HIGHER ORDER QCD EFFECTS AND PARTICLE DENSITY IN FULL PHASE SPACE FROM HIGH p_T INTERACTIONS AT THE ISR

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Abstract

A comparison of QCD parton models with events including a high transverse momentum trigger particle is performed. The data were obtained with the Split Field Magnet (SFM) detector at the CERN ISR. The effective intrinsic transverse momentum, $\langle k_T \rangle$, of a parton is found to be about 1 GeV/c from an analysis of inclusive cross sections based upon lowest order parton-parton scattering. Large values of $\langle k_T \rangle$ are also needed to obtain a good description of the particle density in the azimuthal hemisphere opposite to the trigger. The measured recoil of the spectator jets tends to require much smaller values of $\langle k_T \rangle$. The model is improved by including higher-order QCD effects. Thus, starting from $\langle k_T \rangle = 0.45$ GeV/c, an effective $\langle k_T \rangle$ of about 1 GeV/c at hard scattering is generated through perturbative parton showers, which provides a consistent description of the measurements in full phase space. This analysis shows therefore that well-known problems of lowest-order QCD calculations can be resolved by inclusion of higher-order effects.

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1. Introduction

The production of mesons and baryons at high transverse momentum, p_T , in pp interactions is well described by the parton model [1-4]. The simplest form of the parton model involves factorization of the beam protons into quasi-free partons, the hard scattering of two partons, and the fragmentation into observable hadrons of both scattered and non-participating partons (figure 1a). Quantitative investigations of the model generally rely on Monte Carlo simulations.

The partons inside a hadron are usually assumed to acquire transverse Fermi motion, k_T , due to the confinement within the hadron, with $\langle k_T \rangle \leq 0.45$ GeV/c. The transverse momentum distribution is assumed to be of the form

$$\frac{d\sigma}{dk_T^2} \propto e^{-ak_T^2},$$

commonly called a "Gaussian". Because of a bias introduced by the high p_T trigger, the inclusive cross section at $p_T \leq 5$ GeV/c is sensitive to $\langle k_T \rangle$; rather large values of $\langle k_T \rangle$, i.e. about 1 GeV/c, have been derived from the data [2]. This puzzle of a large apparent mean intrinsic transverse momentum of the partons inside a proton is addressed here.

The experiment is briefly described in section 2. In section 3 the inclusive cross section measurements are reviewed and an appropriate value of $\langle k_T \rangle$ is extracted. A comparison between the simple parton model and data on the observed four-jet structure [5] is performed in section 4. A solution of the k_T problem is then sought in section 5 in the framework of higher-order QCD with emphasis on overall consistency. The conclusions are summarized in section 6, and some details of the Monte Carlo technique are presented in the appendix.

2. Experiment

The experiment was performed at the CERN ISR using the Split Field Magnet detector. Only data taken at the maximum energy $\sqrt{s} = 62$ GeV were considered in this analysis. The detector included systems of multiwire proportional chambers in both central and forward regions which covered nearly the full solid angle, and several arrays of scintillation counters for time-of-flight measurements. Events with a charged particle with high p_T were selected by trigger logic electronics using wire information near a polar angle $\theta \approx 45^\circ$ relative to one of the beams. The trigger particle was identified by threshold

Cerenkov counters. A counter filled with freon 114 at atmospheric pressure, having threshold momentum of 2.7 GeV/c for pions, was used for the separation of pions from kaons. An additional counter filled with freon 13 at 7.5 atm, corresponding to a threshold momentum of 1.3 GeV/c for pions, was used for the separation of kaons from protons. Details of the detector and the trigger system may be found in ref. [6].

The data consist of about 135,000 events with identified charged pion, charged kaon, proton and antiproton triggers. However, only pion and kaon triggers with $p_T > 4$ GeV/c are used in this analysis. All distributions presented in the following are corrected for acceptance.

