Abstract

Results on recent QCD measurements performed at the Tevatron $p\bar{p}$ Collider at $\sqrt{s} = 1.96$ TeV are here reported. The inclusive jet and dijet mass cross sections are compared to NLO pQCD calculations and to Run I results. The production rates and kinematic properties of $W +$ jets production processes are compared to “enhanced” LO theoretical predictions. Non-perturbative “soft” interactions leading to the underlying event are studied and compared to QCD Monte Carlo phenomenological models.
1 Introduction

Measurements aimed to test the predictions of Quantum Chromodynamics (QCD), the currently accepted theory of the strong interactions among quarks and gluons, represent a very important part of the physics program carried out at the Tevatron $p\bar{p}$ Collider. The large amount of data expected to be accumulated during Run II and the increase in center-of-mass energy ($\sqrt{s}$) from 1.8 to 1.96 TeV, give CDF \cite{1} and D0 \cite{2} experiments an unique opportunity to make precision tests of next-to-leading order perturbative QCD (NLO pQCD) and, by looking for deviations from theory, to search for new particles and new interactions down to a distance scale of $\sim 10^{-19}$ m.

An optimal understanding of QCD in hadron collisions allows to improve the constraints on the fundamental parameters of the theory, $\alpha_s$ and the parton distribution functions (PDFs); results in a better control on the standard QCD production which represents the main background for most of the processes of interest, such as top and Higgs production; gives phenomenological input for the modeling of the non-perturbative regime (where the theory fails in its predictivity), such as the “soft” interactions generating the underlying event which accompanies the “hard” collision.

2 Inclusive Jet Cross Section

2.1 Experience from Run I

During Run I, the CDF and DØ Collaborations performed several QCD measurements which, in general, were found to be in reasonable agreement with theoretical expectations. However, initial inclusive jet cross section measurements showed an excess of data at high $E_T^J$ over NLO pQCD predictions, which raised great interest among the high energy physics community and stimulated a reevaluation of the uncertainties associated to theoretical calculations \cite{3}. Subsequent studies have demonstrated that such excess can be explained within the Standard Model in terms of a larger than expected gluon distribution at high $x$. A better agreement of data versus theory was actually observed in subsequent measurements involving an increased data sample when PDFs with an enhanced gluon contribution at high $x$ (CTEQ4HJ) were considered \cite{4,5} (see fig.1 left). Given the large uncertainty in the NLO calculations arising from the flexibility allowed by current knowledge of PDFs as well as the uncertainty in the experimental results, CDF and DØ data were found to be consistent between them, with previous measurements and with NLO pQCD.

Most recent global PDFs fits have used results from these Run I analyses so to include the Tevatron high $E_T$ jet data in the determination of the high $x$ gluon distribution. In particular, by involving jets in a range of rapidity
intervals up to the forward region, the DØ measurement allowed to constrain the partons over a much wider $x$ kinematical range. These new PDF sets (CTEQ6 and MRST02) represent the most complete information available for Run II QCD predictions, but are still characterized by a big uncertainty on the gluon distribution at high $x$ (see fig.1, right).

With larger data samples collected with a higher cross section\textsuperscript{1}, as well as with the improved performances of the upgraded CDF and DØ detectors, Run II jet measurements are expected to reduce this uncertainty so to give the best constraint on PDFs before the LHC era.

2.2 Preliminary Run II measurements

Both CDF and DØ experiments have recently performed preliminary Run II measurements of the inclusive jet cross section.

