1. JET PHYSICS AT TEVATRON II

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1.1 Theoretical Introduction and Overview

It has now been several years since the first evidence for high-p_T jet production was obtained in a series of high-p_T experiments performed at the ISR using a single particle trigger with awayside particle detection. More recently, calorimeter experiments at Fermilab have also found evidence for jet structure in high-p_T events; however, at this point there is still some controversy concerning the question of whether or not jets have indeed been observed in high-p_T experiments. This situation stems from the fact that jets in high-p_T collisions tend to be obscured by the presence of fragments from the beam and target jets. Furthermore, experience at SPEAR and PETRA has shown that jets do not show a clearly defined structure until jet energies on the order of 6-8 GeV are reached. These two facts suggest that unambiguous jet structure in high-p_T events should be observed in the region $p_T \gtrsim$ 8-10 GeV/c. Note, however, that useful jet physics can still be performed at lower values of p_T, although the analysis will be more difficult from both the theoretical and experimental viewpoints.

The theoretical importance of jets should, by now, be well known. At very high p_T and $(s)^{1/2}$ it is widely believed that $2\to2$ parton scattering subprocesses, as predicted by QCD, are dominantly resonsible for the particle production cross section. This belief is supported by a large number of successful QCD-motivated predictions for particle p_T spectra. This same picture predicts that the particles came from jets; if jets are in fact not present at the predicted level, then the picture is wrong.

There are two topics in current theoretical thinking that may cause some difficulty for the above simple picture: higher-twist effects and higher-order QCD corrections. In very simple terms higher-twist refers to contributions which are suppressed by powers of p_T^2 ($\sim Q^2$) relative to the leading QCD subprocesses that ultimately dominate at sufficiently large p_T values. These effects result from higher order diagrams involving bound states, e.g., $qg \to Mq$, where M denotes a meson. Clearly one should be able to avoid these effects by going to large p_T values. Current analyses suggest that in the case of single-particle production $p_T \gtrsim$ 6-8 GeV at $(s)^{1/2} \gtrsim 30$ GeV should be sufficient.

The situation concerning higher-order corrections is somewhat ambiguous at the moment. Two recent calculations for high-p_T particle[1] and jet[2] production based on only the quark-quark scattering subprocess suggest that there are large corrections at all values of p_T. Typically a multiplicative correction factor of about 2.5 is found. However, this calculation has been criticized on technical grounds and arguments have been suggested that may reduce the size of the correction term. For example, the two-loop corrections to the running coupling constant were not included and this alone causes a reduction in the correction factor. Furthermore, the choice of the momentum space subtraction scheme instead of the $\overline{MS}$ scheme causes an additional reduction as does the modification of the Q^2 definition and the choice of the mass scale at which point the distribution and fragmentation factorization is performed. All of these effects taken together may reduce the correction factor to the range of 1.2–1.4. In his review talk at the 1980 Madison Conference, C. Llewellyn-Smith remarked that in 14 out of 15 processes studied the QCD perturbation series appeared to be converging. The sole exception was the high-p_T calculation and the discussion presented at that time indicated that one could be cautiously optimistic that here too the perturbation series would be shown to be under control.

Based on the arguments given above it is reasonable to assume that the study of high-p_T jet physics in the Tevatron energy range will provide valuable information concerning the underlying production mechanisms. The remainder of this section will be devoted to a brief summary of what may be learned from the various types of reactions which can be measured at the Tevatron. Particular emphasis will be placed on those reactions which can best be studied at a 1-TeV fixed-target facility. Mention will also be made of several novel cases for jets that may be of interest at collider energies, but which appear to be impractical for Tevatron II.

1.2 Hadron Production of Jets

The main theoretical motivation for studying jets was mentioned above and it has been thoroughly discussed in the literature. It should be sufficient here to note that much valuable information can be obtained by varying the beam particle type (π, K, p). This option is unique to Tevatron II in this energy range.

1.3 Direct Photon Production

The pointlike coupling of photons to quarks makes it a very useful probe of strong-interaction dynamics at the parton level. In the case of direct photon production, the theoretical situation is greatly simplified since there are only two subprocesses in lowest order: $q\bar{q} \to \gamma g$ and $qg \to \gamma q$. This simplicity results in theoretically cleaner predictions and also gives rise to a wide variety of interesting measurements that can be made by varying the beam type.[3] Note that for this process the next-to-leading corrections from $qq \to qq\gamma$ have been calculated[4] and are of the order of 10% if the colinear bremmstrahlung photons are removed (they are of order 30%-50%). This latter point means that we are considering **direct** photons, i.e., photons produced without any accompanying hadrons nearby in phase space.

