An example of research collaboration between African Institutes

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About this work

Letters in High Energy Physics LHEP-270, 2022

Higgs Portal Vector Dark Matter Interpretation: Review of Effective Field Theory Approach and Ultraviolet Complete Models

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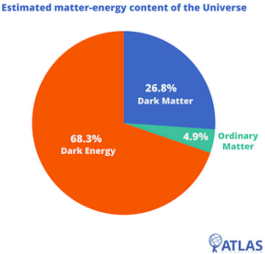
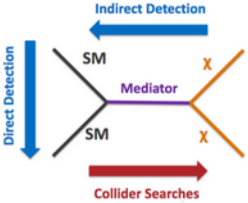
- A collaboration between two intra-African Universities: Mohammed V University (Morocco), University of Johannesburg (South Africa);
- We would like to see more intra-African collaborations on topics of interest;
- and also connection to external collaborators. In this particular case, the external institute is BNL;
- This work is accepted for publication in Letters in High Energy Physics. (link)
- The purpose of this LOI is to encourage research engagements between African institutes/groups on joint projects, with external institutes/groups, with the objective to **enhance African capacity development in education and research**.

Motivation

- Strong evidence that dark matter (DM) exists.
- LHC searches complement evidence from direct and indirect detection.
  - Can actually produce DM mediators.
- Invisible decays of the Higgs boson, are good way of searching for new physics.



- Higgs boson could be a mediator between SM particles and particles that belong to the DM sector.
  - Several extensions of the Standard model have been recently revisited with DM=singlet scalar S, vector V, fermion χ



Overview

Goal: Higgs portal Vector DM (VDM) interpretation on spin-independent DM-nucleon elastic scattering cross section (σ_{WIMP-N}) using Higgs invisible decay width (Γ_{inv}).

- EFT approach for VDM used in run–1
- Objection on EFT approach Phys.Lett.B.2014

$\rightarrow$ The VDM line has been removed in all ATLAS and CMS publication since then.

- Support of EFT approach Phys.Lett.B 805
- UV radiative Higgs portal model JHEP 04 also considered in this work.

Our proposal for the vector DM line/band in the interpretation plot of invisible Higgs searches:

Journal reference: LHEP-270, 2022

Effective Field Theory approach

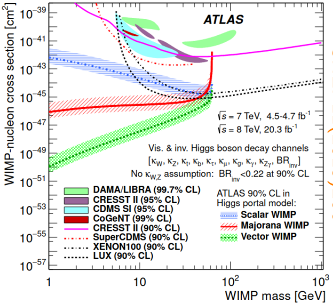
$$\mathcal{L}_V = \frac{1}{2} m_{\mathrm{V}}^2 V_\mu V^\mu + \frac{1}{4} \lambda_V (V_\mu V^\mu)^2 + \frac{\lambda_{\mathrm{hVV}}}{4} H^\dagger H V_\mu V^\mu .$$

- Paper: Phys.Lett.B 709 (2012)
- Only 2 parameters:
  - HVV coupling λ_{HVV}
  - Vector mass m_V
- Derive Higgs invisible decay width Γ_{inv} and spin-independent XS - $\sigma_{\mathrm{WIMP\text{-}N}}$

$$\Gamma^{inv}(H \to VV) = \lambda_{HVV}^2 \frac{v^2 \beta_{VH} m_H^3}{512 \pi m_V^4}$$

$$\sigma^{\mathrm{SI}}(\mathrm{V\text{-}N})_{EFT} = \lambda_{HVV}^2 \frac{m_N^2 f_N^2}{16 \pi m_H^4 (m_V + m_N)^2}$$

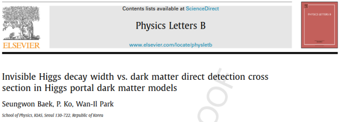
$$\sigma^{\mathrm{SI}}(\mathrm{V\text{-}N})_{EFT} = 32 \mu_{VN}^2 \Gamma_{\mathrm{inv}}^{\mathrm{H}} \frac{m_{\mathrm{V}}^2 m_{\mathrm{N}}^2 f_{\mathrm{N}}^2}{v^2 \beta_{VH} m_H^7}$$



JHEP11(2015)206

Objection on EFT, 1st UV model

Phys.Lett.B.2014.09.040


Contents lists available at ScienceDirect

Physics Letters B

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Invisible Higgs decay width vs. dark matter direct detection cross section in Higgs portal dark matter models

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$$\mathcal{L}_{VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + D_\mu\Phi^\dagger D^\mu\Phi - \lambda_\Phi(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2})^2 - \lambda_{\Phi H}(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2})(H^\dagger H - \frac{v_H^2}{2}),$$

Arguments:

- EFT Lagrangian has mV entered arbitrarily.

  need a UV model:
  - V belongs to a U(1)' gauge group
  - Need a dark Higgs sector with spontaneous symmetry breaking to generate m_V
- 2 additional parameters: mass of the new scalar (m_2), its mixing angle (α) with the SM Higgs.

