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FINAL TECHNICAL REPORT

PSF PROJECT P-PU/PHYS (114)

Pomeron (Odderon) in Soft and Hard Processes

REPORT PERIOD: April 2000 to April 2003

BY

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1. Project No.: PSF Project P-PU/Phy (114)

2. Project Title: Pomeron (Odderon) in Soft and Hard Processes

3. Institution: Centre For High Energy Physics
University of The Punjab, Lahore-54590

4. Total Grant: Rs. 3,36,615/-

5. Report Period: 19 April 2000 to 18 April 2003

6. Signatures of the Principal Investigator: 10/2/2004

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7. Signatures of the Dean Science: 10/2/04

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8. Signatures of the Vice Chancellor: 12.2.04.

SUMMARY

As per year--wise plan, theoretical study of Pomeron/Odderon was undertaken. Both soft and Hard Pomeron/ Odderon in perturbative and non-perturbative QCD have been studied along with some phenomenological approaches. Work in this area of research has been published in International Journals or contributed to International Conferences. More work has been submitted for publication. Three scholars working for M.Phil have been awarded the degree while another has submitted his thesis for the award of Ph.D degree. More scholars are working for their M.Phil / Ph.D in this field.

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(iii) INTRODUCTION

Pomeron and Odderon have been objects of intense study for the last three decades. Recent studies are focused on finding the origin of these particles in perturbative and non-perturbative QCD. Simultaneously, a lot of work is being carried out to understand the soft and hard Pomeron/Odderon in the light of recent and up coming experimental measurements. We now have a positive experimental confirmation of the Pomeron while search for Odderon goes on. In our study, we have highlighted the experimental measurements at future Colliders where Odderon is likely to be observed besides other work being carried out. We will now briefly describe the developments in this field:

The literature on soft and hard Pomeron and Odderon was studied and new ideas were obtained. During the last decade the phenomenon of the Pomeron (Odderon) became a hot subject again, both for theoretical and experimental scrutiny. This included the Regge poles and high energy scattering. This report describes the underlying ideas and modern developments in this important area of research. It confronts the theory with a huge variety of experimental data and compares and contrasts it with Quantum Chromodynamics. It also provides a unique insight into the theory and its phenomenological development. It provides comprehensive coverage of the various different theoretical approaches and considers the key issues for future theory and experiment. In Regge theory, the exchange of particles in a scattering process is described by the singularities of the scattering amplitude in the complex angular momentum plane, the so-called Regge poles and cuts. By way of crossing symmetry, they can be related to the masses and spins of existing hadrons. By that token, every hadron is a Regge particle, or Reggeon. However, some Reggeons do not correspond to any known hadron. One such is the Pomeron, which is the pole with largest real part and therefore dominant at asymptotically high energies. It carries the quantum numbers of the vacuum, and the simplest model for it consists of two gluons in a colour singlet state. Another is its charge-conjugation-odd partner, the Odderon. There are some indications that both Pomeron and Odderon might be related to glueballs. The existence of the Pomeron is universally accepted, and it is the topic of a wide range of phenomenological work. The Odderon, by contrast, has never been measured experimentally beyond doubt and consequently is still a contentious topic. The processes on which the search for the Odderon has concentrated for a long time are proton-proton and proton-antiproton scattering. These processes provide the hitherto only experimental evidence for the Odderon. If the thin experimental evidence for the Odderon were all there is to it, one might have discarded it as a misguided concept. But other concepts of Regge theory remain very valid today. Furthermore, the Odderon can in fact be derived from perturbative QCD. It is described by the BKP equation. Odderon exchange amounts to a simultaneous exchange of at least three gluons in a $C = -1$ state. Since such an exchange is clearly possible in QCD, a failure to find the Odderon at all would be a heavy blow to QCD. In this respect the

Odderon has turned out to be a highly interesting object from a theoretical point of view.

(iv-vi) EXPERIMENTAL STUDY/RESULTS/DISCUSSIONS

a) Pomeron Phenomenology

The fundamental structure and interactions of matter are investigated primarily by scattering experiments. In hadron-hadron scattering, interactions are classified by the characteristics of the final states. In elastic scattering, both hadrons emerge unscathed and no other particles are produced. In diffractive scattering, the energy transfer between the two interacting hadrons remains small, but one (single dissociation) or both (double dissociation) hadrons dissociate into multi-particle final states, preserving the quantum numbers of the associated initial hadron. The remaining configurations correspond to inelastic interactions. The results of observations of scattering events are usually presented as scattering cross sections. The Regge theory relates high energy behavior of scattering cross sections to the spin properties of low-mass particles (or resonances). This unexpected relation between high and low energy is based on the fundamental idea that the force between two strongly interacting particles is due in turn to the exchange of strongly interacting particles. This picture, the force arises from the emission and absorption of particles, leads to many experimental predictions. The exchanges are the mechanism by which momentum is transferred between the projectile and the target in a scattering experiment. Other quantities such as charge and strangeness, can also be exchanged. It should be stressed that the exchange particles are virtual (not real) in the sense that their creation violates energy-momentum conservation, but because of Heisenberg

Uncertainty principle, they can be produced for a sufficiently short interval. This theory is named after the physicist T.Regge who first gave a general discussion of quantum-mechanical scattering using these terms and concepts.

The properties of elastic and diffractive scattering are well-described by the phenomenology of pomeron exchange (Regge theory), where the Pomeron is a color singlet with quantum numbers of the vacuum. Regge theory predates the quark-gluon model, and it is not clear how to combine it with QCD. Definitions of the pomeron vary from a theoretical definition: ``the highest Regge trajectory with quantum numbers of the vacuum, responsible for the growth in the hadronic cross section with $\sqrt{s}$" to an experimental one: ``the thing that causes rapidity gaps". Many experiments have studied diffractive and elastic scattering at different center-of-mass energies, but due to the non-perturbative nature of the interactions, insight into the underlying process has been limited. The two-body hadronic process either shows a peak or a turnover in the angular distribution curve near $t = 0$. This indicates that a helicity non-flip or a helicity-flip amplitude dominates the behavior of the scattering process. However, in the absence of a dynamical theory of hadronic processes, we have no knowledge of the residue function. For the sake of simplicity, the theoretically unknown residue functions are chosen to be of exponential nature. It was then shown by Fazal-e-Aleem and Saleem that even a simple Regge pole model with phenomenological residue functions could be used to fit the experimental data for a scattering process. This model, probably the most economic within the Regge framework, has been successfully exploited to fit the data on many important reactions [Fazal-e-Aleem and Saleem M.].

Fazal-e-Aleem *et al* have used Regge description to explain the total and differential cross section data at ISR, SPS and TEVATRON energies. At these energies, the model gives a satisfactory explanation of the total cross section σ_T, the ratio σ_{el}/σ_T, the slope B in the range $0 < -t < 0.15$ $(\mathrm{GeV}/c)^2$ and the differential cross section up to $-t \approx 2.2$ $(\mathrm{GeV}/c)^2$. The model also predicts a value of 0.167 for the ratio ρ, which is slightly higher than the measured value of .135 ± .015. At 1.8 TeV, the values of σ_T, $\frac{\sigma_{el}}{\sigma_T}$, B and ρ are predicted to be 74.8 mb, 0.25, 15.9 $(\mathrm{GeV}/c)^{-2}$ and 0.174, respectively. All the values are in agreement with the recent experimental data.

b) Pomeron in QCD

Ever since the idea of Pomeron was floated, emphasis was on explaining and correlating the experimental data on the basis of general principles – analyticity, unitarity, crossing symmetry etc. However, in the recent past we have begun to incorporate the ideas of perturbative QCD. Confinement is largely ignored. Most important thing is to learn to reconcile the two approaches. We must learn as to how non-perturbative effects can be included in to the perturbative formalism. Some attempts have recently been made in this direction. As pointed out earlier, in Regge theory, the increase in total cross section is approximated by the intercept of the Pomeron trajectory. Consequently, it would be natural to try to find an origin of Pomeron in QCD. A simple picture is through two-gluon exchange [Donnachie]. This picture however does not give rise to the total cross section. In order to account for increase in total cross section, the exchanged gluons must interact with each other [Donnachie].

At present the two Pomerons - a soft and a hard one, account for the experimental data. The two-fold interpretation of a single object (phenomenon) however has a clear origin: the conventional Pomeron studied in hadronic physics is a soft phenomenon, outside the range of applicability of perturbative quantum chromodynamics (pQCD). What has come to be known, as the hard Pomeron is something that can be calculated from pQCD. The small-x data collected at HERA are interpreted as a manifestation of the hard Pomeron, and thus is an argument in favor of the existence of two Pomerons. More specifically, Pomeron is visualized as a very complicated entity which in different dynamical situations may have different manifestations but whose origin is always the same, diffraction. Various authors have given different pictures about the Pomeron incorporating the ideas of pQCD to fit the experimental data.

Jenkovszky *et al* have proposed a model for the Pomeron at $t = 0$. It is based on the idea of a finite sum of ladder diagrams in QCD. Accordingly, the number of s-channel gluon rungs and correspondingly the powers of logarithms in the forward scattering amplitude depend on the phase space (energy) available, i.e. as energy increases, progressively new prongs with additional gluon rungs in the s-channel open. Explicit expression for the total cross section involving two and three rungs or, alternatively, three and four prongs is fitted to the proton-proton and proton-antiproton total cross section data in the accelerator region.

While both soft and hard Pomeron are used to explain the data in different domains, efforts are also being made to give a unified picture of the Pomeron. In the picture of Bertini *et al*, the Pomeron – as a leading singularity in the *j*-plane is *unique*, but it contains contributions both at large and small distances. The relative weight of these contributions depends on the given process (at given energies) and hence there is no universality. These contributions mutually renormalize and without a scale it is impossible to determine which one is more important. The idea of a *unique* Pomeron has also been described by Wu. It is emphasized that there is only one Pomeron. Soft and hard Pomeron are merely different aspects of the same object.

In a search for the Pomeron, total cross sections for real photon-proton scattering have been measured at HERA. The importance of the HERA data on total cross sections is two-fold. On the one hand, these data reach very high energies (comparable only to the *pp* Tevatron energies) providing information about the Pomeron and, in addition, they give a direct link between hadron-and lepton-induced reactions. On the other hand, they allow a direct probing of composite structures (the proton) by an elementary probe (the electron).

One of the main reasons to assume, as done by some of the authors, that the pomeron couples to valence quarks is the quark counting rule, which seems to work for pion-proton cross sections, as well as for cross sections involving strange quarks. Hence it seems that quark degrees of freedom are relevant for soft cross sections. Similarly, the amplitudes factorize [Goulianos] into one factor associated with the target, 2nd factor associated with the projectile, and a third factor describing the exchange. This implies that the pomeron couples to one quark at a time: otherwise, the exchange would feel the hadronic wave function, and one would have a convolution that does not factorize. These two properties are violated by perturbative QCD, as well as by strong unitarisation. Nevertheless, our ignorance of hadronic wave-functions can easily accommodate the existing data, but one has then to assume that the wave-function of a pion is similar to that of a proton, contrary to the simplest intuition.

Another important and non-trivial argument in favor of the complex angular momentum theory is the observed shrinkage of the diffraction cone. From its rate, the slope of the Pomeron trajectory is calculated to be $\alpha' \approx$ 0.25 GeV^2. This implies that as the energy increases, more and more particles tend to be scattered in the forward direction. This is a prominent feature of hadronic diffraction. At the same time, the near universality of the slope of all Regge trajectories other than the Pomeron makes the latter a rather peculiar trajectory and actually hints at a possibly different origin (diffraction) or type of complex *j*-plane singularity for the Pomeron (may be a cut originated by unitarity rather than a simple moving pole).

Since secondary Regge trajectories are made of valence quarks, the Pomeron (and Odderon) trajectory is considerably more complicated since it is supposed to be composed mainly of gluons (eventually, with some quark admixture). In any case, one expects that, in analogy with secondary Reggeon, observable particles (glueballs) should be found on the Pomeron (and Odderon) trajectory for integer values of spin larger than one. Since the parameters on the trajectory are well defined from the scattering region, the predictions for glueball masses (and widths, in the case of nonlinear trajectories [Desgrolard] are quite definite).

c) The Odderon

Concept of the Odderon was first introduced by Lukaszuk and Nicolescu in 1973 to account for the difference of the total cross section, σ_T and ratio of real to imaginary parts of scattering amplitude, ϱ in *pp* and

$\bar{p}\,p$ scattering. Kang and Nicolescu provided theoretical basis for the Odderon. From the theoretical point of view this concept has been rediscovered in QCD. Dynamical origin of this concept was provided by several authors [Bartels, Kwucinski and Praszalowicz, Islam, and Lipatov]. In QCD, there are not only quark-Reggeons but also glue-Reggeons. More generally, multi-Reggeized-gluon exchanges lead to contributions having the Odderon quantum numbers. This is a very important theoretical fact, which provide physical basis to the concept of Odderon. Several interesting aspects of perturbative Odderon have been explored in various studies. Much work has since been carried out on the origin and meanings of the Odderon [Dosch]. Theoretical status of the Odderon is now firm not only in the perturbative QCD theory but also in the non-perturbative approach. In the perturbative treatment efforts are mainly focused on the determination of the Odderon intercept. Thus, concept of an Odderon has been a very interesting inclusion to our knowledge. The model is based upon general S-matrix principles, the constraints of asymptotic theorems and a dynamical assumption of "maximal strength" of strong interactions.

d) Odderon In QCD

It is now established that existence of the Odderon is predicted by QCD. The idea of the Odderon, partner of the Pomeron, is related to the possibility that the real part of scattering amplitude increases with energy as fast as the imaginary part [Fazal-e-Aleem and Sohail]. The scattering amplitude in the complex angular momentum plane possesses a rightmost singularity (pole) near $j = 1$. In the even (under crossing) amplitude such a singularity is associated to the Pomeron and gives mostly an imaginary contribution, while in the odd case it is mostly real which is associated to the Odderon. Position of the singularity is also called intercept and is related to the asymptotic behaviour of the cross section.

QCD predicts the existence of Pomeron, in the simplest version as a two-gluon exchange in colour singlet state. As the internal gauge symmetry group of QCD has rank greater than one, we can construct a C-odd state from three gluons, which can be associated to the Odderon.

One can see this fact considering the $SU(3)_C$ gauge group associated to the gluon field $A_\mu = \sum_a A_\mu^a t_a$. Since under charge conjugation one has $A_\mu \to -A_\mu^T$, the two possible independent invariants, constructed by three gluon fields, are $Tr([A_1, A_2]A_{3,})$ and $Tr(\{A_{1,} A_{2,}\}A_{3,})$ which are respectively even and odd under charge conjugation. Therefore the Odderon will be related to the composite operator $O_{\alpha\beta\gamma} = d_{abc} A_\alpha^a A_\beta^b A_\gamma^c$.

