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IS LARGE ANGLE EXCLUSIVE SCATTERING CONTROLLED
BY THE HADRONIC RADIUS?

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ABSTRACT

It is pointed out that the large angle $pp \rightarrow pp$ data suggest an exponential behaviour in $p_{\perp}$ modulated by a regular oscillation in $p_{\perp}$ more naturally than a power law s^{-N} . It is argued that these effects are due to a manifestation of the same geometrical length scale $R \simeq 1$ fermi which is known to control small angle scattering.

Exclusive scattering at high energies and small angles ($s \rightarrow \infty$, t fixed) may be characterized by the following simple geometrical picture ¹⁾: the hadron behaves as an extended object with a roughly universal interaction radius $R \simeq 1$ fermi. This radius is the crucial length scale appearing manifestly in the data [equivalently in the language of dual models the scale is set by the universal slope $\alpha' \simeq 1 \text{ GeV}^{-2}$ of the Regge trajectories with $\alpha' \simeq (R/2\pi)^2$]. In particular, the scale R controls the exponential drop-off in momentum transfer as well as the period of occurring oscillations.

Measurements at large transverse momenta, i.e., at large angles ($s \rightarrow \infty$, θ fixed $\Rightarrow t/s$ fixed) probe the fine structure of the proton. This is obviously the kinematical region to look for indications of constituents inside the hadron. As is well known, scaling in deep inelastic ep scattering suggests such a constituent interpretation. In analogy one is led to expect ²⁾ that also in exclusive large angle scattering the hadronic scale $R \simeq 1$ fermi gets lost in the features of the data for sufficiently high transverse momenta. [This is equivalent to $\alpha' \rightarrow 0$ for $t \rightarrow -\infty$ in the Regge language ³⁾.]

It is the purpose of this note to point out that the large angle data of $pp \rightarrow pp$ rather give support to a geometrical interpretation ^{*)}: they seem to be uniformly controlled by the hadronic scale $\simeq 1$ fermi almost from threshold up to the highest transverse momenta available ($0.5 \lesssim p_{\perp} \lesssim 3 \text{ GeV/c}$).

To this end, let us confront the large angle $pp \rightarrow pp$ data with the two different forementioned pictures.

1) Representative for the constituent approach for exclusive reactions, $A+B \rightarrow C+D$ is the quark counting rule ⁴⁾

$$\frac{d\sigma}{dt} \xrightarrow[\theta \text{ fixed}]{s \rightarrow \infty} s^{-(n_A+n_B+n_C+n_D)+2} f(\theta) \quad (1)$$

(n_I = number of valence quarks in particle I). This counting rule seems so far to be compatible with all available, though partly rather poor, large angle data ⁵⁾ for $p_{\text{lab}} \gtrsim 6 \text{ GeV/c}$. For the sake of a subsequent comparison, we plotted in Fig. 1 the large angle $pp \rightarrow pp$ data versus $\log s$. For $p_{\text{lab}} \gtrsim 6 \text{ GeV/c}$ they are consistent with the predicted power law s^{-10} , even though the data at the highest energies seem to prefer a higher power (s^{-12} ?).

*) Unfortunately, the energy range available for large angle data of all other exclusive reactions is much too small ($p_{\perp \text{max}} \lesssim 2 \text{ GeV/c}$) and statistics much too poor to allow for any similarly strong conclusions. But these data are equally compatible with a geometrical interpretation.

2) Let us now look for typical effects of a scale of the order of 1 fermi in the large angle $pp \rightarrow pp$ data. The presence of coherent effects in the deep region has been pointed out already ^{6),7)}. However, our conclusions in detail are different from the observations made in Ref. 6) (see below). How would one proceed with a search for the geometrical scale in large angle data? There is no straightforward extrapolation to the large angle limit for models which have been developed for the peripheral limit s large, t fixed. Therefore we have to rely on a phenomenological extrapolation. There is, however, one fact independent of any specific model: exponential drop-offs in the momentum transfer and regular oscillations -- typical features of the geometrical region -- are only possible in the presence of a dimensional scale ^{*)}. As a guideline for a suitable variable in which we might look for exponentials and oscillations in the deep region, we use the dual peripheral model ⁸⁾. This is an s -channel Regge approach which has been formulated in the limit s large, t fixed, and which has the advantage of being successful up to rather large values of $-t$. Typically for a given s it predicts a behaviour (see Fig. 2)

