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U.S. DEPARTMENT OF ENERGY

Higgs portal vector dark matter interpretation: review of EFT approach and ultraviolet complete models

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Outline

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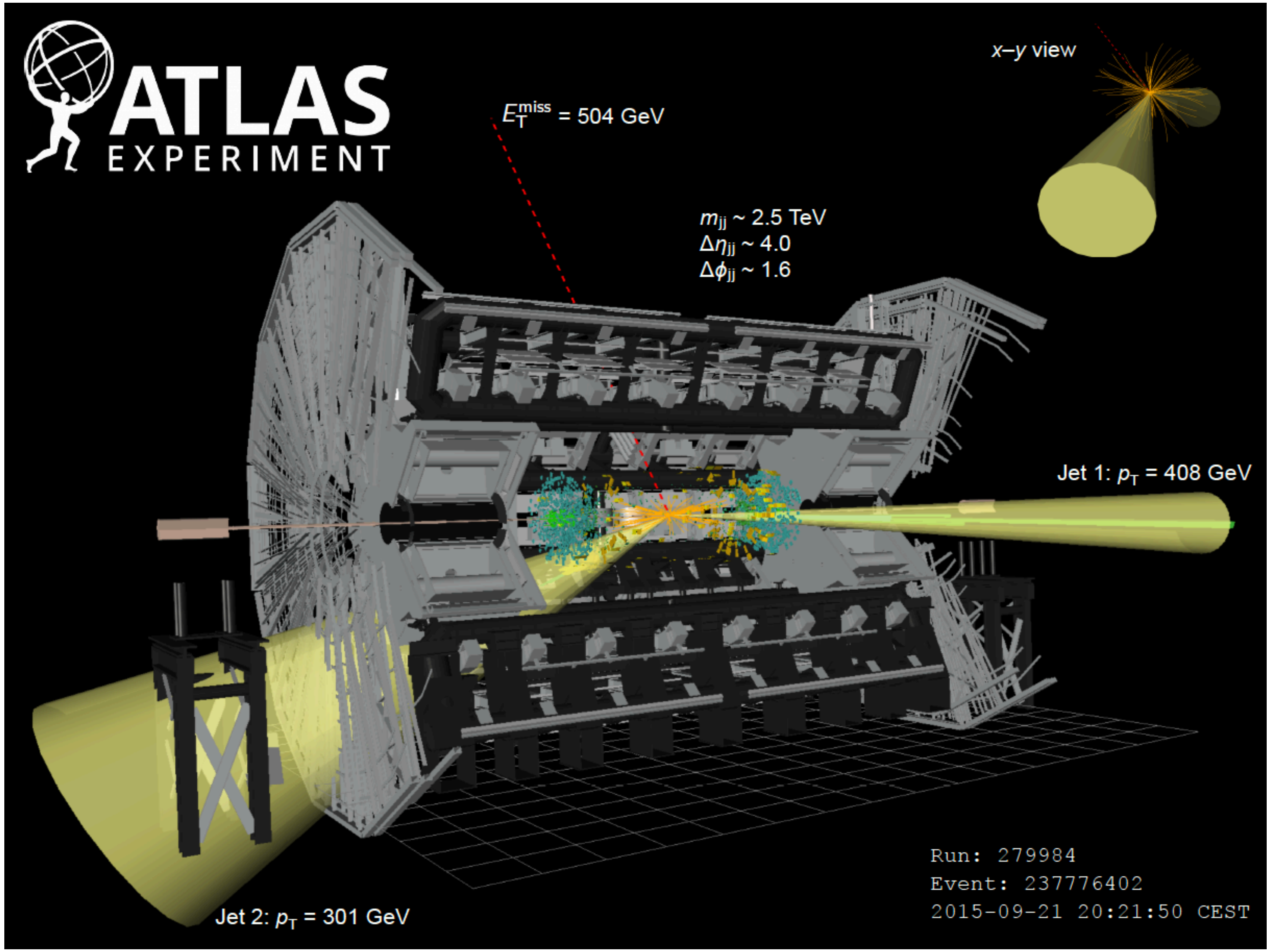
- Effective Field Theory
- Issue with EFT for vector-dark Matter interpretation
- UV-complete model
- Extension below 1 GeV
- Proposal for LHC Higgs port DM interpretation

