Transverse Energy Energy Correlations in NLO at the LHC

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Examples of event shape variables in hadronic collisions

Shape variables are measured using high transverse momentum p_T jets

- $y_{23} = \frac{p_{T,3}^2}{H_{T,2}^2}$; $H_{T,2} = (p_{T,1} + p_{T,2})$: A measure of the third jet-p_T relative to the summed transverse momenta of the two leading jets in a multi-jet event see ALEPH (1998); Banfi, Salam, Zanderighi (2010)
- Sphericity: constructed from the (3×3) momentum tensor of the event: $S_{\alpha\beta} = \frac{\sum_i p_{i\alpha} p_{i\beta}}{\sum_i \mathbf{P}_i^2}$ Eigenvalues $\lambda_1, \lambda_2, \lambda_3$, which can be ordered $\lambda_1 < \lambda_2 < \lambda_3$ with $\sum \lambda_i = 1$: $S = \frac{3}{2}(\lambda_1 + \lambda_2)$, see Bjorken, Brodsky (1970)
- Transverse Sphericity: $S_\perp = \frac{2\lambda_2}{\lambda_1 + \lambda_2}$
- Aplanarity: $A = \frac{3}{2}\lambda_3$: A measure of the p_T out of the plane formed by two leading jets
- Transverse Thrust: $T_\perp = \max \frac{\sum_i |\mathbf{p}_{T,i} . \hat{n}|}{\sum_i p_{T,i}}$: The unit vector $\hat{n}$ defines the transverse thrust axis
- Minor Transverse Thrust: $T_{m,\perp} = \frac{\sum_i |\mathbf{p}_{T,i} \times \hat{n}|}{\sum_i p_{T,i}}$
- Detailed studies of some of these shape variables have been conducted at the Tevatron and the LHC and compared with the MC programs PYTHIA, HERWIG and ALPGEN, see CDF (PR D83, 112007 (2011); CMS (PLB 699 (2011) 48; ATLAS (arxiv:1206.2135)

A Legacy of e^+e^- Annihilation: Energy-Energy Correlations

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

- LO EEC in e^+e^- annihilation [Basham et al., PRL 41, 1585 (1978)]

$$\frac{1}{\sigma_0}\frac{d\Sigma^{EEC}}{d\cos\chi} = \frac{\alpha_S(Q^2)}{\pi}F(\xi);\quad \xi = \frac{1-\cos\chi}{2} \quad (2)$$

$$F(\xi) = \frac{(3-2\xi)}{6\xi^2(1-\xi)}[2(3-6\xi+2\xi^2) + \ln(1-\xi) + 3\xi(2-3\xi)] \quad (3)$$

- Asymmetric EEC in e^+e^- annihilation

$$\frac{1}{\sigma_0}\frac{d\Sigma^{AEEC}}{d\cos\chi} \equiv \frac{1}{\sigma_0}\frac{d\Sigma(\pi-\chi)}{d\cos\chi} - \frac{1}{\sigma_0}\frac{d\Sigma(\chi)}{d\cos\chi} = \frac{\alpha_S(Q^2)}{\pi}[F(1-\xi) - F(\xi)] \equiv \frac{\alpha_S(Q^2)}{\pi}A(\xi) \quad (4)$$

- NLO EEC in e^+e^- annihilation: [A. Ali, F. Barreiro, PL 118B (1982) 155; D. Richards,J. Stirling, S. Ellis, PL B119 (1982) 193]

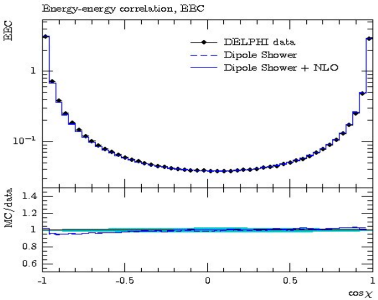
$$\frac{1}{\sigma_0}\frac{d\Sigma^{EEC}}{d\cos\chi} = \frac{\alpha_S(Q^2)}{\pi}F(\xi)[1 + \frac{\alpha_s(Q^2)}{\pi}R^{EEC}(\xi)] \quad (5)$$

$$\frac{1}{\sigma_0}\frac{d\Sigma^{AEEC}}{d\cos\chi} = \frac{\alpha_S(Q^2)}{\pi}A(\xi)[1 + \frac{\alpha_s(Q^2)}{\pi}R^{AEEC}(\xi)] \quad (6)$$

