Multiple Partonic Interaction
Developments in Herwig++

S. Gieseke, C. A. Röhr, A. Siódmok

Institut für Theoretische Physik, Karlsruhe Institute of Technology, Karlsruhe, Germany

We briefly review the status of the multiple partonic interaction model in the Herwig++ event generator. First, we show how a change in the colour structure of an event in Herwig++ results in a significant improvement in the description of soft inclusive observables in pp interactions at √s = 900 GeV. Then we present a comparison of some model results to ATLAS Underlying Event data at √s = 7 TeV.

PRESENTED AT

MPI@LHC 2010: 2nd International Workshop on Multiple Partonic Interactions at the LHC
Glasgow, 29th of November to the 3rd of December 2010

1Speaker.
1 Introduction

The magnificent operation of the LHC in 2010 gave us the opportunity to study physics at the new high-energy frontier. The first physics results from the LHC experiments were measurements of Minimum-Bias (MB) \cite{1} and Underlying Event (UE) characteristics \cite{2}. Understanding the UE and MB interactions is very important for many aspects of LHC physics. The amount of UE activity at the LHC is measured, so one might think that the size of the UE correction is known. However, in practice, there are observables that depend on correlations or fluctuations away from average properties of the UE, including, to varying extents, any measurement relying on jets or isolation criteria. In fact, almost every observable that will be used for new physics searches or precision measurements falls into this class, so the correction must be represented by a model tuned to data, rather than by a single number measured from data. In this short note we present recent developments in the modelling of the multiple partonic interactions in \texttt{Herwig++} and show, for the first time, a comparison of the improved model to 7 TeV UE data.

2 Multiple Parton Interactions in \texttt{Herwig++}

2.1 Eikonal model

The first model for hard multiple partonic interactions in \texttt{Herwig++} was implemented in version 2.1 of the program and is based on the eikonal model described in Ref. \cite{3}. This model derives from the assumption that at fixed impact parameter, $b$, individual scatterings are independent and that the distribution of partons in hadrons factorizes with respect to the $b$ and $x$ dependence. This implies the average number of partonic collisions at a given $b$ value to be

$$\langle n(b, s) \rangle = A(b; \mu) \sigma^{\text{inc hard}}_{\text{hard}}(s; p^\text{min}_\perp), \quad (1)$$

where $A(b; \mu)$ is the partonic overlap function of the colliding hadrons and $\sigma^{\text{inc hard}}_{\text{hard}}$ is the inclusive production cross section of a pair of partons with $p_\perp > p^\text{min}_\perp$. The impact parameter dependence of partons in a hadron is modelled by the electromagnetic form factor,

$$A(b; \mu) = \frac{\mu^2}{96\pi} (\mu b)^3 K_3(\mu b), \quad (2)$$

where $K_3(x)$ is the modified Bessel function of the third kind and $\mu$ is the inverse proton radius. Since the spatial parton distribution is assumed to be similar to the distribution of charge, but not necessarily identical, $\mu$ is treated as a free parameter. This model allows for the simulation of multiple interactions with perturbative scatters with $p_\perp > p^\text{min}_\perp$. Due to the lack of soft scatters below $p^\text{min}_\perp$, this first model is only
able to describe the jet production part of the CDF data \cite{4}, above approximately 20 GeV, but not the more inclusive minimum-bias part.

An extension of the model to include soft scatters (with $p_{\perp} < p_{\perp}^{\text{min}}$) has been implemented in \texttt{Herwig++} and has been the default underlying event model as of version 2.3. The additional soft contribution to the inclusive cross section is also eikonalized. In this way we can calculate the average number of soft scatters from the respective soft inclusive cross section $\sigma_{\text{inc}}^{\text{soft}}$ and the overlap function for the soft scattering centres $A(b; \mu)$. The functional form of $A(b; \mu)$ is assumed to be the same as for the hard scatters, but we allow for a different inverse radius, $\mu_{\text{soft}}$. We keep this model consistent with unitarity by fixing the two additional parameters $\sigma_{\text{inc}}^{\text{soft}}$ and $\mu_{\text{soft}}$ from two constraints. First, we can calculate the total cross section from the eikonal model and fix it to be consistent with the Donnachie–Landshoff (DL) parametrization \cite{5}. In addition, using the optical theorem, we can calculate the elastic $t$-slope parameter from the eikonal model and fix it to a reasonable parametrization. This model is capable of describing the whole spectrum of UE data from the Tevatron including its minimum bias part.

### 2.2 Colour correlations

Despite providing a good description of the CDF UE data, this model turned out to be too simple to describe the Minimum Bias ATLAS data collected at 900 GeV \cite{1}. In particular, the predictions for the charged-particle multiplicity as a function of pseudorapidity and the average transverse momentum as a function of the particle multiplicity, $\langle p_{\perp} \rangle(N_{\text{ch}})$, are extremely far from the data. This discrepancy is shown in Fig. \ref{fig:1} where the red line represents the \texttt{Herwig++} 2.4.2 results, featuring the model as described above\cite{4}. As presented in more detail in \cite{6}, a tuning of the parameters of the MPI model was not able to improve this description.

