Thermal WIMPs and the scale of new physics

Ankit Beniwal
(On behalf of the GAMBIT Collaboration)

P. Athron et al., *Thermal WIMPs and the scale of new physics: global fits of Dirac dark matter effective field theories*, *Eur. Phys. J. C* **81** (2021) 11, 992, [arXiv:**2106.02056**]

TPPC Seminar, King's College London, UK

Dec 8, 2021

Outline

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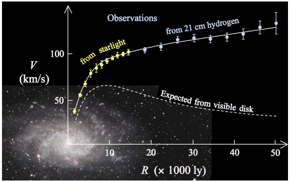
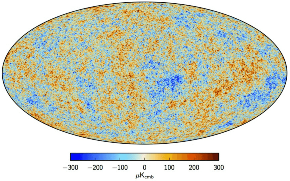
- Multiple evidences for Dark Matter (DM).
- Accounts for $\sim 85\%$ of total matter density.

N. Aghanim et al., (2018)

- Non-luminous, non-baryonic; interacts via gravity (weak?) force.
- Standard Model (SM) has **no** particle DM candidates.
- Popular beyond the SM (BSM) candidates: Weakly Interacting Massive Particles (WIMPs); Axions.

G. Bertone et al., (2005)





Three ways to look for WIMPs:

1. **Direct Detection (DD)**

   Elastic scattering of WIMPs off nucleons in underground labs.

   E.g., PandaX-II, LUX, XENON1T.

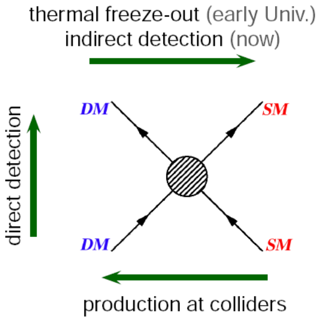
2. **Indirect Detection (ID)**

   Search for WIMP annihilation products in high density regions using ground/space-based telescopes.

   E.g., *Fermi*-LAT, H.E.S.S., HAWC, AMS-02, IceCube, Super-Kamiokande (Super-K).

3. **Collider searches**

   Search for missing transverse energy ($\not{E}_T$) signatures at colliders, e.g., LHC.



- A *bottom-up* approach (c.f. *top-down* approach).
- Include higher-dimensional operators to describe interactions:

$$\mathcal{L}_{\mathsf{EFT}} = \sum_{a,\,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)} \,, \quad d \geq 5 \,, \tag{1}$$

where $\mathcal{C}_a^{(d)}$ = *dimensionless* Wilson Coefficients (WCs), Λ = new physics scale and $\mathcal{Q}_a^{(d)}$ = effective operators.

- EFT valid for energy $E < \Lambda \rightarrow$ suitable for low-velocity environments (e.g., DD, ID); **careful** with collider searches.
- EFTs are model independent (not specific to a UV completion).
- No constraining power in distinguishing range of UV theories.

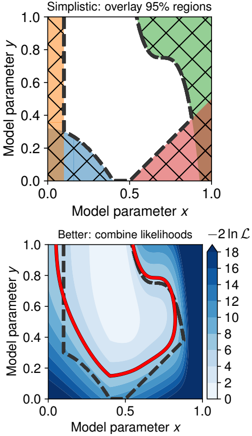
BSM theories with *many* free parameters/constraints?

1. Construct a *joint likelihood* function:

$$\mathcal{L}_{\text{total}}(\boldsymbol{\theta}) = \mathcal{L}_{\text{DD}}(\boldsymbol{\theta})\, \mathcal{L}_{\text{ID}}(\boldsymbol{\theta})\, \mathcal{L}_{\text{Collider}}(\boldsymbol{\theta})\, \mathcal{L}_{\text{Nuis.}}(\boldsymbol{\theta}) \ldots$$

2. Traditional scanning (random, grid) methods are inefficient. S. S. AbdusSalam et al., [arXiv:2012.09874]
3. Better to explore parameter space ($\boldsymbol{\theta}$) with *advanced* sampling techniques (e.g., MCMC, nested sampling).
4. Interpret results in *frequentist* and/or *Bayesian* statistical frameworks.
5. Perform *parameter estimation* and/or *model comparison*.

$\longrightarrow$ **GAMBIT**

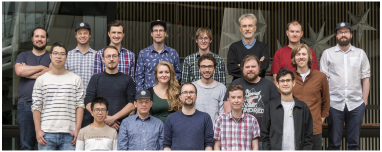


GAMBIT: The Global And Modular BSM Inference Tool

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

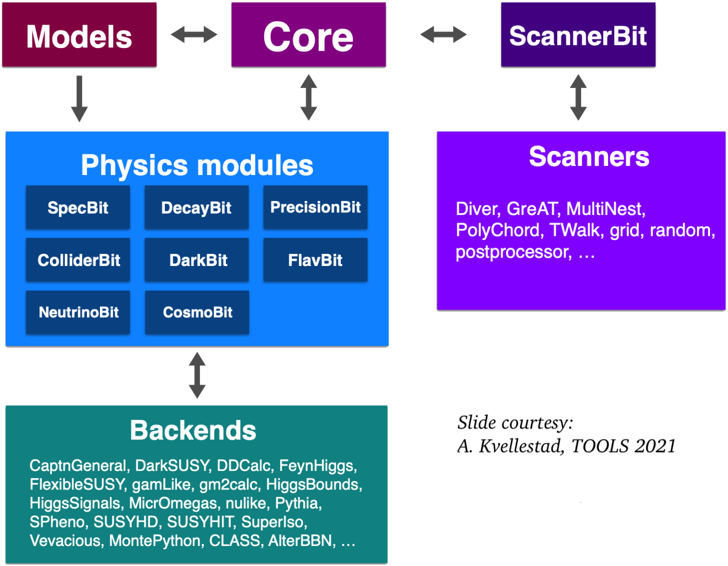


Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of:
DarkSUSY, DDCalc, Diver, FlexibleSUSY, gamlike, GM2Calc, IsaTools, nulike, PolyChord, Rivet, SoftSUSY, SuperISO, SUSY-AI, WIMPSim

