Forward-backward multiplicity and transverse energy correlations

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Abstract

Correlation coefficients for the total transverse energy $\sum E_T$ and the multiplicity n in two regions (forward and backward) of pseudorapidity η are studied for charged hadrons produced in pp collisions using Monte Carlo simulations, with events generated with PYTHIA 8. The results for different center of mass energies $\sqrt{s}$ and PYTHIA 8 tunes are analyzed, as well as the effects of multiparton interactions and parton showers. The transverse momentum p_T and pseudorapidity dependence of the correlation strength is also studied.

1 Introduction

At hadron colliders, the interaction between two incoming hadrons typically results in the production of many outgoing particles. These reactions can be divided in soft and hard processes. The latter involve large momentum transfers and can be treated using perturbative quantum chromodynamics (pQCD). Unfortunately, this type of events are rare. Typical minimum-bias events involve low momentum transfers and cannot be treated in this way, because in this region the coupling constant α_s determining the strength of the interaction increases in such a way that a perturbative expansion in power of α_s is no longer possible. These are the so-called soft QCD processes.

Since there is a limited understanding of non perturbative QCD, complex models have been developed in order to describe the observed phenomenology. The complexity of these models excludes the possibility of obtaining significant information by applying analytical methods, therefore techniques such as Monte Carlos (MC) simulations are implemented.

In a proton-proton collision several mechanisms take part in the production of the outgoing particles. The substructure of the proton is described by the parton distribution functions (PDF) that describe the probability to find a given parton inside of the proton with a given fraction x of the proton momentum. These are non-perturbative quantities which have to be measured.

Hard scattering processes occur at hard scale (high p_T or high mass at the final state). In this regime, pQCD can be used to calculate the partonic cross section. The cross section of hadronic processes is then calculated using the convolution of the partonic cross section (perturbative quantity) with the parton distribution functions (non-perturbative quantity).

By increasing the energy of the collision, lower values of the momentum fraction can be reached, where the parton distribution functions become very high. Because of this, multiparton interactions (MPI) can occur at high energy pp collisions.

At low energy collisions, the internal substructure of the proton consists of only three valence quarks. As resolution increases (higher energies) the proton is seen to be composed of a *sea* of quark-antiquark pairs and gluons.

Colliding protons emit gluon radiation, which produces a decrease in the energy of the beam. Gluons themselves carry color charges and can therefore emit further radiation, leading to parton showers. This emission occurs also for the outgoing particles. These mechanisms are known as Initial State Radiation (ISR) and Final State Radiation (FSR).

At some point and for a brief period of time quarks are released as free particles, until they reach a given separation at which their interaction is so strong that the energy

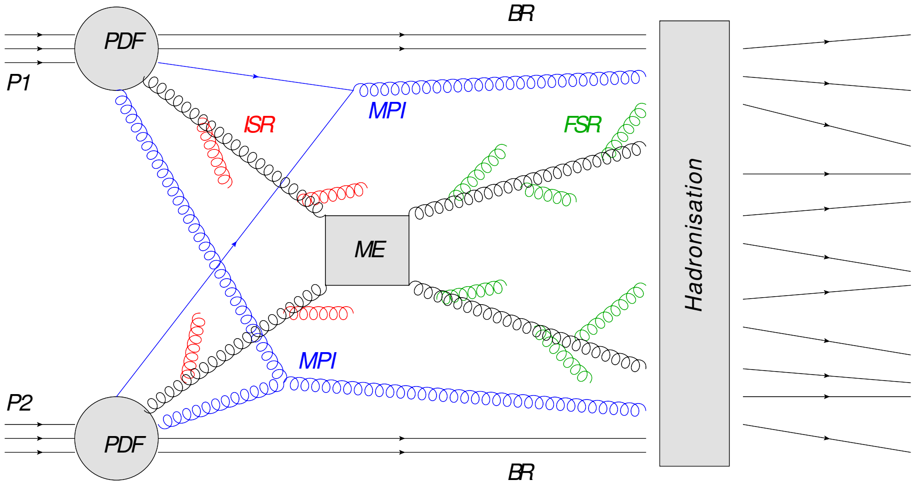


Figure 1: Diagram displaying multiple mechanisms involved in a pp collision.

stored between the quarks is enough to favor the creation of a $q\bar{q}$ pair. The production of hadrons by this mechanism is known as hadronization.

