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LIPATOV'S QCD POMERON AND S$\bar{p}$pS DATA ON THE PHASE OF $\bar{p}$p ELASTIC SCATTERING

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1. Introduction

By virtue of the dispersion relations the ratio $\rho = Re\,F(t=0)/Im\,F(t=0)$ for forward elastic scattering amplitude is sensitive to energy dependence of $\sigma_{tot} = Im\,F(t=0)$ at energies higher than that ρ is measured at. QCD predicts a very specific structure of the pomeron. Namely, in the perturbative QCD pomeron was found/4/ to be a series of poles in the complex angular momentum plane at

$$1 \leqslant j \leqslant 1 + \Delta$$

which accumulate at $j = 1$, rather than a single isolated pole at $j > 1$, since long supposed in the conventional phenomenology of the diffraction scattering of hadrons/6/.

Obviously, the higher the energy the bigger is a relative contribution of the rightmost singularity in the j-plane, which rises like E^{j-1}, so that the "center of gravity" of Lipatov's pomeron moves to higher j with rising energy*). In recent paper/1/ by the authors a strong evidence for the QCD suggested asymptotics of $p(\bar{p})p$ scatte-

*) Retrospective view at $\sigma_{tot}(p(\bar{p})p)$ vs. energy is very instructive: $\sigma_{tot}(pp)$ has been decreasing at BNL-CERN PS energies, which has been attributed to the secondary Regge poles. With secondary poles still alive, at Serpukhov came the first surprise, flattening of $\sigma_{tot}(pp)$ ($\Delta = 0$), followed by a still bigger surprise-steep rise of $\sigma_{tot}(pp)$ from Serpukhov to ISR - , which gave rise to a supercritical pomeron with intercept $\Delta = j - 1 = 0.07$/6/. However, as an extrapolation of that fit up to S$\bar{p}$pS grossly underestimates $\sigma_{tot}(\bar{p}p)$, the S$\bar{p}$pS data call for still bigger Δ.

ring has been inferred from an analysis of the Akeno[2] and Fly's Eye[3] data on absorption of the superhigh energy cosmic rays in the Earth atmosphere. The corollary of this analysis was a prediction of still steeper rise of $\sigma_{tot}(\bar{p}p)$ beyond $\sqrt{s}$ =1 TeV. Typical prediction for Tevatron, $\sqrt{s}$ =1.6 TeV, is $\sigma_{tot}(\bar{p}p)$ = 80-90 mb[1].

Obviously, the steeper the rise of $\sigma_{tot}(\bar{p}p)$, the bigger, and positive, is $\rho_{\bar{p}p}$. In this paper we present predictions of Lipatov's QCD pomeron[4] for the phase of $\bar{p}p$ forward scattering amplitude at $S\bar{p}pS$ - Tevatron and beyond. Our principal conclusion is that recent finding[5] that $\rho_{\bar{p}p}$ = +0.24±0.04 at $\sqrt{s}$=540 GeV is still another evidence for the QCD pomeron.

2. QCD pomeron and its unitarization

The lowest order, two-gluon exchange, QCD perturbation diagram corresponds to a fixed singularity at j =1 and constant σ_{tot}. Remarkably, it reproduces well the absolute value of σ_{tot} in NN, πN and KN scattering at moderate energies[7]. The higher order QCD perturbation theory diagrams give rise to poles at $1 \lesssim j \lesssim 1 + \Delta$, which accumulate at j=1. As it is explained above, relative contributions of different poles depend on energy as $\exp[\xi(j-1)]$, where $\xi = \ln(s/s_0) - i\pi/2$, $s = 2\, m_p E$, s_0 =1 (GeV/c)^2.

