Higgs portal Vector-Dark-Matter Revisit

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EF10 meeting

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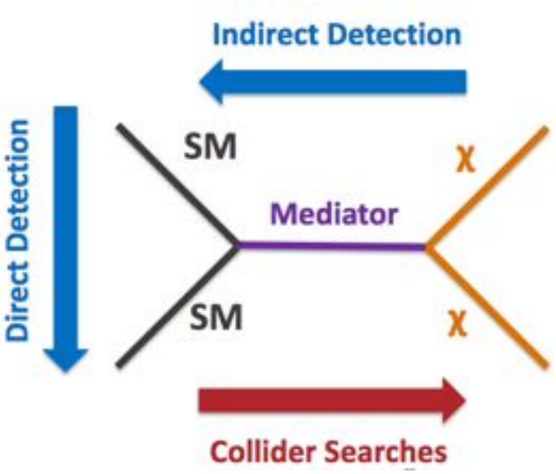
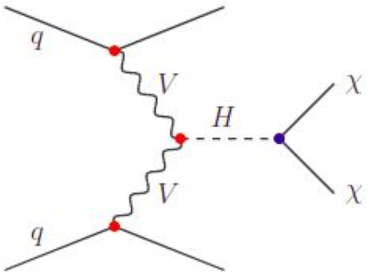
Motivation

- ❖ Wealth of evidence that dark matter (DM) exists
- ❖ LHC searches complement evidence from direct and indirect detection
  - ➢ Can actually produce DM mediators
- ❖ Several extensions of the Standard model have been recently revisited with DM=singlet scalar S, vector V, fermion χ
- ❖ Invisible decays of the Higgs boson, as part of the “Higgs portal model” scenarios, are a good way of searching for new physics





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

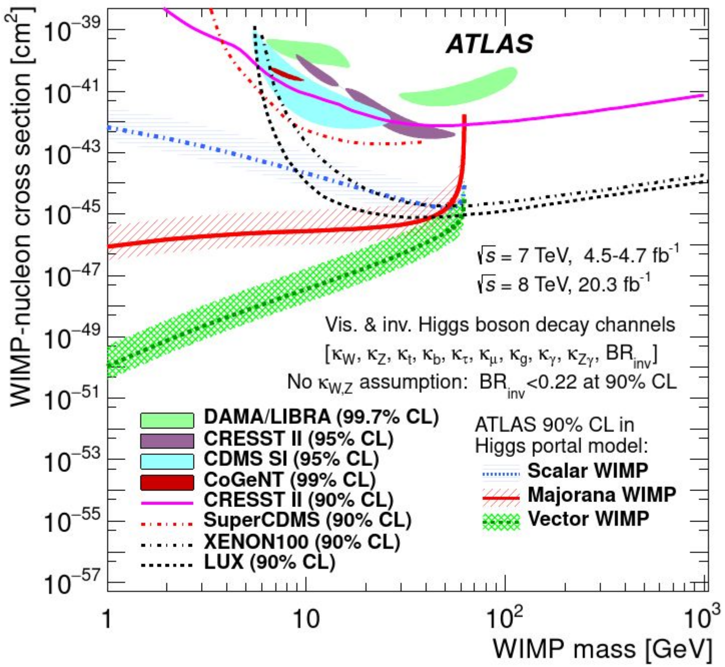
Introduction

- Goal: Higgs portal Vector DM (VDM) interpretation on spin-independent DM-nucleon elastic scattering cross section ($\sigma^{SI}_{V\text{-}N}$) using Higgs invisible decay width (Γ_{inv})

  https://arxiv.org/abs/2107.01252

- EFT approach Phys.Lett.B 709 (2012) was used in Run 1.
  - Then there came objection on EFT approach Phys.Lett.B.2014.09.040
    - The VDM line has been removed in all ATLAS and CMS publication since then
  - Countered by support for EFT approach Phys.Lett.B 805 (2020)

- Some UV completion models came along:
  - In this talk, UV radiative Higgs portal model is considered JHEP 04 (2016) 135
  - Also the UV models in the EFT papers



JHEP11(2015)206

- Green hashed band is ATLAS VDM σ^{SI}(V-N) limit.
- Thick hashed band is due to old high uncertainty of nuclear form factor.
- Comparison with other direct detection results.

