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High Q^2 QCD Physics at the Tevatron

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Abstract. Results in QCD physics at the Tevatron from the DØ and CDF collaborations are presented, including results in jet production, photon production, W/Z bosons plus jets, and heavy-flavor jets. The importance of these topics in tuning Monte-Carlo simulations, constraining the parton distribution functions, and measuring cross sections of QCD processes which contribute significant backgrounds to searches for new and important physics is discussed.

Keywords: QCD, jets, heavy flavor, photons, hadron collider
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INTRODUCTION

The study of QCD physics at the Tevatron is essential for precisely determining the parton distribution functions (PDFs) of the proton, for measuring the cross sections for processes which contribute large backgrounds to new physics searches, and for tuning of Monte Carlo (MC) event generators which are used in all areas of physics at the Tevatron as well as at the LHC. The measurement of jet and photon production cross sections can constrain the PDFs; in particular, the inclusive jet cross section in the forward region is useful to constrain the gluon distribution function at high momentum fraction x but low momentum transfer squared (Q^2), while new physics would be expected to appear at high Q^2. Jets containing b quarks are signatures of many important and possible new physics processes, and the study of different processes involving b-jets tests pQCD by probing different production mechanisms. Besides being interesting probes of QCD processes, the measurement of cross sections for QCD production of diphotons, W or Z plus jets, and Z+b-jets, is important for determining the backgrounds to important and possible new physics processes, as well as testing pQCD predictions.

FRAGMENTATION AND THE UNDERLYING EVENT

Before describing QCD results at high Q^2, we first touch on studies of fragmentation and the underlying event. Physics in all areas at the Tevatron rely on accurate Monte-Carlo modeling of all characteristics of the event, not just the hard scattering which is described by perturbative QCD (pQCD), but also fragmentation and the underlying event (by which we mean the beam-beam remnants, any hard initial or final state radiation, and possible multiple parton interactions). CDF has determined a particular choice of parameters for the PYTHIA event generator which reproduce the underlying event in jet events in Tevatron Run I data, which is referred to as “PYTHIA Tune A” [1]. A CDF Run II study of jet shapes [2], the fraction of transverse momentum p_T of a jet contained within a cone as a function of cone radius, found that PYTHIA Tune A describes the data extremely well. A study by DØ on dijet azimuthal decorrelations [3] also provides a good test of the modeling of multi-parton radiation in MC generators. That measurement depends only on the reconstruction of the difference in azimuthal angle ($\Delta\phi$) between the two highest-p_T jets, and is therefore insensitive to the jet energy scale. Good agreement was found with Next-to-Leading Order (NLO) pQCD, and also with HERWIG MC, however, agreement with PYTHIA was seen only when the amount of initial-state radiation (ISR) was increased from the default value. PYTHIA Tune A also has increased ISR.

CDF has studied jet fragmentation, which includes parton showering and hadronization effects. In Run I, CDF found that the multiplicity and momentum distributions of particles in jets are approximately the same for partons as for hadrons (“Local Parton-Hadron Duality”). A recent Run II study finds that two-particle momentum correlations survive hadronization as well [4]. Studies of the distribution of transverse momentum of particles in jets relative to the jet axis and of event shapes are in progress.

JET PRODUCTION

Measurement of the inclusive jet differential cross section as a function of jet p_T provides a stringent test of pQCD over nine orders of magnitude, and is sensitive to distances as small as $\sim 10^{-19}$ m. The jet cross section is expected to be higher with respect to Run I due to the increased Tevatron center-of-mass energy, and therefore reaches to higher p_T jet production where new physics could appear. The inclusive jet cross section is sensitive to the parton distribution functions (PDFs), and in particular, measurements at forward rapidity (y) can constrain the gluon PDF at high x, where it is not well known, and at low Q^2, which is important since any new physics would be expected to appear at high Q^2.

CDF has published the inclusive jet cross section in the central region ($|y| < 0.7$) [5]. Results using both a cone-based “midpoint” clustering algorithm [6] as well as the k_T algorithm [5] show good agreement with NLO predictions. The k_T algorithm clusters objects according to their relative transverse momenta, is the algorithm preferred for comparison with theory, and has been used successfully at HERA; however, its performance at a hadron-hadron collider in the presence of underlying event was uncertain. The CDF results show that the k_T algorithm works well in a hadron collider environment in the p_T range studied.