The Odderon description in the perturbative QCD is based on re-summation techniques in the small x region. Recent developments on the perturbative analysis have been briefly reviewed in a recent work [Vacca]. A scattering process dominated by the Odderon exchange can be described in the high energy limit, in the context of k_T factorization, by an amplitude

$$A(s,t) = \frac{s}{32}\frac{1}{16}\frac{N_c^2-4}{N_c^2}\frac{N_c^2-1}{3!}\frac{1}{(2\pi)^8}\left(\Phi_\gamma^i \middle| G_3 \middle| \Phi_p\right)$$

At lowest order, when the strong coupling α_S is small, one has a simple three uncorrelated gluon exchange, i.e. the Green function G_3, which is convoluted with the impact factors, is constructed, simply with 3 gluon propagators. Therefore, in momentum representation

$$G_3^{(LO)} = \delta^{(2)}(k_1 - k_1')\delta^{(2)}(k_2 - k_2')1/k_1^2 k_2^2 k_3^2$$

In the high energy limit, when all other physical invariants are much smaller, a LLA resummation of the contributions of the order $(\alpha_s \ln s)^n$, which is not small, can be performed and one obtains, through G_3, an effective evolution in rapidity. The same resummation for the two gluon exchange has lead to the BFKL [Kuraev *et al*; Balitskii and Lipatov] equation where it appears the kernel of the integral equation for the 2-gluon Green function that, in the colour singlet state, describes the perturbative QCD Pomeron in LLA. The same equation in the colour octet state has a simple eigenstate, which corresponds to the reggeized gluon and is in general a composed object at high energies. This fact is seen as a self-consistency requirement and is called bootstrap. In NLA [Fadin and Lipatov], where one is also resumming the contribution of order $\alpha_s^n (\ln s)^{n-1}$, all the same concepts including reggeization [Braun and Vacca] apply.

The general kernel for the *n*-gluon integral equation for the Green function in LLA is given by the BKP equation [Bartels; Kwiecinski and Praszalowicz]. In the large N_c limit and for finite Nc when $n = 3$, it possesses remarkable symmetry properties: discrete cyclic symmetry, holomorphic separability, conformal invariance, integrability, duality [Lipatov; Faddeev and Korchemsky]. Also a relation between solutions with different n exists [Vacca], which is a direct consequence of the gluon reggeization.

The Odderon states in LLA must be symmetric eigenstates of the operator $K_3 = 1/2(K_{12} + K_{23} + K_{31})$ constructed with the BFKL kernel K_{ij} for two reggeized gluons in a singlet state. Using the conformal invariance and integrability properties a set of eigenstates has been found [Janik and Wosiek], which have a maximal intercept below one.

Using the gluon reggeization property (bootstrap) a new set of solutions was later found [Bartels *et al*], characterized by intercept up to one, therefore dominant at high energies. Moreover, for the particular impact factor which couples a photon and an η_c to the Odderon, the LLA calculation has shown that this second set of solution is relevant while the previous one decouples. We present here these Odderon states. In momentum representation they are given by $E_3^{(\nu,n)}$ such that

$$k_1^2 k_2^2 k_3^2 E_3^{(\nu,n)}\left(k_1, k_2, k_3\right) = c(\nu,n) \sum_{(123)} (k_1 + k_2)^2 k_3^2 E^{(\nu,n)}(k_1 + k_2, k_3)$$

where $c(n,\nu)$ is a normalization factor, E is a BFKL pomeron eigenstate and the conformal spin n is odd. The full Green function is constructed summing over all such states but in the high energy limit the asymptotic behaviour can be studied for conformal spin $n = \pm 1$ and performing the saddle point integration around $\nu = 0$.

Very recently Bartels et al. have [Bartels *et al*] used a set of new Odderon states and calculated their contribution to the diffractive photo and electro production process. Their results are in order of magnitude enhancement to previous simple 3-gluon exchange calculations. It is shown that t-dependence of the cross section exhibits a dip structure in the small t region.

Non-perturbative QCD Odderon approach is based on the stochastic vacuum model of Heidelberg group. A brief sketch on the non-perturbative QCD framework used for Odderon studies [Vacca, Rueter *et al*, Berger *et al*] is given below.

A first ingredient is the choice of the eikonal semiclassical approximation [Nachtmann] for high energy scattering of quarks. At first, full quantum colour field behaviour is considered. In particular each quark, which scatters on a colour field, picks up a non abelian eikonal phase $V = P\exp\left[-ig\int_{\Gamma} dz^{\mu}A_{\mu}(z)\right]$.

The functional integral on the physical gluon field is estimated using the stochastic vacuum model (SVM) [Dosch and Simonov], i.e. the calculation of any correlation functions of gluon field strength is associated to a gaussian stochastic process with finite correlation length and, therefore, expanded as $\langle F.\,F...F\rangle = \sum \Pi\langle F.F\rangle$. After some other assumptions and relating the basic two point function $\langle 0|F.F|0\rangle$ to the gluon vacuum condensate, a dipole-dipole or dipole-tripole (as Wegner-Wilson loops) scattering amplitude at fixed transverse size can be computed expanding the ordered exponential. Mesons (barions) are described in term of dipoles (tripoles) and transverse wave functions [Dosch, Ferreira and Kramer].

When expanding the exponentials in the eikonal phases, terms of the kind $\langle Tr(F.F)Tr(F.F)\rangle$ give imaginary contribution and are associated to the Pomeron. Instead the real Odderon contribution is given by subsequent terms of the kind $\langle Tr(F.F.F)Tr(F.F.F)\rangle$, in particular by the piece with the $d_{abc}\ d_{abc}$ colour structure. In this approach the energy dependence is introduced in a phenomenological way. A diquark structure of the hadrons has been preferred. The production of light mesons in Deep Inelastic Scattering [Rueter, Dosch and Nachtmann; Bergereta *et al*] has been studied (π^0, f_2 with N^* resonances production) through Odderon driven processes. Predictions at HERA energies are $\sigma^0_{\gamma p\to\pi^0 N} \approx 400$nb and $\sigma^0_{\gamma p\to f_2\ N} \approx$ 21 nb. The first process has been analyzed at HERA by the H1 collaboration and there is now an upper bound on the cross section of around 39 nb [Golling]. There is a big discrepancy in the predicted and measured value. One possible source of error comes from the parameter fixing in SVM. The most serious one seems to be the badly estimated $\gamma O \pi^0$ vertex. It seems therefore that the f_2 production process would be based on more solid estimates of the coupling.

e) Models Incorporating Odderon

The Odderon picture has been used by Gauron *et al* to account for the various aspects of the *pp* and $\bar{p}p$ including difference of σ_T and dσ/dt in the dip region at ISR. Bernard *et al* , later on showed that UA4 results (ϱ = 0.24 ± 0.04) could be described by the presence of Odderon. Their predictions for the total cross section and ϱ are higher than UA4/2 (ϱ = 0.135 ± 0.02) and E811 (ϱ = 0.135 ± 0.044) data. Similarly predictions for σ_T in the Odderon picture are higher than the E710 (72.2 ± 2.7 mb) and E811 (71.42 ±1.55 mb). These values, however, are consistent with measurements of CDF (80.26 ±2.25 mb). We observe that most recent results (E811) again confirm the fact that Odderon contribution in the forward direction is negligible. It can be seen that the results from RHIC and LHC will be able to clearly identify the need or otherwise of the Odderon. At the same time the differential cross section in the dip region for 500/540 GeV for $pp/\bar{p}p$ from RHIC/SPS will be very important. Contribution from the Odderon would mean a significant difference of $d\sigma/dt$ in this region (around $-t$ = 0.8 (GeV/c)^2) [Fazal-e-Aleem and Sohail] .

Jenkovszky *et al*, extended the idea to relate the small momentum transfer hadron scattering and deep inelastic scattering. This relationship is useful for understanding the origin of cross section from the point of view of hadronic structure and interaction of its constituents. Rafique *et al* used Odderon description to explain the then available data for σ_T and ϱ. Their predictions are in agreement for ϱ but somewhat higher for σ_T. In another attempt, Odderon description was confronted by Fazal-e-Aleem *et al* to fit data for the differential cross section. Predictions of the model for σ_T and ϱ are somewhat higher than the current measurements. We thus find that the models incorporating Odderon predict high ϱ value (~0.2) at FERMILAB, RHIC and LHC [Augier]. Recent results of 0.135 ± 0.02 at UA4/2 and 0.135 ± 0.044 at E-811 Collaboration value do not seem to favour the presence of Odderon. In the simple Regge picture of Landshoff and Donnachie, a constant value of $\varrho = 0.12$ is predicted which is in agreement with the UA4/2 and E811 data.

In the recent work, Gauron and Nicolescu have proposed a QCD inspired two-component pomeron, which gives good fit to the *pp*, πp, $K p, \gamma p$ *and* $\gamma \gamma$ total cross sections. They claim that their 2-Pomeron form is fully compatible with weak Regge exchange-degeneracy, universality, Regge factorization and the generalized vector dominance model.

In a series of papers Desgrolard *et al*, have given account of the various physical parameters using Additive Quark Model (AQM) or Standard Additive Quark Model (SAQM) by incorporating Odderon in addition to other trajactories. They have used this idea to describe the total cross section, ρ and local slope parameter for *pp* and $\bar{p}p$ scattering. They have modified the standard AQM taking into account not only the quark-gluonic content of the Pomeron but also secondary Reggeons as well as the fact that the Pomeron is not just a gluonic ladder. The resulting model, which they call modified Additative Quark Model (MAQM), has been successfully applied to describe the same data with improvement in the fit. As an explicit choice, for the Pomeron contribution they have chosen a simple model, namely a special case of the model of Dipole Pomeron, with a unit intercept that leads to high quality description of the experimental data, both at $t = 0$ as well as at $t \neq 0$

With the new measurements planned at RHIC and LHC, most interesting would be the dip region in *pp* and $\bar{p}p$ elastic scattering from the Odderon point of view. Very recently, Dosch et al., have studied Odderon contribution to elastic *pp* and $\bar{p}p$ scattering. They have used different models for the Odderon-proton coupling and studied the effects on the differential cross section in the dip region. As a framework, they have used the Donnachie-Landshoff fit and replaced the Odderon contribution used in various models. They have also used two models for the Odderon-proton coupling, which are based on impact factors in momentum space. In the process they have constructed a geometric model for the proton in which the effect of a possible diquark cluster can be studied. Odderon is modeled by perturbative three-gluon exchange in the C = -1 channel. They conclude that all models for the Odderon-proton coupling give very similar results by the appropriate choice of model parameters, in particular the strong coupling constant. The available data cannot distinguish between the different models but for a given model the data impose very strong constraints on the parameters of that model. Using their geometric model they find that the average size of the diquark cluster in the proton is quite small, < 0.5 fm. This result is obtained by assuming that reasonable values for strong coupling constant α_s in the dip region are larger than 0.3. In the nonperturbative model used in [Rueter and Dosch] such a small diquark is sufficient to explain the absence of an Odderon signal in the ratio of the real to imaginary part in the forward direction. This can be understood by the fact that in the nonperturbative model for the IR behaviour of QCD, soft gluons dominate and therefore the resolution is much coarser.

It may be stressed that task of reproducing well the entire set of high energy data, though far from simple, as a long (and direct) experience teaches it [Levin], may seem to have a poor theoretical content. This is indeed so in the sense that we have not yet any means of actually knowing soft amplitudes from the first principles. However, just because of this, it is important to explore all the approaches yielding a good agreement with the existing data.

f) Search for Odderon

There has been hot pursuit for the knowledge of Odderon for the last three decades. Theorists as well as experimenters are exploring it in both elastic and deep inelastic scattering. A lot of work has been carried out in theory and the object has firm footings in perturbative QCD. Some work has also been published elaborating non-perturbative treatment of the same. With the possibility of observing Odderon in deep inelastic scattering, extensive theoretical work was carried out in the recent past in this direction. However, our search for Odderon at HERA has not succeeded. Focus is therefore now shifting on observing Odderon at RHIC and LHC where measurements for *pp* elastic scattering will be undertaken in the GeV and TeV range, providing us an opportunity to compare some of the results with

$\bar{p}p$ scattering. The following points briefly highlight our search for the Odderon in theory and experiment.

- A class of scattering processes, where the Odderon contributes, is when one or two of the incoming scattering particles, of definite C-parity, go into a state of opposite C-parity under scattering. One requires a rapidity gap, which allows separating the outgoing scattering states. A reaction of the type $\gamma(\gamma^*)+p \rightarrow PS(T)+p(X_p)$ is a good ground for the study of Odderon. This process is being analyzed at HERA. A study of $\gamma\gamma$ scattering process is another interesting preposition.
- As discussed earlier, perturbative analysis has been performed in the study of η_c production in DIS with an Odderon made by three simply uncorrelated gluons and later by considering the resummed QCD interaction in LLA. Predictions are not in agreement with the measurements.
- Non-perturbative studies have been carried on for the production of light mesons (π^0, f_2). The π^0 production process has been very recently analyzed at HERA by the H1 collaboration. The Odderon has not been seen and an upper bound has been put on the cross section, which is ten times smaller than the predicted cross section.
- Another interesting proposal, based on a more phenomenological approach, has been the study of charge asymmetry in charm states due to Pomeron-Odderon interference [Brodsky *et al*].
- The experimental evidence for the existence of Odderon is not yet convincing despite the fact that QCD suggests presence of an

Odderon. The ambiguity is for the reason that its contribution is very small compared with the dominant C = + 1 exchange contribution. Thus, reactions where C = + 1 is forbidden by selection rules, is the ideal place to test the presence of Odderon.

The only relatively clear experimental evidence for the existence of an Odderon comes from measurements of the differential cross section for high energy elastic *pp* and $\bar{p}p$ scattering in the dip region at around $|t| \approx 1.3$ GeV^2. The Odderon contribution to this process is expected to be sensitive to the proton structure. A comparison of the results for differential cross section in the dip region for 500 GeV for *pp* from RHIC with $\bar{p}p$ at 546 GeV will be very important. Contribution from the Odderon would mean a significant difference of $d\sigma/dt$ in the dip region (around $-t = 0.8$ (GeV/c)^2). The results from RHIC and LHC will therefore clearly identify the need or otherwise of the Odderon.

(VII) CONCLUSIONS

The exact nature of the pomeron (Is it composed of quarks and gluons? hard or soft? the same object as a function of momentum transfer?) remains elusive, although recent theoretical ideas and experimental results are beginning to yield some answers. This brings us to the rather new field of hard diffraction. The experimental data for the total cross section in $p\bar{p}$ scattering at the Tevatron are currently not conclusive. It seems difficult to find a clear signal of the Odderon. The maximal Odderon approach predicts $\Delta\sigma$ = -6mb at LHC energies. Such an effect shows a disagreement of the corresponding *pp* cross section with conventional fits. In addition the correlation of the signs of $\Delta\sigma$ and $\Delta\rho$ could give a hint to the Odderon. In order to find out whether there are Odderon effects in the ρ-parameter and in the total cross section, it needs to measure both quantities in *pp* and $p\overline{p}$ scattering at the same energy preferably in the TeV range.

The solution that no Odderon exists at all would be hard to accommodate within QCD - so the chase must go on! Regge Theory remains one of the great truths of particle physics. Even taking a less optimistic attitude, one can not dispute the phenomenological success of Regge theory in describing in a unified way a large class of reactions for which no alternative theoretical frame work is – at least presently available. The measurements from RHIC and LHC will give us evidence about the presence of the Odderon.

