Transverse energy-energy correlations at NLO for the LHC

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Contribution given at the low-x workshop,
May 30 - June 4 2013, Rehovot and Eilat, Israel

We compute the transverse energy-energy correlation (EEC) and its asymmetry (AEEC) in next-to-leading order (NLO) in α_s in proton-proton collisions at the LHC with the center-of-mass energy $E_{\mathrm{c.m.}} = 7$ TeV. We show that the transverse EEC and the AEEC distributions are insensitive to the QCD factorization- and the renormalization-scales, structure functions of the proton, and for a judicious choice of the jet-size, also the underlying minimum bias events. Hence they can be used to precisely test QCD in hadron colliders and determine the strong coupling α_s. We illustrate these features by defining the hadron jets using the anti-k_T jet algorithm and an event selection procedure employed in the analysis of jets at the LHC and show the $\alpha_s(M_Z)$-dependence of the transverse EEC and the AEEC in the anticipated range $0.11 \leq \alpha_s(M_Z) \leq 0.13$.

1 Introduction and motivation

Jet production at the LHC provides a quantitative tool to test QCD at the highest momentum transfers. Theoretical calculations for jet cross sections in hadronic collisions are known up to NLO accuracy [1, 2] and have been extensively used for comparisons with the data [3, 4].

Studies of event shape variables have been extensively undertaken in e+e- colliders PETRA, PEP, KEK, LEP and SLC, as well as in in the electron proton collider HERA. These studies have recently been extended to hadron colliders with measurements of the transverse thrust and the transverse minor [5] at Tevatron [6] and LHC energies [7, 8].

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Energy-energy correlation (EEC) function measurements - the energy weighted angular distributions of the produced hadron pairs in e^+e^- annihilation - were proposed by Basham et al. [9]. The EEC and its forward-backward asymmetry, AEEC, were subsequently calculated in $O(\alpha_s^2)$ [10, 11], and their measurements [12, 13, 14] have impacted significantly on the precision tests of perturbative QCD and in the determination of α_s in e^+e^- annihilation experiments (for a recent review, see [15]). This is so because, compared to most other event shape measures such as Thrust, the EEC are by construction not affected by soft divergencies, and as a consequence of this they are calculable at higher orders. Second order corrections to the AEEC are of order 10% while for Thrust they are of order 30%. Fig. 1 summarizes the state of the art of these measurements at LEP.

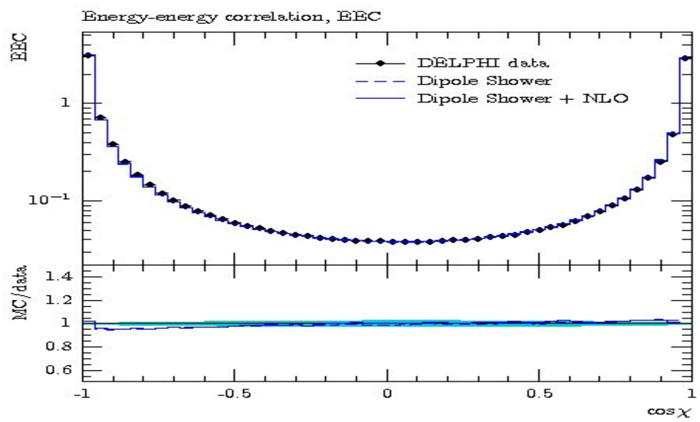

Figure 1: The EEC as measured by Delphi at LEP along with comparison with Monte Carlo expectations where NLO with LL effects taken into account.

The transverse energy energy correlation, TEEC, and its asymmetry [16] represents the appropriate generalization to hadron colliders. The NLO corrections have been recently calculated [17]. They show that at NLO the TEEC and its corresponding asymmetry exhibit a reduced sensitivity to parton distribution functions, PDF's, as well as to renormalization, μ_R, and factorisation, μ_F, scales which render them suitable for precision quantitative tests of QCD including a determination of the strong coupling constant.

