Underlying Event Studies with CASTOR in the CMS Experiment

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Multi-parton interactions (MI) play a significant role in soft and high p_T processes. Especially in case of LHC where the proton beams collide at very large energies, the understanding of MI is becoming crucial for the high precision measurements. Up to now various Monte Carlo (MC) models have been tuned to describe the Tevatron data [1], exploiting mainly the charged particle multiplicities and particle energy flows in the central η region. In the near future the full angular coverage of the CMS detector from the central to the most forward region ($0 < \eta < 6.6$) will allow to study MI over a large rapidity range, which was not possible before.

Since the multi-parton interactions occur between the remnant partons of the colliding particles, the energy flow in the very forward region covered by the CASTOR calorimeter [2] ($5.2 < \eta < 6.6$) is expected to be strongly affected and hence ideal for the MI model tuning. In addition one can study the long range correlations (correlation between activity in central and forward region) which where observed already at HERA and UA5 [3].

Results shown here are based on a generator level analysis of inclusive QCD processes [1] with PYTHIA MC 6.4.14, using several widely used MI tunes, such as Rick Field's tune A, Sandhoff-Skands tune S0 and also extreme scenario with MI being switched off.

In order to study the long range correlations the triggering on energy deposit in CASTOR η region is performed. Four energy ranges in the CASTOR (E_{CAST}) are investigated. For each E_{CAST} bin the charged particle multiplicities as well as particle energy flow in central rapidity region are investigated (see figure 1). In order to mimic the detection threshold effects a minimum energy cut of 1 GeV is applied to all stable generated particles.

One can see that in case without MI no long range correlations are observed, i.e. charge particle multiplicities look the same for all E_{CAST} energy bins, as one would expect. On the other hand, when MI are included there is a clear correlation, larger energies in CASTOR region imply higher charged particle multiplicities and particle energy flow in the central region. Furthermore triggering on CASTOR enhances the differences between various MI tunes, and thus may contribute to better understanding of multi-parton interaction picture.

Study of multi-parton interactions within the hard processes, such as top production, is becoming extremely interesting since they are one of the major items of the LHC physics program. Therefore charged particle multiplicities (Fig.2 - upper plots) and particle energy flow observables were studied for the top processes [2] and were compared with the distributions for inclusive QCD processes (Fig.1). No selection cuts for top-quark reconstruction were applied. Besides much higher charged particle multiplicities and energy flow in central rapidity region in case of top production, which is due to the presence of hard scale, there is clearly more underlying event activity than in QCD processes. This can be easily seen for example by comparing the MC pre-

[1] PYTHIA parameters: MSEL= 1 (hard QCD processes), CKIN$(3) = 5$GeV (min. $\hat{p}_\perp$ for hard process).
[2] PYTHIA parameters: MSEL= 6 ($t\bar{t}$ production).

