QCD at the Tevatron

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Abstract. In this contribution, a number of QCD results on jet production from the CDF and D0 experiments in Run II are discussed in detail.

1. Introduction
The Run II at the Tevatron will define a new level of precision for QCD studies in hadron collisions. Both collider experiments, CDF and D0, expect to collect up to 8 fb\(^{-1}\) of data in this new run period. The increase in instantaneous luminosity, center-of-mass energy (from 1.8 TeV to 2 TeV) and the improved acceptance of the detectors will allow stringent tests of the Standard Model (SM) predictions in extended regions of jet transverse momentum, \(P_{\text{T}}^{\text{jet}}\), and jet rapidity, \(Y_{\text{jet}}\). The hadronic final states in hadron-hadron collisions are characterized by the presence of soft contributions (the so-called underlying event) from initial-state gluon radiation and multiple parton interactions between remnants, in addition to the jets of hadrons originated by the hard interaction. A proper comparison with pQCD predictions at the parton level requires an adequate modeling of these soft contributions which become important at low \(P_{\text{T}}^{\text{jet}}\). In this letter, a review of some of the most important QCD results from Run II is presented.

2. Inclusive Jet Production at the Tevatron
The measurement of the inclusive jet production cross section for central jets constitutes one of the pillars of the jet physics program at the Tevatron. It provides a stringent test of perturbative QCD predictions over almost nine orders of magnitude and probes distances up to \(\sim 10^{-19}\) m. Thanks to the increase in the center-of-mass energy in Run II the jet production rate has been multiplied (by a factor of five for jets with \(P_{\text{T}}^{\text{jet}} > 600\) GeV) and the first measurements have already extended the \(P_{\text{T}}^{\text{jet}}\) coverage by 150 GeV compared to Run I. In addition, both CDF and D0 experiments explore new jet algorithms following the theoretical work that indicates that the cone-based jet algorithm employed in Run I is not infrared safe and compromises a future meaningful comparison with pQCD calculations at NNLO.

Figure 1-left shows the measured cross section using the \(K_{\text{T}}\) algorithm [1] as a function of \(P_{\text{T}}^{\text{jet}}\), based on 385 pb\(^{-1}\) of CDF Run II data, and compared to NLO pQCD predictions. The cross section decreases by more than eight orders of magnitude as \(P_{\text{T}}^{\text{jet}}\) increases from 54 GeV/c up to about 700 GeV/c. The NLO pQCD predictions are computed using the JETRAD program [2] with CTEQ6.1M PDFs [3] and the renormalization and factorization scales (\(\mu_R\) and \(\mu_F\)) set to \(\mu_0 = \text{max}(L_{\text{T}}^{\text{jet}})/2\). The theoretical prediction includes a correction factor that approximately
accounts for non-perturbative contributions from the underlying event and fragmentation into hadrons. It was estimated as the ratio between the nominal transverse momentum distribution and the one obtained by turning off both the interactions between proton and antiproton remnants and the fragmentation in the Monte Carlo. The correction shows a strong $P_{T\text{jet}}$ dependence and decreases as $P_{T\text{jet}}$ increases from about 1.2 at $P_{T\text{jet}}$ of 54 GeV/c, and 1.1 for $P_{T\text{jet}}$ about 100 GeV/c, to 1.02 at high $P_{T\text{jet}}$. Figure 1-right shows the ratio data/theory as a function of $P_{T\text{jet}}$. Good agreement is observed in the whole range in $P_{T\text{jet}}$. A $\chi^2$ test, where the different sources of systematic uncertainty on the data are considered independent but fully correlated across $P_{T\text{jet}}$ bins, and the uncertainty on $C_{\text{HAD}}$ is also included, gives a $\chi^2$ probability of 56%. In addition, Figure 1-right shows the ratio of pQCD predictions using MRST2004 \cite{4} and CTEQ6.1M PDF sets, well inside the theoretical and experimental uncertainties.

Figure 2 shows the measured inclusive jet cross section by D0 based on the first 143pb$^{-1}$ of Run II data. The new midpoint\cite{5} jet algorithm has been used with a cone size $R=0.7$. This algorithm constitutes an improved version of the cone-based algorithm used in Run I and it is shown to be infrared safe when used in fixed-order parton-level calculations. The data is in good agreement with the pQCD NLO predictions using CTEQ6 parton density functions and $R_{\text{sep}}=1.3$. However, the measurement is dominated by a relatively large uncertainty on the absolute jet energy scale. Figure 3 shows the measured cross section by D0 as a function of the dijet invariant mass in dijet production of central jets. This measurement is particularly sensitive to the presence of narrow resonances decaying into jets of hadrons up to masses of 1.3 TeV. The data is well described by pQCD NLO predictions.

