Higgs portals to Dark Matter

Abdelhak DJOUADI

(University of Granada)

Dark Matter and the Higgs portal
Invisible Higgs at the LHC
Comparison with astroparticle physics
Two problems with EFT Higgs portal
Conclusion

Mostly with Giorgio Arcadi and Martti Raidal, arXiv:1903.03616 (Phys. Rept. 842 (2020) 1-180);
and with Giorgio Arcadi and Marumi Kado, arXiv:2001.10750 and arXiv:2101.02507.

The Higgs portal to DM

A very simple DM description, using only Agnosticism and Occam razor:
postulate the existence of a weakly interacting massive particle:
- a singlet particle but of any spin i.e. a scalar, vector or fermion;
- Z_2 parity for stability: no couplings or mixing with fermions.
- QED neutral + isosinglet, no SU(2)xU(1) charge: no Z couplings;

Hence, only couplings with the Higgs bosons $\Rightarrow$ Higgs portal DM:
- annihilates into SM particles through s-channel Higgs exchange;
- interacts with fermionic matter only through Higgs exchange;
- can be produced in pairs via Higgs boson exchange or decays.

Again Occam razor: assume only the SM-like Higgs boson.

Then use an effective Lagrangian, but the simplest (renormalisable?) one:

$$\Delta\mathcal{L}_s = -\frac{1}{2}M_s^2 s^2 - \frac{1}{4}\lambda_s s^4 - \frac{1}{4}\lambda_{Hss}\Phi^\dagger\Phi s^2$$

$$\Delta\mathcal{L}_v = \frac{1}{2}M_v^2 v_\mu v^\mu + \frac{1}{4}\lambda_v (v_\mu v^\mu)^2 + \frac{1}{4}\lambda_{Hvv}\Phi^\dagger\Phi v_\mu v^\mu$$

$$\Delta\mathcal{L}_\chi = -\frac{1}{2}M_\chi \bar{\chi}\chi - \frac{1}{4}\frac{\lambda_{H\chi\chi}}{\Lambda}\Phi^\dagger\Phi\bar{\chi}\chi$$

Mc Donald
Kanemura, ...
Lebedev,AD, ..

EWSB: $\Phi \to \frac{1}{\sqrt{2}}(v+H)$ with v=246 GeV and $m_x^2 = M_x^2 + \frac{1}{4}\lambda_{Hxx}v^2$ ...
Only two free parameters: DM mass m_x and DM-Higgs coupling λ_{Hxx}

Invisible Higgs at the LHC

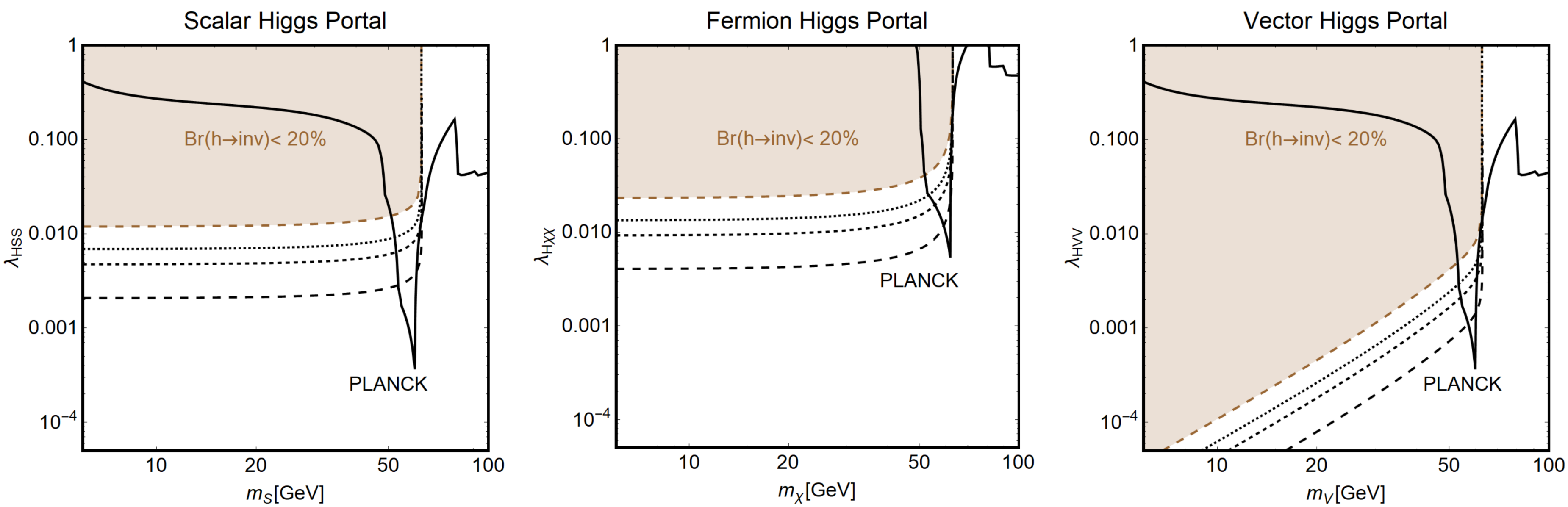
For light DM states, only possible handle at colliders is Higgs decays:

$$\Gamma_{\rm inv}(H \to ss) = \frac{\lambda_{Hss}^2 v^2 \beta_s}{64\pi M_H}$$

$$\Gamma_{\rm inv}(H \to vv) = \frac{\lambda_{Hvv}^2 v^2 M_H^3 \beta_v}{256\pi M_v^4}\left(1 - 4\frac{M_v^2}{M_H^2} + 12\frac{M_v^4}{M_H^4}\right)$$

$$\Gamma_{\rm inv}(H \to ff) = \frac{\lambda_{Hff}^2 v^2 M_H \beta_f^3}{32\pi \Lambda^2}$$

Possible only for $m_X < \frac{1}{2}M_H \approx 62$ GeV; depends on m_X, λ_{HXX}:

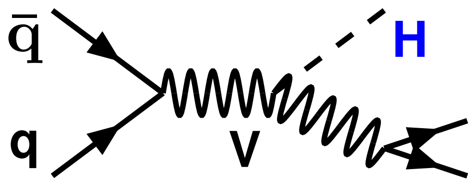


One has to check also the relic density/Planck: only one input?

maybe no, X does not form all DM and/or Ωh^2 obtained via other means...

Invisible Higgs at the LHC

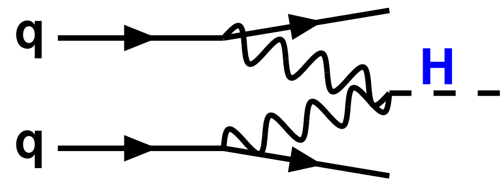
- Direct: measurement of total Higgs decay width via interference.
- Indirect: measurements of the Higgs decay branching ratios.
- Even more direct: search for Higgs decaying invisibly and $E\!\!\!/_T$