A crude approximation to a complete QCD phenomenology of the soft hadronic scattering at high energy is a two-pole pomeron exchange amplitude:

$$f(\vec{q}) = i\, h_{2G}(\vec{q}) + i\, h_{I\!P}(\vec{q}) \exp[\Delta\xi - \alpha'_{I\!P}\xi\vec{q}^{\,2}]. \qquad (1)$$

Here $h_{2G}(\vec{q})$ and $h_{I\!P}(\vec{q})$ are residues of the two-gluon exchange and of the effective singularity at j - 1 = $\Delta > 0$. Lipatov's QCD pomeron possesses specific conformal properties in the impact parameter space, and the residues are basically determined by the quark wave functions of the colliding hadrons. In view of that, $h_{2G}(\vec{q})$ and $h_{I\!P}(\vec{q})$ are expected to have similar $\vec{q}$-dependence, so that we simply put

$$R = \frac{h_{2G}(\vec{q})}{h_{I\!P}(\vec{q})} = Const. \qquad (2)$$

In the conventional single-pole model[6] the intercept Δ defined as $\Delta = d\ln f(\xi, \vec{q}=0)/d\xi$ is a constant. The two-pole approximation (1) results in $\Delta_{eff} = \Delta/(1 + R\exp[-\Delta\xi])$, which rises with energy, what is a major novel feature of the QCD pomeron.

Regarding $h_{2G}(\vec{q})$, it can be computed explicitly[7] and gives a correct magnitude of the diffraction slope. In approximation(1), where $2G$ and $I\!P$ terms do rather comprise in the j - plane, we use simple Gaussian parametrization $h_{2G}(\vec{q}) = \sigma_{2G}\exp(-\frac{1}{2}B_0\vec{q}^{\,2})$.

The resulting partial wave amplitude in the impact parameter representation

$$u(\vec{b}) = -\frac{i}{2}\int\frac{d^2\vec{q}}{(2\pi)^2} f(\vec{q})\exp(-i\vec{q}\vec{b}) = \sigma_{2G}\left\{\frac{1}{4\pi B_0}\exp\left(-\frac{\vec{b}^{\,2}}{2B_0}\right) + \frac{1}{R}\frac{\exp(\Delta\xi)}{4\pi B_{I\!P}}\exp\left(-\frac{\vec{b}^{\,2}}{2B_{I\!P}}\right)\right\}, \qquad (3)$$

where $B_{I\!P} = B_0 + 2\alpha'_{I\!P}\xi$, overshoots the unitarity bound $u(\vec{b}) \leq 1$ at high energies, when $\Delta\xi \gg 1$. The unitarity is restored summing up the eikonal s-channel multipomeron diagrams:

$$F(\vec{b}) = 1 - \exp[-u(\vec{b})]. \qquad (4)$$

The complete unitarized amplitude is affected by inelastic shadowing (IS) coming from the diffraction dissociation (DD) transitions like $h \to h^* \to h$. A convenient approach to IS is a method of the diffraction scattering eigenstates (DSE) which can be summarized as follows[8]: Diffraction scattering eigenstates $|\alpha\rangle$ do diagonalize the diffraction amplitude $\hat{F}$: $\langle\beta|\hat{F}|\alpha\rangle = F_\alpha\delta_{\alpha\beta}$. The real hadrons, the mass matrix eigenstates, are superpositions of DSE: $|h\rangle = \sum_\alpha C_\alpha^h|\alpha\rangle$, so that

$$\langle h|\hat{F}|h\rangle = \sum_\alpha |C_\alpha^h|^2 F_\alpha(\vec{b}) \equiv \langle F_\alpha(\vec{b})\rangle = 1 - \langle\exp[-u_\alpha(\vec{b})]\rangle. \qquad (5)$$

A more realistic model should allow for DD of both the projectile and target. In view of factorization of residues, one can write $u_{\alpha\beta}(\vec{b}) = \alpha\beta\, u(\vec{b})$, where α (β) are relative residues of $|\alpha\rangle|\beta\rangle$ scattering, normalized by $\langle\alpha\rangle = \langle\beta\rangle = 1$. Then, the net result of IS is that ν-pomeron exchange amplitude will be enchanced by a factor $\langle\alpha^\nu\rangle\langle\beta^\nu\rangle$, where

$$\langle\alpha^\nu\rangle = \langle(1+\Delta\alpha)^\nu\rangle = 1 + \frac{1}{2!}\nu(\nu-1)\langle\Delta\alpha^2\rangle + \frac{1}{3!}\nu(\nu-1)(\nu-2)\langle\Delta\alpha^3\rangle + \cdots \qquad (6)$$

