Global study of effective Higgs portal dark matter models using GAMBIT

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(On behalf of the GAMBIT Collaboration)

P. Athron et al., *Global analyses of Higgs portal singlet dark matter models using GAMBIT*, EPJC **79** (2019) no. 1, 38, [arXiv:**1808.10465**]

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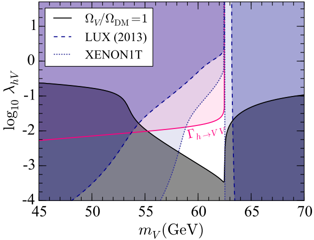
Outline

1. Global fits and GAMBIT
2. Effective Higgs portal models
3. Observables and constraints
4. Results
5. Summary

Global fits and GAMBIT

- Many theories for particle dark matter (DM).
- Test theories with *few* model parameters, e.g., vector Higgs portal.
- Exclude parameter space using theoretical and observational constraints.



[AB, F. Rajec et al., *PRD*, arXiv:1512.06458]

Theories with *many* free parameters/constraints?

- Construct a *composite likelihood* function:

$$\mathcal{L}_{\rm total} = \mathcal{L}_{\rm DM} \times \mathcal{L}_{\rm Higgs} \times \mathcal{L}_{\rm Collider} \times \dots \tag{1}$$

- Explore parameter space using advanced sampling techniques.
- Interpret results in *frequentist* and/or *Bayesian* statistical frameworks.

⟶ **GAMBIT**

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org EPJC **77** (2017) 784 arXiv:1705.07908

- 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

Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON
Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTols, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages

Recent collaborators:
Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danninger, Joakim Edsjö, Ben Farmer, Andrew Fowlie, Tomás E. Gonzalo, Will Handley, Sebastian Hoof, Selim Hotinli, Felix Kahlhoefer, Anders Kvellestad, Julia Harz, Paul Jackson, Farvah Mahmoudi, Greg Martinez, Are Raklev, Janina Renk, Chris Rogan, Roberto Ruiz de Austri, Pat Scott, Patrick Stöcker, Aaron Vincent, Christoph Weniger, Martin White, Yang Zhang

40+ participants in 11 experiments and 14 major theory codes

GAMBIT results

Supersymmetry:

- CMSSM/NUHM1/NUHM2 (EPJC, arXiv:1705.07935)
- MSSM7 (EPJC, arXiv:1705.07917)

Other beyond the SM theories:

- Axion and axion-like particles (JHEP, arXiv:1810.07192)
- Higgs portal: scalar singlet (EPJC, arXiv:1806.11281)
- Higgs portal: vector and fermion singlet **This talk**
  (EPJC, arXiv:1808.10465)

GAMBIT talks @ TeVPA (Particle Physics session):

- Electroweak MSSM **Pat Scott** (Today @ 14:50)
  (EPJC, arXiv:1809.02097)
- GUM: GAMBIT Universal Model **Sanjay Bloor** (Today @ 15:10)
  (coming soon!)
- Right-handed neutrinos **Tomás Gonzalo** (Today @ 15:30)
  (arXiv:1908.02302)

Effective Higgs portal models

(EPJC, arXiv:**1808.10465**)

- $H^\dagger H$ – lowest dimensional, gauge-invariant operator.
- Vector (V_μ) and Majorana fermion[1] (χ) fields with $\mathbb{Z}_2$ symmetry:

$$(V_\mu, \chi) \to -(V_\mu, \chi). \tag{2}$$

- Lagrangians after EWSB and chiral rotation: $\chi \to e^{i\gamma_5 \alpha/2}\chi$ are

$$\mathscr{L}_V \supset \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{2} \lambda_{hV} V_\mu V^\mu \left(v_0 h + \frac{1}{2} h^2\right), \tag{3}$$

$$\mathscr{L}_\chi \supset \frac{1}{2} \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{2} \frac{\lambda_{h\chi}}{\Lambda_\chi} (\cos\xi\, \overline{\chi}\chi + \sin\xi\, \overline{\chi} i\gamma_5 \chi)\left(v_0 h + \frac{1}{2} h^2\right). \tag{4}$$

Note: $\xi = 0, \pi\ (\pi/2) \implies$ pure scalar (pseudo-scalar) interaction.

- Free model parameters:

$m_V,\ \lambda_{hV}$ (Vector DM);
$m_\chi,\ \lambda_{h\chi}/\Lambda_\chi,\ \xi$ (Majorana fermion DM).