CDF measurements of the inclusive jet cross section extended to the forward region [7] using the k_T algorithm and 1 fb^{-1} of data are shown in Fig. 1. Good agreement with NLO predictions is seen. The measurements in the most forward region have the power to reduce PDF uncertainties, as seen by uncertainties on the measurement which are are smaller than the PDF uncertainties. Similar results are found using the midpoint algorithm [8].

DØ has looked at jet production using 0.8 fb^{-1} of data in two rapidity regions, $|y| < 0.4$ and $0.4 < |y| < 0.8$ [9]. Although the data is scaled to theory predictions at $p_T = 100$ GeV for $|y| < 0.4$ in order to remove uncertainties in the luminosity, the shape of the distribution shows good agreement over the entire p_T range.

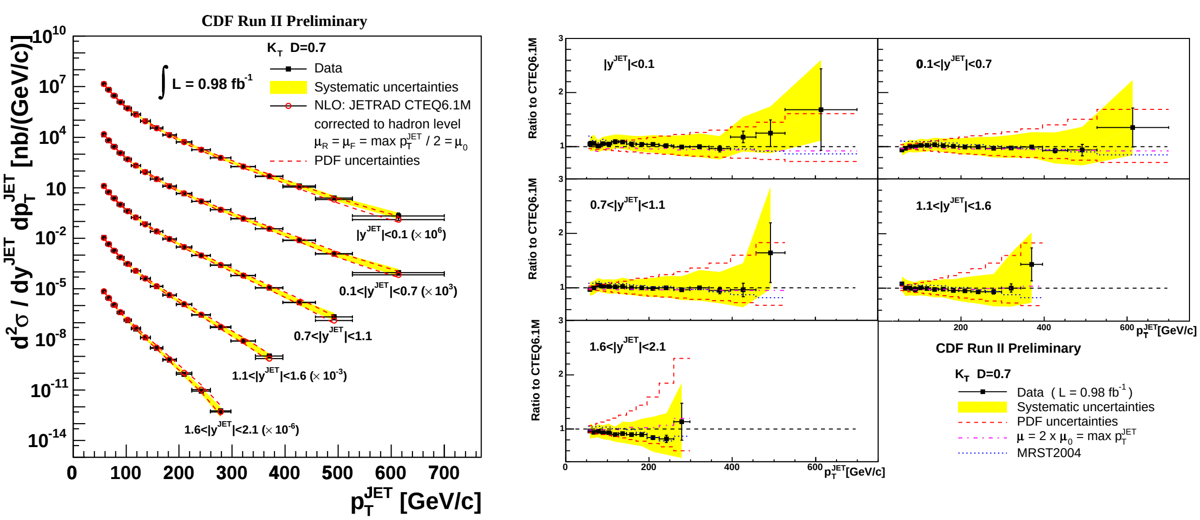

FIGURE 1. (*left*) CDF measured inclusive jet cross section in five rapidity bins (black dots) as a function of p_t^{jet} compared to NLO pQCD predictions (histogram). The shaded bands show the total systematic uncertainty on the measurement. (*right*) Ratio of data to theory as a function of p_t^{jet}. The error bars (shaded band) show the total statistical (systematic) uncertainty on the data. A 5.8% uncertainty on the luminosity is not included. The solid lines indicate the PDF uncertainty on the theoretical prediction. The dashed lines present the ratio of MRST2004 and CTEQ6.1M predictions. The dotted-dashed lines show the ratio of predictions with $2\mu_0$ and μ_0.

PHOTON PRODUCTION

The measurement of prompt photon production provides a good means to study pQCD, since photons have a well-known coupling to quarks, lower p_T is accessible compared to jet production, and measurements of photon production can place constraints on the gluon PDF which are complementary to constraints from jet production. In addition, photons are not sensitive to the problems inherent in jet reconstruction such as clustering algorithms or jet energy corrections.

