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Jet substructure and a possible determination of the QCD coupling

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We review possible avenues toward an extraction of the QCD strong coupling α_s using jet substructure techniques. A range of jet substructure observables have been measured recently at the LHC with unprecedented precision. In addition, theoretical advances make it possible to directly compare LHC data and first principles calculations in QCD. LHC jet substructure observables may provide an independent handle on extracting α_s and they are particularly well suited to complement current extractions from electron-positron annihilation data. However, further theoretical and experimental efforts are needed in order to obtain a competitive extraction.

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Introduction

Jets and jet substructure are important tools for many analyses carried out at the LHC. For example, jet substructure techniques are used extensively for tagging boosted W,Z, discriminating between quark/gluon jets and for searches of particles beyond the standard model. The development of jet grooming techniques now also facilitate QCD precision studies using jet substructure. Jet grooming techniques are designed to remove soft wide-angle radiation from the jet. These techniques reduce the hadronization correction and remove the soft contamination from the underlying event (mostly from multiparton interactions) leaving behind only the hard core of the jet. In particular, the soft drop grooming algorithm [1] allows for first principles calculations within perturbative QCD. Despite the fact that most jet substructure observables are sensitive to very soft scales, it is possible to make direct one-to-one comparisons between theory and data. For example, jet substructure observables can be used for the tuning of parton showers, improving our understanding of the fragmentation/hadronization mechanism, and jets can be used as a well calibrated probe of the quark-gluon plasma in heavy-ion collisions. See [2] for a recent review of jet substructure techniques. Recently, it has been proposed to measure the strong coupling constant α_s using jet substructure observables [3]. Such an extraction is particularly challenging due to the required precision both from the experimental and the theoretical side. Here, we first review the soft drop grooming procedure and the status of theoretical calculations. We then discuss possible avenues toward an extraction of the QCD strong coupling constant.

Soft drop groomed jet substructure observables

We consider inclusive jet production $pp \to \text{jet} + X$ at the LHC where jets are identified in a given transverse momentum p_T and rapidity η interval and no further constraints are imposed on the final state configuration. The soft drop grooming algorithm was introduced in [1] which we briefly review here. First, the jet constituents are reclustered with the Cambridge/Aachen algorithm, where the distance metric between particles only depends on their geometric distance in the η–ϕ plane. The obtained clustering tree is then declustered recursively, where at each step, the soft drop criterion is tested

$$\frac{\min[p_{T1}, p_{T2}]}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{\Delta R_{12}}{R} \right)^{\beta} . \tag{1}$$

Here p_{Ti} denote the transverse momenta of the two branches obtained at each declustering step and $\Delta R_{12}/R$ denotes their distance in the η–ϕ plane divided by the jet radius R. The soft threshold z_{cut} and the angular exponent β are free parameters of the grooming procedure. If the softer branch fails the criterion, it is removed from the jet and otherwise, the algorithm terminates and returns the groomed jet. An important feature of the soft drop grooming algorithm is that non-global logarithms are absent ($\beta = 0$) or power suppressed ($\beta > 0$) for the type of observables discussed here, except for logarithms in the grooming parameter z_{cut}.

Various jet substructure observables in proton-proton collisions have been calculated within perturbative QCD taking into account the effect of soft drop grooming. A class of observables which is particularly well suited for the extraction of the QCD coupling constant are jet shape observables. Similar to event shape observables in e^+e^- collisions, a single number is determined in order to characterize the radiation pattern of the observed jet. The close analogy to e^+e^- event shape observables makes this class of observables particularly well suited for the extraction of the QCD strong coupling constant (see for example [4, 5, 6]). In particular, it may be possible to learn about universality aspects of the relevant nonperturbative physics [7, 8]. Examples of jet shape observables considered in the literature are jet angularities τ_a [9] and two-point correlation functions $e_2^{(\alpha)}$ [10] which are defined as

$$\tau_a = \frac{1}{p_T}\sum_{i\in J} p_{Ti}\Delta R_{iJ}^{2-a}\,, \qquad e_2^{(\alpha)} = \frac{1}{p_T^2}\sum_{i<j\in J} p_{Ti}p_{Tj}\Delta R_{ij}^{\alpha}\,. \tag{2}$$

