1: QCD at Hadron Colliders

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Abstract. This paper reviews the status of Quantum Chromo Dynamics, when compared to measurements at hadron colliders. The emphasis is on a confrontation with results from the Tevatron collider experiments, varying from inclusive cross sections to more exclusive or differential measurements.

1 Introduction

All physics processes at a hadron collider involve the strong interaction and are described within the framework of quantum chromodynamics (QCD). To interpret a measurement in this environment relies heavily on QCD being verified in other more clean circumstances, for example e^+e^- or $lepton - hadron$ scattering. From the point of view of confronting QCD based predictions at a hadron collider machine, we take the view that this environment is rich in QCD, although one might be tempted to think that it borders on chaos.

Within the framework of QCD the interaction between hadrons is seen as the hard interaction between two massless, pointlike partons from the scattering hadrons. The parton-parton interaction is described by a hard parton cross section $\hat{\sigma}$. Because there are several parton species, with varying momenta in the hadron, the theoretical prediction for any measured cross section(σ^{meas})has the following form in perturbative QCD:

$$\sigma^{meas} \propto \sum_{ij} \int_{x_1} \int_{x_2} \phi_i(x_1, \mu_f) \hat{\sigma}_{ij}(\mu_r) \phi_j(x_2, \mu_f) \tag{1}$$

where $\phi_{i,j}$ is the parton momentum distribution (PDF) for parton types i and j in the hadrons, μ_f is the factorization scale at which it is evaluated, $\hat{\sigma}_{ij}(\mu_r)$ is the cross section for an interaction between parton i and j, μ_r is the renormalization scale at which the strong coupling constant (α_s) is evaluated and x_1, x_2 are the momentum fractions of the partons in the hadrons. The PDF 's are derived mainly from lepton hadron (lh) scattering cross section (=structure function) measurements (σ_{lh}^{meas}) using the same underlying QCD theoretical framework ($\phi_i = \sigma_{lh}^{meas}/\hat{\sigma}_{lh}$) and they are only defined within this framework. Since they come from experiment there are uncertainties associated with them, but these uncertainties are not well defined at this time. It should be noted that without the high precision lepton hadron experiments, especially at HERA, it would be practically impossible to study QCD quantitatively at a hadron collider.

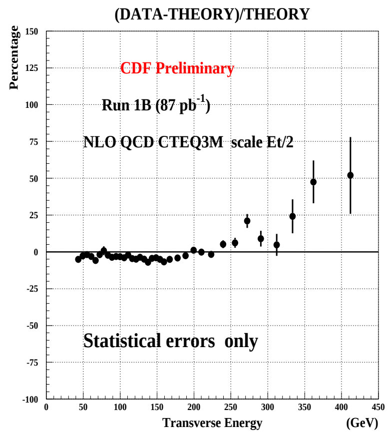

Fig. 1. Inclusive jet cross section from the CDF experiment, $0.1 \leq\mid \eta \mid\leq 0.7$

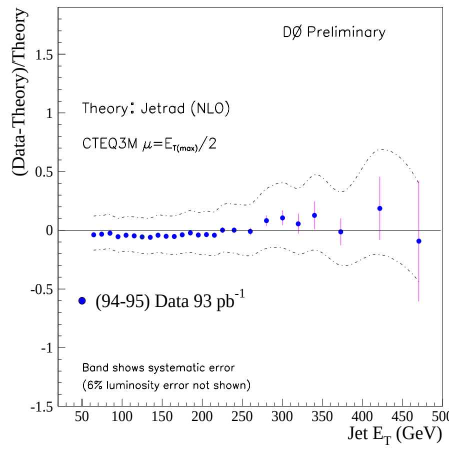

Fig. 2. Inclusive jet cross section from the DØ experiment, $\mid \eta \mid\leq .0.5$

In the following we will concentrate on results from the Tevatron $p\bar{p}$ collider. The theoretical predictions will mainly be based on next-to-leading order (NLO) perturbative QCD. Most experimental measurements presented here are made with quantities that were corrected back to the particle level and are directly compared to the NLO parton level predictions, without any corrections for parton showering and/or fragmentation. Since this is an experimental summary the paper is organized by final states, instead of underlying physics. In many cases the underlying physics is similar, but at this time, the experimental results seem to be requiring additional features in the theoretical predictions, so they dictate the order. Strictly speaking NLO QCD predictions are only valid for inclusive cross section predictions, so in each final state we will start with the inclusive cross section.

