Higgs boson as a gluon trigger: the study of QCD in high pile-up environments

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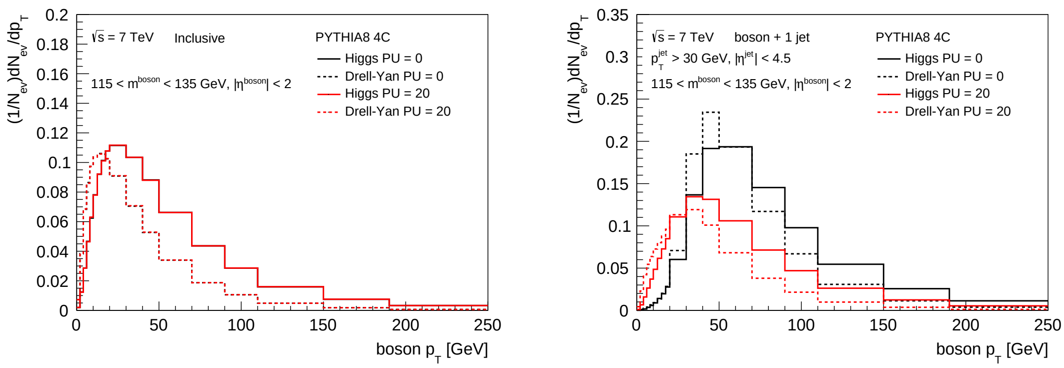
1 Introduction

To study QCD one typically measures processes in single proton-proton collisions. A particular interesting one is the Drell-Yan $q\bar{q} \xrightarrow{\gamma^*/Z^0} l^+l^-$ process, which is produced through an electroweak current that couples to quarks. A big advantage is its clean final state, which only involves the decay leptons. This allows us to use the process to precisely measure quark structure functions, quark induced parton showers, and underlying event properties. The properties and structure functions of gluons however, have to be determined indirectly. But with the recent discovery [1] of the Higgs boson, this picture changes. In the heavy top limit, the Higgs boson directly couples to gluons and can be produced with the gluon fusion $gg \to H$ process through a colour singlet current [2]. The access to this new production process opens up a whole new interesting area of possible QCD measurements, where we can directly study gluon induced effects. In addition, if we only look at decay channels of the Higgs boson like $H \to ZZ \to 4l$, we have access to the same clean final state as in the Drell-Yan process. In order to produce enough statistics for detailed measurements, current accelerators like the LHC at CERN have to operate at very high beam intensities. This high luminosity allows one to measure differential distributions, e.g. the transverse momentum [3] of the Higgs, but it also creates a condition in which on average much more than one proton-proton collision happens per bunch crossing. This so called pile-up (PU) can easily reach, given the LHC run conditions, scenarios where PU = 40 (i.e. 40 additional proton-proton collisions occur on top of the one signal event). This implies that the phase space will be completely filled with extra hadronic activity coming from the pile-up events, which makes a study of QCD in the Higgs or Drell-Yan channels extremely difficult. To assess whether one can still perform QCD measurements in such harsh environments we initiated a new program using the Higgs boson as a gluon trigger [4]. The main idea is to compare Higgs and Drell-Yan production in the same invariant mass range, and then look at different observables, such as the transverse momentum of the bosons, to measure the difference in soft multi-gluon emissions. Here we present pile-up studies to show whether the Higgs to Drell-Yan comparison stays valid in high pile-up environments.

The Monte Carlo event generator samples used in this study are all produced with Pythia 8.185 [5]. All samples contain proton-proton collisions at $\sqrt{s}$ = 7 TeV, with the 4C tune [6] to describe the underlying event properties. The Higgs sample is generated by activating the gluon fusion process $gg \to H$, while the Drell-Yan sample is generated using the single Z^* production process $f\bar{f} \to Z^{0*}$. The bosons are produced within the same invariant mass range of 115 < M < 135 GeV and in addition, to avoid complications with the leptonic final states, they are set stable. The Higgs mass is set to 125 GeV. To study the effect of additional pile-up events, samples with a fixed amount of PU = 5 and PU = 20 are produced. This is done by adding a specified number of small-p_{T} QCD process events to the signal event. All jets are constructed with the anti-k_{T} algorithm [7] with a distance parameter R = 0.5.

2 Transverse momentum spectra

Initial studies presented in [4] show the implicit difference in the inclusive p_{T} spectra of Higgs and Drell-Yan production, due to different soft gluon emissions. Here we analyse what happens when one includes additional PU events. By definition, as we put the bosons stable, the p_{T} spectra should be independent. This is confirmed in figure 1a, where both the PU = 0 and PU = 20 scenarios are compared for Higgs and Drell-Yan production. Thus, if the experimental reconstruction of the leptonic decay products is stable in high PU environments, the p_{T} spectrum should be stable. One can then take the ratio (Higgs/DY) of both spectra and use this observable to directly quantify the gluon versus quark radiation effects.



(a) (b)

Figure 1: The inclusive (a) and boson + 1 jet (b) Higgs and Drell-Yan transverse momentum p_{T} spectra for PU = 0 and PU = 20 scenarios.