3. Inclusive Cross Section

Calculations based upon lowest-order QCD fail to reproduce the observed p_T^n behavior ($n \approx 8$) of the measured inclusive cross section at fixed $x_T = 2 p_T/\sqrt{s}$ and polar angle θ [7]. The difficulty originates from the parton-parton scattering matrix elements, which are proportional to $1/\hat{t}$, where $\hat{t}$ is the t-channel momentum transfer squared. They correspond to $n = 4$. It has been suggested in ref. [2] that the slope parameter of the inclusive cross section can be increased in the parton model by including Fermi motion of initial-state partons. A large momentum of the scattered parton towards the triggering device is favored, which may indeed be provided by the Fermi momentum, k_T (figure 1a). Thus, parton-parton scattering occurs at lower $\hat{t}$, enhancing the inclusive cross section due to the $\hat{t}$ -pole of the lowest order scattering amplitudes. However, the Fermi motion only affects the lower p_T region and becomes negligible as p_T becomes large compared to k_T . Calculations [2] have actually confirmed this expectation, but the predicted inclusive cross section still does not drop as strongly as the data at $p_T \geq 3.5$ GeV/c.

A remedy for this problem comes from measured scale-breaking effects. In perturbative QCD scale-breaking, i.e. a dependence on Q^2 , a four momentum transfer squared on the parton level, is expected e.g. for parton distributions, structure functions, and the coupling constant. Larger values of p_T correspond to larger values of Q^2 . Inclusion of scale-breaking effects in the parton model yields therefore a significantly stronger dependence on p_T of the inclusive cross section, such that agreement between parton model and experiment is achievable [8].

With the shape of the inclusive cross section fixed at higher p_T , the slope at lower p_T can be adjusted by a variation of $\langle k_T \rangle$. In ref. [9], the approach to the pole at small $\hat{t}$ was avoided by a cut in $\hat{t}$. When p_T is significantly larger than $\langle k_T \rangle$, an elimination of the tail of the k_T distribution is equivalent.

In order to extract an appropriate value of $\langle k_T \rangle$, an efficient Monte Carlo program has been developed in the framework of the parton model. It was optimized by extensive use of the importance sampling method. The parton structure functions used are the CDHS [10] and Duke-Owens set 1 [11] parametrizations with scale breaking. The fragmentation functions are the ones used in ref. [12], where the scale-breaking effect was determined from measurements of $e^+ e^-$ annihilations. The Monte Carlo program is summarized in the appendix with a complete description given in ref. [8].

With this Monte Carlo program measured inclusive cross sections for different mesons at various energies and polar angles can be reproduced using a K-factor of 2 [8]. For the present analysis, the minimum p_T is chosen to be 4 GeV/c, which is significantly larger than $\langle k_T \rangle$. The calculated inclusive cross section for π^+ production at different values of p_T is displayed in figure 2 as function of $\langle k_T \rangle$. The dashed line comes from a fit to the data [13] of the functional form $p_T^{-8} e^{-ax_T}$. A value of $\langle k_T \rangle \approx 0.3$ GeV/c, as suggested by the uncertainty principle, provides good agreement with the data beyond $p_T \approx 6$ GeV/c; the calculation is, however, significantly below the measurements at $p_T < 6$ GeV/c. As $\langle k_T \rangle$ increases, the calculated cross section approaches the data such that consistency at $p_T \approx 4$ GeV/c is achieved for $\langle k_T \rangle \approx 1$ GeV/c. Hence, experimental evidence for a large value of an effective $\langle k_T \rangle$, first obtained in ref. [2], is confirmed here.

4. Event Structure

4.1 Trigger Hemisphere

Having extracted a value of $\langle k_T \rangle$ from measured inclusive cross sections, it is then crucial to check the consistency of this value with details of the event structure. A sample of 120,000 Monte Carlo events, reflecting the experimental conditions, is used in the following comparison. A Gaussian k_T distribution is used in the lowest-order parton model with $\langle k_T \rangle = 0.6$ GeV/c; this choice is a compromise between the large value derived from inclusive cross sections, and the expectation from the uncertainty principle.

