Why do we need higher order fully exclusive Monte Carlo generator for Higgs boson production from heavy quark fusion at LHC?

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Abstract

In this paper we argue that having available higher order fully exclusive Monte Carlo generator for Higgs boson production from heavy quark fusion will be mandatory for data analysis at LHC. The $H \rightarrow \tau \tau$ channel, a key for early discovery of the Higgs boson in the MSSM scenario, is discussed. With simplified example and for $m_H = 120$ GeV we show, that depending on choice among presently available approaches, used for simulation of Higgs boson production from $b\bar{b}H$ Yukawa coupling, final acceptance for the signal events being reconstructed inside mass window may differ by a factor of 3. The spread is even larger (up to a factor of 10) for other production mechanisms (promising for some regions of the MSSM parameter space). The complete analysis, which necessarily will add stringent requirements for background rejection (such as identification of b-jet or veto on b-jet) and which will require statistical combination of samples selected with different selection criteria may only enhance the uncertainty.

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1 Introduction

The search for the Higgs boson is one of the primary tasks of the experiments at LHC [1, 2]. Several studies discussed there, concluded both for the Standard Model and Minimal Supersymmetric Standard Model, that Higgs boson can be discovered at LHC, with the high margin of significance, for the full interesting range of its mass.

One of the key signatures for Higgs boson discovery, is with its decay into pair of $\tau$-leptons. For the MSSM Higgs scenario, decay into $\tau$-pair is strongly enhanced at large $\tan \beta$, the parameter of the supersymmetric models. The promising (it depends on the Higgs boson mass and $\tan \beta$) production mechanisms are: the Higgs boson production in association with the b-quarks, inclusive gluon-gluon fusion and, for the lightest MSSM Higgs, also vector-boson-fusion.

The analyses prepared for the MSSM Higgs boson searches in ATLAS, presented in [1], rely mostly on the lepton-hadron decays of the $\tau$-pair, that is the case, when one of the $\tau$-leptons, from the Higgs boson decay, subsequently decays leptonically and another one hadronically (hadron-hadron case was discussed only for the Higgs boson of large mass). The lepton-lepton channel contribution, to the Higgs boson discovery potential, was discussed in [2], in context of the CMS detector.

On theoretical side, the inclusive cross-section at large $\tan \beta$ is dominated by the bottom-quark fusion process $b\bar{b} \rightarrow H$. For the first time it was discussed in [3]. Recently, important progress has been achieved. The total cross-section for the $b\bar{b} \rightarrow H$ process has been evaluated to the next-to-next-to-leading order (NNLO) [4] in the so called variable flavour number scheme (VFS) [3, 5, 6]. The result of this NNLO calculation shows almost no scale dependence. The inclusive $b\bar{b} \rightarrow H$ cross-section was obtained also at the next-to-leading (NLO), fixed order calculations for the parton level process $gg, q\bar{q} \rightarrow b\bar{b}H$ [7, 8]. There, the fixed flavour number scheme (FFS) was used.

Results obtained in these two schemes seem to be compatible now with each other, and show that there is actually no large difference between the NLO fixed order results and use of the b-quark structure functions, if the proper factorisation scale for this process is used [6]. Without the NNLO calculations [4], understanding consistencies between FFS and VFS approaches would be on much weaker foundation. This statement concludes what was discussed since a long time [5, 6, 9, 10]. The fixed order calculation shows a substantial scale dependence and sufficient control of the residual large uncertainties, available only at higher orders, was necessary to compare results of the two approaches.

One should be well aware, that for a given decay channel of $\tau$-pair, the statistical combination of the discovery evidence for events with one identified $b$-jet and events with no identified $b$-jet at all will be required, to achieve maximal (sufficient) sensitivity to the Higgs boson. This defines, what are the relevant hard processes for the analyses, as designed in [1]. For example if the identified final state includes single bottom quark (jet), then the relevant lowest order hard process in the VFS approach should be $gb \rightarrow bH$ [5]. The cross-section for the $gb \rightarrow bH$ production has been also computed at NLO [9] and the residual uncertainties due to the higher order corrections are small. In the FFS scheme the relevant lowest order hard process will still be the $gg, q\bar{q} \rightarrow b\bar{b}H$.

At early stage of LHC operation, also statistical combination of signatures with different $\tau$ decay channels will need to be performed. In addition, in the MSSM scenario, signals from different Higgs bosons (h, H and A) not degenerated in mass, might nonethe-
less overlap in the same mass window.