Because correlation is of main interest for this project, a way of computing its strength is needed. Therefore we define the correlation coefficient b between two observables x and y as

$$b = \frac{\langle xy\rangle - \langle x\rangle\langle y\rangle}{\sigma_x\sigma_y} = \frac{\langle xy\rangle - \langle x\rangle\langle y\rangle}{\sqrt{\langle x^2\rangle - \langle x\rangle^2}\sqrt{\langle y^2\rangle - \langle y\rangle^2}} \quad (1)$$

We consider two pseudorapidity regions of one unit width in η separated by an interval $\Delta\eta$: one region between $\frac{\Delta\eta}{2}$ and $\frac{\Delta\eta}{2} + 1$ (forward), and the other one between $-(\frac{\Delta\eta}{2} + 1)$ and $-\frac{\Delta\eta}{2}$ (backward) as shown on Figure 2, with the pseudorapidity η defined as $\eta = -\ln(\tan\theta/2)$, where θ is the polar angle of the particle.
We call the charged particle multiplicities in the two bins n_F and n_B. Assuming $\langle n_B\rangle = \langle n_F\rangle$ and $\langle n_B^2\rangle = \langle n_F^2\rangle$ the correlation coefficient b for the multiplicities n in the symmetrical intervals takes the following form:

$$b = \frac{\langle n_F n_B\rangle - \langle n_F\rangle^2}{\langle n_F^2\rangle - \langle n_F\rangle^2}. \quad (2)$$

The same relation holds for the transverse energy $E_T = \sqrt{p_T^2 + m^2}$, where p_T is the transverse momentum of the particle and m its mass.

The main purpose of this report is to study the forward-backward correlation between the multiplicities and the forward-backward correlation between the total transverse energies for different production mechanisms, center of mass energies and p_T intervals.

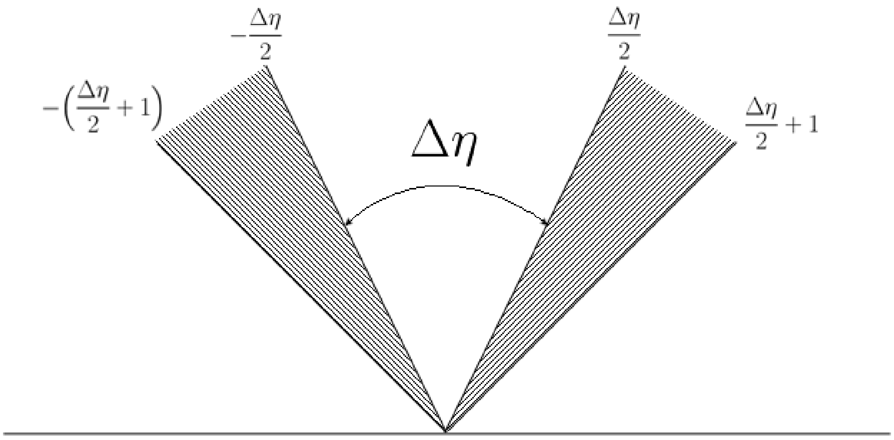


Figure 2: Forward and backward symmetrical regions of pseudorapidity.

2 PYTHIA Tunes

As explained in [1], since some physical aspects cannot be derived from first principles, Pythia 8 contains many parameters that represent a limitation in our understanding of nature. Particularly affected are the areas of hadronization and multiparton interactions, which both involve nonperturbative QCD physics. Hence the need to have tunes involving different settings for a group of parameters.

In the first part of the project the data for the multiplicity correlation in pp collisions at $\sqrt{s} = 540$ GeV [3] are compared with MC simulations generated using different Pythia 8 tunes. The different MC predictions are based on 50 000 events. The following tunes are used:

- Tune 1 - Default tune used up to version 8.126, based on some early comparisons with data [1].
- Tune 2 - Based on some data comparisons by Peter Skands [1].
- Tune 4C - Newer tune with a reduced cross section for diffraction, plus modified multiparton interaction parameters, for better agreement with some early key LHC measurements [1].

The comparison between the data [3] and the MC predictions obtained by using these tunes is shown in Figure 3. The simulation can reproduce the UA5 results and the selection of a particular tune plays an important role.

