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in  $p\bar{p}$  Collisions at  $\sqrt{s} = 1.8$  TeV**

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The CDF Collaboration**

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## The Dijet Angular Distribution in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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## ABSTRACT

The dijet angular distribution is measured in the CDF detector at the Fermilab Tevatron Collider. This measurement covers higher mass ranges and larger scattering angles than previously possible. Good agreement is observed between the data and both leading order ( $O(\alpha_s^2)$ ) and next-to-leading ( $O(\alpha_s^3)$ ) order QCD calculations. A limit on quark compositeness of  $\Lambda_c > 1.0$  TeV is obtained.

The production of jets is one of the fundamental processes observed at  $p\bar{p}$  colliders. The properties of jet events are typically predicted at the parton level with leading order QCD. The lowest-order QCD description of jet events refers to the case in which a parton in each of the incoming hadrons participates in a collision and results in two final state partons. The cross section for dijet events can be factorized, at lowest order, into two terms, one of which depends on the structure functions and the other on the center-of-mass scattering angle ( $\theta^*$ ). The structure function dependence can be determined via the Feynman  $x$  calculated from the dijet mass ( $M_{JJ}$ ) and the longitudinal boost of the dijet system ( $\eta_{boost}$ ). With the CDF jet data sample of  $4.2 \text{ pb}^{-1}$ , measurements of these quantities have been extended to higher masses and larger angular regions than previously possible[1].

The description of events with more than two jets requires higher order calculations and the treatment of these events, both experimentally and theoretically, is a subject of ongoing development. Recently,  $O(\alpha_s^3)$  calculations[2] have become available. These begin to account, at the parton level, for the radiation which can occur from the scattered partons. This paper discusses the measurement of the dijet angu-

lar distribution, the comparison to  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  QCD predictions and a test for quark substructure.

The CDF detector has been described in detail elsewhere[3]. For this analysis, the relevant detector elements are the electromagnetic and hadronic calorimeters. The calorimeters use a projective tower geometry, and they are divided into three regions of pseudorapidity ( $\eta$ ) with respect to the beam line: Central ( $0 \leq |\eta| \leq 1.3$ ), Plug ( $1.1 \leq |\eta| \leq 2.4$ ), and Forward ( $2.2 \leq |\eta| \leq 4.2$ ). The segmentation is  $\approx 0.1$  units of pseudorapidity throughout the calorimeter. In the azimuthal angle  $\phi$ , the central calorimeter has a segmentation of  $15^\circ$  while the plug and forward calorimeters have a segmentation of  $5^\circ$ . An online cluster finder triggered the detector for events with at least one jet above a transverse energy ( $E_T \equiv E \sin \theta$ , where  $\theta$  is the polar angle.) of 20 or 60 GeV. For the 60 GeV threshold, all events were written to tape. For the 20 GeV triggers, 1/300 of the events passing the requirement were kept.

Jets are identified by the CDF clustering algorithm which has been described in detail elsewhere[4]. This algorithm defines a cone in  $\eta - \phi$  space which has, for this analysis, a radius of 0.7. For each calorimeter tower with  $E_T > 0.1$  GeV, we calculate the four-momentum, treating the energy in the tower as if it were deposited by a single massless particle. The towers which fall within the cone are then summed to give a single four-vector for each jet. For this analysis, we only consider events which have two or more jets with  $E_T > 15$  GeV. A similar algorithm is used for the  $O(\alpha_s^3)$  calculations[2] where three partons exist in the final state. If two of the partons fall within a cone, they are summed into one jet.

