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Treating jet correlations in high pile-up at hadron colliders

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A R T I C L E I N F O

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A B S T R A C T

Experiments in the high-luminosity runs at the Large Hadron Collider face the challenges of very large pile-up. Primary techniques to deal with this are based on precise vertex and track reconstruction. Outside tracker acceptances, however, lie regions of interest for many aspects of the LHC physics program. We explore complementary approaches to pile-up treatment and propose a data-driven jet-mixing method which can be used outside tracker acceptances without depending on Monte Carlo generators. The method can be applied to treat correlation observables and take into account, besides the jet transverse momentum pedestal, effects of hard jets from pile-up.

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1. Introduction

Experiments at hadron colliders operating with very high luminosity face the challenge of pile-up, namely, a very large number of overlaid hadron–hadron collisions per bunch crossing. At the Large Hadron Collider (LHC), in Run I data the pile-up is about 20 *pp* collisions on average, while it reaches the level of over 50 at Run II, and increases for higher-luminosity runs [1–11]. In regions covered by tracking detectors, advanced vertexing techniques have been developed to deal with environments characterized by high pile-up. More generally, experiments rely on Monte Carlo simulations which include pile-up for comparisons with data. However, this introduces a significant model dependence, especially in regions where no detailed and precise measurements are available to constrain Monte Carlo modeling.

In this paper we propose a different approach to treating high pile-up, with a view to employing data-driven methods rather than Monte Carlo methods. Our main focus is to deal with potentially large probabilities that jets with high transverse momenta are produced from pile-up events independent of the primary interaction vertex, in a region where tracking devices are not available to identify pile-up jets. A typical application would be Higgs production by vector boson fusion, where the associated jets may be produced outside the tracking detector acceptances. The issue we address is thus quite different from the issues that most of the existing methods for pile-up treatment are designed to deal with, which are the jet transverse momentum pedestal, due to the bias in the jet transverse momentum from added pile-up particles in the jet cone, and the clustering into jets of overlapping soft particles from pile-up.

In what follows we will therefore use standard existing methods to treat soft particles and the jet pedestal, and devise new approaches to tackle the issue of misidentification which arises, in addition, in cases where precise tracking and vertexing are not feasible. The aim is to look for methods which treat pile-up without spoiling the physics of the signal process and which can be used outside the tracking detector acceptances without depending on Monte Carlo modeling. To this end, we suggest using minimum bias (or jet) samples recorded from data in high pile-up runs and applying event-mixing techniques to relate, via these data samples, the "true" signal to the signal measured in high pile-up.

The approach does not address the question of a full detector simulation including pile-up. Rather, it focuses on how to extract physics signals with the least dependence on pile-up simulation, and how to use real data, rather than Monte Carlo events, at physics object level.

The proposed method applies to the regime of high pile-up which is relevant for the LHC as well as for future high-luminosity colliders. It is designed to treat not only inclusive variables but also correlations. One of the features of the method is that it does not require data-taking in dedicated runs at low pile-up. Rather, the data required for event mixing are recorded at the same time as the signal events in high pile-up runs, so that there is no loss in luminosity.

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We will illustrate the approach using Drell–Yan lepton pair production associated with jets as a case study. We discuss two main physical consequences of pile-up collisions, the bias in the jet transverse momentum due to pile-up particles in the jet cone, and the misidentification of high transverse momentum jets from independent pile-up events. The method is general and can straightforwardly be extended to a large variety of processes affected by pile-up.

2. Drell–Yan plus jets at high pile-up as a case study

Let us consider the associated production of a Drell–Yan lepton pair via Z-boson exchange and a jet. We take the jet transverse momentum and rapidity to be $p_T^{(\text{jet})} > 30$ GeV, $|\eta^{(\text{jet})}| < 4.5$, and the boson invariant mass and rapidity to be 60 GeV $< m^{(\text{boson})} <$ 120 GeV, $|\eta^{(\text{boson})}| < 2$. Event samples are generated by Pythia 8 [12] with the 4C tune [13] for the different scenarios of zero pile-up and N_{PU} additional pp collisions at $\sqrt{s} = 13$ TeV. We reconstruct jets with the anti-k_T algorithm [14] with distance parameter $R = 0.5$. Results for the spectrum in the transverse momentum p_T of the Z-boson, for Z + jet events, are shown in Fig. 1 for $N_{\text{PU}} = 0$, $N_{\text{PU}} = 20$ and $N_{\text{PU}} = 50$. For comparison we also show the inclusive $N_{\text{PU}} = 0$ Z-boson spectrum.

