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PRODUCTION OF THE J/ψ IN πp AND pp COLLISIONS

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Abstract

J/ψ production in pp collisions in the energy region from 70 GeV up to ISR energies is studied by means of the π -meson exchange model using the experimental data on J/ψ production in πp collisions. A new parametrization of inclusive cross section of the process $\pi p \longrightarrow J/\psi + X$ in a wide energy region is suggested. It is shown that the π -meson exchange model with parameters found analyzing the nucleon and Δ -isobar inclusive spectra, allows to describe the energy dependence and the shape of J/ψ spectra in pp collisions. The relation between the cross sections of J/ψ associated production with nucleon or Δ isobar is estimated. Possible quark-parton interpretation of the results is discussed.

1. Introduction

The experimental data on hadroproduction of the mesons [1-9] reveal the following regularities: 1) the inclusive cross sections of the J/ψ production depend strongly on energy; 2) distributions of $E\,d\sigma/dx$ in Feynman variable x are much more narrow in pp collisions than in πp collisions; 3) the J/ψ production cross sections in pp collisions are smaller than in πp ones (expecially at low energies) and considerably smaller (at 39.5 GeV/c [2]) than in $\bar{p}p$ collisions.

Those data are interpreted usually in terms of various quark-parton models [10-12]. However, the uncertainties in quark and gluon distributions do not allow to make unambiguos conclusion about the mechanism of J/ψ production in these models.

On the other hand, it is known [13] that an important contribution to the processes of ordinary hadron production is from the π-meson exchange mechanism. In particular, this model gives the quantitative description of inclusive spectra of nucleons [13-15], Δ isobars [16], Λ and $\Sigma^{\pm}$ hyperons [17,18] in the proton fragmentation region. It is interesting in this connection to find out what is the π meson exchange part in the J/ψ hadroproduction processes.

Let us give some preliminary remarks. Firstly, the π-meson exchange mechanism gives undoubtedly some contribution to the processes of J/ψ hadroproduction though this contribution can be not a dominant as it is for ordinary hadron production [*]. Secondly, the meson exchange mechanism does not exclude, generally speaking, the quark-parton mechanisms. The aim of the present paper is to establish the connection between J/ψ production processes in pp and πp collisions by means of the π -meson exchange mechanism. We do not consider the dynamics of the process $\pi + p \to J/\psi + X$, which may be connected with the quark-parton mechanism. The results of the present work should be considered rather as the indication that the π -meson plays an important role at the initial stage of quark-antiquark sea development in the nucleon.

In this paper we calculate the cross section of the J/ψ production in pp collisions by means of the π -meson exchange diagrams. The description of the model is given in Section 2. We suggest as well as in the case of ordinary particles production that the diagrams with nucleon and Δ isobar production in the upper block of the multiperipheral chain are the dominating ones (see fig.1a, b). The form factors which determine the dependence of the amplitudes on the virtual pion mass were taken in the same form as in the analysing of N and Δ spectra [13-16]. To calculate the contribution of the diagrams 1a,b it is necessary to know the cross section of the J/ψ produc-

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[*] In particular, the π meson exchange model gives equal cross sections of J/ψ production in the pp and $\bar{p}p$ collisions. Therefore other mechanism has to dominate in $\bar{p}p$ collisions at not too high energies.

tion in πp collisions in a wide energy region. For this reason in section 2 a parametrization is proposed for the inclusive cross section of the process $\pi^{\pm}p \to J/\psi + X$ in the energy interval from 30 up to 200 GeV.

In Section 3 we discuss the results of calculations: the energy dependence of the J/ψ production cross section in pp collision, the x and $p_{\perp}^{2}$ distributions. Some predictions of the model which can be tested experimentally are discussed in this Section as well. In Section 4 we discuss the accuracy of the model and possible corrections, other mechanisms contributions, in particular, of the annihilation diagram, and the connection of this approach with the quark-parton models.