In both the measurement and the theoretical calculations, the dijet mass of an



event is defined in terms of the four-vectors of the two leading (highest  $E_T$ ) jets. The center-of-mass scattering angle and the longitudinal boost of the dijet system are related to the pseudorapidities of these two jets ( $\eta_1$  and  $\eta_2$ ) by the equations  $\eta_{boost} = \frac{1}{2}(\eta_1 + \eta_2)$ , and  $\cos\theta^* = \tanh\eta^*$ , where  $\eta^* = \frac{1}{2}(\eta_1 - \eta_2)$ . The angular distribution is plotted in terms of the variable[5]  $\chi = e^{2|\eta^*|}$ . For pure Rutherford scattering of massless partons (spin-1 t-channel exchange), the  $dN/d\chi$  spectrum is flat.

At a given  $M_{JJ}$ , the trigger threshold in single jet  $P_T$  results in a loss of efficiency at high  $\chi$ . This can be illustrated by the case in which there is no transverse boost to the dijet system. The two jet  $P_T$ 's would be equal and the dijet mass would be related to the variable  $\chi$  by the equation  $M_{JJ} = P_T(\sqrt{\chi} + 1/\sqrt{\chi})$ . To ensure an efficient trigger (> 90%) over a large angular range, we require  $|\eta_{boost}| < 0.75$  and divide the data into mass bins of  $240 < M_{JJ} < 475$  GeV (using the 20 GeV trigger),  $475 < M_{JJ} < 550$  GeV and  $550 < M_{JJ}$  (both using the 60 GeV trigger). We restrict the analysis to  $|\eta^*| < 1.6$  ( $\chi < 24$ ) for the  $240 < M_{JJ} < 475$  GeV and  $550 < M_{JJ}$  bins, and  $|\eta^*| < 1.5$  ( $\chi < 20$ ) for the  $475 < M_{JJ} < 550$  GeV bin. In addition, we require that the event vertex along the beam axis be within 60 cm of the nominal interaction point. After these cuts, we are left with 411, 903, and 541 events in the low, middle and high mass bins respectively.

The measured distribution,  $dN/d\chi$ , and the corresponding theoretical distribution, are each normalized to unit area and then a chi-square comparison is performed. With this approach we are sensitive to the shape of the  $dN/d\chi$  distribution. Since the relative energy scales of the calorimeters affect the shape of the acceptance, the  $\eta$  dependence of energy scale is the dominant source of systematic uncertainty.

To measure the relative response of the detectors at large pseudorapidity, jet  $P_T$  balancing is used. Events are selected by requiring that there be two and only two jets with  $P_T > 15$  GeV. To avoid trigger biases, the average jet transverse momentum,  $\bar{P}_T$ , must be at least 5 GeV above the trigger threshold. Each jet in an event is then labeled either “trigger”, meaning it is contained in the central region ( $0.2 < |\eta| < 0.7$ ), or “probe”, meaning it can be anywhere in  $\eta$ . With these cuts the central jet is well contained in the central calorimeter where the absolute energy scale has been extensively studied[6, 4]. If both jets fall in the central region, a random assignment of trigger and probe is made. Events with no jet in the central region are excluded from this study.

The balancing is performed using the Missing  $E_T$  Projection Fraction (MPF),

$$MPF = \vec{\cancel{E}}_T \cdot \hat{n}_T^{probe} / \bar{P}_T,$$

where  $\hat{n}_T^{probe}$  is a unit vector along the direction of the probe jet, and  $\vec{\cancel{E}}_T$ , is defined as the vector sum over calorimeter towers with  $E_T > 0.1$  GeV:

$$\vec{\cancel{E}}_T = - \sum_i E_T^i \hat{n}_i, \quad i = \text{calorimeter tower number with } |\eta| < 3.6. \quad (1)$$

The unit vector  $\hat{n}_i$  is perpendicular to the beam axis and points at the  $i^{th}$  calorimeter tower.