In CDF, jets were reconstructed using the same Run I cone algorithm (JetClu, $R = 0.7$) in the rapidity range $0.1 < |\eta| < 0.7$; the same Run I

\textsuperscript{1}The increase in $\sqrt{s}$ from 1.8 to 1.96 TeV leads to a significant increase in jet cross section at high $P_T$, about a factor of 5 at $P_T \sim 600$ GeV.
Figure 2: Inclusive jet cross section as measured in CDF analyzing 177 pb$^{-1}$ of Run II data at $\sqrt{s} = 1.96$ TeV. Upper left: the results are compared on a log scale to the NLO pQCD prediction from EKS ($\mu = E_T/2$, $R_{sep} = 1.3$, CTEQ6.1M PDFs). Upper right: ratio of data to theoretical prediction on a linear scale (the upper plot is a zoom obtained by excluding the last bin). Lower: Ratio of Run II inclusive jet cross section to Run I one compared to theoretical prediction. The increase in cross section due to the increase in $\sqrt{s}$ is evident. Data points include the statistical error, the error band represents the change in the cross section due to the 3% energy scale shift corresponding to the dominant experimental uncertainty. The two solid lines represent the dominant theoretical uncertainty due to PDFs.

correction procedures were also used to properly correct the jet spectrum for both detector and physics effects affecting jet measurements\textsuperscript{[3]}. Four different samples (from 20, 50, 70 and 100 GeV jet $E_T$ trigger threshold requirements),
were combined after correcting for trigger prescale and efficiency effects giving a jet $E_T$ spectrum already extending the Run I reach by about 150 GeV and spanning approximately 9 orders of magnitude. The results reported here and summarized in fig.2 correspond to an integrated luminosity of 177 $pb^{-1}$ collected during the period 2002-3. In general, a reasonably good agreement is found within errors between data and NLO pQCD theory (EKS9) using the latest CTEQ PDF sets. Systematic uncertainties are found to be dominated by the error on jet energy scale in data and on high $x$ gluon distribution function in theoretical calculations. Work is in progress in order to reduce the energy scale uncertainty, to use other jet algorithms like MidPoint and Kt and to extend the analysis to forward jets.

A completely new analysis was performed in D0. Jets were reconstructed with an “optimized” cone algorithm (MidPoint, $R = 0.7$) and then corrected with a new set of jet corrections as derived from $\gamma$-jet and dijet balancing studies on data as well as from Monte Carlo simulations. The jet energy scale derived with this method was characterized by large statistical and systematic uncertainties increasing with jet energy due to extrapolation (mostly generated by small $\gamma$+jet sample statistics above 200 GeV). Jet measurements were restricted to the central region ($|\eta| < 0.5$) to limit the impact of these uncertainties which are the dominant ones, but are expected to be gradually reduced with an increasing amount of collected data. Finally, jet resolution effects were taken into account by unsmearing the measured jet spectrum with an unfolding procedure. Fig.3 summarizes the results of a preliminary measurement from the analysis of four different jets samples (from 25, 45, 65 and 95 GeV jet $P_T$ trigger thresholds) based on an integrated luminosity of 34 $pb^{-1}$. An agreement within the rather large uncertainties (dominated by the systematic error on the jet energy scale) is observed between data and NLO theory (JETRAD) using CTEQ6 and MRST01 PDF sets.

3 Dijet Invariant Mass Distribution

The dijet mass cross section measurement represents another powerful test of NLO pQCD. It is also sensitive to new physics such as quark compositeness (expected to give departure from theory at high masses) and new models beyond the Standard Model predicting new particles decaying to dijet (expected to generate a peak in the dijet invariant mass spectrum at high values).

The CDF and D0 Collaborations have both performed a preliminary Run II measurement of the dijet mass spectrum using similar criteria as well as the same jet trigger samples as the ones involved for the inclusive jet cross

\[ E_T^J = 666 \text{ GeV} \] is the highest jet $E_T$ so far observed.
Figure 3: Inclusive jet cross section as measured in D0 analyzing 34 pb$^{-1}$ of Run II data at $\sqrt{s} = 1.96$ TeV. Upper: the results are compared on a log scale to the NLO pQCD prediction from JETRAD ($\mu = \frac{P_{T}^{\text{max}}}{2}, R_{\text{sep}} = 1.3$, CTEQ6M PDFs). Lower: linear comparison of data to theoretical prediction with CTEQ6M (left) and MRST01 (right) PDF sets. Data points include the statistical error, the error band represents the total systematic uncertainty.

section study. In particular, considering the two leading jets per event in order to reconstruct the invariant mass observable, the same Run I cone algorithm and analysis strategies (Jetclu R = 0.7 jets reconstructed up to $|\eta| < 2.0$ and corrected a the parton level) were used in CDF, while a completely new analysis was performed in D0 using the MidPoint algorithm and applying the same jet scale corrections and unsmearing procedures as the ones used for the inclusive jet cross section measurement to jets reconstructed in the same rapidity range ($|\eta| < 0.5$).