2. Description of the model

The cross section corresponding to the diagrams 1a, b with production of particle $R = N, \Delta$ in the upper vertex has the form

$$d\sigma_R = \frac{1}{4p_0\sqrt{s}}\, g_R^2(t)\, G_R^2(t) \left[4p_\pi \sqrt{s_1}\, \rho_{J/\psi}^{\pi p}(s_1)\right] \frac{d^3p_{J/\psi}}{E_{J/\psi}}\, \frac{d^3p_R}{2E_R(2\pi)^3} \qquad (1)$$

where p_0 is the initial proton momentum in the centre-of-mass frame, p_R is the momentum of particle R, s_1 is the missing mass squared for this particle (the mass of the lower block squared), p_π is the virtual pion momentum in the rest frame of the lower block $\rho_{J/\psi}^{\pi p}(s_1) = E_{J/\psi}\, d^3\sigma(s_1)/d^3p_{J/\psi}$ is invariant inclusive cross section of the J/ψ production in πp collisions at energy squared s_1, $t = (p_R - p_0)^2$ is the virtual pion mass squared;

$g_R^2(t)$ is the square of $\pi p R$ vertex averaged over proton spin and summed over particle R spin

$$g_N^2(t)=G_{\pi NN}^2\cdot t, \quad g_\Delta^2(t)=G_{\pi N\Delta}^2\left[(M_\Delta-m)^2-t\right]\left[(M_\Delta+m)^2-t\right]^2/6M_\Delta^2$$

(we used the same values of coupling constants as in ref. [16] $G_{\pi^+pp}^2 = 14.6$, $G_{\pi^+p\Delta^{++}}^2 = 19 \text{ GeV}^{-2}$).

The functions $G_R^2(t)$ are the form factors describing the dependence of the $\pi p R$ vertices and of the process $\pi p \longrightarrow J/\psi + X$ on the virtual pion mass squared t . These functions were fitted from the analysis of the nucleon inclusive spectra [14]

$$G_N(t) = \exp\left[(R_{1N}^2+\alpha'_\pi \ln s/s_1)(t-\mu^2)\right]\times \begin{cases} \pi\alpha'_\pi/2\sin[\pi\alpha'_\pi(t-\mu^2)/2] & , |t|<|T_N| \\ \pi\alpha'_\pi/2\sin[\pi\alpha'_\pi(T_N-\mu^2)/2]\times\exp[R_{2N}^2(t-T_N)], & |t|>|T_N| \end{cases} \tag{2}$$

with the following values of parameters

$$R_{1N}^2=0.2 \text{ Gev}^{-2}, \; R_{2\Lambda}^2=0.2 \text{ GeV}^{-2}; \; T_N=-0.25 \text{ Gev}^2 \tag{3}$$

and from the analysis of the Δ isobar spectra [16]

$$G_\Delta(t)=\exp\left[\left(R_{1\Delta}^2+\alpha'_\pi \ln\frac{ss_0}{s_1 M_\Delta^2}\right)(t-\mu^2)\right]\times \begin{cases} \pi\alpha'_\pi/2\sin[\pi\alpha'_\pi(t-\mu^2)/2] & , |t|<|T_\Delta| \\ \pi\alpha'_\pi/2\sin[\pi\alpha'_\pi(T_\Delta-\mu^2)/2]\times\exp[R_{2\Delta}^2(t-T_\Delta)], & |t|>|T_\Delta| \end{cases} \tag{4}$$

with the parameter values,

$$R_{1\Delta}^2 = 0.6\ GeV^{-2},\ R_{2\Delta}^2 = 0.2\ GeV^{-2},\ T_\Delta = -1\ GeV^2,\ s_0 = 1\ GeV^2 \quad (5)$$

Due to strong increasing of inclusive cross section $\rho_{J/\psi}^{\pi p}(s_1)$ with energy the essential masses $\sqrt{s_1}$ in the diagrams 1a,b are larger $(s_1/s \sim 0.5)$ than in processes with ordinary hadrons production $(s_1/s \sim 0.2)$. This fact leads to larger values of the momentum transfer $(0.5 \div 2\ GeV^2)$. Therefore the parameter R_{2N}^2 is more important for the J/ψ production and may differ in principle from value (3). The best fit to the J/ψ production data was obtained at the following values of parameters

$$R_{1N}^2 = 0.2\ GeV^{-2},\ R_{2N}^2 = 0.5\ GeV^{-2},\ T_N = -0.25\ GeV^2 \quad (3')$$

Later we shall illustrate the difference in the absolute normalization for the parameterization (3) and (3') in Fig. 4.