Although the NLO and even NNLO calculations became available for the integrated cross-sections, and impressive progress has been achieved in understanding consistencies between (VFS) and (FFS) approaches [4, 5, 6, 9, 10], and even though some results on transverse Higgs momentum distribution are also discussed in the literature (see. e.g. [11]), only the LO matrix element + parton shower approach is available for the full event generation which allow for the subsequent detector simulation\(^1\).

As we will attempt to illustrate in this paper, the foreseen by experiments signal reconstruction procedures are very sensitive to the topology of the signal production process. Therefore, good understanding, from the theoretical perspective, of the Higgs production topologies will be mandatory. This can be achieved only with fully exclusive higher order Monte Carlo generator, what we hope will be visible from the present paper.

In this paper, as an example we will use the SM-like 120 GeV mass Higgs boson. We will compare reconstruction efficiencies and final resolutions for the different hard processes and for lepton-lepton and lepton-hadron \(\tau\) decay modes.

Our paper is organized as follows. In section 2 we discuss Higgs boson production using different hard processes and the appropriate cross sections. In sections 3 and 4 we review basic reconstruction and selection properties to be used by experiments. This in particular will explain how idealized signatures translate into more realistic ones. In section 5 we collect numerical results for the \((\ell \ell p_{T}^{\text{miss}})\) signature, originating from the case when both \(\tau\)-leptons decay leptonically. Similarly, in section 6 we collect numerical results for the \((\ell \tau\text{-jet} p_{T}^{\text{miss}})\) signature, originating from the case when one \(\tau\) decays leptonically and another one hadronically. Finally, conclusions, section 7 close the paper.

2 Different hard processes

Let us start discussion by presenting the naive Table 1 with cross-sections calculated for three different hard processes: the \((2 \to 1)\) process \(b\bar{b}\to H\), the \((2 \to 2)\) process \(gb\to Hb\) and the \((2 \to 3)\) process \(gg, q\bar{q}\to b\bar{b}H\), as obtained from PYTHIA 6.2 [12] generator, according to its default initialisations\(^2\).

Factor 4 difference in normalisation can be reported between \(b\bar{b}\to H\) and \(gg, q\bar{q}\to b\bar{b}H\) hard processes. The first one represents lowest order term in (VFS) scheme, second the lowest order term in the (FFS) scheme for the Higgs boson production mediated by the \(b\bar{b}H\) Yukawa coupling, which does not rely on the \(b\)-quark PDF’s. Given recent clarification in [6] this difference could be minimised by using the proper factorisation scale.

The question, whether differential distributions can impose significant effects on how in experimental conditions, the Higgs boson signature is expected to be defined, was not addressed so far in theoretical calculations. The experimental studies have shown clearly

\(^{1}\)Here we refer explicitly to PYTHIA or HERWIG generators, which provide generation of \(b\bar{b}\to H, gb\to Hb\) and \(gg\to b\bar{b}H\) in the lowest order of the hard process only. We are not aware of any implementation in form of the Monte Carlo event generator of the complete calculations of [4].

\(^{2}\)These means choices for the QCD factorisation scale, minimum bias model, parameters of the shower evolution, etc. etc. We think that, for example, discussion of consequences of the possible alternative choices is beyond the scope of this paper, it could only dilute the aim of the paper. The appropriate theoretical framework, necessary for such a discussion need to be established first. For the structure functions we have used CTEQ5L parametrisation.
that the impact of the topological features of the production process can be significant on the overall efficiency of standard reconstruction procedure, see ref. [1] pages: 746, 747.

One of the characteristic for event topology differential distribution is the transverse momenta of the Higgs boson, as it determines directly the average transverse momenta and angular separation of the decay products. In Fig. 1 we show Higgs boson transverse momenta distribution $p_T^{Higgs}$ as generated with different hard processes used. The average $<p_T^{Higgs}>$ distribution for $b\bar{b} \rightarrow H$ process is 23 GeV, for the $gb \rightarrow bH$ process is 31 GeV, and finally for the $gg \rightarrow b\bar{b}H$ process is 28 GeV. The differences in event topologies seems, at a face value, not to be dramatic but we will study nonetheless their impact further in the paper.

| Hard Process | $\sigma \times BR$ [fb] |
|--------------|------------------------|
| $b\bar{b} \rightarrow H(\rightarrow \tau\tau)$ | 7.2 |
| $gb \rightarrow bH(\rightarrow \tau\tau)$ | 4.1 |
| $gg, q\bar{q} \rightarrow b\bar{b}H(\rightarrow \tau\tau)$ | 1.7 |

Table 1: Cross-section for signal production with b-quark Yukawa coupling. Results for there different hard processes are collected. Branching ratios of $H \rightarrow \tau\tau$ is included. The cross section is for 120 GeV mass SM Higgs boson at 14 TeV pp collision, as generated with default initialisations in PYTHIA.

