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LETTER

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New physics and signal-background interference in associated pp → HZ production

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Abstract – We re-investigate electroweak signal-background interference in associated Higgs production via gluon fusion in the presence of new physics in the top Higgs sector. Considering the full final state $pp \to b\bar{b}\ell^+\ell^-$ ($\ell = e, \mu$), we discuss how new physics in the top Higgs sector that enhances the ZZ component can leave footprints in the HZ limit setting. In passing we investigate the phenomenology of a class of new physics interactions that can be genuinely studied in this process.

Introduction. – After the Higgs discovery in 2012 and initial property measurements [1,2] in the so-called κ framework, the phenomenology community has now moved towards understanding constraints in the dimension-six effective field theory (EFT) extension of the Standard Model (SM), which provides a theoretically clean and well-defined approach to constrain the presence of new physics interactions with minimal assumptions [3–7].

The field of Standard Model EFT has seen a rapid development recently. Not only have the run-I measurements by ATLAS and CMS been interpreted in terms of the dimension-six EFT extension [8–26], but the EFT framework has also been extended to next-to-leading order [27–35]. Measurement strategies that take into account these corrections via renormalization group improved calculations have been presented in [36,37].

Due to the large number of effective operators that are relevant to Higgs physics, it becomes essential to collect information from all possible processes related to the Higgs boson, especially at the LHC run II and the future high-luminosity phase. Since a single effective operator can contribute to different processes, there are correlations among them that can be used to find bounds on the Wilson coefficients of different operators. Measurements of the associated Higgs production [20,36,38], Higgs+jet production [39–45], top-quark–associated and multi-Higgs [46–50] production and the recently developed Higgs off-shell measurements in $gg \to ZZ$ [51–53] will be pivotal to obtain a fine-grained picture of potential compatibility of the Higgs discovery with the SM expectation. In particular, the latter production mechanism has been motivated as an excellent candidate to constrain new physics effects by exploiting large momentum transfers to break degeneracies of new physics interactions in the on-shell Higgs phenomenology [54–57].

Similarly, high momentum transfers in the associated Higgs production $pp \to HZ$ are sensitive probes of new interactions [20,58–60]. The reason is the existence of a destructive interference between the triangle and box contributions in the SM that can be lifted by new or anomalous couplings. Furthermore, the high momentum transfer provides another avenue to discriminate the Higgs signal from the background relying on jet substructure methods [61–65].

While jet substructure analyses provide an extremely versatile and adaptable tool in new physics and Higgs searches, the mass resolution of Higgs decays $H \to b\bar{b}$ in such a search is a limiting factor. This becomes a challenge especially if cross-sections or beyond the SM-induced deviations thereof become small for large backgrounds.

It is known that the gluon fusion-induced associated Higgs production [66–68], while only contributing $\sim 10\%$ of the inclusive HZ production cross-section [69–81], becomes relevant at large momentum transfers due to the top quark threshold [58,59]. A similar argument applies to the non-decoupling of $gg \to H \to ZZ$ at high momentum transfers [51,52,82]. Therefore, the same type of physics can enhance both $pp \to HZ$ and $pp \to ZZ$. We are therefore tempted to ask the following question: when studying the full final state $pp \to b\bar{b}\ell^+\ell^-$ as signal for $pp \to H(\to b\bar{b})$ $Z(\to \ell^+\ell)$ (see footnote [1]) for kinematics that allow the discovery of the Higgs boson in the associated production, how important is the irreducible $pp \to Z(\to b\bar{b})Z(\to \ell^+\ell)$ background, keeping in mind an imperfect $H \to b\bar{b}$ resolution?

To answer this question we organise this letter as follows. First we introduce a minimal set of operators which impact the two contributions $pp \to HZ$ and $pp \to ZZ$ in a different way, but necessarily related through gauge invariance. We then investigate the phenomenology of high-p_T final states at the parton level. Subsequently, we show how our findings translate to the fully hadronized final state before we conclude.

New physics effects in gluon-initiated HZ production. – Gluon-initiated associated production has been shown to contribute significantly to $pp \to HZ$ in the boosted regime at the LHC and important consequences for new physics searches can be obtained by looking at this process [58,59,79]. New physics can potentially modify the associated Higgs production both in the quark- and gluon-initiated channels. The quark-initiated channel may be altered at leading order through modified Higgs couplings [37] or at next to leading order through the influence of new particles or effective operators in loops [59,83]. Similarly, the gluon-initiated channel may receive corrections through modified Higgs and top couplings to SM states.

