Dark matter complementarity discussion

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based on work with

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Mini- overview

- $H \to$ invisible in the HL-LHC Yellow Report [CERN Yellow Rep.Monogr. 7 (2019) 1-220]
- Complementarity: e.g. IDM
- Complementarity: mass-hierarchies from DM constraints

Invisible h_{125} decays at the HL-LHC

A.-M. Magnan, B. Nachman, TR, T. Stefaniak

CERN Yellow Rep.Monogr. 7 (2019) 1-220

(HL-LHC Higgs Yellow Report)

Overview

Higgs portal models

- In the context of **dark matter**:
- models where **SM Higgs mediates to dark sector**
- **collider signature:** $h_{125} \to$ **invisible**

$\Rightarrow$ either **direct constraint on BR**, or **modification of SM branching ratios**

[recent review: O. Lebedev, Prog.Part.Nucl.Phys. 120 (2021) 103881]

High luminosity LHC

- LHC with current (or 14 TeV) cm energy, $\mathcal{L}^{\text{int}} = 300\,(3000)\,\text{ab}^{-1}$
- one of possible future LHC directions

$\Rightarrow$ important: **good physics case !!**

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

$$H \to \mathrm{DM}\,\mathrm{DM}$$

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

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

- double effect:

  $\Rightarrow$ suppression of SM rates

  $\Rightarrow$ direct measurement

Experimental input for HL-LHC projections

VBF, VH and invisible decays

$$\mu_{\text{VBF}} \cdot \text{BR}(H \to \text{inv}) \leq 4\% \quad \text{[CMS-PAS-FTR-18-016]}$$
$$\mu_{VH} \cdot \text{BR}(H \to \text{inv}) \leq 8.0\% \quad \text{[ATL-PHYS-PUB-2013-014]}$$

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:

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

Experimental input for HL-LHC projections

Standard Model Higgs couplings

- use **projected combined projections from ATLAS and CMS**
- 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]

Our study for Yellow Report

A) for **simple parametrization of couplings in κ framework** (rescaled couplings):

complementarity of SM decays and invisible BR

B) for **different DM candidates** (scalar, vector, fermion):

comparison with direct detection limits

C) for a **specific model** (singlet with additional scalar dark matter candidate):

complementarity of different constraints

In all cases, $m_{DM} \leq m_h/2$!!

A) General parametrization/ κ framework

[some slides (adapted) from Tim]

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, $\mathrm{BR}(H \to NP)$;

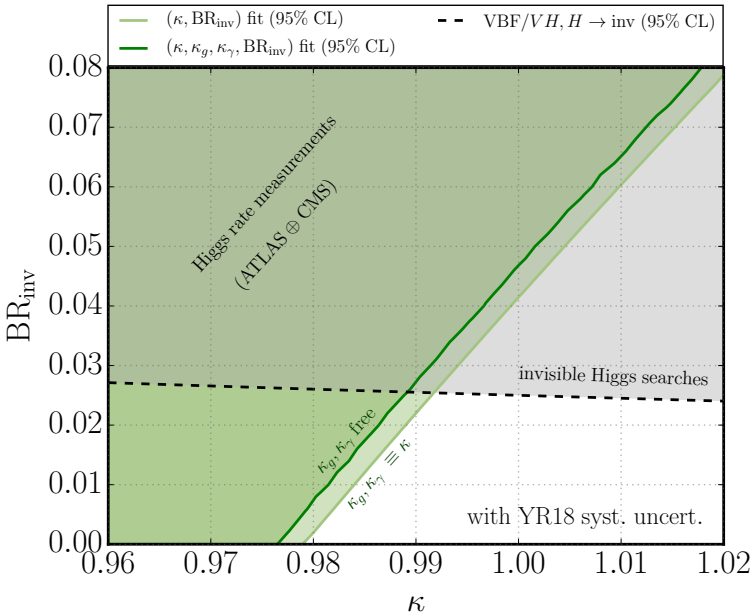
Assume κ_V $(= \kappa) \leq 1$, but no further assumptions on $\mathrm{BR}(H \to NP)$ in fit.