- Snowmass white paper, arXiv:2107.01252
- Results published in LHEP-270, 2022

VBF H → invisible



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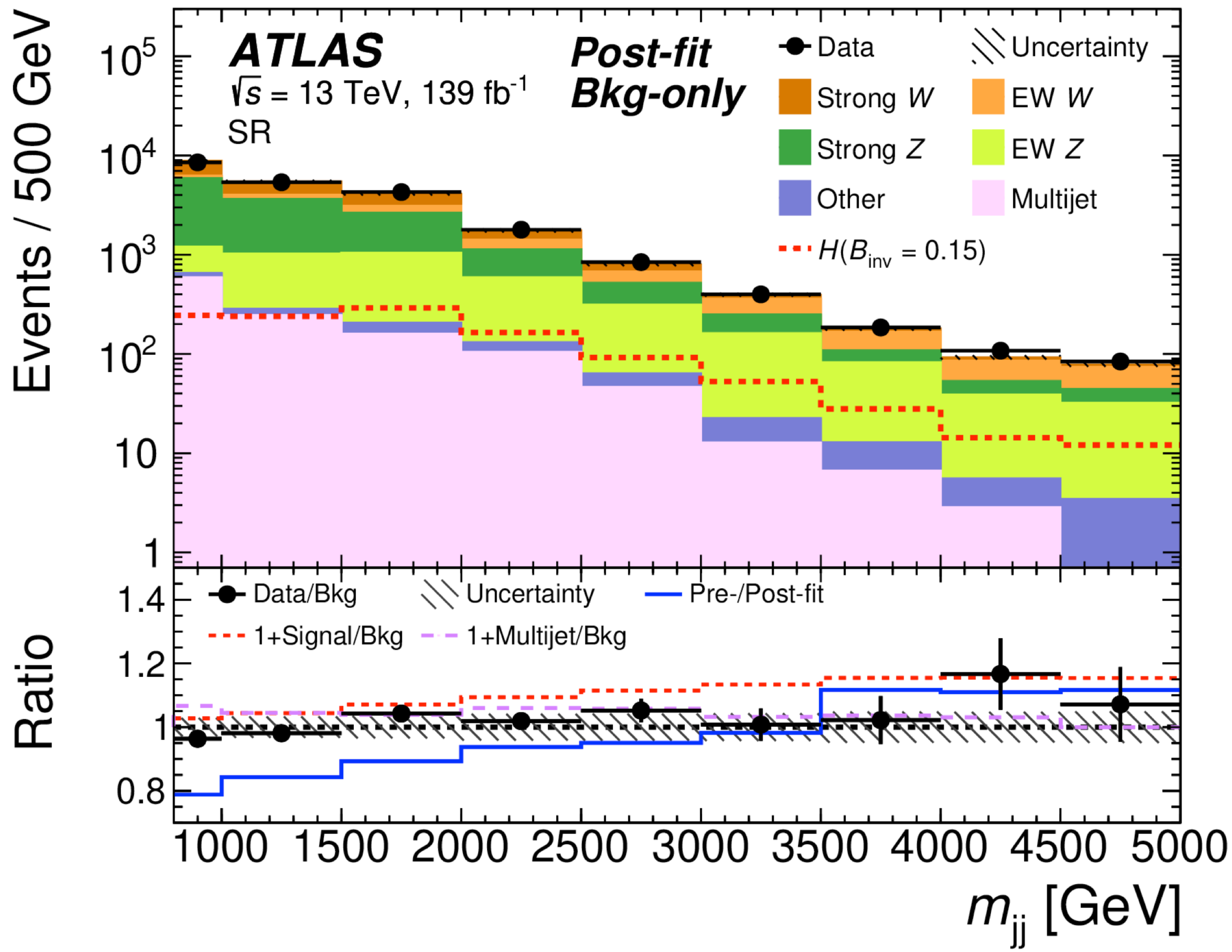
VBF H → Invisible Searches

