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High-Mass Multijet Events at the Fermilab Proton-Antiproton Collider

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Invited Talk at the *XIth Topical Workshop on ppbar Collider Physics*,
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The properties of high-mass multijet events produced at the Fermilab proton-antiproton collider are compared with leading order QCD matrix element predictions, QCD parton shower Monte Carlo predictions, and the predictions from a model in which events are distributed uniformly over the available multibody phase-space. Multijet distributions corresponding to (4N-4) variables that span the N-body parameter space are found to be well described by the QCD calculations for inclusive three-, four-, and five-jet events. The agreement between data, QCD matrix element calculations, and QCD parton shower Monte Carlo predictions suggests that $2 \rightarrow 2$ scattering plus gluon radiation provides a good first approximation to the full LO QCD matrix element for events with three, four, or even five jets.

1 Introduction

Large samples of events containing two or more jets have recently been recorded with the Collider Detector at Fermilab (CDF). A comprehensive analysis of these multijet events would provide an interesting test of perturbative QCD. A detailed understanding of the properties of multijet events produced in high energy hadron-hadron collisions is also important because (i) detailed studies of multijet events enable a search for new phenomena associated with the presence of many final jets, and (ii) the QCD production of multijet events is an important source of background to many more exotic processes. LO matrix element calculations have been performed for $2 \rightarrow N$ scattering with N up to 5, however as N increases the calculations rapidly become complicated and require large CPU resources. One approach we often take is a parton shower Mote Carlo, hence we would also like to see how good an approximation to the full $2 \rightarrow N$ LO matrix element is provided by a parton shower Monte Carlo.

The first step along these lines was made by the CDF collaboration using a data sample containing high-mass multijet events corresponding to an integrated luminosity of ~ 35 pb^{-1} [1]. In that analysis characteristics of multijet events with multijet masses exceeding 600 GeV/c^2 and with up to 6 jets have been compared with (1) LO QCD matrix element calculations (NJETS) and (2) QCD parton shower Monte Carlo calculations (HERWIG). The distributions of the multijet mass, the leading-jet scattering angle, and the mass dependent jet multiplicity were shown to be well described by NJETS for events with up to 5 jets and by HERWIG for events with up to 6 jets.

In the present paper we use a larger data sample and a more comprehensive set of multijet distributions to extend our comparison of the properties of high-mass multijet events with QCD predictions. In particular, we use the set of (4N-4) variables that span the N-jet parameter space and compare the observed three-, four-, and five-jet event characteristics with (a) NJETS LO QCD matrix element predictions, (b) HERWIG parton shower Monte Carlo predictions, and (c) predictions from a model in which events are uniformly distributed over the available multijet phase-space. The NJETS Monte Carlo program [2] provides parton-level predictions based on the LO QCD $2 \rightarrow N$ matrix elements. We have used the KMRSD0 structure function [3] with the renormalization scale chosen to be the average p_T of the outgoing partons. HERWIG [4] is a QCD parton shower Monte Carlo program that includes both initial- and final-state gluon radiation. HERWIG predictions can be thought of as QCD $2 \rightarrow 2$ predictions with gluon radiation, color coherence, hadronization, and an underlying event. We have used version 5.6 of the HERWIG Monte Carlo program together with a simulation of the CDF detector response. In our HERWIG calculations we have used the CTEQ1M [5] structure functions and the scale $Q^2 = stu/2(s^2+u^2+t^2)$. The phase-space Monte Carlo events were generated with single-jet masses and a multijet mass distributed according to the corresponding distributions predicted by HERWIG. Comparisons between the phase-space distributions and the corresponding HERWIG and NJETS Monte Carlo distributions help us to understand which multijet parameters are most sensitive to the behaviour of QCD multijet matrix elements.

2 CDF Multijet Data Sample

A description of the CDF detector can be found in Ref. [6]. Full details of the CDF jet algorithm and jet corrections can be found in Ref. [7]. A description of the trigger and event selection requirements for the high-mass multijet sample are given in Ref. [1]. Results are based on a data sample which was recorded by the CDF collaboration during the period 1992 - 1995, and corresponds to an integrated luminosity of 105 pb^{-1}. The CDF multijet sample is obtained by selecting events with $\sum E_T > 420$ GeV where the sum is over all the jets in the event with $E_T > 20$ GeV and with $|\eta| < 3.0$ reconstructed with the CDF jet clustering algorithm using a cone size of $R = 0.7$. In order to use events with well measured jets, we have set the minimum separation between all jets in η-ϕ space to be 0.9.