Here the p_{Ti} denote the transverse momenta (relative to the beam) of the particles inside the jet, ΔR_{iJ} is their distance to the jet axis, and ΔR_{ij} denotes their pairwise distance in the η–ϕ plane. The parameters a and α in Eq. (2) are free parameters as long as the resulting observable is infrared-collinear safe. For example, the jet mass (jet broadening) case is obtained for $a=0$ ($a=1$). The soft drop groomed jet mass distribution in proton-proton collisions was calculated in [11, 12, 13]. The more general two-point functions can be found in [11] and jet angularities in [14]. The groomed jet mass distribution was measured recently by both ATLAS [15] and CMS [16].

Here we briefly outline the QCD factorization structure using jet angularities as an example [14]. For sufficiently collimated jets, parametrically $R \ll 1$, we may separate the hard-scattering functions H_{ab}^c from the formation of the jet taken into account by a jet function $\mathscr{G}_c$. We have [17, 18, 19, 20]

$$\frac{d\sigma}{d\eta\, dp_T\, d\tau_a} = \sum_{abc} f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H_{ab}^c(x_a,x_b,\eta,p_T/z,\mu)\otimes \mathscr{G}_c(z,p_T R,\tau_a,\mu,z_{\rm cut},\beta)\,, \tag{3}$$

where $f_{a,b}$ are the parton distribution functions and the $\otimes$ denote integrals over the longitudinal momentum fractions $x_{a,b}$ and z. Here z is the fraction of momentum contained in the observed jet relative to the initiating parton. For the phenomenologically relevant kinematic regime of $\tau_a^{1/(2-a)}/R \ll z_{\rm cut} \ll 1$, we can further refactorize the jet function as

$$\begin{aligned}\mathscr{G}_c(z,p_T R,\tau_a,\mu,z_{\rm cut},\beta) \;&= \sum_i \mathscr{H}_{c\to i}(z,p_T R,\mu)\, S_i^{\notin {\rm gr}}(z_{\rm cut} p_T R,\beta,\mu)\\ &\times\; C_i(\tau_a,p_T,\mu)\otimes S_i^{\rm gr}(\tau_a,p_T,R,\mu,z_{\rm cut},\beta)\,.\end{aligned} \tag{4}$$

The factorization and the associated renormalization group evolution equations allow for the simultaneous resummation of three classes of potentially large logarithms $\alpha_s^n \ln^n R$, $\alpha_s^n \ln^{2n}(\tau_a^{1/(2-a)}/R)$ and $\alpha_s^n \ln^{2n} z_{\rm cut}$. Note that in Eqs. (3) and (4) only the collinear C_i and soft function $S_i^{\rm gr}$ depend on the jet angularity τ_a. All other functions can be thought of as perturbatively calculable quark/gluon fractions. In Fig. 1, we show the jet mass distribution for LHC kinematics at next-to-leading logarithmic (NLL) (left) and next-to-next-to-leading logarithmic (NNLL) accuracy. The purely perturbative calculation is shown (dashed black, yellow band) and the result including nonperturbative effects (red) using the shape function of [7] with $\Omega = 1$ GeV. A more rigorous treatment of nonperturbative effects for groomed observables can be found in [8]. In addition, we show the PYTHIA 8 result [21] for comparison. We observe very good agreement and the nonperturbative effects are only important at very small jet mass values.

