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JET PRODUCTION AT COLLIDER ENERGY

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A B S T R A C T

Jet and single particle distributions are discussed for $p\bar{p}$ interactions at ISR (54 GeV) and SPS (540 GeV) centre-of-mass energy. The QCD perturbative calculations are very sensitive to gluon distributions and gluon interactions. Comparison against data would thus provide much information about still elusive gluon effects which are nevertheless expected to be very important. Rapidity distributions for single jet and jet-jet correlation distributions are given. The resulting large background to the jet signal from the production of the weak bosons is discussed.

1. INTRODUCTION

Particle production at high transverse momentum (high p_T) is now clearly associated with hard scattering among hadron constituents. The jet structure which is then expected to result has been verified to correspond to the typical final state configuration whenever the observation of a particle at high p_T is used to signal a special reaction process¹⁾. All features associated with the parton approach have been checked to hold as a first approximation and specific effects proper to Quantum Chromodynamics seem to appear as expected^{2),3)}.

It is well known that the high p_T yield shows a rise with incident energy in contrast with the practically constant behaviour of particle production at low p_T . In the hard scattering approach¹⁾, it is understood in terms of the rise of the relevant parton density as $x_T = 2 p_T / \sqrt{s}$ decreases. The centre-of-mass energy squared is, as usual, denoted as s . The more numerous low x partons play an increasing role at fixed p_T when s increases. Here x denotes the fraction of the incident hadron momentum taken by the relevant parton. Particle yields which are vanishingly small at ISR energy (at $p_T \gtrsim 15$ GeV/c, say) should become sizeable at higher energies and, in particular, in the energy range now referred to as "Collider energies"⁴⁾. Taking 540 GeV as a specific collider centre-of-mass energy, we have a nine-fold increase from the highest energy presently available at the ISR. An important rise of the high p_T yield should follow. This is dramatically displayed in Fig. 1.1, which shows the anticipated jet yield at 90° in $p\bar{p}$ collisions at ISR energy ($\sqrt{s} = 54$ GeV)⁵⁾ and at collider energy ($\sqrt{s} = 540$ GeV). The jet yields have been obtained through a calculation following standard techniques in Quantum Chromodynamics; it is presented in Section 2.

The increase of the inclusive jet cross-section at $p_T = 20$ GeV/c, say, is close to four orders of magnitude between $\sqrt{s} = 63$ GeV (top ISR energy) and collider energy. Even with a luminosity of $10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ ⁴⁾, one may anticipate close to one 20 GeV/c jet every second.

Jet production could be studied up to 60-70 GeV/c and present ideas about jet fragmentation could then be put to a thorough test. The purpose of this paper is, however, to set the stage for such a study, presenting estimates of jet production and of jet-jet correlations which could be used for assessing possibilities. Indeed, the mere observation of the predicted jet yields would already be interesting in so far as it would confirm the gluon-parton relationship and present ideas about scaling violations and factorization properties. A large fraction of the increase in yield as it appears on Fig. 1.1 is associated with the Q^2 dependence of the parton (quark and gluon) distributions at small x .

The "probing" transfer Q^2 is of the order of p_T^2 and, while p_T is set to be large ($p_T > 10$ GeV/c), the relevant values of x , which are of the order of x_T at 90° , become very small. The rather large inclusive cross-section which is predicted results from the relatively large parton density at low x which scaling violation effects build up at large Q^2 . Actually, while it is expected that inclusive yields should eventually reach a p_T^{-4} behaviour⁷⁾, this should apply (up to logarithmic terms) at fixed x_T only. The inclusive yield of Fig. 1.1, for which increasing values of p_T correspond to increasing values of x_T , falls off far steeper despite the high values of both p_T and $\sqrt{s}$, as a result of the sharply peaked parton distributions at low x . Indeed, fitting $d\sigma/dp_T^2 dy$ to an inverse power p_T^{-N} between 20 and 45 (60) GeV one gets $N = 9.5$ (9.2).

The relatively important yield and the relatively steep fall of the inclusive cross-section with p_T are very striking predictions from QCD in so far as they are both very sensitive to scaling violations.

The study of jet production at collider energy is therefore very interesting. Predictions about jet production should be useful as large detectors are built for experimentation at the SPS. Jet studies would provide a very valuable testing ground for QCD calculations as presently conducted in the leading log approximation^{7),8),9)}, and more generally for the gluon structure of the proton.

The energy and luminosity of the $p\bar{p}$ collider are such that the accessible p_T range corresponds to a region where gluon jets are expected to dominate¹⁰⁾ ($x_T < 0.2$). Consequently all predictions about yields are very dependent upon the gluon structure of the colliding hadrons and on gluon coupling. By the same token any experimental information will therefore have a direct impact on the still elusive role of the gluon.

Predictions about jet yields are also interesting in view of the background which thus appears against the dominant two-jet decay modes of the Z and W bosons whose search is the dominant motivation for the collider programme¹¹⁾.

This paper is organized as follows. In Section 2 we present the QCD perturbative computer calculation with which the inclusive distributions of Fig. 1.1 and the different yields given in Sections 3, 4 and 5 are obtained. We actually calculate yields for hadron constituents, quarks and gluons, at high p_T , and identify the corresponding momentum flow with the one actually observed collecting hadrons associated with a jet.