The equation (1) contains the integration of inclusive cross section $\rho_{J/\psi}^{\pi p}(s_1)$ over energy s_1. Therefore it is necessary to have the parametrization of this cross section in the wide region of energy. The available data on the J/ψ production in pion-nuclear collisions are obtained in the momenta interval from 27 up to 225 GeV/c [1-5] mainly for $x_{J/\psi} > 0$. The data for nucleon can be extracted from these data assuming that the inclusive cross sections depend linearly on atomic weight. We use the following parametrization for inclusive J/ψ cross section:

$$\rho^{\pi p}_{J/\psi}(s_1) = A\left(1-\sqrt{\tilde{s}/s_1}\right)^{\alpha} e^{-cp_\perp} f(x_{J/\psi}) ,$$

$$f(x_{J/\psi}) = \begin{cases} (1-x_{J/\psi})^{b_p} & \text{if } y_{min} < y < y_{min} + y_p \\ 1 & \text{if } y_{min} + y_p < y < y_{max} - y_\pi \\ (1-x_{J/\psi})^{b_\pi} & \text{if } y_{max} - y_\pi < y < y_{max} \end{cases} \qquad (6)$$

with parameter values

$\Lambda = 8$ nb/GeV^3, $\tilde{S} = 4$ GeV^2, $\alpha = 5$, $c = 2$ GeV^{-1},
$b_p = 3{,}4$, $b_\pi = 3$, $y_p = 1.4$, $y_\pi = 6.5$.

Here

$$x_{J/\psi} = 2p^{\parallel}_{J/\psi}/\sqrt{s_1} , \quad y = \frac{1}{2}\ln\frac{E_{J/\psi}+p^{\parallel}_{J/\psi}}{E_{J/\psi}-p^{\parallel}_{J/\psi}} ,$$

$$y_{max} = -y_{min} = \ln\frac{1+\sqrt{1+\Delta^2}}{\Delta} , \quad \Delta = 2m_{J/\psi}/\sqrt{s_1}$$

The description of experimental data on J/ψ spectra in πp collisions at different energies by means Eq. (6) is shown in Fig. 2. The x distribution decreases by a power law in the proton ($y < y_{min} + y_p$) and pion ($y > y_{max} - y_\pi$) fragmentation region, being constant in the intermediate region. Let us note that because of different size of the fragmentation region for p and π the x distribution is asymmetric (the centre of the plateau is shifted to the right from zero). At energies $\sim 30 \div 40$ GeV this effect leads to the characteristic form of the spectrum with the maximum at $x \sim 0.3$ in an agreement with experimental data [1,2].

The integration in Eq. (1) was performed on a computer by the Monte-Carlo method taking into account the exact kinematics. The results of calculations are given in the following Section.

3. Discussion

Let us discuss what peculiarities of inclusive J/ψ spectra in pp collisions stem from the π -meson exchange mechanism.

First of all it is evident that the $x_{J/\psi}$ distribution $\rho^{pp}_{J/\psi}(s) = \frac{2E}{\sqrt{s}} \frac{d\sigma^{pp}}{dx_{J/\psi}}$ is determined by the shape of the distribution $\rho^{\pi p}_{J/\psi}$ and by the mean value of the virtual pion momentum $\bar{p}_\pi \simeq p_0(1-\bar{x}_R) \simeq p_0 \bar{s}_1/s$ (as $x^{pp}_{J/\psi} \simeq x^{\pi p}_{J/\psi} \cdot \bar{p}_\pi/p_0 \simeq x^{\pi p}_{J/\psi} \bar{s}_1/s$, where s_1 is the mean mass squared of the lower block). The calculations give the mean value $1-\bar{x}_R \simeq \bar{s}_1/s \sim 0.5$ in the energy region of 40-2000 GeV. Therefore the distribution $\rho^{\pi p}_{J/\psi}(x)$ must be approximately twice more narrow than the $\rho^{\pi p}_{J/\psi}(x)$ one. Certainly, this estimation is valid only for not too large $x^{pp}_{J/\psi}$ as for $x^{pp}_{J/\psi} \gtrsim 0.5$ the essential values of $x^{\pi p}_{J/\psi}$ are close to 1, and the shape of $x^{pp}_{J/\psi}$ distribution in this region is mainly determined by the shape of the form factors. Therefore the contribution of the mechanism under consideration to J/ψ spectrum must strongly decrease at $x^{pp}_{J/\psi} \gtrsim 0.5$ and the contribution from other mechanisms may manifest itself, in particular the J/ψ production in the upper block of multiperipheral chain.

