1 Introduction

In the shower Monte Carlo framework, in processes that already have collinear singularities at the Born level, a generation cut is needed in order to build useful event samples. In dijet production, for example, one chooses a minimum transverse momentum for the $2 \to 2$ parton process. It is assumed, and in fact it must be checked, that, in the final showered sample, the fraction of events that are near the generation cut at the Born level and that pass the required analysis jet cuts after shower is actually negligible. In other words, the final results should be insensitive to the generation cut. Alternatively, one can introduce a Born suppression factor. This is a function of the Born kinematics that multiplies the Born cross section, suppressing its low transverse-momentum region. In this way, the Born cross section times the suppression factor is an integrable function, and one can generate events with a probability proportional to this product. Events are then generated with an associated weight, equal to the inverse of the Born suppression factor.

The use of a Born suppression factor has the advantage that, for sufficiently large samples, it yields a correct result. In this case, events that have particularly low transverse momenta at the Born level, and that after shower do exhibit hard jets, will appear with a very large weight, equal to the inverse of the suppression factor. They should be rare enough so as not to spoil the statistical errors in the results.

It has been observed that, in dijet production [1], these events with large weight do in fact cause problems. In physical distributions large spikes appear from time to time, and it is very difficult to get rid of them by increasing the statistics.
2 Origin of spikes in dijet production

An important mechanism leading to events with large weight in dijet production was recently identified.

The problem is due to the treatment of the $q \to qg$ and $g \to q\bar{q}$ splittings in the **POWHEG BOX**. In order to minimize the number of generated configurations, the **POWHEG BOX** always generates the $q \to qg$ and $g \to q\bar{q}$ configurations, and never generates the $q \to gq$ and $g \to \bar{q}q$ ones. The transverse momentum in final state radiation is defined to be

$$p_T^2 = 2E^2(1 - \cos \theta),$$

where $\theta$ is the angle between the splitting partons, and $E$ is the energy of the emitted parton (i.e. parton $k$ in the $i \to jk$ splitting), both in the partonic centre of mass. Notice that, if the final-state partons are back to back, $p_T^2$ is large. Furthermore, $p_T^2$ is large also if the recoiling parton has small energy, and relatively large angle $\theta$. This region, however, has small impact in the **POWHEG BOX**. If the emitter is a quark, a soft quark yields no infrared singularities, and thus the region of soft quarks is power suppressed. If the emitter is a gluon, the **POWHEG BOX** suppresses this region with a factor of the form

$$\frac{E_{\text{em}}^p}{E_{\text{em}}^p + E^p},$$

where $p$ is a positive number (usually 2) (the emitter is a gluon only if also the emitted parton is a gluon in the **POWHEG BOX**).

In case of jet production, when using the Born suppression factor instead of a generation cut, the above scheme can yield to events with large weights and large transverse momenta after showering. They are produced as follows: an underlying Born event is produced with very small transverse momentum, corresponding to a $2 \to 2$ parton scattering at very small angle. Because of the Born suppression factor, these events are rarely produced, and have a large weight (proportional to the inverse of the suppression factor). Suppose now that a splitting process takes place, where a final-state parton, for example, a gluon, splits into two partons $q\bar{q}$, with $\bar{q}$ carrying most of the energy of the incoming gluon, and $q$ is soft and at a large angle. This event is phase-space suppressed. However, since the splitting pair has a small mass, its matrix element has no further suppression. According to the definition of the radiation transverse momentum in the final states in the **POWHEG BOX**, this event has large transverse momentum (see eq. (1)). When passing the event to **PYTHIA**, further jets with relatively large transverse momentum may be produced. This event would pass the jet cuts, and have a large weight.

3 Fixing the problem

A patch that avoids this problem has been implemented in the SVN revision 2169. In order to activate the fix, the user should put the line `doublefsr 1` in the `powheg.input` file. If not present, or different from 1, the program behaves exactly as before.

In the `doublefsr 1` mode the program does the following:

- Considers all splitting processes, including $q \to gq$ and $g \to \bar{q}q$, and not only the $q \to qg$ and $g \to q\bar{q}$.
• Suppresses all splitting processes with a factor proportional to eq. (2). Thus both processes $i \rightarrow jk$ and $i \rightarrow kj$ are present, with suppression

$$\frac{E^p_j}{E^p_j + E^p_k}, \quad \text{and} \quad \frac{E^p_k}{E^p_j + E^p_k},$$

respectively. Since the two splitting processes are equivalent, and the sum of the two suppression factors is one, one gets back the correct result.

The above prescription is formally correct and avoids the problem of the original POWHEG BOX scheme. Notice that the original prescription was not incorrect. However, it turned out to be not practical for a large number of events, where spikes were showing up, and too much statistics would have been required to smooth them away.