JHEP 08 (2022) 104

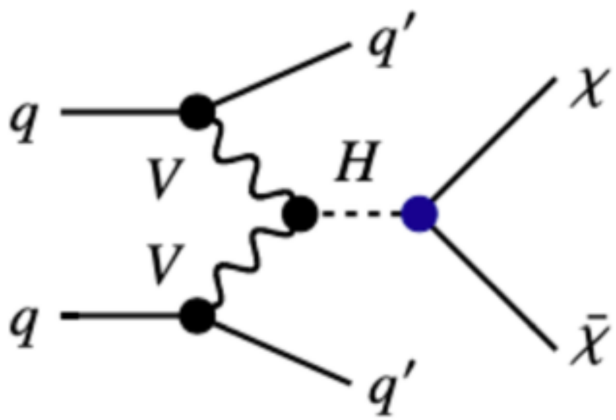


BR [H→ invisible] < 0.145 at 95%CL

EFT in Higgs portal DM interpretation

- Model-independent HVV Lagrangian

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



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

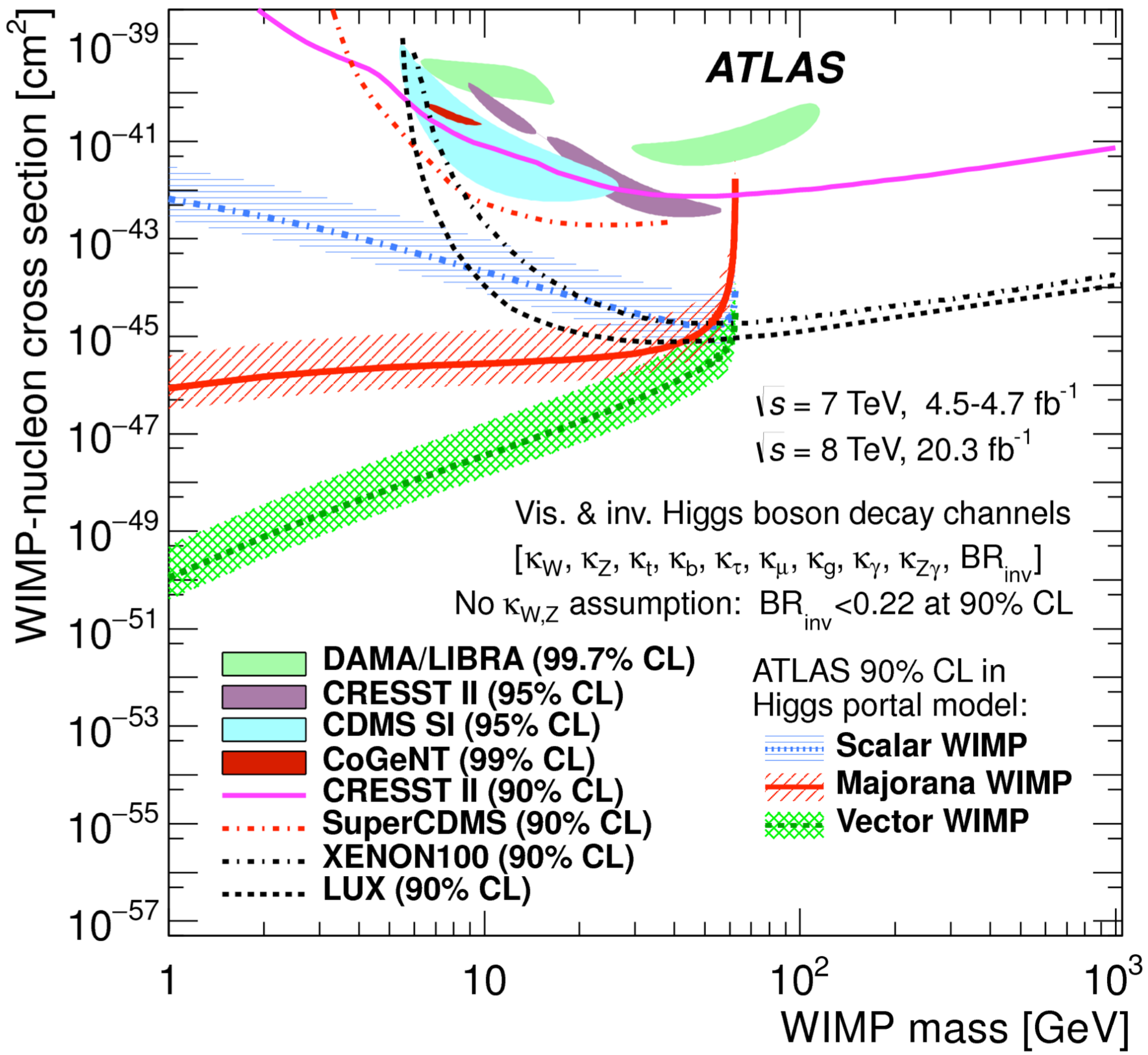
$$\sigma^{\rm SI}(\text{V-N})_{EFT} = \lambda_{HVV}^2 \frac{m_N^2 f_N^2}{16\pi m_H^4 (m_V + m_N)^2}$$

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

A. Djouadi, O. Lebedev, Y. Mambrini,
B. and J. Quevillon, arXiv:1112.3299

EFT Higgs portal interpretations

WIMP–nucleon scattering cross section in a Higgs portal model as a function of the mass of the dark-matter particle, shown separately for a scalar, Majorana fermion, or vector-boson WIMP



