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# SCET for jet physics in the vacuum and the medium

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**Abstract**

In this plenary talk I discuss soft-collinear effective theory (SCET) as a framework for precision QCD phenomenology. Emphasis is placed on jet and heavy flavor observables accessible at current and future collider facilities. One of the principal challenges that calculations of hard probes in heavy ion reactions face is the ambiguity associated with the implementation of medium-induced radiative effects. I demonstrate how extension of SCET to describe parton propagation in QCD matter has helped quantify and reduce the theoretical uncertainty in jet quenching calculations.

*Keywords:* SCET, $\mathrm{SCET_G}$, jets, heavy flavor, heavy ion collisions

## 1. Introduction

The purpose of these proceedings is to highlight selected recent results obtained in the framework of soft-collinear effective theory (SCET) [1, 2] and its extension to describe jet propagation in a background QCD medium via Glauber gluon exchange [3, 4]. Emphasis is placed on observables that illustrate the gains in precision from higher-order calculations and resummation. Observables of direct relevance to experiments at current and future high-energy nuclear physics facilities such as the Relativistic Heavy Ion Collider (RHIC), the Large Hadron Collider (LHC) and an Electron Ion Collider (EIC) are given priority. Results for jets and heavy flavor, strictly within traditional pQCD, are covered elsewhere and summarized in [5]. Experimental results are collected in [6].

## 2. SCET for jet physics in the vacuum

Soft-collinear effective theory has emerged as a new tool to address hard large $Q^2$ processes in lepton-lepton, lepton-hadron, and hadron-hadron collisions. Together with QCD factorization, which has been proven in this framework for a number of processes, it is especially useful in improving the precision of multi-scale calculations through the resummation of large Sudakov-type logarithms. While initially a large body of work was dedicated to $e^+e^-$ annihilation, recently there has been more focused effort toward processes of interest to LHC phenomenology and a future EIC.

As a first example we consider one inclusive jet production in deep inelastic scattering (DIS). The discussed observable is called 1-jettiness in DIS is defined by one jet and one beam axis

$$\tau_1 \equiv \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_J \cdot p_i\} . \tag{1}$$

Here $q_B, q_J$ are lightlike four-vectors along the beam and jet directions. In terms of collimated parton shower structures, this is similar to 2-jettines in $e^+e^-$ (two jets in the final state) and 0-jettiness in $pp$ (Drell-Yan). This event shape distribution has been calculated over the past 15 years with increasing theoretical precision from next-to-leading logarithmic (NLL) accuracy to next-to-next-to-next-to-leading ($\mathrm{N^3LL}$) logarithmic accuracy [7, 8, 9, 10]. An example of these improvements can be seen in Fig. 1 [1]. The uncertainty band is reduced from a factor of few to just a few percent. The kinematics is chosen to be representative of HERA measurements. These improvements can help test the universality of non-perturbative effects and extract the strong

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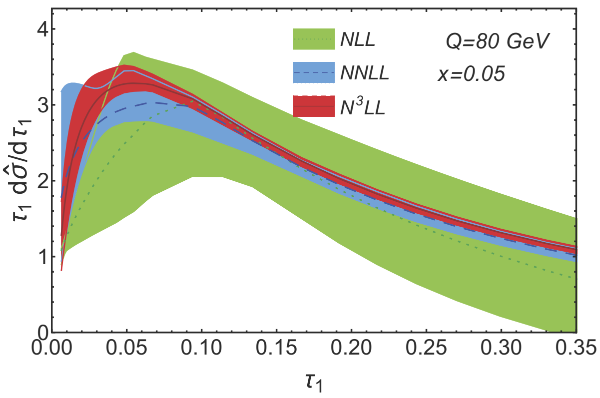


Figure 1: Example of perturbative convergence of the 1-jettiness for NLL, NNLL, N$^3$LL resummation at $x = 0.05$ and $Q = 80$ GeV [10].

coupling constant at the $Z^0$ pole, $\alpha_s(m_Z)$. The development of this technology is also useful in broadening the scope of the future EIC physics program.