In principle, all dimension-six operators that are relevant for the Higgs sector should be considered since at the very least they can change the Higgs width, which affects the full partonic final state. However, several of these operators are already constrained from other observables, such as the Z-pole properties measured at LEP1. In order to keep our discussion transparent, we will focus on only two operators that are weakly constrained and are relevant for Higgs production (we adopt the parameterisation of [7,84,85]):

$$\mathcal{O}_{Ht} = \frac{i\bar{c}_{Ht}}{v^2}(\bar{t}_R\gamma^\mu t_R)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi), \quad (1)$$

$$\mathcal{O}_t = -\frac{\bar{c}_t}{v^2} y_t \Phi^\dagger\Phi\, \Phi^\dagger \cdot \bar{Q}_L\, t_R + \text{h.c.} \quad (2)$$

with Hermitian covariant derivative $\Phi^\dagger \overleftrightarrow{D}_\mu \Phi = \Phi^\dagger(D_\mu\Phi) - (D_\mu\Phi)^\dagger\Phi$, and Φ being the weak doublet that contains the physical Higgs $\Phi \supset H$.

The operator in eq. (1) modifies the coupling of the right-handed top quark to the Z boson $\bar{t}_R t_R Z$ by a factor proportional to the $\bar{c}_{Ht}$ coefficient,

$$\frac{2}{3}g\frac{s_W^2}{c_W} \to \frac{2}{3}g\frac{s_W^2}{c_W} + g\frac{\bar{c}_{Ht}}{2c_W}. \quad (3)$$

It affects the Ztt coupling but not Htt and introduces a new $ttHZ$ coupling. As required by gauge invariance, the derivative coupling of the top quark to the neutral Goldstone boson gets also shifted by the same quantity. Couplings to left-handed quark doublets are constrained by data on $Z \to b\bar{b}$ and will not change the qualitative outcome of our discussion[2]. Operators of this form but involving light fermions are constrained by precision electroweak measurements $|c_{Hu}| \lesssim 2\%$ and assuming a trivial flavor structure of the UV dynamics will directly constrain the interaction of eq. (1), which is otherwise unconstrained at the tree level by electroweak precision data and has no impact on Higgs decays (see, *e.g.*, [7] for a comprehensive discussion). Higher-order corrections, however, re-induce a dependence, see [87]. We will ignore this potential constraint for the time being, but will come back to it later.

The operator in eq. (2) modifies the top Yukawa coupling by a factor proportional to the Wilson coefficient $\bar{c}_t$, $y_t \to y_t(1+\bar{c}_t)$, while leaving the top mass as in the SM with a simple redefinition of the top quark field. The non-derivative couplings of the top quark to the neutral Goldstone boson are unchanged.

We show in fig. 1 the relevant Feynman diagrams for $pp \to HZ$ and $pp \to ZZ$ ignoring the diagrams involving the unphysical Goldstone bosons. Note, in particular, the new effective vertex $\bar{t}tHZ$ introduced by the operator in eq. (1), not present in the SM, which gives rise to the Feynman diagram contribution to the gluon-initiated amplitude shown in fig. 1(a), and which may affect the cancellation between triangle and box diagrams for $pp \to HZ$ in the SM, leading to an enhanced cross-section. This cancellation is also impacted by the change in the top Yukawa coupling introduced by the operator in eq. (2). In fact, the effect of a flipped top Yukawa coupling (*i.e.*, with a coupling of opposite sign with respect to the SM, corresponding to $\bar{c}_t = -2$) on $pp \to HZ$ was studied in [60].

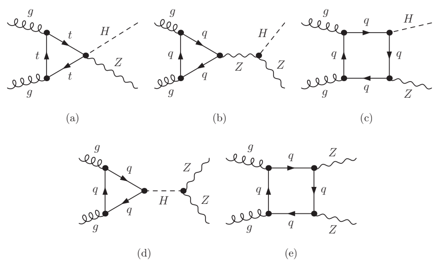

Fig. 1: Representative Feynman diagrams contributing to $pp \to (H,Z)Z \to b\bar{b}\ell^+\ell^-$; we suppress the Higgs and Z boson decays.

[1]The Higgs decay to leptons, *i.e.* $pp \to HH \to b\bar{b}\ell^+\ell^-$, is numerically negligible.

[2]Interactions of this type can typically arise in composite Higgs scenarios [86], which will also leave footprints in $q\bar{q} \to HZ$ as a function of the fine-tuning parameter v^2/f^2, where f is the pion decay constant analogue.