A) SM decays vs invisible branching ratio

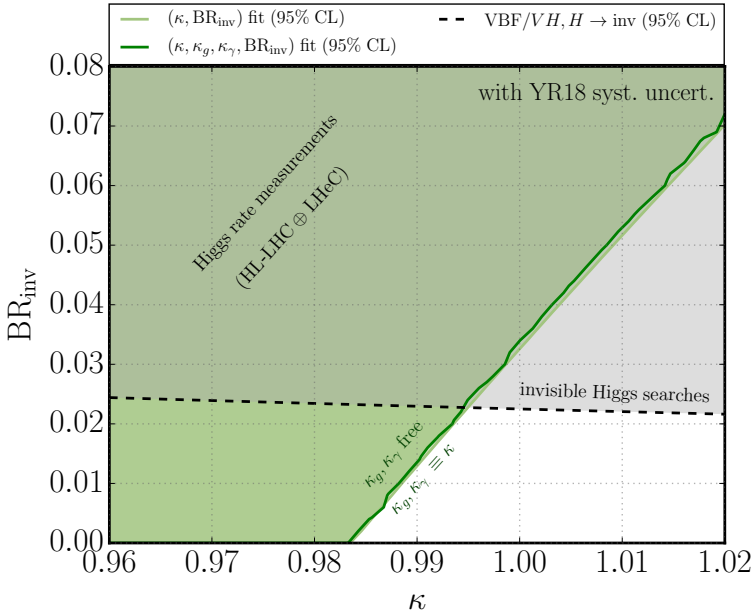
κ fit only:

HL-LHC only, SM couplings: $\mathrm{BR_{inv}} \leq$ **4.2%**

HL-LHC and LHeC, SM couplings: $\mathrm{BR_{inv}} \leq$ **3.3%**



HL-LHC, S2 scenario



...combined with LHeC

B) 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)
$\mathcal{L} \supset -\frac{1}{4}\lambda_{hSS} H^\dagger H S^2$	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 ($\kappa = 1$).

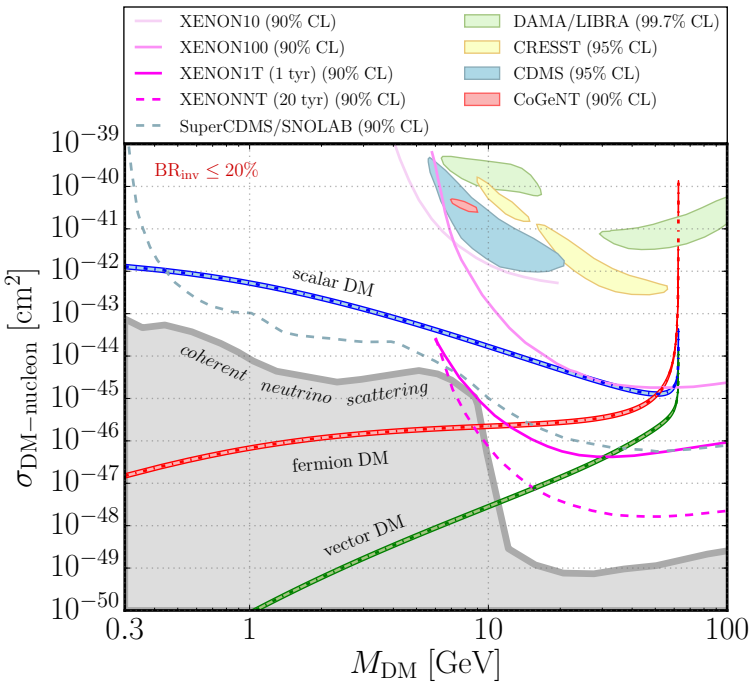
The Higgs portal coupling λ relates

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

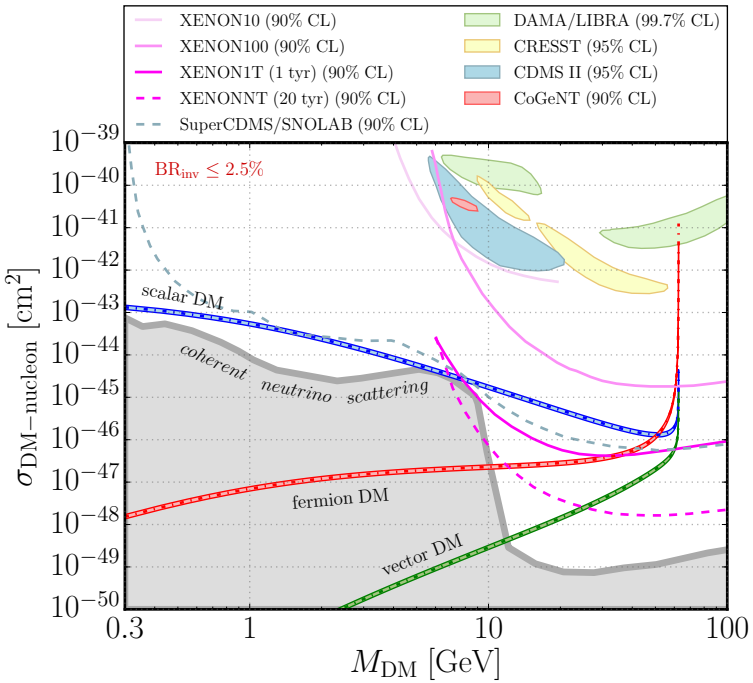
$\Rightarrow$ Complementarity: invisible Higgs searches $\leftrightarrow$ DM direct detection (DD).