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[1] Similar for a Dirac fermion field ψ.

Observables and constraints

Theoretical constraints:

- Perturbative unitarity of $VV \to hh$ scattering amplitudes,
$$0 \leq \lambda_{hV} \leq 2m_V^2/v_0^2.$$
- EFT validity of Majorana fermion DM model,
$$\lambda_{h\chi}/\Lambda_\chi < 4\pi/(2m_\chi).$$

Sanjay Bloor

Observational constraints:

1. Thermal relic density;
2. Higgs invisible decays $(h \to VV,\ \chi\chi)$;
3. Indirect detection via gamma rays;
4. Direct detection (XENON1T 2018; LUX 2016; PandaX 2016, 2017; CDMSlite; CRESST-II; PICO-60 and DarkSide-50);
5. Solar DM capture and annihilation.

+ 7 important Standard Model (SM), nuclear and astrophysical *nuisance parameters*.

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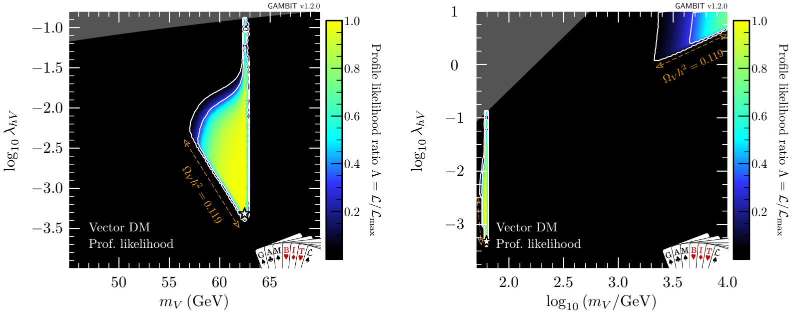
Results

Vector DM

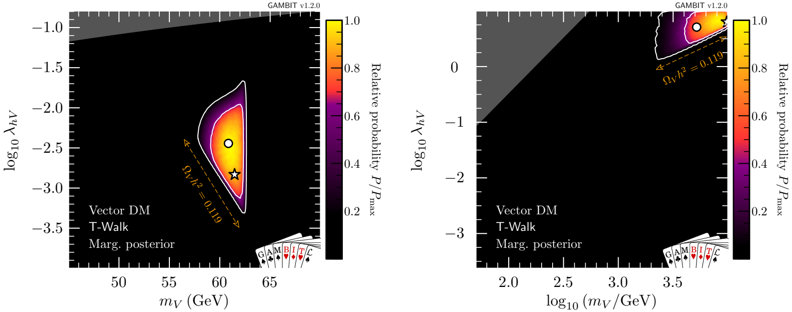
Profile likelihoods



(**White star** = best-fit point)

- Perturbative unitarity (*dark grey*) shortens ‘neck’ region at $m_V \sim m_h/2$, c.f. $\mathbb{Z}_2$ symmetric scalar model. (EPJC, arXiv:1806.11281, arXiv:1705.07931)
- Viable solutions at low and high vector masses.

Marginalised posteriors



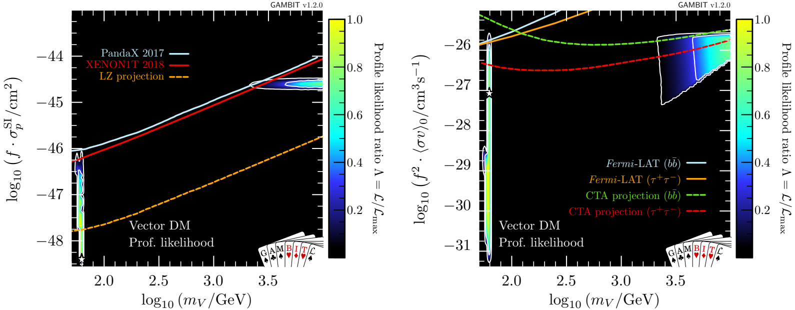
(**White star** = best-fit point, **White circle** = posterior mean)

- ‘Neck’ region disfavoured after marginalising over nuisance parameters, particularly m_h.
- Fine-tuned ‘resonance’ region falls outside 2σ credible interval in full mass-range scan.