The reliability of the Monte Carlo calculation is first demonstrated in the trigger hemisphere ($\theta = 0^\circ - 180^\circ$) of the observed four-jet structure [5]. This region of phase space includes the hadrons near the trigger particle in momentum space (the "trigger jet"), and some of the fragments of spectator partons which are emitted along the beam directions (the "spectator jets"). For charged pion and kaon triggers, the measured particle density as a function of θ is displayed in figure 3 together with results from the Monte Carlo calculation. Rather good agreement is found in the trigger jet, spectator jet, and transition regions. The particle density in the trigger hemisphere is thus well reproduced by this

simple lowest-order parton model. The longitudinal structure of the trigger jet is very sensitive to the fragmentation functions. The scaling variable

$$z_F \equiv \frac{\vec{p}^{\text{sec}} \cdot \vec{p}}{(\vec{p})^2}$$

is used to analyse it; $\vec{p}^{\text{sec}}$ ($\vec{p}$) is the momentum of a secondary (trigger) particle. The calculated particle density is compared, as function of z_F , to the measurements [4] in figure 4 for charged pion and kaon triggers separately. The strong fall off with z_F is predicted by the model. Especially, the measured ratios (not shown) of densities of the secondaries having charges opposite and equal to the trigger particle agree well with the calculations. These ratios reflect local charge compensation. Variations of the k_T distribution do not have any visible influence on the longitudinal structure of the trigger jet.

4.2 Away Hemisphere

The analysis continues into the azimuthal region opposite to the trigger jet ('away hemisphere'). As away jets, formed by the partons recoiling against the trigger, are not fixed in phase space by a trigger particle, they give rise to a wide structure in θ [2,5,14]. An effort has been made to obtain away jet distributions free of spectator background as in the case of the trigger jet [14]. Only secondaries within an azimuthal wedge of $\pm 25^\circ$ opposite to the trigger azimuth are considered. In addition, the scaling variable

$$x_E = - \frac{\vec{p}_T^{\text{sec}} \cdot \vec{p}_T}{(p_T)^2}$$

was restricted to the range $0.5 < x_E < 1.0$ in order to further eliminate spectator secondaries with low momenta. The particle density in terms of the rapidity, y , for away jets from π^+ triggers is displayed in figure 5a. Two observations are made from a comparison between data and predictions based upon lowest order parton processes:

1. The calculation yields a wide structure in rapidity, similar to the data.
2. The predicted particle density exceeds the data by a factor 2 indicating more energetic away jets in the model.

The particle density measured in ref. [14] is presented in figure 5b as function of the longitudinal scaling variable x_E . Only particles with $-2 < y < 2$ were considered in order to minimize the contamination from soft spectator secondaries. From a comparison of the data with predictions from the lowest-order parton model using $\langle k_T \rangle = 0.6 \text{ GeV}/c$ one

concludes the following :

1. A strong dependence on x_E is found in both cases.
2. The data decrease with x_E significantly faster than the model prediction; the large difference between data and model in the region $0.5 < x_E < 1$ reflects the discrepancy observed for the rapidity density (figure 5a).

It is possible in principle to adjust the fragmentation functions for away jets to get a stronger x_E dependence from the model. However, the measured trigger jet distribution constrains the longitudinal structure of any transverse jet, unless the hypothesis of jet universality is discarded.

A consequence of a large value of $\langle k_T \rangle$, is a strong boost towards the trigger direction. This boost has two important consequences (figure 1a) :

1. The transverse momentum of a scattered parton in the parton-parton rest system needed to satisfy the trigger requirement is smaller than without boost. Thus the parton recoiling against the trigger parton has also a smaller transverse momentum.
2. A boost towards the trigger direction lowers furthermore the away parton's momentum in the proton-proton center-of-mass frame.

From this consideration, agreement with the away jet measurements is expected for $\langle k_T \rangle$ larger than the value used (0.6 GeV/c). In fact, a calculation with $\langle k_T \rangle \approx 1$ GeV/c shows significant improvement (not shown, [8b]).