2 Jet final states

Jets observed in hadron-hadron collisions are the clearest manifestation that the interaction between two hadrons is described by the scattering of two partons and results in final state partons, which are experimentally observed as a localized deposition of energy in the form of jets. The production of jets is copious and the inclusive jet cross section ($d^2\sigma/dE_T d\eta$) is typically measured by counting all jets in a bin of transverse energy (E_T) and pseudorapidity ($\eta = -\ln(\tan(\theta/2))$), where θ is the polar angle with respect to the beam. This cross section has been measured in the central rapidity region ($\mid \eta \mid\leq 0.7$) at $\sqrt{s} = 1800$ GeV[1, 2], by the CDF and DØ experiments. Over the E_T range 50-450 GeV the cross section drops by seven orders of magnitude. The high E_T region probes the smallest distance scales accessible by experiments today and is therefore the most sensitive probe of substructure in quarks.

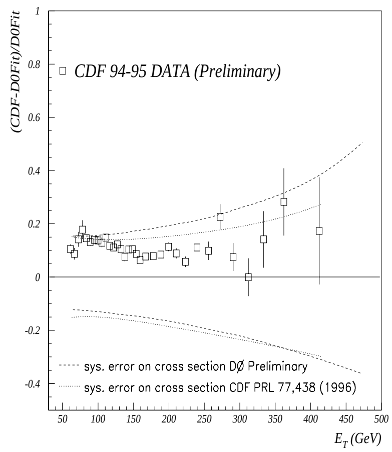

Fig. 3. Comparison of experimental CDF and DØ cross sections in $0.1 \leq \mid \eta \mid \leq 0.7$

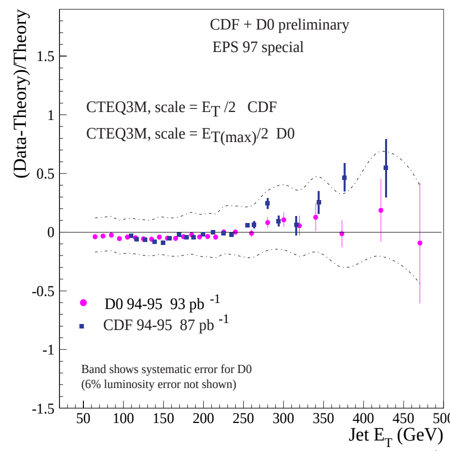

Fig. 4. Overlay of CDF and DØ (DATA-THEORY) / THEORY graphs.

To facilitate a comparison with QCD based theoretical predictions, Figs. 1 and 2 show the quantity (DATA-THEORY) / THEORY for this measurement by both experiments. In both cases jets are defined by a fixed cone algorithm with a cone size $\Delta R = \sqrt{\Delta^2\eta + \Delta^2\phi} = 0.7$ in pseudorapidity and azimuthal coordinates, according to the Snowmass definition [4]. The same algorithm is used in the NLO ($O(\alpha_s^3)$) theory prediction, because a jet at the parton level can consist of two partons. To obtain better matching between experimentally defined jets, with experiment specific merging/splitting criteria, and parton jets the distance between two partons belonging to one jet is required to be less than $R_{sep} \times 0.7$ with $R_{sep} = 1.3$ for DØ and 2.0 for CDF. The rapidity regions covered are slightly different: CDF covers $0.1 \leq \mid \eta \mid \leq 0.7$ and DØ covers $\mid \eta \mid \leq 0.5$. The theory predictions used are both $O(\alpha_s^3)$, but based on the EKS program [5] with $\mu_f, \mu_r = E_T^{jet}/2$ for CDF and on JETRAD [6] with $\mu_f, \mu_r = E_T^{max}/2$ for DØ . Here E_T^{max} is the largest transverse energy observed among all jets in an event. Both predictions use the CTEQ3M [7] parton distributions. The DØ data agree with the NLO QCD predictions rather well, especially with the systematic error taken into account. The CDF data agree very well at medium transverse energies, but the data seem to show an excess at large E_T. There is no apparent excess in the DØ data.

