Experimental tests of QCD at hadronic colliders

C. Royon
DAPNIA-SPP, CE Saclay, F 91 191 Gif-sur-Yvette cedex, France

We present a general overview of recent QCD results at hadronic colliders.

1 Proton structure function measurements

1.1 Structure function measurements at HERA

The H1 and ZEUS experiments at HERA, at DESY, Hamburg, Germany allow to probe directly the quark and gluon contents of the proton by measuring $F_2$, the proton structure function in bins of $x$, the proton momentum fraction carried by the struck quark and $Q^2$, the squared energy transferred at the lepton vertex. The advantage of an $ep$ collider is that different methods are available to measure $x$ and $Q^2$ using either the lepton or the jets in the final state or both. The kinematical plane reached by the HERA collaborations is given in Fig. 1. We notice that the proton structure can be probed over a large kinematical plane ($10^{-6} < x < 0.1$, $Q^2 < 3.10^4$), and has a common domain with the previous fixed target experiments (SLAC, BCDMS, NMC...), which allows a direct comparisons of the measurements.

The proton structure function $F_2$ measurement at HERA is given in Fig. 2. We notice the high precision of the measurement performed at HERA, in good agreement with the fixed target data. The lowest HERA $Q^2$ data benefit from a good acceptance of the calorimeters at low $Q^2$ (SPACAL for H1, and Beam Pipe Calorimeter for ZEUS) and from special runs with shifted positions of the interaction vertex which allow to measure lower angles for the scattered electrons, and thus lower $Q^2$ events.

At moderate $Q^2$ and high $x$ ($0.015 < x < 0.65$, $1 < Q^2 < 100 \text{ GeV}^2$), the NuTeV collaboration has recently released new measurements of the proton structure functions $F_2$ and $xF_3$ with high precision, in agreement with QCD expectations.
The high luminosity obtained at HERA allows to measure the neutral and charged cross section with higher precision. A good agreement is found between the standard model expectations and the measurements.

1.2 DGLAP fits and extraction of the parton densities in the proton

The $F_2$ data allow to test precisely the Dokshitzer Gribov Lipatov Altarelli Parisi (DGLAP) evolution equations and to obtain the quark and gluon contents in the proton at NLO. In Fig. 2, we also see the good agreement between the measurement and the H1 and ZEUS DGLAP NLO fits. The parton distributions - quark and gluon densities from the H1, ZEUS and CTEQ fits⁹ are given in Fig. 3. The H1 and ZEUS collaborations use the data from their own experiments, together with the data from the BCDMS and NMC experiments to constrain high-$x$ distributions and valence quarks. We notice the high increase of the gluon density towards low values of $x$, which was first discovered at HERA ten years ago. We also notice the good agreement between the different fits. It would also be interesting to perform more global fits involving jet cross section measurements, as the ZEUS collaboration started to do.⁶

⁹Results from MRS fits are similar, except for the gluon at high $x$ which shows much difference
HERA $F_2$

$F_2^{em} \log_{10}(x)$

- ZEUS NLO QCD fit
- H1 PDF 2000 fit
- $x=6.32E-5$
- $x=0.0000102$
- $x=0.000102$
- $x=0.000161$
- $x=0.000253$
- $x=0.0004$
- $x=0.000632$
- $x=0.0008$
- $x=0.0013$
- $x=0.0021$
- $x=0.0032$
- $x=0.005$
- $x=0.008$
- $x=0.013$
- $x=0.021$
- $x=0.032$
- $x=0.05$
- $x=0.08$
- $x=0.13$
- $x=0.18$
- $x=0.25$
- $x=0.4$
- $x=0.65$

Figure 2: Proton structure function $F_2$ from the H1 and ZEUS experiments
The gluon distribution at high $x$ is still badly known. The uncertainty of $xG$ at $Q^2 = 100$ GeV$^2$, $x \sim 0.5$, is of the order of 50%. We will see in the following that the complementarity between the HERA and Tevatron measurements will allow to bring some knowledge on the high $x$ gluon density.

