DY processes in high pile-up environments

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Abstract: The recent discovery of the Higgs boson at LHC allows for the direct QCD measurements in the $gg \to H$ and Drell-Yan channels. However QCD measurements through DY and Higgs channels are heavlily hindered by the presence of extra proton-proton collisions per beam crossing (pileup), we expect this effect to be further amplified as LHC moves into its next high luminosity phase. In the project hither described Pythia 8 simulations of DY processes were carried out in the presence of SoftQCD pileup and the results analysed with Rivet routines. The visual effect of pileup in angular, pseudorapidity and transverse momenta distribution was observed and quantified against pileup through the measurement of p_T for the outgoing charged particles in the transverse region, i.e. due to the pileup. A linear fit was obtained and used to correct outgoing jet p_T. It was found that there was reasonable agreement at high transverse momentum, while the presence of low p_T pileup jets obstrused agreement at low p_T. Further analysis is required for which the Pythia and Rivet routines written by the author can be used and improved upon in the future.

1 Introduction

In p-p colliders the Drell-Yan $q\bar{q} \xrightarrow{Z/\gamma} l^+l^-$ process it is of particular importance for Quantum Chromodynamics (QCD) measurements. The Drell-Yan (DY) process occurs through an electroweak current coupling to quarks, and its clean final state allows for the easy measurement of quark parameters; gluon properties, on the other hand, need be determined indirectly. With the recent discovery of the Higgs boson by CMS and ATLAS one can directly probe into gluon processes through the $gg \to H$ channel in the heavy top limit, opening new doors in research in QCD.[1] In order to produce accurate and reliable Higgs measurements, modern particle accelerators like LHC operate at very high beam intensities. While high beam intensity or luminosity allows one to carry out precise differential measurements, high luminosities create a condition on which, on average, more than one proton-proton collision occurs per proton bunch crossing (see figure 1). The latter condition is known as Pile-Up (PU) and events with up to 30 PU occurences (i.e. 30 p-p vertices on top of the one-signal event) have been observed during LHC's 2012 run leading up to the Higgs discovery.[4] Pile-up effects can hinder measurements as the phase space will be filled with extra hadronic activity coming from this surplus collisions, clouding the data pertaining to the channel of interest.

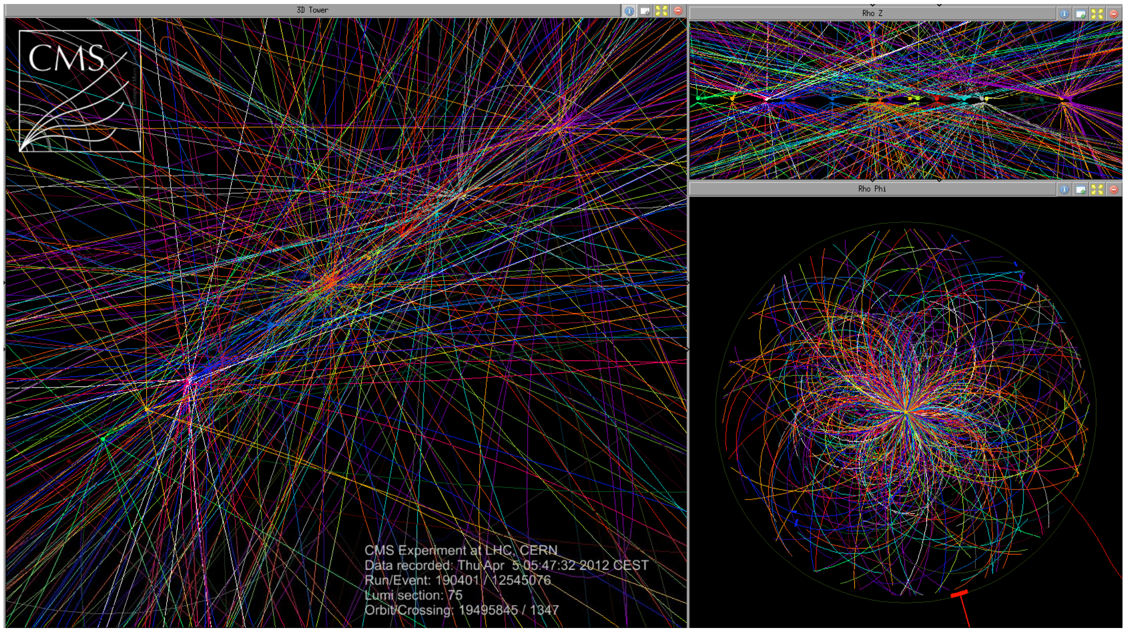

Figure 1: *Visualisation of pile-up; 29 vertices reconstructed from 29 distinct collisions during one beam crossing of the LHC beam. Source: CMS.*