Inclusive isolated prompt photon cross section

DØ has measured the inclusive isolated prompt photon cross section [10] as a function of photon p_T. Compton scattering $(q+g \to q+g)$ is the dominant process at low p_T and probes the gluon PDF. Prompt photons suffer a large background from π^0 and η^0 decays at low p_T, which is suppressed by a requirement that the photons be isolated. Isolated electrons from W/Z production are a background at high p_T. The DØ analysis uses a neural net to further suppress background, which is mainly from jets with a large fraction of energy deposited in the electromagnetic calorimeter.

Figure 2 shows the DØ inclusive isolated photon cross section as a function of photon p_T along with a comparison to a NLO pQCD prediction from JETPHOX, which agrees within uncertainties. Experimental uncertainties are $\sim 20\%$, dominated by photon purity. Advances in the theoretical prediction would be needed in order for the measurement to constrain the gluon PDF.

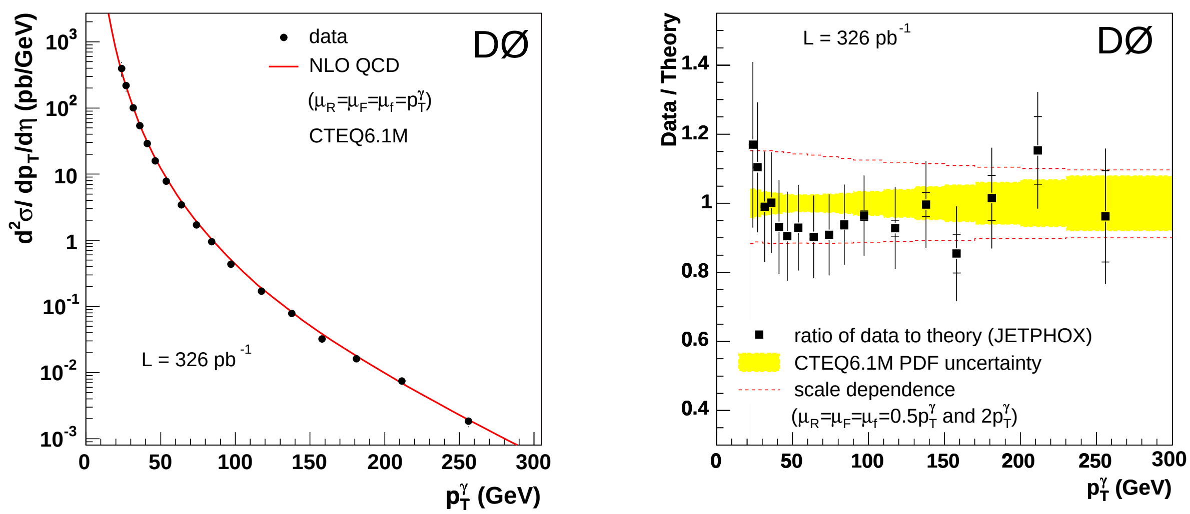

FIGURE 2. (*left*) DØ measured inclusive cross section for the production of isolated photons as a function of p_T^γ. The results from the NLO pQCD calculation with JETPHOX are shown as the solid line. (*right*) The ratio of the measured cross section to the theoretical predictions from JETPHOX. The full vertical lines correspond to the overall uncertainty, while the internal line indicates just the statistical uncertainty. Dashed lines represent the change in the cross section when varying the theoretical scales by factors of two. The shaded region indicates the uncertainty in the cross section estimated with CTEQ6.1 PDFs.

Prompt diphoton cross section

CDF has measured the prompt diphoton cross section [11] as a function of diphoton mass, transverse momentum of the diphoton system (q_T), and $\Delta\phi$ between the photons, which tests NLO pQCD and is sensitive to initial state soft gluon radiation in q_T. The measurement is also important in order to determine the QCD background to searches for new physics processes which have a diphoton signature. Prompt diphotons are mainly produced through $qq \to \gamma\gamma$, $gg \to \gamma\gamma$ (at low diphoton mass), and also in processes where one or both of the photons comes from fragmentation of the hard parton. The CDF analysis again requires the photon to be isolated in order to reduce background from π^0 and η^0 decays. A consequence is that the isolation requirement also reduces photons coming from fragmentation. Residual background is removed statistically based on the shape of the electromagnetic shower in the calorimeter. Comparisons were made to several Monte-Carlo generators, and it was found that NLO processes, including fragmentation contributions, along with soft gluon resummation were needed in order to describe all features observed in the differential cross sections. The published measurement uses $\sim 200\text{pb}^{-1}$ of data and is still dominated by statistical uncertainties.