Effective Field Theory approach

Common convention

1. v: vev of the Higgs potential.
2. $m_p = m_N$: proton-nucleon mass.
3. $m_V = M_V$: vector boson mass.
4. $m_h = M_H$: Higgs boson mass.
5. $\beta_V = \sqrt{1 - 4\frac{m_V^2}{m_h^2}}$
6. $\beta_{VH} = \sqrt{1 - 4\frac{m_V^2}{m_h^2}}\left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)$
7. $m_r^2 = \mu_{Vp}^2 = \frac{m_V^2 m_p^2}{m_V^2 + m_p^2}$: vector DM reduced mass.
8. $\Gamma^{inv}(h \to VV) = BR_{inv}\Gamma_H^{tot} = \frac{BR_{inv}}{1 - BR_{inv}}\Gamma_h^{SM}$

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

- Only 2 parameters:
  - hVV coupling λ_{hVV}
  - vector mass m_V
- Derive Higgs invisible decay width Γ_{inv} and spin-independent XS - σ^{SI}(V-N)

$$\Gamma^{inv}(h \to VV) = \lambda_{hVV}^2 \frac{v^2 \beta_V m_h^3}{512\pi m_V^4} \times \left(1 - 4\frac{m_V^2}{m_h^2} + 12\frac{m_V^4}{m_h^4}\right)$$

$$\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^2 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$$

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

Objection on EFT, 1st UV model

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

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

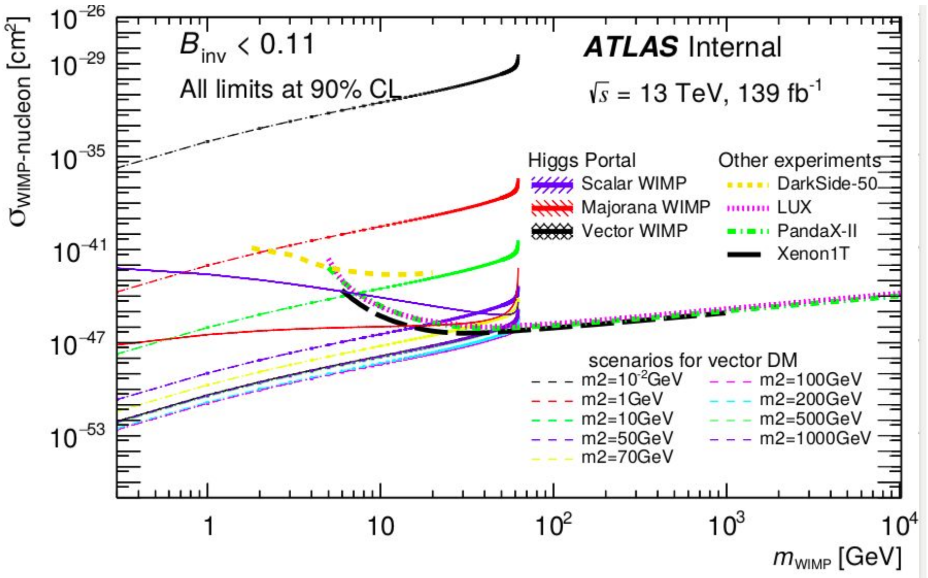
$$\sigma_{V-N} = 32\mu_{Vp}^2 \Gamma_{inv} \frac{m_V^2 m_N^2 f_N^2}{v^2 \beta_{VH} m_h^7}$$

★ **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.

