Global Fits of vector-mediated simplified dark matter models with GAMBIT

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LHC Reinterpretation 2022

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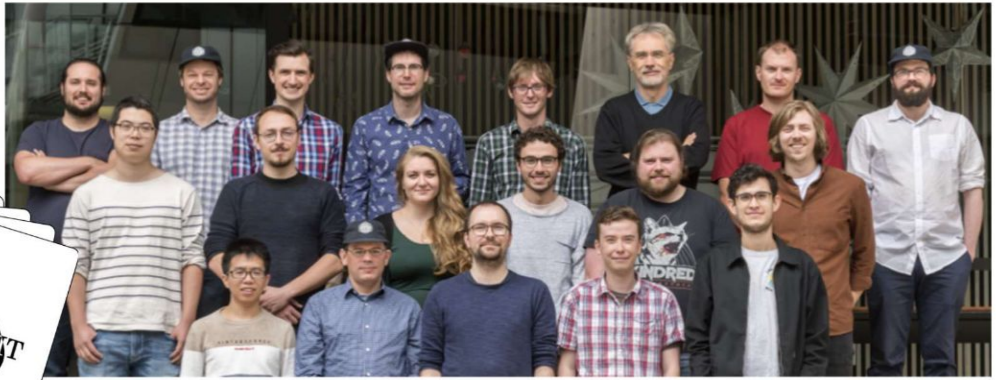
GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org   github.com/GambitBSM   EPJC 77 (2017) 784   arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- 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: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

70+ participants in many experiments and numerous major theory codes

Simplified dark matter models

Simplified dark matter models describe effective dark matter (DM) interactions without integrating out the mediating particle.

They're a useful tool for studying how both low and high energy experimental probes affect BSM physics.

In this talk I will discuss recent global constraints of s-channel vector-mediated simplified dark matter models with GAMBIT (arXiv:2209.13266).

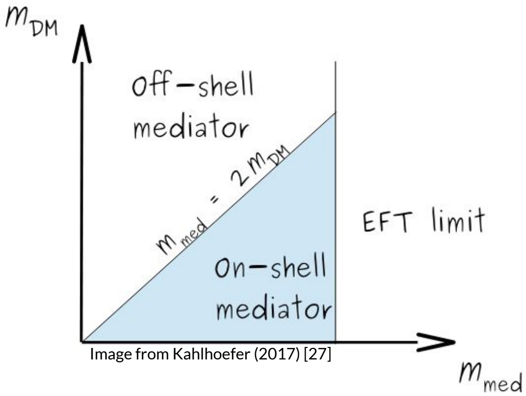
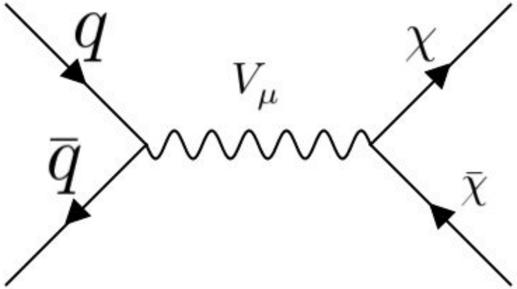


Image from Kahlhoefer (2017) [27]



Models

Scalar DM:

$$\mathcal{L}_{BSM} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_{DM}^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu$$
$$+ g_q V_\mu \bar{q}\gamma^\mu q + i g_{DM}^V V_\mu \left(\phi^\dagger(\partial^\mu\phi) - (\partial^\mu\phi^\dagger)\phi\right)$$

Dirac fermion DM:

$$\mathcal{L}_{BSM} = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_{DM}\bar{\chi}\chi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu$$
$$+ g_q V_\mu \bar{q}\gamma^\mu q + V_\mu \bar{\chi}(g_{DM}^V + g_{DM}^A\gamma^5)\gamma^\mu\chi$$

Majorana fermion DM:

$$\mathcal{L}_{BSM} = \frac{1}{2}i\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{2}m_{DM}\bar{\psi}\psi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{1}{2}m_M^2 V_\mu V^\mu$$
$$+ g_q V_\mu \bar{q}\gamma^\mu q + \frac{1}{2}g_{DM}^A V_\mu \bar{\psi}\gamma^5\gamma^\mu\psi$$

Assumptions:

No lepton couplings
-> To avoid strong di-lepton searches.

No axial-vector quark couplings

Flavour universal couplings
-> To require minimal flavour violation.

