Underlying Event Studies at ATLAS

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Abstract
This paper summarises the studies of the Underlying Event (UE) in ATLAS and the impact of its uncertainties on early LHC physics. Emphasis is given to the methods that are currently under investigation in ATLAS to constrain the models of UE at the LHC. The recent ATLAS tune of the new PYTHIA model (PYTHIA version 6.416) for the UE is described and extrapolated to the LHC energies. Studies of UE in Drell-Yan and Top events will also be discussed.

1 Introduction

At the LHC essentially all physics will arise from quark and gluon interactions, giving rise to both the small and the large transverse momentum (p_{T}) regimes. The high p_{T} regimes associated with the hard parton-parton interactions are well described by QCD, whereas the low p_{T} regimes, i.e. soft or semi-hard interactions, which are the dominating processes at hadron colliders, are only described by phenomenological models.

Great progress has been made at Tevatron in understanding the phenomenological aspects of the soft and semi-hard interactions, however several models are available and compatible with Tevatron data. Since many of these models extrapolated to the LHC energy provide strikingly different predictions, we are confident that the LHC data will bring new insight of the soft physics and will provide stringent constraints on many aspects of its modelling.

The Underlying Event (UE) is an important element of the soft and semi-hard physics in the hadronic environment, which affects all physics, from Higgs searches to physics beyond the standard model. In a hard scattering process it can be defined in many ways, the most general definition is that the UE is everything accompanying an event but the hard scattering component of the hadronic collision.

The correct modelling of the UE is a necessary condition for a good understanding of the high p_{T} physics. For example the UE is important for the understanding of event characteristics such as the energy flow, the jet and the lepton isolation and the jet flavour tagging.

The underlying event has been extensively studied by CDF and compared to predictions from different models, such as PYTHIA [1], HERWIG [2] and JIMMY [3, 4]. Several tunes of these models to Tevatron and previous experimental data have been investigated so far, however all these models give different predictions for the amount of UE activity at the LHC due to the large uncertainties in extrapolating from the lower energy data. The large uncertainties on the UE at the LHC strongly depend on the limited knowledge of the parton density functions at the LHC energy regime, the amount of the initial and final state QCD radiation (ISR and

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FSR respectively) and the modelling of the Multi Partonic Interactions (MPI). From previous experiments, such as CDF and D0, there is strong experimental evidence for the occurrence of more than one hard or semi-hard interaction in one proton-(anti)proton collision (MPI). Since multi partonic interactions will be enhanced at the LHC energies we believe that the LHC and the ATLAS experiment can provide stringent constraints on the current models and shed new light on its underlying mechanism.

2 The Multi Partonic Interaction at the LHC

The multi partonic interaction is critical for describing low-p_{T} effects in the underlying event and ATLAS plans to measure its contribution at the LHC by studying low-p_{T} Drell-Yan events and jet-jet + jet-$\pi(\gamma)$ events, as done at Tevatron. The cross section for a double partonic interaction, σ_{D}, i.e. the simultaneous occurrence of an hard and a semi-hard interaction, A and B, can be approximated as follows

$$\sigma_{\mathrm{D}}(p_{\mathrm{T}}^{\mathrm{cut}}) \propto \frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{2\sigma_{\mathrm{eff}}} \tag{1}$$

where σ_{A} and σ_{B} are the cross sections for the single partonic interactions, A and B respectively, and σ_{eff} is an effective cross section that contains the information of the parton correlation in the transverse space (see the pictorial representation in Fig. 1(a)). The double partonic interaction σ_{D} depends on the minimum transverse momentum cut applied, $p_{\mathrm{T}}^{\mathrm{cut}}$.

The double partonic cross section σ_{D} grows more rapidly than the single partonic cross section as function of $\sqrt{s}$, the collider centre-of-mass energy. For this reason its contribution becomes more important at the LHC energy regime.