B) Collider measurements vs direct detection experiments

idea: measure BR_{inv} at collider, translate to DM nucleon scattering cross section (dependence on same coupling), for different DM candidates



past



future

C) Higgs scalar portal in more detail

Singlet scalar–DM portal: the model

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

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

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

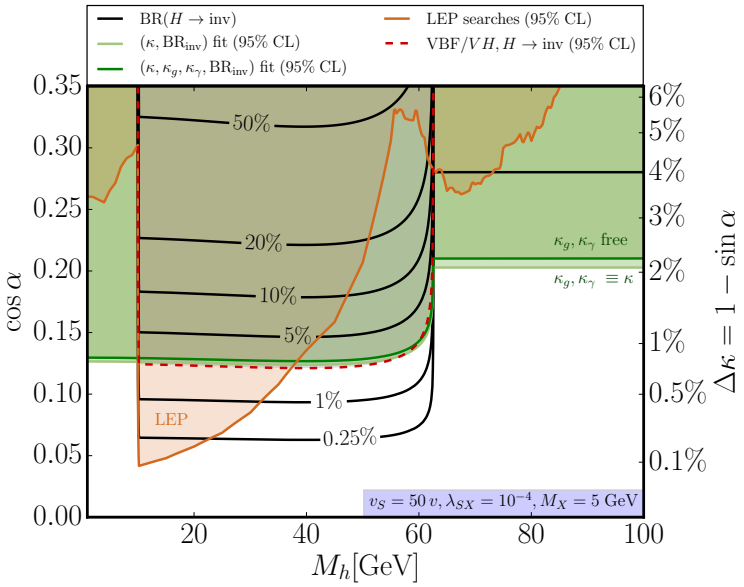
$$\mathcal{L}_{\text{DM}} \supset -\tfrac{1}{4} \lambda_{SXX} S^2 X^2.$$

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

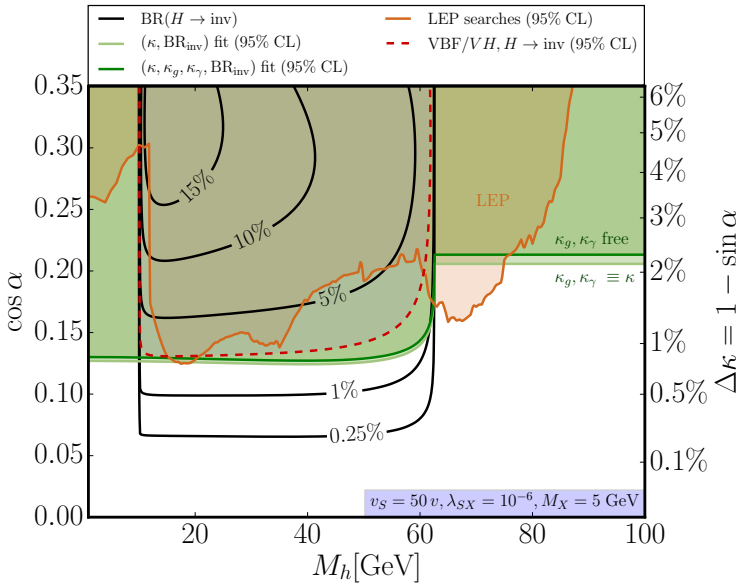
$M_h, \cos\alpha, v_S$ (visible sector), $\quad M_X, \lambda_{SXX}$ (DM sector)

C) Complementarity of different limits for singlet + scalar DM

parameters: $\underbrace{M_h,\ \cos\alpha,\ v_s}_{\text{as in singlet}},\ \underbrace{M_X,\ \lambda_{SXX}}_{\text{new}}$



invisible decays enhanced



invisible decays suppressed

Complementarity in the Inert Doublet Model

Inert doublet model: The model

- idea: take **two Higgs doublet model, add additional Z_2 symmetry**

$$\phi_D \rightarrow -\phi_D, \phi_S \rightarrow \phi_S, \text{SM} \rightarrow \text{SM}$$