Section 3 presents inclusive yields for different types of jets. We calculate explicitly the rate for production of u , d , s , c and gluon jets in pp and $p\bar{p}$ collisions. Yields at 90° as a function of p_T are given for

$\sqrt{s} = 54 \text{ GeV}$ (ISR) and $\sqrt{s} = 540 \text{ GeV}$ (SPS collider). We also give rapidity distributions at $p_T \sim 10\text{-}15 \text{ GeV}/c$, where rather large yields are expected, and at $p_T \sim 40\text{-}45 \text{ GeV}/c$, where yields are low but where more specific effects appear.

Section 4 gives the quark jet yields as expected from Z and W production. In this case we merely consider a Drell-Yan calculation which is expected to give the correct order of magnitude despite the importance of higher order effects¹²⁾. As is well known, the relevant x range is such that scaling violations are expected to be minimal and gluons enter only higher order effects. As a result calculations done a few years ago¹¹⁾, when QCD did not have its present currency, and which relied on a simple parton model, remain valid to a good approximation. The corresponding distributions obtained using varying structure functions are given so that they can be compared with those obtained in Section 3. The importance of the hadronic background is overwhelming. It remains so when considering invariant mass distributions for two jets.

In Section 5 we consider single pion production at high p_T . As is well known, jet yields are much larger than single particle yields at the same p_T ¹⁾. At $p_T > 10 \text{ GeV}/c$, constituent fragmentation is usually expected to win over higher twist effects such as those parametrized by the Constituent Interchange Model²⁾. It is therefore the only production model considered here.

Fragmentation functions are yet rather poorly known and this corresponds to less reliable predictions than those made for jets in Section 3. While scaling violations should be included it is also not clear to which extent they manifest themselves in so far as $\ln Q^2$ is still not very large. We therefore give inclusive pion yields as obtained without and with full scaling violations so that the role of scaling violation effects can easily be assessed.

Section 6 provides a summary and also includes some speculation about the possible connection between the lower p_T jet yield and the emergence of new configurations as reported in Cosmic Ray reactions at similar energies¹³⁾.

2. THE INCLUSIVE JET YIELD

In the parton model, the inclusive yield is obtained in terms of a folding integral over the parton distributions, each contribution being weighted by the relevant parton-parton differential cross-section, namely:

$$p \frac{d\sigma^R}{d^3p} = \sum_{ij} \int F_i(x_1) F_j(x_2) \frac{\hat{s}}{\pi} \delta(\hat{s} + \hat{t} + \hat{u}) \frac{d\sigma^{ijk}}{d\hat{t}} dx_1 dx_2 \quad (1)$$

The suffixes i, j and k refer to quarks, antiquarks and gluons. The Mandelstam variables relevant to the parton-parton subprocesses are denoted by $\hat{s}, \hat{t}$ and $\hat{u}$, the parton mass being neglected. The jet momentum and production angles are denoted by p and θ , respectively, and these parameters, together with the centre-of-mass energy squared s , can be used to express the Mandelstam variables as:

$$\begin{aligned}\hat{s} &= \frac{1}{2} x_T s (x_1 t_g^{\theta/2} + x_2 \cot g^{\theta/2}) = x_1 x_2 s \\ \hat{t} &= -\frac{1}{2} x_T s x_1 t_g^{\theta/2} \\ \hat{u} &= -\frac{1}{2} x_T s x_2 \cot g^{\theta/2}\end{aligned}\tag{2}$$

with $x_T = 2p_T/\sqrt{s}$; $p_T = p \sin \theta$.

The δ function, together with the $\hat{s}$ factor appearing in (1), translate the kinematical constraints spelled out in (2).

Such a standard parton approach remains valid in the "leading log" approximation of QCD provided that the structure functions $F_i(x)$ are replaced by varying structure functions $F_i(Q^2, x)$ ⁹⁾. Such a calculation should be adequate to estimate the jet yield, each jet being detected over a calorimeter of wide enough opening angle.

There are seven basic subprocesses corresponding to the different types of constituents¹⁾.

The differential cross-section is written as

$$\frac{d\sigma}{d\hat{t}} = \pi \alpha_s^2(Q^2) \frac{|A|^2}{\hat{s}^2}\tag{3}$$

and expressions for $|A|^2$ as obtained for the various subprocesses are given in Table 2.1¹⁴⁾. Sum and averages over colour give the different numerical factors. Combining (1), (2) and (3), differential cross-sections for jet production can be obtained following by now standard lines¹⁵⁾. Special to this paper is a detailed computer calculation incorporating scaling violations and providing a variety of yields and correlations. It uses a value of $\Lambda = 0.5$ GeV/c in the expression for the running coupling constant and takes p_T^2 as a characteristic scale Q^2 . It thus differs from other choices such as $Q^2 = 2 \hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$ but by numerical factors of order one¹⁵⁾ (in this example at most 4/3). This is irrelevant in view of the neglect of non-leading terms.