Figure 1: The $p_T^{Higgs}$ distribution for the three hard processes used: $b\bar{b} \rightarrow H$ (left), $gb \rightarrow bH$ (middle) and $gg \rightarrow b\bar{b}H$ (right). Distribution normalised to total $\sigma \times BR$ (pb). Each of these distribution is expected to include significant deficiencies. In the first case generation of $p_T$ above certain value (max. shower scale) is not performed, the later two, are valid only when respectively one/two final state b-quarks have $p_T$ above Sudakov turnover. These condition do not translate into constraint on $p_T^{Higgs}$ in a straightforward manner.

To perform realistic studies it was not enough to generate Higgs production process. For that purpose, PYTHIA [12] Monte Carlo was used. Essential element consisted of simulating the decays of the $\tau$-leptons. For that purpose TAUOLA [13, 14, 15] and PHOTOS [16, 17] Monte Carlos were used. The three segments of the generation were combined using interface presented in [18]. In this way, correct simulation of the $\tau$-decays and
the radiative photons emission from the Higgs boson decay cascade, relevant in particular for the hadron-lepton mode were achieved. Also full spin correlation effects in the Higgs boson decays were assured.

3 Reconstruction of the basic experimental signatures

Reconstruction of the basic experimental signatures: leptons, τ-jets, missing transverse energy, have been done with the fast simulation of the simplified LHC detector, AcerDET [19]. Although to large extend it is representing the best performance of the detector, we believe that it is fairly adequate for the studies presented in this paper. The principle of AcerDET operation is quite similar to the official fast simulation package of ATLAS Collaboration, ATLFAST [20]. In contrary to the latter it relies on only those parameters of the detector which are available in the literature, eg [1], thus public. It is however missing regular internal updates of ATLFAST.

The key experimental issues, which are relevant for discussed analyses can be shortly summarised as: • Both discussed channels have leptons (e or µ) in the final state and can be triggered by either single- or the dilepton trigger. • The hadronically decaying tau’s can be identified in the detector with good efficiency and purity. The important ingredient in the τ-jet identification is the profile of the energy deposition in calorimeter and the number of tracks pointing to the calorimeter cluster. • Missing transverse energy, \( p_T^{\text{miss}} \), is calculated after summing up all reconstructed visible signatures in the final states, including also cells and clusters in the calorimeter.

We have checked that if the ATLFAST is used in simulation instead of AcerDET, a bit worse mass resolution and efficiency for the τ-jet reconstruction is obtained. This does not lead to changes in final conclusions of the paper. For more detailed discussion on the comparison of full ATLAS detector simulation and AcerDET results, relevant for the present analysis, see [19].

4 Selection criteria

Discussed here selection criteria are the minimal one for triggering of a given event (at least one lepton in the final state) and for a good reconstruction of the τ-pair mass. Reconstruction of the invariant mass of the τ-lepton system is made under assumption that the τ-lepton is massless and decays collinearly\(^3\) [21, 1, 2]. The procedure which have been used in [1, 2] is equivalent, for the physical solutions, to the one used in [22, 23] and described below. Fractions of the two τ’s momenta which are carried by measured visible decay products, \( x_{\tau_1}, x_{\tau_2} \), can be calculated from solving equations of conservation of the transverse momenta components of the Higgs boson, reconstructed from the visible products (leptons, τ-jets) and missing transverse energy. The physical solutions (events with resolved neutrinos) are those for which \( 0 < x_{\tau_1}, x_{\tau_2} < 1 \). For events with physical solution, the invariant mass of the system of the visible decay products of τ’s is calculated and the invariant mass of the τ-system is expressed as \( m_{\tau\tau} = m_{\text{vis}} \sqrt{x_{\tau_1} \cdot x_{\tau_2}} \).

\(^3\)We have checked that this assumption leads to about 2.5-3.5 GeV contribution to the gaussian width of reconstructed invariant mass of the ττ system.
We start with selection procedure as defined in [1] and refined in [24] for the lepton-lepton final state. The basic selection consists of requiring: two isolated leptons within acceptance of the detector; threshold on the minimal angular separation between leptons; threshold on the reconstructed missing transverse energy and kinematics of events which allow to resolve equations for neutrinos momenta, i.e. for invariant mass of the τ-pair system to be calculable. The additional selection, also introduced already in [1, 24], is necessary to optimise resolution of the reconstructed invariant mass of the τ-lepton pair.