(VIII) NEED FOR THE ADDITIONAL RESEARCH

High-energy elastic and diffractive studies are needed to resolve the picture. Included in these studies are the TOTEM project for CERN's LHC collider and Brookhaven's RHIC heavy-ion collider. The further experimentation at the LHC is also needed to test the saturation of the fundamental Froissart bound on high-energy scattering behaviour and to see if dispersion relations continue to hold true or a breakdown of locality occurs.

(IX) PUBLICATIONS

- *Search for Odderon in Theory and Experiment*, **International Journal of Modern Physics - A** (Singapore) (2003) (to be published) (with Sohail Afzal Tahir et al).

- *How fast is the growth of Total Cross Section at High Energies?* **28th International Cosmic Ray Conference, pp 1575-78** (2003) with Haris Rashid, Sohail Afzal Tahir, M. Ayub Faridi and M.Qadeer Afzal.

- *Total cross sections at high energies-An update:* **Comm. Theor. Phys.** (China) **38** (2002) pp 687-690 (with Sohail Afzal Tahir, M Alam Saeed and M.Qadeer Afzal).

- *Recent results for ρ and Odderon Picture-* Proceeding of "**XXII Physics in Collision**", Stanford, California, USA (June 2002) (hep-ph-0207285) with Sohail Afzal Tahir.

- *Radii of Hadrons/Lighter Nuclei and the Geometrical Picture*, Contributed to "**PaNic02" Osaka,** Japan, 1-4 Oct. 2002 (with Sohail Afzal Tahir, M Alam Saeed).

- *Predictions for the Dip Structure at RHIC and LHC*, Contributed to **Diffraction** 2002 (with Sohail Afzal Tahir, Haris Rashid).

- *Multiple Dip Structure and Geometrical Models*, Submitted for publication (with Sohail Afzal Tahir and Haris Rashid).

- *Elastic Scattering at Current and Future Colliders*,- Submitted for publication (with Sohail Afzal Tahir).

- *Recent Results from Fermilab and Odderon Description-* submitted for publication (with Sohail Afzal Tahir).

(X) M.PHIL/PH.D DEGREES

1. Thesis entitled "Study of Soft and Hard Pomeron at high energies" was completed and awarded *M.Phil degree.*
2. Thesis entitled "Total Cross Sections in electron-positron annihilation" was completed and awarded *M.Phil degree.*

3. Thesis entitled "Odderon Description at high energies" has been submitted for the award of *M. Phil degree.*
4. Thesis entitled "Elastic Scattering at current and Future Colliders" has been *submitted for the award of Ph.D degree.*

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Revised Manuscript

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Accepted for publishing in International Journal of Modern Physics A

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Abstract

The presence of Odderon at high energy has been in question for quite some time. We have confronted the Odderon description to the available data especially for pp and $\overline{p}p$ scattering including the most recent measurements by UA4/2, E710, CDF and E811 Collaborations. The Odderon in perturbative and non-perturbative QCD has also been discussed along with some phenomenological approaches. A comparison of the Odderon description with other models has also been made for $p(\overline{p})p$ data including the measurements from cosmic ray, which corresponds to the LHC energy of 14 TeV. Our study especially focuses on the measurements at RHIC and LHC and the presence or otherwise of Odderon.

There has been a hot pursuit for the knowledge of Odderon for the last three decades. Theorists as well as experimenters are exploring it in both elastic and deep inelastic scattering. A lot of work has been carried out in theory and the object has firm footings in perturbative QCD. Work has also been published elaborating non-perturbative treatment of the same. Search for Odderon at HERA has not succeeded. With the possibility of observing Odderon in deep inelastic scattering, extensive theoretical work was carried out in the recent past in this direction. These attempts are briefly described in the short reviews [1-2]. With no success at HERA, focus is now shifting on observing Odderon at RHIC and LHC where measurements for *pp* elastic scattering will be undertaken in the GeV and TeV range, providing us an opportunity to compare some of the results with $\bar{p}p$ scattering. In this paper we will take up different aspects of the Odderon study with a focus on *pp* and $\bar{p}p$ scattering. The paper is subdivided into six parts: Experimental data, Odderon description, Odderon and QCD, Phenomenological studies, Search for Odderon in experiment and Conclusions.

1. EXPERIMENTAL DATA

Current status of the measurements for *pp* and $\bar{p}p$ scattering for various parameters along with the proposed experiments at RHIC and LHC are briefly discussed in the following sections.

1.1 Current Data

The total and differential cross section, σ_T and $d\sigma/dt$, elastic cross section, σ_{el}, the local slope parameter, B and ratio of the real and imaginary parts of the scattering amplitude, ρ have been measured by several authors at CERN-ISR, CERN-SPS, and FERMILAB [3-22]. Recent measurements are - UA4 and UA4/2 at CERN and CDF, E710, E811, SELEX from FERMILAB. Cosmic ray data corresponding to LHC energy has also been reported for *pp* scattering [23-25]. These measurements are shown in Figs.1- 5. We will describe the salient features of these measurements together with future agenda in the next section.

1.2 Future Measurements

Measurements in the future are planned at PP2PP [26] experiment at RHIC and CMS [27], FELIX [28], TOTEM [29] experiments at LHC.

The PP2PP experiment [26] will study *pp* total and elastic scattering in c.m energy range from 60 GeV to 500 GeV at RHIC, BNL using both polarized and unpolarized beams. The measurements will be made in the two kinematical regions. In CNI (Coulomb Nuclear Interference) region $0.0005 < -t < 0.12$ (GeV/c) ^{2}, σ_T, σ_{el}, ρ and B will be measured. In the medium -t region, $-t < 1.5$ (GeV/c) ^{2}, a study of the evolution of the dip structure with $\sqrt{s}$ is planned. These measurements will provide us a unique opportunity to compare the results for *pp* and $\bar{p}p$ at 63 and 540 GeV.

CMS (Complex Muon Solenoid) [27] will study *pp* collisions at Large Hadron Collider (LHC). The LHC running at reduced c.m. energy of 1.8 TeV will provide us an opportunity to compare the results with $\bar{p}p$ as measured at FERMILAB. A comparison of *pp* and $\bar{p}p$ at 1.8 TeV is therefore of considerable interest from the theoretical point of view. This experiment will also check $\sqrt{s}$ dependence of the total and elastic scattering in going from 1.8 TeV to 14 TeV.

At FELIX (Forward ELastic and Inelastic eXperiment) [28], experiment is planned at $\sqrt{s}$ = 14 TeV with a luminosity of 10^{34} cm^{-2} sec^{-1}. Measurements in the forward direction will be undertaken at FELIX full acceptance detector covering the extreme forward directions. Motivation for the "Forward Physics" is for the reason that it has never been taken up in the past at ISR, SPS or FERMILAB colliders. Physics agenda also includes measurements of the total and elastic cross sections. At the same time, TOTEM (TOTal cross section and Elastic scattering Measurement) [29] collaboration proposes to measure the total and elastic scattering over a large range of -t along with single diffractive scattering and double Pomeron exchange cross section in *pp* collisions at 10-14 TeV.

General Features of these measurements can be summarized as follows:

1. Elastic and total cross sections (σ_{el} and σ_T) are slowly increasing functions of energy and their ratio (σ_{el} / σ_T) also increases with the increase in energy. This is shown in

Figs. 1-2. Rise of the total cross sections with energy as measured at ISR, SPS, FERMILAB-TEVATRON and cosmic ray is depicted in Fig. 1. Will the rise of total cross section be as $\ln s$ or $\ln^2 s$? This is an open question and measurements at LHC will throw more light on it.

2. The ratio ρ = [Re T (s, t = 0)] / [Im T (s, t = 0)] is small and rises slowly with energy, crossing zero near $P_L \approx 300$ GeV/c for *pp* and around $P_L \approx 150$ GeV/c for $\bar{p}p$. It becomes almost constant at $\sqrt{s} \geq 100$ GeV. This is shown in Fig. 3. Will it remain constant or increase/decrease at LHC energies?
3. For both *pp* and $\overline{pp}$ elastic scattering, the local slope, B, of the diffraction peak increases with an increase in energy (Fig 4). Shape of the slope at ISR and SPS in the extreme forward region suggests a concave curvature. At FERMILAB this curvature seems to have disappeared. Measurements at RHIC and LHC will throw more light on this.
4. Measurements at ISR for the differential cross section for *pp* and $\overline{pp}$ over large *-t* region have a rather complex behaviour, with a dip near $-t = 1.4$ $(\text{GeV/c})^2$ as shown in Fig. 5. Position of the dip moves towards $-t = 0$ with an increase in energy. This dip seems to convert in to a shoulder at SPS and FERMILAB energies for $\overline{pp}$ elastic scattering. The differential cross section at the dip first decreases and then increases at ISR energies. At SPS and FERMILAB energies, this dip turns into a shoulder and the differential cross section is two orders of magnitudes higher. At ISR, a secondary maximum is present beyond the dip, followed by a large *-t* regime, which can be described by a smaller slope. There is no evidence of a second diffraction minimum.

2. ODDERON DESCRIPTION

To study the development of the Odderon description, we will start with Regge models, development of Pomeron and then move to the concept of Odderon.

2.1 Regge Models

In 1959, Regge [30] first showed that the generalization of the angular momentum to a complex variable, when applied to a wide variety of potentials, leads to very useful results in high energy physics. He showed that the only singularities of the non-relativistic scattering amplitude in the complex angular momentum plane were poles, which move with energy. In the pristine Regge pole model, the partial wave expansion for the scattering amplitude is written as

$$T(s,t) = \frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\ a(l,\in)\ P_l(z)$$

where k is the c.m. momentum, $P_l(z)$ is a Legendre polynomial containing the angular dependence and $a(\ell,\in)$ is the partial wave amplitude. It is assumed that $a(\ell,\in)$ is an analytic function of the angular momentum ℓ, considered to be a complex variable. Only singularities of the functions are simple poles, called Regge poles. As s changes, the pole moves in the complex angular momentum plane describing what is called a Regge trajectory. A Regge trajectory passing close to $\ell = 0,1,2, \ldots.$ describes a resonance. The scattering amplitude due to the exchange of Regge trajectory is then written as

$$T(s,t) = \gamma_1(t)\gamma_2(t)F(\alpha)(s/s_0)^{\alpha}$$

where $\gamma_1(t)$ represents the coupling of the trajectory, to the particles 1 and 3 at the upper vertex while $\gamma_2(t)$ represents coupling to particles 2 and 4. $F(\alpha)$ represents a function containing the Reggeon propagator and s_0 is the hadronic mass scale taken to be equal to I GeV^2.

If Regge pole exchange is the dominant mechanism at high energy, then the amplitude at large s is dominated by the trajectory $\alpha(t)$ with the largest intercept at $t = 0$. The scattering amplitude and total cross section can then be expressed as

$$T(s,t) \approx h(t)\,(s/s_0)^{\alpha} \quad \text{and} \quad \sigma_T \approx (s/s_0)^{\alpha-1}$$

where h(t) is a function of the four momentum transfer. For $\sqrt{s} = 10$ GeV, the total and differential cross section was found to vary slowly with energy. This variation was associated with the exchange of Pomeron. Evidence for the Pomeron has been found in the experiments measuring diffraction dissociation and successful efforts have been made to find its origin in QCD [31]. Assuming the trajectories to be straight lines we can write

$$\alpha(t) \cong \alpha_0 + \alpha' t$$

Then the differential cross section can be written as

$$\frac{d\sigma}{dt} = F(t)\left(s/s_0\right)^{2\alpha-2}$$

This expression is a good approximation to the experimental data in the small -t region. However, in the dip region and beyond, further modifications are needed [32]. The exchange of Pomeron leads to identical behavior for pp and $\overline{p}p$ scattering. The difference between pp and $\overline{p}p$ is accounted for through the exchange of mesonic trajectories, which consists of quark exchange.

In order to explain the experimental data beyond the dip for the differential cross section, Regge cuts, arising out of the exchange of two or more Reggeons and giving rise to branch cuts in the complex angular momentum plane, (arising from a 2 Pomeron exchange) were employed [33]. However the problem of difference between pp and $\overline{p}p$ differential cross section in the dip region remained unaccounted for. In order to take this fact in to account, odd charge conjugation 3 gluon exchange or Odderon was introduced. The Regge cut gives rise to a flatter dependence while the Odderon explains the difference between pp and $\overline{p}p$ at high energies. We now take up the Odderon description in some detail.

2.2 The Odderon

Lukaszuk and Nicolescu first introduced the Odderon [34] in 1973 when it was discovered at ISR that total cross section for pp scattering rises with an increase in energy. They made an assumption that the strong interactions are as strong as possible in the form

$$\sigma_T \longrightarrow C_+ \ln^2 s (C_+ \succ 0) \text{ and } \Delta\sigma \longrightarrow C_- \ln s, \text{as s} \longrightarrow \infty$$

where C_+ and C_- are real constants and $\Delta\sigma$ represents the difference of the total cross sections for pp and $\overline{p}p$. At t = 0, this hypothesis corresponds to a double pole in the spin flip amplitude at J = 1 in the complex J-plane, also termed as "maximal Odderon". Kang and Nicolescu [35] in 1975 provided theoretical basis for the Odderon. From the theoretical point of view, this concept has been rediscovered in QCD. Several authors [36-39] have provided the dynamical origin of this concept. In QCD, there are not only quark-Reggeons but also glue-Reggeons. More generally, multi-Reggeized-gluon exchanges lead to contributions having the Odderon quantum numbers. This is a very important theoretical fact, which provide physical basis to the concept of Odderon. Several interesting aspects of Odderon in perturbative QCD have been taken up in various studies [40-49]. Much work has since been carried out on the origin and meanings of the Odderon [50]. Theoretical status of the Odderon is now firm not only in the perturbative QCD theory but also in the non-perturbative approach. In the perturbative treatment, efforts are mainly focused on the determination of the Odderon intercept.

Thus, concept of an Odderon has been a very interesting inclusion to our knowledge. Models incorporating Odderon are thus based upon general S-matrix principles, the constraints of asymptotic theorems and a dynamical assumption of "maximal strength" of strong interactions. We will now take up Odderon in QCD in some more details.

3. ODDERON IN QCD

It is now established that existence of the Odderon is predicted by QCD [2]. Idea of the Odderon is related to the possibility that the real part of scattering amplitude increases with energy as fast as the imaginary part. The scattering amplitude in the complex angular momentum plane possesses a rightmost singularity (pole) near $j = 1$. In the even (under crossing) amplitude, such a singularity is associated to the Pomeron and gives a mostly imaginary contribution, while in the odd case one has a mostly real contribution which is associated to the Odderon. The position of the singularity is also called intercept and is related to the asymptotic behaviour of the cross section [2].

QCD predicts the existence of Pomeron. A simple picture is through two-gluon exchange. This picture however does not give rise to the total cross section indicating that at least three-gluon exchange is involved. In order to account for increase in total cross section, the exchanged gluons must interact with each other [51]. Calculations must undertake the relation (maybe only qualitatively) between Pomeron trajectory and QCD. This is an interesting issue, but so far, qualitatively, they do not coincide with each other. As the internal gauge symmetry group of QCD has rank greater than one, we can construct a C-odd state from three gluons, which can be associated to the Odderon.