Results from CDF, corresponding to an integrated luminosity of 75 pb$^{-1}$,
are summarized in the upper plots of Fig. 4. The comparison to Run I data (upper left) shows that the Run II dijet mass spectrum already extends the Run I one by about 350 GeV. The effect of the increase in cross section as consequence of the increase in $\sqrt{s}$ is more evident in terms of the Run II over Run I cross section ratio (upper right). A good agreement with a LO calculation is observed within systematic uncertainties (dominated by the one on jet energy)

$^3$The highest dijet mass value was $M_{JJ} = 1364$ GeV.
scale). The ongoing work performed in order to optimize the jet corrections, to use the MidPoint algorithm as well as to implement a comparison to a NLO calculation is expected to update these preliminary results.

The lower plots of fig.4 summarize the results obtained from DØ relatively to an integrated luminosity of \(34 \text{ pb}^{-1}\). Here the dijet mass spectrum measurement is compared to a NLO calculation (JETRAD) on a linear scale considering two different choices for the PDF sets: CTEQ6 (lower left) and MRST01 (lower right). As in the case of the inclusive jet cross section, a reasonable agreement between data and NLO theory is observed within the errors (dominated by the jet energy uncertainty) for both the PDF sets.

4 W + Jets Production

The production of W bosons in association with high energy hadronic jets at the Tevatron \(p\bar{p}\) collider provides the opportunity to test pQCD at large momentum transfer. Understanding the QCD production for W + jets events is also important for the study of many Standard Model and new physics processes (such as top quark measurements and Higgs and Susy searches) for which it represents a major background.

A preliminary study was performed in CDF using \(127 \text{ pb}^{-1}\) of Run II data at \(\sqrt{s} = 1.96\) TeV collected in the period 2002-3. The production rates and kinematic properties of \(W + \geq n\) jets events were studied and compared to the predictions of an “enhanced” LO QCD Monte Carlo (MC). The well understood electroweak \(W \rightarrow e\nu\) decay channel was considered as it provides an efficient and clean identification of \(W\) candidate with a low background contamination. Jets, reconstructed with the standard CDF cone algorithm (JetClu) with \(R = 0.4\) and corrected to the parton level, were selected by requiring \(E_T^J > 15\) GeV and \(|\eta| < 2.4\). QCD production, faking \(W + n\) jet events, was found to be the largest source of background in all jet multiplicity bins up to \(n = 3\), with top production becoming dominant at higher \((\geq 4)\) multiplicities. The inclusive cross sections for \(p\bar{p} \rightarrow (W^{\pm} \rightarrow e^{\pm}\nu) + n\) jets production \((\sigma_{W^{\geq n}\text{jets}})\) were obtained after backgrounds and detection efficiencies (as derived from data and MC studies) were properly taken into account. The “enhanced” LO QCD MC consisted of the ALPGEN program \((\mu = M_W^2, \langle P_T^J \rangle^2 >; \text{CTEQ5L PDFs})\), used to generate \(W \rightarrow e\nu + n\) partons \((n = 1 \text{ to } 4)\) at LO, interfaced with HERWIG for the implementation of the shower evolution for the initial and final state radiation, of the hadronization process and for the simulation of the underlying event; finally, the full detector simulation and event reconstruction were applied.

