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MULTIPLE PARTONIC INTERACTIONS IN HERWIG++*

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We review the implementation of a model for multiple partonic interactions in Herwig++. Moreover, we show how recent studies on the colour structure of events in Herwig++ led to a significant improvement in the description of soft inclusive observables in pp interactions at the LHC.

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1. Introduction

Multiple partonic interaction (MPI) models are crucial for a successful description of the underlying event (UE) in hard hadronic collisions and minimum-bias (MB) data from the Tevatron and the Large Hadron Collider (LHC). The modern Monte Carlo event generators Herwig++ [1], Pythia [2, 3] and Sherpa [4] all include an MPI model in order to simulate the underlying event. In this short note, we summarize the modelling of multiple parton interactions in the Herwig++ event generator, present its recent developments and show a comparison of the improved model to LHC data.

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2. MPI model in Herwig ++

The modelling of underlying events in Herwig++ is based on the fact that at high enough energies the hard inclusive cross section for dijet production

$$\sigma^{\rm inc}\left(s;p_{\rm t}^{\rm min}\right)=\sum_{i,j}\int\limits_{p_{\rm t}^{\rm min\,2}} dp_{\rm t}^2 f_{i/h_1}\left(x_1,\mu^2\right)\otimes\frac{d\hat{\sigma}_{i,j}}{dp_{\rm t}^2}\otimes f_{j/h_2}\left(x_2,\mu^2\right) \tag{1}$$

will eventually exceed the total cross section [5]. This leads to the interpretation that, in fact, the inclusive cross section counts not only single hard events but all hard events that occur in parallel during the very same hadron–hadron collision.

2.1. Eikonal model

With the eikonal assumption that at fixed impact parameter, $\vec{b}$, individual scatterings are independent[1] and that the distribution of partons in hadrons factorizes with respect to the $\vec{b}$ and x dependence, we can express the average number of hard interactions in a hadron–hadron collision as

$$\bar{n}\left(\vec{b},s\right)=A\left(\vec{b};\mu^2\right)\sigma^{\rm inc}\left(s;p_{\rm t}^{\rm min}\right)\,, \tag{2}$$

where the function $A(\vec{b};\mu^2)$ describes the spatial overlap of the two colliding hadrons (protons) as a function of the impact parameter $\vec{b}$. In both Fortran Herwig [6] with a Jimmy plug-in [7] and Herwig++, the overlap function is modelled according to the electromagnetic form factor [8] and the parameter μ interpreted as the inverse radius of the proton. Since the spatial parton distribution (the colour distribution) is assumed to be similar to the distribution of electric charge, but not necessarily identical, μ is treated as a free parameter. This model allows for the simulation of multiple interactions with perturbative scatters which have $p_{\rm t}>p_{\rm t}^{\rm min}$.

The extension to soft scatterings (with $p_{\rm t}<p_{\rm t}^{\rm min}$) is kept as simple as possible. The additional soft contribution to the inclusive cross section is also eikonalized, such that we can also calculate an average number of soft scatters from the resulting $\sigma_{\rm soft}^{\rm inc}$ and an overlap function $A_{\rm soft}(\vec{b})$ for the soft scattering centres. The functional form $A_{\rm soft}(\vec{b})$ is assumed to be the same as for the hard scatters, but we allow for a different inverse radius, $\mu_{\rm soft}$. The consistency of this model with unitarity is given by fixing the two additional parameters $\sigma_{\rm soft}^{\rm inc}$ and $\mu_{\rm soft}^2$ from two constraints. First, we

[1] Of course, some basic correlations are incorporated into the model later on, for example by requirement of momentum conservation.

can calculate the total cross section from the eikonal model and fix it to be consistent with the Donnachie–Landshoff parametrization [9]. In addition, using the optical theorem, we can calculate the t-slope parameter from the eikonal model and fix it to a reasonable parametrization. This model and its extension to soft scatterings were implemented in HERWIG++ [5, 10] and proved to be capable of describing the whole spectrum of UE data from the Tevatron [11, 12] (including its minimum bias part). However, the MPI model is too simple to describe the first MB data from ATLAS [13, 14] (see dashed/red line in Fig. 1). A tuning of the parameters of the model [15] did not improve the description. This observation led to new developments of the MPI model to include non-perturbative colour reconnections (CR) [16, 17].

