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# Phenomenological study of exclusive binary light particle production from antiproton-proton annihilation at FAIR/PANDA

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**Abstract.** Exclusive binary annihilation reactions induced by antiprotons of momentum from 1.5 to 15 GeV/c can be extensively investigated at FAIR/PANDA [1]. We are especially interested in the channel of charged pion pairs. Whereas this very probable channel constitutes the major background for other processes of interest in the PANDA experiment, it carries unique physical information on the quark content of proton, allowing to test different models (quark counting rules, statistical models,...). To study the binary reactions of light meson formation, we are developing an effective Lagrangian model based on Feynman diagrams which takes into account the virtuality of the exchanged particles. Regge factors [2] and form factors are introduced with parameters which may be adjusted on the existing data. We present preliminary results of our formalism for different reactions of light meson production leading to reliable predictions of cross sections, energy and angular dependencies in the PANDA kinematical range.

## 1. Introduction

Large experimental and theoretical efforts have been going on since decades in order to understand and classify high energy processes driven by strong interaction. We revisit here hadronic reactions at incident energies above 1 GeV, and focus in particular on two body processes. Antiprotons are a very peculiar probe, due to the fact that scattering and annihilation reactions may occur in the same process, with definite kinematical characteristics. We discuss the annihilation reaction of antiproton-proton into two charged pions and the crossed channels of pion-proton elastic scattering. These reactions have been studied in the past at FermiLab and at LEAR at lower energies.

Charged pion production data are scarce, and do not fill continuously in a large angular or energy range [1, 2, 3]. According to the foreseen performances of the PANDA experiment at FAIR, a large amount of data related to light meson pair production from  $\bar{p}p$  annihilation is expected in the next future. The best possible knowledge of light meson production is also requested prior to the experiment, as pions constitute an important background for many other channels making a timely development of a reliable model.

We develop here an effective Lagrangian model (ELM), with meson and baryon exchanges in  $s$ ,  $t$ , and  $u$  channels, applicable in the energy range  $2 \leq \sqrt{s} \leq 15$  GeV, that is the accessible domain for the PANDA experiment at FAIR. It is known that first order Born diagrams give cross sections much larger than measured, as Feynman diagrams assume on-shell point-like particles.



Form factors are added in order to take into account the composite nature of the interacting particles at vertices. Their form is, however, somehow arbitrary, and parameters for masses of the exchanged particles, coupling constants or cutoff are adjusted to reproduce the data. Therefore these models should be considered in an effective way to take into account microscopic degrees of freedom and quark exchange diagrams. A “Reggeization” of the trajectories is added to reproduce the very forward and very backward scattering angles.

To get maximum profit from the available data, we consider also existing elastic scattering  $\pi^\pm p$  data, and apply crossing symmetry in order to compare the predictions based on the annihilation channel, at least in a limited kinematical range.

## 2. Formalism and Comparison with data

The annihilation reactions are best described in the centre of mass (CMS) frame, whereas the kinematics of elastic scattering is simpler in Laboratory (Lab) frame. We consider the reaction:

$$\bar{p}(p_1) + p(p_2) \rightarrow \pi^-(k_1) + \pi^+(k_2) \quad (1)$$

The notation of four momenta is indicated in the parenthesis. The following notations are used:  $q_t = (-p_1 + k_1)$ ,  $q_t^2 = t$ ,  $q_u = (-p_1 + k_2)$ ,  $q_u^2 = u$  and  $q_s = (p_1 + p_2)$ ,  $q_s^2 = s$ . where  $s$ ,  $t$  and  $u$  are the Mandelstam variables,  $s + t + u = 2M_p^2 + 2m_\pi^2$ ,  $M_p$  is the proton mass,  $m_\pi$  is the pion mass.

The general expression for the differential cross section in CMS of reaction (1) is:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2^8\pi^2} \frac{1}{s} \frac{\beta_\pi}{\beta_p} |\overline{\mathcal{M}}|^2, \quad \frac{d\sigma}{d\cos\theta} = 2E^2 \beta_p \beta_\pi \frac{d\sigma}{dt} \quad (2)$$

where  $\beta_p(\beta_\pi)$  is the velocity of the the proton(pion), and  $E$  is the energy in CMS.  $d\Omega = 2\pi d\cos\theta$  due to the azimuthal symmetry of binary reactions.