In order to make maximum use of the theoretical simplicity of direct photon production it is necessary to be able to detect the awayside jet. If this is done and if π, K, and p beams are used, then it is possible to separately obtain information on the quark and gluon distributions in the beam and target hadrons. Note that the coupling of the photon to the quark's charge together with the presence of only two types of diagrams combine to make the separate quark and gluon measurements possible.

If one also has particle identification (or just charge identification) for the awayside jet, then it becomes possible to separately determine quark and gluon fragmentation functions. This process provides an excellent tool for studying the properties of gluon jets.

It is not an exaggeration to suggest that direct photons measured in conjunction with an awayside spectrometer may be one of the most versatile tools at our disposal for studying both the parton structure of mesons as well as the structure of jets themselves.

1.4 High-p_T Photoproduction

The many advantages of using photon beams for high-p_T experiments have not received the recognition that is desirable. This is reflected by a regretable lack of high-p_T photoproduction experiments both here and at CERN. Fermilab has a unique opportunity to utilize Tevatron II to obtain the world's highest energy photon beam which will, in turn, make possible a wide variety of worthwhile experiments.

As in the previous discussion, the point-like coupling of the photon greatly simplifies the theoretical situation at high-p_T. There are two basic processes involving the direct coupling of the photon: $\gamma g \rightarrow q\bar{q}$ and $\gamma q \rightarrow gq$. These are exactly analogous to the subprocesses giving rise to direct γ production at high-p_T. The events arising from these two subprocesses have a three-jet topology--two high-p_T jets and one target jet. Since the beam interacts directly in the subprocess, there is no jet of beam fragments.

By now it is well known that the photon can also interact with partons by first creating a $q\bar{q}$ pair which, in turn, can emit gluons, etc. These distribution functions for quarks and gluons in the photon can be calculated using QCD. The partons from the photon interact with the target partons, according to all of the usual QCD subprocesses and, therefore, these events look like the typical four-jet hadron initiated events, two high-p_T jets together with both beam and target jets.

Finally, a third class of interactions consists of vector dominance events. Here the photon interacts as if it were a vector meson (dominantly a ρ^0) and the events have the typical four-jet configuration. Since the parton distributions in a ρ^0 fall off as powers of $(1 - x)$ these terms have a more rapid fall off in p_T than the three-jet events. In the latter case the photon contributes all of its energy to the subprocesses and therefore more easily gives rise to high-p_T jets. Note here that the quark distribution in a photon is relatively flat in x so that the four-jet events don't fall off in p_T as fast as the vector dominance events, but they do fall off faster than the three-jet events. Typically one expects at $(s)^{1/2}$ = 20 GeV and y = 0 that the vector dominance background is negligible above about 4 GeV and that above 6 GeV only the three-jet events remain.

It is interesting to note that if one can identify both the recoil and the trigger jet, then the three-jet events can be separated kinematically. This is because the awayside jet rapidity in the three-jet events is fixed once the trigger rapidity is specified. Details of this as well as all the other points discussed above may be found in Ref. 5.

In some ways it may turn out that jet physics will be easier with photon beams than with hadron beams. At high-p_T values where the three-jet events dominate, the absence of the beam jet fragments should make the separation and identification of the high-p_T jets less ambiguous. Furthermore, as discussed above, the photon deposits all of its energy into the subprocess in this type of event. This means that photons are relatively more efficient than hadrons for producing high-p_T jets. This fact more than makes up for the factor of α coming from the electromagnetic coupling of the photon to the quarks.

In summary, jet photoproduction at high-p_T has the following advantages:

- absence of beam jet fragments makes the analysis cleaner;

- the cross section exceeds the hadronic cross section for $p_T > 6$ GeV at $(s)^{1/2}$ = 20 GeV;

- the process is theoretically simple so that the predictions can be placed on a firmer basis.

1.5 Dilepton Triggers

Dilepton production by the Drell-Yan process and the production of heavy quark bound states have provided much information about the underlying parton interactions. At high-p_T values additional information can be obtained by studying the recoiling system. In QCD it is expected that this will be either a quark or gluon jet; therefore, a large jet detection capability would be able to provide valuable new tests of the current models for both of these processes. This type of experiment need not be limited to hadron beams as a recent calculation[6] of high-p_T J/ψ photoproduction (p_T 1 GeV) suggests that this process may be a useful source of gluon jets. The problems of a joint dilepton plus jet detector will be discussed later on in this report.