The component of  $\vec{\cancel{E}}_T$  along the probe jet is measured by MPF, and should be zero if the correct relative energy scale is used. By using the  $\vec{\cancel{E}}_T$  of the event, rather than the  $P_T$  imbalance of the jets, the effects of any transverse boosts of the system are minimized. The MPF is measured as a function of the  $\eta$  of the probe jet for five bins of  $\bar{P}_T$ . From this we derive a function which corrects the energy of each jet

based on the  $\eta$  and the  $P_T$  of the jet. Figure 1 shows the MPF as a function of  $\eta$  before and after the relative jet energy correction function has been applied for five bins of  $\bar{P}_T$ . After the jet energy corrections, the relative energy scales are equal at the 1-2% level.

The absolute energy response for all jets is derived[4] from Monte Carlo jets generated in the central region and passed through a detector simulation. We determined a correction which accounts for losses in jet energy in cracks between the calorimeter towers and nonlinear response at low energy in the hadronic calorimeters. The effects on the measured jet energy from the underlying event and from fragmentation particles falling outside the cone are model-dependent. We do not attempt to correct for these effects.

To estimate the acceptance and its systematic uncertainties, a fast jet-detector simulation was constructed by using the inverse of the relative energy scale corrections, smearing the jet response with the resolution of the detector and adding an estimate of the underlying event and transverse momentum of the system. The jet directions are smeared in  $\eta$  and  $\phi$  with resolutions which are determined using a more detailed Monte Carlo. The resolution in  $\eta$  leads to a resolution in  $\chi$  of  $\sigma_\chi/\chi \approx 5\%$ , however the flatness of the expected distribution at high  $\chi$  makes us insensitive to the exact value of this smearing. After jet corrections were applied, Monte Carlo studies indicated that the acceptance is flat in  $\chi$  and thus does not influence the comparisons to theoretical calculations. Varying the relative energy scales in different detector regions by  $\pm 2\%$ , resulted in acceptance curves that deviated from flat at the 5-10% level. The resolutions in the different detector regions were independently

varied by  $\pm 20\%$  yielding no change in the shape of the acceptance. Systematic uncertainties due to these changes were included in the chi-square comparison, along with the bin-to-bin correlations. The statistical correlations induced by the normalization condition were also included.

Figure 2 shows the data compared to  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  calculations[7] for HMRSB[8] structure functions with renormalization scale  $Q^2 = (P_T/2)^2$ . The error bars represent the statistical uncertainty in the data. Table 1 contains the data with the statistical uncertainty for the three mass bins. The absolute size of the systematic uncertainty is small (5-10%), but the bin-to-bin correlations make them of roughly equal importance as the statistical uncertainties in the comparisons to theory. Table 2 summarizes the results of fits to the  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  predictions with renormalization scales  $Q^2 = (P_T/2)^2$  and  $Q^2 = P_T^2$ . The renormalization scale is seen to make very little difference in the confidence levels. Four sets of Morfin-Tung structure functions[9] were also tested (S, B1, B2 and E); they gave the same confidence levels as HMRSB to within 2%.

In addition, a test for possible quark substructure has been done by comparing the angular distribution to a model[10] which adds a contact term to the leading order QCD Lagrangian. This model predicts that, if quarks are composite structures, an excess of events in the  $dN/d\chi$  distribution at low  $\chi$  and high  $M_{JJ}$  would be observed. We calculate the ratio  $R(7,24)$  of events with  $\chi < 7$  to those with  $7 < \chi < 24$ . In the sample with  $M_{JJ} > 550$  GeV we find  $R(7,24) = .374 \pm 0.036 \pm 0.040$ , or  $R(7,24) < 0.46$  at the 95% confidence level. The compositeness is characterized in terms of the variable  $\Lambda_c$ . Leading order calculations of compositeness with  $\Lambda_c < 1.0$

TeV would predict  $R(7, 24) > 0.50$ , which is above our 95% confidence level upper limit. To be exact,  $R(7, 24) > 0.50$  is excluded at the 99% confidence level. Figure 3 shows the data compared to the  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  QCD curves and to the curve with  $\Lambda_c = 1.0$  TeV. This result is less stringent than the  $\Lambda_c > 1.4$  TeV limit obtained from the CDF inclusive jet cross section[6] however, it is an independent method with different systematic uncertainties. Our result can be compared directly to previous limits obtained from the dijet angular distribution[1] of  $\Lambda_c > 0.33$  TeV from an earlier CDF data set, or  $\Lambda_c > 0.41$  TeV from the UA1 collaboration at  $\sqrt{s} = 630$  GeV.

