# ISMD08
# What we learn from forward detectors at LHC ?

*Armen Bunyatyan*[1,2]
[1] MPI für Kernphysik, Heidelberg, Germany,
[2] Yerevan Physics Institute, Armenia

**Abstract**
Small-angle detectors at the LHC give access to a broad physics programme within and beyond the Standard Model. We present here some studies of forward physics processes related to underling event, multi-parton interactions and low-x QCD dynamics.

## 1 Introduction

The LHC collider will provide the highest energy proton-proton and ion-ion collisions in the lab to date, opening up a phase space for particle production in an unprecedented range spanning $\Delta\eta$ ~20 units of rapidity. As a general feature, particle production in hadronic collisions is peaked at central rapidities, whereas most of the energy is emitted at very low angles. The ATLAS and CMS detectors not only cover the largest $p_T - \eta$ ranges at mid-rapidity, but they feature extended instrumentation at lager distances far away from the interaction point: $\pm$ 11m (ATLAS FCal and CMS HF hadronic calorimeters), $\pm$14 m (ATLAS LUCID and CMS CASTOR sampling calorimeter), $\pm$140 m (Zero-Degree-Calorimeters, ZDCs), and $\pm$240 m (ATLAS Roman Pots). The forward coverage of the CMS interaction region is complemented with the two trackers (T1 and T2 telescopes) and the proton-taggers (Roman Pots) at $\pm$147 and $\pm$220 m of the TOTEM experiment which has common forward physics program with CMS [1]. The rapidity coverage of ATLAS and CMS forward detectors is summarised in Fig.1.

The forward detectors give access to a broad physics program within and beyond the standard model [1, 2]. Here we present studies related to the physics of underlying events and multi-parton interactions and low-x QCD parton dynamics.

## 2 Underlying Event Studies with CASTOR in the CMS Experiment

Multi-parton interactions (MI) play a significant role in soft and high $p_T$ processes. Especially in case of LHC the understanding of MI is becoming crucial for the high precision measurements. Various Monte Carlo (MC) models have been tuned to describe the Tevatron data [3], exploiting mainly the charged particle multiplicities and particle energy flows in the central $\eta$ region. The large angular coverage of the LHC detector from the central to the most forward region ($0 < \eta < 6.6$) will allow to study MI over a large rapidity range. Since the multi-parton interactions occur between the remnant partons of the colliding particles, the energy flow in the very forward region is strongly affected and hence are ideal for the MI model tuning. In addition one can study the long range correlations between the activities in central and forward regions.

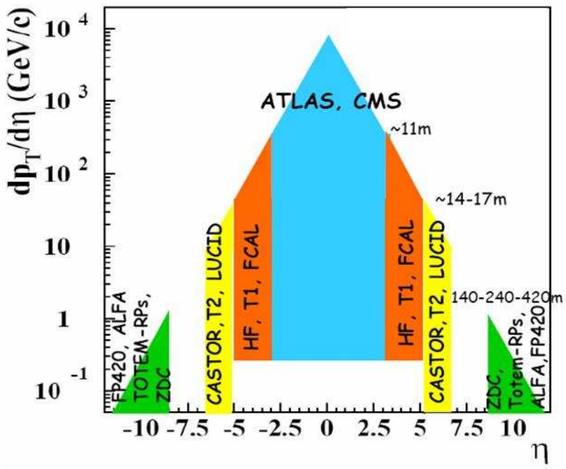


Fig. 1: The rapidity coverage of CMS and ATLAS detectors

The long range correlations were investigated [4] with the PYTHIA MC [5], at the level of generated hadrons, using several MI tunes. The charge particle multiplicities in the central rapidity range were calculated for four different energy deposits in the rapidity range $5.2 < \eta < 6.6$, which corresponds to the coverage of CMS-CASTOR calorimeter [6, 7]. The distributions for inclusive (minimum bias) QCD processes are shown in the upper part of Fig.2 and for the $top$ production processes in the lower part of the figure. When MI are not generated, the charge particle multiplicities are the same for all energy bins. On the other hand, a clear correlation is seen when MI are included– larger energies in the forward region imply higher charged particle multiplicities and 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. Comparison of charged particle multiplicities in the inclusive QCD and the $top$ production shows that the $top$ processes not only have higher charged particle multiplicities and energy flow, but also contain more underlying event activity than the inclusive QCD processes. 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 [3] the underlying event properties depend strongly on the collision centrality. The harder the collision is, the more underlying event activity one expects to see. After demanding a hard scale for the inclusive QCD events in form of $E_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV the differences between underlying event in QCD and in $top$ events almost disappear (Fig.3).