Thus the integration of the strongly asymmetric distribution $\rho^{\pi p}_{J/\psi}(x)$ in the Eq. (1) results in that the spectrum at $x_{J/\psi} > 0$ narrows approximately by two times. The left part of the spectrum at $x_{J/\psi} < 0$ does not change in this model (the limited fragmentation). It gives approximately symmetric output distribution $\rho^{pp}_{J/\psi}(x)$ although the input distribution was nonsymmetric.

In Fig. 3 the value $2E/\sqrt{s}\, d\sigma_{pp}/dx$ is compared with the experimental data for the proton momenta of 150 and 225 GeV/c and the theoretical predictions for proton momentum of 400 GeV/c are presented.

At high energies the theoretical calculations contain some uncertainty because the energy dependence (6), (7) of inclusive spectra in πp collisions is extrapolated into the high energies region. The validity of such extrapolation can be checked when comparing the data on energy dependence of the J/ψ spectra in pp collisions with theoretical predictions. The energy behaviour of these spectra depends on two factors: on the energy dependence of $\rho^{\pi p}_{J/\psi}(s_1)$ and on the shape of the form factors which determines essential values of s_1. In Fig. 4 the energy dependence of $d\sigma/dy\,(pp \to J/\psi + X)|_{y=0}$ is shown. The curves 1 and 2 are calculated with the form factors parametrized in accordance with (3), (5) and (3'), (5) respectively. These two parametrizations correspond to different contributions from diagrams 1a. The difference between the curves 1 and 2 illustrates the uncertainty of model predictions connected with the choice of the form factor.

The shape of the spectra does not change practically at these variations.

The contributions from diagrams 1a and 1b can be distinguished experimentally by measuring the associated J/ψ production with neutron (the diagram 1a mainly) or with Δ isobar. It is worth to note that the $x_N(x_\Delta)$ distribution in the J/ψ production processes will have the maximum at $x_N(x_\Delta) \sim 0.5$ but not at $x_N(x_\Delta) \sim 0.7 + 0.8$

as in the case of ordinary hadrous production. The contribution of diagram 1b is represented in Fig. 4 by the curve 2. The parametrization (3'), (5) corresponds to approximately equal contributions of the diagrams 1a and 1b.

The $p_\perp$ distributions for the process $pp \to J/\psi + X$ in this model are similar to the ones for $\pi p \to J/\psi + X$ at high energies. The $p_\perp$ distribution at 150 GeV/c is represented in Fig. 5.

The J/ψ polarization in this model should be the same for πp and pp collisions.

4. Conclusion

The comparison of theoretical calculations with experimental data shows that the π -meson exchange mechanism takes an important part in the J/ψ meson production in pp collisions. The model predicts the absolute value of cross section, energy dependence and the shape of the x and $p_\perp$ distributions. Theoretical uncertainties are connected first of all with the uncertainties in the pion off-mass-shell form factors . It should be emphasized that these form factors have the phenomenological meaning because they take into account effectively at not low t values the absorption corrections and the contributions from other meson exchanges.

As it has been said above the π-meson exchange mechanism shouldn't be put in opposition to the quark-parton models of the J/ψ production [10-12] . We did not concretize the J/ψ production mechanism in πp collisions, which can be connected with quark-gluon interactions. It is essential that in this case the results of the present paper point out the important contribution of π -mesons to the quark see development, at the initial stage. The pions as the suppliers of quarks and antiquarks were discussed in ref. [19] in connection with the lepton pair production. Let us emphasize that the estimation for antiquark distribution function in nucleon obtained within the framework of the model under consideration is consistent with the estimation obtained from the analysis of deep inelastic electroproduction *) .

The J/ψ mesons production in $\bar{p}p$ collisions [2] shows that in this case the different mechanisms are important, in particular the annihilation one. Let us note that at the antiproton momentum of about 40 GeV/c as in ref. [2] the mean energy of quark-antiquark pair in $\bar{p}p$ system corresponds just to the J/ψ mass, i.e. the conditions for J/ψ production due to direct annihilation of valence quark-antiquark are quite favourable at this energy. Moreover the annihilation mechanism has much lower threshold than the nonannihilation one. At asymptotic energies the contribution due to annihilation decreases according to a power law when energy increases. Therefore the relative difference between J/ψ production in $\bar{p}p$ and pp collisions must decrease.