In summary, the dijet angular distribution has been measured over a large angular region. Both  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  calculations provide adequate representations of the data. The agreement between the  $O(\alpha_s^3)$  calculation and the data is slightly better. A limit on quark compositeness of  $\Lambda_c > 1.0$  TeV has been obtained.

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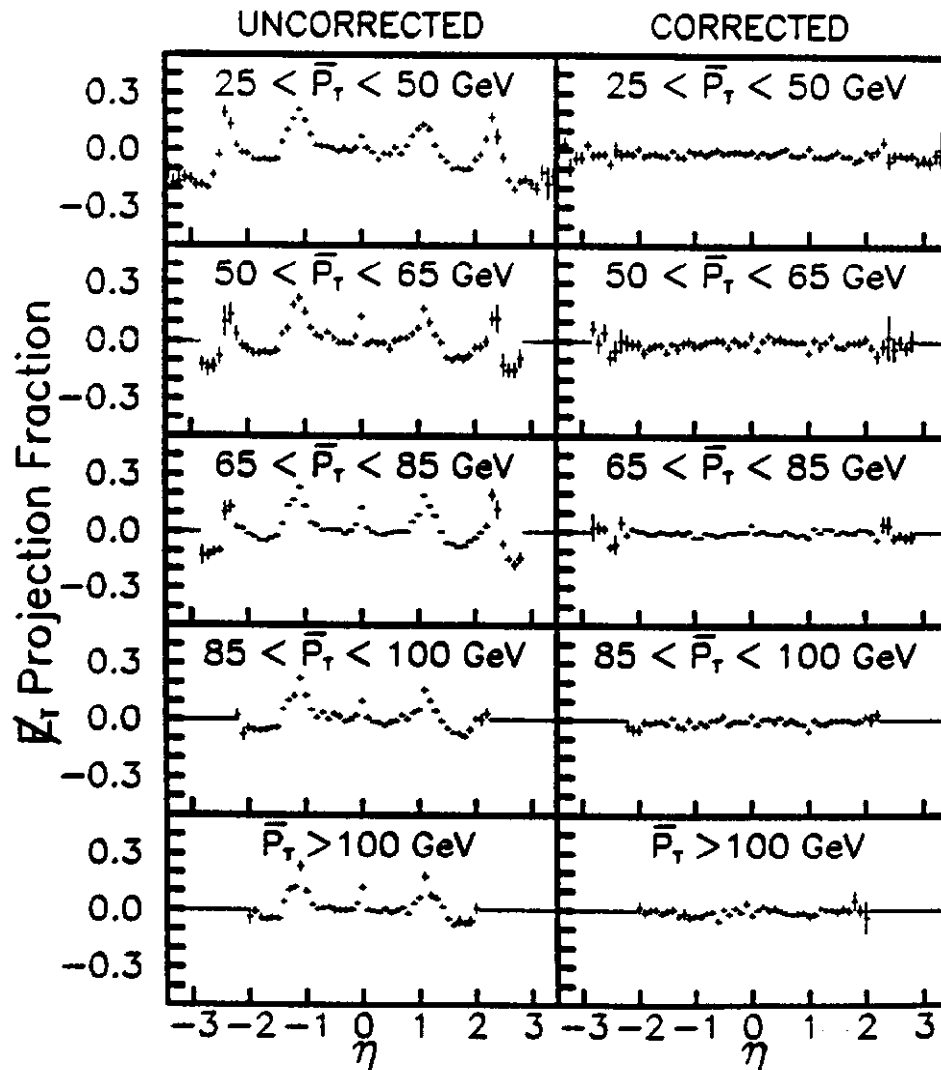


Figure 1: The jet balancing variable,  $\bar{E}_T$  projection fraction (MPF, see text), is plotted as a function of  $\eta$  before and after the jet energy corrections for 5 bins of  $\bar{P}_T$ . The  $\eta$ 's of the structures in the uncorrected plot correspond to the boundaries between the different calorimeters.