Table 2.1

The contributions of the different QCD subprocesses

<u>Subprocess</u>	<u>$A ^2$</u>
1. $q_i q_j \rightarrow q_i q_j, q_i \bar{q}_j \rightarrow q_i \bar{q}_j (i+j)$	$\frac{4}{9} (\hat{s}^2 + \hat{u}^2) / \hat{t}^2$
2. $q_i q_j \rightarrow q_i q_j$	$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{s}^2 + \hat{t}^2}{\hat{u}^2} \right) - \frac{8}{27} \frac{\hat{s}^2}{\hat{u}\hat{t}}$
3. $q_i \bar{q}_j \rightarrow q_i \bar{q}_j$	$\frac{4}{9} \left(\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} + \frac{\hat{t}^2 + \hat{u}^2}{\hat{s}^2} \right) - \frac{8}{27} \frac{\hat{u}^2}{\hat{s}\hat{t}}$
4. $q_i \bar{q}_j \rightarrow g g$	$\frac{32}{27} \left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} \right) - \frac{8}{3} \left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} \right)$
5. $g g \rightarrow q_i \bar{q}_j$	$\frac{1}{6} \left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{u}\hat{t}} \right) - \frac{3}{8} \left(\frac{\hat{u}^2 + \hat{t}^2}{\hat{s}^2} \right)$
6. $q_i g \rightarrow q_i g$	$-\frac{4}{9} \left(\frac{\hat{u}^2 + \hat{s}^2}{\hat{u}\hat{s}} \right) + \left(\frac{\hat{u}^2 + \hat{s}^2}{\hat{t}^2} \right)$
7. $g g \rightarrow g g$	$\frac{9}{2} \left(3 - \frac{\hat{u}\hat{t}}{\hat{s}^2} - \frac{\hat{u}\hat{s}}{\hat{t}^2} - \frac{\hat{s}\hat{t}}{\hat{u}^2} \right)$

It is indeed well known that contributions neglected in the lowest order QCD calculations could be important at medium p_T values ($p_T < 10$ GeV/c, say), and it is only for $p_T > 10$ GeV/c that we can consider, with some confidence, calculated rates based on the QCD subprocesses of Table 2.1. At medium p_T the relative success of the "black box" approach of Feynman, Field and Fox¹⁶⁾, with an empirical parametrization of $d\sigma/d\hat{t}$ as $(\hat{s}\hat{t})^{-1}$, indeed shows that correction terms conspire to give an over-all $\hat{s}$ and $\hat{t}$ dependence much different from that read directly from the perturbative contributions of Table 2.1.

While some non-leading terms may be included and parametrized in model calculation at medium p_T , our main concern here is to test the relevance of QCD calculations against collider data and we may therefore consider large enough values of p_T ($p_T > 10$ GeV/c), where the perturbative contributions should already provide a good approximation.

The most original ingredient of the calculation does not meet the eye. This programme incorporates scaling violations which are parametrized as already performed in a previous calculation¹⁷⁾. While the Q^2 dependence of the leading terms is now imposed in a fairly general way¹⁸⁾, parametrizations differ as a result of the uncertainty in the gluon distribution at low Q^2 and the relative importance presumed for non-leading terms. Our parametrization is of the Owen-Reya-Glück type¹⁹⁾ and tested to give a satisfactory description of high p_T π^0 production at ISR energies, combining single π^0 and prompt photon when not resolved. The calculation of the structure functions for large Q^2 evolves from a gluon distribution which is taken to be somewhat softer than that for a valence quark. At low Q^2 we choose distributions to be compatible with the standard

counting rules^{1),20)}. The starting sea quark distribution is taken to be fairly steep, namely proportional to $(1-x)^7$.

A simple inspection of the relative magnitude of the cross-sections in Table 2.1 shows the importance of the gluon structure function in computing high p_T yields. While it is generally assumed that gluon distributions are sharply cut off at large x and therefore that little yield from gluons should be expected at large x_T , the importance of the gluon contribution remains strong over the whole p_T range practically covered by the collider, which corresponds to $x_T < 0.2$ ¹⁰⁾. Consequently our results are very sensitive to the gluon density at low x the size of which is related by the momentum sum rule to its behaviour for larger x . By the same token one may say that jet measurement at collider energy will allow us to replace present estimates of the gluon distribution by a more accurate parametrization.

At large angles, the relevant values of $\hat{s}$, $\hat{t}$ and $\hat{u}$ are in the neighbourhood of $4p_T^2$, $-2p_T^2$ and $-2p_T^2$, respectively, hence all of the same order of magnitude in the cross-sections of Table 2.1. At the same time one emphasizes low x values of the distribution functions, $x \approx x_T$. It results that the relative contributions of the various cross-sections depend very much on simple weighting involving the colour factors together with the structure functions through the mean value theorem.

As we here put together a large set of results, a few of which have been presented already³⁾, we show that anticipated effects are clear and large enough to provide a direct access to the gluon structure of the proton.

3. INCLUSIVE JET CROSS-SECTIONS

We choose to present the inclusive yields for gluon jet, u and d jets, and s and c jets. The difference between u and d as p_T varies translates the changing leading role of the valence and sea quarks. The strange quark production rate has been obtained with an $SU(3)$ symmetric sea while the charm quark content of the sea was put to zero. As a result the s and c curves should actually be interpreted as upper and lower bounds for quark jets of non-valence flavours. Figure 3.1 gives the inclusive distribution at 90° in $p\bar{p}$ and pp collisions at collider energy.

