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The characteristics of three-jet, four-jet, and five-jet events observed by the CDF and D0 experiments at the Fermilab Tevatron $\overline{p}p$ collider are compared with leading order QCD matrix element predictions, and with the predictions from a parton shower Monte Carlo program.

INTRODUCTION

Within the framework of leading order (LO) perturbative QCD, multijet events produced in high energy proton-antiproton collisions arise from hard parton-parton scattering in which the outgoing quarks or gluons have a significant component of momentum transverse to the beam direction (p_T). The LO QCD predictions for the rate and characteristics of events with n jets in the final state require calculations at order α_S^n. The LO $2 \rightarrow n$ matrix elements, which have been calculated for topologies with up to 5 final state jets, are embodied in the NJETS (1) Monte Carlo program. In the following CDF and D0 measurements are compared with QCD predictions from NJETS and from the QCD parton shower Monte Carlo program HERWIG (2), which can crudely be thought of as providing predictions based on $2 \rightarrow 2$ scattering plus gluon radiation.

In the multijet analyses described in this paper, both CDF and D0 use a cone algorithm to reconstruct jets, with a cone of radius $R = 0.7$ where R is defined in (pseudorapidity, azimuthal-angle)-space by $R^2 \equiv (\Delta\eta^2 + \Delta\phi^2)$. Jets are required to have transverse energies in excess of 20 GeV. Although the CDF and D0 collaborations use similar jet definitions, the multijet selection criteria are very different. The CDF multijet sample is obtained by selecting events with $\sum E_T > 420$ GeV where the sum is over all jets in the event, and the total data sample corresponds to an integrated luminosity of about 70 pb^{-1}. The D0 sample is obtained by requiring at least one jet with $E_T > 60$ GeV, which is recorded with a trigger which is necessarily prescaled by a significant factor, and hence corresponds to relatively small integrated luminosity, about 1.5 pb^{-1}. With these event selection criteria the D0 multijet events have multijet mass m typically around 200 GeV, whereas the CDF analysis focuses on the highest mass multijet events with m typically greater than 500 GeV or more.

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PUBLISHED RESULTS

Before describing new results from CDF and D0, we summarize results from previous multijet analyses at the Fermilab collider. In 1992 CDF published an analysis of three-jet events (3) based on a $4pb^{-1}$ data sample. For this analysis the three-jet mass was required to be > 250 GeV. The observed three-jet distributions for the traditional three-jet variables first introduced by UA1 (4) and described below were found to be well described by the LO QCD predictions. In 1992 CDF also published a comparison of the properties of multijet events with the HERWIG parton shower Monte Carlo predictions, for a data sample with multijet masses of typically 500 GeV (5). The QCD predictions gave a good description of the characteristics of this data sample, suggesting that to a first approximation multijet production can be modelled as $2 \rightarrow 2$ scattering plus gluon radiation. More detailed CDF four-jet results (6) for events with lower multijet masses were published in 1993 for a data sample selected by requiring $\sum p_T > 140$ GeV, where the sum is over the 4 jets. These results showed that the basic characteristics of the events are well described by LO QCD predictions, with room for a small contribution from double parton scattering. Finally, CDF has recently published (7) a comparison of observed multijet distributions with HERWIG and NJETS predictions based on a data sample of $35pb^{-1}$ for multijet events with masses exceeding 600 GeV. In particular for two–jet, three-jet, four-jet, five-jet, and six-jet events the QCD predictions have been shown to give good descriptions of the multijet mass distributions, the leading-jet angular distributions, and the jet multiplicity distribution. There is some discrepancy between the HERWIG and NJETS predictions for the jet-p_T distributions for three- and four-jet events, the data favoring the NJETS predictions.

