PROCEEDINGS OF SCIENCE

Precision QCD at FCC-ee

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We discuss the status and challenges of predicting QCD effects at the FCC-ee, in the context of the FCC-ee QCD working group. In this presentation we focus on multi-purpose event generators, and parton showers and hadornization in particular, which will become the relevant topics for the most precise and detailed simulations at future e^+e^- colliders.

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1. Introduction: QCD at FCC-ee

The strong interaction, as described by Quantum Chromodynamics (QCD), is almost inevitable at any future collider. This applies first and foremost to reconstructing jets and using event shape variables to search for and isolate signals in and beyond the Standard Model at the highest precision. In order to increase how we can predict and model QCD final states, a deep understanding of the strong interaction at all relevant scales in collider events is thus necessary. QCD is of course also of interest in its own right, given the simple fundamental building blocks which lead to the rich phenomenology of hadronic final states, and the fundamental constants of nature, like the strong coupling, attached to it.

The QCD working group within the FCC-ee feasibility study is focusing on QCD at a future e^+e^- collider and has recently addressed many of the relevant issues in a series of workshops. This included a general kick-off meeting to take stock of the status of theoretical and experimental methods [1], one focusing on jet physics and fragmentation functions [2], on jet and flavour tagging [3], and an extensive programme on recent and future development of parton shower algorithms held at CERN [4].

While precision analytic resummation of event shape variables and other observables set the stage for the most reliable theoretic predictions, it is event generator simulations which solely are capable of predicting all thew details and complexity of the observed final states. Factorisation and resummation at high logarithmic orders have thus not only become a tool for precision predictions but also one to inspire and benchmark the development of event generators. n-jet observables at high multiplicities and high perturbative orders complement such efforts for fixed-order matching and as input to multi-jet merging algorithms in event generators. Fig. 1 summarizes for which (resummed) event generator predictions we now have fixed-order corrections available: for almost all of those next-to-leading order (NLO) has become the standard, and is used as such within state-of-the-art event generators. Since event generators are sill at the heart of multi-purpose theoretical predictions, the present talk will focus on the status and prospects of event generators in the precision era.

2. Event generators: parton showers

The precision of event generators has generally been attributed to perturbative input for the hard process and the development of more precise parton shower algorithms, both of which are fields in which the community has been and is very active. However, such developments cannot ignore the need for a much deeper understanding of the hadronization of partonic final states, and the uncertainties induced through this, connecting to the physics of colour reconnection as well as parton evolution beyond the large-number-of-colours limit. Similar remarks apply to analytic calculations: how precisely hadronization corrections are modeled and constrained through different orders in resummed perturbation theory is currently a very active field, in particular with respect to the three-jet limit see *e.g.* [6–9], and might turn out to be equally inspired by event generators or used vice-versa.

Current LHC-age event generators [10–12] offer to use different parton shower algorithms and hadronization models and become much more flexible in the combinations of such modules to constrain and evaluate systematic differences. Two algorithms are mainly used for parton showering:

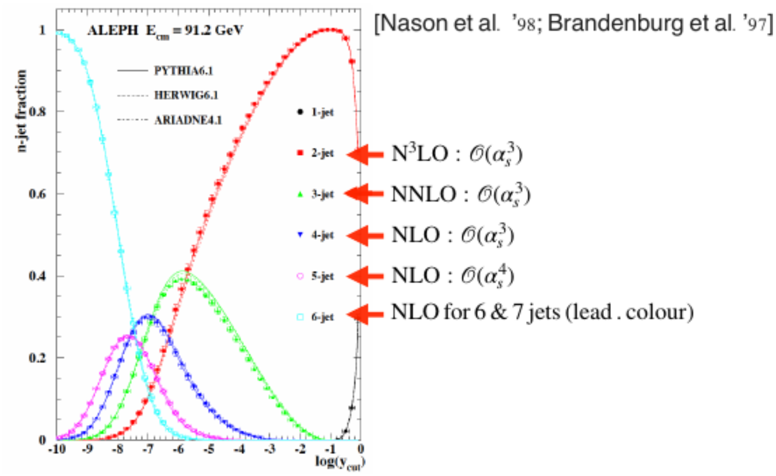

Figure 1: Integrated jet rates compared to ALEPH data. The arrows indicate at what fixed-order perturbative precision these jet rates are available and could be used to improve the event generator predictions. Annotated plot taken from [5].