The dominant feature is the importance of gluon jets. While the relative importance of the u quark increases with x_T , it only reaches the gluon jet value by $p_T \approx 70$ GeV ($x_T \approx 0.3$) in pp collisions where it benefits from contributions from valence quarks on both sides. In what should be the relevant p_T range at the SPS collider, the expected gluon jet rates in $p\bar{p}$ and pp

collisions are very similar and hence so are the global jet yields. It is only at $p_T \approx 30$ GeV/c that the charmed jet yield in $p\bar{p}$ departs significantly from that in pp because of the then dominant contribution from $q\bar{q}$ annihilation. Summing up the contributions read from Fig. 3.1a, one gets the global jet yield of Fig. 1.1. At collider energies single jet yields should hardly distinguish $p\bar{p}$ from pp collisions.

Expectations at collider energy (Fig. 3.1) are compared to calculations at ISR energy. We choose a centre-of-mass energy of 54 GeV which corresponds to the chosen $\bar{p}$ feeding energy⁵⁾. Figure 3.2 displays the inclusive distributions for jets in pp and $p\bar{p}$ collisions. The gluon jet contribution does not have the overwhelming role which it has at much higher energies. This is due to the fact that we are dealing with larger values of x_T . Figures 3.2a and 3.2b show the expected differences between $p\bar{p}$ and pp induced reactions. Jet production does not show striking differences. At $p_T = 10$ GeV/c the calculated inclusive jet yield is ~ 150 times larger than the single π^0 yield, as recently measured^{2),3)}.

We now consider the jet rapidity distributions. Figure 3.3 gives the rapidity distribution for different jet species as expected for $p\bar{p}$ collision at collider energy. Figure 3.3a gives the yield integrated over p_T from 10 to 15 GeV and Fig. 3.3b shows the same yields now integrated from 40 to 45 GeV.

The rapidity distribution does not vary very much in the interval $-1 < y < +1$. The relative peaking of the valence quark contributions in the forward direction is interesting in so far as it corresponds to the dominance of the gluon exchange term at low $\hat{t}$. Contrary to what one finds at 90° , the gluon jet production is no longer dominant over quark jet at small angles. This becomes the more pronounced the larger p_T is.

Figure 3.4 corresponds to $p\bar{p}$ reactions at ISR energy at a value of p_T which is large enough that a QCD calculation might be accurate. The distributions shown integrate over p_T from 12 to 13 GeV/c. The valence quark jets now dominate because of the larger value of x_T . This is more pronounced at angles away from 90° , but the characteristic structure met with in Fig. 3.3, showing the peaking at small angle, is now reversed and the yield is largest at wide angle. This is a simple phase space effect due to the vanishing of the structure functions at values relevant to larger x_T . Producing a large p_T jet at relatively small angle imposes a rather large value of x for which the parton density is small.

We also note that at wide angle quark jets dominate at such a p_T value, whereas gluon jets would dominate at lower p_T ^{15),21)}, or as previously found at higher energies at the same p_T . In so far as the charge distributions of the

pions into which each jet fragments can be used to distinguish between quark and gluon jets²²⁾, the expected change in the relative roles of different jet species at different angles between ISR and collider energies offers many tests of perturbative QCD in a kinematical domain where it should apply.

Our calculations of jet yields also give jet correlations. At high p_T the typical configuration is that of two jets balancing their transverse momenta¹⁾. For each value of p_T one may then compare the relative weight of different combinations of jets. Expectations at wide angle (integrated over the $60^\circ < \theta < 120^\circ$ range) are put together in Fig. 3.5. One sees that over the whole observable range (over one event per day per GeV) the two gluon configuration dominates. Only for p_T values as high as 70 GeV does the quark-antiquark configuration become competitive. The variation with p_T of the relative value of the gg and $u\bar{u}$ contributions corresponds to the difference in x dependence of the gluon and quark distributions. The ug contribution has an intermediate behaviour. Conversely, measurements of such ratios would test present ideas about gluon momentum distributions. This implies experimentation at 60 GeV/c where rates are low but where charge correlations should become important. We also include expectation for prompt photons in association with a quark and a gluon jet. Quark jet recoils dominate up to rather large p_T values.

In Fig. 3.5a we also give the two-jet distribution expected from W^+ decay into $u\bar{d}$ and Z^0 decay into $u\bar{u}$. For unidentified jets the hadronic background appears as overwhelming. Identifying the nature of the jet could provide a manageable signal over background ratio. Nevertheless, tagging a c jet (through high p_T muons) as needed for the Z^0 can probably not be achieved in an efficient enough way. This leads us to a discussion of jet production from weak boson.

4. QCD JETS AS A BACKGROUND TO THE DOMINANT JET DECAY OF THE WEAK BOSONS

The dominant decay modes of the weak bosons are expected to correspond to two jet final states. For their production we limit ourselves to the Drell-Yan process with scaling violations for the structure functions. While this is incomplete it should give the correct order of magnitude¹²⁾ and is enough for our purpose of estimating a signal over background ratio. We repeat the calculations outlined in Section 2 picturing only the $q\bar{q} \rightarrow q\bar{q}$ contribution, and replacing the QCD perturbative differential cross-section of Table 2.1 by the relevant expression. Whether considering W or Z production we limit ourselves to the dominant formation ($\hat{s}$ channel) process. For jet production through W , we have

$$\frac{d\sigma^j}{d\cos\theta} = \frac{1}{32\pi} \left(\frac{\hat{s}^2}{[s-M_W^2]^2 + \Gamma_W^2 M_W^2} \right) \frac{2 M_W^4 G^2}{\hat{s}^2} (1+\cos\theta)^2 \quad (4)$$