Mass generation mechanism has no observable impact on experiments
-> Could be achieved by e.g. a dark Higgs with mass well above the other particle masses.
-> example model studied in [2]

In each model, there are 4 or 5 model parameters: DM mass (m_{DM}), Mediator mass (m_M), mediator-quark coupling (g_q), mediator-DM coupling (g_{DM}) (either vector or axial-vector)

[2] M. Duerr, F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, How to save the WIMP: global analysis of a dark matter model with two s-channel mediators, JHEP 09 (2016) 042

Unitarity violation

The presence of an axial-vector couplings for the Dirac and Majorana models implies a bound from unitarity: [3]

$$m_{DM} \leq \sqrt{\frac{\pi}{2}} \frac{m_M}{g_{DM}^A}$$

Vector DM models will face strong unitarity violation, but to date no unitarity bound for this model exists in the literature. -> An upcoming paper…

[3] F. Kahlhoefer, K. Schmidt-Hoberg, T. Schwetz, and S. Vogl, Implications of unitarity and gauge invariance for simplified dark matter models, JHEP 02 (2016) 016

Constraints

Experiment
CDMSlite [4]
CRESST-II [5]
CRESST-III [6]
DarkSide 50 [7]
LUX 2016 [8]
PICO-60 [9, 10]
PandaX [11, 12]
XENON1T [13]
LZ 2022 [28]
LHC Dijets [14–22]
ATLAS monojet [23]
CMS monojet [24]
Fermi-LAT [25]
Planck 2018: Ωh^2 [26]
Nuisances

Constraints - Direct Detection

Effective Operator	Relevant models
$1_{DM} 1_N$	Scalar, Dirac
$i\hat{\mathbf{S}} \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{q}}{m_N}\right)$, $\hat{\mathbf{S}} \cdot \hat{\mathbf{v}}^{\perp} 1_N$	Dirac, Majorana

Relic DM should be non-relativistic -> Majorana model should be suppressed.

This should have very weak direct detection constraints relative to the other models.

Experiment
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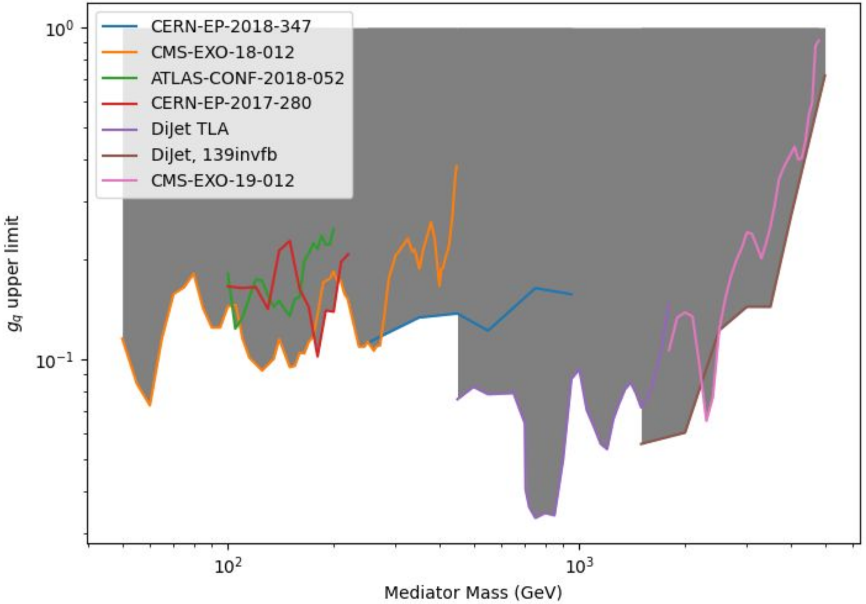
Nuisances

Constraints - Dijets

Limits are formed from the most constraining dijet search at a given mediator mass, scaled by the branching fraction into quarks.



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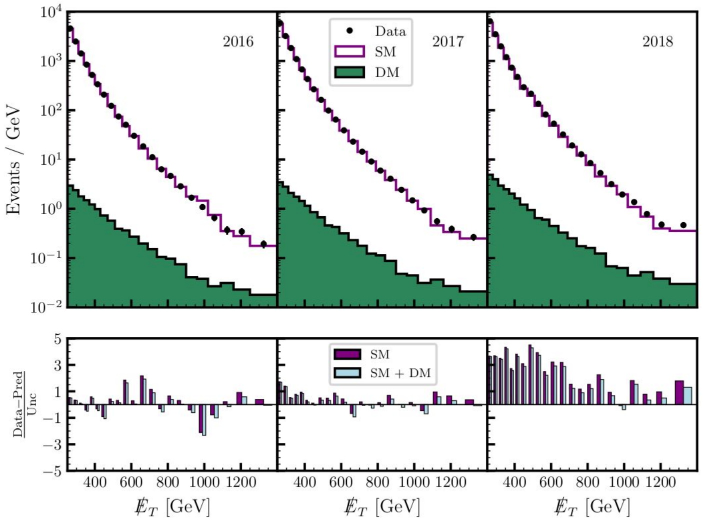
Nuisances

Constraints - Monojets



Fluctuations in individual signal regions tends to drive our likelihood to regions that fit these. In particular, the 2018 data for the CMS significantly underpredicts the # of events.

This is an artifact of the simplified likelihood, and is avoided in their full fit of control and signal regions.

Experiment
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Nuisances

Constraints - Indirect Detection

2 Annihilation channels:

- DM DM -> quark pair
- DM DM -> mediator pair

Only the Dirac fermion DM model has dominant velocity independent (s-wave) annihilation to quarks.

The other models will have weak gamma ray signatures when the mediator channel is closed.