Objection to EFT Vector-DM interpretation

- In the EFT approach, the mass of the VDM was entered arbitrarily, which leads to a non-renormalisable Lagrangian and violation of unitarity
- For this reason, it is safer to consider a better framework, i.e. a simple UV completion with a dark Higgs sector that gives mass to the vector DM via spontaneous electroweak symmetry breaking
- The simplest renormalisable Lagrangian for the Higgs portal VDM in such a UV model

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

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

S. Baek, P. Ko, and W.-I. Park, arXiv:1405.3530
G. Arcadi, A. Djouadi, and M. Kado, arXiv:2001.10750

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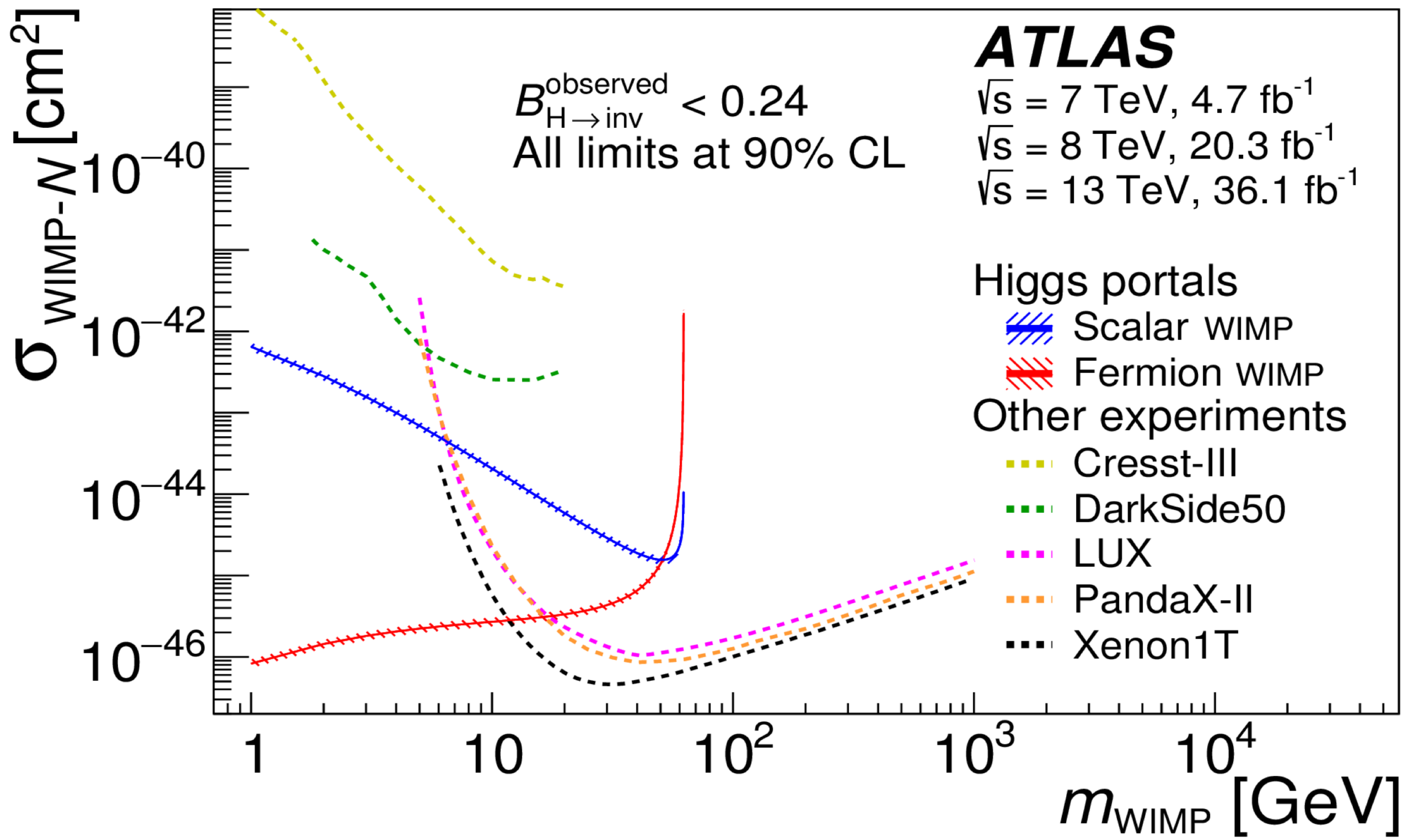
Higgs portal dark matter interpretation



