THE PROBLEMS OF THE ACCOUNT FOR ENERGY-MOMENTUM CONSERVATION LAW AND INTERFERENCE EFFECTS AT HADRON-HADRON SCATTERING

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We present the new method for the calculation of inelastic scattering cross-section, which doesn't require the use of any additional Regge-like assumptions and accurately accounts for energy-momentum conservation law. This leads to a new mechanism of cross-section growth, which has not been considered before, and is related to the behavior of hadrons longitudinal momenta. Second, it has been shown that interference diagrams, originating from the identity of final-state hadrons, put a significant contribution to the cross-section. The approximate method for taking into account such interference contributions has been developed. Altogether, this results in a fact that the dependence of the total and inelastic scattering cross-section on energy can be qualitatively reproduced by fitting only one single parameter of the model.

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1. INTRODUCTION

At the calculation of inelastic scattering cross-section (Fig. 1) one usually deals with the assumption that, at high energies, the main contribution to integral for the cross-section comes from multi-Regge domain (see e.g. [1–9]. The approximations applied to a delta-function which is responsible for energy-momentum conservation law and the neglect of dependence of integrand on longitudinal momentums is based on this assumption. As the result, different points of phase space correspond to different values of total energy-momentum of final-state particles.

In this paper we present a new method for the calculation of inelastic scattering cross-section, which is based on the following concerns. It is shown that the there is a class of Feynman diagrams, for which the absolute values of corresponding scattering amplitudes have conditional maximum upon the condition of accurate account for the entanglement of scattering amplitude arguments, caused by the energy-momentum conservation law. This fact enables us to apply the well-known Laplace [10] method for the calculation of cross-section.

As the result, the new mechanism of cross-section growth is discovered, related to the behavior of longitudinal momentum components of final-state particles with the energy growth.

At the same time, according to the Wick's theorem, the scattering amplitude is the sum of diagrams of all possible orders of external lines attaching to the diagram in Fig. 1, b (interference terms). In order to take into account these interference contributions one needs to modify the aforementioned method in the way, which will be outlined further in the paper.

Finally, we obtain the qualitative agreement with experiment for the total and inelastic scattering cross-section dependence on the energy by fitting only one free model parameter (coupling constant).

The paper is structured as follows. In Section 2 we set ourselves the problem of finding the constrained maximum point of multi-peripheral scattering amplitude under the condition of energy-momentum conservation. Furthermore, the analytical solution of this problem is outlined. Section 3 represents the application of Laplace's method for cross-section calculation, assuming scattering amplitude has a point of constrained maximum. The method for taking into account the interference contributions to cross-section at high final state multiplicity is outlined in Section 4. The comparison of calculated total scattering cross-section with the experimental results is presented in Section 5. Finally, summary and conclusions are given in Section 6.

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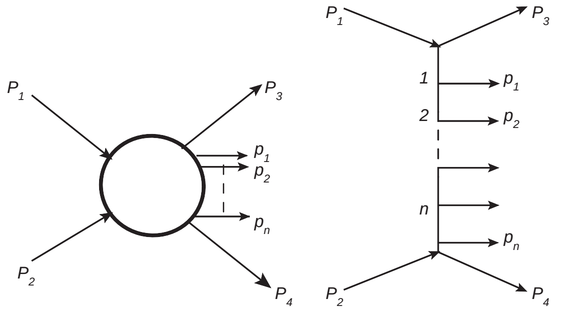


a b

Fig. 1. *A general view of an inelastic scattering diagram (a); an elementary inelastic scattering diagram in the multi-peripheral model ("the comb") (b)*

2. THE CONSTRAINED MAXIMUM PROBLEM

The starting point of the new approach to the calculation of inelastic scattering cross-section is the fact that scattering amplitude has a point of constrained maximum upon the condition of the account for energy-momentum conservation law. Consider the scattering amplitude corresponding to a comb diagram on Fig. 1b.

