Effective vector and fermion Higgs portal: A global study

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Based on:


▶ Ongoing work with the GAMBIT Collaboration.

CosPA 2016, University of Sydney
November 29, 2016
1. Dark Matter (DM)
2. Higgs portal
   ▶ Models
   ▶ Constraints
   ▶ Results
3. Global fits
   ▶ GAMBIT
   ▶ Bayesian vs Frequentist Inference
   ▶ Initial scan details
   ▶ Preliminary results
4. Conclusions
Dark Matter (DM)

- Accounts for $\sim 27\%$ of the total matter-energy density.$^1$
- Has no electromagnetic or strong interactions $\implies$ “dark” and non-luminous.
- Evidence and properties are inferred from gravitational influences on visible matter, e.g.,
  - Galactic rotation curves,
  - Cosmic Microwave Background (CMB),
  - Gravitational lensing (e.g., Bullet cluster).
- No viable candidates for DM in the Standard Model (SM) $\implies$ beyond the SM (BSM) candidates.
- WIMPs are well-motivated DM candidates due to the “WIMP miracle.”

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Higgs portal

- Models with the following interaction Lagrangian

\[ \mathcal{L}_{\text{int}} \supset \frac{1}{\Lambda^n} X^2 H^\dagger H, \]

where \( \Lambda \) is the EFT cut-off scale, \( X \) is the DM field and \( H \) is the SM Higgs doublet.

- \( X \) can be a vector \( (V_\mu) \), Majorana \( (\chi) \) or Dirac \( (\psi) \) fermion. Model Lagrangians are

\[
\mathcal{L}_V = \mathcal{L}_{\text{SM}} - \frac{1}{4} W_{\mu\nu} W^{\mu\nu} + \frac{1}{2} \mu_V^2 V_\mu V^\mu - \frac{1}{4!} \lambda_V (V_\mu V^\mu)^2 + \frac{1}{2} \lambda_{hV} V_\mu V^\mu H^\dagger H,
\]

\[
\mathcal{L}_\chi = \mathcal{L}_{\text{SM}} + \frac{1}{2} \overline{\chi} (i\not\! \partial - \mu_\chi) \chi - \frac{1}{2} \frac{\lambda_{h\chi}}{\Lambda_\chi} \left( \cos \theta \overline{\chi} \chi + \sin \theta \overline{\chi} i\gamma_5 \chi \right) H^\dagger H,
\]

\[
\mathcal{L}_\psi = \mathcal{L}_{\text{SM}} + \overline{\psi} (i\not\! \partial - \mu_\psi) \psi - \frac{\lambda_{h\psi}}{\Lambda_\psi} \left( \cos \theta \overline{\psi} \psi + \sin \theta \overline{\psi} i\gamma_5 \psi \right) H^\dagger H.
\]

- In the fermion models, \( \cos \theta = 1(0) \implies \) pure scalar (pseudoscalar) and parity conserving (violating) interaction.

- DM is stabilised by imposing an assumed \( \mathbb{Z}_2 \) symmetry: \( X \rightarrow -X \) for \( X \in (V_\mu, \chi, \psi) \).
After Electroweak Symmetry Breaking (EWSB),

\[ X^2 H^+ H \rightarrow X^2 \left( \frac{1}{2} v_0^2 + v_0 h + \frac{1}{2} h^2 \right), \]

where \( v_0 = 246.22 \) GeV is the SM Higgs VEV and \( h \) is the physical SM Higgs field.

The term \( \propto v_0 h X^2 \) leads to all the known DM phenomenology.

Fig. 3: Methods to look for Higgs portal DM at colliders (left), indirect (center) and direct (right) detection experiments. Here, \( N \in (p, n) \) and SM \( \in q\bar{q}, l\bar{l}, W^+ W^-, ZZ, hh. \)
The physical vector DM mass is

\[ m_V = \sqrt{\mu_V^2 + \frac{1}{2} \lambda_{hV} v_0^2}. \]  

(1)

If \( \sin \theta \neq 0 \) in the fermion models \( \Rightarrow \) non-mass-type contributions. Redefine fields by performing a chiral rotation

\[ X \rightarrow \exp(i\gamma_5 \alpha/2)X, \quad \overline{X} \rightarrow \overline{X} \exp(i\gamma_5 \alpha/2), \]

where \( X \in (\chi, \psi) \) and \( \alpha \) is a constant.