Crossing symmetry relates annihilation and scattering cross sections. Crossing symmetry states that the amplitudes of the crossed processes are the same, i.e., the matrix element  $\mathcal{M}(s, t)$  for the scattering (s) process  $\pi(-k_1) + p(p_2) \rightarrow \pi(k_2) + p(-p_1)$  and the annihilation (a) (1), is the same, at corresponding  $s$  and  $t$  values. In order to find the correspondence, kinematical replacements should be done, as  $s \leftrightarrow t$ . The cross sections are related by:

$$\sigma^a = \frac{1}{2} \frac{|\vec{k}_s|^2}{|p_a|^2} \sigma^s. \quad (3)$$

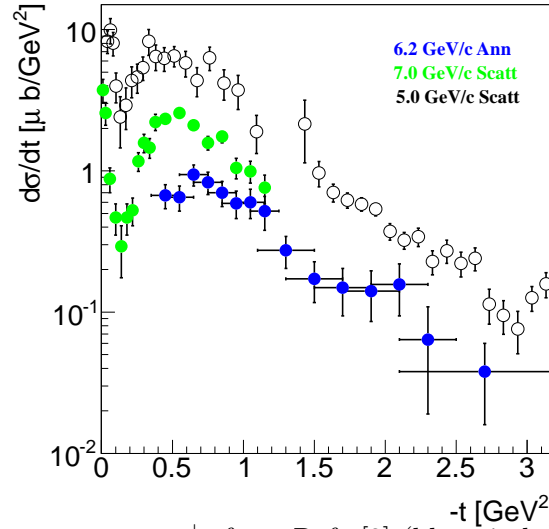
where  $p_a$  is the CM momentum for  $\bar{p}p$  annihilation and  $|k_s|$  is the CM momentum for  $\pi^-p$  scattering, evaluated at the same  $s$  value:

$$|\vec{k}_s|^2 = \frac{1}{4s} \left[ m_\pi^4 - 2m_\pi^2(M_p^2 + s) + (M_p^2 - s)^2 \right]. \quad (4)$$

If the scattering cross section is measured at a value  $s^s = s_1$  different from  $s^a = s$ , at small  $t$  values one can rescale the cross section, using the empirical dependence:  $\sigma^s \simeq \text{const} \cdot s^{-2}$ . An example of cross section for annihilation and scattering processes at similar incident momenta are reported in Fig. 1.

In order to calculate  $\mathcal{M}$ , one needs to specify a model for the reaction. In this work we consider the formalism of effective meson Lagrangians. The following contributions to the cross section for reaction (1) are calculated: baryon exchange:  $t$ -channel nucleon (neutron) exchange,  $t$ -channel  $\Delta^0$  exchange,  $u$ -channel  $\Delta^{++}$  exchange,  $s$ -channel  $\rho$ -meson exchange. The total amplitude is written as a coherent sum of all the amplitudes:

$$\mathcal{M} = \mathcal{M}_N + \mathcal{M}_{\Delta^0} + \mathcal{M}_{\Delta^{++}} + \mathcal{M}_\rho. \quad (5)$$



**Figure 1.** Data for  $\bar{p} + p \rightarrow \pi^- + \pi^+$ , from Ref. [2] (blue circles), for  $\pi^+ + p \rightarrow \pi^+ + p$  from Ref. [4] (green solid circles), and from Ref. [5] (black empty circles) - for  $\pi^+$  emission at small  $t$ -values (or large  $u$ -values). The  $\pi^+p$  data have been scaled by the crossing constant factor 0.589 according to formula (3).

In case of charged pions, the dominant contribution in forward direction is  $N$  exchange, whereas  $\Delta^{++}$  mostly contribute to backward scattering. We neglect the difference of masses between different charge states of particles, like nucleons, pion and  $\Delta$ . Central scattering is driven by  $s$ -channel exchange of vector mesons, with the same quantum numbers as the photon. We limit our considerations to  $\rho$ -meson exchange.

