy ion collisions (*e.g.* pion annihilation, Bremsstrahlung, Dalitz-decay of meson or baryon resonances) making it difficult to identify vector mesons in the dilepton spectrum. Theoretical models should deal with all possible reaction channels.

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In the study of dilepton production in nucleon–nucleon collisions, we have learnt that an effective Lagrangian treatment is needed to describe the experimental data [1, 2].

In a heavy ion collision, the most abundant secondary particles are pions, therefore, the second most frequent elementary reaction channel (after $N+N$) is $\pi+N$. The HADES Collaboration in GSI has plans for experiments with pion beams. During these experiments, dilepton production in elementary pion–nucleon collisions will be studied too. Motivated by the above, we developed an effective Lagrangian model for the reaction $\pi+N \to N+e^+e^-$. Details of the model are published in [3].

2. Elements of the effective Lagrangian model

The Feynman diagrams contributing to the process $\pi+N \to N+e^++e^-$ are depicted in Fig. 1. These are: the Born contributions [(a) s-, (b) u-, and (c) t-channel diagrams, and (d) contact interaction term], (e) vector meson exchange diagram, (f) s-channel and (g) u-channel baryon resonance contributions.

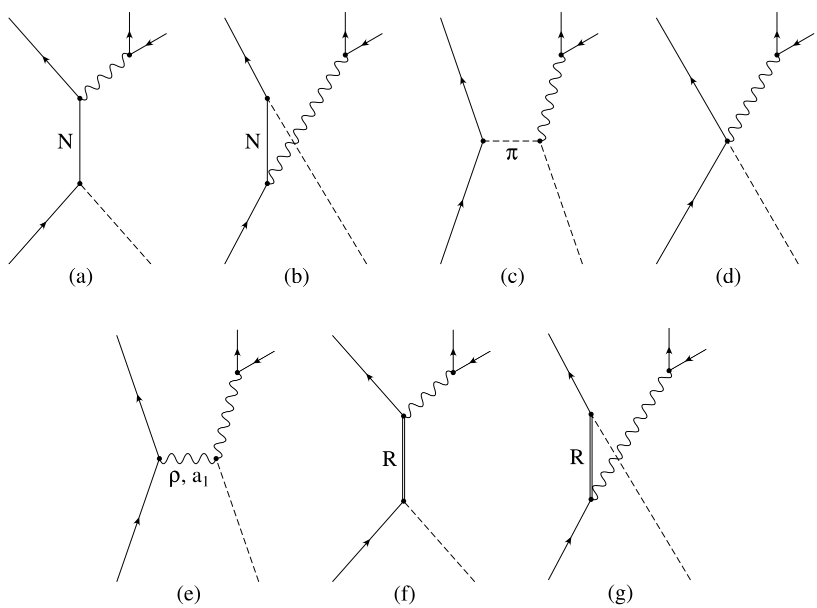

Fig. 1. Feynman diagrams contributing to the process $\pi + N \to N + e^+ + e^-$.

2.1. Electromagnetic interaction of hadrons

The main assumption of the vector meson dominance (VMD) model is that all hadrons couple to the electromagnetic field via an intermediate neutral vector meson which then converts to a photon. Here, we use a simplified version of VMD where only the ρ^0 meson is taken into account, and the ρ–γ conversion is described by the Lagrangian

$$\mathcal{L}_{\rho\gamma} = -\frac{e}{2g_\rho} F^{\mu\nu} \rho^0_{\mu\nu} \,, \tag{1}$$

where $F^{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field strength tensor and $\rho^0_{\mu\nu} = \partial_\mu \rho^0_\nu - \partial_\nu \rho^0_\mu$.

This form of the $\rho\gamma$ coupling has some advantages over the more frequently used $\mathcal{L}_{\rho\gamma} \propto \rho^0_\mu A^\mu$. First, the Lagrangian Eq. (1) is gauge invariant. Second, it does not contribute to decays with real (on-shell) photons in the final state. Indeed, the intermediate vector meson in electromagnetic vertices results in the appearance of a form factor given by

$$F_{\mathrm{VMD}}\left(k^2\right) = -\frac{e}{g_\rho} \frac{k^2}{k^2 - m_\rho^2 + i\sqrt{k^2}\,\Gamma_\rho\left(k^2\right)} \,, \tag{2}$$

where k is the photon four-momentum. One is then forced to introduce a direct photon coupling for all hadrons in addition to the VMD coupling. The coupling constant of the direct photon coupling is determined from processes with real photons in the final state (*e.g.* $N\gamma$ decays of baryon resonances), while the vector meson couplings are obtained from decays to vector mesons.

To ensure the electromagnetic U(1) gauge invariance, we introduce the direct photon couplings of hadrons and couplings of ρ mesons to other hadrons via the gauge covariant derivative

$$\nabla_\mu = \partial_\mu + ieA_\mu Q - i\tilde{g}_\rho \vec{\rho}_\mu \cdot \vec{T} \,, \tag{3}$$

where Q is the electric charge, and $\vec{T}$ denotes the generators of the isospin SU(2) group. The inclusion of the ρ-meson field in the covariant derivative is necessary because the full electromagnetic vertex contains the VMD contribution, which is related to the hadron-ρ vertex.

2.2. Form factors and gauge invariance

At the level of the effective Lagrangians, hadrons appear as elementary fields. The internal structure, or, in other words, the non-point-like nature of hadrons is accounted for by the inclusion of form factors at every vertex containing internal (off-shell) hadron lines. In this work, we used form factors of the form

$$F\left(p^2\right) = \frac{1}{1 + \left(p^2 - m_N^2\right)^2 / \Lambda^4}\,, \tag{4}$$

where p^2 is the four-momentum squared of the internal (off-shell) hadron.