- For $[-0.95 \le \cos\chi \le 0.95]$ one gets: $6 < R^{EEC}(\xi) < 11$ and $2.5 < R^{AEEC}(\xi) < 3.5$

- A lot of theoretical effort has gone into matching the NLO calculations with multiple parton showers at Next-to-Leading-Log (NLL) acccuracy in e^+e^- annihilation
- An state of the art example: Matching dipole showers following the Catani-Seymour subtraction scheme in the NLO accuracy as an add-on to the HERWIG++ Monte Carlo [S. Platzer, S. Gieseke, arxiv:1109.6256]

Comparison of the DELPHI data at LEP on EEC and NLO/NLL calculations



- Analogue of the EEC in e^+e^- annihilation is the transverse EEC in hadronic collisions

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} = \frac{\int_{E_T^{min}}^{\sqrt{s}} dE_T d^2\Sigma(E_T,\eta)/dE_T d\phi}{\int_{E_T^{min}}^{\sqrt{s}} dE_T d^2\sigma(E_T,\eta)/dE_T d\phi} = \frac{1}{N}\sum_{A=1}^{N}\frac{1}{\Delta\phi}\sum_{\mathrm{pairsin}\Delta\phi}\frac{2E_{T_a}^A E_{T_b}^A}{(E_T^A)^2} \quad (7)$$

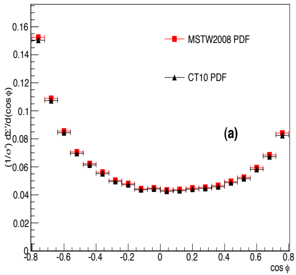
- In the LO in $\alpha_S(\mu)$, the l.h.s. is calculated by the following expression

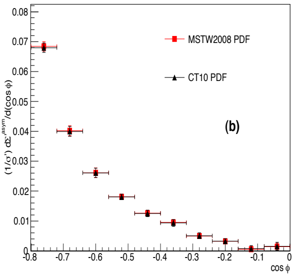
$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} = \frac{\sum_{a_i,b_i} f_{a_1/p}(x_1,\mu) f_{a_2/p}(x_2,\mu)\otimes \hat{\Sigma}^{a_1 a_2\to b_1 b_2 b_3}}{\sum_{a_i,b_i} f_{a_1/p}(x_1,\mu) f_{a_2/p}(x_2,\mu)\otimes \hat{\sigma}^{a_1 a_2\to b_1 b_2 b_3}} \quad (8)$$

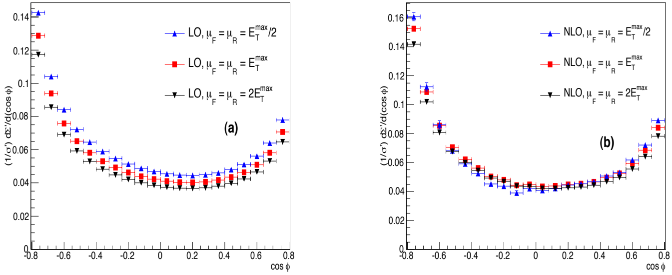
- There are crucial differences between the $\mathrm{EEC}(e^+e^-)$ and $\mathrm{TEEC}(pp)$ due to: (i) several initial state partons participating in pp collisions leading to $2\to n$ hard processes with different weighting in the (E_T,η) in the numerator and denominator, (ii) high jet multiplicity at the LHC, depending on jet-definitions and the jet-size parameter R , and (iii) the underlying minimum bias events
- It was shown in [AA, E. Pietarinen, J. Stirling, PL B141 (1984) 447] that certain *normalized* distributions for the various subprocesses contributing to the $2\to 2$ subprocesses are similar, and the *same* combinations of the PDFs enter in the $2\to 2$ and $2\to 3$ cross sections, thus the l.h.s. above is (approximately) independent of the structure functions, yielding

$$\frac{1}{\sigma'}\frac{d\Sigma'}{d\phi} \sim \frac{\alpha_s(\mu)}{\pi}F^{pp}(\phi) \quad (9)$$

