

Transverse Energy Energy Correlations at the LHC

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Considering all pairs of hadrons (a, b) , the EEC is defined as

$$\frac{1}{\sigma} \frac{d\Sigma}{d \cos \chi} = \frac{1}{\sigma} \sum_{a,b} \int \frac{E_a E_b}{Q^2} d\sigma(e^+ e^- \rightarrow h_a h_b + X) \delta(\cos \chi - \cos \theta_{ab})$$

- Basham et al., PRL 41, 1585 (1978): Leading order EEC

$$\frac{1}{\sigma} \frac{d\Sigma^{\text{EEC}}}{d \cos \chi} = \frac{\alpha_s(Q^2)}{\pi} F(\xi); \quad \xi = \frac{1 - \cos \chi}{2}$$

$$F(\xi) = \frac{(3 - 2\xi)}{6\xi^2(1 - \xi)} \left[2(3 - 6\xi + 2\xi^2) + \log(1 - \xi) + 3\xi(2 - 3\xi) \right]$$

- Asymmetry on the EEC at leading order:

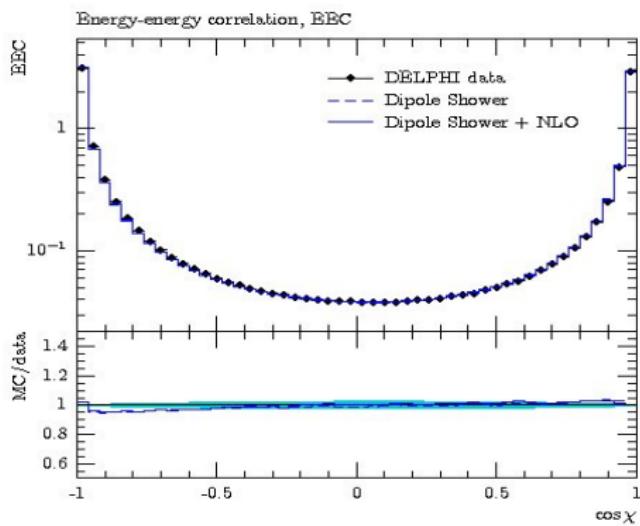
$$\frac{1}{\sigma} \frac{d\Sigma^{\text{AEEC}}}{d \cos \chi} \equiv \frac{1}{\sigma} \frac{d\Sigma(\pi - \chi)}{d \cos \chi} - \frac{1}{\sigma} \frac{d\Sigma(\chi)}{d \cos \chi} = \frac{\alpha_s(Q^2)}{\pi} [F(1 - \xi) - F(\xi)] = \frac{\alpha_s(Q^2)}{\pi} A(\xi)$$

The NLO expressions for both observables can be written as

$$\frac{1}{\sigma} \frac{d\Sigma^{\text{EEC}}}{d\phi} = \frac{\alpha_s(\mu)}{\pi} F(\xi) \left(1 + \frac{\alpha_s(\mu)}{\pi} R^{\text{EEC}}(\xi) \right)$$

$$\frac{1}{\sigma} \frac{d\Sigma^{\text{AEEC}}}{d\phi} = \frac{\alpha_s(\mu)}{\pi} A(\xi) \left(1 + \frac{\alpha_s(\mu)}{\pi} R^{\text{AEEC}}(\xi) \right)$$

[Ali, Barreiro, PL 118B (1982) 155]; [Richards, Stirling, Ellis, PL B119 (1982) 193] $6 < R^{\text{EEC}}(\xi) < 11$ and $2.5 < R^{\text{AEEC}}(\xi) < 3.5$



The Transverse Energy Energy Correlation function (EEC) in hadron-hadron collisions is defined as

$$\begin{aligned} \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} &= \frac{\int_{E_T^{\min}}^{\sqrt{s}} dE_T d^2\Sigma(E_T, \eta)/dE_T d\phi}{\int_{E_T^{\min}}^{\sqrt{s}} dE_T d^2\sigma(E_T, \eta)/dE_T d\phi} = \frac{1}{N} \sum_{A=1}^N \frac{1}{\Delta\phi} \sum_{a,b} \frac{2E_{T_a}^A E_{T_b}^A}{(E_T^A)^2} = \\ &= \frac{\sum_{a_i, b_i} f_{a_1}(x_1, \mu) f_{a_2}(x_2, \mu) \otimes \hat{\Sigma}^{a_1 a_2 \rightarrow b_1 b_2 b_3}}{\sum_{a_i, b_i} f_{a_1}(x_1, \mu) f_{a_2}(x_2, \mu) \otimes \hat{\sigma}^{a_1 a_2 \rightarrow b_1 b_2 b_3}} \end{aligned}$$