For jet production through Z^0 , we have:

$$\frac{d\sigma^j}{d\cos\theta} = \frac{1}{32\pi} \left(\frac{\hat{s}^2}{[s-M_Z^2]^2 + \Gamma_Z^2 M_Z^2} \right) \frac{M_Z^4 G^2}{8 \hat{s}} \cdot \quad (5)$$

$$\left\{ (v_i^2 + a_i^2)(v_j^2 + a_j^2)(1 + \cos^2\theta) + 8a_i v_i a_j v_j \cos\theta \right\}$$

The scattering angle θ is defined for quark production (of species j) with respect to the direction of the incident quark (of species i). All vector couplings in the second case are expressed in terms of $\sin^2 \theta_W$ ²³⁾, for which we take a value of 0.23²⁴⁾. All the approximations made are justified at the present level of investigation. We also take $\theta_c = 0$.

The mass and width of the Z^0 and W are taken as obtained from three doublets, namely

$$M_Z = 88 \text{ GeV} , \quad \Gamma_Z = 2.8 \text{ GeV}$$

$$M_W = 78 \text{ GeV} , \quad \Gamma_W = 2.7 \text{ GeV}$$

We first consider inclusive jet production and give in Fig. 4.1 the u (or $\bar{u}$) and d (or $\bar{d}$) differential cross-sections at 90° obtained from Z and W^+ formation. They are presented against the inclusive cross-sections of Fig. 3.1a.

For W production all jet contributions are equal and moreover at 90° W^+ and W^- production give the same yields in $p\bar{p}$ reactions. For Z^0 production, c and u quarks are on the same footing. More explicitly, the parametrization used in Eq. (5) corresponds to

$$a_i = 1, \quad v_i = 1 - \frac{8}{3} \sin^2 \theta_w \quad \text{for } u, c, t \text{ quarks} \quad (6)$$

$$a_i = -1, \quad v_i = -1 + \frac{4}{3} \sin^2 \theta_w \quad \text{for } d, s, b \text{ quarks}$$

The global jet yield for $W^\pm$ and Z put together is therefore a factor of 8 and 10, respectively, compared with the u quark yields of Fig. 4.1. It is still an order of magnitude below the QCD jet yield. Despite the Jacobian peaks which appear at $p_T \sim M/2$ for each of the weak bosons, the corresponding contributions are both well below background at the inclusive level. As seen from Fig. 4.1, only the identification of a charmed jet could give large enough a signal. Efficiency for such an identification may, however, be low. As often emphasized, it is clear that lepton triggers are of prime importance in searching for the W and Z production. While the leptonic branching ratios are relatively small, the signal over background ratio is then very large as opposed to that found for the dominant jet modes.

The signal over background ratio changes with production angle but the main point is that both distributions are rather wide in rapidity, the perturbative hadronic one remaining always above that corresponding to W and Z production. This is illustrated by Fig. 4.2 which gives the rapidity distribution for a u jet integrated over a p_T interval which corresponds to a reasonable calorimeter resolution at such energy. Figure 4.2a gives the u jet distribution calorimeter over the $p_T = 44 \pm 2.5$ GeV/c range, whether due to hadronic interaction or Z^0 formation, while Fig. 4.2b gives the u jet distribution integrated over the $p_T = 39 \pm 2.5$ GeV/c range, whether due to hadronic interactions or $W^\pm$ formation.

Such choices for the p_T intervals are the most favourable ones. Taking a lower value of p_T quenches seriously the contribution from W and Z formation, while the QCD yield is of course much larger. This is shown in Fig. 4.2c which puts together the u quark distributions expected from perturbative QCD calculations (upper curve) and from Z (solid lower curve) and from $W^\pm$ (dashed lower curve) formation, when a p_T range of similar extension is taken around $p_T = 12.5$ GeV/c. One may come back to Figs 3.3a and 3.3b to compare the y distribution of the u quark jet given in Fig. 4.2 to those expected for other jets in similar p_T ranges.

We already saw (Fig. 3.5a) that even a jet-jet correlation does not result in a strong enough signal, unless jet identification is possible with good efficiency. While the loose back to back configuration defined in Section 3 already emphasizes the contribution from the weak bosons, one may impose a tighter constraint. This is done in Fig. 4.3 where we give some two-jet distributions as a function of the p_T of the jets for fixed invariant mass. Figure 4.3a gives the distribution for the $u\bar{d}$ jets as obtained from hadronic interactions (upper curve) and from W^+ formation (lower curve). The differential cross-section with respect to the mass is integrated over the 78 ± 6 GeV interval. While the signal over background ratio may look reasonable, it corresponds to an identified jet. Considering the invariant mass of two unidentified jets, the selected $u\bar{d}$ configuration is not very frequent as compared to others (Fig. 3.5a). Figure 4.3b gives the $u\bar{u}$ jet correlation expected from hadronic interaction (upper curve) and from Z^0 formation (lower curve). The differential cross-section is now integrated over the 88 ± 6 GeV interval.

Figures 4.1, 4.2 and 4.3 show how difficult it is to identify the W and the Z through their dominant hadronic decay modes. The background expected from perturbative QCD appears as overwhelming.

