Probing Higgs-Portal Dark Matter with VBF Signatures at the HL-LHC

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Abstract

We investigate current and projected constraints on Higgs-portal dark matter (DM) models, focusing on both scalar and fermionic DM candidates, using vector boson fusion (VBF) production of the Higgs boson at the LHC. By analyzing the parameter space in the plane of DM mass versus the Higgs-DM coupling, we aim to reinterpret existing LHC VBF + MET searches to set bounds on the invisible Higgs decay channels.

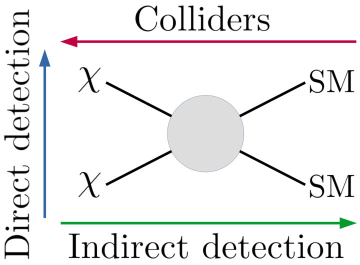
To this end, we perform simulations in MadGraph5_aMC@NLO under LHC conditions to compute cross sections for VBF Higgs production followed by invisible decays. Experimental efficiencies are estimated through a recast of public analyses targeting the process $pp \to jj + \text{MET}$. We then rescale the integrated luminosity to project the reach of the High-Luminosity LHC (HL-LHC), identifying both currently excluded regions and those potentially probed with 3 ab^{-1}. Our results provide updated exclusion contours and projections in the Higgs-portal to DM parameter space.

Dark Matter: A Missing Piece

One of the Main Problems in Contemporary Physics

Key Properties:

- **26%** of universe's energy density (Planck 2018)
- **Cold & non-relativistic** ($\Rightarrow$ structure formation)
- **Weakly interacting**: No EM/strong forces
- **Invisible**: Only gravitational evidence



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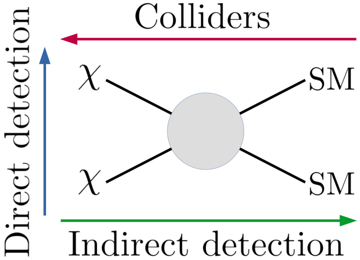


The Higgs Portal Advantage:

Simplest SM-DM connection via Higgs boson (spin-0 mediator)

Higgs $\rightarrow$ invisible: a window to new physics

- In the Standard Model (SM), the Higgs is a fundamental scalar with $m_H = 125.1$ GeV and $\Gamma_H^{\mathrm{SM}} \approx 4.07$ MeV.

- The current measurement of the total Higgs width is $\Gamma_H = 3.7^{+1.9}_{-1.4}$ MeV, $\Rightarrow$ **there is still window for non-SM contributions.**

- In SM extensions, the Higgs can couple to the dark sector with a sizable fraction:

$$\mathrm{BR}(H \rightarrow \mathrm{inv}) = \frac{\Gamma_H^{\mathrm{inv}}}{\Gamma_H^{\mathrm{SM}} + \Gamma_H^{\mathrm{inv}}}$$

- Experimental limit from VBF + MET:

$$\mathrm{BR}(H \rightarrow \mathrm{inv}) < 0.145$$

- **Invisible Higgs decays offer a window to explore new physics and hint at the presence of dark particles.**

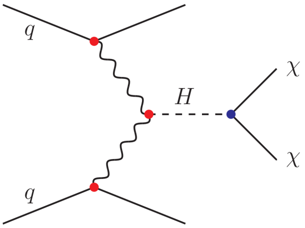
Vector Boson Fusion (VBF) Production

One of the most studied and well known production mechanisms of the Higgs boson at the LHC is VBF.

In proton-proton collisions, the quark components of the protons interact via the exchange of vector bosons (W or Z), leading to the production of a Higgs boson in association with two forward jets.

The Higgs boson is narrow, so the total cross section can be approximated as production cross section times the branching ratio to invisible decays