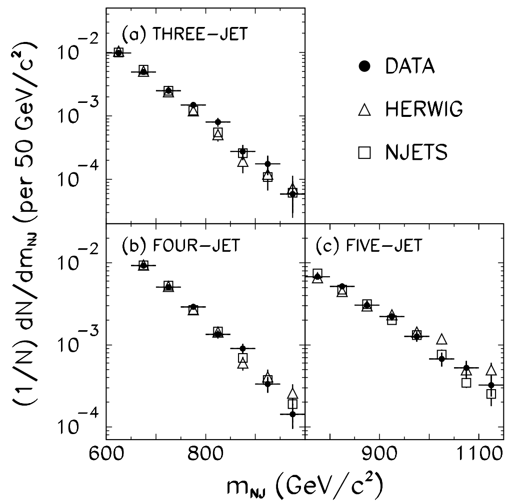

Figure 1: Multijet mass distributions: (a) three-jet events, (b) four-jet events, and (c) five-jet events.

3 Multijet Analysis

To completely specify a system of N jets in the N-jet rest-frame we require (4N-3) independent parameters. However, the N-jet system can be rotated about the beam direction without losing any interesting information. Hence we need only specify (4N-4) parameters. We will use the N-jet mass (m_{NJ}) and the (4N-5) dimensionless variables introduced and discussed in Ref. [8]. The variables are defined by first of all reducing N-jet system to a three-body system by combining pairs of bodies with the lowest two-body mass. Using the resulting three bodies we define seven dimensionless variables to describe the three-body system. We also need to define additional four variables to describe each of two-body system in which we combined two bodies. We begin by comparing the observed multijet mass distributions with QCD predictions. Following that distributions of the new set of three-, four-, and five-jet variables will be compared with QCD predictions and phase-space model predictions.

Shown in Fig.s 1(a)-(c) are multijet mass distributions for three-, four-, and five-jet inclusive events compared with QCD predictions. NJETS and HERWIG are shown to give a good description of the shapes of the multijet mass distributions.

Consider the three-jet case. The outgoing three jets are ordered such that $E_3 > E_4 > E_5$, where E_i is the energy of object i in the three-jet rest frame. The three-jet variables are then chosen to be Dalitz variables (X_3 and X_4, where $X_i \equiv \frac{2E_i}{m_{3J}}$), the cosine of the polar angle of the leading jet with respect to the average beam direction ($\cos\theta_3$), the angle between the plane containing the average beam direction and the leading jet and the three-body plane (ψ_3, where all of three-jets are contained in a plane if $\psi_3 = 0$ or π.), and mass fractions of outgoing jets (f_3, f_4, and f_5, where $f_i \equiv \frac{m_i}{m_{3J}}$ and m_i is the mass of object i). We have applied the requirements of $m_{3J} > 600$ GeV/c^2, $|\cos\theta_3| < 0.6$, and $X_3 < 0.9$ to restrict the three-jet parameter space into the region for which the $\sum E_T$ requirement is efficient and jets are well measured. The observed X_3 and X_4 distributions are compared with QCD and phase-space model predictions in Fig.s 2(a) and (b). Both HERWIG and NJETS predictions well describe the observed distributions. Note that the observed distributions are not very different from the phase-space model predictions. The observed $\cos\theta_3$ and ψ_3 distributions are shown to be compared with predictions in Fig.s 2(c) and (d). QCD predictions give a reasonable description of the observed angular distributions, which are very different from the phase-space model predictions. Shown in Fig. 3(i) are the f_i ($i = 3, 4, 5$) distributions compared with the HERWIG predictions. There is no NJETS prediction for single-jet masses because NJETS does not use a parton fragmentation model. HERWIG predictions are seen slightly to overestimate the observed event rates at the low f_i regions.

