HADRONIC PHYSICS AND QCD:
STATUS AND FUTURE *

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Abstract

Studies of hadronic final states are entering a new phase where very precise experimental measurements require better theoretical predictions for a meaningful comparison. Recent results and future developments are briefly reviewed both for the experiments and the theory.

1 Introduction

Since quite some time the experimental results have supported Quantum Chromo Dynamics (QCD) as the theory of strong interactions. In recent years the increasing precision of the experiments has prompted a more detailed comparison between data and theoretical predictions.

The thirteen talks given in the hadronic physics session of this conference stimulated an extremely lively discussion between theorists and experimentalists. On the experimental side particular attention is currently devoted to the development of techniques which could bring to a cleaner comparison between data and QCD predictions. From the theoretical point of view the main efforts are towards the extension of the present accuracy of

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perturbative calculations and a better understanding of the hadronization (non-perturbative) regime.

In this short summary only few of the many interesting topics discussed will be covered. For more details we refer the reader to the other contributions to these proceedings.

2 Status of measurements.

QCD started with Deep Inelastic Scattering analysis. Still now the large amount of Structure Function measurements ($F_2$) at HERA provide the best probe to parton distribution functions (PDFs) inside the proton and an invaluable test for QCD predictions [1]. A compilation of the available data is reported in fig. 1. Next-to-leading order (NLO) DGLAP fits to these data provide measurements of the gluon density in the proton if the value of the QCD coupling $\alpha_S$ is given as input, but first attempts for a combined extraction of the two quantities are already available with the following

![Figure 1: Measurements of the proton Structure Function $F_2$ as a function of $Q^2$ for the intermediate/high (left) and very low (right) $Q^2$ regions. $x$ is the Bjorken variable, $y$ is the inelasticity in DIS events.](image-url)
results: $\alpha_S(M_Z) = 0.1150 \pm 0.0017\,_{(exp)}^{+0.0009 \, (mod)}_{-0.0005\, (scale)}$ [2] and $\alpha_S(M_Z) = 0.1166 \pm 0.0008\,_{(uncor)}^{+0.0032\, (corr)}_{-0.0005\, (norm)}$ [3] which demonstrate the remarkable precision reached.

In the last years much interest has been raised by precise measurements of $F_2$ in the very low $Q^2$ region down to 0.1 GeV$^2$. These data (fig. 1 right) [4] have stimulated many theoretical works, the challenge being to extend QCD predictions towards this kinematical region, that cannot be reached by standard perturbative approaches, and to allow a connection between Regge phenomenology and QCD calculations [5].

Although now closed, LEP is still producing many interesting results for our understanding of hadronic physics [6]. Among these the measurements of $\alpha_S$ have reached a remarkable precision: thanks to the various energies scanned it was possible to study its running from PETRA energies up to 208 GeV. An example of the impressive amount of data available is given in fig. 2, where the distributions for the thrust variable are reported from different experiments and energies. The data are fitted in terms of analytical calculations which rely on two parameters: the QCD coupling $\alpha_S$ and its non-perturbative extrapolation $\alpha_0$, which is assumed to be universal [7]. By using five different shape variables this approach provides the following measurements: $\alpha_S(M_Z) = 0.1171 \pm 0.0032$ and $\alpha_0 = 0.513 \pm 0.066$ [8]. The QCD coupling constant is measured precisely, and the approximated universality of $\alpha_0$ is confirmed, within the uncertainties. The accuracy of the measurement is definitely limited by the theory.

Also the ep collider HERA has now started to produce $\alpha_S$ measurements using different jet analysis, both in photoproduction and in DIS [9]. A compilation of $\alpha_S$ determinations is given in fig. 3, compared with the world average: the precision reached is comparable to other measurements. It
should be noted that all these studies require high transverse energy $E_T$ of the jets or high $Q^2$ of the events in the case of the DIS samples.

It would have been interesting also to use the data to measure the gluon distribution using lower $Q^2$ events to reach interesting low $x$ intervals to compare with the standard Structure Function analysis. In this kinematical region the experiments have reached a good precision, but unfortunately the NLO QCD prediction has a large theoretical uncertainty, making the extraction of QCD parameters not reliable [10].

Also the CDF collaboration at the Tevatron has recently produced a first measurement of $\alpha_S$ from high-$E_T$ jet data [11]. Several efforts are going on both from the experimental and theoretical side to study how jet physics at hadron colliders is affected by beam-spectator effects, initial-final state radiation and multiple parton scattering and to find possible alternatives to the standard jet algorithms [12]. These studies are fundamental for the present Run II data and, on longer time scale, for the LHC analysis.