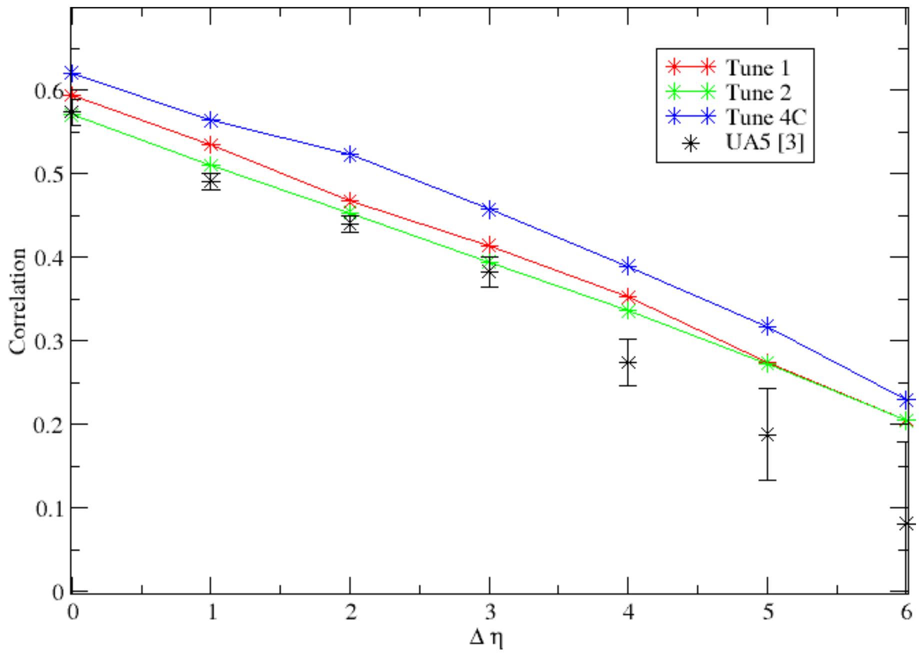


Figure 3: Forward-backward multiplicity correlation at $\sqrt{s} = 540$ GeV. A comparison between UA5 data [3] and MC predictions by different tunes is made.

3 Center of mass energy dependence

The next step is to study the behavior of the correlation strength for different center of mass energies. This parameter can be changed via the PYTHIA program. Figure 4 shows the multiplicity and total transverse energy per event distributions. We observe that at higher collision energies the number of particles increases significantly. The same occurs for $\sum E_T$.

The results for the multiplicity and total transverse energy correlations are shown in Figure 5. We observe that the correlation becomes higher for increasing values of $\sqrt{s}$. This behavior is observed for the multiplicity as well as for E_T.

In Figure 6 the MC predictions for these correlations are shown normalized to the lowest center of mass energy $\sqrt{s} = 540$ GeV. The plot shows that for increasing pseudorapidity separation $\Delta\eta$ between the two intervals the correlation at high $\sqrt{s}$ tends to deviate more from the correlation at low $\sqrt{s}$.

It is interesting to see how the ratio between the total transverse energy correlation and the multiplicity correlation behaves for each center of mass energy. As shown in Figure 6, this ratio seems to be constant and around 0.85. This means that regardless of $\sqrt{s}$, the total transverse energy and multiplicity correlations have a very similar strength.

