

Global study of effective Higgs portal dark matter models using GAMBIT

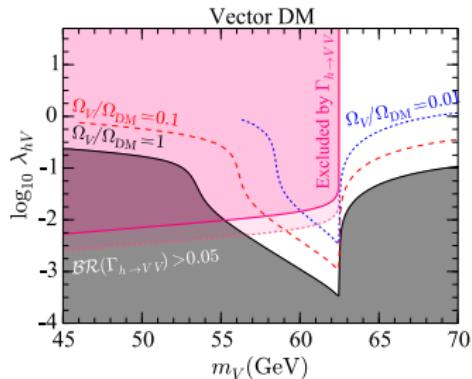
Ankit Beniwal
(on behalf of the GAMBIT collaboration)

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

EPS-HEP 2019, Ghent, Belgium
July 11, 2019

- 1 Global fits and GAMBIT
- 2 Effective Higgs portal models
- 3 Constraints
- 4 Results
- 5 Summary

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



A. Beniwal et al., PRD, arXiv:1512.06458

Theories with *many* free parameters and constraints?

- Construct a *combined likelihood* function:

$$\mathcal{L}_{\text{total}} = \mathcal{L}_{\text{DM}} \times \mathcal{L}_{\text{Higgs}} \times \mathcal{L}_{\text{Collider}} \times \dots \quad (1)$$

- Explore parameter space with advanced sampling techniques, e.g., MCMC.
- Interpret results in frequentist and/or Bayesian statistical frameworks.
→ All of the above possible within **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
- Fast definition of new datasets and theories
- Plug and play scanning, physics and likelihood packages



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



Recent collaborators:

Peter Athron, Csaba Balázs, Ankit Beniwal, Sanjay Bloor, Torsten Bringmann, Andy Buckley, José Eliel Camargo-Molina, Marcin Chrząszcz, Jonathan Cornell, Matthias Danner, 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 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]

Related papers

- \mathbb{Z}_2 and \mathbb{Z}_3 symmetric scalar models [EPJC, 1806.11281]
- Axion models [JHEP, arXiv:1810.07192]
- Electroweak MSSM see talk by P. Athron
Today @ 12 pm (NP session)
- Effective Higgs portal models This talk

- $H^\dagger H$ – lowest dimensional, gauge-invariant operator.
- Vector (V_μ) and Majorana fermion¹ (χ) fields with \mathbb{Z}_2 symmetry:

$$(V_\mu, \chi) \rightarrow - (V_\mu, \chi). \quad (2)$$

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

$$\mathcal{L}_V \supset \frac{1}{2} \textcolor{green}{m}_V^2 V_\mu V^\mu + \frac{1}{2} \textcolor{red}{\lambda}_{hV} V_\mu V^\mu (v_0 h + \frac{1}{2} h^2), \quad (3)$$

$$\mathcal{L}_\chi \supset \frac{1}{2} \bar{\chi} (i\partial^\mu - \textcolor{green}{m}_\chi) \chi - \frac{1}{2} \frac{\lambda_{h\chi}}{\Lambda_\chi} (\cos \xi \bar{\chi} \chi + \sin \xi \bar{\chi} i \gamma_5 \chi) (v_0 h + \frac{1}{2} h^2). \quad (4)$$

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

- Free model parameters: m_V , λ_{hV} (Vector DM); m_χ , $\lambda_{h\chi}/\Lambda_\chi$ and ξ (Majorana fermion DM).

¹Similar for a Dirac fermion field ψ .

Observational constraints

- Thermal relic density;
- Higgs invisible decays;
- Indirect detection using γ rays;
- Direct detection, e.g., XENON1T, LUX;
- Solar DM capture and annihilation.