4.3 Spectator Jets

Despite these strong indications for $\langle k_T \rangle \approx 1$ GeV/c from inclusive cross sections and away jet analyses, a direct measurement of the k_T distribution is difficult. In principle, the recoil of spectator jets can be used to measure directly the Fermi component of k_T at the "beam splitting" stage (figure 1a). Note that the trigger particle at $\theta \approx 45^\circ$ and the spectator jets at $\theta \approx 0^\circ$ come from the same incident proton in general. Unfortunately, it is very difficult in practice to measure separately the spectator jet momenta due to losses in the beam pipes and to backgrounds from other jets. However, because of the rather "hard" fragmentation function for leading baryons [15], the fast particles in each spectator jet carry a large fraction of the jet energy; therefore, they should reflect the k_T distribution through their recoil.

For the following investigation, an event plane is defined by the beam momentum and the trigger momentum; the longitudinal direction is along the beam momentum. The average momentum, $\langle p_x^{\text{sec}} \rangle$, normal to the longitudinal direction in the event-plane, of fragments with large longitudinal momentum, p_L^{sec} , reflects the recoil of the spectator

parton against a transverse momentum k_T imparted to the colliding partons. Measurements of $\langle p_x^{\text{sec}} \rangle$ at $|p_L| = 22$ and 27 GeV/c, are shown in figure 6 for all triggers. The simple parton model with $\langle k_T \rangle = 0.6$ GeV/c yields a recoil exceeding the measurement. This observation definitely excludes any value of $\langle k_T \rangle$ larger than about 0.6 GeV/c but is compatible with previous results [2]. A serious dilemma arises at this point, as $\langle k_T \rangle \approx 1$ GeV/c was favored in sections 3 and 4.2.

5 Higher-Order QCD Showers

So far, the present analysis clearly indicates the need of a large transverse boost in the trigger direction, but only a small Fermi component of $\langle k_T \rangle$ is allowed by the spectator recoil. One way to resolve this problem is through higher-order QCD showers of the initial-state partons (figure 1b). In this picture, the initial state partons are space-like, and go through a series of perturbative branchings in $O(\alpha_s)$ before interacting with another parton. This kind of branching process is analogous to the bremsstrahlung process in QED. The parton shower formalism for space-like showers was developed in refs. [16,17]. Time-like (final-state) parton showers in the leading logarithm approximation (LLA) were investigated in ref. [18].

The parton shower formalism of ref. [17] is implemented here for both time-like and space-like showers in the parton model code. A sample of 70,000 complete events were generated. Due to initial state parton showers, it is possible to obtain a large “effective” $\langle k_T \rangle$ (≥ 1 GeV/c) at hard scattering from an input distribution with $\langle k_T \rangle = 0.45$ GeV/c at beam factorization [8b]. Hence inclusive cross sections are well reproduced for $p_T \geq 3$ GeV/c [8b] (not shown).

The predicted away jet densities are shown in figures 5a and 5b, as function of y and x_E , respectively, superimposed onto the previous results. The normalization of the rapidity density is lowered by almost a factor of 2; it thus agrees with the data. This softening of the away jet is also reflected by the x_E distribution where the fall off is now considerably faster, also in reasonable agreement with the data. Thus, consequences of a larger effective value of $\langle k_T \rangle$ at hard scattering are clearly observed.

Before the higher-order parton model can be compared to data on spectator recoil, a technical difficulty of the simulation must be clarified. In space-like LLA shower formalisms, the production of soft radiation is unavoidable. These low-energy partons are truncated by the fragmentation scheme of ref. [21] which is used in this work for its simplicity. In other words, energy-momentum conservation is violated at the fragmentation stage. This violation is typically at the 0.5 GeV/c level, so that analyses of secondaries with $p_T^{\text{sec}} > 2$ GeV/c from away jets are not seriously affected.

