Tests of Pythia8 Rescattering Model

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Abstract

One of the most poorly understood phenomenon in hadron collisions, is the so called multiple parton interaction (MPI). Apart from one quark or gluon each from each colliding proton, additional quarks or gluons can interact as well, and these can not be calculated from first principles. The concept of rescattering has been introduced recently in Pythia 8 event generator, where particles originating from these secondary interactions can interact again with quarks or gluons from incoming protons. In this paper, we look at events with a Z-boson, to find observables which can potentially be sensitive to this rescattering effect. While jet-balance observables do not show visible difference, charged particle distributions in different azimuthal regions show some difference. The parameters controlling MPI can be tuned to give a good description of data with rescattering.

1 Introduction

Monte Carlo event generators are used extensively in collider physics. Pythia 8 is one of the most commonly used generator [1], using the parton shower approach. The parton shower approach is based on the assumption that a $2 \rightarrow n$ process, with a complex final state is achieved by starting from a simple $2 \rightarrow 2$ process that approximately defines the directions and energies of the hardest partons, and adding a succession of simple parton branchings to build up the full event structure. The different components of the model are initial and final state radiation
I/FSR), multiple parton interactions (MPI), fragmentation and hadronisation. In this paper, the focus is on MPI.

The collider coordinate system needs to be specified in order to define the variables. The colliding beams are taken along the $z$-axis, while the $x$-$y$ plane represents the transverse direction with respect to the beams, where the collision output particles are. Transverse momentum, $p_T$ is defined relative to the beam axis. The azimuthal angle $\phi$ is measured around the beam axis, and the polar angle $\theta$ is measured with respect to the $z$-axis. The pseudorapidity is given by $\eta = -\ln \tan(\theta/2)$.

The analysis and plots are done using the Rivet [2] analysis framework.

2 MPI and Rescattering

Since each incoming proton in hadron colliders such as LHC is a composite object, consisting of many partons, the actual collision happens between two partons, which is referred to as hard scatter (HS). However, there exists the possibility of several parton pairs interacting when two hadrons collide, which is termed as multiple parton interactions (MPI). Double parton intercation (DPI), is a special case of MPI, with only one additional scattering. Figure 1, left schematically represents an MPI event, taken from [3].

Among the parameters controlling the strength of MPI in Pythia 8 model, a $p_T$ cutoff, and $\alpha_s$, the strong coupling constant for MPI will be looked at here. The $p_T$ cutoff is necessary to regularise the divergence of partonic interaction cross-section at low-$p_T$, and larger/smaller values result in less/more MPI. The $\alpha_s$ value is usually evaluated at the $Z$-mass, and results in more/less activity from MPI for higher/lower value.

The concept of rescattering [3] off MPI has been introduced recently in Pythia 8. This occurs when a parton produced from the HS can interact directly with a parton from an incoming proton. This is the simplest example, and termed single rescattering, as shown in Figure 1, right, again taken from [3]. Double rescattering can also happen, which can be considered as the more general case.
3 Setup

The first step was to check if any kinematic observables can be sensitive to the presence of rescattering. The $Z$-boson production, in association with extra jets was chosen, at it offers a relatively clean final state. Events with at least 3 extra jets, each with transverse momentum, $p_T > 20$ GeV and absolute rapidity, $|y| < 4.4$ were used.

The assumption is that the highest $p_T$ jet (leading jet) will balance the $Z$-boson momentum, and the additional two jets can either originate from ISR, or from MPI. In case they originate from MPI, they are allowed to undergo rescattering. Now on an individual event-by-event basis it is unphysical to try to label jets depending on their origin (HS, ISR or MPI), and no attempt is made to do so. Rather a set of kinematic distributions were looked at, once generating the events once with rescattering, once without. This is done by:

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MultipartonInteractions:allowRescatter = on
MultipartonInteractions:allowDoubleRescatter = on
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The samples were generated with Monash tune [4] using NNPDF2.3LO PDF set [5]. 5 million events were generated in each case.

The next step was to compare the simulation to actual data distributions. For this, the published ATLAS $Z$-boson underlying event (UE) analysis [6] was used. In this analysis, the direction of the $Z$-boson in each event was taken as the direction of HS, and the azimuthal plane was divided into the toward, transverse and away regions on an event-by-event basis, as shown in Figure [2]. Additionally again on an event-by-event basis, the more (less) active transverse side was labeled as transmax (transmin).

The transverse region, being perpendicular to the direction of hard scattering, is expected
to be most sensitive to underlying event, which is defined as the additional activity in an event with an identified HS. However, at the busy LHC environment, the transverse regions receives significant contribution from additional HS jets, so it can no longer be used as a clean probe of UE. However, after the subtraction of the contribution from the leptons from the Z-boson decay, the activity in the toward region is also sensitive to the underlying event. Since there is no final-state gluon radiation. It is also expected that transmin region, by construction, will have less contribution from HS jets, hence it is also used to probe UE. Following that, the modeling of charged particle activity in this two regions will be looked at.

