Precision tests of QCD with jets and vector bosons at HERA and TevaTron

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Recent results from HERA and TevaTron on precision tests of QCD with jets, W and Z bosons and photons associated with jets and heavy flavors are presented. The measurements were used to probe QCD at the highest energies, to provide experimental constraints on SM processes that constitute background to new physics, to extract values of the coupling of the strong interaction and to constrain the proton parton distribution functions. The implications of the results on LHC physics are discussed.

1. Introduction

Parton-parton scattering via QCD interactions is the main process at hadron colliders. Besides their intrinsic interest, these processes represent some of the irreducible background to other Standard Model (SM) processes and to new physics.

The ep collider HERA, which provides a simple hadronic environment to test QCD, and the pp collider TevaTron, which provides the highest available energies, have produced over the years comprehensive precision measurements of the parameters of the theory and precise tests of its underlying dynamics. All this knowledge will be crucial for understanding any physics at LHC. For instance, the gluon density at low x is a necessary input ingredient for calculating the Higgs production cross section, whereas the predictions for W or Z bosons production cross sections require knowledge of the quark densities.

This report summarises the most recent results from jet cross sections, forward jets, photons and W and Z bosons and the underlying event presented by the CDF, D, H1 and ZEUS experiments at ICHEP08.

2. Studies of the underlying event

The main experimental uncertainties for jet cross sections arise from the jet energy scale and the underlying event (UE), which contributes with additional energy density on top of the hard interaction but is not related to it; this is a non-perturbative effect which is not included in the calculations. These effects can be simulated with Monte Carlo simulations and are extremely model dependent, so a good understanding of the UE at the available energies is crucial to model its effects at LHC energies.

The CDF collaboration has performed a new study of the UE using Drell-Yan processes [1]. In this analysis, all particles in the final state, except the lepton pair, can be considered as the UE. Thus, the Drell-Yan events constitute a very clean probe of the UE. The study of the UE observables was done for lepton-pair masses around that of the Z boson (70 < M_Z < 110 GeV). The transverse plane was separated in four regions: the forward region, which corresponds to the Z-boson direction, the opposite direction, which is called the away region, and the two transverse regions. The transverse regions are most sensitive to the UE. Several observables, such as the charged particle density shown in Fig. 1a, are studied as functions of the transverse momentum of the lepton pair. The measurements are approximately constant for the transverse and forward regions and increase with lepton-pair $p_T$ in the away region. The PYTHIA tune AW M C predictions describe very well the data. Figure 1b shows the comparison of the UE observables in Drell-Yan events with the same observable for the leading-jet analysis in the transverse region. The results are in good agreement so the Drell-Yan studies provide insight into the UE in a cleaner environment.

Photoproduction at HERA also allows the study of the UE. At leading order (LO), there are two processes that contribute to jet photoproduction: direct, in which the photon interacts as a point-like particle with the partons from the proton, and resolved, in which the photon interacts via its partonic structure, giving rise to a hadronic-like final state. The observable $x^{obs} = (1-E_T)/(p_T^3 E_T^p e^{-x})$, where $E_T^p$ is the jet transverse energy, $E_T$ is the jet
3. Probing QCD at the highest energies

The CDF [4] and the D [3] Collaborations have measured the inclusive-jet cross section in pp collisions at \(\sqrt{s} = 1.96\) TeV as a function of \(E_T^{\text{jet}}\) for different regions of rapidity using the mid-point jet algorithm (see Fig. 2). These are high precision measurements, especially at high \(E_T^{\text{jet}}\), where new physics might show up. These cross sections are also sensitive to the gluon density at high \(x\). The next-to-leading-order (NLO) QCD calculations give a good description of the data. These measurements constitute the most stringent test of pQCD at the highest available energies so far.

Jet production provides the highest energy reach with highest statistics. In particular, dijet production is ideal to test the SM and search for new physics, which might show up as narrow resonances in the dijet invariant mass spectrum. Figures 3a and 3b show the measurement of the dijet invariant mass from CDF [4]; the data reach values of up to 1.4 TeV, which constitute the highest energies measured so far. The NLO calculations give a good description of the data in the whole measured range. Since no evidence for new physics is observed, 95% CL limits were set for various models, which include excited quarks, new heavy vector bosons and gravitons. Figures 4a and 4b show the limits obtained from the data as functions of the new particle mass.
Figure 2: Mean charged multiplicity as a function of $^{3c}$ for (a) $x^{3c} < 0.7$ and (b) $x^{3c} > 0.7$; mean charged multiplicity as a function of $p_T^{3c}$ in the (c) toward, (d) away, (e) high-activity and (f) low-activity regions.

Figure 3: (a) Three-jet cross section as a function of $x^{bs}$; (b) four-jet cross section as a function of the four-jet invariant mass.

