ATLAS NOTE

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ATLAS Monte Carlo Tunes for MC09

ATLAS Collaboration

Abstract

This note describes the ATLAS tunes of underlying event and minimum bias description for the main Monte Carlo generators used in the MC09 production. For the main physics event generators, PYTHIA and HERWIG (with JIMMY), the MRST LO* parton distribution functions (PDFs) were used for the first time in ATLAS. Special studies on the performance of these, conceptually new, PDFs for high p_{T} physics processes at LHC energies are presented. In addition, a tune of JIMMY for CTEQ6.6 is presented, for use with MC@NLO.

1 Introduction

In view of the LHC start-up ATLAS has developed new tunes to be used for simulations of the first data. The aim of these tunes is to constrain the model predictions as much as possible by adding the most recent data and new theoretical developments to the tuning effort. In this spirit, the parton density functions (PDFs) were also updated to those including new measurements and theoretical developments.

ATLAS has decided to use the MRST LO* parton density functions (PDFs) [1] for mass production of Monte Carlo (MC) data. These PDFs implement a conceptually new ansatz, especially developed for the use of PDFs in MC event generators. The aim is that the cross sections and the shapes of many differential distributions should become more similar to the next-to-leading order calculation when used with leading order matrix elements, such as implemented in PYTHIA and HERWIG.

Since new PDFs require the modification of phenomenological model parameters, the generator predictions using the LO* PDFs have been tuned to describe existing data. In particular, it can be expected that due to the high gluon density at low x, the underlying event (UE) activity would be estimated to be too high if one uses the same parameters as for the CTEQ6L1[1] PDF. As these PDFs were developed for the use in hard processes, the usability of LO* PDFs for UE had not been shown before. Therefore this tune also includes the validation of these PDFs for the UE.

In addition, it was decided to use CTEQ6.6 for the NLO generator MC@NLO [2]. As MC@NLO uses HERWIG/ JIMMY for the parton shower and requires the same PDF in the ME and the shower calculation, a tune of HERWIG/ JIMMY for CTEQ6.6 has been developed.

This note describes the tuning to underlying event (UE) and minimum bias (MB) distributions, of the main shower MC generators, PYTHIA and HERWIG, for the ATLAS MC production which started in autumn 2009 (hence called MC09). The tunes presented here are based on the physics models and PDFs, as agreed between all physics working groups in ATLAS. Only published data sets were used to derive the tunes. Comparisons with the previous tune used for production (MC08 [3]) are also shown. Other tunes, especially for PYTHIA, have recently been published [4, 5]. However, these tunes were obtained with different PYTHIA models, and a discussion of the comparisons goes beyond the scope of this note.

Since this is the first use of LO* PDFs in a general MC production, we will also report on studies of possible effects, due to the use of these PDFs, in various high-p_T physics distributions at LHC energies.

This note is structured as follows: Section 2 gives a short overview of the data sets used for tuning. Sections 3 and 4 give the details of the tuning of the PYTHIA and HERWIG/ JIMMY models respectively. The data sets and distributions used for the tuning of the underlying event parameters are listed in Table 1. More detail is given in the respective sections. Section 5 shows comparisons between the tuned PYTHIA and HERWIG/ JIMMY models at LHC energies. In Section 6, studies presented in [1] are extended with studies using the PYTHIA generator and exploring effects of the LO* PDFs on the soft QCD predictions in events with high-p_T scattering.

2 Data Sets for Underlying Event Tuning

In this section the data sets used to derive the various tunes described in this note are briefly presented. They consist of published measurements by the CDF and D0 collaborations at different centre-of-mass energies in $p\bar{p}$ collisions. Not all observables are used in all tunings. The data sets and used distributions

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[1] CTEQ6L1, also sometimes denoted CTEQ6LL, refers to a LO fit with LO α_s, LHAPDF set number 10042.

for the different tunes presented in this note are summarised in Table 1.

2.1 Underlying Event Measurements in Tevatron Run I (CDF)

The CDF collaboration has published two analyses [6, 7] on the underlying event properties. Both are aimed at separating out regions of phase-space that are not dominated by the hard scattering process. In these regions observables like the charged particle and transverse momentum density are reconstructed.

- **Leading Jet Analysis:**
  This measurement by the CDF collaboration [6] at $\sqrt{s} = 1800\,\text{GeV}$ divides the event into regions of azimuthal angle towards, transverse and away from the leading track-jet in the event. The thus defined transverse region is expected to be the most effected by the underlying event. The underlying event observables are presented in dependence of the transverse momentum of the leading track-jet for two different trigger conditions (min-bias and JET20). Additional observables are the transverse momentum distributions of charged particles in the transverse region for different minimal transverse momenta of the leading track-jet.
- **“MIN-MAX”-Analysis:**
  This measurement by the CDF collaboration as described in Ref. [7] is similar to the leading jet analysis. The event is divided into cone-shaped regions perpendicular in the transverse plane to the leading calorimeter jet. The two cones defined in this way are in addition sorted according to charged particle activity into a max cone and a min cone. This data set consists of data taken both at $\sqrt{s} = 630\,\text{GeV}$ and $1800\,\text{GeV}$ and is thus sensitive to the energy dependence of the models. Additionally so-called “Swiss-Cheese” observables are presented, where the transverse momentum sum of charged particles is measured after removing the two (three) hardest jets from the event.

2.2 Minimum Bias in Tevatron Run I (CDF)

The CDF collaboration has measured the charged particle multiplicity in minimum bias events in Run I [8]. This data set comprises both data taken at $\sqrt{s} = 630\,\text{GeV}$ and 1800 GeV.

2.3 Dijet Angular Correlations in Tevatron Run II (D0)

The D0 collaboration has measured the angular correlations between jets in dijet events for different leading jet transverse momenta in Ref. [9]. This observable is sensitive to initial state gluon emission.

2.4 Minimum Bias in Tevatron Run II (CDF)

The CDF collaboration has recently published a result [10] on minimum bias events in Run II. The main result useful for tuning purposes consists of a measurement of the mean transverse momentum of charged particles in dependence of the charged multiplicity, as this is sensitive to colour reconnection parameters.

Observable	Pythia 6		Jimmy/Herwig		
	MC08	MC09(c)	MC08	MC09	CTEQ6.6
CDF Run I underlying event in dijet events [6] (leading jet analysis)					
N_{ch} density vs leading jet p_T (transverse), JET20	●	●	●	●	●
N_{ch} density vs leading jet p_T (toward), JET20		●			●
N_{ch} density vs leading jet p_T (away), JET20		●			●
$\sum p_T$ density vs leading jet p_T (transverse), JET20	●	●	●	●	●
$\sum p_T$ density vs leading jet p_T (toward), JET20		●			●
$\sum p_T$ density vs leading jet p_T (away), JET20		●			●
N_{ch} density vs leading jet p_T (transverse), min bias	●	●	●	●	
N_{ch} density vs leading jet p_T (toward), min bias		●			
N_{ch} density vs leading jet p_T (away), min bias		●			
$\sum p_T$ density vs leading jet p_T (transverse), min bias	●	●	●	●	
$\sum p_T$ density vs leading jet p_T (toward), min bias		●			
$\sum p_T$ density vs leading jet p_T (away), min bias		●			
p_T distribution (transverse), leading $p_T > 5$ GeV			●	●	●
p_T distribution (transverse), leading $p_T > 30$ GeV	●		●	●	
CDF Run I charged multiplicity in min bias [8]					
Charged multiplicity distribution, $\sqrt{s} = 630\,\mathrm{GeV}$		●			
Charged multiplicity distribution, $\sqrt{s} = 1800\,\mathrm{GeV}$		●			
CDF Run I underlying event in MIN/MAX-cones [7] ("MIN-MAX" analysis)					
$\langle p_T^{\mathrm{max}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800\,\mathrm{GeV}$	●		●	●	●
$\langle p_T^{\mathrm{min}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800\,\mathrm{GeV}$	●		●	●	●
$\langle p_T^{\mathrm{diff}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800\,\mathrm{GeV}$					●
$\langle N_{\mathrm{max}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800\,\mathrm{GeV}$	●		●	●	●
$\langle N_{\mathrm{min}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 1800\,\mathrm{GeV}$	●		●	●	●
Swiss Cheese p_T^{sum} vs. E_T^{lead} (2 jets), $\sqrt{s} = 1800\,\mathrm{GeV}$					●
$\langle p_T^{\mathrm{max}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630\,\mathrm{GeV}$	●		●	●	●
$\langle p_T^{\mathrm{min}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630\,\mathrm{GeV}$	●		●	●	●
$\langle p_T^{\mathrm{diff}} \rangle$ vs. E_T^{lead}, $\sqrt{s} = 630\,\mathrm{GeV}$					●
Swiss Cheese p_T^{sum} vs. E_T^{lead} (2 jets), $\sqrt{s} = 630\,\mathrm{GeV}$					●
D0 Run II dijet angular correlations [9]					
Dijet azimuthal angle, $p_T^{\mathrm{max}} \in [75, 100]$ GeV					●
Dijet azimuthal angle, $p_T^{\mathrm{max}} \in [100, 130]$ GeV					●
Dijet azimuthal angle, $p_T^{\mathrm{max}} \in [130, 180]$ GeV					●
Dijet azimuthal angle, $p_T^{\mathrm{max}} > 180$ GeV					●
CDF Run II minimum bias [10]					
$\langle p_{\mathrm{T}} \rangle$ of charged particles vs. N_{ch}, $\sqrt{s} = 1960\,\mathrm{GeV}$		(●)			

Table 1: Observables used for the various tunings of underlying event parameters of the Pythia 6 and Jimmy/Herwig generators. The different tunes (MC08, MC09, MC09c for Pythia 6 and MC08, MC09 and CTEQ6.6 for Jimmy/Herwig are described in Sections 3 and 4.

3 Tuning of PYTHIA 6

In this section the tuning of the PYTHIA 6 [11] generator is described. The tune was developed as an adaptation of the PYTHIA models used by ATLAS for the new PDFs and as an update to incorporate recent developments in tuning activities of Tevatron data for LHC predictions.

For all comparisons and in the tuning procedure PYTHIA version 6.420 was used, since earlier versions cannot be used with the modified leading order (LO*) PDF set from [1].

The tuning of these parameters was performed by comparing the output of the MC generator to measured quantities from other experiments that are sensitive to the necessary parameters. For this, the RIVET toolkit [12] was used, mainly in version 1.1.2 and, for some analyses, also version 1.1.3. This software package contains many published and preliminary analyses, and makes an easy comparison between data and MC possible.

3.1 Physics models and parameters

PYTHIA contains a large variety of different models and steerable parameters. In this section, details on the physics models used for the tune are given. Sometimes an optimal description of existing data sets conflicts with practical aspects in physics analysis, such as stability in the data samples used to derive MC based correction factors. The model choices for MC09 aimed at a balance between the two requirements.

The main model choices were:

- we use the newer p_{T}-ordered parton shower with the interleaved shower and multi-parton interaction (MPI) model;
- initial state radiation (ISR) and MPI cutoff scales were separated from each other, thus allowing the underlying event to be re-tuned without simultaneously changing the radiation pattern, the latter of which might lead to changes in jet kinematics;
- the matter distribution in the proton is described as a double Gaussian probability density function (p.d.f.), with a central, denser Gaussian part, and an outer, less dense Gaussian. This decision was based on studies done in [13];
- the description of the beam remnant follows the "colour annealing" scenario, i.e. the strategy for colour reconnection is to minimise the total string length.The most recent version of this model at the time of the tuning was used by setting MSTP(95) = 6.
- Bowler fragmentation [14] is used for heavy quarks (see Section 3.1.2).

3.1.1 Multi-parton Interactions in PYTHIA 6

Details of the multiple interaction model implemented in PYTHIA 6 are described in [11]. Multiple interactions are modelled as 2 → 2 scattering processes, in addition to the hard interaction of the event. The majority of these scatterings happen at low momentum transfer, corresponding to small x of the partons involved, and a rather low Q^2 scale. In this region of phase space, the gluon density in MRST LO* is significantly higher than in CTEQ6L1.