3.1 Perturbative QCD Odderon

The Odderon description in the perturbative QCD is based on re-summation techniques in the small x region. Recent developments on the perturbative analysis have been briefly reviewed in a recent work [2]. A scattering process dominated by the Odderon exchange can be described in the high energy limit, in the context of k_T factorization, by amplitude

$$A(s,t)=\frac{s}{32}\frac{1}{16}\frac{N_c^2-4}{N_c^2}\frac{N_c^2-1}{3!}\frac{1}{(2\pi)^8}\left(\Phi_\gamma^i\middle|G_3\middle|\Phi_p\right)$$

At lowest order, when the strong coupling α_S is small, one has a simple three uncorrelated gluon exchange, i.e. the Green function G_3, which is convoluted with the impact factors, is constructed with 3 gluon propagators. In momentum representation

$$G_3^{(LO)}=\delta^{(2)}\left(k_1-k_1^{'}\right)\delta^{(2)}\left(k_2-k_2^{'}\right)1/k_1^2k_2^2k_3^2$$

In the high energy limit, when all other physical invariants are small, a *LLA* (Leading Logarithmic Approximation) resummation of the contributions of the order $(\alpha_s \ln s)^n$, which is not small, can be performed and one obtains, through G_3, an effective evolution in rapidity. The same resummation for the two gluon exchange has lead to the BFKL (*Balitsky-Fadin-Kuraev-Lipatov*) [52] equation where it appears the kernel of the integral equation for the 2-gluon Green function that, in the colour singlet state, describes the perturbative QCD Pomeron in *LLA*. The same equation in the colour octet state has a simple eigenstate, which corresponds to the reggeized gluon and is in general a composed object at high energies. This fact is seen as a self-consistency requirement and is called bootstrap. In *NLA* (Next-to-Leading Approximation) [53], where one is also resumming the contribution of order $\alpha_s^n(\ln s)^{n-1}$, all the same concepts including reggeization [54], apply.

The general kernel for the *n*-gluon integral equation for the Green function in LLA is given by the BKP (Bartels, Kwiecinski and Praszalowicz) equation [55]. In the large N_c limit and for finite N_c *(number of colours)* when n = 3, it possesses remarkable symmetry properties: discrete cyclic symmetry, holomorphic separability, conformal invariance, integrability and duality [56]. Also a relation between solutions with different n exists [57], which is a direct consequence of the gluon reggeization.

The Odderon states in LLA must be symmetric eigenstates of the operator $K_3 = 1/2(K_{12} + K_{23} + K_{31})$ constructed with the BFKL kernel K_{ij} for two reggeized gluons in a singlet state. Using the conformal invariance and integrability properties, a set of eigenstates is found [58], which have a maximal intercept below one.

Using the gluon reggeization property (bootstrap), a new set of solutions was later found [59], characterized by intercept up to one and dominant at high energies. For the particular impact factor, which couples photon and η_c to the Odderon, the LLA calculation has shown that the second set of solution is relevant while the previous one decouples. In momentum representation the Odderon states are given by $E_3^{(\nu,n)}$ such that

$$k_1^2 k_2^2 k_3^2 E_3^{(\nu,n)}(k_1, k_2, k_3) = c(\nu,n) \sum_{(123)} (k_1 + k_2)^2 k_3^2 E^{(\nu,n)}(k_1 + k_2, k_3)$$

where $c(n,\nu)$ is a normalization factor, E is a BFKL pomeron eigenstate and the conformal spin n is odd. The full Green function is constructed summing over all such states but in the high energy limit the asymptotic behaviour can be studied for conformal spin n = ±1 and performing the saddle point integration around $\nu = 0$.

Very recently, a set of new Odderon states has been used [60] to calculate contribution to the diffractive photo and electro production processes. Results are an order of magnitude enhancement to previous simple 3-gluon exchange calculations. It is shown that t-dependence of the cross section exhibits a dip structure in the small t region.

3.2 Non-perturbative QCD Odderon

Non-perturbative QCD Odderon approach is based on the stochastic vacuum model of Heidelberg group. A brief sketch on the non-perturbative QCD framework used for Odderon studies [2,61] is given below.

A first ingredient is the choice of the eikonal semi classical approximation [62] for high energy scattering of quarks. At first, quantum colour field behaviour is considered. In particular each quark, which scatters on a colour field, picks up a non-abelian eikonal phase $V = P\exp\left[-ig\int_{\Gamma} dz^{\mu} A_{\mu}(z)\right]$.

The functional integral on the physical gluon field is estimated using the stochastic vacuum model (SVM) [63], i.e. the calculation of any correlation functions of gluon field strength is associated to a gaussian stochastic process with finite correlation length and, therefore, expanded as $\langle F.\,F...F\rangle = \sum \Pi \langle F.F\rangle$. After some other assumptions and relating the basic two point function $\langle 0|F.F|0\rangle$ to the gluon vacuum condensate, a dipole-dipole or dipole-tripole (as Wegner-Wilson loops) scattering amplitude at fixed transverse size can be computed expanding the ordered exponential. Mesons (barions) are described in term of dipoles (tripoles) and transverse wave functions [64].

When expanding the exponentials in the eikonal phases, terms of the kind $\langle Tr(F.F)Tr(F.F)\rangle$ give imaginary contribution and are associated to the Pomeron. Instead the real Odderon contribution is given by subsequent terms of the kind $\langle Tr(F.F.F)Tr(F.F.F)\rangle$, in particular by the piece with the d_{abc} d_{abc} colour structure where d_{abc} is the fundamental symmetric tensor in SU(3).

In this approach, the energy dependence is introduced in a phenomenological way. A quark-diquark structure of the hadrons has been preferred. The production of light mesons in Deep Inelastic Scattering [61] has been studied (π^0, f_2 with N^* resonances production) through Odderon driven processes. Predictions at HERA energies are $\sigma^0_{\gamma p \to \pi^0 N} \approx 400$nb and $\sigma^0_{\gamma p \to f_2\ N} \approx$ 21 nb. The first process has been analyzed at HERA by the H1 collaboration and there is now an upper bound on the cross section of around 39 nb [65]. There is a big discrepancy in the predicted and measured value. One possible source of error comes from the parameter fixing in SVM. The most serious one seems to be the badly estimated $\gamma O \pi^0$ vertex. It seems therefore that the f_2 production process would be based on more solid estimates of the coupling.

4. PHENOMENOLOGICAL STUDIES

4.1 σ_T, ρ and dσ/dt in pp and $\overline{p}p$ scattering

Several authors have used the Odderon picture since the idea was first floated.

Gauron *et al.* [66] gave an account of various aspects of the *pp* and $\overline{p}p$ scattering including difference of σ_T and dσ/dt in the dip region at ISR. Bernard *et al* [16] later on showed that UA4 results (ρ = 0.24 ± 0.04) could be described by the presence of Odderon. Their predictions for the total cross section and ρ are higher than UA4/2 (ρ = 0.135 ± 0.02) and E811 (ρ = 0.135 ± 0.044) results that replaced the earlier measurements of UA4. Jenkovszky *et al* [67] extended the idea to relate the small momentum transfer hadron scattering and deep inelastic scattering. This relationship is useful for understanding the origin of cross section from the point of view of hadronic structure and interaction of its constituents. Rafique *et al* [68] used Odderon description to explain the then available data for σ_T and ρ. Their predictions are in agreement for ρ but higher for σ_T. In another attempt, Odderon description was confronted by Fazal-e-Aleem *et al* [69-70] to fit data for the differential cross section. Predictions of their results [69] for σ_T and ρ are somewhat higher than the current measurements [22]. We thus find that the models incorporating Odderon predict higher ρ value (~0.2) at FERMILAB, RHIC and LHC [71]. Recent results of 0.135 ± 0.02 at UA4/2 and 0.135 ± 0.044 at E-811 do not seem to favour the presence of Odderon in the forward direction. In the simple Regge picture of Landshoff and Donnachie [72], a constant value of ρ = 0.12 is predicted which is in agreement with the UA4/2 and E811 data. In the geometrical model [51] this value is predicted to be ≈ 0.14 at SPS, FERMILAB and LHC and is consistent with E811 results.

The ratio ρ is of major interest in theory and experiment because of its close relationship with the energy integrated inelasticity of the collision via the dispersion relation. This quantity will in principle be accessible to measurements at RHIC and LHC energies. The kinematical range to be covered corresponds to the Coulomb-nuclear interference region. The expected $|t_0|$ value at the RHIC and LHC are estimated to about 0.0005 and 0.0007 $(\mathrm{GeV/c})^2$ respectively. Measurement at smallest possible -t value will therefore minimize the extrapolation error and provide us an ideal opportunity to have a very precise measurement for ρ. This will give us a clearer picture of Odderon contribution in the forward scattering. In the Eikonal models, the dip of the differential cross section is very sensitive to the ρ value which suggests that in case of higher measured value of ρ at RHIC and LHC (as predicted by Odderon), the structure in dσ/dt would disappear and turn into a shoulder.

Similarly predictions of σ_T in the models incorporating Odderon are higher than E710 (72.2 ± 2.7 mb) [20] and E811 (71.42 ±1.55 mb) [22] measurements at FERMILAB. These values, however, are consistent with measurements of CDF (80.26 ±2.25 mb) [21]. Predictions of various models at 0.1, 0.5, 1.8 and 14 TeV for σ_T and ρ are given in Table 1. We observe that most recent results (E811 [22]) again confirm the fact that Odderon contribution in the forward direction is negligible. It can thus be concluded that the results from RHIC and LHC will be able to clearly identify the presence or otherwise of the Odderon in the forward scattering. At the same time, differential cross section in the dip region for 500/540 GeV for $pp/\bar{p}p$ from RHIC/SPS will be very important. Contribution from the Odderon would mean a significant difference of dσ/dt in this region (around $-t = 0.8\ (\mathrm{GeV}/c)^2$). A representative result for σ_T and ρ with and without Odderon is given in Fig. 6.

With the new measurements planned at RHIC and LHC, most interesting would be the dip region in pp and $\bar{p}p$ elastic scattering from the Odderon point of view. Very recently, H.G. Dosch et al., [50] have studied Odderon contribution to elastic pp and $\bar{p}p$ scattering. They have used different models for the Odderon-proton coupling and studied the effects on the differential cross section in the dip region. As a framework these authors have used the Donnachie-Landshoff fit and replaced the Odderon contribution used in various models. They have also used two models for the Odderon-proton coupling, which are based on impact factors in momentum space. In the process, they have constructed a geometric model for the proton in which the effect of a possible diquark cluster can be studied. Odderon is modeled by perturbative three-gluon exchange in the $C = -1$ channel. They conclude that all models for the Odderon-proton coupling give very similar results by the appropriate choice of model parameters, in particular the strong coupling constant. The available data cannot distinguish between the different models but for a given model the data impose very strong constraints on the parameters of that model. Using their geometric model, they find that the average size of the diquark cluster in the proton is quite small, < 0.5 fm. This result is obtained by assuming that reasonable values for strong coupling constant α_s in the dip region are larger than 0.3. In the non-perturbative model used by Rueter and Dosch [73], such a small diquark is sufficient to explain the absence of an Odderon signal in the ratio of the real to imaginary part in the forward direction. This can be understood by the fact that in the non-perturbative model for the IR behaviour of QCD, soft gluons dominate and therefore the resolution is much coarser. In the models based on Odderon-proton impact factors, the data imposes rather strong constraints on the choice of strong coupling constant α_s, which appears as a parameter in these models.

Results depicting the behaviour of the differential cross section at high energies with [87] and without Odderon [69] contribution are shown in Fig.7.

4.2 Diffractive η_c photo and electro-production

Calculations in perturbative QCD have been made for processes where heavy quarks are involved [2, 60]. One such example is diffractive η_c production in DIS, which has been studied at lowest order [74, 75]. The calculations give $\sigma \approx 11$ pb at $Q^2 = 0$ and 0.1 pb at $Q^2 = 25$ GeV^2, with no energy dependence. As pointed out earlier, this process has recently been reanalyzed [59] in LLA. The amplitude has been calculated in the saddle point approximation using the Green function G^3, constructed with the non-forward Odderon states. In order to compare the effect of LLA, QCD resummation to the lowest order calculations, the same impact factors for the $\gamma O \eta_c$ and for pOp vertices have been used. The $\gamma O \eta_c$ impact factor has been computed perturbatively [76]. It has an interesting symmetry, which allows a partial analytical computation [77] of its scalar product with the Odderon eigenstates. For the proton side, the same ansatz has been used [75]. Due to the structure of the Odderon states, which manifests a strong correlation between the constituent reggeized gluons, the Odderon coupling to the impact factor has the dominant real part, which changes sign for a value of the momentum transfer squared -t. The results of computation for the differential cross section for $\gamma^* + p \rightarrow \eta_c + X$ are given in Fig.8, where a dip in the small -t region is present. Due to the cut nature of these Odderon singularities the cross section is slightly suppressed (as $1/\ln s$) with energy.

The total cross section, which results from the LLA Odderon states contribution, has been found to be $\sigma \approx 50$ pb at $Q^2=0$ and 1.3 pb at $Q^2=25$ GeV^2, an order of magnitude higher than in the simple three gluon exchange case. Quantitative and qualitative differences are introduced by the gluon interaction but the cross sections are too small to be measured at HERA. The Odderon still poses a challenge for experimentalists.

Fukugita and Kwiecinski proposed another model of particular interest for the Odderon-proton impact factor [78]. Recently, this model has been used for the calculation of different processes, among them the diffractive photo and electroproduction of η_c mesons at HERA. This process is currently considered to be one of the best possible ways to observe the Odderon experimentally. The corresponding calculations [74,75, 79] use a rather large value $\alpha_s = 1$ in the impact factor. In order to describe the data for *pp* elastic scattering with this impact factor, however, it is found that α_s needs to be chosen as 0.3. This observation indicates that the current estimates for diffractive η_c production at HERA might be somewhat optimistic.

In this study it has been assumed that Odderon can be described as perturbative three-gluon exchange. However, the dip region of *pp* elastic scattering is located at momentum transfers $\sqrt{t}$ just slightly above 1 GeV that is at the lowest edge of the applicability of perturbation theory. It would therefore be very desirable to study this process in the non-perturbative region as well.

5. EXPERIMENTAL SEARCH

There have been many attempts for experimental search of Odderon while further search is planned in the measurements at RHIC and LHC. These are briefly discussed below:

1. A class of scattering processes, where the Odderon contributes, is when one or two of the incoming scattering particles, of definite C-parity, go into a state of opposite C-parity under scattering. One requires a rapidity gap, which allows separating the outgoing scattering states. A reaction of the type

$\gamma(\gamma^{*})+p\rightarrow PS(T)+p(X_p)$ is a good ground for the study of Odderon. This process is being analyzed at HERA. A study of $\gamma\gamma$ scattering process is another interesting preposition.