Questions are: are the theoretical predictions the same and do the experimental data agree? The main difference in the prediction would be due to a difference in the choice of scale . The variations of the theory predictions, due to uncertainties in the parameters used, has been studied extensively [8]. It was found that the different choice of scale results in roughly a 2% normalization shift above E_T =300GeV and an additional 5% change in shape

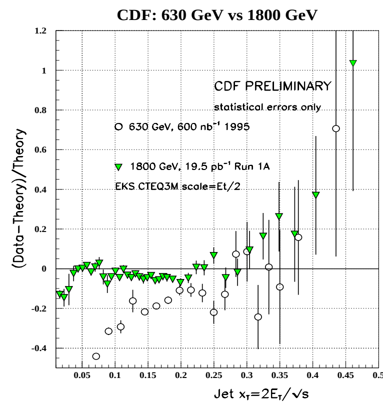

Fig. 5. Inclusive jet cross sections compared to theory at 630 and 1800 GeV from the CDF experiment as a function of x_T.

as a function of E_T between 50 and 300GeV. This cannot explain the difference between the experiments. To check the experimental results, DØ has repeated the measurement for $0.1 \leq |\eta| \leq 0.7$ where the systematic errors are not as well understood as in the $|\eta| \leq 0.5$ region. A functional form was fit to these data points and called $D0fit$. Figure 3 shows the quantity $(CDF - D0fit)/D0fit$, where CDF are the values of the cross section measured by CDF and systematic error bands are shown for both experiments. The experimental data measured in the same η region agree very well within errors. In Fig. 4 the data from the Fig. 1 have been put on the DØ graph and both results are shown in the same graph. From this figure it is evident that the two results are in very good agreement, even if only the DØ systematic error is taken into account. There is no need to invoke new physics yet and combining the data might result in a better and more clear conclusion.

The CDF experiment has also measured the same inclusive jet cross section at 630 GeV $p\bar{p}$ collisions. Fig. 5 displays the (DATA-THEORY) / THEORY quantity but now plotted as a function of $x_T = 2E_T/\sqrt{s}$ for $\sqrt{s}$=1800 and 630 GeV. The 630 GeV data show a strong E_T dependence and the shape is in obvious disagreement with the NLO prediction. At this time this is not understood. Previous results at the same center of mass energy by the UA2 experiment [3], are in very good agreement with leading order $(O(\alpha_s^2))$ QCD predictions. The DØ results for this energy are eagerly awaited.

Predictions of the inclusive jet cross section assume that the partonic hard scattering cross sections ($\hat{\sigma}_{ij}$ in Eq. 1) are correctly given by QCD. The angular distribution of the two final state jets in the center of mass system (cms) of the two initial partons is dominated by t-channel vector gluon exchange. This results in the characteristic Rutherford type angular distribution for spin=1 exchange: $dN/d\cos\theta^* \propto (1-\cos\theta^*)^{-2}$, where θ^* is the angle between the incoming and outgoing partons. The shape of this distribution with its pole at $\cos\theta^* = 1$ is not very well suited for a detailed comparison