As a consequence, the multiple parton interaction parameters were re-tuned. The most important of these is the p_{T} cut-off parameter of the multiple parton interaction model. As the $2 \rightarrow 2$ scattering cross section is divergent for zero momentum transfer, obviously an infrared regularization parameter has to be introduced. This energy scale can be translated into a wavelength which is then of the order of the size of the proton. At lower scales, the individual partons in the proton are no longer resolved; instead only the coherent scattering of the complete proton is possible. This can also be seen as a screening parameter. In the PYTHIA 6 model used (new MPI, new shower), this cut-off is described as a smooth cut-off at a scale $p_{\mathrm{T}}^{\mathrm{min}}$. The screening parameter is allowed to be energy dependent, with a dependence described by:

$$p_{\mathrm{T}}^{\mathrm{min}}(E) = p_{\mathrm{T}}^{\mathrm{min}}(E_{\mathrm{ref}}) \left(\frac{E}{E_{\mathrm{ref}}} \right)^{\alpha} , \tag{1}$$

where E_{ref} is a reference energy scale, described by PARP(89), $p_{\mathrm{T}}^{\mathrm{min}}$ is the cutoff at this scale (PARP(82)), and α describes the energy dependence (PARP(90)). In this study PARP(89) was fixed to the default value of 1800 GeV, leaving PARP(82) and PARP(90) as parameters that need to be adjusted.

In the following it is important to remember the effects of these two parameters at different energies. The cutoff parameter at the reference energy scale PARP(82) has the same effect at all energies: increasing it, and thus enhancing the screening, decreases the UE activity. Decreasing it increases the activity. For the rescale exponent, PARP(90), the behaviour depends on the energy: exactly at the reference energy scale, PARP(90) has no influence at all. For energies below the reference scale, increasing PARP(90) means effectively decreasing the cutoff scale, and thus increasing the underlying event activity. For energies above the reference energy it is exactly the reverse: an increase of PARP(90) leads to an increased screening, and thus to reduced activity.

Evidently, to tune these two parameters one needs to consider data taken at different centre of mass energies.

3.1.2 Fragmentation Model

Independent of the change to another PDF set, the fragmentation model for heavy quarks was also changed. In all ATLAS Monte Carlo production runs until MC09, the heavy quark fragmentation function was modelled according to the Peterson fragmentation function [15], while the light quarks were treated with a symmetric Lund function [16]. A detailed study of the bottom quark fragmentation function in comparison with OPAL [17] and SLD data [18] showed that the data are better described using the symmetric Bowler fragmentation function $r_Q = 0.75$, assuming the same modification for b and c quarks. The a and b parameters of the symmetric Lund function were left at the PYTHIA 6 default values of 0.3 and $0.58\,\mathrm{GeV}^2$ respectively.

Figure 1 shows the b quark fragmentation function in $e^+e^- \rightarrow b\bar{b}$ events at the Z^0 pole. The data points consist of a measurement by the DELPHI collaboration [19]. Compared to the data are the following tunes: the MC08 tune, the MC09 and the PerugiaX(2) tune, as defined in [4]. It should be noted that the PerugiaX tune uses the fragmentation parameters given by the PROFESSOR collaboration in [5].

The updated fragmentation parameters used in the ATLAS setup give an improved description of the b quark fragmentation function compared to the MC08 behaviour. The PerugiaX tune, based on the fragmentation parameters by the PROFESSOR collaboration, gives a further improvement – however, in this tune there are also many changes to the flavor parameters, which was deemed to be unsuitable for the ATLAS MC09 tuning, in the interest of compatibility with MC08 samples.

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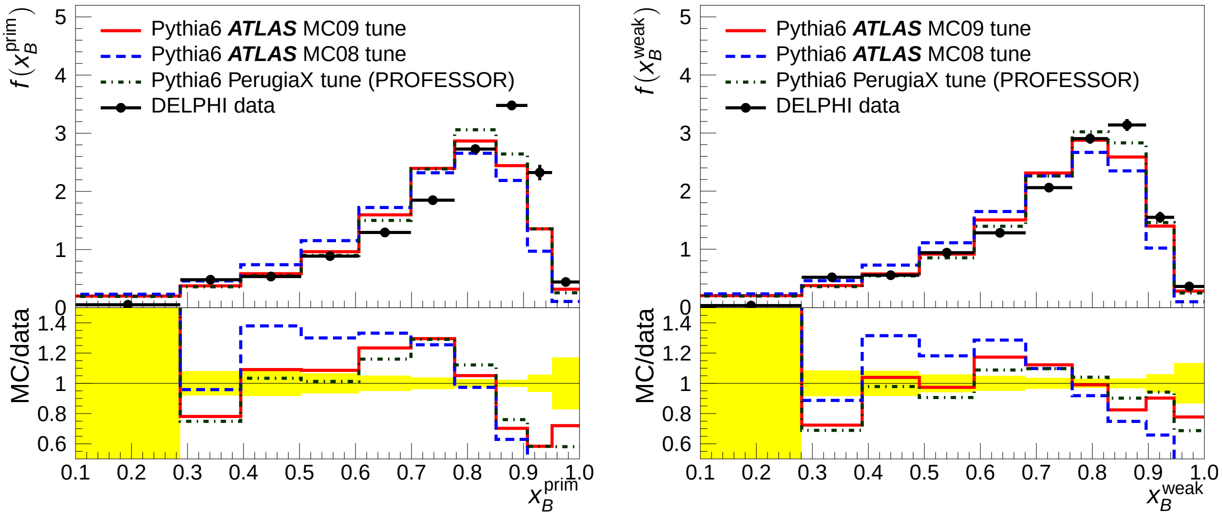
(2) Referred to as "Perugia$*$" in the PYTHIA 6 release notes and PYTUNE routine.



(a) b-fragmentation ($x_{\mathrm{B}}^{\mathrm{prim}}$)

(b) b-fragmentation ($x_{\mathrm{B}}^{\mathrm{weak}}$)

Figure 1: Comparison of the b quark fragmentation function; (a): as function of the ratio of the energy of the primary B hadron to the beam energy, (b): as function of the ratio of the energy of the weakly decaying B hadron to the beam energy for the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), and the PerugiaX tune with the fragmentation from the PROFESSOR tune (dark green, dashed dotted line). The data points correspond to the DELPHI measurement from [19]. The data were not used in the MC09 tune.

3.2 Tuning Procedure for the Underlying Event

The parameters described above were tuned in an iterative procedure to published Tevatron data sets. In this procedure, the parameters were varied one at a time, the parameter that had most impact on the observables under study was identified and set to a new value. This procedure was repeated until a satisfactory result was found through visual comparisons.

As a starting point, the parameters were set to the values of MC08 except for the new fragmentation model and the colour reconnection.

This tuning procedure obviously retains a certain level of subjective interpretation of parameter changes and data sets. However, in this procedure it becomes very clear which parameters have most impact on the observables.

3.2.1 Data sets and observables used for tuning

For the tuning, the leading jet analysis by the CDF collaboration [6], as described in Sec. 2.1 and the measurement of the charged particle multiplicity in minimum bias events at 1.8 TeV [8] (see Sec. 2.2) were used to determine the cut-off scale. The charged particle multiplicity measured in minimum bias events at 630 GeV [8] was used to for the first time in ATLAS to determine the energy extrapolation exponent of the cut-off scale.

The “MIN-MAX” analysis by the CDF collaboration [7] was not used to derive the MC09 tune. At the time that the MC09 tune was made, it was not possible to simultaneously describe the leading jet analysis and the MIN-MAX data in the software framework used for the PYTHIA tune. It was therefore decided to discard the MIN-MAX analysis from the tuning procedure. After completing the tuning, a problem in the implementation of this analysis in RIVET was found and corrected3) in RIVET 1.1.3.

3.2.2 Parameter selection

The following parameters were explored, but found to be of small influence on the observables used in the tuning:

- PARP(83) and PARP(84), the size of and the matter fraction in the inner core of the double Gaussian p.d.f. used to describe the matter distribution.
- PARP(78), the amount of colour reconnection in the final state.
- PARP(80), the probability that colour partons are kicked out of the beam remnant.
- PARJ(81), the value of running α_S for parton showers.
- Setting MSTP(70) to 2 was also explored i.e. setting the cut-off scale of the MPI model to be the same as for ISR. Although, in principle, a tune could also have been achieved in this case, it was instead decided to keep the MPI and ISR settings separate from each other, in order that the MC jet energy scale was not changed too significantly.

The only parameters that were changed in the MC09 tune were thus PARP(82), the cut-off scale, and PARP(90), the rescale exponent.

Of the two parameters used in the tuning, PARP(90), does not affect observables at $\sqrt{s} = 1.8\,\text{TeV}$. Thus, it is possible to fix the value of PARP(82) by looking at the observables at this centre-of-mass energy.

The toward and away regions were also looked at for the tuning but, as expected, the effect is most pronounced in the charged particle density and transverse momentum sum in the transverse region. For the minimum bias measurement of Ref. [8] a value of 2.3 for PARP(82) seems to be the optimal value, 2.4 would significantly underestimate the data for large multiplicities.

For the leading jet analysis from Ref. [6], a small discrepancy between the data sets was observed: PARP(82) set to 2.3 describes both the charged particle density and the transverse momentum density better for low p_T of the leading jet. For the high p_T (JET20) region, this setting gives about 5 to 7% too large activity compared to data, see Figure 2. This could in principle be solved by increasing PARP(82) to 2.4, however, in this case the low p_T region would be described less well.

Despite these small discrepancies, PARP(82) was set to 2.3 for the MC09 tune, since a good description of the data is achieved overall.

After fixing PARP(82) to 2.3 using the analyses at $\sqrt{s} = 1.8\,\text{TeV}$, the minimum bias analysis at 630 GeV was used to fix the rescale exponent PARP(90) to 0.25.

The final parameter set for the ATLAS MC09 tune of PYTHIA 6 is summarised in Table 2.

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3) The leading jet was defined as a track-jet instead of a calorimeter jet, thus skewing the mantissa of all plots.

3.2.3 MC09c tune

The CDF measurement [10] of the mean transverse momentum of charged particles as a function of the charged particle multiplicity (see Sec. 2.4 was published after the MC09 tune was completed and was not used in the tuning. It turned out that the MC09 tune, just as the MC08 tune, does not completely describe this data set. Therefore a new tune was deduced using the semi-automatic tuning tool PROFESSOR [5] to optimize the same parameters as MC09 but with the color reconnection[4] in addition as a free parameter. The MC predictions were compared to the same data sets as MC09 and the new CDF measurement. As a result, it was found that the data description can be significantly improved by lowering only one parameter, the strength of the color reconnection from 0.3 to 0.224. The p_T cut-off and the value of the energy scaling parameter α basically reproduced the values of the MC09 tune, see Table 2. We will denote this MC09 tune alternative with a lower color reconnection as MC09c tune in the following.

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[4] The strength of the color reconnection is set by the `PARP(78)` parameter in PYTHIA.

			ATLAS tune		
PYTHIA parameter	Default	MC08	MC09	MC09c	Description
General Setup					
PDF	CTEQ5L	CTEQ6L1	LO*	LO*	
PMAS(6,1)	175.0	172.5	172.5	172.5	M_t[GeV]
PMAS(24,1)	80.450	80.403	80.403	80.403	M_W[GeV]
PMAS(23,1)	91.1880	91.1876	91.1876	91.1876	M_Z[GeV]
MSTP(128)	0	1	1	1	event record
MSTU(21)	2	1	1	1	error checking
MSTP(81)	1	21	21	21	treatment for MI, ISR, FSR and beam remnants
MSTP(82)	4	4	4	4	MI model: double gaussian matter distribution
MSTP(70)	0	0	0	0	virtuality scale for ISR, separate MI and ISR cut-off
MSTP(72)	1	1	1	1	maximum scale for FSR
Multi Parton Interactions					
PARP(78)	0.025	0.3	0.3	0.224	colour reconnection in final state
PARP(80)	0.1	0.1	0.1	0.1	probability of colour partons kicked out from beam remnant
PARP(82)	2.0	2.1	2.3	2.315	cut off scale in MI model in GeV
PARP(83)	0.5	0.8	0.8	0.8	matter dist., size of inner gaussian
PARP(84)	0.4	0.7	0.7	0.7	matter dist., fraction in inner gaussian
PARP(89)	1800	1800	1800	1800	reference energy scale in GeV
PARP(90)	0.16	0.16	0.25	0.2487	rescale exponent of MI cut-off
PARJ(81)	0.29	0.29	0.29	0.29	Lambda value in running α_S
MSTP(95)	1	2[5)]	6	6	strategy for colour reconnection
Fragmentation					
MSTJ(11)	4	3	4	4	3: hybrid: Peterson for c/b, symmetric Lund for light quarks; 4: Lund-Bowler for c and b quarks
PARJ(54)	-	-0.07	-	-	c hadronization
PARJ(55)	-	-0.006	-	-	b hadronization
PARJ(41)	0.3	-	0.3	0.3	Lund-Bowler a
PARJ(42)	0.58	-	0.58	0.58	Lund-Bowler b
PARJ(46)	1.0	-	0.75	0.75	Lund-Bowler r_Q
MSTJ(22)	1	2	2	2	def. of stable particles

Table 2: PYTHIA 6 parameters in the MC08, MC09 and MC09c tunes. PYTHIA 6.420 default parameter values are added for reference. Parameters that are not mentioned explicitly were left at the default values of PYTHIA 6.420.