Let us recall the definition of the TEEC:

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} \equiv \frac{\int_{\mathrm{E_T^{min}}}^{\sqrt{s}} dE_T\, d^2\Sigma/dE_T\, d\phi}{\int_{\mathrm{E_T^{min}}}^{\sqrt{s}} dE_T\, d\sigma/dE_T} = \frac{1}{N}\sum_{A=1}^{N}\frac{1}{\Delta\phi}\sum_{\mathrm{pairs\ in}\ \Delta\phi}\frac{2\mathrm{E_{Ta}^{A}}\,\mathrm{E_{Tb}^{A}}}{(\mathrm{E_T^{A}})^2}\ , \tag{1}$$

with

$$\sigma' = \int_{\mathrm{E_T^{min}}}^{\sqrt{s}} dE_T\, d\sigma/dE_T \tag{2}$$

The first sum on the right-hand side of Eq. (1) is over the events A with total transverse energy $E_T^{\mathrm{A}} = \sum_a E_T{}_a^{\mathrm{A}} \geq E_T^{\mathrm{min}}$, with the E_T^{min} set by the experimental setup. The second sum is over the pairs of partons $(a,\, b)$ whose transverse momenta have relative azimuthal angle ϕ to $\phi + \Delta\phi$. For a given event the sum of the weights in this second sum is 1. In addition, the fiducial volume is restricted by the experimental acceptance in the rapidity variable η.

In leading order QCD, the transverse energy spectrum $d\sigma/dE_T$ is a convolution of the parton distribution functions (PDFs) with the $2 \to 2$ hard scattering partonic sub-processes. Away from the end-points, i.e., for $\phi \neq 0^\circ$ and $\phi \neq 180^\circ$, in the leading order in α_s, the energy-weighted cross section $d^2\Sigma/dE_T\, d\phi$ involves the convolution of the PDFs with the $2 \to 3$ sub-processes, such as $gg \to ggg$. Thus, schematically, the leading contribution for the transverse EEC function is calculated from the following expression:

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} = \frac{\Sigma_{a_i,b_i} f_{a_1/p}(x_1) f_{a_2/p}(x_2) \star \hat{\Sigma}^{a_1 a_2 \to b_1 b_2 b_3}}{\Sigma_{a_i,b_i} f_{a_1/p}(x_1) f_{a_2/p}(x_2) \star \hat{\sigma}^{a_1 a_2 \to b_1 b_2}}\ , \tag{3}$$

where $\hat{\Sigma}^{a_1 a_2 \to b_1 b_2 b_3}$ is the transverse energy-energy weighted partonic cross section, x_i $(i = 1, 2)$ are the fractional longitudinal momenta carried by the partons, $f_{a_1/p}(x_1)$ and $f_{a_2/p}(x_2)$ are the PDFs, and the $\star$ denotes a convolution over the appropriate variables. The function defined in Eq. (3) depends not only on ϕ, but also on the ratio $E_T^{\mathrm{min}}/\sqrt{s}$ and rapidity η. In general, the numerator and the denominator in Eq. (3) have a <u>different</u> dependence on these variables, as the PDFs are weighted differently. However, as already observed in [16], certain *normalized* distributions for the various sub-processes contributing to the $2 \to 3$ hard scatterings are similar, and the *same* combination of PDFs enters in the $2 \to 2$ and $2 \to 3$ cross sections; hence the transverse EEC cross section is to a good approximation *independent* of the PDFs (see, Fig. 1 in [16]). Thus, for a fixed rapidity range $|\eta| < \eta_c$ and the variable $E_T/\sqrt{s}$, one has an approximate factorized result, which in the LO in α_s reads as

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} \sim \frac{\alpha_s(\mu)}{\pi} F(\phi)\ , \tag{4}$$

where

$$\alpha_s(\mu) = \frac{1}{b_0 \log(\mu^2/\Lambda^2)} \left[1 - \frac{b_1 \log(\log(\mu^2/\Lambda^2))}{b_0^2 \log(\mu^2/\Lambda^2)} \right], \quad b_0 = \frac{33 - 12n_f}{12\pi}, \quad b_1 = \frac{153 - 19n_f}{24\pi^2}. \quad (5)$$

