Invisible Higgs vs. Higgs rates at HL-LHC:

(some) theory implications

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Introduction

What is dark matter? How does DM interact with SM particles?

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$\rightarrow$ we don't know.

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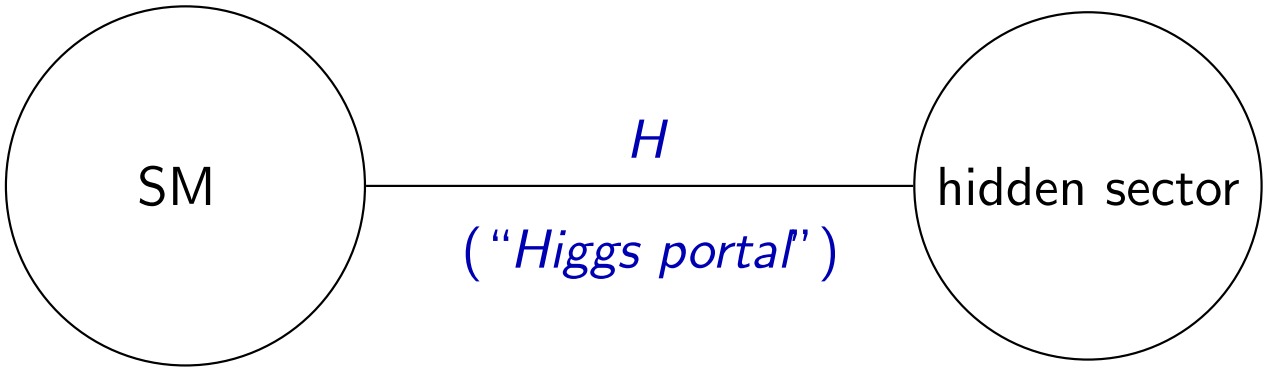
$\rightarrow$ we don't know.

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

$|H|^2$ = the only gauge and Lorentz-invariant dim-2 operator

$\mathcal{L} \supset a|H|^2 S^2$ (S : stable hidden scalar)



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

In this talk we focus on $M_{\mathrm{DM}} < M_H/2 \Rightarrow$ invisible Higgs decays.

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

- Minimal Higgs portal ($\simeq$ 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...
- ...

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:

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

$$\mu_{VH} \cdot \mathrm{BR}(H \to \mathrm{inv}) \leq 8.0\% \quad \text{(ATLAS, “realistic” scenario)}$$

(with $\mu_i = \sigma_i / \sigma_{i,\text{SM}}$) [ATL-PHYS-PUB-2013-014]

more studies are under way. . . (?)

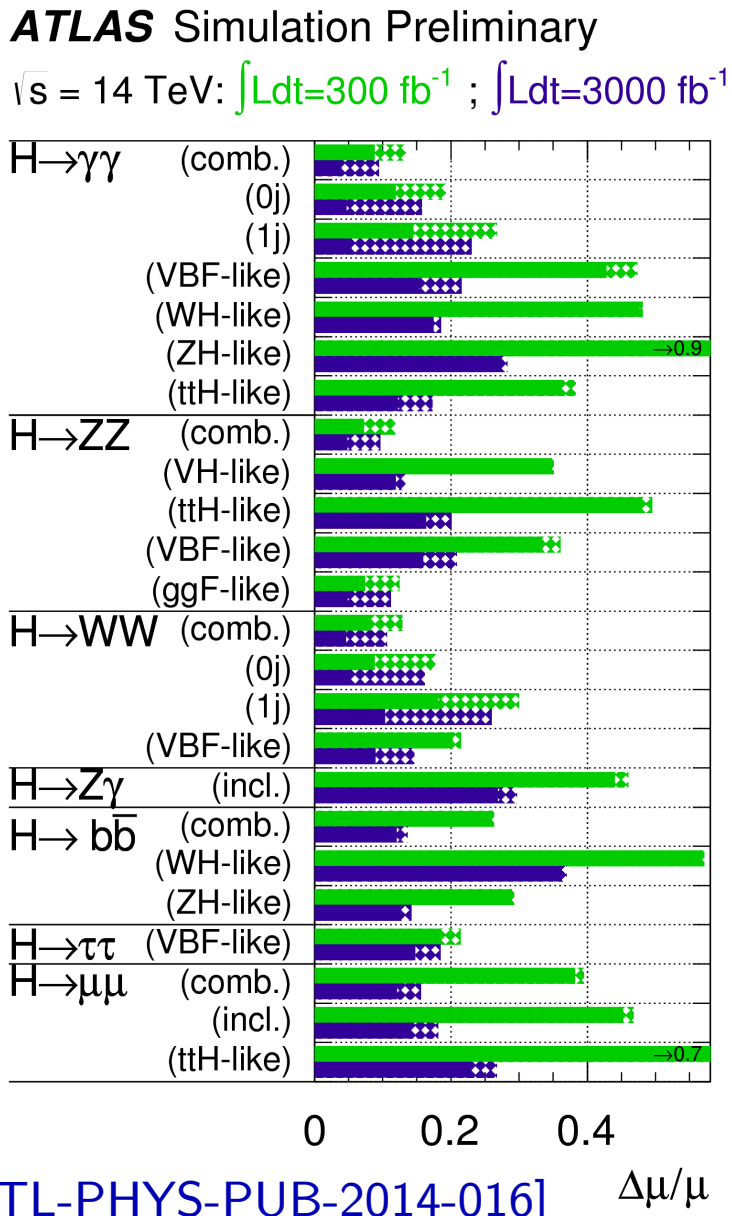
Let’s make a tentative assumption:

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

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

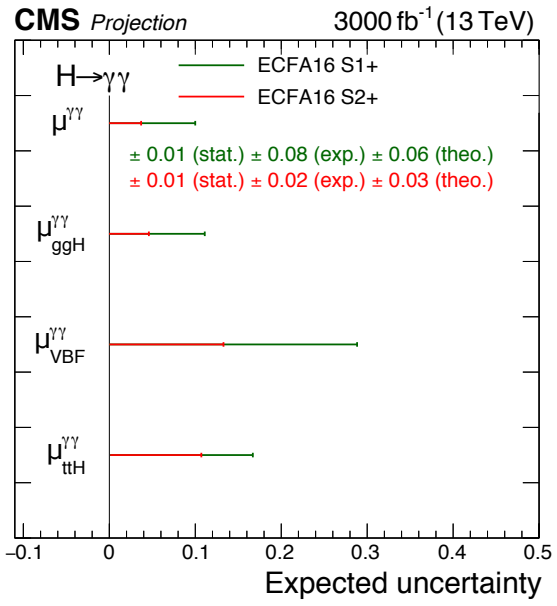
$$\Rightarrow \quad \mu_{\text{VBF},VH} \cdot \mathrm{BR}(H \to \mathrm{inv}) \lesssim 3.5\% \quad (\text{ATLAS} \oplus \text{CMS})$$

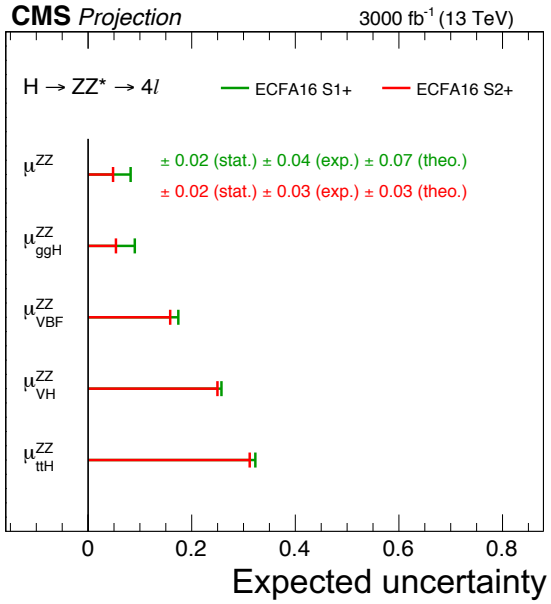
Future HL-LHC Higgs rate measurements



[ATL-PHYS-PUB-2014-016]

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





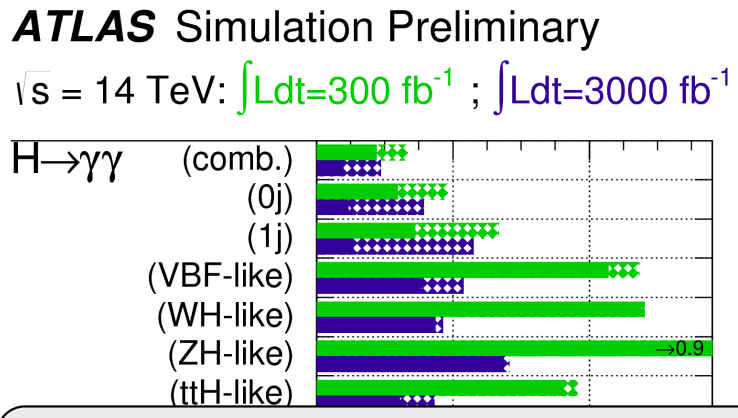
CMS Snowmass report: [CMS, 1307.7135]

$\Delta\mu_{H\to WW} = 4\%$ $\Delta\mu_{H\to Z\gamma} = 20\%$

$\Delta\mu_{H\to bb} = 5\%$ $\Delta\mu_{H\to\mu\mu} = 20\%$

$\Delta\mu_{H\to\tau\tau} = 5\%$ (*Scenario 2*)

Future HL-LHC Higgs rate measurements



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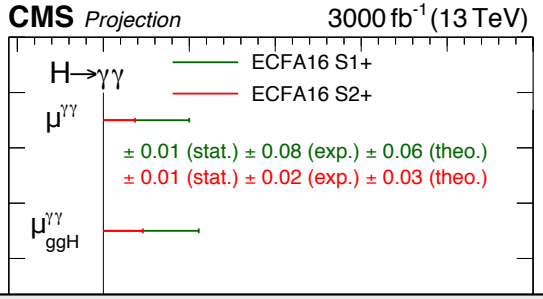
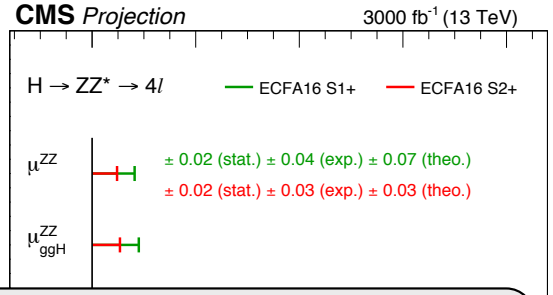




Implementation of HL-LHC observables in `HiggsSignals` (for global χ^2 fit):

- Assume theory uncertainties are halved ($\simeq$ CMS scenario S2+);
- Correlations of theory/parametric uncertainties included in χ^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 (κ framework) –

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]