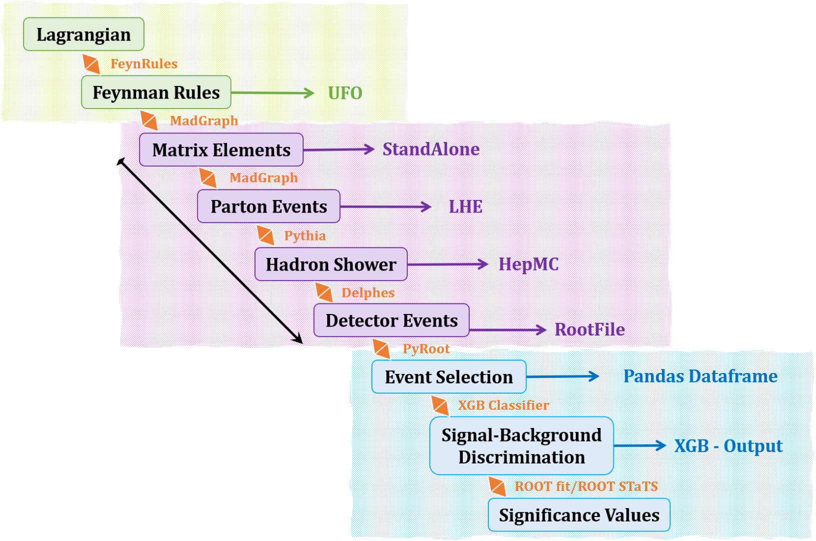
$$\Gamma_h/m_h \sim 3 \times 10^{-5} \quad \Longrightarrow \quad \sigma_{\text{total}} \approx \sigma_{\text{prod}}(pp \to jjh) \times \text{BR}(h \to \text{inv.})$$



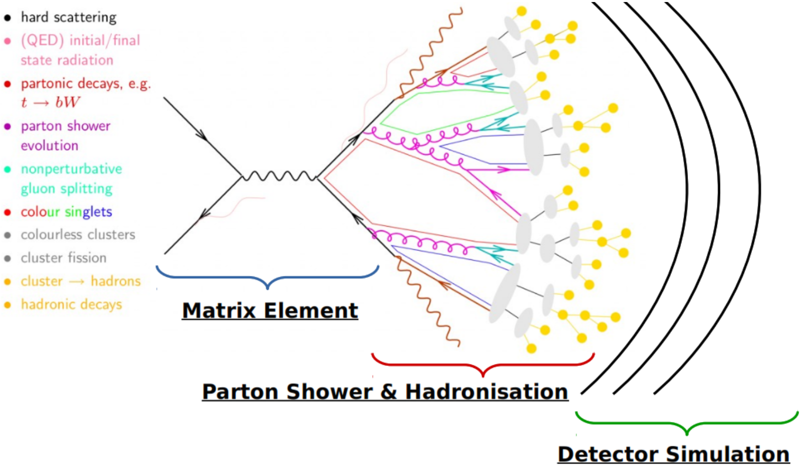
(a) Signal process

- This process is characterized by the exchange of two vector bosons in t-channel that produces a Higgs boson in association with two jets.
- The Higgs to invisible decay channel could be characterized by the lost momentum in a detector in the final state.