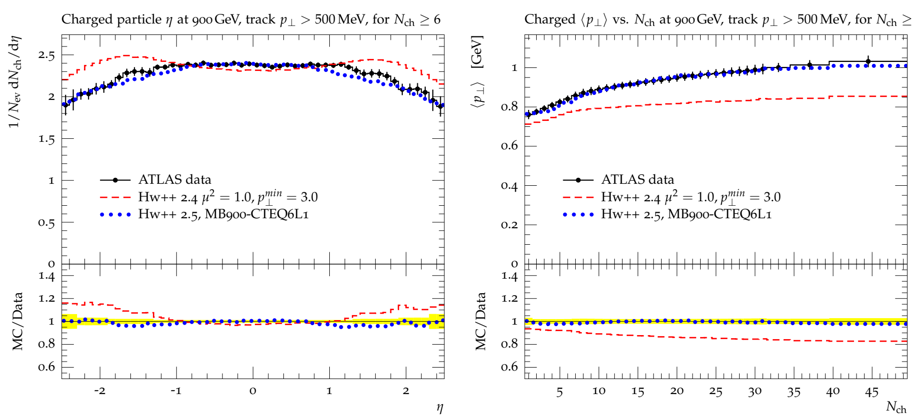

Fig. 1. Comparison of HERWIG 2.4.2 without CR and HERWIG 2.5 with PCR to ATLAS minimum-bias distributions at $\sqrt{s} = 0.9\,\text{TeV}$.

2.2. Colour reconnection

The colour structure of multiple interactions can cause non-trivial changes to the colour topology of the colliding system as a whole, with potentially major consequences for the particle multiplicity in the final state. The colour connections between partons define colour singlet objects known as clusters (see Fig. 2). The cluster hadronization model [18], which is used in HERWIG++, generates clusters which are used as the starting point for the generation of hadrons via cluster decays. The idea of CR is based on colour preconfinement [19], which implies that parton jets emerging from different partonic interactions are colour-connected (clustered) if they are located closely in phase space. As the MPI model does not take that into account, those colour connections have to be adapted afterwards by means of a CR procedure pictured in Fig. 2. In our CR model, we define the distance between two partons to be small when their invariant mass (cluster mass) is small. Therefore, the aim of the CR model is to reduce the colour length $\lambda \equiv \sum_{i=1}^{N_{\rm cl}} m_i^2$, where $N_{\rm cl}$ is the number of clusters in an event and m_i is the invariant mass of cluster i. Based on this physical motivation, there are two colour reconnection models implemented in Herwig++. The first CR model, so-called plain CR (PCR), has been included in Herwig++ as of version 2.5 [20]. This model iterates over all cluster pairs in a random order. Whenever a swap of colours is preferable, *i.e.* when the new cluster masses are smaller, this is done with a given probability (the only parameter of the model). The PCR model has been shown to give the desired results (see dotted/blue line in Fig. 1). However, as the clusters are presented to the model only in a given sequence, it is hard to assess which clusters are affected and to what extent the sequence is physically relevant. Therefore, we implemented another model, the statistical CR model (SCR) [17], which adopts the Metropolis algorithm to reduce λ. This allowed us to systematically study the consequences of the introduction of CR, the results of which are presented in details in [17, 21].

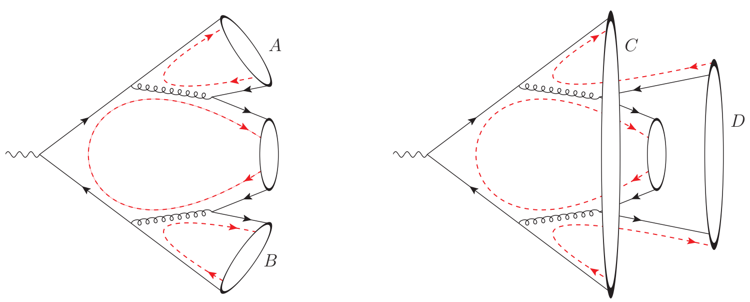

Fig. 2. Formation of clusters, which we represent by ovals here. Colour lines are dashed. The right diagram shows a possible colour-reconnected state: the partons of the clusters A and B are arranged in new clusters, C and D.