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

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

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

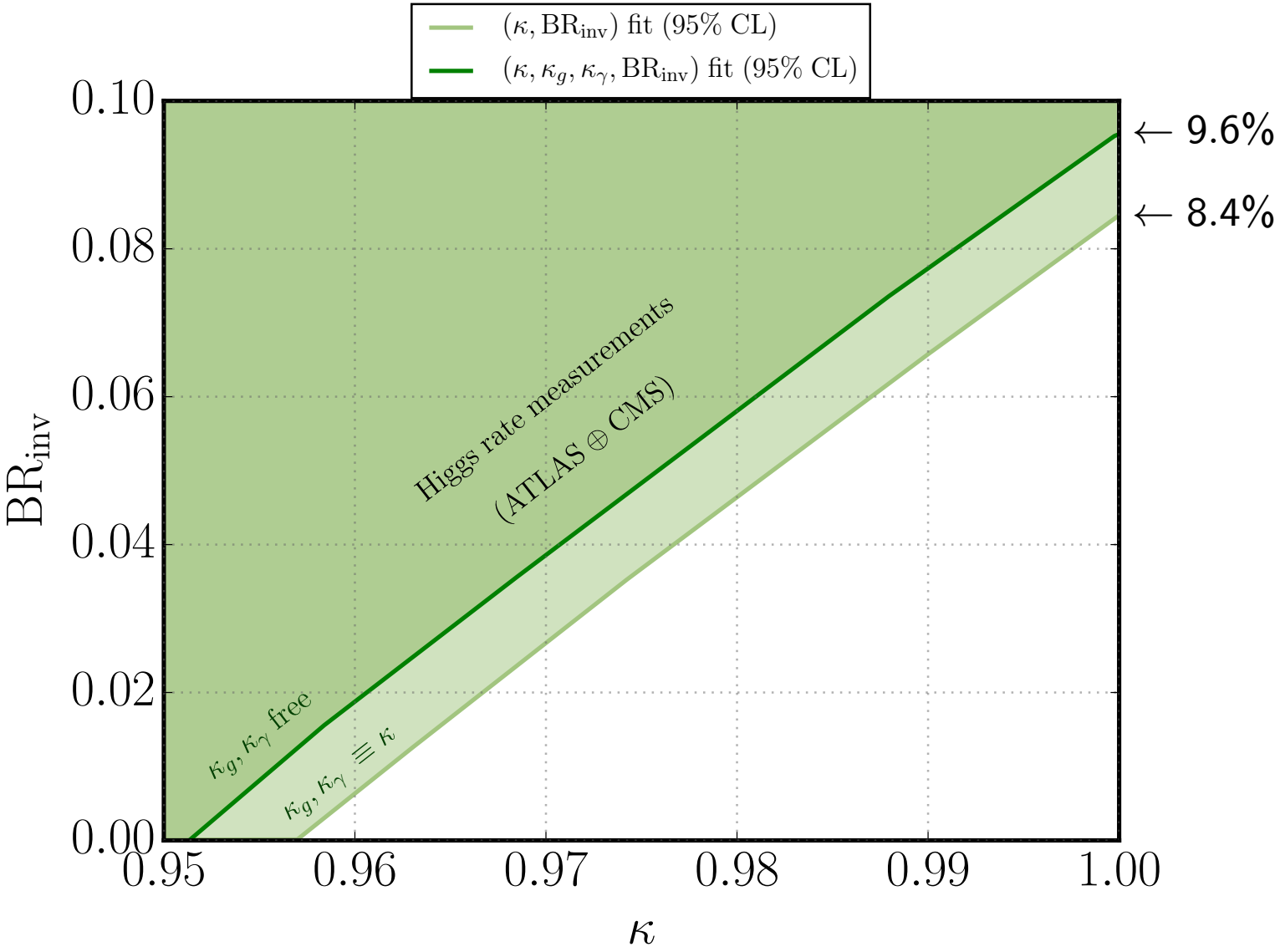
Our strategy:

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

HL-LHC prospects: κ parametrization



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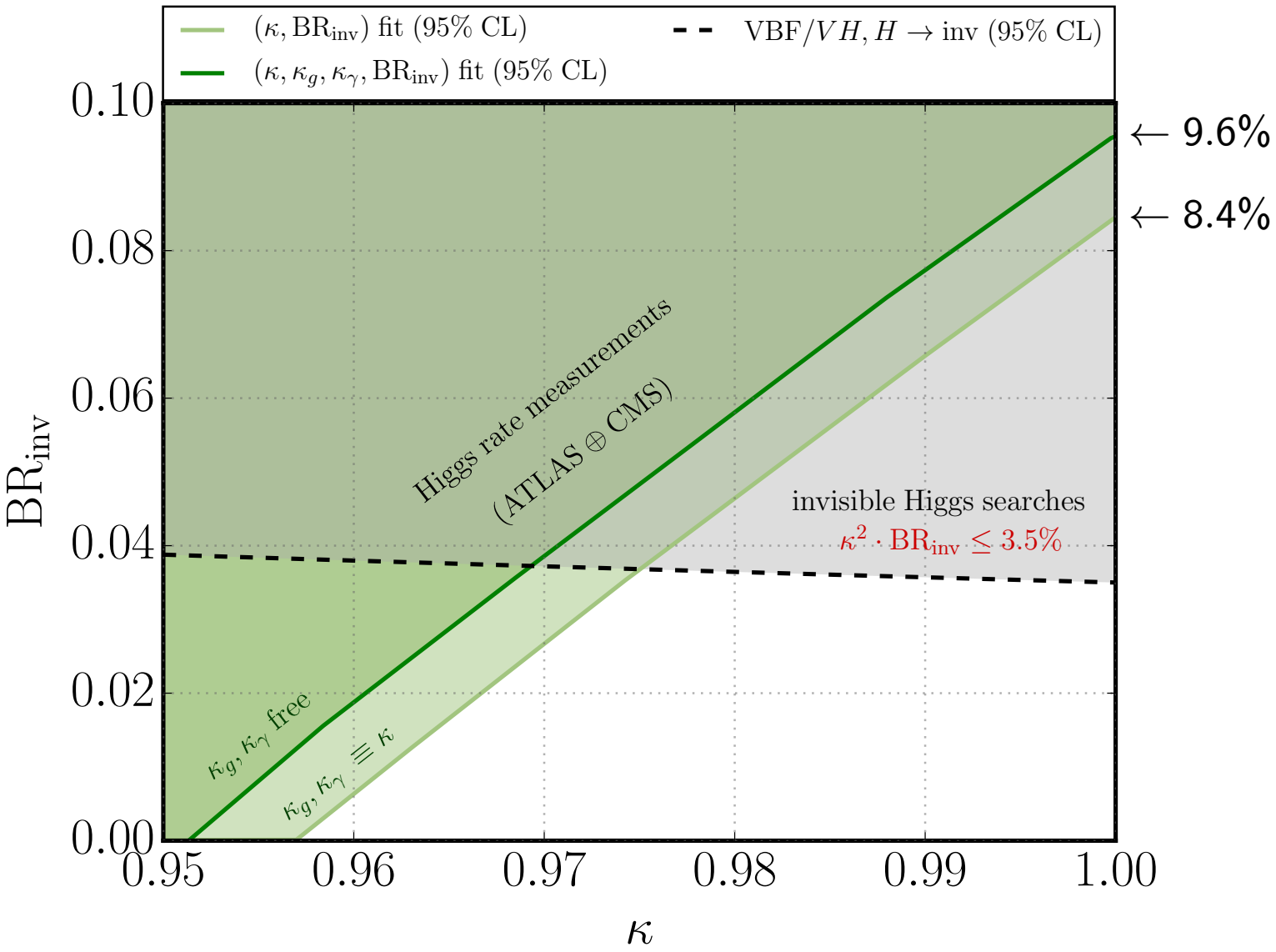


Theory implications of HL-LHC results

– 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:

	(scalar DM)		(vector DM)		(fermion DM)
$\mathcal{L} \supset$	$-\frac{1}{4}\lambda_{hSS} H^\dagger H S^2$	or	$+\frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu$	or	$-\frac{1}{4}\frac{\lambda_{h\chi\chi}}{\Lambda} H^\dagger H \bar{\chi}\chi.$

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

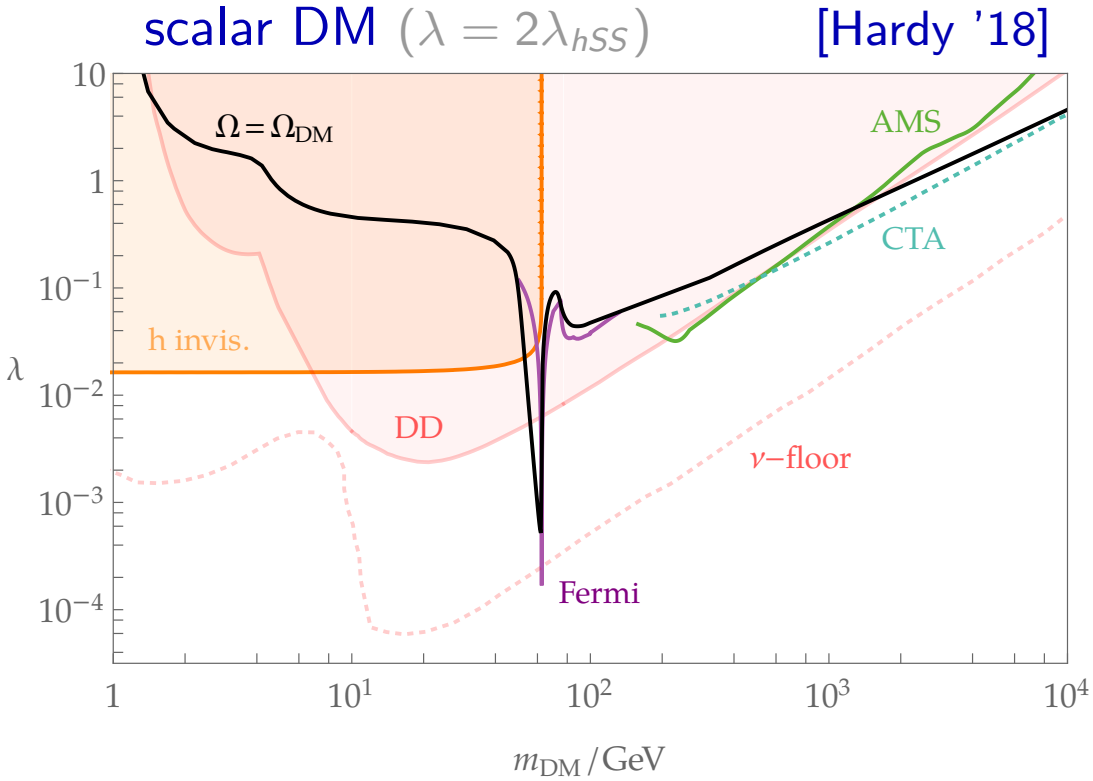
The Higgs portal coupling λ relates

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).

