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HIGH ENERGY SOLLISIONS OF HADRONS AT THE SONSTITUENT QUARK LEVEL

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HIGH ENERGY COLLISIONS OF HADRONS AT THE CONSTITUENT QUARK LEVEL

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Abstract

The role of events is studied in which more than one pair of constituent quarks participate, including analysis of shadow effects, diffractive dissociations and multiplicity distribution. It increases with energy and significant changes at CERN $p\bar{p}$ Collider energy are predicted, reflecting the about 100% grouth of quark-quark cross section.

1. Introduction

Discovery of the fundamental theory of strong interaction, the quantum chromodynamics (QCD), has provided the solid ground for the understanding of hadronic physics. However, so far the main progress is related with hard processes, for which QCD can be applied in its simplest, perturbative form. The nonperturbative QCD turns out to be very complicated and our progress here is more slow. One of the recent achievements is the so called QCD sum rule method, suggesting at least some ideas concerning the boundaries of the asymptotic freedom domain. We refer to original works [1] and subsequent papers for details and only mention that depending on particular example the perturbative behaviour is violated at virtualities $Q^2 = 1\text{-}10\ \mathrm{GeV}^2$.

At the same time, hadronic dimensions are of the order of 1 fermi, respectively the typical momentum transfer in soft processes is only about 0.1 GeV^2. So, before we will be able to understand them we have to deal with phenomena taking place at Q^2 about 1 GeV^2.

This was the subject of the recent works of one of the authors [2], in which the existence of two scales in QCD was suggested. According to this picture, confinement forces are far from being the strongest nonperturbative effects in QCD vacuum, while the energy density about one order of magnitude larger is related to strong instanton-type fluctuations of relatively small dimensions. Among other effects, their interaction with quarks inside hadrons leads to some "bubbles" around them, identified with constituent quarks.

Resulting picture of hadrons as being made of spatially separated constituent quarks is not new, of course. It was suggested on phenomenological grounds many times since the pioneer works [3], but only during last few years new analysis of broad range of data (see sections 2,3) has demonstrated its reality good enough. Therefore we believe that now the so called additive quark model is not just one of the models, but the most fundamental outcome of studies of soft hadronic physics.

Being more specific, it provides rather general framework for the discussion of hadron-hadron and hadron-nuclei collisions at high energies, as a combination of more fundamental subprocesses at constituent quark level. Such view point opens new perspectives for real understanding of these phenomena.

The present situation with their understanding is rather unsatisfactory. Experimental data on inclusive spectra are reasonably well fitted by multiple models, using conflicting and sometimes quite arbitrary assumptions.

One of the main difficulty in understanding of high energy collisions is the fact that it is very fluctuating phenomenon. By this we mean that all parameters of the collision may differ by the order unity from one event to another. This fact suggests that there exist completely different interactions, all mixed together in inclusive measurements.

To give an example, let us mention diffractive dissociation of one or two hadrons which is considered as separate phenomenon with its own physics. So, the problem is to formulate some qualitatively different types of interactions and try to study them separately, not in the inclusive sum.

The additive quark model suggests as such interaction types events in which different number of constituent quarks are involved. The main content of the present work is to study such possibility at semiquantitative level.

Before we outline the content of this work in more details one more general comment is needed. We do not use any particular dynamical model describing constituent quark collisions. Our aim is purely phenomenological: to extract these properties from data concerning hadron-hadron collisions. We make some simplifying assumptions, mostly suggested by earlier works, but they do not seem to be very important. Our results, the properties of quark-quark interactions, can be considered as a subject for further theoretical studies in any theoretical framework, e.g. that of Reggion phenomenology, parton model, hydrodynamical model etc.

The next two sections are devoted to discussion of main observations and main questions concerning constituent quarks.

Such mini-review should partly compensate for the absence of comprehensible discussion of all these questions in literature. Section 4 is devoted to shadow corrections in hadronic collisions, which allow for determination of our main parameter, quark-quark cross section. Then we come to calculation of diffractive dissociation (section 5) and probabilities of multiquark interactions (section 6). Section 7 is devoted to multiplicity distribution and the last section 8 contains some implications for future experiments.

2. Constituent quarks
The main observations

Let us start with the original statement [3], present in any textbook related with modern physics:

(i) Hadrons consist of quarks.

However, the meaning of the word "consist" should be explained. First of all, quark flavours give the famous SU_3 classication of hadrons. Second, it was much more nontrivial idea that quarks are dynamical objects in the meaning of nonrelativistic quantum mechanics, so that "the hadron wave function" in terms of quarks makes sense. After some period of misunderstanding it was clearly stated by Gell-Mann that "constituent" and "current" quarks are completely different objects. The former are massive and of finite size, their theoretical status is unclear. The latter are nearly massless and pointlike, they are objects of the field theory. Recently R.Hwa has proposed the new word "valon" for constituent quark.

The central idea of the additive quark model is:

(ii) Constituent quarks interact independently at high energies.

It was first suggested in [4] on the basis of famous experimental relation:

$$\sigma_{\pi N} / \sigma_{NN} \simeq 2/3 \qquad (1)$$

Similar ideas were expressed in [9] for elastic or quasielastic processes.

For many years the statement (ii) was considered as some interesting but questionable possibility. The situation seems to be changed now due to analysis of hadron-nuclei collisions, see review papers [5,6] for details and references. The main point is that data reasonably well correspond to calculated probability for one, two and three quarks of the projectile to interact. There are striking indications that interaction of quarks is really independent. To give an example, let us mention the Anisovich ratio for multiplicities [8]:

$$\langle n\rangle_{\pi A} / \langle n\rangle_{NA} \xrightarrow[A\to\infty]{} 2/3 \qquad (2)$$

Another one, discussed in [6,7], is related to correlation data. In particular, the ratio $\mathcal{D}/\langle n\rangle$ ($\mathcal{D}^2 \equiv \langle n^2\rangle - \langle n\rangle^2$) for events with large number of knocked out protons is smaller than that for small number of protons by $1/\sqrt{3}$ for the incoming proton and $1/\sqrt{2}$ for pion. It means, that we really have 3 or 2 collision centers similar to those in hadronic collisions.

In order to explain quark additivity it was suggested that

(iii) Dimensions of the constituent quarks are essentially smaller than that of hadrons.

One of the arguments considered in [5] is based on the expression [9] for elastic amplitude

$$\frac{d\sigma}{dt}(a+b \to a+b) = F_a^2(t)\, F_b^2(t) \exp\left(\alpha' t \ln\frac{s}{s_0}\right) \qquad (3)$$

where F(t) is the e.m. formfactor, and the last factor is connected with the structure of constituent quark. This suggests that

(iv) Interaction range of constituent quarks grows with collision energy

and produces the estimate

$$r_q^2 \simeq \frac{3}{2}\alpha' \ln\frac{s}{s_0} \qquad (4)$$

Whatever is the real accuracy of such estimate, it definitely leads to the prediction [10] of violation of quark additivity in its simplest form $\sigma_{NN} = 9\sigma_{qq}$ at very high energy, at which (4) is comparable with hadronic dimensions. The fragmentation region, normally determined by spectator quarks 11 , should also be qualitatively changed. These questions we are going to discuss in more details below.