It was shown in [A. Ali, E. Pietarinen, J. Stirling, PL B141 (1984) 447] that the r.h.s of the above is approximately independent of the PDF, thus at NLO

$$\frac{1}{\sigma'} \frac{d\Sigma'^{\text{EEC}}}{d\phi} = \frac{\alpha_s(\mu)}{\pi} F(\phi) \left(1 + \frac{\alpha_s(\mu)}{\pi} G(\phi) \right)$$

As before, the asymmetry is defined as

$$\frac{1}{\sigma'} \frac{d\Sigma'^{\text{AEEC}}}{d\phi} = \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \Big|_{\pi-\phi} - \frac{1}{\sigma'} \frac{d\Sigma'}{d\phi} \Big|_\phi$$

Both observables EEC and AEEC are studied using NLOJET++ with the MSTW NNLO parton densities. They exhibit the following properties:

- Large dependence on α_s .
- Moderate dependence on μ_R , μ_F .
- Small dependence on the PDF choice.
- Expected small sensitivity to experimental uncertainties (JES,JER...) because of the energy-energy weighting.

These properties make them ideal for a determination of the strong coupling α_s in the ATLAS and CMS experiments.

The jet kinematical requirements are:

- Two jets with $p_{T1} + p_{T2} > 500$ GeV.
- Additional jets with $p_T > p_T^{\min}$.
- All jets should be within $|\eta| < 2.5$.

Both the renormalization and factorization scales are set to the mean transverse momentum of the two leading jets

$$\mu_R = \mu_F = \mu_0 = \frac{p_{T1} + p_{T2}}{2}$$

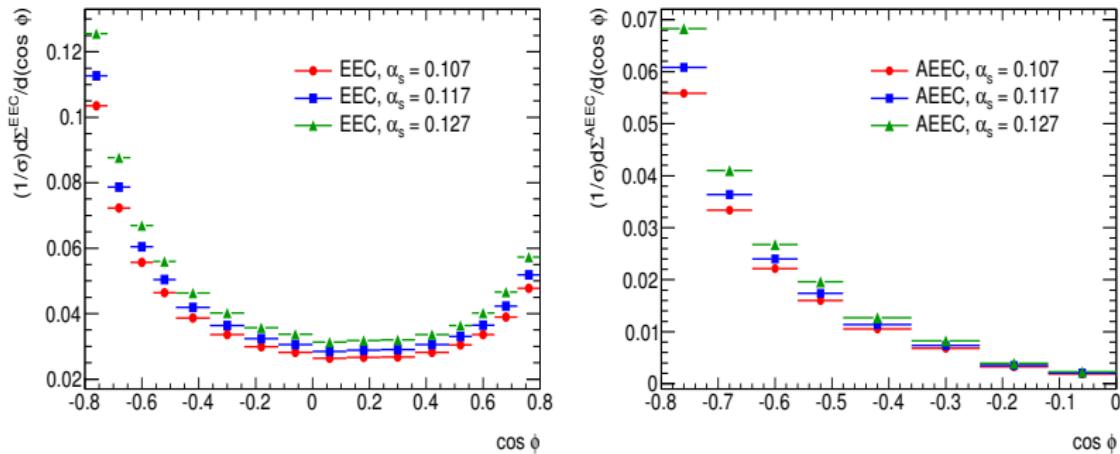
This choice is motivated by previous studies by the CMS Collaboration in [Eur. Phys. J. C 73 2604 (2013)].

The uncertainty on the scale choice is obtained by considering the following variations

$$\left(\frac{\mu_R}{\mu_0}, \frac{\mu_F}{\mu_0} \right) \in \left\{ \left(\frac{1}{2}, \frac{1}{2} \right), \left(\frac{1}{2}, 1 \right), \left(\frac{1}{2}, 2 \right), \left(1, \frac{1}{2} \right), (1, 2), \left(2, \frac{1}{2} \right), (2, 1), (2, 2) \right\}$$

Dependence on α_s

The following figures show the dependence of EEC and its asymmetry on the strong coupling constant for $\sqrt{s} = 7$ TeV, $p_T^{\min} = 50$ GeV.

