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QUARK/GLUON JETS DISCRIMINATION AND ITS CONNECTION TO COLOUR RECONNECTION*

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The possibility of discriminating quark and gluon jets is important for searches for BSM physics, where signals of interest are often dominated by quarks, while the corresponding backgrounds are dominated by gluons. Working in the idealized context of electron–positron collisions, where one can unambiguously define quark and gluon jets, we find an interesting interplay between perturbative parton shower effects and nonperturbative colour reconnection effects. These results triggered new developments in the simulation of quark and gluon jets in parton-shower generator Herwig 7 which are presented at the end of this note.

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1. Introduction

The possibility of distinguishing quark/gluon jets is important for searches for BSM physics, where signals of interest are often dominated by quarks, while the corresponding backgrounds are dominated by gluons. However, recent LHC measurements showed that the difference in the properties of quarks and gluons is not well-described by the Monte Carlo generators. More precisely PYTHIA [1] is predicting a larger, while Herwig [2] a smaller difference between the jets than is observed by the LHC experiments [3]. In order to understand better this intriguing observation, we use idealized electron–positron collisions as described in details in [4]. These results serve as a guidance to improve the simulation of quark and gluon jets in parton-shower generator Herwig 7 [5], which is presented in Section 2 of this note.

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2. Idealized electron–positron collisions

We begin with an idealized case of e^+e^- collisions (see Section 5 of [4]), where we use the process $e^+e^- \to (\gamma/Z)^* \to u\bar{u}$ as a source for a "quark jet" sample and $e^+e^- \to h^* \to gg$ for a "gluon jet" sample. There are many different ways to define quark and gluon jet discrimination power, however, we follow [4] and use five generalized angularities λ^κ_β [6]

$$\begin{array}{cccccc} (\kappa,\beta) & (0,0) & (2,0) & (1,0.5) & (1,1) & (1,2) \\ \lambda^\kappa_\beta: & \text{multiplicity} & p_\mathrm{T}^D & \text{LHA} & \text{width} & \text{mass}\,, \end{array}$$

where $\lambda^\kappa_\beta = \sum_{i\in\mathrm{jet}} z_i^\kappa \theta_i^\beta$, i runs over the jet particles constituents, $z_i \in [0,1]$ is a momentum fraction, and $\theta_i \in [0,1]$ is an angle to the jet axis. To quantify discrimination performance, we use a separation classifier

$$\Delta = \frac{1}{2}\int \mathrm{d}\lambda\, \frac{\left(p_q(\lambda) - p_g(\lambda)\right)^2}{p_q(\lambda) + p_g(\lambda)}\,,$$

where p_q (p_g) is the probability distribution for λ in a generated quark jet (gluon jet) sample. $\Delta = 0$ corresponds to no discrimination power and $\Delta = 1$ corresponds to perfect discrimination power. Firstly, in the left panel of Fig. 1, we show the discrimination power as a function of an angularity predicted by PYTHIA 8.215 [1], Herwig++ 2.7.1 [7] and Sherpa 2.2.1 [8]. The results confirm what was also observed by the ATLAS measurement: PYTHIA [1] predicts larger, while Herwig [2] smaller differences between quark/gluon jets. In order to understand better the source of the difference, we investigate the following setting variations for Herwig++ 2.7.1:

— Herwig: no $\mathrm{g} \to \mathrm{q}\bar{\mathrm{q}}$. Turning off $g \to q\bar{q}$ splittings in the parton shower.

— Herwig: no Colour Reconnection (CR). The variation turns off colour reconnection.

In the right panel of Fig. 1, we can see that the results are not very sensitive to the switching off the $g \to q\bar{q}$ splittings in the parton shower, whereas the colour reconnection has a significant effect on the discrimination power. In fact, a similar effect of colour reconnection was also observed in PYTHIA and Ariadne [9], see [4] for details. The importance of the colour reconnection is a big surprise from this study, since it is meant to improve the description of multiple interactions which are not present in lepton–lepton collisions. This motivated future detailed studies on how to improve and constrain a CR model in order to refine the simulation of quark and gluon jets in the parton-shower generator Herwig 7 [5]. This effort is presented in the next section.