W/Z BOSONS PLUS JETS

The production of W/Z+jets provides a good test of pQCD in a multijet environment since the presence of the W/Z ensures that the event has a high Q^2. More importantly, W/Z+jets is a possible signature for many new and important processes such as the production of top pairs and single top quarks, the Higgs boson, and Supersymmetric particles. QCD production of W/Z+jets is a large background for these processes, and therefore it is important to measure its cross section. QCD Matrix Element (ME) calculations are used to describe the hard scattering in W/Z+jet events, and then Parton Showering (PS) MC is used to simulate the soft radiation and hadronization. An overlap in phase space between $W/Z+n$-partons and $W/Z+(n+1)$-partons can lead to double-counting when combining MC samples to obtain $W/Z+N$-jets. There have been recent advances in ME-PS matching, including CKKW and MLM prescriptions, which will be important for the simulation of new physics with a W/Z+jet signature, and can be tested using W/Z+jet samples at the Tevatron. Recent theory advances also include NLO predictions.

CDF has measured the W+jets cross section [12] for W plus at least 1, 2, 3, or 4 jets as a function of the jet transverse energy (E_T), and for events with two or more jets as a function of dijet invariant mass, shown in Fig. 3, and also as a function of the distance in η-ϕ space between the leading jets (not shown). The cross section is reported for a restricted W kinematic phase space in order to be model-independent. With this definition, the W acceptance is very flat as a function of jet E_T, and thus does not alter the shape of the cross sections. Currently the comparison is made to LO Alpgen plus PYTHIA in shape only; comparisons to NLO predictions are in progress.

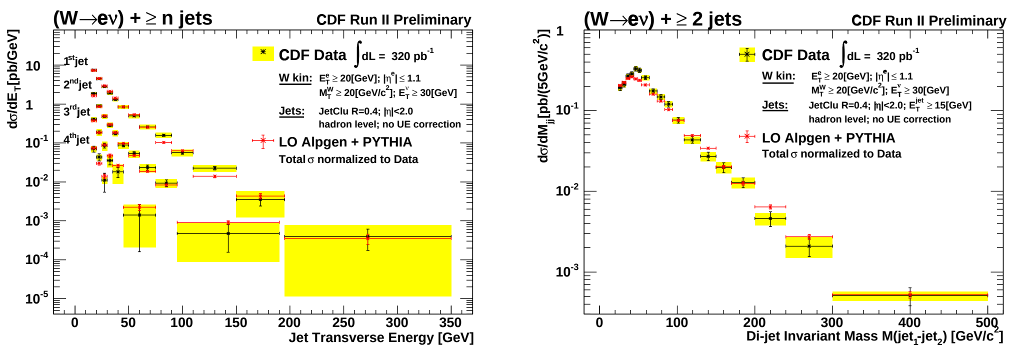

FIGURE 3. (*left*) Differential cross section $d\sigma(W \to e\nu + \geq n\text{-jets})/E_T^{jet}$ for the first, second, third, and fourth inclusive jet sample. (*right*) Differential cross section $d\sigma(W \to e\nu + \geq 2\text{-jets})/dM_{j1j2}$ as a function of the invariant mass of the two leading jets in the $W+\geq 2$ jet events. Data are compared to Alpgen+PYTHIA predictions normalized to the measured inclusive cross section in all cases.

DØ has recently made comparisons [13] of Z+jet production to MC predictions from PYTHIA (LO) and Sherpa (ME+PS with CKKW matching). It was found that PYTHIA predicts fewer hard jets than are seen in the data, and the discrepancy increases with jet multiplicity, as shown in Fig. 4. Sherpa looks promising, as it agrees well for the p_T of the Z, jet multiplicities (Fig. 4), jet p_T, and $\Delta\eta$(jet-jet) and $\Delta\phi$(jet-jet) correlations.