1.6 Effects of Polarization

Both polarized hadron beams and targets will be discussed in detail in a separate report; however, a few theoretical comments may be in order. Lowest order QCD with massless quarks predicts[7] zero for all single spin asymmetry measurements. In this regard, the large polarization observed in $pp \rightarrow \Lambda + X$ for $p_T < 2$ GeV will become troublesome if it doesn't become small again at higher p_T values. On the other hand, QCD does predict some non-zero (typically ~10%) two spin asymmetries and these can be looked for in high-p_T particle and/or jet measurements, and interpreted in terms of our knowledge of polarized quarks in polarized hadrons. Historically spin measurements have always placed stringent constraints on theoretical models and there is every expectation that this will continue to be the case.

Additional consideration should be given to the construction of a polarized photon beam at Fermilab. A recent calculation[8] has shown that there is a large linearly polarized photon asymmetry predicted by QCD for the production of charm. This asymmetry is large (~-30%) for vector gluons), it peaks where the cross section peaks in rapidity, and it is nearly constant in magnitude (at the peak) with variations in energy. Furthermore, for scalar or pseudoscalar gluons it is predicted to be ~60% or 0%, respectively. The observation of this asymmetry at the predicted level would be a striking confirmation of our current theoretical ideas concerning the use of perturbative QCD.

1.7 Nuclear Effects

The use of various nuclear targets can provide useful information concerning the space-time development of high-p_T interactions by, roughly speaking, varying the size of the interaction region. A recent theoretical analysis[9] has suggested that the use of a nuclear target should enhance the percentage of gluon jets through a multiple scattering mechanism. Interesting information could also be gained by comparing the A dependence of both $\mu^+\mu^-$ production and direct γ production--the simplest arguments say that in both cases the cross section should go as A^α with $\alpha = 1$. The same argument says that high-p_T jet photoproduction should also have $\alpha = 1$, but the mechanism of Ref. 8 may result in deviations from this. Both the p_T and x_F dependence of α should be explored in high-p_T photo- and hadroproduction as well as the dependence of α on Q^2 in $\mu^+\mu^-$ production.

1.8 New Uses for Jets

In a rather speculative vein it is interesting to contemplate whether or not jets (or jet detectors) can be used as a tool for searching for new effects in high-p_T collisions. For example, multijet final states could signal the production of heavy flavors and effective masses calculated using jets could be useful in searches for new heavy states; however, we have found that unfortunately all such schemes suffer from essentially the same problems at current energies, namely that the jets are just not sufficiently well defined to provide a reliable technique for effective mass determinations. Smearing introduced by missing one or more soft particles gives rise to an unacceptably large mass resolution. Furthermore, multijet signals can hardly be used to search for new types of final states if the jets can not be well defined. (This problem has already been observed in $e^+e^- \to \gamma \to 3g$ where the gluon jets are not clearly defined.) On an optimistic note, however, it should be pointed out that these problems decrease with energy (nonperturbative jet angular widths decrease as $\langle k_T \rangle / E$) so that techniques of the type discussed above may prove to be useful at collider energies [$(s)^{1/2} \sim 10^2 - 10^3$ GeV).

An example of a reaction where jet detection may be useful is

$$pp \to W^{\pm} + \text{jet} + X. \\ \hookrightarrow \mu \pm \nu$$

The conventional idea is to look for the Jacobian peak in the μ^+ distribution which sets in at $p_T = m_W/2$; however, this peak will be strongly smeared if the $W^{\pm}$ is produced with a large p_T. This is precisely what is expected in QCD where the $W^{\pm}$ will be recoiling against a quark or gluon jet. If this jet is detected in an awayside spectrometer, then the μ spectrum can be corrected for the transverse smearing, thereby aiding in the unfolding of the Jacobian peak. Furthermore, it should also be possible to detect two jets resulting from the hadronic $W^{\pm}$ decays and to see the $W^{\pm}$ in a two-jet effective mass plot.

The above discussion is meant to provide a brief theoretical overview of the type of jet physics that we anticipate can be done at Tevatron II. The remainder of the report will be devoted to experimental consideration of these topics.

References

The following list of references is neither complete nor comprehensive. It is hoped that it will serve as a useful guide to the available literature. Additional references are contained in the papers listed here.

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