(⇒ implies CP conservation)

⇒ obtain a **2HDM with (a) dark matter candidate(s)**

- potential

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right],$$

- only one doublet acquires VeV v, as in SM (⇒ implies analogous EWSB)

Number of free parameters

Model has 7 free parameters

- choose e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_2,\ \lambda_{345}\ [= \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**
- **choosing** M_H as dark matter: $M_H \leq M_A,\ M_{H^\pm}$

Production and decay

- Z_2 symmetry:

only pair-production of dark scalars $H, A, H^{\pm}$

- production modes:

$$\mathbf{p\,p} \to \mathbf{HA},\ \mathbf{HH^{\pm}},\ \mathbf{AH^{\pm}}, \mathbf{H^{+}H^{-}},\ \mathbf{A\,A}\ (+\text{dijet})$$

$$\ell^{+}\,\ell^{-} \to \mathbf{HA},\ \mathbf{H^{+}H^{-}},\ \mathbf{A\,A}\ (+\nu_{\ell}\,\bar{\nu}_{\ell})$$

- decays:

$$\mathbf{A} \to \mathbf{Z\,H}:\ \mathbf{100\%},\ \mathbf{H^{\pm}} \to \mathbf{W^{\pm}H}:\ \text{dominant}$$

signature: **electroweak gauge boson(s) + MET**

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X \in \left[A,\, H^{\pm}\right]\right)$

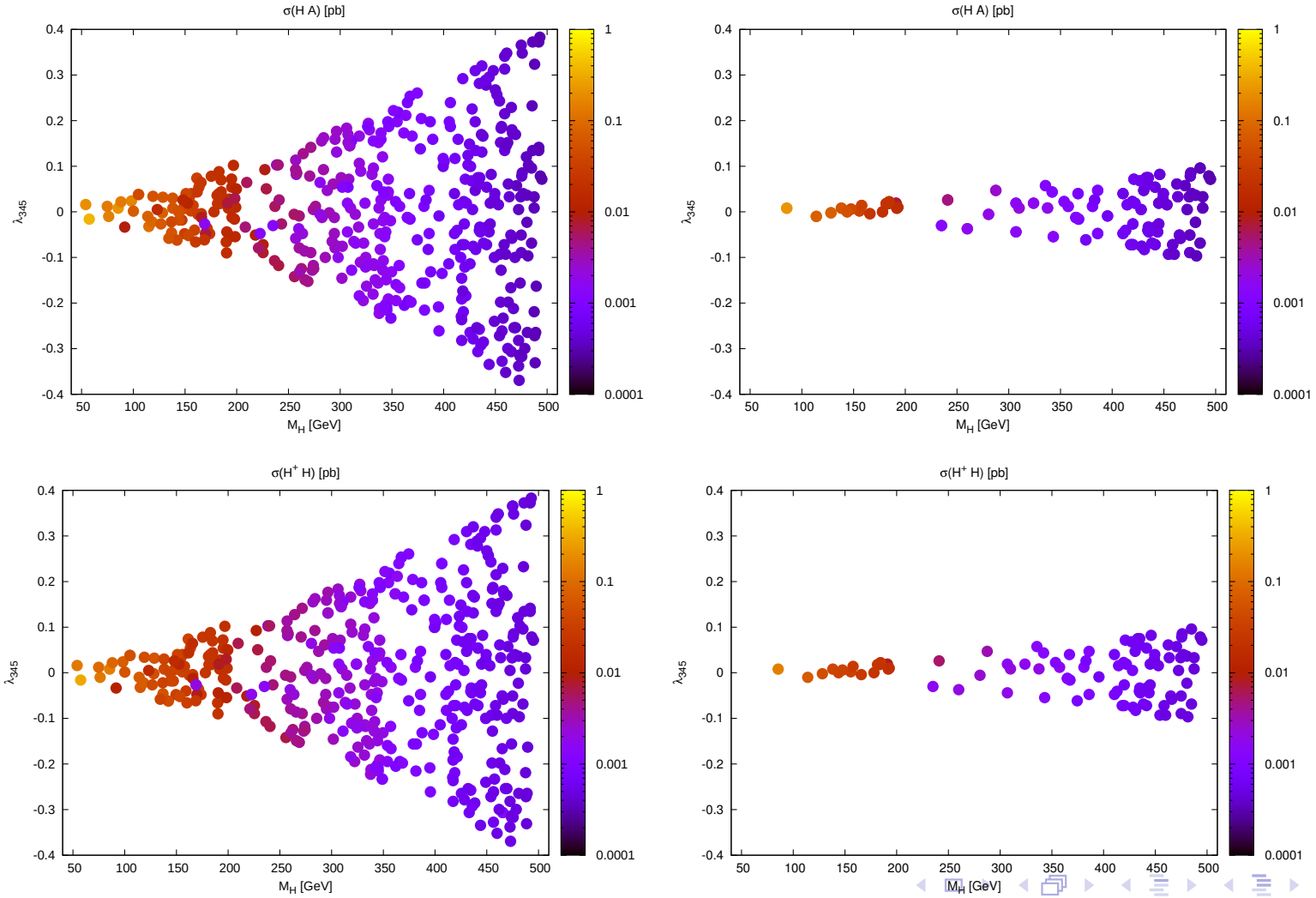
important interplay between astroparticle physics and collider searches

