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QCD CORRECTIONS TO HADRONIC LARGE $p_T$ SCATTERING*

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ABSTRACT

QCD corrections to large $p_T$ scattering are calculated. The status of the perturbation expansion is discussed.

This talk is an account of the work by R.K. Ellis, H. Haber, M. Furman, and myself, however, the contents of this talk reflect my views and not necessarily those of my collaborators.

The aim of this work is to decide whether QCD perturbation theory makes reliable predictions for the production of particles at large transverse momentum in hadron-hadron collisions. I will briefly recall the ingredients of the QCD prediction. The process $h_1 + h_2 \rightarrow h_3 + X$ is indicated in Fig. 1. Hadrons $h_1$ and $h_2$ of momenta $P_1$ and $P_2$ emit constituents of momenta $x_1 P_1$ and $x_2 P_2$ which then scatter at wide angle resulting in parton of momentum $p_3$ which then fragments into the observed hadron $h_3$ with momentum $P_3$. (Throughout upper case letters refer to hadrons and lower case refers to partons.)

Defining $t = (p_1 - p_3)^2$, $s = (p_1 + p_2)^2$, $u = (p_2 - p_3)^2$ and $v = 1 + t/s$, $w = -u/(s + t)$, the cross-section for production of $h_3$ is

$$\frac{1}{SV} \frac{d\sigma}{dVdw} = \sum_{ijk} \int_0^1 dx_1 dx_2 \frac{dx_3}{sx_3^2} \left[ F_i(x_1, M^2) F_j(x_2, M^2) D_{i,j}(x_3, M^2) \right] \cdot$$

$$x \left[ \frac{1}{v} \frac{d\sigma_{ij}^K}{dv} (s, v) \delta(1 - w) + \frac{\alpha_s^3}{2\pi} K_{ij}^K (s, v, w) \right]$$  (1)

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where $F_i(x, M^2)D_i(x, M^2)$ is the probability of extracting a parton (hadron) of momentum fraction $x$ from a hadron (parton). $\frac{d\sigma}{d\nu}$ is the lowest order parton parton scattering cross-section. $\frac{d\sigma}{d\nu}$ is proportional to $\alpha_s^2$ and has support only at the elastic limit. The aim of the work I describe is to calculate the quantity $K(s, v, w)$. If it is small then the phenomenology based on the lower order is believable, if it is large then some doubt must be cast on the validity of the phenomenology.

Since only the size of $K$ is relevant we chose the simplest process (simplest gauge invariant set of diagrams). Consider $q_1 + q_2 \rightarrow q_3 + X$ where $q_1$ and $q_2$ are quarks of distinct flavour, and we will ignore (initially) incoming gluons. A physical process can be found where this is the dominant process (e.g. $K^+ + \pi^- \rightarrow K^+ + X$, at large $p_T$ where valence quarks dominate). In $\frac{d\sigma}{d\nu}$ there is only one graph, that involving t-channel gluon exchange. The calculation of $K$ is tedious and I will merely outline it here (details are given in ref. 1).

1.) Calculate the graphs which contribute through order $\alpha_s^3$.
2.) Renormalize the ultraviolet divergence.
3.) Remove the mass singularities. The graph shown in Fig. 2, has a mass divergence when the propagator $A$ goes on mass shell. These divergences must be reabsorbed into $F$ and $D$. We are guaranteed that this procedure will work by the factorization proof. In order to avoid confusion, one merely has to remember where the $F$'s and $D$ come from. $F$ is extracted from deep inelastic lepton scattering. The structure function

$$F_2(x, M^2) = \sum_i e_i^2 F_i(x, M^2)$$

(2)

where the sum $i$ runs over quarks of charge $e_i$ and $M^2$ is the scale at which the structure function is measured. If $F_2$ is calculated in perturbation theory the same mass divergences are encountered so that one uses $F_i$ defined by equation (2) all the mass singularities cancel. The singularities in $D$ are removed in a similar way by defining it from one particle inclusive $e^-\bar{e}$ annihilation.

4.) There is a complication associated with gluons of Fig. 3. A singularity arises when the propagator $A$ goes on shell. This process corresponds to the incoming quark decaying into a gluon which then undergoes a hard scattering against the other quark. Now the gluon distribution is not measured in any other process,
so we are forced to define it. This leads to a (finite) ambiguity in \( K \). However, the gluon distribution is not totally arbitrary. The singular part is defined and there is a constraint on the finite part from energy momentum conservation.

Having calculated \( K \) we now substitute back into equation (1), using some parton distributions and look at the effect of \( K \) on \( \frac{d\sigma}{dVdW} \). It is important to discuss the ambiguities in \( K \).

1. The scale \( M^2 \) is characteristic of the hard scattering process; a change in \( M \) is equivalent to a change in \( K \). In lowest order \( M \) is arbitrary (a popular choice is \( t_{\mathrm{meas}} = 2stu \)).

\[
M^2 = \frac{2stu}{s^2 + t^2 + u^2}
\]

2. Part of \( K \) is the expansion of \( \alpha_s(\mu) \) which appears in lowest order. Again \( \mu \) is same scale characteristic of the hard scattering (\( \mu = M \) is usually used in lowest order but there is no reason why they should be the same), and a change in \( \mu \) results in a change in \( K \). There is an additional ambiguity in the prescription used to define \( \alpha_s \). We used the so called \( \overline{\text{MS}} \) prescription, but one could equally use a momentum space scheme.

3. There is an ambiguity associated with the gluon distribution \( G(x, M^2) \) as discussed earlier. It is "obvious" that for some values of \( \mu, M^2, \) and \( G(x, M^2) \), \( K \) can be made small, and it is also probably true that having found those values somebody will come up with an a posteriori "proof" that these are the natural values. I will try to guess the scales before doing the calculation. \( \mu = t \) seems natural since the coupling constant renormalization comes from dressing the lowest order (t channel) graph. We do not know what \( M \) is. An obvious upper value is \( s \), and a lower one \( p^2_{\text{out}} \) of the outgoing parton (= tu/s at 90° in the center mass frame). Figure 4 shows the function

\[
R = \frac{1}{SV} \frac{d\sigma}{dWdV} \text{ including } K \text{ and } \frac{1}{SV} \frac{d\sigma}{dWdV} \text{ at } K = 0 \text{ at } 90° \text{ in the center of mass as a function of } x_1 = \frac{2p_T}{\sqrt{5}}. \text{ If } R \approx 1 \text{ the correction is small and the perturbation expansion is reliable. The dashed line at } M^2 = tu/s \text{ illustrates the size of the ambiguity associated with } G(x, M^2) \text{. It disappears at large } p_T \text{ where gluons are irrelevant. } M^2 = t \text{ and } M^2 = \frac{2stu}{s^2 + t^2 + u^2} \text{ produce curves}
which lie between the solid lines. I have shown an unnatural value of \( \mu \) and \( M \) in the dotted line on Fig. 4. \( \mu^2 = M^2 = p_T^2/4 \). The correction is still large. The correction can be reduced by using a momentum space subtracted coupling constant. It will reduce the correction by about 40%. However, even for \( p_T^2/4 = \mu^2 = M^2 \) the corrections are still substantial.

In conclusion it appears that QCD perturbation theory does not make sound predictions for large \( p_T \) hadron scattering at current energies. As the energy increases the corrections reduce but only logarithmically, not until \( \sqrt{s} \approx 1000 \) GeV do they become reasonably small.

REFERENCES

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