Exploring dark matter models with global fits

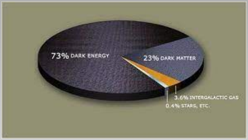
Tomás Gonzalo

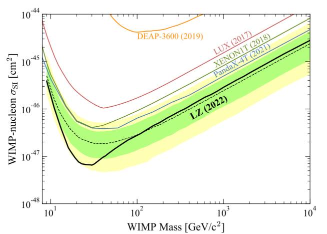
Karlsruhe Institute for Technology

Exploring the Dark Side of the Universe Tools 2024,
7 June 2024

Dark Matter

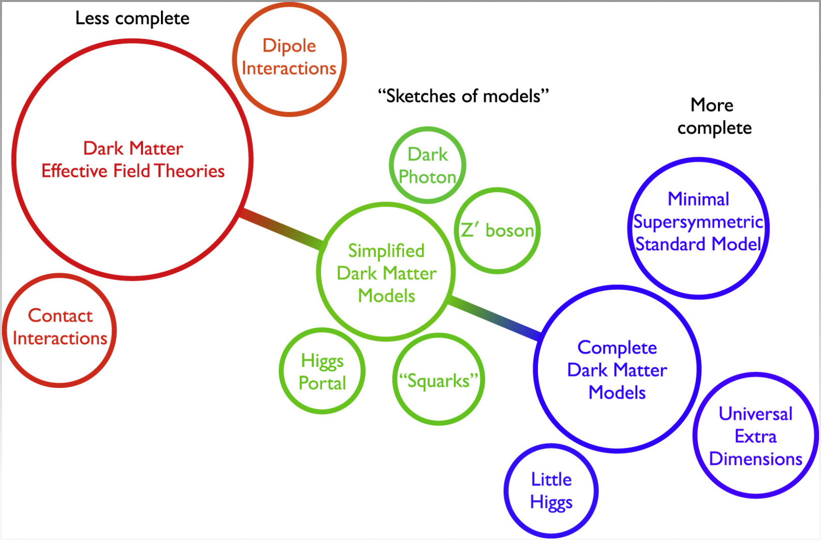
- Plenty of evidence for DM from astrophysics (e.g bullet cluster) and cosmology (e.g CMB)
- If DM is a particle and if interacts then we should be able to detect it
- Most popular DM models are WIMPs
  - → EW-scale mass, accesible at colliders
  - → Just right RD through freeze-out
  - → Form part of complete models (e.g. MSSM)





- No evidence of WIMPs
- Very strong contraints from experimental searches (e.g LZ)
- Survivability of DM models depends on a combination of many constraints
- DM models must be tuned to survive

Dark Matter


Less complete
Dipole Interactions
Dark Matter Effective Field Theories
"Sketches of models"
More complete
Dark Photon
Z′ boson
Simplified Dark Matter Models
Minimal Supersymmetric Standard Model
Contact Interactions
Higgs Portal
"Squarks"
Complete Dark Matter Models
Universal Extra Dimensions
Little Higgs

Dark Matter

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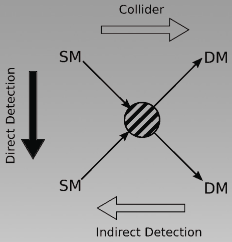
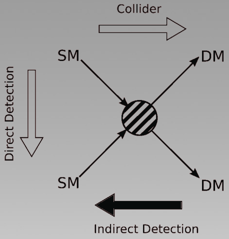
- Searches for DM in particle physics, astrophysics and cosmology



→ DM interacting with nuclei

→ LZ, XENON1T, PandaX, LUX, CDMSlite, CRESST, PICO-60, DarkSide-50



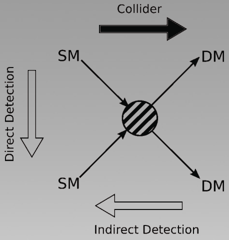
→ DM annihilates into SM particles

→ γ rays, νs, $\bar{p}$, ...

→ Fermi-LAT, IceCube, AMS02

→ BBN and CMB

→ $\Omega_{\rm DM} h^2 \leq 0.120 \pm 0.001$



→ LHC searches for large $\not{E}_T$

→ Mono-X (jet, ...)

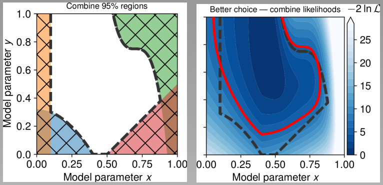
$pp \to \chi\chi j \to j + \not{E}_T$

→ Mediator searches (e.g. $\Gamma_{H\to \rm inv}$, dijets)

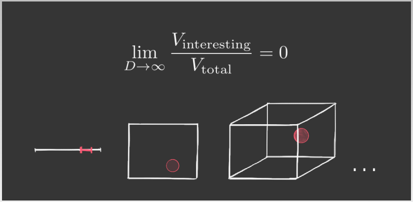
Global fits of DM models

- Multitude of constraints
- Exclusion regions do not properly represent the model predictions
- Composite likelihood

$$\mathcal{L} = \mathcal{L}_{Direct}\mathcal{L}_{Indirect}\mathcal{L}_{Collider}\mathcal{L}_{Astro}\cdots$$



[arXiv:2012.09874 [hep-ph]]



- Multitude of parameters
- Hard to find interesting regions
- Random methods are inefficient
- Need smart sampling strategies (differential, nested, genetic,...)

- Rigorous statisical interpretations (frequentist / Bayesian)
- Parameter estimation, goodness-of-fit, model comparison, ...

GAMBIT

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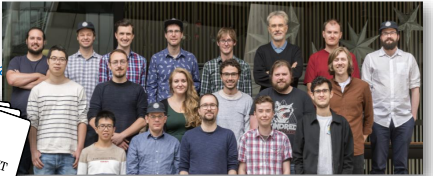
GAMBIT: The Global And Modular BSM Inference Tool

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 packa
- 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: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE Marsh, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, R Ruiz, A Scaffidi, P Scott, W Shorrock, C Sierra, P Stöcker, W Su, J Van den Abeele, A Vincent, M White, A Woodcock, Y Zhang ++

70+ participants in many experiments and numerous major theory codes

- Global fits of BSM models: DM, ALPs, SUSY, νs, flavour, ...
- Other applications: nuclear physics, COVID spread models, ...

Higgs portal DM

- Scalar DM (S) [GAMBIT, Eur.Phys.J.C 77 (2017) 8, 568] [S.Balan et al, arXiv:2303.07362 [hep-ph]]

$$\mathcal{L}_S = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S,$$

$$m_S{}^2 = \mu_S^2 + \frac{1}{2}\lambda_{hS} v^2$$

- Vector DM (V_μ) [GAMBIT. Eur.Phys.J.C 79 (2019) 1, 38]

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

$$m_V{}^2 = \mu_V^2 + \frac{1}{2}\lambda_{hV}^2$$

- Fermionic DM (Dirac, ψ) [GAMBIT. Eur.Phys.J.C 79 (2019) 1, 38]

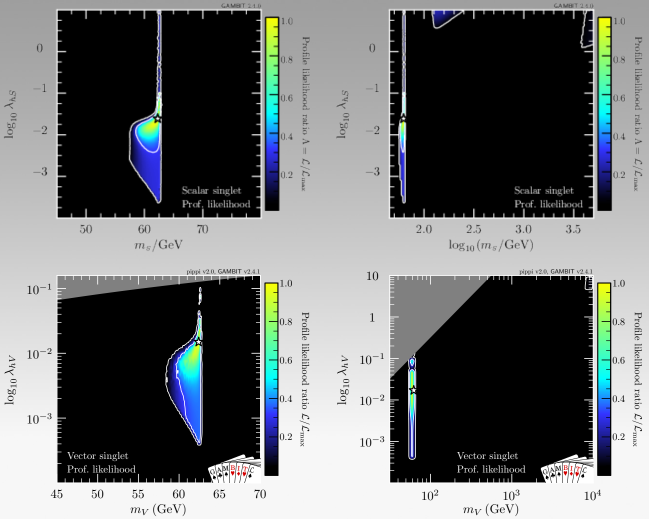
$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - m_\psi)\psi - \frac{\lambda_{h\psi}}{\Lambda_\psi}(\cos\xi\bar{\psi}\psi + \sin\xi\bar{\psi}i\gamma_5\psi)(vh + \frac{1}{2}h^2)$$

- Fermionic DM (Majorana, χ) [GAMBIT. Eur.Phys.J.C 79 (2019) 1, 38]