Scaling violations which are generally of great importance in the leading log approximation do not affect much the W and Z production cross-sections. The relevant x range is such that their effect is minimal. Using invariant structure function (standard parton model) gives at most a factor 3 increase. Uncertainties due to higher order effects are certainly at the same level! In any case, the calculation over background ratio is less sensitive to such effects.

5. SINGLE PARTICLE PRODUCTION

Our perturbative approach considers quarks and gluons "on their mass shell" and should be adequate for the computation of jet yields. What will eventually be more interesting is the "virtualness" with which they enter the scattering subprocess and the complicated jet structure which may be associated with it²⁵⁾. Hadronization will, however, be treated in a very global way, associating a fragmentation function $D_k^\pi(z)$ for the production of a pion with fractional momentum z of the constituent k . The inclusive pion yield corresponding to (1) is:

$$p_0 \frac{d\sigma^\pi}{d^3p} = \sum_{i,j} \int F_i(x_1) F_j(x_2) \frac{1}{\pi} \frac{1}{z} D_i^\pi(z) \frac{d\sigma^{ijk}}{d\hat{t}} dx_1 dx_2 \quad (7)$$

The fragmentation functions D are chosen such as to satisfy the standard counting rules at low Q^2 ¹⁾ and the Q^2 evolution is parametrized as done for the structure function F ^{7),8)}.

While p_T^2 "measures" the probing momentum and can be used in the computation of $F(Q^2)$, using it also in the computation of $D(Q^2)$ is valid only in the leading log approximation. While the "virtualness" of the constituent may reach a value of order Q^2 , what to take in practice at this level of perturbative approximation is not precisely known. It seems therefore appropriate to compute two extreme pion yields, one including standard scaling violations in both F and D , with probing momentum squared $Q^2 \equiv p_T^2$ and one including it in F but not in D . The two resulting curves for the π^0 yield in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV are given in Fig. 5.1 while the difference corresponds to a factor of the order of two at 15 GeV/c, it is close to a factor 10 at 60 GeV/c. This is due to be the fact that the fragmentation function falls the more rapidly with z the larger Q^2 is. Hence it becomes more difficult to give a large fraction of the jet momentum to a fragment pion with scaling violations than without. As implied by the well-known trigger bias effect, the overwhelming fraction of the very high p_T π^0 's corresponds to rather special fragmentation modes whereby a rather important fraction of the jet momentum is carried by the observed pion. Scaling violations make the effect less acute, hence the changing ratio from 2 to 10 previously mentioned. It should also be weaker than at ISR energies ($p_T < 10$ GeV/c) where the CIM contribution, which may provide a sizeable fraction of the single pion yield while giving a very small fraction of the jet yield, adds to the trigger bias effect. At $p_T \gg 10$ GeV/c, easily probed at the collider, the CIM contribution should be negligible. Comparing the pion yield in Fig. 5.1 to the global jet yield in Fig. 1.1 one finds a ratio of the order of 10^{-3} at 20 GeV/c, which hardly changes as one goes to 60 GeV/c. This may sound peculiar since the jet over pion ratio is known to increase with x_T where it has been measured, at Fermilab ²⁶⁾. What occurs is a compensating effect between the increase of the relative amount of quark jets, which are favoured by a single pion trigger as p_T increases and the decrease of the probability of producing a pion fragment as $z(x_T)$ increases.

The π^0 yield should be the average between the π^+ and π^- yields (equal for $p\bar{p}$ at 90° as a result of CP invariance). Measuring the π^0 yield it becomes, however, increasingly difficult to dissociate it from the single γ yield as p_T increases ²⁷⁾. Part of the latter comes from prompt γ production but part of it (an equal amount at 10-20 GeV/c) comes from quark bremsstrahlung. The γ/π^0 ratio increases with x_T . With full scaling violation (lower curve in Fig. 5.1) it is expected to exceed 1 at about 40 GeV/c to reach 2 at about 60 GeV/c.

Measurements of the π^0 (actually $\pi^0 + \gamma$)/ π^+ ratio as well as measurements of the π/jet ratio would provide tests of the present parametrization of scaling violations in the fragmentation functions.

We already mentioned that while the inclusion of scaling violations in the structure function was partly responsible for the large jet yield at 10-20 GeV/c, it was also much responsible for the rather fast fall-off with increasing p_T . This is also the case, and even more so, for single particle distributions. Triggering on a single particle emphasizes the large z contribution and this now corresponds to a decrease in yield as opposed to what is expected in the simple parton model. The simple π^0 yield obtained without any scaling violation (standard parton model) is indicated as a dashed curve on Fig. 5.1. While scaling violation effects are almost negligible at 10 GeV, one concludes with an order of magnitude difference at 50 GeV/c.

Another way to test scaling violations is to trigger on a π^+ (thus favouring the observation of a u quark jet in the first place) and analyze the nature of the recoiling jet together with its x_e dependence (the fraction of the trigger transverse momentum which it carries), as a function of recoil angle. Results are shown in Fig. 5.2.

Changes in the distribution as one moves from wide angles to forward angles correspond to the increasing role of valence quarks.