Slightly modified selection is used for lepton-hadron final state, the basic selection criteria have to be adjusted, already from the beginning, to reject expected reducible backgrounds (tτ, W + j).

For the explicit definition of basic selection and additional selection cuts\(^4\) see later: Tables 2 and 5 respectively in sections 5 and 6.

### 5 The (ℓ ℓ \(p_T^{\text{miss}}\)) final state

In Fig. 2 we show distributions of the kinematical variables in the transverse plane: \(\sin(\Delta \phi_{\ell\ell})\), \(p_T^{\text{miss}}\), \(\cos(\Delta \phi_{\ell\ell})\), used for event selection. One can observe some differences in the shape of the distributions, which do not seem very significant (except for \(\cos(\Delta \phi_{\ell\ell})\)), but nevertheless lead to the cumulated effect on the acceptances of order of a factor 3 (see Table 2) for signal events in lepton-lepton mode, generated with different LO processes. The very initial acceptances are comparable (first line of Table 2), divergences start with adding selection and reconstruction requirements.

| Selection          | \(bb \rightarrow H\) | \(gb \rightarrow bH\) | \(bbH\) | \(gg \rightarrow H\) | \(qqH\) |
|--------------------|----------------------|----------------------|--------|----------------------|--------|
| Basic selection    |                      |                      |        |                      |        |
| 2 iso \(\ell\), \(p_T^{\ell} > 15\) GeV | 18.6 \(\cdot 10^{-2}\) | 18.4 \(\cdot 10^{-2}\) | 19.2 \(\cdot 10^{-2}\) | 18.6 \(\cdot 10^{-2}\) | 21.3 \(\cdot 10^{-2}\) |
| \(|\sin(\Delta \phi_{\ell\ell})| > 0.2\) | 9.3 \(\cdot 10^{-2}\) | 10.1 \(\cdot 10^{-2}\) | 10.1 \(\cdot 10^{-2}\) | 10.4 \(\cdot 10^{-2}\) | 19.0 \(\cdot 10^{-2}\) |
| \(p_T^{\text{miss}} > 15\) GeV | 5.5 \(\cdot 10^{-2}\) | 7.0 \(\cdot 10^{-2}\) | 6.4 \(\cdot 10^{-2}\) | 7.9 \(\cdot 10^{-2}\) | 17.7 \(\cdot 10^{-2}\) |
| resolved neutrinos | 4.4 \(\cdot 10^{-2}\) | 5.8 \(\cdot 10^{-2}\) | 5.1 \(\cdot 10^{-2}\) | 7.0 \(\cdot 10^{-2}\) | 16.5 \(\cdot 10^{-2}\) |
| Additional selection |                      |                      |        |                      |        |
| \(p_T^{\text{miss}} > 30\) GeV | 1.4 \(\cdot 10^{-2}\) | 3.0 \(\cdot 10^{-2}\) | 2.2 \(\cdot 10^{-2}\) | 4.2 \(\cdot 10^{-2}\) | 13.4 \(\cdot 10^{-2}\) |
| \(\cos(\Delta \phi_{\ell\ell}) > -0.9\) | 1.0 \(\cdot 10^{-2}\) | 2.5 \(\cdot 10^{-2}\) | 1.8 \(\cdot 10^{-2}\) | 3.8 \(\cdot 10^{-2}\) | 12.8 \(\cdot 10^{-2}\) |
| \(R_{\ell\ell} < 2.8\) | 9.5 \(\cdot 10^{-3}\) | 2.5 \(\cdot 10^{-2}\) | 1.8 \(\cdot 10^{-2}\) | 3.7 \(\cdot 10^{-2}\) | 12.7 \(\cdot 10^{-2}\) |

Table 2: The cumulative acceptances of the selection criteria for different approaches of modeling production process. For each subsequent line effect of the additional cut off is added.

From the Table 2 we can read, that a large systematic theoretical uncertainty must be assumed for the efficiency of the selection and reconstruction procedure, as a consequence

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\(^4\)Angle \(\phi\) is measured in the plane transverse to the beam axis. The \(R_{\ell\ell}, R_{\ell\ell-jet}\) denote cone separation, expressed by the difference in pseudorapidity \(\eta\) and angle \(\phi\), \(R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}\). The transverse mass in lepton-hadron channel is calculated as \(m_{\ell,\text{miss}} = \sqrt{(p_T^{\ell})^2 + (p_T^{\text{miss}})^2}\). For more comments on definition of variables see [24].
of the different choices in modeling of the production process topology. For illustration, we include results for the other production processes\(^5\): gluon-fusion \(gg \rightarrow H\), and vector-boson-fusion, \(qq \rightarrow qqH\) as well. These processes will be included in the complete analysis of the Higgs signal observability as the channels are expected to be promising for some regions of the MSSM parameter space [22, 23]. The final spread on the efficiency is then even larger.