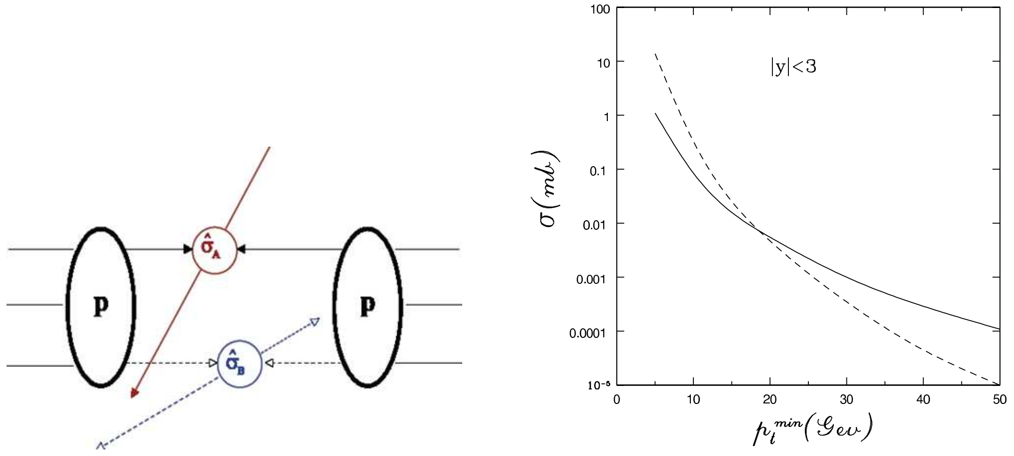
As Fig. 1(b) [5] shows for the 4-jet production, the double partonic cross section σ_{D} decreases more rapidly than the single partonic cross section for increasing values of the jet p_{T} while it grows more rapidly as $p_{\mathrm{T}} \rightarrow 0$. In fact the double partonic cross section becomes dominant at the LHC for the jet $p_{\mathrm{T}} \leq 20$ GeV.

Multi partonic interactions are expected to have large effects on various processes at the LHC, for example HW, W/Z+jets, $\mathrm{t\bar{t}}$ and multi jet final state for $p_{\mathrm{T}}^{\mathrm{min}} \sim 20, 30$ GeV.

2.1 The Underlying Event Models

There are many models available for the underlying event and the multi partonic interaction mechanism. These models can be well tuned at Tevtron energies, but there is no well justified way to extrapolate them to the LHC energies due to the lack of a fundamental theory. Here follows a short and non-exhaustive overview of some models, focused on those mentioned in the following sections.

JIMMY [3, 4] implements the eikonal model, which derives from the observation that for partonic scatters above some minimum transverse momentum, $\hat{p}_{\mathrm{T}}^{\mathrm{min}}$, the values of the hadronic momentum fraction, x, decrease as the centre-of-mass energy, $\sqrt{s}$, increases. Since the parton density functions rise rapidly at small x, the perturbatively-calculated cross section grows rapidly with $\sqrt{s}$. At such high densities, the probability of more than one partonic scattering in a single hadron-hadron event may become significant. Allowing such multiple scatters reduces the total cross section, and increases the activity in the final state of the collisions. The JIMMY model



(a) (b)

Figure 1: (a) Pictorial representation of a double partonic interaction in a proton-proton collision. (b) The integrated cross section for production of four jets with $|y| < 3$ as a function of minimum jet $p_{\rm T}$ cut. The continuous curve is the leading single partonic interaction $2 \to 4$, the dashed curve is the contribution of double parton collisions $(2 \to 2)^2$ [5].

assumes some distribution of the matter inside the hadron in impact parameter (b) space, which is independent of the momentum fraction, x. The multi partonic interaction rate is then calculated using the cross section for the hard subprocess, the conventional parton densities, and the area overlap function, $A(b)$.

PYTHIA [1] introduces an effective $\hat{p}_{\rm T}^{\rm min}$ scale (of the order of 1.5-2.5 GeV), below which the perturbative cross section is strongly damped and allows the possibility to use different models for the MPI. From PYTHIA version 6.3, a more advanced model is available. In this new model, each multiple interaction is associated with its set of ISR and FSR and the ISR is interleaved with the MPI chain, in one common sequence of decreasing $p_{\rm T}$ values. In other words, a semi-hard second interaction is considered before a soft ISR branching associated with the hardest interaction. This is made possible by the adoption of the $p_{\rm T}$ scale as the common evolution variable.