### 4 Modification of the scalup prescription

We have also studied in the past a modification of the scalup assignment that gets rid of the spike problem. Rather than using the scalup value provided by the POWHEG BOX, we suggested to recompute its value as follows. We go to the partonic centre-of-mass frame of the Les Houches event, and compute the smallest transverse momentum of each final state parton with respect to the incoming beams and with respect to each others, and set scalup to this value. The relative squared transverse momentum of two final-state partons $j$ and $k$ is defined as

$$p_T^2 = \left( p_j \cdot p_k \right) \frac{E_j E_k}{(E_j + E_k)^2}.$$  

### 5 Effects in the output

We have considered the LHC at 7 TeV. We have generated two samples of 6M Les Houches events with the new version of the POWHEG BOX Dijet program, one with the doublefsr flag set to 1 (the D1 sample from now on), and one with no doublefsr (the D0 sample). We have showered these samples with PYTHIA 6 [2], keeping the hadronization turned off. Our PYTHIA settings were:

- **Perugia tune**
  
  CALL PYTUNE(320)

- **No QED radiation off quarks**
  
  MSTJ(41)=11

- **Hadronization off**
  
  MSTP(111)=0

- **Primordial kt off**
  
  MSTP(91)=0

- **No multiparton interactions**
  
  MSTP(81)=20

We have used the CTEQ6M [3] parton densities.

We have also considered the alternative scalup definition of sec. 4, that will be referred to as the RS (for recomputed scalup) choice in the following.
In all the figures, two curves are shown, a red and a green one. In the lower panel, the ratio (displayed in red) of the red over the green is shown.

We begin by comparing samples D1 and D0 at the level of Les Houches events (i.e. before shower). In fig. 1 we show the inclusive transverse-momentum distributions at various rapidity intervals, for jet production. Jets are built with the anti-$k_T$ algorithm [4], with $R = 0.4$. One can notice the very good agreement between the two samples.

In figs. 2 and 3 we compare the Les Houches versus the showered results in the D0 and D1 samples. We see that spikes are present, but are much less important in the D1 sample.

The trend in the contribution of shower effects seems to be similar in the D0 and D1 samples. It is thus interesting to compare the two samples directly, to see if drastic changes of the final distributions are present. This comparison is shown in fig. 4. It is clear from the comparison that, aside from the large spikes, no significant differences, above a few percent, are visible in the two samples.

We now consider the effect of changing the way that the upper bound for radiation in the shower is computed. We show in figs. 5 and 6 the comparison of the result with the RS choice for scalup versus the standard one, in sample D0 (fig. 5) and D1 (fig. 6). We see that in both cases, the use of the RS choice leads to some differences that can reach the 10% level for small transverse momenta.

As a final note, we also consider the effect of a further improvement in the separation of regions in the POWHEG BOX, that has been recently found to be useful in processes of vector boson production in association with jets [3]. We have generated a sample using this method, in association with the doublefsr 1 setting. The comparison of the result at the Les Houches level versus the showered one is shown in fig. 7. We see a slight improvement, with even less spikes, when the new option is applied. On the other hand, no sensible differences are seen between this new sample and sample D1, as shown in fig. 8.

6 Conclusions

In this note we have introduced a refinement of the way in which the POWHEG BOX separates the singular regions. This refinement constitutes without doubt and improvement, although this improvement is only relative to a small region of phase space.

We have observed that, from a practical point of view, the introduction of the new feature helps in reducing the appearance of spikes in the computed distributions. We thus recommend that this feature should be used always in dijet production.

We have also studied the sensitivity of the results due to a modification of the way the POWHEG events are passed to the shower Monte Carlo program. We see no reason why the modified scheme (referred to as RS in the text) should not be considered as valid as the original POWHEG one. We thus conclude that the variation that we have found should be considered an intrinsic theoretical uncertainty related to NLO+PS matching. We do not have, at the moment, a systematic way to assign a theoretical error to this uncertainty.

References

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Fig. 1: Comparison of the inclusive jet $p_T$ distribution in the D1 (red) and D0 (green) samples, at the Les Houches level (i.e. before shower).
Fig. 2: Comparison of the inclusive jet $p_T$ distribution in sample D0, at the Les Houches level (red), and after shower (green).
Fig. 3: Comparison of the inclusive jet $p_T$ distribution in sample D1, at the Les Houches level (red), and after shower (green).
Fig. 4: Comparison of the inclusive jet $p_T$ distribution from the showered sample D1 (red) and D0 (green).
Fig. 5: Comparison of the inclusive jet $p_T$ distribution from the showered D0 sample. We compare the output obtained using the RS choice for $\text{scalup}$ (red) versus the standard one (green).
Fig. 6: Comparison of the inclusive jet $p_T$ distribution from the showered D1 sample. We compare the output obtained using the RS choice for scalup (red) versus the standard one (green).
Fig. 7: Comparison of the inclusive jet $p_T$ distribution, at the Les Houches level (red) and after shower (green), for the sample obtained with the `doublefsr` option and with the new separation of regions.
Fig. 8: Comparison of the inclusive jet $p_T$ distribution after shower, between the sample obtained with the `doublefsr 1` option and with the new separation of regions of ref. [5], and sample D1.