Monte Carlo Method Workflow



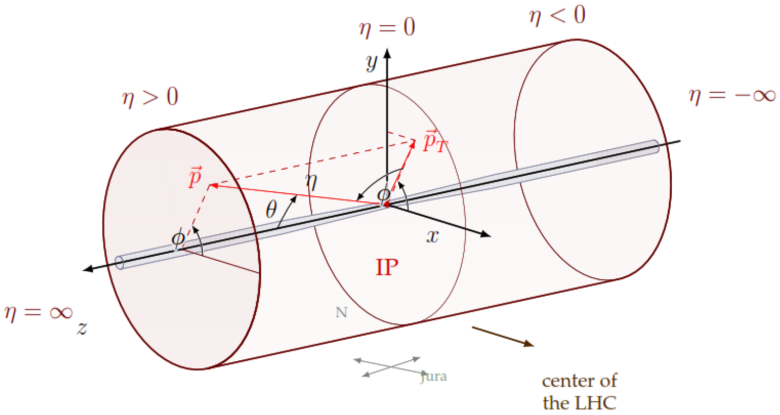
Madgraph-Pythia8-Delphes for Colliders



Kinematic Variables

From Spherical coordinates,

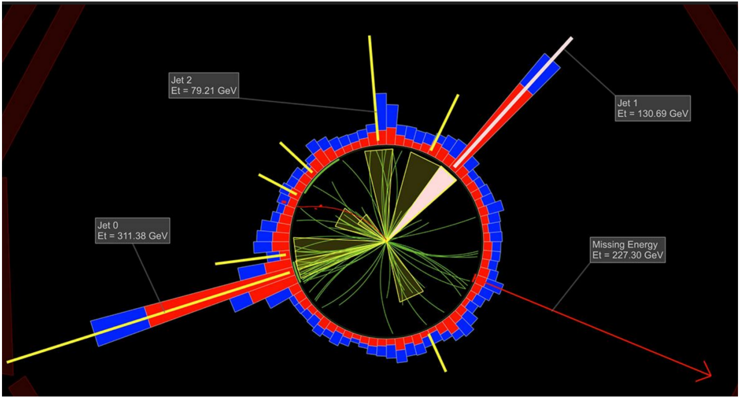
$$\begin{cases} \text{Pseudorapidity: } \eta = -\ln\tan(\theta/2) \\ \text{Transverse momentum: } p_T = p\sin(\theta) \\ \text{Azimuthal angle: } \phi \\ \text{Deposited energy: } E \end{cases}$$



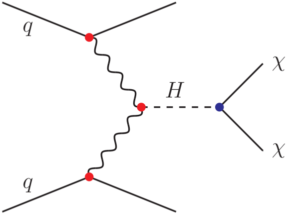
Example of a VBF + MET Event in the CMS Detector

There is not initial momentum in the transverse plane, so from the conservation of momentum, we define the missing transverse momentum as

$$\vec{p}_T^{\,\mathrm{mis}} = -\sum_i \vec{p}_{T,i}^{\,\mathrm{vis}}$$



Current Results from VBF + MET Searches



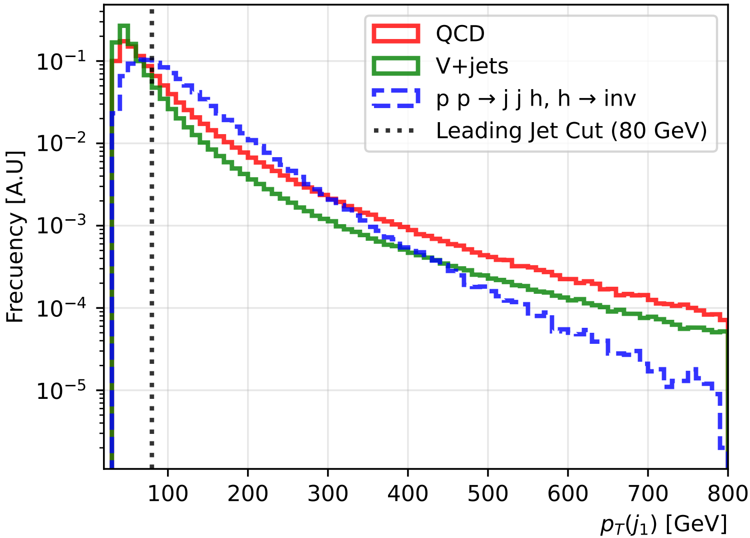
(a) Signal process

Based on Criteria from

- CMS: Tumasyan et al., “Search for invisible decays of the Higgs boson produced via vector boson fusion in proton-proton collisions at s=13 TeV” (2022)
- ATLAS:Aad et al., “Search for invisible Higgs-boson decays in events with vector-boson fusion signatures using 139 fb^{-1} of proton-proton data recorded by the ATLAS experiment” (2022)

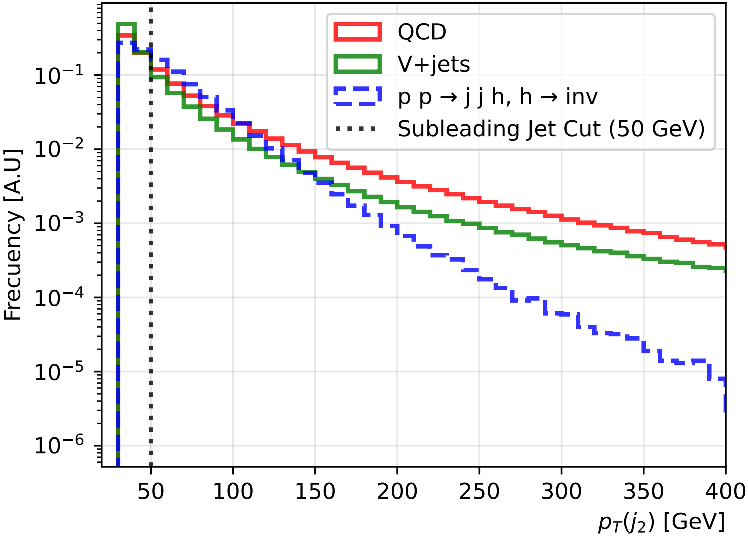
VBF Jets are boosted with High-PT signatures