$$\frac{d\sigma}{dt} \underset{(t \neq 0)}{\propto} \frac{1}{\sqrt{-t}} e^{-R \cdot A \sqrt{-t}} \left(1 + C \cos(R \sqrt{-t} + \varphi) \right) \quad (2)$$

$$|C| \leq 1, \quad A = \frac{2}{\pi} \log \frac{S}{S_0}, \quad C \text{ weakly dependent on } \log \frac{S}{S_0}, \\ R \approx 1 \text{ fermi}$$

and a similar behaviour for $s \rightarrow \infty$, u fixed, with $\sqrt{-t}$ replaced by $\sqrt{-u}$. The dual peripheral model being an s -channel Regge approach, it is not in principle limited to near forward and backward angles. The only reason which prevents us from extending it straightforwardly to the large angle region is that it does not properly take care of t, u crossing properties, which become crucial near $\theta_{\text{cms}} = 90^\circ$, i.e., near $t = u$ (in fact it is only able to simulate t, u crossing symmetry crudely).

It is then very suggestive to try instead of $\sqrt{-t}$ (or $\sqrt{-u}$) the t, u crossing symmetric variable $p_\perp = k_{\text{cms}} \sin \theta$ with the additional property

$$p_\perp \underset{-t \text{ small}}{\simeq} \sqrt{-t} \quad \text{and} \quad p_\perp \underset{-u \text{ small}}{\simeq} \sqrt{-u} \quad (3)$$

*) Evidently the counting rule also involves a length scale L which appears multiplicatively as $L^{(n_A + n_B + n_C + n_D - 4)}$ in $d\sigma/dt$. This scale has apparently nothing to do with the scale under discussion.

Thus for fixed θ_{cms} we might look for a behaviour of the following type

$$\frac{d\sigma}{dt} \propto e^{-R \cdot g \cdot p_{\perp}} \left(1 + C \cos(R p_{\perp} + \varphi) \right), \quad (4)$$

$$|C| \leq 1, R \simeq 1 \text{ fermi and}$$

with $g = g(\theta)$, $C = C(\theta)$ dimensionless; i.e., an exponential drop-off in $p_{\perp}$, possibly modulated by an oscillation which is regular in $p_{\perp}$ with a period $2\pi/R$ given in terms of the hadronic scale $R \simeq 1$ fermi.

Figure 3 shows the same large angle $pp \rightarrow pp$ data as in Fig. 1 at fixed angles $\theta = 90^\circ, 68^\circ, 55^\circ$, but this time with $\log(d\sigma/dt)$ plotted versus $p_{\perp}$ (similar to the Orear plot!). We realize first of all: there does not seem to be any indication of a change in the characteristics of the $p_{\perp}$ behaviour for fixed θ almost from threshold up to 25 GeV/c -- in contrast to the power law behaviour which agrees with the data only for $p_{\text{lab}} \gtrsim 6$ GeV/c (cf. Fig. 1). Secondly, the data seem to oscillate regularly around a straight line corresponding to an exponential ^{*)} of the type $e^{-p_{\perp} R \cdot g(\theta)}$ (in case of the 55° data, the oscillation vanishes in statistical fluctuations of the data).

In order to be able to study the oscillations more closely, we divided the data for $d\sigma/dt$ by the appropriate exponential. The result for 90° is shown in Fig. 4a: a clear indication of a strikingly regular oscillation in $p_{\perp}$; the curve corresponds to an eyeball fit to $1 + C \cos(R \cdot p_{\perp} + \varphi)$ with a period of $2\pi/R \simeq 1.7$ GeV/c, i.e., with $R \simeq 0.73$ fermi. Figure 4b shows the same analysis for the 68° data resulting in the same oscillation (the zeros remain fixed ^{**) in $p_{\perp}$, independent of θ) only with a smaller amplitude. Altogether $d\sigma/dt(pp \rightarrow pp)$ seems to behave for large fixed angles as suggested in Eq. (4).}

Let us mention incidentally: what had been interpreted earlier as a break ^{9),6)} in the data plots of $\log d\sigma/dt(pp \rightarrow pp)$ versus $p_{\perp}^2$ or t seems actually to be a minimum of an oscillation in a plot versus $p_{\perp}$

*) It is interesting to note that in $\theta_{\text{cms}} = 90^\circ$ inclusive $pp \rightarrow \pi + X$ data, one finds a significant deviation from an exponential $e^{-6p_{\perp}}$ already much below $p_{\perp} \simeq 3$ GeV/c.