angular ordered ones [13], constructed directly from QCD coherence, and dipole-type algorithms, available in all major event generators *e.g.* [14–17], which have the advantage that they can be ordered with hardest emissions occurring first, and so come in much more handy towards fixed-order matching, and momentum mappings on an emission-by-emission basis. Recently, shortcomings have been identified in the first generation of dipole shower algorithms, limiting them to below next-to-leading logarithmic (NLL) accuracy for a large number of observables, and possibly creating more shortcomings. From the accuracy point of view, NLL is desirable for event shapes, since, for exponentiating observables this is the first level at which we can make a quantitative prediction, with corrections in the exponent genuinely suppressed by α_S. At the same time, leading logarithmic (LL) accuracy needs to be achieved for non-global and other intra-jet observables, which, with probabilistic algorithms is currently only achievable in the large-N limit. It is clear that a large community effort is currently trying to push these borders even further, focusing on evolution beyond the large-N limit, and beyond the $\text{NLL}_{\text{global}}/\text{LL}_{\text{non-global}}$ level, which in turn has only been achieved recently, see e.g. [18–21]. However also QED radiation, as well as electroweak effects, need ultimately be taken into account. In this presentation, I will, however, focus on QCD.

Building blocks for higher order evolution start to become available, see for instance in [22–25], however *constructing* a functional algorithm which would leverage these building blocks to improve on shower accuracy is a largely complicated endeavor so far not achieved, with some structures only highlighted recently [26–28]. Specifically in the soft evolution, progress has been made to identify the structure of evolution equations for soft parton showers at and even beyond the large-N limit [27, 29], and there are exploratory steps within other parton showers [30]. However, beyond leading colour, the probabilistic interpretation of parton showers is lost. In fact, the main item to consider now is the colour density operator (which, in turn can be generalized to other quantum numbers), and evolution equations which stem from iterating fundamental building blocks at the amplitude level. One approach which implements this numerically in a systematic way has been

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presented in [31], where we consider the resummation of non-global observables beyond leading-N and compare this to a calculation using equivalent Langevin formulation of the problem, and find full agreement. The latter method, however, does not generate any parton shower events which could be used in a universal way.

Let us also stress that the detailed control of parton shower accuracy is mandatory to interpret parameters entering these simulations. In particular, this relates to the way parton showers do instantiate virtual corrections, and subject to which renormalization scheme this is happening. These questions intimately connect to the impact of the parton shower infrared cutoff, as well as the phase space region chosen to be available to the parton shower both of which thus identify what the region is in which infrared singularities are removed from virtual corrections. First steps into this direction have been undertaken in [32], where we have demonstrated that the shower cutoff relates to power corrections for certain massless event shapes, and on top of this to the definition of a heavy quark's mass parameter, which thus can be determined in a meaningful scheme from, in this case, a coherent branching NLL accurate parton shower algorithm.

3. The interface to hadronization

The factorization at the parton shower infrared cutoff is a central point in constructing parton shower algorithms and constraining hadronization models. We have been studying the cutoff dependence in [32] in connection to power corrections in event shapes and the top quark mass parameter, and also have exploited this fact in [27] to construct entire evolution equations for a parton shower algorithm *and* a soft factor which would be able to describe hadronization. This has up until now happened in the soft gluon case, though with obvious generalizations beyond this. In this case, our analysis is driven by acknowledging the infrared cutoff as a factorization scale, of which the cross section as a physical quantity should be independent at the level of the accuracy one considers.

This question directly relates to what the intrinsic uncertainty within current hadronization models is, and has been explored in a study of the Les Houches workshop by re-tuning hadronization parameters at different parton shower variations on the same data. The resulting uncertainty bands are typically more narrow than the ones from parton shower variations alone, however in this study parameter variations which to some extent mimic the change in the infrared cutoff have been considered, but not the cutoff itself.

In ongoing work [33], we are currently exploring this further and confront it with developing a new kind of hadronization model, which has been designed with such an RGE picture in mind. We stress that this enforces us to smoothly match shower and hadronization dynamics at the infrared cutoff, which in turn tells us that a large portion of dynamics in the hadronization model might actually be of perturbative origin, something we have to some extent explored in the case of colour reconnection models in [34]. Confronting such novel hadronization models with analytic power corrections is then of course another important task to fulfill.

4. Conclusions and outlook

Precision QCD at future colliders is a wide field, and has seen tremendous development. Monte Carlo event generators, and parton showers and hadronization models in particular, are already a vital part of predicting and understanding QCD, but face a number of challenges to keep up with precision measurements. Their current development, however, will turn them into tools for precision QCD, and it is thus important to further bridge the gaps between analytic resummation and the event generators to obtain reliable resummation properties of parton showers and to understand and constrain hadronization models. Emerging event generator methods like amplitude evolution can of course also be used as theory tools and algorithms in their own right and aid challenging problems like the resummation of non-global observables beyond leading colour.

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