In addition, one can look at the boson + 1 jet production process. This topology is expected to be more sensitive to gluon versus quark emission effects, as hard radiation accompanies the boson production. However, requiring an additional hard jet (p_{T} > 30 GeV/c, $|\eta|$ < 4.5) shifts the spectrum towards higher transverse momenta as a result of the induced p_{T} balance between the boson and the hard jet. As such, the contribution of gluon versus quark induced effects will actually become less pronounced in the p_{T} spectrum. These effects are illustrated in figure

1b. Furthermore, figure 1b also shows the results of adding additional PU events. In this case, both spectra shift to lower values. This is the consequence of jet mismatching that occurs due to the extra PU activity. That is, in the presence of PU, there is a higher probability that a high p_{T} jet comes from an independent PU interaction and is identified as the jet coming from the signal event, which can result in a matching of a high p_{T} jet with a low p_{T} boson.

3 Underlying event observables

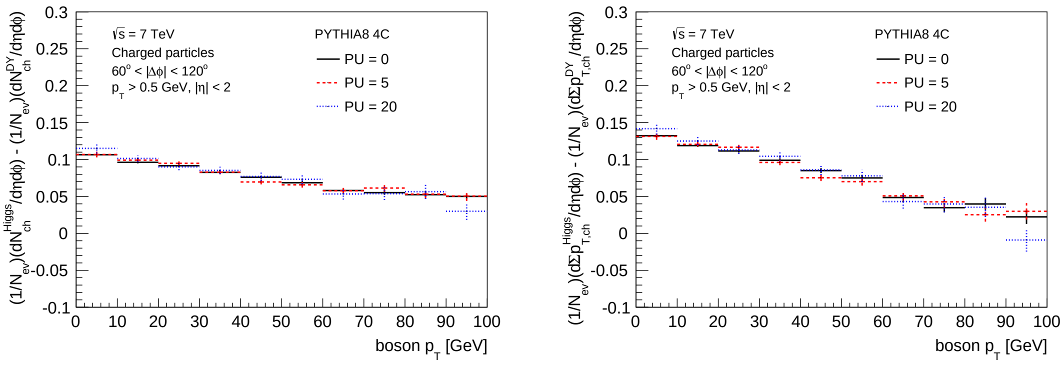
A very interesting observable to study QCD in proton-proton collisions is the underlying event activity [8]. Common measurements [8, 9] look at the charged particle multiplicity and scalar p_{T} sum in the so called *transverse* region, which is defined as $60^{\circ} < |\Delta\phi| < 120^{\circ}$, with $\Delta\phi$ the difference in azimuthal angle between the charged particle and the leading (high p_{T}) object, in our case the Higgs or Z boson, that defines the hard scale of the event. With the produced boson in the *towards* region ($|\Delta\phi| < 60^{\circ}$), and the recoil jet in the *away* region ($|\Delta\phi| > 120^{\circ}$), the transverse region is only sensitive to the underlying event. Furthermore, when only the leptonic decay channel of the bosons is considered, one has access to a clean final state, with no contributions from final state radiation (FSR), resulting in a sensitivity to only initial state radiation (ISR) and multiple parton interactions (MPI). Obviously, when including additional proton-proton collisions to the event, the number of charged particles (and the scalar p_{T} sum) will increase drastically and directly scale to the number of PU events. However, we can show that when we subtract the underlying event activity in the Drell-Yan process, from the underlying event in the Higgs process, i.e.:

$$\frac{dn}{dp_{\mathrm{T}}}(\mathrm{H}-\mathrm{DY}) = \frac{dn}{dp_{\mathrm{T}}^{\mathrm{H}}} + \frac{dn}{dp_{\mathrm{T}}^{\mathrm{PU}}} - \left(\frac{dn}{dp_{\mathrm{T}}^{\mathrm{DY}}} + \frac{dn}{dp_{\mathrm{T}}^{\mathrm{PU}}}\right), \tag{1}$$

the PU contribution completely cancels out. This is confirmed in figures 2a and 2b that show the result of the subtraction. For both additional PU activity of 5 and 20 the subtracted underlying event stays stable. This implies that even in high PU environments one is able to measure small-p_{T} QCD physics. It is possible to subtract the PU contribution and study the difference in underlying event activity between Higgs and Drell-Yan production, which is directly sensitive to gluon versus quark induced ISR.

4 Summary

The Higgs $gg \to H$ production process provides new perspectives for interesting QCD measurements that allow us to directly probe gluon physics. This is possible due to the electroweak current, which, in the heavy top limit, directly couples to gluons. In addition, the colour singlet state and leptonic decay channels allow us to study events in which no complications from final state effects occur. We presented a novel method that compares Higgs and Drell-Yan production in the same invariant mass and rapidity range to perform a direct measurement of gluon versus quark induced processes. First we investigated the inclusive and boson + 1 jet p_{T} spectra. The inclusive spectrum is found to be sensitive to soft multi-gluon emissions, and is stable in high PU environments. The boson + jet event topologies however suffer from PU effects, that originate from the jet mismatching between signal and PU events. In addition we also studied the underlying event activity by looking at the charged particle multiplicity and scalar Σp_{T} in



(a) (b)

Figure 2: The subtracted average charged particle multiplicity (a), and average scalar sum of transverse momenta ($\Sigma p_{\rm T}$) (b) in the transverse region of the azimuthal plane versus transverse momentum $p_{\rm T}$ of the produced boson. For PU = 0, PU = 5 and PU = 20 scenarios.

the transverse region. We constructed the subtracted underlying event observable (see eq. 1) and found that it is stable in high PU environments. Thus, by comparing Higgs to Drell-Yan production we can subtract the PU contributions, and directly measure the difference in gluon versus quark induced initial state radiation effects. Such that one can still access (small-$p_{\rm T}$) QCD physics in high pile-up environments.

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