2nd UV model, Reanalyse EFT

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

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

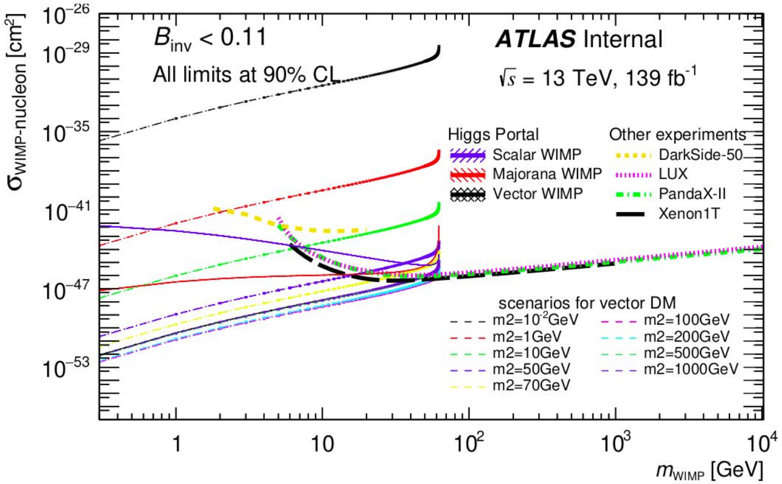
- Viable limit from EFT as of the renormalizable model in large region of its parameter space.

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

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

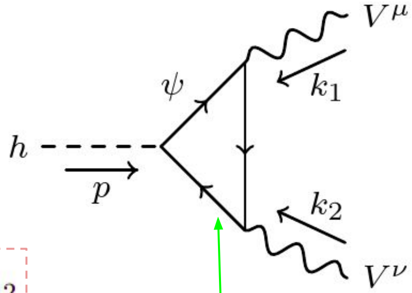
- Recover EFT prediction in the limit:

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



- 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, 3rd model



Vector Dark Matter through a Radiative Higgs Portal [JHEP 04 (2016) 135]

Anthony DiFranzo (Fermilab and UC, Irvine), Patrick J. Fox (Fermilab), Tim M. P. Tait (UC, Irvine) (Dec 21, 2015)

Published in: *JHEP* 04 (2016) 135 • e-Print: 1512.06853 [hep-ph]

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

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

- Same approach as 1st UV model: Dark Higgs sector added.
- λ_P : mixing parameter between the SM Higgs boson and the dark Higgs mode of Φ.
- Extra: fermions charged under SMxU(1)’ are added in ⇒ loop induced hVV interaction

Additional fermion UV model

- **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 σ^{SI}_{V-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)

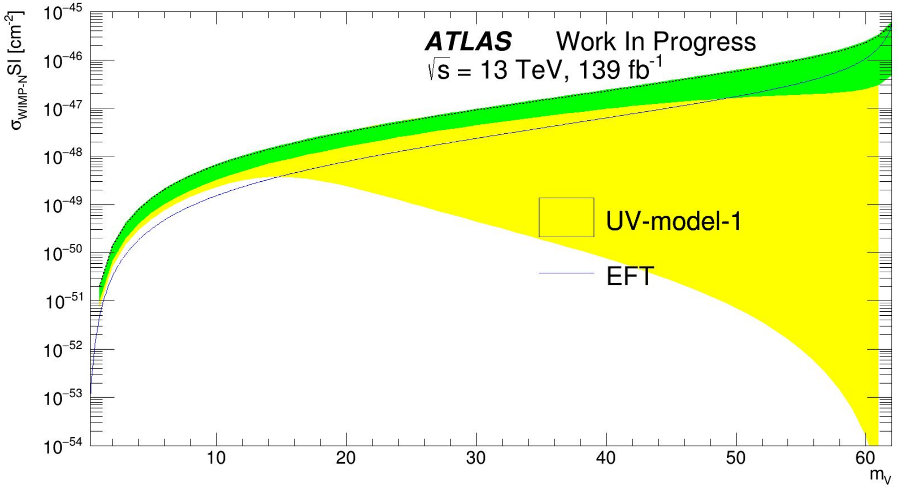
★ **Available model constraints:**
- mV < mH/2
- mf > mH/2
- $0 < g, y < 4\pi$ and $0 < g^2 y < 40$