NEW CDF AND D0 THREE-JET RESULTS

To completely describe a system of 3 massless particles in the three-body rest-frame we must specify the three-body mass plus four additional variables. It is traditional to label the outgoing jets 3, 4, and 5, and order the jets such that $E_3 > E_4 > E_5$, where E_j is the energy of jet j in the three-jet rest-frame. The three-jet variables are then chosen to be:

(i) X_3, the leading jet energy fraction, defined by:

$$X_j \equiv \frac{2\, E_j}{E_3 + E_4 + E_5} \,, \tag{1}$$

(ii) X_4, the next-to-leading jet energy fraction,

(iii) $\cos\theta_3^\star$, the cosine of the leading jet scattering angle:

$$\cos\theta_3^\star \equiv \frac{\overrightarrow{P}_{AV} \cdot \overrightarrow{P}_3}{|\, \overrightarrow{P}_{AV} \,||\, \overrightarrow{P}_3 \,|} \,, \tag{2}$$

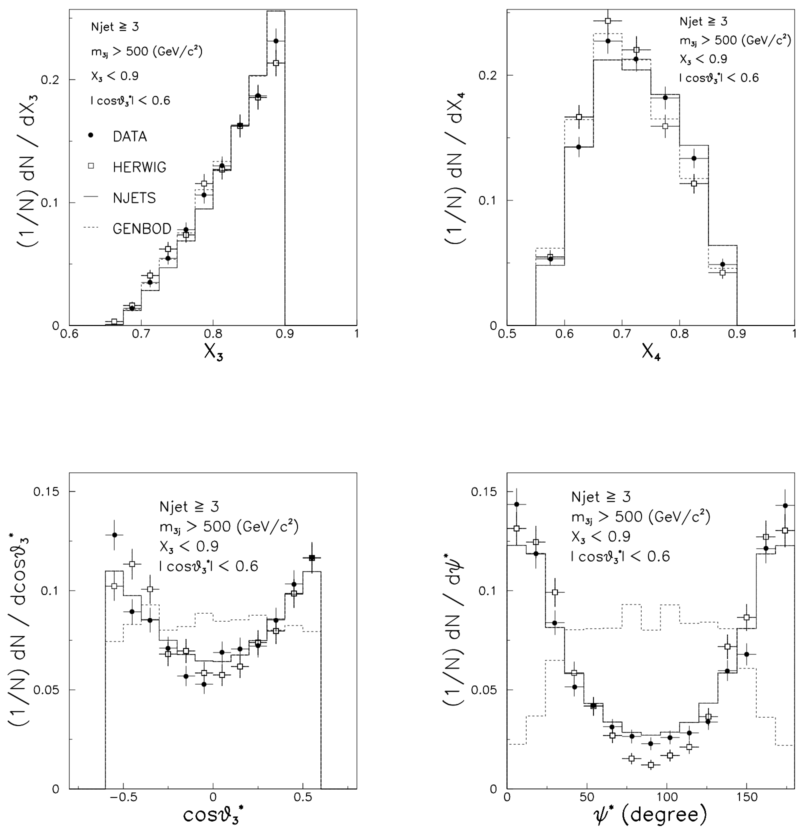

FIG. 1. Preliminary CDF distributions (points) for traditional three-jet variables compared with LO QCD predictions (histogram), parton shower Monte Carlo predictions (open circles), and three-body phase space predictions (broken histogram).

(iv) $\psi^\star$, the angle between the three-jet plane and the plane containing jet 3 (the leading jet) and the average beam direction:

$$\cos\psi^\star \equiv \frac{(\overrightarrow{P}_3 \times \overrightarrow{P}_{AV}) \cdot (\overrightarrow{P}_4 \times \overrightarrow{P}_5)}{\mid \overrightarrow{P}_3 \times \overrightarrow{P}_{AV} \mid\mid \overrightarrow{P}_4 \times \overrightarrow{P}_5 \mid}, \tag{3}$$

where P_{AV} is the average beam direction in the three-jet rest-frame.