In the forthcoming high luminosity phase of LHC (HL-LHC) we expect beam intensities several times the current values; these very high luminosity beams will be accompanied with a correspondingly elevated amount of pileup events per bunch crossing. It is of utmost importance, therefore, to device methods to correct or mitigate undesired pileup effects from measurements. One commonly used procedure to deal with pileup involves vertex reconstruction; if several simultaneous collisions occur sufficiently far away form each other a track reconstruction algorightm can isolate the products of each one. Track and vertex reconstruction allows for the identification of charged of contaminating charged particles coming from the pileup.[4, 2] Track and vertex reconstruction does not prove sufficiently effective, however, in collisions with ultra-high rapidity particles (outgoing particles going almost in the beam direction), nor with neutral outgoing particles where tracks can only be estimated.

In [1, 3] the CMS-DESY group proposes a research programme in QCD physics using Higgs processes as probes in gluon measurements, taking p_T distribution ratios between Higgs and DY production and angular distribution differences as means to stabilise results against pileup effects. Following this proposal's line of attack, Monte Carlo simulations of DY processes in high pileup environments were studied, and the transverse momentum contribution of charged particles in the transverse region was analysed. We expect to be able to device a correction which, substracting p_T pileup contribution from the jet p_T, brings the results with pileup back to the desired no pileup scenario.

2 Objective

We seek a systematic method for analysing the underlying Drell-Yan or gg-H events in high pileup p-p collisions. The latter was sought after through the measurement of the pT contribution of charged particles in the transverse region of DY processes as a function of pileup in Monte

Carlo-simulated event samples. Results thus obtained would provide a method to accurately correct high pileup measurements back to the non-pileup case.

3 Pile-up, Drell-Yan and Higgs processes

The processes of interest mentioned in 1 are the Drell-Yan and the Higgs and their corresponding Feynman diagrams are pictured in figures 2 and 3.

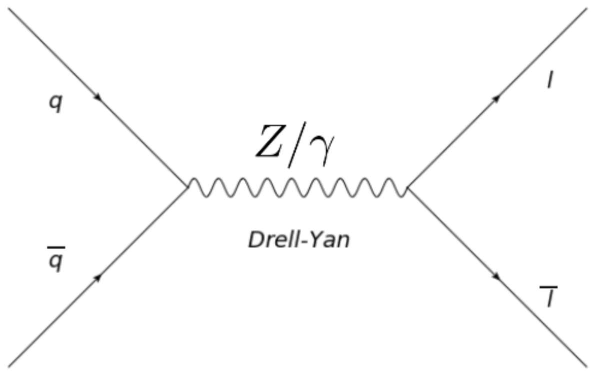

Figure 2: *Feynman diagram for the Drell Yan* $q\bar{q} \xrightarrow{Z/\gamma} l\bar{l}$ *process.*

The Drell-Yan process is a high-energy scattering phenomenon that occurs when a quark one hadron and an antiquark from another one annihilate through electroweak decay, emitting a virtual γ or Z which in turn decays into a lepton and its antiparticle. The process' extremely clean final state, involving only two decay leptons, The Drell-Yan process provides valuable information about the parton distribution function of the incoming hadrons. The process's extremely clean final state, involving only decay leptons, allows us to accurately measure quark struction functions, quark structure parton showers and uderlying event properties.[3]. Gluon properties have to be determined indirectly, however. With the recent discovery of the Higgs boson, the picture changes drastically as gluon properties can be directly measured through the Higgs $gg \to H$ channel in the heavy top limit. In the heavy top limit the gluons couple directly to the Higgs, the top loop seen in the lower right corner of figure 3 being absorbed into the coupling parameters, the Higgs being produced in a color-singlet current. A whole new area of QCD measurements become available through this direct Higgs-gluon interaction.

4 Monte Carlo simulations and Rivet analysis

Following the train of thought of [1, 3], we carry out Pythia 8 Monte Carlo simulations of DY processes with the following run conditions:

- The underlying event is a $p-p$ collision at $\sqrt{s} = 7$ TeV decaying through the $f\bar{f} \xrightarrow{Z^*} l\bar{l}$ channel and set to Z only.