The expression given above is the NLO expression for $\alpha_s(\mu)$, which is used in deriving the NLO results for the TEEC and its asymmetry in [17], and in relating $\alpha_s(\mu)$ to the value at the default scale $\alpha_s(M_Z)$. In the above equation, n_f is the active quark flavor number at the scale μ and the hadronization scale Λ is determined by the input $\alpha_s(m_Z)$. The function $F(\phi)$ and the corresponding transverse EEC asymmetry defined as

$$\frac{1}{\sigma'} \frac{d\Sigma'^{\text{asym}}}{d\phi} \equiv \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi}|_\phi - \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi}|_{\pi-\phi} \ , \quad (6)$$

were worked out in [16] in the leading order of α_s for the CERN SPS $p\bar{p}$ collider at $\sqrt{s} = 540$ GeV. In particular, it was shown that the transverse EEC functions for the gg-, gq- and $q\bar{q}$-scatterings had very similar shapes, and their relative contributions were found consistent to a good approximation with the ratio of the corresponding color factors 1:4/9:16/81 for the gg, $gq(= g\bar{q})$ and $q\bar{q}$ initial states over a large range of ϕ. In the

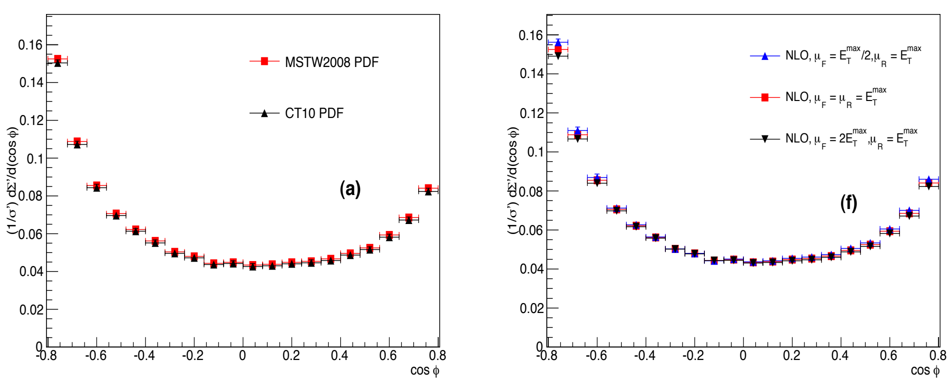

Figure 2: Dependence of NLO calculations for the TEEC on PDF and scale choices, from [17], at $\sqrt{s} = 7\ TeV$ and the anti-k_T algorithm with two assumed values of the jet-size parameter $R = 0.4$ and $p_T^{min} = 25\ GeV$.

NLO accuracy, one can express the EEC cross section as

$$\frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \sim \frac{\alpha_s(\mu)}{\pi} F(\phi) \left[1 + \frac{\alpha_s(\mu)}{\pi} G(\phi) \right] \ . \quad (7)$$

It is customary to lump the NLO corrections in a so-called K-factor (which, as shown in [17], is a non-trivial function of ϕ), defined as $K^{\rm EEC}(\phi) \equiv 1 + \frac{\alpha_s(\mu)}{\pi} G(\phi)$. The transverse EEC asymmetry in the NLO accuracy is likewise defined as

$$\frac{1}{\sigma'}\frac{d\Sigma'^{\rm asym}}{d\phi} \sim \frac{\alpha_s(\mu)}{\pi} A(\phi) \left[1 + \frac{\alpha_s(\mu)}{\pi} B(\phi)\right] \ . \tag{8}$$

and the corresponding K-factor is defined as $K^{\rm AEEC}(\phi) \equiv 1 + \frac{\alpha_s(\mu)}{\pi} B(\phi)$.

These K-factors, $K^{\rm EEC}(\phi)$ and $K^{\rm AEEC}(\phi)$, have been recently calculated to NLO accuracy in [17]. The NLO corrections to the TEEC are found to be smaller than 20%. At NLO the results are pretty insensitive to the choice of PDF and show a very mild dependence of the factorization and renormalization scale choices, Fig. 2.

A summary of these theoretical results are presented in Fig.3, where we show for $|\eta| < 2.5$ and $p_T^{min} = 25\ GeV$ the TEEC and its asymmetry at NLO for three values of the strong coupling constant i.e. $\alpha_s(M_Z) = 0.11, 0.12, 0.13$ as well as the corresponding K-factors for the central value $\alpha_s(M_Z) = 0.12$. In deriving the results shown in Fig. 3, the scales are set to the value $\mu_F = \mu_R = E_T^{\rm max}$, where $E_T^{\rm max}$ is the transverse energy of the leading jet, and the MSTW NLO pdfs have been employed [18]. The jets are defined using the anti-k_t jet algorithm. The K-factors shown in Figs. 4(a) and 4(b) are

