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Higgs as a gluon trigger

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Abstract

In the forthcoming high-luminosity phase at the LHC many of the most interesting QCD measurements so far become prohibitively difficult due to the high pile-up. We suggest a program of QCD measurements based on the observed Higgs boson which can be started now and can be carried through also in the large pile-up environment at high luminosity. It focuses on gluonic processes at high mass scales, and their distinctive QCD features compared to classic probes such as Drell-Yan. It explores the strong-interaction sector of the Standard Model both at high transverse momenta and at low transverse momenta, by investigating issues on gluon fusion processes which have never been addressed experimentally before. We discuss a few specific examples and present results of Monte Carlo simulations.

The observation of the Higgs boson by the ATLAS and CMS experiments [1] marks the beginning of a revolutionary era in high-energy physics. It affects profoundly the paradigms by which we define the limits of our knowledge on the nature of interactions of elementary particles. This observation gives us confidence in the physical picture of fundamental interactions encoded by the Standard Model (SM) Lagrangian and provides us with guidance in the search for its generalizations.

The electro-weak sector of the SM and the nature of electro-weak symmetry breaking will be explored in detail in the coming years of operation of the LHC by measuring properties of the observed boson [2]. In this note we remark that the observation of the Higgs boson opens up the possibility of a rich experimental program in the strong-interaction sector of the SM as well. In particular, we propose that a program of QCD measurements at high luminosity can be carried out at the LHC by using the Higgs boson as a trigger. It focuses on QCD gluonic processes at high mass scales and explores questions about these processes which have never been addressed before.

Classic collider probes of QCD in e^+e^- annihilation, deep inelastic *ep* scattering (DIS), Drell-Yan production (DY) all involve color-singlet currents which couple to quarks. With the Higgs, for the first time, LHC experiments will probe QCD by a color-singlet current which, in the heavy top limit, couples to gluons. The physics of gluon fusion processes will be explored from a new perspective compared to experimental investigations over the past three decades. As illustrated below, we propose measuring systematically differences of differential distributions for Higgs and Drell-Yan final states. This comparison allows one to access experimentally distinctive QCD features of gluon fusion physics.

In the forthcoming high-luminosity phase at the LHC, one faces high pile-up conditions leading to large numbers of overlaid events. In these conditions many of the most interesting QCD measurements so far become prohibitively difficult - see e.g. [2, 3]. We point out in this paper that by studying differences of Higgs and Drell-Yan for masses around 125 GeV the effects of pile-up largely drop out. This offers the possibility of a program of QCD measurements of great physics interest in the high-luminosity runs of the LHC.

The Higgs trigger can be contrasted with other LHC short-distance probes such as jets, heavy flavors, vector boson pairs which either couple perturbatively to color-octet and color-triplet sources on an equal footing, or imply final-state color-charged particles, or both. This implies that the Higgs trigger allows LHC experiments to single out processes which measure the physics of gluon fields in the initial state of the collision. These measurements can be carried out based on the Higgs data already taken. Most importantly, they can be carried out in the high-luminosity phase. We give a few examples below.

The experimental program proposed in this paper focuses on the strong-interaction sector of the SM and involves QCD physics both at high transverse momenta and at low transverse momenta. It allows one to study both high-x and low-x physical effects. In the following we illustrate this by Monte Carlo simulations in the case of three specific examples: the ratio of Higgs vs. Drell-Yan $p_\perp$ spectra; the structure of the associated underlying event, charged-particle and jet multiplicities; the scattering angle in the center-of-mass reference frame.

Very recently the ATLAS collaboration has presented first measurements of Higgs differential cross sections based on the 2012 dataset in the diphoton decay channel [4].

Higgs vs. Drell-Yan

Consider first transverse momentum spectra for Higgs bosons and for Drell-Yan (DY) pairs in the invariant mass range 115 GeV $< M <$ 135 GeV. These can be described by QCD factorization in the form

$$d\sigma/dp_\perp = \int H \otimes S \otimes J_1 \otimes J_2 \quad , \qquad (1)$$

decomposing the cross section into hard (H), soft (S) and collinear-to-initial-states (J_1, J_2) contributions - see e.g. [5] for analysis of how this decomposition arises. In

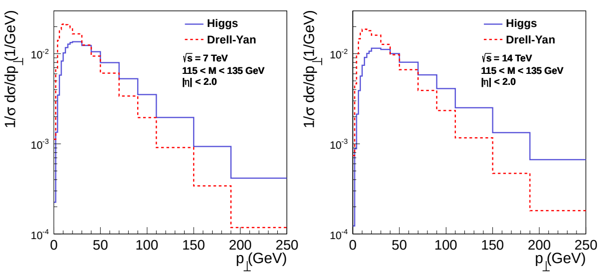

Figure 1: Normalized transverse-momentum spectra for Higgs bosons and for Drell-Yan pairs.