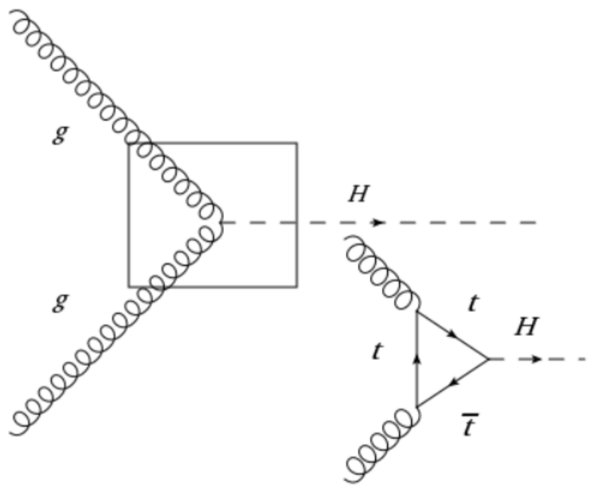

Figure 3: *Feynman diagram for the Higgs $gg \to H$ process in the heavy top limit. The actual process occuring in the box is shown in the lower right corner.*

- As soft (low momentum transfer, diffractive) QCD events dominate cross section at LCH energy for hadron collisions, pileup effects were set to SoftQCD $p-p$ collisions.

- Pileup number N_P is fixed and set to 0, 2, 5, 10, 15 and 20 instead of Poisson-distributed to guarentee identical simulation conditions.

- Z boson mass is set within the 115-135 GeV mass range.

- In order to avoid messy trajectory reconstructions for the decay leptons, Z boson is set to stable.

- A 20 GeV p_T threshold was set in place for the pileup jets.

- Our virtual detectors are set to accept particles with $|\eta| \leq 4$.

PYTHIA 8 is a C++ program used in the generation of high-energy physics events to compare with experimental data. PYTHIA contains theoretical models and predictions for the description of colliding particles at high energies and generates Monte Carlo (randomized) samples of results one would expect to see in real particle experiments.

5 Analysis and results

With the run conditions as mentioned in section **??**, we histogrammed observables such as pseudorapidity η, trasnverse momentum p_T and azimuthal angle φ, as well as ratios and differences between these observables. The obtained histograms show expected distributions for DY process' observables, as well as the effects of Soft QCD pileup on measurements.

We now show the obtained histograms with their physical interpretation. In order to avoid cluttered plots or an innecesary amount of figures only the cases with 0, 10 and 20 pileup are shown, the omitted ones behaving accordingly in-between the latter. Figure 4 (a) and (b) show Drell-Yan and jet transverse momentum distributions. We see that the DY p_T distribution is stable in the presence of pileup, as it should be. Jet transverse momentum spectrum does not, however, remain stable, as pileup will produce additional jets with an uncorrelated (relative to DY) p_T distribution.