Require coefficients of \( \overline{X}i\gamma_5X \rightarrow 0 \) in the real mass basis, leading to the following post-EWSB Lagrangian

\[
\mathcal{L}_X = \mathcal{L}_{SM} + \kappa \overline{X}(i\not\!\partial - m_X)X - \kappa \frac{\lambda_{hX}}{\Lambda_X} \left( \cos \xi \overline{XX} + \sin \xi \overline{X}i\gamma_5X \right) \left( v_0 h + \frac{1}{2} h^2 \right),
\]

where \( \xi \equiv \theta + \alpha \) and \( \kappa = 1/2 \) (1) for the Majorana (Dirac) fermion DM.

The physical fermion DM mass is

\[ m_X = \sqrt{\left( \mu_X + \frac{1}{2} \frac{\lambda_{hX}}{\Lambda_X} v_0^2 \cos \theta \right)^2 + \left( \frac{1}{2} \frac{\lambda_{hX}}{\Lambda_X} v_0^2 \sin \theta \right)^2}. \]  

(2)
Constraints

1. **Relic density**: model’s relic density \((\Omega_X h^2)\) must match with the Planck (2013) measured value\(^2\)

\[
\Omega_{\text{DM}} h^2 = 0.1199.
\]

2. **Higgs invisible width**: require the Higgs invisible branching ratio\(^3\)

\[
\mathcal{BR}(h \to XX) \leq 0.19 \quad (2\sigma \text{ C.L.})
\]

3. **Indirect detection (ID)**: satisfy constraints from\(^4\)

- cosmic microwave background (CMB) radiation,
- combined analysis of 15 dwarf galaxies by Fermi-LAT,
- projected limits from the Cherenkov Telescope Array (CTA).

In the fermion models, \(\cos \xi = 1 \implies \) weak indirect search limits (due to a \(v^2\)-suppressed annihilation cross section).

4. **Direct detection (DD)**: constraints from the LUX (2013) and projected XENON1T experiments\(^5\)

In the fermion models, \(\cos \xi = 0 \implies \) weak direct search limits (due to a \(q^2\)-suppressed SI cross section).

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\(^3\) G. Belanger et al., PRD, 88, 075008 (2013), [arXiv: 1306.2941].


Results

Vector DM: Low mass range

Fig. 4: Indirect (left) and direct (right) search limits in the low mass range.

- Grey (pink) region: excluded by relic density (Higgs invisible width) constraint.
- Current ID limits: CMB (WMAP7) + Fermi-LAT (15 dSphs, 6 years);
- Future ID limits: CMB (Planck) + proj. Fermi-LAT + proj. CTA.
Fig. 5: Indirect (left) and direct (right) search limits in the low mass range when $\cos \xi = 1$ (top) and 0 (bottom).
For these simple portal models, we have

- Combined limits from various DM searches;
- Overlayed the exclusion limits on top of each other;
- Showed the allowed and/or excluded regions of the model parameter space.

What if we instead want to

- Combine *all* constraints consistently (e.g., using a composite likelihood function)?
- Vary SM, nuclear and astrophysical parameters (i.e., “nuisance parameters”) within their allowed ranges?