$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi}(\cos\xi\bar{\chi}\chi + \sin\xi\bar{\chi}i\gamma_5\chi)(vh + \frac{1}{2}h^2)$$

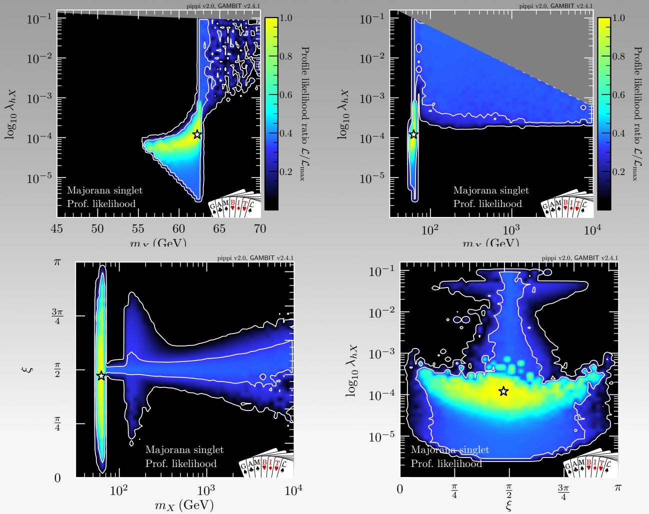
Higgs portal DM

- Bosonic DM (scalar and vector)



Higgs portal DM

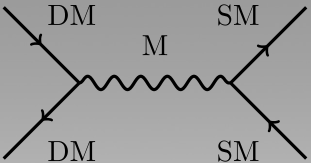
- Majorana fermion DM ($\approx$ Dirac DM)



Simplified DM models

- Singlet DM candidate plus vector mediator that couples to SM particles (quarks)

$$\mathcal{L}_{\rm V} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}{m_{\rm M}}^2 V_\mu V^\mu + g_{\rm q} V_\mu \bar{q}\gamma^\mu q$$



- DM can be a scalar (ϕ), a fermion (ψ or χ) or a vector (X_μ)

[C.Chang et al, Eur.Phys.J.C 83 (2023) 3, 249]

$$\mathcal{L}_\phi = \partial_\mu\phi^\dagger\partial^\mu\phi - {m_{\rm DM}}^2\phi^\dagger\phi + i g^{\rm V}_{\rm DM} V_\mu\Big(\phi^\dagger(\partial^\mu\phi) - (\partial^\mu\phi^\dagger)\phi\Big)\,,$$

$$\mathcal{L}_\chi = i\bar{\chi}\gamma^\mu\partial_\mu\chi - m_{\rm DM}\bar{\chi}\chi + V_\mu\bar{\chi}(g^{\rm V}_{\rm DM} + g^{\rm A}_{\rm DM}\gamma^5)\gamma^\mu\chi\,,$$

$$\mathcal{L}_\psi = \frac{1}{2}i\bar{\psi}\gamma^\mu\partial_\mu\psi - \frac{1}{2}m_{\rm DM}\bar{\psi}\psi + \frac{1}{2}g^{\rm A}_{\rm DM}V_\mu\bar{\psi}\gamma^5\gamma^\mu\psi$$

[C.Chang et al, arXiv:2303.08351 [hep-ph]]

$$\mathcal{L}_X = \frac{1}{2}X^\dagger_{\mu\nu}X^{\mu\nu} + {m_{\rm DM}}^2 X^\dagger_\mu X^\mu - i g_{\rm DM}\Big(X^\dagger_\nu\partial_\mu X^\nu - (\partial_\mu X^{\dagger\nu})X_\nu\Big)V^\mu$$

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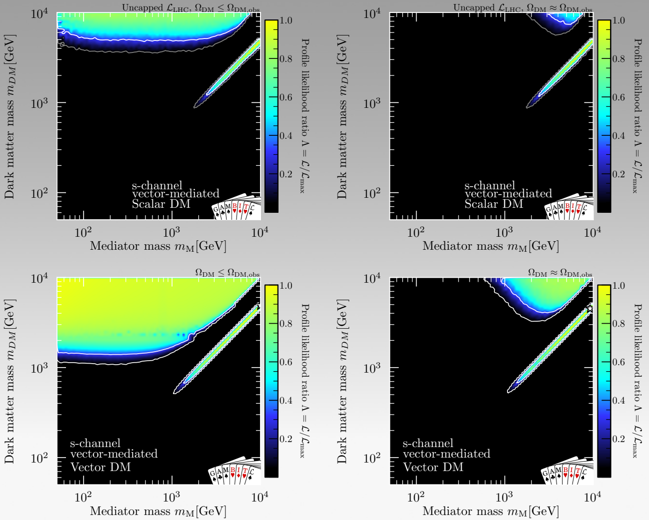
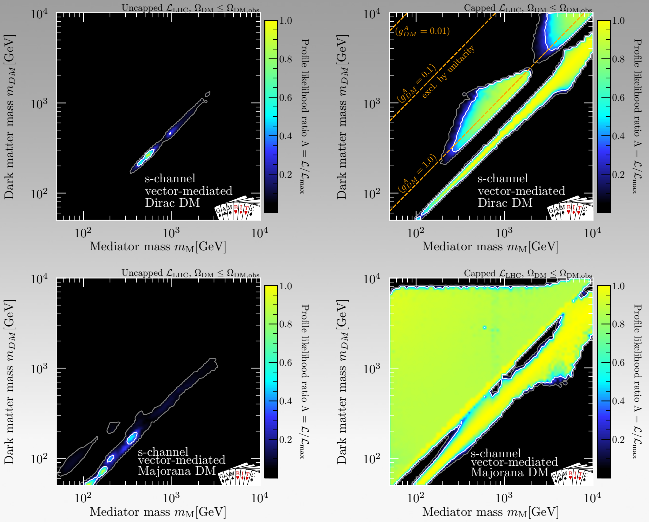
Simplified DM models

- Bosonic DM (scalar and vector)



Simplified DM models

- Fermion DM (Dirac and Majorana)



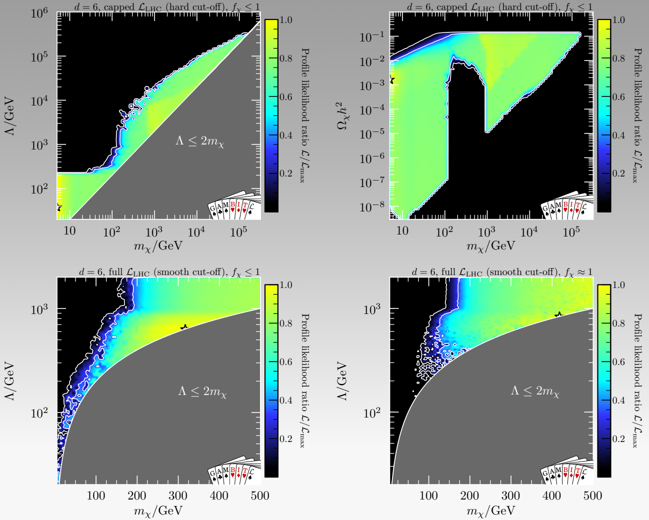
DM EFT

[GAMBIT, Eur.Phys.J.C 81 (2021) 11, 992]

- Dirac fermionic DM χ: $\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{int}} + \overline{\chi}\left(i\not{\partial} - m_\chi\right)\chi$
- Effective interactions (quarks/gluons): $\mathcal{L}_{\text{int}} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\overline{\chi}\sigma_{\mu\nu}\chi)F^{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\overline{\chi}i\sigma_{\mu\nu}\gamma_5\chi)F^{\mu\nu}$$
$$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{2,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,,$$
$$\mathcal{Q}_{3,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,,$$
$$\mathcal{Q}_{4,q}^{(6)} = (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,.$$
$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$
$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$
$$\mathcal{Q}_{5,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{6,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}q)\,,$$
$$\mathcal{Q}_{7,q}^{(7)} = m_q(\overline{\chi}\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{8,q}^{(7)} = m_q(\overline{\chi}i\gamma_5\chi)(\overline{q}i\gamma_5 q)\,,$$
$$\mathcal{Q}_{9,q}^{(7)} = m_q(\overline{\chi}\sigma^{\mu\nu}\chi)(\overline{q}\sigma_{\mu\nu}q)\,,$$
$$\mathcal{Q}_{10,q}^{(7)} = m_q(\overline{\chi}i\sigma^{\mu\nu}\gamma_5\chi)(\overline{q}\sigma_{\mu\nu}q)\,.$$