[5)] 2 was used for the original tune and is used for the comparisons within this note. However, due to technical problems 1 was used in the central production.

3.3 Comparison of the different PYTHIA tunes to Tevatron data

In the following, the MC08, MC09 and MC09c tunes of PYTHIA 6 (see Table 2) are compared to the available data sets from the Tevatron experiments. In addition, comparisons to the PerugiaX tune [4] are shown. PerugiaX uses MRST LO* PDF as MC09 but includes more model variations and different data sets. In particular it uses no underlying event data, but only minimum bias data from SPS and Tevatron and Drell-Yan data from Tevatron.

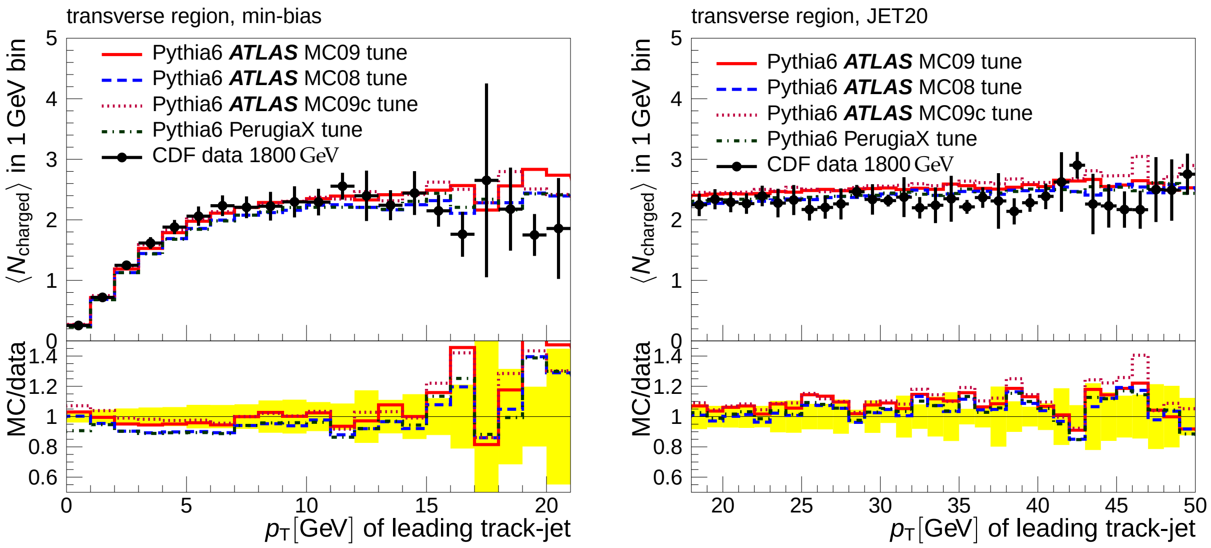
- The comparison of the described tunes and the data from the leading jet analysis [6] (see Sec. 2.1) is shown in Figures 2 and 3 for the transverse region. All distributions show reasonable agreement for the compared tunes. The MC09 tune performs a bit better at low p_{T}, while slightly overestimating the activity slightly for high p_{T}. This behaviour is expected from the tuning procedure and is well within the experimental uncertainties. The p_{T} distribution is also well-described.

- A comparison to the minimum bias analysis of the CDF collaboration in Run I [8], is shown in Figure 4. The MC09 tune describes the data reasonably well, while the MC08 tune massively underestimates the multiplicity distributions at both energies. It should be noted that this analysis was not used in the MC08 tuning. The MC09c tune predicts a slightly larger multiplicity at high charged multiplicities compared to the MC09 tune.

- In Figure 5 a comparison of observables in the "MIN-MAX" analysis [7] (see Sec. 2.1) with the different tunes. For this comparison, RIVET 1.1.3, where the problem described in Sec. 3.2.1 was fixed. Overall, the different parameter settings agree within the experimental uncertainties of the data.

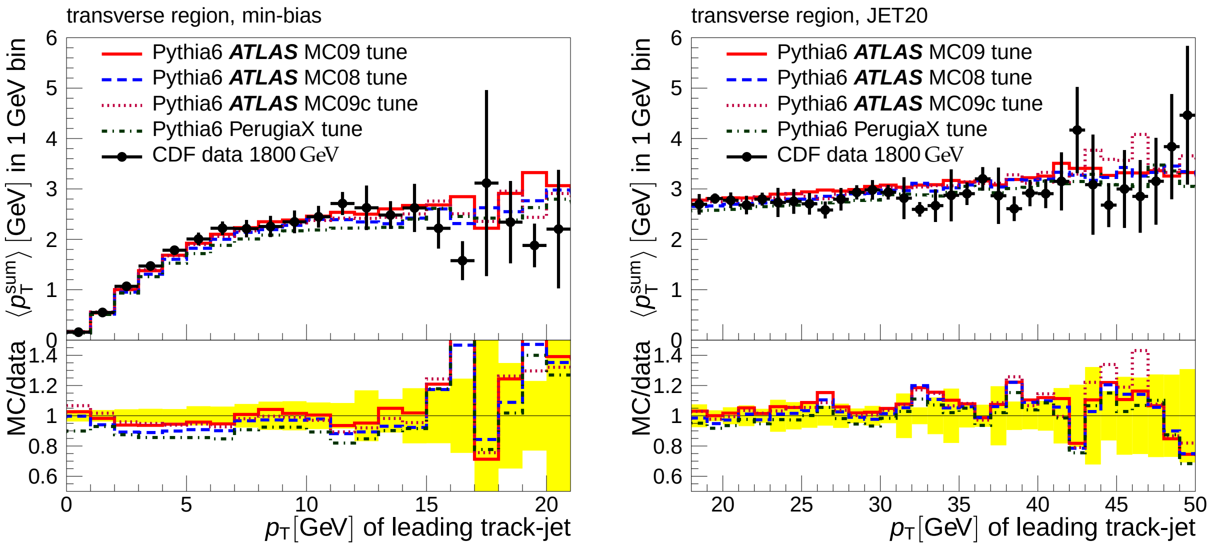
- Figure 6 shows a comparison of the different tunes to the measured mean charged particle transverse momentum as a function of the charged multiplicity in minumum bias events as measured by the CDF collaboration [10]. For multiplicities $N_{\mathrm{ch}} > 10$, the MC08 and MC09 ATLAS tunes overestimate the mean transverse momentum. The MC09c tune with a reduced colour reconnection probability gives a better description of the data. These data are also very well described by the PerugiaX tune. The PerugiaX tune uses the same colour reconnection model but differs in other aspects of the configuration.

- Figure 7 shows the comparison of the different tunes to the D0 measurement of angular correlations in dijet events [9]. All the tunes considered here have difficulty in describing the data completely. This measurement was not used for the MC09 tuning effort, since the observables are more sensitive to parameters of the parton shower, which were not varied for the MC09 tune.



(a) N_{ch}, transverse region, min-bias trigger

(b) N_{ch}, transverse region, JET20 trigger



(c) $p_{\mathrm{T}}^{\mathrm{sum}}$, transverse region, min-bias trigger

(d) $p_{\mathrm{T}}^{\mathrm{sum}}$, transverse region, JET20 trigger

Figure 2: Comparison of tunes to data for the transverse region of the leading jet analysis. These distributions were used in the MC09 tune. Black data points: CDF data [6]. The lines show predictions of the PYTHIA 6.420 Monte Carlo generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line).

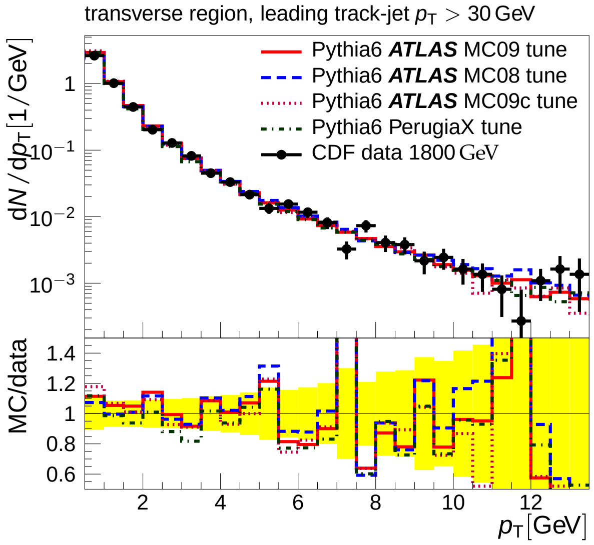
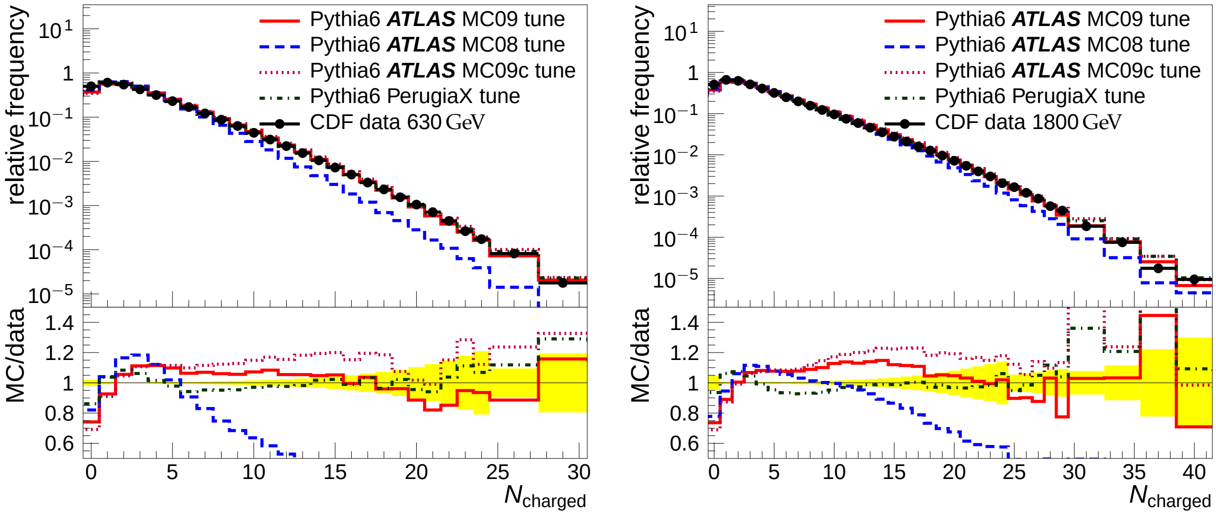


Figure 3: Transverse momentum spectrum of charged particles in the transverse region, if requiring the leading track-jet to have a transverse momentum of at least 30 GeV. Black data points: CDF data [6]. The lines show predictions of the PYTHIA 6.420 Monte Carlo generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line)



(a) $\sqrt{s} = 630\,\mathrm{GeV}$

(b) $\sqrt{s} = 1800\,\mathrm{GeV}$

Figure 4: Charged multiplicity in minimum bias events. (a): $\sqrt{s} = 630\,\mathrm{GeV}$, (b): $\sqrt{s} = 1800\,\mathrm{GeV}$. These data were used for the MC09 tune. Black data points: CDF data [8]. The lines show predictions of the PYTHIA 6.420 Monte Carlo generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line).

