Search for invisible Higgs bosons produced via vector boson fusion at the LHC using ATLAS detector

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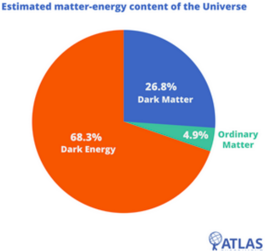
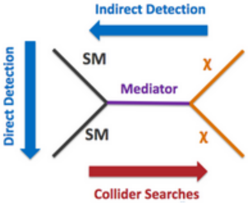
Motivation

- 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.



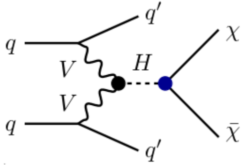
- Higgs boson could be a mediator between SM particles and ones that belong to the DM sector.



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

The experimental signature:

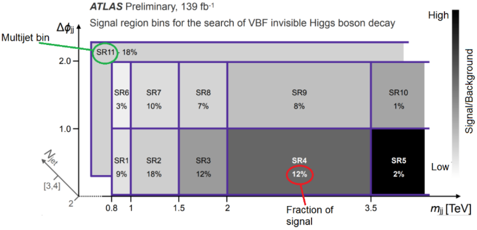
- pair of energetic jets
- wide gap in η_{jj}
- large invariant massess m_{jj}

Previous analysis result: (link)

- Limit on $B_{H\to inv}$: 0.37 at 95% CL.

Changes and improvements:

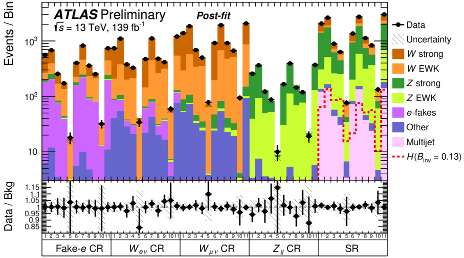
- Relaxed selection criteria on m_{jj}, $\Delta\eta_{jj} > 3.8$ and $\Delta\Phi_{jj}$
- $E_T^{miss} > 200$ GeV slightly increased



Improvements efficiency:
Better S/B ratio for selections with larger m_{jj} and smaller $\Delta\Phi_{jj}$

Results:

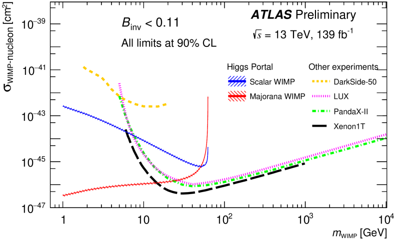
Postfit results of all SR and CR bins.

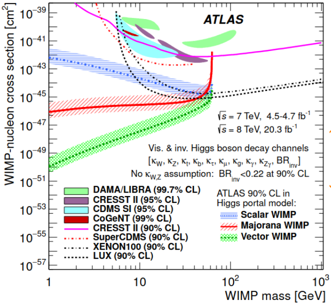


- good agreement of expected background yields and observed data
- set an upper limit on the $B_{H\rightarrow inv}$ of 13%.
- EFT approach for VDM used in run–1
- Objection on EFT approach Phys.Lett.B.2014
- Support of EFT approach Phys.Lett.B 805
- UV radiative Higgs portal model JHEP 04

Interpretation:

Upper limits on the SI $\sigma_{WIMP-nucleon}$ using Higgs portal interpretations





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Objection on EFT, 1st UV model

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

- EFT approach has Only 2 parameters: hVV coupling & vector mass.

$$\boxed{\sigma_{V-N} = 32\mu_{Vp}^2\Gamma_{inv}\frac{m_V^2 m_N^2 f_N^2}{v^2\beta_{VH} m_h^7}}$$

★ **Arguments:**

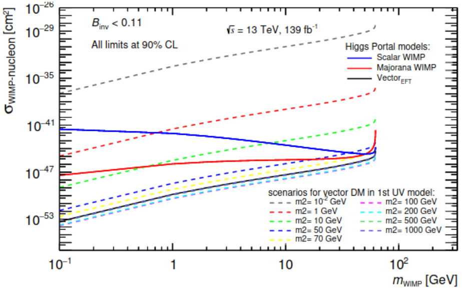
- EFT Lagrangian has m_V entered arbitrarily ⇒ need a UV model:
  - V belongs to a U(1)' gauge group
  - Need a dark Higgs sector with spontaneous symmetry breaking to generate m_V
- ⇒ 2 additional parameters: mass of the new scalar (m_2), its mixing angle (α) with the SM Higgs.