Experiment
CDMSlite [4]
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Planck 2018: Ωh^2 [26]
Nuisances

Constraints - Relic Abundance

The 2 different annihilation channels will give 2 regions in parameter space where DM is not overproduced.

Direct and indirect detection signals are scaled by the proportion of DM that each candidate would comprise:

$$f_{DM} = \frac{\Omega_{DM}}{\Omega_{DM,obs}}$$

Experiment
CDMSlite [4]
CRESST-II [5]
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Nuisances

Scans

Each scan has 4 or 5 model parameters and 7 nuisance parameters.

Collider:

1) uncapped

2) capped collider likelihood

Relic Density: DM candidate …

1) is a subcomponent of the observed abundance

2) saturates the observed abundance.

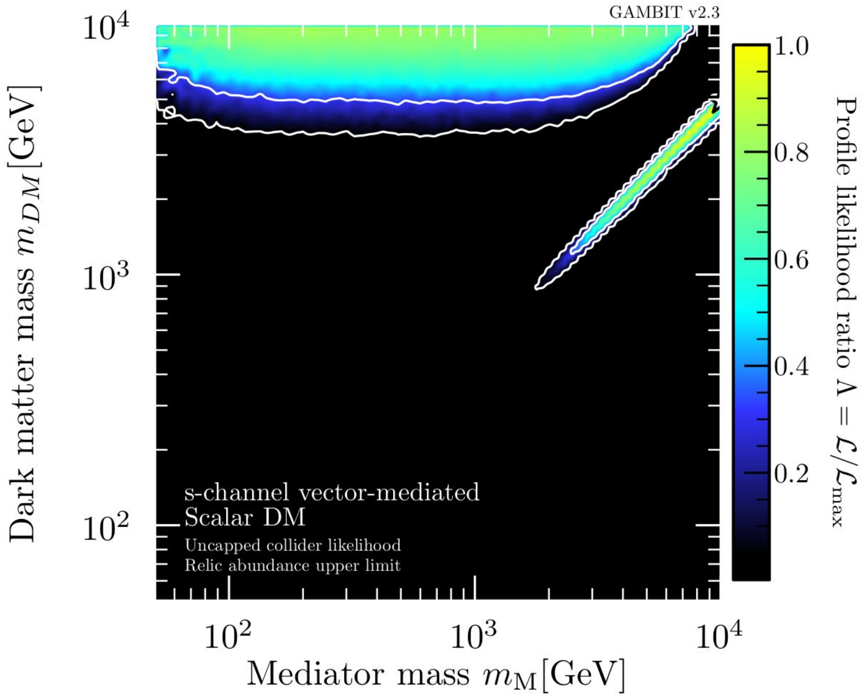
Up to 4 scans per model.

I will only show a subset of these results.

Parameters	**Range**
DM mass, m_{DM}	$[50, 10000]$ GeV
Mediator mass, m_M	$[50, 10000]$ GeV
quark-mediator coupling, g_q	$[0.01, 1.0]$
mediator-DM coupling (vector), g_{DM}^V	$[0.01, 3.0]$
mediator-DM coupling (axial vector), g_{DM}^A	$[0.01, 3.0]$
Nuisance Parameters	
Pion-nucleon sigma term, $\sigma_{\pi N}$	$[5, 95]$ MeV
strange quark cont. to nucleon spin, Δ_s	$[-0.062, -0.008]$
strange quark nuclear tensor charge, g_T^s	$[-0.075, 0.021]$
strange quark proton charge radius, r_s^2	$[-0.22, -0.01]$ GeV^{-2}
Local DM density, ρ_0	$[0.2, 0.8]$ GeV cm^{-3}
Most probably speed, v_{esc}	$[216, 264]$ km s^{-1}
Galactic escape speed, v_{peak}	$[453, 603]$ km s^{-1}