DM EFT



$d = 6$, capped $\mathcal{L}_{\rm LHC}$ (hard cut-off), $f_\chi \leq 1$
Λ/GeV
m_χ/GeV
$\Lambda \leq 2m_\chi$
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{\max}$
$\Omega_\chi h^2$
$d = 6$, full $\mathcal{L}_{\rm LHC}$ (smooth cut-off), $f_\chi \leq 1$
$d = 6$, full $\mathcal{L}_{\rm LHC}$ (smooth cut-off), $f_\chi \approx 1$
GAMBIT

Sub-GeV DM

[S. Balan et al, arXiv:2405.17548]

- WIMP-like DM at $\gtrsim$ GeV scale is extremely constrained
- Sub-GeV DM (scalar or fermion) can avoid strong DD signals

$$\mathcal{L}_\Phi = |\partial_\mu\Phi|^2 - m_{\rm DM}^2|\Phi|^2 + ig_{\rm DM}A'^\mu[\Phi^*(\partial_\mu\Phi) - (\partial_\mu\Phi^*)\Phi] - g_{\rm DM}^2 A'_\mu A'^\mu|\Phi|^2,$$
$$\mathcal{L}_\psi = \bar\psi(i\partial\!\!\!/ - m_{\rm DM}\psi + g_{\rm DM}A'^\mu\bar\psi\gamma_\mu\psi.$$

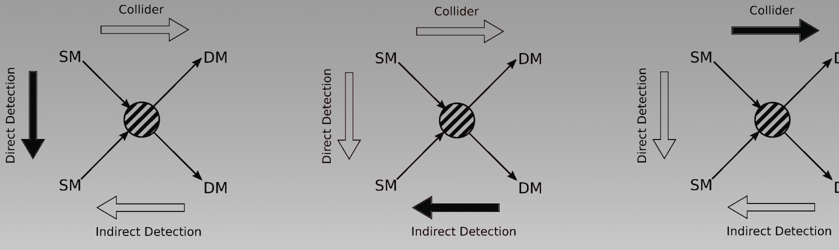
- Mediated by a dark photon with $m_{A'} \geq 2m_{\rm DM}$ and

$$\mathcal{L}_{A'} = -\frac{1}{2}m_{A'}^2 A'^\mu A'_\mu - \frac{1}{4}A'^{\mu\nu}A'_{\mu\nu} - \kappa e A'^\mu \sum_f q_f \bar f \gamma_\mu f$$

- Strongly constrained annihilation cross section (CMB & X-rays)
  - $\rightarrow$ Resonant enhancement $\quad \epsilon_R = (m_{A'}^2 - 4m_{\rm DM}^2)/(4m_{\rm DM}^2)$
  - $\rightarrow$ Particle-antiparticle asymmetry $\quad \eta_{\rm DM} = (n_\xi - n_{\bar\chi})/s$
  - $\rightarrow$ Underabundant DM $\quad f_{\rm DM} = \Omega_{\rm DM}/\Omega_{\rm DM,obs} < 1$

Sub-GeV DM

- Constraints change a lot with respect to GeV-scale WIMPs



$\rightarrow$ Nuclear (CRESSTIII)

$\rightarrow$ Migdal (DarkSide-50, XENON1T, PandaX4T)

$\rightarrow$ Electron (XENON1T, SENSEI, DarkSide-50, PandaX4T, DAMIC, SuperCDMS)

$\rightarrow$ X-rays (INTEGRAL)

$\rightarrow$ Bullet Cluster $\sigma_0/m_{\rm DM} < 1.4\ {\rm cm}^2{\rm g}^{-1}$

$\rightarrow$ CMB E injection

$\rightarrow$ $N_{\rm eff}$ at BBN

$\rightarrow$ RD of asym DM $\Omega_{\rm DM}h^2 \leq 0.120 \pm 0.001$

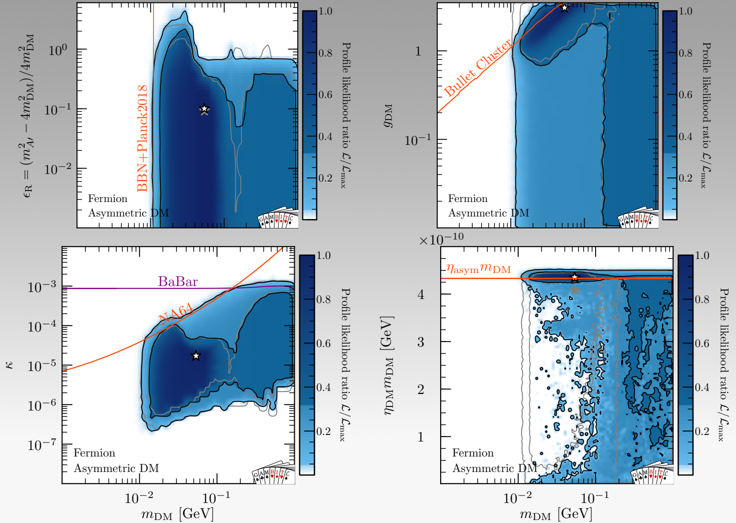
$\rightarrow$ Beam dumps: LSND, MiniBooNE $\pi^0, \eta \rightarrow \gamma A'$

$\rightarrow$ Fixed target: NA64 $e^- Z \rightarrow e^- Z A'$

$\rightarrow$ Single-γ search: BaBar $e^+e^- \rightarrow \gamma A'$

Sub-GeV DM

- Results (frequentist) for fermionic asymmetric DM

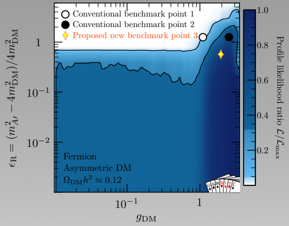


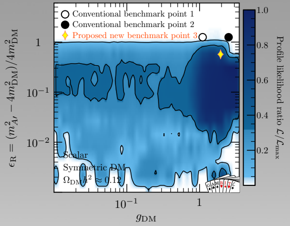
Sub-GeV DM

- Past bechmark points are excluded by current constraints

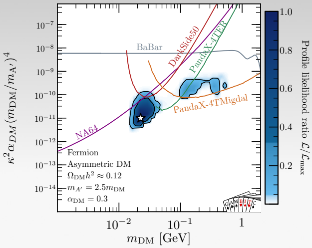
$m_{A'}/m_{\rm DM} = 3$

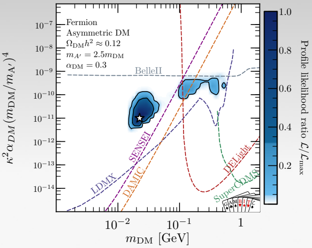
$g_{\rm DM} = 1.1$ or 2.5





- We propose new BP: $m_{A'} = 5/2 m_{\rm DM}$, $g_{\rm DM} = 1.94$





Conclusions and outlook

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- There are many models of DM constrained by multitude of constraints from different sources
  - → Global studies the only way to give definitive status of models
- GeV scale WIMPs are in trouble in simplified models
  - → Bosonic DM survives only on the resonance (HP models) or for high $m_{\rm DM}$ (vector mediator), but underabundant
  - → Fermionic DM way more promising due to suppressed DD, but requires maxiimal CP violation
  - → EFT study shows maximal value of $\Lambda \lesssim 200$ GeV for $m_\chi \lesssim 100$ GeV
- Light (sub-GeV) DM might be the next most interesting model
  - → Mostly survives in the resonance $m_{A'} \sim 2m_{\rm DM}$
  - → Promising solution with asymmetric DM, avoiding resonance
  - → Bayesian evidence favours asym vs sym fermion $\mathcal{Z}_{\rm asym}/\mathcal{Z}_{\rm sym} = 15.6$
  - → Old benchmarks are (mostly) excluded with recent data
  - → New bechmarks can be discovered in the next gen of searches

$$m_{A'} = \frac{5}{2} m_{\rm DM} \quad \text{or} \quad \epsilon_R = \frac{9}{16}, \qquad \alpha_{\rm DM} = 0.3 \quad \text{or} \quad g_{\rm DM} = 1.94$$