Vector Dark Matter Interpretation later removed from LHC results

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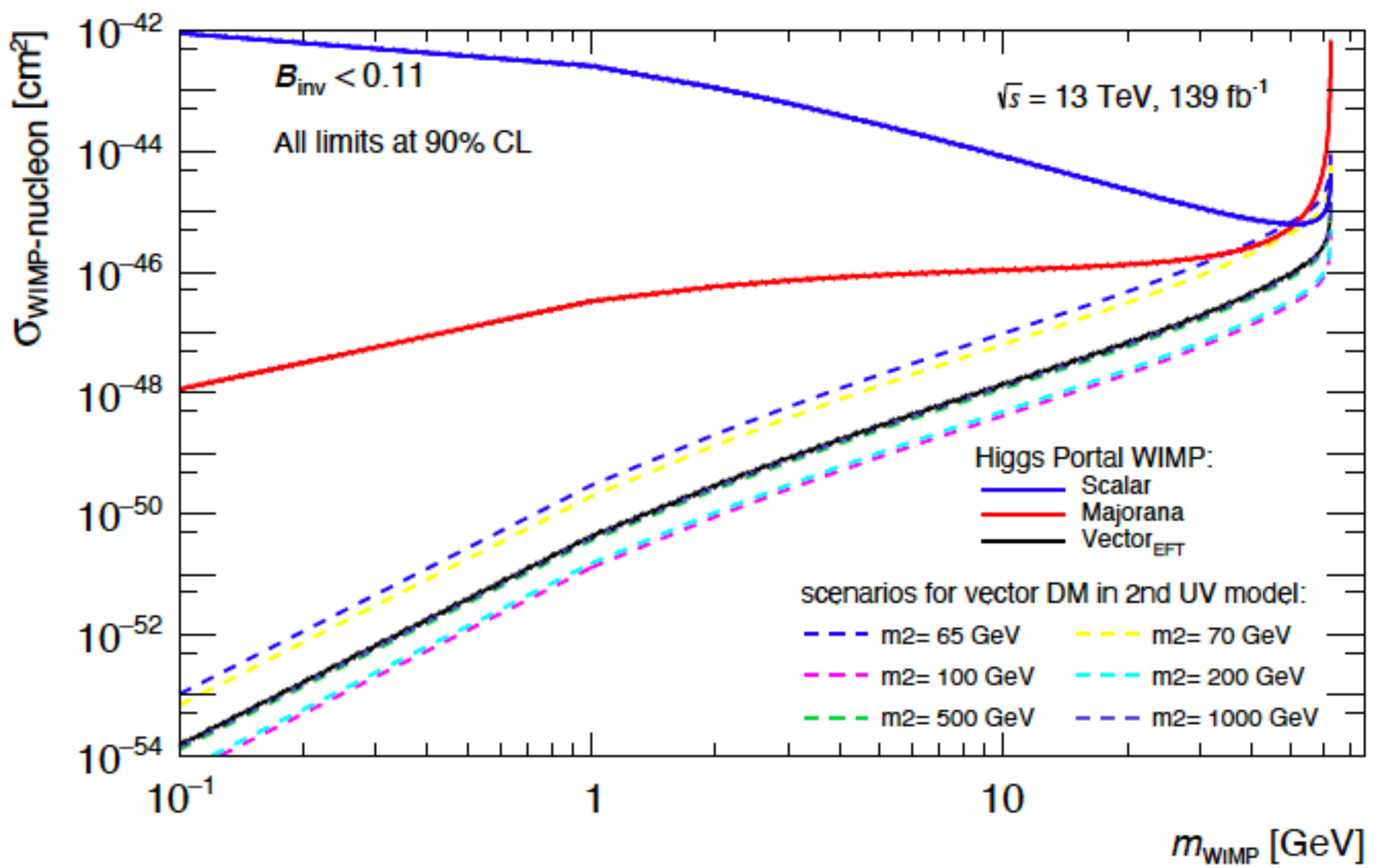
UV Complete Vector-DM interpretation



- The UV model tends to coincide with EFT as the dark Higgs mass get larger
- The usual EFT approach applies only in $m_2 \to \infty$ and $\cos(\theta) \to 1$

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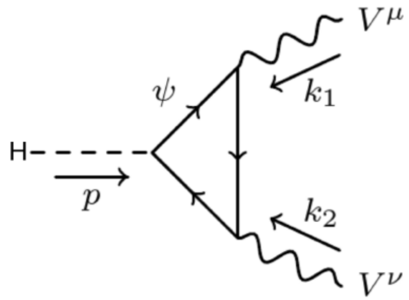
Radiative Higgs portal (1)

- The vector DM is introduced as a gauge field of a U(1)' group which extends the SM symmetry; a Dark Higgs sector is added in to produce the vector boson mass via the Higgs spontaneous symmetry breaking mechanism. The Lagrangian of the vector part is as the following :

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



This model has a distinctive feature in generating the HVV coupling, and the fermions charged under SM×U(1)' are added in