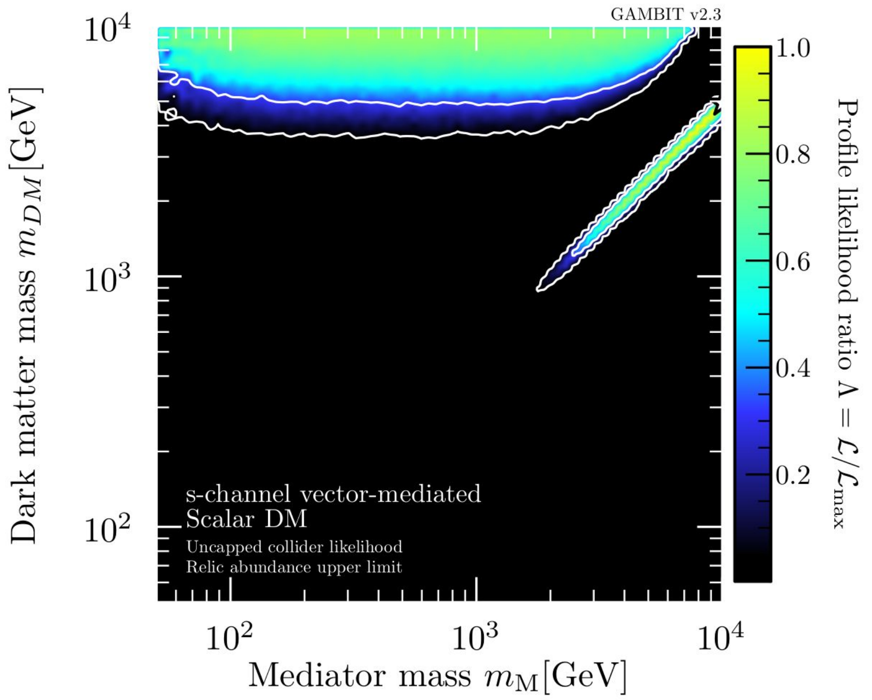
Results - Scalar DM

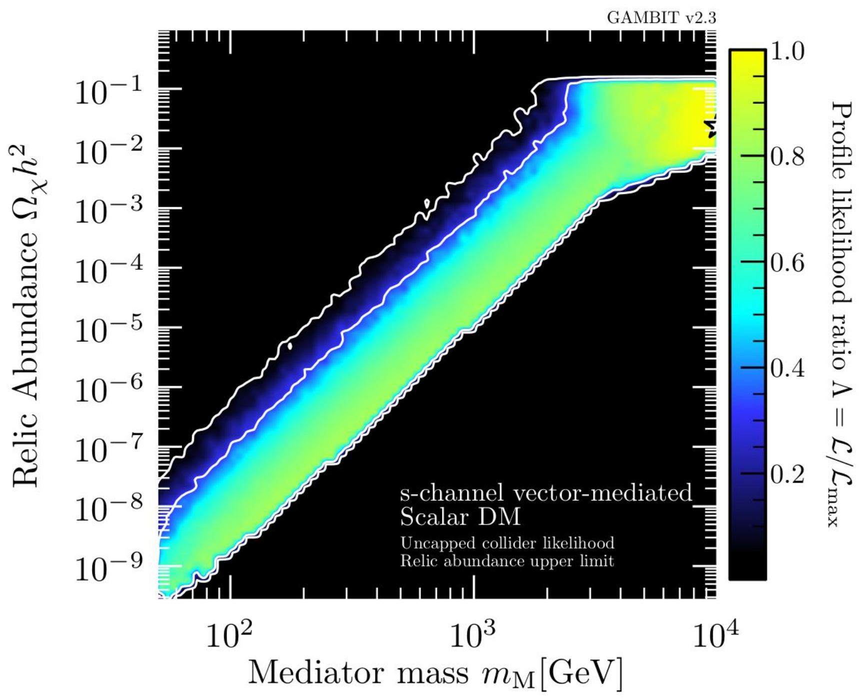
Capped results are not necessary as any collider preferences occur where already excluded by other experiments.



Results - Scalar DM

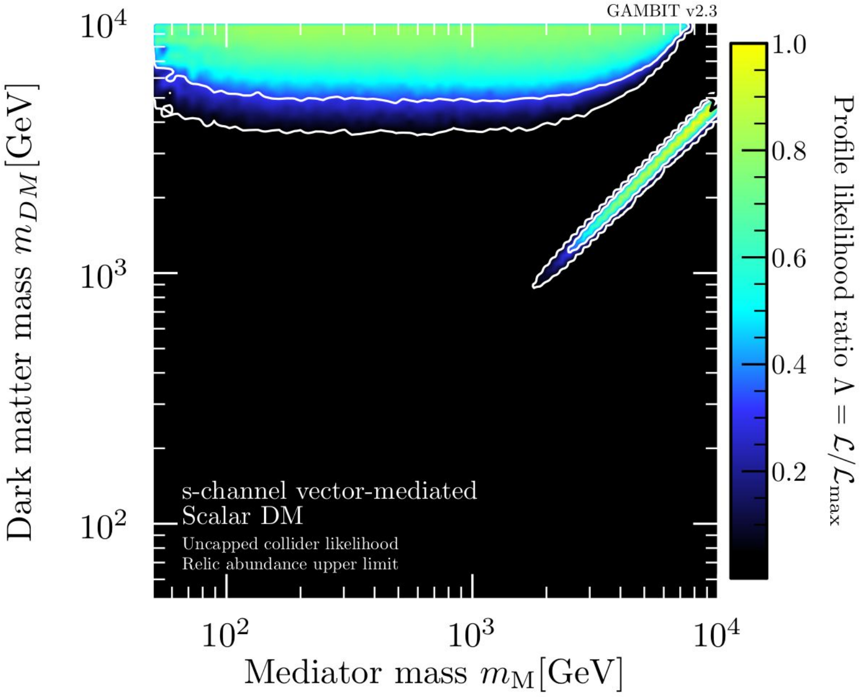
Much of the surviving parameter space predicts a very low DM relic abundance.