Consider next the four-jet case. We combine the two jets A and B with the lowest two-jet mass, where $E_A > E_B$. The resulting three bodies are ordered such that $E_{3'} > E_{4'} > E_{5'}$. Then we define the three-body system using the three-jet variables $X_{3'}$, $X_{4'}$, $\cos\theta_{3'}$, $\psi_{3'}$, and $f_{i'}$ ($i' = 3', 4', 5'$). After applying the requirements of $m_{4J} > 650$ GeV/c^2, $|\cos\theta_{3'}| < 0.8$, and $X_{3'} < 0.9$, the observed distributions for these variables are compared with predictions in Fig.s 4(a)-(d) and Fig. 3(ii). HERWIG and NJETS give a reasonable description of the observed four-jet three-body distributions. In Fig. 3(ii), although the NJETS calculations do not provide predictions for the single-jet part of the $f_{j'}$ distributions, they are seen to correctly predict the tails associated with two-jet systems. We now define the two-body (AB)-system with the following four additional variables: the energy fraction taken by jet A ($X_A \equiv \frac{E_A}{E_A+E_B}$), the angle between the plane containing jet A and B and the plane containing the (AB)-system and the average beam direction (ψ'_{AB}), and mass fractions (f_A and f_B). Shown in Fig.s 5(a)-(d) are distributions for these variables, which specify the two-body (AB)-system. Again both the QCD predictions give a reasonable description of the observed distributions.

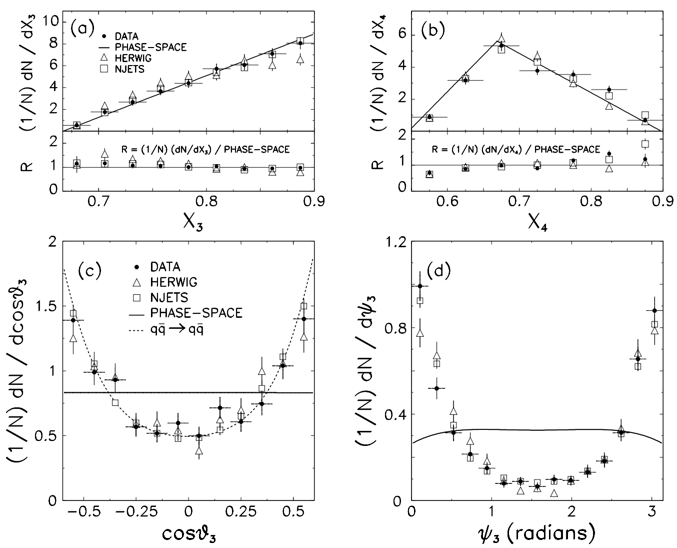

Figure 2: Three-jet results: (a) X_3, (b) X_4, (c) $\cos\theta_3$, and (d) ψ_3.

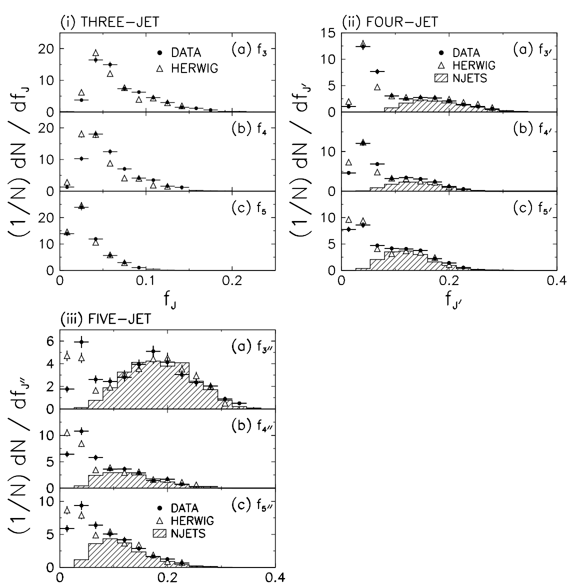

Figure 3: Three-body mass fraction distributions: (i) three-jet events, (ii) four-jet events, and (iii) five-jet events.

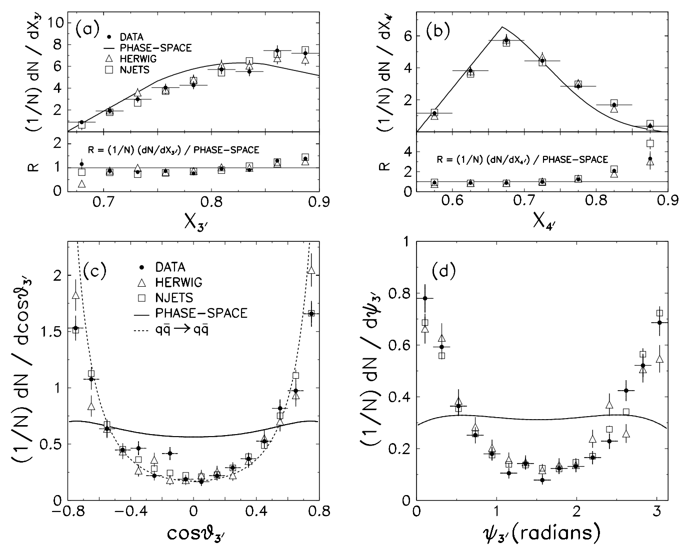

Figure 4: Four-jet results: (a) $X_{3'}$, (b) $X_{4'}$, (c) $\cos\theta_{3'}$, and (d) $\psi_{3'}$.

