PROCEEDINGS OF SCIENCE

Searches for Higgs invisible

Vukašin Milošević[a,*] **on behalf of the CMS Collaboration**

[a] *IHEP Beijing,*
19 Yuquan Rd, Shijingshan District, Beijing, China

E-mail: vukasin.milosevic@cern.ch

A summary of searches for Higgs bosons decaying to invisible particles using the data collected by the CMS experiment is presented. This report focuses on three stages of these analyses. First, the combination of results using data collected during the Run 1 ($\sqrt{s}$ = 7 and 8 TeV, with 24.6 fb^{-1} of total integrated luminosity) and early Run 2 ($\sqrt{s}$ = 13 TeV, with 38.2 fb^{-1}) data taking periods is presented. This combination places a limit on the $\mathcal{B}$(H → inv) at 0.20 (0.19) in terms of the observed (expected) 95 % Confidence Level (CL) upper limit. It is followed by a look into the currently available results focusing on the entire Run 2 phase of data collection (137 fb^{-1}), namely the analyses targeting the VH production mode of the Higgs boson. Lastly, a summary of future prospects is presented in terms of the most sensitive channel of this search, indicating the possibility of further constraining the $\mathcal{B}$(H → inv) to 0.038 during the High Luminosity (HL) phase of operation of the Large Hadron Collider (LHC).

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*Speaker

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1. Introduction

The searches for the Higgs boson [1, 2] decaying invisibly present an interesting way of probing for the physics beyond the Standard Model (BSM) at the Large Hadron Collider (LHC). From the SM point of view, a decay mode invisible to the CMS experiment [3], H $\to 4\nu$, has a small probability of happening, thus making any deviation from it an indication of new physics. This is further supported by the fact that, even though all of the measurements of the properties of the Higgs boson show a good agreement with the SM, their large uncertainties can still harbour BSM physics. The following sections are going to introduce the main analyses focusing on this final state as well as to summarise the, currently available, results from the CMS Collaboration, followed by projections for the HL-LHC phase of operation.

2. Analysis strategies

The most sensitive production mode for this study is the scenario where the Higgs boson is produced via the Vector Boson Fusion (VBF). Due to its characteristic dijet signtaure, energetic jets with a large geometrical separation[1], it allows for a good control of background processes. The invisible part of this process is characterised through the appearance of a large E_T^{miss}. The main SM backgrounds are found in the form of V + 2 jet processes (where V = W, Z), which are irreducible for the following decay scenarios: Z $\to \nu\nu$ and W $\to$ lν, where the lepton has been lost during the detection process in the latter case. Their contribution is estimated through the use of dedicated control regions (CR) which are made orthogonal to the signal region (SR), while keeping the same dijet topology (i.e. leading to the formation of a Z $\to \mu\mu$ + jets enriched region). Additional major source of SM background originates from QCD multijet processes and is estimated using data driven techniques. The rest of the relevant SM processes provide a minor overall contribution and are estimated from simulation. This approach to background treatment is shared between the rest of the analyses focusing on this process.

The second most sensitive category can be formed around the Higgs production in association with a vector boson (VH). Analyses targeting this production mode can be separated into two categories following their subsequent, leptonic or hadronic, decay modes. The Z(ll)H analysis targets the final state where an event is comprised from a large E_T^{miss} and a pair of leptons originating from the Z boson decay. On the other hand, the main focus of the mono-V analysis is the other possible scenario, in which the hadronic vector boson decays allow for the formation of an event with a large E_T^{miss} and energetic jets. Lastly, the monojet analysis looks for events with a jet originating from ISR accompanied with the large E_T^{miss}. This analysis is interpreted as the one targeting the gluon fusion Higgs boson production (ggH) in association with one jet.