Fig. 1 we show the result of Monte Carlo simulations for the $p_\perp$ spectra in the central region based on the next-to-leading-order (NLO) Powheg [6] event generator interfaced with Pythia [7] shower, at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 14 TeV. In Fig. 2 we plot the ratio of the Higgs and DY spectra at invariant mass 115 GeV $< M <$ 135 GeV.

The $p_\perp \ll M$ region of the spectrum measures infrared aspects of the cross section in Eq. (1), i.e. i) the ratio of the gluon vs. quark Sudakov form factor (factor S in Eq. (1)), and ii) the evolution of the collinear-to-initial-states functions (factors J_1, J_2 in Eq. (1)). In particular, gluon polarization terms $p_\perp^\mu p_\perp^\nu$ in gluon fusion, related to eikonal polarizations at high energy [8], give rise to distinctive radiation patterns from initial-state functions in the Higgs case - see e.g. [8, 9]. The $p_\perp \geq M$ region measures the ultraviolet function H in Eq. (1) and the features of hard jets recoiling against Higgs and DY pair. In particular, the leading-jet contribution to the measured ratio depends on the $p_\perp$ distribution for spin-1 vs. spin-1/2 exchange and on the corresponding color emission probabilities. Further aspects on jet recoil are discussed below in Sec. 3.

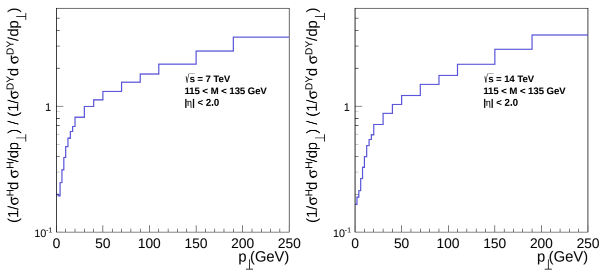

Figure 2: Ratio of Higgs to DY spectra versus $p_\perp$.

In the large pile-up environment of the high-luminosity LHC runs, one has to deal with the contribution of large numbers of overlaid events. However, this contribution cancels in the comparison of Higgs to DY spectra at fixed invariant mass. In particular, using this comparison one can go to low $p_\perp$ and access QCD effects in this region experimentally also at high pile-up.

Measurements on gluon fusion which can be performed using the Higgs trigger open an entirely new experimental field. They may also be relevant to interpret data for other, more complex processes, e.g. processes that depend on both quark and gluon channels on an equal footing, or involve color-charged particles in the final state. For instance, the top quark $p_\perp$ spectrum [10] receives contribution at low $p_\perp$ from the gluon Sudakov form factor and gluonic initial-state recoil analogous to those discussed above. The Higgs trigger will be instrumental in understanding these contributions.

For observables more exclusive than the cross section in Eq. (1), e.g. measuring the associated jets, full QCD factorization formulas are still lacking. For parton shower event generators, inclusive measurements are still useful to control methods [11] for merging parton showers and matrix elements. Higgs vs. DY studies similar to those considered above can be done, for instance, in boson + jet states, now fixing, in addition to invariant mass, the jet transverse momentum or rapidity.

Underlying events

In the case of vector bosons it was pointed out [12] that the treatment of parton showers, and in particular of the recoils in the shower, is essential for a proper description of W/Z spectra. This affects the amount of multi-parton interactions needed to describe the events [12, 13]. The analysis of underlying events associated with Higgs final states will measure gluonic showers [14].

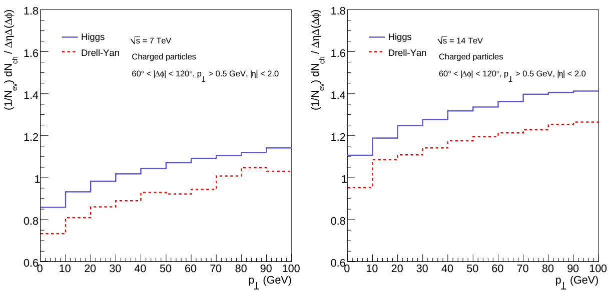

Figure 3: Normalized charged-particle average multiplicity in the transverse region of the azimuthal plane versus Higgs transverse momentum (solid blue line) and DY transverse momentum (red dashed line).