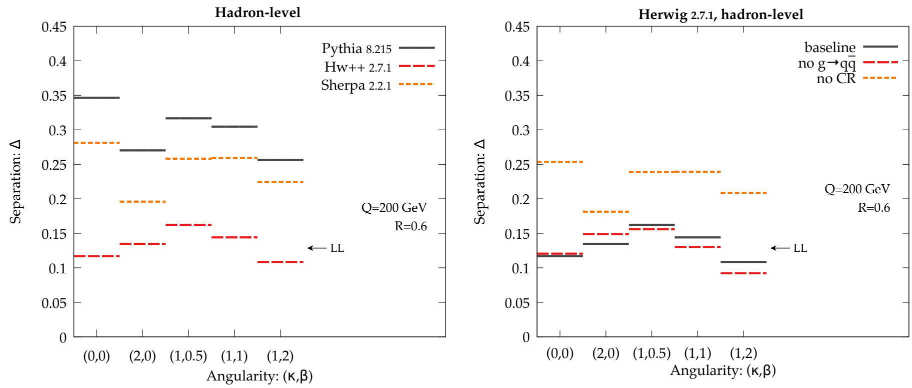

Fig. 1. The classifier separation Δ for five angularities for an idealized case of e^+e^- collisions. Left panel shows results of various generators. The right panel shows different setting variations for Herwig++ 2.7.1.

3. Improvements of colour reconection model in Herwig 7

In order to describe the Underlying Event [10–13] and Minimum Bias data [14–17], the cluster hadronization model [18] is supplemented with a model of colour reconnections (CR) [19]. The colour reconnection model defines the distance between two partons based on their invariant mass, *i.e.* the distance is small when their invariant mass (cluster mass) is small. 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. In this model, it is possible that the colour lines of a gluon produced at any other stage of the shower can be reconnected, leading to the production of a colour-singlet object. While this is possible, one would expect that it occurs with a rate $\sim \frac{1}{N_{\rm C}^2} = \frac{1}{9}$, where $N_{\rm C}$ is the number of colours, not the much higher reconnection rate $\sim 2/3$ which is necessary to describe the Underlying Event data [20]. This can potentially lead to the production of a colour-singlet gluon jet at a much higher rate than expected. In order to check this, we have used the data on gluon jets in e^+e^- collisions from the OPAL experiment [21, 22] which have not been previously used in the development and validation of the Monte Carlo event generators. We also modified the CR model, such that it forbids to make a reconnection which would lead to a gluon produced in any stage of the parton-shower evolution, becoming a colour-singlet after hadronization. The effects of changing the CR model is clearly seen in Fig. 2. In the results of Herwig++ 2.7.1 or Herwig 7.0, there is an unphysical tendency of the gluon jets to contain an even number of charged particles due to the production of

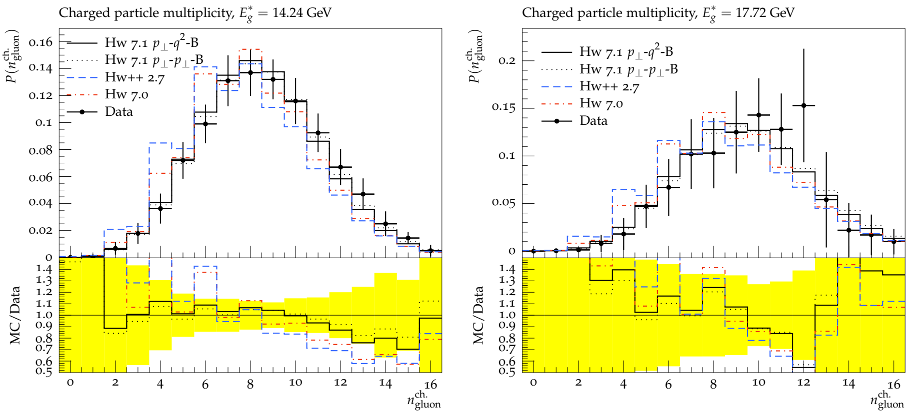

Fig. 2. Multiplicity distribution of charged particles in gluon jets for two different gluon energies compared to data from OPAL [21].