Understanding of underlying event is essential also for the measurements which involve high $E_{\mathrm{T}}$ jets in the final state. As the hadronic jets are the results of the parton hadronisation, their measurements give a chance to look inside the dynamics of hard interaction. However, the underlying event produces additional energy in the available phase space which is added by the jet algorithms to the 'true' jet energy, thus spoiling the relation of the jets to the partons. However, it is possible to estimate this 'pedestal' energy from the measurements in the forward calorimeters and subtract it from the reconstructed jet energy [4]. Left side of Figure 4 shows the transverse energy flow around the jet as a function of pseudorapidity for the jets from the PYTHIA MC

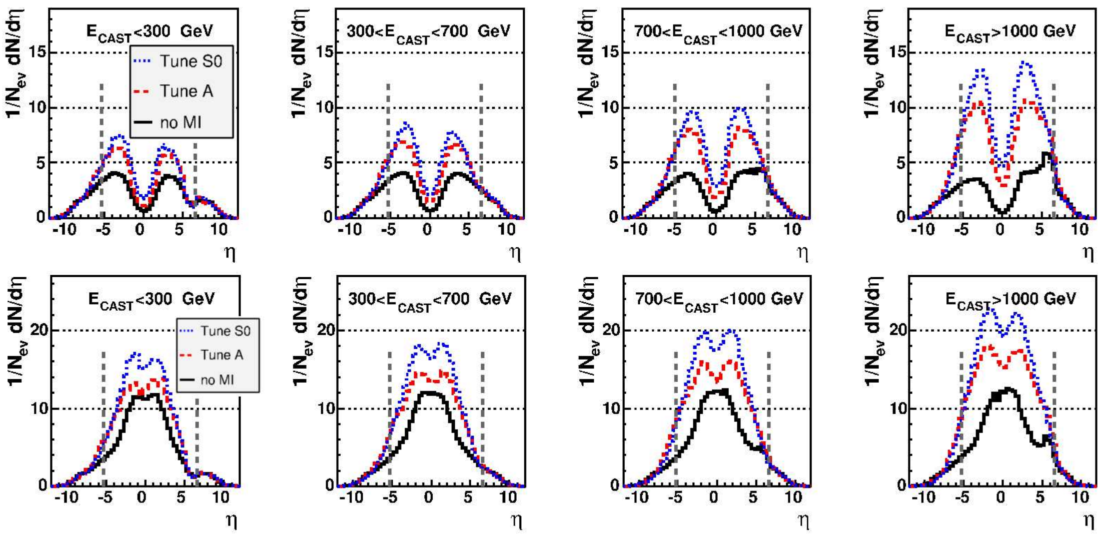

Fig. 2: Charged particle multiplicities as function of $\eta$ for four different CASTOR energy bins. Shown is PYTHIA MC prediction for inclusive QCD processes (up) and *top* production (down) processes.