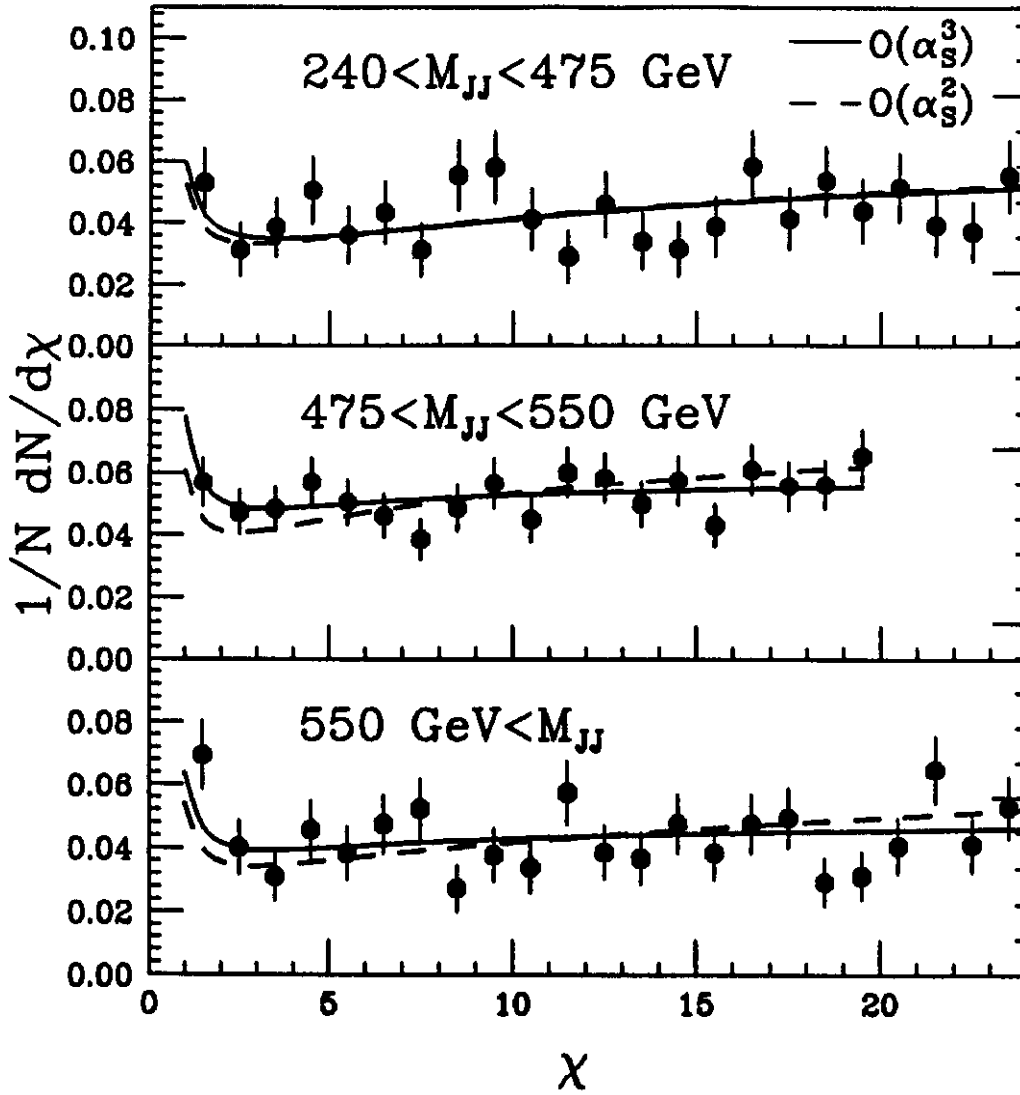


Figure 2: CDF dijet angular distribution compared to  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  QCD calculations.