3 The ATLAS Tunes

The current ATLAS tune for JIMMY version 4.3 has not changed since [6] , whereas the ATLAS tune for PYTHIA has changed considerably since the introduction of the new MPI model and parton shower in PYTHIA (MSTP(81)=21). Here the tune of PYTHIA version 6.416 will be briefly discussed, for a more detailed description please refer to the contribution by Arthur Moraes [7]. The tunes are done using CTEQ6ll (LO fit with LO α_s). In PYTHIA version 6.416 better agreement with CDF data is found by minimising the total string length in the colour reconnection between the hard scatter and the soft systems (MSTP(95)=2, PARP(78)=0.3), slightly increasing the $p_{\rm T}$ cut-off (PARP(82)=2.1), increasing the fraction of matter in the hadronic core (PARP(83)=0.8) and increasing the hadronic core radius (PARP(84)=0.7) with respect to the default values.

In the contribution by Arthur Moraes we can see reasonable agreement between Tevatron data and both JIMMY version 4.3 and PYTHIA version 6.416 ATLAS tunes in jet events for the leading jet $p_{\rm T} > 6$ GeV, in various observables sensitive to the UE and MPI. Furthermore, both PYTHIA and JIMMY extrapolated at low energies provide a good description of the data from $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV.

3.1 Predictions for the LHC

The current plan to increase the LHC beam energy in discrete steps, $\sqrt{s} = 10, 14$ TeV, offers the opportunity to constrain the energy dependent parameters in UE models in the high energy regime. For example, one major issue in extrapolating the UE to LHC energies is the possible energy dependence of the transverse momentum cut-off between hard and soft scatters, $\hat{p}_{\rm T}^{\rm min}$ in the models.

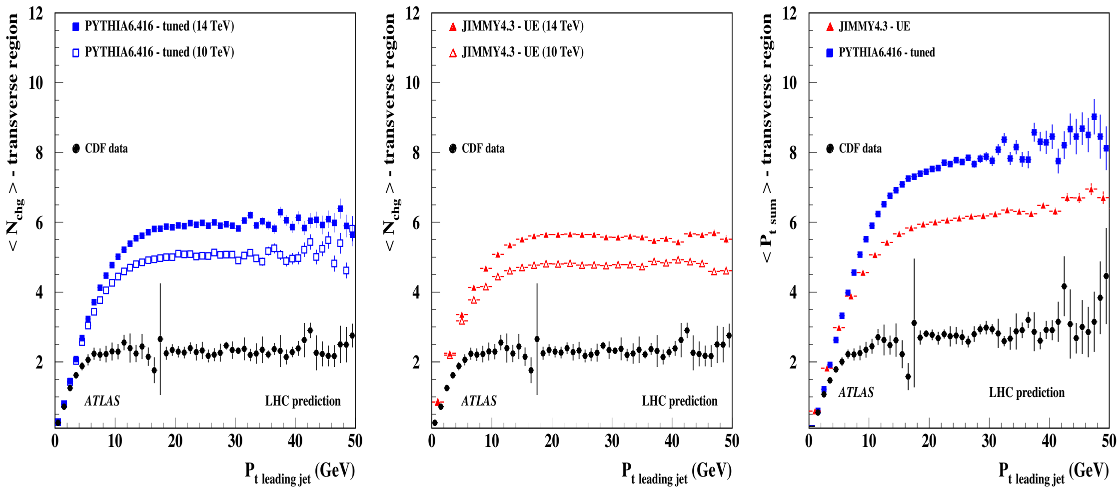
It has been established by the CDF Collaboration that we can define regions in the $\eta - \phi$ space that are sensitive to the UE components of the hadronic interaction. In jet events the direction of the leading jet is used to define regions of $\eta - \phi$ space that are sensitive to the UE, in particular, the "Transverse Region", defined by $60^\circ < |\phi - \phi_{\text{ leading jet}}| < 120^\circ$, is particularly sensitive to the UE.