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

Ranges and steps of scanned variables

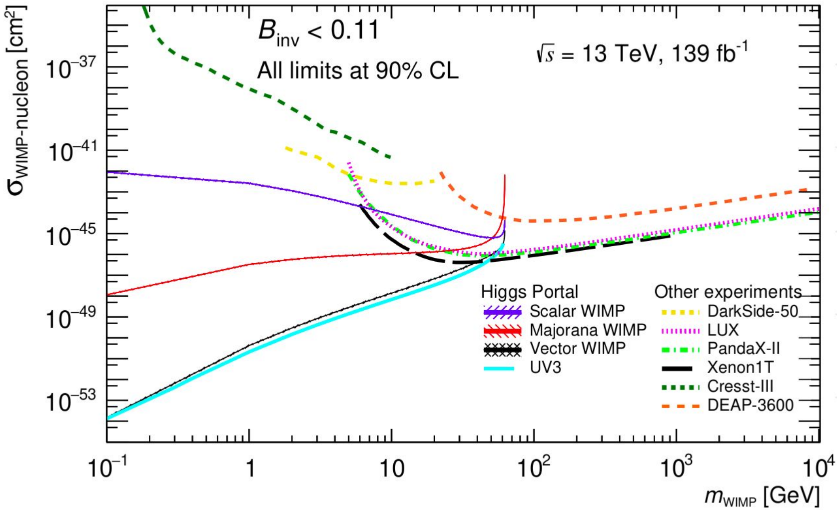
Variable	1st bin	last bin	Step
mV	1	62	1
mf	64	499	5
g	0	12	0.1(0.01)
y	0	12	0.1(0.01)

Additional fermion UV model



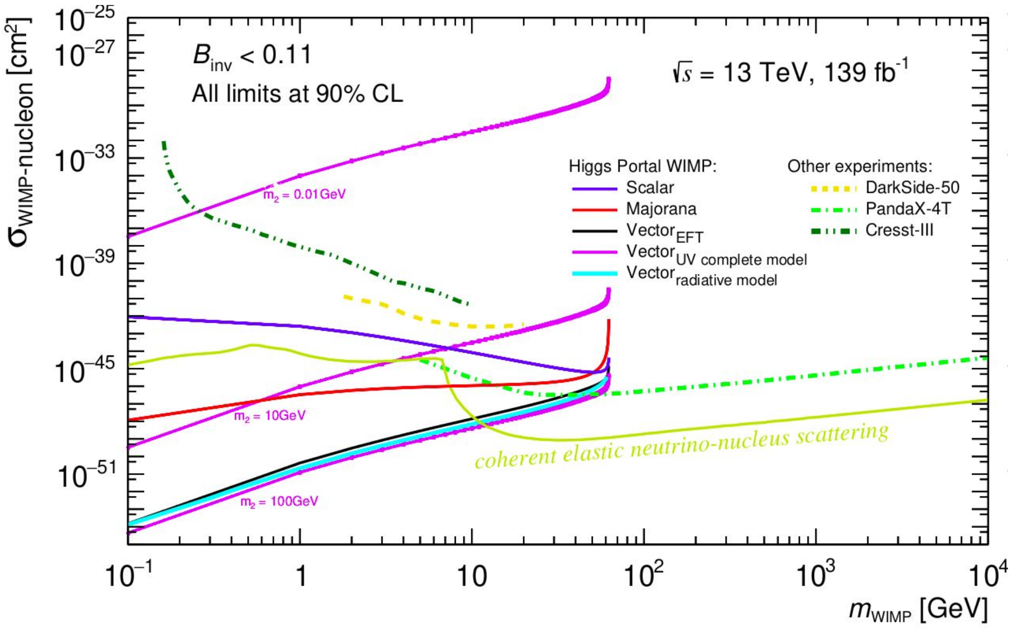
- Green: coarse scan with a step of 0.1 for g, y. Uncertainty 0.1% on Γ_{inv}
- Yellow: fine scan with a step of 0.01 for g, y. Uncertainty 1% on Γ_{inv}
- The upper bounds coincide for the 2 scanning schema.

The upper bounds that coincide for the 2 scanning schema is added to the overlay DM plot.



Summary and Proposal

- 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.
- Work documented in the following arxiv paper: https://arxiv.org/abs/2107.01252



Back Up

Objection on EFT, 1st UV model

Phys.Lett.B.2014.09.040

PHYSICAL REVIEW D **90,** 055014 (2014)

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

Seungwon Baek,[*] P. Ko,[†] and Wan-Il Park[‡]
School of Physics, KIAS, Seoul 130-722, Korea
(Received 19 May 2014; published 11 September 2014)

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

★ **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.