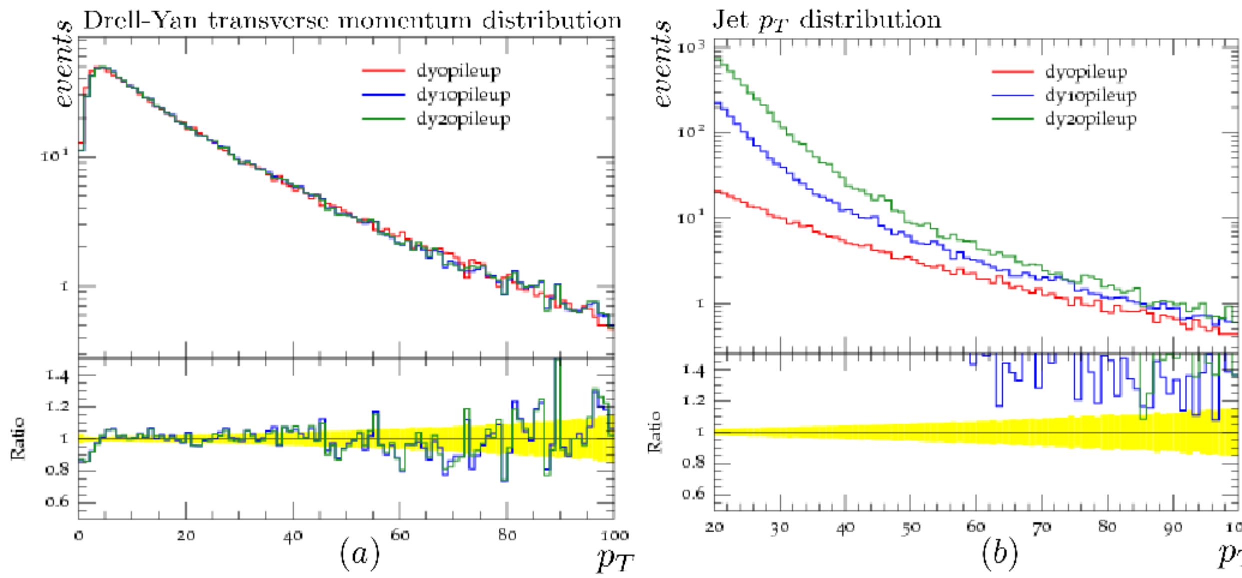

Figure 4: *(a) Transverse momentum distribution for the Drell-Yan process. Histogram is not normalised. We see that the occurence of pileup does not modify p_T spectrum of the outgoing Z boson which peaks in the vicinity of 4 GeV. (b) Transverse momentum distribution for the outgoing jets. Histogram is not normalised. We see that pileup increases the amount of registered jets, this being more visible at the lower end of the spectrum.*

Visual corroboration of the uncorrelation of pileup and DY processes is given in figures 5 (a), (b), (c) and (d). These figures shows the pseudorapidity jet distribution as well as the differences in pseudorapidity and φ between the Z boson and the leading jet, and φ differences between outgoing charged particles and the leading jet. In an environment with no pileup we expect, on the basis of conservation of momentum, a back-to-back arrangement of the Z and the associated jet; the spreading effect of pileup on previously sharply peaked distributions can be seen in (b), (c) and (d).

Figure 6 probes into the p_T distribution of jets relative to DY; we histogram the difference in DY and leading jet transverse momentum relative to DY momentum:

$$\frac{p_T^Z - p_T^{Jet}}{p_T^Z}.$$

A symmetric plot would indicate an equal amount of higher and lower p_T jets, instead the biasing towards negative values indicates the presence of a disproportionate bigger amount of jets with higher transverse momentum than the Z. This effect being more pronounced at higher