Figures 2(a) and 2(b) show different LHC predictions for the average density of charged particles, $< N_{\rm chg} >$, in the Transverse Region for tracks with $|\eta| < 1$ and $p_{\rm T} > 0.5$ GeV versus the transverse momentum of the leading jet [1]. The charged particle density is constructed by dividing the average number of charged particles per event by the area in $\eta - \phi$ space. The multiple parton interactions make the predictions rise rapidly and then reach an approximately flat plateau region.

Figures 2(a) and 2(b) show that the particle density in the Transverse Region grows substantially from the Tevatron energy to the LHC energies of 10 TeV and 14 TeV, by the factors ≈ 2.5 and ≈ 3.0 respectively. The plots also show that ATLAS tunes for PYTHIA and JIMMY are in reasonable agreement at both LHC collision energies. However, figure 2(c) shows that the agreement between PYTHIA and JIMMY is not universal, in fact they disagree considerably on the $< P_{\rm T}^{\rm sum} >$ distribution, i.e. the average scalar $p_{\rm T}$ sum of charged particles per event divided by the area in $\eta - \phi$ space. This PYTHIA tune predicts harder particles than the JIMMY tune: the $< P_{\rm T}^{\rm sum} >$ plateau predicted by PYTHIA is about 30% higher than JIMMY. This is a result of the tuning of the colour reconnection parameters in PYTHIA version 6.4 model, which has been specifically adjusted to produce harder particles to fit better the CDF data. This feature is not available in JIMMY version 4.3.

It is interesting to notice that, whereas the discrepancy in $< P_{\rm T}^{\rm sum} >$ between the two models is small at Tevatron, it becomes considerable when the models are extrapolated to the LHC energy regime. This gives us an estimate of the large uncertainty on the current UE models

[1] ATLAS Cone jet finders with $\Delta R = 0.7$



(a) (b) (c)

Figure 2: The ATLAS tunes of PYTHIA version 6.416 and JIMMY version 4.3 extrapolated to LHC energies. The $< N_{\rm chg} >$ distributions at $\sqrt{s} = 10, 14$ TeV for PYTHIA (a) and JIMMY (b) and the $< P_{\rm T}^{\rm sum} >$ distributions at $\sqrt{s} = 14$ TeV for both PYTHIA and JIMMY (c).

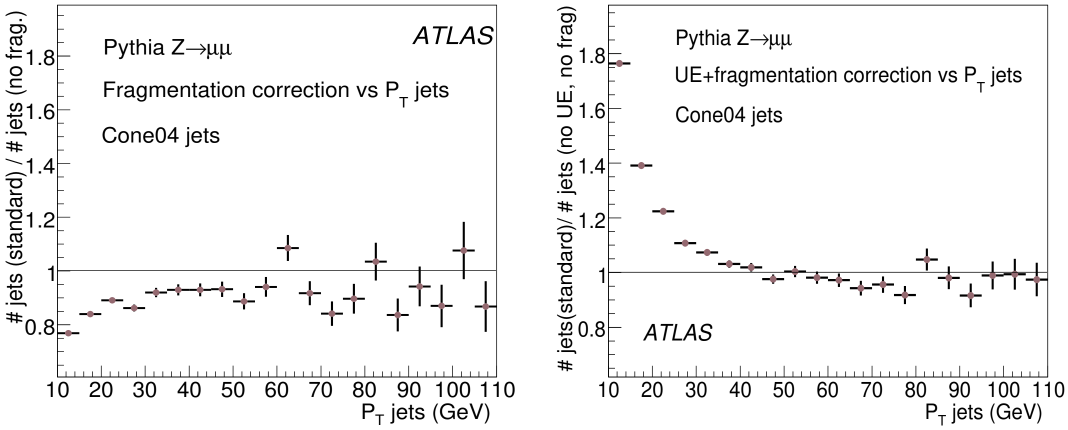
for the LHC.

4 UE studies with Z+jets and top quark events

By measuring the UE in various Standard Model production processes like jet, Drell-Yan and top quark events one can investigate the possible process dependence of the UE and partially isolate the various components contributing to the UE.

Drell-Yan lepton pair production provides a very clean environment to study the UE: after removing the lepton-pair from the event everything else is UE. The LHC will copiously produce Drell-Yan events with and without associated jets and the large statistics available will allow an important cross check of the jet results from early LHC running.

