GLUON DENSITY INSIDE THE PROTON FROM CURRENT-TARGET CORRELATIONS ?

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The possibility to determine the gluon density inside the proton in deep inelastic ep collisions using current-target multiplicity correlations is discussed.

1 Introduction

A significant fraction of deep inelastic scattering (DIS) events contain two jets in addition to the proton remnant. They are usually denoted as (2+1) jet events. At small Bjorken \( x \), the (2+1) jet events are predominately due to the Boson-Gluon Fusion (BGF) processes. Therefore, from a study of (2+1) jet rates one can learn about the gluon density inside the proton.

The measurement of jet rates relies upon various jet clustering algorithms (see a review\(^1\)). The choice of jet algorithm and the associated resolution scale is, in some extent, arbitrary. The jet algorithm should match to a theoretical scheme used to calculate a cross section and reflect as much as possible the parton structure. However, there are some factors that complicate the study of the parton level using jet algorithms. Smearing effects and “mischlustering” are unwanted effects that are inherent to any algorithm. The separation of perturbative and non-perturbative QCD is also never perfect: The study of the hadronization contribution to (2+1) jet rates is customarily based on Monte Carlo (MC) models used to compare the parton and hadron levels. The problem is that there is no uniquely defined parton cascade in the MC simulations. A cut-off used to stop the perturbative cascade is unnatural to QCD and can be different for different MCs with different tunings. This problem is compounded by the fact that the contribution from the hadronization is also model dependent. Depending on the jet algorithm and Monte Carlo used, the hadronization corrections to (2+1) jet cross-section can vary from 15% to 30%.

Besides BGF, the QCD Compton (QCDC) process gives rise to (2+1) jet events as well. From the jet algorithms themselves, this background, in principle, cannot be isolated. For DIS, the remnant is another complication:

\(^{1}\)Presented at XXVIII International Symposium on Multiparticle Dynamics, Delphi, Greece, September 1998.
The jet algorithms always suffer from the problem of separation between the spectator jet and the jets from hard QCD processes.

Recently it was noticed that the BGF events can be studied without involving the jet algorithms. For this one can measure a linear interdependence between the current- and target-region multiplicities in the Breit frame. Since, instead of clustering separate particles, the approach involves the measurement of the particle multiplicities in large phase-space regions, one could expect that high-order QCD and hadronization effects are minimized. Below we shall discuss a few aspects of this method.

The DIS processes can be characterized by the 4-momentum transfer $Q^2 = -q^2$ and the Bjorken scaling variable $x = Q^2/(2Pq)$, where $P$ is the 4-momentum of the proton. The fractional energy transfer $y$ is related to $x$ and $Q^2$ by $y \approx Q^2/xs$, where $\sqrt{s}$ is the positron-proton centre-of-mass energy. For the quark-parton model in the Breit frame, the incident quark carries $Q/2$ momentum in the positive $z$-direction and the outgoing struck quark carries the same momentum in the negative $z$-direction (Fig. 1). The phase space of the event can be divided into two regions. All particles with negative $p_{z}^{\text{Breit}}$ components of momenta form the current region. In the quark-parton model, all these particles are produced from hadronization of the struck quark. Particles with positive $p_{z}^{\text{Breit}}$ are assigned to the target region, which is associated with the proton remnant.
2 Current-Target Correlations. Analytical Estimates

The correlation between the current and target region multiplicities can be measured with the covariance

$$\text{cov}(n_c, n_t) = \langle n_c n_t \rangle - \langle n_c \rangle \langle n_t \rangle,$$

(1)

where $n_c$ ($n_t$) is the number of particles in the current (target) region. For the first-order QCD effects leading to $(2+1)$ jet events, the covariance receives a negative contribution. At a fixed $Q^2$, the covariance can be written as

$$\text{cov}(n_c, n_t) \approx -A_1 R_1(x) - A_2 R_2(x),$$

(2)

where $A_1$ and $A_2$ are positive, $x$-independent constants. $R_1(x)$ is the probability for back-to-back jet events with one jet in the current and one in the target region and $R_2(x)$ is that for an event without jet activity in the current region (both hard jets populate the target region). For small $Q^2$, both probabilities are mainly determined by the BGF events. The contribution from QCD scattering is relatively small because of the small fraction of such events involved and since some QCD events have two hard jets in the current region, i.e. do not produce such correlations.