in the end kinematic test

(holds for $M_H \geq \frac{M_h}{2}$)

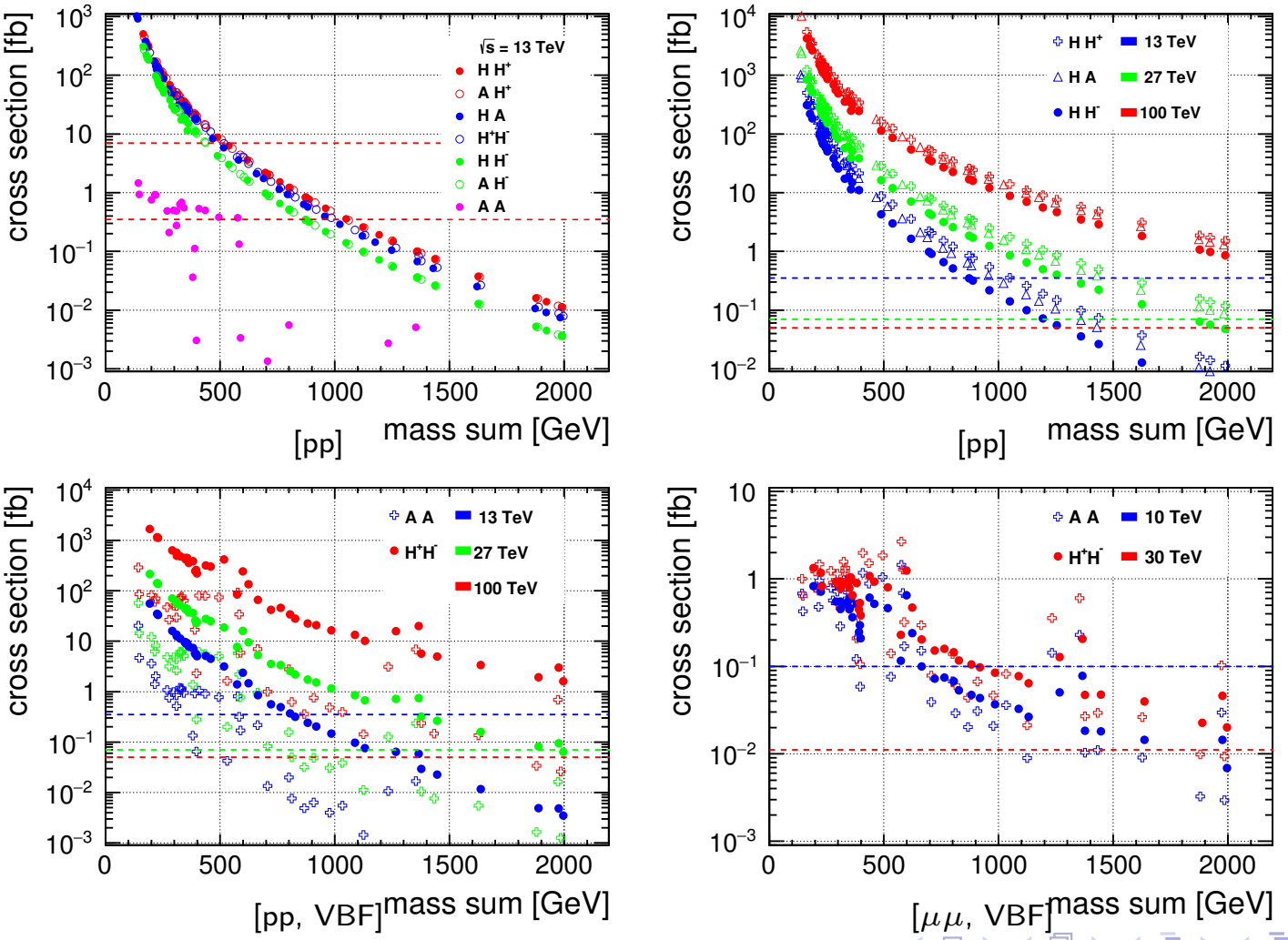
Updated constraints [XENON1T] [Phys.Rev.Lett. 121 (2018) no.11, 111302]