$$T = \left(-ig(2\pi)^4\right)^2 \left(-i\lambda(2\pi)^4\right)^n \left(\frac{-i}{(2\pi)^4}\right)^{n+1} A \tag{1}$$

with

$$\begin{aligned} A = & \frac{1}{m^2-(P_1-P_3)^2-i\varepsilon}\frac{1}{m^2-(P_1-P_3-p_1)^2-i\varepsilon}\cdots \\ & \cdots\frac{1}{m^2-(P_1-P_3-p_1-p_2-\cdots-p_{n-1}-p_n)^2-i\varepsilon}, \end{aligned} \tag{2}$$

where g is a coupling constant in the outermost vertices of the diagram; λ is a coupling constant in all other vertices; m is the mass of virtual particle field and also secondary particles. As in the original version of multi-peripheral model [2], pions are taken both as virtual and secondary particles.

Energy of each particles in the finite state can be expressed by their momentum using the mass shell conditions, having $n+2$ particles in finite state, that give us $3(n{+}2)$ momentum components of these particles. Moreover, taking into account four relations, expressing the energy-momentum conservation law will result in the fact that amplitude Eq. (2) can be represented as a function of $3n+2$ independent variables. The first $3n$ variables we choose are longitudinal and transverse components of momentums $\vec{p}_1, \vec{p}_2, \ldots, \vec{p}_n$ of particles produced along the "comb". The other two variables are the transverse components of momentum $\vec{P}_{3\perp}$.

If z-axis coincides with momentum direction $\vec{P}_1$ in c.m.s. and x and y axes are the coordinate axes in the plane of transverse momentums, the conservation laws look like

$$\begin{aligned} & P_{30}+P_{40} = \sqrt{s} - (p_{10}+p_{20}+\ldots+p_{n0}), \\ & P_{3\parallel}+P_{4\parallel} = -\left(p_{1\parallel}+p_{2\parallel}+\ldots+p_{\parallel}\right), \\ & P_{4\perp x} = -\left(p_{1\perp x}+p_{2\perp x}+\ldots+p_{n\perp x}+P_{3\perp x}\right), \\ & P_{4\perp y} = -\left(p_{1\perp y}+p_{2\perp y}+\ldots+p_{n\perp y}+P_{4\perp y}\right). \end{aligned} \tag{3}$$

As was shown in [13], the scattering amplitude as a function of aforementioned independent $3(n+2)$ variables has a point of maximum, which is attained at zero transverse momentums of secondary particles. Moreover, scattering amplitude in the point of maximum can be expressed as follows [13]

$$\begin{aligned} & A^{(0),n} = \left(1+a(\sqrt{s},n)\right)^{-2}\times \\ & \times\left(1+b(\sqrt{s},n)\right)^{-(n-1)}\exp\left(c(\sqrt{s},n)\right), \end{aligned} \tag{4}$$

where

$$\begin{aligned} & a(\sqrt{s},n) = \left(\frac{1}{(\sqrt{s}/M)^{\frac{2}{n+1}}-1}\right)^2, \\ & b(\sqrt{s},n) = \left(\frac{(\sqrt{s}/M)^{\frac{1}{n+1}}}{(\sqrt{s}/M)^{\frac{2}{n+1}}-1}\right)^2, \\ & c\left(\sqrt{s},n\right) = 2\left(a^{-1}\left(\sqrt{s},n\right)+\left(\sqrt{s}/M\right)^{\frac{2}{n+1}}\right)^{-1}\times \\ & \times\left(1-(n-1)\left(\sqrt{s}/M\right)^{-\frac{n}{n+1}}a^{-\frac{1}{2}}\left(\sqrt{s},n\right)\right). \end{aligned} \tag{5}$$

The $a(\sqrt{s},n)$ and $b(\sqrt{s},n)$ determine the characteristic value of virtuality at the maximum point of scattering amplitude and $c(\sqrt{s},n)$ determines the variation of virtuality along the "comb". In other words, the following estimate takes place

$$a(\sqrt{s},n) \le \left|\left(q^{(j)}\right)^2\right| \le b(\sqrt{s},n), \tag{6}$$

where $\left|\left(q^{(j)}\right)^2\right|$ is the absolute value of virtuality corresponding to j-th internal line on the "comb" (Fig. 1b) in the point of constrained maximum.