The expressions for the amplitudes and their interferences follow the Feynman rules. The coupling constants are fixed from the known decays of the particles, or we use the values from effective potentials like in ref. [6]. Masses and widths are taken from [7]. The effects of strong interaction in the initial state coming from the exchange of vector and (pseudo)scalar mesons between proton-antiproton are essential and effectively lead to the Regge form of the amplitude. The  $t$  and  $u$  diagrams are modified by adding a general Regge factor  $R_x$  (where  $x = t, u$ ) with the following form:

$$R(x) = \left(\frac{s}{s_0}\right)^{2[\alpha(x)-1]}, \quad \alpha(x) = \frac{1}{2} + r \frac{\alpha_s}{\pi} \frac{x - M^2}{M^2}; \quad (6)$$

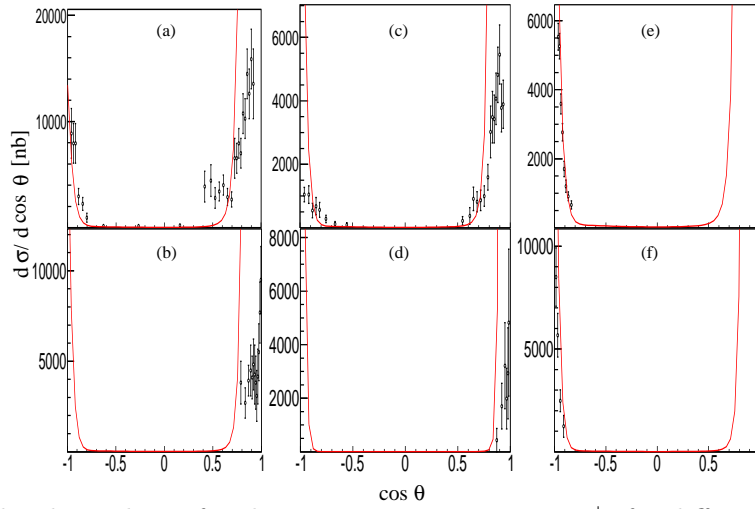
where  $s_0 \simeq 1 \text{ GeV}^2$  can be considered a fitting parameter [8] and  $r\alpha_s/\pi \simeq 0.7$  is fixed by the slope of the Regge trajectory. And  $M$  here is the mass of exchange particle. In the present model the values have been set at  $s_0 = 1.4 \text{ GeV}^2$  and  $r\alpha_s/\pi = 0.7$  for the nucleon.

A form factor of the form:  $F = 1/(x - p_{N,\Delta}^2)^2$ , was introduced in the  $Np\bar{p}$  and  $Np\bar{\Delta}$  vertices, with  $p_N = 0.8 \text{ GeV}$  and  $p_\Delta = 5 \text{ GeV}$ .

The  $\rho NN$  vertex includes the proton structure in the vector current form with two form factors (FF)  $F_{1,2}^\rho$ :

$$\Gamma_\mu(q_s) = F_1^\rho(q_s^2)\gamma_\mu(q_s) + \frac{i}{2M_N}F_2^\rho(q_s^2)\sigma_{\mu\nu}q_s^\nu, \quad (7)$$

where  $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu\gamma_\nu - \gamma_\nu\gamma_\mu]$  is the antisymmetric tensor. We fix the form, the constants and



**Figure 2.** Angular dependence for the reaction  $\bar{p} + p \rightarrow \pi^- + \pi^+$ , for different value of the total CMS energy  $\sqrt{s}$ : (a)  $\sqrt{s} = 3.362$  GeV from Ref. [3], (b)  $\sqrt{s} = 3.627$  GeV from Ref. [11], (c)  $\sqrt{s} = 3.680$  GeV from Ref. [2], (d)  $\sqrt{s} = 4.559$  GeV from Ref. [12]. The corresponding data from the elastic reactions  $\pi^\pm p \rightarrow \pi^\pm p$  are also reported: (e)  $\sqrt{s} = 3.463$  GeV from Ref. [13], (f)  $\sqrt{s} = 3.747$  GeV from Ref. [4]. Black points are data taken from each reference, and the red lines are from the formula (2).

the parameters of  $F_{1,2}^\rho(s)$  according to [6, 9, 10] as:

$$F_1^\rho(s) = g_{\rho NN} \frac{\Lambda^4}{\Lambda^4 + (s - M_\rho^2)^2}, \quad F_2^\rho(s) = \kappa_\rho F_1^\rho(s), \quad (8)$$