LUX **XENON**



Sensitivity in figures [Symmetry 13 (2021) 6, 991]

lines: 1000 events for design luminosity



Complementarity:
Mass-hierarchies from DM constraints

THDMa [arXiv:2105.06231, arXiv:2106.02962]

setup: 2 Higgs Doublet Model (Type II), + **pseudoscalar** a (mixing with A), + **dark matter candidate** χ (fermionic)

- **DM couples to additional field in gauge-eigenstates**

$\Rightarrow$ promoted by LHC Dark Matter Working group in Phys.Dark Univ. 27 (2020) 100351

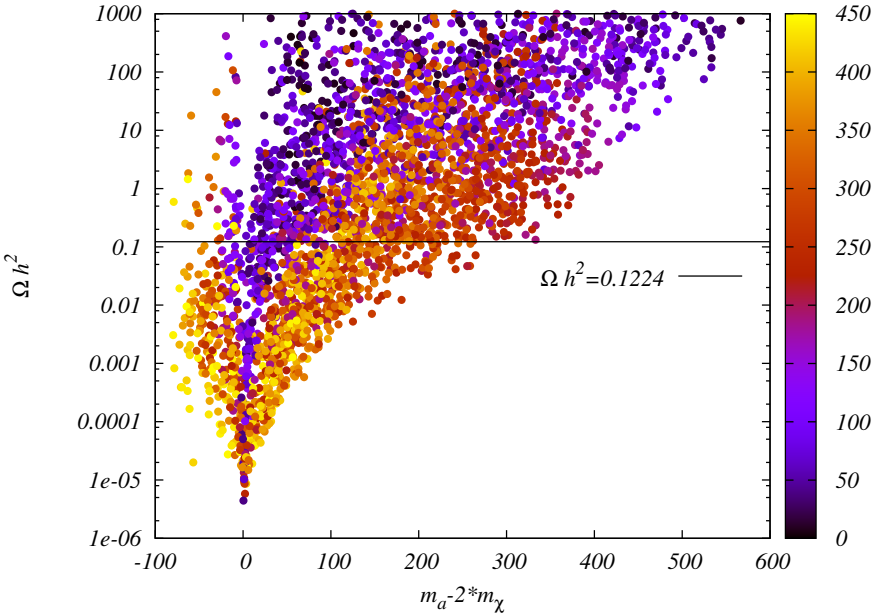
THDMa scalar sector particle content: h, H, $H^{\pm}$, a, A, χ

parameters:

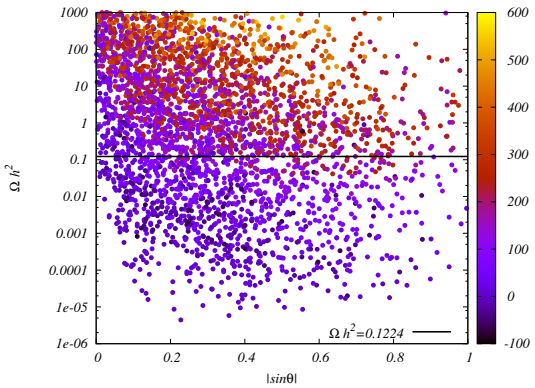
v, m_h, m_H, m_a, m_A, $m_{H^{\pm}}$, m_χ; $\cos(\beta-\alpha)$, $\tan\beta$, $\sin\theta$; y_χ, λ_3, λ_{P_1}, λ_{P_2}

Example: Dark matter constraints

using MadDM



color coding: m_χ



color coding: $m_a - 2\, m_\chi$

dominant channels: $\chi\,\bar{\chi} \to t\,\bar{t},\ b\,\bar{b}$, depending on m_a

main result: $|m_a - 2\, m_\chi| \leq 300\,\mathrm{GeV}$