$q\bar{q} \to WH \to \ell\nu + E\!\!\!/_T$

$q\bar{q} \to ZH \to \ell\ell + E\!\!\!/_T$

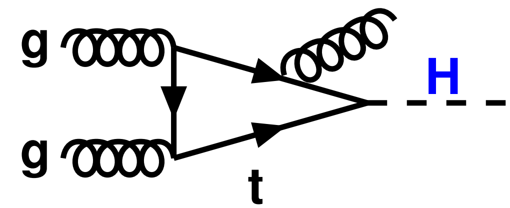
Choudhury+Roy, ...,



$qq \to qqH \to jj + E\!\!\!/_T$

high-mass, p_T, η jets

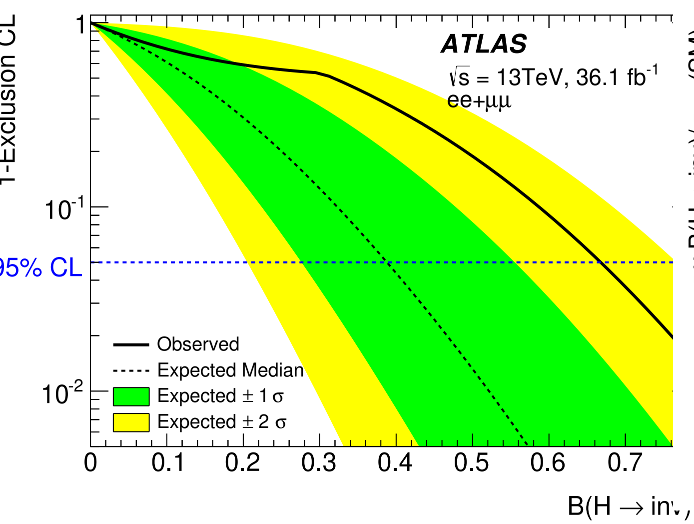
Eboli+Zeppenfeld

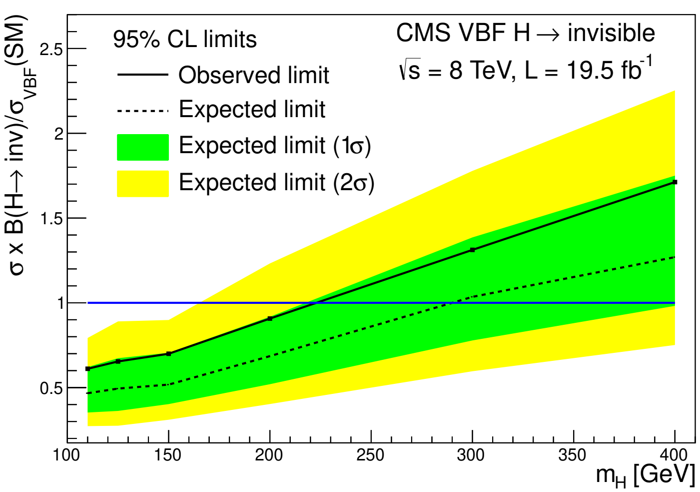


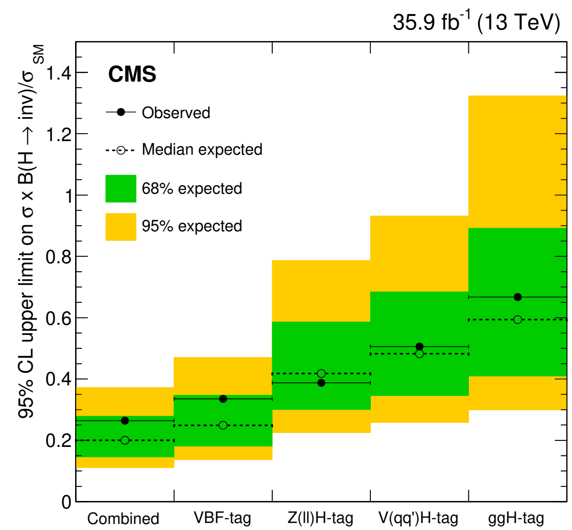
$gg \to Hg \to j + E\!\!\!/_T$

also 2j, high rate.

AD,Falkowski,Mambrini...

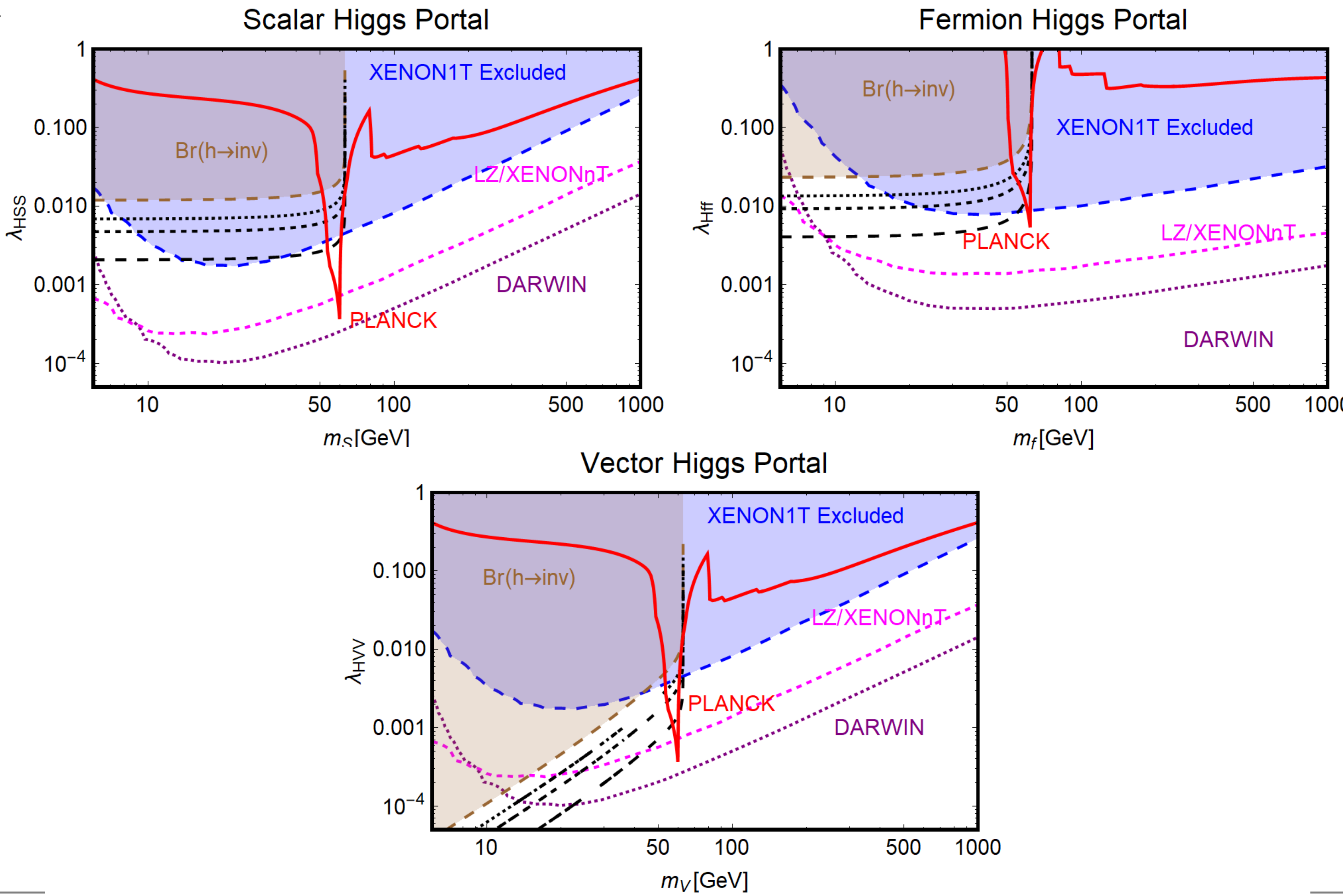






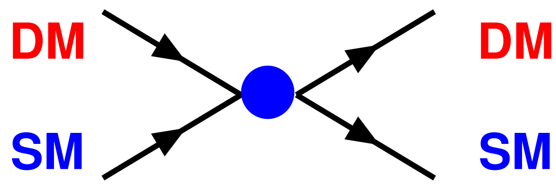
ATLAS+CMS measurements give BR(H→invisible) $\lesssim 10-20\%$@95%CL