2. As discussed earlier, perturbative analysis has been performed in the study of η_c production in DIS with an Odderon made by three simply uncorrelated gluons and later by considering the resummed QCD interaction in LLA. Predictions are not in agreement with the measurements.
3. Non-perturbative studies have been carried out for the production of light mesons (π^0, f_2). The π^0 production process has been very recently analyzed at HERA by the H1 collaboration. The Odderon has not been seen and an upper bound has been put on the cross section, which is ten times smaller than the predicted cross section.
4. Another interesting proposal, based on a more phenomenological approach, has been the study of charge asymmetry in charm states due to Pomeron-Odderon interference [80].
5. The experimental evidence for the existence of Odderon is not yet convincing despite the fact that QCD suggests presence of an Odderon. The ambiguity is for the reason that its contribution is very small compared with the dominant C = + 1 exchange contribution. Thus, reactions where C = + 1 is forbidden by selection rules, is the ideal place to test the presence of Odderon.
6. The only relatively clear experimental evidence for the existence of an Odderon comes from measurements of the differential cross section for high energy elastic pp and $\overline{p}p$ scattering in the dip region at around $-t\approx 1.3$ GeV/c ^{2}. The Odderon contribution to this process is expected to be sensitive to the proton structure. A comparison of the results for differential cross section in the dip region for 500 GeV for pp from RHIC with $\overline{p}p$ at 540 GeV will be very important. Contribution from the Odderon would mean a significant difference of dσ/dt in the dip region (around –t = 0.8 (GeV/c) ^{2}). The results from RHIC and LHC will therefore clearly identify the need or otherwise of the Odderon.

6. CONCLUSIONS

In order to clarify the presence of Odderon it is important that the future measurements take the following fact in to account. Unlike the simple Regge picture, Odderon predicts that σ_T, ρ and $d\sigma/dt$ in the vicinity of dip region are not equal for pp and $\bar{p}p$. It would be of interest, therefore, to make a simultaneous measurement of these parameters at LHC for both pp and $\bar{p}p$. Also, as proposed by the RHIC, measurements of the total cross section in the region between ISR and SPS Collider, which has remained unexplored, would be quite crucial. A small value of $\Delta\sigma$ would provide strong evidence in favor of the maximal Odderon. Another reason for the ambiguity is that the contribution of Odderon, in the region where perturbative QCD can be applied, is very small compared with the dominant $C = +1$ exchange contribution. Thus, reactions where $C = +1$ is forbidden by selection rules, is the ideal place to test the presence of Odderon.

ACKNOWLEGMENT

One of us FA gratefully acknowledges the financial assistance from Pakistan Science Foundation (PSF) under grant No.114.

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Table-1

Predictions of various models for σ_T and ρ.

$\sqrt{s}$ (GeV/TeV)				σ_T (mb)	ρ	References
100				45.96	0.0962	Petrov & Prokudin [81]
	500			59.05	0.1327	Petrov & Prokudin [81]
	500			63.5	0.15	Selyugin [82]
		1800		76.5 ± 2.3	0.142 ± 0.015	Augier et al [71]
		1800		74.8	0.174	Fazal-e-Aleem et al [33]
		1800		73	0.14	Hufner & Povh [86]
			14	113 ± 5 140 ± 7	0.142 ± 0.01 0.173 ± 0.013	Avila, Luna & Menon [83]
			14	106.73	0.1378	Petrov &.Prokudin [81]
			14	103	0.11	Kaidalov *et al* [84]
			14	108 ± 3.4	0.117 ± 0.001	Block *et al* [85]

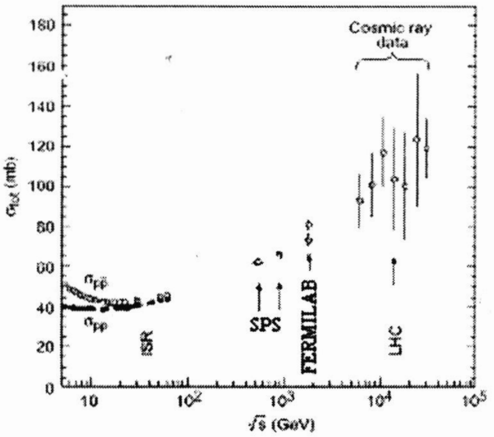


Fig.1: Experimental data for total cross sections at ISR[11], SPS [15-17], FERMILAB[18-22] and Cosmic Ray energies [22].

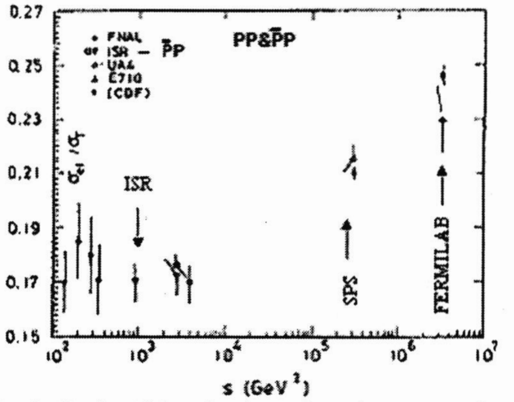


Fig. 2: Ratio of the elastic and total cross section as measured by at ISR [11], SPS [15-17], FERMILAB[18-22] energies.

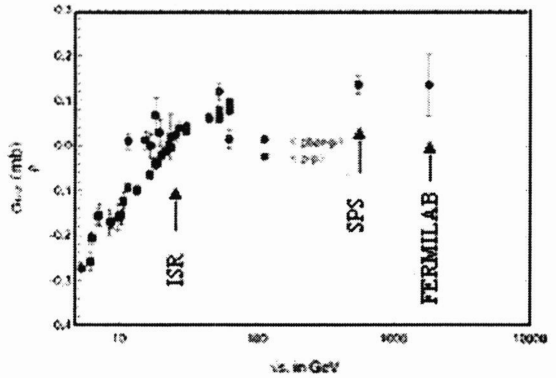


Fig.3: Experimental measurements for the ratio of the real and imaginary part of the forward scattering amplitude as measured at ISR [11], SPS [15-17], FERMILAB [18-22]

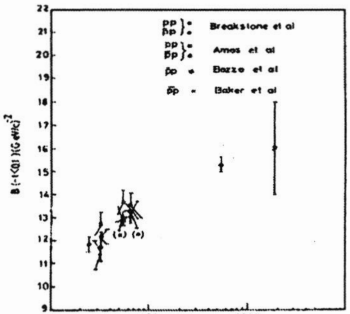


Fig. 4: The slope parameter B for *pp* and $\overline{p}p$ elastic scattering at ISR[11], SPS [15-17] and FERMILAB[18-22] energies.

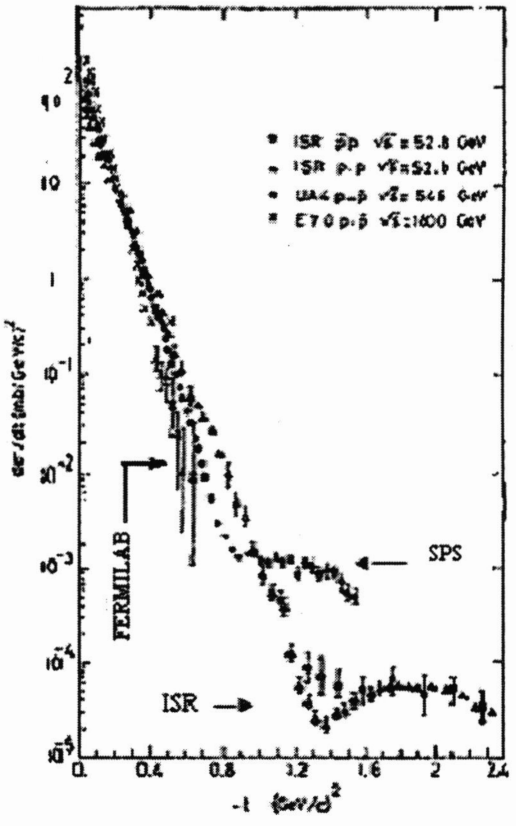


Fig.5: Differential cross sections at ISR [11], SPS [15-17 and FERMILAB [18-22]

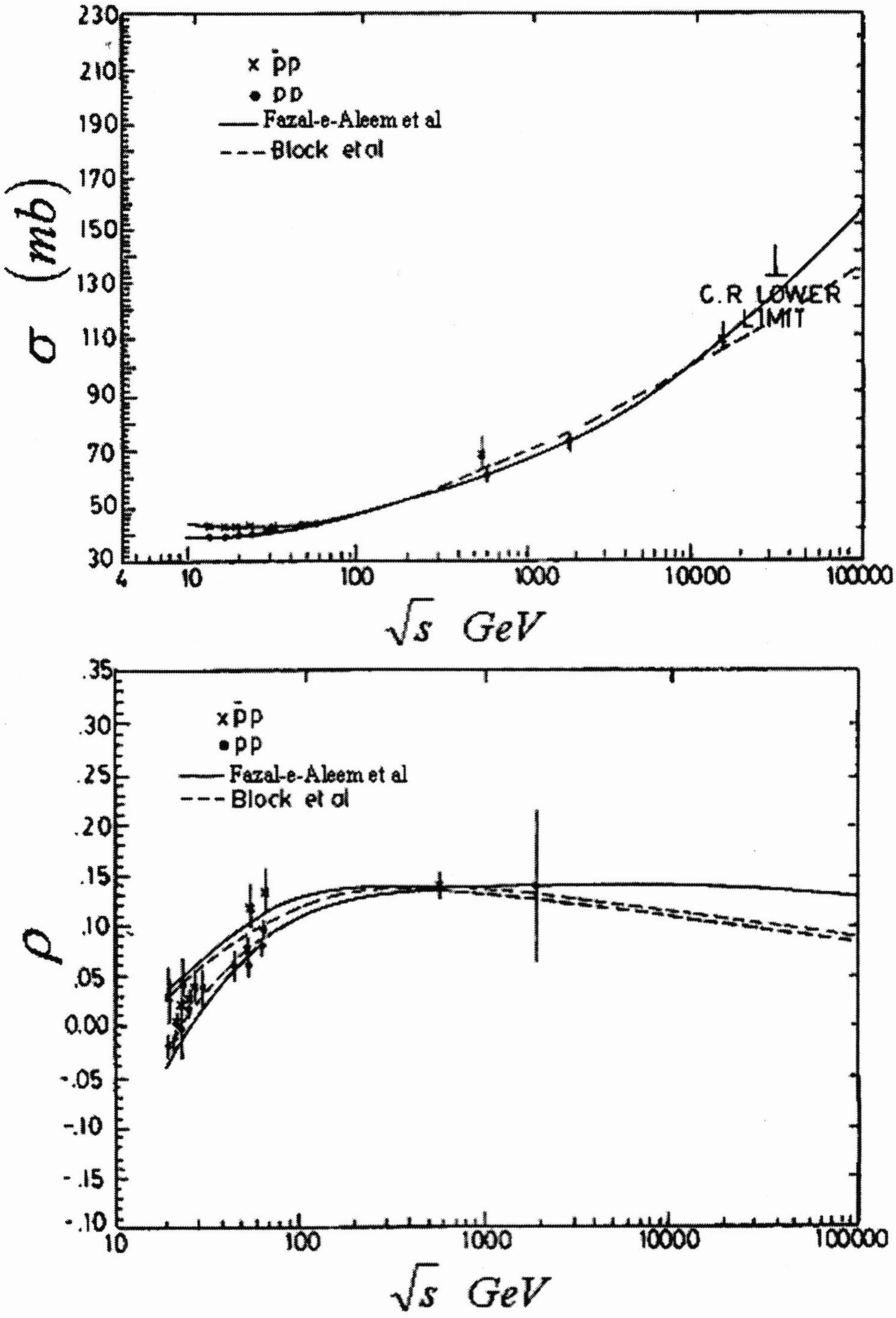
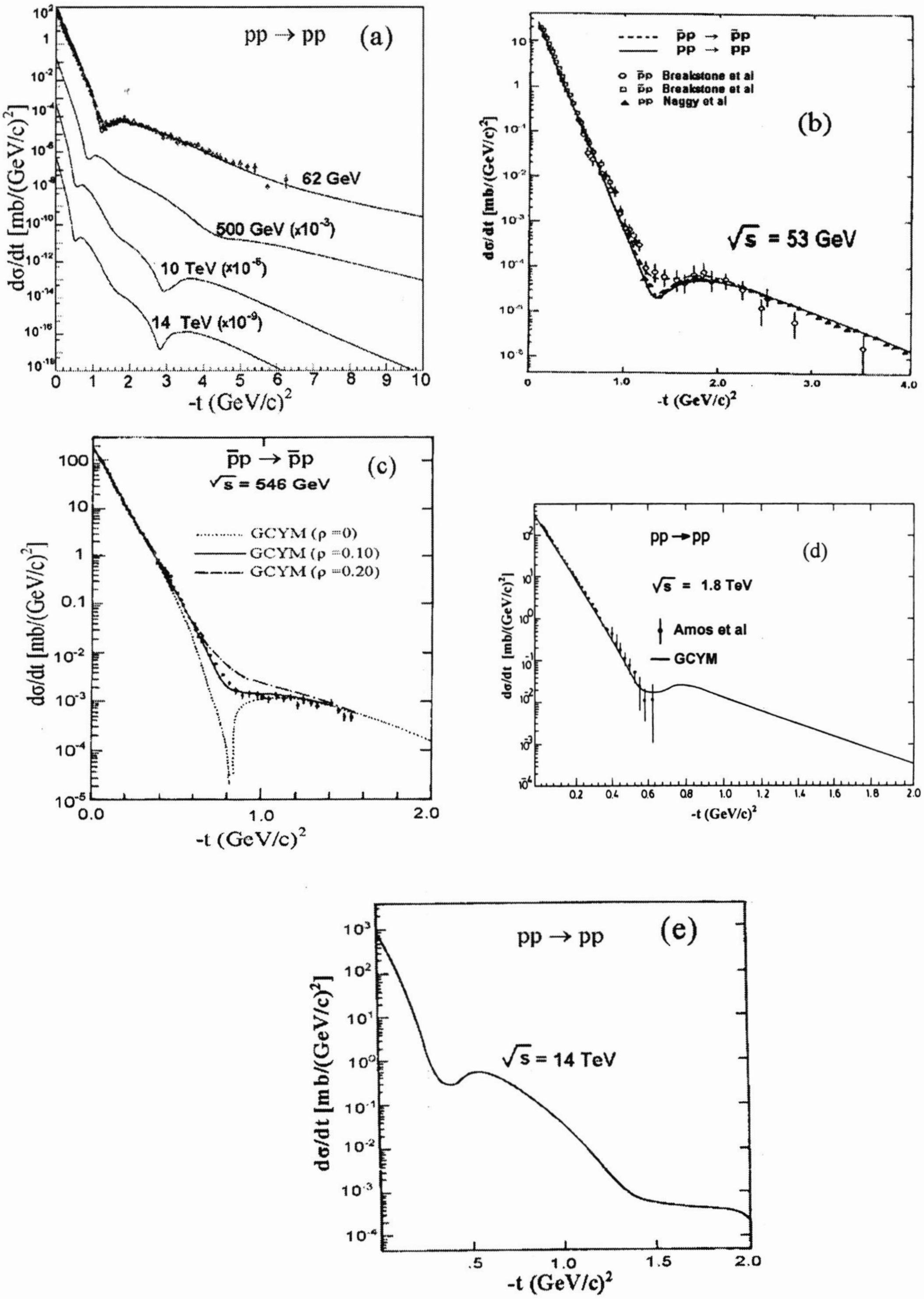


Fig.6: Total cross section measurements compared with the predictions of models with [70] and without [85] Odderon contribution at current and future energies.



