At the 2011 Blois Workshop, \( pp \) elastic scattering measurements at the LHC at 7 TeV were presented by the TOTEM Collaboration. They showed that our predicted \( d\sigma/dt \) in the momentum transfer region \(|t| \simeq 0.5–2.5 \text{ GeV}^2 \) disagreed significantly with TOTEM results. This led us to consider an extensive investigation of the large \(|t| \) \( pp \) elastic scattering that included: (i) multiple \( \omega \)-exchanges; (ii) valence quark–quark scattering via low-\( x \) gluon–gluon interactions; and (iii) the single \( \omega \)-exchange amplitude and the quark–quark scattering amplitude having opposite signs. We found a satisfactory description of the 7 TeV \( d\sigma/dt \) in the region of \( 0.6 \text{ GeV}^2 < |t| < 2.5 \text{ GeV}^2 \). This result was presented by us at the Blois 2013 Workshop. However, as noted by others, there was still a significant difference between our calculated \( d\sigma/dt \) and TOTEM data in the forward direction: \(|t| < 0.6 \text{ GeV}^2 \). This led us to envisage a new aspect of our \( q\bar{q} \) Condensate-Enclosed Chiral-Bag Model of the proton. In this model, the proton has a core of baryonic shell with valence quarks inside. The proton baryonic-charge core polarizes the \( q\bar{q} \) condensate cloud and creates a layer of antiquarks surrounding the baryonic core. This, in turn, leads to a layer of positive quarks at the boundary of the proton. For an antiproton, the opposite happens — a layer of negative antiquarks appears at the boundary of the antiproton. In \( pp \) forward scattering, the two polarization layers at the boundary interact giving rise to a new scattering amplitude. For \( \bar{p}p \), the same thing happens except the amplitude has the opposite sign as in D0 1.96 TeV. Our phenomenological investigation has now shown that we can describe quantitatively the \( pp \) \( d\sigma/dt \) TOTEM data at 7 TeV throughout the entire \(|t| \) range. We now predict the \( pp \) \( d\sigma/dt \) at the LHC at 13 TeV, which will test our model of the proton structure.

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Our investigation of high-energy pp and $\bar{p}p$ elastic scattering over the last ten years has led us to the following physical picture of the proton (Fig. 1) [1–7]:

Fig. 1. Physical picture of the proton — a Condensate-Enclosed Chiral-Bag.

The proton has three regions: an outer region consisting of a quark–antiquark ($q\bar{q}$) condensed ground state; an inner shell of baryonic charge — where the baryonic charge is topological (or, geometrical); and a core of size 0.2 fm, where the valence quarks are confined. The part of the proton structure comprised of a shell of baryonic charge and three valence quarks has been known as “Chiral Bag” model of the nucleon in low-energy studies. What we are finding from high-energy elastic scattering is that the proton is a “Condensate-Enclosed Chiral-Bag”.

The proton structure shown in Fig. 1 leads to three main processes in elastic scattering as shown in Fig. 2. The first process occurs in the small-$|t|$ region, i.e., in the near forward direction, when the outer cloud of $q\bar{q}$ condensed ground state of one proton interacts with that of the other. It gives rise to diffraction scattering, which underlies: (i) the observed increase of the pp total cross section with energy: $\sigma_{\text{tot}}(s) \sim (a_0 + a_1 \ln s)^2$, i.e., qualitative saturation of the Froissart–Martin Bound ($a_0, a_1$ are parameters determined phenomenologically); (ii) it leads to $\rho(s) = \pi a_1 / (a_0 + a_1 \ln s)$: ratio of the real part over the imaginary part of the forward scattering amplitude asymptotically; (iii) it is a crossing-even scattering amplitude, and therefore, yields equal pp and $\bar{p}p$ total cross sections.

The diffraction amplitude $T_D^+(s,t)$ is represented by a profile function

$$T_D^+(s,t) = ipW \int_0^\infty bdb J_0(bq) \Gamma_D^+(s,b),$$

(1)
diffraction $\omega$-exchange short-distance collision ($b \lesssim 0.1$ fm)

Fig. 2. Elastic scattering processes.

where the profile function $\Gamma_{+}^{D}(s, b)$ is taken to be

$$\Gamma_{+}^{D}(s, b) = g(s) \left[ \frac{1}{1 + \exp (b - R)/a} + \frac{1}{1 + \exp (- (b + R)/a)} \right]. \tag{2}$$