Brief comment on the DM relic density constraint

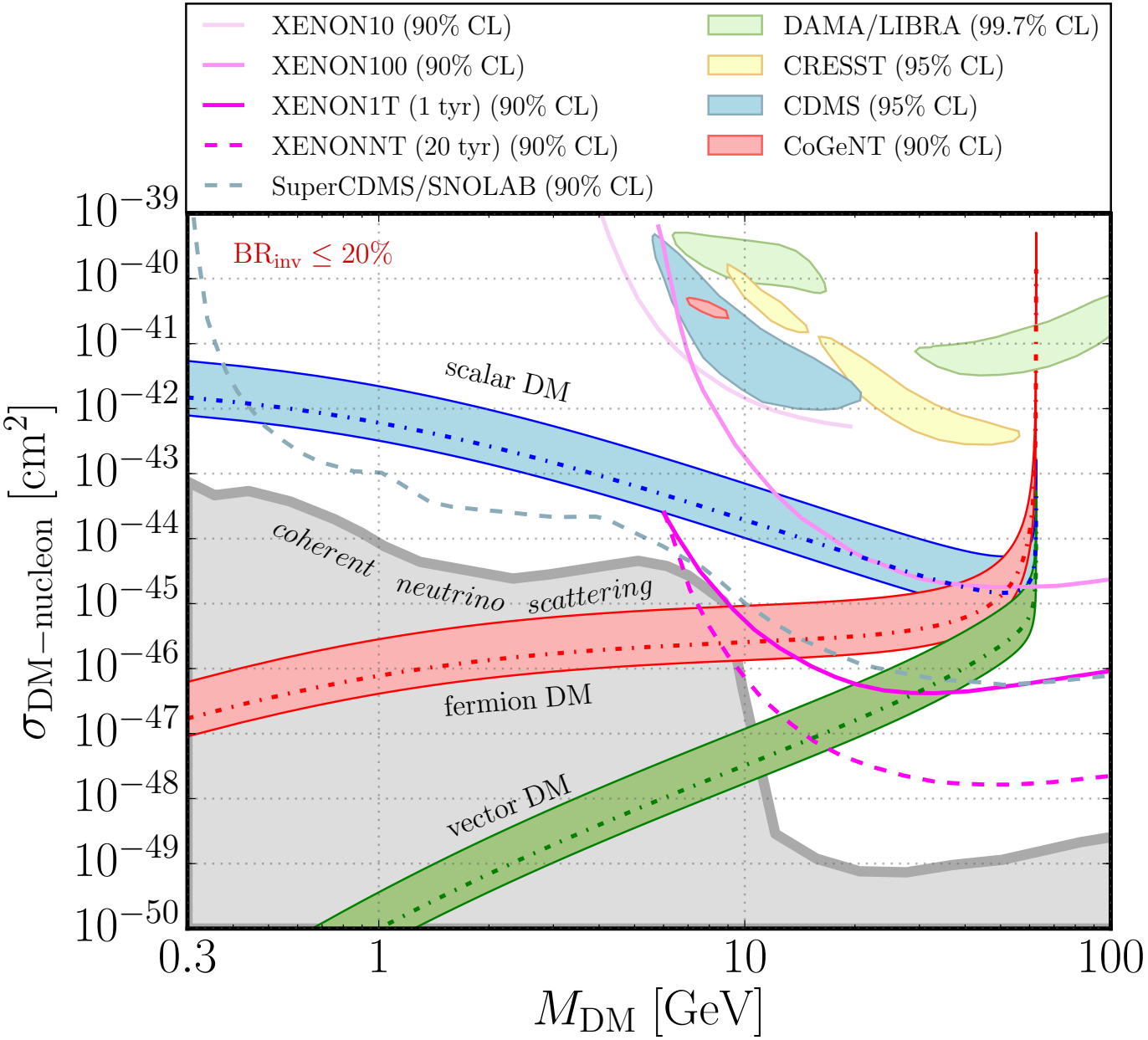
In thermal freeze-out picture: DM relic density $\Omega_{\rm DM}$ highly constraining!



$\mathrm{BR}_{\rm inv} \oplus \mathrm{DD} \oplus \Omega_{\rm DM}$ limits $\Rightarrow$ only near-resonant region $M_{\rm DM} \lesssim M_h/2$ 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:

$\mathrm{BR_{inv}} \leq 22\%$ (90% CL)

CMS Run-1/2:

$\mathrm{BR_{inv}} \leq 20\%$ (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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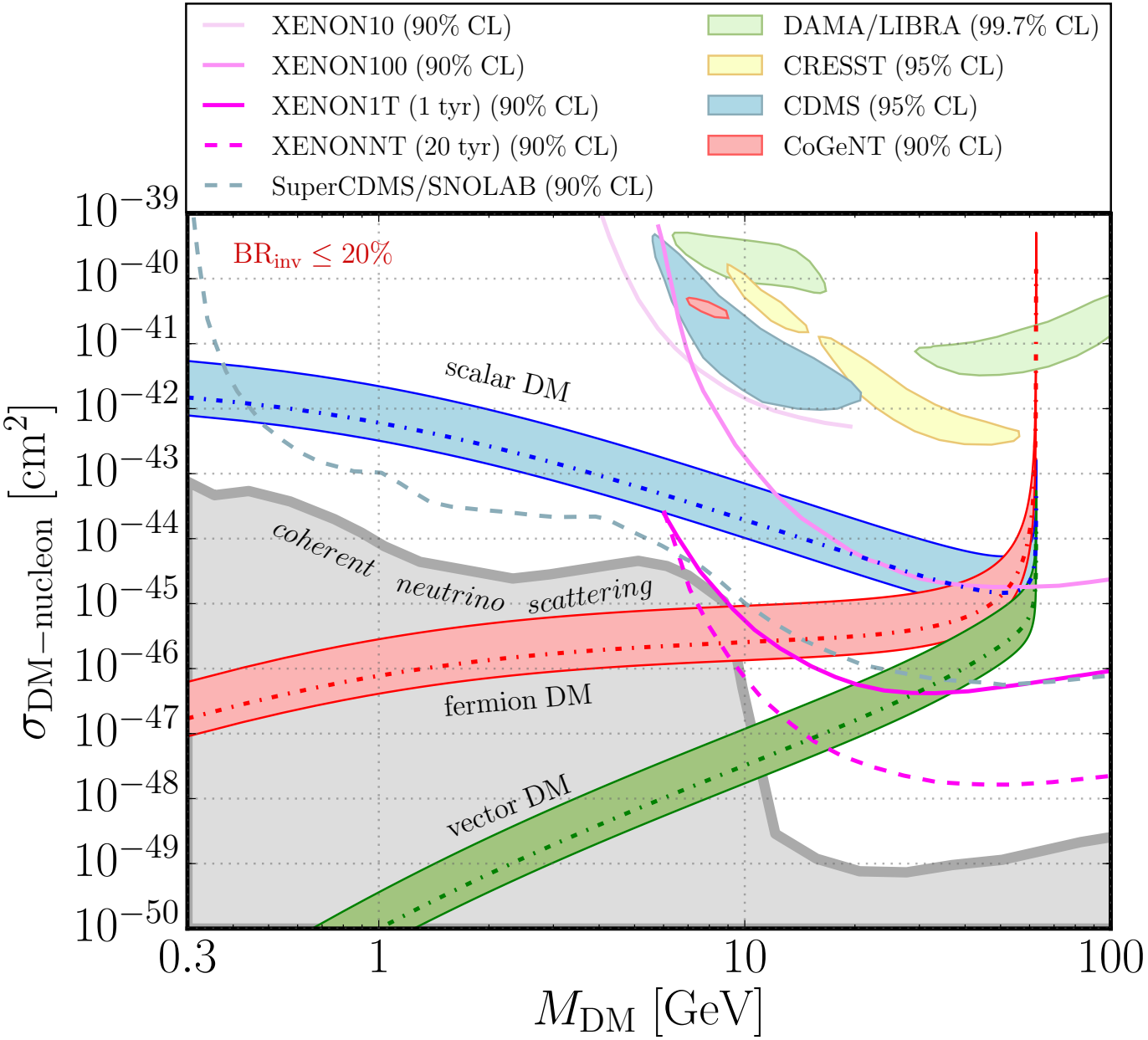

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[Hoferichter, et al. '17]

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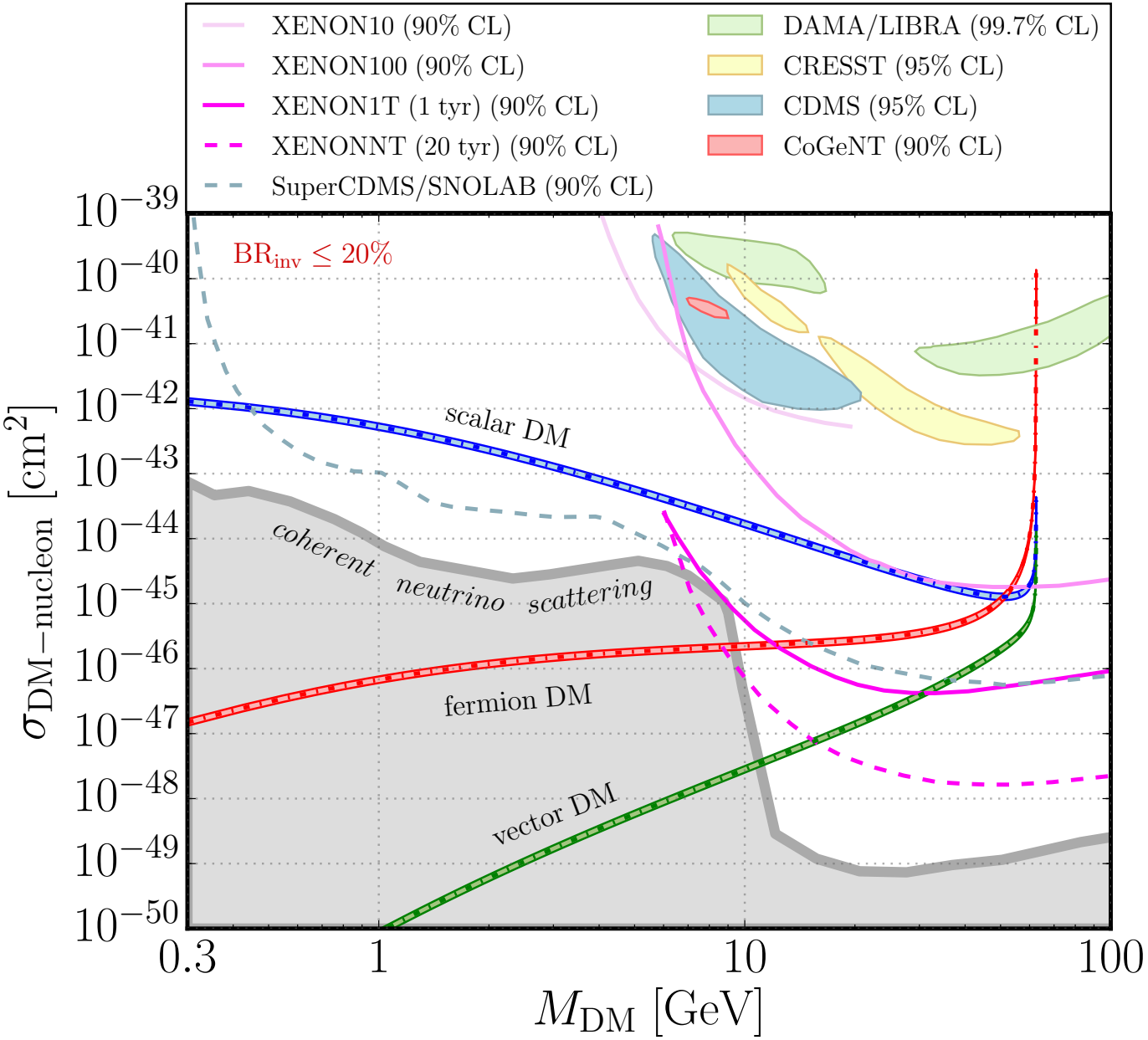