Let us note in conclusion that the similar calculations which connect the particle production in πp and pp collisions can be made for a wide class of processes such as heavy lepton pair, φ -meson, K-meson, antiproton, upsilon production and so on. It should be emphasized

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*) We are indebted to A.B.Kaidalov for discussion of that question and relative ones. More detailed analysis will be reported elsewhere

that from the standpoint of considered mechanism the investigation of the production processes of such particles which can be not produced in the upper block of multiperiperal chain is more favourable to be carried out on the pion beams.

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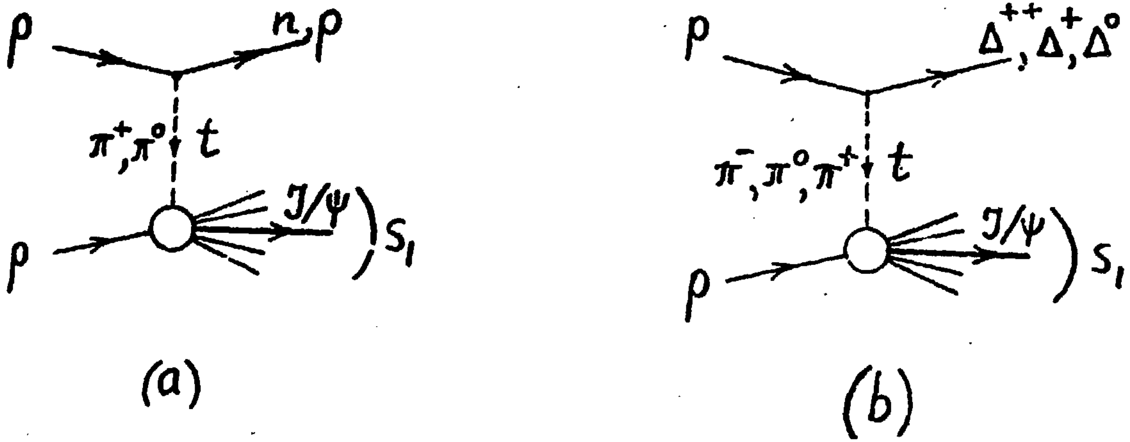

Fig. 1. The π-meson exchange diagrams for the J/ψ production in pp collisions

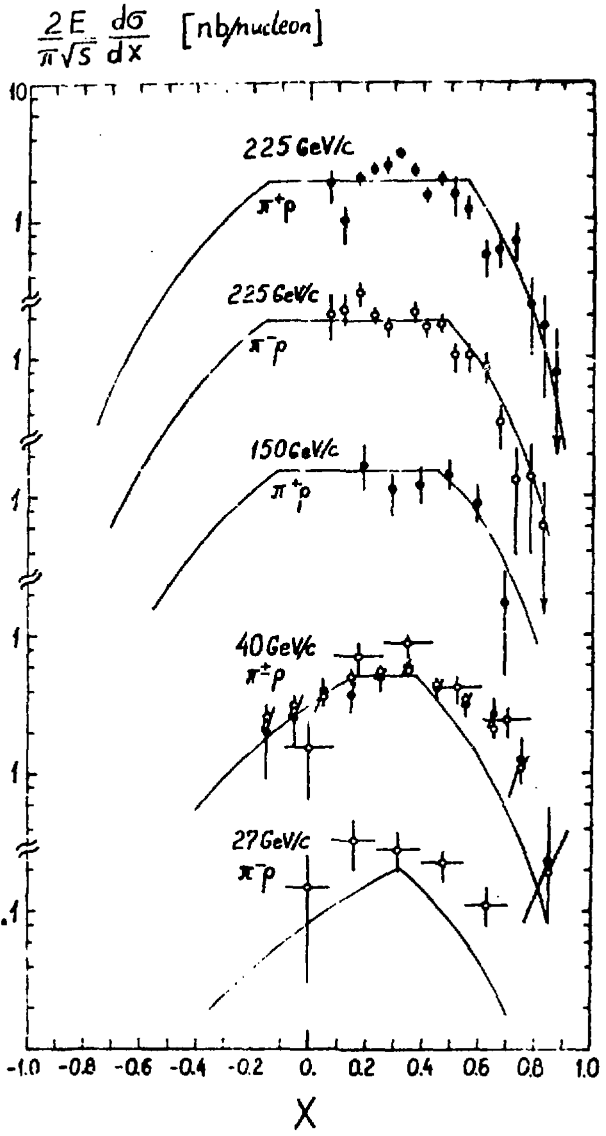

Fig. 2. Comparison of theoretical parametrization for dependence of $\rho^{\pi p}_{J/\psi} = \frac{2E}{\pi\sqrt{s}} \frac{d\sigma}{dx_{J/\psi}}$ on $x_{J/\psi} = \frac{2p^{\parallel *}_{J/\psi}}{\sqrt{s}}$ with experimental data at momenta: 27 GeV/c, 40 GeV/c [1], 39.5 GeV/c [2], 150GeV/c [4], 225 GeV/c [5]. The closed points correspond to π^+p collisions, the open points correspond to π^-p ones.