Nowadays, the Tevatron high-$P_{T\text{jet}}$ jet data is used, together with prompt-photon data from fixed target experiments, to constrain the gluon distribution at high-$x$. Jet measurements at large rapidities are important because they constrain the gluon density in a region in $P_{T\text{jet}}$ where no effect from new physics is expected. The CDF \cite{6} and D0 experiments \cite{1} have already extended the jet cross section measurements to the forward region for jets with $|y| < 2.4$ (see Figure 4). At the moment, the D0 results are affected by large systematic errors. In the near future the experiments will highly reduce their uncertainties and precise cross section measurements will allow to further constrain the gluon distribution and thus enhance their sensitivity to new physics at very high $P_{T\text{jet}}$.

\footnote{CDF results on forward jets using the $K_T$ algorithm are discussed in \cite{6}.}
Figure 2. The measured inclusive jet cross section by D0 compared to pQCD NLO predictions. Jets are searched for using the midpoint jet algorithm.

Figure 3. The measured inclusive dijet cross section by D0 as a function of the dijet mass compared to pQCD NLO predictions.

3. Study of the Underlying Event
As mentioned in previous section, the hadronic final states at the Tevatron are characterized by the presence of soft underlying emissions, usually denoted as underlying event, in addition to highly energetic jets coming from the hard interaction. The underlying event contains contributions from initial- and final-state soft gluon radiation, secondary semi-hard partonic interactions and interactions between the proton and anti-proton remnants that cannot be described by perturbation theory. These processes must be approximately modeled using Monte Carlo programs tuned to describe the data. The jet energies measured in the detector contain an underlying event contribution that has to be subtracted in order to compare the measurements to pQCD predictions. Hence, a proper understanding of this underlying event contribution is crucial to reach the desired precision in the measured jet cross sections. In the analysis presented here, the underlying event in dijet production has been studied by looking at regions well separated from the leading jets, where the underlying event contribution is expected to dominate the observed hadronic activity. Jets have been reconstructed using tracks...
with $p_{\text{track}} > 0.5$ GeV and $|\eta_{\text{track}}| < 1$ and a cone algorithm with R=0.7. The $\phi$ space around the leading jet is divided in three regions: towards, away and transverse (see Figure 5-left), and the transverse region is assumed to reflect the underlying event contribution. Figure 5-right shows the average track density in the transverse region as a function of $E_T^{\text{jet}}$ of the leading jet for the dijet inclusive sample and for events where the leading jets are forced to be back-to-back in $\phi$, in order to further reduce extra hard-gluon radiation. The observed plateau indicates that the underlying event activity is, to a large extend, independent from the hard interaction. The measurements have been compared to the predictions from PYTHIA [7] and HERWIG [8] Monte Carlo programs including leading-order QCD matrix elements plus initial and final parton showers. The PYTHIA samples have been created using a special tuned set of parameters, denoted as PYTHIA-Tune A, which includes an enhanced contribution from initial-state soft gluon radiation and a tuned set of parameter to control secondary parton interactions.
It was determined as a result of similar studies of the underlying event performed using CDF Run I data [9]. PYTHIA-Tune A describes the hadronic activity in transverse region while HERWIG underestimates the radiation at low $E_{\text{jet}}^T$. Similar measurements in $Z+\text{jet}(s)$ events would allow to explore the universality of the underlying event contribution in events with a very different colour configuration in the final state.

4. Jet Shapes
The internal structure of jets is dominated by multi-gluon emissions from the primary final-state parton. It is sensitive to the relative quark- and gluon-jet fraction and receives contributions from soft-gluon initial-state radiation and beam remnant-remnant interactions. The study of jet shapes at the Tevatron provides a stringent test of QCD predictions and tests the validity of the models for parton cascades and soft-gluon emissions in hadron-hadron collisions. The CDF experiment has presented results on jet shapes for central jets with transverse momentum in the region $37 \text{ GeV} < P_{\text{jet}}^T < 380 \text{ GeV}$, where jets are searched for using the midpoint\(^2\) algorithm and a cone size $R = 0.7$. The integrated jet shape, $\Psi(r)$, is defined as the average fraction of the jet transverse momentum that lies inside a cone of radius $r$ concentric to the jet cone:

$$\Psi(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{P_T(0, r)}{P_T(0, R)}, \quad 0 \leq r \leq R$$

where $N_{\text{jet}}$ denotes the number of jets. The measured jet shapes have been compared to the predictions from PYTHIA-Tune A and HERWIG Monte Carlo programs.

![Figure 6.](image)

Figure 6. The measured integrated jet shape compared to different Monte Carlo predictions.