Leading Jet

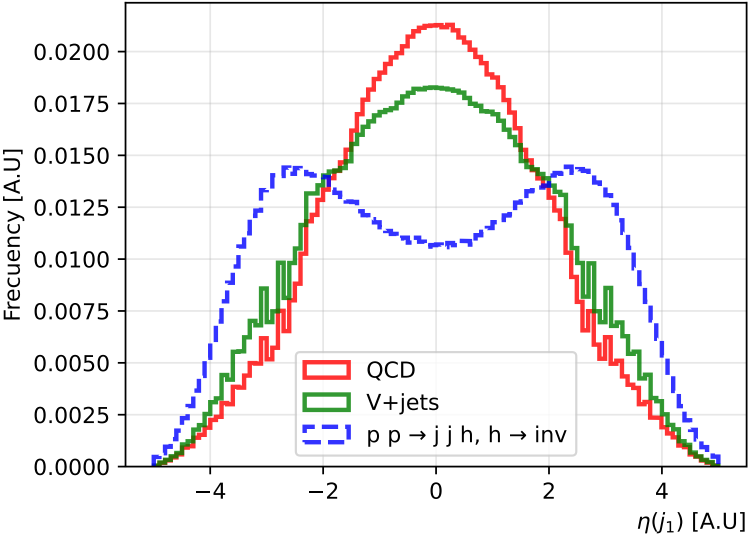


VBF Jets are boosted with High-PT signatures

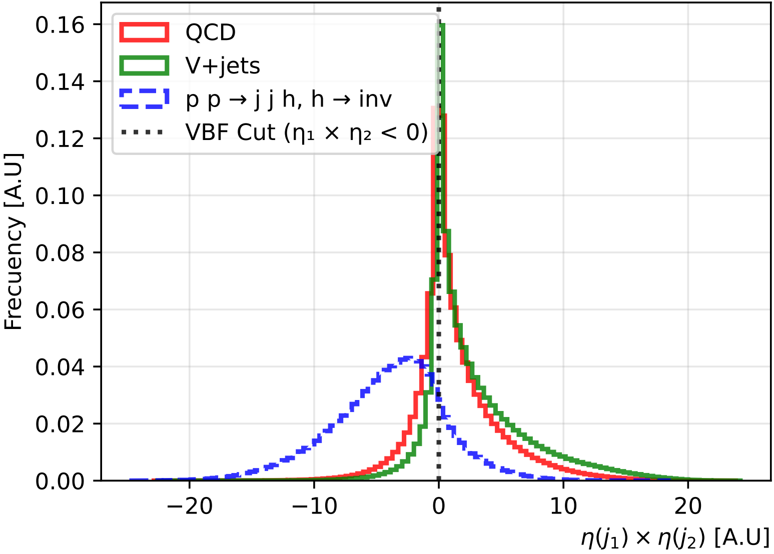
Subleading Jet



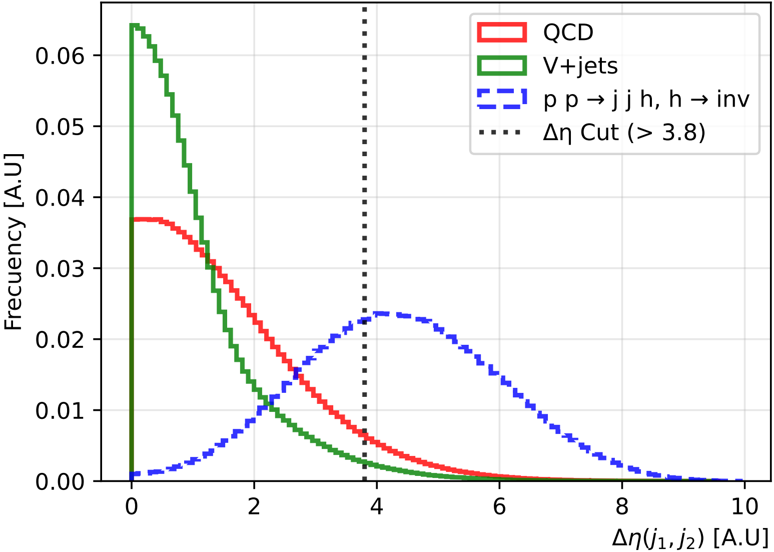