4The selection of this cone size was motivated by related studies on top quark physics.
Figure 5: Upper: $W + \geq n$ jets cross sections measured in CDF analyzing 127 pb$^{-1}$ of Run II data at $\sqrt{s} = 1.96$ TeV compared to LO theoretical predictions (left); ratio of cross sections ($\sigma_{W \geq n \text{jets}} / \sigma_{W \geq n-1 \text{jets}}$) as a function of jet multiplicity (right). Error bars on data points include both statistical and systematic uncertainties. The filled band corresponds to the variation of the theoretical predictions with $\mu_R/F$. Lower: differential cross section as a function of jet $E_T$ for the leading jet in $W \geq 1$ jets events, the second highest jet $E_T$ in $W \geq 2$ jets events and so on up to $W \geq 4$ jets events, respectively from top to bottom (left); $M_{JJ}$ distribution for the two leading jets in $W \geq 2$ jets events (right). Data points include statistical errors, while the band represents the jet energy systematic uncertainty. The two lines are fits to the theoretical distributions for two different values of $\mu_R/F$.

The measured $W + \geq n$ jets cross section as a function of the jet multiplicity is compared to the theoretical calculations in fig.5 (upper left). Error bars on data points represent both statistical and systematic uncertainties which, being dominated by the systematic error on jet energy and ranging from $\sim$...
13% for $\sigma_{W \geq 1\text{jets}}$ to $\sim 45\%$ for $\sigma_{W \geq 4\text{jets}}$, clearly limit the sensitivity of this measurement. The filled band shows the variation of the theoretical prediction with the renormalization/factorization scale ($\mu_{R/F}$), the dominant theoretical systematic uncertainty as expected for a LO calculation. Also shown in fig.5 (upper right) is the ratio $\sigma_{W \geq n\text{jets}} / \sigma_{W \geq n-1\text{jets}}$ as a function of the jet multiplicity which gives a measure of the decrease in cross section with the addition of 1 jet. Being characterized by a reduced dependence on systematic uncertainties for both data and theory measurements this ratio is related to the magnitude of $\alpha_s$ (even if not giving a direct measure of it). For comparison, Run I results \[16\] are also reported in the same figure. The measured Run II over Run I cross section ratios are found to be in agreement with theoretical expectations. In general, it can be concluded that a reasonable data to theory comparison is observed.

Furthermore, the theory to data comparison was also investigated in some jet kinematic variable distributions: the differential cross section as a function of the jet $E_T$ and the dijet invariant mass ($M_{JJ}$) and angular separation ($\Delta R_{JJ}$). Fig.5 (lower left) shows the distributions for the leading jet $E_T$ in $W \geq 1$ jets events, the second highest jet $E_T$ in $W \geq 2$ jets events, and so on up to $W \geq 4$ jets events, respectively going from the top to the bottom plot. Fig.5 (lower right) reports the $M_{JJ}$ distribution for the two leading jets in $W \geq 2$ jets events. Data points include statistical errors, while the band represents the jet energy systematic uncertainty (the dominant one). The two lines are fits to the theoretical distributions calculated at different values for $\mu_{R/F}$. In general, a fair data to theory comparison is found within errors\[6\] especially for the $M_{JJ}$ and $\Delta R_{JJ}$ distributions (which, at low values, are in particular sensitive to soft and collinear jet production) indicating that the LO calculation convoluted with the HERWIG parton shower approach, even if representing a partial higher order correction, can reproduce the data. However, the not negligible discrepancies between data and theory in the differential cross section at high $E_T$\[7\] can indicate some limitations of the parton radiation in the shower approach in properly describing the high multiplicity topologies.

---

\[5\] The inclusive W cross section ($\sigma_{W \geq 0\text{jets}}$) was generated at LO by HERWIG. This LO calculation, being independent of QCD effects, is not sensitive to the choice for $\mu_{R/F}$ and is lower than data due to the LO approximation.

\[6\] Theoretical uncertainties are characterized by a reduced dependence on $\mu_{R/F}$ with respect to the predictions on $\sigma_{W \geq n\text{jets}}$.

\[7\] A major theoretical limitation in such kind of studies comes from the difficulty to properly merge matrix element calculations for different parton multiplicities avoiding double counting. For this reason only inclusive quantities are considered.
5 Underlying Event Studies

The hard scattering process at hadron colliders is usually accompanied by the so-called “underlying event” (UE) which, consisting of the contributions from beam-beam remnants, initial and final state radiation and (“semi-hard”) multiple parton interactions, has to be removed in order to achieve precise comparisons between jet measurements and pQCD predictions. Consequently, an accurate modeling of the UE is important for all analyses involving jets in the final state, especially at low energies. At the same time our current understanding of this process is limited as it involves both perturbative and non-perturbative QCD. It is clearly important to check how current QCD MC models describe the observed properties of the UE and, if possible, to device an optimal tuning so that to improve their fitting to data results.

