Testing dark matter using the Higgs boson

Diallo Boye, Ketevi Assamagan

Snowmass Community Summer Study in Seattle
EF10: BSM: Dark Matter at colliders

July 21, 2022

The Higgs boson exists and then...

- **The Higgs boson exists and it's discovered in 2012 → scrutinize its properties and the Higgs sector nature.**
- Recent search set a 95% CL upper limit of 21% on the branching ratio for H boson decays via undetected modes. arXiv:1909.02845
  - ⇒ **Exotic decays of the Higgs boson remain a high priority.**

- Even with its excellent successes in providing experimental predictions, the SM leaves some phenomena unexplained.
  - hierarchy problem, baryon asymmetry, **Dark Matter**/energy etc...
- **Many Beyond Standard Model (BSM) theories predict the Higgs as mediator between SM particles and dark matter** PhysRevD.82.055026, doi.org/10.1016/, Phys. Rev. Lett. 112, 201802

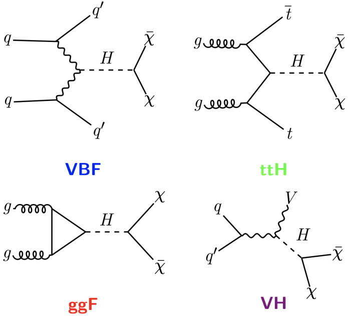
Higgs to invisible search at the LHC

- **Invisible Higgs carries off momentum, characterised by large missing transverse momentum in the events**

- **Four different channels for the Higgs to invisible search**

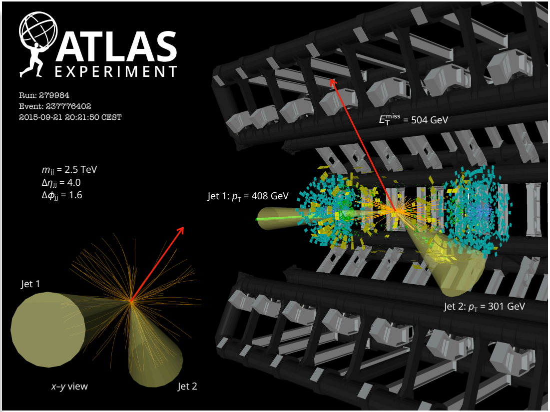
- **Very unlikely process in Standard Model; branching ratio $\mathcal{B}_{H\to inv} \sim 1.05 \times 10^{-3}$ from $H \to ZZ^* \to 4\nu$**

- **Can be significantly enhanced in various BSM scenarios, including Higgs coupling to dark matter ("Higgs portal").**

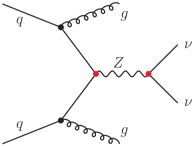


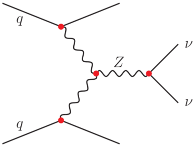
Vector Boson Fusion: VBF

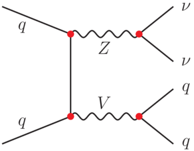
- Strong background rejection due to its distinct event topology.
- The most sensitive mode for invisible decays of a Higgs boson at hadron colliders
- Three mains backgrounds: Z strong, Z electroweak and di-boson production.

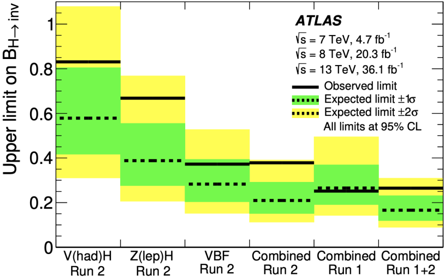


arXiv:2202.07953

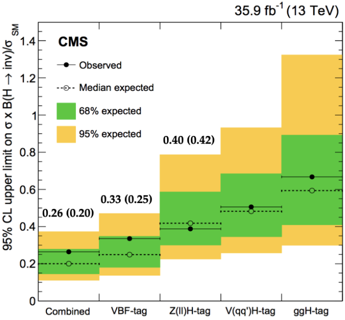








▸ Phys. Rev. Lett. 122, 231801



▸ Phys.Lett.B 793 (2019) 520-551

Channel	ATLAS (Run 2)		CMS	
	Observed	Expected	Observed	Expected
VBF	0.37	0.28	0.33	0.25
ZH	0.67	0.39	0.40	0.42
VH	0.83	0.58	0.32	0.38
Combined	0.38	0.21	0.26	0.20