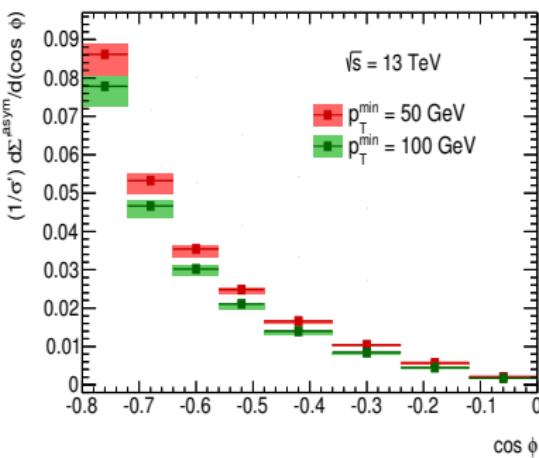
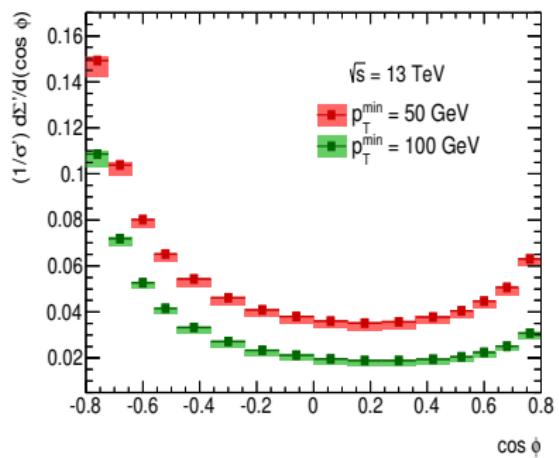


As expected, the dependence of both $i = \text{EEC}$ and AEEC is parabolic at NLO

$$\frac{1}{\sigma} \frac{d\Sigma_i}{d\phi} = \frac{\alpha_s(\mu)}{\pi} F_i(\phi) \left(1 + \frac{\alpha_s(\mu)}{\pi} G_i(\phi) \right)$$

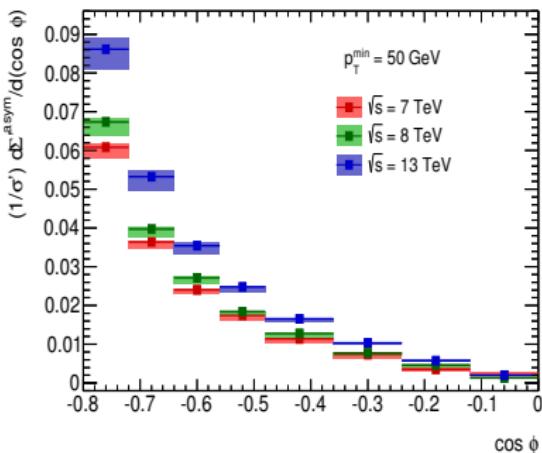
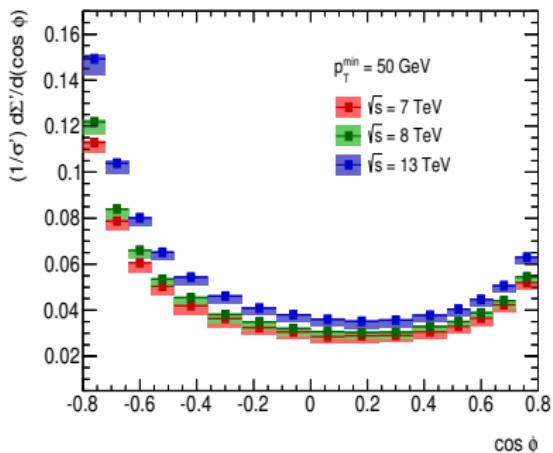
Dependence on p_T^{\min}

As the threshold in the jet p_T is increased, the amount of soft radiation is decreased. Therefore, the height of the central valley is smaller. The plots below illustrate this dependence for $\sqrt{s} = 13$ TeV.