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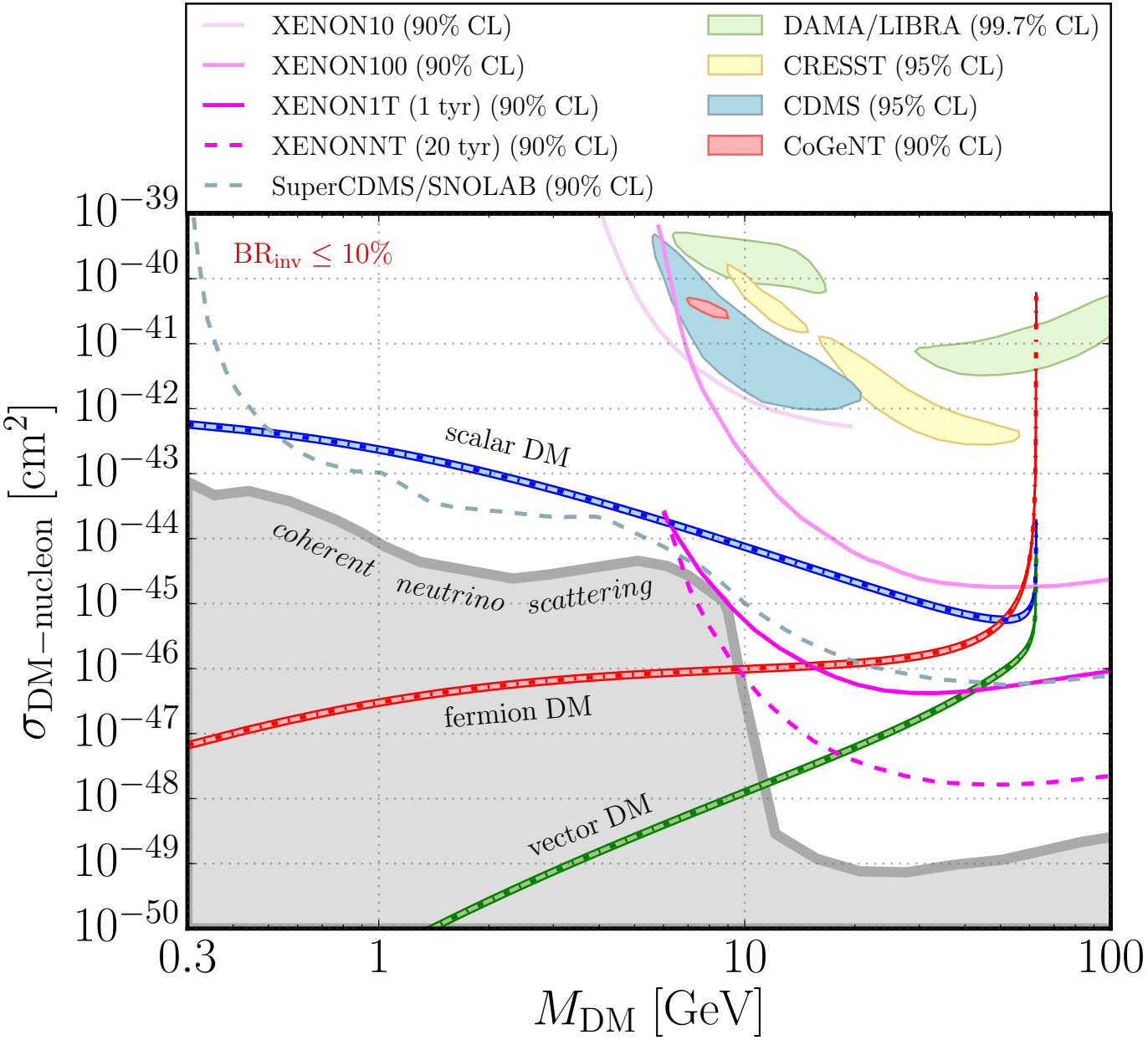
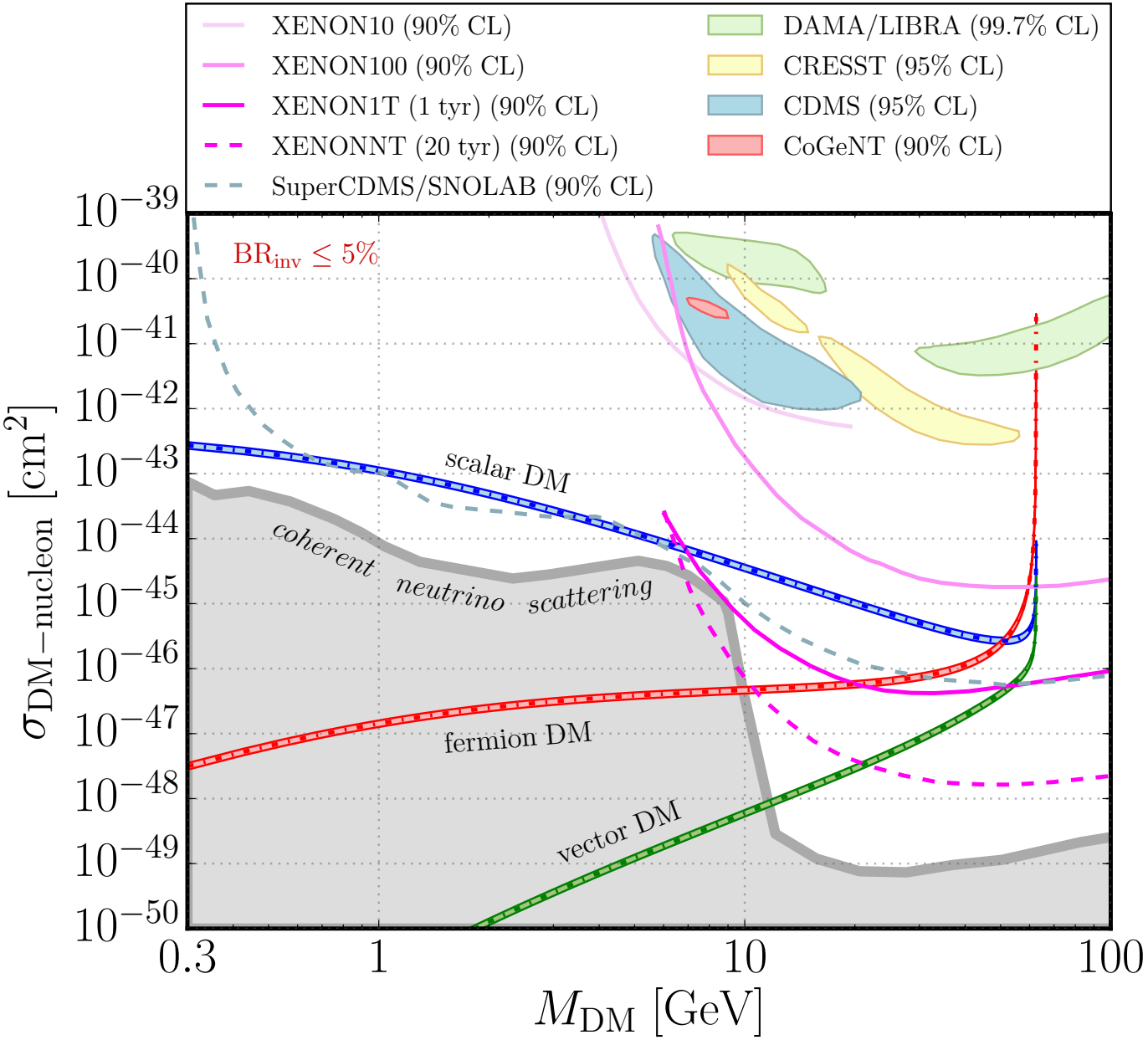


Future projections:

$\mathrm{BR_{inv}} \leq 10\%$

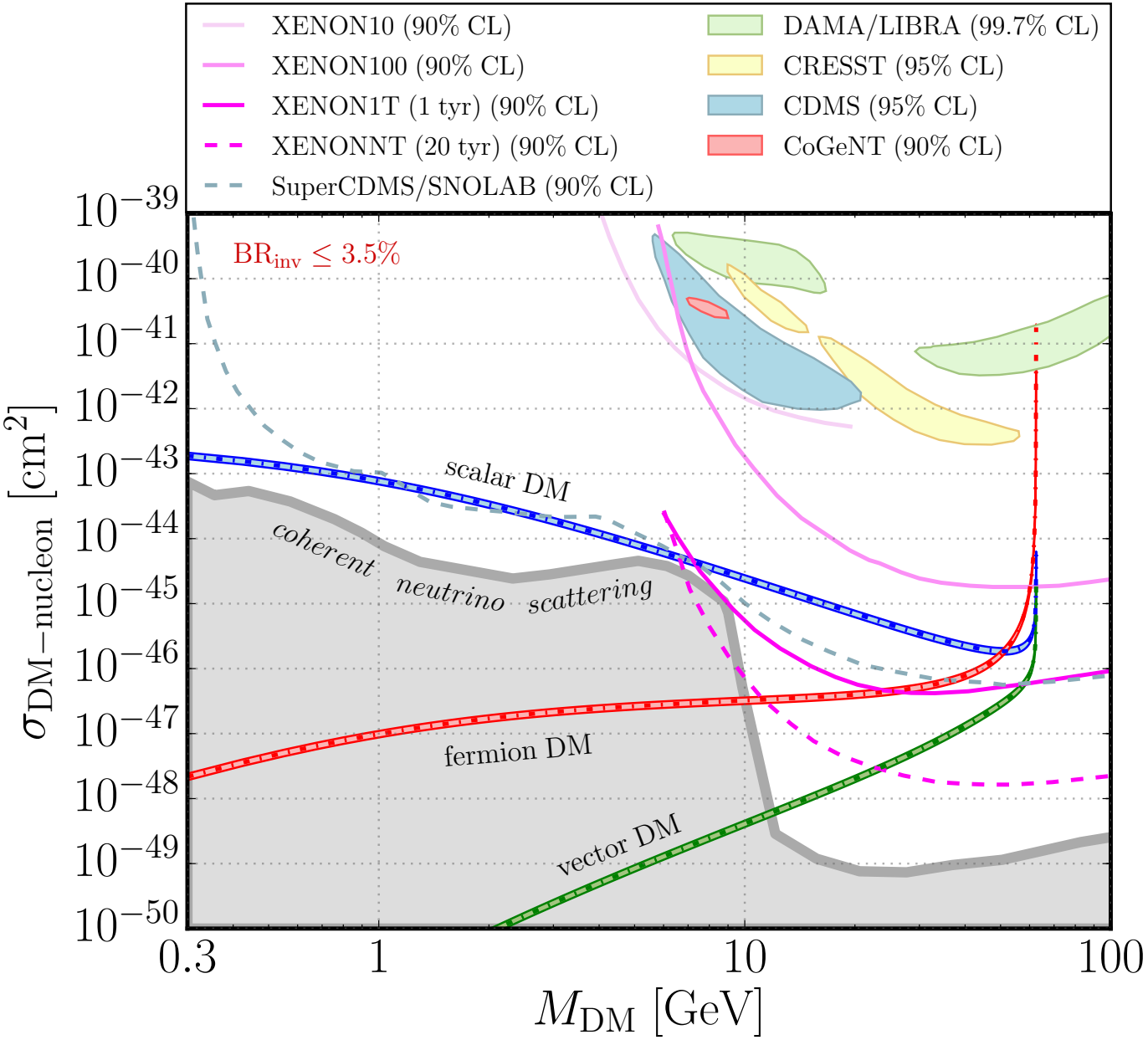
Minimal Higgs portal: Comparison with DM direct detection



Future projections:

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

Minimal Higgs portal: Comparison with DM direct detection

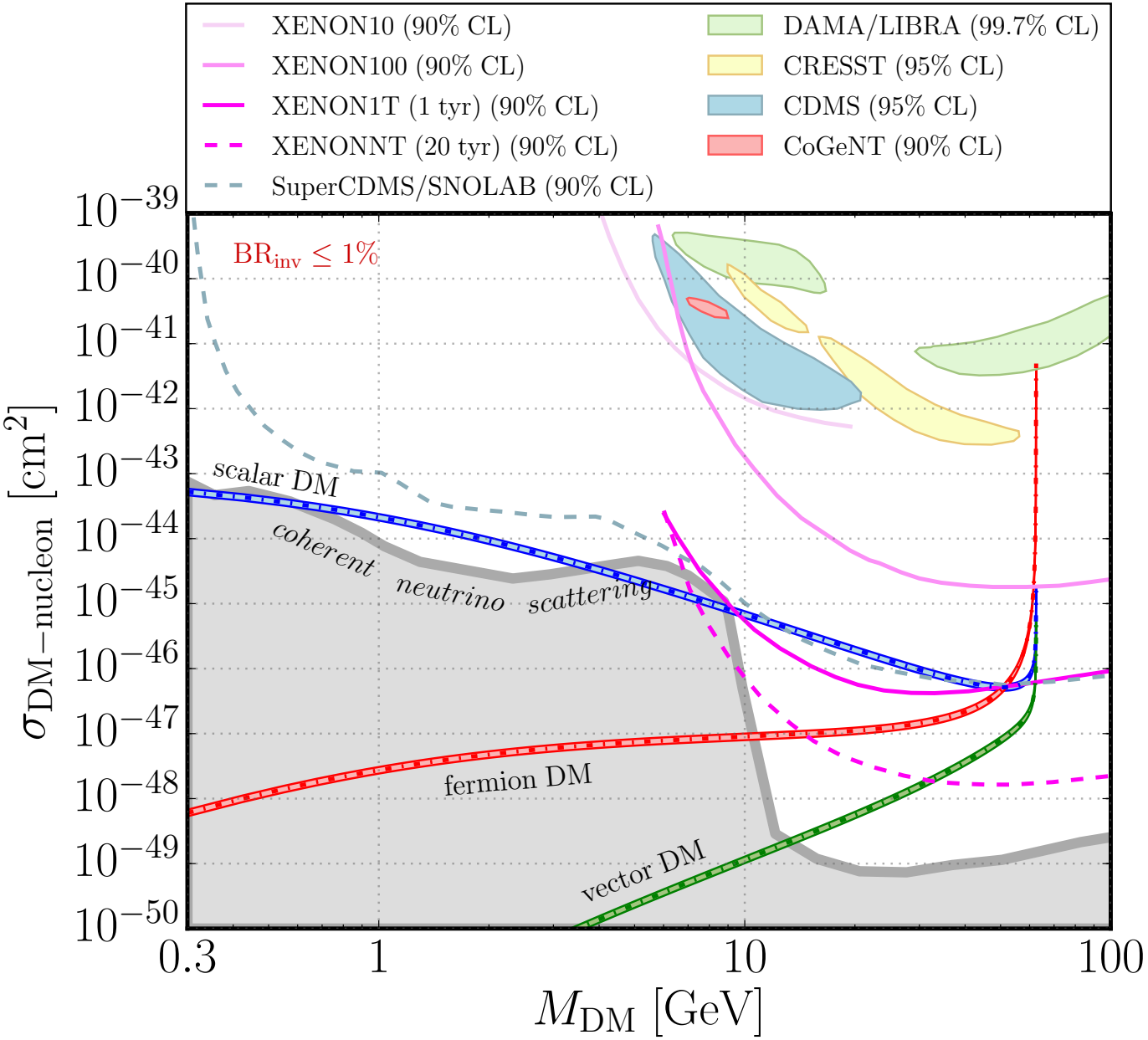


Future projections:

$\mathrm{BR_{inv}} \leq 3.5\%$

(HL-LHC expectation)

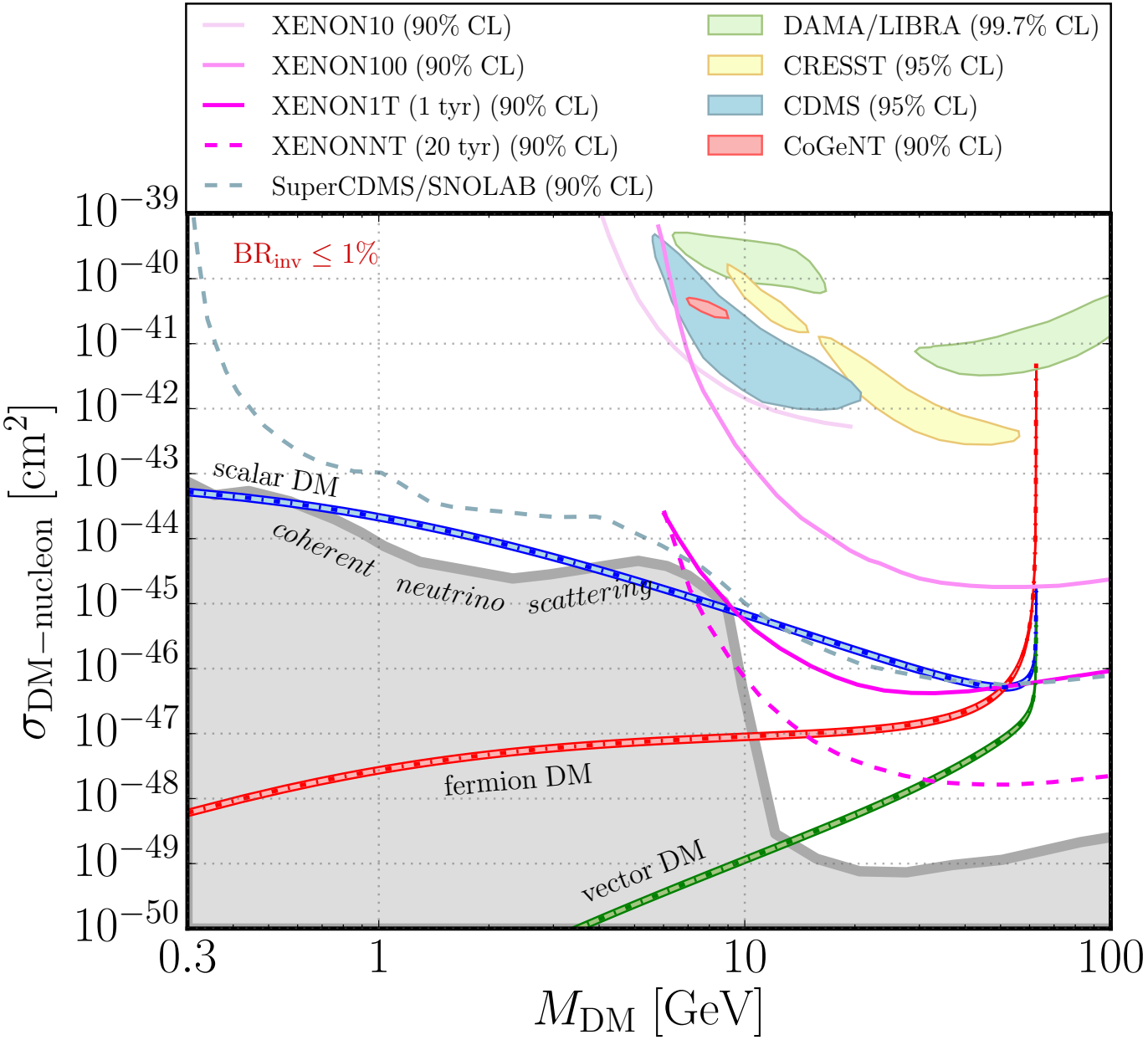
Minimal Higgs portal: Comparison with DM direct detection



Future projections:

$\mathrm{BR_{inv}} \leq 1\%$

Minimal Higgs portal: Comparison with DM direct detection



Future projections:

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

Comments:

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

For low $M_{\mathrm{DM}} \lesssim 10$ GeV, $\mathrm{BR}_{\mathrm{inv}}$ 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: (Φ: $\mathrm{SU}(2)_L$ doublet, S: $\mathrm{SU}(2)_L$ singlet)

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

$\langle \Phi \rangle \equiv v$, $\langle S \rangle \equiv v_S \neq 0 \Rightarrow$ 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:

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

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

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

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

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

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:

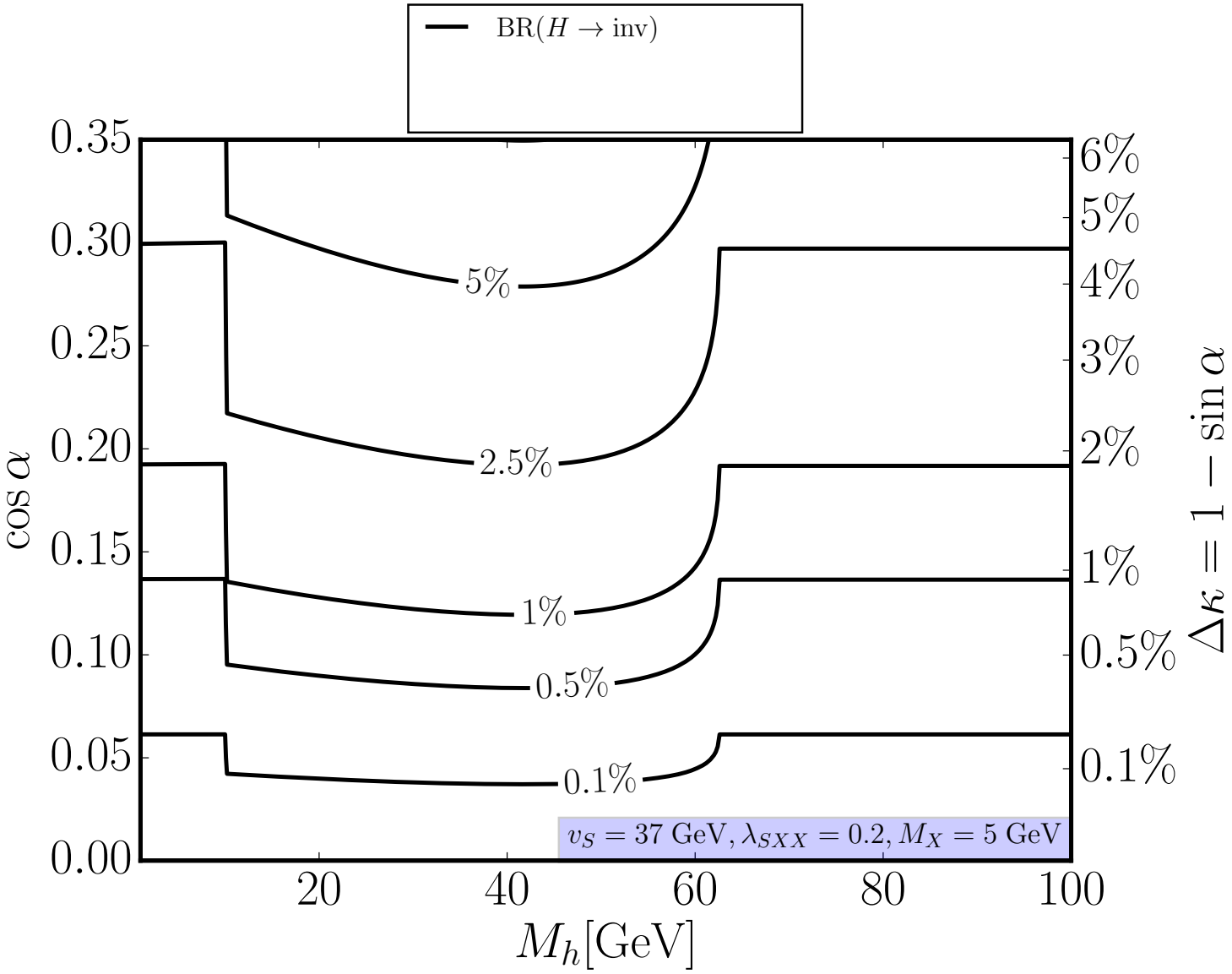
$$\Gamma(h \to XX) = \sin^2\alpha \cdot \Gamma_{XX}(M_h) \qquad \text{with} \quad \Gamma_{XX}(M) = \frac{\lambda_{SXX}^2 v_S^2}{128\pi M}\sqrt{1 - \frac{4M_X^2}{M^2}}$$
$$\Gamma(H \to XX) = \cos^2\alpha \cdot \Gamma_{XX}(M_H)$$