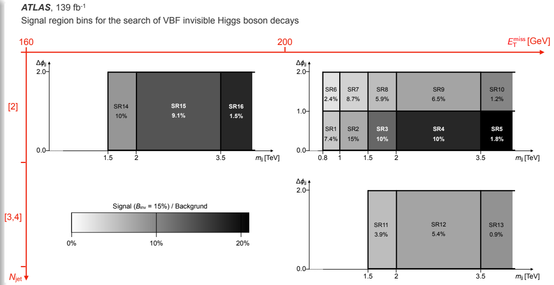
- The most recent search on Higgs to invisible will be discussed in the rest of the talk.
- **By focusing on the more sensitive channel: VBF**.

VBF search in ATLAS: Analysis strategy

arXiv:2202.07953

Event selection

- Two jets with $p_T(j_1/j_2) > 80/50$ GeV.
- Small add. jet activity: $p_T(j_3) < 25$ GeV.
- Jets in opposite hemispheres.
- $\Delta\eta_{jj} > 3.8$.
- $m_{jj} > 0.8$ TeV
- Veto on e and μ
- A 3D $m_{jj}, \Delta\phi_{jj}$ and N_{jets} binning used.



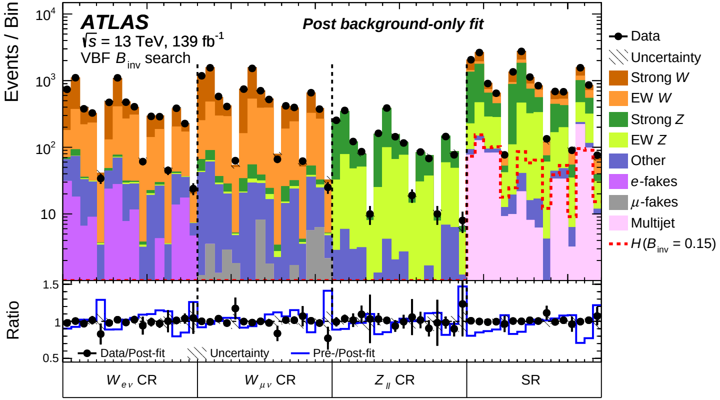
Bkg estimates

- The V+jets (95% bkgs) estimates by data-driven technique.

Systematics uncertainties

- Lepton and JER (32% and 40%)
- theoretical uncertainties on V+Jets bkg $\sim$ 28%.

arXiv:2202.07953



Total bkg.	14 990 ± 2990	1880 ± 510	6210 ± 1260	9150 ± 1890	4560 ± 760	2110 ± 390	2030 ± 110
H (VBF)	886 ± 81						3.9 ± 1.3
H (ggF)	106 ± 41		Predicted signal for $\mathcal{B}_{inv}$ = 15%				$1.0 \pm ^{1.5}_{1.0}$
H (VH)	0.9 ± 0.2						-
Data	16 490	2051	6361	9294	4563	2110	2033

VBF search in CMS: Analysis strategy

arXiv:2201.11585

Event selection

- Two complementary trigger strategies:
  - missing momentum triggered region (MTR)
  - VBF jets triggered region (VTR).

