Invisible Higgs vs. Higgs rates at HL-LHC: (some) theory implications

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in collaboration with Tania Robens
What is dark matter? How does DM interact with SM particles?

→ we don’t know.

But: The Higgs field $H$ might play a special role!

$|H|^2$ = the only gauge and Lorentz-invariant dim-2 operator $L \supset a |H|^2 S^2$ ($S$: stable hidden scalar)

SM hidden sector $H$ ("Higgs portal")

Great opportunity: The 125 GeV Higgs could be our portal to exploring DM!

In this talk we focus on $M_{DM} < M_H/2$ ⇒ invisible Higgs decays.
Introduction

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($S$ : stable hidden scalar)

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An incomplete list of Higgs portal models (increasing in complexity)

- Minimal Higgs portal ($\propto$ quartic interaction of SM Higgs field with DM)
  - scalar DM [Silveira, Zee '85]
  - vector DM [Lebedev, Lee, Mambrini '11]
  - fermion DM [Kim, Lee '06]

- SM + complex scalar singlet [Barger, et al. '08]

- SM + real scalar singlet + DM field [Englert, Plehn, Zerwas, Zerwas '11]

- SM + extended hidden sector (e.g. singlet + doublet fermions)
  [Cohen, Kearney, Pierce, Tucker-Smith '11]

- Two Higgs Doublet Model (2HDM) portals
  - scalar DM [Bai, Barger, Everett, Shaughnessy '12]
  - fermion DM [Berlin, Gori, Lin, Wang '15]

- supersymmetric versions of the above...
- ...

Tim Stefaniak (DESY) Invisible Higgs: Theory HL/HE-LHC Meeting 3 / 21
Our study of HL-LHC Higgs portal implications

Goal of our study:

Estimate sensitivity of direct invisible Higgs searches and Higgs signal rate measurements at the HL-LHC and highlight a possible complementarity.

We follow two approaches by employing:

1. **effective description** of 125 GeV Higgs properties that commonly appear in many Higgs portal models,

2. **two simple and predictive Higgs portal models:**
   - Minimal Higgs portal,
   - SM + real scalar singlet + scalar DM.
Experimental input: HL-LHC projections
Future HL-LHC limits from invisible Higgs searches

Official HL-LHC projections found in literature:

\[
\mu_{VBF} \cdot \text{BR}(H \rightarrow \text{inv}) \leq 5.6\% \quad \text{(CMS, S2+ scenario)} \quad [\text{CMS PAS FTR-16-002}]
\]

\[
\mu_{VH} \cdot \text{BR}(H \rightarrow \text{inv}) \leq 8.0\% \quad \text{(ATLAS, “realistic” scenario)} \quad [\text{ATL-PHYS-PUB-2013-014}]
\]

(with \( \mu_i = \sigma_i / \sigma_{i,\text{SM}} \))

more studies are under way... (?)

Let’s make a tentative assumption:

“ATLAS (CMS) performs equally well as CMS (ATLAS) in missing channel!”

(Naive) combination of VBF and VH channels from ATLAS and CMS:

\[
\Rightarrow \mu_{VBF, VH} \cdot \text{BR}(H \rightarrow \text{inv}) \lesssim 3.5\% \quad \text{(ATLAS \oplus CMS)}
\]
Future HL-LHC Higgs rate measurements

ATLAS Simulation Preliminary
\( s = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1} ; \int L dt = 3000 \text{ fb}^{-1} \)

CMS ECFA 2016 report: [CMS PAS FTR-16-002]

CMS Snowmass report: [CMS, 1307.7135]

\[
\begin{align*}
\Delta \mu_{H \rightarrow WW} &= 4\% \\
\Delta \mu_{H \rightarrow bb} &= 5\% \\
\Delta \mu_{H \rightarrow \tau\tau} &= 5\% \\
\Delta \mu_{H \rightarrow ZZ} &= 20\% \\
\Delta \mu_{H \rightarrow \mu\mu} &= 20\% \\
\end{align*}
\]