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

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

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

Singlet scalar–DM portal: HL-LHC prospects



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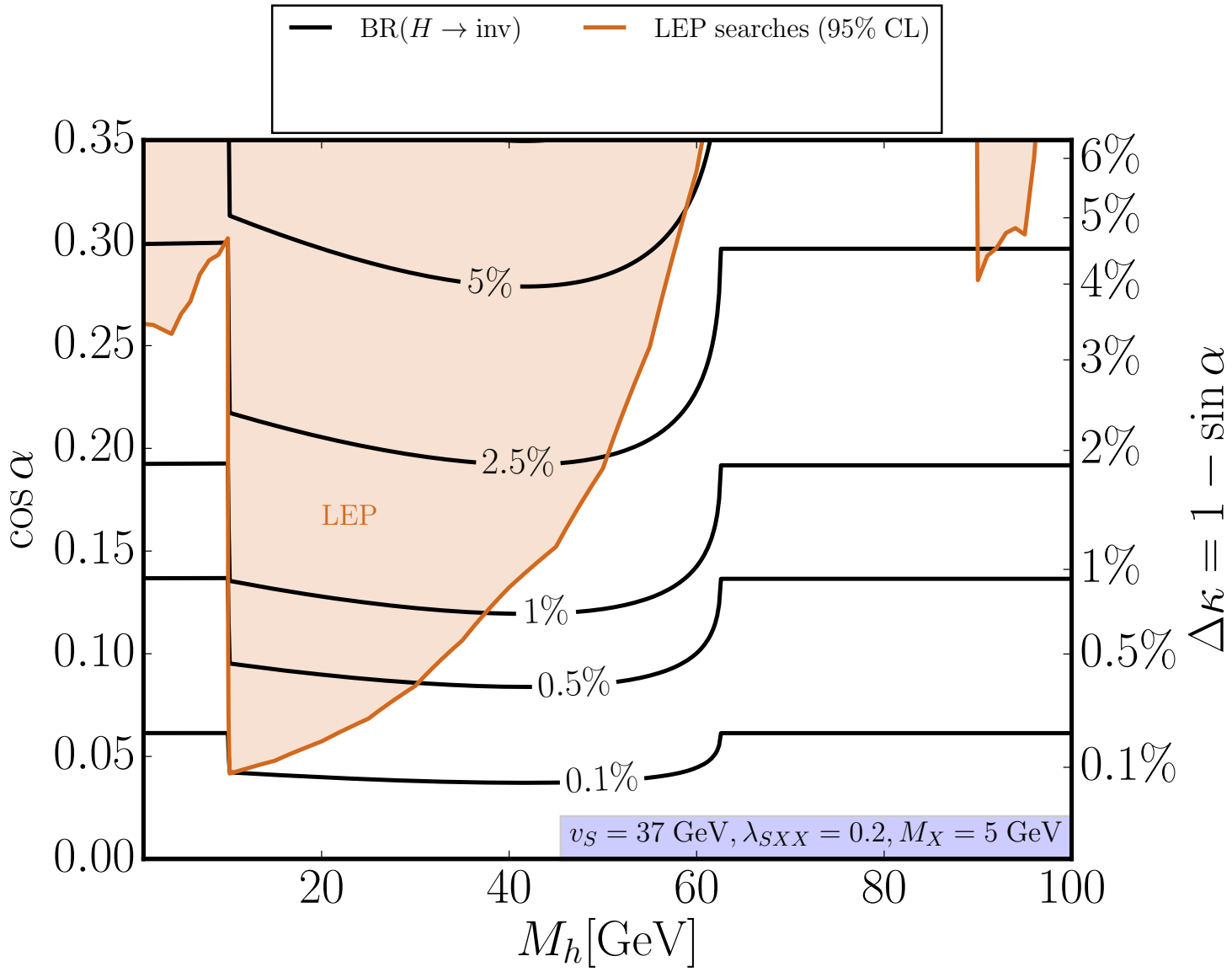

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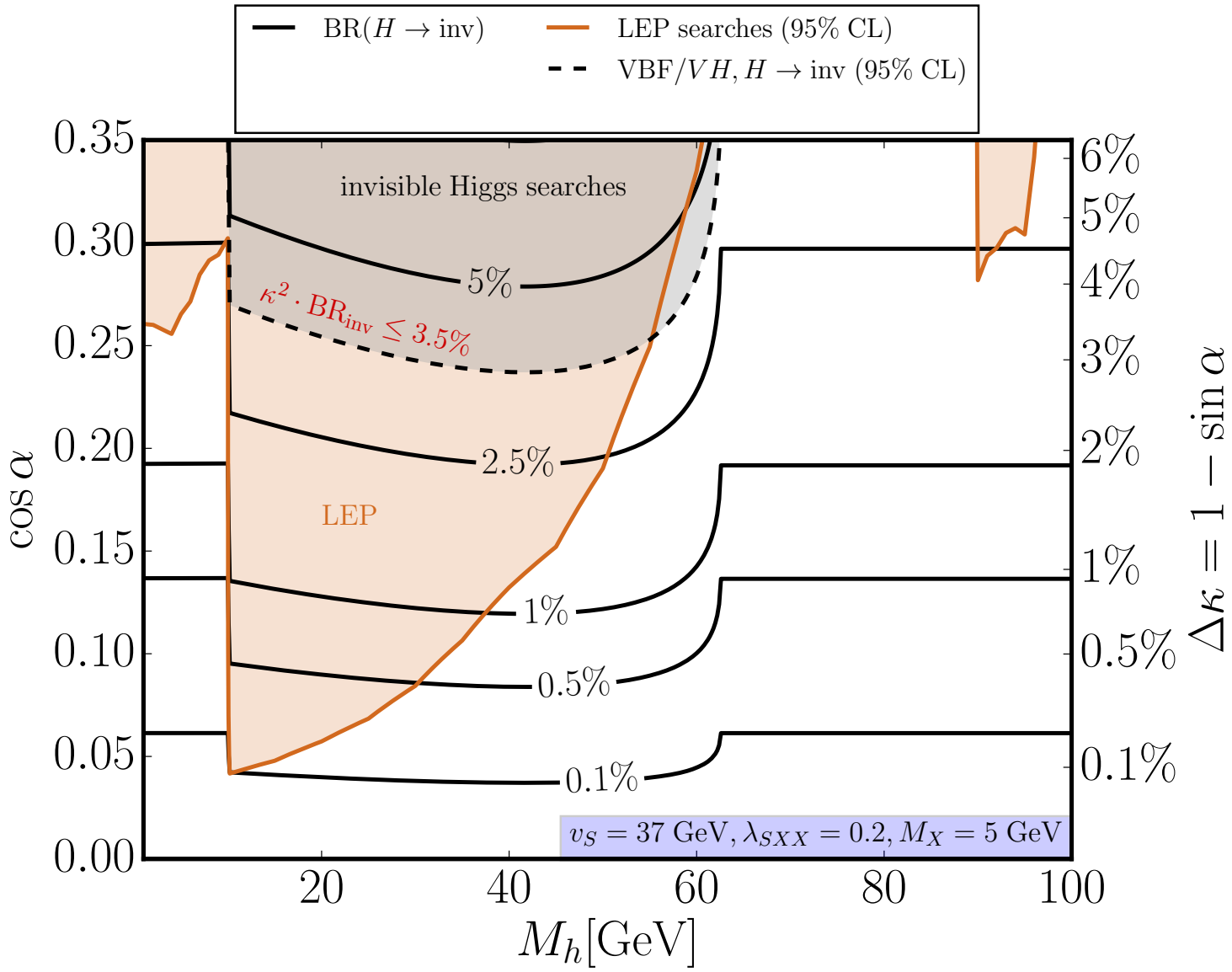

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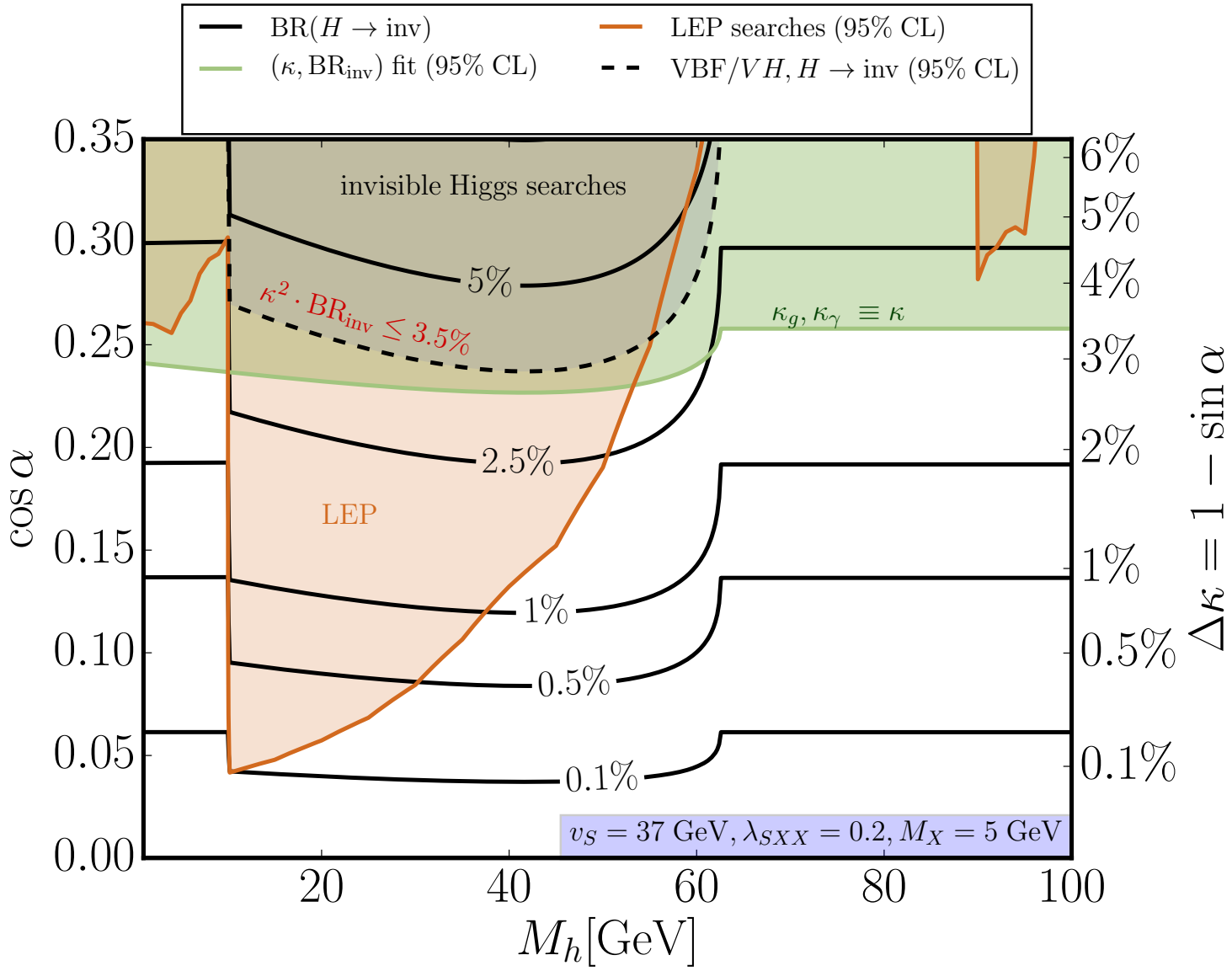