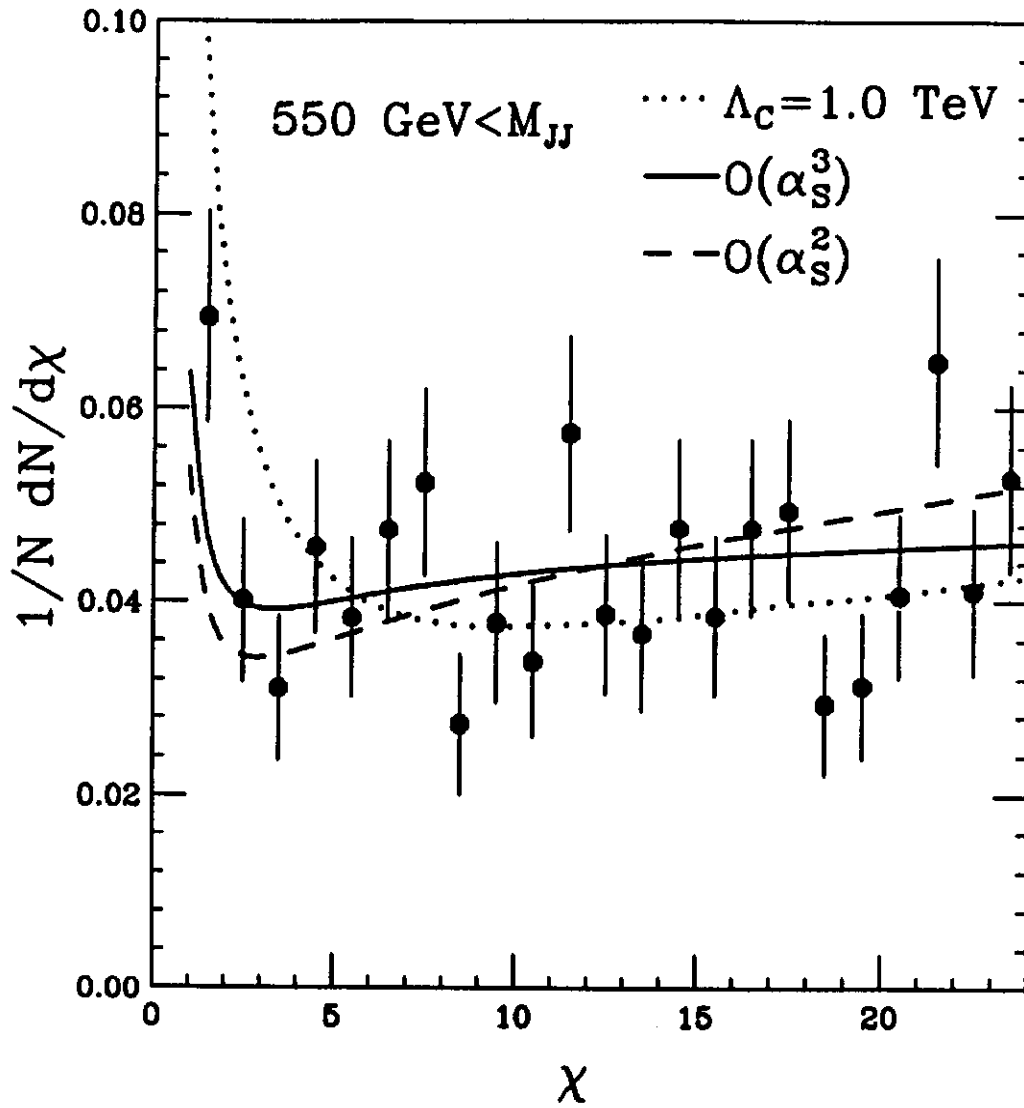


Figure 3: CDF dijet angular distribution compared to  $O(\alpha_s^2)$  QCD with and without the addition of a contact term,  $\Lambda_c = 1.0 \text{ TeV}$ , to represent quark substructure. The  $O(\alpha_s^3)$  curve is also shown.