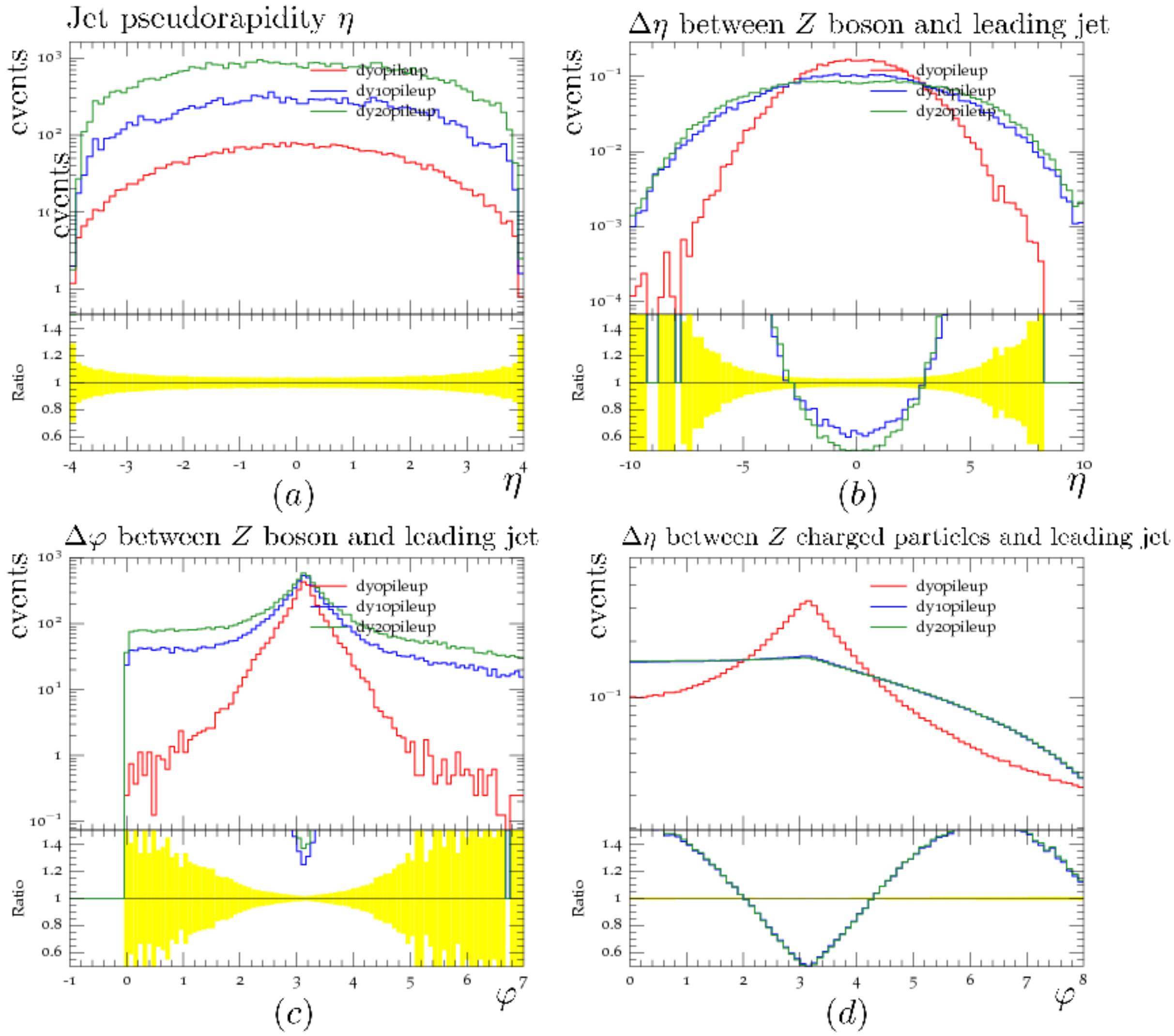

Figure 5: *(a) Jet pseudorapidity η distribution. Histogram is not normalised. We see that the occurence of pileup does not modify the shape of the distribution, shifting it only towards higher values because of the extra independent pileup jets. (b) η difference distribution between the Z boson and the outgoing leading jets. Histogram is not normalised. We see that the presence of pileup spreads out the shape, which formerly peaked at $\Delta\eta = 0$. The latter occurs due to the independence of the leading jet orientation from the DY process when the former comes from pileup. (c) Difference in azimuthal angle φ between the outgoing Z particle and the leading jet. As required by momentum conservation, in absence of pileup the $\Delta\varphi$ distribution peaks at π i.e. the jet and the Z are back-to-back. Pileup flattens the distribution, as the leading jet need not be associated with Z production. (d) Difference in azimuthal angle φ between the outgoing charged particles and the leading jet. As in (c), the peak at π implies that the the outgoing charged particles are back-to-back with the jet. Pileup further flattens the distribution, as the charged particles need not come from the same collision as the leading jet Z boson.*

pileup. The peak at 0 is obtained from the jets originating from the DY process and therefore back to back with it.

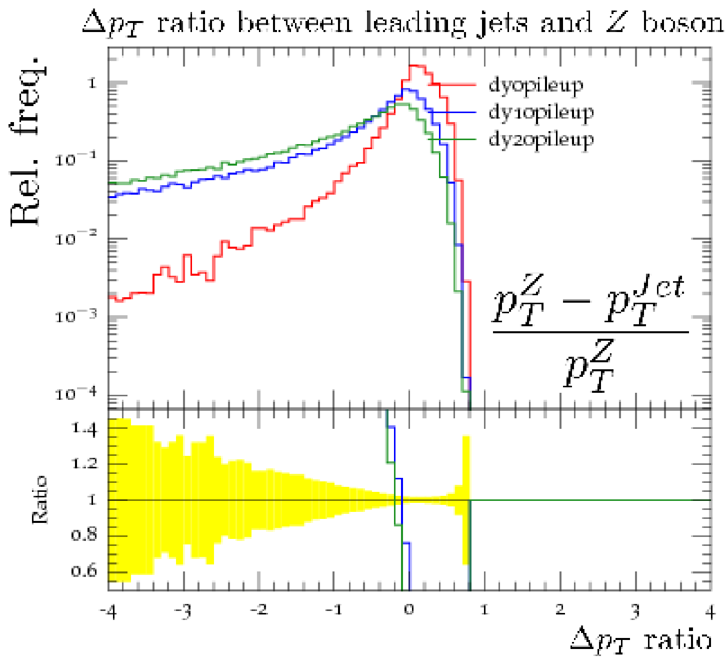

Figure 6: *Δp_T ratio between Z and leading jet, normalized. The shape of this plot provides information as to the jet momentum distribution relative to the Z. The biasing towards negative values indicates the presence of a disproportionate bigger amount of jets with higher transverse momentum than the Z, this effect being more pronounced at higher pileup. The peak at 0 is obtained from the jets originating from the DY process and therefore back to back with it.*