The prediction of \texttt{Herwig++} for $\langle p_{\perp} \rangle(N_{\text{ch}})$ was close to insensitive to the parameters of the MPI model. Moreover, this observable is known to be very sensitive to non-perturbative colour reconnection. This triggered new developments of the MPI model to include non-perturbative colour reconnections (CR). The CR model presented in this work can be regarded as an extension of the cluster model \cite{7}, which is used for hadronization in \texttt{Herwig++} \cite{8}. Hadronization in \texttt{Herwig++} is based on the pre-confinement property of perturbative QCD \cite{9}. According to that, a parton shower evolving to the cut-off scale $Q_0$ ends up in a state of colourless parton combinations with finite mass of $\mathcal{O}(Q_0)$. In the cluster hadronization model, these parton combinations – the clusters – are interpreted as highly excited pre-hadronic states. They act as a starting point for the generation of hadrons via cluster decays, which can be performed in multiple steps. Colour reconnection in the cluster

\*Currently there is no model for soft diffractive physics in \texttt{Herwig++}. Therefore we use diffraction-reduced ATLAS MB analysis with an additional cut on the number of charged particles: $N_{\text{ch}} \geq 6$.\footnote{Current there is no model for soft diffractive physics in \texttt{Herwig++}. Therefore we use diffraction-reduced ATLAS MB analysis with an additional cut on the number of charged particles: $N_{\text{ch}} \geq 6$.}
model occurs at the stage where clusters are formed from the parton-shower products. Starting with the clusters, produced generically by virtue of pre-confinement, cf. Fig. 2(a) the cluster creation procedure is slightly modified. Pairs of clusters are allowed to be ‘reconnected’. This means the coloured constituent of cluster $A$ and the anti-coloured constituent of cluster $B$ form a new cluster, as do the remaining two partons, cf. Fig. 2(b). The following steps describe the full algorithm of the colour reconnection model implemented in Herwig++ 2.5:

1. Do the subsequent steps for all quarks in random order.
2. The current quark is part of a cluster. Label this cluster $A$.
3. Consider a colour reconnection with any other cluster $B$. For the possible new clusters $C$ and $D$, which emerge during reconnecting $A$ and $B$ as in Fig. 2, the following must be satisfied:
   
   $m_C + m_D < m_A + m_B$.

   Here, $m_i$ denotes the invariant mass of cluster $i$.  

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**Figure 1**: Comparison of Herwig++ 2.4.2 and Herwig++ 2.5 to ATLAS minimum-bias distributions at $\sqrt{s} = 0.9$ TeV with $N_{ch} \geq 6, p_{\perp} > 500$ MeV and $|\eta| < 2.5$. The ATLAS data was taken from plots published in Ref. [1].
Figure 2: Formation of clusters, which are represented by ovals. Colour lines are dashed. (a) shows colour-singlet clusters formed according to the dominating colour structure in the $1/N_C$ expansion. (b) shows a possible colour-reconnected state: the partons of the clusters $A$ and $B$ are arranged in new clusters, $C$ and $D$.

- $C$ and $D$ do not consist of a $q\bar{q}$ pair produced in a preceding gluon splitting.

4. Amongst the found reconnection possibilities select the one that results in the smallest sum of cluster masses, $m_C + m_D$. Accept this colour reconnection with an adjustable probability $p_{\text{reco}}$. This parameter steers the amount of colour reconnection in the CR model.

A further extension of the MPI model is to restore the possibility of changing the colour connections in the soft component of the model. The model provides a parameter $p_{\text{disrupt}}$, which is the probability of soft scatters to be disconnected in colour space from the rest of the event. $p_{\text{disrupt}} = 1$, the default in Herwig++, physically corresponds to no colour strings between the beam remnants and the soft particles produced in the soft underlying event.

So in total, there are four main parameters of the MPI model: The inverse hadron radius squared $\mu$, $p_{\perp}^{\text{min}}$, the colour reconnection probability $p_{\text{reco}}$ and the probability of colour disruption of the soft scatters $p_{\text{disrupt}}$.

3 Results

In the first step we check whether with the new colour reconnection model allows us to describe the ATLAS MB data at 900 GeV, which was the main motivation for extending the model. For that purpose, we tuned the four model parameters using
Figure 3: Charged multiplicity and scalar $\sum p_\perp$ density of charged particles with $p_t > 100$ MeV and $|\eta| < 2.5$ in the transverse region. The predictions of the UE7-2 tune are compared to ATLAS UE data at 7 TeV [2].

the Professor tool [10] to the diffraction-reduced ATLAS MB sample. The results of the tune are shown by the blue lines in Fig. 1.

