MESON PRODUCTION IN PROTON–PROTON SCATTERING WITHIN AN EXTENDED LINEAR SIGMA MODEL*

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We study the production of non-strange mesons in proton–proton scattering reactions within an effective model of mesons and baryons with global chiral symmetry. The model includes the nucleon (N) and its chiral partner (N^*) and their couplings to the $N_\mathrm{f} = 2$ multiplets of (pseudo)scalar and (axial-)vector mesons. Results for the production of ω, η mesons are presented.

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1. Introduction

Phenomenological models of QCD are suitable for the study of hadrons and their interactions at energies of a few GeV, where perturbative methods are not applicable, see *e.g.* [1–6].

In this work, we use an effective chiral model of QCD, denoted as the extended Linear Sigma Model (eLSM) [7–11], in order to study proton–proton scattering in which a meson is produced in the final state. In the eLSM, the nucleon (N) and its chiral partner (N^*) are introduced according to the mirror assignment [6]. To this end, we first introduce the baryonic fields Ψ_1 and Ψ_2 which transform under chiral transformations $U(2)_\mathrm{L} \times U(2)_\mathrm{R}$ as follows:

$$\begin{aligned} \Psi_{1\mathrm{R}} &\longrightarrow U_\mathrm{R}\Psi_{1\mathrm{R}}\,, \qquad \Psi_{1\mathrm{L}} \longrightarrow U_\mathrm{L}\Psi_{1\mathrm{L}}\,, \\ \Psi_{2\mathrm{R}} &\longrightarrow U_\mathrm{L}\Psi_{2\mathrm{R}}\,, \qquad \Psi_{2\mathrm{L}} \longrightarrow U_\mathrm{R}\Psi_{2\mathrm{L}}\,, \end{aligned} \tag{1}$$

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where $\Psi_{i\mathrm{R}}$ and $\Psi_{i\mathrm{L}}$ denote the right- and left-handed components of the baryon field Ψ_i, respectively. This configuration allows to write down a chirally symmetric mass term of the baryons of the form

$$\mathcal{L}_1 = -m_0 \left(\overline{\Psi}_{1\mathrm{R}} \Psi_{2\mathrm{L}} + \overline{\Psi}_{2\mathrm{L}} \Psi_{1\mathrm{R}} - \overline{\Psi}_{1\mathrm{L}} \Psi_{2\mathrm{R}} - \overline{\Psi}_{2\mathrm{R}} \Psi_{1\mathrm{L}} \right) . \tag{2}$$

The physical fields (N) and (N^*) are given by

$$\begin{pmatrix} N \\ N^* \end{pmatrix} = \frac{1}{\sqrt{2\cosh\delta}} \begin{pmatrix} e^{\delta/2} & \gamma_5 e^{-\delta/2} \\ \gamma_5 e^{-\delta/2} & -e^{\delta/2} \end{pmatrix} \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix} . \tag{3}$$

The interaction of the baryons with the (pseudo)scalar fields is given by the term $\mathcal{L}_2$

$$\mathcal{L}_2 = -\hat{g}_1 \left(\overline{\Psi}_{1\mathrm{L}} \Phi \Psi_{1\mathrm{R}} + \overline{\Psi}_{1\mathrm{R}} \Phi^\dagger \Psi_{1\mathrm{L}} \right) - \hat{g}_2 \left(\overline{\Psi}_{2\mathrm{L}} \Phi \Psi_{2\mathrm{R}} + \overline{\Psi}_{2\mathrm{R}} \Phi^\dagger \Psi_{2\mathrm{L}} \right) , \tag{4}$$

where Φ represents the matrix of states with zero spin

$$\Phi = (\sigma + i\eta_{\mathrm{N}})\, t^0 + (\boldsymbol{a}_0 + i\boldsymbol{\pi}) \cdot \boldsymbol{t} \tag{5}$$

with t^0 and $\boldsymbol{t}$ as the identity and Pauli matrices divided by 2 respectively, and η_{N} as the non-strange component of the η meson. The interaction with the (axial-)vector states is obtained via the term $\mathcal{L}_3$

$$\mathcal{L}_3 = \overline{\Psi}_{1\mathrm{L}} i\gamma_\mu D^\mu_{1\mathrm{L}} \Psi_{1\mathrm{L}} + \overline{\Psi}_{1\mathrm{R}} i\gamma_\mu D^\mu_{1\mathrm{R}} \Psi_{1\mathrm{R}} + \overline{\Psi}_{2\mathrm{L}} i\gamma_\mu D^\mu_{2\mathrm{R}} \Psi_{2\mathrm{L}} + \overline{\Psi}_{2\mathrm{R}} i\gamma_\mu D^\mu_{2\mathrm{L}} \Psi_{2\mathrm{R}} \tag{6}$$

with

$$\begin{aligned} D^\mu_{1\mathrm{R}} &= \partial^\mu - i c_1 R^\mu , \qquad D^\mu_{1\mathrm{L}} = \partial^\mu - i c_1 L^\mu , \\ D^\mu_{2\mathrm{R}} &= \partial^\mu - i c_2 R^\mu , \qquad D^\mu_{2\mathrm{L}} = \partial^\mu - i c_2 L^\mu \end{aligned} \tag{7}$$

and

$$\begin{aligned} R^\mu &= (\omega^\mu - f_1^\mu)\, t^0 + (\boldsymbol{\rho}^\mu - \boldsymbol{a}_1^\mu) \cdot \boldsymbol{t} , \\ L^\mu &= (\omega^\mu + f_1^\mu)\, t^0 + (\boldsymbol{\rho}^\mu + \boldsymbol{a}_1^\mu) \cdot \boldsymbol{t} . \end{aligned} \tag{8}$$

The values of the parameters m_0, $\hat{g}_1$, $\hat{g}_2$, c_1 and c_2 are fixed using the following physical quantities: the masses of the nucleon and nucleonic resonance, the decay width $N^* \to N\pi$, the axial coupling constant of the nucleon and the axial coupling constant of the nucleonic resonance. Further details on the determination of parameters and assignment of the fields to physical particles are presented in Refs. [7–9, 11].