The parameters $A_1$ and $A_2$ determine the average value and width of the multiplicity distributions of the hard jets. Therefore, it is expected that these quantities are sensitive to the higher-order QCD and hadronization contributions.

3 Hadronization

We illustrate some points concerning the hadronization using the LEPTO 6.5 Monte Carlo model. The model has been tuned as described in [4]. The hard process in LEPTO is described by a leading order matrix element. The parton emission is based on the parton shower described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi evolution equation. The JETSET Monte Carlo based on the LUND string fragmentation model is used to describe hadronization.

To generate DIS events, the energy of the positron and that of the proton are chosen to be 27.5 GeV and 820 GeV, respectively. The following cuts are used: $10 \text{ GeV}^2 < Q^2 < 50 \text{ GeV}^2$, $E \geq 10 \text{ GeV}$, where $E$ is the energy of the scattered electron. No additional cuts for the track acceptance have been applied. For the given cuts, we investigate the correlations as a function of $x$. For the given range of this variable, $\langle Q^2 \rangle$ varies from 19.2 GeV$^2$ to 20.6 GeV$^2$. In total, 250k events are generated.
The behavior of the covariance for partons and hadrons is shown in Fig. 2. Since the covariance is sensitive to the total multiplicity, the QCD cut-off $Q_0$ used to stop the parton cascade is decreased from 1 GeV to 0.68 GeV to obtain about the same parton multiplicity in the current region as for hadrons. Open symbols show the parton shower model (PS) with hadronization (no first-order matrix elements). The parton shower with QCD Compton (QCDC+PS) shows about the same behavior since the number of the QCDC events is relatively small. The contribution from PS and QCDC is nearly independent of $x$. Note that without contributions from QCD processes, i.e. BGF, QCDC and PS but including the LUND hadronization, the covariance is equal to zero (not shown).

The correlations for PS and PS+QCDC are negative due to current-region particles with high $p_\perp$ which have a large probability to migrate into the target region. This is in contrast to the remnants in the target region where no large $p_\perp$ is expected. From this consideration it is clear that the correlations for gluon radiation should depend on $Q^2$, rather than on $x$.

The covariance receives an additional negative contribution from BGF events (BGF+PS, closed squares in Fig. 2). The closed circles show LEPTO with all first-order QCD effects. Since the results for the default LEPTO and LEPTO with BGF+PS are very similar, we conclude that the behavior of the current-target correlations is dominated by the BGF.

The line shows the BGF rate $R_{\text{BGF}}$ rescaled using the constant -6.5. The rate is obtained from LEPTO by counting events labeled as the BGF. The correlations follow the BGF rate rather well, in spite of the background from PS contributing to the absolute magnitude of the correlations (see more examples in Fig. 3).

No large difference between the parton and hadron levels is observed. This illustrates the fact that the LUND string model does not produce a strong effect on the current-target correlations. Some effect, however, is seen for the covariance measured at the smallest $x$ value. It could be that this effect comes from the strings connecting the partons from current and target regions. Since the remnants have high longitudinal momentum $\sim Q/2x$, opposite to relatively small $x$-independent momenta of the current-region partons, the strings should carry particles away from the current to the target region, producing negative correlations which could be seen at a sufficiently small $x$. From the MC study, however, it is seen that this effect is relatively small for the experimentally accessible $x$ region.
Figure 2: Covariance for different bins in $\langle Q^2 \rangle$ and $\langle x \rangle$ obtained from the LEPTO 6.5 MC model on parton and hadron levels. The statistical errors on the symbols are negligible. The shaded band on the line shows statistical uncertainties in the determination of the BGF rate.
Figure 3: Different gluon densities and corresponding current-target correlations as a function of $\langle x \rangle$ for LEPTO with the default parameters. Note that in LEPTO an increase of the gluon density leads to a decrease of the BGF rate. This trend drives the behavior of the current-target correlations shown on the bottom figure.
4 Structure-Function Study