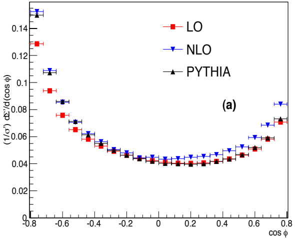
- We have calculated NLO Transverse EEC cross sections and its Asymmetery at the LHC for $\sqrt{s} = 7$ TeV
- Use NLOJet++ [Z. Nagy, PRL 88, 122003 (2002); PR D68, 094002 (2003)], a C++ code for calculating NLO jet-distributions at hadron colliders
- Modified the C++ code: Use anti-k_T jet algorithm and state of the art PDFs MSTW and CT10; generated $O(10^{10})$ events to get stable results
- Jet-trigger and Jet-size:
  $p_T > 25, 50, 100$ GeV; $(p_{T1} + p_{T2}) > 500$ GeV; $|\eta| < 2.5$; $R = 0.4$
- Default scale choice: $\mu_F = \mu_R = p_T^{\max}$
- PDF-dependence is negligible; largest difference in some bins up to 3%

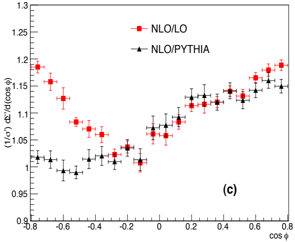




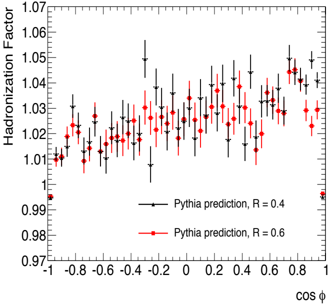


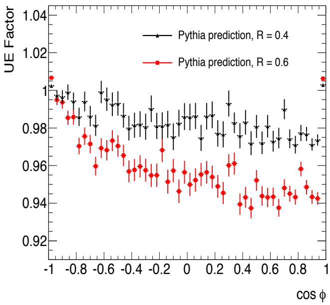
- QCD-scale (μ_F and μ_R)-dependence is significantly reduced in going from the LO, l.h.s, to the NLO calculations, r.h.s.
- Residual scale-dependence: a few %; crucial for quantitative tests of QCD



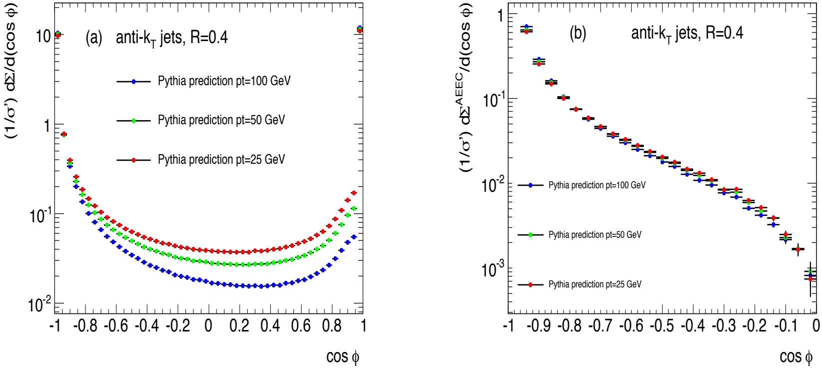


- NLO contributions distort the shape of the transverse EEC distributions
- NLO effects are discernible both compared to the LO and *current* MC programs, such as PYTHIA

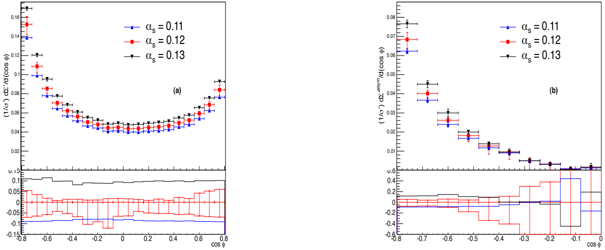

Hadronization Factor
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
0.98
0.97
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos ϕ
Pythia prediction, R = 0.4
Pythia prediction, R = 0.6


UE Factor
1.04
1.02
1
0.98
0.96
0.94
0.92
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos ϕ
Pythia prediction, R = 0.4
Pythia prediction, R = 0.6

The plots below show the PYTHIA expectations for $P_T^{min} = 25, 50, 100\,GeV$.



$\alpha_S(M_Z)$-sensitivity of Transverse EEC and its Asymmetry



- $\alpha_S(M_Z)$-dependence of the transverse EEC and its Asymmetry is measurable, as it lies above other parametric uncertainties
- End-point angular regions in the transverse EEC require calculation of the NLL resummed expressions and/or the MC programs implementing full NLO/NLL matching (work in progress)

- 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) do not depend on modelling the underlying event
  (iii) have small sensitivity to the QCD scales, and
  (iv) 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