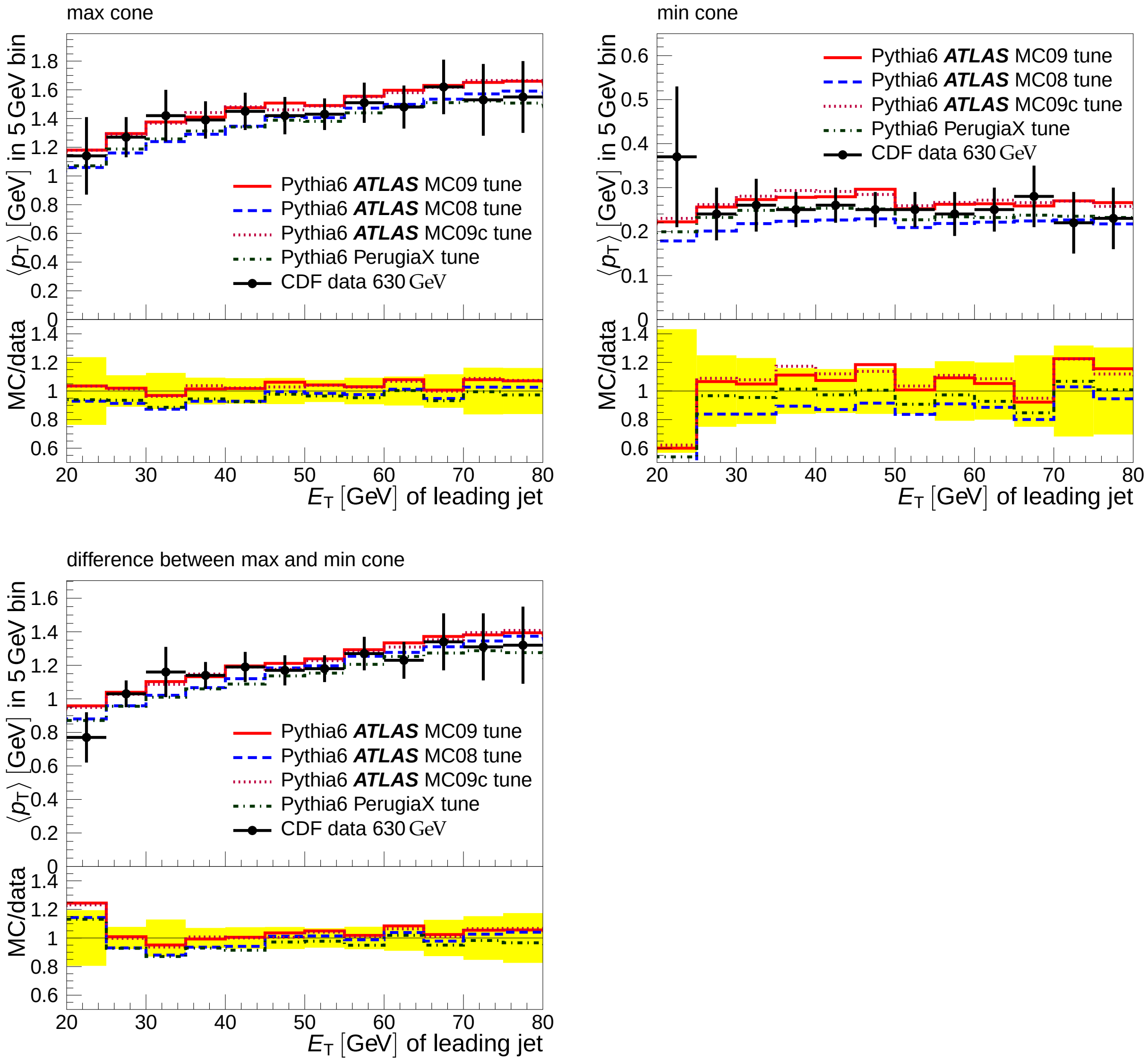


Figure 5: Mean charged particle transverse momentum sum vs. E_T of the leading jet in $p\bar{p}$ collisions at $\sqrt{s} = 630\,\text{GeV}$ as described in the text and in [7]. These distributions were not used in the MC09 tune. (a): max cone, (b): min cone, (c): difference between max and min cone. The data points show the measurement by the CDF collaboration [7]. The lines show predictions of the PYTHIA 6.420 Monte Carlo generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line).

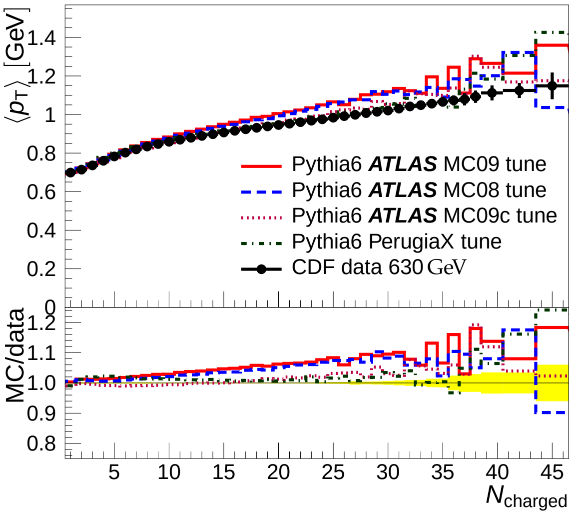
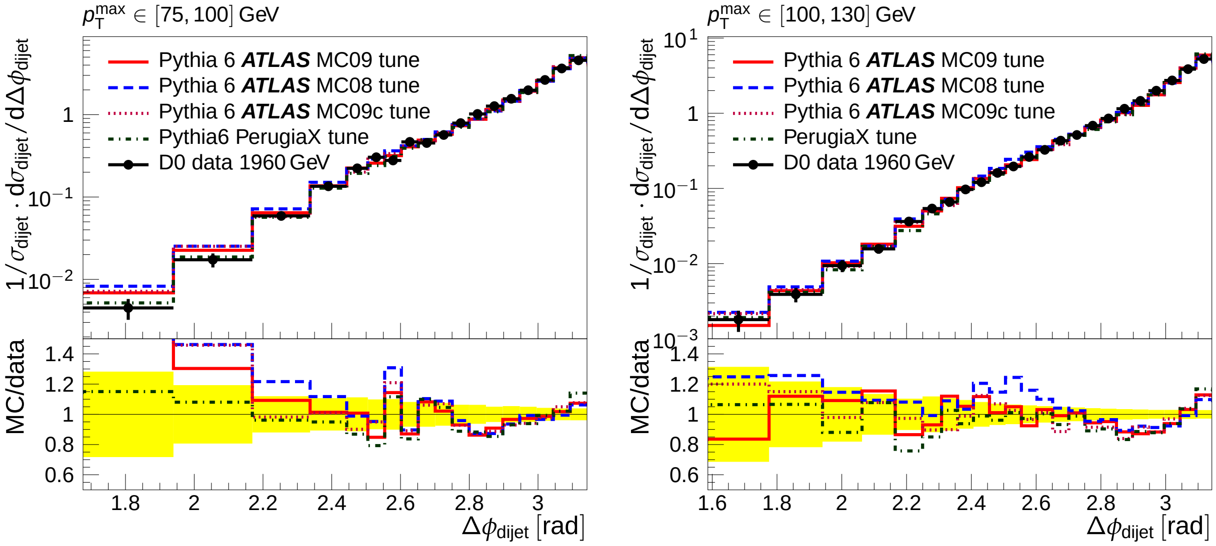


Figure 6: Mean charged particle transverse momentum vs. the charged multiplicity in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$. The data points show the measurement by the CDF collaboration [10], the lines show predictions of the PYTHIA 6.420 MC generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line). These data were not used for the MC09 and MC08 tune.



(a) $\phi\,(\text{jet}_1,\text{jet}_2)$ for $75 < p_T^{\text{max}} < 100$ GeV

(b) $\phi\,(\text{jet}_1,\text{jet}_2)$ for $100 < p_T^{\text{max}} < 130$ GeV

Figure 7: Azimuthal angle between the two leading jets in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$. (a): p_T of the leading jet between 75 and 100 GeV, (b): 100 to 130 GeV. The data points show the measurement by the D0 collaboration [9]. These distributions were not used in the MC09 tune. The lines show predictions of the PYTHIA 6.420 Monte Carlo generator using the MC09 tune (red, solid line), the MC08 tune (blue, dashed line), the MC09c tune (purple, dotted line) and the PerugiaX tune (green, dashed dotted line).

3.4 Effects at LHC Energies

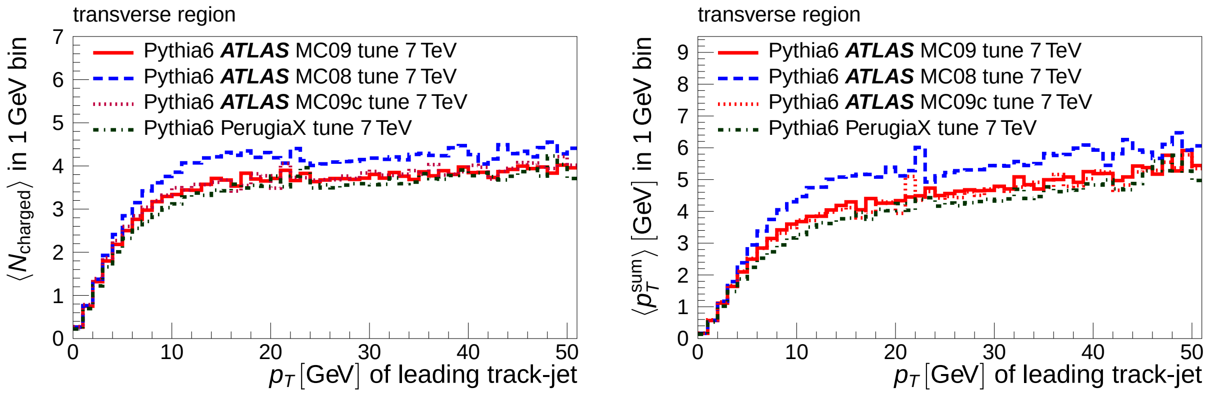
The effect of the tunes presented in this note on the underlying event activity in the transverse region at LHC energies is estimated by performing an analysis as in [6], but for pp collisions with $\sqrt{s} = 7\,\text{TeV}$. The result of this is shown in Figure 8.

The MC08 tune shows significantly higher underlying event activity, as evidenced by the charged particle density and the charged transverse momentum density in the transverse region. The MC09 tune shows about 15% less activity. The toward and away regions are less affected by differences of the underlying event, since they are dominated more by the hard component of the event. The MC09c tune is, as expected, very similar to the MC09 tune.

This behaviour is mainly caused by the different choices of the rescale exponent. For MC08, it was left at the PYTHIA 6 default value of 0.16, but was increased to 0.25 for MC09 in order to fit the charged multiplicity distribution measured by the CDF collaboration at 630 and 1800 GeV (see Figure 4). This results in a substantial suppression of activity at LHC energies.

The MC09 tune is quite close to the PerugiaX tune for the mean charged multiplicity. It predicts a slightly higher mean transverse momentum sum at LHC energies, but the discrepancy is mostly in the region of low transverse momenta of the leading track-jet. For higher transverse momenta the two tunes agree well. It is interesting to note that for leading track-jet transverse momenta above 20 GeV the MC09 and PerugiaX tunes agree even though they use many different models, but about the same value for the rescale exponent.

It should be noted that due to the different energy extrapolation behaviour, the differences between the presented tunes will be larger at higher centre-of-mass energies, i.e. the design energy of the LHC of 14 TeV.



(a) N_{ch} at $\sqrt{s} = 7\,\text{TeV}$, LHC

(b) $p_{\text{T}}^{\text{sum}}$ at $\sqrt{s} = 7\,\text{TeV}$, LHC

Figure 8: Prediction of different PYTHIA 6 tunings for the underlying event activity in the transverse region at the LHC. (a): charged particle density vs. the leading track-jet p_{T}, (b) charged transverse momentum density vs. the leading track-jet p_{T}. Red solid line: ATLAS MC09 tune, blue dashed line: ATLAS MC08 tune, purple dotted line: ATLAS MC09c tune, green, dash-dotted line: PerugiaX tune.

3.5 Summary of the PYTHIA 6 tunes

The PYTHIA 6 tune for the MC09 ATLAS production was derived from the MC08 tune using partially different data sets:

- The model for colour reconnection is set to the newest version at the time of the tuning. This has the additional advantage of a much faster processing time.
- The heavy quark fragmentation function is changed to the Bowler fragmentation function.
- The MC09 tune to the LO* PDF set is derived from the MC08 tune by increasing the cut-off scale to 2.3 GeV (PARP(82)) and the rescale exponent to 0.25 (PARP(90)). It is able to adequately describe almost all of the data sets used. The biggest differences are in the measurement of minimum bias events in Run II [10].
- The MC09 tune predicts a significantly lower underlying event activity compared to the MC08 tune at LHC energies.
- The MC09 and MC08 tune do not fully describe and were not tuned to the recent measurement of minimum bias events by the CDF collaboration [10]. The MC09c tune, which was derived using the PROFESSOR tool using this new data set, gives a better description and describes the other data sets at the same level as the MC09 tune.

4 Tuning of JIMMY

In this section the tuning of the JIMMY 4.31 [20] generator is described.

JIMMY [20] is a library of routines which can be linked to the HERWIG MC event generator [21], to generate multiple parton scattering events in hadron-hadron collisions in addition to the built-in HERWIG soft UE. JIMMY implements an eikonal model similar to the core of that in PYTHIA, which is discussed in more detail in references [20, 22]. The multiparton interaction process is calculated using the cross-section for the hard subprocess, the conventional parton densities and the area overlap function, $A(b)$ [20]. However, JIMMY is limited to the description of the underlying event and should not be used to predict minimum bias events [20].