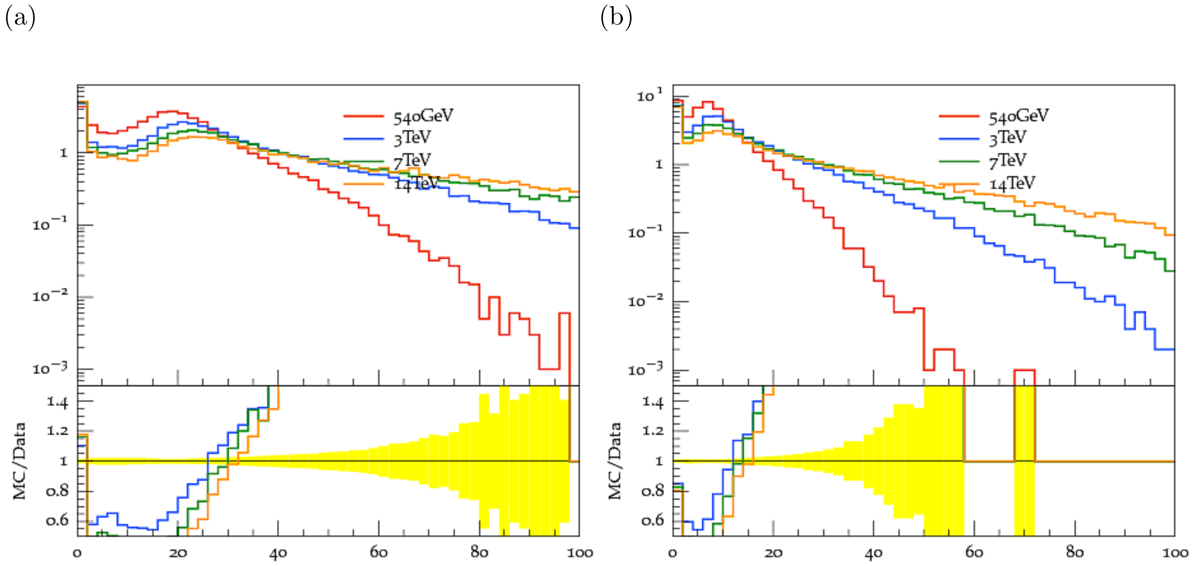


Figure 4: (a) Multiplicity and (b) total transverse energy distributions at different $\sqrt{s}$.

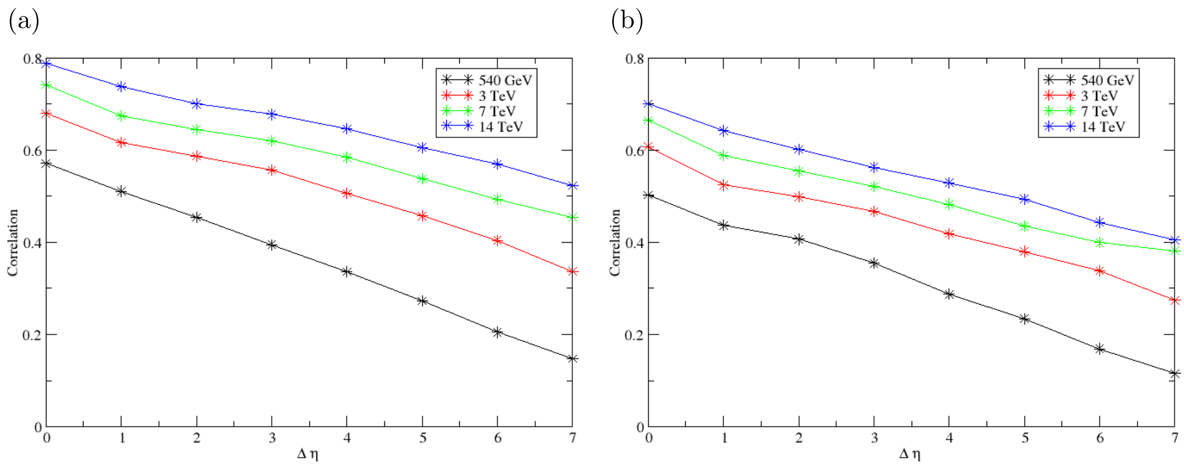


Figure 5: (a) Multiplicity and (b) total transverse energy correlations at different $\sqrt{s}$.