Another simple estimate of the quark interaction range is connected directly with quark-quark cross section. Assuming them to interact as black discs [12] one has

$$\sigma_{qq} \simeq \frac{1}{9}\sigma_{NN} \simeq 2\pi(2r_q)^2 \quad , r_q \simeq 0.15\,\mathrm{fm} \qquad (5)$$

However, as noted in [14], quarks can not interact as black discs because

(v) Interaction probability of constituent quarks should strongly fluctuate

The basis for this statement is given by data on diffractive dissociation, see section 5.

Since the works [13] it became usual to consider the simplest model in which quark has two states, "active" and "passive", with probabilities P_q and $(1-P_q)$ respectively. These works consider mainly shadow effects in collisions with nuclei, their estimated $P_q \simeq 0.6$ which is consistent with our results below.

However, as we show in section 5, even "active" quarks can not interact with a profile of black disc, for it gives too large cross section of diffractive dissociation. The gaussian-type profile is about of needed form. All this, of course, shows that the constituent quark itself has complicated internal structure.

3. Constituent quarks
The main questions

Recognizing constituent quarks as a true building blocks of hadrons in soft hadronic reactions one may ask many questions concerning their properties and interaction. The first obvious question is

(i) How hadrons are made of constituent quarks? What is hadronic wave function?

As far as we are going below to calculate probabilities of constituent quark to interact, we are mainly interested in the quark distribution in the plane orthogonal to collision axis. In principle, the quark cross section is energy dependent and therefore depends on longitudinal momentum fraction as well, but this dependence is weak and we neglect it.

For simplicity we use Gaussian shape of the wave function, in which transverse and longitudinal momenta are separated. For nucleons and pions we use the following wave functions

$$\Psi_N = e^{-(\vec{b}_1^2+\vec{b}_2^2+\vec{b}_3^2)/2R_N^2}\ \delta^2(\vec{b}_1+\vec{b}_2+\vec{b}_3)$$

$$\Psi_\pi = e^{-3(\vec{b}_1^2+b_2^2)/2R_\pi^2}\ \delta^2(\vec{b}_1+\vec{b}_2) \qquad (6)$$

where we have fixed the particle center. Integration over its position is also done, it defines the impact parameter of hadrons as whole. Both functions (6) lead to formfactor

$$F(t) = \exp\left(\frac{1}{6}R^2 t\right) \qquad (7)$$

which is, of course, different from precise experimental formfactor shape. Still it is able to describe it reasonably in the region where formfactor is not small. We use the following values of the parameters

$$R_N = 0.75\,fm\ , \qquad R_\pi = 0.56\ fm \qquad (8)$$

Apart from approximate shape of the wave function, one may ask why quarks are not correlated inside hadrons. From theoretical side this question is discussed in the work 2 . It is demonstrated that instantons produce strong attraction at distances comparable to their size for pions, but not for mesons or nucleons. The resulting clustering of constituent quarks may qualitatively explain why deviations from (1) have different sign compared to shadow corrections found below.

The main content of the present work is connected with a question

(ii) How constituent quarks interact in high energy collisions?

Let us make here some general remarks. It can be asked how the

quark-quark cross section depends on relative colour and flavour states. For example, introducing cross sections for any colour states one may write

$$\frac{\sigma_{\pi N}}{\sigma_{NN}} = \frac{\frac{1}{9}\sigma_0^{q\bar{q}} + \frac{8}{9}\sigma_8^{q\bar{q}} + \frac{1}{3}\sigma_{\bar{3}}^{qq} + \frac{2}{3}\sigma_6^{qq}}{3\left(\frac{1}{3}\sigma_{\bar{3}}^{qq} + \frac{2}{3}\sigma_6^{qq}\right)} \qquad (9)$$

It can be equal to 2/3 in two simple limiting cases: no dependence on colour at all and one-gluon exchange in which

$$\sigma_0^{q\bar{q}} : \sigma_8^{q\bar{q}} : \sigma_{\bar{3}}^{qq} : \sigma_6^{qq} = 64:1:16:4 \qquad (10)$$

Note also, that already in second approximation in α_s the cross sections qq and $q\bar{q}$ are no longer equal and (9) is violated. The possibility that physical nature of quark interaction is just the one gluon exchange, leading to creation and breakdown of colour tubes are intensly discussed since the works [15]. However, it is difficult to explain in this case the observed dependence on quark flavour

$$\sigma_{uu} : \sigma_{su} : \sigma_{cu} = 1 : 0.5 : 0.1 \qquad (11)$$

It is also difficult to understand why constituent quarks, which are evidently of nonperturbative origin, interact in the simple perturbative way.

Let us note, that such strong dependence on quark mass is consistent with the instanton mechanism. Really, as it was first found by t'Hooft, light quarks interact strongly with instantons, while heavy quarks do not. The strange quark is the intermediate case because its mass is of the order of that generated by instantons, see [2] for details.

This question can be studied experimentally, in particular in photoproduction of upsilons on heavy nuclei. We predict b quark to be so "passive" that no shadowing be seen.

Our last comments concerns the question

(iii) What is the constituent quark structure?

It is clear that this question should be answered by hard collisions, in which the constituent quarks are split up to current quarks and gluons. In papers [16] deep inelastic scattering on constituent quark is studied, as well as of the nucleon wave function in terms of constituent quark.

Next level of considerations, including the so called higher twist physics, can in principle provide much more. In simplest parton model language the question deals with parton transverse momentum, e.g. determined from measurements of Drell-Yan pairs of leptons. It turns out that they are very large, about 1-2 GeV (see e.g. discussion in [17]), which suggests that partons are confined in the object much smaller than hadrons. More detailed analysis in the operator product expansion method is contained in [18]. The analysis of data on scaling violation provides, roughly speaking, the probability to find two quarks in the same point, which turns out to be one order of magnitude larger than that given by valent quarks alone. So, one more evidence for complicated structure of constituent quark is given.

4. Shadow effects in hadron-hadron collisions

According to additive quark model most cases of hadron-hadron collisions are related with interaction of only one pair of constituent quarks. However, there are also more complicated events resulting in shadow corrections to simple relations

$$\sigma_{NN} = 9\,\sigma_{qq} \quad , \quad \sigma_{\pi N} = 6\,\sigma_{qq} \qquad (12)$$

Such effects for hadron-nuclei collisions were considered in the works [13]. Apart from some methodical differences of our calculations, the main difference is due to the fact that in hadron-hadron case one has to consider fluctuations of the target and projectile simultaneously, while nuclei were considered in [13] as nonfluctuating optical potential. We also consider the case of very high energies, of the order of CERN collider and even higher.

We have chosen quark-quark interaction to be of Gaussian shape (see more on this in next section):

$$P_{int} = \exp\left(-\vec{b}^2 / 2 r_q^2\right) \qquad (13)$$

This expression is assumed to be valid for <u>active</u> quarks, so the probability of the interaction involving n quarks also contains P_q^n.