colour-singlet gluons by the reconnection model. This feature is not present after the modification of the CR model, see lines denoted by Hw 7.1 $p_\perp$–q^2–B and Hw 7.1 $p_\perp$–$p_\perp$–B[1], which provide a much better description of the distribution of charged particles in the gluon jets. Now, let us return to the Les Houches observables presented in the previous section and see how the change of the CR model affects the Herwig 7 results. In Fig. 3, we show similar plots as before in Fig. 1, however, this time we show also two tunes Hw 7.1 $p_\perp$–q^2–B and Hw 7.1 $p_\perp$–$p_\perp$–B which include changes to the CR model. In the left panel of Fig. 3, we can see that the results of both new tunes are not very sensitive to the change of CR. This was not the case for Herwig++ 2.7.1, where a colour reconnection had a huge effect on the discrimination power (right panel Fig. 1). Secondly, in the right panel of Fig. 3, we see that results of the both Herwig 7.1 tunes are quite similar and closer to the other predictions giving more constrained prediction on the quark/gluon jet discrimination power in e^+e^- collisions. This was recently observed also in [23], where the new version of Herwig and its tune reduced the tension between PYTHIA and Herwig and brought Herwig results closer to NNLL' results from [23]. It is important to stress that so far the results from the MC generators do not include any uncertainties due to Parton Shower calculations. It would be interesting to include them in a similar manner as was presented in [24–27], but this time, in the context of the quark and gluon jet discrimination observables to see whether the remaining discrepancy in the predictions is covered by the uncertainty band.

[1] In [5], the authors not only discuss improvements of the CR model, but also study different options for the kinematics in the Parton Shower. The two tunes Hw 7.1 $p_\perp$–q^2–B and Hw 7.1 $p_\perp$–$p_\perp$–B include the changes to the CR model, however they differ in the kinematics of the parton shower, which we do not discuss here.

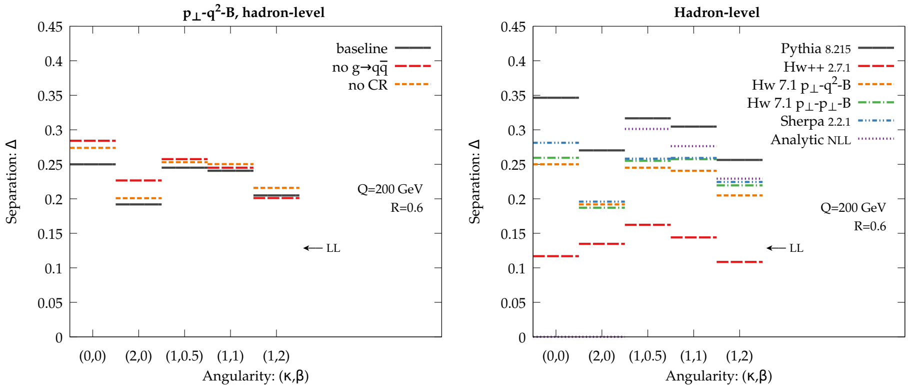

Fig. 3. The classifier separation Δ for five angularities, determined from various generators for an idealised case of e^+e^- collisions. The first two columns correspond to IRC-unsafe distributions (multiplicity and p_{T}^D), while the last three columns are the IRC-safe angularities.

4. Conclusion

In this note, I have briefly presented one of the most interesting results from the Les Houches quark/gluon jet tagging studies [4], namely a surprising dependence of q/g discrimination power in lepton–lepton collisions on the colour reconnection. This interesting outcome served as a starting point for an improvement of the CR model in the Herwig 7 Monte Carlo Generator, which has been presented in the second part of the note. It has been showed that the change of the colour reconnection model in Herwig not only reduced the gap between predictions for the quark/gluon separation power of different MC generators, but also leads to much better description of the OPAL data on the distribution of charged particles in gluons jets.

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