In the past few years there has been a proliferation of NNLO calculations for the LHC ($H$+jet, $W^\pm/Z^0$+jet, etc). While NLO $V$+N jet calculations, that can also be matched to parton showers, generally work well, there are notable exceptions. One such example is the scalar momentum sum $p_T$ distributions of associated jets. One of the main challenges in such calculations is the treatment of infrared (IR) singularities. Generally, two approaches are commonly adopted, local and non-local subtraction schemes. SCET, and the N-jettiness variable has found a novel application in a non-local subtraction scheme [11, 12]. At NNLO the cross section can have up to two additional partons in the final state and can be expressed schematically as follows

$$\sigma_{NNLO} = \int d\Phi_N\, |\mathcal{M}_N|^2 + \int d\Phi_{N+1}\, |\mathcal{M}_{N+1}|^2\, \theta_N^< + \int d\Phi_{N+2}\, |\mathcal{M}_{N+2}|^2\, \theta_N^< + \int d\Phi_{N+1}\, |\mathcal{M}_{N+1}|^2\, \theta_N^> + \int d\Phi_{N+2}\, |\mathcal{M}_{N+2}|^2\, \theta_N^> \,. \tag{2}$$

Here, $\theta_N^>$ and $\theta_N^<$ represent a cut for a small value of the N-subjettiness variable $\tau_N$. Below $\tau_N$ one uses the factorization theorems of SCET to evaluate the cross section. If the cross section is expanded to the appropriate fixed order it will reproduce the NNLO result. Above $\tau_N$ the fixed order calculation works well, in particular one needs the results with N+1 and N+2 jets. An example of the calculation of the scalar sum of transverse momenta of jets associated with a $Z^0$ boson is shown in

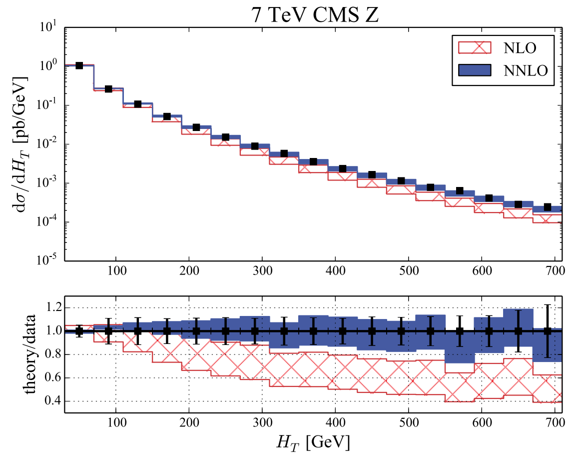


Figure 2: The scalar sum of jet transverse momenta distribution in Z+jet processes measured by CMS. The ratio of the NLO and NNLO predictions to the measured data is shown [12].

Fig. 2 [2]. The theoretical uncertainties are reduced and there is much better agreement between theory and experiment.

A noteworthy development in the past year was the development of SCET resummation for semi-inclusive jet observables. For jet production, logarithms of the jet radius parameter arise. When the jet radius $R$ is small, such logarithms can become large and require resummation. It was recently shown that when the out-of-cone radiation is not power suppressed, $O(\Lambda/E_J)$, these terms are of the form $(\alpha_s \ln R)^n$ [13, 14, 15, 16]. The new semi-inclusive jet functions follow DGLAP-type evolution equations [17]. For more details see the contribution by Ringer [18].

## 3. SCET for jet physics in a QCD medium

An effective field theory (EFT) for hard processes in heavy ion collisions can be constructed by coupling the jets to the QCD medium by off-shell $t$-channel Glauber gluon exchanges with momentum scaling $q \sim (\lambda^2, \lambda^2, \lambda)$, where $\lambda$ is a small parameter. Building upon the soft-collinear effective theory of jet production [1], the collinear quark-Glauber and collinear gluon-Glauber sectors of the extended theory SCET$_\mathrm{G}$ were derived in [3] and [4]. In this background field approach, the properties of the QCD medium that determine the jet-medium interactions enter the potential that sources the Glauber gluons and first applications discussed the transverse momentum broadening of

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