It is useful to rewrite the energy term, which enters both sides of Eq. (6) in the form

$$\left(\sqrt{s}/M\right)^{\frac{1}{n+1}} = \exp\left(\frac{1}{n+1}\ln\left(\sqrt{s}/M\right)\right). \tag{7}$$

It is obvious that the growth of exponent with energy $\sqrt{s}$ is much weaker than the corresponding decrease with the growth of number of particles n. Thus, one can see that at not very small n the value of $(\sqrt{s}/M)^{\frac{1}{n+1}} \sim 1$ even at high energies ($\sqrt{s} >> M$). As the result, the difference of energy and longitudinal momentum squares is at least not negligible with respect to transverse momentum for each virtuality on the "comb". This result comes in contradiction with the statement that virtualities can be reduced to transverse momentum squares, which is usually claimed in the standard approach [1, 3–9]. Taking into account the growth of $(\sqrt{s}/M)^{\frac{2}{n+1}}$ with energy $\sqrt{s}$ growth, we see that virtuality at the maximum point really decreases and the maximum value of amplitude grows with the growth of energy $\sqrt{s}$. Note also that at not very small n the $(\sqrt{s}/M)^{\frac{1}{n+1}}$ is close to unity at rather wide energy range which results in the much steeper growth than the one which is attained in Regge-based theories [2,4] and described by factor of $ln^{n-2}\left(\sqrt{s}/M\right)$. Moreover, the higher n, the wider is the energy range. Thus the asymptotic behavior for different n is reached at different $\sqrt{s}$ which enables to doubt the validity of the asymptotic formulas of multi-Regge kinematics.

3. ON THE LAPLACE'S METHOD

In this section we will outline the calculation of inelastic scattering cross-section with the Laplace's method. The cross-section is described by the multidimensional integral of scattering amplitude squared modulus over the phase volume of finite state:

$$\begin{aligned} \sigma_n = & \frac{(2\pi)^8 g^4 \lambda^{2n}}{4n!\sqrt{(P_1P_2)^2-(M_1M_2)^2}}\times \\ & \times \int \frac{d\vec{P}_3}{2P_{30}(2\pi)^3}\frac{d\vec{P}_4}{2P_{40}(2\pi)^3}\prod_{k=1}^{n}\frac{d\vec{p}_k}{2p_{0k}(2\pi)^3}\times \\ & \times |A(n,p_1,p_2,...,p_n,P_1,P_2,P_3,P_4)|^2\times \\ & \times \delta^{(4)}\left(P_3+P_4+\sum_{k=1}^{n}p_k-P_1-P_2\right). \end{aligned} \tag{8}$$

Since scattering amplitude is not a product of functions of some variables, and also due to the complexity of integration domain, the multidimensional integral in Eq. (8) is not a product of smaller-dimensional ones. In considered inelastic process this domain of phase space of finite state particles is determined by the energy-momentum conservation law. As a result, the integration limits for one variable depend on the values of others. However, the existence of constrained maximum point of scattering amplitude enable to overcome these problems.

As was shown in the previous section, an integrand $A(n,P_3,P_4,p_1,p_2,\ldots,p_2,P_1,P_2)$ in Eq. (8), expressed as a function of independent integration variables, has a maximum point in the domain of integration. At the neighborhood of this maximum point it can be represented in the form

$$\begin{aligned} & A\left(n,P_3,P_4,p_1,p_2,...,p_n,P_2,P_1\right) = A^{(0),n}\left(\sqrt{s}\right) \\ & \times\exp\left(-\frac{1}{2}\sum_{a=1}^{3n+2}\sum_{b=1}^{3n+2}D_{ab}\left(X_a-X_a^{(0)}\right)\left(X_b-X_b^{(0)}\right)\right), \end{aligned} \tag{9}$$

where $A^{(0),n}(\sqrt{s})$ is the value of the function Eq. (2) at the point of constrained maximum; $D_{ab} = -\frac{\partial^2}{\partial X_a \partial X_b}\ln(A)$; the derivatives are taken at the constrained maximum point of scattering amplitude. In other words, the real and positive magnitude A determined by Eq. (2) is represented as $A = \exp\ln(A)$, and the power of the exponential function is expanded into the Taylor series in the neighborhood of the maximum point with an accuracy up to the second-order summands.The applicability of such approximation has been verified in [14].