The asymmetry of $\langle p_x^{\text{sec}} \rangle$ due to spectator recoil is of the order 0.1-0.2 GeV/c, and the influence of energy-momentum non-conservation may be strong. In order to perform a study of this sort, any simplified fragmentation scheme must be discarded. In figure 6, the values of $\langle p_x^{\text{sec}} \rangle$ at large p_L are displayed for both spectator jets; they were calculated at the parton level for the parton model without showers. The result is indeed consistent with that at the hadron level. Therefore, one may conclude that $\langle p_x^{\text{sec}} \rangle$ at large p_L can be reliably derived at the parton level also for the higher-order parton model. The results from higher-order calculations are shown in figure 6; they reproduce the data from both spectator jets with $\langle k_T \rangle = 0.45$ GeV/c at beam factorization.

6. Conclusions

The question of an intrinsic transverse momentum, k_T , of partons inside the proton is explored in terms of the parton model for high p_T events obtained from pp collision at $\sqrt{s} = 62$ GeV. A very efficient Monte Carlo code is employed in order to extract relevant quantitative information. A lowest-order parton model is proven to be successful in reproducing the measured particle density in the polar hemisphere of the trigger particle; a value of $\langle k_T \rangle \approx 1$ GeV/c is needed to reproduce measured inclusive cross sections for meson production and away jet distributions. A paradox arises when a measurement of the spectator jet recoil excludes values of $\langle k_T \rangle > 0.6$ GeV/c. The only consistent solution to this difficulty found so far is to interpret the large value of $\langle k_T \rangle$ as an effective description of a boost towards the trigger direction. Higher-order parton showers in leading log QCD provide a favorable boost corresponding to $\langle k_T \rangle \approx 1$ GeV/c starting from a parton "Fermi motion" with $\langle k_T \rangle = 0.45$ GeV/c. A code has therefore emerged which reproduces quantitatively inclusive cross sections for mesons (modulo the K-factor), densities of charged particles over full phase space, quantum number correlations within the trigger jet and measured jet-jet correlations [8b] in the framework of QCD. The consistency of all observations in this experiment with higher-order Monte Carlo calculations supports the existence of higher-order QCD contributions to hard parton-parton scattering at the ISR.

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Appendix : The Parton Model Monte Carlo Code

Parton model phenomenology of the inclusive process $AB \Rightarrow CX$ is based upon the differential cross section formula

$$d\sigma(AB \rightarrow CX) = \sum_{abcd} dx_a dx_b dz_c dt G_{a/A}(x_a, Q^2) G_{b/B}(x_b, Q^2) D_{C/c}(z_c, Q^2) \\ \times \delta\left(z_c + \frac{\hat{u}/\hat{s}}{x_a} + \frac{\hat{t}/\hat{s}}{x_b}\right) \frac{d\sigma(ab \rightarrow cd)}{\hat{t}},$$

where A, B, C , and X are hadrons; a, b, c , and d are partons; $\hat{u}$, $\hat{t}$, and $\hat{s}$ are the Mandelstam variables of the parton-parton interaction; x_a and x_b are the fractional light-cone momenta of the incoming partons; z_c is the fractional light-cone momentum of the triggering hadron; and G and D are the parton distribution functions and fragmentation functions, respectively. The most practical way to calculate these cross sections numerically is the Monte Carlo method [19]. In addition, this method also allows the simulation of entire events.

A.1 The Simple (Lowest-Order) Parton Model

The simple parton model involves three stages (figure 1a) : factorization of beam protons, hard scattering of partons, and fragmentation of all final state partons. Each beam proton is first split into a single parton, which is to participate in the hard scattering, and a collection of non-interacting partons, which are called the spectator partons. The momentum sharing between the active parton and the remnant is controlled by the parton distribution functions $G(x, Q^2)$.