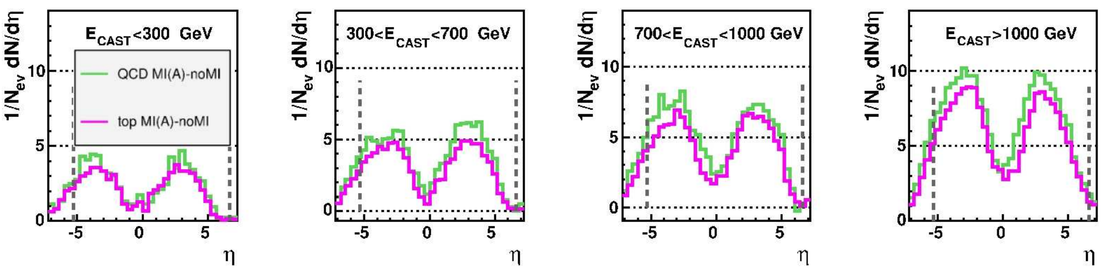

Fig. 3: Charged particle multiplicities due to underlying event activity (MC with MI - MC without MI) as a function of $\eta$ in *top* and in inclusive QCD processes after demanding a presence of a hard jet $E_{\mathrm{T}}^{\mathrm{jet}} > 40$ GeV in the central rapidity region $|\eta| < 2.5$. The dashed vertical lines indicate the acceptance of the CMS detector.

sample, in five different pseudorapidity bins between -3 and 2.5 and two jet transverse energy ranges. The plot clearly shows the underlying event pedestal, when the MI are simulated, and that the level of pedestal does not depend on the jet pseudorapidity but gets higher for higher jet energies, i.e. it depends on the hardness of the interaction.

In the right side of Fig.4 the jet profile as a function of pseudorapidity is shown for the PYTHIA simulation with MI. The transverse energy measured in the acceptance range of the CASTOR calorimeter ($5.2 < \eta < 6.6$) is indicated with the dash hatched area. As the underlying event pedestal is rather independent on the position of the jet in the central detector, we attempt to fit the pedestal by a universal function, e.g. $f(\eta) = A/(1 + B \cdot e^{|\eta|-4})$, which also reasonably describes the pedestals for the different MI tunes and for the different cuts on jet transverse energies and pseudorapidities. The two free parameters can be represented by the measured energies in the very forward calorimeters, e.g. CASTOR or HF. An example of the the

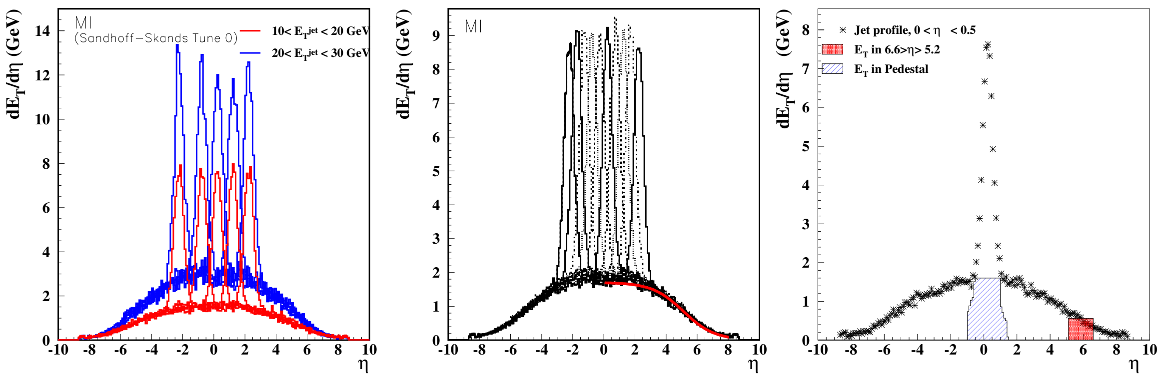


Fig. 4: *(left)* The transverse energy distributions around the jets (jet profile) as a function of pseudorapidity. The different lines represent the different pseudorapidity ranges and the different transverse energy ranges of the jets; *(middle)* The jet profile as a function of pseudorapidity. The 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 as described in the text; *(right)* The 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 dash hatched histogram is the level of transverse energy in the pseudorapidity range of the CASTOR ($5.2 < \eta < 6.6$). The right hatched histogram below the jet area is the pedestal level determined from the method described in the text.

fit of pedestal by this function is shown in Fig.4 (middle) and the level of pedestal under the jet determined by this method is shown in the right side of Fig.4 as a right hatched histogram. This approach gives reasonable result and can be developed further. In principle, using another Monte Carlo or fragmentation models (CASCADE, ARIADNE, etc.) may lead to the different energy distribution of the underlying event, which may require the optimisation of the fitting function.