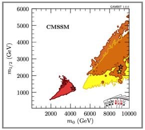
Recent collaborators:
F Agocs, V Ananyev, P Athron, C Balázs, A Beniwal, J Bhom, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, B Farmer, A Fowlie, T Gonzalo, P Grace, W Handley, J Harz, S Hoof, S Hotinli, F Kahlhoefer, N Avis Kozar, A Kvellestad, P Jackson, A Ladhu, N Mahmoudi, G Martinez, MT Prim, F Rajec, A Raklev, J Renk, C Rogan, R Ruiz, I Sáez Casares, N Serra, A Scaffidi, P Scott, P Stöcker, W Su, J Van den Abeele, A Vincent, C Weniger, M White, Y Zhang

70+ participants in 11 experiments and 14 major theory codes

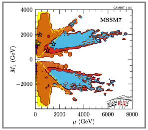


Slide courtesy:
A. Kvellestad, TOOLS 2021

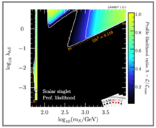
Recent (GAMBIT) physics results



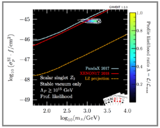
GUT-scale SUSY: 1705.07935



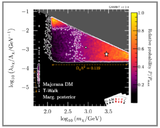
MSSM7: 1705.07917



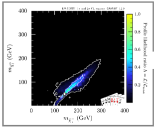
Scalar Higgs portal DM: 1705.07931



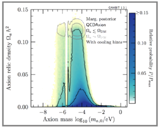
Scalar Higgs portal DM w/ vac. stability: 1806.11281



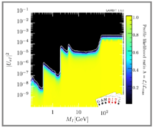
Vector and fermion Higgs portal DM: 1808.10465



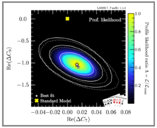
EW-MSSM: 1809.02097



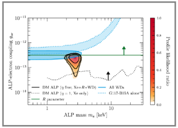
Axion-like particles: 1810.07192



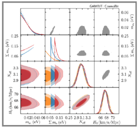
Right-handed neutrinos: 1908.02302



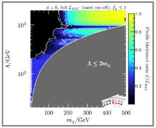
Flavour EFT: 2006.03489



More axion-like particles: 2006.03489



Neutrinos and cosmo: 2009.03287



Dark matter EFTs: 2106.02056

Slide courtesy:
A. Kvellestad, TOOLS 2021

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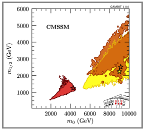

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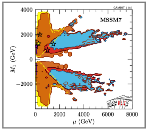

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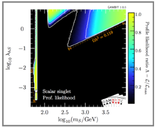

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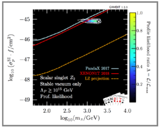

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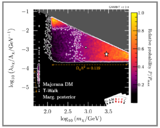

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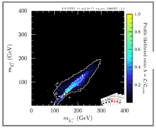

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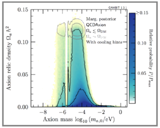

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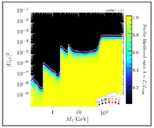

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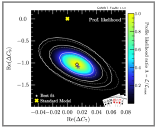

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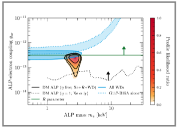

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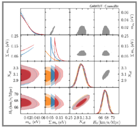

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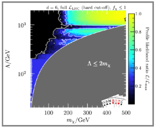

Dark matter EFTs: 2106.02056

Today's talk!

Slide courtesy:
A. Kvellestad, TOOLS 2021

Outline

Dirac fermion DM EFTs

- Dirac fermion WIMP DM (χ) interaction with SM quarks or gluons via effective operators:

$$\mathcal{L}_{\text{int}} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}, \quad d \leq 7\,, \qquad (2)$$

where $\mathcal{Q}_a^{(d)}$ = DM-SM operator.

F. Bishara et al., [arXiv:1708.02678]
J. Brod et al., *JHEP*, [arXiv:1710.10218]

- Full Lagrangian:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{int}} + \overline{\chi}(i\partial\!\!\!/ - m_\chi)\chi\,. \qquad (3)$$

$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,.$$

Dimension-6 operators

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)\,,$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)\,.$$

Dimension-7 operators

Dirac fermion DM EFTs

- Assume *minimal flavour violation*:

$$\mathcal{C}_{i,d}^{(d)} = \mathcal{C}_{i,s}^{(d)} = \mathcal{C}_{i,b}^{(d)}\,, \tag{4}$$

$$\mathcal{C}_{i,u}^{(d)} = \mathcal{C}_{i,c}^{(d)} = \mathcal{C}_{i,t}^{(d)}\,, \tag{5}$$

and *isospin invariance*:

$$\mathcal{C}_{i,d}^{(d)} = \mathcal{C}_{i,u}^{(d)}\,. \tag{6}$$

- Free model parameters:

$$\mathcal{C}_{i=1,\ldots,4}^{(6)},\ m_\chi,\ \Lambda\ (d=6)\,,$$

$$\mathcal{C}_{i=1,\ldots,4}^{(6)}, \mathcal{C}_{i=1,\ldots,10}^{(7)},\ m_\chi,\ \Lambda\ (d=6\,\&\,7)\,.$$

$$\begin{aligned}
\mathcal{Q}_{1,q}^{(6)} &= (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,\\
\mathcal{Q}_{2,q}^{(6)} &= (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,\\
\mathcal{Q}_{3,q}^{(6)} &= (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,\\
\mathcal{Q}_{4,q}^{(6)} &= (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,.
\end{aligned}$$

Dimension-6 operators

$$\begin{aligned}
\mathcal{Q}_{1}^{(7)} &= \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,\\
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\end{aligned}$$

Dimension-7 operators

Dirac fermion DM EFTs

- **Mixing and threshold corrections:**
  - $\mathcal{C}_a^{(d)}$'s needed at energy scale $\mu = 2\,$GeV for direct detection;
  - Threshold corrections when μ is below/above m_q, e.g., m_t;
  - All of above handled via `DirectDM` `v2.2.0`.