This simple model and wave functions (6) allows us to calculate the average probability for two hadrons to interact at impact parameter b , let us call it W(b) . The well known expressions give us total and elastic cross sections

$$\sigma_{tot} = 2\int \langle W(b) \rangle\, d^2b \quad , \quad \sigma_{el} = \int \langle W(b) \rangle^2 d^2b \qquad (14)$$

The main parameter in this calculation is not P_q and r_q separately, but quark-quark cross section

$$\sigma_{qq} = 4\pi r_q^2 P_q^2 \qquad (15)$$

Therefore, results of our calculations are plotted at Fig. 1 as the dependence of the ratio σ_{hh}/σ_{qq} on σ_{qq}.

The calculations were done by the Monte-Carlo simulation of the "events" with definite positions of all quarks in the transverse plane and definite "activities". Let us add, that apart from the region of very small σ_{qq} (not physically relevant) several hundreds of events at each impact parameter was sufficient to obtain accuracy of several percent.

A few words about the limit $\sigma_{qq} \to \infty$. It was assumed in 10 that such limit is reached as soon as quark cross section becomes compatible with that of hadrons. We see that approach to it is very slow. In principle, for $\sigma_{qq} \to \infty$ the probability for all three quarks of the nucleon to be passive is $(1-P_q)^3$, or negligible, so the nucleon acts as an active quark and the ratio considered has a limit about $(P_q)^{-2} \simeq 3$.

Although the shadowing effects behaviour is not very dramatic, it is surely important for quantitative consideration of values of quark-quark cross sections. Using Fig. 1 and experimental data $\sigma_{NN}^{tot} = 39$ mb ($s = 400$ GeV^2) and 66 mb ($s = 10^5$ GeV^2 [19]) we have the following estimates for respective values of quark-quark cross sections

$$\sigma_{qq}(s=400) \simeq 5.7\ \text{mb} \quad , \quad \sigma_{qq}(s=10^5) \simeq 10\ \text{mb} \qquad (16)$$

Note that σ_{qq} grows with energy stronger than σ_{NN}, which is exactly the effect of shadowing corrections.

Our calculations give the following values of elastic cross sections:

$$\sigma_{el}^{NN}(s{:}400) \simeq 6.2 \text{ mb} \qquad (6.8)$$
$$\sigma_{el}^{NN}(s{:}10^5) \simeq 12 \text{ mb} \qquad (12.7) \tag{17}$$

The numbers in brackets are experimental values, the second is derived from the Gaussian parameterization of $\langle w(b)\rangle$

$$\langle w(b)\rangle = \frac{\sigma_{tot}}{4\pi B}\exp\left(-\frac{b^2}{2B}\right), \ \sigma_{el} = \frac{\sigma_{tot}^2}{16\pi B} \tag{18}$$

and the measured value of the elastic slope $B \simeq$ 17 GeV^2 [19].

Although the agreement is very good, the direct comparison of calculated $\langle w(b)\rangle$ with (18), shown at Fig. 2, demonstrate some deviations at b = 0, not very important for integrated cross sections. Unfortunately, we do not know the accuracy of gaussian fit (18) in this region as well.

Finally, in the same model we have calculated properties of pion-nucleon interactions:

$$\sigma_{tot}^{\pi N}(s=400) = 28.6 \text{ mb} \ (24), \quad \sigma_{el}^{\pi N}(s=400) = 4.3 \text{ mb} \ (3.0)$$
$$\sigma_{tot}^{\pi N}(s=10^5) = 49 \text{ mb} \quad , \quad \sigma_{el}^{\pi N}(10^5) = 9.3 \text{ mb} \tag{19}$$

Analogous result can be calculated for KN scattering, in this case new parameter is the cross section of the strange quark.

Our last remark in this section deals with energy behaviour of hadronic cross sections. Assuming the quark-quark cross section to be more fundamental and having some simple energy behaviour, say the Froissart one, one may then use results plotted at Fig. 1 to have NN and π N cross sections. In this way the nearly constant cross sections at s = 10-1000 GeV^2 is connected with growth of shadowing, significantly compensating the growth of σ_{qq}. At much higher energies shadowing is surprisingly constant, as seen from Fig. 1, so the proportionality between σ_{hh} and σ_{qq} is restored.

5. Diffractive dissociation

The physical nature of this phenomenon was clarified in papers [20]. It is due essentially to complicated structure of hadrons, which can be found in states with very different ability to interact. As a result, the through-going wave is not just the weakened incoming one, therefore it decays into some states more complicated than just one nucleon.

This general argument is clearly demonstrated by the expression [21] for the diffractive dissociation cross section:

$$\frac{d\sigma^{dd}}{d^2b} = \langle w^2(b)\rangle - (w(b))^2 \tag{20}$$

where, as before, W(b) is the probability to interact in some state of the system at impact parameter b, and angular brackets mean the average over all states. Comparing (20) and (14) one can obtain the so called Pumplin bound

$$\frac{1}{2}\frac{d\sigma^{tot}}{d^2b} - \frac{d\sigma^{el}}{d^2b} - \frac{d\sigma^{dd}}{d^2b} = (\langle w(b)\rangle - \langle w^2(b)\rangle) > 0 \tag{21}$$

where the nonequality follows from $W(b) < 1$.

In the work [14] some model was used for more quantitative discussion of this phenomenon. It was shown there that there are essentially two sources of fluctuations: those in the number of constituents and in impact parameter. The latter is more peripherial and have a dip at b = 0, so if it is the only one present (which is the case if P_q = 1) the same is predicted for total diffraction, which is experimentally wrong. In other terms, in any model with nonfluctuating constituents the forward diffraction is zero due to orthogonality of the wave functions.

Comparing our calculations with those in [14] we may say that, first of all, our model is more realistic, and second, the fluctuations of the target and the projectile are taken into account simultaneously. By the way, dissociation cross section found in [14] is related with projectile dissociation only, for only its fluctuation is considered. Its identification with $^1/2$ of the total cross section of diffractive dissociation made in [14] is just a crude approximation.

The first point we are going to consider is the shape of the quark-quark interaction profile. The interaction of the black discs is not in agreement with data in very general context. Really, if the ensemble of W consists of only W = 0 and W = 1, then the Pumplin bound (21) is reached. Experimentally, diffractive cross section is essentially smaller.

So, we have considered the Gaussian shape (13). In our Monte-Carlo set of events we have certain ensemble of W, so the calculation of the dispersion (20) is straightforward.

With the values of the quark activity P_q = 0.6-0.65 suggested in earlier works [13] we have found the following values of the diffractive cross section with inelastic excitation of any of the colliding hadrons

$$\sigma_{dd}^{NN}(s=400) \simeq 6\,mb \qquad (6.2\,mb) \tag{22}$$

$$\sigma_{dd}^{NN}(s=10^5) \simeq 9.5\,mb$$

The number in brackets is the experimental value, and the agreement is good enough. The profile of this cross section is shown at Fig. 2 by the dotted line for each energy. Dip at b = 0 is absent, for quarks can fluctuate in the model considered.