Full model cross section

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

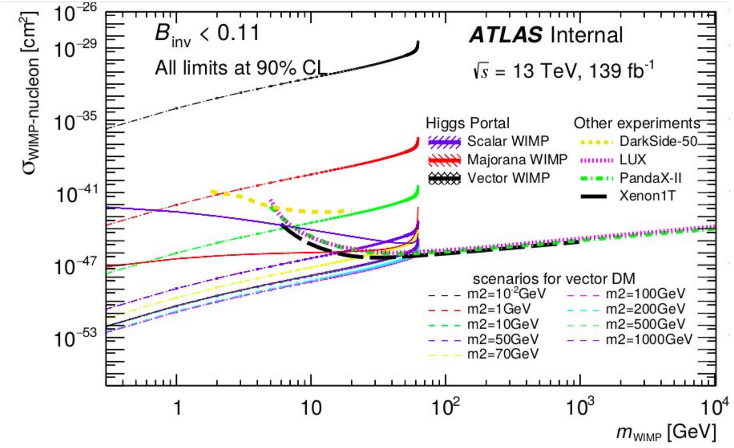
$$\simeq (\sigma_p^{\rm SI})_{\rm EFT} c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2} \right)^2,$$

2nd UV model

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

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

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



- Recover EFT prediction in the limit:

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

- Corrected factor 32 is used instead of 8
- The latter is typo in their paper
- Verified with theorists.

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

$$\sigma^{SI}_{Vp}|_{U(1)} = 8\cos^2\theta\mu^2_{Vp}\frac{M_V^2}{M_{H_1}^3}\frac{BR(H_1\to VV)\Gamma_{H_1}^{tot}}{\beta_{VH_1}}\left(\frac{1}{M_{H_2}^2}-\frac{1}{M_{H_1}^2}\right)^2\frac{m_p^2}{v^2}|f_p|^2.$$

Additional fermion UV model

- **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
- **What to do:**
  We need to find (mV, mf, g, y) satisfying $BR_{inv} = 11\%$ (current limit) ATLAS-CONF-2020-008

- **Available model constraints:**
  - $mV < mH/2$
  - $mf > mH/2$
  - $0 < g, y < 4\pi$ and $0 < g^2 y < 40$
- **Require an uncertainty on Γ_{inv}**

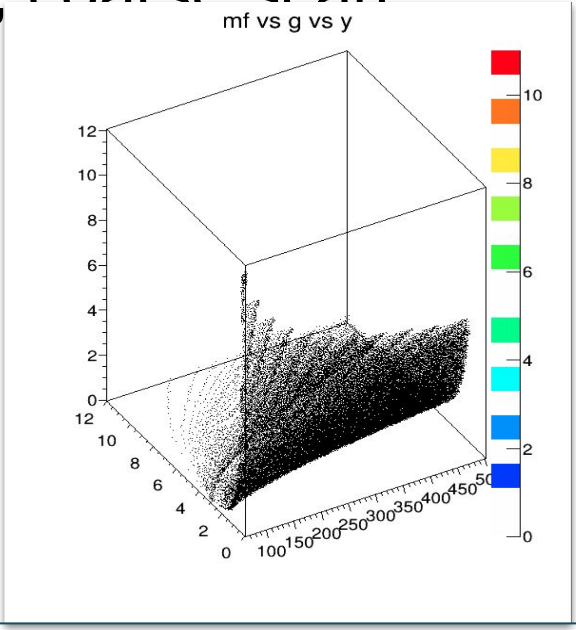
- **We proceed with two approaches:**
  - **1st approach:** Select groups of (mf, g, y) which satisfy all mV ∈ [1, 62] GeV.
  - **2nd approach:** use the entire scanned phase space for (mf,g,y)