F. Bishara et al., [arXiv:1708.02678]; J. Brod et al., *JHEP*, [arXiv:1710.10218]

- **EFT validity**:
  1. $\Lambda \gtrsim 2\,$GeV (direct detection);
  2. $\Lambda > 2m_\chi$ (relic density and indirect detection);
  3. $\not{E}_T < \Lambda$ (collider searches). For $\not{E}_T > \Lambda$, modify $\not{E}_T$ spectrum:

$$\frac{d\sigma}{d\not{E}_T} \rightarrow \begin{cases} 0\,, & \text{hard cut-off}\,, \\ \frac{d\sigma}{d\not{E}_T}\left(\frac{\not{E}_T}{\Lambda}\right)^{-a}\,, & \text{smooth cut-off}\,. \end{cases} \tag{7}$$

Here $a \in [0,\, 4] =$ *nuisance* parameter.

- **Perturbative couplings**: $|\mathcal{C}_a^{(d)}| < 4\pi$.
- **Parameter ranges**: $m_\chi \in [5,\, 500]\,$GeV and $\Lambda \in [20,\, 2000]\,$GeV.

Constraints and likelihoods

Direct detection

- Differential event rate for a given nuclear recoil energy E_R:

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_T m_\chi} \int_{v_{\rm min}}^{\infty} v f(v) \frac{d\sigma}{dE_R}\, d^3v\,, \tag{8}$$

where $\rho_0 =$ local DM density, $m_T =$ target nucleus mass and $f(v) =$ DM velocity distribution, minimum DM speed $v_{\rm min} = \sqrt{\frac{m_T E_R}{2\mu^2}}$.

- Computing Eq. (8) non-trivial for EFT operators $\rightarrow$ map relativistic DM-quark/gluon interactions to non-relativistic DM-nucleon ones:

$$\mathcal{L}_{\rm NR} = \sum_{i,\,N} c_i^N(q^2)\, \mathcal{O}_i^N\,, \tag{9}$$

where $\mathcal{O}_i^N$ depends only on DM spin $\boldsymbol{S}_\chi$, nucleus spin $\boldsymbol{S}_N$, momentum transfer $\boldsymbol{q}$ and relative velocity $\boldsymbol{v}$.

- Coefficients $c_i^N(q^2)$ computed from $\mathcal{C}_i^{(d)}$ at $\mu = 2\,\text{GeV}$.
- Implicit dependance on $q \equiv \sqrt{2M_T E_R}$ from RG-evolution of effective operators and nuclear form factors → handled via `DirectDM v2.2.0`. F. Bishara et al., [arXiv:1708.02678]; J. Brod et al., *JHEP*, [arXiv:1710.10218]
- Combine `DirectDM v2.2.0` with `DDCalc v2.2.0` to compute likelihoods for:
  1. XENON1T;
  2. LUX (2016);
  3. PandaX (2016) and (2017);
  4. CDMSlite;
  5. CRESST-II and CRESST-III;
  6. PICO-60 (2017) and (2019);
  7. DarkSide-50.

P. Athron et al., *EPJC*, [arXiv:1808.10465]

	SI scattering	SD scattering
Dimension-6 operators		
$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$	unsuppressed	—
$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)$	suppressed	—
$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)$	—	suppressed
$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$	—	unsuppressed
Dimension-7 operators		
$\mathcal{Q}_{1}^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}$	unsuppressed	—
$\mathcal{Q}_{2}^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}$	suppressed	—
$\mathcal{Q}_{3}^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$	—	suppressed
$\mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$	—	suppressed
$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)$	unsuppressed	—
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$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)$	—	suppressed
$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)$	loop-induced	unsuppressed
$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)$	loop-induced	suppressed

- DM number density n_χ evolves according to the Boltzmann equation:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v_{\mathrm{rel}} \rangle \left(n_\chi n_{\bar{\chi}} - n_{\chi,\mathrm{eq}} n_{\bar{\chi},\mathrm{eq}} \right), \tag{10}$$

where $n_{\chi,\mathrm{eq}}$ = equilibrium number density and $\langle \sigma v_{\mathrm{rel}} \rangle$ = thermally averaged annihilation cross-section:

$$\langle \sigma v_{\mathrm{rel}} \rangle = \int_{4m_\chi^2}^{\infty} ds \, \frac{\sqrt{s - 4m_\chi^2}(s - 2m_\chi^2) K_1(\sqrt{s}/T)}{8 m_\chi^4 T K_2^2(m_\chi/T)} \, \sigma v_{\mathrm{lab}} \, . \tag{11}$$

- Tree-level cross-sections computed with `CalcHEP` `v3.6.27`, `GUM` and `DarkSUSY` `v6.2.2`. A. Belyaev et al., *CPC.*, [arXiv:1207.6082]; S. Bloor et al., *EPJC*, [arXiv:2107.00030]; T. Bringmann et al., *JCAP*, [arXiv:1802.03399]
- Require $n_\chi + n_{\bar{\chi}} = 2n_\chi$ (Dirac DM) and $\Lambda > 2m_\chi$ (EFT validity).
- Rescale all DD and ID signals by $f_\chi \equiv (\Omega_\chi + \Omega_{\bar{\chi}})/0.120$ and f_χ^2 respectively.
- Likelihood is either one-sided Gaussian ($f_\chi \leq 1$) or Gaussian ($f_\chi \approx 1$).