Backup

Sub-GeV DM

- Resonant enhancement of anniliations at freezeout and suppression of indirect signals
- Resonant parameter

$$\epsilon_R = \frac{m_{A'}^2 - 4m_{\rm DM}^2}{4m_{\rm DM}^2}$$

- The kinetic energy available in an annihilation process can be parametrised as

$$\epsilon = \frac{s - 4m_{\rm DM}^2}{4m_{\rm DM}^2}$$

which is around $\epsilon \sim 0.1$ at freezeout and $\epsilon \sim 10^{-6}$ in the MW

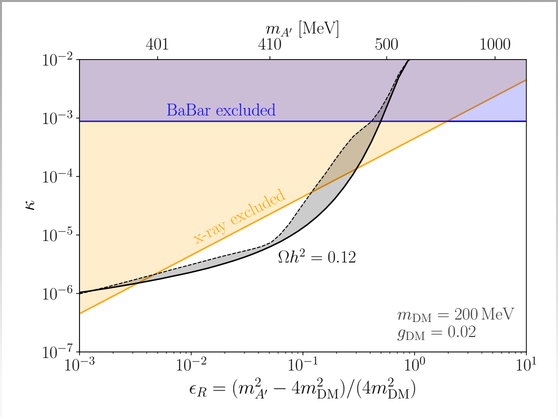
- In the non-relativistic limit, $\epsilon = v_{\rm DM}^2$, so the propagator of A' is

$$\frac{1}{(s - m_{A'}^2)^2 + m_{A'}^2\Gamma_{A'}^2} = \frac{1}{16m_{\rm DM}^4(\epsilon - \epsilon_R)^2 + m_{A'}^2\Gamma_{A'}^2}$$

- So a value of $\epsilon_R \sim 0.1$ enhances annihilations at freeze-out but suppresses them at present time.

Sub-GeV DM

- Examplification of resonant enhancement of relic abundance
- $m_{\rm DM} = 200$ MeV, $g_{\rm DM} = 0.02$



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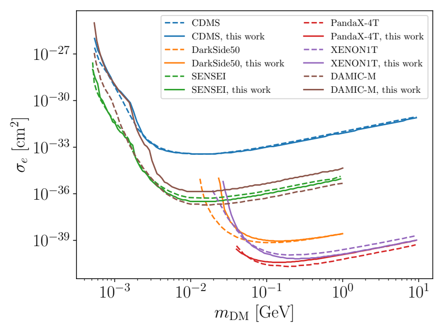
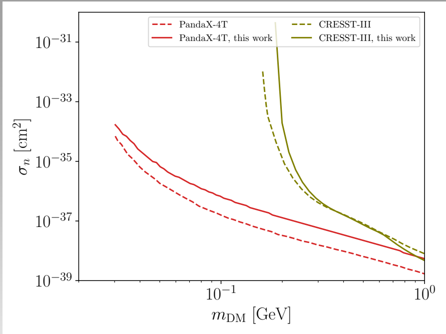
- Parameter ranges and priors

Parameter name	Symbol	Unit	Range	Prior
Kinetic mixing	κ	–	$[10^{-8}, 10^{-2}]$	logarithmic
Dark sector coupling	$g_{\rm DM}$	–	$[10^{-2}, \sqrt{4\pi}]$	logarithmic
Asymmetry parameter	$\eta_{\rm DM}$	–	$[0, 10^{-9}\,{\rm GeV}/m_{\rm DM}]$	linear
Dark matter mass	$m_{\rm DM}$	MeV	[1,1000]	logarithmic
Dark photon mass	$m_{A'}$	MeV	[2,6000] with $m_{A'} \geq 2m_{\rm DM}$	logarithmic
or				
Resonance parameter	ϵ_R	–	$[10^{-3},8]$	logarithmic

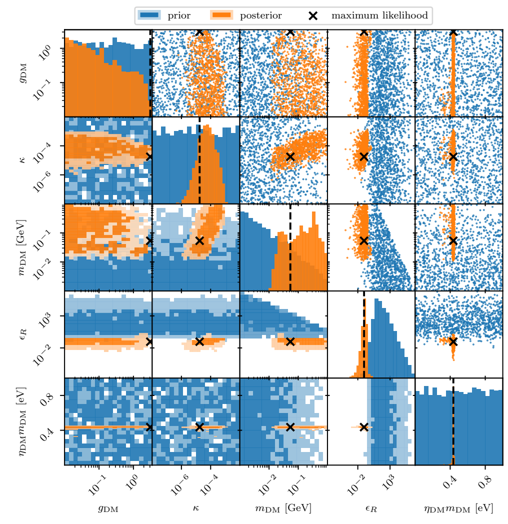
Sub-GeV DM

- Reproduction of the DD results (ER, NR and Migdal)



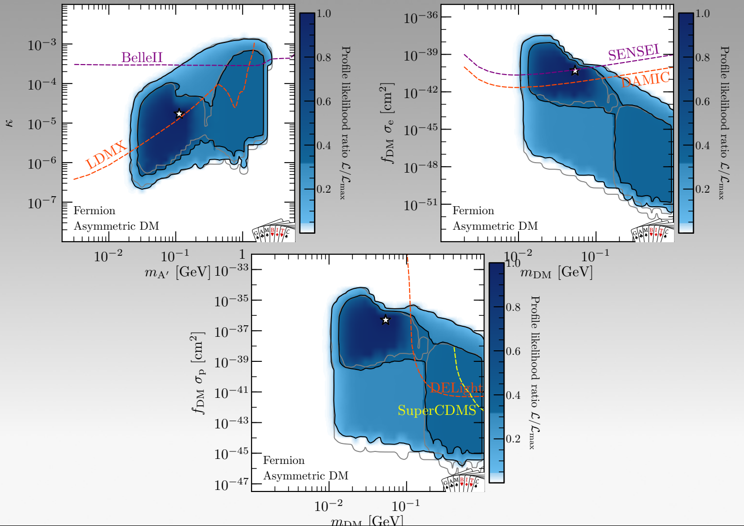


- Results (Bayesian) fermionic asymmetric DM



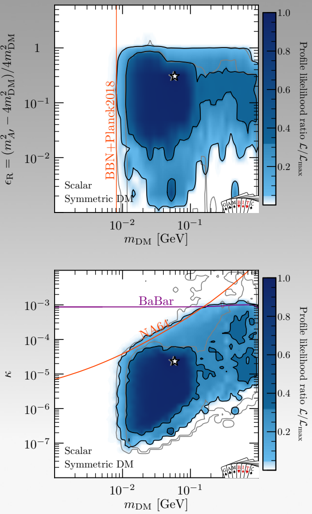
Sub-GeV DM

- Future sensitivities (fermion asymmetric)

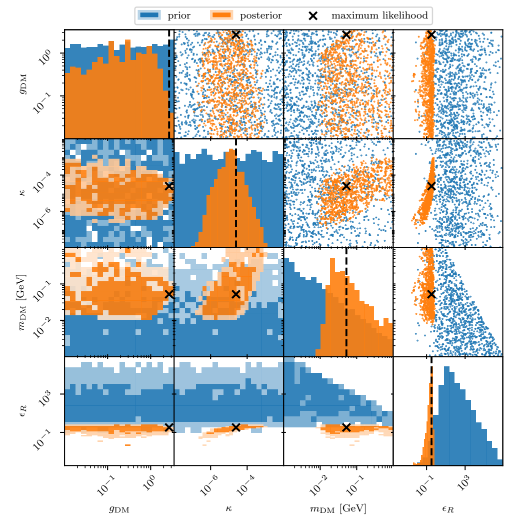


Sub-GeV DM

- Results (frequentist) for scalar symmetric DM



- Results (Bayesian) for scalar symmetric DM

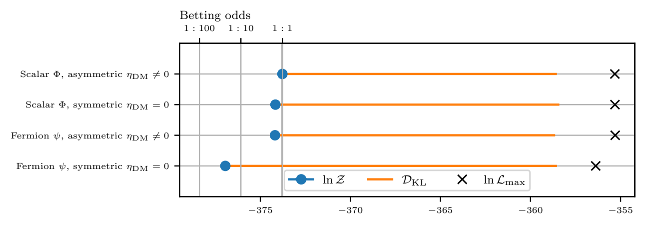


Sub-GeV DM

- Bayesian model comparison
  → Bayesian evidence

$$\mathcal{Z} = \int \mathcal{L}(\theta)\pi(\theta)d\theta \quad \rightarrow \quad \log \mathcal{Z} = -\langle \log \mathcal{L} \rangle_{\mathcal{P}} - \mathcal{D}_{\text{KL}}$$