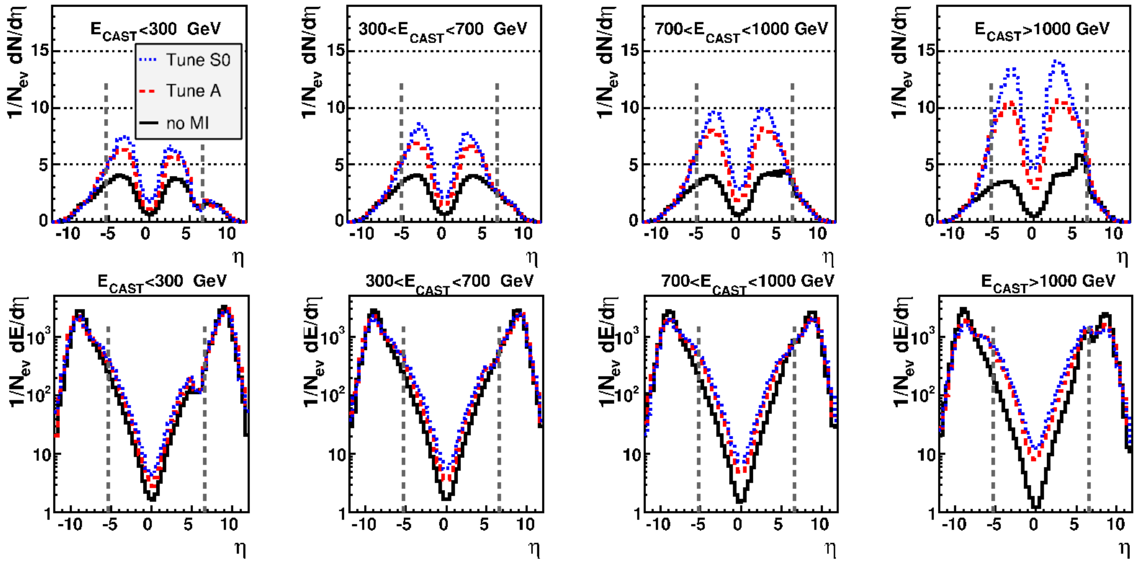

Fig. 1: Charged particle multiplicities (upper plots) and particle energy flow (lower plots) as function of η for four different CASTOR energy bins. Shown is PYTHIA MC prediction for inclusive QCD processes. The dashed vertical lines indicate the acceptance of the CMS detector.

diction with and without MI for inclusive QCD processes and for top processes separately. The differences amount to 2-5 particles per rapidity bin (Fig.2 - middle plots).

This suggests that a naive approach of subtracting underlying event contribution as determined for inclusive QCD processes from the top events would not work. As already seen from CDF measurements [1] the underlying event depends strongly on the collision centrality. The harder the collision is, the more underlying event activity one expects to see. This feature is also implemented into PYTHIA MC which is used in this analysis. After demanding a hard scale for inclusive QCD events in form of $E_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV the differences between underlying event in QCD and in top events do almost disappear (Fig.2 - bottom plots).

Understanding of underlying event is essential also for all kind of measurements which involve high E_{T} jets in the final state. As the hadronic jets are the direct products of the parton hadronisation, the jet measurements give a look inside the dynamics of hard interaction. However, the underlying event produces additional energy in the available phase space which is largely uncorrelated with the partons originating from the hard interaction. This additional 'pedestal' energy is added by the jet reconstruction algorithms to the 'true' jet energy, thus spoiling the relation of the 'jets to the partons. However, as shown below, it is possible to estimate the 'pedestal' energy from the measurements in the forward calorimeters and subtract it from the reconstructed jet energy.

The analysis is done using the PYTHIA simulation using the different options for multiparton interactions as well as without multi-parton interactions. Events are selected in which the jets are reconstructed by the inclusive $k_{\perp}$ algorithm with transverse energies above 10 GeV and the jet axis at the central pseudorapidities ($-3 < \eta^{\mathrm{jet}} < 3$). Figure 3 shows the transverse energy