Theoretical constraints

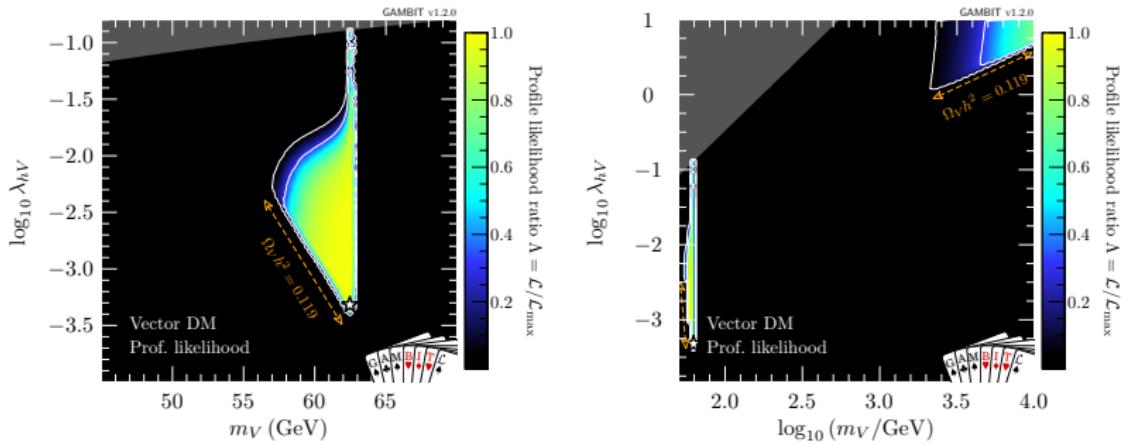
- Perturbative unitarity of $VV \rightarrow hh$ scattering amplitudes,
- EFT validity of Majorana fermion DM model,

$$0 \leq \lambda_{hV} \leq \frac{2m_V^2}{v_0^2}.$$

$$\frac{\lambda_{h\chi}}{\Lambda_\chi} < \frac{4\pi}{2m_\chi}.$$

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

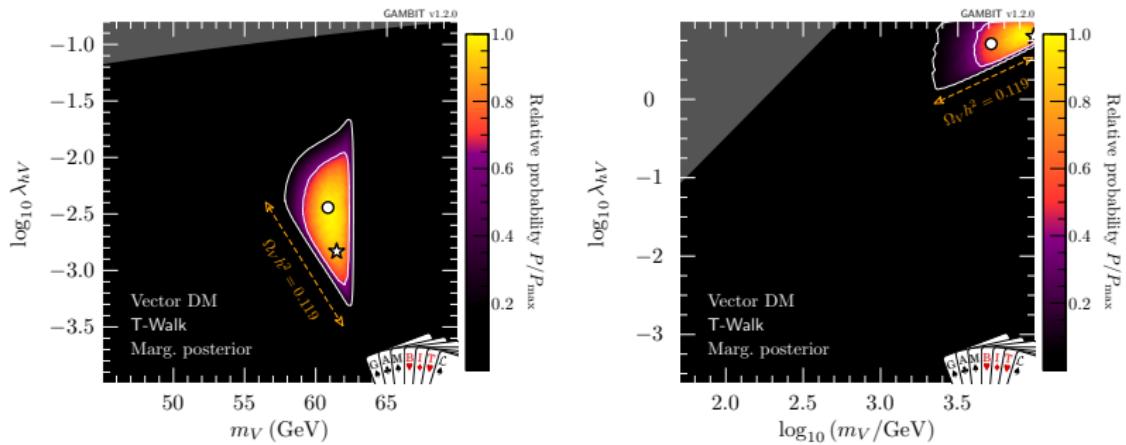
Profile likelihoods



(White star = best-fit point)