![Figure 3: Quark and gluon densities obtained from a NLO DGLAP fit to the proton structure function $F_2$](image)

1.3 $\alpha_S$ measurement

The value of $\alpha_S(M_Z)$ comes directly as an output of the QCD DGLAP fits of the proton structure functions. Other measurements performed at hadronic colliders are made using inclusive jet cross section in $pp$ colliders, jet shapes, subjet multiplicities, inclusive jet cross section measurements in $ep$ colliders. The different measurements, together with the references, are given in Fig. 4. We notice that the experimental uncertainties on $\alpha_S$ measurements at hadronic colliders approaches the uncertainties of the LEP measurements (see the world average in Fig. 4), but the theoretical uncertainties are much larger.
2 Jet cross section measurements at the Tevatron

As we mentioned earlier (see Fig. 1), the kinematical plane reached at the Tevatron is complementary from the reach at HERA. We noticed that the high-$x$ gluon density was purely constrained using HERA data, and the acceptance of the DØ and CDF experiments at high-$x$ will allow to obtain a better constraint of the parton distributions in this kinematical domain. The Tevatron measurements are specially important for searches at the LHC (multijet environment specially for searches for $R$-parity violated SUSY), and the constraint of the high-$x$ gluon density (search for higher dimensions).

The inclusive jet cross section from the DØ collaboration as a function of the transverse momentum is shown in Fig. 5 (left) in different bins of rapidity. This measurement is motivated by the run I excess observed by the CDF and DØ collaborations at high jet $p_T$ which lead to a modification of the high-$x$ gluon density. The uncertainties, dominated by the systematic errors on jet energy scale are still large especially at high rapidity, and will be notably improved in the near future. The CDF collaboration has similar results. Due to the size of the uncertainties, it is too early to constrain the parton distributions - and especially, the gluon density at high $x$ - using these data sets. The DØ collaboration has also performed a measurement of the dijet cross section as a function of their mass.

The DØ collaboration has also measured the distribution in difference in azimuthal angle $\Delta \Phi$ between jets in multi-jet events (see Fig. 5, right). The advantage of that measurement is that it is sensitive to multijet events (3, 4, 5 jets...) without measuring the jet $p_T$ and is thus less sensitive to jet energy scale uncertainties. Fig. 7 shows the good agreement between NLO QCD and the measurement except at high values of $\Delta \Phi$ where the measurement is sensitive to soft radiation effects. At low $\Delta \Phi$, this measurement is also sensitive to higher order calculation. The measurement also allows to tune the generators like PYTHIA because of its sensitivity on the amount of initial radiation which is important for the LHC. The CDF collaboration
has also measured the underlying event properties by analyzing the charged particle energy and multiplicity emitted in the region in azimuthal angle outside the jets region in clean dijet events (see Ref. 7) which is found to be in good agreement with PYTHIA expectations.

3 BFKL resummation effects and saturation

QCD evolution equations based on a resummation of $x$ terms have been proposed some time ago by Baltiskii, Fadin, Kuraev and Lipatov first at LO and then at NLO. There is so far no evidence of the need of the BFKL resummation at low $x$ in inclusive quantities such as the proton structure function $F_2$ even if some studies show the compatibility of the low $x$ $F_2$ data and the BFKL resummation approach and the BFKL effects can explain the rise of the gluon towards low $x$. As a consequence, BFKL resummation effects have been looked at in less inclusive quantities such as the production of jets in the forward region at HERA or Mueller-Navelet jets at the Tevatron. The idea is quite simple: one looks for jets with similar $k_T$ separated with large intervals in rapidity to suppress DGLAP evolution and favour BFKL effects at the Tevatron or the LHC. In the same sense, at HERA, it is possible to look for jets in the forward direction, far away from the scattered electron, and with $p_T \sim Q^2$ of the virtual photon.