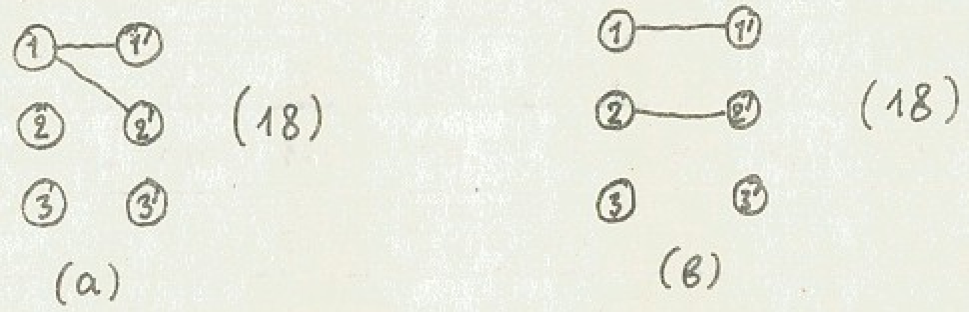
The measurements of diffractive dissociation cross section at CERN Collider is very interesting: it can show whether P_q is really energy independent and is the intrinsic quark property, as assumed in our estimates.

6. Probabilities of the multiquark processes

Having demonstrated that the model is able to describe well the average probability of hadronic interactions (in section 4) and even the dispersion of this probability (in section 5) we are encouraged to estimate the probabilities for more

complicated phenomena such as multiquark interactions.

There exist two types of double interactions, involving 3 and 4 quarks, respectively:



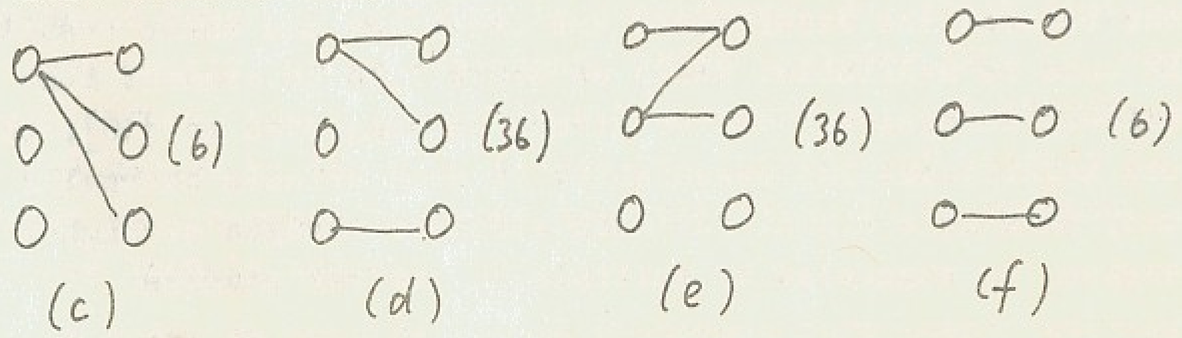
(18)

Notations are selfevident, circles are quarks of one and another nucleon, lines are interactions and the numbers in brackets is the number of combinatorial combinations of such type. The correspondant probabilities are

$$(a)\quad (P_q)^3 \exp\left\{-\left[(\vec{b}_1-\vec{b}_{1'})^2+(\vec{b}_1-\vec{b}_{2'})^2\right]/2r_q^2\right\} \tag{23}$$

$$(b)\quad (P_q)^4 \exp\left\{-\left[(\vec{b}_1-\vec{b}_{1'})^2+(\vec{b}_2-\vec{b}_{2'})^2\right]/2r_q^2\right\}$$

We also consider triple interactions, which are of four types:



and neglect more complicated possibilities. Note, that even quartic interactions involve 5 out of 6 quarks with nearly unit probability, so it is hardly possible to separate their multiple types.

The results of our calculations for two energies are as follows:

	dd	"qq"	a	b	c	d	e	f
$S=400$, NN	.16	.60	.142	.060	.005	.013	.033	.001
$S=400$, N	.19	.63	.105	.040	.003	.005	.030	0
$S=10^5$, NN	.18	.43	.18	.11	.011	.031	.070	.0025
$S=10^5$, N	.155	.52	.17	.070	0.007	.012	.065	0

(24)

where we have also included the probabilities of diffractive dissociation P_{dd} and of nondiffractive single interaction of one quark pair P_{qq}. The numbers in (24) are $\rho_i = \sigma_i / \sigma_{inel}$.

These results allow us to make some predictions concerning fragmentation at Collider energies, $S \simeq 10^5$ GeV^2.

(i) Spectra at $x \simeq 2/3$, connected with spectator diquark, should decrease by about 20% as compared to $s \simeq 10^2$ GeV^2 region.

(ii) Spectra at $x \simeq 1/3$, related with fragmentation of a spectator quark, should increase by the factor about two.

It is not reasonable now to present more detailed calculations because the experiments are under way and their results will soon be available. Still we would like to comment that the predicted changes are not so strong as suggested in [10], but quite significant and measurable. If such effects be really found, this is a signal for much stronger changes at higher energies, as suggested by multiple cosmic ray studies.

7. Multiplicity distribution

The striking property of the multiplicity distribution in hadronic collisions is its nonstatistical character. Although the number of particles can be rather large, the dispersion $\mathcal{D}$ ($\mathcal{D}^2 \equiv \langle n^2\rangle - \langle n\rangle^2$) does not behave as $\langle n\rangle^{1/2}$, but is proportional to $\langle n\rangle$. The more strong statement of such type is known as the KNO scaling [22]:

$$P_n = \frac{\sigma_n}{\sigma_{in}} = \frac{1}{\langle n\rangle} \psi\left(\frac{n}{\langle n\rangle}\right) \qquad (25)$$

However, the physical nature of such behaviour is not so far clear. Its relation to Feynman scaling, discussed in [22], is not so evident, in addition, the Feynmann scaling is violated more strongly. However, for our discussion below it is important that the KNO scaling is violated as well, the available data on P_n [22-25] are shown at Fig. 3 as $C_q = \langle n^q\rangle / \langle n\rangle^q$.

As we have already discussed in the introduction, such broad distribution is probably related to mixture of some qualitatively different phenomena. The particular dynamical schemes have suggested such examples, for example, in Regge phenomenology the contribution of cuts produce double multiplicity as compared to pomerons, etc.

In the additive quark model the natural candidates are the multiquark subprocesses. Qualitatively, it allows one to understand the approximate KNO scaling and its slow violation in certain direction with the energy growth.

The probability of several quarks to interact in one collision event is determined mainly by the quark-quark cross section. Its energy dependence is rather weak and is seen only if very broad range of energies is considered. So, their probabilities are weakly energy dependent, which explains KNO. In second approximation, their probability is increasing with energy, so the KNO should be violated toward the increase of moments C_q , showing the increase in large multiplicities to be somehow stronger than in average ones.

In order to consider these phenomena more quantitatively one needs to know: (1) the probabilities of multiquark subprocesses and; (2) the multiplicity distribution corresponding to them. The former ingredient was estimated above, the latter one needs some assumptions to be additionally made.

Let it be the simplest statistical assumption, the Poisson distribution of tracks with negative charge. It has only one parameter, the average multiplicity, which is essentially known for two main subprocesses "a" and "b".

For the case "b" we have just two independent collisions of two pairs of quarks, evidently

$$\langle n\rangle_b = 2\langle n\rangle_{qq} \qquad (26)$$

For the case "a" we may use data for hadron-nuclei collisions, in which collisions of quark with ν ones is the dominant process. For power fit

$$\langle n \rangle_{q-\nu q} = \nu^{\alpha} \langle n \rangle_{qq} \tag{27}$$

one have $\alpha \simeq 0.7$, see e.g. [7]. Such behaviour is suggested by the model [26], but now we are just interested in the experimental fact.