VBF Jets are forward



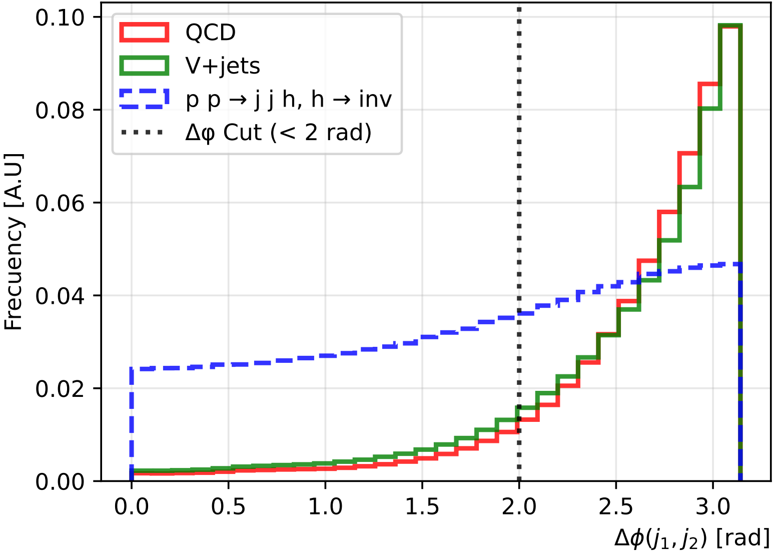
VBF Jets are in opposite longitudinal hemispheres



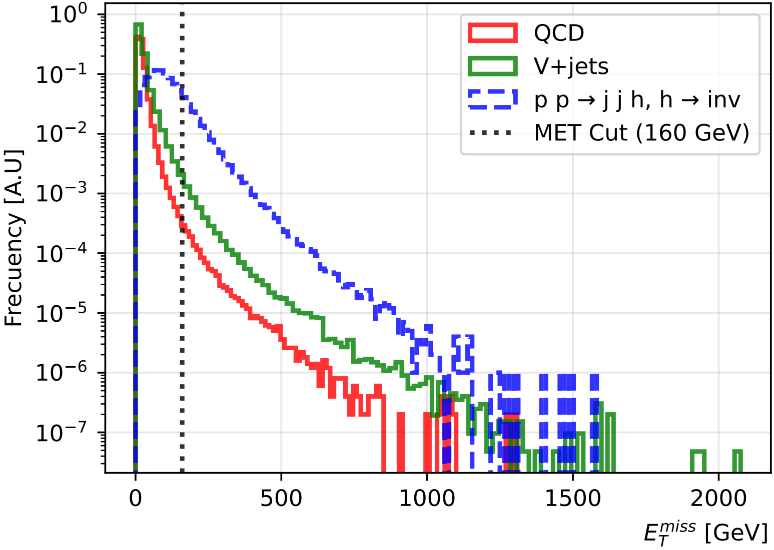
VBF Jets have a large Delta-η separation