  → Posterior-weighted log-likelihood $\langle \log \mathcal{L} \rangle_{\mathcal{P}} = \int \mathcal{P}(\theta) \log \mathcal{L}(\theta) d\theta$
  → Kullback-Leibler divergence $\mathcal{D}_{\text{KL}} = \int \mathcal{P}(\theta) \log \frac{\mathcal{P}(\theta)}{\pi(\theta)} d\theta$



DM EFT

- Running and mixing
  - → For direct detection WCs are needed at $\mu = 2$ GeV (DirectDM)
  - → For $\Lambda > m_t(m_t)$:

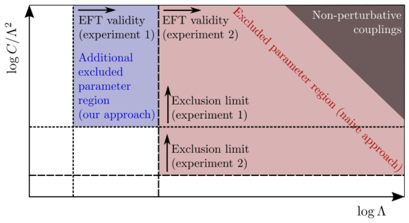
$$\mathcal{C}^{(5)}_{1,2} = -4\frac{m_t(m_t)^2}{\Lambda^2}\log\frac{\Lambda^2}{m_t(m_t)^2}\mathcal{C}^{(7)}_{9,10}$$

$$\Delta\mathcal{C}^{(7)}_i = -\mathcal{C}^{(7)}_{i+4,q} \quad (i = 1,2)$$

$$\Delta\mathcal{C}^{(7)}_i = \mathcal{C}^{(7)}_{i+4,q} \quad (i = 3,4)$$

- EFT validity, Λ free parameter
  - → DD requires $\Lambda > 2$ GeV
  - → Annihilation processes (ID/RD) require $\Lambda > 2m_\chi$
  - → Collider searches $\Lambda > \not{E}_T$

$$\Lambda < \not{E}_T \quad \begin{cases} \dfrac{d\sigma}{d\not{E}_T} = 0 \\ \dfrac{d\sigma}{d\not{E}_T} \to \dfrac{d\sigma}{d\not{E}_T}\left(\dfrac{\not{E}_T}{\Lambda}\right)^{-a} \end{cases}$$



Likelihoods

- Direct Detection

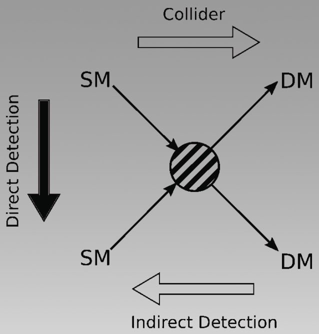
$$\frac{dR}{dE_R} = \frac{\rho}{m_T\, m_\chi} \int_{v_{\min}}^{\infty} v f(v) \frac{d\sigma}{dE_R} d^3v$$

$$v_{\min}(E_R) = \sqrt{\frac{m_T E_R}{2\,\mu^2}}$$

$\rightarrow$ Non-relativistic operators

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

$\rightarrow$ XENON1T, LUX 2016, PandaX 2016-17, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017-19, and DarkSide-50



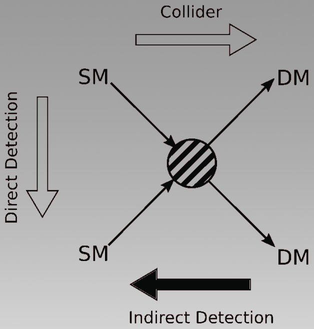
- Relic abundance $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v_{rel}\rangle\left(n_\chi n_{\bar\chi} - n_{\chi,eq}n_{\bar\chi,eq}\right)$

$\rightarrow$ Planck 2018: $\Omega_{DM}h^2 \leq 0.120 \pm 0.001$

- Indirect detection with γ-rays
  - → γ-rays from DM annihilation in dSphs

$$\ln \mathcal{L}^{\text{prof.}}_{\text{dwarfs}} = \ln \mathcal{L}_{ki}\left(\Phi_i \cdot J_k\right) + \ln \mathcal{L}_J$$

  - → Pass-8 combined of 15 dSphs from *Fermi*-LAT data
- Indirect detection with νs
  - → Solar capture of DM leads to very high energy νs $>$ solar νs
  - → 79-string IceCube search



- Indirect detection constraints from CMB
  - → Injected energy $(\gamma, e^{\pm})$ changes reion history and optical depth τ
  - → CMB is sensitive to energy deposition efficiency f_{eff} via combination

$$p_{\text{ann}} = f_\chi f_{\text{eff}} \frac{\langle \sigma v \rangle}{m_\chi}$$

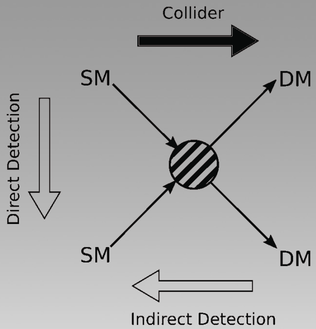
Likelihoods

- Collider constraints
  - → Many signatures for DM searches

$$pp \to \chi\chi j \to j + \not{E}_T$$

  - → MadGraph_aMC@NLO ⇝ Pythia
  - → Interpolated grids for σ and ϵA
  - → Events per $\not{E}_T$ bin (signal regions)

$$N = L \times \sigma \times (\epsilon A)$$



→ ATLAS 139fb^{-1} mono-jet
- ⇝ SR with best significance
- ⇝ $\mathcal{L}_{\text{ATLAS}}(s_i) \equiv \mathcal{L}_{\text{ATLAS}}(s_i, \hat{\hat{\gamma}}_i)$

→ CMS 36fb^{-1} mono-jet
- ⇝ Profile over systematics
- ⇝ $\mathcal{L}_{\text{CMS}}(\mathbf{s}) \equiv \mathcal{L}_{\text{CMS}}(\mathbf{s}, \hat{\hat{\gamma}})$

→ *Capped* likelihood

$$\mathcal{L}_{\text{cap}}(\mathbf{s}) = \min[\mathcal{L}_{\text{LHC}}(\mathbf{s}), \mathcal{L}_{\text{LHC}}(\mathbf{s} = \mathbf{0})]$$

Scan framework

- Model parameters

DM mass	m_χ
New physics scale	Λ
Wilson coefficients	$\mathcal{C}_a^{(d)}$

- Nuisance parameters

Local DM density	ρ_0
Most probable speed	v_{peak}
Galactic escape speed	v_{esc}
Running top mass ($\overline{\text{MS}}$ scheme)	$m_t(m_t)$
Pion-nucleon sigma term	$\sigma_{\pi N}$
s-quark contrib. to nucleon spin	Δs
s-quark nuclear tensor charge	g_T^s
s-quark charge radius of the proton	r_s^2

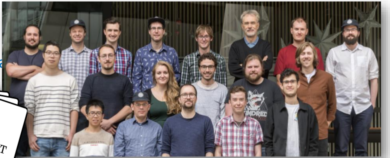
- Needs smart sampling to efficiently scan over all parameters and explore interference effects among WCs

Scan framework

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 packa
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source



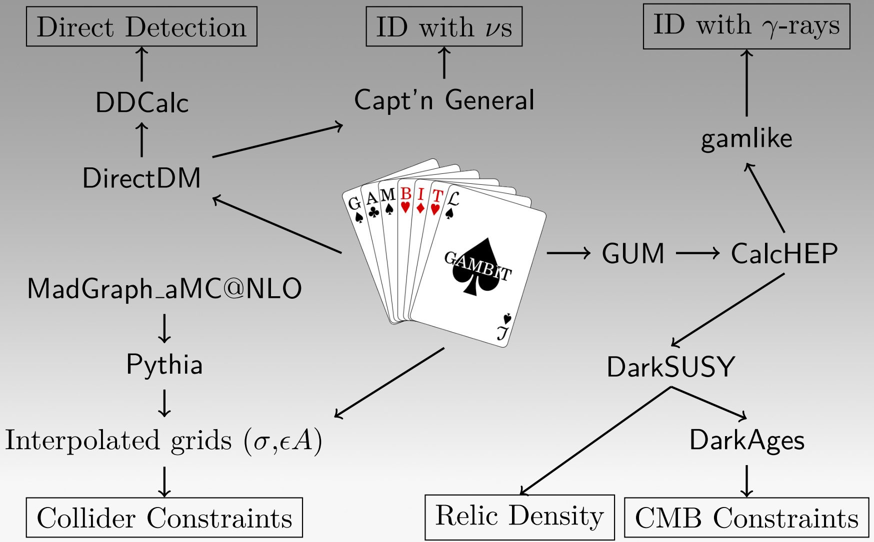
Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