Results

Vector DM

DM observables

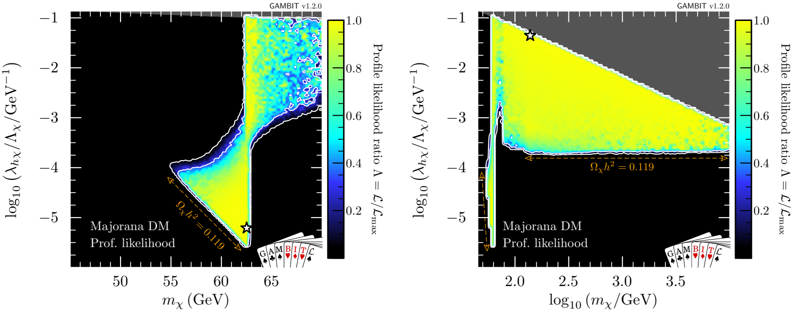


- Direct (indirect) detection signals scaled by $f \equiv \Omega_V/\Omega_{\mathrm{DM}}$ (f^2).
- Future direct searches will (fully) explore high vector masses.

Results

Majorana fermion DM

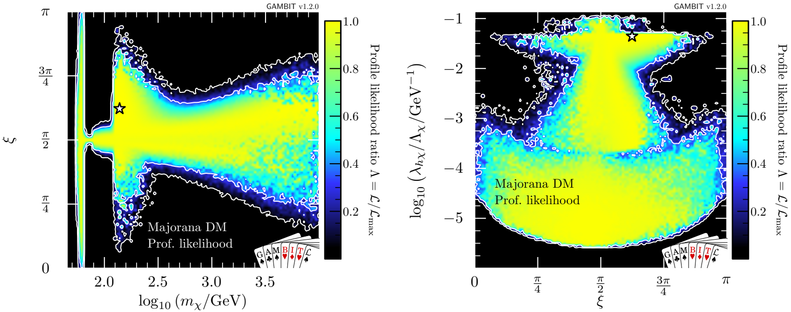
Profile likelihoods



- Resonance and high mass regions now connected → effect of mixing parameter ξ.
- EFT validity constraint (*dark grey*) cuts out large $\lambda_{h\chi}/\Lambda_\chi$ values.

Results

Majorana fermion DM



Suppressed direct detection rates when $\xi = \pi/2$ (CP-violating coupling):

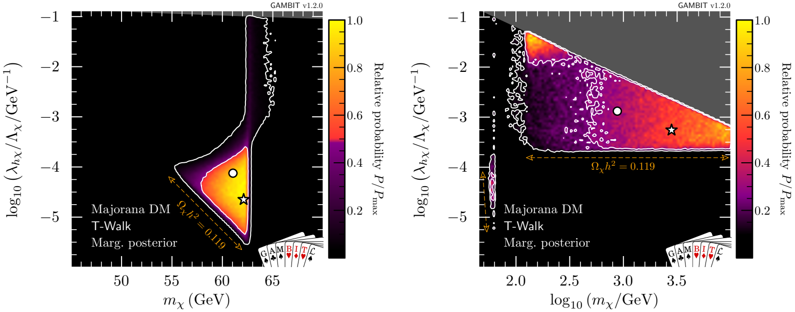
$$\frac{d\sigma_{\text{SI}}}{dq^2} \propto \frac{1}{v^2}\left(\frac{\lambda_{h\chi}}{\Lambda_\chi}\right)^2\left[\cos^2\xi + \frac{q^2}{4m_\chi^2}\sin^2\xi\right], \qquad (5)$$

where $|q| \simeq (1 - 100)$ MeV $\ll m_\chi$.

Results

Majorana fermion DM

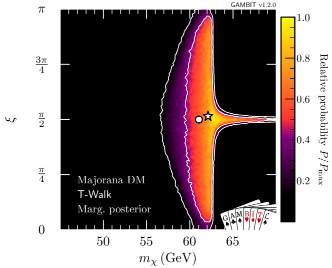
Marginalised posteriors

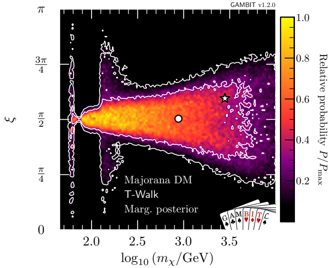


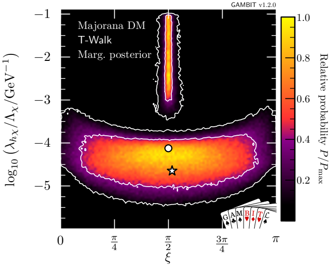
- Free parameter $\xi \implies$ larger (allowed) parameter space than $\xi = 0$ case.
- Resonance region less favoured in full mass-range scan.