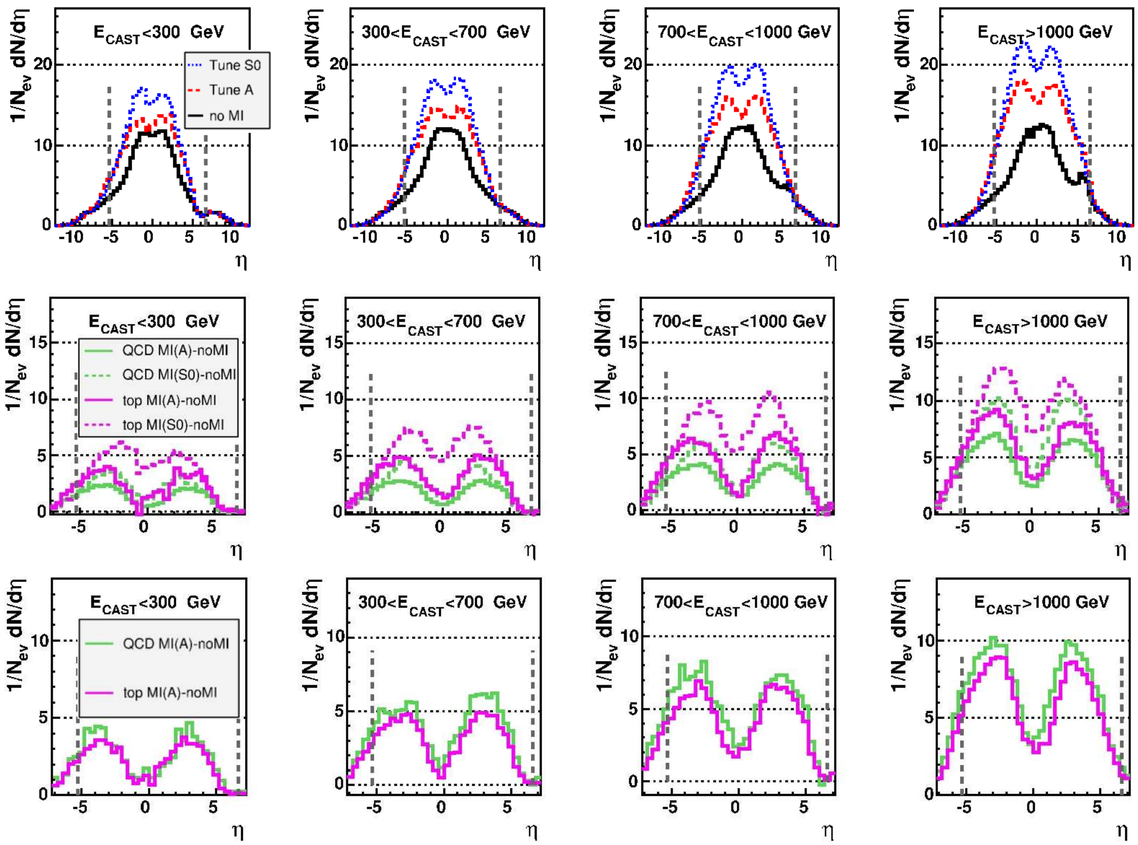

Fig. 2: Upper plots: charged particle multiplicities as a function of η for four different CASTOR energy bins. Shown is PYTHIA MC prediction for top processes. Middle plots: the charged particle multiplicities due to underlying event activity (MC with MI - MC without MI) as a function of η in top as well as inclusive QCD processes. Bottom plots: the charged particle multiplicities due to underlying event activity as a function of η in top and in inclusive QCD processes after demanding a presence of a hard jet $E_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV in the central rapidity region $|\eta| < 2.5$. The dashed vertical lines indicate the acceptance of the CMS detector.

flow around the jet as a function of pseudorapidity. The different lines correspond to the different ranges of jet pseudorapidities ([-3,-2.5], [-1.5,-1], [0,0.5], [1,1.5], [2,2.5]), and two different jet transverse energy ranges ([10-20 GeV], [20-30 GeV]). Only transverse energies within one radian in azimuth of the jet are included. The left plot corresponds to the simulation without multi-parton interaction and the right plot for simulation with multi-parton interaction. The plots clearly show the effect of the underlying event pedestal when the multi-parton interactions are simulated. It is also observed that the level of pedestal doesn't depend on the jet pseudorapidity, but it gets higher for higher jet energies, i.e. it depends on the hardness of the interaction.

The idea of the method to determine and subtract the pedestal energy within the jet is demonstrated in the Fig.4. In the left upper figure the jet profile as a function of pseudorapidity is shown for the PYTHIA simulation which includes multi-parton interaction. For this figure the events are used which contain a jet with transverse energy above 10 GeV in the pseudorapidity