The MC results show that the current-target correlations are approximately proportional to the rate of BGF events. The same conclusion follows from the analytical estimates showing a linear dependence of the correlations on $R_1$ and $R_2$ probabilities determined by BGF rate at small $Q^2$. Therefore, one might expect that the correlations are sensitive to the behavior of the parton density. Fig. 3 shows different gluon densities obtained from the PDFLIB and the corresponding current-target correlations. The sensitivity of the covariance to the input structure functions is apparent. Note that the gluon densities with a steeper increase do not lead to stronger correlations since the covariance is determined by an interplay between the BGF cross-section and the total differential cross section,

$$\text{cov}(n_c, n_t) \bigg|_{Q^2=\text{cons}} \propto -\frac{d\sigma_{\text{BGF}}}{dx} \frac{d\sigma}{dx}.$$  \hspace{1cm} (3)

Note that the behavior of the BGF rate for the different gluon densities has the same trend (not shown) as the correlations. This trend is Monte-Carlo dependent: The BGF cross-section in (3) is evaluated in LEPTO using cut-offs to prevent divergences in the QCD matrix elements.

As we have discussed, the coefficient of proportionality in (3) is determined by the structure of the multiplicity distributions of the outgoing quarks. Therefore, it absorbs non-BGF effects, high-order QCD corrections and hadronization effects. Note also that relation (3) can be used to determine the $x$-behavior of $d\sigma_{\text{BGF}}/dx$ from the measured $\text{cov}(n_c, n_t)$ and the overall differential cross section.

5 Discussion: Open Questions

Theoretical aspects. As for any measurement of the differential $(2+1)$ cross section, it is important to understand the Monte Carlo dependence of the discussed results.

A recent ZEUS study showed that only ARIADNE can quantitatively describe the current-target correlations. Nevertheless, comparing different MC results, one could see that all MCs show about same $x$-behavior. ARIADNE, however, shows systematically larger values of the covariance. This observation is consistent with the assumption that all differences in the treatment of the parton showers and hadronization stage are absorbed into the coefficient of the proportionality in (3), rather than contribute to the $x$-dependence of the correlations.
From a perturbative QCD point of view, the higher-order effects are not sufficiently understood. For example, for the next-to-leading order QCD calculations, the two-jet cross section receives contribution from the 3-parton final state. The hope is that, to a large extend, the behavior (but not the magnitude) of the correlations stay the same. For example, “unresolvable” partons mainly determine the structure of the jets, rather than their locations in the Breit frame.

**Experimental aspects.** The most important experimental question is how to measure the current-target correlations having a detector with a small track acceptance for the target region. The absolute value of the covariance is sensitive to the fraction of tracks measured in the target region. In this respect, there are two possibilities. Since we are interested in the \( x \)-behavior of BGF cross-section, one could assume that a small track acceptance cannot affect such a behavior, but rather the absolute normalization which is absorbed into a unknown coefficient of proportionality in (3). This question should be carefully examined using Monte Carlo simulations. Another approach could be the use of the other characteristics of the correlations which are less sensitive to the mean value of the multiplicity distribution measured in the target region. For example, the coefficient of the correlation \( \sigma_c^{-1} \sigma_t^{-1} \text{cov} \), (\( \sigma_c \) and \( \sigma_t \) being the standard deviations of the multiplicity in the current and target regions) could be useful, once the \( x \)-behavior is understood.

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