## 3 Low-x QCD physics

One of the main HERA observations is that the proton structure function is almost purely gluonic for the low values of the fractional momenta $x = p_{parton}/p_{proton} \lesssim 0.01$. Below $x \simeq 10^{-4}$ the gluon PDF in the proton is however poorly constrained. In this small-x regime one expects non-linear gluon-gluon fusion processes not accounted for in the standard DGLAP/BFKL evolution equations to become important and tame the rise of the parton densities.

Forward instrumentation provides an important lever arm for the measurement of the low-x structure and evolution of the parton densities. Indeed, in a $2 \to 2$ parton scattering the minimum momentum fraction probed when a particle of momentum $p_T$ is produced at pseudo-rapidity $\eta$ is $x_{min} \sim p_T \cdot e^{-\eta}/\sqrt{s}$ i.e. $x_{min}$ decreases by a factor of $\sim 10$ every 2 units of rapidity. The measurement of jets with $p_T \sim 20 - 100$ GeV at forward rapidities ($3 < |\eta| < 6.6$) allows one to probe the PDFs at $x$ values as low as $x \sim 10^{-6}$. In addition to the single inclusive cross sections, the production of events with two similar transverse-momentum jets emitted in each one of the forward/backward directions, the so called “Mueller-Navelet jets”, is a particularly sensitive measure of BFKL as well as non-linear parton evolutions. Preliminary CMS analyses indicate that such studies are well feasible measuring jets in each one of the HF calorimeters [8].

## 4 Forward Jets in the CASTOR calorimeter in the CMS experiment

Events in which an energetic jet is produced in the forward direction close to the proton remnant are sensitive to the higher order processes due to the long rapidity range available for radiation between the jet and the hard scattering vertex. The longitudinal momentum fraction of the proton, $x$, can be related to the rapidity, $y$, by approximately $x \sim e^{-y}$, which further suggests that forward physics provides valuable information about low $x$ parton dynamics. The analyses of forward jets at HERA [9, 10] have improved our understanding of higher order processes. Available fixed order calculations (NLO $O(\alpha_s^2)$) as well as the higher order processes approximated by DGLAP parton showers underestimate the HERA data by up to a factor of 2. The data can be described only if the ordering of the transverse momenta of the radiated gluons is broken in the theoretical predictions.

The study is made [11] using the Monte Carlo events generated with the PYTHIA [5] and ARIADNE [12] MC models. PYTHIA is based on LO DGLAP parton showers, which give gluon radiation ordered in transverse momentum with respect to rapidity. In ARIADNE, parton showers are generated by the Color Dipole Model (CDM), resulting in gluon radiation without any ordering in transverse momentum. This corresponds to a BFKL like final state. Events are selected which contain a hadron level jet with a transverse momentum $E_T > 10$ GeV and a pseudorapidity $5.2 < \eta < 6.6$. To suppress events with DGLAP like dynamics, two jets with $E_T > 10$ GeV are required in the central region, $|\eta| < 1.5$. The resulting cross-section is shown in left side of Fig. 5 as a function of the forward jet energy. The CDM model produces more jets at higher energies, while the events with gluon emissions generated according to DGLAP dynamics have a suppressed jet production. At the highest forward jet energies the difference between the models reaches two orders of magnitude.

The feasibility of such measurement with the CASTOR calorimeter at CMS has been studied. Since CASTOR has no segmentation in polar angle it is not possible to define jets according to conventional jet algorithms which use the energy, polar and azimuthal angles of particles. However, a reasonable jet reconstruction is achieved by summing the energy in the most active phi segmenet with the two neighbouring cells. In addition the particle energies were smeared according to resolutions measured in the CASTOR beam test [7] and a noise cut was applied. The predictions from PYTHIA and CDM show that the very high sensitivity to the scheme used for the QCD radiation is still preserved. The response to multiple interactions was studied as well and is shown in right side of Fig. 5. Excluding MI lowers the cross section by roughly an order of magnitude. Except of that, the sensitivity to the different MI tunes and models are fairly small in comparison to the impact of using the CDM. The sensitivity of this measurement to PDF variation was also investigated. The predicted forward jet cross section can not clearly distinguish between the different PDFs.