With the assumptions specified above we may try to estimate the shape of the multiplicity distribution and its evolution with energy. The results are shown at Fig. 4-6 for energies $s = 400,\ 4000,\ 1.5 \cdot 10^5$ GeV^2, respectively, together with data [23-25]. Note, that the contribution of diffractive events is present in data, but it is not included in the model. Therefore, disagreement as small n_{ch} should not be taken seriously.

It is seen that general agreement at lowest energy is the worst, probably Poisson is too broad and one should also account for negative correlations due to conservation laws.

At larger energies the agreement is better and we consider the results to be satisfactory for so simplified model. The essential lesson from these calculations is that narrowing of the Poisson and the growth of multiquark event rate can nearly ideally compensate each other, approximately conserving the KNO shape of the experimental distribution. We think this is a real explanation of the KNO scaling. Note also, that for πN case predictions are very similar, see the results (24).

8. Summary and conclusions for experiments

Assuming constituent quarks to be the true building blocks of hadrons in soft hadronic reactions one can ask a lot of questions concerning the properties of these objects. In fact they have all the properties relevant for hadrons themselves: total and elastic cross section, diffractive dissociation, one can speak about the average multiplicity in quark-quark collision etc. In first approximation in hadron collisions we have interaction of only one pair of quarks, so the relation between the hadronic and constituent quark properties are very simple. In next approximation one should include shadowing and other phenomena related to multiquark subprocesses. This was attempted in the present work.

With parameters of quark-quark interaction $P_q = 0.6 - 0.65$ and r_q (depending on collision energy) we have calculated total and elastic cross sections as well as that of diffractive dissociation. They all agree with data reasonably well for NN and N cases, demonstrating reliability of the model used. We have also estimated the probabilities of multiquark subprocesses, and have calculated multiplicity distribution using some additional simple assumption. The results again reasonably well describe data.

We think therefore that the main idea of the present work, of the existence of several qualitatively different collision types due to different number of quarks involved, deserves further experimental investigations. In order to make them one have to use detectors much more complicated than those for inclusive measurements. The experimental information about each event should be sufficient to ascribe it to some of the interaction types. So, we are going to discuss shortly what is desirable to measure in such experiments.

The fragmentation of both hadrons is important, for the measurements of the momentum fraction of the secondary protons is by itself sufficient for rough determination of the event type. It is reasonable to separate diffraction region as x very close to 1, the region around 2/3 as diquark fragment, and x about 1/3 as a fragment of a quark. The marked asymmetry of fragmentation and of all secondaries is a signal to asymmetric collision of the type "a" (see section 6). The separation of the events according to multiplicity intervals is also very important.

The final aim of such investigations should be the check of whether the interaction types as described above really exist. In principle, if the spread of parameters inside each kind of the interactions is only statistical, we may say that we finally understand dynamics of the collision. Evidently, that large multiplicity does not make such analysis more complicated, but on the contrary, it suppresses the unwanted statistical fluctuations. It can be said that high energy collision is a calorimeter for studies of nucleon structure, and the higher is energy the better calorimeter works. This statement can be illustrated by Fig. 4-6, which show that separation of different interactions is simpler at higher energy.

In conclusion, we suggest new generation of experiments with high energy hadron-hadron and hadron-nuclei be made, specially designed in order to separate more fundamental subprocesses involving different number of constituent quarks.

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Figure captions

Fig. 1. Dependence of σ_{hh}/σ_{qq} on quark-quark cross section σ_{qq} due to shadow corrections. Two arrows indicate the values of σ_{qq} at energies of ISR and SPS Collider.

Fig. 2. Average probability for two nucleons to interact versus impact parameter b at energies S = 400 GeV^2 and 10^5 GeV^2. The solid curves are predictions of the model, the dashed ones are the Gaussian parametrization of data, the dotted curves show the profile of diffractive dissociation.

Fig. 3. Complication of modern data on $C_q \equiv \langle n_{ch}^q\rangle/\langle n_{ch}\rangle^q$ at different energies. The energy dependence, violating the KNO scaling, is clearly present.

Fig. 4. Multiplicity distribution of charged secondaries at $\sqrt{S}$ = 20 GeV. Data points are from [23], solid curves are the predictions of the model. The curves marked 1,2,3 correspond to contributions of one quark pair collision and processes (a),(b) of section 6, respectively. The dashed line is the Slattery fit. Note that the model does not include the diffractive component.

Fig. 5. The same as Fig. 4 but for $\sqrt{S}$ = 63 GeV and data [24].

Fig. 6. The same as Fig. 4 but for $\sqrt{S}$ = 540 GeV and data [25].

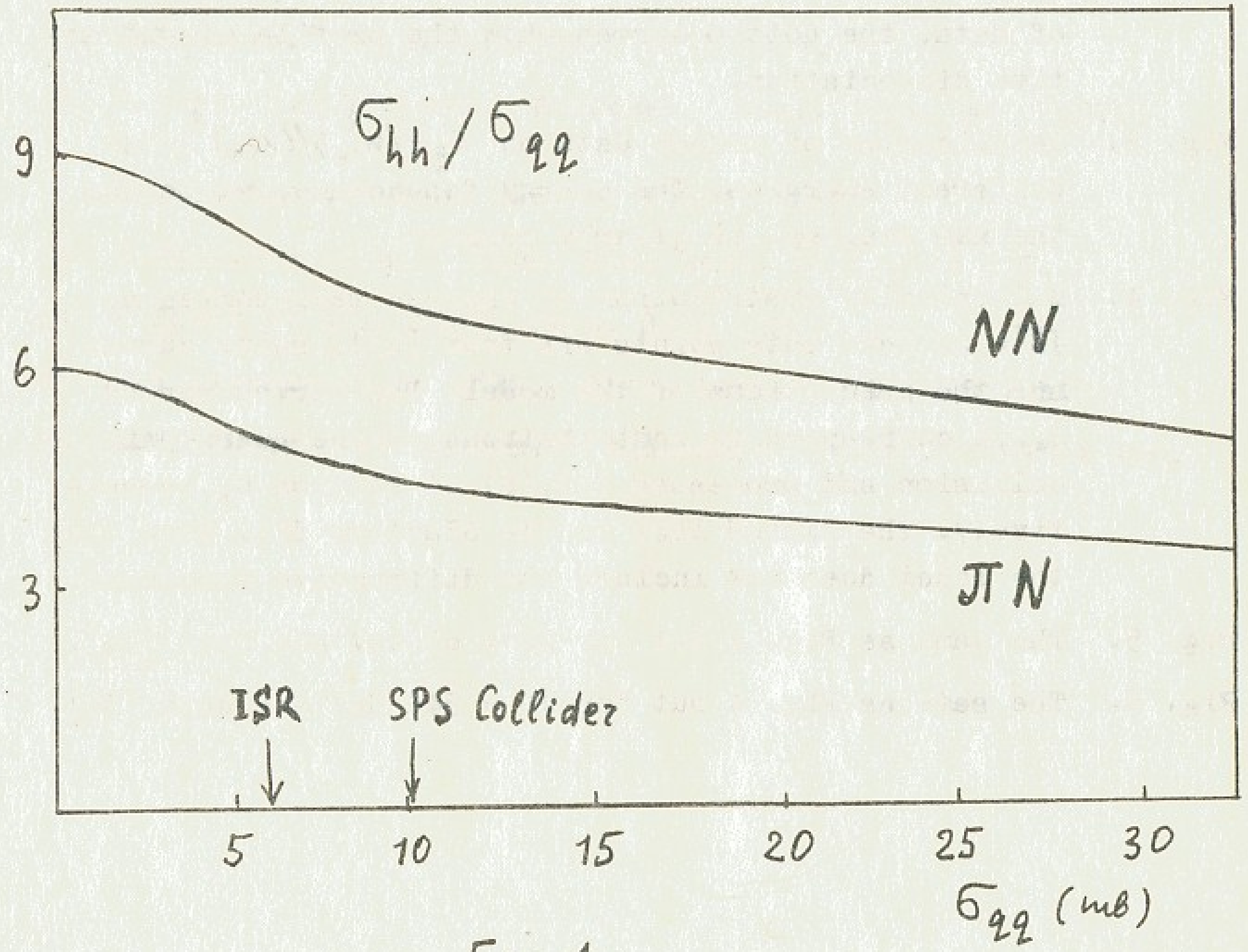
σ_hh / σ_qq
9
6
3
NN
πN
ISR
SPS Collider
5
10
15
20
25
30
σ_qq (mb)