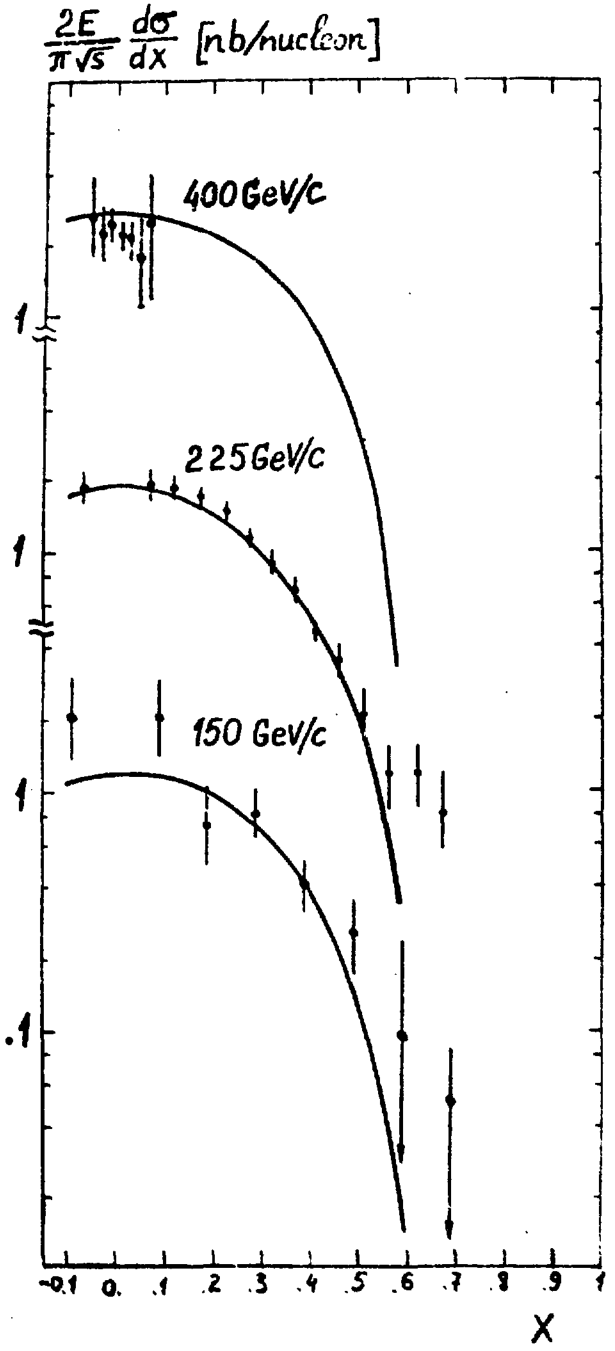

Fig. 5. $X_{J/\psi}$ distribution in process $pp \to J/\psi + X$ at 150 GeV/c [4], 225 GeV/c [5] and 400 GeV/c [7].