Angular correlations in the dijet system are directly sensitive to the underlying parton dynamics and can also be used to search for new physics. The angular correlation, defined as $\Delta \phi_{\text{dijets}} = \exp(y_1 - y_2)$, is expected to be constant for Rutherford scattering; QCD processes induce a small deviation from this behavior, but new physics is expected to have a very different shape at low values of $\Delta \phi_{\text{dijets}}$. The D Collaboration has measured $\Delta \phi_{\text{dijets}}$ in different regions of dijet invariant mass from 0.25 to above 1.1 TeV, as shown in Fig. 3a. The NLO predictions give a good description of the data in the whole measured range. Since there is no indication for the presence of new physics, 95% CL limits were set for various models which include quark compositeness and extradimensions. Figures 3b, 3c and 3d show the $^2$ likelihood and probability as a function of the characteristic parameter of each model. These constitute the most stringent limits for these models from hadron colliders up to date.

4. Precision tests of QCD

Recently, very precise measurements of jet cross sections in neutral current (NC) DIS and photoproduction, which are directly sensitive to the gluon content of the proton, have been incorporated in a QCD fit to determine the proton PDFs. The result was an improved determination of the gluon density for mid- to high-$x$ values, a region relevant for new physics searches at LHC. In some regions of phase space the uncertainty in the gluon density...
decreased by up to a factor of two. Now, the H1 and ZEUS Collaborations are making new and more precise jet measurements with full HERA luminosity and extended phase space to take full advantage of this technique. The ZEUS Collaboration has measured double-di erential jet cross sections in NC DIS and photoproduction as functions of $x_b = x_b(1 + M_z^2/Q^2)$ and $x_b^{bs} = (1 + 2E_p)/(x_b E^p_{ZP} E^{bs})$, respectively, which are both estimators of the fractional momentum carried by the struck parton. The measurements are shown in Fig. 7 and are well described by the NLO calculations. These analyses provide a stringent test of QCD and were optimized to obtain the best sensitivity to the gluon density in the proton.

Inclusive-jet cross sections in charged current DIS have been measured by the ZEUS Collaboration. Figure 8 shows the cross section as a function of $x$ for electron beam (sensitive to the $u$-quark density) and positron beam (sensitive to the $d$-quark density). The NLO calculations give a good description of the data. Figure 9 shows the
The therefore, the semianalytic measurement have the potential to constrain further the valence-quark PDFs if included in global fits.

Inclusive-jet cross sections in NC DIS were measured by the H1 Collaboration as a function of $E_T^\text{jet}$ in different regions of $Q^2$ in the range $5 < Q^2 < 100 \text{ GeV}^2$ (see Fig. 6). The NLO predictions give a good description of the data. However, the theoretical uncertainty, which is dominated by the PDFs beyond NLO, is large; it reaches up to 30\% at the lowest $Q^2$ values. This shows the need for higher-order corrections. These measurements can help to constrain the gluon PDF at low $Q^2$ (low $x$) when higher-order calculations become available for NC DIS.

4.1. Precision measurements of $s$

The success of pQCD lies on the precise and consistent determination of $s$ from many diverse phenomena, such as structure functions, decays, Z-line shape, lattice, jets, etc. At HERA, many inelastic cross sections of $s$, mostly extracted from jet observables, give values as precise as those from more inclusive measurements. The H1 and ZEUS Collaborations have made new determinations of $s$, focusing on decreasing the uncertainties further. The H1 Collaboration has determined $s(M_Z) = 0.186 \pm 0.004 (\text{exp.)} \pm 0.013 (\text{th.)}$ and $s(M_W) = 0.196 \pm 0.010 (\text{exp.)} \pm 0.025 (\text{th.)}$ from the inclusive-jet cross sections at low $Q^2$ and the norm above inclusive-jet cross sections (see Fig. 7) in the regions $5 < Q^2 < 100 \text{ GeV}^2$ and $150 < Q^2 < 15000 \text{ GeV}^2$, respectively.
In this way, a region of phase space was selected in which experimental uncertainties are well under control and also, the use of normalised cross sections yields a cancellation of correlated uncertainties. New determinations of $s$ were performed by ZEUS from the inclusive-jet cross sections in NC DIS [11] and photoproduction [12] at high $Q^2$ and high $E_T^m$, respectively, where the theoretical uncertainties are minimised. Figure 10a shows the cross section in NC DIS as a function of $Q^2$ for different values of the jet-radius parameter $R$ in the $k_T$ algorithm. The NLO calculations give a good description of the data for $R = 0.5$ with similar accuracy. Figure 10b shows the cross section as a function of $E_T^m$ in photoproduction; the NLO calculation also gives a good description of the data for these processes. Values of $s$ were extracted from these measurements: $s(M_Z) = 0.1207 \pm 0.0014$ (stat) $^{+0.0035}_{-0.0033}$ (syst); $^{+0.0022}_{-0.0023}$ (th) (NC DIS, $Q^2 > 500 \text{ GeV}^2$) and $s(M_Z) = 0.1223 \pm 0.0001$ (stat) $^{+0.0023}_{-0.0023}$ (syst); $^{+0.0030}_{-0.0030}$ (th) (photoproduction, $E_T^m > 17 \text{ GeV}$).