	SI scattering	SD scattering	Annihilations
Dimension-6 operators			
$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$	unsuppressed	—	s-wave
$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)$	suppressed	—	p-wave
$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)$	—	suppressed	s-wave
$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$	—	unsuppressed	s-wave $\propto m_q^2/m_\chi^2$
Dimension-7 operators			
$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}$	unsuppressed	—	p-wave
$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}$	suppressed	—	s-wave
$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$	—	suppressed	p-wave
$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$	—	suppressed	s-wave
$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)$	unsuppressed	—	p-wave $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)$	suppressed	—	s-wave $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)$	—	suppressed	p-wave $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)$	—	suppressed	s-wave $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)$	loop-induced	unsuppressed	s-wave $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)$	loop-induced	suppressed	s-wave $\propto m_q^2/m_\chi^2$

1. Fermi-LAT via gamma rays from dwarf galaxies

- For s-wave annihilation:

$$\Phi_i = \frac{f_\chi^2}{4} \sum_j \frac{(\sigma v)_{0,j}}{4\pi m_\chi^2} \int_{\Delta E_i} dE \, \frac{dN_{\gamma,j}}{dE}, \quad (12)$$

where $(\sigma v)_{0,j}$ = zero-velocity limit of cross-section for $\chi\bar{\chi} \to j$ and $N_{\gamma,j}$ = number of photons per annihilation and final state j.

- Photon yields provided by `DarkBit` (based on tabulated `Pythia` runs from `DarkSUSY`).
- Use `gamLike` `v1.0.1` to compute *Fermi*-LAT gamma-ray likelihood:

$$\ln \mathcal{L}_{\text{exp}} = \sum_{k=1}^{N_{\text{dSphs}}} \sum_{i=1}^{N_{\text{eBins}}} \ln \mathcal{L}_{ki}(\Phi_i \cdot J_k) \, . \quad (13)$$

T. Bringmann et al., *EPJC*, [arXiv:1705.07920]

- Profile over J-factor of each dwarf: $\ln \mathcal{L}_J = \sum_k \ln \mathcal{L}(J_k)$ to get full likelihood:

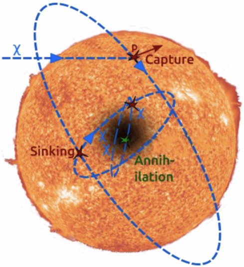
$$\ln \mathcal{L}_{\text{dSphs}}^{\text{prof.}} = \max_{\{J_k\}} \left(\ln \mathcal{L}_{\text{exp}} + \ln \mathcal{L}_J \right) \, . \quad (14)$$

2. Solar capture

- DM capture in the Sun via non-zero elastic scattering with nuclei.
- Search for high-energy neutrinos from the Sun as probe for DM.
- For given annihilation cross-section, captured DM population reaches equilibrium based on *capture rate* $C_{\odot}(t)$.
- Non-relativistic WCs from `DirectDM v2.2.0` passed onto `Capt'n General` to compute $C_{\odot}(t)$.

  N. Avis Kozar et al., [arXiv:2105.06810]
- Annihilation cross-sections (after equilibrium) passed to `DarkSUSY` to compute neutrino yields vs energy.
- Use `nulike v1.0.9` to compute event-level likelihoods for 79-string IceCube DM search.

  IceCube Collab., *JCAP*, [arXiv:1601.00653]



3. CMB bounds

- Observations of cosmic microwave background (CMB) $\rightarrow$ additional constraints on DM annihilation.
- Additional DM particles inject energy into primordial plasma (affects reionisation and alters optical depth τ).
- Details encoded in effective efficiency coefficient f_{eff} (depends on injected yields of γ, e^+ and e^-).
- CMB sensitive to

$$p_{\text{ann}} \equiv f_\chi^2 f_{\text{eff}} \frac{\langle \sigma v_{\text{rel}} \rangle}{m_\chi}\,, \quad \langle \sigma v_{\text{rel}} \rangle \approx (\sigma v)_0\,. \tag{15}$$

- *Planck* quotes only 95% credible interval on p_{ann} $\rightarrow$ obtain likelihood for p_{ann} from cosmological data.
- We adopt

J. J. Renk et al., *JCAP*, [arXiv:2009.03286]

$$\mathcal{L}(p_{\text{ann}}) = \mathcal{L}_0 \exp\left[-\left(\frac{p_{\text{ann}}^{28} + 0.48}{2.45}\right)^2\right]\,, \tag{16}$$

where $p_{\text{ann}}^{28} \equiv p_{\text{ann}}/(10^{-28}\ \text{cm}^3\,\text{s}^{-1}\,\text{GeV}^{-1})$.

Constraints and likelihoods

ATLAS and CMS monojet searches

- Collider process: $pp \to \chi\chi j$ with missing transverse energy $\not{E}_T$.
- Monojet searches based on 36 fb^{-1} (CMS) and 139 fb^{-1} (ATLAS) of Run II data, respectively. G. Aad et al., [arXiv:2102.10874]; A. M. Sirunyan et al., *PRD*, [arXiv:1712.02345]
- Expected # of events in given bin of $\not{E}_T$ distribution:

$$N = L \times \sigma \times (\epsilon A)\,. \tag{17}$$

- Produce separate interpolations of σ and (ϵA) within `ColliderBit` (using `MadGraph_aMC@NLO` `v2.6.6` and `Pythia` `v8.1`).
  C. Balazs et al., *EPJC*, [arXiv:1705.07919]
  J. Alwall et al., *JHEP*, [arXiv:1106.0522]; T. Sjostrand et al., *CPC*, [arXiv:0710.3820]
- Matching between `MadGraph` and `Pythia` done according to CKKW prescription; detector simulation with `Delphes` `v3.4.2`.
  J. de Favereau et al., *JHEP*, [arXiv:1307.6346]
- Only $\mathcal{C}_i^{(6)}$ and $\mathcal{C}_{i=1,\dots,4}^{(7)}$ relevant for collider searches; others suppressed by either PDFs (for heavy quarks) or mass term (for light quarks).
- Separate grids generated for operators that *do not* interfere. For $d = 6$, non-zero interference between $\mathcal{Q}_{1,q}^{(6)}/\mathcal{Q}_{4,q}^{(6)}$ and $\mathcal{Q}_{2,q}^{(6)}/\mathcal{Q}_{3,q}^{(6)}$ $\to$ parametrise tabulated grids with θ as $\mathcal{C}_{1,2}^{(6)} = \sin\theta$ and $\mathcal{C}_{3,4}^{(6)} = \cos\theta$.