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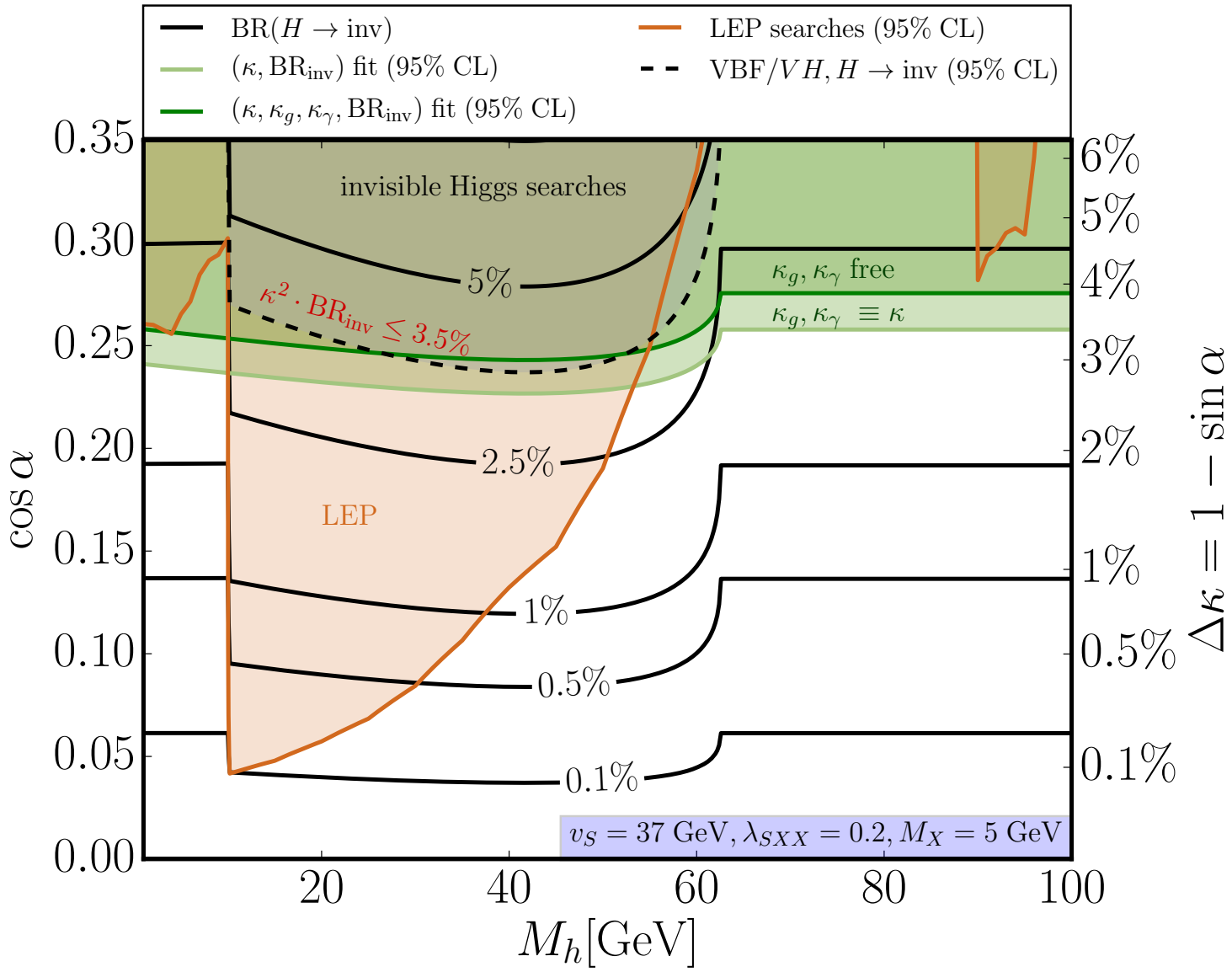

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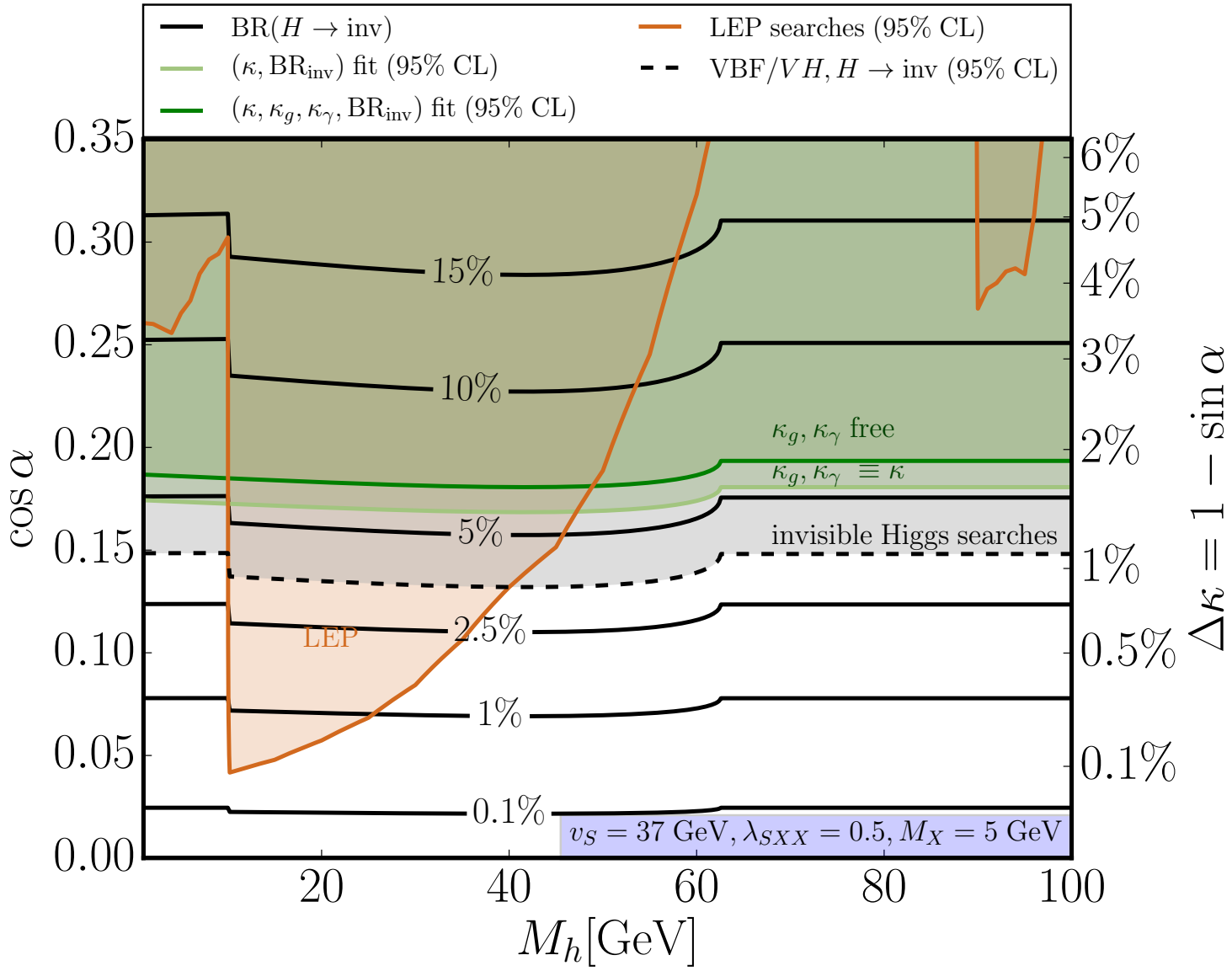

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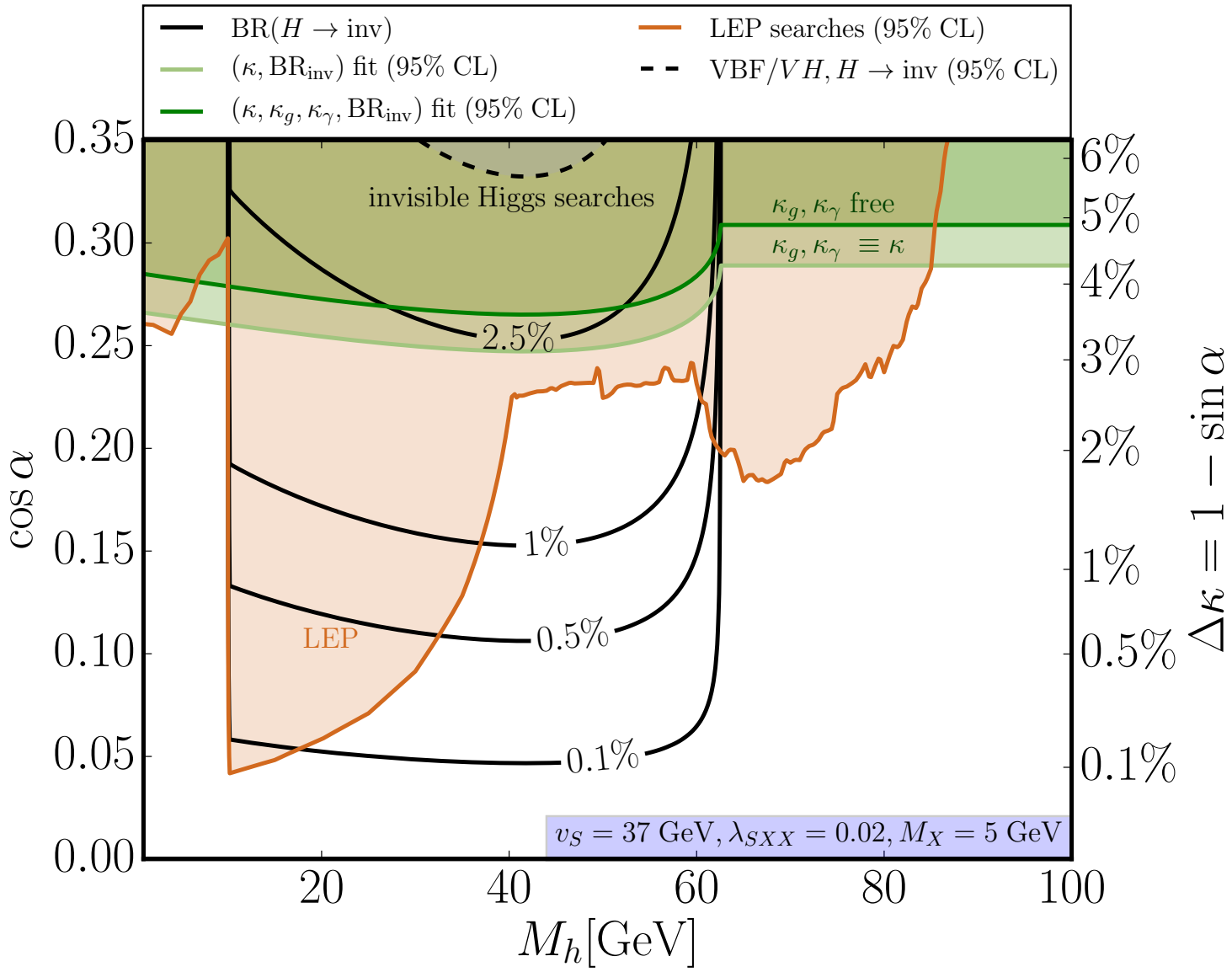