VBF SR selection (Full table available in the backup)

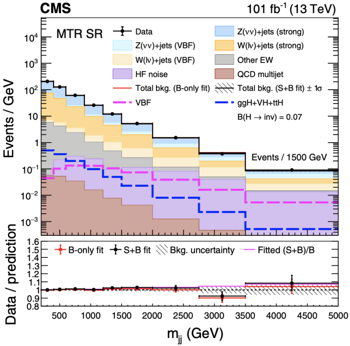
Observable	MTR	VTR
Choice of pair	Leading-pT jets	Leading-m_{jj} jets
Leading (subleading) jet	$p_T > 80(40) GeV, \|\eta\| < 4.7$	$p_T > 140(70) GeV, \|\eta\| < 4.7$
p_T^{miss}	> 250 GeV	$160 < p_T^{miss} < 250$ GeV
$\min(\Delta\phi(p_T^{miss}, p_T^{jet}))$	> 0.5	> 0.8
$\|\Delta\phi_{jj}\|$	< 1.5 GeV	1.8 GeV
m_{jj}	< 200 GeV	900 GeV

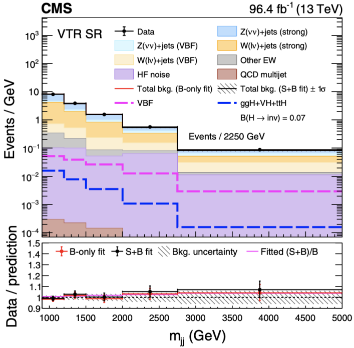
Bkg estimation

- V+jets bkg, estimated by independent CRs.
- Data driven method used for the mutiljet backgrounds.

Systematics uncertainties

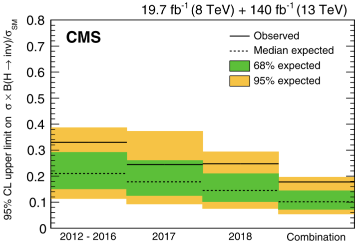
- Jet energy scale and resolution (up to 35%) , Theory uncertainty taken from another ref.





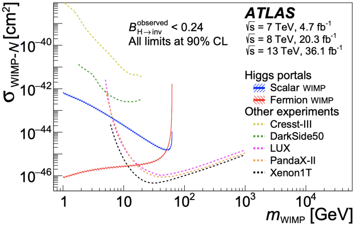
Results

- No significant deviations from the SM expectations are observed.
- Combination of 2017 and 2018 results yields an observed (expected) upper limit of $\mathcal{B}(H \to inv) < 0.18(0.12)$.

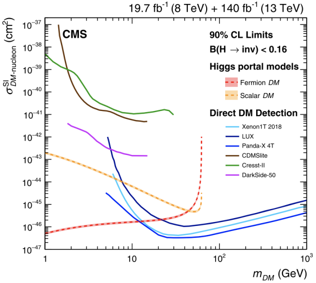


VBF search in ATLAS: Interpretation

- **Interpretation in the context of Higgs-portal models of DM interactions →stable DM particle couples to the SM Higgs boson.**
- **Higgs boson as mediator between a DM particle and an atomic nucleus.**
- **If $m_{DM} < \frac{m_H}{2}$, then Γ_{inv} can be translated within and EFT approach into a spin-independent DM-nucleon elastic scattering cross section.**
- **Transformation performed assuming the DM candidate is either a scalar or a Majorana fermion.**

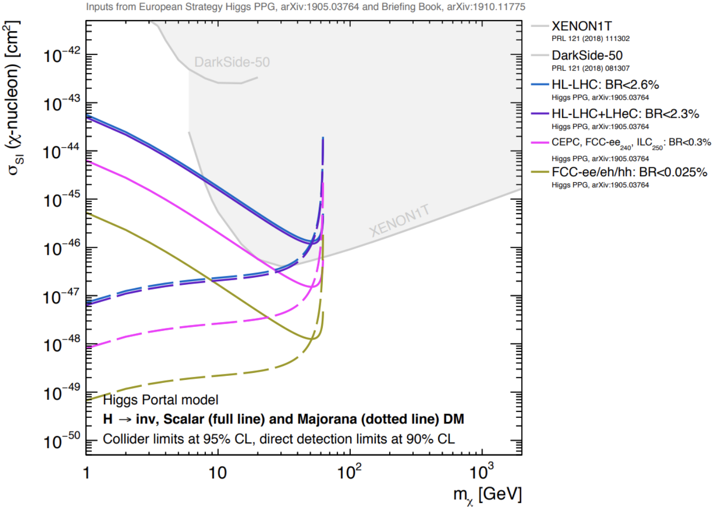


Phys. Rev. Lett. 122, 231801



arXiv:2201.11585

More interpretation: ‣ snowmass2021BSMReportV1



- The authors propose to extend the results to DM masses below the GeV since the translation between collider parameters of the theory and DM-nucleon cross-section are still valid in all regimes of momentum transfer