- 22 and 13 exclusive signal regions in CMS and ATLAS monojet analyses, respectively.
- For CMS, combine all signals using public data. For ATLAS, only a single signal region used $\rightarrow$ maximise sensitivity by combining 3 highest $\not{E}_T$ bins.
- For CMS:

$$\mathcal{L}_{\mathsf{CMS}}(\boldsymbol{s},\boldsymbol{\gamma}) = \prod_{i=1}^{22}\left[\frac{(s_i+b_i+\gamma_i)^{n_i}\, e^{-(s_i+b_i+\gamma_i)}}{n_i!}\right]\frac{1}{\sqrt{\det 2\pi\Sigma}}e^{-\frac{1}{2}\boldsymbol{\gamma}^T\boldsymbol{\Sigma}^{-1}\boldsymbol{\gamma}}\,.$$

- Use *profiled CMS likelihood* ($\mathcal{L}_{\mathsf{CMS}}(\boldsymbol{s}) \equiv \mathcal{L}_{\mathsf{CMS}}(\boldsymbol{s},\hat{\hat{\boldsymbol{\gamma}}})$): profile over 22 nuisance parameters in $\boldsymbol{\gamma}$.
- For ATLAS, $\mathcal{L}_{\mathsf{ATLAS}}(s_i) \equiv \mathcal{L}_{\mathsf{ATLAS}}(s_i,\hat{\hat{\gamma}}_i)$, where $i =$ signal region with best expected sensitivity (one with lowest likelihood when $n_i = b_i$).
- Total LHC likelihood:

$$\ln\mathcal{L}_{\mathsf{LHC}} = \ln\mathcal{L}_{\mathsf{CMS}} + \ln\mathcal{L}_{\mathsf{ATLAS}}.$$

- Capped LHC likelihood:

$$\Delta\ln\mathcal{L}^{\mathsf{cap}}_{\mathsf{LHC}}(\boldsymbol{s}) = \mathsf{min}\left[\Delta\ln\mathcal{L}_{\mathsf{LHC}}(\boldsymbol{s}), \Delta\ln\mathcal{L}_{\mathsf{LHC}}(\boldsymbol{s}=\boldsymbol{0})\right]\,,$$

where $\Delta\ln\mathcal{L}_{\mathsf{LHC}} = \ln\mathcal{L}_{\mathsf{LHC}}(\boldsymbol{s}) - \ln\mathcal{L}_{\mathsf{LHC}}(\boldsymbol{s}=\boldsymbol{0})$.

Nuisance parameters

- 8 nuisance parameters varied simultaneously with DM EFT model parameters:

Nuisance parameter		**Value** ($\pm 3\sigma$ **range**)
Local DM density	ρ_0	0.2–0.8 GeV cm^{-3}
Most probable speed	$v_{\rm peak}$	240 (24) km s^{-1}
Galactic escape speed	$v_{\rm esc}$	528 (75) km s^{-1}
Running top mass ($\overline{\rm MS}$ scheme)	$m_t(m_t)$	162.9 (6.0) GeV
Pion-nucleon sigma term	$\sigma_{\pi N}$	50 (45) MeV
Strange quark contrib. to nucleon spin	Δs	−0.035 (0.027)
Strange quark nuclear tensor charge	g_T^s	−0.027 (0.048)
Strange quark charge radius of the proton	r_s^2	−0.115 (0.105) GeV^{-2}

- Likelihoods are Gaussian except for ρ_0 (log-normally distributed).

Global fit

- Total log-likelihood function for global fit:

$$\mathcal{L}_{\text{total}}(\boldsymbol{\theta}) = \mathcal{L}_{\text{DD}}(\boldsymbol{\theta})\,\mathcal{L}_{\text{RD}}(\boldsymbol{\theta})\,\mathcal{L}_{\text{ID}}(\boldsymbol{\theta})\,\mathcal{L}_{\text{LHC}}(\boldsymbol{\theta})\,\mathcal{L}_{\text{nuis.}}(\boldsymbol{\theta})\,. \tag{18}$$

- Explore 14- ($d = 6$) and 24-dimensional ($d = 6$ & 7) parameter space with `Diver v1.4.0`. G. D. Martinez et al., *EPJC*, [arXiv:1705.07959]
- Run scans where
  1. $f_\chi \leq 1$ vs $f_\chi \approx 1$;
  2. Capped vs full LHC likelihood;
  3. Hard vs smooth cut-off.
- Adopt frequentist approach and use *profile-likelihood ratio* (PLR):

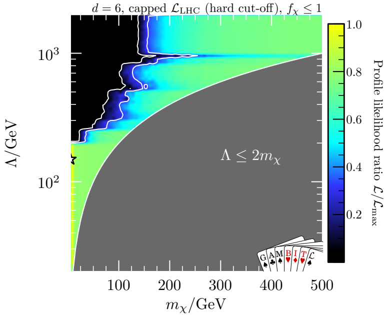
$$\mathcal{F}(\theta_i,\,\theta_j) \equiv \frac{\mathcal{L}_{\text{total}}(\theta_i,\,\theta_j,\,\hat{\hat{\boldsymbol{\nu}}}(\theta_i,\,\theta_j))}{\mathcal{L}_{\text{total}}(\hat{\boldsymbol{\theta}})}\,, \tag{19}$$

  where $\hat{\hat{\boldsymbol{\nu}}}(\theta_i,\,\theta_j)$ = *conditional* maximum likelihood estimate (MLE) and $\hat{\boldsymbol{\theta}}$ = MLE/best-fit point.
- Construct iso-likelihood contours at fixed confidence level, e.g., 68.3% (1σ) and 95.4% (2σ).