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: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, LL Braseth, T Bringmann, A Buckley, J Butterworth, JE Camargo-Molina, C Chang, J Cornell, M Danninger, A Fowlie, T Gonzalo, W Handley, S Hoof, A Jueid, F Kahlhoefer, A Kvellestad, M Lecroq, C Lin, M Lucente, FN Mahmoudi, DJE Marsh, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, R Ruiz, A Scaffidi, P Scott, W Shorrock, C Sierra, P Stöcker, W Su, J Van den Abeele, A Vincent, M White, A Woodcock, Y Zhang ++

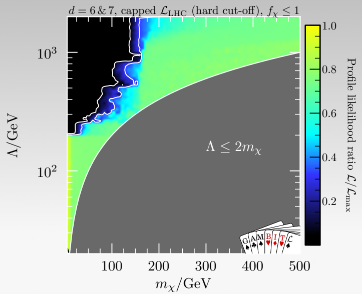
70+ participants in many experiments and numerous major theory codes

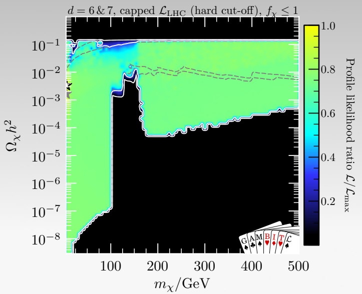
Scan framework



Results

- Include dim-7 operators, $\Omega_{\rm DM}h^2$ upper limit, LHC loglike *capped*
  - → No change on large Λ - small m_χ region
  - → Neither $\mathcal{Q}^{(7)}_{1-4}$ (LHC) nor $\mathcal{Q}^{(7)}_{5-10,q}$ (suppressed) contribute to ann xsec
  - → However, RD can be saturated for $m_\chi < 100$ GeV (and small Λ)
  - → $\mathcal{Q}^{(7)}_3$ and $\mathcal{Q}^{(7)}_{7,q}$ give unconstrained signals in DD and ID
  - → Similar fits to LHC excesses, even when dim-6 ops are zero





Global fits

- Combine all constraints into a **composite likelihood**

$$\mathcal{L} = \mathcal{L}_{Collider}\mathcal{L}_{Higgs}\mathcal{L}_{DM}\mathcal{L}_{Flavour}\ldots$$

- Perform an extensive **parameter scan**

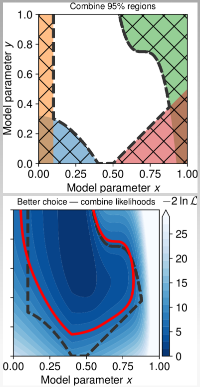
→ Old-school sampling methods (random, grid) are inefficient

→ Harder to make statement about statistics

→ Need **smart sampling strategies** (differential, nested, genetic,...)

→ **Rigorous** statistical interpretation (frequentist/Bayesian)

  - Goodness-of-fit
  - Parameter estimation
  - Model comparison



[arXiv:2012.09874 [hep-ph]]

Modules (Bits)

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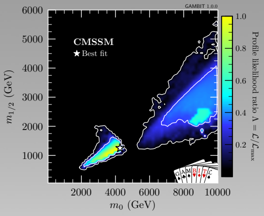
- Physics Modules
  - → **ColliderBit**: collider searches [Eur.Phys.J. C77 (2017) no.11, 795]
  - → **DarkBit**: relic density, dd,... [Eur.Phys.J. C77 (2017) no.12, 831]
  - → **FlavBit**: flavour observables [Eur.Phys.J. C77 (2017) no.11, 786]
  - → **SpecBit**: spectra, RGE running [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **DecayBit**: decay widths [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **PrecisionBit**: precision tests [Eur.Phys.J. C78 (2018) no.1, 22]
  - → **NeutrinoBit**: neutrino likelihoods [Eur.Phys.J.C 80 (2020) no.6, 569]
  - → **CosmoBit**: cosmological constraints [JCAP 02 (2021) 022]
- **ScannerBit** : stats and sampling [Eur.Phys.J. C77 (2017) no.11, 761]
  - → Diver, GreAT, Multinest, Polychord, ...
- **Models**: hierarchical model database
- **Core** : dependency resolution [Eur.Phys.J. C78 (2018) no.2, 98]
- **Backends** : External tools to calculate observables
- **GUM**: Autogeneration of code [S. Bloor, TG, P. Scott et. al., soon]

Examples

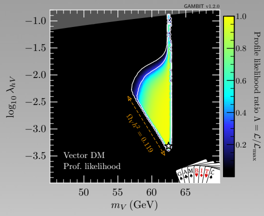
CMSSM

[Eur.Phys.J.C 77 (2017) 12,824]



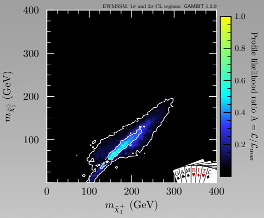
Higgs-portal DM

[Eur.Phys.J.C 79 (2019) 1, 38]



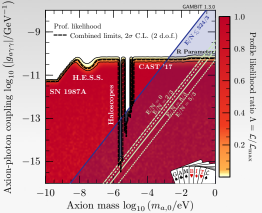
MSSM-EW

[Eur.Phys.J.C 79 (2019) 5, 395]



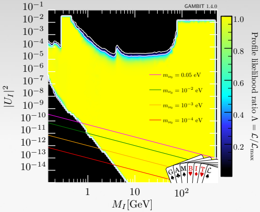
QCD axions

[JHEP 03 (2019) 191]



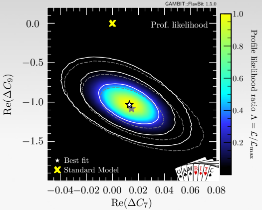
Right-Handed Neutrinos

[Eur.Phys.J.C 80 (2020) 6, 569]



Flavour EFT

[Eur.Phys.J.C 81 (2021)12,1076]



Examples

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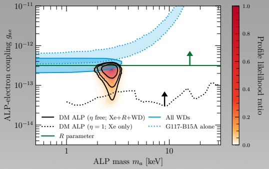
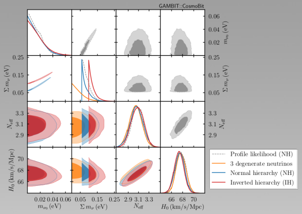
DM ALPs

[JHEP 05 (2021) 159]



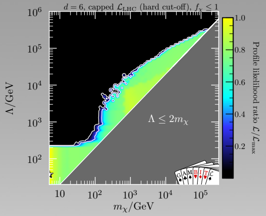
Neutrino Masses

[Phys.Rev.D 103(2021)12,123508]



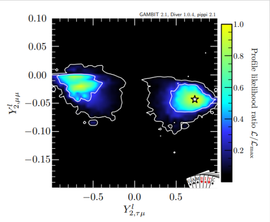
DMEFT

[Eur.Phys.J.C 81 (2021) 11,992]



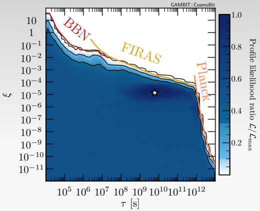
THDM-III

[JHEP 01 (2022) 037]



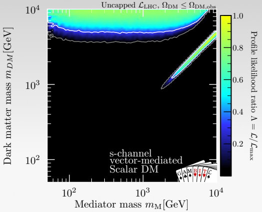
Cosmo ALPs

[arXiv:2205.13549[astro-ph.CO]]



S-channel DM

[arXiv:2209.13266 [hep-ph]]



Core

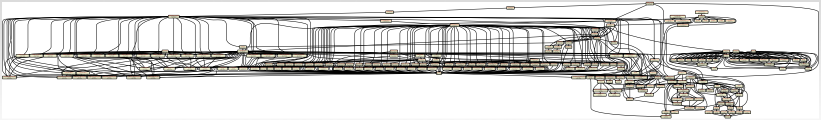
- Each module contains a collection of module functions
- Module functions provide a *capability*
- They have dependencies and backend requirements
- Allowed for specific models
- At run time a dependency tree is generated and resolved

```
// SM-like Higgs mass with theoretical uncertainties
#define CAPABILITY prec_mh
START_CAPABILITY

  #define FUNCTION FH_HiggsMass
  START_FUNCTION(triplet<double>)
  DEPENDENCY(unimproved_MSSM_spectrum, Spectrum)
  DEPENDENCY(FH_HiggsMasses, fh_HiggsMassObs)
  ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)
  #undef FUNCTION

  #define FUNCTION SHD_HiggsMass
  START_FUNCTION(triplet<double>)
  DEPENDENCY(unimproved_MSSM_spectrum, Spectrum)
  BACKEND_REQ(SUSYHD_MHiggs, (), MReal, (const MList<MReal>&))
  BACKEND_REQ(SUSYHD_DeltaMHiggs, (), MReal, (const MList<MReal>&))
  ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)
  #undef FUNCTION

#undef CAPABILITY
```