First, from Fig. 1(b) we can see that – as expected – colour reconnection helps to achieve a better description of $\langle p_T \rangle (N_{ch})$. Secondly, also the $\eta$ distribution is now well described. The old MPI model, whose results are comprised in the dashed Herwig++ 2.4.2 lines in Fig. 1 generates pronounced peaks in the forward directions. The reason for that behaviour is that the soft scatters in this model are disconnected from the rest of the event, $p_{\text{disrupt}} = 1$. In combination with the small transverse momenta of the soft scatters, $p_t < p_{\text{min}}\perp$, this colour disruption accounts for a strong population of particles of the forward region of the event. Changing the value of $p_{\text{disrupt}}$ to smaller value, as done in the Herwig++ 2.5 model, helps to get a better shape, however the colour reconnection model is vital to describe this observable. Other MB observables provided by ATLAS, for instance the charged-particle multiplicity as a function of the transverse momentum, are also well described with the extended model.

Finally, for the first time we show the results of the new model against the UE data collected by ATLAS [2] at 7 TeV. As before we use the Professor tool to tune the parameters of the model. This time we used two observables for the tune: The mean number of stable charged particles per unit of $\eta$-$\phi$, $\langle d^2N_{ch}/d\eta d\phi \rangle$, and the mean scalar $p_\perp$ sum of stable particles per unit of $\eta$-$\phi$, $\langle d^2\sum p_\perp/d\eta d\phi \rangle$, both as a function of $p_{\text{lead}}^{\perp}$ in the kinematic range $p_\perp > 500$ MeV and $|\eta| < 2.5$. As a result,
we obtained a tune named UE7-2, which gives very satisfactory results for the tuned observables. The full comparison with all ATLAS UE and MB data sets is available on the Herwig++ tune page [11] – here we just present a few selected examples. In Fig. 3 we show \( \langle d^2 N_{\text{ch}}/d\eta d\phi \rangle \) and \( \langle d^2 \sum p_{\perp}/d\eta d\phi \rangle \) as a function of \( p_{\perp}^{\text{cut}} \) for the lower \( p_{\perp} \) cut (\( p_{\perp} > 100 \text{ MeV} \)) in the transverse region (which is the most sensitive region with respect to multiple interactions) compared to the Herwig++ UE7-2 results. The observables with the lower \( p_{\perp} \) cut were not available during the preparation of the tune, and these excellent results can therefore be treated as a prediction of the model.

In Fig. 4 we see that the standard deviation of the charged particle multiplicity and charged particle scalar \( \sum p_{\perp} \) densities in the transverse region, which were not included in the tuning procedure, are also described correctly. In the last plot, Fig. 5 we present the angular distributions of the charged particle multiplicity and \( \sum p_{\perp} \), with respect to the leading charged particle (at \( \Delta \phi = 0 \)). The data sets are shown for four different lower \( p_{\perp} \) cut values in the transverse momentum of the leading charged particle. With the increase of the leading charged particle \( p_{\perp}^{\text{lead}} \), the development of a jet-like structure can be observed. The overall description of the data is satisfactory but we can also see that the description improves as the lower cut value in \( p_{\perp}^{\text{lead}} \) gets higher. Finally, the values of the model parameters used in the UE7-2 tune are

\[
p_{\perp}^{\text{min}} = 3.36 \text{ GeV}, \quad \mu^2 = 0.81 \text{ GeV}^2, \quad p_{\text{disrupt}} = 0.35, \quad p_{\text{reco}} = 0.616 .
\]
Figure 5: Azimuthal distribution of charged particle multiplicity and $\sum p_\perp$ densities, with respect to the direction of the leading charged particle (at $\phi = 0$), for $|\eta| < 2.5$. The densities are shown for $p_{\perp}^{\text{lead}} > 1 \text{ GeV}$, $p_{\perp}^{\text{lead}} > 2 \text{ GeV}$, $p_{\perp}^{\text{lead}} > 3 \text{ GeV}$ and $p_{\perp}^{\text{lead}} > 5 \text{ GeV}$. The data is compared to the UE7-2 tune.

For completeness, having the value of $\mu$, using Eq. 2 we can calculate $\sigma_{\text{eff}} = [\int db A^2(b, \mu)]^{-1} = 42.28 \text{ mb}$. Since, as we have shown in [11], there is some freedom in choosing the parameters during a tune it is possible to describe data at the same level of accuracy having $\mu^2$ in the range between 0.8 – 1.35 GeV$^2$. Therefore, the value of $\sigma_{\text{eff}}$ in other tunes can be significantly different to the one calculated above. In the case of the highest possible value of $\mu^2 = 1.35 \text{ GeV}^2$, we find $\sigma_{\text{eff}} = [\int db A^2(b, \mu)]^{-1} = 25.37 \text{ mb}$.

4 Summary and outlook

We have shown that introducing colour reconnections and stronger colour correlations of soft scatters with the beam remnants enables a proper description of non-diffractive MB observables. Moreover, we presented a comparison of the Herwig++ UE7-2 tune to ATLAS UE data at 7 TeV. Despite these very promising results, there are still open questions concerning the MPI model in Herwig++, which we would like to address in the future. In particular, we hope to obtain a deeper physical understanding of the colour reconnection model. Also the energy dependence of the model parameters is to be surveyed since, with the current model, different tunes for different $\sqrt{s}$ are mandatory. Another physically appealing question is whether and how a united description of UE and MB data sets can be achieved.
The new model is implemented and available in the current version of Herwig++ 2.5. News concerning Herwig++ tunes are available [11].

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