Outline

Results

Capped $\mathcal{L}_{\rm LHC}$ likelihood (hard cut-off), $f_\chi \leq 1$

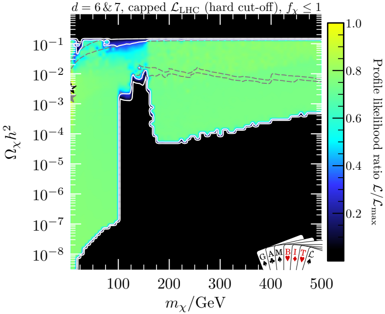


Left panel: $d = 6$; **Right panel**: $d = 6$ & 7; White star = best-fit point.

- Small m_χ and large Λ: strong constraints from LHC; impossible to satisfy relic density constraint. LHC constraints absent for $\Lambda < 200\,$GeV.
- Slight upward fluctuation in *Fermi*-LAT data fitted with (for $d = 6$)

$$m_\chi = 5.0\,\mathrm{GeV}, \quad f_\chi^2\,\langle\sigma v\rangle_0 = 1.1 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\,.$$

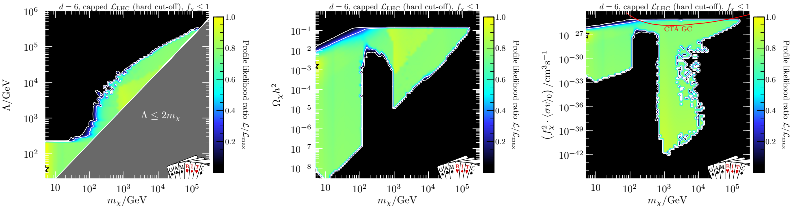
Capped $\mathcal{L}_{\text{LHC}}$ likelihood (hard cut-off), $f_\chi \leq 1$



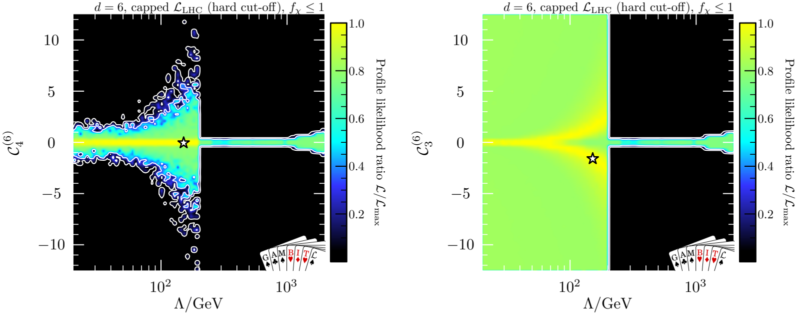
- For $d = 6$ (*dashed lines*) and $m_\chi \lesssim 100\,\text{GeV}$, impossible to obtain $\Omega_\chi h^2 = 0.12$ with combined ID and DD constraints.
- For $d = 6$ & 7 (*solid lines*), now possible to saturate relic density bound for small m_χ (and small Λ) thanks to suppressed signals from $\mathcal{Q}_{3,q}^{(7)}$ and $\mathcal{Q}_{7,q}^{(7)}$.

Results

Capped $\mathcal{L}_{\mathrm{LHC}}$ likelihood (hard cut-off), $f_\chi \leq 1$, $d = 6$



- Cherenkov Telescope Array (CTA) sensitive enough to probe TeV-scale DM masses with s-channel annihilation cross-section.
- Projected sensitivity based on DM signal from galactic center (GC) when assuming $b\bar{b}$ final state (right panel).



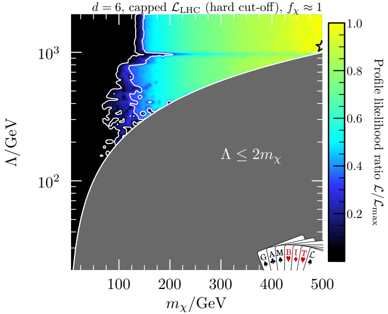
Left panel: $(m_\chi, \mathcal{C}_4^{(6)})$ plane. **Right panel**: $(m_\chi, \mathcal{C}_3^{(6)})$ plane.

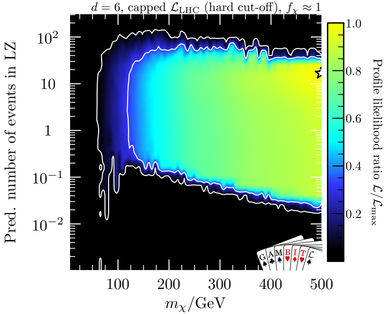
- $\mathcal{C}_1^{(6)} \to$ heavily constrained by DD (unsuppressed SI interaction).
- $\mathcal{C}_4^{(6)} \to$ weak limits (SD interaction);

  $\mathcal{C}_3^{(6)} \to$ very weak limits (momentum-suppressed SD interaction).