The hard scattering cross section, $d\sigma(ab \rightarrow cd)/d\hat{t}$ has been calculated to lowest-order in the QCD coupling constant, α_s [20]. The scattering kinematics is defined once the trigger parton momentum is selected. The effective Q^2 used here is the symmetrized form of ref. [21].

$$Q^2 = \frac{2\hat{s}\hat{t}\hat{u}}{\hat{s}^2 + \hat{t}^2 + \hat{u}^2}.$$

The independent fragmentation scheme of ref. [21] is adopted in this work. The fragmentation function for a single quark is obtained from the splitting function

$$f(1-z) \propto (1-z)^{1+P}, \text{ with } P = \frac{16}{25} \ln \frac{\ln Q^2 / \Lambda^2}{\ln Q_0^2 / \Lambda^2}, \text{ and } \Lambda = 0.3 \text{ GeV},$$

at each step in the fragmentation chain. The longitudinal spectrum of fragments from single quarks is shown to fit measurements from e^+e^- annihilation experiments [8]. The scale breaking pattern used here also agrees with experiment [8, 12]. A gluon is first split into a quark-antiquark pair with the gluon momentum shared uniformly between the pair. The fragmentation function of a single gluon jet follows from

$$f(1-z) \propto (1-z)^{P'}, \text{ with } P' = 2.6 \ln \frac{\ln Q^2 / \Lambda^2}{\ln Q_0^2 / \Lambda^2},$$

Due to the different strengths of scale breaking for gluons and quarks $P' \neq P$ [12]. The multi-parton spectator jet has a fragmentation function based upon the form $f(z) = a + bz$ which was fitted to diquark jets observed in muon-proton interactions [8].

A.2 Higher-Order Parton Model

The higher-order corrections of the $2 \rightarrow n$ ($n > 2$) type of parton-parton scattering are implemented as initial-state and final-state parton showers. The shower formalism of ref. [18] was adapted to both cases. The actual algorithms are described in detail in ref. [8b].

The initial-state and final-state showers are generated according to ref. [18]. The efficiency of the resulting code is a factor 2 smaller than that of the lowest order parton model.

The initial-state parton showers are first generated in the parton-parton center-of-mass frame. A boost back to proton-proton frame is then performed. The final-state parton showers are inserted between the hard scattering and fragmentation stages [8]. All the final-state partons are evolved towards the cutoff virtual mass. The invariant $\hat{s}$ of the parton-parton hard scattering is used as the evolution scale according to ref. [18].

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Figure Captions

- Figure 1** Schematic representation of hard parton-parton scattering in lowest-order (a) and (b) including higher-order terms (bremsstrahlung of gluons).
- Figure 2** Invariant cross section $Ed\sigma/dp^3$ as function of $\langle k_T \rangle$ at various values of p_T from the lowest-order parton model calculation using a "Gaussian" k_T distribution. Invariant cross sections obtained from a phenomenological fit to π^+ data are included as well (dashed lines).
- Figure 3** Particle density $d^2N/d\theta d\phi$ for particles with total momentum component in the event-plane between 1.5 to 2 GeV/c and in an azimuthal wedge of $\pm 45^\circ$ about the trigger track, given as a function of the polar angle θ . The approximate position of the trigger is indicated, and lowest order Monte Carlo predictions with $\langle k_T \rangle = 0.6$ GeV/c are included (solid line).
- Figure 4** Particle density $\rho^\pm(z_F) = dN/dz_F$ in the trigger jet versus z_F for particles with charges equal (circles) and opposite (solid dots) to the charge of the trigger : (a) π^+ , (b) K^+ , (c) π^- , and (d) K^- triggers. Model predictions are also shown.
- Figure 5a** Rapidity distribution $d^2N/dy d\phi$ for leading fragments at $0.5 < x_E < 1.0$ in the away jet using π^+ triggers [14] only, shown together with parton model predictions (lowest order : full dots; higher order : crosses).
- Figure 5b** x_E distribution $d^2N/dx_E d\phi$ for leading fragments with $-2 < y < 2$ in the away jet using π^+ triggers [14] only, and parton model predictions (lowest order : full dots; higher order : crosses).
- Figure 6** The spectator recoil $\langle p_x^{\text{sec}} \rangle$ for $|p_L^{\text{sec}}| > 20$ GeV/c, displayed for the two spectator jets. The data are compared to predictions from the higher-order parton model at the parton level. A comparison between results obtained at the parton level and hadron level using the simple parton model is also presented.

fig. 1

fig. 2

fig.3.

fig. 4

fig. 5 a

fig. 5b

fig. 6