The observed CDF and D0 three-jet distributions are shown respectively in Figs. 1 and 2. All distributions are reasonable well described by the NJETS predictions, although there is some indication in the CDF $\psi^\star$-distribution that the observed three-jet events tend to be slightly more planar than the

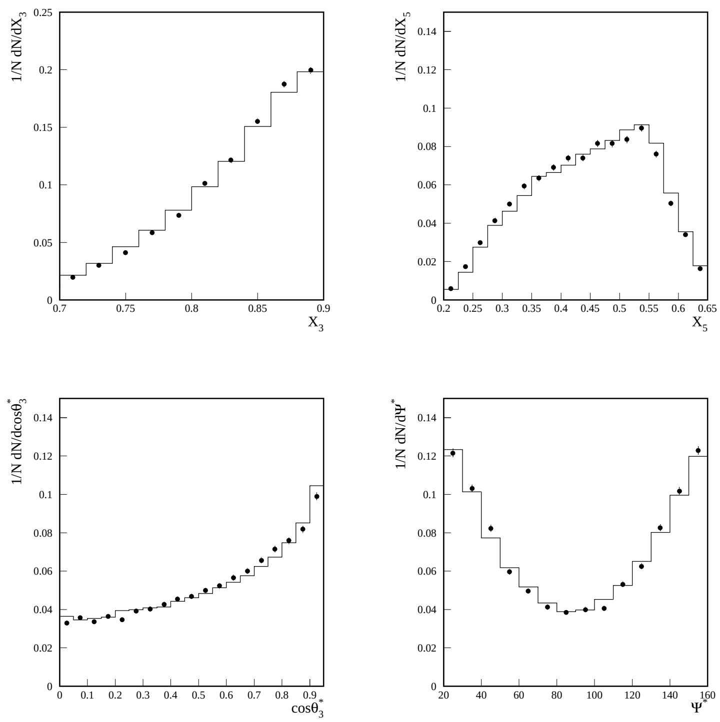

FIG. 2. D0 preliminary distributions (points) for traditional three-jet variables compared with LO QCD predictions (histogram).

LO QCD prediction. This discrepancy seems to be larger for the HERWIG predictions, and may indicate the need for a NLO three-jet calculation. The CDF distributions are also compared with a phase-space model. It should be noted that the X_3- and X_4-distributions are not very different from the phase-space predictions. In contrast, the angular variables are strikingly different from those of the phase-space model.

NEW D0 FOUR-JET RESULTS

D0 have compared observed distributions with NJETS predictions for a number of different four-jet variables. In particular the following have been examined and shown to be well described by the LO QCD predictions; (a) $\cos\omega_{ij}$, the cosines of the space angles between all pairs of jets i and j (Fig. 3), (b) $\mu_{ij} \equiv m_{ij}/m_{4J}$, the normalized two-jet masses for all pairs of jets (Fig. 3), (c) X_j, the Dalitz variables for the four jets, and (d) $cos\theta_j^\star$, the cosine of the angle between each jet j and the beam direction in the four-jet rest-frame.

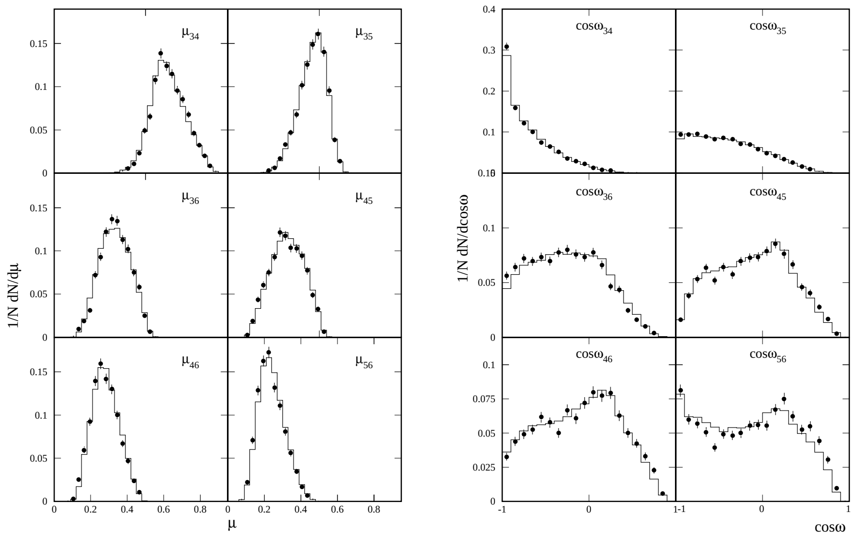

FIG. 3. D0 preliminary four-jet distributions (points) compared with LO QCD predictions (histograms) for the masses of all pairs of jets divided by the four-jet mass (left plots) and the cosines of the angles between all jet pairs (right plots).