3. Tuning and results

Initially, we were primarily aiming at an improved description of MB data, therefore, we started by tuning the PCR model to ATLAS MB data[2] (results are shown in Fig. 1). The next important question was whether the new model is able to describe the UE data sets at different collider energies. A dedicated tuning procedure [22] resulted in energy-extrapolated

[2] Since currently there is no model for soft diffractive physics in Herwig++, we use the diffraction-reduced ATLAS MB measurement with an additional cut on the number of charged particles, $N_{\rm ch} \geq 6$.

tunes UE–EE, for both PCR and SCR, in which all parameters are fixed except for $p_t^{\min}$, which varies with energy. These tunes allow us to describe data at different energies [11, 23] (see Fig. 3) with a simple parametrization of the $p_t^{\min}$ energy dependence. This was an important step towards the understanding of the energy dependence of the model. Finally, we show the

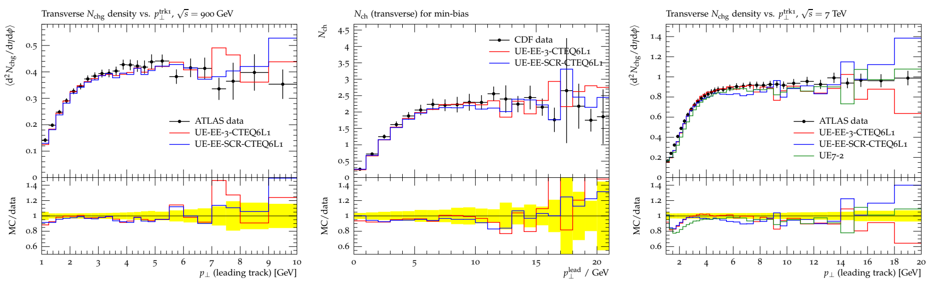

Fig. 3. ATLAS data at 900 GeV (1st column), CDF data at 1800 GeV (2nd column) and ATLAS data at 7 TeV (3rd column), showing the multiplicity density of the charged particles in the "transverse" area as a function of $p_\perp^{\text{lead}}$.

results of the model for energy flow as a function of η for minimum-bias events at $\sqrt{s} = 0.9$ and 7 TeV (Fig. 4) presented by the CMS Collaboration during this workshop and also published in [25]. This observable was not available during the preparation of the tunes and these very good results can, therefore, be treated as a prediction of the model. The new model is implemented and available with the recent tunes in Herwig++ version 2.6 [24].

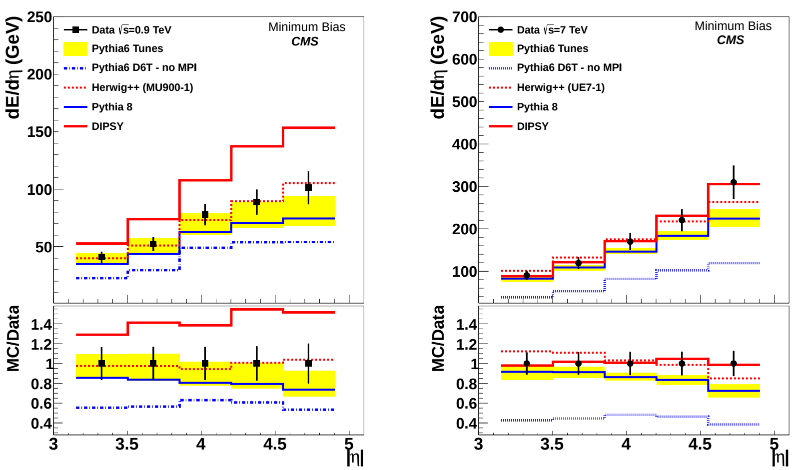

Fig. 4. Energy flow as a function of η for MB events at $\sqrt{s} = 0.9$ and 7 TeV.

4. Summary

We have summarized the multiple partonic interaction models in Herwig++ and expanded on the motivation and modelling of colour reconnection. Furthermore, we have shown that (sufficiently diffraction-suppressed) MB data from the LHC and underlying-event observables are well described by the present model which makes it useful for the LHC collaborations.

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