Table 1: Data and statistical uncertainties for the CDF dijet angular distribution, where columns A, B and C refer to Mass Bins:  $240 < M_{JJ} < 475$ ,  $475 < M_{JJ} < 550$  and  $550 < M_{JJ}$  GeV, respectively.

$\chi$	$dN/Nd\chi (\times 10^{-2})$		
	A	B	C
1.5	$5.3 \pm 1.1$	$5.7 \pm 0.8$	$6.9 \pm 1.1$
2.5	$3.1 \pm 0.8$	$4.7 \pm 0.7$	$4.0 \pm 0.8$
3.5	$3.9 \pm 0.9$	$4.8 \pm 0.7$	$3.1 \pm 0.7$
4.5	$5.1 \pm 1.1$	$5.7 \pm 0.8$	$4.6 \pm 0.9$
5.5	$3.6 \pm 0.9$	$5.0 \pm 0.7$	$3.8 \pm 0.8$
6.5	$4.3 \pm 1.0$	$4.6 \pm 0.7$	$4.8 \pm 0.9$
7.5	$3.1 \pm 0.8$	$3.9 \pm 0.6$	$5.2 \pm 1.0$
8.5	$5.5 \pm 1.1$	$4.8 \pm 0.7$	$2.7 \pm 0.7$
9.5	$5.8 \pm 1.1$	$5.6 \pm 0.8$	$3.8 \pm 0.8$
10.5	$4.1 \pm 1.0$	$4.5 \pm 0.7$	$3.4 \pm 0.8$
11.5	$2.9 \pm 0.8$	$6.0 \pm 0.8$	$5.7 \pm 1.0$
12.5	$4.6 \pm 1.0$	$5.8 \pm 0.8$	$3.9 \pm 0.8$
13.5	$3.4 \pm 0.9$	$5.0 \pm 0.7$	$3.7 \pm 0.8$
14.5	$3.2 \pm 0.9$	$5.7 \pm 0.8$	$4.8 \pm 0.9$
15.5	$3.9 \pm 0.9$	$4.3 \pm 0.7$	$3.8 \pm 0.8$
16.5	$5.8 \pm 1.1$	$6.1 \pm 0.8$	$4.8 \pm 0.9$
17.5	$4.1 \pm 0.9$	$5.6 \pm 0.8$	$4.9 \pm 0.9$
18.5	$5.4 \pm 1.1$	$5.6 \pm 0.8$	$2.9 \pm 0.7$
19.5	$4.4 \pm 1.0$	$6.5 \pm 0.8$	$3.1 \pm 0.7$
20.5	$5.1 \pm 1.1$		$4.1 \pm 0.8$
21.5	$3.9 \pm 1.0$		$6.5 \pm 1.1$
22.5	$3.7 \pm 0.9$		$4.1 \pm 0.8$
23.5	$5.5 \pm 1.1$		$5.3 \pm 1.0$

Table 2: Confidence levels (%) for  $O(\alpha_s^2)$  and  $O(\alpha_s^3)$  theory compared to the CDF dijet angular distribution.

HMRSB	Mass (GeV)	$O(\alpha_s^2)$	$O(\alpha_s^3)$
$Q = P_T/2$	240-475	52	60
$Q = P_T$	240-475	56	63
$Q = P_T/2$	475-550	56	80
$Q = P_T$	475-550	60	84
$Q = P_T/2$	>550	9	16
$Q = P_T$	>550	10	13