The minimal parameter space to be explored includes the vector mass m_V, the fermion mass m_f, the U(1)' coupling g and the Yukawa coupling y of the added fermion to the SM Higgs

No direct analytical relation between $\Gamma^{\mathrm{H}}_{\mathrm{inv}}$ and σ^{SI}(V-N)

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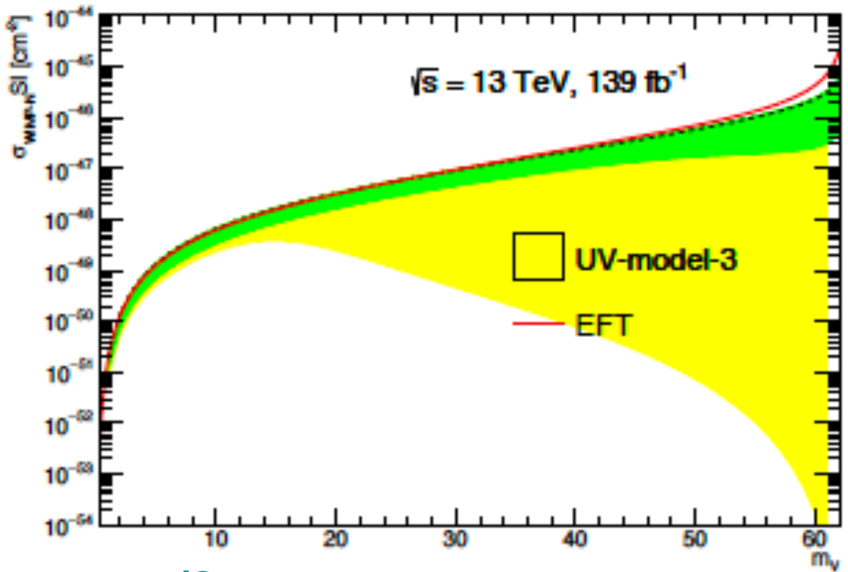
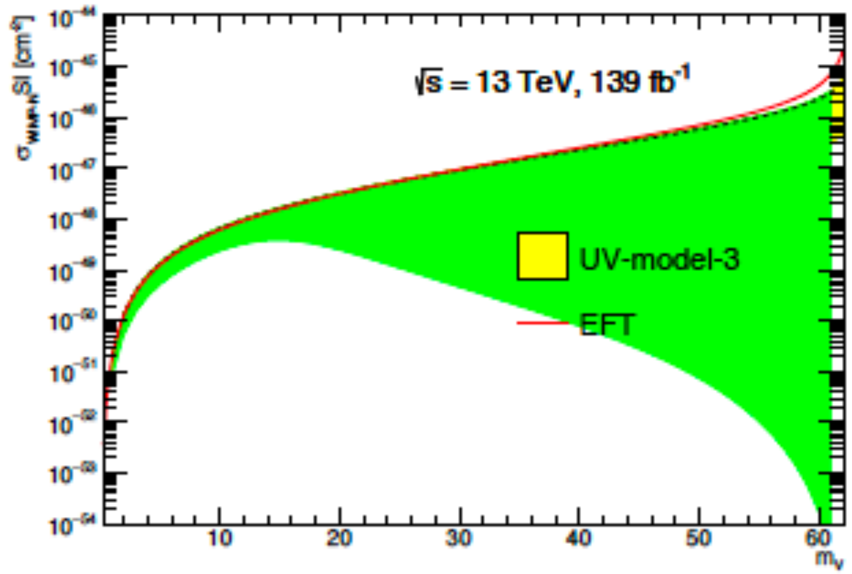
A. DiFranzo, P. J. Fox, and T. M. P. Tait, arXiv:1512.06853

Radiative Higgs portal (2)

- To obtain upper limit of $\sigma^{SI}(V\text{-}N)$ versus m_V based on the upper limit on BR ($H\rightarrow inv$),
- one has to find values of (m_f, g, y) which satisfy the BR($H\rightarrow inv$) upper limit within a certain precision, then calculate $\sigma^{SI}(V\text{-}N)$
- Explicitly, the task requires a scan through the set (mf, g, y) for each mV point to find values of Γ^{Hinv} corresponding to BR ($H\rightarrow inv$) of 11% within a relative precision of 0.1-1.0%





We also scan $m_f > m_H/2$

The fine scanning of (g, y) extends the lower bound of the green bands meaning that going finer in (g, y) one can achieve much better limits on $\sigma^{SI}(V\text{-}N)$ compared to EFT limit