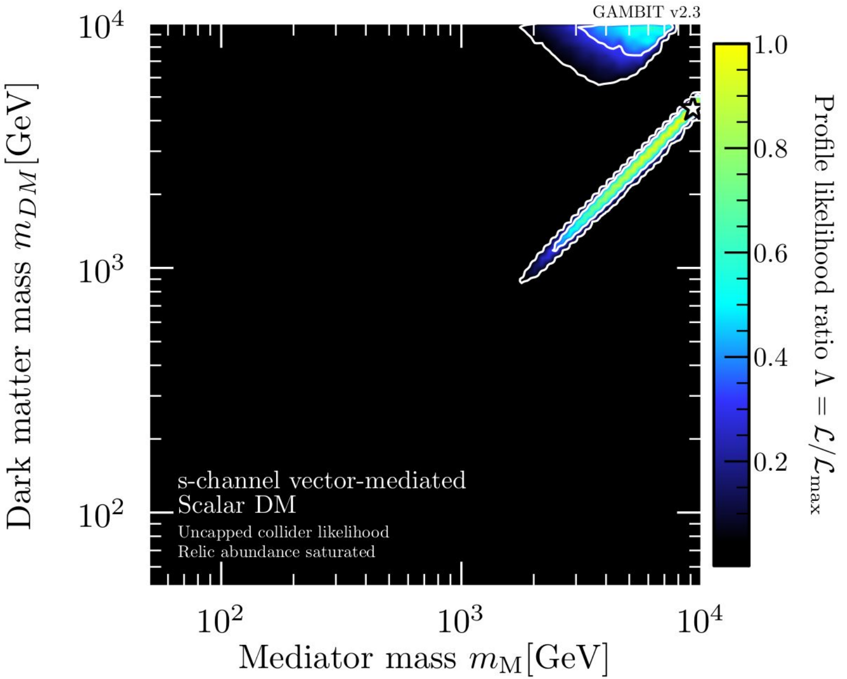




Results - Scalar DM

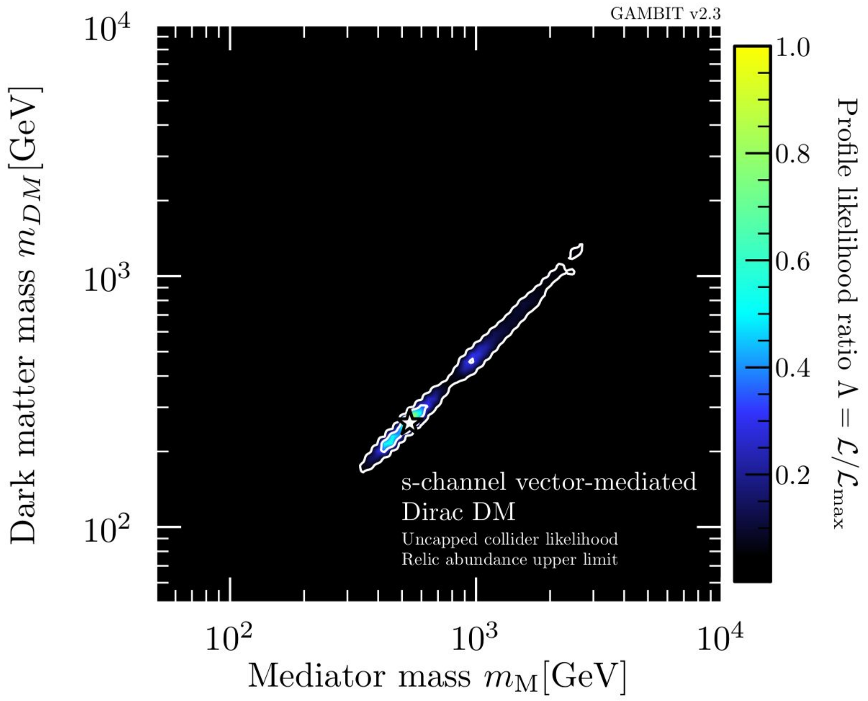
Requiring DM abundance is saturated reduces the off-resonance allowed parameter space.