Figure 2: The characteristic kinematical distributions before respective selection, for different hard processes used: \(b\bar{b} \rightarrow H\) (left column), \(gb \rightarrow bH\) (middle column) and \(qq \rightarrow bbH\) (right column). The shaded (yellow) area will be accepted by selection. Distributions normalised to total \(\sigma \times BR\) [pb]. Every line of the plots correspond to variables as used in cuts: lines 2, 3 and 6 of table 2. Symmetric shape of the distributions of the first line of the plots provides technical test of the simulation.

\(^5\)For the production processes \(gg \rightarrow H\) and \(qqH\), which we will also include later in our discussion of acceptance, default initialisations of PYTHIA 6.2 are used as well.
Table 3: Resolution of the Gaussian fit to the reconstructed invariant mass of the $\tau\tau$ system for different approaches of modeling production process. In brackets is shown acceptance within mass window of $m_H \pm 20$ GeV.

| Selection          | $bb \to H$ | $gb \to bH$ | $bbH$  | $gg \to H$ | $qqH$  |
|--------------------|------------|-------------|--------|------------|--------|
| Basic selection    | 17.3 GeV   | 14.1 GeV    | 16.0 GeV | 11.6 GeV   | 8.8 GeV |
|                    | (63.6 %)   | (68.6 %)    | (67.4%) | (79.1%)    | (88.7%) |
| $p_T^{miss} > 30$ GeV | 15.8 GeV   | 11.9 GeV    | 13.0 GeV | 9.8 GeV    | 8.3 GeV |
|                    | (73.0 %)   | (77.7 %)    | (76.9%) | (86.5%)    | (91.3%) |
| $\cos(\Delta\phi_H) > -0.9$ | 14.5 GeV   | 11.4 GeV    | 12.3 GeV | 9.3 GeV    | 8.1 GeV |
|                    | (80.8 %)   | (82.6 %)    | (82.0%) | (90.0%)    | (93.1%) |
| $R_{\ell\ell} < 2.8$ | 14.4 GeV   | 11.4 GeV    | 12.1 GeV | 9.2 GeV    | 8.1 GeV |
|                    | (81.6 %)   | (83.2 %)    | (82.9%) | (90.6%)    | (93.4%) |

Figure 3: The reconstructed mass of the $\tau'$s pair, for the $gg \to b\bar{b}H$ events. Distribution after $\cos(\Delta\phi_H)$ selection cut off is shown. Only those events which are reconstructed in constrained mass window, eg. $m_H \pm 20$ GeV, will be considered as contributing to the Higgs signature.

In Table 3 we compare resolution of the Gaussian fit to the reconstructed invariant mass of the $\tau$-pair system, and acceptances inside mass window of $m_H \pm 20$ GeV. The natural width is negligible for the Higgs boson with 120 GeV mass, the non-zero resolution spread comes exclusively from the reconstruction procedure (assumptions of the collinearity in the $\tau$’s decay, and $p_T^{miss}$ reconstruction). As an example, in Fig. 3 we show reconstructed invariant mass for the $gg \to b\bar{b}H$ events. Resolutions for $bb \to H$ and $gb \to bH$ topologies (Table 3) differ up to 30%. This additional effect will enhance the impact of choice of the hard process on the total acceptance, on top of the one, introduced by the differences in the selection efficiencies discussed in Table 2.
Estimates for the total cumulative acceptance inside mass window, as presented in Table 4, give clear indication of the size of the systematic uncertainty which should be (at present) assigned to the predictions on the expected number of signal events.

Note that the very initial acceptances (first line(s) in Table 2) were comparable for all discussed processes. Then the selection was designed for signal reconstruction only. Additional features of topologies, like presence of extra hard partons was not explored yet. The difference for the total cumulated acceptances, which arose after additional selection necessary for the signal reconstruction inside mass window, is a factor of 3 for $b\bar{b}\rightarrow H$ versus $gb \rightarrow bH$ topologies. It is even a factor of 4 for $gg \rightarrow H$ versus $b\bar{b}\rightarrow H$ topologies.