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

Marginalised posteriors



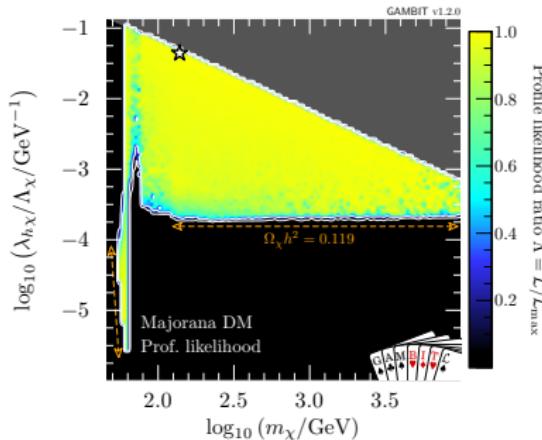
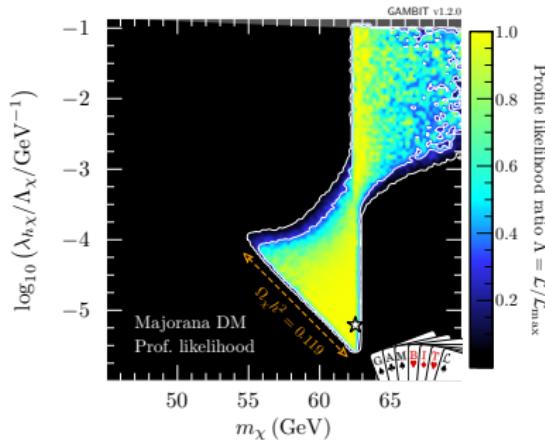
(White star = best-fit point, White circle = posterior mean)

- ‘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

Majorana fermion DM

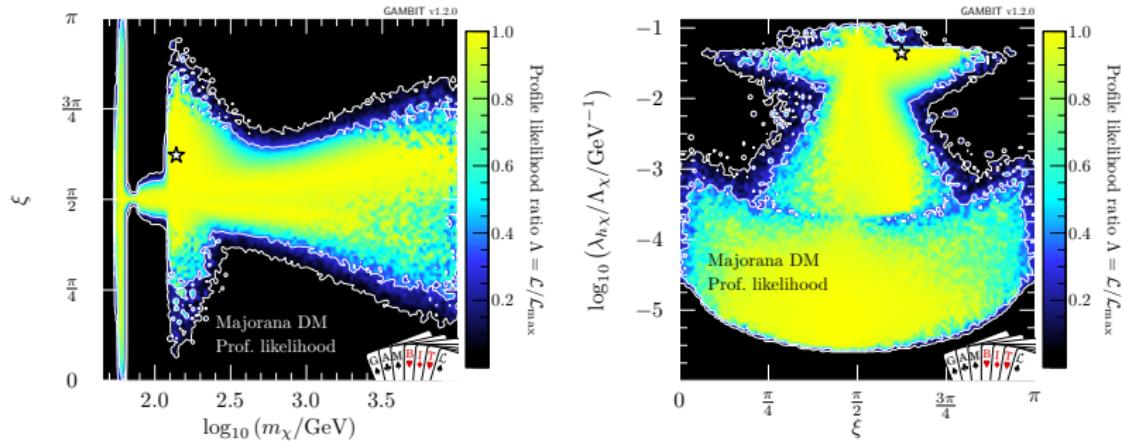
Profile likelihoods



- 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



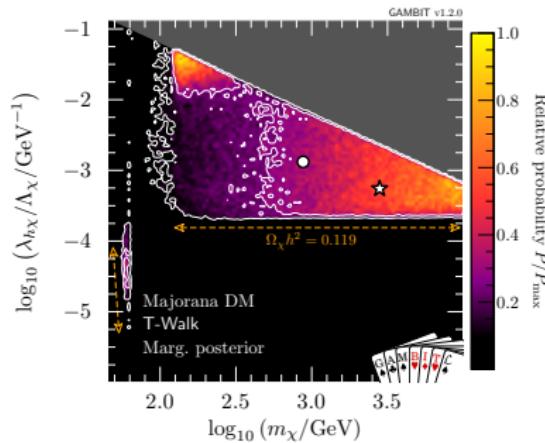
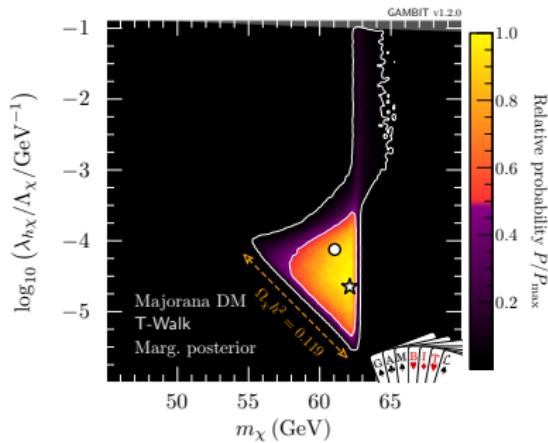
Suppressed direct detection rates when $\xi = \pi/2$:

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

Results

Majorana fermion DM

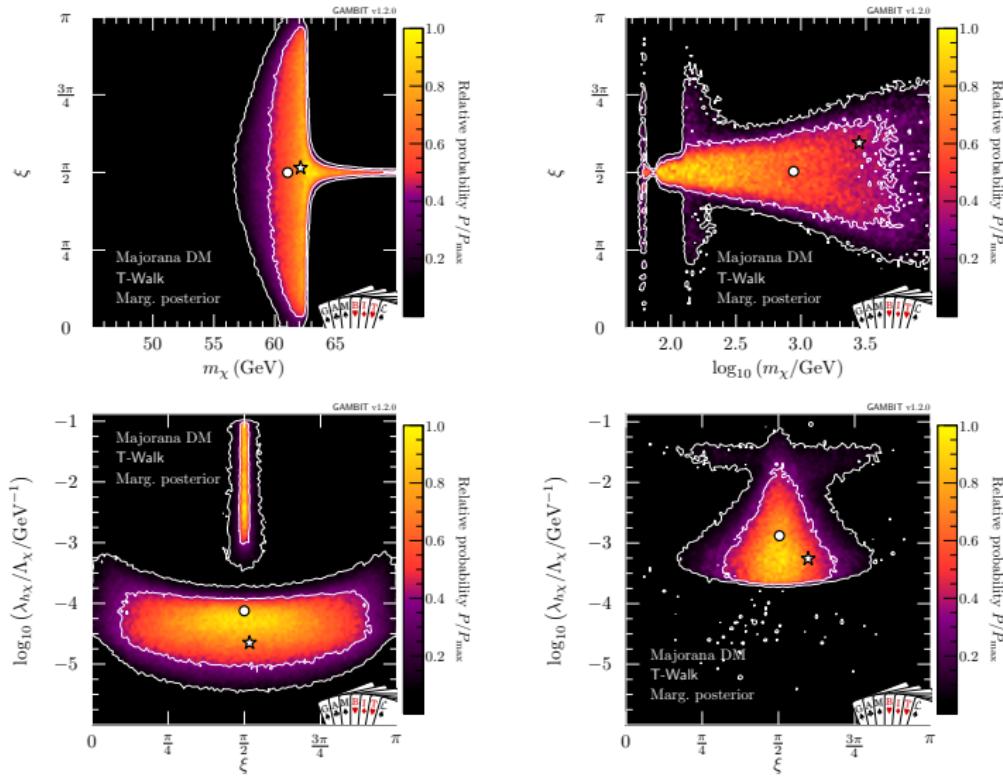
Marginalised posteriors



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

Results

Majorana fermion DM

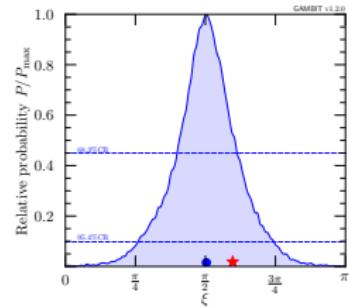


UCLouvain



Summary

- Resonance ($m_V, \chi \simeq m_h/2$) and high mass regions consistent with all experimental constraints.
- Fermion DM models with CP-violating ($\xi \approx \pi/2$) couplings favoured due to q^2 suppression.
- Future direct and indirect 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 public:

<https://gambit.hepforge.org>

Backup slides

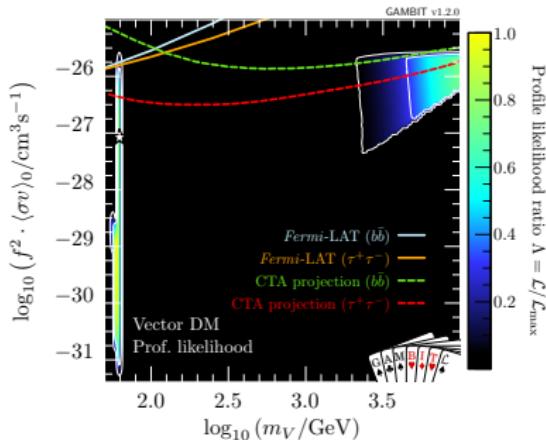
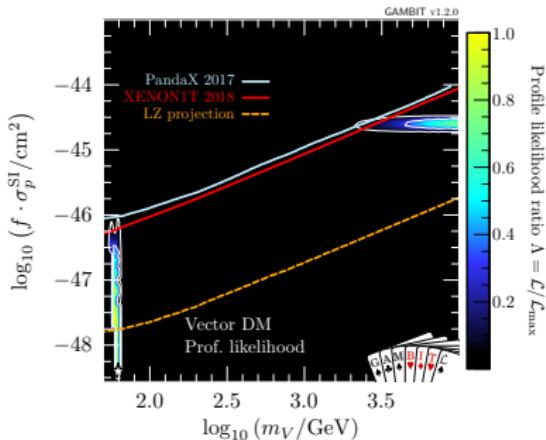


UCLouvain



DM observables

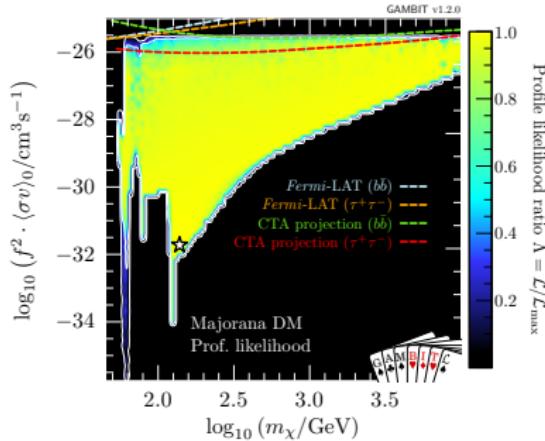
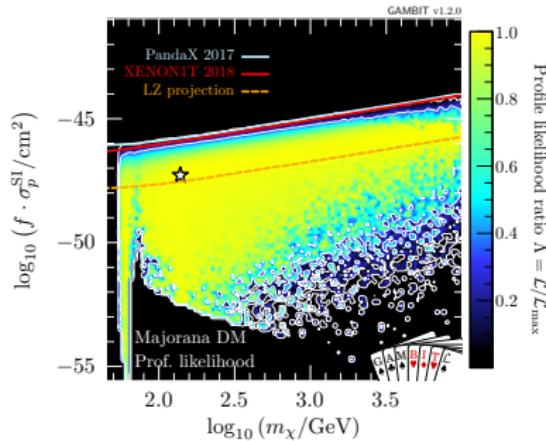
Vector DM