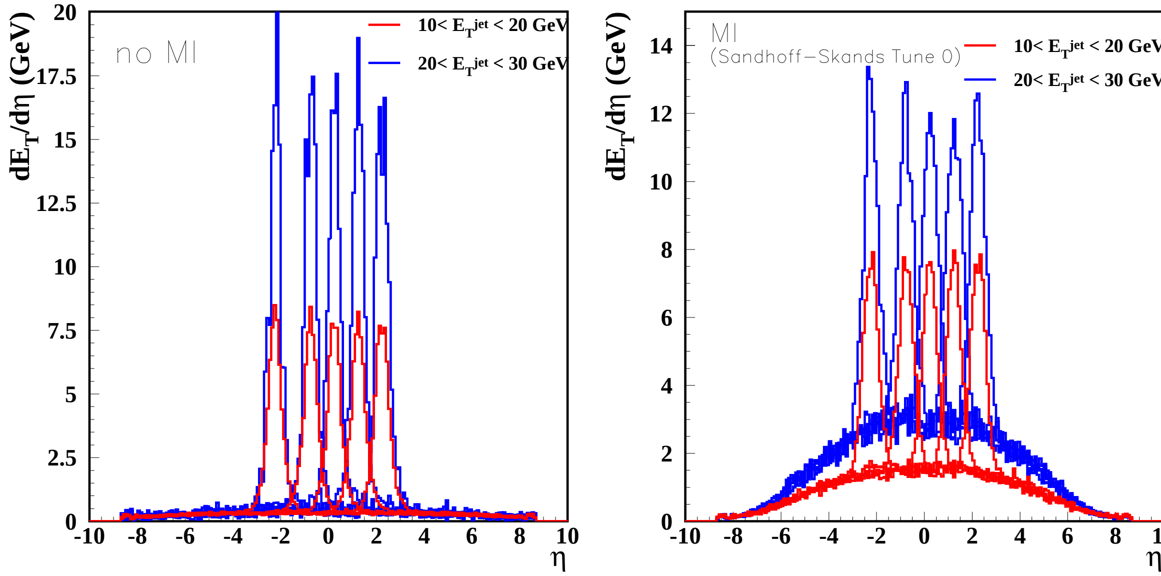

Fig. 3: The transverse energy distributions around the jets (jet profile) as a function of pseudorapidity. The left plot is obtained from the PYTHIA simulation without multi-parton interactions, while the right plot is for PYTHIA with multi-parton interactions. The different lines represent the different pseudorapidity ranges of the jets ([-3,-2.5], [-1.5,-1], [0,0.5], [1,1.5], [2,2.5]) and the different transverse energy ranges of the jets ([10-20 GeV], [20-30 GeV]).

range $0 < \eta^{\rm jet} < 0.5$. The transverse energy measured in the acceptance range of the CASTOR calorimeter ($5.2 < \eta < 6.6$) is also shown by the red hatched area. The blue hatched area below the jet cone is the contribution of pedestal to the jet energy measurement determined with the method described here.

As the underlying event pedestal seem to be independent on the position of the jet in the central detector, we may attempt to describe the pedestal by a simple function. The possible function can be

$$f(\eta) = \frac{A}{1 + B \cdot e^{|\eta|-4}} \tag{1}$$

This function depends on two free parameters A and B and seems to describe the pedestals for the different models of multi-parton interactions and for the different cuts on jet transverse energies and pseudorapidities. The two free parameters could be the measured energies in the forward calorimeters, like CASTOR, which are away from the central region and don't get contribution from the energy of hard interaction. The function doesn't contain direct dependence on the $E_{\rm T}$ of the jet, because there are strong correlations of $E_{\rm T}^{\rm jet}$ with the energy of pedestal and, correspondingly, with the energy in the forward calorimeters (see Fig.3). Therefore the $E_{\rm T}^{\rm jet}$ dependence can be absorbed in the A and B parameters. In principle, the parameters A and B in eq.1 are strongly correlated, thus even the single energy measurement in the CASTOR can already provide the estimate of the pedestal under the jet. An example of the the fit of pedestal by this function is shown in Fig.4 (right) and the level of pedestal under the jet determined by this method is shown in the Fig.4 (left) as a blue hatched histogram. As is seen, this approach gives reasonable result and can be developed further and used in analyses.

It should be noted, that presented studies have been done using the Lund fragmentation mechanism in PYTHIA. In principle, using another Monte Carlo or fragmentation models (CASCADE, ARIADNE, etc.) may lead to the different energy distribution of the underlying event. This may require the optimisation of the function of eq.1. The reliability of this method can be also improved by using an additional measurements of forward energy (in addition to the CASTOR), for example from the HF calorimeter.