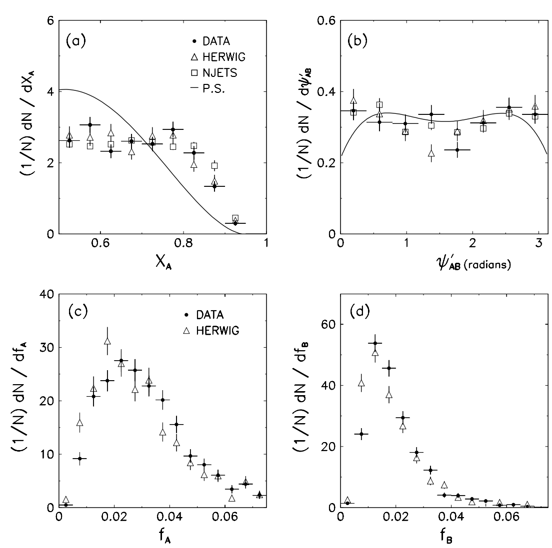

Figure 5: Four-jet distributions for the two-jet (AB)-system: (a) X_A, (b) ψ'_{AB}, (c) f_A, and (d) f_B.

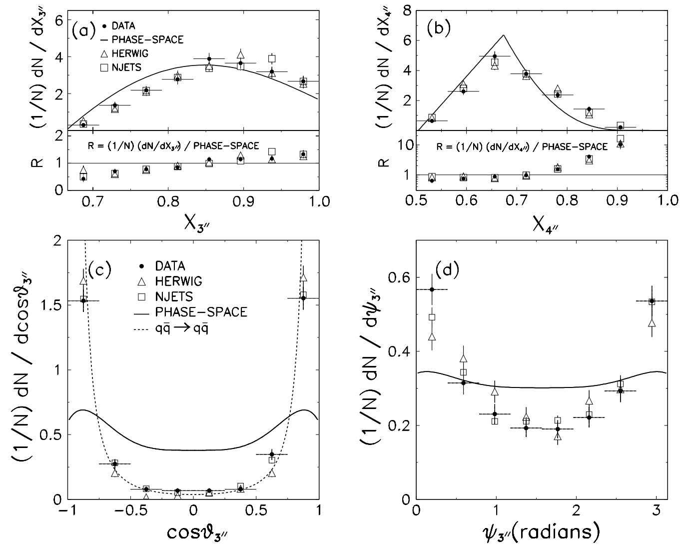

Figure 6: Five-jet results: (a) $X_{3''}$, (b) $X_{4''}$, (c) $\cos\theta_{3''}$, and (d) $\psi_{3''}$.

Consider finally the five-jet case. We begin by combining the two jets C and D with the lowest two-jet mass to obtain a four-body system, where $E_C > E_D$. We can then reduce this system to a three-body system by combining two bodies A′ and B′ with the lowest two-body mass, where $E_{A'} > E_{B'}$. The resulting three bodies are ordered such that $E_{3''} > E_{4''} > E_{5''}$. The three-body system is then described using the three-jet variables $X_{3''}$, $X_{4''}$, $\cos\theta_{3''}$, $\psi_{3''}$, and $f_{i''}$ ($i'' = 3'', 4'', 5''$). After applying the requirement of $m_{5J} > 750$ GeV/c^2, the observed distributions for these variables are compared with predictions in Fig.s 6(a)-(d) and Fig. 3(iii). We now define four variables to describe the two-body (A′B′)-system and four variables to describe the two-body (CD)-system. These variables are chosen to be $X_{A'}$, $\psi''_{A'B'}$, $f_{A'}$, and $f_{B'}$ for the (A′B′)-system, and X_C, ψ''_{CD}, f_C, and f_D for the (CD)-system respectively. The observed distributions for these variables are shown in Fig.s 7(a)-(d) for the (A′B′)-system and Fig.s 8(a)-(d) for the (CD)-system. Again both the QCD predictions give a good first description of the observed distributions for these variables.