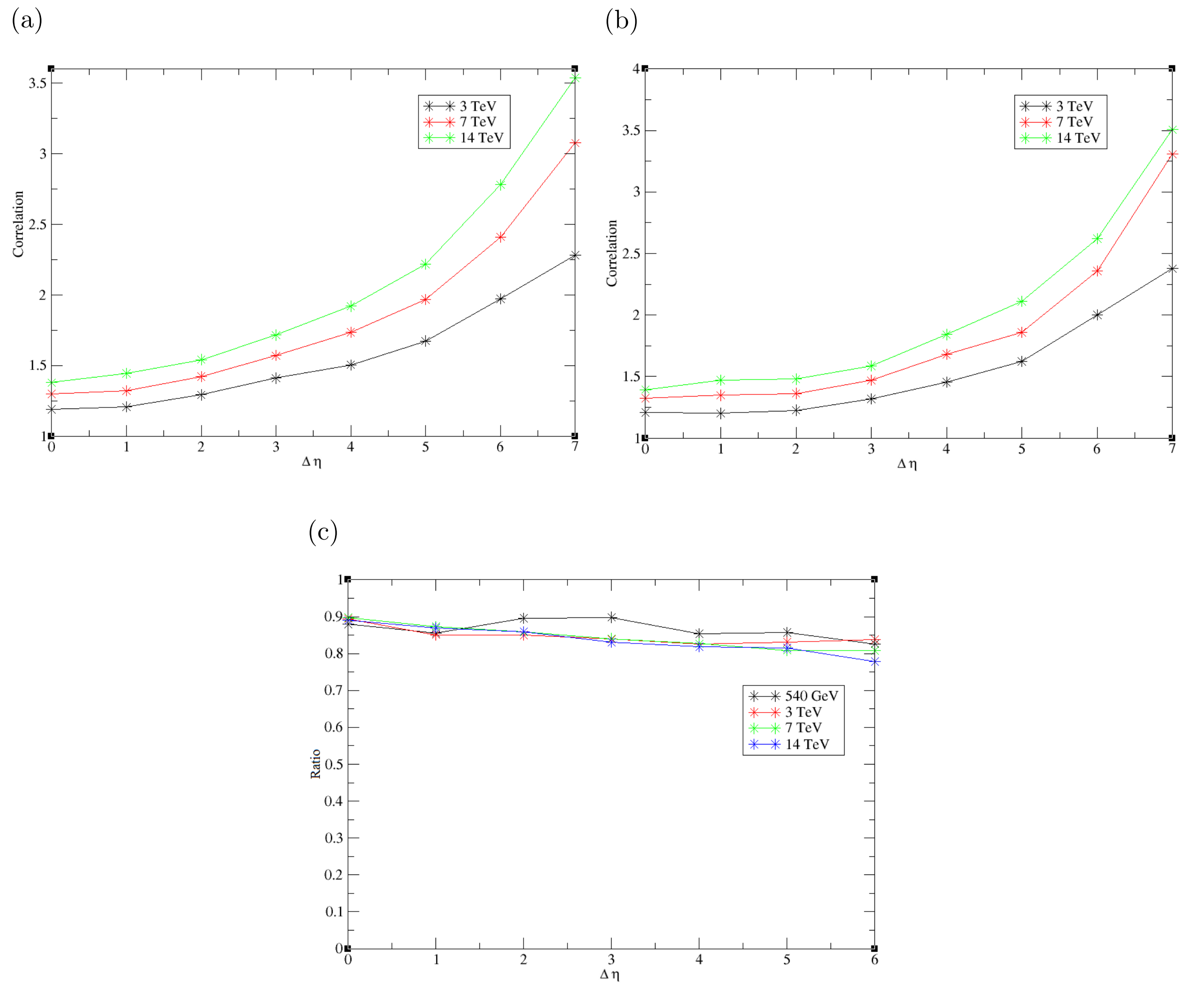


Figure 6: (a) Multiplicity and (b) total transverse energy correlations, normalized to $\sqrt{s} = 540$ GeV. The ratio (c) between both correlations is shown below.

4 MPI and showers effects on the correlations

As stated before, one of the main purposes of this project is to study the effect of different production mechanisms on the correlation strength. In particular two processes are investigated: Multiparton interactions (MPI) and parton showers. Protons contain a large number of partons, because of this it is likely to observe multiple parton-parton interactions in high energy *pp* collisions. Simple models (as shown in [2]) that do not include MPI in hadron collisions cannot well reproduce experimental data. Parton showers refer to gluon radiation in the initial and final state of the collisions. Figure 7 shows the multiplicity and the total transverse energy distributions for the different components of the interaction.