3. Current status

The first milestone of previously defined analysis efforts in the Run 2 era was the combination of measurements performed using the entire Run 1 dataset ($\sqrt{s}$ = 7 and 8 TeV, with 24.6 fb^{-1} of total integrated luminosity) with the ones focusing on the early Run 2 era of data collection ($\sqrt{s}$ = 13 TeV,

[1]With a large dijet invariant mass m_{jj} as a consequence.

with 38.2 fb^{-1}) [4]. Figure 1 shows the summary of these searches using the 2016 data (36.9 fb^{-1}), where the results are expressed as the 95 % CL upper limits on the $\mathcal{B}$(H→inv). It also illustrates the importance of the VBF analysis, as it places the limit at 0.33 (0.25), while the full combination yields 0.26 (0.20) for the observed (expected) value of $\mathcal{B}$(H→inv). The subsequent combination with the Run 1 data places the limit on $\mathcal{B}$(H→inv) at 0.19 (0.15) for the observed (expected) value, as shown in Figure 2 (left). This result is currently the best constraint of this process coming from the CMS Collaboration. These measurements were interpreted in terms of the dark matter (DM)-nucleon scattering cross section for the Higgs portal models [5], as shown in Figure 2 (right) alongside results coming from other relevant direct detection experiments.

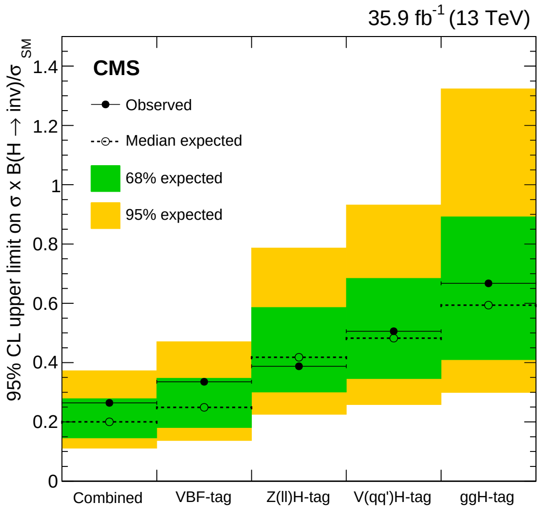

Figure 1: The results of per-analysis measurement of the 2016 dataset, expressed in terms of the 95 % CL upper limit on the $(\sigma/\sigma_{SM})\mathcal{B}$(H→inv) [4].

The first measurement focusing on the entire Run 2 dataset (with 137 fb^{-1} of total integrated luminostity) comes from the Z(ll)H analyses. It is an interpretation of a wider search for DM in association with a Z boson [6]. It places a constraint on the $\mathcal{B}$(H→inv) at 0.29 (0.25) for the observed (expected) 95 % CL upper limit. The latest[2] relevant publication summarises the monojet/V measurement using the full Run 2 dataset. Similarly to the Z(ll)H analysis, this measurement comes as an interpretation of a wider search for new particles in association with E_T^{miss} and jets [7]. This measurement brings an update to the previous analysis strategy by adding an implementation of machine learning (ML) techniques in search for the V(qq) event. The main purpose of this is to separate signal from QCD multijet background events. A neural network tagger is deployed, introducing subcategories which are based on the DeepAK8 tagger score (as detailed in Ref. [9]). The resulting subcategories are defined as follows: High purity VH (comprised of 90 % VH), Low purity VH (40 % VH) and monojet (75 % ggH, 20 % VBF), as shown in Figure 3 (left). No significant deviation from the SM is reported and an upper limit of 0.28 (0.25) for the observed (expected) value is placed for the $\mathcal{B}$(H→inv). Results from the most sensitive (VBF) analysis are being prepared and

[2]At the time of writing this report.

are expected to follow soon accompanied with the combination of all aforementioned measurement strategies, creating a legacy result for the Run 2 phase of data collection.