Our interpretation study proposal: arXiv:2107.01252

- As shown in the slide 10 and 11, Higgs portal Vector DM (VDM) line has been removed in all ATLAS and CMS publication since Run 1.
  - This is motivated by some objection on the EFT approach.
- In our study we propose to reconsider the VDM interpretation.
- UV radiative Higgs portal model also considered in this work.
- **We also do the extension to the low mass regime (below 1 GeV)**.

Effective Field Theory approach

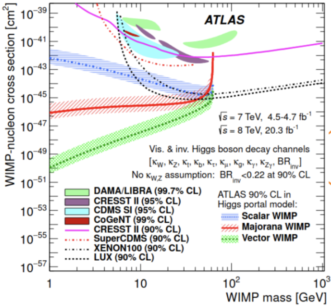
$$\mathcal{L}_V = \frac{1}{2}m_{\rm V}^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{\lambda_{\rm hVV}}{4} H^\dagger H V_\mu V^\mu .$$

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

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

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

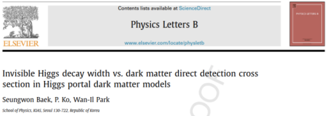
$$\sigma^{\rm SI}({\rm V\text{-}N})_{EFT} = 32\mu_{VN}^2 \Gamma_{\rm inv}^{\rm H} \frac{m_{\rm V}^2 m_{\rm N}^2 f_{\rm N}^2}{v^2 \beta_{VH} m_H^7}$$



JHEP11(2015)206

Objection on EFT, 1st UV model

Phys.Lett.B.2014.09.040


Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

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

Seungwon Baek, P. Ko, Wan-Il Park

School of Physics, KIAS, Seoul 130-722, Republic of Korea

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.

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

Full model decay width:

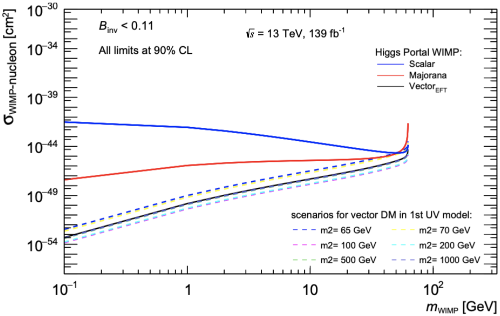
$$\Gamma^{\rm H}_{\rm inv} = \frac{g_X^2}{32\pi}\frac{m_H^3}{m_V^2}(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4})(1 - 4\frac{m_V^2}{m_H^2})^{1/2},$$

Full model cross section:

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

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

1st UV mode



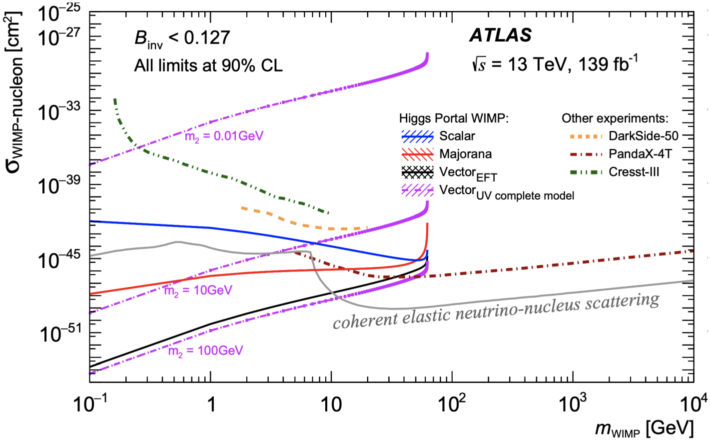
Scenario:

- 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 $m_2 >> m_1$

- Two more UV modes are also proposed and available in backup for discussion.