The additional selection as it was already pointed out, is necessary for resolution of the reconstructed invariant mass of the $\tau\tau$-lepton pair.

| Selection | $bb \rightarrow H$ | $gb \rightarrow bH$ | $bbH$ | $gg \rightarrow H$ | $qqH$ |
|-----------|-------------------|-------------------|-------|-------------------|-------|
| Basic selection | $2.8 \cdot 10^{-2}$ | $4.0 \cdot 10^{-2}$ | $3.4 \cdot 10^{-2}$ | $5.6 \cdot 10^{-2}$ | $14.6 \cdot 10^{-2}$ |
| $p_T^{miss} > 30$ GeV | $1.0 \cdot 10^{-2}$ | $2.3 \cdot 10^{-2}$ | $1.7 \cdot 10^{-2}$ | $3.7 \cdot 10^{-2}$ | $12.2 \cdot 10^{-2}$ |
| $\cos(\Delta \phi_{\ell \ell}) > -0.9$ | $8.2 \cdot 10^{-3}$ | $2.1 \cdot 10^{-2}$ | $1.5 \cdot 10^{-2}$ | $3.4 \cdot 10^{-2}$ | $12.0 \cdot 10^{-2}$ |
| $R_{\ell \ell} < 2.8$ | $7.8 \cdot 10^{-3}$ | $2.1 \cdot 10^{-2}$ | $1.5 \cdot 10^{-2}$ | $3.4 \cdot 10^{-2}$ | $11.9 \cdot 10^{-2}$ |

Table 4: The cumulative acceptance in the mass window $m_H \pm 20$ GeV, for different approaches of modeling production process.

6 The $\ell \tau$-jet $p_T^{miss}$ final state

Let us now turn to the second case, where one of the $\tau$’s decays hadronically. We will proceed similarly as in the previous section. We start with Fig. 4 where we show distributions of the kinematical variables used later for events selection: $\sin(\Delta \phi_{\ell \tau - jet})$, $m_T^{miss}$, $\cos(\Delta \phi_{\ell \tau - jet})$. One can observe some differences in the shape of these distributions, depending on the choice of the hard process (similarly as for lepton-lepton channel, the $\cos(\Delta \phi_{\ell \tau - jet})$ is the most sensitive to this choice). The cumulated effect on the acceptances is of the order of a factor of 3 in this case (see Table 5) similarly as it was in the lepton-lepton channel.

The Gaussian resolution for the reconstructed invariant mass of the $\tau\tau$ system mass is specified in Table 6. Obtained resolution on average is 10\% better than for the lepton-lepton channel, which might seem contrary to the intuition (we need to reconstruct $\tau$-jet, what is less precise than reconstruction of a lepton). The contradiction is due to the fact that the $\tau$-jet spectrum from $\tau \rightarrow$ had $\nu_\tau$ decay is harder than the lepton spectrum from $\tau \rightarrow \ell \nu_\tau \nu_\bar{\ell}$ decay (in the second case we have two neutrinos). Thus, in the first case the assumption of the collinear decay for $\tau$ lepton works better for the invariant mass reconstruction, simply because there is less of neutrino energy.

Estimates for the total cumulative acceptance inside mass window, presented in Table 7, give clear indication of the size of the systematic uncertainty which should be assigned to the predictions for the expected number of signal events. The difference for the total cumulated acceptance for the signal reconstruction inside mass window are similar in size to the one in the lepton-lepton final state.
Figure 4: The characteristic kinematical distributions before respective selection, for different hard process used: $b\bar{b} \rightarrow H$ (left column), $g b \rightarrow b H$ (middle column) and $q\bar{q} \rightarrow b\bar{b}H$ (right column). The shaded (yellow) area will be accepted by the selection. Distributions normalised to total $\sigma \times BR$ [pb]. Every line of the plots correspond to variables as used in cuts: lines 2, 3 and 6 of table 5. Symmetric shape of the distributions of the first line of the plots provides technical test of the simulation.

Let us stress that results presented in Sections 5 and 6 should be considered as illustration of the problem, and not as an optimised expected performance of the LHC experiments.
The cumulative acceptances of the selection criteria for different approaches of modeling production process. For each subsequent line effect of the additional cut off is added.