Up to this moment we ignored the interference effects. Nevertheless, according to Wick's theorem, the scattering amplitude is the sum of diagrams with all possible orders of external lines attaching to the "comb". Therefore, partial cross-section σ_n can be represented [14, 15] as a sum of $n!$ cut diagrams on Fig. 2, and we can write down instead of Eq. (8)

$$\begin{aligned} \sigma_n = & \frac{\left((2\pi)^4\right)^2 g^4 \lambda^{2n}}{4\sqrt{(P_1P_2)^2-(M_1M_2)^2}}\times \\ & \times \int \frac{d\vec{P}_3}{2P_{30}(2\pi)^3}\frac{d\vec{P}_4}{2P_{40}(2\pi)^3}\prod_{k=1}^{n}\frac{d\vec{p}_k}{2p_{0k}(2\pi)^3}\times \\ & \times \delta^{(4)}\left(P_3+P_4+\sum_{k=1}^{n}p_k-P_1-P_2\right)\times \\ & \times \Phi\left(n,P_3,P_4,p_1,p_2,...,p_n,P_2,P_1\right), \end{aligned} \tag{10}$$

where

$$\begin{aligned} & \Phi\left(n,P_3,P_4,p_1,...,p_n,P_2,P_1\right) = \\ & A\left(n,P_3,P_4,p_1,...,p_n,P_2,P_1\right)\times \\ & \times \sum_{P(j_1,j_2,...,j_n)} A\left(n,P_3,P_4,p_{j_1},...,p_{j_n},P_2,P_1\right). \end{aligned} \tag{11}$$

Here, the summation is assumed over all possible $n!$ permutations of n indices. Each integral in Eq. (10) can be analytically evaluated using Laplace's method [10]. Finally one gets partial cross-section is expressed as follows

$$\begin{aligned} \sigma_n' = & \left(A\left(\hat{X}^{(0)}\right)\right)^2 v\left(\sqrt{s}\right)\times \\ & \times \sum_{P(j_1,...,j_n)} \frac{\exp\left(-\frac{1}{2}\left(\left(\Delta\hat{X}_j^{(0)}\right)^T\hat{D}^{(j)}\Delta\hat{X}_j^{(0)}\right)\right)}{\sqrt{\det\left(\frac{1}{2}\left(\hat{D}+\hat{P}_j^T\hat{D}\hat{P}_j\right)\right)}}, \end{aligned} \tag{12}$$

where we use the following designations: $\Delta\hat{X}_j^{(0)} = \hat{X}^{(0)} - \hat{P}_j^{-1}(\hat{X}^{(0)})$, $\hat{D}^{(j)} = \left(\hat{D}^{-1}+\hat{P}_j^T\hat{D}^{-1}\hat{P}_j\right)^{-1}$, $v(\sqrt{s}) \equiv \left(2\sqrt{s}\sqrt{s/4-M^2}\left(\frac{E_P}{2}\right)\sqrt{\left(\frac{E_P}{2}\right)^2-M^2}\right)^{-1}$ (here $A\left(\hat{X}^{(0)}\right) \equiv A^{(0),n}$ is the value of scattering amplitude at the constrained maximum point), $\hat{P}_j$ is the permutation matrix.

Note, that here and further we will use the "prime" sign in our notation to indicate that we use a dimensionless quantity that characterized the dependence of the cross-sections on energy, but not their absolute values.

4. ANALYTICAL APPROXIMATION FOR INTERFENCE CONTRIBUTIONS

Each interference contribution in Eq. (12) can be calculated numerically, for instance by the Lagrange method. However, the large number of terms in Eq. (12) represents the severe computational difficulty, which we are able to overcome only for the number of particles $n \leq 8$. Therefore, we introduce an analytical approximation for calculating the sum of interference contributions at any multiplicity of final-state particles.