Our proposal adopted by ATLAS

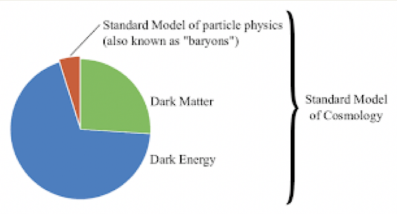


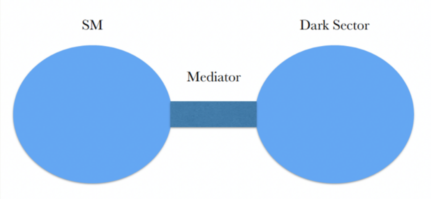
- Our proposal has been adopted by ATLAS in its latest results on the Higgs to invisible search.; ▸ arXiv:2202.07953

More General models

Dark Sector

- Dark Sector states as "New Physics" beyond the SM





Need new force / interaction
to connect SM to Dark Sector — portals.
Weak couplings through kinetic mixing,
Higgs or mass mixings

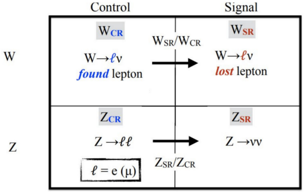
Dark Matter could just be one example of Dark Sector State

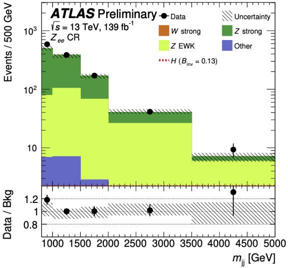
Conclusion

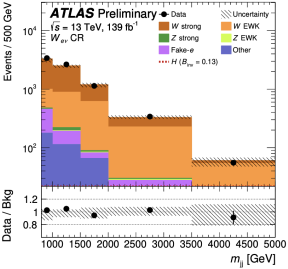
- The Higgs to invisible search at the LHC is presented:
  - Previous search results are reminded.
  - The most recent searches by ATLAS and CMS are reviewed.
- In their interpretation results ATLAS and CMS removed the EFT VDM line.
- We showed that the EFT approach is still viable and we propose to reconsider it.
- We also do the extension to the low mass regime (below 1 GeV).
- Our proposal has been adopted by ATLAS in its latest results on the Higgs to invisible search.; arXiv:2202.07953

BACKUP

V+jets Background Modelling: Slide from Ben







$$B^{\mathrm{SR}}_{\mathrm{estimate}} = N^{\mathrm{CR}}_{\mathrm{data}} \frac{B^{\mathrm{SR}}_{\mathrm{MC}}}{B^{\mathrm{CR}}_{\mathrm{MC}}}$$

- Partially data-driven technique: transfer factors from one (W), two (Z) lepton control regions.
- Collaborated with Sherpa authors to enhance high m_{jj} phase space in NLO V+jets MC.
- Signal region MC ($B^{\mathrm{SR}}_{\mathrm{MC}}$) rescaled by control region data/MC ratio ($N^{\mathrm{CR}}_{\mathrm{data}}/B^{\mathrm{CR}}_{\mathrm{MC}}$).
- Procedure done for each bin; separate transfer factors for W and Z processes.

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

GIORGIO ARCADI[1], ABDELHAK DJOUADI[2] and MARUMI KADO[3,4]

[1] Dipartimento di Matematica e Fisica and INFN, Università di Roma Tre, Via della Vasca Navale 84, 00146, Roma, Italy.
[2] Université Savoie–Mont Blanc, USMB, CNRS, LAPTh, F-74000 Annecy, France.
[3] Department of Physics and INFN, "Sapienza" Università di Roma, Pizzale Aldo Moro 5, I–00185 Roma, Italy.
[4] LAL, Université Paris-Sud, CNRS/IN2P3, Universit Paris-Saclay, Orsay, France.

- 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.)