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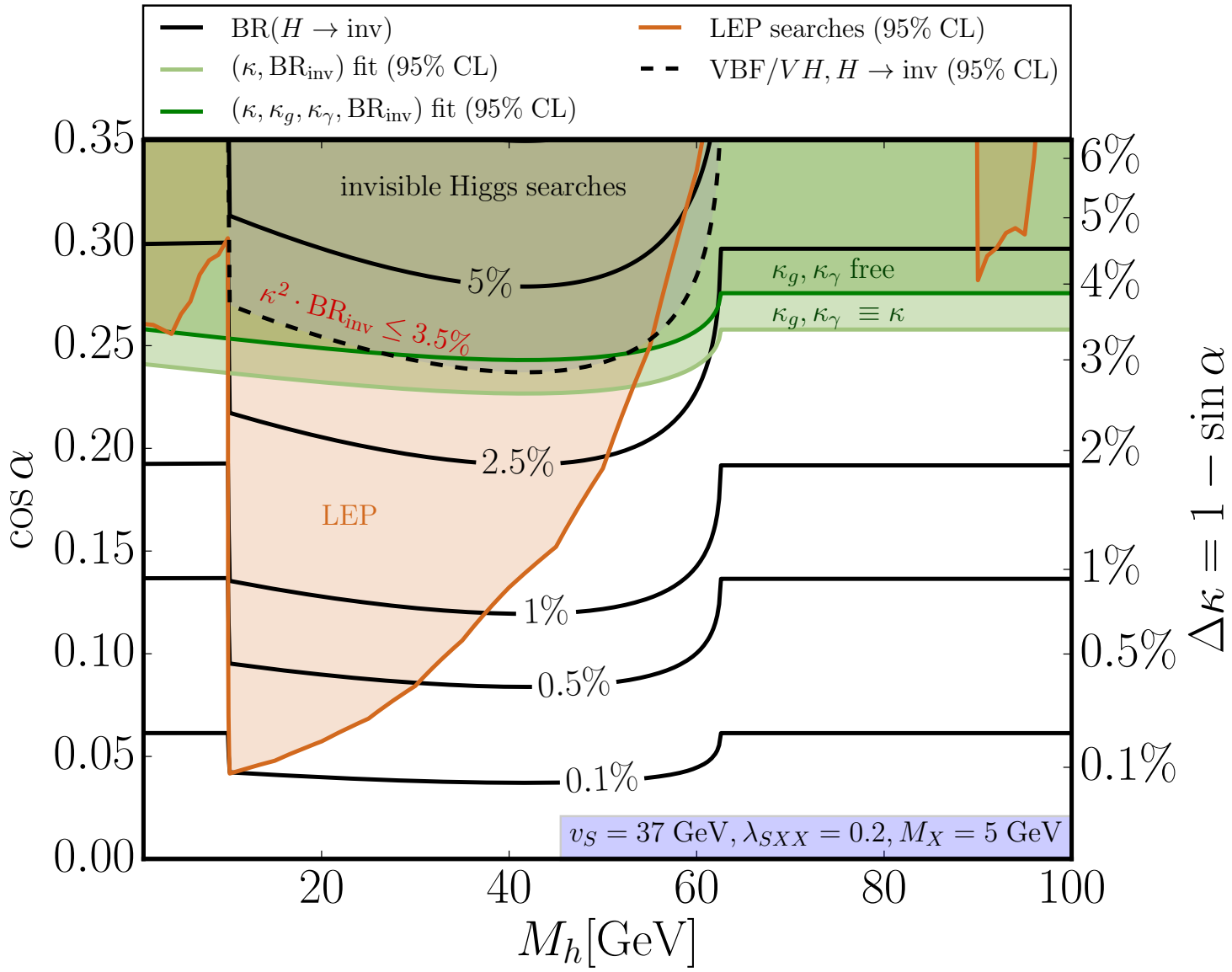

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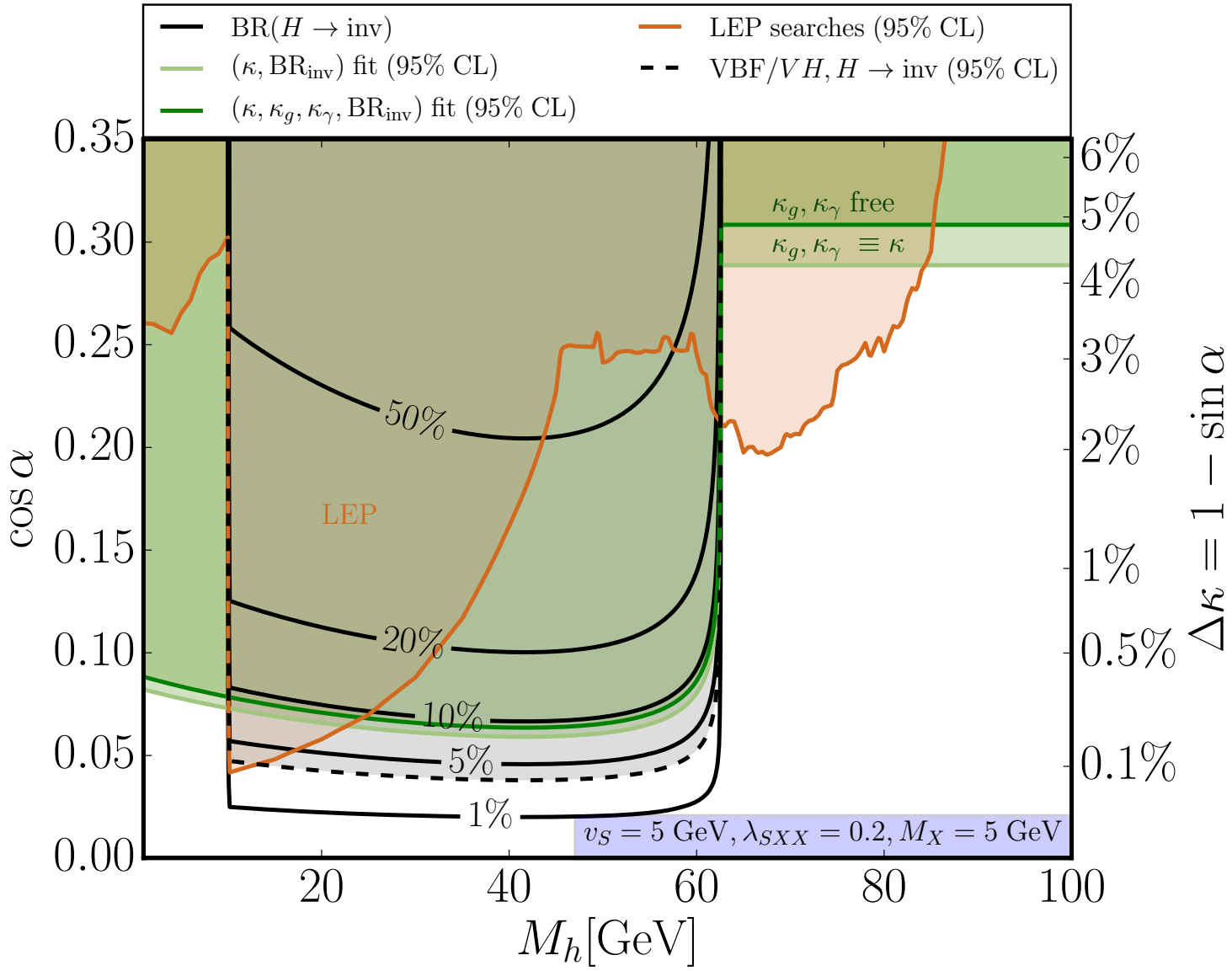

Conclusions & Outlook

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 $M_{\mathrm{DM}} \lesssim 10\ \mathrm{GeV}$ invisible Higgs searches probe parameter space where direct detection is insensitive.

Singlet scalar–DM portal:

With the additional possibility of invisible Higgs cascade decays, $H \to hh \to \mathrm{inv.}$, 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!

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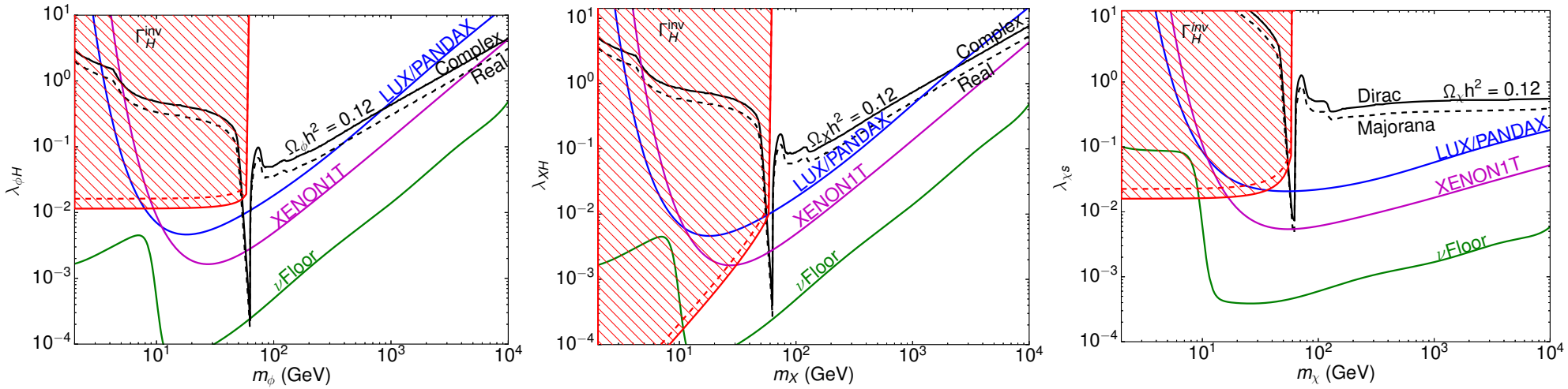
Thank you for your attention!

Backup slides

Minimal Higgs portal: DM relic density constraints

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



[Escudero, Berlin, Hooper, Lin '16]