Comparison with astroparticle experiments



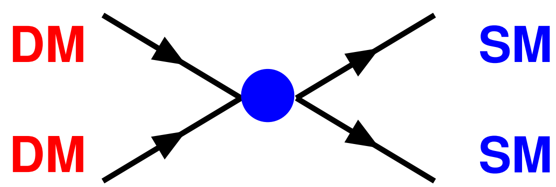
Comparison with astroparticle experiments

Direct Detection:



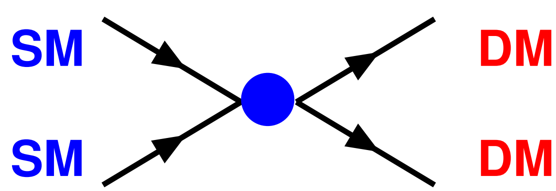
scattering on nucl. target:
XENON $\Rightarrow$ LZ,DARWIN

Indirect Detection:

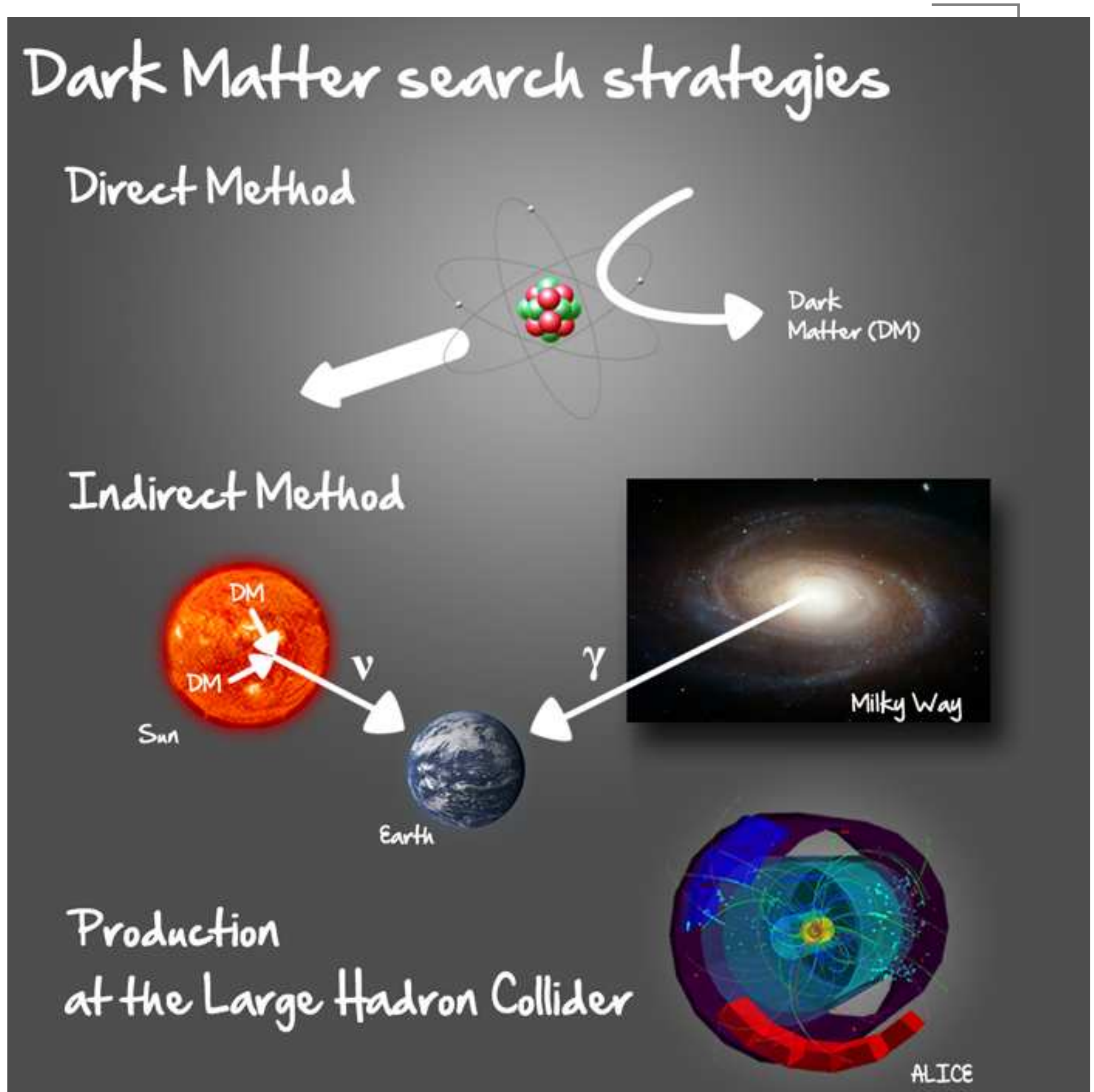


annihilation products: γ, ν
HESS,Fermi $\Rightarrow$ CTA, ...

