A DATA-DRIVEN APPROACH TO PILE-UP AT HIGH LUMINOSITY

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Abstract

We discuss recent results on pile-up based on a data-driven jet-mixing method. We illustrate prospects for experimental searches and precision studies in high pile-up regimes at high-luminosity hadron colliders, showing how the jet mixing approach can be used, also outside tracker acceptances, to treat correlation observables and effects of hard jets from pile-up.

Experiments at high-luminosity hadron colliders face the challenges of very large pile-up, namely, a very large number of overlaid hadron-hadron collisions per bunch crossing. At the Large Hadron Collider (LHC), for instance, in data taken at Run I the pile-up is about 20 pp collisions on average, while

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1Talk given at the Workshop LFC15: Physics Prospects for Linear and Other Future Colliders, ECT* Trento, 7-11 September 2015.
it reaches the level of over 50 at Run II, and increases for higher-luminosity runs 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11.

Current methods to deal with pile-up at the LHC employ precise vertex and track reconstruction, in regions covered by tracking detectors. More generally, they rely on Monte Carlo simulations to model pile-up for data comparisons. This however brings in a model dependence which is particularly significant in regions where no detailed and precise measurements are available to constrain Monte Carlo generators.

Ref. 12 proposes a complementary approach to pile-up treatment, using data-driven methods rather than Monte Carlo modeling. The main purpose of this approach is to deal with potentially large contributions from jets with high transverse momenta, 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. The goal is to treat not only inclusive observables but also correlations, and to rely on data recorded in high pile-up runs, rather than requiring dedicated runs at low pile-up.

The basic idea of Ref. 12 can be illustrated using Drell-Yan lepton pair production associated with jets. This can straightforwardly be extended to a large variety of processes affected by pile-up. Fig. 1 shows a cartoon picture of different effects due to pile-up in Z-boson + jets production. One effect, denoted as jet pedestal, consists of additional pile-up particles in the jet cone, leading to a bias in the jet transverse momentum. Another is the overlapping of soft particles from pile-up, which are clustered into jets. A further effect is the misidentification of high transverse momentum jets produced from independent pile-up events.

Several methods exist to take the first two effects into account and correct for them. These include techniques based on the jet vertex fraction 3 and charged hadron subtraction 5, 13, the PUPPI method 14, the SoftKiller method 15, the jet cleansing method 16. These methods correct for transverse momenta of individual particles, but not for any misidentification. The objective of the approach 12 is to analyze and treat the third effect, due to the mistagging of high transverse momentum pile-up jets.

Fig. 2 illustrates the overall contributions of pile-up to Z-boson + jet correlation variables. In the top plot is the leading jet $p_T$ spectrum, while in the bottom plot is the Z-boson $p_T$ spectrum. Event samples for Z-boson +
jet production, with boson rapidity and invariant mass $|\eta^{(\text{boson})}| < 2$, 60 GeV $< m^{(\text{boson})} < 120$ GeV, and jet transverse momentum and rapidity $p_T^{(\text{jet})} > 30$ GeV, $|\eta^{(\text{jet})}| < 4.5$, are generated, using the anti-$k_T$ jet algorithm with distance parameter $R = 0.5$, by Pythia 8 with the 4C tune for the different scenarios of zero pile-up and $N_{PU}$ additional $pp$ collisions at $\sqrt{s} = 13$ TeV. The solid black curve is the signal, represented by the result in absence of any pile-up collision. The dot-dashed black curve is the result for $N_{PU} = 50$ pile-up collisions. The dashed blue curve is the result of applying the method SoftKiller to remove contributions of soft pile-up particles in the event.

We see from Fig. 2 that the effects of pile-up on $Z$-boson + jet spectra are large. Further we see that, while the leading jet $p_T$ spectrum can be corrected
well by the pile-up removal method SoftKiller, the $Z$-boson $p_T$ spectrum is still affected by significant deviations from the signal even after applying SoftKiller. Ref. 12) interprets this as an effect of mistagged pile-up jets, and devises an approach based on jet mixing to treat it.

The jet mixing method 12) uses uncorrelated event samples to express the signal in the pile-up scenario in terms of the signal without pile-up and a minimum bias sample of data at high pile-up. The results of this approach are shown in Fig. 3 where samples containing $N_{PU}$ minimum bias events are used for the mixing, in the cases $N_{PU} = 50$ (top plot) and $N_{PU} = 100$ (bottom plot). The solid black curve is the “true” $Z$-boson plus jet signal. The dashed blue curve is the high pile-up, SoftKiller-corrected result ($N_{PU} = 50$ SK and $N_{PU} = 100$ SK), representing the pseudodata in high pile-up. The long-dashed red curve is the jet-mixed curve obtained from mixing the signal with the minimum bias sample. The solid red curve is the final result, obtained by a simple “unfolding”, defined by multiplying the signal by the ratio of the pile-up (dashed blue) curve to the jet-mixed (long-dashed red) curve.

We see from Fig. 3 that without the need to use Monte Carlo events to simulate pile-up the true signal is extracted nearly perfectly from the mixed sample. This conclusion can be strengthened by checking 12) that if the mixing is applied to a different starting distribution the unfolding still returns the true signal. Also, control checks on the jet resolution are carried out in Ref. 12), verifying that features of the “true” signal in the parton-jet $p_T$ correlation and $\Delta R$ distribution are well reproduced by the jet mixing. As Fig. 3 indicates, the performance of the mixing technique, unlike the SoftKiller pile-up removal method, improves with increasing $N_{PU}$.

In summary, the approach described in this article, while not addressing the question of a full detector simulation including pile-up, 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. It can be applied to the high pile-up regime relevant for the LHC and for future high-luminosity colliders, and does not require data-taking in special runs at low pile-up, so that there is no loss in luminosity. It implies good prospects.

2Here we use a Monte Carlo to generate minimum bias events but under real running conditions this sample should be taken from real events recorded at high pile-up.
both for precision Standard Model studies at moderate scales affected by pile-up, e.g. in Drell-Yan\cite{20,21} and Higgs production\cite{22,23}, and for searches for rare processes beyond Standard Model in high pile-up regimes.

**Acknowledgments.** Many thanks to the organizers of the Workshop *LFC15* for the invitation to a very interesting meeting. The results presented in this article have been obtained in collaboration with H. Jung and H. Van Haevermaet. Useful comments from M. Dittmar, E. Gallo, B. Murray, P. Van Mechelen and M. Wielers are gratefully acknowledged. This work is supported in part by the DFG SFB 676 programme “Particles, String and the Early Universe” at the University of Hamburg and DESY.

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Figure 2: Effects of pile-up in Z-boson + jet production at the LHC: (top) the leading jet $p_T$ spectrum; (bottom) the Z-boson $p_T$ spectrum.
Figure 3: The $Z$-boson $p_T$ spectrum in $Z + \text{jet}$ production from the jet mixing method \cite{12}: (top) $N_{PU} = 50$; (bottom) $N_{PU} = 100$. 