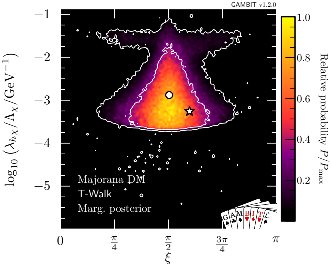
Results

Majorana fermion DM





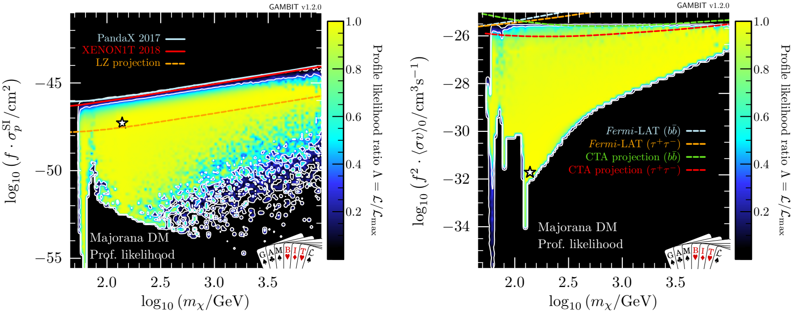




Results

Majorana fermion DM

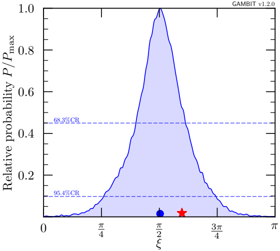
DM observables



- Cross section (σ_{SI}) at reference momentum exchange of $q = 50\,\mathrm{MeV}$.
- Large portions of parameter space will remain unexplored due to q^2 suppression.

Summary

- Resonance ($m_{V,\chi} \simeq m_h/2$) and high mass regions compatible with all experimental constraints.
- Fermion DM models with CP-violating ($\xi \approx \pi/2$) couplings favoured due to q^2 suppression.
- Future indirect/direct searches will probe high mass regions, albeit less so for CP-violating case.



All results, samples and input files available via Zenodo:

https://www.zenodo.org/communities/gambit-official/

GAMBIT code is publicly available:

https://gambit.hepforge.org

Backup slides

GAMBIT modules

1. DarkBit (EPJC, arXiv:1705.07920)
   Relic density, indirect and direct detection.
2. SpecBit, DecayBit and PrecisionBit (EPJC, arXiv:1705.07936)
   Spectrum calculation, decay widths and precision observables.
3. FlavBit (EPJC, arXiv:1705.07933)
   Flavour physics, observables and likelihoods.
4. ColliderBit (EPJC, arXiv:1705.07919)
   Collider observables and likelihoods.
5. ScannerBit (EPJC, arXiv:1705.07959)
   Module for scanners and printers
6. NeutrinoBit (arXiv:1908.02302)
   Neutrino observables and likelihoods.
7. CosmoBit (coming soon!)
   Cosmological observables and likelihoods.

Majorana fermion DM (Case $\xi = 0$)

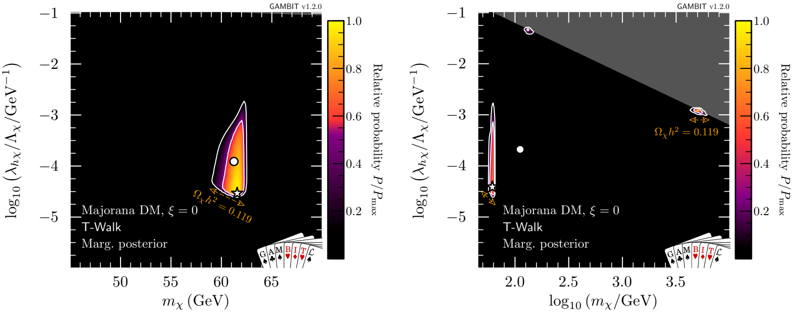


Fig. 1: Marginalised posteriors in (m_χ, $\lambda_{h\chi}/\Lambda_\chi$) plane for the case ξ = 0.