Such kind of studies were performed in CDF during Run I [17]. The “transverse” region perpendicular to the leading jet of the event in the azimuthal angle (see fig. 6 left) is expected to be very sensitive to the UE and it was studied using charged particles [8]. In general, it was observed that HERWIG 15), ISAJET 18) and PYTHIA 19) QCD MC models with their default parameters do not describe correctly all the properties of the “transverse” region when compared to minimum bias and jet trigger data. In particular, it was found that a simple minimum bias modeling for the “beam-beam remnants” contribution to the UE (HERWIG, ISAJET) is not able to account for the observed charged particle multiplicity while, with the inclusion of multiple parton interactions, PYTHIA gives better results. It was actually found that PYTHIA, with an adequate tuning of its parameters in order to enhance this contribution, is able to fit data very well [20].

Similar studies have been performed in CDF using Run II data at $\sqrt{s} = 1.96$ TeV. As in Run I, the topological structure of $p\bar{p}$ collisions was considered in order to make a phenomenological study of the UE in minimum bias and jet trigger data samples to be compared to HERWIG and PYTHIA QCD MC predictions. In the study reported here, the direction of the leading calorimeter jet (JetClu R = 0.7, $|\eta| < 2$) was used to isolate regions of $\eta$-$\phi$ space that are sensitive to the UE (fig. 6 left) and observables related to charged particles (reconstructed by the central tracking system with $P_T > 0.5$ GeV/c and $|\eta| < 1$) were considered. Two classes of events were defined according to the jet topology: “leading jet” events, with no restriction applied on the second highest $E_T$ jet and “back-to-back” events, where the two jets were required to be

---

8 As the study of the UE mostly involves very low energy particles, only the charged particle component of the UE was considered because the CDF tracking system (immersed into a 1.4 T magnetic field) measures the momenta of low $P_T$ tracks more accurately than the calorimeter measures their energies.
Figure 6: Left: The leading jet direction is used to define three regions in azimuthal angle (each spanning 120°) with different hadronic activities in the event. The “transverse” region is very sensitive to the UE contribution. Right: average charged particle $P_T$ sum density $\langle d\Sigma P_T/d\eta d\phi \rangle$ in the “transverse” region as a function of the leading jet $E_T$ ($E_{T1}$) for “leading jet” and “back-to-back” events (as defined in the test) in Run II data, compared with predictions from HERWIG and PYTHIA (tuned on Run I data: “Tune A”).

nearly back-to-back ($\Delta\phi_{12} > 150^\circ$, $E_{T2}/E_{T1} > 0.8$). This classification was introduced in order to select a subsample (“back-to-back” configuration) where hard initial and final state radiation are suppressed to increase the sensitivity of the “transverse” region to the “beam-beam remnants” and multiple parton scattering component of the UE. Fig.6 (right) shows the average charged particle $P_T$ sum density $\langle d\Sigma P_T/d\eta d\phi \rangle$ in the “transverse” region as a function of the leading jet $E_T$ ($E_{T1}$) in “leading jet” and “back-to-back” events. Also shown are the predictions from HERWIG and PYTHIA after a full detector simulation. The charged track activity is different for the two configurations: for the “leading jet” case the density rises with increasing $E_{T1}$, while for the “back-to-back” one it slightly falls with increasing $E_{T1}$. The rise for “leading jet” events is attributed to hard initial and final state radiation which has been suppressed in “back-to-back” events whose opposite trend with increasing $E_{T1}$ might be due to a “saturation” of the multiple parton interaction at small impact parameter. Such effect is expected to be included in PYTHIA (with multiple parton interactions included) but not in HERWIG (without multiple parton interactions). Indeed, in fig.6 (right) we see how PYTHIA tuned on Run I data (“Tune A”, version 6.206) fits very well the data for both configurations, while HERWIG looks working only at higher $E_{T1}$. Similar results are observed considering the average charged particle number density $\langle dN/d\eta d\phi \rangle$ as well as in additional studies involving, for instance, the $\Delta\phi$ dependence of these
densities \( d\Sigma_{P_T}/d\eta d\phi \) and \( dN/d\eta d\phi \) relative to the direction of the leading jet.