The two parameters optimised in the different tunings are the "inverse proton radius", JMRAD(73) (or RAD in Section 4.3) and a cut-off for multiple parton interactions, PTJIM.

JMRAD(73) allows the redistribution of probability of generating a harder parton-parton scatter with respect to the accompanying soft interactions. It corresponds to the inverse proton radius squared. In this model, the proton (or anti-proton) size is used to calculate the probability of how central the generated hadronic collisions will be: small radii favour more central collisions while large radii allow for a larger fraction of more peripheral events.

PTJIM acts as an energy dependent screening parameter (similar to $p_{\mathrm{T}}^{\mathrm{min}}$ in the PYTHIA model). The higher PTJIM, the lower is the mean number of multiple parton scatters in the generated event and vice-versa.

Notice that an energy dependent term has been introduced in PTJIM for the UE tuning. This leads to a value of PTJIM= 2.1 for $p\bar{p}$ collisions at $\sqrt{s} = 630$ GeV and PTJIM= 4.9 for the LHC centre-of-mass energy of 14 TeV in pp collisions. JIMMY does not intrinsically attempt any scaling of this parameter with energy, so we use a running ansatz based on that used in PYTHIA:

$$\mathrm{PTJIM} = \mathrm{PTJIM}_{1800} \cdot \left(\frac{\sqrt{s}}{1800\ \mathrm{GeV}} \right)^{0.274}, \tag{2}$$

where PTJIM_{1800} is the value of PTJIM at the reference scale $\sqrt{s} = 1800$ GeV. The exponent 0.274 is not touched in the tuning process.

As for the PYTHIA tuning described in the previous section, the primary motivation of this effort was to obtain a description of the underlying event, when using the modified leading order, or LO* PDFs [1]. Changing the PDF requires a new tune of the parameters describing the underlying event, especially the multi-parton interactions.

Since JIMMY has not been designed to generate minimum bias events, no minimum bias datasets were used in the tuning processes. An overview of the observables tuned to can be found in Table 1.

This section is structured as follows: Section 4.1 describes the tune used for MC08, Section 4.2 the tuning for the LO* PDFs and Section 4.3 the tune for CTEQ6.6. The latter was necessary in order to use HERWIG/ JIMMY for showering the events from the MC@NLO [2] generator.

4.1 CTEQ6L1 tune for JIMMY (MC08)

The previous tune of JIMMY to the underlying event used by ATLAS was obtained for JIMMY version 4.1 linked to HERWIG version 6.507 [23]. At that time, JIMMY 4.1 was tuned to describe the UE as measured by CDF during Run I [6,7] – namely the leading jet and ”MAX-MIN” analyses. The resulting set of parameters, labelled MC08, is shown in Table 3. As for PYTHIA’s MC08 tune, the tuned settings were obtained for CTEQ6L1.

4.2 LO* PDF tune for JIMMY (MC09)

MC models need to be re-tuned whenever new PDF sets are adopted for a new round of MC production. The choice of LO* as the baseline PDF for the MC09 series demanded a re-tune of the JIMMY parameters to the underlying event. The MC08 set of parameters, obtained for CTEQ6L1, was used as a starting point to produce the new tune. The UE datasets used to derive the MC08 and MC09 tunes are the same (Table 3).

In order to correct for the increased particle density due to higher low-x gluon activity we adjusted the parameters PTJIM and JMRAD(73) to better describe the data. Note that JMRAD(91) is set to the same value of JMRAD(73) when anti-protons are included in the event.

A combination of changes in both parameters was used to obtain the MC09 JIMMY tune. We increased the constant term in PTJIM from 2.8 GeV to 3.6 GeV, to account for the extra gluon density at small x. The energy dependent term was kept the same as the one used in the MC08 tune. JMRAD(73) changed from 1.8 to 2.2. The full list of tuned JIMMY parameters for LO*, labelled as MC09, is shown in Table 3.

4.3 CTEQ6.6 tune for JIMMY

ATLAS decided to use CTEQ6.6 for the NLO MC event generators MC@NLO and POWHEG. Since MC@NLO requires the same PDF to be used also for the showering MC, HERWIG/ JIMMY [20, 21], a tuning of HERWIG/ JIMMY [6)] for CTEQ6.6 was required. In this study only the JIMMY parameters JMRAD and PTJIM were tuned. RIVET [7)] and AGILe[8)] [24] were used for the comparison to data. The tuned parameters were obtained with PROFESSOR [5], a tool for systematic event generator tuning, by tuning to the observables found in Table 1.

Tuning procedure

PROFESSOR is a statistical tool for event generator tuning, based on the idea of a fast analytic model of the generator by bin-wise parameterisation. The parameterisation is constructed based on input MC observables with randomly-chosen parameters in the ranges of interest. Subsequently, a goodness-of-fit measure between the parameterisation and experimental data is defined and numerically minimised. The output of the minimiser is then considered a best tuning estimate and validated by an explicit run of the generator with those parameters.

The PROFESSOR method requires a minimal number of Monte Carlo runs, N_{min}, to work. For this tuning we chose to use polynomials of second order for the parameterisations[9)], so that $N_{\text{min}} = 6$ for the two dimensional parameter space of PRRAD and PTJIM. However, a degree of oversampling ($N_{\text{runs}}/N_{\text{min}}$) of three or more is recommended. Therefore we produced 30 MC runs with RIVET, which also gives some

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[6)] HERWIG 6.510, JIMMY 4.31

[7)] version 1.2.0a0

[8)] version 1.1.4

[9)] $N_{\text{min}} = 1 + p + p(p+1)/2$ for p tuning parameters and polynomials of second order room for validation of the obtained tuning results. The observables used for the tuning can be found in Table 1.

For the validation of the tuning result obtained with the maximum information parameterisation ($N_{\text{runs}} = 30$) we compare the goodness-of-fit measure at the best tuning estimate of each parameter to that of 100 minimisation results coming from 100 different generator parameterisations that use combinations of 20 of the 30 available MC generator runs. We find a very stable behaviour, with the parameter values cited in Table 3 being well-centered in the distribution of minimisation results.

The full set of tuned parameters are listed in Table 3.

Constructing this tune required roughly one day of parallel batch processing time to produce high statistics MC runs of the tuning observables at the 30 random parameter points: this required 12 runs with various energies and kinematic cuts per point, each run consisting of typically 1M events. Computing the optimum parameters for goodness of fit required minimal interactive CPU time. A further day of batch processing time was required to confirm the agreement of the generator with the predicted response and to cross-check with various MC tunes' predictions of track η-distribution in $t\bar{t}$ events (since this tune is most relevant for physics to be simulated with MC@NLO.)

The Professor system was systematically checked to replicate MC pseudo-data in 2- and 4-parameter tunes using Pythia 6, and the stability/optimality of this tune was verified manually. The Rivet implementation of the CDF Run I leading jet analysis was confirmed to agree with the analysis implementation used in Section 4.2 and the MC08 tunes.

There is evident room for improvement on this tune by including the Herwig shower parameters as well as the Jimmy MPI parameters in the tune. This extension may particularly be expected to improve the description of dijet event azimuthal decorrelation (Figure 9), since this distribution is sensitive to the description of extra initial state gluon emissions. It is also very likely that the Jimmy tunings can be further improved if the exponent in equation 2 is treated as a free parameter, as for the MC09 tune of Pythia 6.

Parameter/Switch	MC08	MC09	MC09 CTEQ6.6
PDF-set	CTEQ6L1 (ID: 10042)	LO* (ID: 20650)	CTEQ6.6 (ID: 10550)
PTMIN	10.0	10.0	10.0
PTJIM	$2.8 \times \left(\frac{\sqrt{s}}{1.8\ \text{TeV}}\right)^{0.274}$	$3.6 \times \left(\frac{\sqrt{s}}{1.8\ \text{TeV}}\right)^{0.274}$	$3.14 \times \left(\frac{\sqrt{s}}{1.8\ \text{TeV}}\right)^{0.274}$
JMRAD(73)	1.8	2.2	2.64
JMUEO	——	1	——
PRSOF	——	0	——

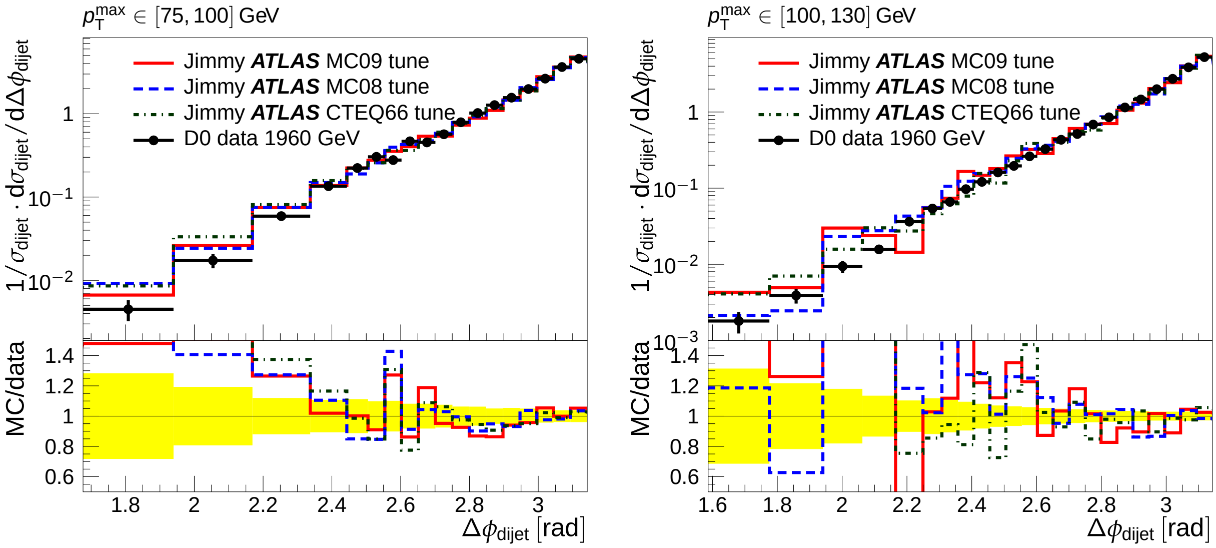
Table 3: Parameters tuned to the underlying event for Jimmy 4.31. Comparison between MC08 (tuned with CTEQ6L1), MC09 (tuned with LO*) and MC09 (tuned with CTEQ6.6) ATLAS tunes. Note that JMRAD(91) should also be changed to the same value used for JMRAD(73) when antiprotons are used in the simulation (e.g. Tevatron events).

4.4 Comparison of different HERWIG/ JIMMY tunes to Tevatron data

In the following, three different parameter sets for HERWIG/ JIMMY are compared with data

- The tune used for the MC08 production, using the CTEQ6L1 PDF set, see Section 4.1
- The resulting MC09 tune using the LO* PDF set, as described in 4.2
- The tune for CTEQ6.6 as described in Section 4.3

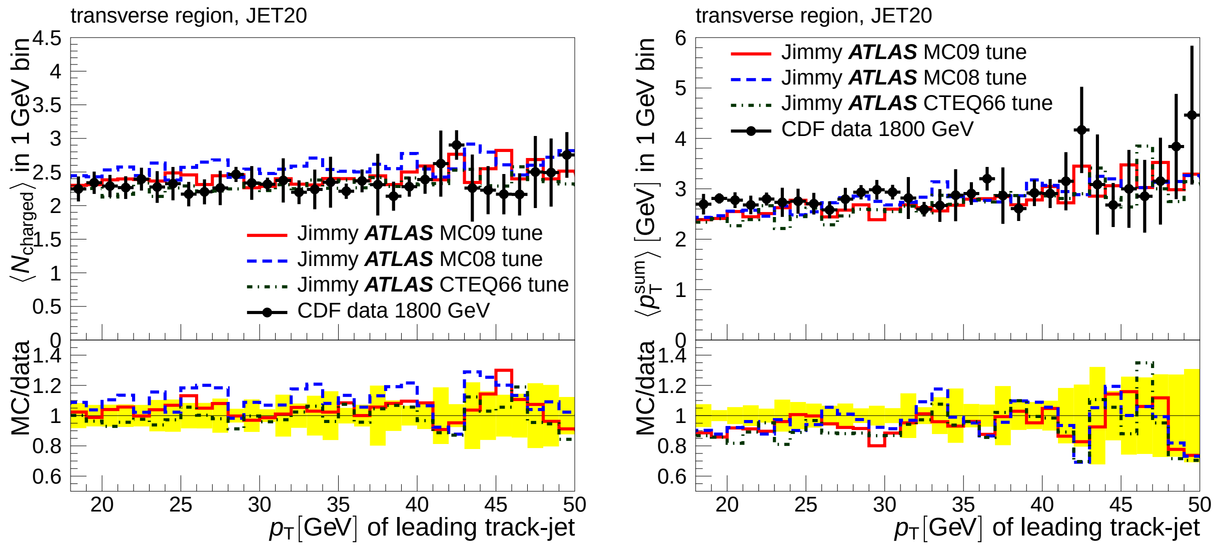
All of the data sets shown here were used for the CTEQ6.6 tune, but not all of them were used for the MC08 and MC09 JIMMY tune, see Section 1. In general, the CTEQ6.6 tune agrees with the JIMMY MC09 tune for modified-LO PDFs.