(a) (b)

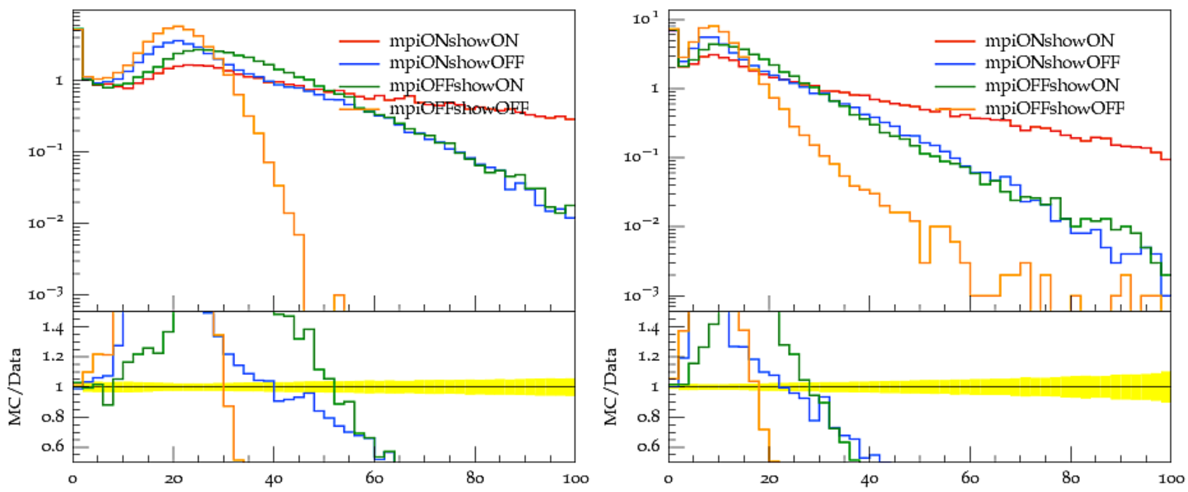


Figure 7: (a) Multiplicity and (b) total transverse energy distributions for different mechanisms.

In order to study the behavior of the correlation coefficient for these different components, the MPI and parton shower parameters are modified on Pythia 8 and the MC simulations ran for each case. This is done for $\sqrt{s}$ = 540 GeV and $\sqrt{s}$ = 14 TeV, as shown in Figure 8.

It can be seen from the plots that the correlation is stronger when both processes are turned on. The weakest correlations occur when MPI and parton showers are both turned off. Multiparton interactions seem to play a bigger role in correlation strength than parton radiation. Also, the sum of the individual effects of these two components is not equal to the effect of both mechanisms turned on together at the same time. This could imply that they are not completely independent phenomena.