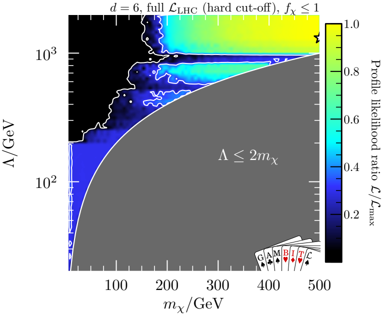
Results

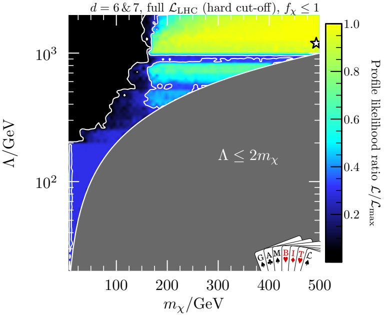
Capped $\mathcal{L}_{\mathrm{LHC}}$ likelihood (hard cut-off), $f_\chi \approx 1$





- Impossible to get $\Omega_\chi h^2 = 0.12$ for $m_\chi \lesssim 100\,$GeV; relic density requirement *incompatible* with *Fermi*-LAT and CMB bounds.
- Up to 10 events predicted in LZ (next-generation DD experiment); requires a non-zero $\mathcal{Q}_2^{(6)}$ with spin-independent (momentum-suppressed) interaction.





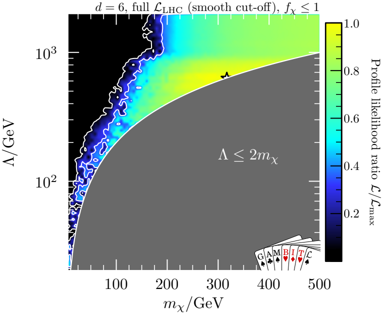
- For $d = 6$, excesses in few high-$\not\!\!E_T$ bins in ATLAS & CMS monojet searches. Preferred values for Λ at 1σ level:

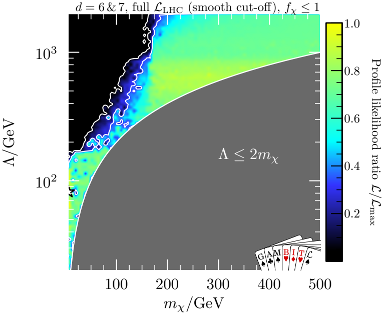
$$\Lambda \approx 700\,\text{GeV}\,(\text{CMS}), \quad \Lambda \gtrsim 1\,\text{TeV}\,(\text{ATLAS})\,. \tag{20}$$

- Similar results for $d = 6$ & 7 (right panel).

Results

Full $\mathcal{L}_{\mathrm{LHC}}$ likelihood (smooth cut-off), $f_\chi \leq 1$





- For $d = 6$, best-fit partially improves fit to both excesses (*Fermi*-LAT and LHC) simultaneously than in hard cut-off case (similar for $d = 6$ & 7).
- Best-fit requires $\Lambda \sim 80\,\mathrm{GeV}$ and $a \approx 1.7$.

Outline

Summary

1. *First* global fit of effective operators up to $d = 7$ involving a Dirac fermion DM and SM quarks or gluons.
2. Fully automated calculation of direct and indirect detection constraints.
3. Novel approach to address EFT validity at the LHC using a cut-off parameter.
4. Highly efficient likelihood calculations and sampling algorithms to scan over 24-dimensional parameter space.
5. Strong constraints on small m_χ and large Λ; slight preference for DM signal at relatively small Λ.
6. Large hierarchy *not* possible between m_χ and Λ without violating the relic density constraint.
7. Large regions of parameter space still viable for $f_\chi \approx 1$.

All results, samples and input files are publicly available via `Zenodo`**:**

https://zenodo.org/record/4836397

GAMBIT v2.1 out now! (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` — *EPJC*, [arXiv:1908.02302]
   Neutrino observables and likelihoods.
7. `CosmoBit` — *JCAP*, [arXiv:2009.03286]
   Cosmological observables and likelihoods.

- Threshold corrections when energy scale $\mu < m_q$ $\rightarrow$ reduced degrees of freedom:

$$\mathcal{C}^{(7)}_{i,q} = \mathcal{C}^{(7)}_{i,q} - \mathcal{C}^{(7)}_{i+4,q}\,(i=1,\,2), \quad \mathcal{C}^{(7)}_{j,q} = \mathcal{C}^{(7)}_{j,q} + \mathcal{C}^{(7)}_{j+4,q}\,(j=3,\,4). \tag{21}$$

- Tensor operators $\mathcal{Q}^{(7)}_{9,q}$ and $\mathcal{Q}^{(7)}_{10,q}$ mix above EW scale $\implies$ dim-5 dipole operators:

$$\mathcal{Q}^{(5)}_1 = \frac{e}{8\pi^2}(\overline{\chi}\sigma_{\mu\nu}\chi)F^{\mu\nu}\,, \quad \mathcal{Q}^{(5)}_2 = \frac{e}{8\pi^2}(\overline{\chi}i\sigma_{\mu\nu}\gamma_5\chi)F^{\mu\nu}\,. \tag{22}$$

- For $\Lambda > m_t$, $\mathcal{Q}^{(7)}_{9,10,t}$ gives a contribution to $\mathcal{Q}^{(5)}_{1,2}$ at one-loop level:

$$\mathcal{C}^{(5)}_{1,2}(m_Z) = \frac{4m_t^2}{\Lambda^2}\log\left(\frac{m_Z^2}{\Lambda^2}\right)\mathcal{C}^{(7)}_{9,10;t}(\Lambda)\,. \tag{23}$$

- Axial-vector top-quark current $\mathcal{Q}^{(6)}_{3,t}$ mixes into operators $\mathcal{Q}^{(6)}_{1,q}$:

$$\mathcal{C}^{(6)}_{1,u/d}(m_Z) = \mathcal{C}^{(6)}_{1,u/d}(\Lambda) + \frac{2s_w^2 \mp (3-6s_w^2)}{8\pi^2}\frac{m_t^2}{v^2}\log\left(\frac{m_Z^2}{\Lambda^2}\right)\mathcal{C}^{(6)}_{3,t}(\Lambda)\,.$$

WIMP annihilations in the Sun

- WIMP capture in the Sun (for $v_{\rm WIMP} < v_{\rm esc}^{\odot}$).