6 Conclusions

A very exciting and important QCD physics program is ongoing at the Tevatron \( p\bar{p} \) collider where the increase in center-of-mass energy from 1.8 to 1.96 TeV and the higher statistics of Run II data samples are expected to extend Run I results at high \( E_T^J \).

Some preliminary Run II results have been reported in this contribution. The measured inclusive jet and dijet mass cross sections are in reasonable agreement with NLO pQCD (EKS, JETRAD) within the uncertainty on jet energy scale in the data and on gluon PDF at high \( x \) in the theoretical predictions. The production of \( W + \) jets events is fairly described by an “enhanced” LO QCD Monte Carlo (ALPGEN + HERWIG). Data to theory comparison is limited by the systematic error on the jet energy scale and by the \( \mu_R/F \) dependence of LO calculations. The underlying event is well described by the model implemented in PYTHIA using parameters tuned on Run I data.

7 Acknowledgements

I’m very grateful to the Conference Organizers, G. Bellettini, G. Chiarelli and M. Greco, for their warm hospitality in the unique atmosphere of La Thuile. I would like also to acknowledge the QCD Group members of the CDF and DØ Collaborations for their work in achieving the results shown in this presentation. Many thanks to Mario Martinez for his precious comments leading to the final version of the manuscript.

References

1. R. Blair et al (CDF Coll.), FERMILAB-Pub-96/390-E, (1996).
2. S. Abachi et al (DØ Coll.), FERMILAB-Pub-96/357-E, (1996).
3. F. Abe et al (CDF Coll.), Phys. Rev. Lett. 77, 438 (1996).
4. T. Affolder et al., (CDF Coll.), Phys. Rev. D 64, 032001 (2001).
5. B. Abbott et al., (DØ Coll.), Phys. Rev. Lett. 86, 1707 (2001).
6. J. Pumplin et al., JHEP, 0207 (2002).
   D. Stump et al., [hep-ph/0303013] (2003).
7. A.D. Martin et al., Eur. Phys. J. C28, 455 (2003).
   A.D. Martin et al., [hep-ph/0308087] (2003).
8. F. Abe et al., (CDF Coll.), Phys. Rev. D 45, 1448 (1992).
9. S.D. Ellis et al., Phys. Rev. Lett. 64, 2121 (1990).
10. G.C. Blazey et al., FERMILAB-Conf-00/092-E, hep-ex/0005012 (2000).
11. B. Abbott et al., (DØ Coll.), Nucl. Instr. and Meth. A 424, 352 (1999).
12. W.T. Giele et al., Phys. Rev. Lett. 73, 2019 (1994).
13. A.D. Martin et al., Eur. Phys. J. C 23, 73 (2002).
14. M.L. Mangano et al., JHEP, 0307 (2003).
15. G. Marchesini and B.R. Webber, Nucl. Phys. B349, 635 (1991) (v. 5.9).
16. T. Affolder et al., (CDF Coll.), Phys. Rev. D 63, 072003 (2001).
17. T. Affolder et al., (CDF Coll.), Phys. Rev. D 65, 092002 (2002).
   D. Acosta et al., (CDF Coll.), hep-ex/0404004 (2004) (sub. Phys. Rev. D).
18. F. Paige and S. Protopopescu, BNL Report BNL38034 (1986) (v. 7.32).
19. T. Sjostrand and M. van Zijl, Phys. Rev. D 36, 2019 (1987) (v. 6.115-125).
20. R.D. Field, ‘ME/MC Tuning Workshop’, Fermilab, October 2002.