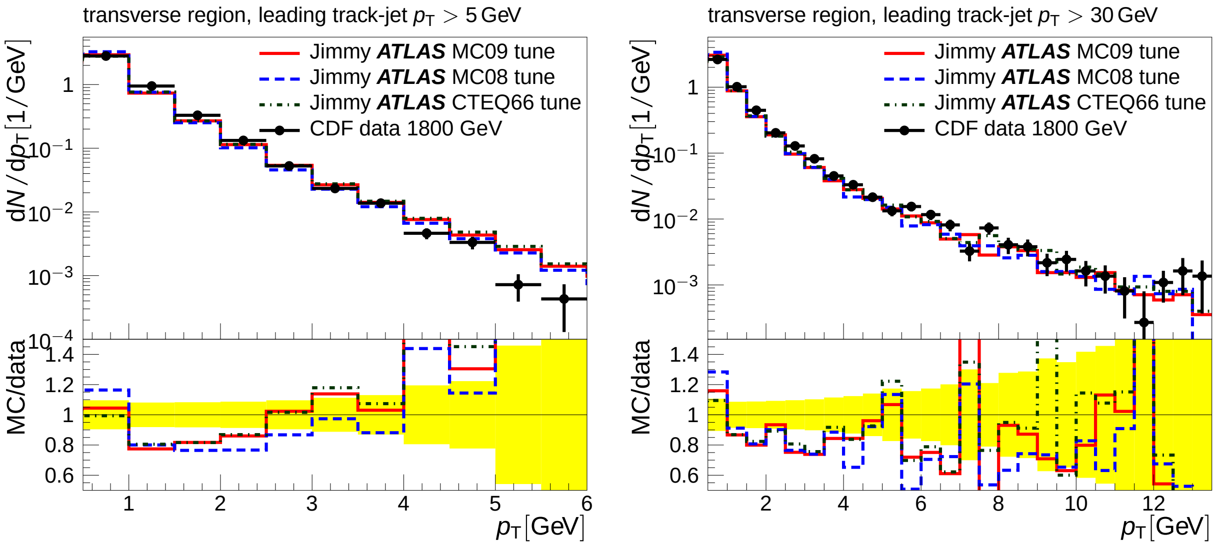
(a) $\phi\,(\mathrm{jet}_1,\mathrm{jet}_2)$ for $75 < p_T^{max} < 100$ GeV

(b) $\phi\,(\mathrm{jet}_1,\mathrm{jet}_2)$ for $100 < p_T^{max} < 120$ GeV

Figure 9: D0 measurement of the azimuthal angle between the two hardest jets [9]. These measurements are very sensitive to extra gluon emissions. These distributions are used in the CTEQ6.6 JIMMY MC09 tune (dash-dotted green line), but not in the LO* JIMMY MC09 (solid red line) and not in the MC08 tune (dashed blue line).

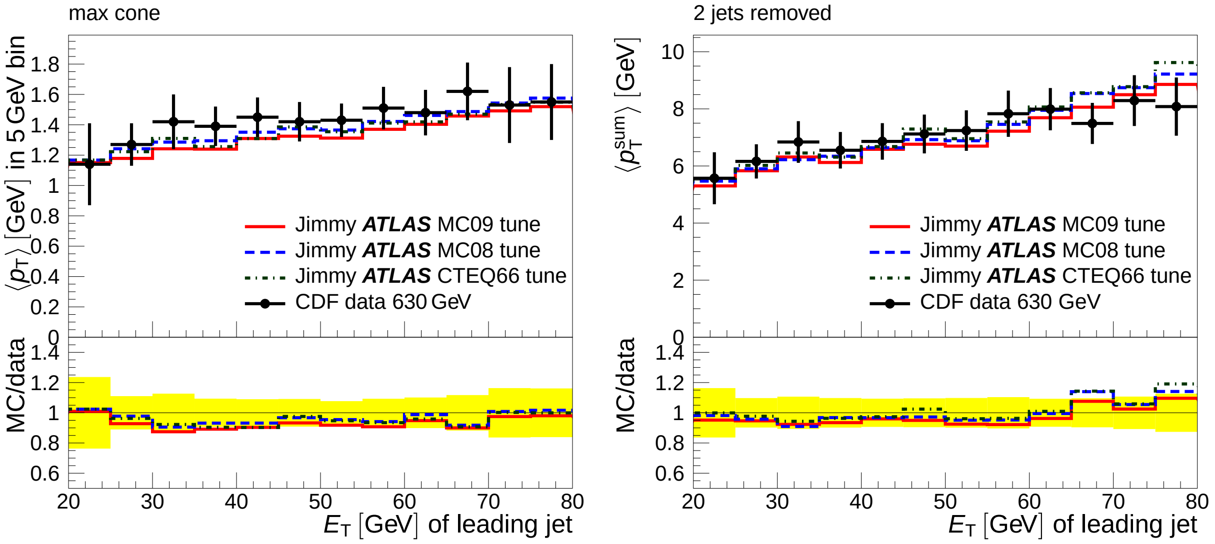


(a) N_{ch}, transverse region (b) $\sum p_{\mathrm{T}}$, transverse region



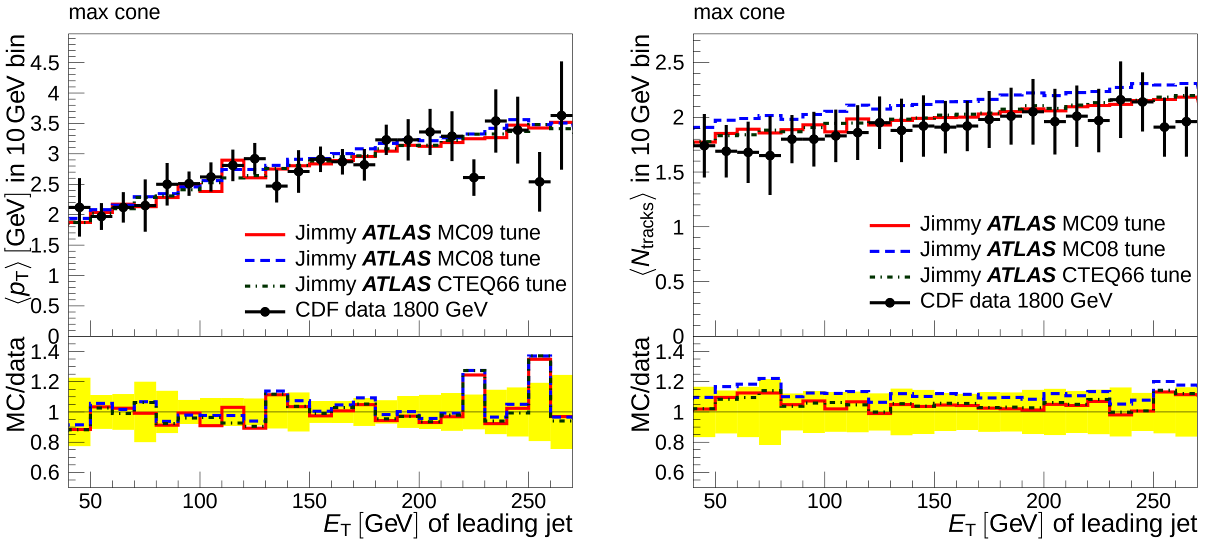
(c) track-jet $p_{\mathrm{T}} > 5$ GeV (d) track-jet $p_{\mathrm{T}} > 30$ GeV

Figure 10: CDF Run I underlying event measurements at $\sqrt{s} = 1800$ GeV. The underlying event activity, N_{ch} in (a) and $\sum p_{\mathrm{T}}$ in (b), is studied in the "transverse" region using a jet trigger as a function of the leading jet's p_{T} [6] and in track p_{T} spectra ((c), (d)). These distributions are used in all presented JIMMY tunes, MC09 with LO* (solid red line), MC08 with CTEQ6L1 (dashed blue line) and MC09 with CTEQ6.6 (dash-dotted green line).



(a) p_T^{max}, transverse region, $\sqrt{s} = 630$ GeV

(b) "Swiss cheese", transverse region, $\sqrt{s} = 630$ GeV



(c) p_T^{max}, transverse region, $\sqrt{s} = 1800$ GeV

(d) N_{ch}^{max}, transverse region, $\sqrt{s} = 1800$ GeV

Figure 11: CDF Run I underlying event measurements. (a) & (b) at $\sqrt{s} = 630$ GeV, (c) & (d) at $\sqrt{s} = 1800$ GeV. The underlying event activity is studied using cones ("MIN", "MAX") in the transverse region as a function of the leading calorimeter jet's transverse energy [7]. The "Swiss cheese" distribution shown in (b) was used in the CTEQ6.6 JIMMY MC09 tune (dash-dotted green line) only. The solid red line shows the MC09 tune with LO*, the dashed blue line shows the MC08 tune with CTEQ6L1.

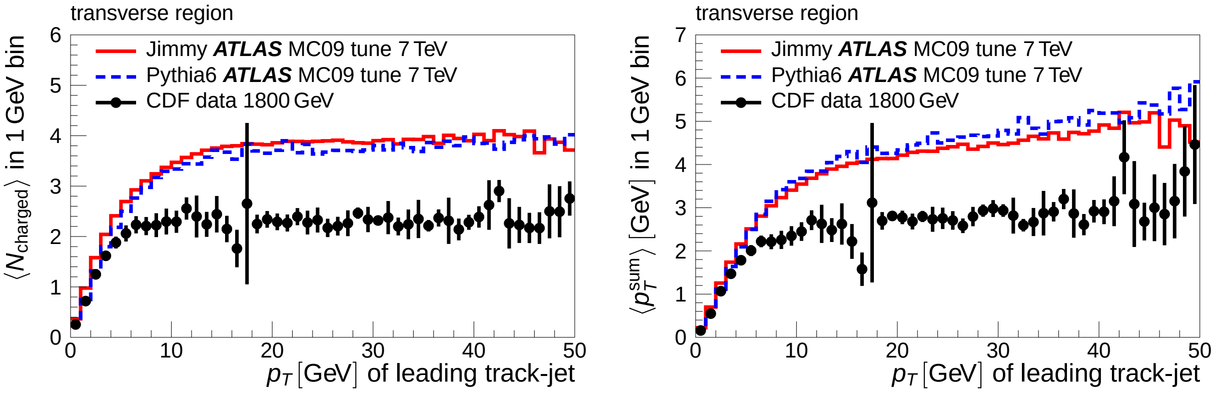
5 Comparison of JIMMY and PYTHIA MC09 tunes

Figure 12 shows a comparison of the predictions of the PYTHIA 6.420 Monte Carlo generator and of JIMMY 4.31 using the MC09 tunes presented in this note. For this comparison an analysis similar to [6] was performed for pp collisions with $\sqrt{s} = 7\,\text{TeV}$. For reference, the measurement of the CDF collaboration from [6] is also shown.

The two generators with the MC09 tunes give very similar predictions for the charged particle and charged transverse momentum density in the transverse region. JIMMY predicts a slightly higher multiplicity and lower transverse momentum sum compared to PYTHIA 6.420. This is probably due to the colour reconnection model that is present in PYTHIA, but not in JIMMY.

Both the charged particle and the transverse momentum density are predicted to be about a factor of 1.8 higher at LHC energies than at the Tevatron.

It should be noted that the energy dependence is completely described by the rescale exponent in the MPI model. This can not be uniquely fixed with the data sets at low energies that are available for a Monte Carlo and data comparison. Any change of the rescale exponent has a large influence on the underlying event activity at the LHC due to the large increase in centre-of-mass energy.