In the case of Born contributions [diagrams (a)–(d) in Fig. 1], a subtle problem related to gauge invariance arises. Only the sum of all Born diagrams is gauge invariant, the individual diagrams are not. Consequently, gauge invariance is lost if one introduces different form factors for each of the Born diagrams.

This problem has been solved for the case of pion-photoproduction in Ref. [4], and the solution can be generalized for the present case. The main idea is that although the Born contribution is not gauge-invariant after the inclusion of the hadronic form factors, it can be shown, that the non-gauge-invariant part is free from (propagator) poles. Therefore, this non-gauge-invariant part can be removed by adding a suitably chosen contact $NN\pi\gamma$ interaction term to the Lagrangian. The contribution of this extra contact term can be written down explicitly, and gauge-invariance of the resulting Born amplitude can be demonstrated by an explicit analytic calculation of the Born diagrams. For the details of this calculation, we refer the Reader to Ref. [3].

2.3. Contributions of baryon resonances

It can be achieved by a suitable choice of the interaction Lagrangians that diagrams containing baryon resonances are individually gauge-invariant. This means that problems similar to the case of Born contributions do not appear. In our simplified model, we use only one term for each vertex containing baryon resonances. Calculation of baryon resonance contributions is straightforward, but lengthy. The calculation is carried out numerically.

3. Numerical results

3.1. Parameters of the model

We included 16 baryon resonances up to spin-5/2 and below 2 GeV in our model. We determined the $RN\pi$ and $RN\rho$ coupling constants from the width of the $N\pi$ and $N\rho$ decay modes of resonances. Since the $N\gamma$ width is not very well known for many resonances, we determined the $RN\gamma$ coupling constants by fitting the pion photoproduction total cross section data. During this fit, we varied the sign of the $RN\gamma$ couplings, and also the cutoff parameter Λ of the form factor Eq. (4).

3.2. Dilepton spectra

The dilepton invariant mass spectra obtained from the model are shown in Fig. 2 for various collision energies. Although only the $\sqrt{s} = 1.9$ GeV energy is above the threshold of ρ-meson production, peaks appear at the high dilepton mass end of the spectrum for two lower collision energies too. This is because — due to the wide spectral function of the ρ — low mass ρ mesons appear with large probability in sub-threshold collisions.

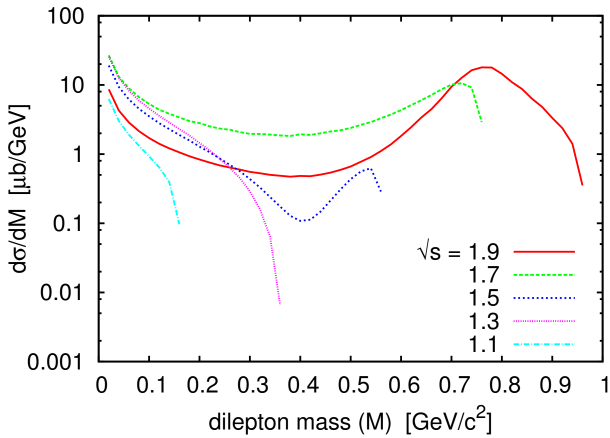

Fig. 2. Dilepton invariant mass spectra from the reaction $\pi^- + p \to n + e^+ + e^-$ for various collision energies.

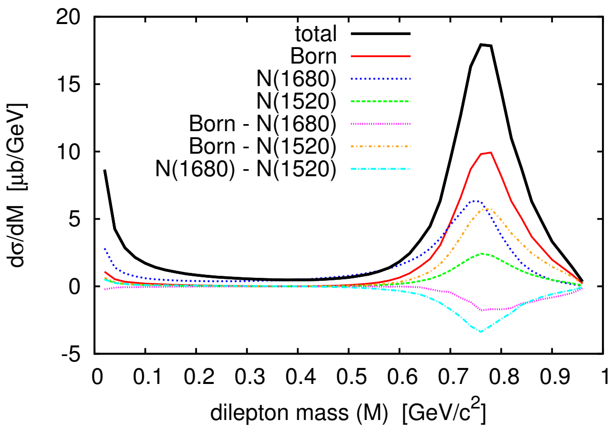

Fig. 3. Contributions of the dominant channels to the dilepton invariant mass spectrum of the reaction $\pi^- + p \to n + e^+ + e^-$ at $\sqrt{s} = 1.9$ GeV energy.

Figure 3 shows the dominant contributions to the dilepton spectrum at the $\sqrt{s} = 1.9$ GeV collision energy. These are the Born contribution and the $N(1680)$ and $N(1520)$ resonance contributions. Interference terms of these contributions are also important, some of them are negative.

4. Outlook

The presented model is a first step towards an EFT description of the considered process. It contains several simplifications: vector mesons other than ρ are absent from the applied VMD model, some possible terms from interaction Lagrangians with baryon resonances are excluded, the model has not been tested on differential cross sections of *e.g.* pion photoproduction, *etc.*

We point out one problem related to the application of the model in transport codes for heavy ion collisions. We have seen that interference terms of diagrams with different baryon resonances can give important contributions to the cross section. In transport models, however, baryon resonances are propagated explicitly, therefore such interference terms cannot be implemented in a straightforward way.

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