Invisible Higgs decays at the HL-LHC

(Contribution to the upcoming HL/HE-LHC Yellow Report)

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After Higgs discovery: Open questions

Higgs discovery in 2012 $\Rightarrow$ last SM building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  $\Rightarrow$ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  $\Rightarrow$ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

Role of Higgs couplings (I)

one way to search: **direct searches**

⇒ HL-LHC: can profit from enhanced statistics
(cross sections very similar to 13 TeV run)

other ways: **indirect constraints**

⇒ prominent example: Higgs couplings

study of Higgs couplings at HL-LHC combines direct searches with indirect constraints

Role of Higgs couplings (II)

- **direct Higgs channels:** e.g. $H \to$ invisible, $H \to$ exotics, ...
- **indirect constraints: modifications of SM decays**, via
  a) suppression of BRs into SM particles (through new decay channels)$^{(*)}$
  b) modification of relative BRs (new physics contributions)
- b): especially sensitive: loop-induced processes

$$H \to \gamma\gamma,\, H \to gg$$

$^{(*)}$ change in rates can be compensated by additionally enhancing production couplings...

Higgs to invisible: general setup

Higgs decay to invisible:

- typical realization in models with dark matter candidates

$$H \rightarrow \text{DM}\,\text{DM}$$

- in the SM: $H \rightarrow \nu\nu\bar{\nu}\bar{\nu} \leq 0.1\%$

  $\Longrightarrow$ **any (measurable) deviation: new physics** $\Longleftarrow$

- double effect:

  $\Rightarrow$ suppression of SM rates

  $\Rightarrow$ direct measurement

Discussion in the literature

- Widely discussed in the literature

  [e.g. Kanemura, Matsumoto, Nabeshima, Okada, Phys.Rev.D82 (2010); Djouadi, Lebedev, Mambrini, Quevillon, Phys. Lett. B709 (2012)]

- **typically considered:**
  portal coupling to scalar/ vector/ fermion DM candidates

$$\mathcal{L} \supset \qquad \lambda H^\dagger H\, S^2,\; \lambda H^\dagger H\, V_\mu V^\mu,\; \frac{\lambda}{\Lambda} H^\dagger H\, \overline{\chi}\chi$$

"minimal" Higgs portal model

$\Rightarrow$ **nice feature:**
can be related to dark matter direct detection
(same coupling !!)

Experimental input for HL-LHC projections

VBF, *VH* and invisible decays

$$\mu_{\text{VBF}} \cdot \text{BR}(H \rightarrow \text{inv}) \leq 4\% \quad \text{(see Anne-Maries talk)}$$

$$\mu_{VH} \cdot \text{BR}(H \rightarrow \text{inv}) \leq 8.0\% \quad \text{([ATL-PHYS-PUB-2013-014])}$$

No (!) official update for *VH*, old number !!

Assumption:

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

(Naive) combination of both channels from ATLAS and CMS:

$$\Rightarrow \quad \mu_{\text{VBF},VH} \cdot \text{BR}(H \rightarrow \text{inv}) \lesssim 2.5\% \quad (\textbf{ATLAS} \oplus \textbf{CMS})$$

Experimental input: $Z\,H$

(slides from A.-M. Magnan, Autumn WG2 meeting, 23.10.18)

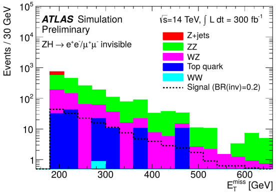
Z(ll)H(inv) projections ATL-PHYS-PUB-2013-014

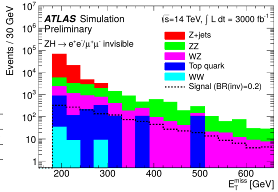
Final state

- Two isolated leptons (e,μ) from the Z.
- Real MET.
- Selection optimised for HL-LHC.