6. CONCLUSIONS

With the present confidence in leading log calculations, we conclude that the jet yield should be very sizeable at collider energies. Its actual value depends much, however, on the gluon distribution which is still, to say the least, uncertain. On the other hand, measurements of jet yields should, in comparison with our curves, provide conclusions about scaling violations, gluon effects and certainly about QCD assumptions about subprocesses. Once the important jet yield is ascertained many more detailed effects could be studied.

Even though we relied on QCD calculations which should apply only to p_T values greater than 10 GeV/c, there is no reason why the extrapolation of our curves to lower values of p_T (down to 2 GeV/c, say) should be utterly wrong. We have to face the fact that at collider energies large Q^2 can be associated with very low x values which make parton distributions particularly large. Even though individual cross-sections are low the parton flux is important and large effects result.

We have still very little knowledge of the parton distribution in this region. It seems, however, difficult to escape a rather large jet yield at medium p_T values by present standards ($p_T < 10 \text{ GeV}/c$) and such a process could correspond to a sizeable part of the cross-section. With fragmentation of the produced jets, one thus expects an increase in the mean value of the transverse momentum of secondaries, together with an increase of the particle yield at wide angle. It is then interesting to note that Cosmic Ray results from emulsion chambers at $E \sim 100 \text{ TeV}$ indicate the emergence of a new type of process whose characteristic features are similar to those expected from medium p_T jet production. The corresponding cross-section is comparable to that for configurations similar to those typically observed at the ISR. Rapidity correlation for such configurations should signal fluctuations associated with the production of jets.

Correlation measurements for jets and single particles at medium p_T should also give interesting information about the role of higher twist effects and in particular the presence of fusion processes $q\bar{q} \rightarrow MM$ which is unhampered.

Jet studies with very high event rates should be possible at collider energies. While they should eventually allow detailed studies of jet fragmentation, the mere measurement of jet yields should already give much information on the gluon structure of the proton.

REFERENCES

- 1) For general reviews of large p_T production and jet studies see:
D.I. Sivers, R. Blankenbecler and S.J. Brodsky, Phys. Rep. 23C (1976) 1;
S.D. Ellis and R. Stroynovski, Rev. Mod. Phys. 49 (1977) 753;
M. Jacob and P.V. Landshoff, Phys. Rep. 48 (1978) 285;
R. Stroynovski, QCD phenomenology of the large p_T processes, SLAC-PUB-2433 (1979).
- 2) Proc. Copenhagen meeting on "Jets in High Energy Collisions, Physica Scripta 19 (1979) 69.
- 3) M. Jacob "High p_T and jets", Rapporteur talk EPS Conference, Geneva (1979), CERN-TH. 2700.
- 4) Protons and antiprotons will be accelerated in the CERN SPS and the two beams will be held coasting at momenta up to 270 GeV/c. This will give collisions up to 540 GeV centre of mass energy. C. Rubbia, Invited talk EPS Conference, Geneva (1979).
The CERN project will be completed in 1981. The Fermilab Doubler, when completed could be used in a similar way as the SPS with coasting beams up to 1 TeV. The Isabelle machine is a dedicated pp collider with beam momentum up to 400 GeV.
In this paper we shall consider $\sqrt{s} = 540$ GeV as a typical collider energy.
- 5) For a review of anticipated $p\bar{p}$ physics at the ISR, see G. Giacomelli and M. Jacob, Phys. Rep. 55 (1979) 1. We consider $\sqrt{s} = 54$ GeV as a typical energy. It is the feeding energy at which the beam intensity can be gradually increased as new loads of antiprotons are injected.
- 6) H.D. Politzer, Phys. Rep. 14C (1974) 129;
W. Marciano and H. Pagels, Phys. Rep. 36C (1978) 137.
- 7) R.D. Field, Physica Scripta 19 (1979) 131;
J.F. Owens, Phys. Rev. D19 (1979) 3288.
- 8) For a recent and detailed review see:
J. Ellis and C. Sachrajda, Proceedings of the Cargèse Summer School (1979).
- 9) C. Sachrajda, Phys. Letters 76B (1978) 100.
- 10) W. Furmanski and S. Pokorski, preprint CERN-TH.2665, Nucl. Phys. to be published.
- 11) C. Quigg, Rev. Mod. Phys. 49 (1977) 287;
R.F. Peierls, T.L. Trueman and L.L. Wang, Phys. Rev. D16 (1977) 1397;
F.E. Paige, T.L. Trueman and T.N. Tudron, Phys. Rev. D19 (1979) 935.
- 12) F.E. Paige and J. Kubar André, Phys. Rev. D19 (1979) 1221.
- 13) Y. Fujimoto, Rapporteur talk, International Conference on cosmic rays Kyoto (1979) and Phys. Rev. to be published (1980).
- 14) R. Combridge, J. Kripfganz and J. Ranft, Phys. Letters 70B (1977) 234;
R. Cutter and D. Sivers, Phys. Rev. D16 (1977) 679, ibid. D17 (1978) 196.

