Elastic Scattering in Near Forward Direction at LHC and Nucleon Structure

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Abstract

We predict $pp$ elastic differential cross section at LHC at the c.m. energy $\sqrt{s} = 14$ TeV and momentum transfer range $|t| = 0 – 10$ GeV$^2$, which is planned to be measured by the TOTEM group. The field theory model underlying our phenomenological investigation describes the nucleon as a composite object with an outer cloud of quark-antiquark condensate, an inner core of topological baryonic charge, and a still smaller quark-bag of valence quarks. The model satisfactorily describes the asymptotic behavior of $\sigma_{tot}(s)$ and $\rho(s)$ as well as the measured $\bar{p}p$ elastic $d\sigma/dt$ at $\sqrt{s} = 546$ GeV, 630 GeV, and 1.8 TeV. The large $|t|$ elastic amplitude of the model incorporates the QCD hard pomeron (BFKL Pomeron plus next to leading order approximations), the perturbative dimensional counting behavior, and the confinement of valence quarks in a small region within the nucleon. Our predicted $pp$ elastic $d\sigma/dt$ at LHC is compared with those of Bourrely et al. and Desgrolard et al.

As we all know, this is the 20th anniversary of the Blois Workshop. So, delving a bit in history is only natural, and we find in the Proceedings of the First Blois Workshop, the editors – Basarab Nicolescu and Tran Thanh Van – quoted a foresightful observation by Elliot Leader in CERN Courier: “...although asymptopia may be very far away indeed, the path to it is not through a desert but through a flourishing region of exciting physics...” With the advent of the Large Hadron Collider (LHC) and the planned Total and Elastic Measurement (TOTEM) experiment, we are indeed entering a region of exciting physics – the 10 TeV c.m. energy region. TOTEM aims at measuring $\sigma_{tot}$, $\rho$ and $d\sigma/dt$ up to $|t| \approx 10$ GeV$^2$ at LHC at an unprecedented c.m. energy 14 TeV- an ambitious and challenging task.

Three groups have predicted $pp$ elastic differential cross section at LHC from $|t| = 0$ all the way up to $|t| = 10$ GeV$^2$ on the basis of three different models: 1) impact-picture model based on the Cheng-Wu calculations of QED tower diagrams; 2) eikonalized pomeron-reggeon model using conventional regge pole approach, but with multiple pomeron, reggeon exchanges included; 3) nucleon-structure model where the nucleon has an outer cloud of quark-antiquark condensed ground state, an inner core of topological baryonic charge, and a still smaller quark-bag of valence quarks (Fig.1). A QCD-inspired eikonalized model has also been proposed to predict $pp$ $d\sigma/dt$ at $\sqrt{s} = 14$ TeV for $|t| = 0 – 2.0$ GeV$^2$.

Our initial investigation led us to the following description. The nucleon has an outer cloud and an inner core. High energy elastic scattering is primarily due to two processes: a) a glancing collision where the outer cloud of one nucleon interacts with that of the other giving rise to diffraction scattering; b) a hard, or large $|t|$ collision where one nucleon core scatters off the other core via vector meson $\omega$ exchange, while their outer clouds overlap and interact.
independently. In the small $|t|$ region diffraction dominates, but the hard scattering takes over as $|t|$ increases.

We describe diffraction scattering using the impact parameter representation:

$$T_D(s, t) = i p W \int_0^\infty b \, db \, J_0(bq) \Gamma_D(s, b);$$

(1)

here $\Gamma_D(s, b)$ is the profile function, which is related to the eikonal function $\chi_D(s, b)$: $\Gamma_D(s, b) = 1 - \exp(i\chi_D(s, b))$. We choose $\Gamma_D(s, b)$ to be an even Fermi profile function:

$$\Gamma_D(s, b) = g(s) \left[ \frac{1}{1 + \exp((b-R)/a)} + \frac{1}{1 + \exp(-(b+R)/a)} - 1 \right].$$

(2)

Besides $g(s)$, the parameters $R$ and $a$ are also energy dependent. Further studies show that $R$ and $a$ have the following energy dependences: $R = R_0 + R_1 (lns - \frac{T}{2})$, $a = a_0 + a_1 (lns - \frac{T}{2})$; $g(s)$ is a complex crossing even energy-dependent function that asymptotically becomes a real positive constant. The diffraction amplitude we obtain satisfies a number of general properties associated with the phenomenon of diffraction:

1. $\sigma_{tot}(s) \sim (a_0 + a_1 lns)^2$ (Froissart-Martin bound)
2. $p(s) \simeq \frac{n_{pa}}{a_0 + a_1 lns}$ (derivative dispersion relation)
3. $T_D(s, t) \sim i s lns f(|t|/ln^2 s)$ (AKM scaling)
4. $T^{pp}_D(s, t) = T^{pp}_D(s, t)$ (crossing even).

Incidentally, the profile function (2) has been used by Frankfurt et al. to represent the impact parameter distribution of soft inelastic collisions in diffractive Higgs production at LHC.

We take the hard scattering amplitude due to $\omega$ exchange to be of the form

$$T^H(s, t) \sim \exp[i \chi(s, 0)] s^{F^2(t)/m_\omega^2 - 1}. \quad (3)$$

The $t$-dependence is the product of two form factors and the $\omega$ propagator. It shows that $\omega$ probes two density distributions corresponding to the two form factors. The density distributions represent the nucleon cores. The factor of $s$ originates from spin 1 of $\omega$. Such an $s$-dependence is not expected in a regge pole model, but can occur in the nonlinear $\sigma$ model where $\omega$ couples to the baryonic current and the baryonic current is topological.