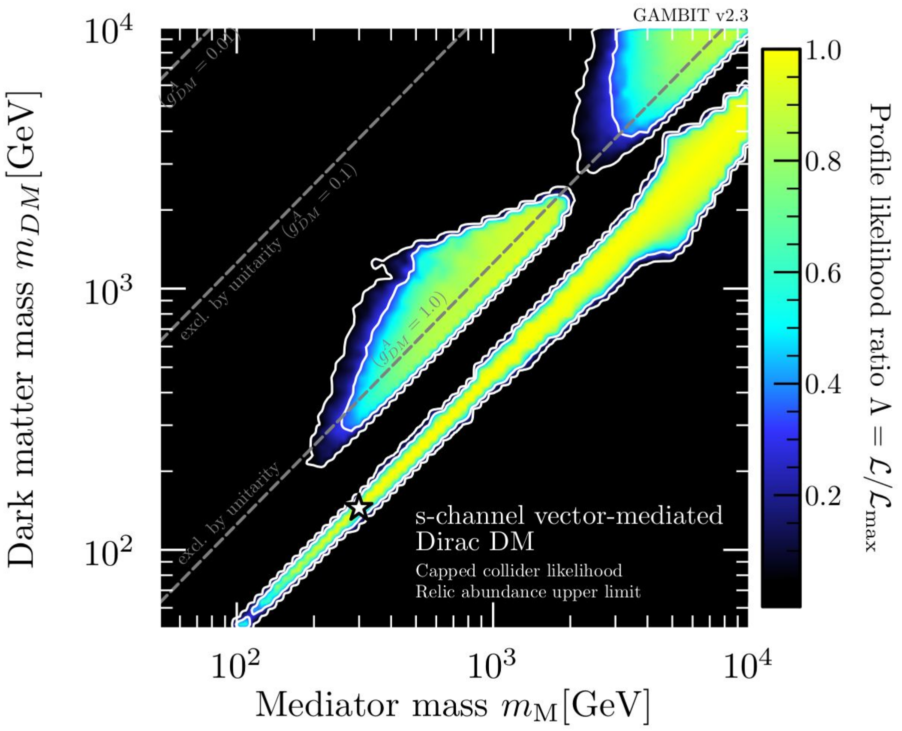




Results- Dirac Fermion DM

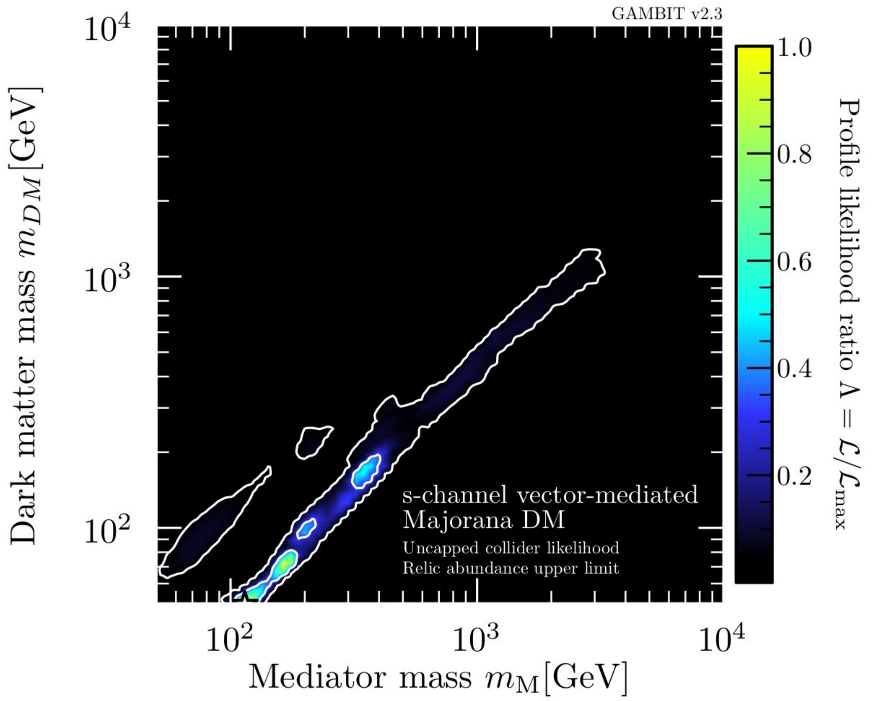
Monojet likelihood gives preference to regions along the resonance.