| Selection                  | $bb \to H$ | $gb \to bH$ | $bbH$ | $gg \to H$ | $qqH$ |
|----------------------------|------------|-------------|-------|-----------|-------|
| Basic selection            |            |             |       |           |       |
| $1 \text{ iso } \ell$, $p_T^\ell > 20 \text{ GeV}$ | $19.5 \cdot 10^{-2}$ | $19.3 \cdot 10^{-2}$ | $19.7 \cdot 10^{-2}$ | $19.5 \cdot 10^{-2}$ | $22.2 \cdot 10^{-2}$ |
| $1 \text{ } \tau\text{-jet}, p_T^{\tau-jet} > 30 \text{ GeV}$ | $9.6 \cdot 10^{-2}$ | $10.5 \cdot 10^{-2}$ | $10.4 \cdot 10^{-2}$ | $10.9 \cdot 10^{-2}$ | $19.8 \cdot 10^{-2}$ |
| $|\sin(\Delta \phi_{\ell \tau-jet})| > 0.2$ | $8.9 \cdot 10^{-2}$ | $9.8 \cdot 10^{-2}$ | $9.7 \cdot 10^{-2}$ | $10.1 \cdot 10^{-2}$ | $18.4 \cdot 10^{-2}$ |
| $m_T^{miss} < 50 \text{ GeV}$ | $5.5 \cdot 10^{-2}$ | $6.6 \cdot 10^{-2}$ | $6.0 \cdot 10^{-2}$ | $7.6 \cdot 10^{-2}$ | $15.3 \cdot 10^{-2}$ |
| Additional selection       |            |             |       |           |       |
| $p_T^{miss} > 30 \text{ GeV}$ | $9.1 \cdot 10^{-3}$ | $2.1 \cdot 10^{-2}$ | $1.4 \cdot 10^{-2}$ | $3.0 \cdot 10^{-2}$ | $10.1 \cdot 10^{-2}$ |
| $\cos(\Delta \phi_{\ell \tau-jet}) > -0.9$ | $6.5 \cdot 10^{-3}$ | $1.8 \cdot 10^{-2}$ | $1.2 \cdot 10^{-2}$ | $2.7 \cdot 10^{-2}$ | $9.8 \cdot 10^{-2}$ |
| $R_{\ell \tau-jet} < 2.8$ | $6.1 \cdot 10^{-3}$ | $1.7 \cdot 10^{-2}$ | $1.1 \cdot 10^{-2}$ | $2.6 \cdot 10^{-2}$ | $9.7 \cdot 10^{-2}$ |

Table 5: Gaussian resolution for the reconstructed $\tau\tau$ system for different approaches of modeling production process. In brackets acceptance within mass window of $m_H \pm 20 \text{ GeV}$ is shown.

| Selection                  | $bb \to H$ | $gb \to bH$ | $bbH$ | $gg \to H$ | $qqH$ |
|----------------------------|------------|-------------|-------|-----------|-------|
| Basic selection            |            |             |       |           |       |
| $p_T^{miss} > 30 \text{ GeV}$ | $13.6 \text{ GeV}$ | $11.4 \text{ GeV}$ | $12.5 \text{ GeV}$ | $9.8 \text{ GeV}$ | $9.0 \text{ GeV}$ |
| $\cos(\Delta \phi_{\ell \tau-jet}) > -0.9$ | $13.1 \text{ GeV}$ | $11.1 \text{ GeV}$ | $11.9 \text{ GeV}$ | $9.7 \text{ GeV}$ | $8.9 \text{ GeV}$ |
| $R_{\ell \tau-jet} < 2.8$ | $13.0 \text{ GeV}$ | $11.1 \text{ GeV}$ | $11.8 \text{ GeV}$ | $9.7 \text{ GeV}$ | $8.9 \text{ GeV}$ |

Table 6: Gaussian resolution for the reconstructed $\tau\tau$ system for different approaches of modeling production process. In brackets acceptance within mass window of $m_H \pm 20 \text{ GeV}$ is shown.

| Selection                  | $bb \to H$ | $gb \to bH$ | $bbH$ | $gg \to H$ | $qqH$ |
|----------------------------|------------|-------------|-------|-----------|-------|
| Basic selection            |            |             |       |           |       |
| $p_T^{miss} > 30 \text{ GeV}$ | $5.7 \cdot 10^{-3}$ | $1.5 \cdot 10^{-2}$ | $1.0 \cdot 10^{-2}$ | $2.3 \cdot 10^{-2}$ | $8.6 \cdot 10^{-2}$ |
| $\cos(\Delta \phi_{\ell \tau-jet}) > -0.9$ | $4.7 \cdot 10^{-3}$ | $1.4 \cdot 10^{-2}$ | $9.0 \cdot 10^{-3}$ | $2.2 \cdot 10^{-2}$ | $8.5 \cdot 10^{-2}$ |
| $R_{\ell \tau-jet} < 2.8$ | $4.5 \cdot 10^{-3}$ | $1.4 \cdot 10^{-2}$ | $8.8 \cdot 10^{-3}$ | $2.1 \cdot 10^{-2}$ | $8.5 \cdot 10^{-2}$ |

Table 7: The cumulative acceptance in the mass window $m_H \pm 20 \text{ GeV}$, for different approaches of modeling production process.
7 Conclusions

In the paper we have discussed one of the key signatures at LHC: $(\ell \ell p_T^{\text{miss}})$ and $(\ell \tau - \text{jet} p_T^{\text{miss}})$. They are important for searches of the Higgs boson if it decays into $\tau$-lepton pair. Numerical results were collected in sections 5 and 6.