Fig. 1.

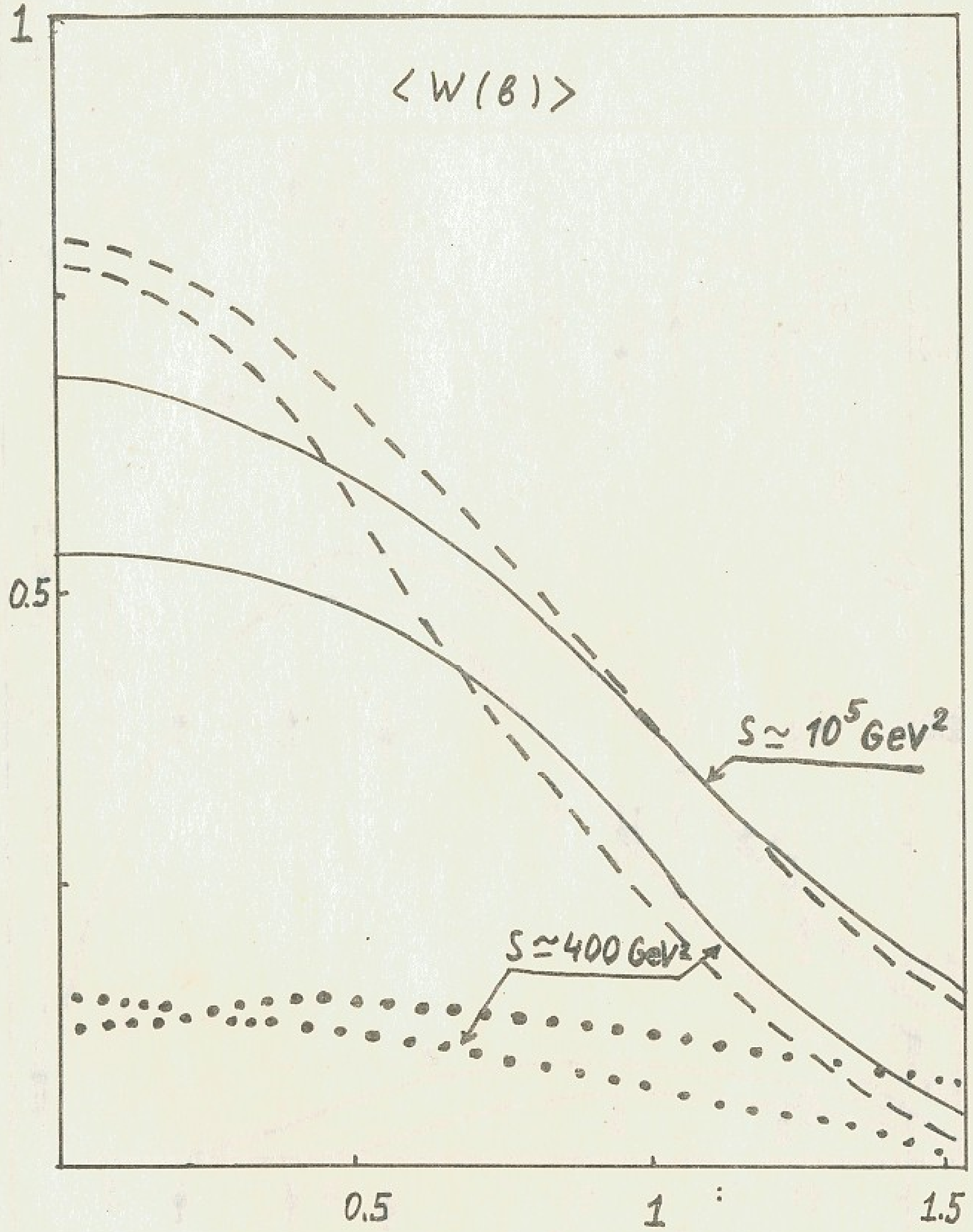
1
0.5
⟨W(b)⟩
S ≃ 10⁵ GeV²
S ≃ 400 GeV²
0.5
1
1.5