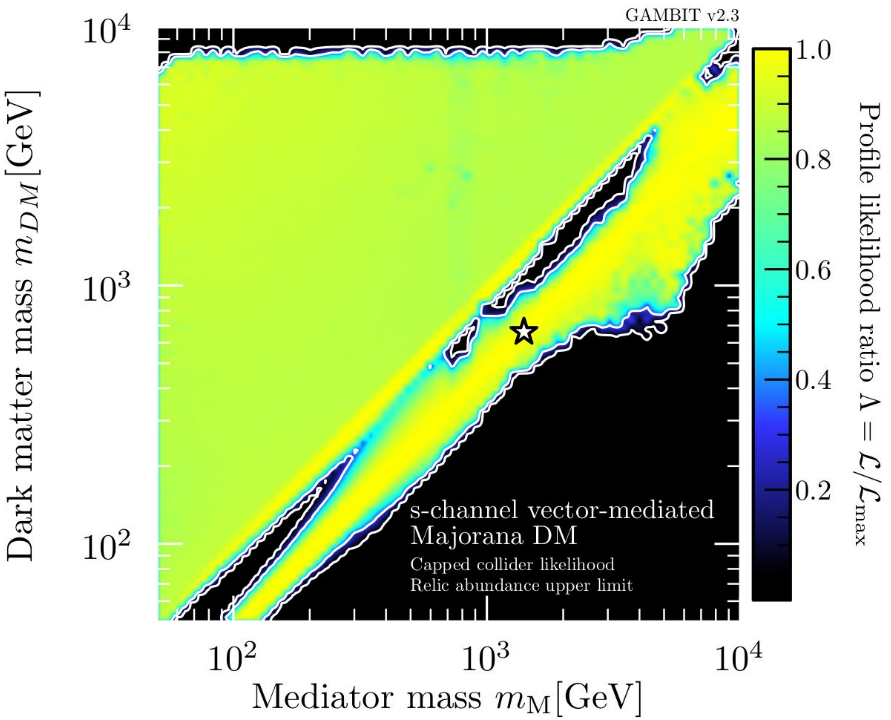




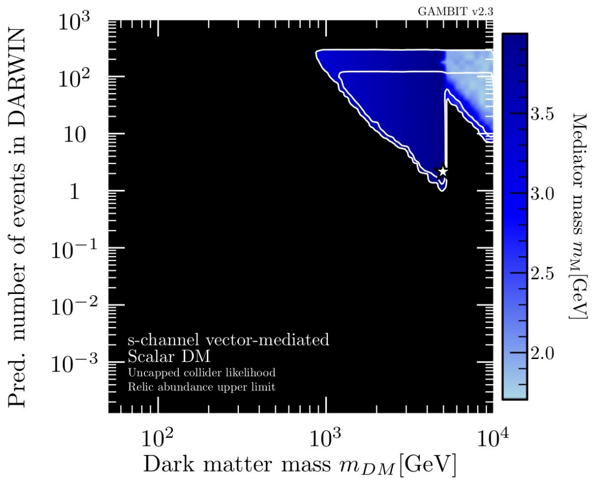
Results - Majorana fermion DM

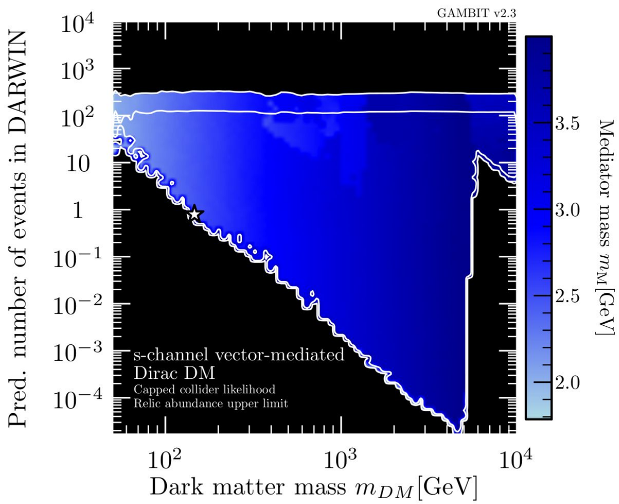
Monojet excesses are also fit by this model, but not only along the resonance.

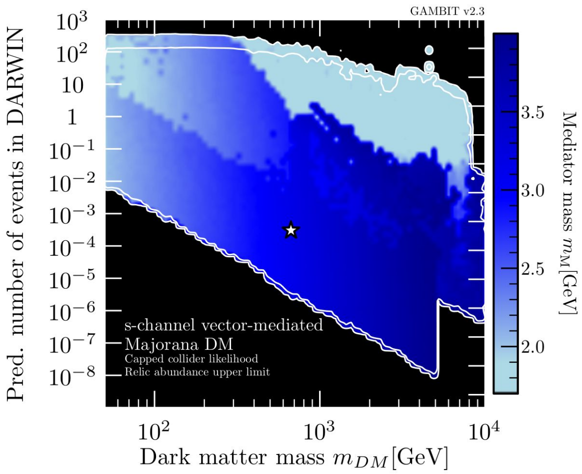




Future Prospects - DARWIN







Summary

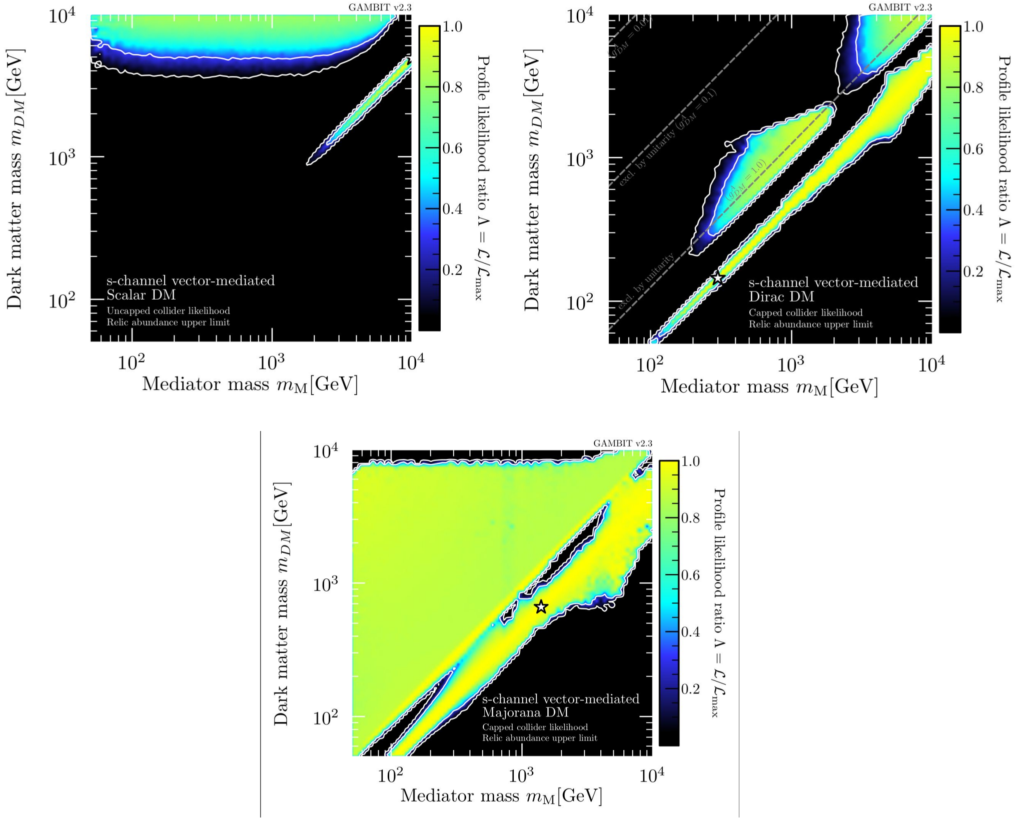
By combining constraints from direct detection, indirect detection and colliders, simplified dark matter models can be constrained greatly.