Cut variables	Thresholds
E_T^{miss}	> 180 GeV
$d\phi(\ell,\ell)$	< 1.2
$d\phi(\vec{p}_T^{\,\ell,\ell}, \vec{E}_T^{miss})$	> 2.7
$\lvert E_T^{miss} - p_T^{\ell,\ell}\rvert / p_T^{\ell,\ell}$	< 0.6
Jet veto	> 25 GeV

BR($H \to$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)





A.-M. Magnan VBF Hinv @ HL-LHC CERN, 23/10/2018 3 / 16

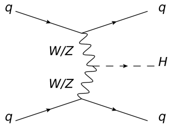
Experimental input: VBF

(slides from A.-M. Magnan, Autumn WG2 meeting, 23.10.18)

Snapshot of the VBF analysis

Final state

- Two jets with VBF topology: high rapidity gap, high dijet mass, small angle in transverse plane.
- Real MET.
- Nothing else: veto on identified electrons/muons/photons, tau and b jets.
- Control regions: with one (W CR) or two (Z CR) identified e/μ.



2016 data 36.1 fb^{-1} 13 TeV ATLAS

- arXiv:1809.06682
- Observed 0.37 @ 95% CL, expected 0.28.

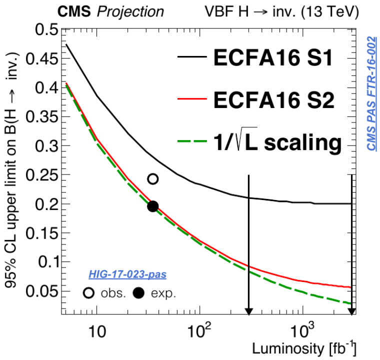
2016 data 35.9 fb^{-1} 13 TeV CMS

- arXiv:1809.05937
- Observed 0.33 @ 95% CL, expected 0.25.

Experimental input: old projection

(slides from A.-M. Magnan, Autumn WG2 meeting, 23.10.18)

Status of existing projections



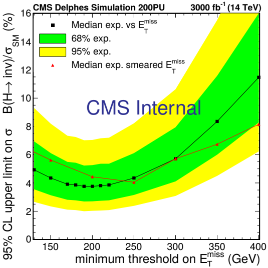
With 3000 fb^{-1} of luminosity

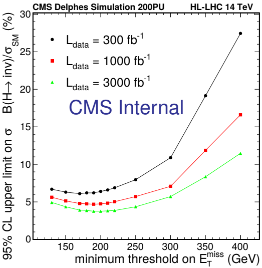
- scaling from 2015 13 TeV data (2.3 fb^{-1}).
- Ball park: BR(inv)$<$ 6%.
- Very optimistic scaling: BR(inv)$<$ 3%.

Experimental input: HL-LHC projection

(slides from A.-M. Magnan, Autumn WG2 meeting, 23.10.18)

Final results **In YR**





- Little impact from MET smearing after reoptimisation of the selection.
- Final limit ≃ 4%.

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Experimental input for HL-LHC projections

Standard Model Higgs couplings

- use **projection prescription recommendations documented on TWiki** (currently: details from CMS only)
  [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/GuidelinesCouplingProjections2018]
- study 2 scenarios:

  S1: systematic uncertainties as in current run

  S2: theoretical systematic uncertainties halved, experimental reduced

  details: [https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCCommonSystematics]
- implemented in `HiggsSignals` [see Bechtle ea, JHEP 1411 (2014) 039 for details]
  (assume ATLAS=CMS, and including correlation matrix)

S1 vs S2, as off October (slide from A. Gilbert, CMS)

Signal strength per prod x decay

- Primarily to be used as input for other studies (eg. EFT reinterpretation)
- NB: small change to μ_{ttH}^{bb} still expected to account for recommended reduction of tt+HF theory uncertainty