Figs. 7(a-e): Predicted Differential cross section for *pp* and $\overline{p}p$ elastic scattering at ISR, SPS, Tevatron, RHIC and LHC energies with Odderon contribution (a) [87] together with prediction of Generalized Chou-Yang model [69] (b to e).

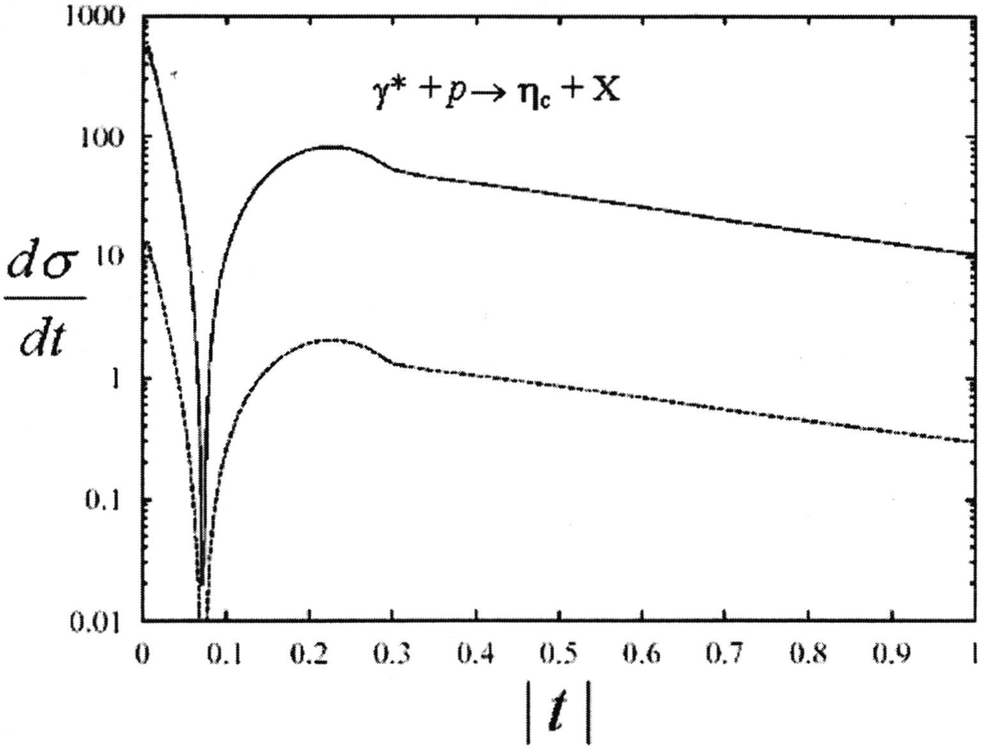


Fig. 8: The differential cross sections for $\gamma^* + p \rightarrow \eta_c + X$ (in pb = GeV^2). The upper curve refers to $Q^2 = 0$ as calculated by Bertal et al [60].

How fast is the growth of Total Cross Section at High Energies?

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Abstract

Relativistic Heavy Ion Collider and Large Hadron Colliders have special agenda for the measurements of the total cross sections at high energies giving us an opportunity to touch cosmic ray energies. Recent analyses of the cosmic ray data together with earlier experimental measurements at ISR and SPS gives us an insight about the behaviour of this important parameter at asymptotic energies. We will study the growth of total cross section at high energies in the light of various theoretical approaches with special reference to measurements at RHIC and LHC.

1. Introduction

One of the most fundamental parameters, in the realm of hadronic scattering is the total cross section, σ_T. It is a common belief that the dynamics of strong interactions, explaining the hadronic scattering processes, would become understandable and simple at high energies. In order to develop a theory, information about the rise of total cross section at cosmic energies would be very important [12]. Experimental information on the behavior of hadronic total cross sections at ultrahigh energies can be obtained from cosmic ray experiments. In this respect, analyses of extensive air showers observations provide an important source of information. The primary cosmic ray data for total cross sections has been observed in the Utah "Fly's Eye" detector [7]. A recent analysis of the same data [4–6] further enhances the need for a comprehensive study at ultrahigh energies. In our study we would briefly give an overall picture of the total cross section with special reference to existence or otherwise of Odderon at very high energies.

2. Theoretical studies

A large amount of work has been carried out using various approaches [18, 19]. In almost all the models attempts have been made to fit the world data for the total cross section. The models give a fit at ISR energies. As we move to

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higher energies of SPS and Fermilab-Tevatron [3], there is a difference of predicted values. This difference becomes visible at LHC/Cosimc Ray energies. The same is symbolically depicted in Fig.1. We will discuss this phenomenon in more detail in the following discussion.

A typical dispersion relation result as done by Augier et al [2] gives total cross section, which is shown in Fig.1. Here data over a wide range of $5 \leq \sqrt{\mathrm{s}} \leq 546$ GeV has been used to fit the parameters. The resulting asymptotic dependence found for the total cross section is.$\sigma_{\mathrm{T}} \approx [\log\,(\mathrm{s}/\mathrm{s}_0)]^{2.2\,\pm\,0.3}$. This analysis favours $\log^2 s$ dependence of σ_T as compared to log s. This kind of behaviour corresponds to the maximum rate of rise of energy allowed by the analyticity and unitarity and is close to the Froissart bound. The extrapolated values for 10 TeV and 14 TeV are 103 ± 7 mb and 112 ± 10 mb respectively. Using dispersion relations, Avila et al [4] have recently presented the results of several parameterizations to two different ensembles of data on *pp* total cross sections at the highest center-of-mass energies including cosmic-ray information. The results are statistically consistent with two distinct scenarios at high energies. From one ensemble the prediction for σ_T at LHC ($\sqrt{s} = 14$ TeV) is 113 ± 5 mb and from the other ensamble 140 ± 7 mb. In both cases good description of the experimental data is obtained mainly due to large error bars of the cosmic ray measurements. This therefore reiterates the need for precise measurements at RHIC and LHC.

In Regge models [14], increase in the total cross section is approximated by the intercept of the Pomeron trajectory. High energy data is fitted well by this approximation although at ISR contributions from mesonic trajectories are needed [17]. The predicted cross section at 1.8 and 14 TeV is 75 and 95 mb respectively and is consistent with *logs* behaviour. The σ_{T} value is predicted to be significantly higher when Odderon is taken in to account [10–11] within the

Regge framework A comparison of the theoretical results with [11] and without [8] Odderon contribution is shown in Fig.2. It is evident that predictions differ in the RHIC and LHC regions. However, the simple Regge pole picture does not satisfy unitarity. Due to this violation, predictions of this model can only be taken as an upper bound to the predicted cross sections of the future accelerators. Donnachie and Landshoff also obtained a good fit to the data using the exchange of soft Pomeron and the f_2, ω, ρ, and A_2 families of particles [9].

Hufner and Povh [13] gave an elegant account of this parameter in the geometrical picture. Here, total cross section is described by the shape of the colliding hadrons, which varies with energy. The geometrical picture thus gives a good fit to the experimental data for $\sqrt{s} > 20$ GeV. Real part of the radius (which has been taken as energy dependent) increases linearly with logs, which makes predictions to higher energy straightforward. The model predicts $\sigma_{\mathrm{T}} = 73$ and 95 mb respectively for 1.8 and 14 TeV respectively. Other geometrical models make similar predictions. Measurements of RHIC will therefore give us a good

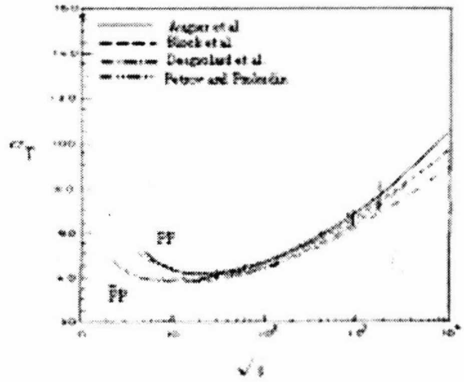

Fig. 1. Predicted of different models- for total cross section for pp and $\bar{\mathrm{p}}$p [1,16].

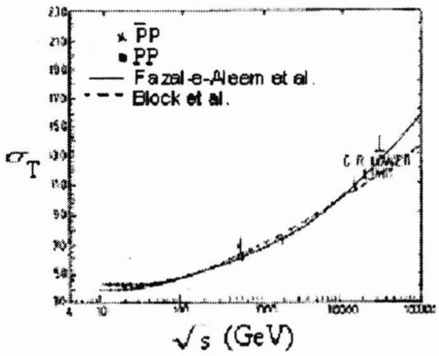

Fig. 2. Total cross section measurements compared with the predictions of models with [11] and without [8] Odderon contribution at current and future energies.

indication of the trend for the total cross section. However, measurements in the near forward direction would be of significant importance at LHC as it would unambiguously establish or definitely contradict $\log^2 s$ behaviour which emerges as a consequence of Odderon. QCD based models generally predict total cross section between 100 and 110 mb at LHC. This is significantly different from the predictions of Odderon-based models. COMPETE collaboration in their most recent work [15] have reported on fits of a large class of analytic amplitude models for forward scattering against the comprehensive data for all available reactions. Their work is based on the results of studies on the fits of the comprehensive analytic amplitude models for the high energy forward scattering amplitude against all available data of the cross sections and real part of the hadronic amplitudes. In order to differentiate the goodness of the fits of many possible parameterizations to a large sample of data, they developed and used a set of quantitative indicators measuring statistical quality of the fits over and beyond the typical criterion of the χ^2/dof. They conclude that these indicators favour models with a universal log^2s Pomeron term.

3. Conclusions

From the above discussion we find that at LHC predictions of different approaches are significantly different (Fig.1). A comparison of these models thus reveals that total cross section values will begin to differ from the RHIC energies. More important would be the difference in the total cross section values for proton-proton and proton-antiproton scattering. This difference will become very prominent at the LHC energies in case of the Odderon contribution. We also observe that the value of total cross section for different models varies from about 95 to about 145 mb. Although cosmic ray data due to large error bars accommodate these values, accurate measurements at LHC will be very important.

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Commun. Theor. Phys. (Beijing, China) **38** (2002) pp. 687–690
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Vol. 38, No. 6, December 15, 2002

Total Cross Sections at High Energies — An Update

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(Received March 27, 2002; Revised June 13, 2002)

Abstract *Current and future measurements for the total cross sections at E-811, PP2PP, CSM, FELIX, and TOTEM have been analyzed using various models. In the light of this study an attempt has been made to focus on the behavior of total cross section at very high energies.*

PACS numbers: 13.85.Lg
Key words: total cross section, Pomeron, Odderon

1 Introduction

Total cross section is one of the fundamental parameters being measured at various machines. It provides us information about the strong interaction mechanism, which controls hadron scattering and is believed to become simpler at very high energies. At current and future colliders, total cross section is therefore a primary focus of both the experimental measurements and theoretical models. In this paper, we will take an update on the total cross sections at E-811, PP2PP, CSM, FELIX, and TOTEM.

2 Current and Future Measurements

In the last twenty years, total cross sections for *pp* and $p\bar{p}$ scatterings have been measured at FNAL, ISR, UA4, UA4/2, UA5, CDF, and E710.[1] These measurements are shown in Fig. 1. There is a general consistency of the experimental data measured at different colliders except the CDF results at FERMILAB. Their results are $\sigma_T = 80.03\pm2.24$ mb, $B = 16.98\pm0.25\ (\text{GeV/c})^2$, $\sigma_{\text{el}} = 19.70 \pm 0.85$ mb at $\sqrt{s} = 1.8$ TeV. This is significantly different from E710[2] results of $\sigma_T = 72.2\pm2.7$ mb, $B = 16.99\pm0.47\ (\text{GeV/c})^2$, $\sigma_{\text{el}} = 16.60\pm1.6$ mb. Using a detector of solid scintillating fibers, E-811 collaboration,[2] which is a successor to E710 collaboration, has measured the elastic scattering in small momentum region. The scattering angle is small enough for observing Coulomb interference and for using the optical theorem to get total cross section. These measurements give $\sigma_T = 71.1 \pm 2.02$ mb at 1.8 TeV and further confirm discrepancy with CDF. Recently, total cross sections have also been measured by SELEX collaboration[3] at around 600 GeV. Their results for *pp* are in agreement with earlier measurements.

Measurements in the future are planned at PP2PP[4] experiment at RHIC, CMS,[5] FELIX,[6] and TOTEM[7] experiments at LHC. These are briefly described below.

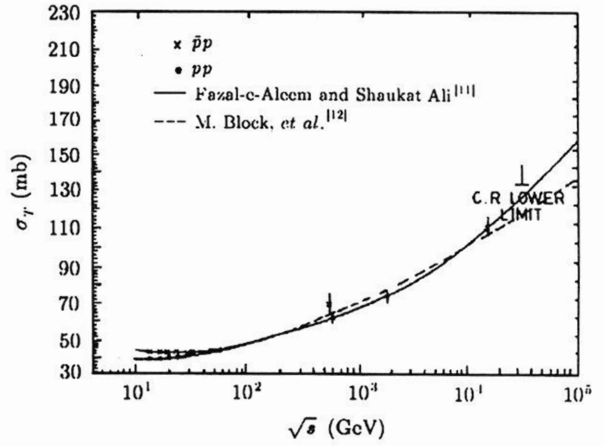

Fig. 1 Total cross section measurements compared with the predictions of models with[11] and without[12] Odderon contribution at current and future energies.

The PP2PP experiment[4] will be conducted to study proton-proton (*pp*) total and elastic scatterings with c.m. energy ranging from 60 GeV to 500 GeV at the RHIC at BNL using both the polarized and unpolarized beams. The measurements will be made in the two kinematical regions. In Coulomb Nuclear Interference region, 0.0005 $< -t < 0.12\ (\text{GeV/c})^2$, total and elastic cross sections σ_T, σ_{el}, ratio of the real and imaginary parts of the scattering amplitude ρ, and the slope parameter B will be measured. In the medium region, $-t < 1.5\ (\text{GeV/c})^2$, a study of the evolution of the dip structure with $\sqrt{s}$ is planned. These measurements will provide us a unique opportunity to compare the results with $p\bar{p}$ at 63 and 540 GeV.[8]

The Complex Muon Solenoid[5] will be one of the two large multipurpose experiments designed to study proton-proton (*pp*) collisions at the CERN LHC. The experiment will pursue a study of low $-t$ elastic scattering as well as single and double diffractive dissociations. A variety of compelling physics topics will be addressed by exploiting the ability of LHC to run at different c.m. energies. In particular, LHC running at reduced energy of 1.8 TeV

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will provide us an opportunity to compare the results with FERMILAB[8] for $p\bar{p}$. This is of considerable interest from theoretical point of view. The experiment will also check $\sqrt{s}$ dependence of the total and elastic scatterings in going from 1.8 TeV to 14 TeV.

At FELIX,[6] a survey experiment sensitive to everything and optimized for nothing, is planned with $\sqrt{s}$ = 14 TeV and luminosity of 10^{34} cm$^2\cdot$ sec^{-1}. For this purpose, a detector that is sensitive to the entire kinematical ranges is envisaged. This will enable us to search for new physics in unexplored regions of phase space, in addition to a substantial agenda covering a wide variety of conventional physics. In an urge to look for the unforeseen, measurements in the forward direction will be undertaken at FELIX full acceptance detector covering the extreme forward directions. Motivation for the forward physics is for the reason that it has never been taken up in the past at ISR, SPS, or FNAL colliders. In addition to many other aspects, physics agenda includes elastic scattering and measurements of the total cross section and hard diffraction.