Should the angular and momentum distributions of products of pileup be entirely uncorrelated to the underlying events, measured p_T for DY-induced jets must have a "pileup component", that is, momentum carried by particles flying in the same direction as the jet, but coming from pileup, will seep into the measured jet p_T, biasing measurements. In order to test this hypothesis and develop a pileup correction we isolate charged particles from pileup from the ones corresponding to the DY event by looking into the transverse region $\pi/3 \leq \varphi \leq \frac{2}{3}\pi$, see figure 7. We sum momentum p_T over all charged particles in the transverse region, normalize to $\eta - \varphi$ space with $\Delta\eta = 8$ and $\Delta\varphi = \frac{\pi}{3}$, and adjust to jet-cone area πR^2 for $R = 0.5$:

$$p_T^X = (\Sigma_{\text{Charged}} p_T) \frac{\pi R^2}{\Delta\eta\Delta\varphi}. \tag{1}$$

The latter quantity is the extra momentum given to jet p_T by the charged particles in the jet cone. This extra momentum p_T^X seeps into momentum jet measurements but comes from the pileup and not necessarily the jet event itself.

Figure 8 shows the histogram for eq. (1) in (a) and profiles it as a function of boson p_T in (b). We observe definite non-zero peaks of extra momentum p_T^X that grow with pileup. The momentum profile shows that this p_T^X is, in a reasonable range, independent of boson momentum; the small rise that accompanies the non-pileup is due to the production of charged particles in the underlying process. The dependence of p_T^X with pileup can naïvely be expected to be linear: the independence of extra p_T of the underlying events' angular or momentum

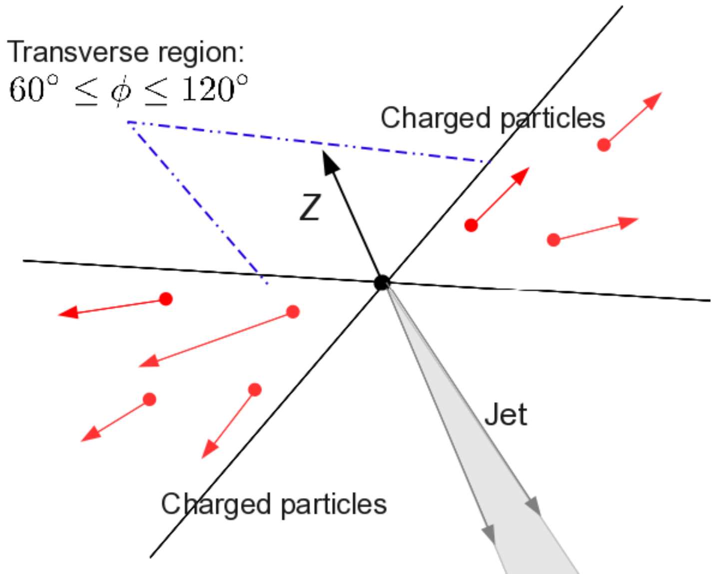

Figure 7: *Schematic view of the geometry of the transverse region. Pileup-generated charged particles (red) in the outside of the cone determined by the Z boson and its accompanying jet.*

distribution would suggest that doubling the amount of pileup would roughly double the amount of charged particles in all directions, on average doubling the momentum carried by them, the underlying DY event amounting to a constant baseline. A plot of p_T^X against pileup (figure 9) shows that this is indeed the case. The points in 9 were taken from figure 8 (b) at zero boson momentum, as this would avoid particles coming from the event of interest and not from pileup.