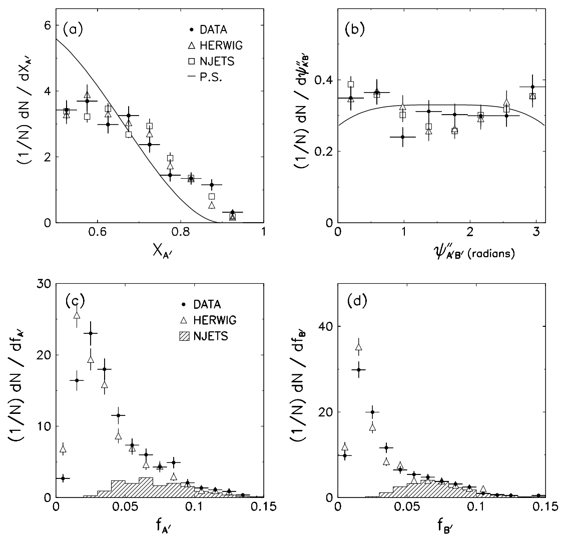

Figure 7: Five-jet distributions for the two-body (A′B′)-system: (a) $X_{A'}$, (b) $\psi''_{A'B'}$, (c) $f_{A'}$, and (d) $f_{B'}$.

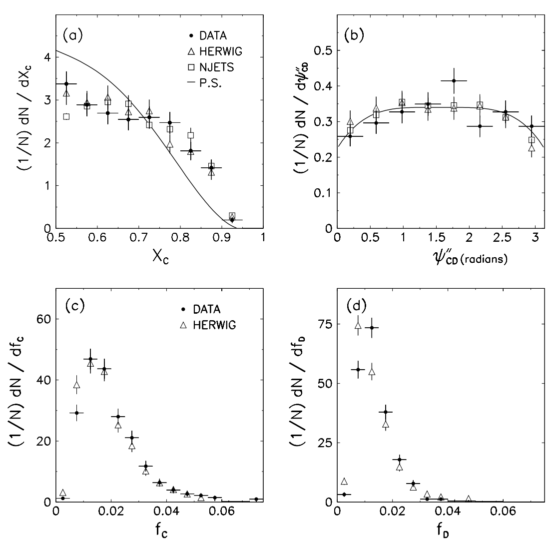

Figure 8: Five-jet distributions for the two-body (CD)-system: (a) X_C, (b) ψ''_{CD}, (c) f_C, and (d) f_D.

4 Conclusions

The properties of high-mass three-, four-, and five-jet events produced at the Fermilab Tevatron proton-antiproton collider have been compared with NJETS LO QCD matrix element predictions, HERWIG QCD parton shower Monte Carlo predictions, and predictions from a model in which events are distributed uniformly over the available multibody phase-space. The phase-space model is unable to describe the shapes of multijet distributions in regions of parameter space where the QCD calculations predict large contributions from initial- and final-state gluon radiation. In contrast, the QCD predictions give a good first description of the observed multijet distributions, which correspond to (4N-4) variables that span the N-body parameter space. We do not see clear evidence for any deviation from the predicted multijet distributions that might indicate new phenomena associated with the presence of many hard partons in the final state. The general agreement between data, NJETS, and HERWIG suggests that $2 \rightarrow 2$ scattering plus gluon radiation provides a good first approximation to the full LO QCD matrix element for events with three, four, or even five jets in the final state.

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References

1. F. Abe et al. (CDF Collaboration), *Phys. Rev. Lett.* **75**, 608 (1995).
2. F.A. Berends, W. Giele, and H. Kuijf, *Nucl. Phys.* **B333**, 120 (1990); F.A. Berends, W. Giele, and H. Kuijf, *Phys. Lett.* **232B**, 266 (1990); F.A. Berends and H. Kuijf, *Nucl. Phys.* **B353**, 59 (1991).
3. A.D. Martin, R.G. Roberts, W.J. Stirling; *Phys. Lett.* **306B**, 145 (1993).
4. G. Marchesini, B.R. Webber, G. Abbiendi, I.G. Knowles, M.H. Seymour and L. Stanco, *Comput. Phys. Commun.* **67**, 465 (1992).
5. H.L. Lai et al; Preprint MSU-HEP-41024, CTEQ-404, (to be published).
6. F. Abe et al. (CDF Collaboration), *Nucl. Instr. and Meth.* **A271**, 387 (1988).
7. F. Abe et al. (CDF Collaboration), *Phys. Rev.* **D45**, 1448 (1992).
8. S. Geer and T. Asakawa, *Phys. Rev.* **D53**, 4793 (1996).
9. CERN Program Library Manual 1989.10.03, Routine W515, p. 6.503.