2. Feynman diagrams

Using the model described above, we study processes of the type $pp \longrightarrow ppX$, where X is a single ω or η meson. In figure 1, two sample diagrams of the process are presented. The diagrams represent either the nucleonic current (Fig. 1 (a)) or the resonant current (Fig. 1 (b)). To each current 36 different diagrams contribute (9 exchange mesons, t- and u-channels and early and late emission of the produced meson).

The results presented in Section 3 are obtained using either only the nucleonic current or the coherent sum of both the nucleonic and resonant currents. The corresponding curves are labelled 'nucleonic' or 'resonant', respectively.

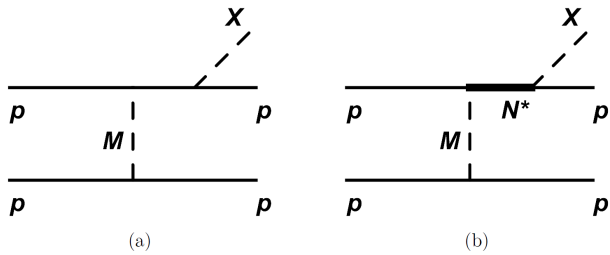


Fig. 1. Feynman diagrams of the process $pp \longrightarrow ppX$: (a) the nucleonic current and (b) the resonant current. M represents an exchanged σ, a_0, π, η, $\eta\prime$, ω, ρ, f_1 or a_1 meson.

3. Results

The total cross section for the reaction $pp \longrightarrow pp\omega$ is shown in figure 2 as a function of the center-of-mass momentum of the incoming protons. The dashed (black) curve shows the calculations using only the nucleonic current and the solid (blue) one shows the calculations using the resonant and nucleonic currents. As seen in figure 2, calculations with the nucleonic current only underestimate the data points near the production threshold. Including the resonant contribution leads to a significant improvement of the description of the data near threshold. It is worth mentioning that the data points shown in the figure were not used for the determination of the model parameters. At higher energies, both calculations (nucleonic and resonant) tend to overestimate the data points.

In the case of the η meson, the difference between the nucleonic and resonant calculations is not significant as can be seen in figure 3. Again, the dashed (black) curve shows the calculated cross section considering the nucleonic current only and the solid (blue) curve shows the sum of the resonant and nucleonic currents. Both curves overestimate the data considerably even at threshold.

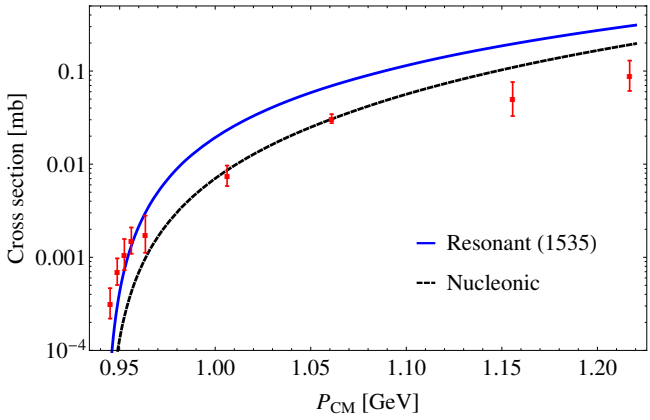


Fig. 2. The total cross section for the reaction $pp \longrightarrow pp\omega$. The data points show experimental results and are referenced in [12].

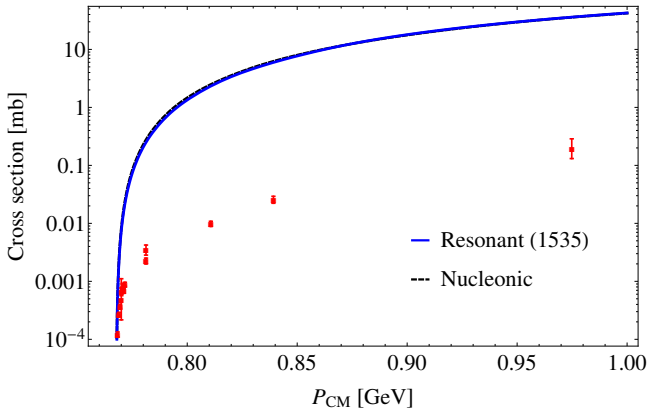


Fig. 3. The total cross section for the reaction $pp \longrightarrow pp\eta$. The difference between the nucleonic- (dashed curve) and resonant-calculations (solid curve) is hardly visible. The data points show experimental results and are referenced in [13].

4. Discussion and outlook

The overestimation of the production cross section at high energies (especially the case of the η meson) hints at a missing ingredient in the calculation. So far, we have only considered the production from a baryon–baryon–meson vertex. The possibility for the produced meson to come from a three-meson vertex was not included. Including such vertices is expected to have a considerable effect on the results. In addition, vertex form factors might be needed for a better agreement with the data at higher energies.

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