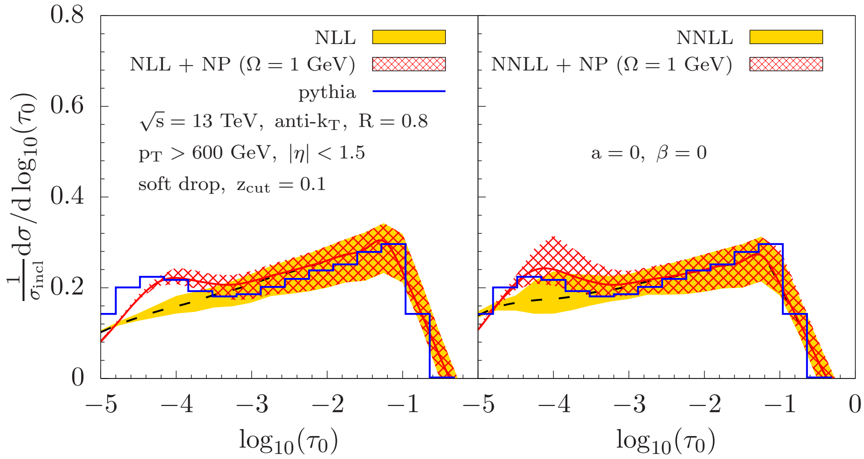

Figure 1: The soft drop groomed jet mass distribution at NLL (left) and NNLL (right) compared to PYTHIA 8 results for $\beta = 0$ and $z_{\rm cut} = 0.1$ [14]. Exemplary LHC kinematics are chosen as shown in the figure.

A possible determination of the QCD strong coupling constant

Observables that are well suited for an extraction of the QCD strong coupling constant should be rather insensitive to nonperturbative effects and, at the same time, retain the sensitivity to α_s. Following the arguments in [3], soft drop groomed observables have a significantly reduced sensitivity to nonperturbative effects compared to their ungroomed counterparts which can be seen as follows. The smallest scale that appears in the calculation of the groomed jet mass is $\mu_S^{\rm gr} = p_T\tau/R(z_{\rm cut}R^2/\tau^2)^{1/(2+\beta)}$. Instead without grooming it would be $\mu_S = p_T\tau/R$. If we set $\mu_S = \Lambda_{\rm QCD} \sim 1$ GeV, we find that the onset of nonperturbative physics is shifted to significantly lower values when the grooming procedure is included

$$\tau_{\rm gr} = \tau_{\rm ungr}\left(\frac{\Lambda_{\rm QCD}}{z_{\rm cut}p_T R}\right)^{\frac{1}{1+\beta}}. \tag{5}$$

For typical values of jet kinematics at the LHC, one finds that the onset of nonperturbative effects is pushed down by two orders of magnitude in τ. The fact that the nonperturbative physics start to dominate only at very small values of τ can be seen also in Fig. 1. We note that grooming can also be considered in e^+e^- collisions [22]. In proton-proton collisions it is necessary in particular to also remove from the jet soft particles resulting from the underlying event.

In Ref. [3] a range of observables and grooming parameters $z_{\rm cut}, \beta$ were explored. The criteria to determine which observables and parameters are most suitable for an extraction of α_s were as follows. First, the robustness to nonperturbative physics was assessed by turning hadronization effects on/off in a parton shower event generator. Second, the sensitivity to α_s as a function of τ was determined by varying α_s by $\pm 10\%$. The main takeaways are that gluon dominated regions exhibit a larger sensitivity to α_s and observables such as jet broadening, $a = 1$ in Eq. (2), may be better suited than the jet mass. Given the current status of experimental results and theoretical calculations, the overall uncertainty of an extraction of α_s was estimated to be of the order of 10%. However, this estimate is expected to improve significantly in the future.

On the theoretical side, the accuracy of the existing calculations will have to be extended to full NNLO+NNLL$'$ or even N^{3}LL in order to achieve a competitive determination of α_s. See for example [23, 24] for recent precision calculations at fixed order. While the quark/gluon fractions may be calculated perturbatively following the factorization in Eqs. (3) and (4) above, a fit of α_s might have to be combined with a determination of the PDFs [3]. In addition, it will be interesting to explore universality aspects of nonperturbative physics using either shape functions or Monte Carlo techniques [8]. Possible extensions are also multi-observable fits, see for example [25]. On the experimental side, the current precision may be increased by considering track based observables. However, this would require further theoretical efforts to achieve the required precision.

Conclusions

Jet substructure techniques may help in the future to precisely constrain the QCD strong coupling constant α_s. Soft drop grooming allows for first principles calculations in perturbative QCD which may be compared directly to data taken at the LHC. The grooming procedure largely removes soft wide-angle radiation making jet substructure observables robust in the complicated LHC environment while retaining the sensitivity to α_s. In addition, new insights into universality aspects of the relevant nonperturbative physics may be obtained. In the future, it will be important to make further progress and achieve an improved precision both from the experimental and the theoretical side.

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