Scalar DM: Most of the parameter space that survives is for large DM masses. However, most of that underpredicts the DM abundance.

Dirac/Majorana DM: Scans are driven toward monojet fluctuations. No lower bound on DM masses for the parameters in these scans.

Look out for vector DM unitarity study coming soon.

Thanks for Listening!



References

[4] SuperCDMS: R. Agnese et. al., New Results from the Search for Low-Mass Weakly Interacting Massive Particles with the CDMS Low Ionization Threshold Experiment, Phys. Rev. Lett. 116 (2016) 071301

[5] CRESST: G. Angloher et. al., Results on light dark matter particles with a low-threshold CRESST-II detector, Eur. Phys. J. C76 (2016) 25

[6] CRESST: A. H. Abdelhameed et. al., First results from the CRESST-III low-mass dark matter program, Phys. Rev. D 100 (2019) 102002

[7] DarkSide: P. Agnes et. al., DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon, Phys. Rev. D 98 (2018) 102006

[8] LUX: D. S. Akerib et. al., Results from a search for dark matter in the complete LUX exposure, Phys. Rev. Lett. 118 (2017) 021303

[9] PICO: C. Amole et. al., Dark Matter Search Results from the PICO-60 C_3F_8 Bubble Chamber, Phys. Rev. Lett. 118 (2017) 251301,

[10] PICO: C. Amole et. al., Dark Matter Search Results from the Complete Exposure of the PICO-60 C_3F_8 Bubble Chamber, Phys. Rev. D 100 (2019) 022001

[11] PandaX-II: A. Tan et. al., Dark Matter Results from First 98.7 Days of Data from the PandaX-II Experiment, Phys. Rev. Lett. 117 (2016) 121303

[12] PandaX-II: X. Cui et. al., Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment, Phys. Rev. Lett. 119 (2017) 181302

[13] XENON: E. Aprile et. al., Dark Matter Search Results from a One Ton-Year Exposure of XENON1T, Phys. Rev. Lett. 121 (2018) 111302

[14] CMS: A. M. Sirunyan et. al., Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s}$ = 13 TeV, JHEP 05 (2020) 033

[15] ATLAS: G. Aad et. al., Search for new resonances in mass distributions of jet pairs using 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector, JHEP 03 (2020) 145,

[16] ATLAS: M. Aaboud et. al., Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at $\sqrt{s}$ = 13 TeV, Phys. Rev. Lett. 121 (2018) 081801

References

[17] CDF: T. Aaltonen et. al., Search for new particles decaying into dijets in proton-antiproton collisions at √s = 1.96 TeV, Phys. Rev. D 79 (2009) 112002

[18] ATLAS: M. Aaboud et. al., Search for light resonances decaying to boosted quark pairs and produced in association with a photon or a jet in proton-proton collisions at √s = 13 TeV with the ATLAS detector, Phys. Lett. B 788 (2019) 316–335

[19] ATLAS Collaboration, Search for boosted resonances decaying to two b-quarks and produced in association with a jet at √s = 13 TeV with the ATLAS detector, 2018

[20] CMS: A. M. Sirunyan et. al., Search for low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions at √s = 13 TeV, Phys. Rev. D 100 (2019) 112007

[21] ATLAS: M. Aaboud et. al., Search for low-mass resonances decaying into two jets and produced in association with a photon using pp collisions at √s = 13 TeV with the ATLAS detector, Phys. Lett.B 795 (2019) 56–75

[22] CMS: A. M. Sirunyan et. al., Search for Low-Mass Quark-Antiquark Resonances Produced in Association with a Photon at √s =13 TeV, Phys. Rev. Lett. 123 (2019) 231803

[23] ATLAS: G. Aad et. al., Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at √s = 13 TeV with the ATLAS detector

[24] CMS collaboration, Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at √s = 13 TeV, CMS-PAS-EXO-20-004 (2021)

[25] Fermi-LAT: M. Ackermann et. al., Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data, Phys. Rev. Lett. 115 (2015) 231301

[26] Planck: N. Aghanim et. al., Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. 641 (2020) A6

[27] F. Kahlhoefer, Review of LHC Dark Matter Searches, Int. J. Mod. Phys. A32 (2017) 1730006