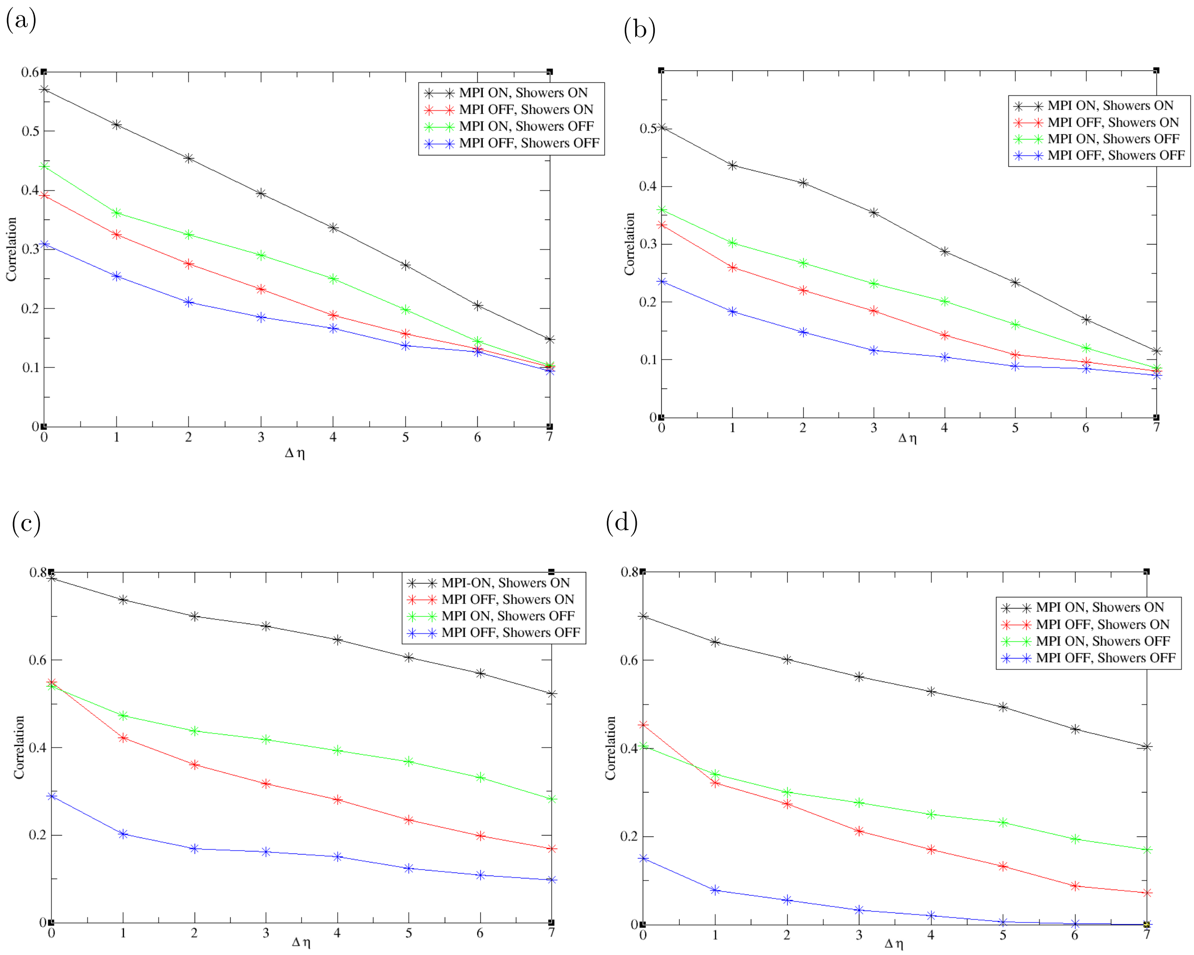


Figure 8: Correlation strength for different mechanisms. Above: (a) n and (b) $\sum E_T$ correlations at $\sqrt{s} = 540$ GeV. Below: (c) n and (d) $\sum E_T$ correlations at $\sqrt{s} = 14$ TeV.

It is also interesting to notice that the difference between the correlation obtained with both mechanisms turned on and with both turned off is increasing with the center of mass energy.

5 Transverse momentum dependence

At last the effect of p_T on the correlation strength is studied. For this, different p_T intervals are defined and pp collisions at $\sqrt{s} = 14$ TeV are simulated.

The four p_T regions considered are:

$$0 < p_T < 0.5 \text{ GeV},$$
$$0.5 < p_T < 1 \text{ GeV},$$
$$1 < p_T < 2 \text{ GeV},$$
$$p_T > 2 \text{ GeV}.$$

Figure 9 shows the n and $\sum E_T$ distributions as observed in different intervals. It is important to remark that the multiplicity of particles with low transverse momentum is considerably bigger than the one for high p_T. A similar behavior can be notice for the transverse energy, with low p_T particles carrying a big fraction of E_T. Thus the importance of using non perturbative QCD methods.

(a) (b)

