QCD at the Tevatron

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Recent measurements of selected QCD processes at the Tevatron are reviewed and confronted with theoretical calculations. Results on inclusive jet production at large transverse momentum ($p_T$) are compared to predictions from next-to-leading order (NLO) perturbative QCD (pQCD). Kinematic distributions of jets with light and heavy flavor produced in association with electroweak bosons are compared to expectations from leading-order (LO) QCD calculations supplemented with parton-shower models. Properties of QCD radiation in hard-scatter events are investigated using azimuthal correlations between two leading jets in multi-jet events, while aspects of softer radiation are examined through properties of energy flow within jets. Finally, characteristics of soft interactions underlying the hard scatter are explored in the context of tuning the parameters of phenomenological models employed in QCD Monte Carlo event generators.

The ongoing physics program at the Tevatron offers an unprecedented opportunity to explore a wide variety of QCD issues at a level of high precision. In Run II, the collision energy increased to $\sqrt{s} = 1.96$ TeV, from 1.8 TeV in Run I, providing an increase by a factor of 5 in the inclusive jet cross section at $p_T \approx 600$ GeV/c. Now, in the early phase of Run II, the CDF and DØ experiments have already collected substantially more luminosity than in all of Run I. As a consequence, the current reach in $p_T$ of the inclusive jet spectrum exceeds that of Run I by $\approx 150$ GeV/c, and events with dijet masses in the range of 1.2–1.3 TeV/c$^2$ have been collected by both collaborations, probing interaction length scales of $10^{-19}$ m. With steadily increasing data samples, we are all looking forward to improved precision measurements and to exploiting the discovery potential for new physics.

Production of jets at large $p_T$ has been long recognized as one of the most interesting probes of pQCD. Within the pQCD framework, hard-scattering processes are described by a convolution of partonic cross sections with parton distribution functions (PDFs). Thus, measurements of high-$p_T$ interactions probe PDFs and the strong coupling constant, $\alpha_s$, and test current phenomenological tools (among others, high-order matrix-element calculations, models of parton showers, the interplay between these two approaches, resummation techniques etc.). Deviations from pQCD, not accommodated by uncertainties in these components, may indicate presence of physics beyond the Standard Model (e.g., parton compositeness).

Production of objects at low and moderate $p_T$ is sensitive to fragmentation, multiple-parton interactions, and to the nature of remnants of the colliding particles not participating in the hard collision. Studies of these effects help develop phenomenological descriptions of such soft physics and in the tuning of event generators.

The hard-scattered quarks and gluons in the final state fragment into jets of
particles that subsequently interact in the detectors. Experimentally, jets are usually defined by their energy deposition in multiple calorimeter towers. For Run II, both CDF and DØ collaborations adopted a new iterative fixed-radius cone algorithm. While Run-I jets consisted of $E_T$-weighted sums of calorimeter towers, the Run II cone algorithm defines jets by summing 4-momenta of towers within a cone, using midpoints between such jets as additional seeds for the algorithm to minimize sensitivity to infrared divergence of gluon radiation \[1\]. Analogous procedure can be applied at parton or particle levels. (CDF is also using their Run I version of the cone algorithm JetClu \[2\] for easier comparison with previous results.) Both collaborations continue using the $K_T$ clustering algorithm, based on relative transverse momenta between clustered objects.

The high-$x$ behavior of PDFs has been scrutinized intensely for the past several years. The Run I measurement from DØ \[3\] of the inclusive jet cross section in several regions of pseudorapidity has provided powerful new information for the global determinations of PDFs by the CTEQ \[4\] and MRST \[5\] groups. Similar measurements are being pursued in Run II. DØ has recently presented the preliminary inclusive jet cross section as function of $p_T$ in 3 rapidity ($y$) bins (Fig. 1), and a dijet cross section for central rapidities $|y| < 0.5$ (Fig. 2), based on data corresponding to an integrated luminosity of 143 pb$^{-1}$. Given the large systematic errors, the data are in good agreement with NLO pQCD \[6\], for the parameters of the calculations noted in the figures. So far, there is no indication of parton substructure or presence of narrow resonances decaying to jets. The uncertainties, shown as bands on the plots of data/theory ratio, are dominated by the current understanding of the jet energy scale, and are expected to be reduced in near future.

![Image](image_url)
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Fig. 2. Left: Inclusive dijet cross section as function of dijet mass measured by DØ. Right: Ratio to NLO theory; the bands show the experimental and PDF uncertainties.

CDF has presented a measurement of the inclusive jet cross section for central rapidities ($0.1 < |y| < 0.7$) using a data sample of 177 pb$^{-1}$. It is compared to NLO pQCD [7] and to Run I result in Fig. 3 (both Run II and Run I results were obtained with their JetClu algorithm). The expected increase in the Run-II cross section as function of $p_T$ for the larger $\sqrt{s}$ is clearly visible. While there is reasonable agreement between data and theory, it will be interesting to re-examine these comparisons when experimental uncertainties become reduced.