W. Press & D. Spergel (1985); J. Silk, K. Olive & M. Srednicki (1985)

- Scattering with solar material $\rightarrow$ WIMPs sink to solar core.
- Evolution of $N(t)$ given by (ignoring evaporation)

$$\frac{dN(t)}{dt} = C_{\odot}(t) - C_A N^2,$$

$C_{\odot}(t)$ = capture rate (s^{-1}), $C_A = 2\Gamma_A(t)/N^2(t)$ and Γ_A = annihilation rate (s^{-1}).

- In equilibrium,

$$\Gamma_A = \frac{C_{\odot}}{2} \tanh^2\left(\frac{t}{\tau}\right), \quad \tau = 1/\sqrt{C_{\odot} C_A}.$$

- $C_{\odot}$ and Γ_A are DM model specific:

$$\begin{aligned} C_{\odot}: &\quad m_\chi, \quad \sigma_{\chi p}^{\rm SI}, \quad \sigma_{\chi p}^{\rm SD}, \\ \Gamma_A: &\quad m_\chi, \quad \langle \sigma v_{\rm rel} \rangle. \end{aligned}$$

DM capture rate

The DM capture rate involves an integral over solar radius r and DM halo velocity u:

$$C_\odot(t) = 4\pi \int_0^{R_\odot} r^2 \int_0^\infty \frac{f(u)}{u} w\,\Omega(w,\,r)\,du\,dr\,, \tag{24}$$

where $w(r) = \sqrt{u^2 + v_{\mathrm{esc},\odot}^2(r)}$ = DM velocity at position r and

$$\Omega(w) = w \sum_i n_i(r,t) \frac{\mu_{i,+}^2}{\mu_i} \Theta\left(\frac{\mu_i v^2}{\mu_{i,-}^2} - u^2\right) \int_{m_\chi u^2/2}^{m_\chi w^2 \mu_i/2\mu_{i,+}^2} \frac{d\sigma_i}{dE_R}\,dE_R$$

is the probability of scattering with velocity w, $d\sigma/dE_R$ = DM-nucleus scattering cross-section, $n_i(r)$ = number density of species i with atomic number $m_{N,i}$ and $\mu_i = m_\chi/m_{N,i}$.

Likelihoods

Experiment	$\ln \mathcal{L}^{\text{bg}}$	$\ln \mathcal{L}^{\text{max}}$
CDMSlite [84]	-16.68	
CRESST-II [85]	-27.59	
CRESST-III [86]	-27.22	
DarkSide 50 [87]	-0.09	
LUX 2016 [88]	-1.47	
PICO-60 [89, 90]	-1.496	
PandaX [91, 92]	-3.436	
XENON1T [93]	-3.651	
ATLAS monojet [94]	0	
CMS monojet [95]	0	
Fermi-LAT [96]	-33.245	
IceCube 79-string [97]	0	
Planck 2018: p_{ann} [98]	-1.507	
Planck 2018: Ωh^2 [98]		5.989
Nuisances (see Table 4)		5.141

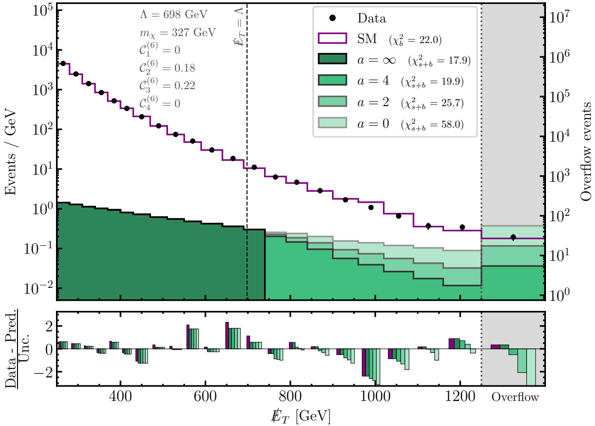
Table 1: Likelihoods included in our scans and their respective values for background-only hypothesis.

Best-fit points

LHC likelihood	Relic density constraint	$2\Delta \ln \mathcal{L}$	Best-fit m_χ (GeV)	Best-fit Λ (GeV)	Best-fit constrained coupling combination(s) (TeV^{-2})
Capped	Upper bound	0.3	5.0	< 200	$\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 67$
Capped	Saturated	-0.5	500	> 1000	$\lvert\mathcal{C}_2^{(6)}\rvert/\Lambda^2 = 0.22$ $\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 0.041$
Full (hard cut-off)	Upper bound	2.2	500	> 1250	$\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 0.14$
Full (smooth cut-off)	Upper bound	2.6	320	640	$\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 0.18$
Full (hard cut-off)	Saturated	1.9	500	> 1250	$\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 0.047$ $\sqrt{(\mathcal{C}_2^{(6)})^2 + (\mathcal{C}_4^{(6)})^2}/\Lambda^2 = 0.15$
Full (smooth cut-off)	Saturated	2.0	420	840	$\lvert\mathcal{C}_3^{(6)}\rvert/\Lambda^2 = 0.052$ $\sqrt{(\mathcal{C}_2^{(6)})^2 + (\mathcal{C}_4^{(6)})^2}/\Lambda^2 = 0.23$

Table 2: Best-fit points from our various scans involving dimension-6 operators with restricted parameter ranges ($5\,\mathrm{GeV} \leq m_\chi \leq 500\,\mathrm{GeV}$ and $20\,\mathrm{GeV} \leq \Lambda \leq 2\,\mathrm{TeV}$). Here we only quote the combination that is well-constrained rather than each parameter individually.

Example $\not{E}_T$ spectrum



Top panel: Examples of missing transverse energy ($\not{E}_T$) spectrum for the CMS monojet search. **Bottom panel**: Pull ($\equiv$ (data - predicted)/uncertainty) per bin.