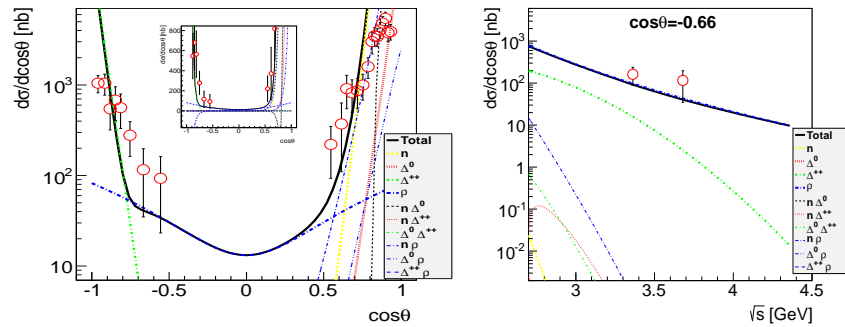
with normalization  $F_1^\rho(M_\rho^2) = g_{\rho NN}$ , where the constant  $g_{\rho NN}$  corresponds to the coupling of the vector meson  $\rho$  with the nucleon ( $g_{\rho NN}^2/(4\pi) = 0.55$ ),  $\kappa_\rho = 3.7$  is the anomalous magnetic moment of the proton with respect to the coupling with  $\rho$ , and  $\Lambda = 0.911$  is an empirical cut-off.

The angular dependence for the reaction  $\bar{p} + p \rightarrow \pi^- + \pi^+$  is shown in Fig. 2 (a-d) with satisfactory agreement. The results for the crossed channels  $\pi^\pm$  elastic scattering are also reported in Fig. 2 (e-f), where data for the differential cross section span a small very forward or very backward angular region, bringing an additional test of the model.

The angular distribution for  $\sqrt{s} = 3.680$  GeV is shown in Fig. 3. The total result (black, solid line) gives a good description of the data (red open circles) from Ref. [2] for charged pion production. All components and their interferences are illustrated. The main contribution at central angles is given by  $\rho$  s-channel exchange, whereas  $n$  exchange dominates forward angles ( $t$  channel) followed by  $\Delta^0$  exchange.  $\Delta^{++}$  represents the largest contribution for backward angles ( $u$  channel). The interferences are also shown. Their contribution affects the shape of the angular distribution, some of them being negative in part of the angular region.

### 3. Conclusions

A model, based on effective meson Lagrangian, has been built in order to reproduce the existing data for two pion production in proton-antiproton annihilation at moderate and large energies. Form factors and Regge factors are implemented and parameters adjusted to the existing data for charged pion pair production. Coupling constants are fixed from the known properties of the corresponding decay channels. The agreement with a large set of data is satisfactory for the angular dependence as well as the energy dependence of the cross section.



**Figure 3.** (color online)  $\cos \theta$ -dependence for the reaction  $\bar{p} + p \rightarrow \pi^- + \pi^+$  for  $\sqrt{s} = 3.680$  GeV (black, solid line) where the different components are illustrated (see text):  $n$ -exchange (yellow thick short dash line) and  $\Delta_0$  (red thick dotted line)  $\Delta^{++}$  (green thick dash-dotted line),  $\rho$  channel (blue thick long dash line) dominates at large angles, The interferences are  $n\Delta^0$  (thin black short-dash line),  $n\Delta^{++}$  (thin red dotted line),  $\Delta^0\Delta^{++}$  (green thin short dash-dotted line),  $n\rho$  (blue thin long-dashed dotted line),  $\Delta^0\rho$  (blue thin dash-dotted line),  $\Delta^{++}\rho$  (blue thin long dash line). Data are taken from Ref. [2].

A comparison with data from elastic  $\pi^\pm p \rightarrow \pi^\pm p$ , using crossing symmetry prescriptions shows a good agreement within the uncertainty, which verifies that crossing symmetry works well at backward angles, where one diagram is dominant.

This model can be extended to other binary channels, with appropriate changes of constants. The implementation to Monte Carlo simulations for predictions and optimization future experiments is also foreseen.

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