

Vector boson fusion invisible Higgs decays as constraints on Higgs-portal vector dark matter

Abstract

This paper explores how invisible Higgs boson decays in vector boson fusion (VBF) can be used to place constraints on Higgs-portal vector dark matter. The exploration uses published limits from ATLAS and CMS on the invisible branching ratio of the Higgs boson, $BR(H \rightarrow \text{inv})$, being the starting point. These limits are first converted into bounds on the maximum invisible decay width of the Higgs boson, using $\tilde{\Lambda}_{SM} = 4.1 \text{ MeV}$, and then into limits on the Higgs-portal coupling in the mass region $m_V < m_h / 2$, where the decay $h \rightarrow VV$ is kinematically allowed. The collider-based limits are further translated into spin-independent dark matter–nucleon scattering limits, σ_{SI} , and compared with direct detection results from LZ, XENONnT, and PandaX-4T. The results show that collider limits from invisible Higgs decays are important, especially near the threshold region $m_V \approx m_h / 2$, while direct detection experiments are stronger over most of the allowed mass range. This shows that collider searches and direct detection experiments work well together in testing Higgs-portal dark matter models.

Keywords: invisible higgs decays, vector boson fusion, higgs-portal dark matter, vector dark matter, spin-independent scattering

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Introduction

Dark matter remains one of the main open problems in particle physics and cosmology. Evidence from galaxy rotation curves, gravitational lensing, and large-scale structure shows that much of the matter in the universe is invisible, but its particle nature is still unknown.¹⁻³ The discovery of the Higgs boson at CERN in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) was a major step in particle physics.^{4,5} With a mass near 125 GeV, the Higgs completed the Standard Model and also opened a path to studies beyond it, including dark matter. One widely studied idea is the Higgs-portal dark matter model, in which dark matter interacts with Standard Model particles through the Higgs boson.^{6,7} If $m_V < m_h / 2$ the Higgs can decay invisibly through $h \rightarrow VV$. This

makes $BR(H \rightarrow \text{inv})$ useful quantity for testing the model. At the LHC, one of the most sensitive channels for this search is vector boson fusion (VBF).^{7,8}

In this work, published limits on $BR(H \rightarrow \text{inv})$ with focus on the VBF channel, are used to constrain Higgs-portal vector dark matter. The limits are converted into bounds on the maximum invisible Higgs width, $\tilde{\Lambda}_{inv}^{\text{max}}$ using $\tilde{\Lambda}_{SM} = 4.1 \text{ MeV}$, and then into bounds on the portal coupling in the region $m_V < m_h / 2$. These collider-based limits are also mapped into spin-independent dark matter–nucleon scattering limits and compared with direct detection results.

Theoretical framework

In the Higgs-portal vector dark matter model, the dark matter particle is a neutral vector boson V that couples to the Higgs boson.^{6,7,12} The interaction is written as

$$\mathcal{L} \supset \frac{1}{2} g_{hVV} h V_\mu V^\mu, \lambda = \frac{g_{hVV}}{v} \text{ with } =$$

246 GeV. If $m_V < m_h / 2$ the Higgs boson can decay invisibly through $h \rightarrow VV$, contributing to $BR(H \rightarrow \text{inv})$.

For vector dark matter, the invisible decay width is given by^{6,7}

Experiment	Channel	\sqrt{s} (TeV)	Luminosity (fb^{-1})	Observed BR($H \rightarrow \text{inv}$)	Expected BR($H \rightarrow \text{inv}$)
CMS	VBF+ZH combined	8	19.5	0.65	0.49
CMS	VBF-only	13	35.9	0.33	0.25
CMS	VBF-only	13	101	0.18	0.10
ATLAS	Combined	13	139	0.107	0.077
ATLAS	VBF-only	13	139	0.145	0.103

$$\tilde{\Lambda}(h \rightarrow VV) = \frac{g_{hVV}^2 m_h^3}{128\pi m_V^4} (1 - 4x + 12x^2) \sqrt{1 - 4x},$$

$$x = \frac{m_V^2}{m_h^2}.$$

Using the published ATLAS and CMS limits on $\text{BR}(H \rightarrow \text{inv})$, the maximum invisible Higgs width is written as

$$\tilde{\Lambda}_{\text{inv}}^{\text{max}} = \frac{\text{BR}(H \rightarrow \text{inv})}{1 - \text{BR}(H \rightarrow \text{inv})} \tilde{\Lambda}_{\text{SM}},$$

with $\tilde{\Lambda}_{\text{SM}} = 4.1 \text{ MeV}$. The condition $\tilde{\Lambda}(h \rightarrow VV) \leq \tilde{\Lambda}_{\text{inv}}^{\text{max}}$ is then used to obtain the upper bound $g_{hVV}^{\text{max}}(m_V)$. Special attention is given to the threshold region $m_V \approx m_h/2$, where the phase space becomes small and the collider bound changes rapidly.

Data and method

This study uses published ATLAS and CMS upper limits on $\text{BR}(H \rightarrow \text{inv})$, with emphasis on the VBF channel. The main collider inputs are listed in **Table 1**, where the VBF results are treated as the main inputs and the ATLAS combined result is used as a reference.^{8–11}

Table 1 Collider inputs

Each branching-ratio limit was converted into a maximum invisible Higgs width using

$$\tilde{\Lambda}_{\text{inv}}^{\text{max}} = \frac{\text{BR}(H \rightarrow \text{inv})}{1 - \text{BR}(H \rightarrow \text{inv})} \tilde{\Lambda}_{\text{SM}},$$

with $\tilde{\Lambda}_{\text{SM}} = 4.1 \text{ MeV}$.¹³ This was then combined with the $h \rightarrow VV$ decay-width expression to obtain the upper bound $g_{hVV}^{\text{max}}(m_V)$ in the region $m_V < m_h/2$, with special attention to the threshold region $m_V \approx m_h/2$.