The H1 collaboration has measured the differential forward jet cross section $d\sigma/dx dQ^2 dp_T^2$ in different bins of jet $p_T$, $x$, and $Q^2$ (see Ref. 12 and Fig. 6). The measurement is compared with NLO DGLAP expectation and a clear excess is observed in the low $x$, low jet $p_T$ region. However, it is not obvious that this is a pure BFKL resummation effect since the hadronisation corrections for low $p_T$ jets are high, and results could be also interpreted as being due to the resolved component of the photon itself.

The forward jets at HERA and the Mueller-Navelet jets at the Tevatron, and at the LHC, can also be a nice measurement to look for saturation effects. An attempt to look for saturation at HERA using the forward jet measurement was performed recently (see Ref. 13) and leads to
two possible solutions with weak or large saturation effects. Mueller-Navelet jet measurements at the LHC will allow to distinguish between these two solutions.

4 Conclusion

In this short report, we presented many recent results concerning QCD at hadronic colliders. The precision of the present inclusive cross section measurements allow to obtain the parton densities in the proton with high accuracy over a wide kinematical range. A measurement of the longitudinal structure function at HERA by reducing the beam energies towards the end of the HERA program would be of great importance to complete the determination of the parton distributions and to test further the DGLAP evolution equations. The Tevatron jet data allow to constrain further the gluon distribution especially at high $x$ and some more measurements with higher precision are expected in the near future. The $\alpha_S$ measurements at hadronic colliders reach the experimental precision obtained at LEP, but the theoretical uncertainties are still large. Searches for BFKL resummation and saturation effects have also been made at HERA especially in the forward jet cross section measurements, and more measurements, especially at the LHC will be of great importance. Many other topics in QCD such as event shapes, diffraction... have not been described in this talk because of the lack of time.
References

1. H1 Collab., Eur. Phys. J. C21 (2001) 33; ZEUS Collab., Eur. Phys. J. C21 (2001) 443, Phys. Rev. D67 (2002) 012007.
2. V. Radescu for the NuTeV collaboration, talk given at the low x meeting, Prague, September 2004, see /www.particle.cz/conferences/low-x04.
3. H1 Collab., Eur. Phys. J. C30 (2003) 1.; ZEUS Collab., preprint DESY03-093, accepted by Eur. Phys. J. C.
4. G. Altarelli and G. Parisi, Nucl. Phys. B126 18C (1977) 298; V. N. Gribov and L. N. Lipatov, Sov. Journ. Nucl. Phys. (1972) 438 and 675; Yu. L. Dokshitzer, Sov. Phys. JETP. 46 (1977) 641.
5. D. Stump, J. Huston, J. Pumplin, W.-K. Tung, H.L. Lai, S. Kuhlmann, J. F. Owens, JHEP 0310 (2003) 046; A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Eur. Phys. J. C23 (2002) 73.
6. A. Cooper-Sarkar, talk given at the low x meeting, Prague, September 2004, see /www.particle.cz/conferences/low-x04.
7. For preliminary results, see http://www-d0.fnal.gov/Run2Physics/qcd/ , and http://www-cdf.fnal.gov/physics/new/qcd/QCD.html .
8. DO Collaboration, hep-ex0409040 , submitted to Phys. Rev. Lett.
9. T. Sjöstrand et al., Computer Phys. Commun. 135 (2001) 238.
10. L.N.Lipatov, Sov. J. Nucl. Phys. 23 (1976) 642; V.S.Fadin, E.A.Kuraev and L.N.Lipatov, Phys. lett. B60 (1975) 50; E.A.Kuraev, L.N.Lipatov and V.S.Fadin, Sov.Phys.JETP 44 (1976) 45, 45 (1977) 199; I.I.Balitsky and L.N.Lipatov, Sov.J.Nucl.Phys. 28 (1978)
11. H Navelet, R.Peschanski, Ch. Royon, S.Wallon, Phys. Lett. B385 (1996) 357.
12. A. Knutsson for the H1 collaboration, proceedings of the DIS 2004 conference, Strske Pleso, Slovakia, 14-18 April 2004.
13. J. G. Contreras, R. Peschanski and C. Royon, Phys. Rev. D62 (2000) 034006; C. Marquet, R. Peschanski, C. Royon, Phys.Lett. B599 (2004) 236.