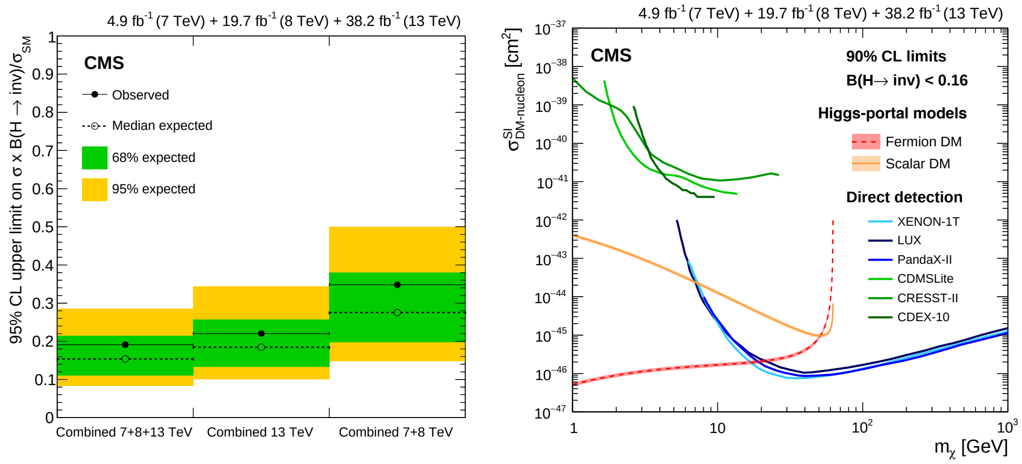

Figure 2: Combination of measurements from the Run 1 and early Run 2 phase of data collection expressed as the 95 % CL upper limits on the $(\sigma/\sigma_{SM})\mathcal{B}$(H→inv) (left), [4]. Interpretation of this combination in terms of the DM-nucleon scattering cross section in Higgs portal models (right). [4].

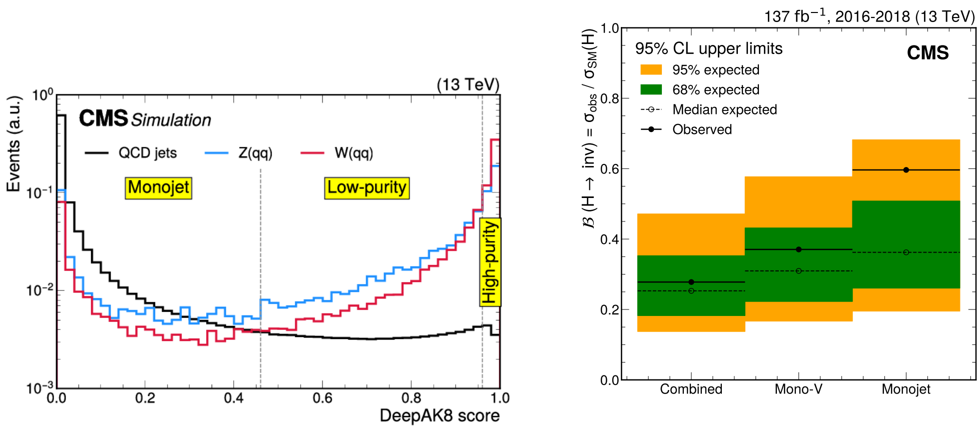

Figure 3: Analysis categorisation for mono-V/jet subcategories (left) [7]. Per-category results interpreted as the 95 % CL upper limits on $\mathcal{B}$(H→inv) [7] (right).