(Scenario 2)

[ATL-PHYS-PUB-2014-016]
Future HL-LHC Higgs rate measurements

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\( s = 14 \text{ TeV}: \int L dt = 300 \text{ fb}^{-1}; \int L dt = 3000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Process</th>
<th>(comb.)</th>
<th>(0j)</th>
<th>(1j)</th>
<th>(VBF-like)</th>
<th>(WH-like)</th>
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<td>( H \rightarrow \gamma\gamma )</td>
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CMS ECFA 2016 report: [CMS PAS FTR-16-002]

Implementation of HL-LHC observables in HiggsSignals (for global \( \chi^2 \) fit):

- Assume **theory uncertainties** are halved (\( \sim \) CMS scenario S2+);
- Correlations of theory/parametric uncertainties included in \( \chi^2 \) calculation;
- Assume signal (i.e. production mode) compositions similar to current measurements.

\( \Rightarrow \) Get a rough estimate of the combined ATLAS \( \oplus \) CMS reach with 3000 fb\(^{-1}\).

for more details, see [Bechtle, Heinemeyer, Stål, TS, Weiglein, 1403.1582]
Theory implications of HL-LHC results

– Effective description ($\kappa$ framework) –
**Coupling scale factor ($\kappa$) parametrization**

For many BSM theories, the 125 GeV Higgs collider pheno can be parametrized in terms of $\kappa$ scale factors, \[ [LHC HXSWG: YR3, '13] \]

\[
\frac{\Gamma(H \to XX)}{\Gamma(H \to XX)_{SM}} = \kappa_X^2 \quad (X = W, Z, g, \gamma, b, \tau, \ldots)
\]

\[
\frac{\sigma(gg \to H)}{\sigma(gg \to H)_{SM}} = \kappa_g^2, \quad \frac{\sigma(qq \to VH)}{\sigma(qq \to VH)_{SM}} = \kappa_V^2 \quad (V = W, Z), \text{ etc.}
\]

and a rate for additional *new physics* (NP) Higgs decays, $\text{BR}(H \to \text{NP})$.

**Our strategy:**

Perform global fit to HL-LHC Higgs rates in two parametrizations

1. $\kappa$ (common scale factor), $\text{BR}(H \to \text{NP})$;
2. $\kappa$ (common for tree-level couplings), $\kappa_g$, $\kappa_\gamma$, $\text{BR}(H \to \text{NP})$;

Assume $\kappa_V (= \kappa) \leq 1$, but no further assumptions on $\text{BR}(H \to \text{NP})$ in fit.
HL-LHC prospects: $\kappa$ parametrization

$\kappa$, $\kappa_g$, $\kappa_\gamma$ free $\kappa$ $\kappa_g$, $\kappa_\gamma$ free $\equiv \kappa$

Higgs rate measurements (ATLAS $\oplus$ CMS)

$\kappa$, $\kappa_{inv}$ fit (95% CL)

$\kappa$, $\kappa_g$, $\kappa_\gamma$, $\kappa_{inv}$ fit (95% CL)
HL-LHC prospects: $\kappa$ parametrization

$$\kappa \, \text{parametrization}$$

$$0.95 \, 0.96 \, 0.97 \, 0.98 \, 0.99 \, 1.00$$

$$\kappa$$

$$0.00 \, 0.02 \, 0.04 \, 0.06 \, 0.08 \, 0.10$$

$$\text{BR}_{\text{inv}}$$

$$\kappa, \text{BR}_{\text{inv}} \leq 3.5\%$$

$$\kappa^2 \cdot \text{BR}_{\text{inv}} \leq 3.5\%$$

Invisible Higgs searches

Higgs rate measurements

(\text{ATLAS} \oplus \text{CMS})

$$(\kappa, \kappa_g, \kappa_\gamma, \text{BR}_{\text{inv}}) \text{ fit (95\% CL)}$$

$$(\kappa, \text{BR}_{\text{inv}}) \text{ fit (95\% CL)}$$

VBF/VH, $H \rightarrow \text{inv} \text{ (95\% CL)}$
Theory implications of HL-LHC results