The essence of our method is as follows. multidimensional volume cutout by resulting Gaussian function from an integration domain (which we call the "width" of the maximum). If we compose the n-dimensional vector (we denote it through $\vec{y}^{(0)}$) from the particle rapidities, maximizing the function associated with the diagram with the initial arrangement of momenta (left-hand side part of "cut" diagram on Fig. 2), then vectors maximizing the functions with another momentum arrangement will differ from the initial vector only by the permutation of components (right-hand side part on Fig. 2), i.e., these vectors have the same length.

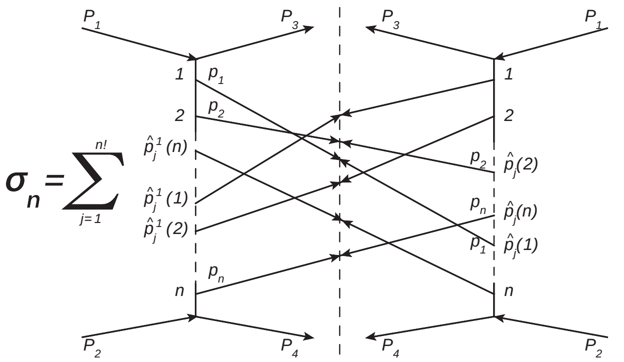


Fig. 2. *Representation of the partial cross-section as a sum of "cut" diagrams. The order of joining of lines with four-momenta p_k from the left-hand side of the cut is as following: the line with p_1 is joined to the first vertex, the lines with p_2 is joined to the second vertex, etc. The order of joining of lines from the right side of cut corresponds to one of the $n!$ possible permutations of the set of numbers $1, 2, \ldots, n$. Here $\hat{P}_j(k), k = 1, 2, \ldots, n$ denote the number into which a number k goes due to permutation $\hat{P}_j$. An integration is performed over the four-momenta p_k for all "cut lines" taking into account the energy-momentum conservation law and mass shell condition for each of p_k*

Consider two such n-dimensional vectors, one of which corresponds to the initial arrangement, and another — to some permutation, then in the n-dimensional space it is possible to "stretch" a two-dimensional plane on them (as a set of their various linear combinations), where two-dimensional geometry takes place. Therefore, the distance r will be determined by cosine of an angle between the considered equal on length n-dimensional rapidity vectors in the two-dimensional plane, "stretched" on them. An angle corresponding to the $\hat{P}_j$ permutation we designate through θ_j, $0 \leq \theta_j \leq \pi$.

Thus, each of the terms in the sum Fig. 2 can be uniquely match to its angle θ_j. At the same time the variable $z = \cos(\theta)$ is more handy for consideration than an angle θ_j.

It has been shown [15] that the value of each interference contribution can be approximately represented as a unique function $\sigma'_n(z)$ of z in the following way

$$\sigma'_n(z) = \sigma'_n(1) \exp\left(\frac{\left|\vec{y}^{(0)}\right|^2 \mathrm{Tr}\left(\hat{D}_y\right)}{2n}(z-1)\right). \quad (13)$$

Here $\sigma'_n(1)$ is the interference contribution, corresponding to a "cut" diagram with initial line rearrangement of momenta ("ladder" type diagram).

Thus, now we have the dependence for the value of interference contribution on z. The only thing left is to find out, how many contributions correspond to some given interval $[z; z+dz]$ or, in other words, the intereference contribution density function.