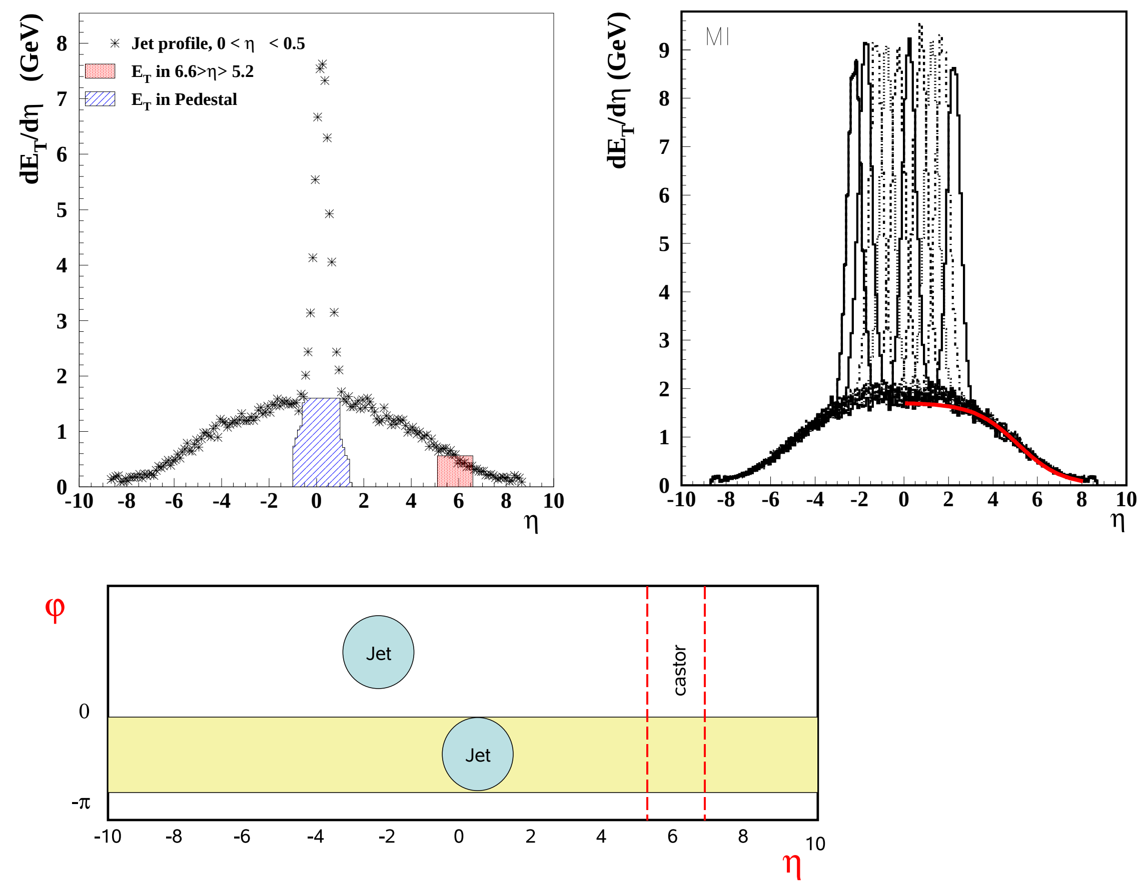

Fig. 4: *(left)* The transverse energy distributions around the jets (jet profile) as a function of pseudorapidity for the jets with $0 < \eta^{\rm jet} < 0.5$ and $10 < E_{\rm T}^{\rm jet} < 20\ GeV$. The red hatched histogram is the level of transverse energy in the pseudorapidity range of the CASTOR ($5.2 < \eta < 6.6$). The blue hatched histogram below the jet area is the pedestal level determined from the method described in this report. *(right)* The jet profile as a function of pseudorapidity for jets with $10 < E_{\rm T}^{\rm jet} < 20\ GeV$. The different lines correspond to the different ranges of the jet pseudorapidity. The solid line on the right tail of distribution shows the result of the fit of pedestal by a function of eq.1.

In conclusion, the studies presented here show that the forward region is very sensitive to the multi-parton interactions. The measurements in the forward calorimeters, such as CASTOR, can be used to discriminate between the various MI models and to improve the jet reconstruction in the central region. Nevertheless further studies with detailed simulation of detector response are essential. Simple smearing of particle energies in η CASTOR region according to the resolution as measured in test beam 2007 has already been tried, and leads to similar results.

References

[1] [CDF Collaboration], Phys. Rev. D **70** (2004) 072002.

[2] CASTOR web page, $http : //cmsdoc.cern.ch/castor$.

[3] T. Sjostrand and M. van Zijl, *A multiple-interaction model for the event structure in hadron collisions*, Phys. Rev. D **36** (1987) 2019-2041.