Figure 3 shows the competing effects of the fragmentation and the UE on the $p_{\rm T}$ distribution of the leading jet in Z+jets events. The impact of fragmentation is to reduce the amount of energy in the jet cone. Thus, from fragmentation effects alone, jets at the hadron level tend to have lower $p_{\rm T}$ than jets at the parton level, see Fig. 3(a). The impact of the underlying event is to add energy to the hadron level jet. In general, the underlying event tends to add more energy to the jet than that lost by fragmentation, see Fig. 3(b), but the exact ratio depends on the radius of the jet: the effect of the UE increases for larger radii, whereas the effect of fragmentation becomes smaller for larger radii. The non-perturbative effects become negligible for jets with $p_{\rm T} > 40$ GeV in the PYTHIA tune used for this analysis.



(a) (b)

Figure 3: Ratio of ATLAS Cone $\Delta R = 0.4$ jet p_{T} distributions (a) between standard PYTHIA version 6.403 and PYTHIA version 6.403 without fragmentation and (b) between standard PYTHIA version 6.403 and PYTHIA version 6.403 without non-perturbative corrections.

Soft and semi-hard sub-processes in top production events may potentially have a serious impact on top reconstructed parameters, e.g. the top mass, the single top and $\mathrm{t\bar{t}}$ production cross sections. Variations on the level of UE and ISR/FSR affect observables on which selections cuts are applied to identify the top quark, for example: the jet multiplicity and the particle transverse momentum. It is important to estimate the uncertainties on the reconstructed top parameters from UE and ISR/FSR. These two contributions are strongly coupled together. The ATLAS collaboration has studied the effect of ISR/FSR by varying some of their parameter values in PYTHIA to maximise [2] and minimise [3] the reconstructed top mass. These two different settings give a variation on the $\mathrm{t\bar{t}}$ event selection efficiency of about 10% and contribute by about 10% to the systematic uncertainty of the $\mathrm{t\bar{t}}$ cross section measurement with early LHC data.

5 Conclusions

In this paper we have discussed the importance of underlying event studies for the whole LHC physics program. We have reported on the large uncertainties for the UE predictions at the LHC and the opportunity for the LHC and the ATLAS experiment to provide unprecedented constraints on the current models.

The ATLAS tunes of JIMMY version 4.3 and the new PYTHIA model, version 6.416, is discussed and the extrapolations to the LHC collider energies are presented. The plateau in the $< N_{\mathrm{chg}} >$ distribution increases by a factor ≈ 2.5 and ≈ 3.0 from $\sqrt{s} = 1.8$ TeV to $\sqrt{s} = 10$

[2]PARP(61)=0.384, MSTP(70)= 0, PARP(62)=1.0, PARJ(81)=0.07

[3]PARP(61)=0.096, MSTP(70)=0, PARP(62)=3.0, PARJ(81)=0.28

TeV and $\sqrt{s} = 14$ TeV respectively. The tunes of PYTHIA version 6.416 and JIMMY version 4.3 are in good agreement in the $< N_{\rm chg} >$ prediction, but show a large discrepancy in the $< P_{\rm T}^{\rm sum} >$ distribution: PYTHIA predicts the level of the $< P_{\rm T}^{\rm sum} >$ plateau $\approx 30\%$ higher than JIMMY.

Drell-Yan processes at the LHC will provide an important cross check of the results obtained in jet events in early LHC data and offer a very clean environment to study the process dependence of the UE mechanism. ATLAS has studied the competing effects of the fragmentation and the UE in the $p_{\rm T}$ distribution of the leading jet in Z+jets events. This study shows the importance of non-perturbative physics in the low $p_{\rm T}$ jet spectrum, below 40 GeV.

We have also shown that the UE and ISR/FSR can bring a significant contribution to the systematic uncertainty on the top mass reconstruction, single top and $\rm t\bar{t}$ cross section measurements. We have estimated an uncertainty of about 10% on the $\rm t\bar{t}$ event selection efficiency and a contribution of about 10% to the systematic uncertainty of the $\rm t\bar{t}$ cross section measurement, due to the ISR/FSR uncertainty at the LHC.

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