VBF Jets are not back-to-back

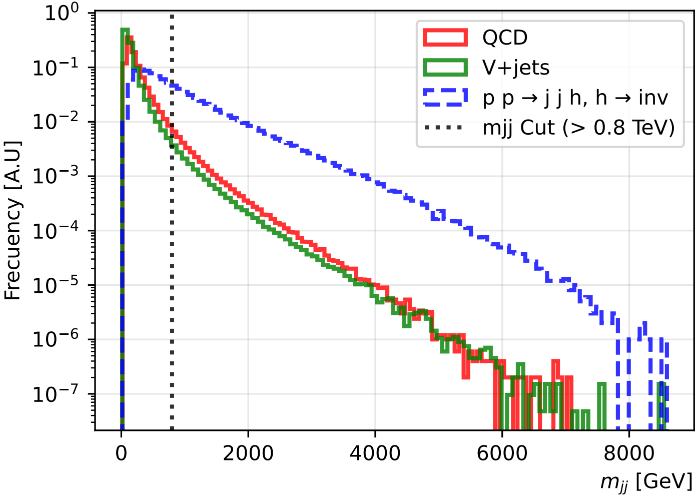


The Higgs-to-invisible decay left a High-MET signature

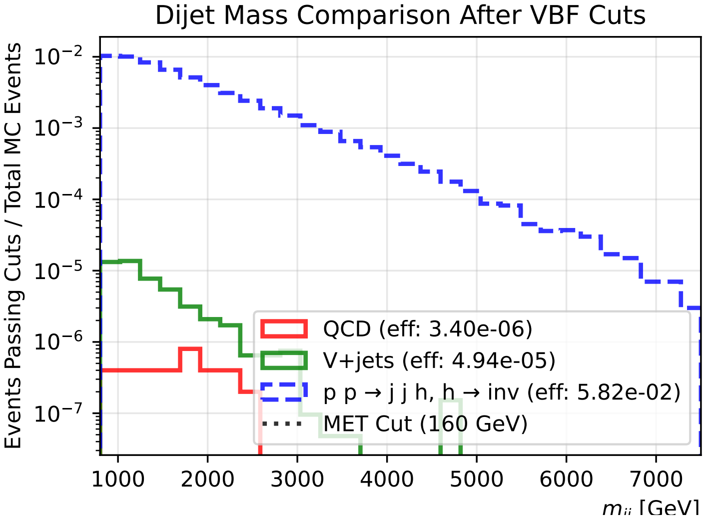


VBF Jets have a large invariant mass

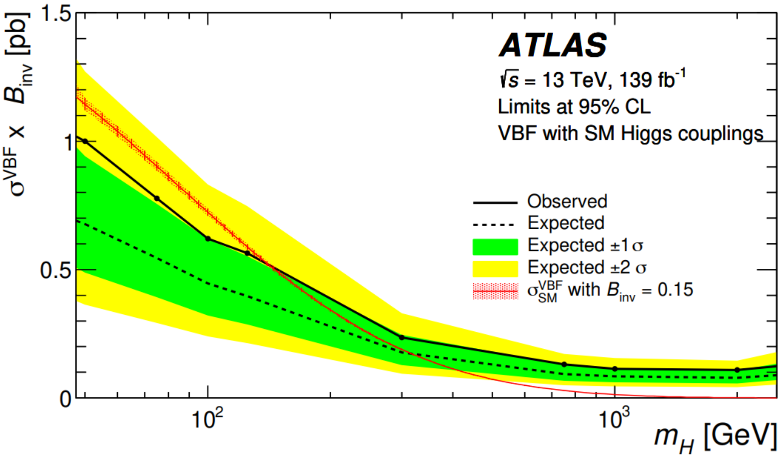
$$m_{jj} = \sqrt{2p_{T,1}p_{T,2}\left(\cosh(\Delta\eta) - \cos(\Delta\phi)\right)} \approx \sqrt{2p_{T,1}p_{T,2}\cosh(\Delta\eta)}$$



All the cuts suppres the background



Higgs-Portal Dark Matter Models



$$BR(H \to \text{inv}) < 0.145 \quad \text{(ATLAS, 2019, 95\% CL)}$$

Statistical Significance

The statistical significance is

$$\kappa = \frac{\langle t \rangle_B - \langle t \rangle_{S+B}}{\sigma_{S+B}} \quad (1)$$

where the optimal statistical test is $t = -2\ln\frac{\mathcal{L}(n|S+B)}{\mathcal{L}(n|B)}$, with n the number expected of events in each hypothesis, $\mathcal{L}$ the likelihood function for N a independet Poissonic distribution. so

$$\kappa = \frac{\sum_i s_i w_i}{\sqrt{\sum_i (s_i + b_i + \delta_{sys}^2)^2 w_i^2}} \quad (2)$$

where s_i and b_i are the signal and background events in the i-th bin, $w_i \sim \ln\left(1 + \frac{s_i}{b_i}\right)$ is the weight of the i-th bin, and δ_{sys} is the systematic uncertainty in the background estimation.

Hypothesis with a significance of $\kappa \leq 1.69\sigma$ will be excluded in searches with a 95% confidence level (CL).

