Snowmass proposal

Precision Physics with Energy-Energy Correlators in DIS

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Abstract

In this LoI we discuss the event shape observables Energy-Energy correlators (EEC) and Transverse Energy-Energy correlators (TEEC) which have presently received significant theoretical attention. Here we focus on the case of deep inelastic scattering (DIS) and we introduce a novel definition of EEC tailored to DIS in the Breit frame, which is the natural generalization from the case in e^+e^- collisions. This class of observables (EEC/TEEC) can be reliably studied through perturbative QCD since, non-perturbative corrections are expected to be significantly smaller in comparison to other event shape observables. EEC and TEEC in DIS can cleanly probe the three-dimensional distribution of parton momenta inside hadrons and constitute a laboratory for testing transverse momentum dependent factorization of QCD without the dependence of the non-perturbative fragmentation functions. Promptly, calculations up to N^{3}LL+NLO QCD corrections are expected from our work.

1 Introduction

Event shape observables describe the patterns, correlations, and energy flow of hadronic final states in high energy processes and have played a prominent role in studies of various dynamical aspects of QCD in e^+e^-, ep, pp, and heavy-ion collisions. In addition, event shape variables have been widely used to determine the strong coupling α_s and test asymptotic freedom, to tune the nonperturbative Quantum Chromodynamics (QCD) power corrections, and to search for new physics phenomena.

The EEC event shape was originally introduced [1] in the context of e^+e^- collisions and is defined as

$$\mathrm{EEC} = \sum_{a,b} \int d\sigma_{e^+e^- \to a+b+X} \frac{2E_a E_b}{|\sum_i E_i|^2} \delta(\cos\theta_{ab} - \cos\theta)\,, \tag{1}$$

where E_i is the energy of hadron i and θ_{ab} is the opening angle between hadrons a and b. The EEC is analytically known up to NLO [2] and the all-order factorization in QCD is studied by ref. [3, 4]. TEEC is an extension of EEC in hadronic collisions where only the momenta in the transverse plane are used to construct the observable. The definition is

$$\mathrm{TEEC} = \sum_{a,b} \int d\sigma_{pp \to a+b+X} \frac{2E_{T,a} E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)\,, \tag{2}$$

where $E_{T,i}$ is the transverse energy of hadron i and ϕ_{ab} is the azimuthal angle between hadrons a and b. The NLO QCD corrections for the TEEC observable were calculated in ref. [5] and in ref. [6] TEEC was investigated in the dijet limit. The first study of TEEC in DIS was performed in [7], where the observable is defined by the correlation between the final state hadron and lepton in the transverse plane,

$$\mathrm{TEEC} = \sum_{a} \int d\sigma_{lp \to l+a+X} \frac{E_{T,a}}{\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)\ . \tag{3}$$

One of the advantages of EEC/TEEC is that the contribution from soft radiation is suppressed as it carries parametrically small energy. Therefore, hadronization effects are expected to be small in comparison to other event shape observables, such as thrust, where soft and energetic but collinear radiation contribute on equal footing. It is thus possible to control the perturbative behavior of this observable with high precision, making it feasible to study transverse-momentum dependent (TMD) physics using TEEC in DIS.

2 EEC in Breit frame

In Breit frame, the virtual photon moves along z-axis with momentum $q = Q(0,0,0,1)$ and the incoming proton moves in the opposite direction with momentum $P = Q(1,0,0,-1)/(2x)$, where x is the standard Bjorken-x variable. The Born-level process is described by the partonic process $e + q_i \to e + q_f$ and the momenta of the incoming and outgoing quarks are $p_i = xP = Q(1,0,0,-1)/2$ and $p_f = q + xP = Q(1,0,0,1)/2$, respectively. Hadronization of the outgoing quark will form a collimated spay of radiation close the the z-axis. On the other hand, initial state radiation and beam remnants are moving in the opposite direction close to the proton's direction of motion. Is this feature of the Breit frame, which leads to clean separation of target and current fragmentation, that we utilize to construct the novel EEC observable in DIS.

We propose the new observable in Breit frame which is

$$\text{EEC} = \sum_a \int d\sigma_{\ell+h\to\ell+a+X}\, \frac{P\cdot p_a}{P\cdot(\sum_i p_i)}\, \delta(\cos\theta_{ap} - \cos\theta) \tag{4}$$

where p_a and P are the momenta of the hadron a and the incoming proton respectively. The angle θ_{ap} is the polar angle of hadron a in with respect to the incoming proton.[1] Note that the asymmetric weight function is Lorentz invariant and is suppressed for soft radiation and radiation close to the proton's direction. Furthermore, this definition of EEC naturally separates the contribution to the $\cos(\theta)$ spectrum from: i) wide angle soft radiation, ii) initial state radiation and beam remnants, and iii) radiation form the hadronization of struck quark. This unique feature makes the new observable insensitive to experimental cutoffs on the particle rapidity (in the Laboratory frame) due to limitations in backward and forward regions of the detector, making the comparison of theory and experiment even more accurate.

For $\theta \ll \pi$ the distribution is very well described by the fixed order QCD calculations, while in the back-to-back limit ($\theta \to \pi$) resummation of enhanced logarithms is required for reliable predictions. To this end, in the back-to-back limit, the cross section can be factorized as a convolution of TMD beam, soft and TMD fragmentation functions, which share the same operator definitions as in the usual single hadron semi-inclusive DIS factorization. This ensures the universality of TMD PDFs appearing in EEC to other observables such as Drell-Yan and semi-inclusive DIS. Moreover, the TMD beam or TMD fragmentation function can be matched to the collinear PDF and collinear fragmentation function, respectively, and thus, as discussed in ref. [3], after summing over all the final sate hadrons, the fragmentation function can be removed by the momentum sum rules. Therefore, the only non-perturbative object in the back-to-back limit is the so-called TMD PDFs. As a result EEC provide a novel approach to TMD physics without the dependence of the non-perturbative fragmentation functions.

In this is on-going project, we aim to obtain the NLO corrections to the new EEC observable using NLOJet++. The factorization formula can then be tested at NLO (and at leading power) by comparing to full QCD prediction in the back-to-back limit. The resummation in the back-to-back limit can be achieved upto N^3LL accuracy using soft-collinear effective theory (SCET), which will be the highest order currently possible and we can finally provide the N^3LL+NLO prediction for $\cos(\theta)$ distribution for EEC in DIS.

[1] Note that what we propose is different to what is done in [8] where a fixed order QCD calculation for TEEC in eq. (2) (as defined for hadronic colliders) is performed in the Briet frame DIS for the dijet configuration. This observable exhibit very different characteristics and is suppressed by α_s compared to what we propose here.

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