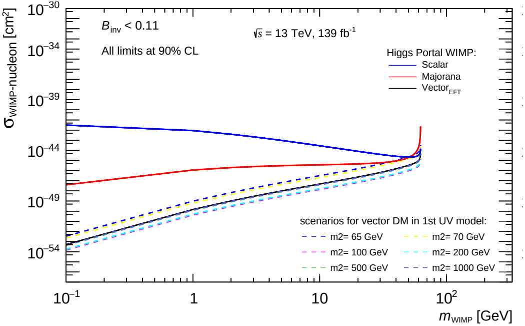
Full model decay width:

$$\Gamma^H_{\rm inv} = \frac{g_X^2}{32\pi}\frac{m_H^3}{m_V^2}(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4})(1 - 4\frac{m_V^2}{m_H^2})^{1/2},$$

Full model cross section:

$$\sigma^{\rm SI}(\text{V-N}) = cos^4(\theta) m_H^4 F(m_V, m_i, v) \times \sigma^{\rm SI}(\text{V-N})_{EFT},$$

$$\simeq cos^4(\theta)(1 - \frac{m_H^2}{m_2^2}) \times \sigma^{\rm SI}(\text{V-N})_{EFT},$$



Scenario:

- Small mixing angle $\alpha = 0.2$
- Scan through m_2 in [65,1000]GeV
- Drop the region of $[0, m_H/2]$ since Γ^H_{inv} does not count for H$\rightarrow H_2 H_2$

- With different m_2 and α, full model limit can be very different in many order of magnitudes compared to EFT one.
- EFT results recovered if: $cos(\alpha) \approx 1$ and $m_2 >> m_1$

2nd UV model, Reanalyse EFT

Phys.Lett.B 805 (2020)

The Higgs-portal for vector Dark Matter and the Effective Field Theory approach: a reappraisal

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- Same approach as 1st UV model

  Introduce a dark Higgs sector ϕ reproduce the masse of the vector through SSB.
- 2 additional parameters: mass of the new scalar (m_2), its mixing angle (α) with the SM Higgs.
- Corrected factor 32 is used instead of 8. (Verified with theorists.)

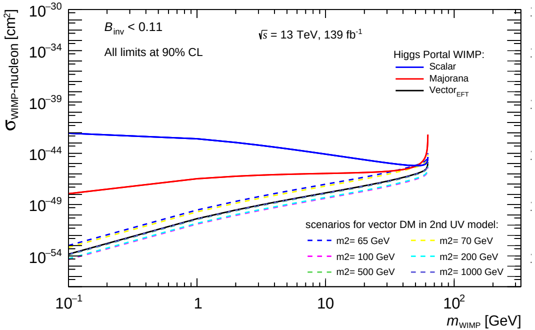
$$\mathcal{L} = \frac{1}{2}\tilde{g}M_V(H_2 cos(\theta) - H sin(\theta))V_\mu V^\mu + \frac{1}{8}\tilde{g}^2(H^2 sin^2(\theta) \\ -2HH_2 sin(\theta)cos(\theta)) + H_2^2 cos^2(\theta)V_\mu V^\mu,$$

Decay width and cross section:

$$(\Gamma^{\rm H}_{\rm inv})_{U(1)} = \frac{\tilde{g}^2 sin^2(\theta)}{32\pi}\frac{m_H^3}{m_V^2}\beta_{VH},$$

$$\sigma^{\rm SI}(\text{V-N}) = 32 cos^2(\theta)\mu_{VN}^2 \frac{m_V^2}{m_H^3}\frac{BR(H\to VV)\Gamma_H^{tot}}{\beta_{VH}} \\ \times(\frac{1}{m_2^2} - \frac{1}{m_H^2})^2\frac{m_{N^2}}{v^2}|f_N^2|,$$

2nd UV model



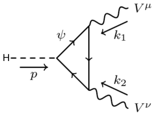
- Small mixing angle
- scan through the additional scalar mass [65,1000]GeV
- similarly to 1st UV model, consider only [65,1000]GeV for m_2

- EFT result recovered if $sin(\theta) << 1$ and $m_2 >> m_H$
- EFT approach could represent a viable limit of the renormalizable model in large region of its parameter space.