It turns out [15] that the ends of vectors $\hat{P}_j^{-1}\left(\vec{y}^{(0)}\right)$ are uniformly lying on the sphere in $n-1$ dimensional space. The interval $[z; z+dz]$ corresponds to a belt on this sphere, and one gets the density function [15]

$$\rho(z) = \frac{n!}{\sqrt{\pi}} \frac{\Gamma\left(\frac{n-1}{2}\right)}{\Gamma\left(\frac{n-2}{2}\right)} \left(1 - z^2\right)^{\frac{n-4}{2}}, \quad (14)$$

where Γ is the Euler's gamma function. The number of interference contributions corresponding to $[z; z+dz]$ is equal to

$$dN(z, dz) = \rho(z)\, dz. \quad (15)$$

And the partial cross-section can be approximately represented as

$$\sigma'_n = \int_{-1}^{1} \sigma'_n(z) \rho(z)\, dz. \quad (16)$$

Substituting Eqs. (13), (14) into Eq. (16) we get an analytical approximation for calculating the partial cross-section as a sun af all interference contributions. The comparison of this approximation with the "exact" cross-sections, for which all the interference contributions were calculated directly (Eq. (12)) is given in Fig. 11 of [15] for relatively small n ($n = 8, 9$).

5. TOTAL AND INELASTIC SCATTERING CROSS-SECTION

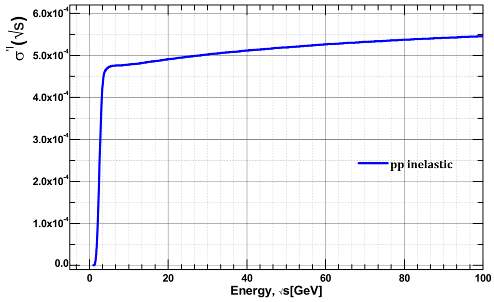
Finally, since we have an expression for calculating partial cross-sections σ'_n which can be evaluated at any multiplicity of final-state particles, let's proceed to the expression for the total and inelastic scattering cross-sections:

$$\sigma'^{\Sigma}\left(\sqrt{s}\right) = \sum_{n=0}^{n_{\max}} L^n \sigma'_n\left(\sqrt{s}\right), \quad (17)$$

$$\sigma'^{I}\left(\sqrt{s}\right) = \sum_{n=1}^{n_{\max}} L^n \sigma'_n\left(\sqrt{s}\right). \quad (18)$$

Within the framework of the examined ϕ^3 model $\sigma'^{\Sigma}\left(\sqrt{s}\right)$ is the analogue of total scattering cross-section. Here n_{max} is the maximum number of secondary particles allowed by energy-momentum conservation law and L is the dimensionless coupling constant, which we considered as an adjustable parameter. Fitting the constant L we achieve a qualitative agreement $\sigma'^{I}(\sqrt{s})$ and $\sigma'^{\Sigma}(\sqrt{s})$ with observed in proton-proton collisions [16,17] dependences on $\sqrt{s}$. The result of such a fitting presented in Fig. 3 and it qualitatively agrees with experimental data not only at the high energies that is usually accepted in the Regge based theories, but also near the threshold of two-particle production (the first minimum of the total cross section Fig. 3, c). This is due to the fact that the proposed method of calculation does not require any approximations, based on the asymptotically large energies. This may indicate that the experimentally observed behavior of cross sections is determined not by high energy asymptotic of the scattering amplitude as it is assumed in the contemporary approaches [8, 9, 11, 12].

However, the quantitative agreement with the experimental results requires the application of more realistic model than the self-acting scalar ϕ^3 field model.



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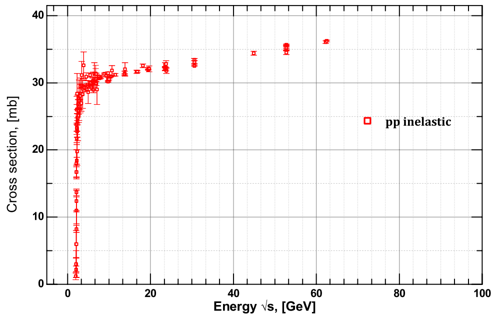

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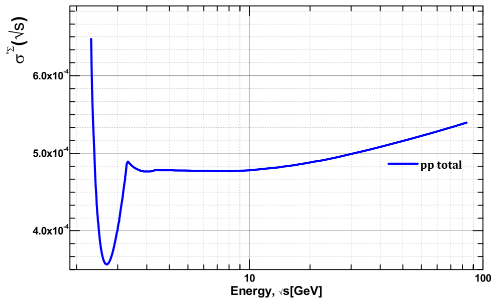