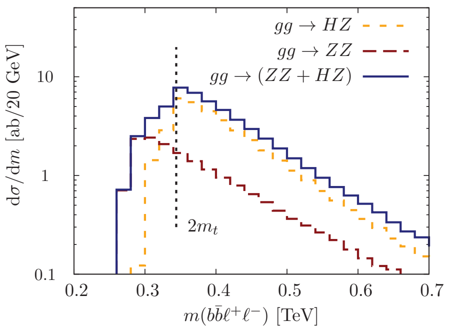

Fig. 2: (Colour online) Invariant mass distribution of the $b\bar{b}\ell^+\ell^-$ (in this plot $\ell = \mu$) system for the final state $gg \to b\bar{b}\ell^+\ell^-$ in the SM and the phase space region $p_T(\ell^+\ell^-) \gtrsim 100$ GeV relevant for a boosted $H \to b\bar{b}$ analysis.

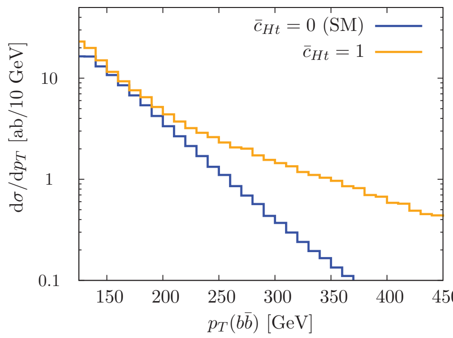

Fig. 3: (Colour online) Transverse Higgs p_T distribution and its sensitivity to the operator $\bar{c}_{Ht}$. It can be seen that the boosted regime $p_T(\ell^+\ell^-) \simeq p_T(b\bar{b}) \gtrsim 150$ GeV is highly sensitive to the operator in eq. (1) which also modifies the continuum ZZ production.

Together these operators provide a parameterisation that allow us to "template" the $gg \to ZZ$ and $gg \to HZ$ components of the full partonic final state $pp \to b\bar{b}l^+l^-$ in a gauge-invariant fashion, and, therefore, gives us a well-defined approach to study the signal-background interference in this final state. Note that since these operators only modify the ttH and ttZ couplings, they do not affect the tree-level $q\bar{q} \to HZ$ process. Only the operator in eq. (2) changes the Higgs branching ratios (by a few percent in the relevant $BR(H \to b\bar{b})$ in the cases explored here) and it has been taken into account.

The new interactions arising from eq. (1) and eq. (2) were implemented using FeynRules [88]. We calculate the one-loop gluon-initiated $gg \to (HZ + ZZ) \to b\bar{b}\ell^+\ell^-$ production amplitudes using the FeynArts, FormCalc and LoopTools [89,90] framework which we interface with Vbfnlo [91] to perform the phase space integration and generate events in the Les Houches standard and keep the full quark mass dependences throughout. We pass these events to Herwig++ [92] for showering and hadronization. The $q\bar{q}$-initiated process is simulated with MadGraph5 [93] using an identical input parameter setting and passed through Herwig++ to obtain the full hadronic final state. The respective samples are normalised to the NLO QCD predictions of the SM [68,69]. We use a K-factor of 1.2 and 1.8 for qq and gg-initiated processes, respectively. We focus on collisions at 13 TeV centre-of-mass energy.

Parton level analysis. Before we analyse the full hadron level, it is worthwhile to re-investigate the order of magnitude of the expected interference effects between the $gg \to HZ$ and $gg \to ZZ$ parts in the full $pp \to HZ + ZZ$ final state (see also [79] for an earlier discussion). To this end, we show in fig. 2 the parton level comparison of the invariant mass distribution between HZ and ZZ production for the gluon-initiated $b\bar{b}\ell^+\ell^-$ (in this case $\ell = \mu$) production. Note the rise of the cross-section near the $2m_t$ threshold. For these selection requirements we find a SM cross-section of 0.9 fb (including the flat K-factor). A choice of $\bar{c}_{Ht} = 1, \bar{c}_t = 0$ increases this cross-section by 70%. A quantitatively identical enhancement can be achieved for $\bar{c}_{Ht} = 0, \bar{c}_t \simeq 0.33$.

Signal-background interference between the two contributions is in general a small effect and the relative size of HZ dominates over ZZ as a consequence of the relative branching ratio suppression of $H \to b\bar{b}$ (60%) and $Z \to \bar{b}b$ (15%). This is left unchanged for changes in $\bar{c}_t$ [79], however, there will be modifications from eq. (2).