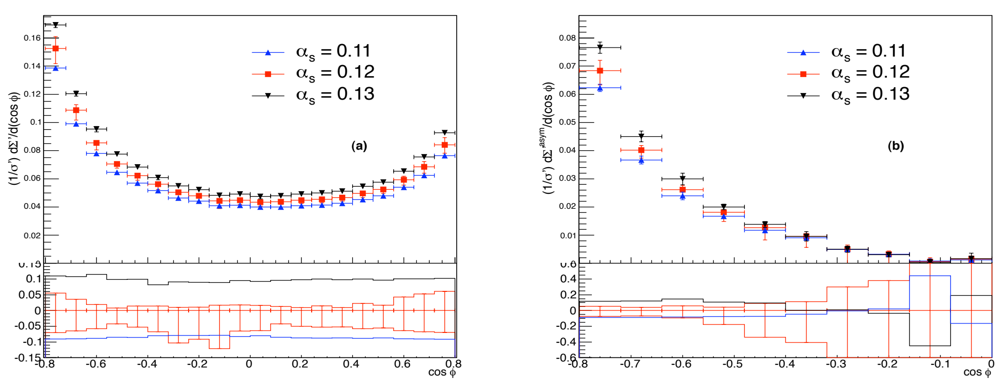

Figure 3: Theoretical calculations for the TEEC and its asymmetry at NLO [(a),(b)] from [17].

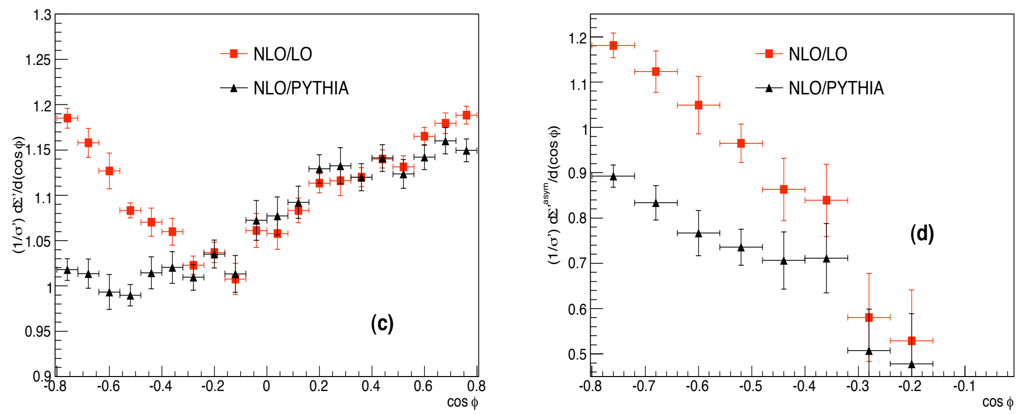

Figure 4: Theoretical calculations for the TEEC and its asymmetry at NLO [(a),(b)] as given by the corresponding K-factors defined in the text, taken from [17].

obtained for $\alpha_s(M_Z) = 0.12$. The two distributions shown in these figures are labelled as NLO/LO and NLO/PYTHIA. They represent the ratio of the partonic distributions (NLO vs. LO), and the ratio of the NLO distributions at the partonic level to the one from the PYTHIA MC program (NLO vs. PYTHIA), which includes the LO matrix elements and multiparton showers. It is worth emphasizing that the NLO corrections change both the normalization and the shapes.

2 Truth level MC expectations: hadronization effects and the choice of the jet cone size R

In this section we would like to discuss the Monte Carlo expectations for both the TEEC and AEEC. We generate QCD final states at the truth level with PYTHIA with the same requirements as those used in the theoretical calculations discussed in the previous section i.e. demanding at least two jets within $|\eta| < 2.5$ with the sum of the two leading jets transverse momenta above 500 GeV. Initial and final state radiation is taken into account. We then study the TEEC as a function of different choices :

- $p_T^{\min} = 25\ GeV, 50\ GeV, 100\ GeV$ for the subleading jets transverse momentum cut
- $R = 0.4, 0.6$ for the jet cone size

- multiparton interactions on/off

Clearly $R = 0.4$ is preferred over $R = 0.6$ if only because smaller R values induce smaller distortions in the measurements for small $\Delta\phi$ values. Underlying event effects are also smaller when jets are defined with smaller jet cone sizes, as illustrated in Fig. 5. The hadronization factor i.e. the ratio between the TEEC at the parton- and hadron-jet level is very similar for the two choices $R = 0.4$ and $R = 0.6$ as shown in this figure also.