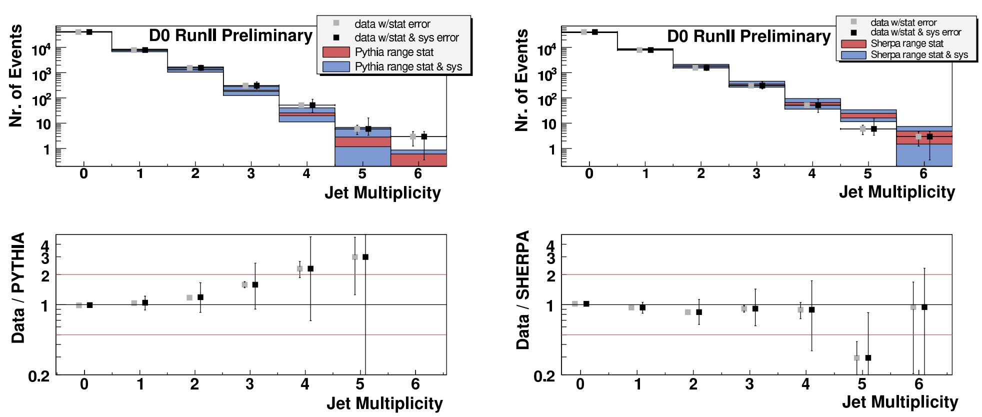

FIGURE 4. Jet multiplicity in events with a Z boson as measured by DØ and compared to PYTHIA (*left*) and Sherpa (*right*).

HEAVY-FLAVOR JETS

Jets containing b quarks are signatures of many important and possible new physics processes. The PDFs for b quarks have evolved significantly in recent years and it is interesting to test theoretical predictions. It is also important to study different processes, such as b, $b\bar{b}$, $\gamma + b$, and $Z + b$ production, since these probe different production mechanisms, including flavor creation at leading order, and at NLO: flavor excitation, gluon splitting, and radiative corrections to LO processes.

b-jet cross section

CDF has measured the b-jet cross section [14] as a function of jet p_T, shown in Fig. 5. The b-jets are tagged by reconstructing the secondary vertex from B hadron decays. Templates of the shape of the invariant mass distribution of tracks from the secondary vertex for b- and light-quark jets are used to extract the fraction of tagged jets which are b-jets (the "b-fraction"). Systematic uncertainties in the jet energy scale and in the b-fraction dominate for the data, while the main uncertainties on the NLO prediction are due to the renormalization and factorization scales, μ_R and μ_F, respectively. The measured cross section agrees with the NLO pQCD prediction within the large systematic uncertainties.

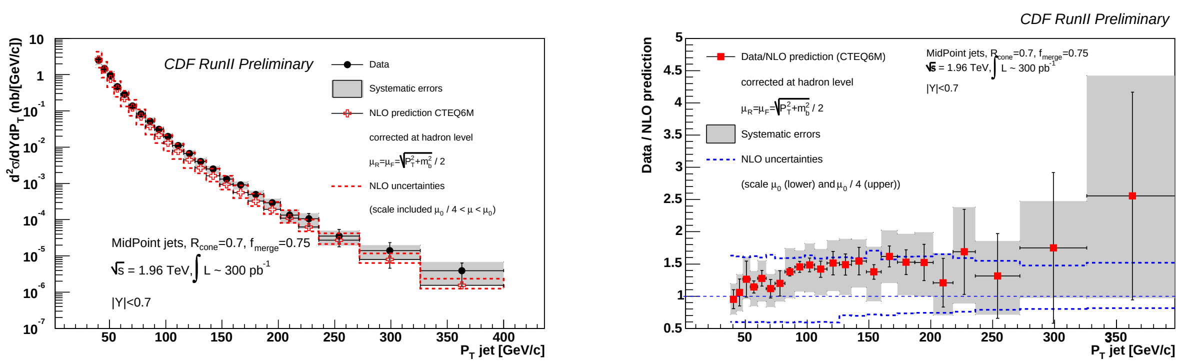

FIGURE 5. (*left*) CDF measured inclusive b-jet cross section (filled circles) as a function of p_T^{jet} compared with NLO pQCD prediction (open crosses). The shaded band represents the systematic uncertainty on the data and the dashed band represents the uncertainties on the theory. (*right*) Ratio of data to theory as a function of p_T^{jet}. The central value is obtained using renormalization and factorization scales set to $\mu = \mu_0/2 = 1/2\sqrt{(p_T^{b-jet})^2 + m_b^2}$. The shaded band is the systematic uncertainty on the data and the dashed band is the uncertainty on the theory,