– Minimal Higgs portal –
Minimal Higgs portal

[Kanemura, Matsumoto, Nabeshima, Okada '10],
[Djouadi, Lebedev, Mambrini, Quevillon '11]

Impose *portal interaction* between SM Higgs field $H$ and the DM field:

\[
\mathcal{L} \supset -\frac{1}{4} \lambda_{hSS} H^\dagger H S^2 \quad \text{or} \quad +\frac{1}{4} \lambda_{hVV} H^\dagger H V_\mu V^\mu \quad \text{or} \quad -\frac{1}{4} \frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi} \chi.
\]

- If $M_{\text{DM}} < M_h/2 \Rightarrow$ invisible Higgs decays;
- Higgs couplings to SM fields unaffected ($\kappa = 1$).

The Higgs portal coupling $\lambda$ relates

infrared Higgs decay width $\quad \iff \quad$ DM-nucleon scattering cross section

$\left( \Gamma_{\text{inv}} \propto \lambda^2 v^2 \right) \quad \iff \quad \left( \sigma_{\text{DM-nucleon}} \propto \lambda^2 \right)$

$\Rightarrow$ Complementarity: invisible Higgs searches $\iff$ DM direct detection (DD).
Brief comment on the DM relic density constraint

In thermal freeze-out picture: DM relic density $\Omega_{DM}$ highly constraining!

**Figure 1.** The constraints on scalar Higgs portal DM models assuming a thermal cosmological history. Requiring that the relic abundance matches the measured value fixes the value of portal coupling as a function of the DM mass to the contour labeled $\Omega = \Omega_{DM}$. Direct detection experiments (DD) lead to strong constraints, and LHC searches for invisible Higgs decays are also relevant ($h$ invis.). Indirect detection searches by Fermi and AMS are potentially constraining, although the latter is highly sensitive to astrophysical uncertainties (these are plotted only in parts of parameter space in which they are competitive with direct detection searches). The reach of the future CTA experiment is shown, and this could probe the high DM mass region. The neutrino floor ($\nu$-floor), below which direct detection searches become extremely challenging, is also shown.

$\text{BR}_{inv} \oplus \text{DD} \oplus \Omega_{DM}$ limits $\Rightarrow$ only near-resonant region $M_{DM} \lesssim M_h/2$ allowed!

Alternative cosmological histories (late matter domination) and/or alternative DM production mechanisms (e.g. freeze-in) can open up parameter space!

[Hardy '18], [Bernal, Cosme, Tenkanen '18]
Minimal Higgs portal: Comparison with DM direct detection

Current picture:

ATLAS Run-1:
\( \text{BR}_{\text{inv}} \leq 22\% \) (90% CL)

CMS Run-1/2:
\( \text{BR}_{\text{inv}} \leq 20\% \) (90% CL)

Higgs-nucleon coupling form factor:
\( f_N = 0.33^{+0.30}_{-0.07} \)

[Young, Thomas ’09]
[MIlC Collaboration ’09]
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Recent new result:

\[ f_N = 0.308 \pm 0.018 \]

[Hoferichter, et al. '17]
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[Hoferichter, et al. '17]
Minimal Higgs portal: Comparison with DM direct detection

**Future projections:**

\[ \text{BR}_{\text{inv}} \leq 10\% \]
Minimal Higgs portal: Comparison with DM direct detection

Future projections:

$\text{BR}_{\text{inv}} \leq 5\%$

$\sigma_{\text{DM-nucleon}} \text{[cm}^2\text{]}$

$M_{\text{DM}} \text{[GeV]}$

$0.3 \quad 1 \quad 10 \quad 100$

$10^{-50} \quad 10^{-49} \quad 10^{-48} \quad 10^{-47} \quad 10^{-46} \quad 10^{-45} \quad 10^{-44} \quad 10^{-43} \quad 10^{-42} \quad 10^{-41} \quad 10^{-40} \quad 10^{-39}$
Minimal Higgs portal: Comparison with DM direct detection

**Future projections:**

\[ \text{BR}_{\text{inv}} \leq 3.5\% \]

(90% CL)
Minimal Higgs portal: Comparison with DM direct detection

Future projections:

$$\text{BR}_\text{inv} \leq 1\%$$
Minimal Higgs portal: Comparison with DM direct detection

**Future projections:**

$$\text{BR}_{\text{inv}} \leq 1\%$$

**Comments:**

For $$M_{\text{DM}} \lesssim M_H/2$$, direct detection is more sensitive than $$\text{BR}_{\text{inv}}$$.

For low $$M_{\text{DM}} \lesssim 10 \text{ GeV}$$, $$\text{BR}_{\text{inv}}$$ searches probe DM below the neutrino floor.
Theory implications of HL-LHC results
– Singlet scalar–DM portal –

inspired by
[Englert, Plehn, D. Zerwas, P. Zerwas ’11], [Robens, TS ’15]
Singlet scalar–DM portal: the model

Visible sector: \( (\Phi: SU(2)_L \text{ doublet}, \ S: SU(2)_L \text{ singlet}) \)

\[
\mathcal{L}_{\text{vis}} = \mu_\Phi \Phi^\dagger \Phi + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \mu_S S^2 + \lambda_S S^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2
\]

\( \langle \Phi \rangle \equiv \nu, \langle S \rangle \equiv \nu_S \neq 0 \Rightarrow \text{mixing of scalar fields } \phi \text{ and } s:\)

\[
\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \phi \\ s \end{pmatrix} \quad \text{with} \quad M_h < M_H.
\]

\( \Rightarrow \text{Higgs couplings to SM fields are universally suppressed by mixing:} \)

\[ g_h / g_{h,\text{SM}} = \cos \alpha, \quad g_H / g_{H,\text{SM}} = \sin \alpha (\equiv \kappa). \]

Only \( S \) couples to DM sector: \( \text{(assume scalar DM particle } X \text{ here)} \)

\[
\mathcal{L}_{\text{DM}} \supset -\frac{1}{4} \lambda_{SXX} S^2 X^2.
\]

After fixing \( M_H = 125.09 \text{ GeV}, \nu \approx 246 \text{ GeV}, \) five input parameters remain:

\( M_h, \cos \alpha, \nu_S \) (visible sector), \( M_X, \lambda_{SXX} \) (DM sector)
Singlet scalar–DM portal: Higgs decays

If $M_h < M_H/2$, the decay $H \rightarrow hh$ becomes kinematically allowed:

$$\Gamma(H \rightarrow hh) = \frac{\lambda_{Hhh}^2}{32\pi M_H} \sqrt{1 - \frac{4M_h^2}{M_H^2}}$$

where $\lambda_{Hhh} = f(M_h, \cos \alpha, v_S)$, and roughly $\lambda_{Hhh} \propto \sin 2\alpha/v_S$.

If $M_X < M_h/2$, we have direct invisible Higgs decays to $XX$:

$$\Gamma(h \rightarrow XX) = \sin^2 \alpha \cdot \Gamma_{XX}(M_h)$$
$$\Gamma(H \rightarrow XX) = \cos^2 \alpha \cdot \Gamma_{XX}(M_H)$$

with

$$\Gamma_{XX}(M) = \frac{\lambda_{SXX}^2 v_S^2}{128\pi M} \sqrt{1 - \frac{4M_X^2}{M^2}}$$