Fig. 2

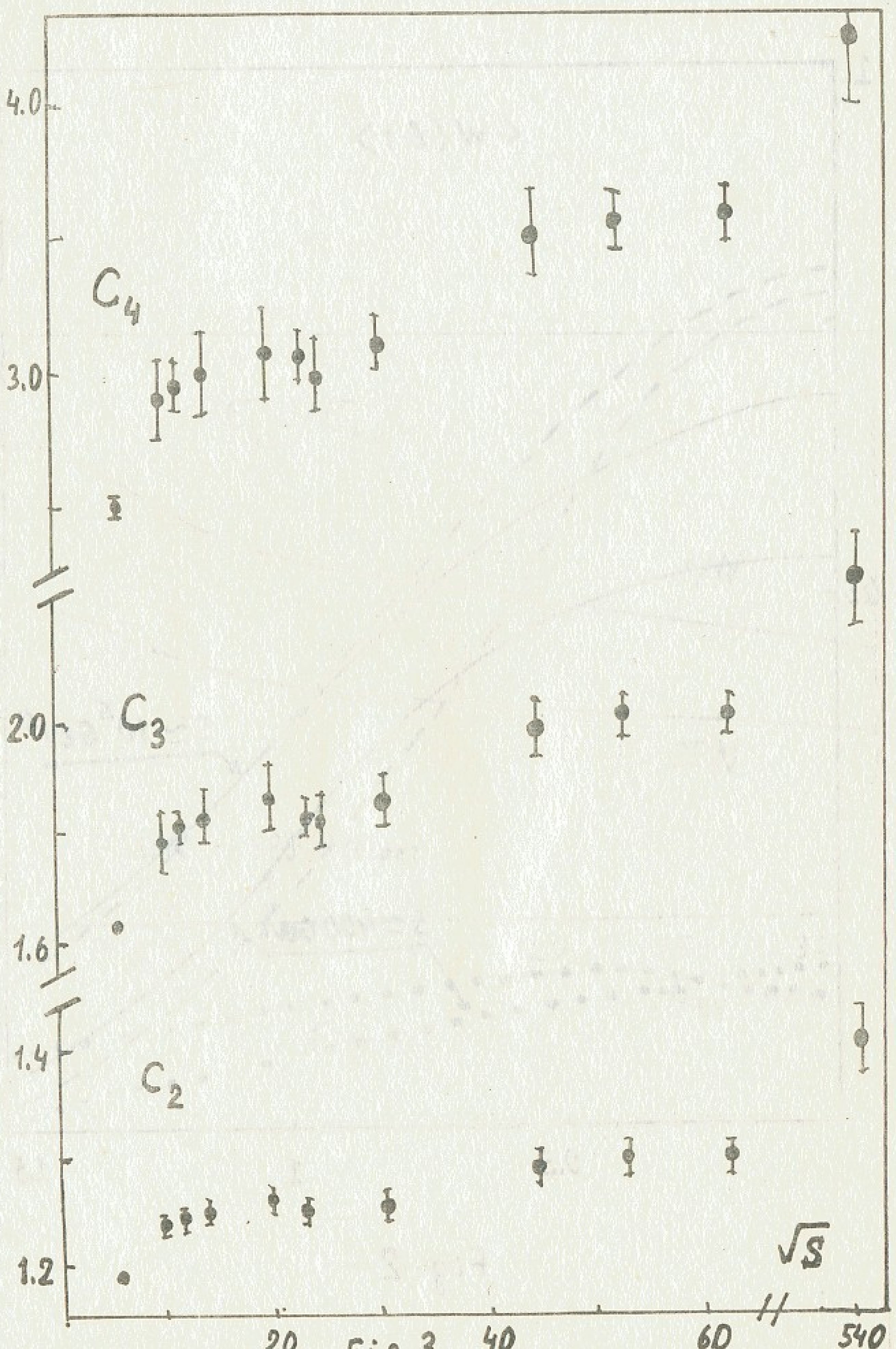
4.0
3.0
2.0
1.6
1.4
1.2
C_4
C_3
C_2
$\sqrt{S}$
20
40
60
540

Fig.3

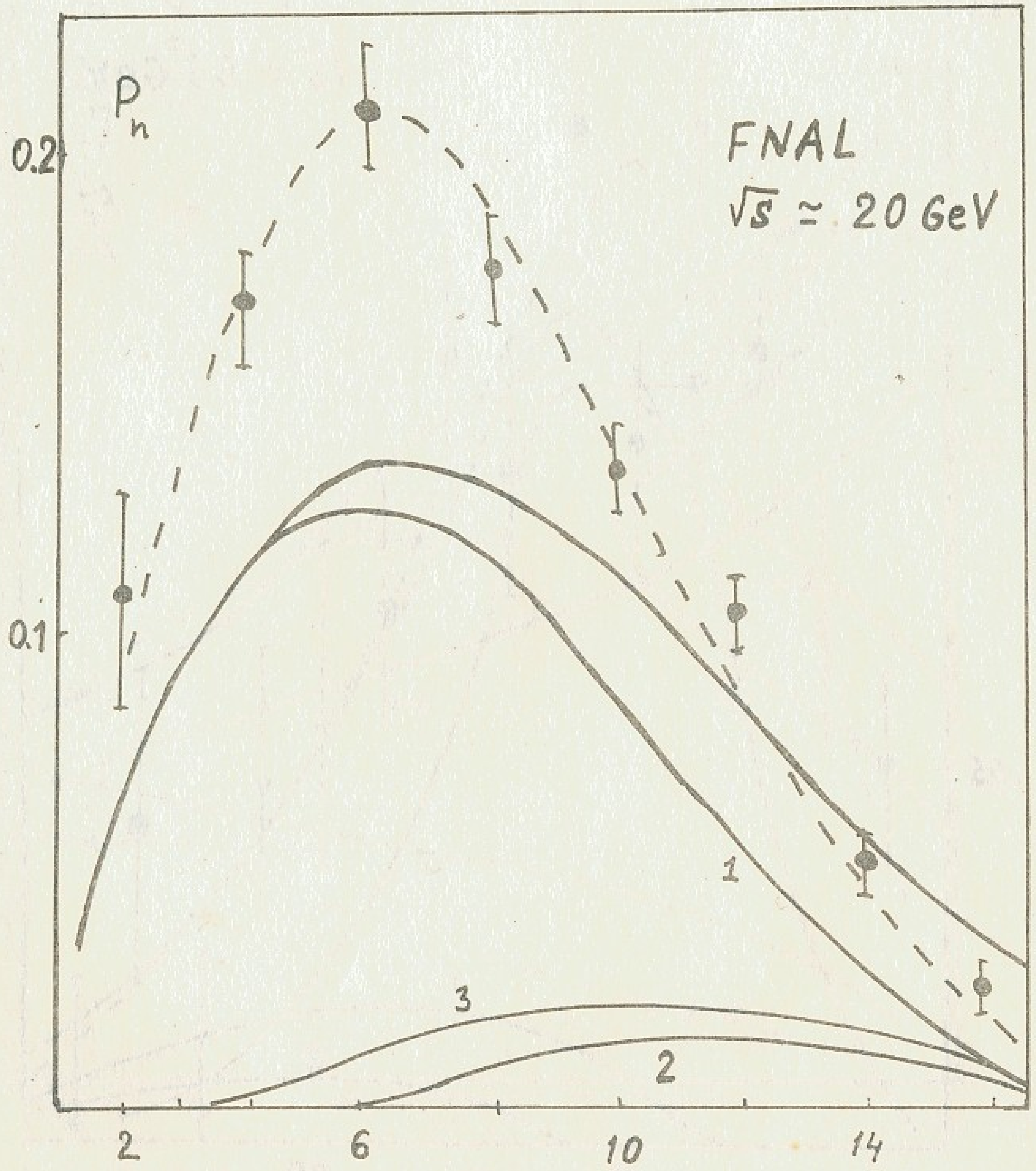
P_n
0.2
0.1
FNAL
$\sqrt{s} \simeq 20$ GeV
1
2
3
2
6
10
14