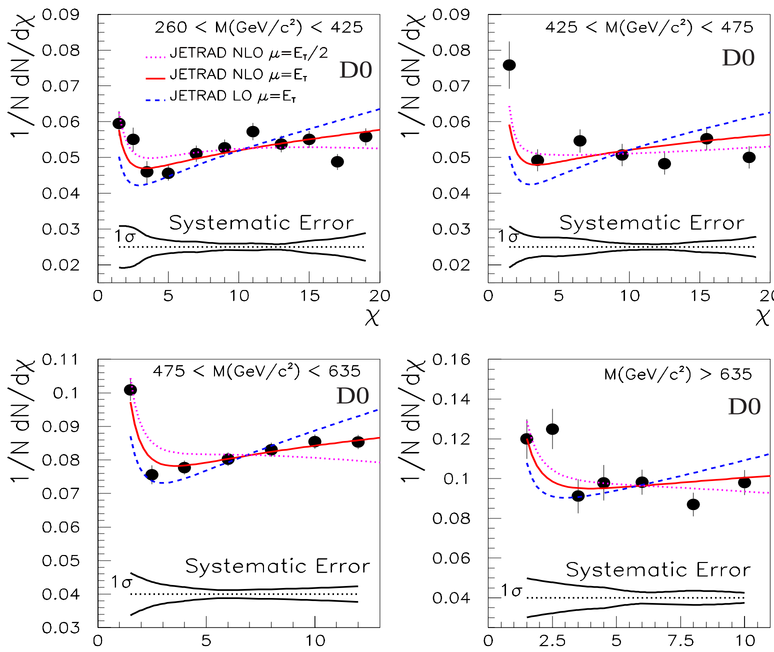

Fig. 6. The normalized dijet angular distribution $N^{-1}dN/d\chi$ for different regions of M_{jj}.

between theory and experiment. For that reason the variable χ, defined in Eq. 3 is used. This variable transforms a $(1-\cos\theta^*)^{-2}$ distribution into a flat distribution. The relationships between the variables used to describe the dijet system are given by following equations.

$$\eta^* = \frac{\eta_1 - \eta_2}{2} \qquad \cos\theta^* = \tanh\eta^* \qquad \eta_{boost} = \frac{\eta_1 + \eta_2}{2} \tag{2}$$

$$M_{jj} = 2E_T^1 E_T^2(\cosh 2\eta^* - \cos(\phi_1 - \phi_2)) \qquad \chi = e^{2|\eta^*|} = \frac{(1+\cos\theta^*)}{(1-\cos\theta^*)} \tag{3}$$

Here all the quantities with a "*" are in the *cms* system and the indices 1, 2 refer to the final state jets. The inclusive cross section describing the final state is $d^3\sigma/dM_{jj}d\eta^*d\eta_{boost}$. Integrating over large fractions of the dijet invariant mass M_{jj} and η_{boost} space results in the normalized distribution $N^{-1}dN/d\chi$. This is typically referred to as the dijet angular distribution and its shape is practically independent of parton distributions, because all contributing graphs are dominated by one gluon exchange and have the same angular distribution. Experimentally the pseudorapidities (η_1, η_2) of the two leading E_T jets are used. Figure 6 shows the angular distribution as measured by the DØ experiment in different regions of M_{jj}. The data are compared

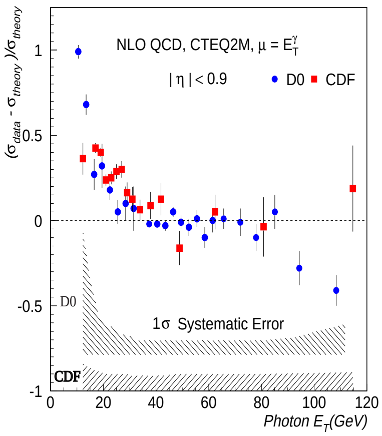

Fig. 7. $d\sigma/dE_T^\gamma$, from both experiments compared to theory.

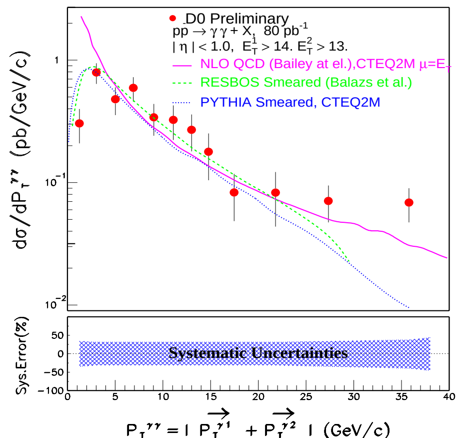

Fig. 8. $d\sigma/p_T^{\gamma\gamma}$ from DØ and corresponding theory predictions.

to LO and NLO predictions. Because the distribution is normalized, the LO prediction hardly exhibits a scale dependence, whereas the NLO one does. In this case LO predictions are not sufficient to describe the data. The CDF experiment has also measured these distribution over a somewhat smaller range in χ and those data are described well by LO and/or NLO predictions. In the highest M_{jj} bin these data can be used set a limit on quark compositeness. If a contact interaction with a uniform angular distribution and strength proportional to $(1/\Lambda)^2$, is added to the QCD Lagrangian, the DØ data require $\Lambda > 2.0$ TeV for all contact interaction scales [1, 2].