4 Results

The kinematic distributions of several variables which are expected to sensitive to DPI topology are compared between samples generated with and without rescattering.
The first variable is indicative to $p_T$ balance between hard objects. In the following, $\vec{p}_T^i$, indicates the vector transverse momentum of the $i$th hard object. Since at least 3 additional jets are required along with the Z-boson, $i = 1$ will denote the $p_T^Z$, and $i = 2, 3, 4$ will denote the jets, in order of decreasing $p_T$. The value closer to unity denotes the hard objects are more $p_T$ balanced.

$$\Delta_{ij}^{p_T} = \frac{|\vec{p}_T^i + \vec{p}_T^j|}{|\vec{p}_T^i| + |\vec{p}_T^j|}$$

As Pythia 8 do not produce enough 3-jet events, the distributions suffer from a lack of statistics, which makes arriving at any strong conclusions difficult. However, some general trends can be observed. In Figure 3, the $\Delta_{ij}^{p_T}$ variable is can be seen for two combinations. While the difference between events generated without and with rescattering is not expected to affect the $p_T$ balance between the Z-boson and the leading jet, the 1st and 2nd jet, and 2nd and 3rd jet balances are also fairly insensitive to rescattering.

The angular distributions also suffer from a similar lack of statistics. In Figure 4, the $\eta$ differences are looked at, with the indices defined as before. Again the $\eta$ difference between the Z-boson and the leading jet is essentially non-existent for events without and with rescattering, but the $\eta$ difference between the Z-boson and 3rd leading jet seems to a bit more when rescattering happens.

Finally, in Figure 5 the $\phi$ difference is probed, again the indices are defined as before. The term $\phi_{i+j}$ represents the $\phi$ of resultant four-vector by adding the four-vectors of hard objects $i$ and $j$. This $\phi$ balance two supposedly balanced pair of hard objects show hardly any difference, as well as the difference of $\phi$ of the Z-boson and the 3rd leading jet, for events without and with rescattering.

The next part of the study was the comparison ATLAS UE analysis in Z-boson events. In Figure 6, the average charged particle $p_T$-sum density is shown in toward and tranmin regions, compared with three different Pythia 8 predictions. The red line, which is generated with the Monash tune, without any extra settings, describes the data reasonably well at the low $p_T^Z$ range. It must be noted, that Pythia 8 being a leading order PS generator, it is not expected to describe the production of extra jets from HS, which is occurs more with increasing $p_T^Z$. So the focus will be on the relatively low $p_T^Z$ range, $p_T^Z < 50$ GeV in this distributions. When rescattering option is turned on, as in the blue line, it produces too much activity, and the previous decent agreement between data and simulation is destroyed. To restore the agreement, a simple tuning of the two MPI parameters is done. It can be seen that with this tuning, the

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1 The average value in each angular region is divided by the angular area to arrive at the densities, which allows for direct comparisons between different regions.
Figure 3: Comparisons between Pythia 8 predictions without and with rescattering for $p_T$ balance observables.

original agreement of Monash tune can be restored with rescattering. The tuned values of the parameters are:

MultipartonInteractions:pT0Ref = 2.2
MultipartonInteractions:alphaSvalue = 0.126

Similar conclusions can be arrived at charged particle multiplicity density shown in Figure 7. In Figure 8, the mean $p_T$ against Z-boson $p_T$ and multiplicity are not affected at all by rescattering.
Figure 4: Comparisons between Pythia 8 predictions without and with rescattering for $\eta$ difference observables

Figure 5: Comparisons between Pythia 8 predictions without and with rescattering for $\phi$ difference observables
Figure 6: ATLAS data for underlying event distributions in Z-boson event is compared with Pythia 8 Monash tune without and with rescattering and after tuning prediction for charged particle sum $p_T$ density.

Figure 7: ATLAS data for underlying event distributions in Z-boson event is compared with Pythia 8 Monash tune without and with rescattering and after tuning prediction for charged particle multiplicity density.
Figure 8: ATLAS data for underlying event distributions in Z-boson event is compared with Pythia 8 Monash tune without and with rescattering and after tuning prediction for mean charged particle $p_T$. 
5 Conclusions

The effect of rescattering in the framework of multiple parton interactions in Pythia 8 are probed. While kinematical observables constructed from Z-boson events with 3 additional jets did not show a strong sensitivity, the charged particle distributions sensitive to UE is affected by rescattering. A similar level of agreement with ATLAS Z-boson UE data can be achieved with rescattering by a simple tuning of MPI parameters.

References

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