We follow the treatment [15] of underlying events in the azimuthal plane, with the direction of the Higgs momentum and the DY pair momentum, respectively, defining the origin in the azimuthal plane. In Figs. 3 and 4 we show the result of NLO Powheg + Pythia Monte Carlo calculations for charged-particle multiplicities associated with Higgs and DY. (Analogous calculations can be usefully performed for multiplicities of mini-jets defined e.g. as in [16].) We plot the average multiplicity versus Higgs and DY $p_\perp$ (Fig. 3) and the multiplicity distribution (Fig. 4) in the transverse region of the azimuthal plane ($60^\circ < |\Delta\Phi| < 120^\circ$).

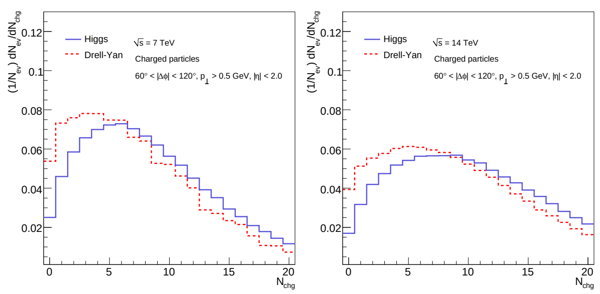

Figure 4: Charged-particle multiplicity distribution in the transverse region of the azimuthal plane in the Higgs (solid blue line) and Drell-Yan (red dashed line) cases.

The distributions in the Higgs case are dominated by higher multiplicities from gluon cascades.

Similarly to the case of the previous section, the effects of large number of overlaid events due to pile-up will be reduced if one measures the difference between Higgs and DY underlying event distributions.

Angular distributions

Besides soft radiation from underlying events, we consider Higgs versus DY distributions in the case of hard radiation accompanying the heavy bosons, for example boson + jet. For the Higgs trigger the angular distribution in the scattering angle θ^* of the boson-jet center-of-mass frame is characterized by the scalar coupling to gluons partially canceling the small-angle Coulomb singularity $d\theta^{*2}/\theta^{*4}$ from gluon scattering - see e.g [8]. The Drell-Yan θ^* distribution is determined by spin-1/2 exchange. As a result, the angular distributions have the same small-angle asymptotics in the two cases. This $\theta^* \to 0$ behavior constitutes a test of the spin of the Higgs, based on production cross section.

In Fig. 5 we consider one-jet production associated with Higgs and Z bosons, and show the differential distributions in $\cos\theta^*$, for jet $p_\perp > 20$ GeV and boson-jet invariant mass m such that 200 GeV $< m <$ 500 GeV. The fact that the two distributions have the same rise for increasing $\cos\theta^*$ tests the cancellation of the Coulomb singularity in the Higgs case and the spin-0 nature of the coupling. This large $\cos\theta^*$ power counting is the basic reason why the difference between Higgs and DY in the low-$p_\perp$ region of Figs. 1 and 2 provides a measurement of higher-loop radiative contributions. Further effects from higher-order color emission may be analyzed via angular correlations in the boson-jet azimuthal plane in the laboratory frame.

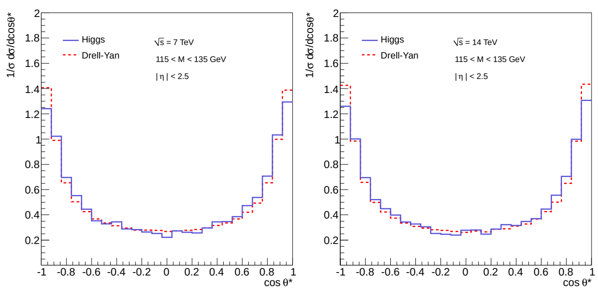

Figure 5: Angular distribution in the center-of-mass scattering angle.

In summary, this paper points out that a program of QCD measurements can be carried out in the high luminosity phase at the LHC, using the Higgs boson as a gluon trigger. We have observed that by measuring systematically differences between Higgs and Drell-Yan differential distributions for masses around 125 GeV the effects of pile-up largely cancel. Such measurements allow one to access experimentally, for the first time, gluon fusion processes at high mass scales, and thus provide a new perspective on Standard Model physics in the strong interaction sector. The examples discussed in this paper illustrate that this program spans a broad range of physics issues on strong interactions, from soft gluon dynamics showing up in the ratio of Higgs to DY low-$p_\perp$ spectra, to underlying events and multiple parton interactions associated with gluonic showers, to hard-QCD contributions to large-$p_\perp$ spectra and angular distributions for boson + jet production. These angular distributions in particular may be used to test the spin of the Higgs at the level of production processes.

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