3 Photon production

The production of photons in hadron-hadron collisions has been pursued for about 20 years. The two basic processes contributing are $q\bar{q} \rightarrow \gamma g$ and $qg \rightarrow \gamma q$. Because of the qg initial state this process has always been considered as the best way to probe the gluon density. Practically, it has not been possible to achieve this in a quantitative way either because of experimental difficulties (π^0 backgrounds) and/or uncertainties in the theoretical predictions. Experimentally only the isolated photon cross section can be measured, because photons inside jets can not be resolved. Theoretical predictions attempt to take the experimental isolation cuts into account. Both Tevatron experiments have measured the isolated, inclusive photon cross section for $\mid \eta \mid < 0.9$. Fig. 7 shows the comparison of both data sets with a NLO QCD prediction in the familiar form (DATA-THEORY) / THEORY as a function of the transverse energy of the photon (E_T^γ). The bulk of the experimental data are in very good agreement and both data sets show a clear excess of events for $E_T^\gamma < 50$ GeV compared to the prediction. The significance is greatest in the

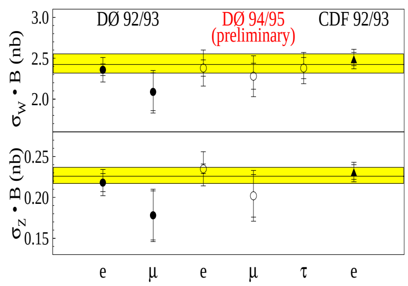

Fig. 9. W, Z cross sections from both experiments compared to theory.

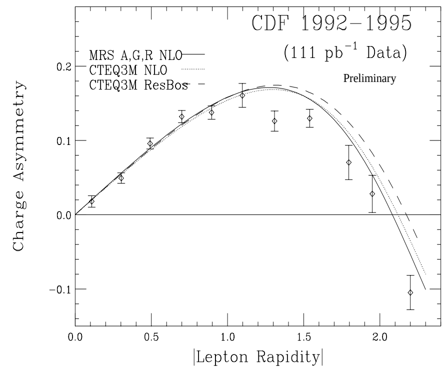

Fig. 10. The W asymmetry measurement from CDF and theory predictions.

CDF data, because of the smaller systematic error. In this case the CTEQ2M [7] PDF was used. In the meantime more precise HERA data have resulted in the CTEQ4M [7] distribution, which reduces the discrepancy around $E_T^\gamma = 15$ GeV by about 15%. This is in the right direction but not sufficient to explain the difference between data and theory. In a comprehensive study by the CTEQ group [9] it has been shown that this behavior is observed in all direct photon experiments, performed at different energies and in fixed target or collider mode. The NLO prediction is believed to lack a sufficient amount of additional gluon radiation. It has been shown [10] that adding parton showers to the NLO partons improves the data-theory comparison significantly. Also adding an ad hoc "k_T" to the initial state partons (equivalent to more radiation) improves the comparison. Especially the very precise data from the E706 [11] experiment, which studied γ and π^0 production in 800 GeV pBe collisions, exhibit the clearest need for additional radiation. They clearly require an average $k_T \approx 1.5$ GeV to even begin to agree with perturbative QCD predictions. Because of these problems the impact of direct photon data in determining PDF 's has been less then orginally expected.

Diphoton final states allow an independent and sensitive test of the need for additional radiation in the NLO predictions. Fig. 8 shows $d\sigma/dp_T^{\gamma\gamma}$ where $p_T^{\gamma\gamma}$ is the transverse momentum of the two photon final state. In lowest order $p_T^{\gamma\gamma} = 0$, but higher order processes cause it to increase. The NLO prediction shown in the figure clearly keeps rising for $p_T^{\gamma\gamma} \to 0$. Only the analytical predictions including resummed higher order contributions (RESBOS) [14] or predictions based on parton showers (PYTHIA) agree with the data. Unfortunately the RESBOS calculation is not available for single photon final states. Direct photon production is an area where theoretical work is needed and it is obvious that strict NLO predictions are not good enough to describe the rather precise experimental data.