One can relate $\langle \Delta\alpha^2 \rangle$ to the inclusive forward DD cross section:

$$\frac{d\sigma_{DD}}{dt}\Big|_{t=0} = \int dM^2 \frac{d\sigma_{DD}}{dt\,dM^2}\Big|_{t=0} = \frac{1}{16\pi}\left(\langle\sigma_\alpha^2(1+\rho_\alpha^2)\rangle - |\langle\sigma_\alpha(1-i\rho_\alpha)\rangle|^2\right). \qquad (7)$$

We notice that $\langle \Delta\alpha^\nu \rangle$ is an energy-independent factor. In what follows we only retain terms $\sim \langle \Delta\alpha^2 \rangle$, borrowing $\langle \Delta\alpha^2 \rangle = 0.35$ from an analysis[9].

3. Total cross section and $\rho_{\bar{p}p}$ at superhigh energies

We have fitted the accelerator data on $\sigma_{tot}(pp)$ and pp diffraction slope at $|t| = 0.02$ (GeV/c)^2 above E=100 GeV, including the S$\bar{p}$pS data[10], adding in the Regge term $\sigma_R/\sqrt{S}$ on top of the pomeron cross section. We have assumed the conventional Regge-like vanishing $\Delta\sigma_{tot} = \sigma_{tot}(\bar{p}p) - \sigma_{tot}(pp) = 70\ S^{-0.56}$ mb, so that at S$\bar{p}$pS and beyond $\sigma_{tot}(\bar{p}p) = \sigma_{tot}(pp)$. The fitted parameters are cited in the Table.

Table. Sets of fitted parameters of the bare QCD pomeron at different choices of the ratio R and intercept $1+\Delta$

R	Δ	σ_{2G} mb	B_0 (GeV/c)^2	α'_{P} (GeV/c)$^{-2}$	σ_R mb
36	0.32	48.7	10.15	0.105	8.3
8	0.22	37.9	9.88	0.132	31.5
0	0.097	28.7*)	8.87	0.141	65.0

*) This entry for the single-pole fit is the residue of the pole at $j = 1 + \Delta$

R and Δ are very strongly correlated and cannot be fixed uniquely. R - Δ correlation is shown in Fig.1. The entries in the Table correspond to fits with fixed R.

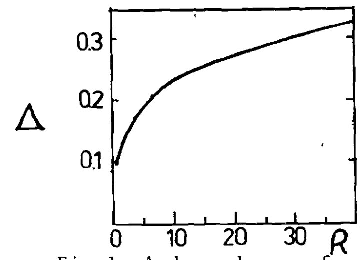

Fig. 1. A dependence of the intercept Δ on R.

The resulting predictions for $\sigma_{tot}(pp)$ are shown in Fig.2. The Akeno [2] and Fly's Eye[3] data points, plotted in Fig.2, were obtained by us in Ref.1. We warn the readers that the often quoted in the literature previous determinations of $\sigma_{tot}(pp)$ from the cosmic ray data [2,3] on $\sigma_{abs}(pAir)$ are quite wrong (for more details see Ref.1). The cosmic ray data do obviously favour high - Δ fits with $\Delta \gtrsim 0.2$.