Additional fermions UV model

Vector terms
$$\mathcal{L} \supset -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\Phi)^\dagger (D^\mu\Phi) - V(\Phi) + \lambda_P\, |H|^2|\Phi|^2$$

Fermion terms
$$\mathcal{L} \supset -m\;\epsilon^{ab}\,(\psi_{1a}\chi_{1b} + \psi_{2a}\chi_{2b}) - m_n\; n_1 n_2$$
$$- y_\psi\;\epsilon^{ab}\,(\psi_{1a}H_b n_1 + \psi_{2a}H_b n_2) - y_\chi\,(\chi_1 H^* n_2 + \chi_2 H^* n_1) + h.c.$$



- **Phase space we used:**
  - ➢ the simplified case:
    - $\lambda_P << 1$;
    - charged fermions & 2 heavier neutral states' masses >> the lightest neutral state mass ==> decouple.
  - ➢ Model has no direct relation between $\sigma^{SI}_{V\text{-}N}$ and Γ_{inv} ⇒ explore the minimal parameter space: mV, mf, g, y
    - Vector mass, fermion mass, U(1)' coupling, Yukawa coupling of the added fermion to the SM Higgs

- We need to find (mV, mf, g, y) satisfying BR_{inv} = 11% (current limit) ATLAS-CONF-2020-008
  - ➢ use the entire scanned phase space for (mf,g,y)

★ **Available model constraints:**
- mV < mH/2
- mf > mH/2
- 0 < g, y < 4π and 0 < g^2y < 40

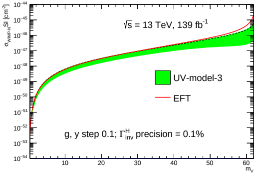
★ **Require an uncertainty 1(0.1)% on Γ_{inv}**

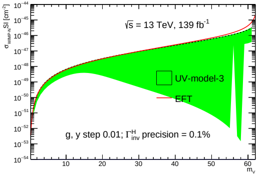
Ranges and steps of scanned variables

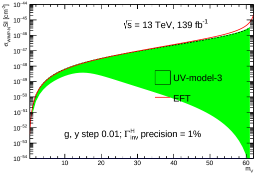
Variable	1st bin	last bin	Step
mV	1	62	1
mf	64	499	5
g	0	12	0.1(0.01)
y	0	12	0.1(0.01)

Additional fermions UV model

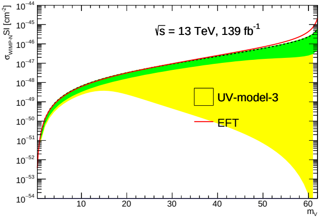
Upper limit on σ_{WIMP-N} from different scans and precision of Γ^{H}_{inv}

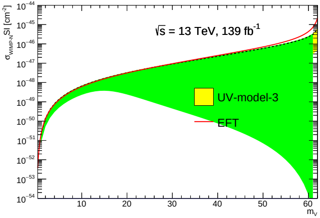






Superimposition of the limits for a coarse scan on top of a fine scan, and vice versa.

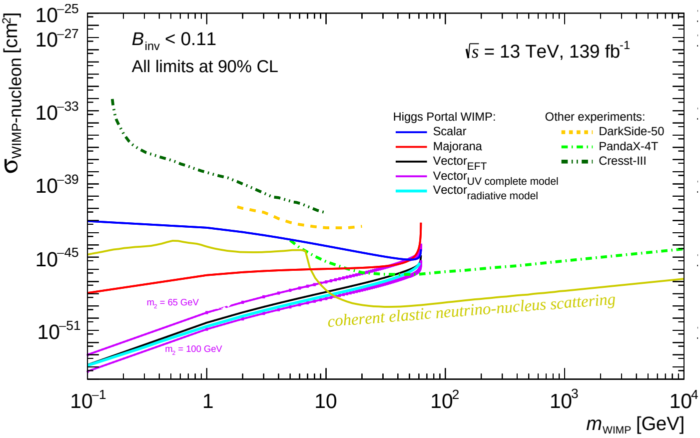




Green: coarse scan with a step of 0.1 for g, y. Uncertainty 0.1% on Γ_{inv}

Yellow: fine scan with a step of 0.01 for g, y. Uncertainty 1% on Γ_{inv}

Proposal [doi.org/10.31526/lhep.2022.270]



- Re-introduce the EFT with the updated form factor uncertainty,
- Include the UV lines/bands for the 1st, 3rd models
- include the sub-GeV range for the WIMP masse.
- Add the neutrino floor (limit for direct detection experiments)

Conclusion

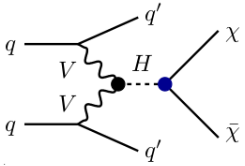
- This work was considered for the interpretation of VBF+MET analysis results (link)
- will be considered considered by the invisible Higgs combination group in the coming paper.
- Other groups using Higgs portal models for their results interpretation too!
- Submitted as a white paper in the Energy Frontier of Snowmass.

Backup

data sample: L=139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV

Invisible decays of the Higgs boson:

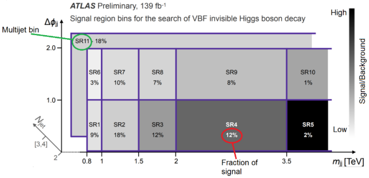
$B^{SM}_{H\to inv}$: 0.1% vs. $B^{BSM}_{H\to inv}$: 10%



(e.i: H → WIMPs)

- powerful topology: VBF + MET
- signal: VBF, ggF
- main background: V+j, QCD

SR bins:



Analysis results: (link)

- Limit on $B_{H\to inv}$: 0.13 at 95% CL.