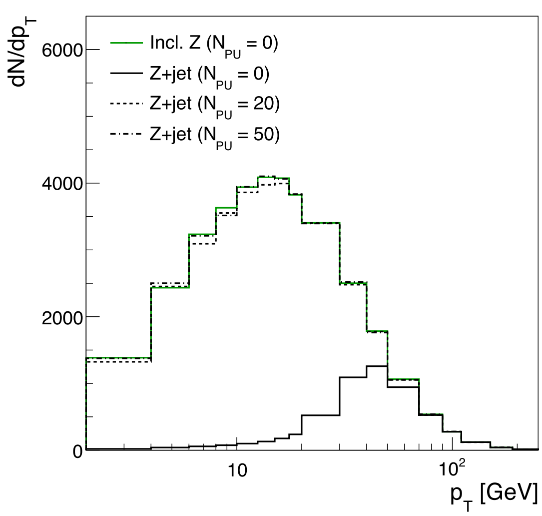

Fig. 1. Effect of pile-up on the Z-boson transverse momentum p_T in Z-boson + jet production at the LHC. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

We see from Fig. 1 that the effects of pile-up on Z-boson + jet scenarios are large. As a result of pile-up the shape of the p_T spectrum is changed and the peak is shifted to lower values. This can be interpreted by noting that, as the Z + jet event sample becomes dominated by pile-up collisions, even with the jet transverse momentum selection cut $p_T^{(\text{jet})} > 30$ GeV the Z-boson p_T distribution in boson + jet events will tend to approach the inclusive Drell–Yan spectrum, given by the solid green curve.

More precisely, we can identify two main implications of pile-up collisions: a large bias in the jet transverse momentum due to added pile-up particles in the jet cone leading to a jet pedestal, and a large probability that jets with high transverse momentum come from independent pile-up events.

Several methods exist to deal with the jet p_T pedestal. These include techniques based on the jet vertex fraction [3] and charged hadron subtraction [5,15], the Puppi method [16], the SoftKiller method [17]. These methods correct for transverse momenta of individual particles, but not for any mistagging. So do approaches inspired by jet substructure studies, such as jet cleansing [18]. In Fig. 2 we apply SoftKiller [17], a new event-wide particle-level pile-up removal method, which can also be used with calorimeter information only. We present results at zero pile-up ($N_{\text{PU}} = 0$), at pile-up $N_{\text{PU}} = 50$, and the result at pile-up $N_{\text{PU}} = 50$ with SoftKiller subtraction ($N_{\text{PU}} = 50$ SK).

Fig. 2 illustrates different physical effects of pile-up in the leading jet spectrum and in the Z-boson spectrum. In Fig. 2a we compute the leading jet p_T spectrum, and verify that SoftKiller efficiently removes the jet pedestal from pile-up: the zero pile-up jet spectrum (solid black curve) is shifted toward larger p_T by pile-up collisions (dot-dashed black curve for $N_{\text{PU}} = 50$) but the application of SoftKiller (dashed blue curve $N_{\text{PU}} = 50$ SK) corrects for this and restores the original signal with very good approximation. In Fig. 2b, on the other hand, we compute the Z-boson p_T spectrum. The solid black curve is the zero pile-up result, the dot-dashed black curve is the $N_{\text{PU}} = 50$ result, and the dashed blue curve is the result of applying SoftKiller. In the higher p_T part of the spectrum we observe that there is no need for any correction. In contrast, in the lower p_T part significant contributions are present from misidentified pile-up jets. These are not corrected for, and need to be properly treated, particularly in regions outside

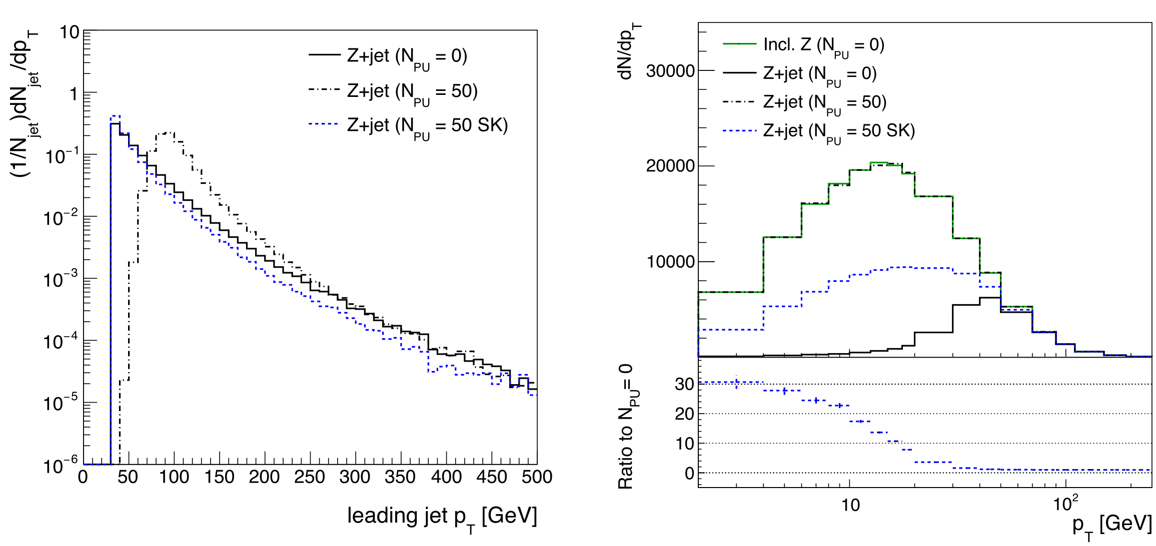

Fig. 2. Application of SoftKiller [17] to Z-boson + jet production. Left: (a) the leading jet p_T spectrum; right: (b) the Z-boson p_T spectrum. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

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