		3000 fb^{-1} Total	Stat	SigTh	BkgTh	Exp
$\mu_{ggH}^{\gamma\gamma}$	S1	7.1	1.9	5.9	0.0	3.3
	S2	4.2	1.9	3.1	0.2	2.1
μ_{ggH}^{ZZ}	S1	6.5	2.1	5.3	1.6	2.7
	S2	4.0	2.1	2.7	0.7	1.8
μ_{ggH}^{WW}	S1	6.6	1.2	6.2	1.0	1.5
	S2	3.8	1.2	3.2	0.9	1.2
$\mu_{ggH}^{\tau\tau}$	S1	8.1	2.6	6.6	1.6	3.5
	S2	5.5	2.6	3.9	0.7	2.9
μ_{ggH}^{bb}	S1	33.8	20.6	3.1	6.6	25.3
	S2	21.1	20.6	2.6	1.5	4.1
$\mu_{ggH}^{\mu\mu}$	S1	16.6	13.4	5.5	0.2	7.9
	S2	13.8	13.4	3.2	0.7	2.0
$\mu_{VBF}^{\gamma\gamma}$	S1	22.1	5.2	8.3	0.3	19.9
	S2	12.8	5.2	4.2	0.5	10.9
μ_{VBF}^{ZZ}	S1	15.1	11.7	9.0	2.1	1.8
	S2	13.4	11.7	6.0	0.8	1.3
μ_{VBF}^{WW}	S1	8.5	6.3	5.1	1.6	2.0
	S2	7.3	6.3	3.1	1.1	1.6
$\mu_{VBF}^{\tau\tau}$	S1	5.4	3.8	2.9	1.6	2.0
	S2	4.4	3.8	1.7	0.7	1.3
$\mu_{VBF}^{\mu\mu}$	S1	57.4	53.2	18.5	0.8	11.0
	S2	54.1	53.2	9.9	2.0	2.6

		3000 fb^{-1} Total	Stat	SigTh	BkgTh	Exp
$\mu_{WH}^{\gamma\gamma}$	S1	14.5	13.6	3.3	0.2	3.7
	S2	13.9	13.6	2.0	0.2	1.7
μ_{WH}^{ZZ}	S1	47.9	46.6	11.3	1.4	7.4
	S2	47.8	46.6	4.1	1.0	3.8
μ_{WH}^{WW}	S1	15.7	12.9	5.7	1.8	6.5
	S2	13.8	12.9	3.2	1.5	3.1
μ_{WH}^{bb}	S1	16.1	5.6	5.5	10.1	9.8
	S2	9.4	5.6	2.2	5.1	5.1
$\mu_{ZH}^{\gamma\gamma}$	S1	23.8	23.1	5.2	0.2	2.7
	S2	23.3	23.1	3.2	0.4	1.2
μ_{ZH}^{ZZ}	S1	82.3	75.8	26.8	5.8	15.6
	S2	78.6	75.8	15.9	2.1	9.9
μ_{ZH}^{WW}	S1	20.6	17.2	10.2	1.7	3.4
	S2	18.4	17.2	5.7	1.7	3.0
μ_{ZH}^{bb}	S1	9.6	4.2	7.7	3.0	2.3
	S2	6.5	4.2	3.9	2.6	1.9
$\mu_{ttH}^{\gamma\gamma}$	S1	12.4	7.7	8.7	0.2	3.9
	S2	9.4	7.7	4.4	0.2	2.7
μ_{ttH}^{ZZ}	S1	26.4	23.7	10.1	2.9	4.1
	S2	24.6	23.7	5.0	1.9	3.1
μ_{ttH}^{WW}	S1	13.8	4.2	8.1	4.4	9.1
	S2	9.7	4.2	4.1	3.1	6.9
μ_{ttH}^{bb}	S1	10.4	2.8	8.4	3.6	3.9
	S2	6.8	2.8	4.2	3.5	2.7
$\mu_{ttH}^{\tau\tau}$	S1	18.5	8.7	9.0	3.3	13.1
	S2	14.9	8.7	4.8	2.2	10.9

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Applications of fit

$\Rightarrow$ simple fit in κ framework

$\Rightarrow$ simple Higgs portal models

$\Rightarrow$ specific portal with 2 new scalars

General parametrization

[some slides (adapted) from Tims talk in June]

Coupling scale factor (κ) parametrization

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

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

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

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

Our strategy:

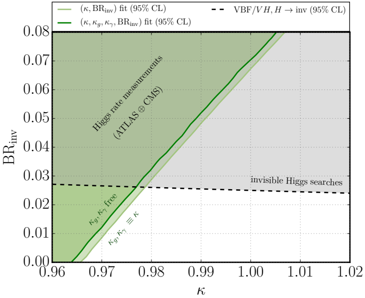
Perform global fit to HL-LHC Higgs rates in two parametrizations

1. κ (common scale factor), $\mathrm{BR}(H \to NP)$;
2. κ (common for tree-level couplings), κ_g, κ_γ, $\mathrm{BR}(H \to NP)$;

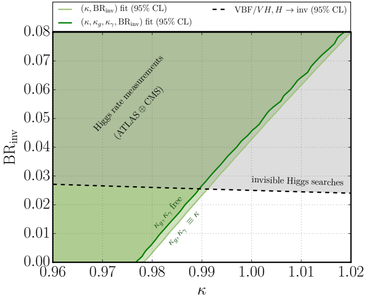
Assume κ_V $(= \kappa) \leq 1$, but no further assumptions on $\mathrm{BR}(H \to NP)$ in fit.

Simple fit: results

Result of combination: $\mathrm{BR}_{\mathrm{inv}} \leq 2.5\%$



S1 scenario



S2 scenario

$\Longrightarrow$ can be interpreted in many models !! $\Longleftarrow$

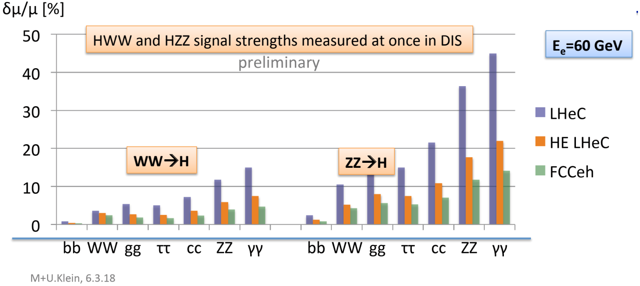
(current results: 30% from fit, 25% from direct search)

… and including LHeC projections…

[slide from U. Klein, June meeting]

Uta & Max Klein, Contribution to HL/HE Workshop, 4.4.2018, preliminary

Signal Strengths @ LHeC - HE-LHeC - FCCeh



Charged Currents: ep → νHX   Neutral Currents: ep → eHX

Note: HWW and HZZ requires different e+e- machine settings / c.m.s. energies for high precision
→NC and CC DIS together over-constrain Higgs couplings in a combined fit.

E_e = 60 GeV LHeC E_p = 7 TeV L=1ab^{-1} HE-LHC E_p = 14 TeV L=2ab^{-1} FCC: E_p = 50 TeV L=2ab^{-1}

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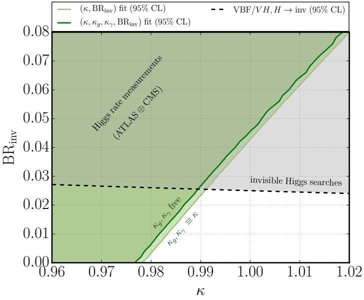
HL-LHC only vs combination

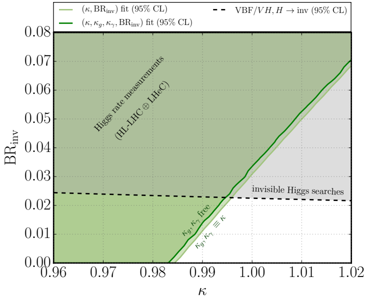
κ fit only:

HL-LHC only, SM couplings: $\text{BR}_{\text{inv}} \leq$ **4.3%**

HL-LHC and LHeC, SM couplings: $\text{BR}_{\text{inv}} \leq$ **3.1%**



HL-LHC, S2 scenario



...combined with LHeC

More details on Higgs portal model

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:

(scalar DM) (vector DM) (fermion DM)