Detection at colliders:



missing energy signature
LHC $\Rightarrow$ HL-LHC,e^+e^-,pp



Comparison with astroparticle experiments

- **Relic density** $\propto 1/\langle\sigma(\mathrm{xx}\to \mathrm{H}\to \mathrm{f\bar{f}})\mathrm{v_r}\rangle$ **annihilation rate.**

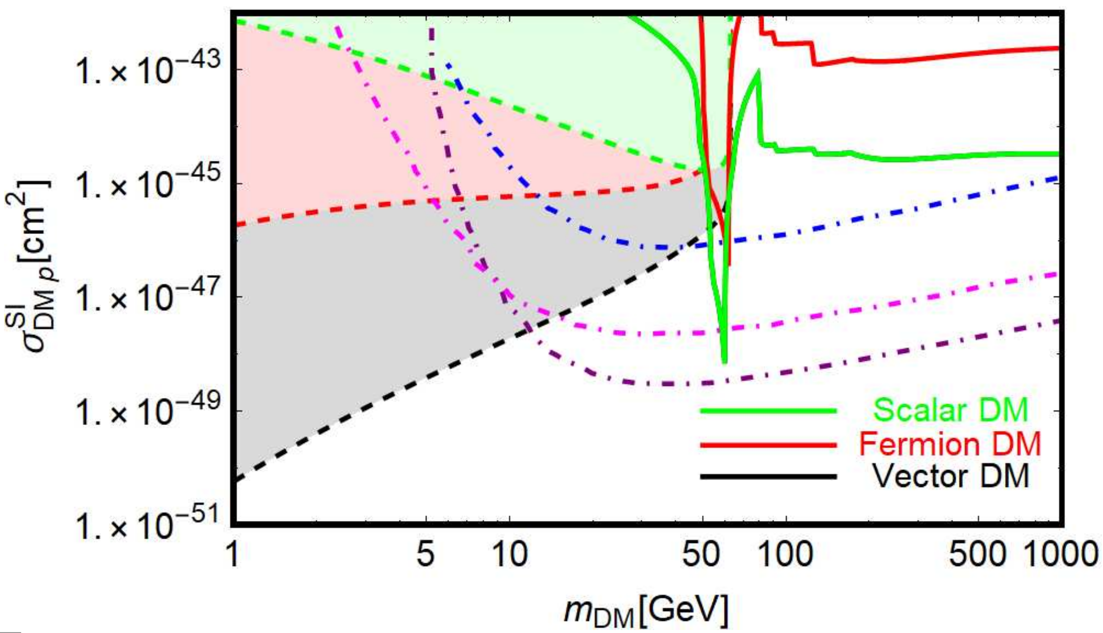
$$\langle\sigma^{\mathrm{x}}_{\mathrm{ferm}}\mathrm{v_r}\rangle = \frac{\lambda^2_{\mathrm{Hxx}}\mathrm{m}^2_{\mathrm{ferm}}}{16\pi}\frac{1}{(4\mathrm{m}_\mathrm{x}^2-\mathrm{M}_\mathrm{H}^2)^2}\delta_\mathrm{x}, \quad \delta_\mathrm{s}=1, \delta_\mathrm{v}=\frac{1}{3}, \delta_\mathrm{f}=\frac{1}{2}\frac{\mathrm{v}_\mathrm{r}^2}{\Lambda^2}$$

In principle needs to comply with the Planck value: $\Omega_{\mathrm{DM}}\mathrm{h}^2 \approx 0.1 \pm 0.001$

- **Spin–independent direct detection, simple for s, v, f DM states:**

$$\sigma^{\mathrm{SI}}_{\mathrm{x-N}} = \frac{\lambda^2_{\mathrm{Hxx}}}{16\pi \mathrm{M}_\mathrm{H}^4}\frac{\mathrm{m}_\mathrm{N}^4 \mathrm{f}_\mathrm{N}^2}{(\mathrm{m_x}+\mathrm{m_N})^2}\delta'_\mathrm{x}, \delta_\mathrm{s}=\delta_\mathrm{v}=1, \delta_\mathrm{f}=\frac{4}{\Lambda^2}$$

$$\mathrm{BR}^{\mathrm{inv}}_\mathrm{x} \equiv \mathrm{BR}(\mathrm{H}\to \mathrm{inv}) = \frac{\Gamma(\mathrm{H}\to\mathrm{xx})}{\Gamma^{\mathrm{SM}}_\mathrm{H}+\Gamma(\mathrm{H}\to\mathrm{xx})} = \frac{\sigma^{\mathrm{SI}}_{\mathrm{xp}}}{\Gamma^{\mathrm{tot}}_\mathrm{H}/\mathrm{r_x}+\sigma^{\mathrm{SI}}_{\mathrm{xp}}}$$



ATLAS
CMS
Theorists
(Arcadi,AD,Raidal)

Problem 1: connexion with UV models

The EFT Higgs portal DM approach suffers from some drawbacks:

- except for the scalar DM case, not complete models in the UV regime;
- UV completeness in realistic models calls additional degrees of freedom.