Lastly, a study of future prospects was performed in order to estimate the performance of the upgraded CMS detector during the HL-LHC phase of operation in terms of this search [8]. The VBF analysis was chosen as the model analysis, being the most sensitive for this search. The analysis strategy from the early Run 2 study [4] was applied to the upgraded conditions, while the final measurement was performed for various selection requirements of the E_T^{miss}. Figure 4 (left) summarises the results expressed as 95 % CL upper limits on $\mathcal{B}$(H→inv) for three different values of total integrated luminosity ($\mathcal{L}$ = 300, 1000 and 3000 fb^{-1}). Figure 4 (right) focuses on the $\mathcal{L}$ = 3000 fb^{-1} era, yielding the best scenario for the E_T^{miss} > 190 GeV. This would place the projected 95 % CL upper limit on $\mathcal{B}$(H→inv) at 0.038. The conclusion of this study points out that a significant advancement in lowering the E_T^{miss} threshold (from current 250 GeV to 190 GeV) is needed in order to be able to achieve this level of sensitivity. This would require a novel approach to triggering for this analysis and could be taken in two directions: optimisation of standard "cut and count" algorithms or investigating the possibility of utilising ML techniques at the first, Level-1, triggering level.

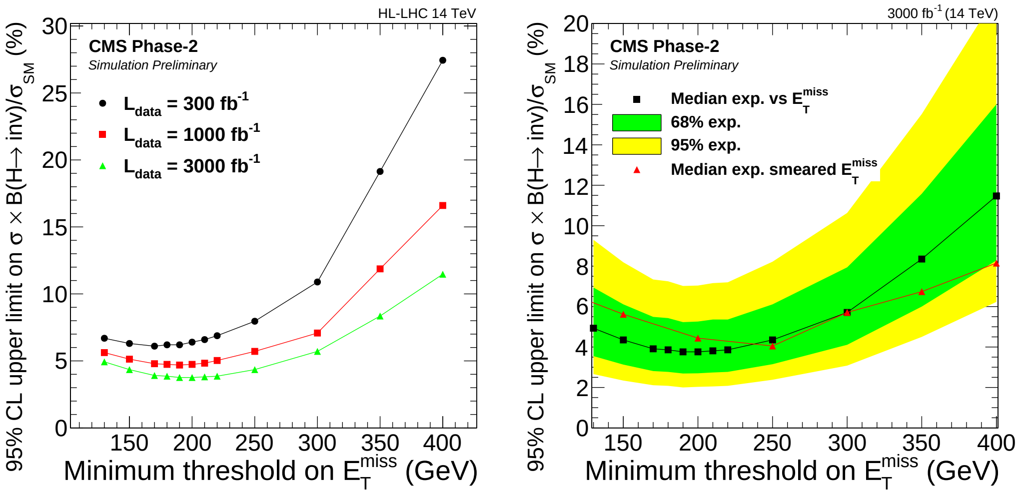

Figure 4: Summary of values for the 95 % CL upper limits on the $(\sigma/\sigma_{SM})\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv})$ for three different eras: $\mathcal{L}$ = 300, 1000 and 3000 fb^{-1} [8] for different values of the E_T^{miss} selection requirement (left). A more detailed presentation of the measurement projection for the $\mathcal{L}$ = 3000 fb^{-1} era [8] (right).

4. Conclusion

This report presented an overview of the searches for Higgs bosons decaying invisibly performed by the CMS Collaboration. The first combination of measurements made using data collected during the Run 1 (24.6 fb^{-1}) and early Run 2 (38.2 fb^{-1}) phases of operation places a 95 % CL upper limit on the $\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv})$ at 0.20 (0.19) for the observed (expected) value. The mono-V/jet and the Z(ll)H analyses were the first ones to reach the goal of analysing the complete Run 2 dataset (2016-2018, 137 fb^{-1}) and have placed a 95 % CL upper limit on the $\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv})$ at 0.28 (0.25), and 0.29 (0.25), respectively. Lastly, a study of future prospects for these searches, presented from the point of view of the VBF analysis, has indicated that the limit for $\mathcal{B}(\mathrm{H}\rightarrow\mathrm{inv})$ could be further lowered to 0.038 during the course of the HL-LHC phase. Its summary pointed out a necessity for a better approach when selecting interesting events at the triggering stage in order to be able to reach the projected constraints on the invisible decays of the Higgs boson.

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