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

Full model cross section

$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}c_\alpha^4 m_h^4\mathcal{F}(m_{\rm DM}, \{m_i\}, v)$$

$$\simeq (\sigma_p^{\rm SI})_{\rm EFT}c_\alpha^4\left(1 - \frac{m_h^2}{m_2^2}\right)^2.$$



- **Scenarios:** α=0.2, scan through m2 :0.01 ,1000 GeV.
- Limits ranges in many different orders of magnitude
- If cos(α)~1 and m2>>m1, **recover EFT prediction**
- **Conclusion:** With different m_2 and α, full model limit can be very different in many order of magnitudes compared to EFT one.

$$\mathcal{L}=\frac{1}{2}\tilde{g}M_V\left(H_2c_\theta-H_1s_\theta\right)V_\mu V^\mu+\frac{1}{8}\tilde{g}^2\left(H_1^2s_\theta^2-2H_1H_2s_\theta c_\theta+H_2^2c_\theta^2\right)V_\mu V^\mu+\mathcal{L}_S^{\rm SM}+\mathcal{L}_S^{\rm tril}$$

- H1: the 125GeV SM-like Higgs boson.
- H2: the additional DM scalar state
- Mv: DM mass.
- $\tilde{g}$: the new gauge coupling

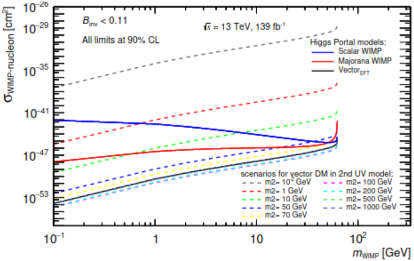
- Viable limit from EFT as of the renormalizable model in large region of its parameter space.

$$\left(\sigma_{Vp}^{SI}\right)_{EFT}=32\mu_{Vp}^2\frac{M_V^2}{M_H^3}\frac{BR(H\to VV)\Gamma_H^{tot}}{\beta_{VH}}\frac{1}{M_H^4}\frac{m_p^2}{v^2}|f_p|^2$$

$$\left(\sigma_{Vp}^{SI}\right)_{U(1)}=\left(\sigma_{Vp}^{SI}\right)_{EFT}\cdot\cos^2(\theta)M_H^4\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)$$

- Recover EFT prediction in the limit:

$$\cos^2\theta\, M_H^4\left(1/M_{H_2}^2-1/M_{H_1}^2\right)^2\approx 1.$$



- The Higgs–portal with a vectorial DM state could represent a consistent EFT limit of its simplest UV completion, dubbed dark U(1)' model.
- EFT approach could represent a viable limit of the renormalizable model in large region of its parameter space.

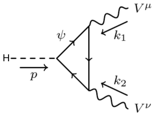
Additional fermion UV model

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

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

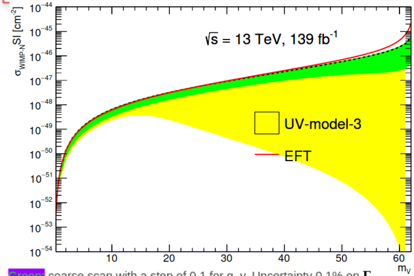


- **Phase space we used:**
  - the simplified case:
    - $\lambda_P << 1$;
    - charged fermions & 2 heavier neutral states' masses >> the lightest neutral state mass ==> decouple.
  - Model has no direct relation between $\sigma^{SI}_{V\text{-}N}$ and Γ_{inv} ⇒ explore the minimal parameter space: 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)

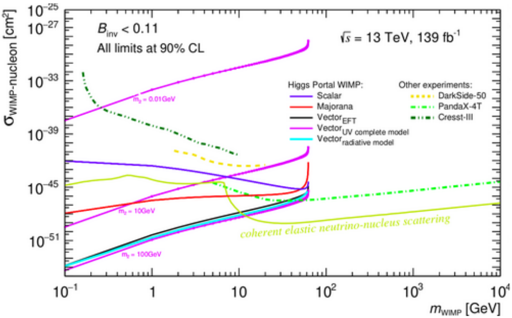
★ **Available model constraints:**
- mV < mH/2
- mf > mH/2
- $0 < g, y < 4\pi$ and $0 < g^2 y < 40$

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



- 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}

- 3 different models are presented:
  - Calculated XS at UV seems to use approximation in 1st and 2nd models
  - Complicated XS calculation in 3rd UV model
- EFT is viable even though being opposed for diverse limits at UV
- Proposals for the vector DM interpretation in the DM overlay plot:
  - Re-introduce the EFT with the the new form factor uncertainty, since EFT is supported by 2nd UV model and is the same in all the models, and same calculation as in Run1.
  - Include the UV lines/bands (best and worst limits) for the 1st model, and also for 3rd models.
  - Add the sub-GeV domain.



"We submitted this work (link) as a white paper in the Energy Frontier of Snowmass"