Our phenomenological investigation progressively led us to an effective field theory model—a gauged linear $\sigma$ model of the Gell-Mann-Levy type, and the physical structure of the nucleon that emerges is that shown in Fig.1. This structure indicates that at very large $|t|$ and therefore small $b$, the quark-bag of one nucleon overlaps that of the other and large $|t|$ elastic scattering originates from valence quark-quark scattering. We view this process as shown in Fig. 2. A valence quark from one proton makes a hard, i.e. a large $|t|$ collision with a valence quark from the other proton. The collision carries off the whole momentum transfer. This dynamical picture brings new features into our calculations: 1) probability amplitude of a quark to have, say, momentum $\vec{p}$ when the proton has momentum $\vec{P}$ in the c.m. frame; 2) quark-quark elastic amplitude at high energy and large momentum transfer, which we take as the BFKL pomeron with next to leading order corrections included. The latter amplitude is referred by us as the QCD hard pomeron.

To obtain the $pp$ elastic amplitude $T_{q\bar{q}}(s, t)$ due to quark-quark scattering as depicted in Fig. 2, we have to introduce two “structure factors” that take into account the momentum function of each valence quark in a proton and the fractional longitudinal momentum it carries. The net result is that we now have a second hard amplitude of the form

$$T^H_{q\bar{q}}(s, t) \sim i s \exp[i \chi(s, 0)] (s e^{-i_\pi^2})^\omega \frac{F^2(q_\perp)}{|t| + r_0^2}, \quad (4)$$

where $\omega_{BFKL} = 1 + \omega$ and $r_0$ defines the black disk radius of asymptotic quark-quark scattering. $F(q_\perp)$ is the structure factor which should be distinguished from a form factor. Our study of large $q^2$ behavior of $F(q_\perp)$ leads to $T_{q\bar{q}}(s, t)/s \sim |t|^{-5}$ and results in a differential cross section behavior $d\sigma/dt \sim |t|^{-10}$ as predicted by perturbative QCD quark counting rules for fixed $s$ and large $|t|$ ($s >> |t| >> M^2$).
We determine the parameters of the model by requiring that the model should describe satisfactorily the asymptotic behavior of $\sigma_{\text{tot}}(s)$ and $\rho(s)$ as well as the experimentally measured $\bar{p}p$ elastic $d\sigma/dt$ at $\sqrt{s} = 546$ GeV, 630 GeV and 1.8 TeV. The results of this investigation for $\sigma_{\text{tot}}(s)$ and $\rho(s)$ are given in Figs. 3 and 4, where the dotted curves represent the error bands given by Cudell et al. (COMPETE Collaboration) to their best fit. Our prediction for $pp$ elastic differential cross section at LHC at $\sqrt{s} = 14$ TeV for $|t| = 0 – 10$ GeV$^2$ is given in Fig. 5. Also shown in this figure are separate $d\sigma/dt$ due to diffraction (dotted curve), due to hard $\omega$ exchange (dot-dashed curve), and due to hard $qq$ scattering (dashed curve). As we mentioned earlier, two other groups, Bourrely et al. and Desgrolard et al. have predicted $pp$ elastic $d\sigma/dt$ at LHC from $|t| = 0 – 10$ GeV$^2$. In Fig. 6, a comparison of our prediction (solid curve) with those of Bourrely et al. (dot-dashed curve) and Desgrolard et al. (dashed curve) are given. We notice that while we predict smooth fall-off of $d\sigma/dt$ for $|t| \gtrsim 1$ GeV$^2$, the latter authors predict oscillations. Furthermore, we predict much larger differential cross section at large $|t|$ than them.

We conclude by noting that precise measurement of $pp$ elastic $d\sigma/dt$ by the TOTEM group at LHC at c.m. energy 14 TeV and $|t| = 0 – 10$ GeV$^2$ will be able to verify the composite structure of the nucleon and the QCD hard pomeron contribution, which have emerged from our investigation.

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Figure 1: Nucleon structure emerging from our investigation. Nucleon has an outer cloud of $q\bar{q}$ condensed ground state analogous to the BCS ground state in superconductivity, an inner core of topological baryonic charge probed by $\omega$, and a still smaller quark-bag of massless valence quarks.
Figure 2: Hard collision of valence quarks from two different protons.

Figure 3: Solid curve represents our calculated total cross section as a function of $\sqrt{s}$. Dotted curves represent the error band given by Cudell et al.

Figure 4: Solid and dashed curves represent our calculated $\rho_{pp}$ and $\rho_{pp}$ as functions of $\sqrt{s}$. Dotted curves represent the error band given by Cudell et al.

Figure 5: Solid curve shows our predicted $d\sigma/dt$ for $pp$ elastic scattering at $\sqrt{s}=14$ TeV at LHC. Dotted curve represents $d\sigma/dt$ due to diffraction only. Similarly, dot-dashed and dashed curves represent $d\sigma/dt$ due to hard $\omega$-exchange and hard $qq$ scattering only.

Figure 6: Comparison of our predicted differential cross section (solid curve) with those of Bourrely et al. (dot-dashed curve) and Desgrolard et al. (dashed curve).