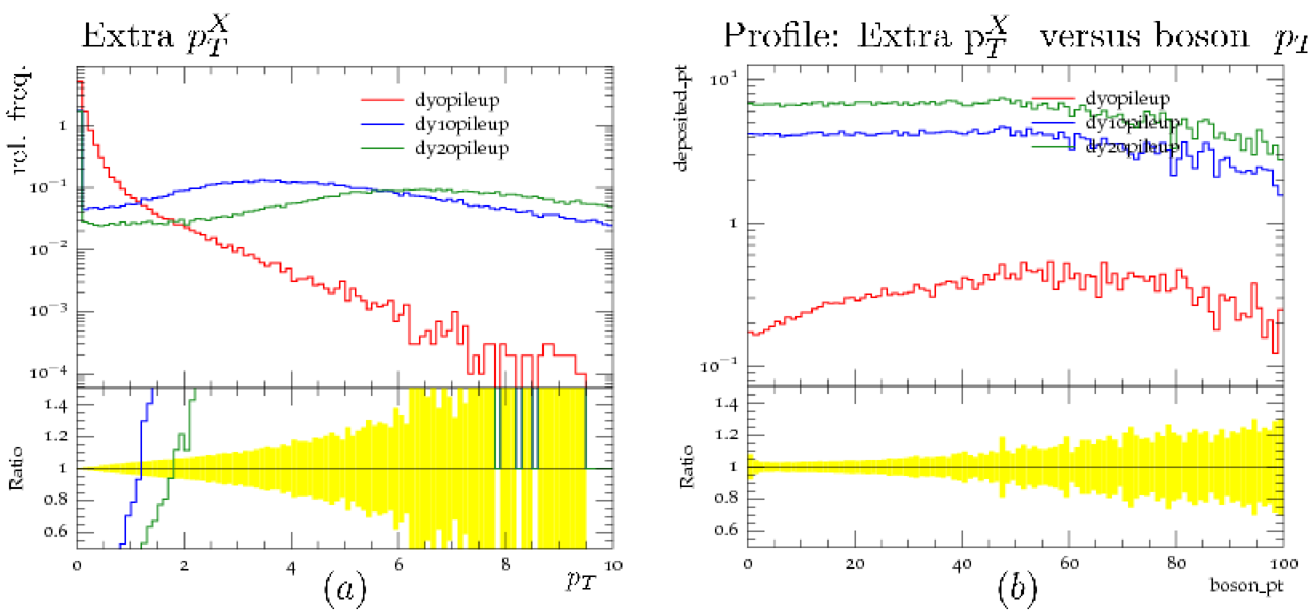

Figure 8: *(a) Extra transverse momentum due to pileup charged particles. Normalized. (b) Profile of extra transverse momentum due to the pileup charged particles profiled against boson transverse momentum.*

The linear fit (m = 0.3078 GeV/pileup, b = 06822 GeV) pictured in 9 we hoped would

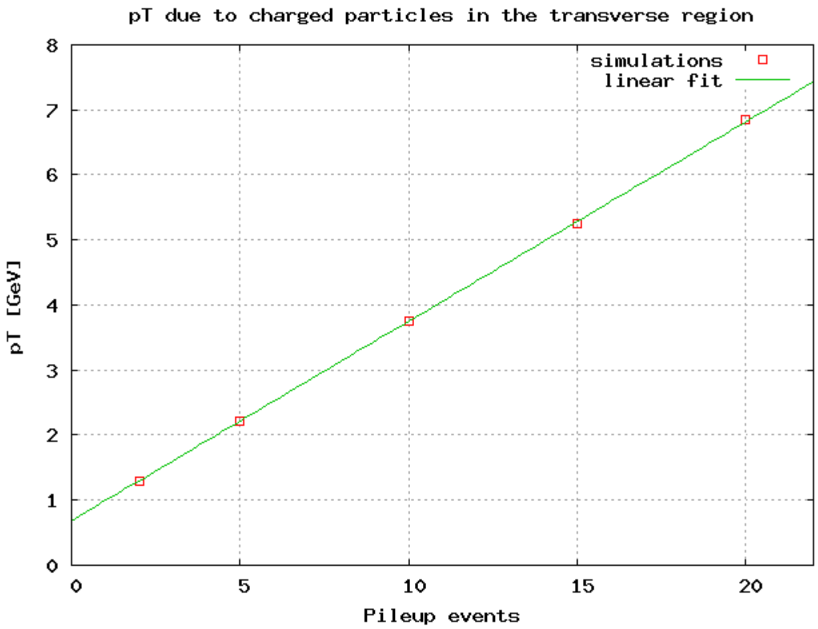

Figure 9: *Linear fit of extra transverse momentum due to the pileup charged particles as a function of pileup. We expect this linear fit to allow for the correction of measured jet p_T in pileup environments back to the non-pileup case.*

allow us to correct jet momentum measurements with different pileup scenarios back to the non pileup case. As it is shown in figure 10, this was not the case; the correction proved effective for high transverse momentum jets, however, discrepancies between non-pileup and pileup are still visible for the low p_T end of the spectrum. At high transverse momenta we expect a low incidence of simultaneous high-p_T jets coming from both the pileup and the underlying process of interest; in this case the correction works, with reasonable agreement between the corrections and the no pileup case. At low p_T however, the pileup collisions produce a high multiplicity of jets, biasing the amount of low-momenta jets recorded and hindering agreement between curves in 10 (b).