$\Rightarrow$ Complementarity between astroparticle and collider constraints is lost (in model independent way $\rightarrow$ needs to rely on details of the UV model).

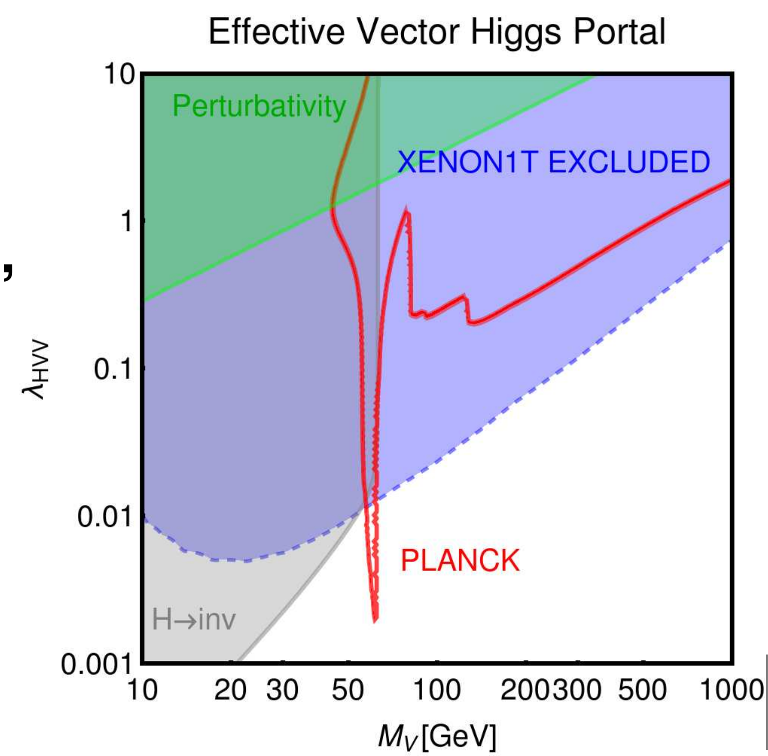
The problem is particularly severe in the case of the vectorial DM states:

– renormalisability: VDM should be related to spontaneously broken U(1) symmetry; leads to new light degrees of freedom...

– because of perturbative unitarity bounds, EFT description becomes questionable at DM masses below a few tens of GeV.

correlation between collider and direct detection searches become less trivial,

$\Rightarrow$ the spin-1 vector DM case removed from invisible Higgs ATLAS/CMS analyses.



Problem 1: connexion with UV models

However, can show that in some limits this correlation can be recovered.

Simplest and most economical example of a renormalisable VDM model:
V DM is a dark photon with couplings to additional singlet scalar field S:
Scalar potential accounting for mixing between the S and SM H fields:

$$\mathrm{V(H,S)} = \frac{\lambda_\mathrm{H}}{4}\mathrm{H}^4 + \frac{\lambda_\mathrm{HS}}{4}\mathrm{H}^2\mathrm{S}^2 + \frac{\lambda_\mathrm{S}}{4}\mathrm{S}^4 + \frac{1}{2}\mu_\mathrm{H}^2\mathrm{H}^2 + \frac{1}{2}\mu_\mathrm{S}^2\mathrm{S}^2.$$

Fields S,V identified with the Higgs and gauge boson of a broken U(1):

$$\mathcal{L} = -\frac{1}{4}\mathrm{v}_{\mu\nu}\mathrm{v}^{\mu\nu} + \mathrm{D}^\mu\mathrm{s}^\dagger\mathrm{D}_\mu\mathrm{s} - \mathrm{V}\ ;\ \mathrm{D}_\mu = \partial_\mu + i\tilde{\mathrm{g}}\mathrm{v}_\mu,\ \mathrm{s} = \omega + \rho \to \mathrm{M_V} = \frac{1}{2}\tilde{\mathrm{g}}\omega$$

After EWSB: $\mathcal{L} = \frac{1}{2}\tilde{g}M_V(H_2c_\theta - H_1s_\theta)V_\mu V^\mu + \cdots + \mathcal{L}_\mathrm{S}^\mathrm{SM} + \mathcal{L}_\mathrm{S}^\mathrm{tril}$

EFT vector DM Higgs-portal obtained for $\sin\theta \ll 1$ and $\mathrm{M_{H_2}} \gg \mathrm{M_{H_1}}$ and:
– the gauge coupling $\tilde{g}$ should remain perturbative, $\tilde{g}^2/(4\pi) \leq 1$;
– the rates for processes like $H_iH_i \to H_jH_j$ unitary $\Rightarrow \lambda_i \leq \mathcal{O}(4\pi/3)$.