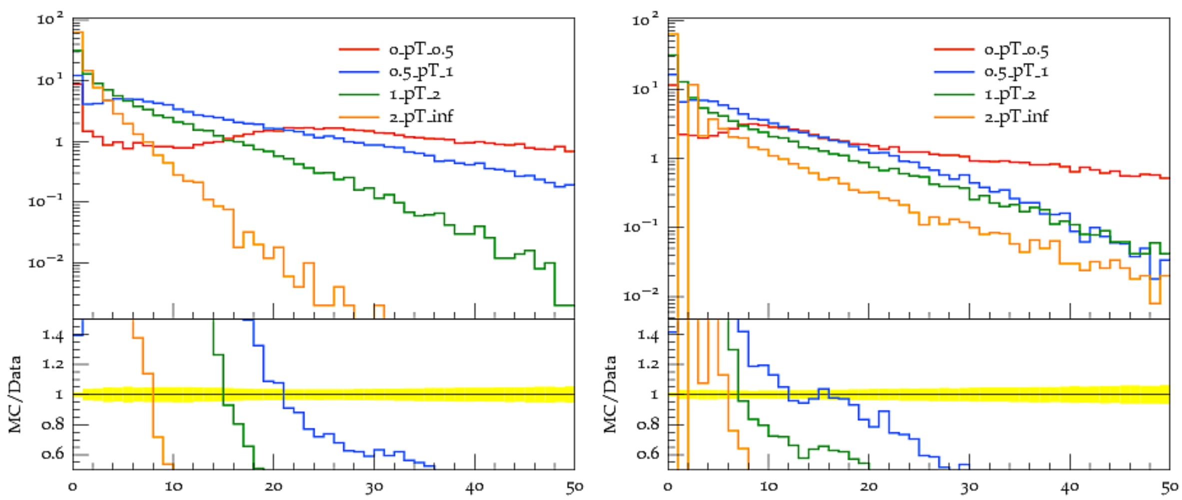


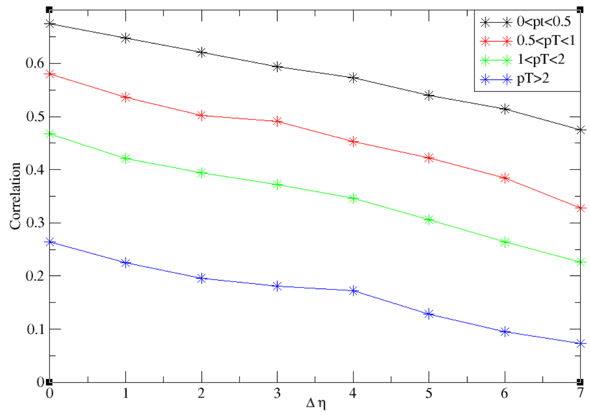
Figure 9: (a) Multiplicity and (b) total transverse energy distributions for different intervals of p_T.

Figure 10 shows that low transverse momentum particles show more correlation than high p_T particles for both n and $\sum E_T$.

6 Conclusion

The predictions for the forward-backward multiplicity at 540 GeV are compared to the UA5 data and found to be in relatively good agreement with them. The correlation strength is shown as a function of $\Delta\eta$, $\sqrt{s}$ and p_T. The effects of multiparton interaction and parton showers on the correlation are also studied.

(a)



(b)

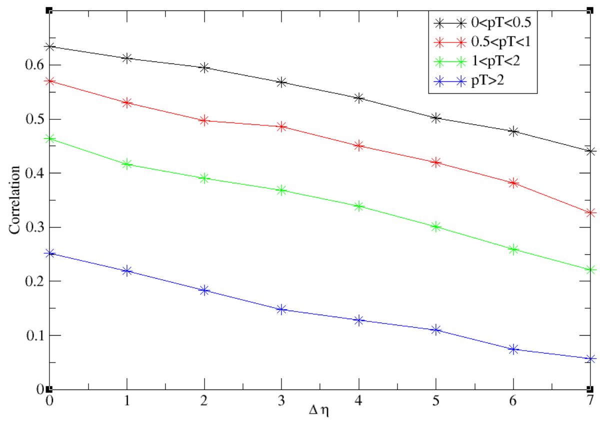


Figure 10: (a) Multiplicity and (b) total transverse energy correlations for different intervals of p_T.

The Monte Carlo predictions show that forward-backward correlations for the multiplicity and the total transverse energy increase with the center of mass energy, this increment being bigger at higher values of $\Delta\eta$.

The results show that the effect of multiparton interactions is greater than the effect of parton showers. Also, particles with low transverse momentum have more correlation than those with high p_T.

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References

[1] T. Sjöstrand et al. *An Introduction to PYTHIA 8.2.* arXiv:1410.3012v1 (2014).

[2] T. Sjöstrand and M. van Zijl. *A multiple-interaction model for the event structure in hadron collisions.* Physical Review D 36 (1987).

[3] J. Gaudean, Ph.D. thesis, Universiteit Antwerpen (1984).

[4] K. Wraight and P. Skands. *Forward-Backward Correlations and Event Shapes as probes of Minimum-Bias Event Properties.* arXiv:1101.5215v1 (2011).

[5] The ALICE Collaboration. *Forward-backward multiplicity correlations in pp collisions at* $\sqrt{s} = 0.9, 2.76$ *and* 7 *TeV.* arXiv:1502.00230v2 (2015).

[6] R. K. Ellis et al. *QCD and Collider Physics.* Cambridge University, United Kingdom (1996).