3rd model,1st approach, coarse scan

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
y	0	12	0.1

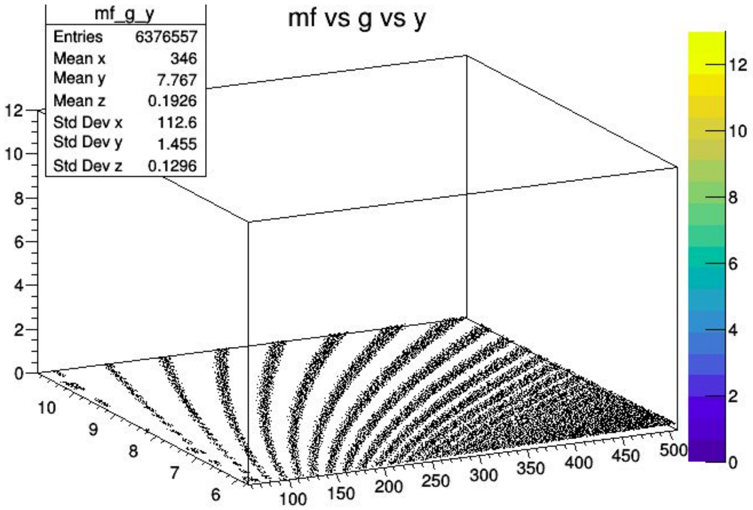
- Uncertainty of 0.1% (±10^-5) on Γ_{inv}



- # of events which have the same (mf, g, y) = 62 (since scanning 62 values of mV).
- How to read this plot: don’t care about the black dots, just care about the colz scale if it can reach 62.
- This plot: max # events is 11, so none is satisfied for the entire interested mV set

3rd model,1st approach, finner scan

- Use finner step for g and y: 0.01
- Uncertainty of 1%(±10^-5) on invisible Higgs width.



- We need at least one event (combination) to be repeated 62 times (for 62 values of mV), we have only 13!
- Going for more finer steps will exhaust resources.
- Moreover Γ_{inv} changes rapidly when fixing (mf,g,y) and scanning over mV.

3rd model,1st approach, finner scan

- Going for more finer steps will exhaust resources.
- Γ_{inv} change rapidly when fixing (mf,g,y) and scanning mV:
  - ~ 7e-4 GeV for mV < 15 GeV
  - ~ 5e-4 GeV for mV > 40 GeV

➔ Cannot get the same Γ_{inv} for all mV < mH/2

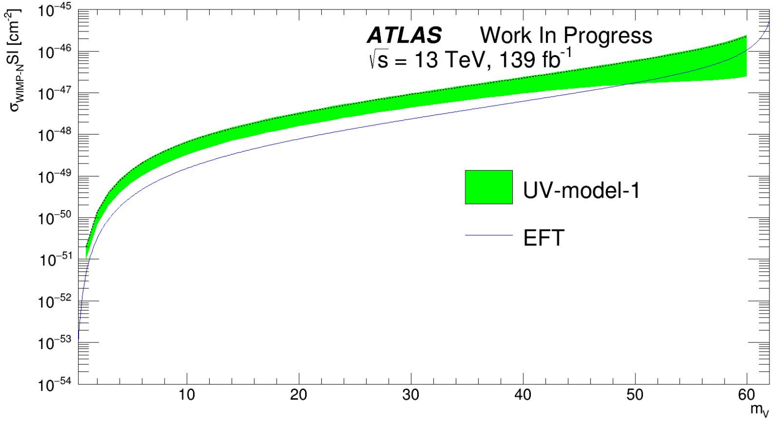
```
#mf     g       y
#65     10.37   0.01

Our invisible Higgs width = 11%/(1-0.11)*0.004 = 0.00049 GeV
```