We have concentrated on the discussion of the reconstruction efficiency and mass resolution of the LHC experiments. We have varied the production processes, also, we have used different methods for the simulation of the same channels, effectively re-shuffling parts of the hard process into parton shower. In this way we have obtained different event topologies. Even though we have applied rather simplified analysis, for example we have neglected additional cut-offs related to the background suppression and we have used simplified simulation for the detector response only, our analysis give an insight into the complexity of the problem. We have shown that the choice of production hard process affects the cumulative acceptance in the mass window for the signal reconstruction by a factor of few (even up to a factor of 10 for VBF fusion channel). The main effect comes from interplay of average transverse momentum of the Higgs boson, simulated differently depending on the way how the hard process is chosen and ambiguities in measurement of $p_T^{\text{miss}}$. This have an impact on the efficiency for finding physical solution of the neutrino system, necessary for the $m_{\tau\tau}$ reconstruction. Transverse momentum determines quality of the resolution, in particular in the regions of tails.

Strong sensitivity on the production topology indicates that for the more complicated production processes, such as $b\bar{b} \rightarrow H$ Yukawa induced mechanism, the possible large theoretical systematic error may still need to be assumed for the predictions, even if small theoretical uncertainties obtained for the overall normalisation can be nowadays well controlled with NNLO calculations. For inclusive quantities effects related to the QCD regularisation and renormalisation scale are well understood. However, the fully exclusive Monte Carlo implementation is mandatory for the experimentally useful analysis. To convince the reader, we have explicitly studied effects of principal selection cut-offs which experiments will be most probably forced to use in data analysis.

Let us stress, that we have not even touched the subject of the impact of those selection criteria which must be applied to optimise rejection against expected background (b-jet identification or b-jet veto). It will only add complexity to the discussion. Asking for b-jet identification or b-jet veto will enhance contribution from some NLO or NNLO terms, with respect to the total inclusive cross-section, in a manner which is difficult to predict analytically, as predictions need to be convoluted with detector effects (jets reconstruction and jets identification). Thus even stronger argument for the availability of the existing theoretical calculations in the form of exclusive Monte Carlo, suitable for more educated studies than the one presented here. Without such a tool it will be difficult to decide in unambiguous way, how much of the mentioned above, factor of 3 to 10, ambiguity on cumulative acceptance, indeed contributes to theoretical uncertainty for the realistic signature of the Higgs boson. Note, that ambiguity depends drastically on how complete is the choice of selection cuts. If we had taken only first step (first lines of tables 2 and 5) of the basic selection cuts, then we could conclude that acceptance is independent, both from different approaches to modelling of production process and from production process as well. Thus that it can be represented by an universal factor, up to about $\pm 10\%$ precision level. The conclusion would be, as we could see, overwhelmingly false. On the
other hand, turning the question around, one can ask, if experimental selections can be modified to diminish dependence on the topological features of the events (namely quality of reconstruction and absolute value of the $p_T^{miss}$).

Let us note also, that for the Higgs boson at 120 GeV dominant background will come from the irreducible Drell-Yan $Z/\gamma^* \rightarrow \tau\tau$ production. The signal will appear above steeply failing edge of the resonant peak at the nominal Z-boson mass, and will be dominated by the misreconstructed on-shell Z-boson events. Calibration of the background from the shape outside signal mass window will be extremely difficult.

Finally, let us recall again, that for the MSSM Higgs scenarios in the parameter space corresponding to the A/H/h masses in range of 100-200 GeV, one will have to combine distinct production modes ($gg \rightarrow H$ and $b\bar{b} \rightarrow H$), and different final states of $h \rightarrow \tau^+\tau^-$ with subsequent decays either into lepton-lepton or lepton-hadron channels. The signatures of the Higgs bosons h/H/A may overlap (even if there is no mass degeneracy between h/H/A). The goal of the experiment will be not only to establish evidence for the signal, but also to measure properties of the model (e.g. couplings) from the observed versus predicted signal rates. The key challenge for evaluating remaining theoretical systematic error will require not only the proper normalisation of total cross section but also modeling of the production mechanism including differential distributions, essential as demonstrated here, for experimental signal reconstruction.

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