**) Figures 4a,b demonstrate that the data show oscillations fixed in $p_{\perp}$ rather than structures (breaks) fixed in t as advertized in Ref. 6).

(notice that in such a plot the minimum appears more pronounced than the maximum due to the typical distortions of a logarithmic plot!).

Our analysis leads us to the following conclusion. The exponential and, in particular, the oscillations are a strong indication for the presence of a length scale. Moreover, this scale looks very much like the well-known hadronic radius $R \simeq 1$ fermi.

An important aspect of this analysis is that oscillations are at least as good an indicator for a length scale as exponentials which are after all not easily distinguishable experimentally from a power law s^{-N} with a high power N .

Besides future experimental tests of exponentials and oscillations versus power laws without oscillations at SPS (CERN) and at FNAL, it seems also interesting to look for oscillations in reactions like πN , KN , etc., in the upper range of the PS energies.

Our results support the following conclusions. Present experiments do not exclusively probe the substructure of the proton in the deep region; the proton (still?) behaves as an extended object with the radius $R \simeq 1$ fermi up to the highest available transverse momenta.

The interpretation of a parton optimist: at highest available transverse momenta we see the transition region where the resolution is just good enough to make out constituents within the extended proton (remember the compatibility of the data with a power law s^{-10} for $p_{lab} \gtrsim 6$ GeV/c). The pure parton behaviour, i.e., the loss of the length scale characterizing the size of the proton, will show up at higher transverse momenta $p_{\perp} \gtrsim 3.5$ GeV/c. The oscillations will then die away.

A parton pessimist might conclude: there is no convincing evidence for partons in the large angle exclusive data. Instead a geometrical picture, in terms of an exponential in $p_{\perp}$ modulated by a regular oscillation, describes the data uniformly almost from threshold up to $p_{lab} \simeq 25$ GeV/c.

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FIGURE CAPTIONS

- Fig. 1 : Data for $\log d\sigma/dt(pp \rightarrow pp)$ versus $\log s$ at the fixed angles $\theta_{\text{cms}} = 90^\circ, 68^\circ$ and 55° . The solid lines correspond to a power law behaviour like s^{-10} , the broken lines to one like s^{-12} . Data from Ref. 9).
- Fig. 2 : Data for two representative reactions plotted in the form $\log[\sqrt{-t}(d\sigma/dt)]$ versus $\sqrt{-t}$. This is to illustrate the agreement with a characteristic prediction of the dual peripheral model: an exponential drop-off in $\sqrt{-t}$ modulated by an oscillation which is regular in $\sqrt{-t}$. Figure from Ref. 8).
- Fig. 3 : Data for $\log d\sigma/dt(pp \rightarrow pp)$ versus $p_\perp$ at the fixed angles $\theta_{\text{cms}} = 90^\circ, 68^\circ$ and 55° . The straight lines correspond to an exponential behaviour like $e^{-8.13p_\perp}$, $e^{-8.42p_\perp}$ and $e^{-8.95p_\perp}$ respectively. Data from Ref. 9).
- Fig. 4a : Data for $d\sigma/dt(pp \rightarrow pp)_{90^\circ}$ divided by the exponential of Fig. 3: $d\sigma/dt(pp \rightarrow pp)_{90^\circ} [\text{cm}^2/\text{GeV}^2]/(1.15 \times 10^{-24} e^{-8.13p_\perp})$ versus $p_\perp$. The solid line $[1 - 0.54 \cos(3.7p_\perp - 0.774)]$ is an eyeball fit indicating a regular oscillation of the data. Data from Ref. 9).
- Fig. 4b : The same as in Fig. 4a, but for 68° . Data points: $d\sigma/dt(pp \rightarrow pp)_{68^\circ} [\text{cm}^2/\text{GeV}^2]/(1.445 \times 10^{-24} e^{-8.42p_\perp})$, curve: $[1 - 0.35 \cos(3.7p_\perp - 0.774)]$, i.e., the same oscillation as in Fig. 4a, only with a smaller amplitude. Data from Ref. 9).

FIG. 1

FIG.2

FIG.3

FIG. 4a

FIG. 4b