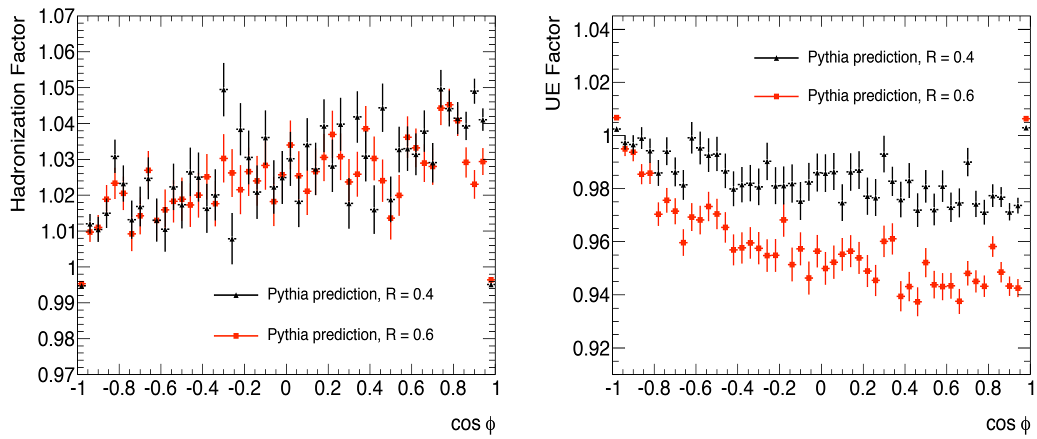

Figure 5: Normalized distribution of the hadronization factor (left) and underlying events effects (right) obtained with the PYTHIA6 MC at $\sqrt{s} = 7\ TeV$ for the two indicated values of R and $p_T^{\min} = 25\ GeV$.

The TEEC is very sensitive to the p_T^{min} cut while the AEEC is not, as shown in Fig. 6

3 Conclusions

The asymmetry associated to the transverse energy-energy correlations is

- little sensitive to underlying event and hadronization effects as well as to the $p_T^{\min}$ cut for subleading jets
- stable upon higher order corrections as well as upon PDF and factorization and renormalization scale choices

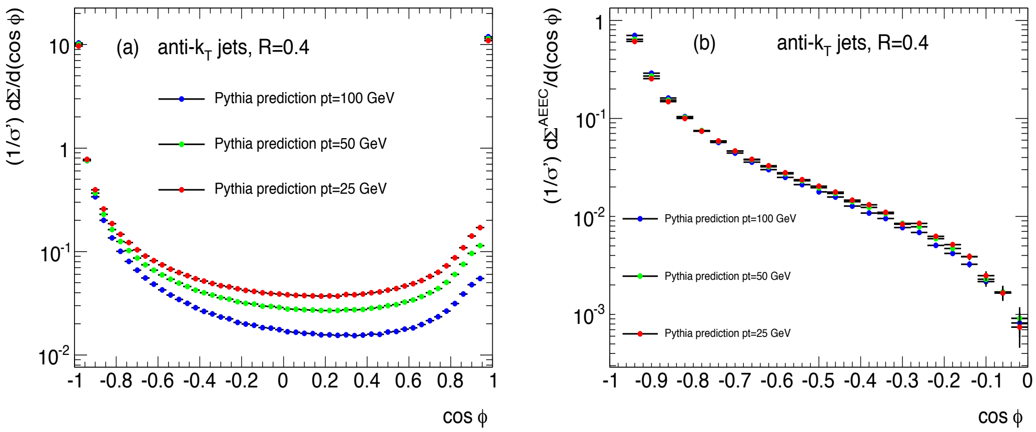

Figure 6: Expectations for the TEEC (left) and its asymmetry (right) obtained with the PYTHIA6 MC at $\sqrt{s} = 7\ TeV$ for $R = 0.4$ and three different values for $p_T^{\min}$.

- sensitive to a_s

Measurements of the TEEC and its associated asymetry at the LHC will provide stringent tests of QCD at unprecedented large scales.

4 Acknowledgements

I would like to thank the local organizers for providing a very pleasant atmosphere both at the WIS and Eilat.

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