mV	mf	g	y	Higgs invisible width
1	65.0	10.37	0.01	0.0007441391208616785
2	65.0	10.37	0.01	0.0007435423413102227
3	65.0	10.37	0.01	0.0007425481038199402
4	65.0	10.37	0.01	0.0007411570227112913
5	65.0	10.37	0.01	0.0007393700011593538
6	65.0	10.37	0.01	0.0007371882737907611
7	65.0	10.37	0.01	0.0007346134607016891
8	65.0	10.37	0.01	0.0007316476323468402
9	65.0	10.37	0.01	0.0007282933846408165
10	65.0	10.37	0.01	0.0007245539235130258
11	65.0	10.37	0.01	0.0007204331580671486
12	65.0	10.37	0.01	0.0007159358014179564
13	65.0	10.37	0.01	0.0007110674782137479
14	65.0	10.37	0.01	0.00070583483780394
15	65.0	10.37	0.01	0.0007002456719801719
16	65.0	10.37	0.01	0.0006943090362080227
17	65.0	10.37	0.01	0.000688035373276829
18	65.0	10.37	0.01	0.000681436638329341
19	65.0	10.37	0.01	0.0006745264242927281
20	65.0	10.37	0.01	0.0006673200868193398
21	65.0	10.37	0.01	0.0006598348679607486
22	65.0	10.37	0.01	0.0006520900179421977
23	65.0	10.37	0.01	0.0006441069145761542
24	65.0	10.37	0.01	0.0006359091800509722
25	65.0	10.37	0.01	0.0006275227950495402
26	65.0	10.37	0.01	0.0006189762103862148
27	65.0	10.37	0.01	0.0006103004565872978
28	65.0	10.37	0.01	0.0006015292520644614
29	65.0	10.37	0.01	0.0005926991107182459
30	65.0	10.37	0.01	0.0005838494499266199
31	65.0	10.37	0.01	0.0005750226998747284
32	65.0	10.37	0.01	0.0005662644150014899
33	65.0	10.37	0.01	0.0005576233878876937
34	65.0	10.37	0.01	0.000549151765065565
35	65.0	10.37	0.01	0.0005409051628249478
36	65.0	10.37	0.01	0.0005329427788957867
37	65.0	10.37	0.01	0.0005253274925872037
38	65.0	10.37	0.01	0.0005181259411275749
39	65.0	10.37	0.01	0.0005114085529817785
40	65.0	10.37	0.01	0.0005052495089936981
41	65.0	10.37	0.01	0.0004997265881570525
42	65.0	10.37	0.01	0.0004949208350250934
43	65.0	10.37	0.01	0.0004909159579034785
44	65.0	10.37	0.01	0.0004877973276804533
45	65.0	10.37	0.01	0.0004856503915216859
46	65.0	10.37	0.01	0.0004845582363977869
47	65.0	10.37	0.01	0.000484597923435347
48	65.0	10.37	0.01	0.0004858350482036298
49	65.0	10.37	0.01	0.000488315736914885
50	65.0	10.37	0.01	0.0004920549192700193
51	65.0	10.37	0.01	0.0004970191492506312
52	65.0	10.37	0.01	0.0005031013412812289
53	65.0	10.37	0.01	0.0005100833028864233
54	65.0	10.37	0.01	0.0005175793930465048
55	65.0	10.37	0.01	0.0005249500151845979
56	65.0	10.37	0.01	0.000531164721057104
57	65.0	10.37	0.01	0.0005345759498772379
58	65.0	10.37	0.01	0.0005325206807619932
59	65.0	10.37	0.01	0.0005205498614481623
60	65.0	10.37	0.01	0.0004907014200062816

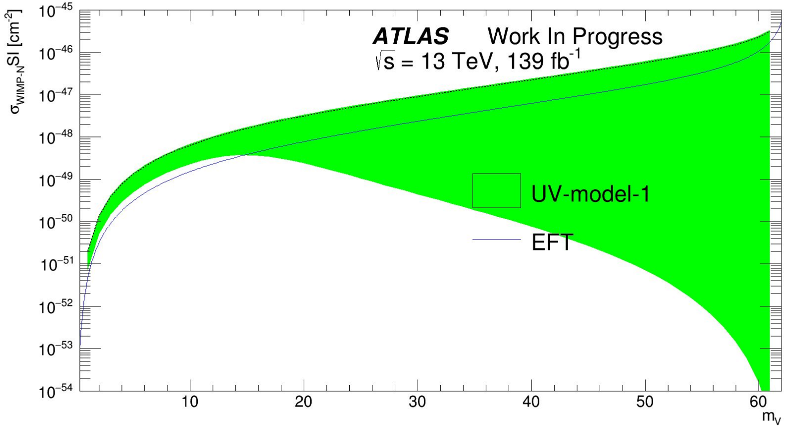
3rd model, 2nd approach

Instead of a single set of (mf,g,y) parameters, NOW exploiting the entire scanned phase space

(step 0.1 for g, y) $\Delta\Gamma_{inv} = \pm 0.1\%$



(step 0.01 for g, y) $\Delta\Gamma_{inv} = \pm 1\%$



- UV model has better bound than the EFT at certain range of the parameters space.