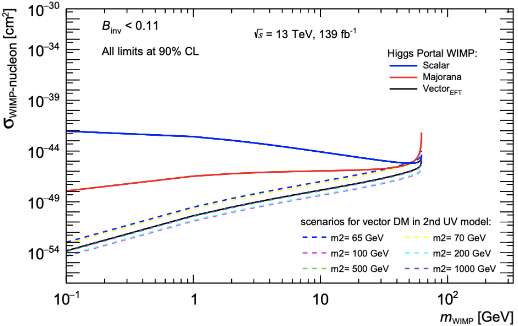
$$\mathcal{L} = \frac{1}{2}\tilde{g}M_V(H_2 cos(\theta) - H sin(\theta))V_\mu V^\mu + \frac{1}{8}\tilde{g}^2(H^2 sin^2(\theta) - 2HH_2 sin(\theta)cos(\theta)) + H_2^2 cos^2(\theta)V_\mu V^\mu,$$

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



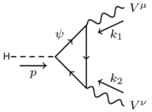
- Small mixing angle
- scan through the additional scalar mass [65,1000]GeV
- similarly to 1st UV model, consider only [65,1000]GeV for m_2

- 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

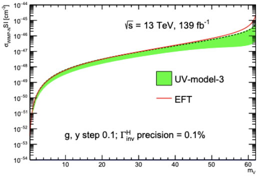
★ **Require an uncertainty 1(0.1)% on Γ_{inv}**

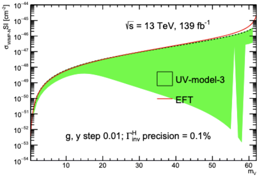
Ranges and steps of scanned variables

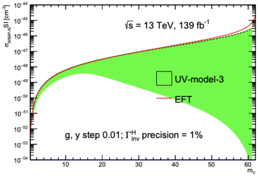
Variable	1st bin	last bin	Step
mV	1	62	1
mf	64	499	5
g	0	12	0.1(0.01)
y	0	12	0.1(0.01)

Additional fermions UV model

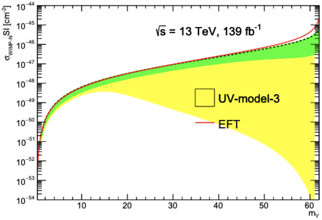
Upper limit on σ_{WIMP-N} from different scans and precision of Γ^H_{inv}

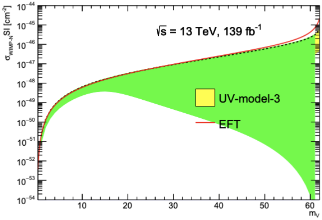






Superimposition of the limits for a coarse scan on top of a fine scan, and vice versa.

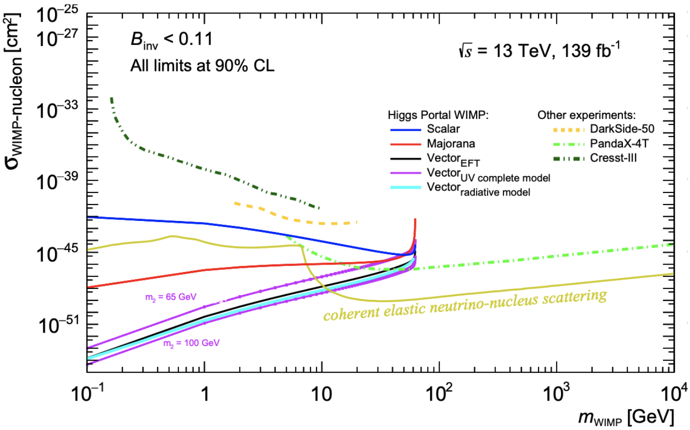




Green: coarse scan with a step of 0.1 for g, y. Uncertainty 0.1% on Γ_{inv}

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

Proposal



- 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)

Full SR selection

Table 2: Summary of the kinematic selections used to define the SR for both the MTR and the VTR categories.