Fig.4

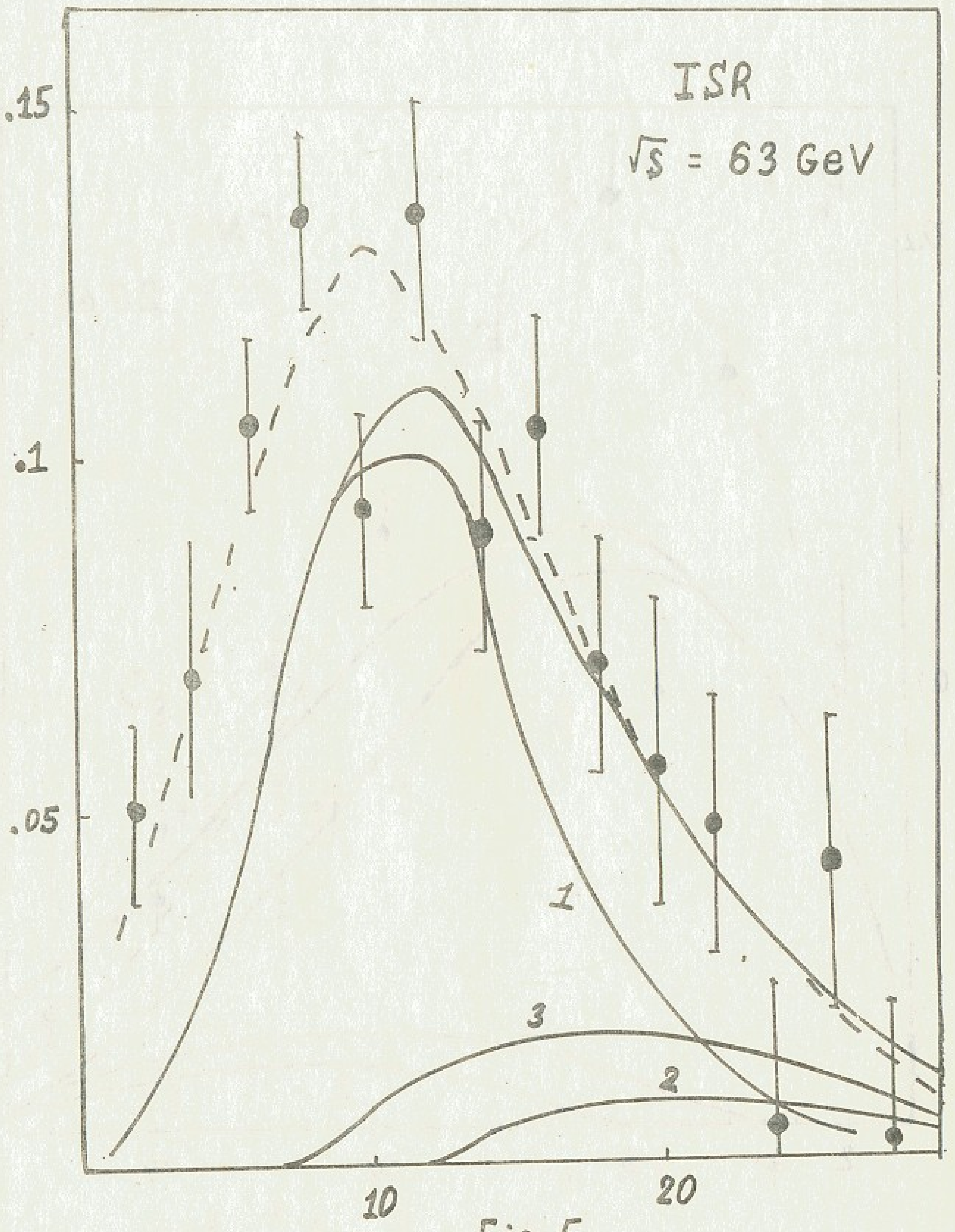
ISR
√s = 63 GeV
.15
.1
.05
10
20
1
2
3

Fig. 5

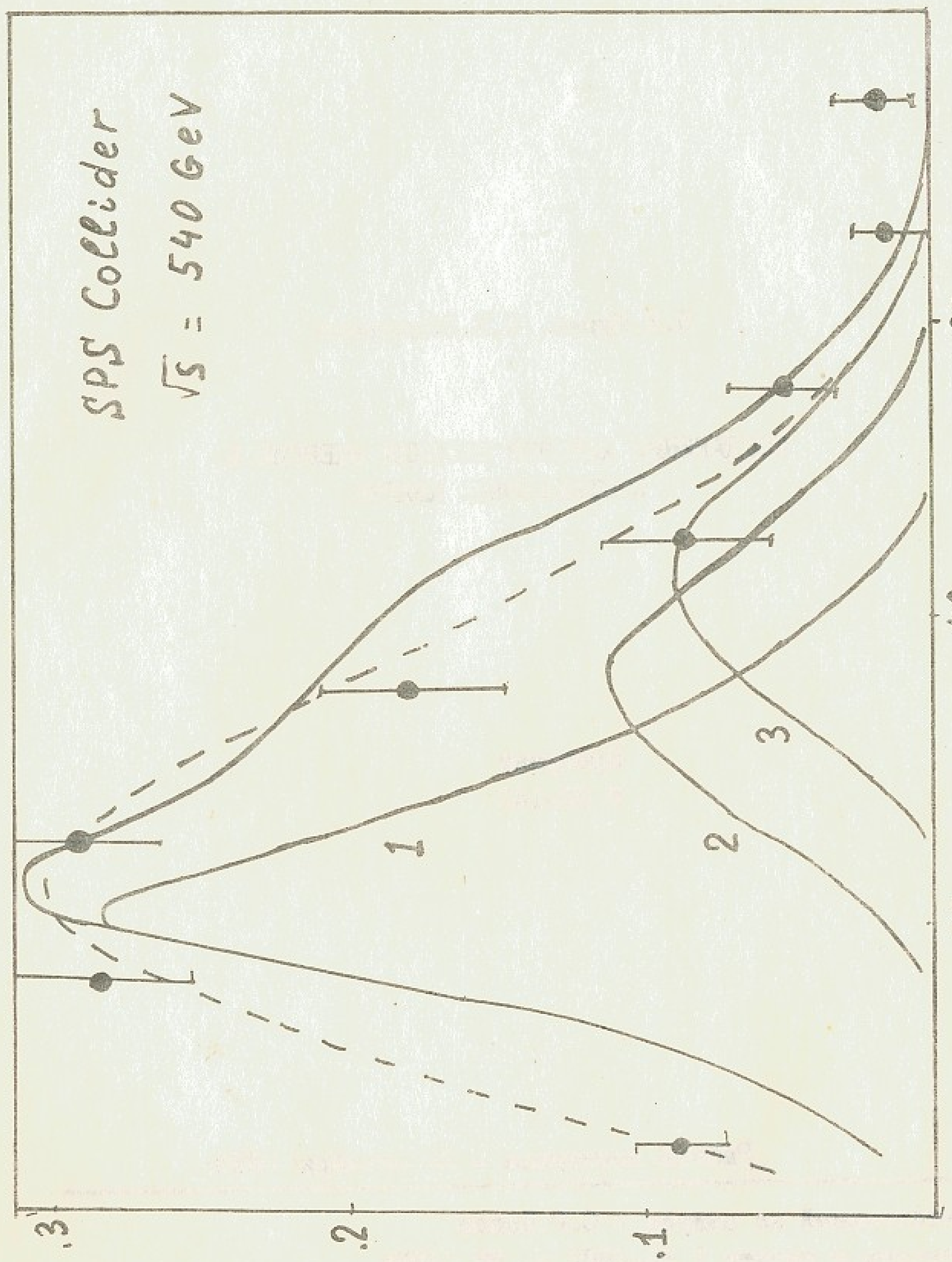
SPS Collider
√s = 540 GeV
.3
.2
.1
20
40
60
1
2
3

Fig. 6.

Э.В.Шуряк, С.И.Эйдельман

СОУДАРЕНИЯ АДРОНОВ ВЫСОКИХ ЭНЕРГИЙ И СОСТАВЛЯЮЩИЕ КВАРКИ

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