- 15) R.P. Feynman, R.D. Field and G.C. Fox, Phys. Rev. D18 (1978) 3320.
- 16) R.D. Field and R.P. Feynman, Phys. Rev. D15 (1977) 2590;
R.P. Feynman, R.D. Field and G.C. Fox, Nucl. Phys. B128 (1977) 1.
- 17) R. Horgan and P.N. Scharbach, Phys. Letters 81B (1979) 215.
- 18) A.J. Buras and K.J. Gaemers, Nucl. Phys. B130 (1978) 249.
- 19) J.F. Owen, E. Reya and M. Gluck, Phys. Rev. D18 (1978) 1501.
- 20) S.J. Brodsky, Physica Scripta 19 (1979) 154.
- 21) A.P. Contogouris, S. Papadopoulos and M. Hongoh, Phys. Rev. D16 (1979) 2607.
- 22) R. P. Feynman and R. Field, Nucl. Phys. 136B (1977) 1.
- 23) J. Ellis, Weak interactions at high energies, SLAC-PUB-2177 (1978).
- 24) F. Dydak, Rapporteur talk, EPS Conference on High Energy Physics, Geneva (1979).
- 25) Yu.L. Dokshitzer, D.I. Dyakonov and S.I. Trojan, Hard processes in Quantum Chromodynamics, Physics Reports, to be published (1980).
- 26) C. Bromberg et al., Phys. Rev. Letters 42 (1979).
- 27) R. Horgan and P. Scharbach, to be published.

FIGURE CAPTIONS

- Fig. 1.1 : Anticipated jet yields at 90° in $p\bar{p}$ collisions at ISR energy ($\sqrt{s} = 54$ GeV) and at collider energy ($\sqrt{s} = 540$ GeV).
- Fig. 3.1 : a) Inclusive distributions for jet production in $p\bar{p}$ collisions at 90° at $\sqrt{s} = 540$ GeV. The letters g,u,d,s and c label distributions for gluon, u quark, d quark, s quark (with a SU(3) symmetric sea) and c quark (with no charmed quark in the sea), respectively.
b) Same distributions as in a) but for pp collisions. In this case the $\bar{u} \bar{d}$ and $\bar{s}$ jet yield are the same as the s jet yield.
- Fig. 3.2 : a) Inclusive distribution for jet production in $p\bar{p}$ collisions at 90° at $\sqrt{s} = 54$ GeV.
b) Same distributions as in a) but for pp collisions.
- Fig. 3.3 : a) Rapidity distributions for different types of jets in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. The jet yields are averaged over the interval 10-15 GeV/c.
b) Same as in a) but averaging over the interval 40-45 GeV/c.
- Fig. 3.4 : Angular distribution for inclusive jets at ISR energy ($\sqrt{s} = 54$ GeV). The distributions are averaged over the interval $12 < p_T < 13$ GeV/c. The distribution with respect to rapidity is equal to $\sin^2\theta$ times that with respect to $\cos\theta$.
- Fig. 3.5 : a) Two jet distributions in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. R refers to the angular distributions summed over the $60^\circ < \theta < 120^\circ$ range for two jets in an approximately back-to-back configuration at the same p_T . Shown are the dominant gg configuration and the $u\bar{u} u\bar{d}$ and $c\bar{c}$ ones. The corresponding contribution to $u\bar{u}$ and $u\bar{d}$ configurations from Z and W production, respectively, are also shown.
b) Same as a) for other jet-jet configurations, including prompt photon emitted at high p_T together with a quark jet or gluon jet.

- Fig. 4.1 : Inclusive production cross-section at 90° for $u(\bar{d})$ and $u(\bar{u})$ jets obtained from W^+ and Z^0 formation. They are presented against the inclusive cross-sections of Fig. 1.3a which correspond to perturbative QCD yields. The calculations correspond to $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV.
- Fig. 4.2 : a) Rapidity distribution for u jet corresponding to hadronic interactions (upper curve) and Z^0 formation (lower curve). The yields are integrated over a $5 \text{ GeV}/c$ p_T range centered on $M_Z/2$.
b) Same as a) but the lower curve now corresponds to W^+ formation and the yields are integrated over a $5 \text{ GeV}/c$ range centered on $M_W/2$.
c) Rapidity distribution for u jet corresponding to hadronic interactions (upper curve) Z^0 formation (solid lower curve) and W^+ formation (dashed lower curve). The yields are integrated over the $p_T = 12.5 \pm 2.5 \text{ GeV}/c$ interval.
- Fig. 4.3 : Differential cross-section for fixed jet-jet invariant mass
a) $u\bar{d}$ from hadronic interactions (upper curve) and W^+ formation (lower curve). The selected mass range covers the $72\text{--}84 \text{ GeV}$ interval.
b) $u\bar{u}$ from hadronic interactions (upper curve) and Z^0 formation (lower curve). The selected mass range covers the $82\text{--}94 \text{ GeV}$ interval.
- Fig. 5.1 : Inclusive π^0 production at 90° in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. The π^0 cross-section is calculated with full scaling violation (lower solid curve) and with scaling violation in the $p(\bar{p})$ structure functions only (upper solid curve). The cross-section which would result from the standard parton model is plotted as a dashed curve. The prompt γ production is indicated as a dot-dashed curve.
- Fig. 5.2 : Jet distributions in cone 3 (upper) and cone 2 (lower) when a trigger with $20 < p_T < 25 \text{ GeV}/c$ is imposed in cone 1. The jet momentum is equal to X_e times that of the trigger momentum.

FIG. 1.1

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FIG. 3.1

FIG. 3.2

FIG. 3.2

FIG. 3.3

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FIG. 3.5

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FIG. 5.1

FIG.5.2