Observable	MTR	VTR
Choice of pair	leading-p_T jets	leading-m_{jj} jets
Leading (subleading) jet	$p_T > 80\,(40)$ GeV, $\|\eta\| < 4.7$	$p_T > 140\,(70)$ GeV, $\|\eta\| < 4.7$
p_T^{miss}	>250 GeV	$160 < p_T^{miss} < 250$ GeV
$\min(\Delta\phi(\vec{p}_T^{miss}, \vec{p}_T^{jet}))$	>0.5	>1.8
$\|\Delta\phi_{jj}\|$	<1.5	<1.8
m_{jj}	>200 GeV	>900 GeV
$\|p_T^{miss} - \text{calo } p_T^{miss}\| / p_T^{miss}$	<0.5	
Leading/subleading jets $\|\eta\| < 2.5$	NHEF < 0.8, CHEF > 0.1	
HF noise jet candidates	0 (using the requirements from Table 1)	
τ_h candidates	$N_{\tau_h} = 0$ with $p_T > 20$ GeV, $\|\eta\| < 2.3$	
b quark jet	$N_{jet} = 0$ with $p_T > 20$ GeV, DeepCSV Medium	
$\eta_{j1}\eta_{j2}$	<0	
$\|\Delta\eta_{jj}\|$	>1	
Electrons (muons)	$N_{e,\mu} = 0$ with $p_T > 10$ GeV, $\|\eta\| < 2.5\,(2.4)$	
Photons	$N_\gamma = 0$ with $p_T > 15$ GeV, $\|\eta\| < 2.5$	

Full SR selection

Table 6: The 95% CL upper limits on $(\sigma_{\mathrm{H}}/\sigma_{\mathrm{H}}^{\mathrm{SM}})\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, assuming an SM Higgs boson with a mass of 125.38 GeV. The observed and median expected results are shown, along with the 68% and 95% interquartile ranges for each category and for the combinations.

Category	Observed	Median expected	65% expected	95% expected
2012–2016	0.33	0.21	[0.15, 0.29]	[0.11, 0.39]
VTR 2017	0.57	0.45	[0.32, 0.66]	[0.24, 0.94]
VTR 2018	0.44	0.34	[0.24, 0.49]	[0.18, 0.69]
VTR 2017+2018	0.40	0.28	[0.20, 0.40]	[0.15, 0.56]
MTR 2017	0.25	0.19	[0.14, 0.28]	[0.10, 0.40]
MTR 2018	0.24	0.15	[0.11, 0.22]	[0.08, 0.31]
MTR 2017+2018	0.17	0.13	[0.09, 0.18]	[0.07, 0.25]
all 2017	0.24	0.18	[0.13, 0.26]	[0.09, 0.37]
all 2018	0.25	0.15	[0.10, 0.21]	[0.08, 0.29]
all 2017+2018	0.18	0.12	[0.08, 0.17]	[0.06, 0.23]
2012–2018	0.18	0.10	[0.07, 0.14]	[0.05, 0.20]

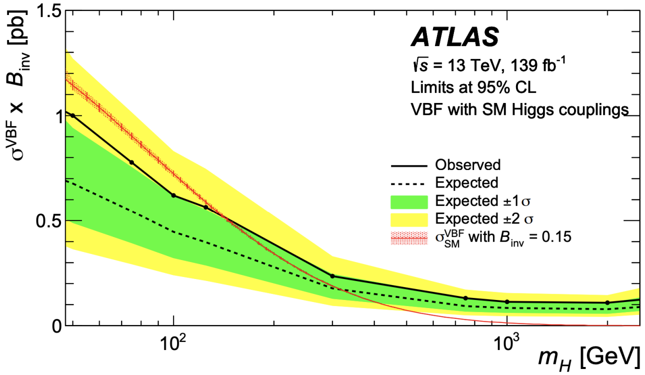


Figure 14: Upper limit on cross section times branching ratio to invisible particles for a scalar mediator as a function of its mass. For comparison the VBF cross section at NLO in QCD, i.e. without the electroweak corrections, for a particle with SM Higgs boson couplings, multiplied by a $\mathcal{B}_{\text{inv}}$ value of 15%, is overlaid.