6 Summary and conclusions

The effects of pileup in DY processes were investigated through the histogramming of multiple physical observables. We recognize the physical effect of pileup, as well as its visual manifestation in experimental (though in this case simulated) data.

A method to correct jet p_T which accounts for the momentum of the pileup charged particles in the event was applied to the outgoing jets. The correction shows reasonable agreements for high p_T while not being sufficient at low momentum due to the presence of extra lower energy pileup jets.

The disagreements between the applied correction and the non-pileup case at the low transverse momenta end of the jet spectrum emphazise the need for further simulations and analysis;

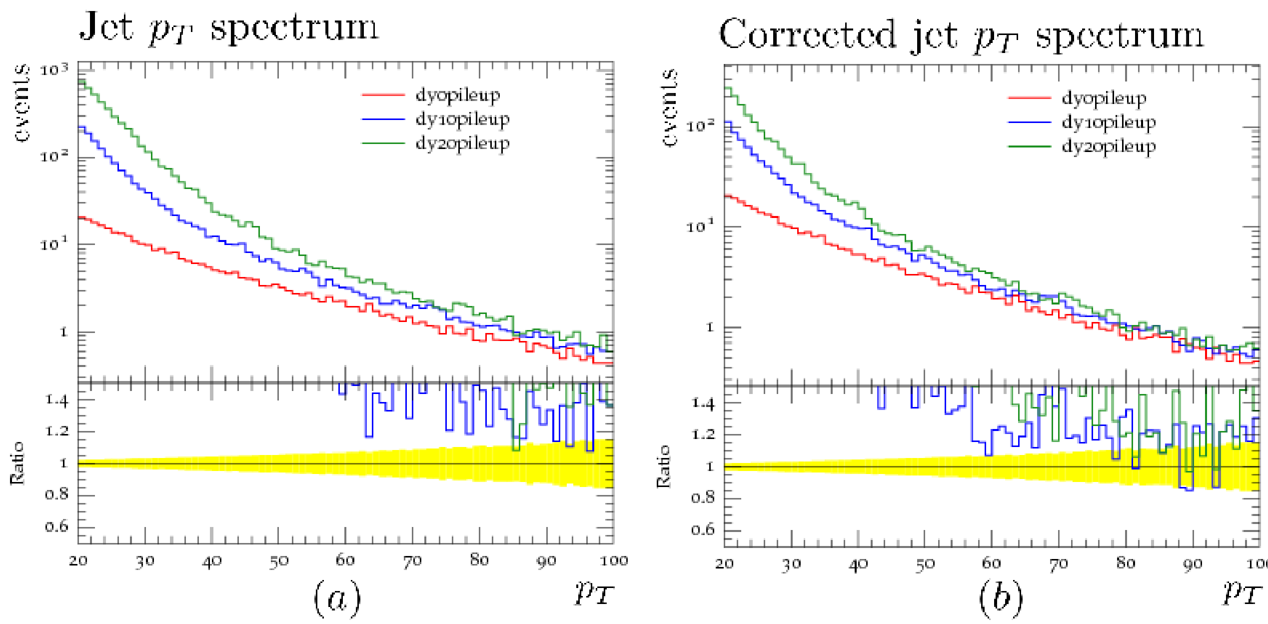

Figure 10: *(a) Jet transverse momenta distribution. Histogram not normalized. (b) Jet transverse momenta distribution corrected for pileup charged particle p_T. Histogram not normalized. We visually appreciate that the correction shortens the gap in transverse momentum distributions, the correction being more accurate at high pT values, though not accounting for all the discrepancies observed at low momenta.*

the performed analysis can be easily built upon and improved in future research, and it's implementation leaves behind Pythia and Rivet routines which can be of future use in further investigations.

7 Acknowledgments

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I would lastly like to thank the physical open software community for their ongoing work developing the software without which none of the analysis here described would have been possible.

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