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

DM observables

Majorana fermion DM



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

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

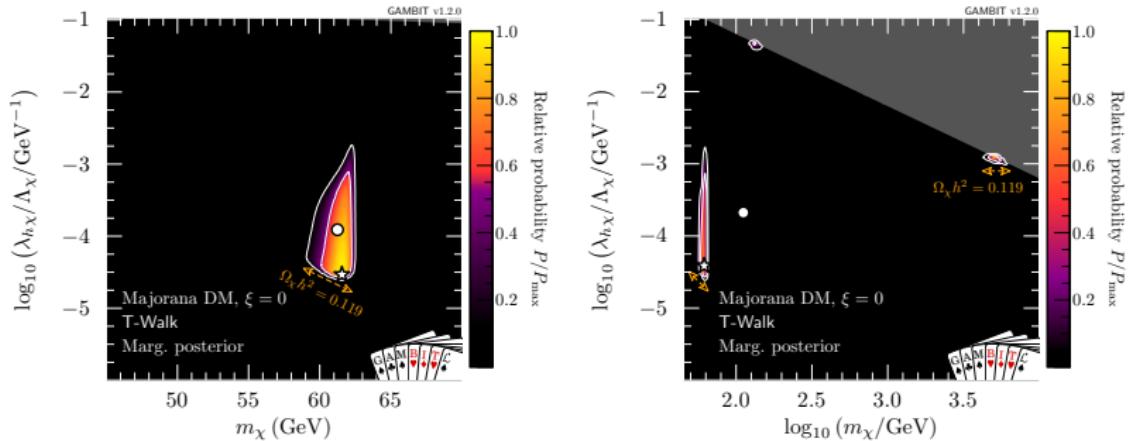


Fig. 1: Marginalised posteriors in $(m_\chi, \lambda_{h\chi}/\Lambda_\chi)$ plane for the case $\xi = 0$.

Dirac fermion DM

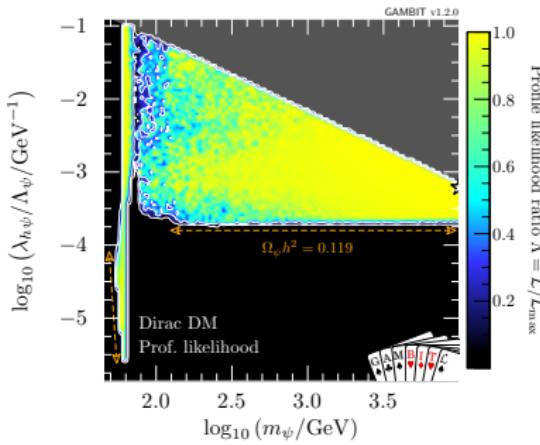
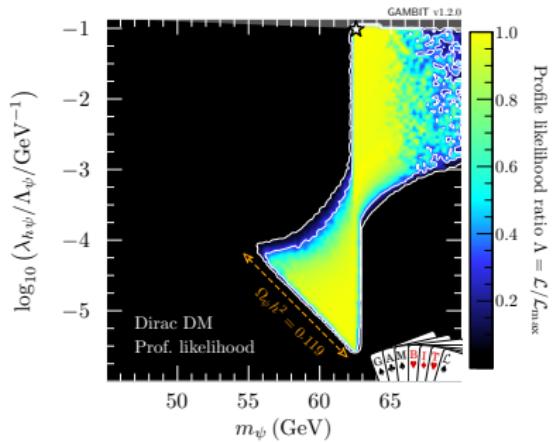


Fig. 2: Profile likelihoods in $(m_\psi, \lambda_{h\psi}/\Lambda_\psi)$ plane for Dirac fermion DM model.



Free model and nuisance parameters

Model	Parameter	Minimum	Maximum	Prior type
Vector DM	$\lambda_{h\nu}$	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: Free model parameter ranges and priors.

Parameter	Value (\pm 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.

Likelihoods and best-fit points

Likelihoods	GAMBIT modules/backends
Relic density (<i>Planck</i>)	DarkBit
Higgs invisible width	DecayBit
<i>Fermi</i> -LAT dSphs	gamLike 1.0.0
IceCube 79-string	nulike 1.0.0
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 parameter points for our effective Higgs portal models.