Thus, the method to measure forward jets in CASTOR in addition to two jets in the central region gives a large sensitity to the dynamics of the parton shower. This is also true if PDF uncertainties and different MI models are taken into account.

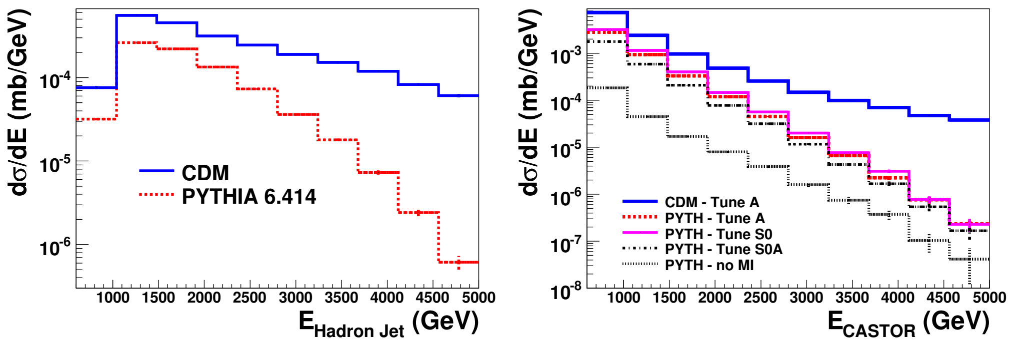


Fig. 5: *(left)* Hadron level cross sections for events with two central jets and a forward jet in the pseudorapidity region of the CASTOR calorimeter. *(right)* Monte Carlo prediction for the 2+forward jet cross section using different MI models and tunes. The predictions are on generator level, but with the forward jet reconstructed as described in the text and forward particle momenta smeared according to CASTOR beam test data.

## 5 Summary

In conclusion, the studies presented here show that the forward region is very sensitive to the underlying event, multi-parton interactions and low-x QCD dynamics. 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. Further possibilities for the improvement of forward particle detection and completing the angular coverage of the detectors have to be investigated [13, 14].

## References


[1] *CMS and TOTEM Note on Prospects for Diffractive and Forward Physics 2006; LHCC-G-124*, 2006.

[2] *ATLAS Forward Physics Program, ATL-PHYS-COND-2008-020*, 2008.

[3] CDF Collaboration, D. E. Acosta *et al.*, Phys. Rev. **D70**, 072002 (2004). `hep-ex/0404004`.

[4] Z.Rurikova and A.Bunyatyan, *Underlying Event Studies with CASTOR Calorimeter at CMS*. Presented at 4-th HERA-LHC workshop, CERN, May 2008.

[5] T. Sjostrand, S. Mrenna, and P. Skands, JHEP **05**, 026 (2006). `hep-ph/0603175`.

[6] *CASTOR web page. http : //cmsdoc.cern.ch/castor*.

[7] X. Aslanoglou et al., Eur. Phys. J. **C52**, 495 (2007). `arXiv:0706.2641`.

[8] D.G. d'Enterria, *Forward Physics at the LHC*. Proceedings of Workshop DIS-2007, Munich 2007; arXiv:0708.0551.

[9] H1 Collaboration, Aktas, A. et al., Eur. Phys. J. **C46**, 27 (2006). `hep-ex/0508055`.

[10] ZEUS Collaboration, Chekanov, S. et al., Phys. Lett. **B632**, 13 (2006). `hep-ex/0502029`.

[11] A.Knutsson, *Forward Jets in the CASTOR calorimeter at CMS*. Presented at 4-th HERA-LHC workshop, CERN, May 2008.

[12] L. Lonnblad, Comput. Phys. Commun. **71**, 15 (1992).

[13] V.Andreev, A.Bunyatyan, H.Jung, M.Kapishin, L.Lytkin, *Proposal to Upgrade the Very Forward Region at CMS*. Proceedings of HERA-LHC Workshop, CERN-2005-014, DESY-PROC-2005-001.

[14] A.Bunyatyan et al., *Calorimetric Coverage at Large Rapidities in CMS*. Presented at 3-d HERA-LHC workshop, DESY, March 2007.