In addition, two different PYTHIA samples have been used with default parameters and with and without the contribution from multiple parton interactions (MPI) between proton and antiproton remnants, the latter denoted as PYTHIA-(no MPI), to illustrate the importance of a proper modeling of soft-gluon radiation in describing the measured jet shapes. Figure 6(left) presents the measured integrated jet shapes, $\Psi(r/R)$, for jets with $37 < P_{\text{jet}}^T < 45 \text{ GeV}$, compared to HERWIG, PYTHIA-Tune A, PYTHIA and PYTHIA-(no MPI) predictions. In\(^2\) A 75% merging fraction has been used instead of the default 50%.
addition, Figure 6(right) shows, for a fixed radius $r_0 = 0.3$, the average fraction of the jet transverse momentum outside $r = r_0$, $1 - \Psi(r_0/R)$, as a function of $P_T^{\text{jet}}$ where the points are located at the weighted mean in each $P_T^{\text{jet}}$ range. The measurements show that the fraction of jet transverse momentum at a given fixed $r_0/R$ increases ($1 - \Psi(r_0/R)$ decreases) with $P_T^{\text{jet}}$, indicating that the jets become narrower as $P_T^{\text{jet}}$ increases. PYTHIA with default parameters produces jets systematically narrower than the data in the whole region in $P_T^{\text{jet}}$. The contribution from secondary parton interactions between remnants to the predicted jet shapes (shown by the difference between PYTHIA and PYTHIA-(no MPI) predictions) is relatively small and decreases as $P_T^{\text{jet}}$ increases. PYTHIA-Tune A predictions describe all of the data well. HERWIG predictions describe the measured jet shapes well for $P_T^{\text{jet}} > 55$ GeV but produces jets that are too narrow at lower $P_T^{\text{jet}}$. Figure 7(left) shows the measured integrated jet shapes, $\Psi(r/R)$, for jets with $37 < P_T^{\text{jet}} < 45$ GeV, compared to PYTHIA-Tune A and the predictions for quark- and gluon-jets$^3$ separately. Figure 7(right) shows the measured $1 - \Psi(r_0/R)$, $r_0 = 0.3$, as a function of $P_T^{\text{jet}}$. The Monte Carlo predictions indicate that the measured jet shapes are dominated by contributions from gluon-initiated jets at low $P_T^{\text{jet}}$ while contributions from quark-initiated jets become important at high $P_T^{\text{jet}}$. This can be explained in terms of the different partonic contents in the proton and antiproton in the low- and high-$P_T^{\text{jet}}$ regions, since the mixture of gluon- and quark-jet in the final state partially reflects the nature of the incoming partons that participate in the hard interaction. For a given type of parton-jet in the Monte Carlo (quark- or gluon-jet), the observed trend with $P_T^{\text{jet}}$ shows the running of the strong coupling constant, $\alpha_s(P_T^{\text{jet}})$. Jet shape measurements thus introduce strong constrains on phenomenological models describing soft-gluon radiation and the underlying event in hadron-hadron interactions. Similar studies with b-tagged jets will be necessary to test our knowledge of b-quark jet fragmentation processes in hadronic interactions, which is essential for future precise Top and Higgs measurements.

$^3$ Each hadron-level jet from PYTHIA is classified as a quark- or gluon-jet by matching ($y - \phi$ plane) its directions with that of one of the outgoing partons from the hard interaction.
5. $\Delta$φ$_{\text{dijet}}$ Decorrelations
The D0 experiment has employed the dijet sample to study azimuthal decorrelations, $\Delta$φ$_{\text{dijet}}$, between the two leading jets. The normalized cross section:

$$\frac{1}{\sigma_{\text{dijet}}} \frac{d\sigma}{d\Delta\phi_{\text{dijet}}}$$

is sensitive to the spectrum of the gluon radiation in the event. The measurements has been performed in different regions of the leading jet $P_T^{\text{jet}}$ starting at $P_T^{\text{jet}} > 75$ GeV and the second jet is required to have at least $P_T^{\text{jet}} > 40$ GeV.

Figure 8. Measured azimuthal decorrelations in dijet production for central jets compared to pQCD predictions in different regions of $P_T^{\text{jet}}$ of the leading jet.

Figure 8 shows the measured cross section compared to LO and NLO predictions from NLOJET++ program [10].