4 W/Z production

The production of colorless W's and Z's in hadron collisions provides one of the cleanest ways to probe QCD, because it is a special case of Drell-Yan production at a fixed and large mass. As in most other processes the first comparison to be done with theory is the inclusive cross section. The prediction in this case is to $O(\alpha_s^2)$ (NNLO) using the CTEQ2M PDF . The experiments measure crossing section $\times$ branching ratio ($\sigma^{W,Z} \cdot B$) for e, μ and τ final states. Because the final state leptons are only detected in instrumented regions of the detectors, the data are corrected for acceptance with simulations that either resum higher order contributions or use parton shower generators. These measurements from both DØ and CDF and the QCD predictions are shown in Fig. 9 for all final states. The experimental results are in excellent agreement with the $O(\alpha_s^2)$ prediction and this is an important confirmation of the assumptions underlying the theoretical QCD predictions. The uncertainty in the prediction is dominated by the error in the PDF .

We now turn to the more differential cross sections and start with the measurement of the W charge lepton asymmetry measured by CDF. The charge asymmetry is defined as: $A(y_L) = [d\sigma^+/dy_L - d\sigma^-/dy_L]/[d\sigma^+/dy_L + d\sigma^-/dy_L]$. Here y_L is the rapidity of the final state lepton and its charge is indicated by the index on the cross section. Considering the basic process for W production: $ud \rightarrow W$, the asymmetry would be zero if the momentum distributions for u and d quarks in the (anti)proton were identical. The asymmetry measures the difference or the ratio of the two distributions and the lepton rapidity corresponds to certain momentum fractions x of the quarks. The x-range probed by this measurement is 0.01 to 0.04. Fig. 10 shows the CDF data for an integrated luminosity of 111 pb^{-1}, which is a factor of 6 more data than a previous measurement. When comparing to NLO predictions using PDF 's including the previous asymmetry results, it is clear that these old PDF 's need to be updated. A prediction based on a resummed calculation, using RESBOS, is also shown, but in this case the difference between resummed and NLO is rather small. This result is a beautiful example of how a single precise measurement can very accurately determine an aspect of parton distributions, in this case the ratio d/u.

Production of W's and Z's to first order is a $q\bar{q}$ annihilation process involving no other constituents. In this picture the bosons are produced with no transverse momentum (p_T), but can be boosted along the beam direction. However any initial or final state radiation will produce a finite p_T. Therefore the measurement of this quantity constitutes an important test of QCD predictions. Only Z production will be considered because the boson transverse momentum is more accurately measured in this case. Fig. 11 shows the experimental result $d\sigma/p_T^Z$, not corrected for acceptances and resolution smearing, obtained by DØ . The peak at small p_T^Z with a rapid fall off towards higher values is evident. The distribution is not well described by NLO

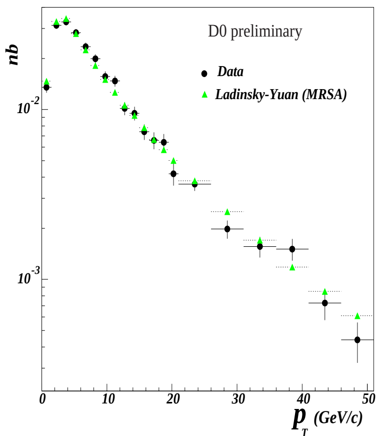

Fig. 11. $d\sigma/dp_T^Z$ from DØ with prediction from ref.[12].

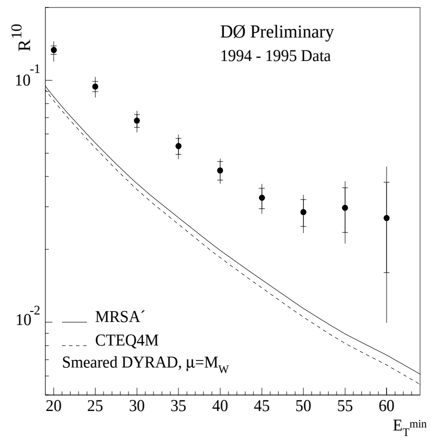

Fig. 12. R^{10} as a function of E_T^{min} as measured by DØ and the NLO prediction.

predictions and especially the turnover at small transverse momenta requires an approach where additional radiation is taken into account. This is done in a resummation approach, which is valid in the small p_T^Z region and which is matched to a perturbative $O(\alpha_s^2)$ calculation at high p_T^Z. This has been implemented [12] in a manner where several parameters are introduced that have to be derived from data. These parameters are considered to be universal i.e. process independent. Using fixed target, low energy Drell-Yan data these parameters were fit and then used to predict $d\sigma/p_T^Z$ at Tevatron energies. Fig. 11 shows this prediction, including detector acceptances and resolutions, and it agrees very well with the data. A fit χ^2 fit gives $\chi^2/dof = 24.4/20$.