Dirac fermion DM

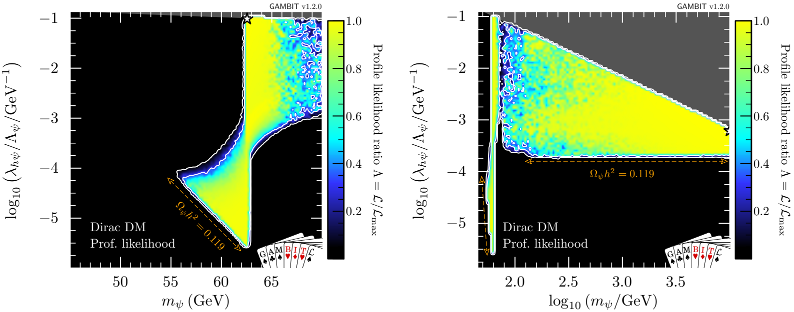


Fig. 2: Profile likelihoods in $(m_\psi,\ \lambda_{h\psi}/\Lambda_\psi)$ plane for Dirac fermion DM model.

Free model and nuisance parameters

Model	**Parameter**	**Minimum**	**Maximum**	**Prior type**
Vector DM	λ_{hV}	10^{-4}	10	Log
	m_V (low mass)	45 GeV	70 GeV	Flat
	m_V (high mass)	45 GeV	10 TeV	Log
Majorana/Dirac DM	$\lambda_{h\chi,h\psi}/\Lambda_{\chi,\psi}$	10^{-6} GeV^{-1}	1 GeV^{-1}	Log
	ξ	0	π	Flat
	$m_{\chi,\psi}$ (low mass)	45 GeV	70 GeV	Flat
	$m_{\chi,\psi}$ (high mass)	45 GeV	10 TeV	Log

Table 1: Ranges and priors for our free model parameters.

Parameter		**Value** (± **Range**)
Local DM density	ρ_0	0.2–0.8 GeV cm^{-3}
Most probable speed	v_{peak}	240 (24) km s^{-1}
Galactic escape speed	v_{esc}	533 (96) km s^{-1}
Nuclear matrix element	σ_s	43 (24) MeV
Nuclear matrix element	σ_l	50 (45) MeV
Higgs pole mass	m_h	124.1–127.3 GeV
Strong coupling	$\alpha_s^{\overline{\text{MS}}}(m_Z)$	0.1181 (33)

Table 2: 7 SM, nuclear and astrophysical parameters varied simultaneously in our scans.

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Likelihoods and best-fit points

Likelihoods	**GAMBIT modules/backends**
Relic density (*Planck*)	DarkBit
Higgs invisible width	DecayBit
Fermi-LAT dSphs	gamLike 1.0.0
IceCube 79-string	nulike 1.0.6
LUX 2016 (Run II)	DDCalc 2.0.0
PandaX (2016, 2017)	DDCalc 2.0.0
XENON1T 2018	DDCalc 2.0.0
CDMSlite, CRESST-II	DDCalc 2.0.0
PICO-60 2017	DDCalc 2.0.0
DarkSide-50 2018	DDCalc 2.0.0

Table 3: List of likelihood functions and relevant GAMBIT modules/backends used in our scans.

Model	Relic density condition	λ_{hX}	m_X (GeV)	ξ (rad)	$\Omega_X h^2$	$\Delta \ln \mathcal{L}$
Vector	$\Omega_V h^2 \lesssim \Omega_{DM} h^2$	4.9×10^{-4}	62.46	—	9.343×10^{-2}	0.322
	$\Omega_V h^2 \sim \Omega_{DM} h^2$	4.5×10^{-4}	62.46	—	1.128×10^{-1}	0.428
Majorana	$\Omega_\chi h^2 \lesssim \Omega_{DM} h^2$	4.5×10^{-2} GeV^{-1}	138.4	1.96	6.588×10^{-8}	0.308
	$\Omega_\chi h^2 \sim \Omega_{DM} h^2$	6.3×10^{-6} GeV^{-1}	61.03	1.41	1.128×10^{-1}	0.439
Dirac	$\Omega_\psi h^2 \lesssim \Omega_{DM} h^2$	6.3×10^{-4} GeV^{-1}	9.950×10^3	2.06	3.813×10^{-2}	0.307
	$\Omega_\psi h^2 \sim \Omega_{DM} h^2$	3.6×10^{-4} GeV^{-1}	9.895×10^3	2.07	1.155×10^{-1}	0.553

Fig. 3: Best-fit point for the model parameters from our global fit.