At the same time, TOTEM[7] collaboration proposes to measure the total and elastic scatterings over a large range of t along with single diffractive scattering and double Pomeron exchange cross section in pp collisions at 10 ∼ 14 TeV.

3 Theoretical Models

Any theory of hadron scattering should have the ability to explain the observed phenomena with some predictable form. A successful model of hadron scattering should therefore reproduce the experimental characteristics, giving insight into the nature of interactions. At present, we do not have any accurate and complete theoretical predictions for elastic and diffractive scatterings from QCD, which is supposed to be the theory of strong interactions. This is because diffractive scattering involves processes with very small $-t$ usually smaller than the QCD mass scale. Hence, as yet QCD is not successful in describing diffractive scattering. At the same time, some basic assumptions of analyticity and crossing symmetry for the scattering amplitude and the unitarity of the scattering matrix have yielded some very useful results. In this section, we will discuss the predictions of these and QCD-based models with reference to available world data. We will discuss questions such as what we know about the total cross sections and what is expected at the future collider energies.

A large amount of works has been carried out using the above-mentioned approaches. Most of the works, using dispersion relations, fit the forward scattering amplitude parameters, σ_T and ρ. A typical dispersion relation was calculated by Augier *et al.*[9] Here data over a wide range of $5 \le \sqrt{s} \le 546$ GeV have been used to fit the parameters. The resulting asymptotic dependence found for the total cross section is $\sigma_T = [\log(s/s_0)]^{2.2\pm0.3}$. This analysis gives $\log^2 s$ dependence of σ_T as compared to $\log s$ predicted by various conventional models. This kind of behavior corresponds to the maximum rate of rise of energy, which is allowed by the analyticity and unitarity and is close to the Froissart bound. The extrapolated values for 10 TeV and 14 TeV are 103 ± 7 mb and 112 ± 10 mb respectively.

In the Regge models, an increase in total cross section is approximated by the intercept of the Pomeron trajectory $\alpha(0) = 1.08$.[10] High energy data are well fitted by this approximation although the contribution from mesonic trajectories at ISR is needed. The predicted cross sections at 1.8 and 14 TeV are 75 and 95 mb, respectively,[10] and is consistent with $\log s$ behavior. The σ_T value is predicted to be significantly higher when Odderon is taken into account.[11] Odderon, which is the $C = -1$ partner of the pomeron, was employed to explain the difference in pp and $\bar{p}p$ scattering. In the lowest order it can be understood as the exchange of three gluons in a symmetric colour singlet state. The Odderon exchange is expected to be close to one in contrast to the intercept of regggeon exchange, which is around 0.5. Attempts to find a conclusive experimental evidence for the existence of Odderons have not yet succeeded. A comparison between the theoretical results with[11] and without[12] Odderon contribution is shown in Fig. 1.

It is evident that predictions differ in the LHC region. However, the simple Regge pole picture does not satisfy unitarity. Due to this violation, predictions of this model can only be taken as an upper bound to the predicted cross sections of the future accelerators.

An elegant account of this parameter is given by Hufner and Povh[13] in the geometrical picture. Here, total cross section is described by the shape of the colliding hadrons, which varies with energy. The geometrical picture thus gives a good fit to the experimental data for $\sqrt{s} > 20$ GeV. Real part of the radius (which has been taken as energy dependent) increases linearly with $\log s$, which makes predictions to higher energy straightforward. The model predicts $\sigma_T = 73$ and 95 mb for 1.8 and 14 TeV respectively. Other models[14−16] based on geometrical picture make similar predictions. Future measurements will therefore give us a good indication of the trend for the total cross section. However, measurements in the near forward direction would be of significant importance at RHIC and LHC as it would unambiguously establish or definitely contradict $(\log s)^2$ behavior, which emerges as a consequence of the Odderon.

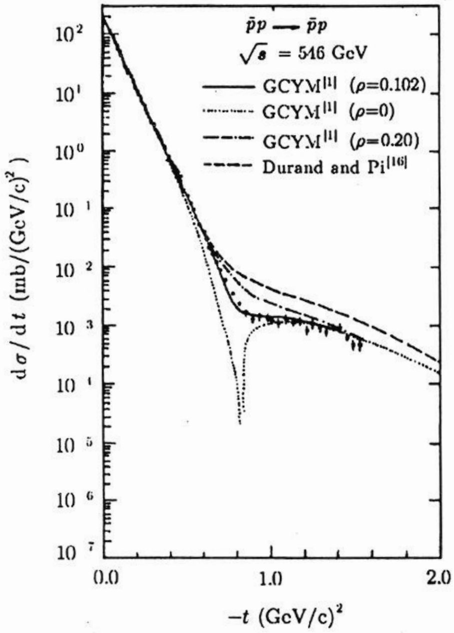

Fig. 2 Differential cross section for proton-antiproton elastic scattering at 546 GeV. Solid, dotted, dot-dash and dashed curves represent the predictions of generalized Chou–Yang model[1] for different values of ρ, respectively.

The ratio ρ is also of major interest because of its close relationship with the energy-integrated inelasticity of the collision via the dispersion relation. This quantity will in principle be accessible to measurements at RHIC and LHC energies. The kinematical range corresponds to the Coulomb-nuclear interference region. The expected $|t_0|$ values at the RHIC and LHC are estimated to about 0.0005 and 0.0007 (GeV/c)^2 respectively. Measurement at the smallest possible $-t$ value will therefore minimize the extrapolation error. Only the models incorporating Odderon predict high values at FERMILAB, RHIC, and LHC ($\rho \approx 0.2$).[9] Recent results of 0.135 ± 0.02 at UA4/2 do not favour the presence of Odderon at current and future energies. In the simple Regge picture of Landshoff and Donnachie,[10] a constant value of $\rho = 0.12$ is predicted which is in agreement with the UA4/2 data. In the geometrical model[13] this value is predicted to be $\rho = 0.14$ at SPS, FERMILAB, and LHC colliders. It is interesting to note that at the time of publication of results of geometrical models, UA4 measurements of $\rho = 0.24 \pm 0.04$ suggested a new threshold and differed from the predicted value of geometrical models. The new results of UA4/2 are consistent with geometrical models. In the geometrical models, the dip of the differential cross section is very sensitive to this value. This is shown in Fig. 2, where differential cross section at 546 GeV is plotted for $\rho = 0.14$ and 0.24. This clearly suggests that in the case of high measured value of this parameter at RHIC and LHC, the structure in dσ/dt will disappear and turn into a shoulder. It can be seen that the current data for differential cross section do not support a higher value of ρ at RHIC and LHC within the framework of geometrical picture.

In a recent presentation[17] Arkhipov has spelled out the importance of the cosmic-ray experimental measurements of proton-proton total cross section for understanding the underlying dynamics. They have mentioned that global structure of pp total cross section is completely compatible with the values obtained from cosmic ray experiments.[18,19] They conclude that more precise measurements at cosmic ray energies are very desirable.

4 QCD Based Interpretations

As pointed out earlier, in Regge theory, the increase in total cross section is approximated by the intercept of the Pomeron trajectory. It would therefore be natural to try to find an origin of Pomeron in QCD. A simple picture is through two-gluon exchange. This picture however does not give rise to the total cross section indicating that at least three-gluon exchange is involved. In order to account for increase in total cross section, the exchanged gluons must interact with each other.[20] Our calculation must undertake the relation (may be qualitatively) between Pomeron trajectory and QCD. This is an interesting issue, but so far, qualitatively, they do not coincide with each other. As we know, the calculated intercept at the leading order is too large, as it was claimed that the next-order contribution is negative, which will suppress it from 1.4 to lower value. One of the most challenging problems of QCD is therefore to find the structure of the Pomeron. As pointed out earlier, in order to explain the soft processes we need soft Pomeron.[10,21] While the data for deep inelastic scattering indicate rather clearly the need for a second (also called a hard or BFKL) Pomeron, whose trajectory has intercept equal to 1.4, in addition to familiar soft Pomeron with the intercept of 1.08. So far we have no clear idea as why the Regge pole with the intercept close to unity (soft Pomeron) could appear in our microscopic theory — QCD. We simply need to devise some mechanism to drive soft Pomeron from the non-perturbative QCD essentially at sufficiently short distances. On the other hand, there has been a general belief that the hard or BFKL Pomeron is calculable in perturbative QCD.[22] Although it was hoped that one might calculate the intercept of hard Pomeron from the BFKL equation, it now seems likely[23] that such a calculation is not within the scope of perturbative QCD. It has been shown that perturbative QCD merely governs how the magnitude of the hard Pomeron's contribution to the structure function increases with Q^2.[23] Therefore, we have three principle questions to answer: (i) why we have Pomeron(s) in QCD; (ii) why the Pomeron intercept is so small ($0.08 \sim 0.1$) for non-perturbartive QCD and how to calculate it (iii) why a typical momentum scale is so high for soft Pomeron.

There have been some recent attempts to account for these parameters through different aspects of QCD. The recent observation[24] of rapid rise of parton density at small x has generated much theoretical interest, as this rise is equivalent to an increase of the total photon-proton cross section. Lam[25] in another approach, by looking at QCD phase shift has attempted to account for the rise of the total cross section, which certainly guarantee the Froissart bound. The author used this idea to compute the quark-quark scattering phase shift in a two-loop orders, in the leading log approximation. Within a limited energy scale $\wedge(Q)$, the theory compares well with the energy variations of hadronic data.

E. Levin[26] in his recent work, views the Pomeron as non-perturbative QCD phenomena but from sufficiently short distances. Their approach is based on the scale anomaly of QCD and emphasizes the role of semi-classical QCD vacuum fields. Both the intercept and the slope of Pomeron trajectory appear to be determined by the energy density of non-perturbative QCD vacuum. The particular example of semi-classical QCD vacuum field is discussed on a new type of instant on-induced interactions that leads to the rise of cross section with energy, which is consistent with the data.

B.Z. Kopeliovich,[27] in his recent work, has employed a colour-dipole light-cone approach which incorporates a strong non-perturbative interaction of the light-cone gluons. In this work, the energy-dependent part of the total hadronic cross section is calculated in a parameter-free way employing the non-perturbative light-cone wave functions of the quark-gluon Fock states. It rises with energy as s^{Δ} and they predict $\Delta = 0.17 \pm 0.01$. However, energy-independent part of the cross section related to inelastic collisions with no gluon radiation cannot be calculated reliably in this model. It is an adjustable parameter, which is fixed by fitting one experimental point for the total cross section. Predictions of the model for the total cross section (Pomeron part), the elastic slope and the effective trajectory in the impact parameter space are in good agreement with data.

The above discussion shows that using different models and QCD based approaches, we can predict the world data and learn about the nature of total and elastic cross sections and also about the Pomeron. Only the future measurements, at RHIC and LHC Colliders confronted with the theoretical predictions of various models will be able to throw more light on the correctness of these approaches.

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Recent Results For ρ And Odderon Picture

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Abstract

Most recent results from the Fermilab on ρ give an opportunity to study the presence or otherwise of the Odderon at very high energies. In the light of these results and future measurements at RHIC and LHC, an analytical study has been made.

Most recently, result for the ratio of the real and imaginary parts of the scattering amplitude has been reported by E-811 Collaboration [1]. The value $\rho = 0.135 \pm 0.044$ poses very interesting question. Does this value indicate the presence of the Odderon or is it consistent with the predictions of the conventional models? We will try to address briefly this question in the light of various models.

Lukaszuk and Nicolescu [2] first introduced the concept of Odderon in 1973 to account for the difference of the total cross section, σ_T and ratio of real to imaginary parts of scattering amplitude, ρ in *pp* and $\bar{p}p$ scattering. Kang and Nicolescu [3] in 1975 provided theoretical basis for the Odderon. From the theoretical point of view this concept has been rediscovered in QCD. Dynamical origin to this concept was provided by Lipatov [4] and collaborators [5], Kwiecinski and Praszalowicz [6] and Islam [7]. In QCD, there are not only quark-Reggeons but also glue-Reggeons. More generally, multi-Reggeized-gluon exchanges lead to contributions having the Odderon quantum numbers. This is a very important theoretical fact, which provide physical basis to the concept of Odderon. Much work has since been carried out on the origin and meanings of the Odderon [8-11]. Theoretical status of the Odderon is now firm not only in the perturbative QCD theory but also in the non-perturbative approach. In the perturbative treatment efforts are mainly focused on the determination of the Odderon intercept [12,13]. However, a conclusive experimental evidence of the Odderon is elusive.

The Odderon picture was first used by Gauron *et al.* [14] to account for the difference of the total and differential cross section in the dip region at ISR. Bernard *et al* [15] later on showed that UA4 results on ρ could be described by the presence of Odderon. Their predictions are higher than UA4/2 and E811 data. Jenkovszky *et al* [16] extended the idea to relate the small momentum transfer hadron scattering and deep inelastic scattering. This relationship is useful for understanding the origin of cross section from the point of view of hadronic structure and interaction of its constituents. Rafique *et al* [17] used Odderon description to explain the then available data for σ_T and ρ. Their predictions are in agreement for ratio but somewhat higher for σ_T. In another attempt, Odderon description was confronted by Fazal-e-Aleem *et al* [18,19] to fit data for the differential cross section. Predictions of the model for σ_T and ρ are higher than the current measurements. We thus find that the models incorporating Odderon predict high ρ value

(~0.2) at FERMILAB, RHIC and LHC [20]. Recent results of 0.135 ± 0.02 at UA4/2 and 0.135 ± 0.044 at E-811 Collaboration value do not seem to favour the presence of Odderon. In the simple Regge picture of Landshoff and Donnachie [21], a constant value of $\rho = 0.12$ is predicted which is in agreement with the UA4/2 and E811 data. In the geometrical model [22] this value is predicted to be ≈ 0.14 at SPS, FERMILAB and LHC, which is again consistent with E811 results. It is interesting to note that at the time of publication of results of geometrical models, UA4 measurements of $\rho = 0.24 \pm 0.04$ suggested a new threshold and differed from the predicted value of geometrical model. The new results of UA4/2 are consistent with geometrical models.

The ratio ρ is of major interest in theory and experiment because of its close relationship with the energy integrated inelasticity of the collision via the dispersion relation. This quantity will in principle be accessible to measurements at RHIC and LHC energies. The kinematical range to be covered corresponds to the Coulomb-nuclear interference region. The expected $|t_0|$ value at the RHIC and LHC are estimated to about 0.0005 and 0.0007 $(\text{GeV/c})^2$ respectively. Measurement at smallest possible -t value will therefore minimize the extrapolation error and provide us an ideal opportunity to have a very precise value for ρ.

In the Eikonal models, the dip of the differential cross section is very sensitive to the ρ value. This clearly suggests that in case of higher measured value of ρ at RHIC and LHC, the structure in dσ/dt would disappear and turn into shoulder. It can be seen that current data for differential cross section does not support a higher value of ρ at RHIC and LHC within the framework of geometrical picture.