Such questions are addressed by global studies/fits.
GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org

- Fast definition of new datasets and theoretical models
- Plug and play scanning, physics and likelihood packages
- Extensive model database – not just SUSY
- Extensive observable/data libraries

- Many statistical and scanning options (Bayesian & frequentist)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

ATLAS
LHCb
Belle-II
Fermi-LAT
CTA
HESS
IceCube
XENON/DARWIN
Theory

A. Buckley, P. Jackson, C. Rogan, M. White,
M. Chrząszcz, N. Serra
F. Bernlochner, P. Jackson
J. Conrad, J. Edsjö, G. Martinez, P. Scott
C. Balázs, T. Bringmann, J. Conrad, M. White
J. Conrad
J. Edsjö, P. Scott
J. Conrad, R. Trotta
P. Athron, C. Balázs, T. Bringmann,
J. Cornell, J. Edsjö, B. Farmer, T. Gonzalo, A. Fowle,
J. Harz, S. Hoof, F. Kahlhoefer, A. Krislock,
A. Kvellestad, M. Pato, F.N. Mahmoudi, J. McKay,
A. Raklev, R. Ruiz, P. Scott, R. Trotta, C. Weniger,
M. White, S. Wild

31 Members, 9 Experiments, 4 major theory codes, 11 countries

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6 Slide taken from P. Scott's talk at IDM, Sheffield, July 2016.
Bayesian vs Frequentist Inference

**Bayesian inference**

- Based on Bayes’ theorem

\[
p(\theta|D) = \frac{p(D|\theta)p(\theta)}{\int p(D|\theta')p(\theta') d\theta'} ,
\]

where \(D\) is the data, \(\theta\) are the model parameters, \(p(\theta|D)\) = posterior PDF, \(p(D|\theta) \equiv L(\theta)\) = likelihood function and \(p(\theta)\) = prior PDF.

- **Marginalised posterior for \(\theta_i\)** is

\[
p_m(\theta_i|D) = \int p(\theta|D) d\theta_1 \ldots d\theta_{i-1} d\theta_{i+1} \ldots d\theta_n.
\]

- \(p_m(\theta_i|D)\) peaks at the region of highest posterior mass.

**Frequentist inference**

- Use a likelihood function \(L(\theta)\).

- **Profile likelihood for \(\theta_i\)** is

\[
L_p(\theta_i) = \max_{\{\theta_1, \ldots, \theta_{i-1}, \theta_{i+1}, \ldots, \theta_n\}} L(\theta).
\]

- \(L_p(\theta_i)\) peaks at the region of highest likelihood.

**Fig. 6:** 1D profile likelihood and marginalised posterior distributions. Figure made by Roberto Trotta.
### Initial scan details

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_V$ (GeV)</td>
<td>[45, 70]</td>
<td>flat</td>
</tr>
<tr>
<td>$\lambda_{hV}$</td>
<td>$[1.0 \times 10^{-4}, 10]$</td>
<td>log</td>
</tr>
</tbody>
</table>

**Table 1:** Vector DM model parameters and their ranges.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Central value</th>
<th>Uncertainty</th>
<th>Range</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_F$ (GeV$^{-2}$)</td>
<td>$1.1663787 \times 10^{-5}$</td>
<td>$6.0 \times 10^{-12}$</td>
<td>$[1.1663769 - 1.1663805] \times 10^{-5}$</td>
<td>flat</td>
</tr>
<tr>
<td>$\alpha - 1$</td>
<td>127.940</td>
<td>0.014</td>
<td>$[127.898, 127.982]$</td>
<td>flat</td>
</tr>
<tr>
<td>$m_d$ (GeV) (@ 2 GeV in MS)</td>
<td>-</td>
<td>-</td>
<td>$[3.84 - 5.76] \times 10^{-3}$</td>
<td>flat</td>
</tr>
<tr>
<td>$m_u$ (GeV) (@ 2 GeV in MS)</td>
<td>-</td>
<td>-</td>
<td>$[1.84 - 2.76] \times 10^{-3}$</td>
<td>flat</td>
</tr>
<tr>
<td>$m_s$ (GeV) (@ 2 GeV in MS)</td>
<td>$95 \times 10^{-3}$</td>
<td>$5.0 \times 10^{-3}$</td>
<td>$(80 - 110) \times 10^{-3}$</td>
<td>flat</td>
</tr>
<tr>
<td>$m_b$ (GeV) (@ $m_b$ in MS)</td>
<td>4.18</td>
<td>0.03</td>
<td>[4.09, 4.27]</td>
<td>flat</td>
</tr>
<tr>
<td>$m_c$ (GeV) (@ $m_c$ in MS)</td>
<td>1.275</td>
<td>0.025</td>
<td>[1.2, 1.35]</td>
<td>flat</td>
</tr>
<tr>
<td>$m_t$ (GeV)</td>
<td>173.34</td>
<td>0.76</td>
<td>[171.06, 175.62]</td>
<td>flat</td>
</tr>
<tr>
<td>$m_h$ (GeV)</td>
<td>125.09</td>
<td>0.24</td>
<td>[124.1, 127.3]</td>
<td>flat</td>
</tr>
<tr>
<td>$\sigma_s$ (MeV)</td>
<td>43</td>
<td>8</td>
<td>[19, 67]</td>
<td>flat</td>
</tr>
<tr>
<td>$\sigma_l$ (MeV)</td>
<td>58</td>
<td>9</td>
<td>[31, 85]</td>
<td>flat</td>
</tr>
<tr>
<td>$\rho_0$ (GeV/cm$^3$)</td>
<td>0.4</td>
<td>0.15</td>
<td>[0.2, 0.8]</td>
<td>flat</td>
</tr>
</tbody>
</table>