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

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

The Higgs portal coupling λ relates

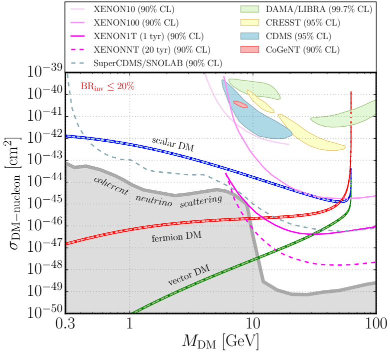
invisible Higgs decay width ($\Gamma_{\rm inv} \propto \lambda^2 v^2$)	$\longleftrightarrow$	DM-nucleon scattering cross section ($\sigma_{\rm DM-nucleon} \propto \lambda^2$)

$\Rightarrow$ Complementarity: invisible Higgs searches $\leftrightarrow$ DM direct detection (DD).

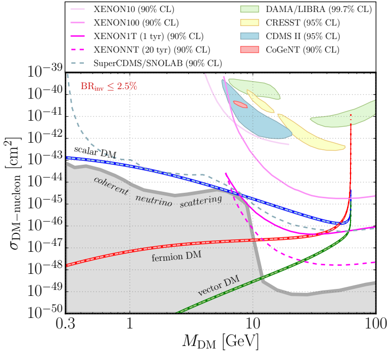
Invisible Higgs decay in minimal portal models

- remember: **relation between $\mathrm{BR}_{\mathrm{inv}}$ and direct detection**

$\Rightarrow$ can translate limits



now



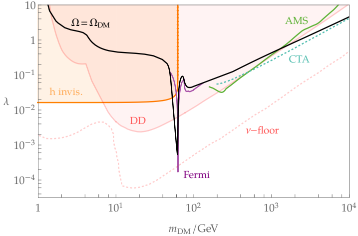
future

[Interlude: what about DM constraints]

Brief comment on the DM relic density constraint

In thermal freeze-out picture: DM relic density Ω_{DM} highly constraining!

scalar DM ($\lambda = 2\lambda_{hSS}$) [Hardy '18]



$\mathrm{BR_{inv}} \oplus \mathrm{DD} \oplus \Omega_{DM}$ 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]

Second example: scalar singlet portal

Example: Scalar singlet portal

⇒ study a more involved model to investigate complementarity

⇒ here: Higgs singlet:

2 scalar states h, H with mixing angle α

with singlet coupling to **scalar dark matter candidate X**

- important parameters

$$\underbrace{M_h,\ \cos\alpha,\ v_s}_{\text{visible sector}},\ \underbrace{M_X,\ \lambda_{SXX}}_{\text{dark sector}}$$

M_i: new masses, λ: new coupling, v_s: singlet vev

(e.g. Englert, Plehn, Zerwas^2, Phys.Lett. B703 (2011))

(Singlet: e.g. TR, T. Stefaniak, Eur.Phys.J. C75 (2015), Eur.Phys.J. C76 (2016))

... in more detail...

Singlet scalar–DM portal: the model

Visible sector: (Φ: $\mathrm{SU}(2)_L$ doublet, S: $\mathrm{SU}(2)_L$ singlet)

$$\mathcal{V}_{\mathrm{vis}} = \mu_\Phi^2 \Phi^\dagger\Phi + \lambda_\Phi(\Phi^\dagger\Phi)^2 + \mu_S^2 S^2 + \lambda_S S^4 + \lambda_{\Phi S}\Phi^\dagger\Phi S^2$$

$\langle\Phi\rangle \equiv v$, $\langle S\rangle \equiv v_S \neq 0 \Rightarrow$ mixing of scalar fields ϕ and s:

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

$\Rightarrow$ Higgs couplings to SM fields are universally suppressed by mixing:

$$g_h/g_{h,\mathrm{SM}} = \cos\alpha, \qquad g_H/g_{H,\mathrm{SM}} = \sin\alpha \; (\equiv \kappa).$$

Only S couples to DM sector: (assume scalar DM particle X here)

$$\mathcal{L}_{\mathrm{DM}} \supset -\tfrac{1}{4}\lambda_{SXX} S^2 X^2.$$

After fixing $M_H = 125.09$ GeV, $v \approx 246$ GeV, five input parameters remain:

$M_h, \cos\alpha, v_S$ (visible sector), M_X, λ_{SXX} (DM sector)

Invisible decays in the singlet portal

- setup

$$M_H = 125\,\mathrm{GeV},\ M_h \in [0;100]\,\mathrm{GeV},\ M_X = 5\,\mathrm{GeV}$$

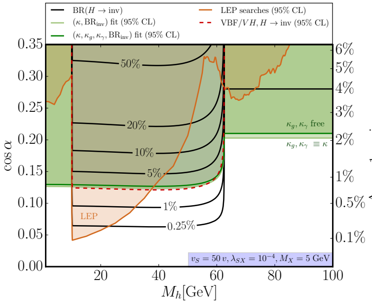
HL-LHC precision vs LEP direct searches for M_h

can either look at **direct $H \to X\,X$**

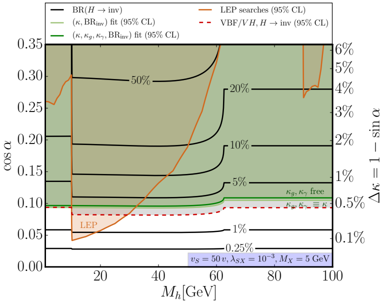
or increase **decay chain via intermediate h**

Singlet portal: results

$$\text{Channels}: (a) H_{125} \rightarrow X\,X \quad (b) H_{125} \rightarrow h\,h \rightarrow 4X$$



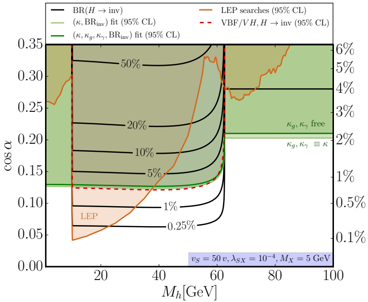
"standard"



(a) enhanced

Singlet portal: results

Channels : $(a) H_{125} \rightarrow X\,X$ $(b) H_{125} \rightarrow h\,h \rightarrow 4X$



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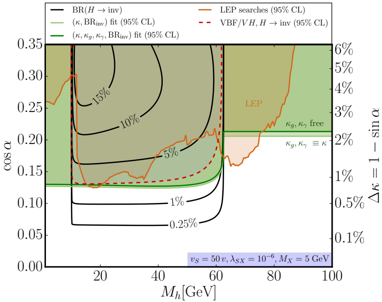
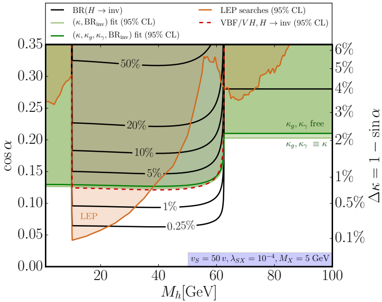


(a) suppressed

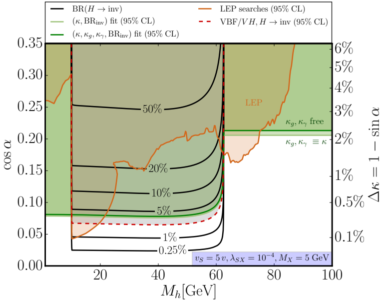
or **increasing decay chain** $H \to h\,h$

Singlet portal: results

Channels : $(a) H_{125} \rightarrow X\,X$ $(b) H_{125} \rightarrow h\,h \rightarrow 4X$



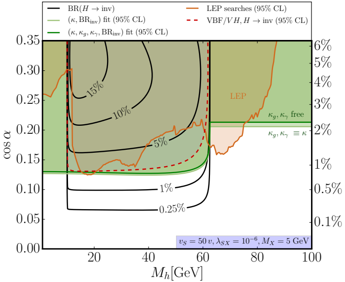
"standard"