To reduce the uncertainties even further and to take advantage of the cross-calibration between experiments, a simultaneous fit to the inclusive-jet cross sections in NC DIS from H1 and ZEUS has been performed [14] to give $s(M_Z) = 0.1198 \pm 0.0019$ (exp) $^{+0.0026}_{-0.0026}$ (th).

The total uncertainty of the combined value, 2.7%, is very competitive with the most recent result from LEP.

5. Probing QCD with vector bosons

Production of isolated photons in $p p$ collisions at Tevatron are a probe of QCD dynamics. Photons coming directly from the hard interaction are largely independent of hadronisation corrections. The understanding of these processes
In QCD is crucial for searches of new particles that decay into photons. The CDF Collaboration has measured [15] the inclusive cross section for isolated photons as a function of the photon transverse momentum integrated over the photon rapidity range $|y| < 1$. Figure 11a shows the measurement together with the NLO predictions. The calculations describe the data adequately within the experimental and theoretical uncertainties.

The D Collaboration has studied [13] in more detail these processes by measuring the cross section of isolated photons in association with jets. The measurements were done as functions of the photon transverse momentum for different configurations of photon and jet rapidities. These measurements have the potential to constrain the proton PDFs and different angular configurations give access to different regions of $Q^2$ and $x$. Figures 11b and c show the measurements together with the NLO calculations. The NLO predictions, using different sets of proton PDFs, can describe the shape of the cross sections simultaneously over the entire range measured. Therefore, the theoretical understanding of these processes needs to be improved before these data can be used to constrain the proton PDFs.

Inclusive prompt photons and in association with jets have been measured at HERA in photoproduction by the H1 Collaboration [14]. These processes are sensitive to the PDFs both in the proton and the photon. Inclusive prompt photon production has been measured as a function of the transverse energy and pseudorapidity of the photon (see Figs. 12a and 12b). The NLO calculations are below the data, especially at low $E_T$ and low $x$. The production of isolated photons in association with jets has been measured as a function of $E_T^\gamma$ and $x^{obs}$ (see Figs. 13a to 13b).
The NLO calculations give a better description of these data than for inclusive photons, except at high $x_{\text{obs}}$.

Figure 12: Inclusive-photon cross sections as functions of (a) $E_\gamma$ and (b) $x_{\text{obs}}$ in photoproduction; exclusive-photon cross sections as functions of (c) $x_{\text{obs}}$, (b) $E_\gamma$ and (c) $p_T$ in photoproduction; (f) inclusive-photon cross section as a function of $E_\gamma$ in NC DIS; exclusive-photon cross sections as functions of (g) $E_\gamma$ and (h) $E_\gamma$ in NC DIS.

Isolated photons have also been measured in NC DIS by the H1 Collaboration. In this case, there are two major contributions to photon emission, from the lepton and from the quark lines. The measurements have been performed inclusively and in association with jets as functions of photon transverse energy and pseudorapidity (see Figs. 12a, g and h). The LO calculations describe the shape of the data but underestimate the normalization by a factor of approximately two, which can be attributed to an underestimation of the quark-line contribution. The NLO calculations, which are only available for photons in association with jets in this process, are higher than the LO predictions, but still below the data. Therefore, the theoretical understanding of these processes needs to be improved.

The production of vector bosons in association with jets in $pp$ collisions is a key channel for studying top production within the SM as well as for searches of Higgs and new physics. The study of the production via QCD processes also provides a stringent test of the theory. The CDF and D Collaborations have measured the production of $W$ and $Z$ bosons in association with jets. Figure 13a shows the measured cross section of $W + 1$ jet from $p_T$, as a function of $E_\gamma$, of the first, second, and third jets, and Fig. 13b shows the measured cross section of $Z + 1$ jet from $p_T$, as a function of $E_\gamma$. The pQCD calculations, which are NLO for up to two jets, are compared with the measurements. The NLO calculations give a good description of the total and differential cross sections.