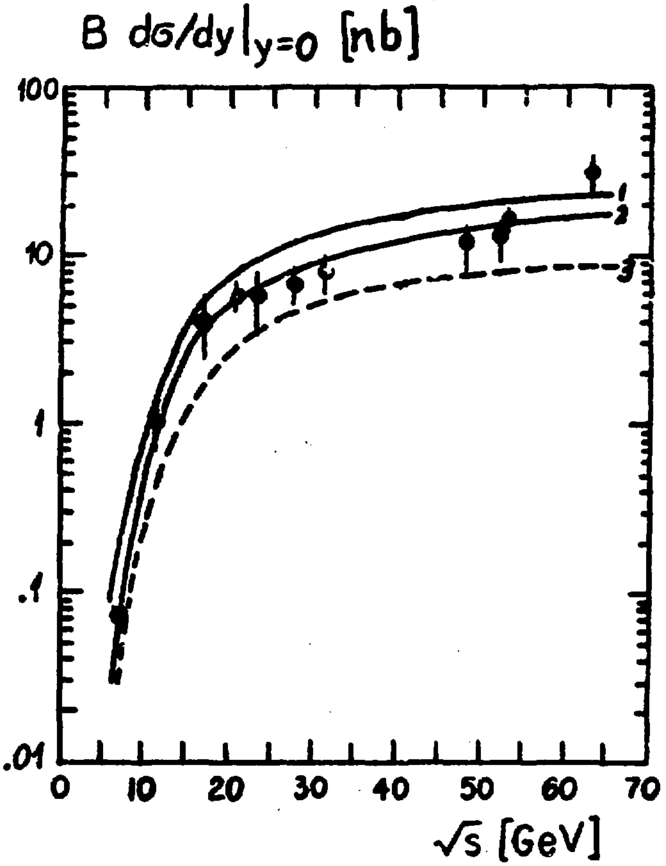

Fig. 4: Energy dependence of $B\, d\sigma/dy(\bar{p}p \to J/\psi + X)|_{y=0}$ The curve 1 corresponds to parametrization of form factor by means of Eqs. (3),(5) (see text), the curve 2 corresponds to Eqs. (3'), (5). The difference between these curves shows the uncertainty of the model predictions. The curve 3 represents the contribution of the diagram 1b for associated J/ψ production with Δ isobar.

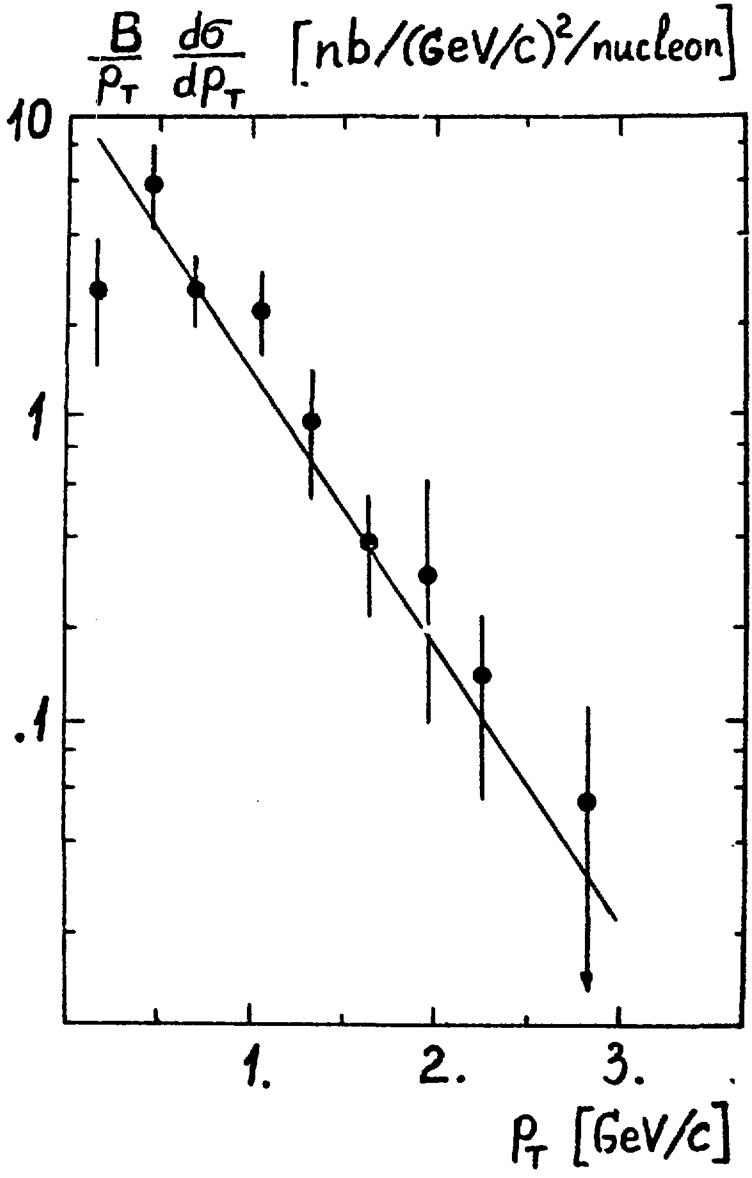

Fig. 5. $p_\perp$ distribution in $pp \rightarrow J/\psi + X$ at 150 GeV/c.

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