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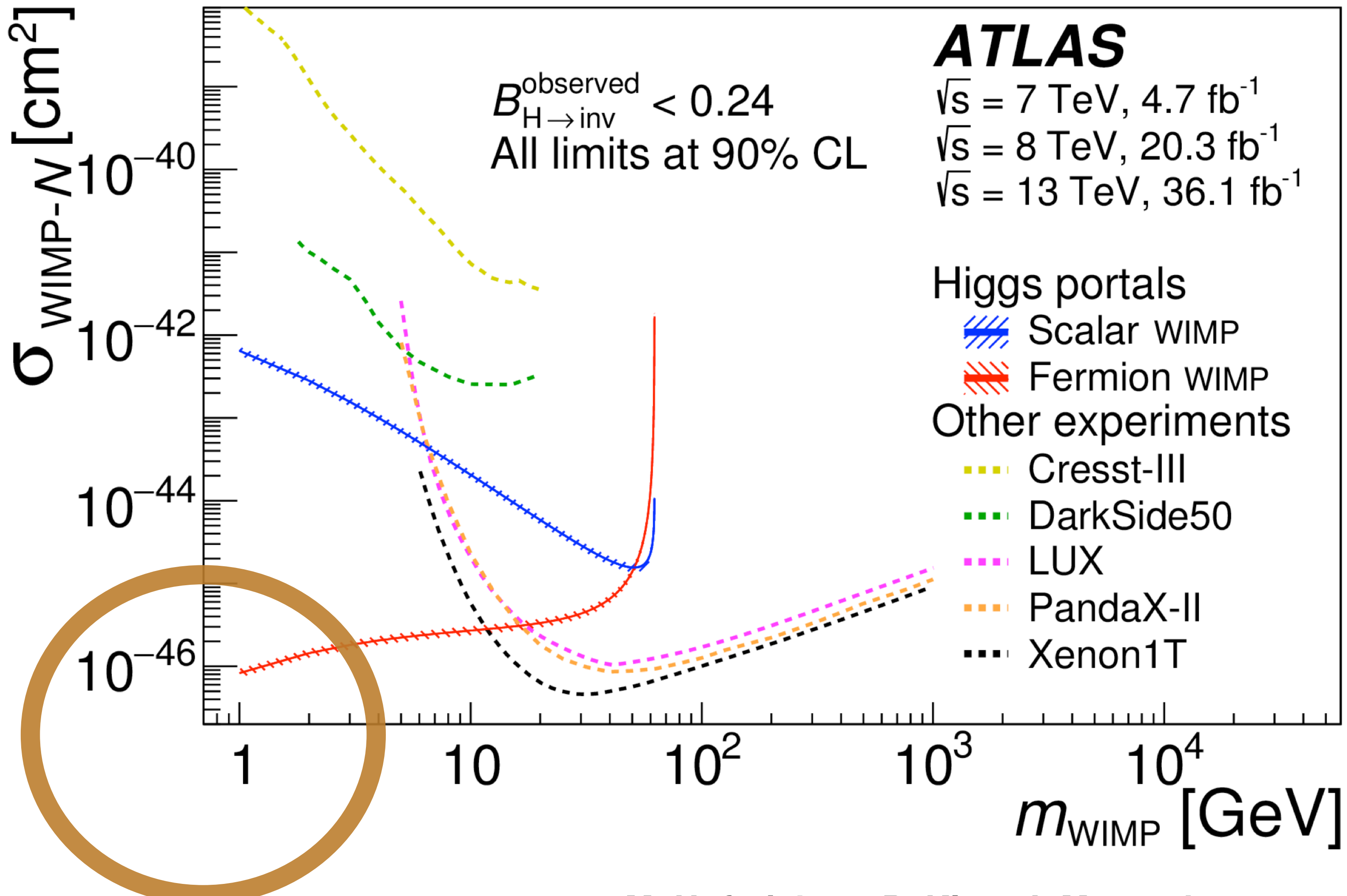
Extension below one GeV

- We propose to extend this plot below 1 GeV. The lower limit at 1 GeV appears arbitrary, from several considerations

- No theoretical or cosmological constraints on the WIMP mass at 1 GeV
- Lattice QCD calculations of Higgs-nucleon coupling valid continuously from negative to positive momentum transfer