Statistical Significance

The contribution to the number of events is of the form $N_i = \sigma_i \cdot \mathcal{L} \cdot \epsilon_i$, where σ_i is the cross section of the process, $\mathcal{L}$ is the integrated luminosity, and ϵ_i is the efficiency of the selection cuts in the i-th bin.
To improve the sensitivity of the search,

$$\kappa = \frac{\sum_i s_i w_i}{\sqrt{\sum_i (s_i + b_i + \delta_{sys}^2)^2 w_i^2}} = \frac{\sum_i \sigma_{s_i} \epsilon_{s_i} w_i}{\sqrt{\sum_i (\sigma_{s_i} \epsilon_{s_i} + \sigma_{b_i} \epsilon_{b_i} + \delta_{\sigma_{sys}}^2)^2 {w_i}^2}} \sqrt{\mathcal{L}} \tag{3}$$

We can

- Increase the integrated luminosity $\mathcal{L}$.
- Optimize the selection cuts to increase the efficiency ϵ_i of the signal and reduce the background.
- increase the cross section σ_i of the signal process increasing the center-of-mass energy $\sqrt{s}$ of the collisions.
- Add information from the correlation between bins of the histogram.
- Select a observable that optimize the form of the w_i weights (e.g. a BDT classifier).
- Reduce the systematic uncertainties δ_{sys} in the background estimation.

Projections on the Higgs-to-invisible decay

So, taking $\kappa = 1.69$ we have

$$\frac{\sum_i \sigma_{s_i}\epsilon_{s_i}w_i}{\sqrt{\sum_i(\sigma_{s_i}\epsilon_{s_i}+\sigma_{b_i}\epsilon_{b_i}+\delta^2_{\sigma_{sys}})^2 w_i^2}} = \frac{\sum_i \sigma^{\mathrm{VBF}}_{s_i}(\mathrm{BR})\epsilon_{s_i}w_i}{\sqrt{\sum_i(\sigma^{\mathrm{VBF}}_{s_i}(\mathrm{BR})+\sigma_{b_i}\epsilon_{b_i}+\delta^2_{\sigma_{sys}})^2 w_i^2}} = \frac{1.69}{\sqrt{\mathcal{L}}} \tag{4}$$

In a conservative approach if we assume that the efficiencies and systematic uncertainties are constant, for future searches the limit on the Branching Ratio (BR) will scale inversely with the integrated luminosity $\mathcal{L}$.

- The current limit, at 139 fb^{-1} on the Higgs-to-invisible decay is $\mathrm{BR}(H \to \mathrm{inv}) < 0.145$.

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- With the HL-LHC, the promised integrated luminosity is 3 ab^{-1}, which will allow us to improve the sensitivity to $\mathrm{BR}(H \to \mathrm{inv}) < 0.008 \sim \mathcal{O}(10^{-2})$.

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- For FCC, the expected integrated luminosity is 30 ab^{-1}, which will allow us to improve the sensitivity to $\mathrm{BR}(H \to \mathrm{inv}) < \mathcal{O}(10^{-3})$.

Higgs Portals

We assume the minimal Higgs portal setup with singlet DM of spin 0 or spin 1/2. In that follows, we consider these options separately and allow for both CP-even and CP-odd couplings of the DM fermion to the Higgs field. The Lagrangian reads

$$\mathcal{L}_{hs} = \frac{\lambda_{hs}}{2}\mathcal{H}^\dagger\mathcal{H}SS$$

$$\mathcal{L}_{h\chi} = \frac{1}{\Lambda}\mathcal{H}^\dagger\mathcal{H}\bar{\chi}\chi, \quad \mathcal{L}_{h\chi}^{\gamma_5} = \frac{1}{\Lambda_5}\mathcal{H}^\dagger\mathcal{H}\bar{\chi}i\gamma_5\chi,$$

where $\mathcal{H}$ is the Higgs doublet, S is a real scalar singlet with mass m_s, and χ is a Dirac fermion with mass m_χ.

$$\Gamma(h \to SS) = \frac{\lambda_{hs}^2 v^2}{32\pi m_h}\sqrt{1 - \frac{4m_s^2}{m_h^2}}$$

$$\Gamma_{\text{CP-even}}(h \to \chi\chi) = \frac{m_h}{4\pi}\frac{v^2}{\Lambda^2}\left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{3/2} \quad ; \quad \Gamma_{\text{CP-odd}}(h \to \chi\chi) = \frac{m_h}{4\pi}\frac{v^2}{\Lambda_5^2}\left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{1/2}$$

These states are assumed to be stable adn thus can be considered as DM candidates. In the fermionic case, the couplings are non-renormalizable and thus are understood as effective operators with Λ and Λ_5 being the cut-off scales.