$W + c$-jet production at Tevatron is dominated by the $s$-gluon fusion channel and so is sensitive to the $V_{cb}$ matrix element. The $W$ measurement is also sensitive to the $s$ and $g$ PDFs. This process constitutes a background to top, Higgs, and stop production as well as to other searches for new physics. The D Collaboration has measured the total fraction of $W + c$-jet to $W + b$-jets, $f_{W + c}/f_{W + b}$, to be $0.074 \pm 0.019$ (stat)$^{+0.012}_{-0.014}$ (syst), as well as di jetically as a function of $E_T$ (see Fig. 14a). The CDF Collaboration has measured the total cross section times the branching ratio of the $W + 1$ channel, $BR(W \to l + 1) = 98 \pm 3.2$ pb. Figures 14b and 14c show the distributions of the di jet events between same-sign and opposite-sign events as a function of the lepton $p_T$, which shows clearly the signal. The predictions are in reasonable agreement with the data. These measurements provide direct experimental evidence for the signal and constitute an experimental validation of the $W + c$ theoretical prediction for use in searches.

$W + b$-jet and $Z + b$-jet production are also important backgrounds to Higgs searches and are sensitive to the $b$ parton density needed to predict the production of Higgs, SUSY, top and other new particles. The CDF Collaboration
The production of photons in association with b- or c-jets also provides a test of QCD. The D Collaboration has...
masured [24] the cross sections for photons plus b- or c-jets as functions of the photon transverse energy in different rapidity configurations. Figure 13 shows the measurements together with the NLO calculations. The predictions are in good agreement with the data for photon+b-jets in all the $E_T$ range and for photon+c-jets for $E_T < 50$ GeV. The disagreement between the photon+c m measurements and the theory is seen to grow with increasing $E_T$. The origin of this discrepancy is not yet clear; it could be attributed, for instance, to intrinsic charm in the proton or to uncertainties in the splitting of gluons into heavy-quark pairs.

![Figure 16: Photon b-jets (left) and photon c-jets (right) cross sections as functions of $p_T$.](image)

6. Parton dynamics at low $x$

One of the main channels of Higgs production at LHC is $gg \rightarrow H$ via a top-quark loop. The predictions for this process need information on the parton evolution at low $x$. This information can be obtained from low-$x$ jet data at HERA. At high scales, calculations at NLO using DGLAP evolution give a good description of the data. However, DGLAP evolution is expected to break down at low $x$. Other approaches to parton dynamics at low $x$ include the BFKL and CCFM evolution schemes. One way to study these effects is the one proposed by Müller and Navelet, which consists of analysing the production of jets close to the proton beam direction at HERA or \( \ell^\pm \) forward jets.

To search for breakdown of DGLAP evolution, the ZEUS Collaboration has measured [25] forward-jet production at low $x$. Figure 17 shows the cross section as a function of $x$, together with the pQCD predictions; the measured cross section increases as $x$ decreases. The $O(\alpha_s)$ predictions are well below the data, whereas the $O(\alpha_s^2)$ calculations are closer to the data, but still fall short. The $O(\alpha_s^2)$ calculation is much larger than the $O(\alpha_s)$ calculation and has large uncertainties; this indicates that higher orders are important. This can be understood by the opening of a new channel (gluon exchange in the t-channel) in these calculations, so that the $O(\alpha_s^2)$ calculation becomes an effective LO estimation.
ZEUS

\[ \frac{d\sigma}{dx}\text{[pb]} \]

(a)

(b)

Figure 17: (a) Forward-jet cross section as a function of \( x_B \); (b) dijet cross sections as functions of \( j \) in different \( x_B \) regions.

Multi-jet cross sections are better suited to test parton dynamics at low \( x \) since for dijet and three-jet cross sections a "genuine" NLO calculation can be performed. The ZEUS Collaboration has measured [26] the angular correlation as a function of \( x \) for dijets in different regions of \( x \) (see Fig. 17). The O(\( \alpha^2 \)) calculations are one order of magnitude below the data for all jet separations, whereas the O(\( \alpha^3 \)) calculations describe the data much better; this demonstrates the importance of the higher orders at low \( x \). The H1 Collaboration has measured [27] the \( x \) distribution for three-jet events and for the configuration of two central jets and one forward jet (see Fig. 18). The O(\( \alpha^3 \)) calculation describes the data at low \( x \) reasonably well.

Figure 18: Three-jet cross section as a function of \( x \) for all events (left) and events with two central jets and one forward jet (right).

7. Summary and conclusions

A wealth of new measurements from HERA and Tevatron test QCD nowadays with high precision. These data probe the theory up to the highest available energies and down to the lowest possible \( x \) values, phase-space regions of special interest at LHC. The exploration of these new regimes may well lead towards a new level of understanding of hard processes which will be crucial for interpreting any physics at LHC.

In particular, the underlying event has been tested in all possible environments, new high precision data will help to constrain further the proton PDFs, more and more precise determinations of the strong coupling are being obtained (see Fig. 15) and successful tests of colour dynamics at the highest available energies and down to the lowest possible...
For further progress in understanding QCD and take full advantage of the available data, higher-orders corrections will be extremely useful.

\[ x \text{ values have been performed.} \]

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