NEW CDF FOUR-JET AND FIVE-JET RESULTS

CDF has taken a somewhat different approach in analysing four- and five-jet events. A new set of multijet variables are defined that (i) span the multijet parameter space, (ii) make it simple to interpret the observed event distributions within the framework of perturbative QCD, and (iii) make it easy to compare the characteristics of events having n jets with the characteristics of events having for example (n+1) jets. The variables are defined by first of all reducing the n-jet system to a three-body system by combining jet pairs with the lowest jet-pair mass. The three body system can then be described using the traditional three-jet variables. Four additional variables are then required to specify each step in which two jets are combined. In the massless jet approximation, only three additional variables per step are required.

Consider the four-jet case. We combine the two jets A and B with the lowest two-jet mass, and describe the resulting three-body system with the variables $X_{3'}$, $X_{4'}$, $\cos\theta^{\star}_{3'}$, and $\psi^{\star'}$, where $E_{3'} > E_{4'}$ and object $5'$ is defined to be the combined system (AB). The primes remind us that two jets have been combined. The CDF observed distributions for these variables are compared with QCD predictions in Fig. 4. Both NJETS and HERWIG give a good first description of these distributions, which are very different from the predictions of the phase-space model. It should be noted that the $\psi^{\star'}$ distribution is a little more planar than the QCD predictions, which was also seen to be the case for the three-jet analysis. We now require three additional variables

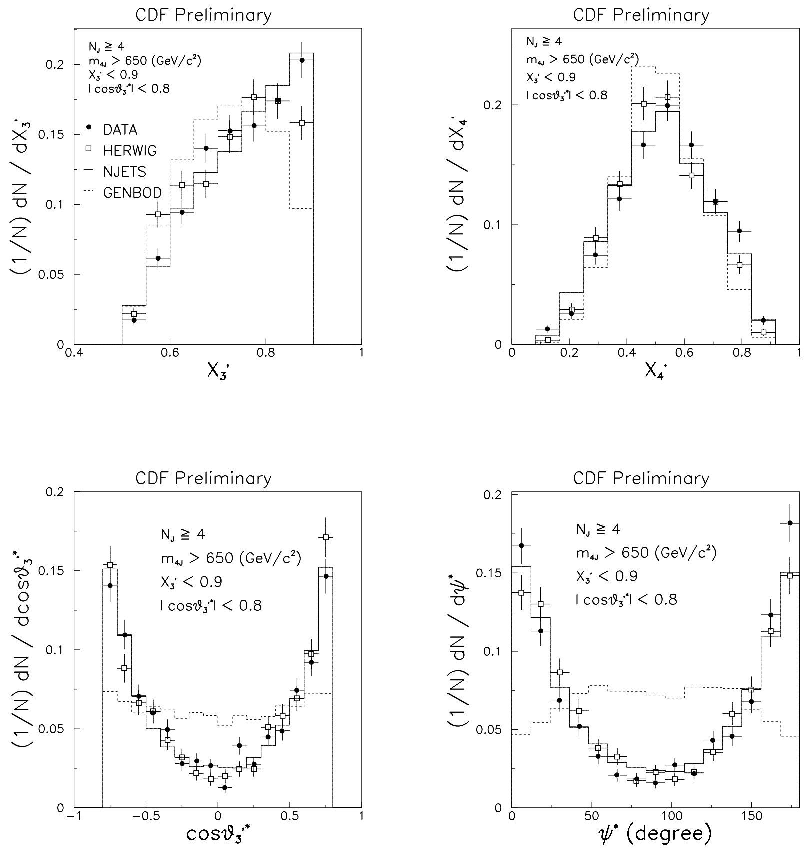

FIG. 4. Four-jet distributions for variables that describe the three-body system obtained by combining the two jets with the lowest two-jet mass. CDF data (points) are compared with LO QCD predictions (histogram), parton shower Monte Carlo predictions (open circles), and four-body phase space predictions (broken histogram).