Models

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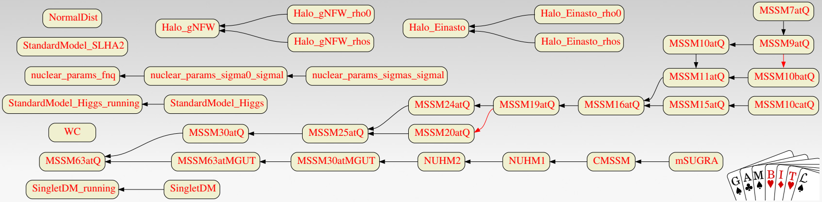
- Extensive model database

SUSY	DM	Cosmo	Others
CMSSM NUHM1,2 MSSM63atQ	Scalar Singlet Fermionic Singlet Vector Singlet Axions	ΛCDM ΔN_{eff} Power-law inflation	SM RH neutrinos WC nuisance models

- Parent-daughter hierarchy
- Module functions are activated for each model



Backends

- C, Fortran ⇝ POSIX `dl`
- C++ ⇝ BOSS + POSIX `dl`
- Mathematica ⇝ WSTP
- Python ⇝ pybind11

CosmoBit

AlterBBN 2.2
DarkAges 1.2.0
MontePythonLike 3.3.0
MultiModeCode 2.0.0
classy 2.9.4
plc 3.0

PrecisionBit

FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

DarkBit

CaptnGeneral 1.0
DDCalc 2.2.0
DarkSUSY 6.2.2
MicrOmegas 3.6.9.2
gamLike 1.0.1
nulike 1.0.9

SpecBit

FlexibleSUSY 2.0.1
SPheno 4.0.3

ColliderBit

HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212
nulike 1.0.9

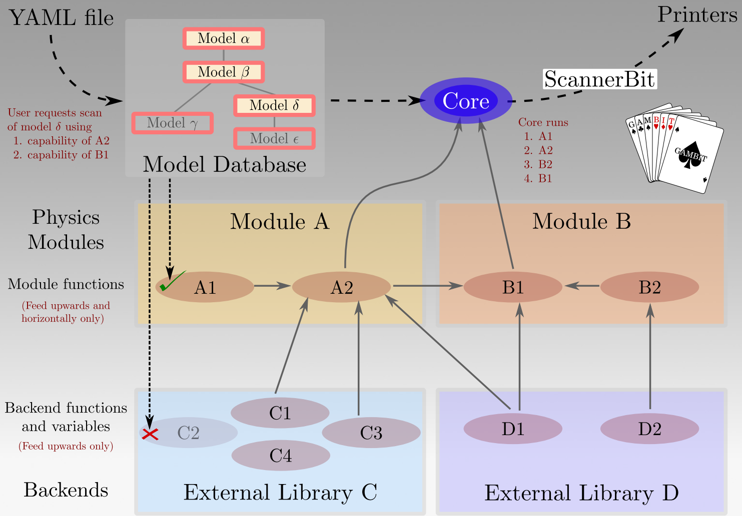
FlavBit

SuperISO 3.6

DecayBit

SUSY_HIT 1.5

An example run



Operators

	SI scattering	SD scattering	Annihilations
$\mathcal{Q}_{1,q}^{(6)} = (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$	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 $\propto m_q^2/m_\chi^2$
$\mathcal{Q}_{1}^{(7)} = \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}$	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 $\propto m_q^2/m_\chi^2$

Hadronic input parameters

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Parameter	Value	Parameter	Value
$\sigma_{\pi N}$	50(15) MeV [1]	μ_p	2.793 - [2]
$Bc_5(m_d - m_u)$	$-0.51(8)$ MeV [3]	μ_n	-1.913 [2]
g_A	1.2756(13) [2]	μ_s	$-0.036(21)$ [4]
m_G	836(17) MeV [1]	g_T^u	0.784(30) [5]
σ_s	52.9(7.0) MeV [6]	g_T^d	$-0.204(15)$ [5]
$\Delta u + \Delta d$	0.440(44) [7]	g_T^s	$-27(16) \cdot 10^{-3}$ [5]
Δs	$-0.035(9)$ [7]	$B_{T,10}^{u/p}$	3.0(1.5) [8]
$B_0 m_u$	0.0058(5) GeV^2 [9]	$B_{T,10}^{d/p}$	0.24(12) [8]
$B_0 m_d$	0.0124(5) GeV^2 [9]	$B_{T,10}^{s/p}$	0.0(2) [8]
$B_0 m_s$	0.249(9) GeV^2 [9]	r_s^2	$-0.115(35)$ GeV^{-2} [4]

[1][F. Bishara et. al., JHEP 11 (2017) 059] [2][PDG 2020] [3][A. Crivellin et. al., Phys. Rev. D 89 (2014) 054021] [4][D. Djukanovic et. al., Phys. Rev. Lett. 123 (2019) 212001, R. S. Sufian et. al.., Phys. Rev. Lett. 118 (2017) 042001] [5][R. Gupta, et. al., Phys. Rev. D 98 (2018) 091501] [6][S. Aoki et. al., Eur. Phys. J. C 80 (2020) 113] [7][J. Liang et. al., Phys. Rev. D 98 (2018) 074505] [8][B. Pasquini et. al., Phys. Rev. D72 (2005) 094029] [9][F. Bishara et. al., arXiv:1708.02678.]

Nuisance parameters

Nuisance parameter		**Value** ($\pm 3\sigma$ **range**)
Local DM density	ρ_0	0.2–0.8 $\mathrm{GeV\,cm^{-3}}$
Most probable speed	v_{peak}	240 (24) $\mathrm{km\ s^{-1}}$
Galactic escape speed	v_{esc}	528 (75) $\mathrm{km\ s^{-1}}$
Running top mass ($\overline{\mathrm{MS}}$ 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) $\mathrm{GeV^{-2}}$

Collider Likelihoods

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- ATLAS, Poisson loglike marginalised over nuisance $\xi =$ relative signal/bkg uncertainties

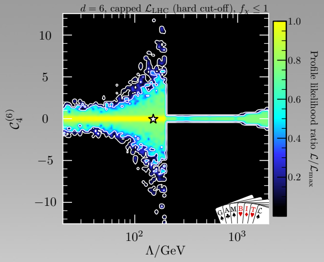
$$\mathcal{L}_{\rm marg}(n|p) = \int_0^\infty \frac{[\xi p]^n \, e^{-\xi p}}{n!} \times \frac{1}{\sqrt{2\pi}\sigma_\xi} \frac{1}{\xi} \exp\left[-\frac{1}{2}\left(\frac{\ln \xi}{\sigma_\xi}\right)^2\right] \mathrm{d}\xi \, .$$

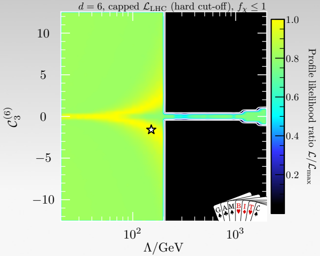
- CMS, convolved Poisson-Gaussian, profiled over systematic uncertainties γ on expected background yields with covariance matrix Σ

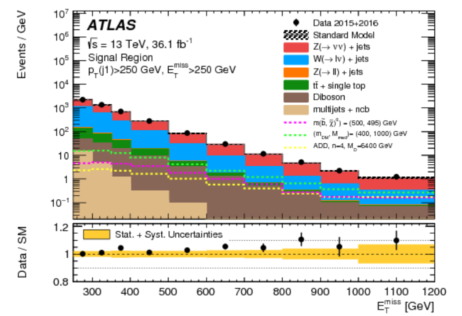
$$\mathcal{L}(\mathbf{s},\gamma) = \prod_i^{N_{\rm bin}} \left[\frac{(s_i + b_i + \gamma_i)^{n_i} e^{-(s_i+b_i+\gamma_i)}}{n_i!}\right] \times \frac{1}{\sqrt{\det 2\pi\Sigma}} e^{-\frac{1}{2}\gamma^{\mathbf{T}}\mathbf{\Sigma}^{-\mathbf{1}}\gamma} \, .$$