$g(s)$ is a crossing-even function of $s$, $R = R(s) = R_0 + R_1 (\ln s - i \frac{\pi}{2})$ and $a = a(s) = a_0 + a_1 (\ln s - i \frac{\pi}{2})$. $\Gamma_{+}^{D}(s, b)$ can be expressed as

$$\Gamma_{+}^{D}(s, b) = g(s) \frac{\sinh \frac{R}{a}}{\cosh \frac{R}{a} + \cosh \frac{b}{a}}. \tag{3}$$

By changing the variable of integration from $b$ to $\zeta = b/a$ and rotating the line of integration of $\zeta$ to the real axis [6], we obtain

$$T_{+}^{D}(s, t) = i p W a^2(s) g(s) \int_{0}^{\infty} \zeta d\zeta J_0(\zeta qa) \frac{\sinh \frac{R}{a}}{\cosh \frac{R}{a} + \cosh \zeta}. \tag{4}$$

At high energy, $a_0 + a_1 \ln s \to \infty$ and $\frac{R(s)}{a(s)} = \frac{R_0 + R_1 (\ln s - i \frac{\pi}{2})}{a_0 + a_1 (\ln s - i \frac{\pi}{2})} \simeq r$, where $r = R_1/a_1$ is a constant. To carry out further the integration on the right-hand side of Eq. (4), we replace $a(s)$ by $\hat{a}(s) = a_0 + a_1 \ln s$ in the integral and obtain

$$T_{+}^{D}(s, t) = i p W \left[ a_0 + a_1 \left( \ln s - i \frac{\pi}{2} \right) \right]^2 g(s) \int_{0}^{\infty} \zeta d\zeta J_0(\zeta q\hat{a}) \frac{\sinh r}{\cosh r + \cosh \zeta}, \tag{5}$$
where at high energy, \( g(s) \) becomes a constant \([1]\)

\[
g_0 = (1 - \eta_0) \frac{1 + e^{-r}}{1 - e^{-r}}. \tag{6}
\]

We note that — similar to the proton — the antiproton has a shell of anti-baryonic charge and a core of antiquarks. The quark–antiquark outer cloud of the antiproton, however, is exactly the same as the quark–antiquark outer cloud of the proton. So, the \( pp \) and \( \bar{p}p \) diffraction scattering are the same: \( T^+_D(s, t) \) and there is no odd diffraction amplitude \( T^-_D(s, t) \).

Beyond diffraction scattering — the next dominant processes are multiple \( \omega \)-exchanges and valence quark–quark scattering via low-\( x \) gluon–gluon interaction (Fig. 3). We also have to keep in mind that in \( pp \) and \( \bar{p}p \) scattering — each \( \omega \)-exchange is accompanied by a glancing collision of scalar particles of one proton (antiproton) with those of the other proton (Fig. 4).

![Fig. 3. Hard collision of a valence quark from one proton with one from the other proton.](image)

![Fig. 4. Single \( \omega \)-exchange accompanied by a glancing collision of scalar particles of one proton with those of the other proton (in momentum space).](image)

The combined amplitude due to \( \omega \)-exchanges and low-\( x \) gluon–gluon interaction can be expressed in terms of a joint eikonal: \( \chi_\omega(s, b) + \chi_{gg}(s, b) \). The amplitude \( T_{\omega+gg}(s, t) \) is, however, screened by diffraction scattering.
and by deep $q\bar{q}$ condensate close to the baryonic-charge shell. The resulting scattering amplitude is then

$$T_{\omega+gg}(s, t) = \left[ \left( \eta_0 + \frac{c_0}{(se^{-i\pi/2})^\sigma} \right) + i \left( \lambda_0 - \frac{d_0}{s^2} \right) \right] ipW \int_0^\infty bdb J_0(bq) \left[ 1 - e^{i(\omega(s,b) + \chi_{gg}(s,b))} \right],$$

where the first two terms on the right-hand side represent the screening effect.

Writing

$$\left[ 1 - e^{i(\omega(s,b) + \chi_{gg}(s,b))} \right] = \left[ \left( 1 - e^{i(\omega(s,b))} \right) + e^{i\omega(s,b)} \left( 1 - e^{i(\chi_{gg}(s,b))} \right) \right],$$

we approximate Eq. (7) as

$$T_{\omega+gg}(s, t) \simeq \left[ \left( \eta_0 + \frac{c_0}{(se^{-i\pi/2})^\sigma} \right) + i \left( \lambda_0 - \frac{d_0}{s^2} \right) \right] \times \left[ T_\omega(s, t) + e^{i\chi_\omega(s,\tilde{b})} T_{gg}(s, t) \right].$$

$T_\omega(s, t)$ is the scattering amplitude due to multiple $\omega$-exchanges; $T_{gg}(s, t)$ is the gluon–gluon scattering amplitude (Fig. 3). $e^{i\chi_\omega(s,\tilde{b})}$ is an average value that shows the additional screening of the scattering amplitude $T_{gg}(s, t)$, because of the baryonic-charge shell.