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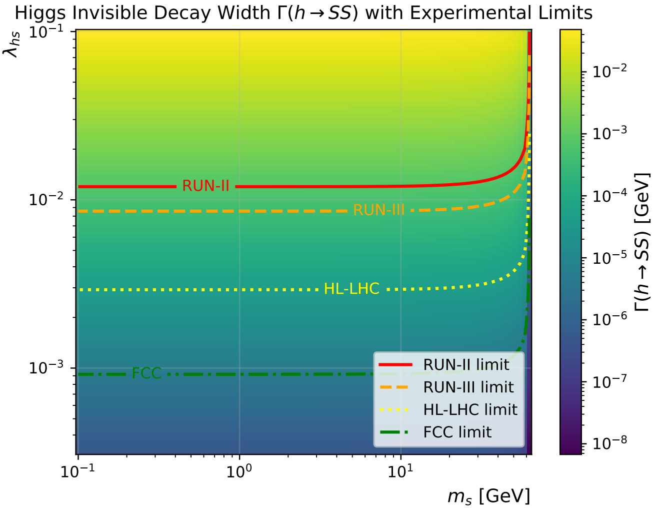

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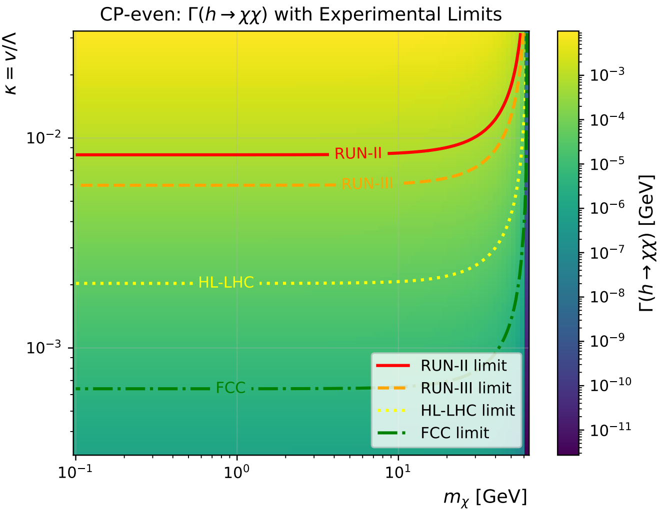

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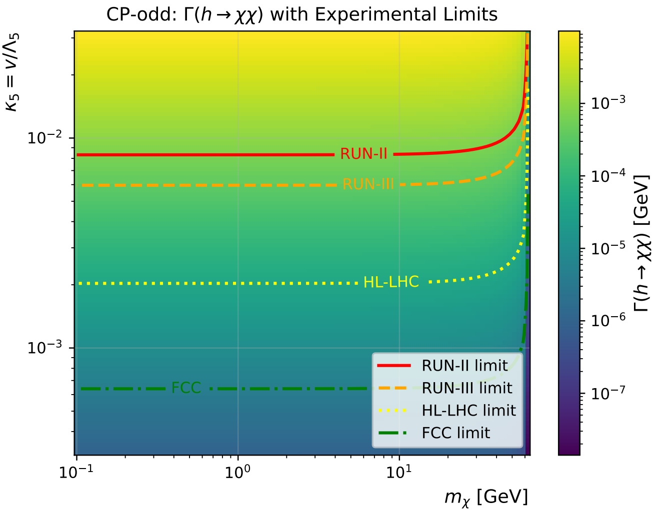
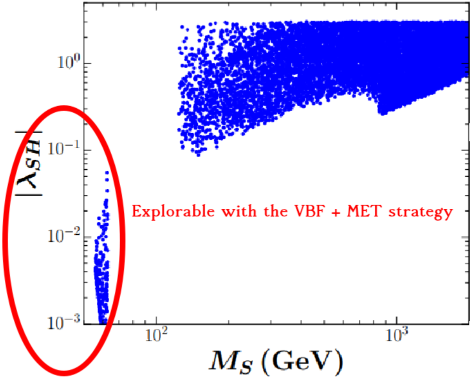


Example: Scalar-Fermion Z4 model

$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \lambda_S S^4 + \frac{1}{2}\lambda_{SH}|H|^2 S^2 + M_\psi \bar{\psi}\psi + \frac{1}{2}\left[y_s \overline{\psi^c}\psi + y_p \overline{\psi^c}\gamma_5 \psi + \text{ h.c. } \right] S,$$

In the $M_S < M_\psi$ regime,



Yaguna and Zapata, "Fermion and scalar two-component dark matter from a Z4 symmetry" (2022)

Thank you for your attention!

Questions?