**Table 2:** Fermion DM model parameters and their ranges.

**Table 3:** A list of SM, nuclear and astrophysical parameters included in the initial scan. Except for the $\rho_0$ likelihood (log-normally distributed), likelihoods for all other parameters were chosen to be **Gaussian**. For the $u$ and $d$ quarks, a Gaussian likelihood was constructed instead from the mass ratios: $m_u/m_d$ and $2m_s/(m_u + m_d)$. The parameters $\sigma_s \equiv m_s \langle N|\bar{s}s|N\rangle$ and $\sigma_l \equiv m_l \langle N|\bar{u}u + \bar{d}d|N\rangle$ where $m_l \equiv (1/2)(m_u + m_d)$ and $N \in (p, n)$ are the strangeness and light quark matrix elements respectively.
Preliminary results: Vector DM

**Fig. 7:** Results from arXiv: 1512.06458.

Current constraints include:

- Planck (2015) measured DM relic density;
- Higgs invisible width (i.e., $BR(h \rightarrow XX) \leq 0.19$ @ 2σ C.L.);
- Fermi-LAT combined analysis of 15 dSphs;

**Fig. 8:** Preliminary results from GAMBIT.
Preliminary results: Dirac fermion DM

Fig. 9: Comparison of results between GAMBIT (top) for \( \cos \xi \in [0, 1] \) and arXiv: 1512.06458 (bottom).
Conclusions

- Higgs portal models provide rich DM phenomenologies.
- The combined DM relic density, Higgs invisible width and direct search limits exclude most of the low mass region (except for $m_X \sim m_h/2$).
- Direct searches are playing, and will continue to play a crucial role in excluding parts of the model parameter space.
- Indirect searches, although weaker, are also important (particularly when the DM-Higgs boson interaction is pure pseudoscalar, i.e., $\cos \xi = 0$).

Coming up:
- First proper global study of the nonscalar portal models.
Backup slides
Fig. 10: Indirect (left) and direct (right) search limits in the low (top) and high (bottom) mass range.
Results

Vector DM: High mass range

Fig. 11: Indirect (left) and direct (right) search limits in the high mass range.
Fig. 12: Indirect (left) and direct (right) search limits in the high mass range when \( \cos \xi = 1 \) (top) and 0 (bottom).

Dirac fermion DM: High mass range
Fig. 13: Indirect (left) and direct (right) search limits in the low mass range when $\cos \xi = 1$ (top) and 0 (bottom).
Fig. 14: Indirect (left) and direct (right) search limits in the high mass range when $\cos \xi = 1$ (top) and 0 (bottom).
Preliminary results: Majorana fermion DM

![Graphs showing results for Majorana fermion DM](image)

**Fig. 15:** Comparison of results between GAMBIT (top) for $\cos \xi \in [0, 1]$ and arXiv: 1512.06458 (bottom).