The collider-implied coupling bound was further translated into a spin-independent dark matter–nucleon scattering limit, σ_{SI} , using Higgs exchange and a central value $f_N \approx 0.30$ for the Higgs–nucleon form factor.^{14,15} The resulting collider limit was then compared with direct detection results from LZ, XENONnT, and PandaX-4T on the same σ_{SI} –versus-mass plane.^{16–18}

Results

The limits in Table 1 were converted into upper bounds on the invisible Higgs width, $\tilde{\Lambda}_{\text{inv}}^{\text{max}}$, and then into limits on the Higgs-portal coupling, $g_{hVV}^{\text{max}}(m_V)$ in the region $m_V < m_h/2$. Figure 1 shows the coupling bounds obtained from the different ATLAS and CMS inputs. The more recent results give stronger collider limits than the earlier ones, while the ATLAS combined result provides the strongest overall reference bound. A rapid change is seen near the threshold region $m_V \approx m_h/2$, where the decay $h \rightarrow VV$ begins to close.

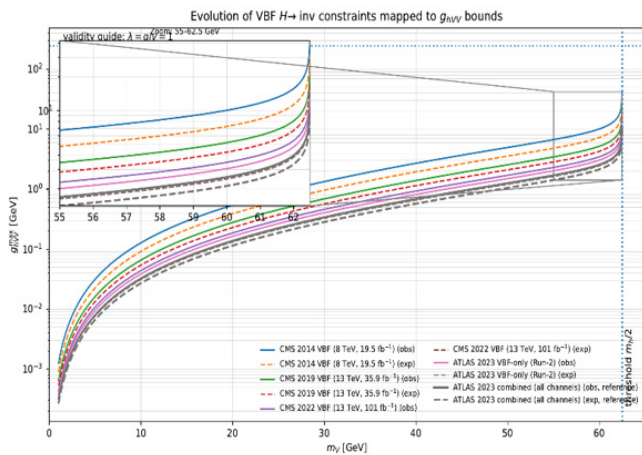


Figure 1 Collider upper bounds on the Higgs-portal coupling $g_{hVV}^{\text{max}}(m_V)$ derived from ATLAS and CMS invisible Higgs decay limits, with a threshold zoom near $m_h/2$.

The collider-implied coupling bounds were then translated into spin-independent scattering limits, σ_{SI} , and compared with LZ, XENONnT, and PandaX-4T in Figure 2. Direct-detection limits are stronger over most of the allowed mass range, but the collider result remains useful at lower masses and near the threshold region.

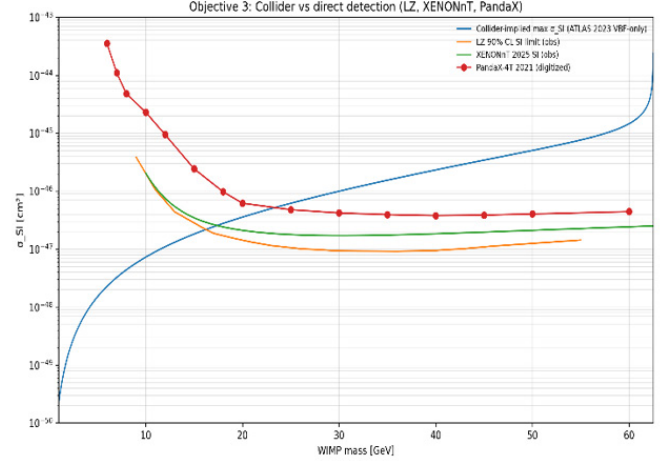


Figure 2 Collider-implied upper bounds on σ_{SI} compared with LZ, XENONnT, and PandaX-4T spin-independent limits.

Data analysis

The behavior in Figure 1 shows that stronger experimental limits on $\text{BR}(H \rightarrow \text{inv})$ directly lead to tighter bounds on the portal coupling. This confirms that invisible Higgs decay searches are a useful way of testing Higgs-portal vector dark matter. The threshold region $m_V \approx m_h/2$ is especially important because the phase space for $h \rightarrow VV$ becomes very small there. As a result, the coupling bound changes quickly, so this region needs careful treatment when collider limits are mapped into model parameters. Figure 2 shows that direct detection currently gives stronger constraints over most of the Higgs-allowed mass window. Even so, the collider result still adds value because it probes the model from the Higgs side and remains relevant in regions where direct-detection sensitivity is weaker.

Conclusion

This study has shown how published VBF invisible Higgs decay limits can be used to constrain Higgs-portal vector dark matter. The ATLAS and CMS bounds on $\text{BR}(H \rightarrow \text{inv})$ were converted into limits on the invisible Higgs width and then into upper bounds on the portal coupling g_{hVV} for $m_V < m_h/2$.

The results show that collider constraints improve as invisible Higgs decay limits become stronger, with important behavior near the threshold region $m_V \approx m_h/2$. When these collider-based bounds are compared with LZ, XENONnT, and PandaX-4T, direct detection is stronger over most of the allowed mass range.

Overall, the study shows that VBF invisible Higgs decay searches and direct-detection experiments provide complementary tests of Higgs-portal vector dark matter.

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None.

Conflicts of interest

The authors declares that there are no conflicts of interest.

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