We now examine $\bar{p}p$ scattering. As we have already observed, the same quark–antiquark cloud encloses an antiproton and a proton. So, the diffraction amplitude is $T_D^+(s, t)$ for $\bar{p}p$ scattering as well. The combined amplitude due to $\omega$-exchanges and low-$x$ gluon–gluon interaction will now be expressed in terms of a joint eikonal: $\bar{\chi}_\omega(s, b) + \bar{\chi}_{gg}(s, b)$. The scattering amplitude is

$$\bar{T}_{\omega+gg}(s, t) = \left[ \left( \eta_0 + \frac{c_0}{(se^{-i\pi/2})^\sigma} \right) - i \left( \lambda_0 - \frac{d_0}{s^2} \right) \right] ipW \int_0^\infty bdb J_0(bq) \left[ 1 - e^{i(\bar{\chi}_\omega(s,b) + \bar{\chi}_{gg}(s,b))} \right].$$

Equation (10) can be further approximated as done earlier

$$\bar{T}_{\omega+gg}(s, t) \simeq \left[ \left( \eta_0 + \frac{c_0}{(se^{-i\pi/2})^\sigma} \right) - i \left( \lambda_0 - \frac{d_0}{s^2} \right) \right] \times \left[ \bar{T}_\omega(s, t) + e^{i\bar{\chi}_\omega(s,\tilde{b})} \bar{T}_{gg}(s, t) \right].$$
We note that the explicit form of $T_{gg}(s, t)$ [7] is

$$T_{gg}(s, t) = i s \gamma_{gg} \left( s e^{-i \pi/2} \right)^\lambda \frac{F^2(q_{\perp}, \lambda)}{\left( 1 + \frac{q^2}{m^2} \right)^{2(\mu+1)}}$$ \hfill (12)

and $\bar{T}_{gg}(s, t) = T_{gg}(s, t)$, as they are crossing even.

In our study of $pp$ and $\bar{p}p$ scattering, we have realized — a new scattering amplitude occurs. To see this, let us go back to Fig. 1, which shows that the proton has a shell of baryonic charge and a core of valence quarks — also of baryonic charge. They are enclosed by the quark–antiquark cloud. The cloud becomes polarized, because its antiquarks are drawn toward the baryonic shell. In turn, a layer of polarization quarks appear near the boundary (Fig. 5). In $pp$ near forward scattering, the two outer layers collide leading to a new scattering amplitude (positive). In $\bar{p}p$ near forward scattering, the outer polarization layer of the antiproton is of antiquarks and the polarization scattering amplitude is negative.

Our investigation has shown that the polarization amplitude $T_{pl}(s, t)$ can be expressed in terms of a profile function

$$T_{pl}(s, t) = i p W \int_0^{\infty} b db J_0(bq) \Gamma_{pl}^{+,-}(s, b) \quad (pp, \ \bar{p}p)$$ \hfill (13)

and we find a suitable profile function to be

$$\Gamma_{pl}^{+,-}(s, b) = \pm A e^{-b^2/B^2} J_0(bC) \quad (pp, \ \bar{p}p)$$ \hfill (14)

with three parameters: $A$, $B$ and $C$. 

![Physical picture of the proton](image-url)
Our prediction for pp elastic $d\sigma/dt$ at 13 TeV is shown in Fig. 6, which will soon be measured at LHC by the TOTEM Collaboration. This measurement will establish how well we have predicted the 13 TeV $pp$ $d\sigma/dt$ and determined the structure of the proton (Fig. 1).

Also shown in Fig. 6 is our calculated $pp$ $d\sigma/dt$ at 7 TeV along with the TOTEM data. We include our calculated $\bar{p}p$ $d\sigma/dt$ at 1.96 TeV and present it with the D0 data and the earlier Tevatron $\bar{p}p$ 1.80 TeV data.

Fig. 6. Comparison of our $d\sigma/dt$ calculation at $\sqrt{s} = 7$ TeV with the TOTEM Collaboration measurements at the LHC [8]. Comparison of our $d\sigma/dt$ calculation at $\sqrt{s} = 1.96$ TeV with the D0 Collaboration and 1.8 TeV data [9,10]. Our $d\sigma/dt$ prediction at $\sqrt{s} = 13$ TeV — which is being measured by the TOTEM Collaboration at the LHC.

REFERENCES