Conclusions

1. The experimental evidence for the existence of Odderon is not yet convincing despite the fact that QCD suggests presence of an Odderon. The ambiguity is for the reason that its contribution is very small compared with the dominant C = + 1 exchange contribution. Thus, reactions where C = + 1 is forbidden by selection rules, is the ideal place to test the presence of Odderon. The only clear experimental evidence for the existence of an Odderon comes from measurements of the differential cross section for high-energy elastic pp and $\bar{p}p$ scattering in the dip region at around $|t| \cong 1.3\ GeV^2$. The Odderon contribution to this process is expected to be sensitive to the proton structure. Measurements at RHIC and LHC will throw more light on this.

2. In order to further clarify the presence of Odderon, which now also has its dynamical origin in QCD, it is important that the future measurements take the following fact in to account. Unlike the conventional models, Odderon predicts that σ_T, ρ and dσ/dt in the vicinity of dip region are not equal for pp and $\bar{p}p$. It would be of interest, therefore, to make a simultaneous measurement of these parameters at LHC for both pp and $\bar{p}p$. Also, as proposed by RHIC, a measurements of the total cross section in the region between ISR and Collider which has remained unexplored, would be quite crucial for

ruling out the presence or otherwise of Odderon. A small value of $\Delta\sigma$ would provide strong evidence in favor of the maximal Odderon.

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Predictions for the dip structure at RHIC and LHC

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Abstract

Possibility of a dip or multiple structures at RHIC and LHC is discussed in the light of Eikonal picture. The results are compared with the predictions of other models and suggestions are proposed for these machines

Some very fascinating observations are in store at PP2PP [1] experiment at RHIC and CMS [2], FELIX [3], TOTEM [4] experiments at LHC. We will try to answer or comment on the possible questions in the light of predictions of Generalized Chou-Yang model along with a comparison with other models.

PREDICTIONS OF GENERALIZED CHOU-YANG MODEL

The Generalized Chou-Yang model has been successful in explaining the present data at ISR, SpS and Tevatron [5]. According to the generalized Chou-Yang model, the scattering amplitude *T (s, t)* is given by

$$T(s,t) = i \int b\, db\, J_0\left(b\sqrt{-t}\right) \left[1 - \exp(-\Omega(s,b))\right]$$

where

$$\Omega(s,b) = K(1 - i\alpha) \int \sqrt{-t}\, d\sqrt{-t}\, J_0(b\sqrt{-t})\ \left[f(t)/f(0)\right] G_A(t) G_B(t)$$

The function $\Omega(s,b)$ represents opacity effective for clusters passing with a relative impact parameter *b,* which is taken to be complex, and thereby includes refractive as well as absorptive effects. Anisotropy of the scattering process is represented by the factor $f(t)/f(0)$. $G_A(t)$ and $G_B(t)$ represent the hadronic form factors of the colliding particles. Suitable choice of parameters α and K help us determined ρ and σ_T. Using the parameters as given in Table 1, the model gives good agreement for the differential cross-section at 1.8 TeV. This is depicted in Fig.1 with a dip at $-t = 0.6$ $(\text{GeV/c})^2$. This fit is obtained for $\rho = 0.118$, a value consistent with the most recent measurements [6], $\rho = 0.135 \pm 0.044$. The dip transforms into a shoulder if we choose a higher value of the ρ. Predictions of the model for the slope parameter and σ_{el} / σ_T are also consistent with the experimental data [5].

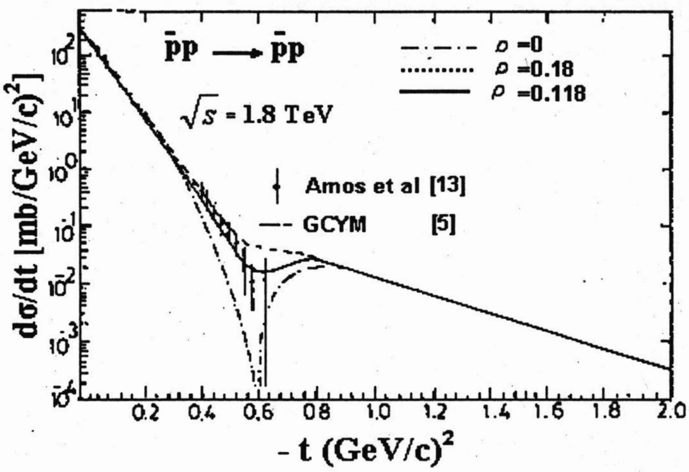

Fig. 1: Predictions of our model for the differential cross section for $\bar{p}p$ elastic scattering at 1.8TeV.

Predicted values of the differential cross section at 14 TeV are shown in Fig. 2. The results have been obtained for a ρ value = 0.07 with a suggested total cross section of 115 mb respectively. We observe a multiple dip structure near - t = 0.4 and 1.5 (GeV/c)^2 at 14 TeV.

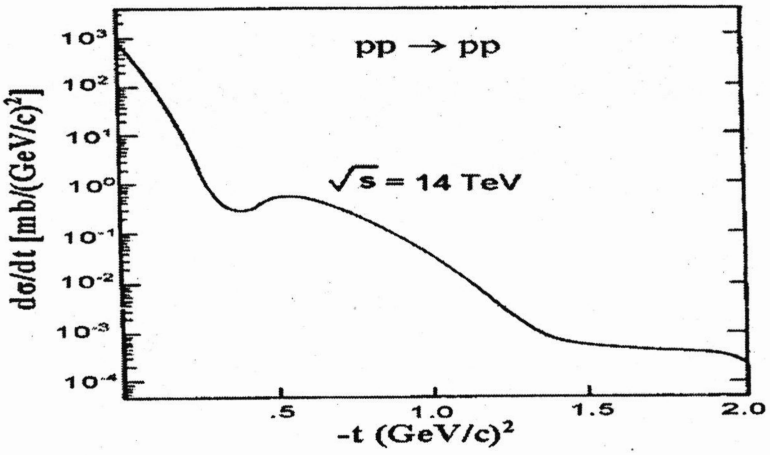

Fig. 2: Predictions of our model for the differential cross section for pp elastic scattering at 14 TeV.

Again, a higher value of ρ (≈ 0. 15) will fill up the first dip and turn the second dip into a shoulder/break. Thus we observe that in our model, the multiple structure (dip near 0.4 and a shoulder or break near 1.5 (GeV/c)^2 should appear at LHC energy of 14 TeV. Although most models predict a smoothening of the ρ value (~ 0.1) at TeV energies, higher value of this parameter as predicted by the models incorporating Odderon picture will mean disappearance of the dip structure.

It is interesting to point out that our model gives a correct account of the difference in the differential cross section for *pp* and $\bar{p}p$ at 53 GeV [5]. The difference in the dip region is

Multiple Dip Structure and Geometrical Models

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Abstract

Shrinkage of the diffraction peak and dip structure in the differential cross section is on the agenda of measurements at the future colliders. These measurements will prove to be a testing ground for the theoretical models. We take up various aspects of these parameters in the light of Generalized Chou-Yang model and compare them with other models with special emphasis on the possibility of multiple dip structure at LHC energies. Role of ρ in the appearance or otherwise of multiple structure has also been considered.

Results from the Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) will open up new dimension to proton-proton physics. Goals of the PP2PP experiment at RHIC [1] include the measurements of total and elastic scattering in c.m energy range from 60 GeV to 500 GeV using both polarized and unpolarized beams. The measurements will study evolution of the dip structure with $\sqrt{s}$ and will provide a unique opportunity to compare the results with $p\bar{p}$ at 63 and 546 GeV [2]. Similarly LHC [3-5] will explore the possibility or otherwise of the dip structure in going from 1.8 TeV to 14 TeV. We have undertaken these aspects in the light of Generalized Chou-Yang model and compared them with the predictions of other models. During the course of this study, many interesting questions arise which need to be addressed. In order to give a detailed account of these developments we have divided this paper into four sections: namely, (1) introduction and review of measurements (2) predictions of Generalized Chou-Yang model (3) comparison with other theoretical models (4) conclusions.

1. INTRODUCTION AND REVIEW OF MEASUREMENTS

1.1. Introduction

Measurements at Fermilab for the differential cross section [2] at 1.8 TeV have brought forward interesting questions. The differential cross section at ISR and Collider energies show a change of slope or shrinkage of the diffraction peak near $-t = 0.15$ (GeV/c)^2. This change of slope disappears at 1.8 TeV. Another interesting feature of these measurements is that up to the highest measured values of -t, it is not clear whether a dip has been observed or not. Some of the models, which explain the measurements of dσ/dt at 53 and 546 GeV, predict a dip, which turns into multiple dip structure at LHC energy of 14 TeV. We know that at ISR, the differential cross section at the dip for pp and $p\bar{p}$ elastic scattering is different with different dip positions. Measurements of the differential cross section for pp at 500 GeV at RHIC will therefore give us an indication as to whether such an effect persists at about 500 GeV.

Thus some very fascinating observations are in view at RHIC and LHC and we will try to answer or comment on these questions in the light of predictions of Generalized Chou-Yang model along with a comparison with other models.

Recent Results from Fermilab and Odderon Description

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Abstract

Most recent results from E811 experiment for σ_T and ρ together with future measurements at RHIC and LHC provide us an opportunity to study the presence or otherwise of the Odderon. In the light of these results and a comparison with other models, an analytical study has been made.

Most recently, results for the total cross section and ratio of the real and imaginary parts of the scattering amplitude have been reported by E-811 Collaboration [1]. The values $\sigma_T = 71.42 \pm 1.55$ mb and $\rho = 0.135 \pm 0.044$ pose very interesting question. Does these values together with other data give us any information about the presence of the Odderon or consistent with the predictions of the conventional models? We will try to address this question afresh in this paper.

Concept of the Odderon was first introduced by Lukaszuk and Nicolescu [2] in 1973 to account for the difference of the total cross section, σ_T and ratio of real to imaginary parts of scattering amplitude, ρ in pp and $\bar{p}p$ scattering. Kang and Nicolescu [3] in 1975 provided theoretical basis for the Odderon. From the theoretical point of view this concept has been rediscovered in QCD. Dynamical origin of this concept was provided by several authors [4-7]. In QCD, there are not only quark-Reggeons but also glue-Reggeons. More generally, multi-Reggeized-gluon exchanges lead to contributions having the Odderon quantum numbers. This is a very important theoretical fact, which provide physical basis to the concept of Odderon. Several interesting aspects of perturbative Odderon have been studied in various studies [8-17]. Much work has since been carried out on the origin and meanings of the Odderon [18]. Theoretical status of the Odderon is now firm not only in the perturbative QCD theory but also in the non-perturbative approach. In the perturbative treatment efforts are mainly focused on the determination of the Odderon intercept. Thus, concept of an Odderon has been a very interesting inclusion to our knowledge. The model is based upon general S-matrix principles, the constraints of asymptotic theorems and a dynamical assumption of "maximal strength" of strong interactions.

The Odderon picture has been used by Gauron *et al.* [19] to account for the various aspects of the pp and $\bar{p}p$ including difference of σ_T and $d\sigma/dt$ in the dip region at ISR. Bernard *et al* [20] later on showed that UA4 results ($\rho = 0.24 \pm 0.04$) could be described by the presence of Odderon. Their predictions for the total cross section and ρ are higher than UA4/2 ($\rho = 0.135 \pm 0.02$) and E811 ($\rho = 0.135 \pm 0.044$) data. Jenkovszky *et al* [21] extended the idea to relate the small momentum transfer hadron scattering and deep inelastic scattering. This relationship is useful for understanding the origin of cross section from the point of view of hadronic structure and interaction of its constituents. Rafique *et al* [22] used Odderon description to explain the then available data for σ_T and ρ. Their predictions are in agreement for ρ but somewhat higher for σ_T. In another attempt, Odderon description was confronted by Fazal-e-Aleem *et al* [23,24] to fit data for the differential cross section. Predictions of the model for σ_T and ρ are somewhat higher than the current measurements. We thus find that the models incorporating Odderon predict high ρ value (~0.2) at FERMILAB, RHIC and LHC [25]. Recent results of 0.135 ± 0.02 at UA4/2 and 0.135 ± 0.044 at E-811 Collaboration value do not seem to favour the presence of Odderon. In

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BY

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LAHORE, PAKISTAN

2001

ABSTRACT

In this thesis we can find answers to such questions as what is Pomeron, what about Pomeron both experimentally and theoretically, what is correct strategy to study Pomeron experimentally, what are “soft” and “hard” Pomeron? This thesis may be considered as the status report of the ideas, hopes, theoretical approaches and phenomenological successes that have been developed to achieve a theoretical understanding of high energy behavior of scattering amplitude.

CONTENTS

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ELECTRON POSITRON ANNIHILATION

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ABSTRACT

The total cross section for e^+e^- annihilation into hadrons, σ_{had}, constitutes one of the most basic quantities of hadronic physics. It can be determined experimentally and calculated theoretically with very high precession. It allows for the fundamental test of QCD and for precise determination of its parameters, the strong coupling constant, and the quark masses.

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It is certified that Mr. Muhammad Qadeer Afzal carried out the work contained in this dissertation under my supervision.

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ABSTRACT

In this thesis we can find answers to such questions as what is Pomeron, what about Pomeron both experimentally and theoretically, what is correct strategy to study Pomeron experimentally, what are "soft" and "hard" Pomeron? This thesis may be considered as the status report of the ideas, hopes, theoretical approaches and phenomenological successes that have been developed to achieve a theoretical understanding of high energy behavior of scattering amplitude.

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Contents

Abstract

In this thesis we review that how the idea of odderon appears in QCD and the origin of the odderon in the Regge theory. As the Odderon is the leading exchange in hadronic scattering processes at high energies in which negative charge conjugation and parity quantum numbers are transferred in the t-channel. We also review the recent theoretical and experimental results by identifying the puzzle of odderon physics via brief study of perturbative and non-perturbative QCD. The phenomenology of Odderon at high energy is also discussed.

Elastic Scattering at Current and Future Colliders

A Thesis Submitted To the University of the Punjab
For the Degree of Doctor of Philosophy

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2002

Contents

ABSTRACT

Current data measurements from ISR, SpS, Tevatron including most recent measurements by E-811 collaboration and future measurements from PP2PP at RHIC as well as from CMS, FELIX and TOTEM at LHC will include various aspects of elastic and diffractive scattering. We have analysed the world data for proton-proton and proton-antiproton scattering in the light of predictions of various models with special emphasis on Eikonal picture and QCD inspired models. Special emphasis has been given on the shrinkage of the diffraction peak and dip structure in the differential cross section besides encompassing other physical parameters. These parameters have been computed in the light of Generalized Chou-Yang model and compared with other models with special emphasis on the possibility of multiple dip structure at RHIC and LHC energies. Role of ρ in the appearance or otherwise of multiple structure has also been considered. At the same time, we know that the presence of Odderon at high energy has been in question for quite some time. We have also probed the Odderon description in theory and possibility of its search at the current and future colliders. The Odderon in perturbative and non-perturbative QCD has been discussed along with some phenomenological approaches. A comparison of the Odderon description with other models has also been made for the available data including the measurements from cosmic ray, which corresponds to the LHC energy of 14 TeV. Our study also focuses on the measurements at RHIC and LHC and the presence or otherwise of Odderon. In the light of this analysis suggestions for future measurements have been made.