(a) N_{ch} density (b) $p_{\text{T}}^{\text{sum}}$ density

Figure 12: (a): charged particle density, (b): charged transverse momentum density in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ vs. the p_{T} of the leading track-jet, both for the transverse region. The black data points show the measurement of the CDF collaboration [6] in $p\bar{p}$ collisions at $\sqrt{s} = 1.8\,\text{TeV}$, the blue dashed line shows the prediction of the PYTHIA 6.420 Monte Carlo generator using the ATLAS MC09 tune and the red solid line the prediction of the HERWIG 6.510 Monte Carlo generator together with JIMMY 4.31 using the ATLAS MC09 tune to CTEQ6L1.

6 Effect of MC tuning and LO* PDFs at high p_{T}

The performance of the LO* MRST2007lomod parton density function [1] and the MC09 tune has also been examined for high-p_{T} processes before the start of the MC09 ATLAS Monte Carlo production. In this Section the validation of PYTHIA 6 and MC09 tune for $t\bar{t}$, Drell-Yan process and Lepto-Quark (LQ) production is presented. Validation goals were to check whether the effects established in [1] are reproduced for Monte Carlo generators used at ATLAS but not used in [1] and to check that effects on low-p_{T} part of the high-p_{T} event has no important effect on the range of distributions PYTHIA 6 generator can describe.

The events were generated with PYTHIA 6 [11] or AcerMC [25] with PYTHIA 6 as a supervising generator. PYTHIA version 6.421 was used, with the MC09 tune as described in Section 3. The studies were performed on standard samples used by the ATLAS physics analysis groups involving their specific cuts for event generation.

All samples were generated at the centre-of-mass energy of 10 TeV. Jets were obtained by running the ATLAS cone jet algorithm on generator-level particles with $|\eta| < 5$, excluding the muons and neutrinos. A cone size of $R = 0.4$ and a split-and-merge fraction of 0.5 were used. Jets with transverse energy greater than 7 GeV were accepted. For the Drell-Yan process, jets that contain a high-p_{T} electron in the jet cone of $R = 0.4$ are excluded from the plotted distributions, while in the $t\bar{t}$ and LQ events, jets overlapping with electrons are included.

6.1 Validation of the MC09 tune for $t\bar{t}$ process

The effects of using LO* PDF for $t\bar{t}$ production have not been published to our knowledge. The process is primarily produced in the region of x for which LO* PDF should provide a better description than the conventional LO ones [1]. A semi-leptonic μ channel $t\bar{t}$ sample was produced with AcerMC 3.7, using PYTHIA version 6.421 as a supervising generator.

In Figure 13(a), the η distribution (in the lab frame, after boosts from ISR, FSR etc.) of t quarks is compared for the MC08 and MC09 tune. The contributions coming from the production channels $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ are considered separately in this Figure. A modulation of the shape of the η distribution is observable. At 10 TeV centre-of-mass energy, most of the $t\bar{t}$ pairs are produced via gg fusion, with the fraction differing between use of the LO* PDF (with a $q\bar{q}$ fraction of $\sim 15\%$) and the LO PDF ($q\bar{q}$ fraction of $\sim 20\%$). The change of the fraction of $q\bar{q}$- produced pairs is documented in Table 4 and discussed in more detail later in the text. In Figure 13(b) the invariant mass spectrum of the produced $t\bar{t}$ events is shown to be similar for events produced with the MC08 and MC09 tunes.

Jet properties have also been studied for the $t\bar{t}$ process. It has been verified that after the underlying event parameters have been tuned the variation of the jet multiplicity distributions (Figures 13(c),13(d)), transverse momentum and η distributions for hard ($p_{\mathrm{T}} > 20$ GeV) and soft ($p_{\mathrm{T}} < 20$ GeV) jets in $t\bar{t}$ events is not comparable to the modeling uncertainty. In order to demonstrate the effects of LO* PDFs on the jet distributions, the LO* PDFs are shown with the MC08 tune which was developed for CTEQ6L1 PDF in Figures 13(c) and 13(d). As shown, the soft jets multiplicity excess is no longer observed when using MC09 tune to the UE data. It has been established that low-p_{T} jets distributions can be controlled by PYTHIA 6 parameters settings at comparable level when using LO and LO* PDF.

While the kinematics distributions in Figure 13 indicate that (after tuning has been performed) the LO* PDF introduce no undesired effects in the $t\bar{t}$ process distributions, we also verify the benefits of using LO*

Generator	PDF set	$q\bar{q}$ ($\pm$ 0.3%)	σ_{NLO}/σ	K-factor [26]
PYTHIA 6.4.21	CTEQ6L1	18%	1.9	2.1
	MRST2007lomod	15%	1.3	1.5
AcerMC 3.7	MSTW2008	19%	1.8	2.0
	CTEQ6L1	19%	1.8	2.0
	MRST2007lomod	16%	1.3	1.4
MC@NLO 3.1 [2]	CTEQ6M	14%	1.0	1.1

Table 4: Fraction of $q\bar{q}$ produced $t\bar{t}$ events and K-factors for $t\bar{t}$ events (qg contribution to samples produced with MC@NLO is consistent with 0). The top quark mass in all samples and cross-section evaluation is set to 172.5 GeV. CTEQ6L1 (MRST2007lomod) is the LO (LO*) PDF used for the MC08 (MC09) tune.

PDF for $t\bar{t}$ generation with LO generators. The anticipated K-factor reductions have been evaluated and are documented in the 4th and 5th columns of Table 4. In the 4th column ratios of cross-sections obtained with running different Monte Carlo generators and the cross-section obtained by running MC@NLO 3.1 [2] generator are given. In the 5th column, K-factors are evaluated against the reference cross-section accurate at the level of next-to-leading order in α_s, and to next-to-leading threshold logarithms (NLO+NLL): $\sigma \sim 407.3$ pb, obtained from [26] for the CTEQ6M PDF, a t quark mass of 172.5 GeV and a centre-of-mass energy of 10 TeV. Using the LO* PDF results in a significant reduction of K-factors for $t\bar{t}$. An additional effect that has been observed is that the discrepancy between the ratio of $t\bar{t}$ events generated via $q\bar{q}$ or gg fusion observed between the samples generated with LO generators and LO PDF and NLO generators using NLO PDF is decreased if LO generators are used with LO* PDF. This is documented in the 3rd column of Table 4. Although the discrepancy is relatively small in the first place, its additional reduction is welcome since the kinematic properties of $t\bar{t}$ pairs produced via $q\bar{q}$ or gg fusion are known to be different. The ratio of $q\bar{q}$- or gg-produced events changes without modulation of the invariant mass spectrum of the produced $t\bar{t}$ events, as can be seen in the invariant mass distribution in Figure 13.

We estimate MRST2007lomod LO* PDF are appropriate for the use for $t\bar{t}$ event generation with PYTHIA 6 and AcerMC [25] LO generators.

6.2 Validation of the MC09 Tune for $Z \to e^+e^-$ process

In reference [1], the effect of LO* PDF on the Drell-Yan process $Z \to e^+e^-$ was studied in detail using the HERWIG [21] generator. These studies are complemented here with the use of a different Monte Carlo generator, PYTHIA 6. Drell-Yan $Z \to e^+e^-$ events were generated with the requirements that the invariant mass of the Z should be greater than 60 GeV and a presence of at least one electron with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.7$.

In [1] it has been established that K-factors obtained when using LO* PDF are smaller that the ones obtained when using LO PDF and modulation of shapes of hard process particles transverse momentum and η distributions has been observed. In Figure 14 the distributions of transverse momentum (Figure 14(a)) and η (Figure 14(b)) of the Z-boson reconstructed from two hardest opposite sign leptons in the event are shown. Leptons with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$ have been used for reconstruction. The jet multiplicities in $Z \rightarrow e^+e^-$ processes, for various cuts on the jet transverse momentum p_T, are also compared for the MC08 and MC09 tunes described in previous sections. The differences are relatively small for hard ($p_\mathrm{T} > 20\,\mathrm{GeV}$) jets (Figure 14(d)), as expected from the fact that the parameters controlling the hard part of the parton shower are set to the same values in the MC08 and MC09 tunes. Observable differences for soft ($p_\mathrm{T} < 20\,\mathrm{GeV}$) jets (Figure 14(c)) are also expected since the soft jet multiplicity is dependent on the underlying event tune used. As for the $t\bar{t}$ production in order to demonstrate the influence of the LO* PDFs on the jet multiplicity Figures 14(c) and 14(d) include the untuned distributions, i.e. MC08 parameter setting with only PDFs changed to LO* PDF. Apparently, the number of soft jets is significantly increased but the excess is no longer observed when using MC09 tune to the UE data.

For the Drell-Yan $Z \rightarrow e^+e^-$ process no problems were observed during validation.

6.3 Validation of the MC09 Tune for Lepto-Quark production

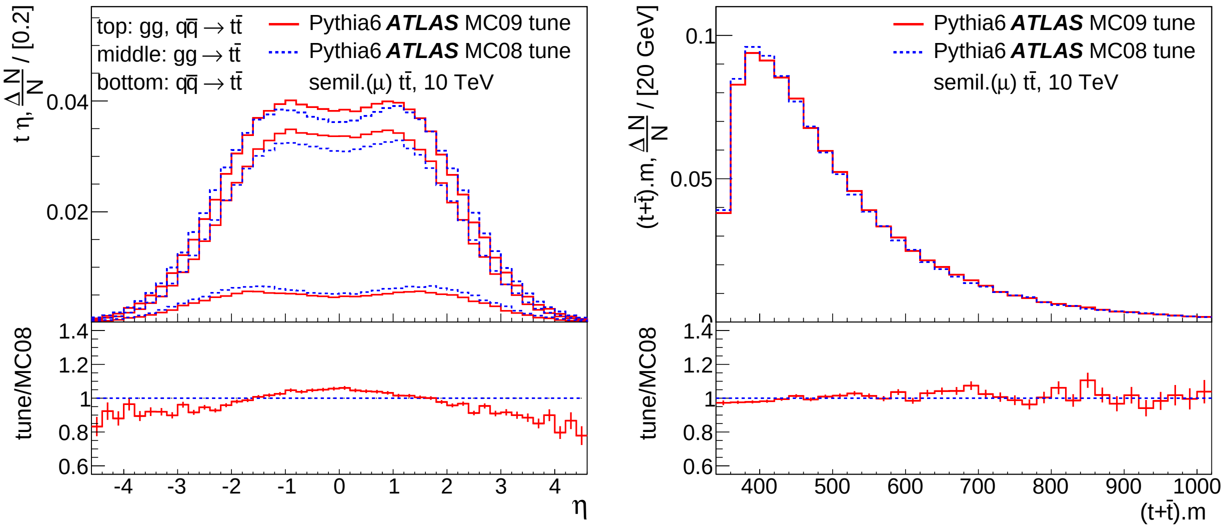
For the mass production at ATLAS it is important that the setup used for generation works well for all processes of interest. Therefore the PDF and tune performance was validated for (relatively high x) Lepto-Quark (LQ) production. PYTHIA 6 internal implementation of LQ production process has been used which also enables tests of Initial State Radiation at higher scales than for the tests reported in previous Sections. A sample containing the processes $qg \rightarrow eLQ$, $gg \rightarrow LQ\bar{LQ}$, $q\bar{q} \rightarrow LQ\bar{LQ}$, with a LQ mass set to $400\,\mathrm{GeV}$ decaying to u and e has been generated with PYTHIA version 6.421.

In Figure 15, η distributions of the high-p_T ($p_\mathrm{T} > 20\,\mathrm{GeV}$) electrons and multiplicity distributions of hard ($p_\mathrm{T} > 20\,\mathrm{GeV}$) jets are compared for the MC09 tune using the LO* (MRST2007lomod) PDF and the MC08 tune using a LO (CTEQ6L1) PDF. For the η distribution some modulation of the shape is observed for small values of η. For the multiplicities the difference between the tunes is relatively small with respect to the modeling uncertainty which can be estimated by comparing the MC08 and MC09 tune to other available PYTHIA tunes. It has also been verified that the jet p_T spectra of the tunes are very similar over a wide range of transverse momenta and multiplicities for different values of p_T cuts, including the low-p_T jets.

For the Lepto-Quark (LQ) production no problems were observed during validation.