The LO predictions, with at most three partons in the final state, is limited to $\Delta$φ$_{\text{dijet}} > 2\pi/3$, for which the three partons define a Mercedes-star topology. It presents a prominent peak at $\Delta$φ$_{\text{dijet}} = \phi$ corresponding to the soft limit for which the third parton is collinear to the direction of the two leading partons. The NLO predictions, with four partons in the final state, describes the measured $\Delta$φ$_{\text{dijet}}$ distribution except at very high and very low values of $\Delta$φ$_{\text{dijet}}$ where additional soft contributions, corresponding to a resummed calculation, are necessary. A reasonable approximation to such calculations is provided by parton shower Monte Carlo programs.

Figure 9 presents the measured cross section compared to PYTHIA-Tune A, PYTHIA and HERWIG predictions in different regions of $P_T^{\text{jet}}$. PYTHIA with default parameters underestimates the gluon radiation at large angles. PYTHIA-Tune A predictions, which include an enhanced contribution from initial-state soft gluon radiation and secondary parton interactions, describe the azimuthal distribution. HERWIG also describes the data although tends to produce less radiation than PYTHIA-Tune A close to the direction of the leading jets.

6. W+jet(s) Production
A detailed study of hard processes involving the associated production of a W boson and a given number of jets in the final state is a main goal of the CDF physics program in Run
2. These processes constitute the biggest background to Top and Higg production in hadron colliders. Therefore, precise measurements of $W^+N_{\text{jet}}$ cross sections will be essential to test the NLO QCD calculations used in order to estimate QCD-related backgrounds to Top/Higgs signals. During the last years a number of new Boson+$N_{\text{jet}}$ programs have become available [11] which include larger jet multiplicities in the final state, in addition to NLO calculations for the W+dijet case. These different programs are being interfaced to parton-shower models using different matching procedures in order to avoid double counting in the gluon radiation. Figure 10 shows the measured inclusive cross section for $W^+ \geq n_{\text{jet}}$ production by CDF based on 127 pb$^{-1}$ of Run II data. Jets have been searched for using the Run I cone algorithm with $R = 0.4$ and only
jets with $E_T^{\text{jet}} > 15$ GeV and $|\eta^{\text{jet}}| < 2.4$ have been considered. The measurements are compared to similar results from Run I [12] and pQCD LO predictions for $W + n_{\text{partons}}$ as implemented in ALPGEN interfaced to the parton cascades from HERWIG. The measured cross section in Run II is about 10% larger than that in Run I thanks to the new centre-of-mass energy. The relative rates as a function of jet multiplicity are similar to those observed in Run I which indicates that the $W$ cross section is reduced by 80% per each jet required. The pQCD LO predictions describe the data well but suffer from large uncertainties due to the strong dependence on the hard scale used in the calculation. Figure 11 present the measured $E_T^{\text{jet}}$ spectrum for the $n^{\text{th}}$ jet in $W + \geq n_{\text{jet}}$ production. The spectrum for the least energetic jet is sensitive to the details of the interface between the pQCD LO calculation and the parton shower evolution taken from HERWIG. The measured spectrum is in agreement with the predictions from ALPGEN+HERWIG within the present uncertainties. In the data the systematic errors are dominated by the jet energy scale determination while the LO theoretical predictions present a strong dependence on the selected renormalization and factorization scales.

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References
[1] Stephen D. Ellis, Davision E. Soper, Phys.Rev. D48 (1993) 3160-3166.
[2] W.T. Giele, E.W.N. Glover, D. A. Kosower, Nucl. Phys. B403 (1993) 633-670.
[3] J. Pumplin et al., JHEP 0207, 012 (2002).
[4] A. D. Martin et al., Eur. Phys. J. C 23, 73 (2002).
[5] G. C. Blazey, et al., hep-ex/0005012.
[6] S.D. Ellis, J. Huston and M. Toennesmann, hep-ph/0111434.
[7] Olga Norniella, this proceedings.
[8] H.-U. Bengtsson and T. Sjöstrand, Comp. Phys. Comm. 46 (1987) 43.
[9] G. Marchesini et al., Comp. Phys. Comm. 67 (1992) 465.
[10] D. Acosta et al., CDF Collaboration, Phys. Rev. D65, 092002, (2002).
[10] Zoltán Nagy, Zoltán Trócsányi, Phys. Rev. Lett. 79 (1997) 3604-3607
[11] M. Mangano et al.: ‘ALPGEN’, preprint hep-ph/0206293.
    E. Boss et al.: ‘CompHEP’, preprint hep-ph/9503280.
    S. Tsuno et al.: ‘GR@APPA’, preprint hep-ph/0204222.
    F. Maltoni and T. Stelzer: ‘MADGRAPH’, preprint hep-ph/0208156.
    K. Ellis and J. Campbell: ‘MCFM’, preprint hep-ph/0202176.
[12] T. Affolder et al., The CDF Collaboration, Phys. Rev. D 63, 072003 (2001).