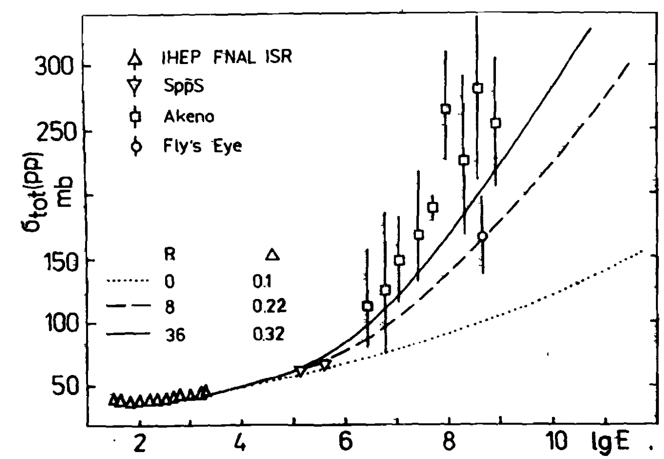

Fig.2. The energy dependence of the pp total cross section versus Δ. —— - R=36, Δ=0.32; - - - - R=8, Δ=0.22; ······ -R=0, Δ=0.097. Shown are also the values of pp total cross section determined from the Akeno-Fly's Eye data on $\sigma_{abs}(pAir)$ and the fitted accelerator data on $\sigma_{tot}(pp)$.

In order to fit the FNAL-SPS-ISR-S$\bar{p}$pS data on $\sigma_{tot}(pp)$ in the single-pole, R=0, approximation one needs Δ=0.097(see the Table) vs. Δ=0.07 fit to the FNAL-SPS-ISR energy range, but even so enlarged Δ=0.097 grossly undershoots the cosmic ray data [2,3].

One could constrain Δ much better at Tevatron. Our prediction for $\sigma_{tot}(\bar{p}p)$ vs. Δ at Tevatron, $\sqrt{s}$=1,6 TeV, is shown in Fig.3.

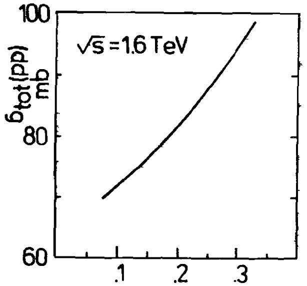

Fig.3. Predictions of the $\bar{p}p$ total cross section at the Fermilab collider.

The future test of the QCD pomeron is provided by the phase of the forward scattering amplitude. Namely, the steeper the rise of $\sigma_{tot}(\bar{p}p)$, the bigger and positive, is $\rho_{\bar{p}p}$. Our predictions for $\sigma_{\bar{p}p}$ and $\rho_{\bar{p}p}$ at ISR and beyond are presented in Fig.4. Here we have included the terms ρ^R coming from the crossing-odd difference of $\sigma_{tot}(\bar{p}p)$ and $\sigma_{tot}(pp)$.

$$\rho^R_{\bar{p}p} = -\frac{\sigma_R/\sqrt{s}}{\sigma_{tot}} \qquad (8)$$

$$\rho^R_{pp} = -\frac{\Delta\sigma_{tot}+\sigma_R/\sqrt{s}}{\sigma_{tot}}$$

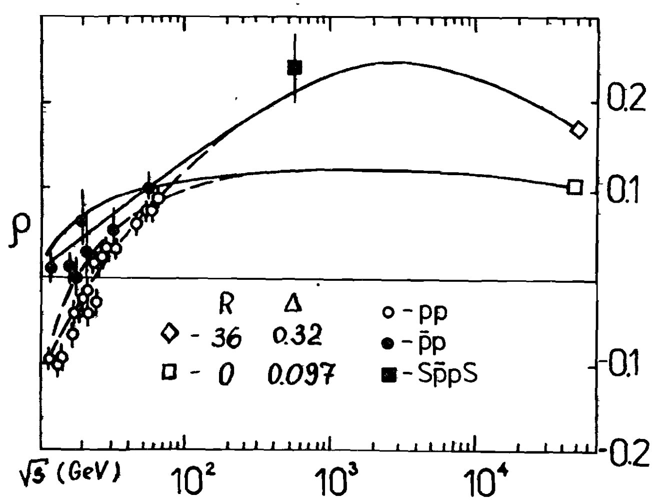

Fig.4.