(massless jet approximation) to describe the (AB)-system. They are chosen to be (a) $F_{5'} \equiv m_{AB}/m_{4J}$, the normalized mass, (b) $\cos\theta_A^{\star\star}$, defined in the (AB)-rest-frame as the cosine of the angle between the highest energy jet (A) and the direction of the four-body system, and (c) $\psi_{AB}^{\star}$, defined in the four-jet rest-frame as the angle between the three-body plane $(3'4'5')$ and the plane containing A and B. The CDF distributions for these variables are compared with QCD predictions in Fig. 5. Both NJETS and HERWIG give a good first description of these distributions, which are very different from the predictions of the phase-space model. In more detail, the NJETS prediction for the $F_{5'}$ distribution is peaked a little lower than the data, which probably reflects the small but finite single-jet masses that are not modelled in the NJETS calculation.

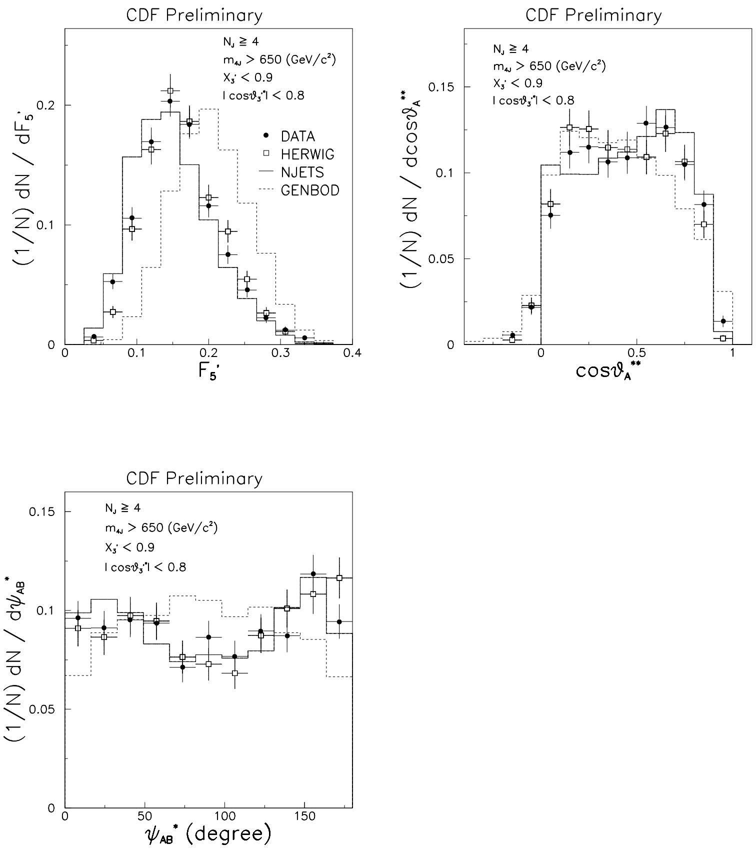

FIG. 5. Four-jet distributions for variables that describe the lowest-mass jet pair. CDF data (points) are compared with LO QCD predictions (solid histogram), parton shower Monte Carlo predictions (open circles), and four-body phase space predictions (broken histogram).