The measurement of the ratio of $W + 1jet$ to $W + 0jet$ is in principle proportional to α_s and the desire to measure α_s motivated the original measurement of this quantity. The availability of $O(\alpha_s^2)$ calculations in the form of the program DYRAD [6] was an additional incentive, because it predicts these cross sections with small scale dependence. DØ has measured $R^{10} = W + 1j/W + 0j$ with the final state $W \to e\nu$. Jets are defined with a fixed cone size of 0.7 and are required to have a transverse energy $> E_T^{min}$. Fig. 12 shows the experimental result for a variety of E_T^{min} values. The theoretical parton level prediction for two PDF 's is shown as well. Contrary to the inclusive W cross section, any acceptance and kinematic cuts as well as experimental resolutions are now applied in the NLO calculation, after clustering partons into jets using the same algorithm as in the data. There is an apparent disagreement between data and theory, which at this time is not understood and is under investigation. A more consistent treatment of the resolution, especially in missing transverse momentum, reduces the discrepancy between data and theory somewhat, but it remains several standard deviations. It is also observed that there is an excess of events in the $W + 1j$

channel at small W transverse momentum in the data compared to the prediction. The CDF experiment has measured the $W, Z + njet$ cross sections, with n = 0,1,2,3,4 [13]. The data are compared to leading order predictions with subsequent HERWIG parton showering and are found to be in good agreement, although the level of agreement depends on the choice of scale. Once these data are compared to NLO predictions they may shine some light on the "R^{10}" puzzle.

5 Summary

Several topics have not been mentioned in this paper: b-quark and J/ψ cross sections, searches for evidence of BFKL signatures, double parton scattering and color coherence measurements in jet and W final states.

The precision of the hadron collider data require NLO QCD predictions and the agreement between data end theory is good as far as inclusive quantities are concerned. The theoretical predictions have greatly improved, through more precise parton distributions. At the moment the vast amount of rather precise hadron collider data are pointing to shortcomings in the theoretical predictions, some of which have been addressed by resumming higher order contributions. In the necessary interplay between theory and experiment it seems for now that experiment is pushing the limits of what theory can predict. The Tevatron data have stimulated a lot of activity in the area of QCD phenomenology and a lot of progress has been made, but there is still a lot of room for improvements and refinements with the goal to achieve more reliable QCD predictions in the future.

References

[1] E.Buckley-Geer, proceedings of this conference
[2] R.McCarthy, proceedings of this conference
[3] J.Alitti *et al.*, Phys. Lett. B257, 232 (1991)
[4] Proc. of the 1990 Summer Study on HEP, July 1990, Snowmass, CO, World Scientific, p.134-136 (Snowmass Jet Accord).
[5] S.Ellis,Z.Kunzst and D.Soper, Phys. Rev Lett. 64, 2121(1990).
[6] W.Giele, E.Glover, D.Kosower, Nucl. Phys. B403, 633 (1993).
[7] H.L.Lai *et al.*,Phys Rev D55, 1280 (1997) and references therein.
[8] B.Abbott *et al.*, hep-ph/9801285.
[9] J.Huston *et al.*, Phys. Rev D51, 51 (1995)
[10] H.Baer and M.Reno, Phys. Rev. D54, 2017 (1996)
[11] L.Apanasevich *et al.*,((E706 collaboration),hep-ex/971017.
[12] G.Ladinsky and C.P.Yuan, Phys. Rev. D50, 4239 (1994) and references therein.
[13] F.Abe *et al.*, Phys. Rev. Lett. 79,4760 (1997)
[14] C.Balazs and C.P.Yuan, Phys. Rev D56, 5558 (1997)