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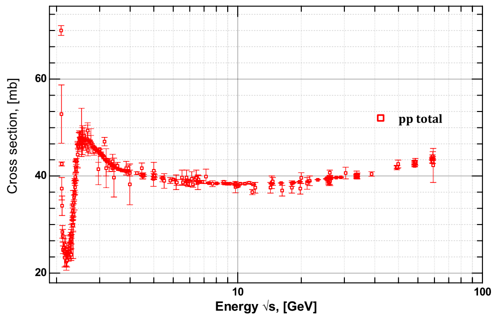

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Fig. 3. *Theoretical dependences of the* $\sigma'^{I}(\sqrt{s})$ *(a) and* $\sigma'^{\Sigma}(\sqrt{s})$ *(c) obtained for the energy range* $\sqrt{s} = 1 \div 100$ Gev *at* $L = 5.51$. *First minimum for the total cross-section can be obtained only when we take into account contributions from the high multiplicities. Experimental data for the inelastic (b) and for the total (d)* pp *scattering cross-section Ref. [16, 17] are presented for qualitative comparison with the prediction from our model. Note: data-points for the inelastic cross-section are obtained from the definition* $\sigma_{inel} = \sigma_{total} - \sigma_{elastic}$

6. CONCLUSIONS

A new method for the calculation of partial inelastic scattering cross-section which, contrary to the state-of-the-art approaches, takes into account the energy-momentum conservation law is presented.

It has been shown that the main contribution to integral expressing inelastic scattering cross-section comes not from multi-Regge domain.

The results for calculated total and inelastic scattering cross-section qualitatively agree with experiment.

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ПРОБЛЕМЫ УЧЕТА ЗАКОНА СОХРАНЕНИЯ ЭНЕРГИИ-ИМПУЛЬСА И ИНТЕРФЕРЕНЦИОННЫХ ЭФФЕКТОВ В АДРОН-АДРОННЫХ ВЗАИМОДЕЙСТВИЯХ

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Предложен новый метод расчета сечения неупругого адрон-адронного рассеяния, не основанный на предположениях Редже-кинематики и точно учитывающий закон сохранения энергии-импульса. В результате расчетов, основанных на методе, был выявлен новый механизм роста сечений, связанный с вкладом продольных компонент импульса в амплитуду неупругого рассеяния. Было показано, что интерференционные слагаемые, возникающие вследствие тождественности адронов в конечном состоянии, вносят значительный вклад в сечение, и могут быть посчитаны в рамках аналитического приближения, представленного в работе. В итоге, путем подгонки только одного свободного параметра модели было получено качественное согласие с экспериментальными данными по неупругому и полному сечениям протон-протонного рассеяния.

ПРОБЛЕМИ ВРАХУВАННЯ ЗАКОНУ ЗБЕРЕЖЕННЯ ЕНЕРГІЇ-ІМПУЛЬСУ ТА ІНТЕРФЕРЕНЦІЙНИХ ЕФЕКТІВ В АДРОН-АДРОННИХ ВЗАЄМОДІЯХ

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Запропоновано новий метод розрахунку перерізу непружного адрон-адронного розсіяння, не заснований на припущеннях Редже-кінематики, такий що точно враховує закон збереження енергії-імпульсу. У результаті розрахунків, заснованих на методі, було виявлено новий механізм зростання перерізів, що пов'язаний з внеском поздовжніх компонент імпульсу в амплітуду непружного розсіяння. Було показано, що інтерференційні доданки, що виникають внаслідок тотожності адронів в кінцевому стані, вносять значний внесок в переріз, і можуть бути розраховані в рамках аналітичного наближення, представленого у роботі. У підсумку, шляхом підгонки лише одного вільного параметра моделі було отримано якісне узгодження з експериментальними даними по непружному і повному перерізам протон-протонного розсіяння.