QCD CHALLENGES AT THE LHC

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In this talk I review some challenges which await perturbative QCD at the Large Hadron Collider. In particular, I consider the underlying event, Monte Carlo methods and next-to-leading order (NLO) calculations.

1 Introduction

With the start of LHC operations next year, high-energy physics will enter a new era of discovery. The LHC is a proton-proton collider that will function at the highest energy ever attained in the laboratory, and will probe a new realm of high-energy physics. The use of a high-energy hadron collider as a research tool makes substantial demands upon the theoretical understanding and the predictive power of QCD, the theory of the strong interactions within the Standard Model. In the non-perturbative (low $Q^2$) regime several approaches to QCD, like lattice gauge theory, Regge theory, chiral perturbation theory, large $N_c$, heavy-quark or soft-collinear effective theories, are used. In this talk I concentrate on the perturbative (high $Q^2$) regime, where QCD purports to be a precision toolkit for exploring Higgs and Beyond-the-Standard-Model (BSM) physics. Precision QCD aims to achieve an ever more precise determination of the strong coupling constant $\alpha_s$, of the parton distribution functions (p.d.f.), of the electroweak parameters, of the LHC parton luminosity, and of the strong corrections to Higgs and BSM signals and to their backgrounds.

2 Breaking factorisation

The tenets of perturbative QCD (pQCD) are the universality of the infrared (IR) behaviour, the cancellation of the IR singularities for suitably defined variables, like jets and event shapes, and in the case of hadron-initiated processes, like electron-proton or (anti)proton-proton collisions,
the factorisation of the short- and long-range interactions. Factorisation in proton-proton (pp) collisions states that the cross section for the production of high-mass states, characterised by the large scale $Q^2$, can be separated into a parton cross section for the primary event, and into p.d.f.’s, measurable experimentally and whose evolution is described by the DGLAP equations.

Outside of the realm of factorisation lies the underlying event (UE), which can be operatively defined as whatever is in the pp interaction besides the primary scattering. In particular, UE includes the multiple-parton interactions as well as the interaction of spectator partons, i.e. other than the ones initiating the primary scattering. The assumption is that if such an interaction occurs it is characterised by a scale $\Lambda$ of the order of a GeV, and so it is suppressed by powers of $\Lambda^2/Q^2$ with respect to the primary scattering. Thus, UE breaks factorisation by means of power-suppressed contributions. How important are they for a precision calculation? There is no obvious answer to this question since of course we cannot use the pQCD framework to model UE, and its analysis must rely solely upon the data. In pp collisions at the Tevatron, UE is being studied by analysing in single-jet production the charged-particle multiplicity in regions which are perpendicular in azimuth to the jet, since that region is expected to be sensitive to UE. A modelling of the data is then performed through the shower Monte Carlo (MC) PYTHIA. The UE sensitivity to beam remnants and to multiple interactions can be reduced by selecting back-to-back two-jet topologies. A similar investigation is being planned also through the Drell-Yan production of vector bosons. Understanding and modelling UE at LHC will represent a major challenge.

Other examples of factorisation-breaking contributions are a) the power corrections: MC and theory modelling of power corrections were laid out and tested at LEP, where they provided an accurate determination of $\alpha_S$. However, models still need be tested in hadron collisions: a study of single-jet production at Tevatron running at two different centre-of-mass energies shows that the Bjorken scaling is violated more than logarithmically, and data can fitted by assuming a power-correction shift in the jet $E_T$; b) diffractive events, which are known to violate factorisation at Tevatron.

3 Monte Carlo models

The detection of Higgs and BSM signals requires a precise modelling of their backgrounds. Examples are QCD production of W + 4 jets and of WW + 2 jets, which are backgrounds to Higgs production through vector-boson fusion (VBF) with the Higgs decaying into a WW pair, as well to $t\bar{t}$ production, or $W + 6$ jets and $WW + 4$ jets, which are backgrounds to $tt\bar{t}$ production. One approach is to model QCD production through matrix-element MC generators, which provide an automatic computer generation of processes with many jets, and/or vector or Higgs bosons. There are several such multi-purpose generators, like e.g. ALPGEN, MADGRAPH/MADEVENT, COMPHEP, GRACE/GR@PPA, HELAC, and SHERPA (which has got its own showering and hadronisation). A different example is PHASE/PHANTOM, a MC generator dedicated to processes with six final-state partons only, thus suitable to $t\bar{t}$ production, WW scattering, Higgs production via VBF and vector-boson gauge coupling studies, but where no approximation is used. Matrix-element MC generators are particularly suitable to studies which involve the geometry of the event, because the jets in the final state are generated at the matrix-element level, and thus exactly at any angle. In addition, they can be interfaced to parton-shower MC generators, like HERWIG or PYTHIA, to include showering and hadronisation. Furthermore, a procedure (CKKW) has been devised to interface parton subprocesses with a different number of final states to parton showers. Finally, MC@NLO, a procedure and a code to match exact NLO computations to shower MC generators. In a way, this is the most desirable procedure, because it embodies the precision of NLO partonic calculations in predicting the overall normalisation of the event,
while generating a realistic event set up through showering and hadronisation. It cannot be, though, multi purpose, being obviously limited to the processes for which the NLO corrections are known. Challenges in this instance are to include as many NLO processes as possible for Higgs and BSM signals and for their backgrounds, as well as to extend the CKKW approach to it.

4 NLO calculations with many jets

NLO calculations have several desirable features. a) the jet structure: while in a leading-order calculation the jets have a trivial structure because each parton becomes a jet, to NLO the final-state collinear radiation allows up to two partons to enter a jet; b) a more refined p.d.f. evolution through the initial-state collinear radiation; c) the opening of new channels, through the inclusion of parton sub-processes which are not allowed to leading order; d) a reduced sensitivity to the (fictitious) renormalisation and factorisation scales allows to predict the normalisation of physical observables, which is usually not accurate to leading order. That is the first step toward precision measurements in general, and in particular toward an accurate estimate of signal and background for Higgs and New Physics at LHC; e) finally, the matching with MC@NLO mentioned in Sect. 3.

IR singularities appear in the intermediate stages of a NLO calculation. However, the structure of QCD is such that those singularities are universal, i.e. they do not depend on the process under consideration, but only on the partons involved in generating the singularity. Thus, in the 90’s process-independent procedures were devised to regulate those divergences, which use universal counterterms to subtract the divergences. However, a look at the history of NLO calculations shows that given a certain process, it is often very time-consuming to compute to NLO the addition of even just one more jet to it. Why in a NLO calculation is it so difficult to add more particles in the final state? The loop integrals occurring in the virtual contributions are involved and process dependent. In addition, more final-state particles imply more scales in the process, and so lenghtier analytic expressions in the loop integral. In fact, except for special cases like the NLO corrections to the electroweak production of a vector-boson pair + 2 jets, there are no processes with more than three final-state particles for which the NLO corrections are known. Recently, a twistor-inspired approach, which has allowed for great advances in the analytic computation of tree and one-loop amplitudes, as well as several semi-numerical approaches which show promise to handle NLO corrections in an automated way, have surfaced. However, the programme of applying sistematically NLO computations to studies of signals and backgrounds for Higgs and New Physics represents yet a major challenge, which will be undoubtely receiving much attention in the next future.

Acknowledgments

Work supported by MIUR under contract 2004021808–009.

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