For the invisible decay of the SM-like Higgs $H$ we get

$$\text{BR}(H \rightarrow \text{inv}) = \text{BR}(H \rightarrow XX) + \text{BR}(H \rightarrow hh) \times \text{BR}(h \rightarrow XX)^2.$$  

Other possible decays: $H \rightarrow hh \rightarrow (\text{SM})(\text{SM})$ and $(\text{SM})(\text{inv})$. 
Singlet scalar–DM portal: HL-LHC prospects

\[ \cos \alpha \]

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

\[ \Delta \kappa = 1 - \sin \alpha \]

\[ \kappa^2 \cdot BR_{\text{inv}} \leq 3.5\% \]

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

LEP searches (95% CL)

$V_{BF/VH}, H \rightarrow \text{inv} (95\% \text{ CL})$

$\Delta \kappa = 1 - \sin \alpha$

$BR(H \rightarrow \text{inv})$

$(\kappa, BR_{\text{inv}}) \text{ fit (95}\% \text{ CL)}$

$\kappa_g, \kappa_\gamma \equiv \kappa$

$v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV}$

Tim Stefaniak (DESY)

Invisible Higgs: Theory

HL/HE-LHC Meeting 18 / 21
Singlet scalar–DM portal: HL-LHC prospects

\[ \kappa, \kappa_g, \kappa_\gamma, \text{BR}_{\text{inv}} \] fit (95% CL)

\[ \kappa^2 \cdot \text{BR}_{\text{inv}} \leq 3.5\% \]

\[ \kappa_g, \kappa_\gamma \text{ free} \]

\[ \kappa_g, \kappa_\gamma \equiv \kappa \]

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

\[ \Delta \kappa = 1 - \sin \alpha \]

\[ M_h [\text{GeV}] \]

\[ \cos \alpha, \kappa_g, \kappa_\gamma \equiv \kappa \]

LEP searches (95% CL)

\[ (\kappa, \text{BR}_{\text{inv}}) \text{ fit (95% CL)} \]

\[ (\kappa, \kappa_g, \kappa_\gamma, \text{BR}_{\text{inv}}) \text{ fit (95% CL)} \]

\[ \text{v}_S = 37 \text{ GeV}, \lambda_{SXX} = 0.5, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.02, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

\[ \Delta \kappa = 1 - \sin \alpha \]

\[ v_S = 37 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV} \]
Singlet scalar–DM portal: HL-LHC prospects

```
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00

20
40
60
80
100
```

$$\Delta \kappa = 1 - \sin \alpha$$

$$v_S = 5 \text{ GeV}, \lambda_{SXX} = 0.2, M_X = 5 \text{ GeV}$$
Conclusions & Outlook
Conclusions

Invisible Higgs decays are well-motivated in Higgs portal models. The HL-LHC will strongly improve our sensitivity to these models, with two complementary probes:

- direct searches for invisible Higgs decays,
- precision Higgs rate measurements.

**Minimal Higgs portal:**

Already highly constrained by DM direct detection and DM relic density. For low $M_{\text{DM}} \lesssim 10$ GeV invisible Higgs searches probe parameter space where direct detection is insensitive.

**Singlet scalar–DM portal:**

With the additional possibility of invisible Higgs cascade decays, $H \rightarrow hh \rightarrow \text{inv.}$, there is an important interplay of Higgs rate measurements, invisible Higgs searches and LEP searches.
Outlook

On our to-do list:

- Update results with final numbers for the HL-LHC projections,
- estimate the HE-LHC sensitivity for our example models.
- study complementarity with DM constraints for the singlet scalar–DM portal model (*probably beyond this study!*).

Our studies are still ongoing: Feedback is very welcome!
Outlook

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Thank you for your attention!
Backup slides
Minimal Higgs portal: DM relic density constraints

(Scalar DM)

(Real Vector DM)

(Complex Scalar DM)

(Real Fermion DM)

(Complex Fermion DM)

[Escudero, Berlin, Hooper, Lin '16]