In order to obtain a first estimate of the sensitivity to the effective operators, we consider first the process $pp \to (HZ + ZZ) \to b\bar{b}\ell^+\ell^-$ again at parton level. Based on the event simulation described above, we select events with

$$p_T(\ell^+\ell^-) > 150\,\text{GeV},\ \ 110\,\text{GeV} < m(b\bar{b}) < 140\,\text{GeV}. \quad (4)$$

As an example, we show in fig. 3 the effect of $\bar{c}_{Ht} = 1$. One can see that this operator can dramatically impact the boosted Higgs regime due to the lifting of the SM cancellation and also the derivative nature of the induced coupling [85].

In order to derive exclusion regions in the $(\bar{c}_t, \bar{c}_{Ht})$-plane we perform a log-likelihood hypothesis test based on a shape comparison of the $p_T(b\bar{b})$ distribution using the CL$_s$ method [94–96].

In fig. 4 we show the expected exclusion for a luminosity of $100\,\text{fb}^{-1}$ based on our parton level results. While the resonant and continuum ZZ contributions are largely suppressed, the gauge-invariant extension of the top loop-induced $gg \to ZZ$ diagram[3] introduces the $t\bar{t}HZ$ interaction. The result of fig. 4 indicates that the modification according to the operator in eq. (1), even for small choices in agreement with precision analyses [7], can in principle impact the limit setting procedure in the associated Higgs production through sculpting the $p_T(b\bar{b})$ distribution, especially when marginalising over eq. (2) in a global fit where degenerate operator directions will influence the expected exclusion.

[3]One can understand the modification of the $Zt\bar{t}$ interaction as replacing $H \to \langle H \rangle$.

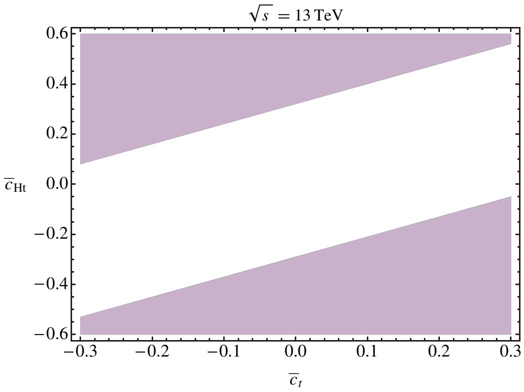

Fig. 4: (Colour online) Projected sensitivity of the boosted parton level analysis of $pp \to b\bar{b}\ell^+\ell^-$ in the conventions of eqs. (1) and (2); the shaded region is excluded at 95% confidence level for the ideal parton level setting described in the text, for $\mathcal{L} = 100\,\text{fb}^{-1}$.

One might worry about the validity of an effective field theory in our analysis. This issue has been a subject of recent discussion, see, *e.g.*, [37,97]. The coefficients of the dimension-6 operators can be related to the scale M where new physics appears by $\bar{c} \approx g^2v^2/M^2$, where g is a coupling constant of the heavy states with SM particles. Further suppression factors arise in the case in which an operator is generated at loop level. We can therefore put an upper bound in the new mass scale from requiring that the underlying theory is strongly coupled, *i.e.*, $g = 4\pi$: $M < 4\pi v/\sqrt{c} \approx 3\,\text{TeV}$ for $c = \mathcal{O}(1)$. Since our analysis relies on $p_T < 1\,\text{TeV}$ we do not violate this upper bound.

Showering and hadronization. The results of the parton analysis detailed in the previous section are known to change substantially when we turn to the full hadron level final state and perform a realistic reconstruction [58]. Based on the event generation strategy outlined above, we apply typical HZ final state selection cuts by

i) requiring exactly 2 oppositely charged same-flavor leptons satisfying $|\eta_\ell| < 2.5$, $p_T(\ell) > 30\,\text{GeV}$,

ii) requiring that these leptons are compatible with the Z boson mass: $80\,\text{GeV} < m(\ell^+\ell^-) < 100\,\text{GeV}$,

iii) and requiring boosted topologies $p_T(\ell^+\ell^-) > 200\,\text{GeV}$.

iv) We then perform a typical BDRS analysis [61]: All the remaining hadronic activity is clustered using FastJet [98] into a Cambridge-Aachen fat jet with $R = 1.2$. The boosted Higgs candidate jet has to satisfy $p_{T,j} > 200\,\text{GeV}$ and at least one such object is required in $|\eta| < 2.5$. The fat jet is filtered, mass-dropped and double b-tagged with a b-tag efficiency of 60% (2% fake rate), yielding a total efficiency of 36%.