3 Theoretical challenges and tools

The previous discussion clearly indicates that the theoretical uncertainty in the measurement of many QCD observables is becoming dominant. The present accuracy of fixed order calculations for jet observables is limited to NLO. It is important to remind that these calculations are affected by soft and collinear singularities. Although cancelling in infrared-safe observables, these singularities separately affect virtual and real contributions and are usually handled with general algorithms that combine the analytic calculation of the singular part with numerical integration. The step forward to next-to-next-to-leading order (NNLO) is non trivial, because, besides involving the calculation of the relevant two-loop amplitudes, it requires the full understanding of the pattern of cancellation of infrared singularities at $\mathcal{O}(\alpha_S^2)$. Considerable progress has been recently achieved in this direction: important two-loop amplitudes have been computed and the singular behaviour of tree and loop amplitudes at $\mathcal{O}(\alpha_S^2)$ has been understood [13].
Hopefully this progress will make NNLO calculations feasible in the next future. To obtain reliable predictions for hadron colliders, precise knowledge of PDFs is needed. In particular, a consistent NNLO calculation requires NNLO PDFs. Recently, a PDF set including an approximated NNLO fit has been produced [14]. Another important subject of theoretical investigation is the one of trying to quantify the PDF uncertainties. Recently, PDF sets with a systematic study of correlated errors have been released [15, 3]: it is thus possible to estimate the ensuing uncertainty on the cross section for the relevant processes at the Tevatron and the LHC.

Remaining on the perturbative side other presentations at this conference reported theoretical progress in soft-gluon resummation [16] and in the study of BFKL effects at hadron colliders [17].

Even though it is important to extend the present accuracy of perturbative calculations, it is clear that it does not make sense to try pushing indefinitely perturbation theory. The theoretical uncertainty affecting a QCD observable is given not only by the missing higher order contributions but also by the hadronization corrections that are often of the same order of magnitude. In recent years a great effort has been devoted in estimating hadronization corrections by using perturbative driven approaches, which lead to power suppressed effects. The best known is certainly the one of Ref. [7] which is based on the definition of an infrared finite coupling $\alpha_0$, which is then fitted to the data (see Sect. 2). The hadronization correction results in a power suppressed shift of the perturbative distribution. A more recent and sophisticated approach is based on the so called “shape function”, which is a non-perturbative quantity assumed to smear the perturbative distribution [18].

Besides “pure” theoretical progress, great importance has the way in which the current understanding of the theory is implemented in the tools the experimentalists have to their disposal. In this respect, a great work is being carried out to improve current Monte Carlo (MC) event generators. A fixed order perturbative calculation correctly incorporates the radiation of hard partons, through the corresponding QCD matrix elements, but fails to reproduce soft and collinear regions, where multiple QCD emissions become important. Moreover fixed order perturbative calculations are not directly suitable to implement hadronization. On the other hand a standard MC parton shower correctly treats soft and collinear radiation and can incorporate hadronization models but does not take into account hard emissions. Thus there are efforts to implement hard matrix element corrections in the current event generators, so as to correctly include the effect of parton emissions in the full phase space. In particular multijet matrix elements are
being implemented in ordinary MC and will provide a more reliable tool to study backgrounds for many new physics processes at hadron colliders [19]. However, it would be of great importance to combine MC with NLO predictions, that are the standard in fixed order calculations. A recent proposal has been described at this conference and encouraging results have been presented [20].

4 The Heavy Flavour Puzzles

The updated $t\bar{t}$ cross section from the CDF collaboration shows an agreement, within the present statistics, with the theoretical QCD predictions with a top mass of 174 GeV/$c^2$. (fig. 4).

Still unclear instead is the situation with the inelastic $J/\psi$ production [21]. The latest ZEUS results in $ep$ collisions indicates that NLO color singlet predictions are enough to explain the data and there is no need for colour octet component as requested by the CDF data.

The most puzzling situation is certainly the one of beauty production, where there are often large discrepancies between data and theoretical QCD predictions. This is a long standing problem, found already in the eighties with the anomalous high heavy flavour cross section measured at the Intersecting Storage Ring [22] and at the $Sp\bar{p}S$ [23]. The CDF collaboration has recently reported an excess of a factor 2.9 of the data over the QCD prediction [24]. A recent reanalysis, which makes use of all the theoretical information available, and, in particular, of a more careful treatment of the fragmentation, brings the 2.9 CDF discrepancy to 1.7 [25].

After the first indication of the excess measured at the Tevatron, also the HERA experiments found a similar excess both in photoproduction and DIS events (fig. 5 left). Recently LEP experiments reported again a discrepancy between data and theory for beauty production in $\gamma\gamma$ interactions.
Figure 5: Beauty cross-section as measured at HERA (left) and in γγ at LEP (right).

This situation is even more embarrassing if compared to what happens in the case of central charm production, where QCD seems to work considerably better, even if, due to the smaller mass of the c quark, one should expect the contrary to happen.

5 Outlook

With the advent of improved experimental techniques and high-luminosity high-energy colliders more challenging QCD tests will become possible. Nonetheless the role itself of the theory is going to change since QCD will be the major source of background for a variety of processes. More precise calculations and refined theoretical tools are needed to perform stringent tests but also to have a reliable control on QCD effects in new physics scenarios.

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\footnote{It should be noted that the $b\bar{b}$ production cross section recently measured by HERA-B is instead in agreement with QCD predictions, although the errors are large.}
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