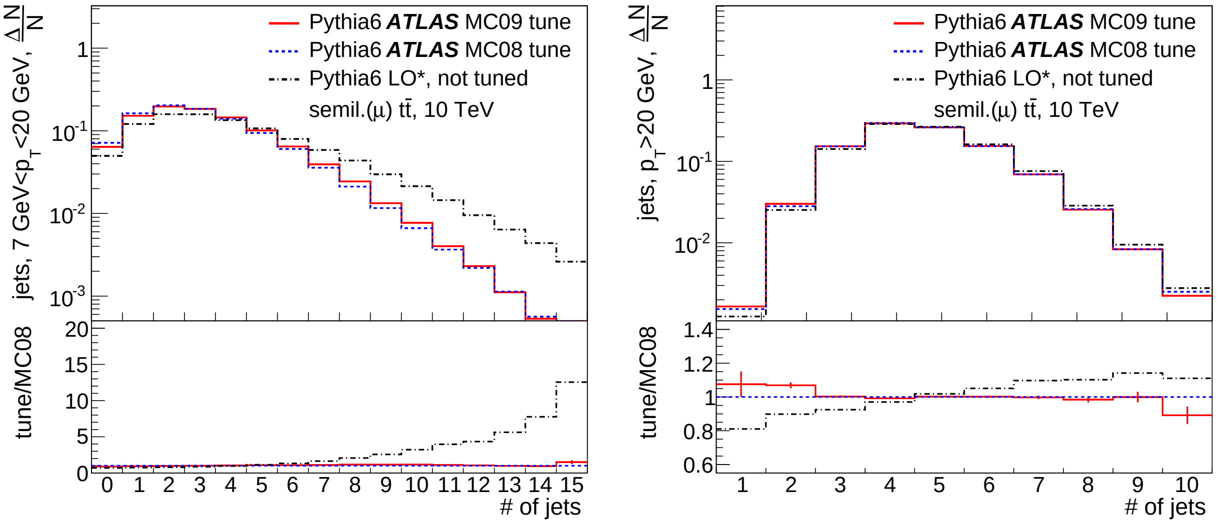
6.4 Conclusion on the validation of the MC09 tune for high-p_T processes

A validation of the MC09 Tune for a selected set of high-p_T processes generated with the LO generators PYTHIA 6.421 [11] or AcerMC 3.7 [25] (using PYTHIA 6.421 as a supervising generator) has been performed. After the underlying event has been tuned, the soft activity in samples using the LO* PDF is comparable to samples using the LO PDF. Apart from the anticipated effects on hard-event kinematics and K-factors (c.f. [1]) the effects of changing the PDF from LO to LO* are small with respect to the modeling uncertainty in all the tested high-p_T processes. The reduction of K-factors when using LO* PDF had been independently confirmed for semi-leptonic $t\bar{t}$ process. It may therefore be anticipated that LO* (MRST2007lomod) PDF is appropriate for the use with LO generators for MC09 ATLAS Monte Carlo production.



(a) η distribution of t quarks in $t\bar{t}$ events, contributions from $q\bar{q} \to t\bar{t}$ and $gg \to t\bar{t}$ channels are also shown separately.

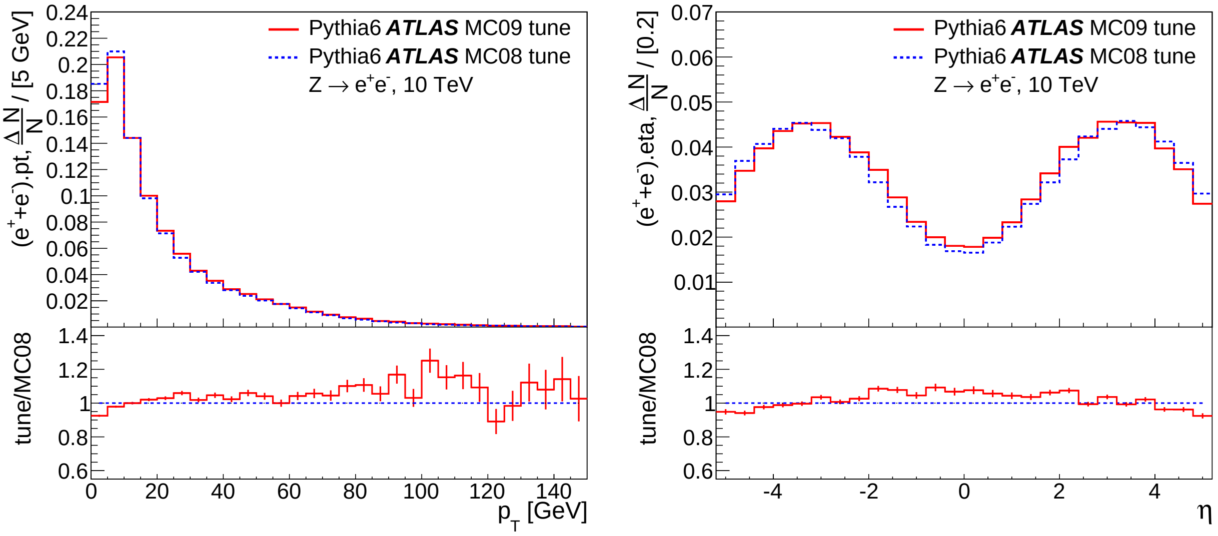
(b) Invariant mass spectrum of the $t+\bar{t}$ pairs in $t\bar{t}$ events



(c) Jet multiplicity of soft jets in $t\bar{t}$ events

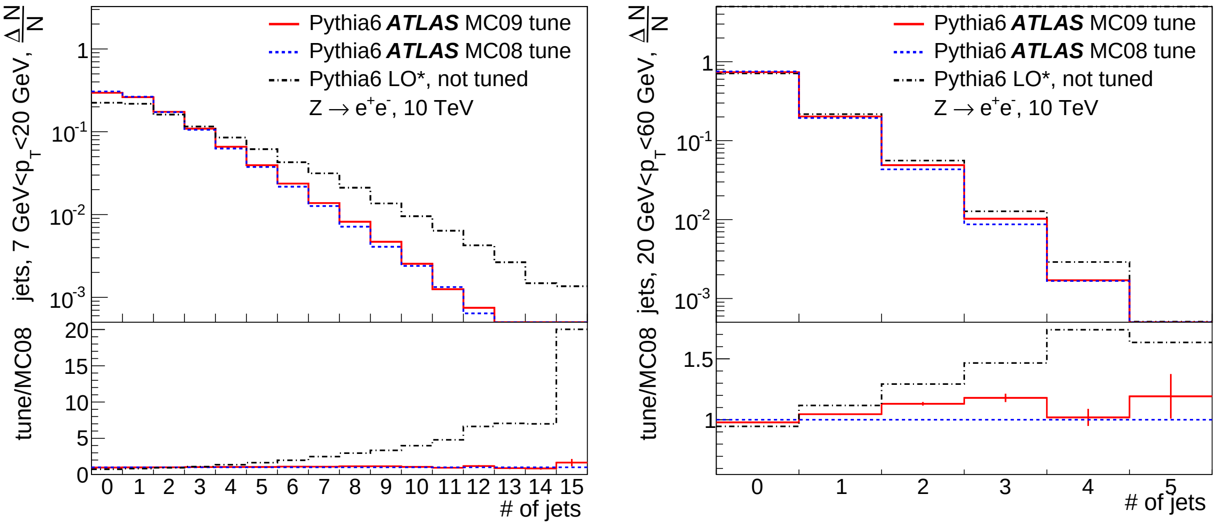
(d) Jet multiplicity of hard jets in $t\bar{t}$ events

Figure 13: Comparison of MC09 tune (using MRST2007lomod LO* PDF) and the MC08 tune (using CTEQ6L1 LO PDF) for kinematic distributions in semi-leptonic μ channel $t\bar{t}$ events. The distributions labeled as *not tuned* in Figures 13(c) and 13(d) are obtained by using (MRST2007lomod) LO* PDF for event generation (matrix element included) with MC08 tune. All Figures are normalised to unit area. AcerMC 3.7 and PYTHIA version 6.421 have been used for the sample production.



(a) p_{T} distribution of Z-bosons in $Z \to e^+e^-$ events

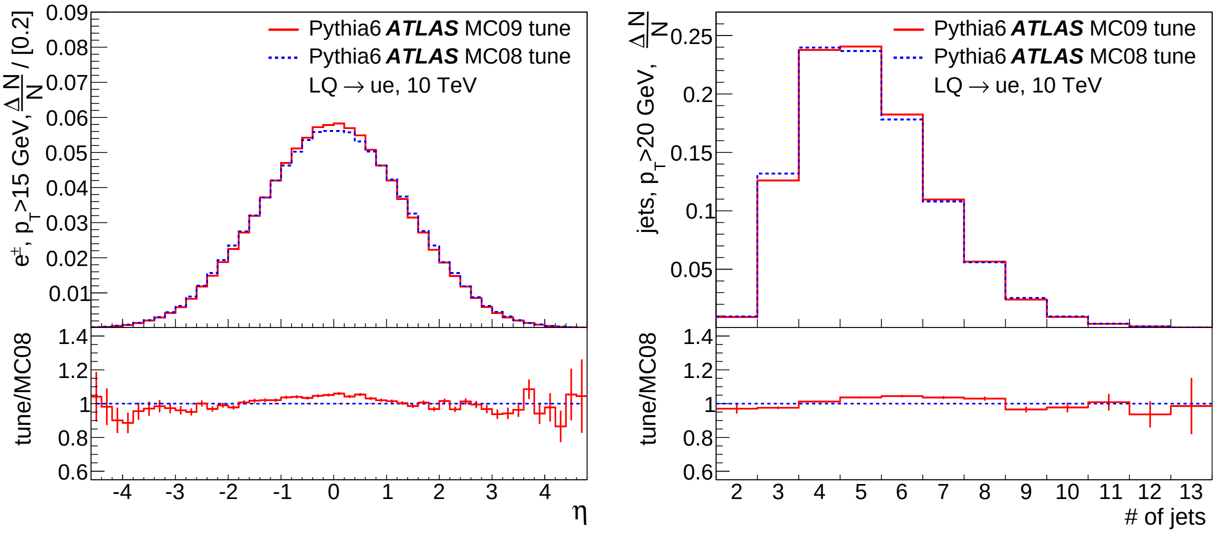
(b) η distribution of Z-bosons in $Z \to e^+e^-$ events



(c) Jet-multiplicity of soft ($p_{\mathrm{T}} < 20\,\mathrm{GeV}$) jets in $Z \to e^+e^-$ events

(d) Jet-multiplicity of hard jets in $Z \to e^+e^-$ events

Figure 14: Comparison of MC09 tune (using MRST2007lomod LO* PDF) and the MC08 tune (using CTEQ6L1 LO PDF) for $Z \to e^+e^-$ process distributions at $\sqrt{s} = 10$ TeV. The Z-bosons are reconstructed from the two hardest opposite sign leptons in an event. The distributions labeled as *not tuned* in Figures 13(c) and 13(d) are obtained by using (MRST2007lomod) LO* PDF for event generation with MC08 tune. All Figures are normalised to unit area. PYTHIA version 6.421 has been used for the sample production.



(a) η distribution of high-p_{T} electrons in Lepto-Quark production

(b) Jet multiplicity distribution of hard jets in Lepto-Quark production

Figure 15: Comparison of MC09 tune (using MRST2007lomod LO* PDF) and the MC08 tune (using CTEQ6L1 LO PDF) for selected observables in Lepto-Quark production, showing (a): η distribution of high-p_{T} ($p_{\mathrm{T}} > 20\,\mathrm{GeV}$) electrons, (b): Jet multiplicity distribution of hard ($p_{\mathrm{T}} > 20\,\mathrm{GeV}$) jets. Both Figures are normalised to unit area. PYTHIA version 6.421 has been used for sample production.

7 Summary

We presented the tunes of PYTHIA and HERWIG/ JIMMY developped by ATLAS for the MC studies of the first LHC data. These new tunes are using the modified LO PDFs in the MC models and partially different minimum bias and underlying event data sets from Tevatron compared to earlier ATLAS tunes.

While the HERWIG/ JIMMY tune is only an adjustement of the free model parameters for the new pdfs, the PYTHIA tune additionally includes a new data-set to tune the energy extrapolation. As a result, the amount of UE activity predicted by PYTHIA at LHC decreased by almost 20% compared to the earlier MC08 tune and agrees now within 10% with those of the HERWIG/ JIMMY tune.

As the original studies introducing modified LO PDFs were done on high-p_T samples [1], the good agreement of the tuned models with the Tevatron data presented here shows that these PDFs can describe the minimum bias and UE data and can hence be used for MC shower generators.

Further studies on the modified LO PDFs at LHC energies confirmed that the PYTHIA tune to adapt for the new PDFs doesn't effect the predictions at high-p_T while the genuine effects of modified LO PDFs - to be closer to the NLO distributions - are still visible. In addition, it has been observed that the ratio of qq to gg fusion processes in $t\bar{t}$ production are also closer to the NLO values.

We presented a tune of JIMMY for the CTEQ6.6 PDF to be used with NLO generators such as MC@NLO.

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