Fig. 3. Left: Central inclusive jet cross section measured by CDF using the JetClu algorithm vs. jet $E_T$. Experimental and PDF uncertainties are also shown. Right: Ratio of jet cross sections for Run II to Run I, compared to NLO pQCD.

For a somewhat smaller data sample of 145 pb$^{-1}$, CDF measured the inclusive jet cross section over central rapidities using the $K_T$ clustering algorithm [9] and jet-size parameter values of $D = 0.5, 0.7, 1.0$. The results are presented in Fig. 4 for $D = 1.0$, in terms of ratios to NLO pQCD [10], using QCD scale $p_T^{\text{max}}/2$, and to the prediction from PYTHIA [11]. While the ratio to NLO exhibits an excess at lower values of $p_T$, that grows as the value of $D$ increases (not shown), no such...
effect is seen when comparing to PYTHIA with parameters tuned to CDF data on the properties of the “underlying event” (so called Tune A, see end of paper). This behavior may be due to the influence of particles in the underlying event on jet properties; the measured cross section is not corrected for this contribution. The underlying-event effects are not present in the NLO calculation, while they are included in the phenomenological model implemented in PYTHIA.

Production of electroweak bosons in association with several jets has become an area of increasing interest for pQCD. The cross section for processes with $n$ jets is directly sensitive to $\alpha_s^n$, and the presence of the heavy boson is expected to assure a more reliable perturbative calculation. NLO predictions are available up to $n=2$, while LO calculations (ALPGEN [10] code being primarily used by CDF and DØ) exist for larger values of $n$. Frequently, such LO calculations are interfaced at the parton level to event generators such as PYTHIA or HERWIG [11] to include the physics of soft emissions, described through the parton-shower approach, and to facilitate full simulation of experimental conditions following hadronization and modeling of underlying event. Such “enhanced-LO” procedures are of obvious interest for investigations of many related physics processes, including top-quark and Higgs-boson production, and searches for SUSY, for which $W/Z$ + jets production represents a major background. Figure 5 shows CDF data on the $W^+ + n$ jets cross section vs. the inclusive number of jets, and the dijet invariant mass distribution in $W^+ \geq 2$ jet events, for jets with $E_T > 15$ GeV and $|\eta| < 2.4$, for a data sample of 127 pb$^{-1}$. The measurements are compared to expectations from ALPGEN+HERWIG (including full detector simulation and event reconstruction) for two choices of QCD scale of $M_W$ and $\sqrt{<p_{T,jet}^2>}$; the calculations bracket the data, but the theoretical uncertainty is large at LO.

CDF and DØ have developed algorithms to identify jets originating from $b$-quarks ($b$-tagging). Figure 6 illustrates results from DØ for 174 pb$^{-1}$ of data on dijet mass distribution in $W^+ \geq 2b$-tagged jet events, compared to ALPGEN+PYTHIA

Fig. 4. Left: Ratio of the central inclusive jet cross section measured by CDF using the $K_T$ algorithm (with $D = 1.0$) to NLO pQCD, as function of jet $p_T$. Right: Similar ratio to prediction from PYTHIA (Tune A).
predictions for several contributing processes, and for jet $p_T$ distribution in $Z + b$ events compared to PYTHIA + experimental background. Good agreement is observed between data and expectations; forthcoming high-luminosity data will challenge NLO calculations with much reduced uncertainties.

Fig. 6. Left: Invariant mass distribution of two leading jets in $W + \geq 2 b$-tagged jet events measured by DØ. Data are compared to the simulated processes using ALPGEN+PYTHIA. Right: $E_T$ spectrum of $b$-tagged jets associated with $Z$ production measured by DØ. The shaded histogram represents background contributions estimated from data. The open histogram is the sum of background and simulation of $Z + b$ production using PYTHIA, normalized to data.
Aspects of radiation in hard-scatter events can be studied without reconstructing multiple jets, by simply investigating the azimuthal angle between the two leading jets, $\Delta \phi_{dijet}$. At lowest-order, the two jets are expected to be produced back-to-back, $\Delta \phi_{dijet} \approx \pi$. Thus, the distribution in $\Delta \phi_{dijet}$ away from $\pi$ reflects the presence of higher-order radiation. DØ data on $\Delta \phi_{dijet}$ for 150 pb$^{-1}$, normalized by the dijet inclusive cross sections integrated over the same phase-space, are presented in Fig. 7 for four ranges of $p_T$ of the leading jet (the second leading jet was required to have $p_T > 40$ GeV/c). Data is compared to pQCD LO and NLO calculations for 3-jet production using nlojet++\[12\]. It is apparent that the LO calculation has a very limited range of applicability, while the NLO prediction, with up to 4 partons in the final state, provides a good description over a large range of $\Delta \phi_{dijet}$. PYTHIA and HERWIG employ parton-shower models to describe higher-order QCD effects. HERWIG agrees with the data well over the entire range of $\Delta \phi_{dijet}$; the default version of PYTHIA provides a rather poor representation (dashed lines). However, the amount of radiation in PYTHIA-generated events can be adjusted, e.g., by varying the scale factor for the maximum $p_T$ allowed in the initial-state parton shower (PARP(67)). The bands correspond to the variations in this parameter between the default value of 1.0 and 4.0 (used in CDF Tune A). The higher values provide a better description, and the data clearly can be used to further tune the PYTHIA model.