Perturbative unitarity thus constrains the hierarchy between $\mathrm{M_V}$ and $\mathrm{M_{H_2}}$.
Not possible having arbitrarily light V and decouple $\mathrm{H_2}$ from phenomenology.
This is the main concern raised by the ATLAS+CMS collaborations.

Problem 1: connectio with UV models

In the case $\mathbf{M_{H_2} > M_{H_1}}$ with $\mathbf{H_1 \equiv H}$, EFT can indeed describe U(1)!

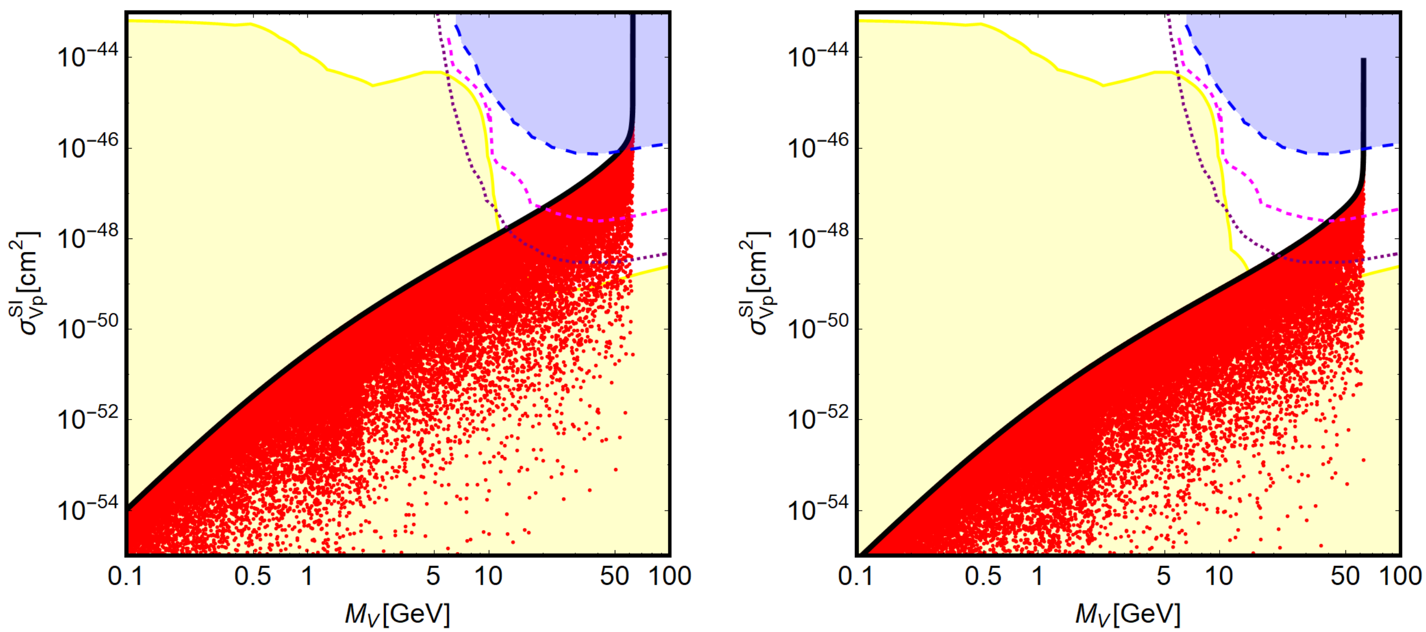
$$\Gamma_{\rm inv}|_{\rm EFT} = \frac{\lambda_{HVV}^2 v^2 M_H^3}{128\pi M_V^4}\beta_{VH}\,, \quad \Gamma_{\rm inv}|_{\rm U(1)} = \frac{\tilde{g}^2 \sin^2\theta}{32\pi}\frac{M_{H_1}^3}{M_V^2}\beta_{VH_1} \,.$$

$$\sigma_{Vp}^{\rm SI}|_{\rm EFT} = 8\mu_{Vp}^2 \frac{M_V^2}{M_H^3}\frac{{\rm BR}(H\to VV)\Gamma_H^{\rm tot}}{\beta_{VH}}\frac{1}{M_H^4}\frac{m_p^2}{v^2}|f_p|^2\,, \; \sigma_{Vp}^{\rm SI}|_{\rm U(1)} = \cdots$$

Predictions of V EFT I and dark U(1) coincide for $\mathbf{c_\theta^2 M_H^4 (\frac{1}{M_{H_2}^2} - \frac{1}{M_{H_1}^2})^2 \approx 1}$.