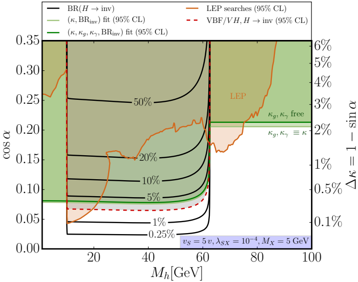
(b) enhanced

Singlet portal: results

Channels : $(a) H_{125} \to X\,X$ $(b) H_{125} \to h\,h \to 4X$



(a) suppressed



(b) enhanced

⇒ depending on parameter space, LEP direct searches can still provide strongest constraints

⇒ same holds for direct vs indirect constraints

Higgs to invisible: summary [(*) highlights]

- simple fit in κ framework:

(*) large improvement wrt current status ✓ [limit BR_{inv}: 2.5 %]

- **dominance of fit or direct measurement depends on parameter point**

⇒ **add LHeC: further improvement**

[$BR_{inv} \leq 4.3\%$ vs 3.1% from indirect constraints]

- "simple" portal models:

interesting complementarity to direct detection experiments

⇒ **(*) for low DM masses, important probe !!**

⇒ in general, **(*) improve by an order of magnitude**

- for concrete model: **depends a lot in parameter space !**

[interesting interplay between LEP searches and HL-LHC probes...]

⇒ **(*) large regions can be tested at HL-LHC**

Summary II: Limits

Limits on invisible BR

machine	indirect	direct
HL-LHC, S1:	6.7%	2.5%
HL-LHC, S2:	4.3%	2.5%
and LHeC:	3.1%	2.25%

at $\kappa = 1$

Appendix: Naive signal strength combination

- input: VBF: 4% [CMS], VH: 8% [ATLAS]
- assume the same for each experiment
- and one degree of freedom (invisible BR)

$$\chi^2 = \mu^2 \sum_i \frac{1}{(\Delta\mu_i)^2} = \mu^2 \left[\frac{2}{(0.5 * 0.04)^2} + \frac{2}{(0.5 * 0.08)^2}\right]$$
$$= 6250\mu^2 \stackrel{!}{=} 4 \quad \Rightarrow \mu = 2.53\%.$$

Appendix: analytic expressions in singlet portal

Singlet scalar–DM portal: Higgs decays

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

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

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:

$$\begin{aligned}\Gamma(h \to XX) &= \sin^2\alpha \cdot \Gamma_{XX}(M_h)\\ \Gamma(H \to XX) &= \cos^2\alpha \cdot \Gamma_{XX}(M_H)\end{aligned} \quad \text{with} \quad \Gamma_{XX}(M) = \frac{\lambda_{SXX}^2 v_S^2}{128\pi M}\sqrt{1 - \frac{4M_X^2}{M^2}}$$

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

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

Other possible decays: $H \to hh \to (\mathrm{SM})(\mathrm{SM})$ and $(\mathrm{SM})(\mathrm{inv})$.

Appendix: Tuning the singlet portal

- $\text{BR}_{\text{inv}} \sim (\lambda_{SXX}\, v_s)^2 \sim (\lambda_{SXX} / \tan\beta)^2$
- $\text{BR}_{H \to h\,h} / \text{BR}_{\text{inv}} \sim \left[1/(v_s^2\, \lambda_{SXX})\right]^2 \sim \left[\tan^2\beta / \lambda_{SXX}\right]$

$\tan\beta = \frac{v}{v_s}$

large BR_{inv}, suppressed $\text{BR}_{H \to h\,h}$: $\tan\beta$ small, $\lambda_{SXX} \sim \tan\beta$

Inferred upper limit on total width of Higgs

$$\mathrm{BR}_{\mathrm{inv}} = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\mathrm{tot}}} \leq x$$

and therefore

$$\Gamma_{\mathrm{tot}} \leq \frac{\kappa^2}{1-x}\,\Gamma_{\mathrm{SM}}$$

assuming a global rescaling factor. $x = 2.5\%$ and therefore

$$\Gamma_{\mathrm{tot}} - \Gamma_{\mathrm{SM}} \leq 1.026\,\left(1-\kappa^2\right)\Gamma_{\mathrm{SM}} \leq 0.32\,[0.16]\mathrm{MeV}$$

in the S1 [S2] scenario.