Consider next the five-jet case. We begin by combining the two jets A and B with the lowest two-jet mass to obtain a four-body system. We can then reduce this system to a three-body system by combining the two bodies C and D with the lowest two-body mass. The resulting three-body system is described using the traditional three-jet variables $X_{3''}$, $X_{4''}$, $\cos\theta^{\star}_{3''}$, and ψ'', where $E_{3''} > E_{4''} > E_{5''}$, and the double primes remind us that we have combined two objects twice. The CDF distributions for these variables are compared with QCD predictions in Fig. 6. HERWIG gives a good first description of these distributions, which are very different from the predictions of the phase-space model. Once again, it should be noted that the ψ'' distribution is a little more planar than the QCD predictions. We now use three additional variables to describe the (AB)-system and three variables to describe the (CD)-system. These variables are chosen to be (a) $F_X \equiv m_{AB}/m_{5J}$, the normalized mass, (b) $\cos\theta_A^\star$, defined in the (AB)-rest-frame as the cosine of the angle between the highest energy jet (A) and the direction of the five-body system, (c) ψ_{AB}, defined in the five-jet rest-frame as the angle between the three-body plane ($3''4''5''$) and the plane containing A and B, and the three equivalent variables for the (CD)-system, namely (d) F_Y, (e) $\cos\theta_C^\star$, and (f) ψ_{CD}. The CDF observed distributions for these variables are compared with QCD predictions in Fig. 7. Once again HERWIG gives a good first description of these distributions. Finally, a more complete discussion of the definition and properties of the four-jet and five-jet variables can be found in Ref. (8).

SUMMARY

Detailed analyses are in progress of large samples of multijet events produced in $\overline{p}p$ collisions at the Fermilab Tevatron collider. CDF and D0 find basic agreement between the observed characteristics and LO QCD predictions for three-jet, four-jet, and five-jet events. The LO predictions are similar to parton shower Monte Carlo predictions, suggesting that $2 \to 2$ scattering plus gluon radiation provides a good first approximation to the full LO QCD matrix element.

I am indebted to Jianming Qian for the D0 facts and figures presented in this paper, and to Takashi Asakawa for help with the CDF figures. Needless to say, the multijet data samples discussed owe their existence to the efforts of the CDF and D0 collaborations.

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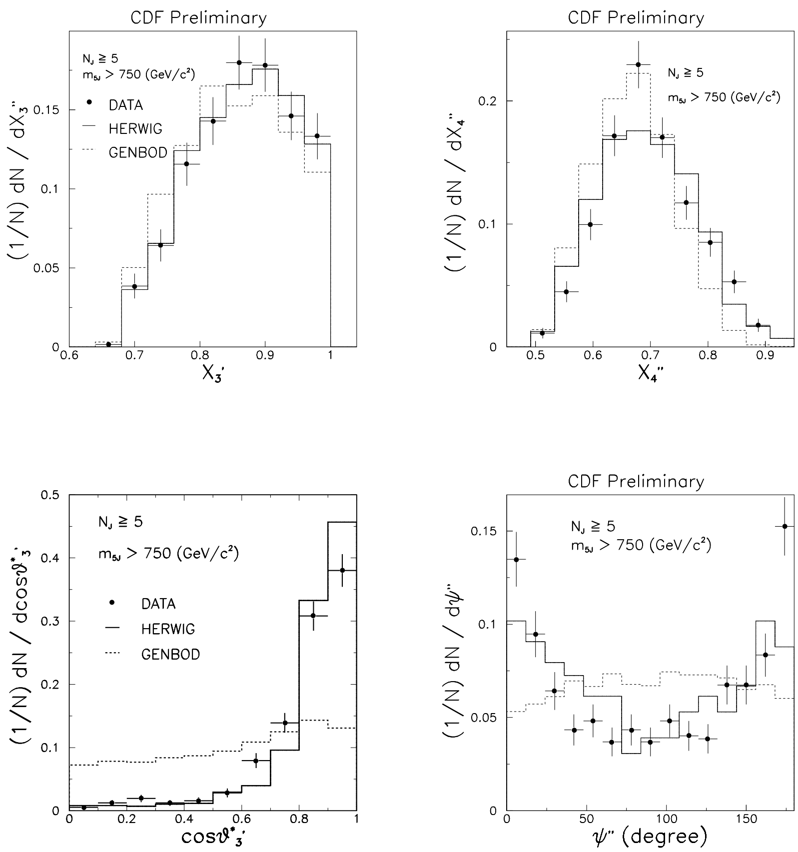

FIG. 6. Five-jet distributions for variables that describe the three-body system obtained by combining the two jets with the lowest two-jet mass to obtain a four-body system, and then combining the two bodies with the lowest two-body mass to obtain a three-body system. CDF data (points) are compared with parton shower Monte Carlo predictions (solid histogram) and five-body phase space predictions (broken histogram).