The energy dependence of the ratio ρ= ReF(t=0)/Im F(t=0) for the forward elastic scattering amplitudes for $\bar{p}p$ (solid curve) and pp (dashed curve) scattering. For the legend of the curves see fig.2. Shown also are the data[5,11].

The single pole fit, R=0, predicts $\rho_{\bar{p}p}$=0.12 at $\sqrt{s}$=540 GeV, half of the experimental value $\rho_{\bar{p}p}$ = 0.24[5]. Lipatov'QCD pomeron

predicts $\rho_{\bar{p}p}$=0.16 with R=8, Δ=0.22 to $\rho_{\bar{p}p}$ ≐0.21 with R=36, Δ=0.32. We conclude that recent data on $\rho_{\bar{p}p}$ do corroborate conclusion[1] on a steep rise of pp total cross section and, consequently, QCD suggested asymptotics of the diffraction scattering of hadrons.

One more comment on $\rho_{\bar{p}p}$ is in order. QCD pomeron predicts slow increase of $\rho_{\bar{p}p}$ by $\Delta\rho$=0.01-0.02 from $\sqrt{s}$=540 GeV at S$\bar{p}$pS to $\sqrt{s}$=1.6 TeV at Tevatron.

Our approach was a conservative one, assuming the conventional Regge-like vanishing difference of $\bar{p}$p and pp total cross sections. The novel feature of QCD is a possibility of the so-called odderon, the crossing-odd singularity at j=1[12]. Such an odderon might give a nonvanishing contribution to ρ_{pp} and $\rho_{\bar{p}p}$, particularily to $\rho_{\bar{p}p}$ - ρ_{pp}[13]. However, according to the perturbative QCD estimations, odderon's residue at t=0 is numerically very small and the odderon can safely be neglected for purposes of the present analysis.

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Померон Липатова в КХД и данные $S\bar{p}pS$ коллайдера для фазы упругого $\bar{p}p$ рассеяния

Анализ[1] данных космических лучей[2,3] по $\sigma_{abs}(pAir)$ привел к заключению о быстром росте $\sigma_{tot}(pp)$ при энергиях выше $\sqrt{s}$ = 1 ТэВ, что хорошо согласуется с предсказаниями схемы померона Липатова в КХД[4]. Быстрый рост $\sigma_{tot}(pp)$ приводит к большой фазе амплитуды рассеяния вперед, которая хорошо согласуется с результатами недавних измерений[5] $\rho = ReF(t=0)/Im(t=0)$ при $\sqrt{s}$ = 540 ГэВ. Сделаны предсказания для энергии Теватрона $\sqrt{s}$ = 1,6 ТэВ: $\sigma_{tot}(\bar{p}p) = 80 \div 90$ мбн, $\rho_{\bar{p}p} \approx 0,2$.

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Lipatov's QCD Pomeron and $S\bar{p}pS$ Data on the Phase of $\bar{p}p$ Elastic Scattering

An analysis[1] of the cosmic ray data[2,3] on $\sigma_{abs}(pAir)$ has lead to the conclusion that $\sigma_{tot}(pp)$ rises steeply beyond $\sqrt{s}$ = 1 TeV, which nicely agrees with predictions of Lipatov's QCD pomeron[4]. A large, positive, phase of the forward $\bar{p}p$ scattering amplitude implied by this rapid rise of $\sigma_{tot}(pp)$, is shown to fit perfectly recent $S\bar{p}pS$ data[5] on $\rho_{\bar{p}p} = ReF_{\bar{p}p}(t=0)/ImF_{\bar{p}p}(t=0)$. Predictions for $\sigma_{tot}(\bar{p}p)$ and $\rho_{\bar{p}p}$ at Tevatron, $\sqrt{s}$=1.6 TeV, are presented: $\sigma_{tot}(\bar{p}p) = 80 \div 90$ mb, $\rho_{\bar{p}p} \approx 0.2$.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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