b-jet shapes

CDF has made a preliminary measurement of the energy flow in b-jets [15] measured in four p_T bins from ~50-300 GeV. PYTHIA predicts jets with b-quarks to be wider on average than light-quark jets, with jets containing a single b-quark narrower and 2 b-quarks wider than inclusive jets. CDF does measure b-jets to be wider on average than inclusive jets, but the agreement with PYTHIA is poor unless the ratio of jets with 1 to 2 b-quarks in PYTHIA is decreased by ~20%. Comparisons to other MC are in progress.

$Z + b$-jet production

The cross section for $Z + b$-jet production is sensitive to the b quark density in the proton, and therefore the measurement tests pQCD predictions. Determining the cross section is also important since $Z + b$-jet production is a background for searches for new physics such as the Higgs boson in the channel $ZH \to Zb\bar{b}$.

DØ has measured the cross section ratio for $Z+b$-jet to Z+jet production [16] for jets with $p_T > 20$ GeV/c and $|\eta| < 2.5$ to be

$$\text{DØ}: \quad \sigma(Z+b-jet)/\sigma(Z+jet) = 0.023 \pm 0.004(stat)^{+0.002}_{-0.003}(syst).$$

The charm content was taken from the theoretical prediction of $Z+b$ and $Z+c$ production: $N_c = 1.69 N_b$ [17].

CDF has measured the cross section [18] for events with $66 < M_{ll} < 116$ GeV$/c^2$ and for jets in the range $p_T^{jet} > 20$ GeV/c and $|\eta^{jet}| < 1.5$ to be

$$CDF: \quad \sigma(Z+b-jet) \times \mathscr{B}(Z \to l^+l^-) = 0.93 \pm 0.29(stat) \pm 0.21(syst)\mathrm{p}b$$

and the ratio to Z+jets

$$CDF: \quad \sigma(Z+b-jet)/\sigma(Z+jet) = 0.0236 \pm 0.0074(stat) \pm 0.0053(syst).$$

This is consistent with the NLO predictions of 0.45 ± 0.07 pb and 0.0181 ± 0.0027, respectively, which are based on [17] using MCFM and CTEQ6M PDFs. The CDF measurement uses a template fit based on the mass of charged tracks at the secondary vertex, in a similar way as was done for the inclusive b-jet cross section measurement, rather than making assumptions on the charm content. The measurement is still statistically limited and is being repeated with the 1 fb^{-1} data sample currently available from the Tevatron.

SUMMARY

The inclusive jet cross section has been measured by CDF in rapidity regions ranging from $|y| < 0.7$ to $1.6 < |y| < 2.1$, finding good agreement with NLO pQCD and placing significant constraints on the gluon PDF at high x. DØ has measured the inclusive isolated prompt photon cross section and finds agreement with NLO within uncertainties. CDF has measured the cross section for isolated prompt diphoton production and finds that NLO processes including fragmentation contributions, as well as soft gluon resummation, are needed to describe the data as a function of diphoton mass, transverse momentum of the diphoton system, and $\Delta\phi$ between the photons. CDF has measured the W+jets cross section and DØ has recent comparisons of Z+jet production to the Sherpa MC which includes Matrix Element to Parton Showering matching using the CKKW prescription, an important test of this MC which may be used to model processes involving the Higgs boson. Heavy flavor jets, in particular b-jet production has been studied at the Tevatron. CDF has measured the inclusive b-jet cross section and finds agreement with NLO pQCD within uncertainties. CDF has a preliminary measurement of the inclusive b-jet shape as a function of p_T. Both DØ and CDF have measured the ratio of $Z+b$-jet to Z+jet cross sections, and CDF has measured the $Z+b$-jet cross section; these are found to be in agreement with NLO predictions. Many of these measurements will benefit from larger data samples, including diphoton production and $Z+b$-jet production, as well as other measurements still in progress including dijet production, $b\bar{b}$ production, and photon + heavy-flavor production.

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