Results

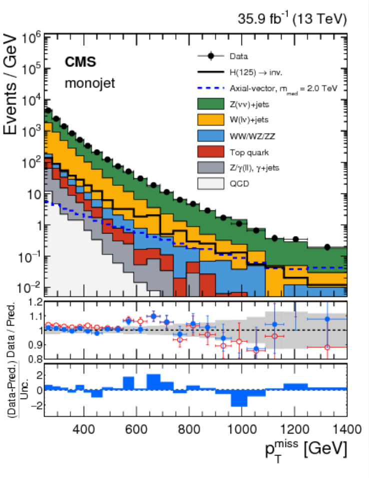
- $\mathcal{C}_1^{(6)}$
  - $\rightarrow$ spin-independent scattering
  - $\rightarrow$ strongly constrained $\rightsquigarrow$ very small
- $\mathcal{C}_2^{(6)}$
  - $\rightarrow$ momentum-dependent scattering
  - $\rightarrow$ $\Lambda < 250$ GeV DD constrained
  - $\rightarrow$ $\Lambda > 250$ GeV LHC constrained
- $\mathcal{C}_3^{(6)}$
  - $\rightarrow$ *both* SD and MD scattering
  - $\rightarrow$ $\Lambda < 250$ GeV weak DD constraints
  - $\rightarrow$ Main contribution to $Fermi - LAT$
  - $\rightarrow$ $\Lambda > 250$ GeV LHC constrained
- $\mathcal{C}_4^{(6)}$
  - $\rightarrow$ spin-dependent scattering
  - $\rightarrow$ identical to $\mathcal{C}_2^{(6)}$







ATLAS
√s = 13 TeV, 36.1 fb-1
Signal Region
pT(j1)>250 GeV, ETmiss>250 GeV
Data 2015+2016
Standard Model
Z(→ νν) + jets
W(→ lν) + jets
Z(→ ll) + jets
tt̄ + single top
Diboson
multijets + ncb
Stat. + Syst. Uncertainties
Events / GeV
Data / SM
ETmiss [GeV]



35.9 fb-1 (13 TeV)
CMS
monojet
Data
H(125) → inv.
Axial-vector, mmed = 2.0 TeV
Z(νν)+jets
W(lν)+jets
WW/WZ/ZZ
Top quark
Z/γ(ll), γ+jets
QCD
Events / GeV
Data / Pred.
(Data-Pred.) Unc.
pTmiss [GeV]

But...

How do I use GAMBIT with my favourite model?
⇝ Adding a model
⇝ Sorting out hierarchy
⇝ Making physics computations work with that model

How do I add a new physical observable or likelihood?
⇝ Create capabilities
⇝ Declare dependencies
⇝ and models
⇝ and backend requirements

1. Add the model to the **model hierarchy**:
   - Choose a model name, and declare any **parent model**
   - Declare the model's parameters
   - Declare any **translation function** to the parent model

```
#define MODEL NUHM1
#define PARENT NUHM2
  START_MODEL
  DEFINEPARS(M0,M12,mH,A0,TanBeta,SignMu)
  INTERPRET_AS_PARENT_FUNCTION(NUHM1_to_NUHM2)
#undef PARENT
#undef MODEL
```

2. Write the translation function as a standard C++ function:

```
void MODEL_NAMESPACE::NUHM1_to_NUHM2 (const ModelParameters &myP, ModelParameters &targetP)
{
   // Set M0, M12, A0, TanBeta and SignMu in the NUHM2 to the same values as in the NUHM1
   targetP.setValues(myP,false);
   // Set the values of mHu and mHd in the NUHM2 to the value of mH in the NUHM1
   targetP.setValue("mHu", myP["mH"]);
   targetP.setValue("mHd", myP["mH"]);
}
```

3. If needed, declare that existing module functions work with the new model, or add new functions that do.

Adding a new module function is easy:

1. Declare the function to GAMBIT in a module's **rollcall header**
   - Choose a capability
   - Declare any **backend requirements**
   - Declare any **dependencies**
   - Declare any specific **allowed models**
   - other more advanced declarations also available

```
#define MODULE FlavBit                             // A tasty GAMBIT module.
START_MODULE

  #define CAPABILITY Rmu                           // Observable: BR(K->mu nu)/BR(pi->mu nu)
  START_CAPABILITY
    #define FUNCTION SI_Rmu                        // Name of a function that can compute Rmu
    START_FUNCTION(double)                         // Function computes a double precision result
    BACKEND_REQ(Kmunu_pimunu, (my_tag), double, (const parameters*)) // Needs function from a backend
    BACKEND_OPTION( (SuperIso, 3.6), (my_tag) )                      // Backend must be SuperIso 3.6
    DEPENDENCY(SuperIso_modelinfo, parameters)     // Needs another function to calculate SuperIso info
    ALLOW_MODELS(MSSM63atQ, MSSM63atMGUT)          // Works with weak/GUT-scale MSSM and descendents
    #undef FUNCTION
  #undef CAPABILITY
```

2. Write the function as a standard C++ function (one argument: the result)

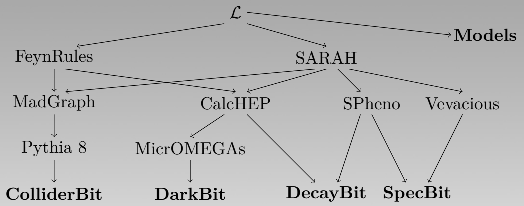
from P.Scott

Solution

The **G**AMBIT **U**niversal **M**odel Machine

GUM

- GUM interfaces LLT SARAH and FeynRules with GAMBIT
- Uses existing HEP toolchains

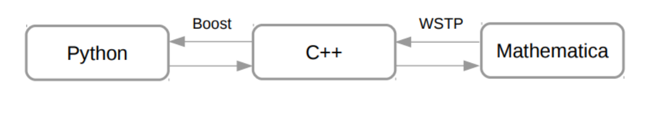


- GAMBIT-compatible outputs from GUM

Generated output	FeynRules	SARAH	Usage in GAMBIT
CalcHEP	✓	✓	Decays, cross-sections
micrOMEGAs (via CalcHEP)	✓	✓	DM observables
Pythia (via MadGraph)	✓	✓	Collider physics
SPheno	✗	✓	Particle mass spectra, decay widths
Vevacious	✗	✓	Vacuum stability

GUM

- Primarily written in Python, with interface to Mathematica via Boost and WSTP



- Automatically generates GAMBIT code
  - → Particles → particle database and parameters → Models
  - → Module functions for ColliderBit, DarkBit, DecayBit and SpecBit
  - → Writes interfaces to requested backends
- GUM will release with GAMBIT 2.0 **VERY SOON**

An example

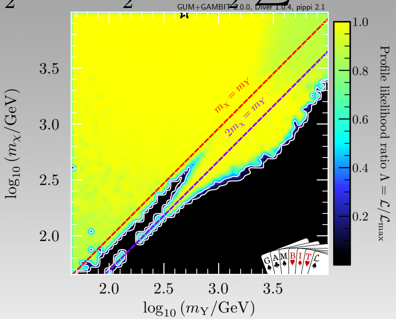
- Majorana DM χ with scalar mediator Y

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \frac{1}{2}\partial_\mu Y \partial^\mu Y - \frac{1}{2}m_Y^2 Y^2 - \frac{g_\chi}{2}\overline{\chi}\chi Y - \frac{c_Y}{2}\sum y_f \overline{f} f Y\,.$$

```
math:
  # Choose FeynRules
  package: feynrules
  # Name of the model
  model: MDMSM
  # Model builds on the Standard Model FeynRules file
  base_model: SM
  # The Lagrangian is defined by the DM sector (LDM),
  # defined in MDMSM.fr, plus the SM Lagrangian (LSM)
  # imported from the 'base model', SM.fr
  Lagrangian: LDM + LSM
  # Make CKM matrix = identity to simplify output
  restriction: DiagonalCKM

# PDG code of the annihilating DM candidate in
↪FeynRules file
wimp_candidate: 52

# Select outputs for DM physics.
# Collider physics is not as important in this model.
output:
  pythia: false
  calchep: true
  micromegas: true
```



⇝ Follow Sanjay's tutorial 3pm Room A