Ratio $\mathbf{r} = \sigma_{\mathbf{Vp}}^{\rm SI}|_{\mathbf{U(1)}}/\sigma_{\mathbf{Vp}}^{\mathbf{SI}}|_{\mathbf{EFT}}$ in $[\mathbf{M_V}, \sigma_{\mathbf{Vp}}^{\mathbf{SI}}]$ in large parameter space scan:

with $\tilde{g}$ fixed such as BR($\mathrm{H}_1 \to$ inv)=25% (left) and 2.5% (right) are obtained.

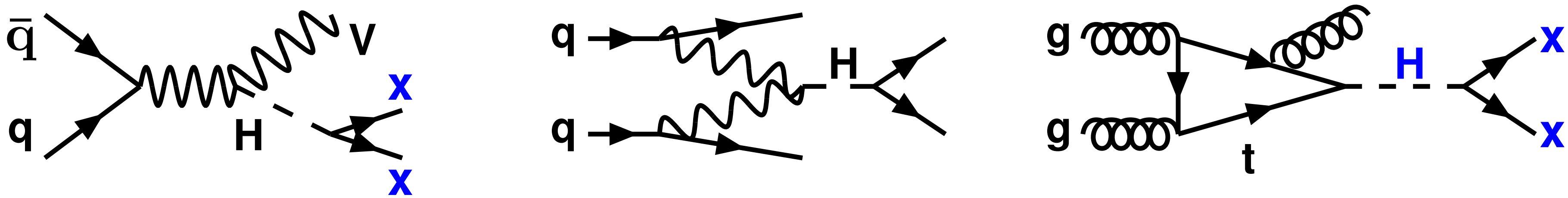


Arcadi
Kado
AD

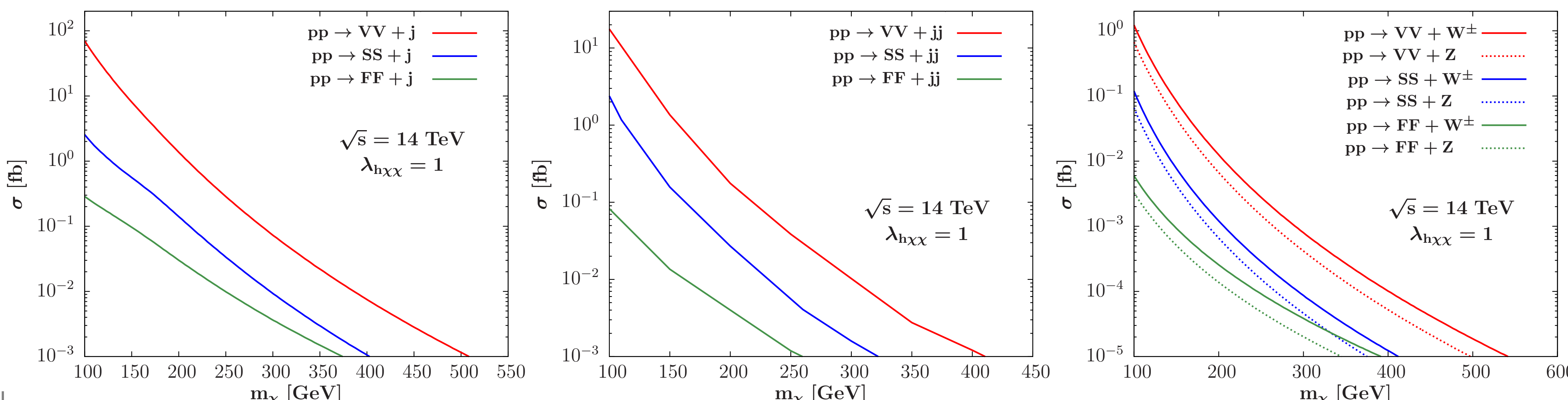
Problem 2: Heavy DM states

Invisible Higgs decays work only for light DM; what if $m_{DM} \gtrsim \frac{1}{2}M_H$?

Only way: produce them in pairs in continuum. At proton colliders:



- **Exactly same channels as before but with an off-shell Higgs boson.**
- **Suppressed by the Higgs virtuality and the small couplings to DM.**
- **Needs high energies, very high luminosities and some real efforts...**



Quevillon, AD

Conclusions

- Dark matter exists, maybe only reachable sign of new physics?
- The Higgs portal to DM is one of the most minimal realizations.
- Even more minimal if only the SM-like Higgs state is considered.
- Scenario being tested at LHC in Higgs searches/measurements:

– measurements of total Higgs width and various visible BRs;
– direct searches for missing energy signature in VH, VBF, ggF;
– possibility of going off-shell for $m_{DM} \gg \frac{1}{2} M_H$ not that promising.

- Limits from LHC challenged by future astrophysics sensitivity

but only with some assumptions on the DM relic density, profile, etc...

- But I didn't tell you the really interesting part of the story:

– concrete realizations of Higgs-DM and search for DM companions;
– extending the Higgs sector makes it even more interesting...

$\Rightarrow$ arXiv:1903.03616.

Needs further investigations at LHC and also future e^+e^- and pp colliders besides all experiments in astroparticle physics.