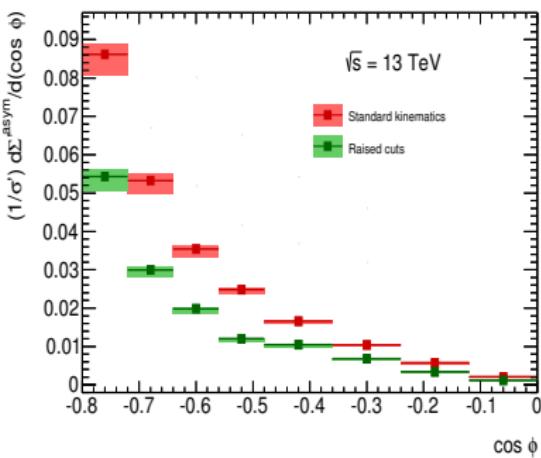
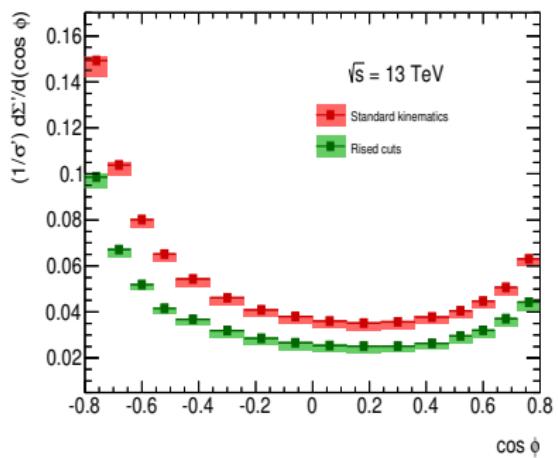
Both the EEC and AEEC depend logarithmically on the center-of-mass energy of the two protons

$$f_i(\sqrt{s}) = A_i \log(\sqrt{s}) + B_i$$



What if we rise the cuts?

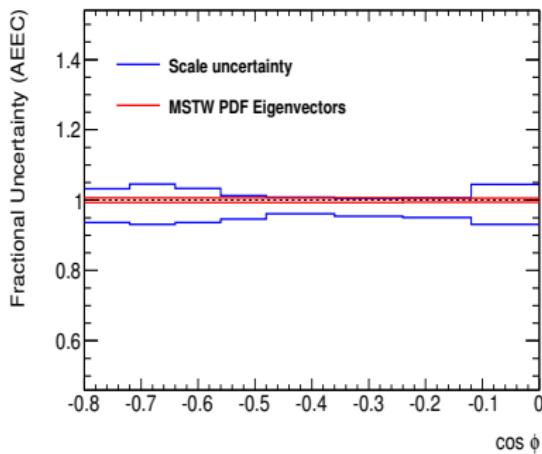
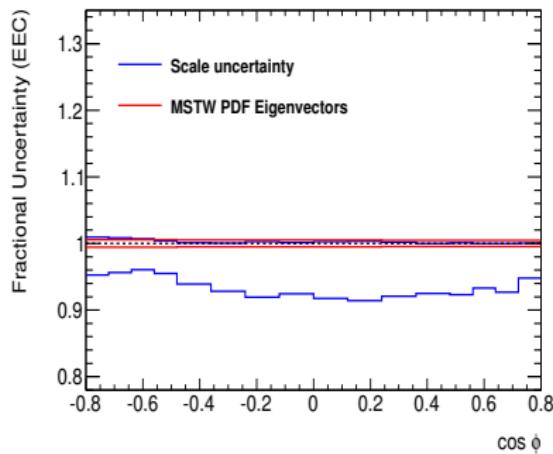
At $\sqrt{s} = 13$ TeV, UE and pileup effects may be large for a 50 GeV cut.
Therefore, a new kinematical selection is investigated: $p_{T1} + p_{T2} > 1$ TeV and
 $p_T > 100$ GeV for extra jets.



The uncertainties on the theoretical predictions come mainly from two sources:

- Renormalization and Factorization scale choices μ_R, μ_F .
- PDF uncertainties, estimated using the MSTWNNLO Eigenvectors.

The figures show the effect of both variations for $\sqrt{s} = 13$ TeV and $p_T^{\min} = 50$ GeV.



- Jet event shapes are useful tools to test QCD, but require NLO calculations and the NLO/NLL matching to be quantitative
- We have provided NLO calculations for the transverse EEC and its Asymmetry in hadron colliders
- Transverse EEC distributions have all the desirable properties
 - (i) they are boost invariant, hence largely insensitive to the PDFs
 - (ii) have a moderate sensitivity to the QCD scales, and
 - (iii) are sensitive to $\alpha_s(m_Z)$
- Analysis of the inclusive jet data in terms of TEEC and AEEC at LHC will provide a stringent test of QCD