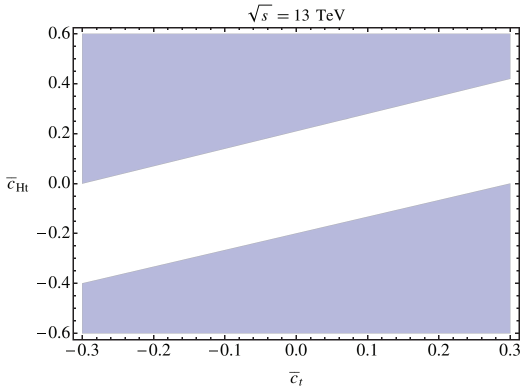

Fig. 5: (Colour online) Projected exclusion at 95% CL$_s$ (blue shaded region) of the boosted hadron level analysis of $pp \to b\bar{b}\ell^+\ell^-$ at 3 ab^{-1} integrated luminosity.

v) Higgs candidates are required to be compatible with $110\,\text{GeV} < m(b\bar{b}) < 140\,\text{GeV}$ evaluated on the b-tagged subjets.

While the high-p_T selection is enough to remove the biggest background $t\bar{t}$ almost entirely, jet substructure approaches remove the QCD-induced $b\bar{b}$ production modes from the selection to a large extent, leaving the Z+jet production as a dominant background (or calibration tool). The Higgs mass resolution quoted in v) is a key factor in the boosted analysis to allow signal *vs.* background extraction in the first place (and veto SM $q\bar{q}$-induced ZZ production). However, as mentioned before, the gluon-induced ZZ contribution could in principle be enhanced through the operator discussed previously, thus adding more significantly to the region v) than expected in the SM and at parton level due to shower and hadronization effects.

After these analysis steps one typically obtains a cross-section of $\sim 0.2\,\text{fb}$ for the SM which includes both $q\bar{q}$- and gg-initiated processes. And again we find the impact of HZ far more dominant than ZZ. As expected, the lowered statistical yield when taking into account the full reconstruction efficiencies requires a larger luminosity to set limits. Setting limits, we obtain a result comparable to the parton analysis of the previous section for $3\,\text{ab}^{-1}$, see fig. 5. This means that when including the constraints from complementary Higgs measurements at this luminosity, which are expected to limit $|\bar{c}_t| \lesssim 10^{-2}$ [26], the presence of $\bar{c}_{Ht}$ for trivial flavor structures, *i.e.* at the level of $\bar{c}_{Ht} = \bar{c}_{Hu}$ is difficult to constrain and can practically be neglected when working with this assumption. However, the associated Higgs production provides a test of non-trivial beyond the SM flavour structures, which can be combined with direct $t\bar{t}Z$ searches (see, *e.g.*, [85,87,99–103]). Comparing to the projections of [99], $-0.13 < \bar{c}_{Ht} < 0.64$, we see that the associated Higgs production can be expected to provide an additional discriminating power to complementary $t\bar{t}Z$ searches. It should be noted that our results do not reflect systematic uncertainties from both theoretical and experimental sources and are therefore very likely to worsen, in particular in a global fit when more operators are included. In particular, the theoretical uncertainties due to missing higher orders in $gg \to HZ$ are currently large for boosted kinematics $\sim \mathcal{O}(30\%)$ [68]. Potential improvements in particular related to experimental systematics are hard to foresee at this stage in the LHC program, but our results suggest that the boosted Higgs analysis should continue to receive attention.

Summary and conclusions. – In this letter we have re-investigated electroweak signal-background interference in the gluon-initiated associated Higgs production in the light of the expected efficiencies and selection requirements of the fully hadronized final state. While the $HZ + ZZ$ signal-background interference is suppressed, new physics effects that impact $pp \to ZZ$ can also leave footprints in the boosted analyses $pp \to HZ$ through new interactions related by gauge invariance. However, a robust limit setting in this channel will require a large luminosity. Even at these large luminosities the constraints on $\bar{c}_{Ht}$ will not be competitive with electroweak precision constraints under the assumption of a trivial flavor structure (as commonly done in Higgs fits at this stage in the LHC phenomenology program). Relaxing this assumption, the associated Higgs production via gluon fusion can act as a test of this hypothesis, especially when other measurements point towards the SM.

* * *

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