Fig. 7. Left: $\Delta \phi_{dijet}$ distributions from DØ in four regions of leading-jet $p_T$. The solid (dashed) lines show the NLO (LO) pQCD predictions. Right: Comparison of $\Delta \phi_{dijet}$ distributions to results from HERWIG (solid line), default PYTHIA (dashed line), and a possible variation in the level of initial-state radiation in PYTHIA (band).
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The distribution of energy flow within the jet cone is sensitive to soft parton radiation. Figure 8 shows CDF data on the fraction of jet $p_T$ integrated over the outer part of the cone ($0.3 < r < 0.7$ for $R = 0.7$ size cones) vs. jet $p_T$, using the midpoint algorithm for 170 pb$^{-1}$. PYTHIA, with the Tune-A set of parameters, as well as HERWIG, properly describe the transition of jet shapes from gluon-dominated at low $p_T$ to quark-dominated at large $p_T$; the default version of PYTHIA, and PYTHIA with multiple-parton interactions switched off, undershoot the data.

![CDF data on the fraction of jet $p_T$ integrated over the outer part of the cone.](image)

**Fig. 8.** Left: CDF measurement of “jet-$p_T$ fraction” in the outer part of the jet cone, $0.3 < r < 0.7$, vs. jet $p_T$, compared to prediction from PYTHIA (Tune A). Expectations for pure quark and gluon-initiated jets are also shown. Right: Same data compared to results from HERWIG, and PYTHIA with default settings and with no multiple-parton interactions.

In addition to objects emerging from the hard scatter, events contain soft particles produced through several mechanisms, often collectively referred to as underlying event (UE). These include fragments of beam remnants, multiple-parton interactions, and initial and final-state radiation. Not all of these contributions are calculable within perturbation theory, and must therefore be modeled using Monte Carlo programs tuned to data. Since particles from UE influence jet properties, especially at low $p_T$, proper modeling of UE is essential to account for such effects. To enhance sensitivity to UE, in Run I CDF studied distributions of charged particles with $p_T > 0.5$ GeV/c and $|y| < 1.0$ in the region of the azimuthal plane transverse to the leading jet (defined using either charged particles or calorimeter information). Examples of similar Run II studies are presented in Fig. 9 for the density of charged particles in the transverse region vs. $p_T$ of the leading jet, and vs. $p_T$ of the charged particles in the transverse region (in bins of $p_T$ of the leading jet). The event generators require tuning of phenomenological parameters to data to describe the details of such distributions. CDF studies established a special tune of PYTHIA parameters, Tune A, which provides a significantly improved descrip-
tion of UE properties compared to default settings. Inclusion of other processes in the tuning is expected in the near future, and should help further constrain the parameters and verify the universality of this approach.

A prediction from PYTHIA Tune A is that, at $\sqrt{s} = 14$ TeV, $\approx 12\%$ of all interactions will result in hard scatters with $p_T > 10$ GeV/c — potentially an important effect on measurements in the high-luminosity environment of the LHC!

Further improvements in the understanding of aspects of QCD at the Tevatron, and development of related physics-analysis and simulation tools, will undoubtedly be of great benefit to the physics program at the start-up of the LHC.

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References
[1] G.C. Blazey et al., hep-ex/0005012 (2000).
[2] F. Abe et al., Phys. Rev. D45 (1992) 1448.
[3] B. Abbott et al., Phys. Rev. Lett. 86 (2001) 1707.
[4] J. Pumplin et al., JHEP 0207 (2002) 012; D. Stump et al., JHEP (2003) 046.
[5] A. Martin et al., Eur. Phys. J. C28 (2003) 455.
[6] W.T. Giele et al., Phys. Rev. Lett. 73 (1994) 2019.
[7] S.D. Ellis et al., Phys. Rev. Lett. 64 (1992) 1448.
[8] S.D. Ellis and D.E. Soper, Phys. Rev. D48 (1993) 3160.
[9] T. Sjostrand et al., Comp. Phys. Comm. 135 (2001) 238.
[10] M.L. Mangano et al., JHEP 0307 (2003).
[11] G. Marchesini et al., Comp. Phys. Comm. 67 (1992) 465.
[12] Z. Nagy, Phys. Rev. Lett. 88 (2002) 122003; Phys. Rev. D68 (2003) 094002.
[13] T. Affolder et al., Phys. Rev. D65 (2002) 092002; D. Acosta et al., hep-ph/0404004