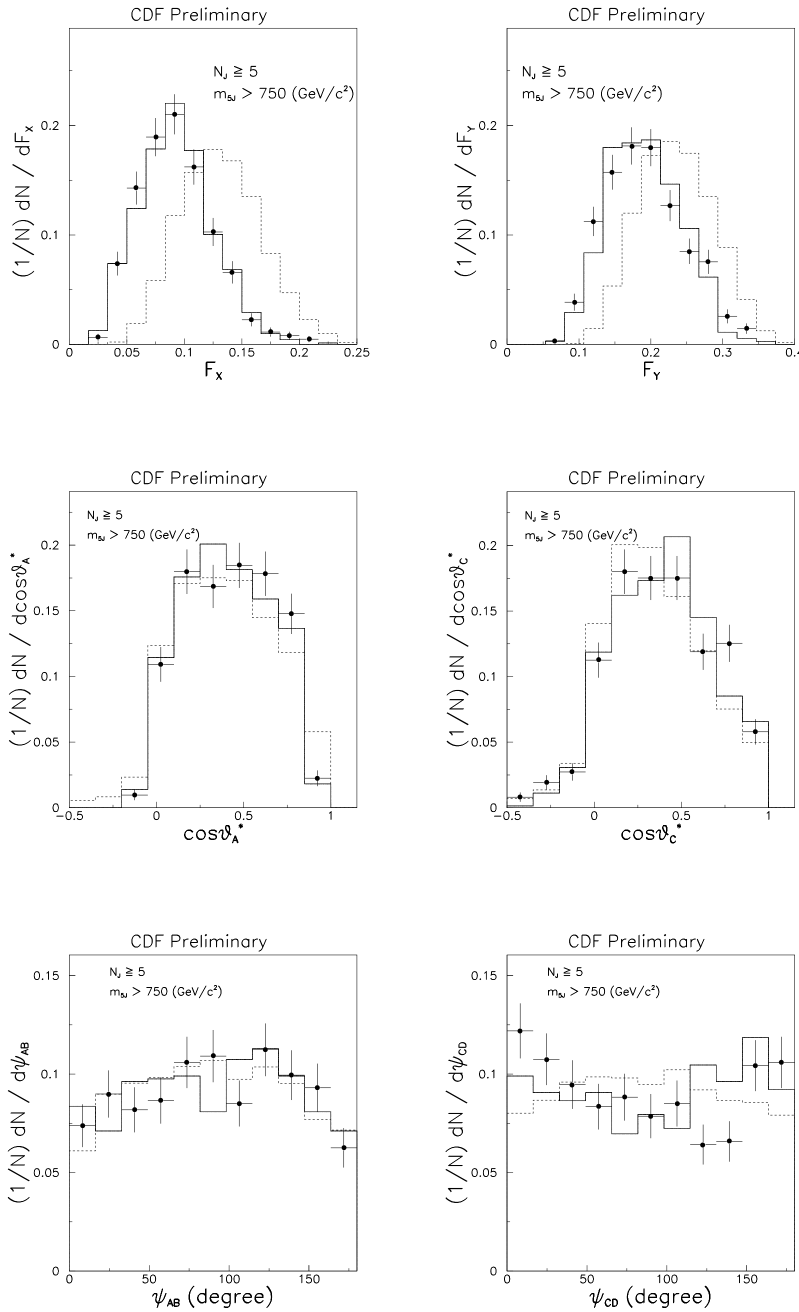

FIG. 7. Five-jet distributions for variables that describe the lowest-mass jet pair (AB) combined to form a four-body system, and the lowest mass two-body pair (CD) subsequently combined to form a three-body system. CDF data (points) are compared with parton shower Monte Carlo predictions (solid histogram), and five-body phase space predictions (broken histogram).