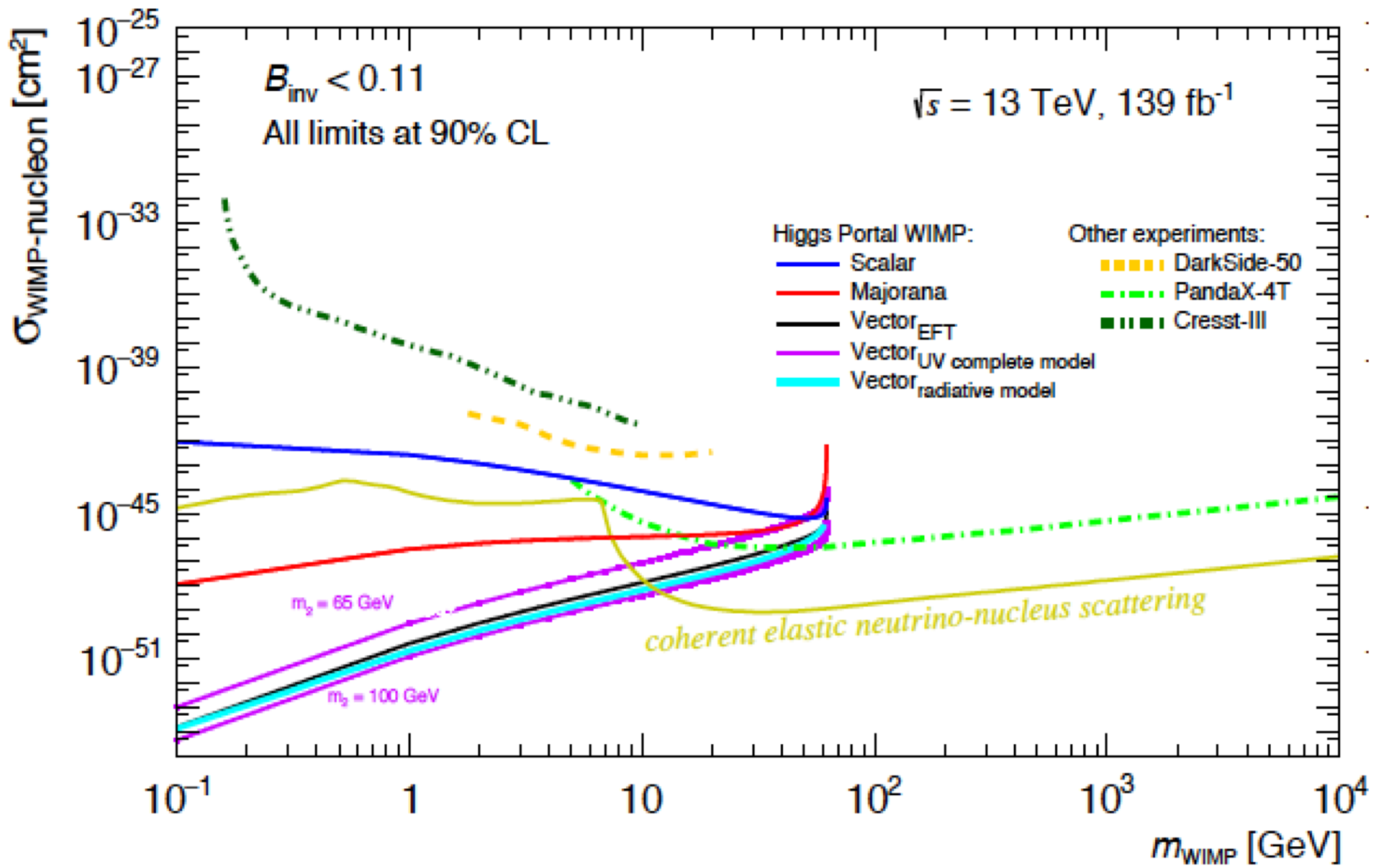
J. Billard, E. Figueroa-Feliciano, L. Strigari Phys. Rev. D 89, 023524 (2014)

M. Hoferichter, P. Klos, J. Menendez, and A. Schwenk, arXiv: 1708.02245

Our complete proposal for LHC Higgs portal DM

- Snowmass white paper, arXiv:2107.01252
- Results published in LHEP-270, 2022

- **This study motivated the re-introduction of vector-DM and also and extension < 1 GeV**
- **Already adopted by ATLAS—see earlier talk by Guglielmo Frattari.**



Conclusions

We studied several approaches for the interpretation of $\sigma^{SI}(V\text{-}N)$ in Higgs-portal DM scenarios. We reviewed EFT approach and showed it be safe to be reinserted in the LHC Higgs portal interpretation

We showed that, in certain regions of parameter space, results from UV complete models converge towards EFT prediction.

Our proposal for the LHC Higgs portal interpretation plot is to reinsert the EFT Vector-DM line, include the upper bound of a benchmark UV complete model, and the worst-best limits of benchmark UV complete models, depending on the dark Higgs mass.

Additionally, we proposed to extend the interpretation plot to 0.1 GeV