Exploring dark matter models with global fits

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Discrete 2022, 8 Nov 2022

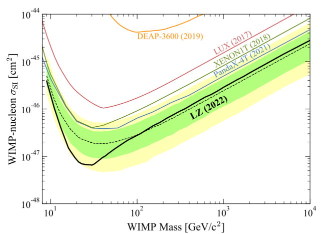
Dark matter and the WIMP miracle

DM and WIMPs

- Dark Matter is a thing and there is evidence for it

  `[Insert obligatory galaxy rotation plot]`

- WIMPs are still kicking
  - → EW-scale mass, accesible at colliders
  - → Just right RD through freeze-out
- Next few years will be critical for the survivability of WIMPS
- Crucial to have rigorous understanding of all possible WIMP models



EFTs — Simplifed models — UV complete models

More general ↔ More complete

⇝ Chris' talk

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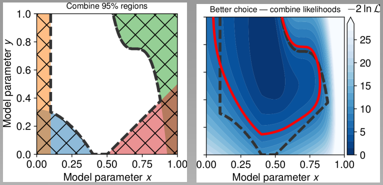
Global fits to explore DM models

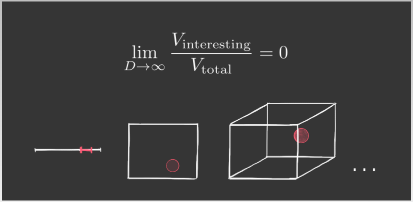
Global fits of DM models

- 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, ...

UV complete model: Higgs portal DM

[GAMBIT, Eur.Phys.J.C 77 (2017) 8, 568]

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

Higgs portal DM

- Scalar DM

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

- Vector DM

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

- Fermionic DM (Dirac)

$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi - \frac{\lambda_\psi}{\Lambda_\psi}(\cos\theta \bar{\psi}\psi + \sin\theta \bar{\psi} i\gamma_5 \psi) H^\dagger H$$

- Fermionic DM (Majorana)

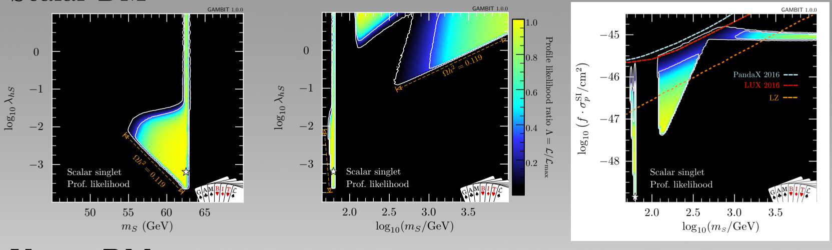
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - i\mu_\chi)\chi - \frac{1}{2}\frac{\lambda_h \chi}{\Lambda_\chi}(\cos\theta \bar{\chi}\chi + \sin\theta \bar{\chi} i\gamma_5 \chi) H^\dagger H$$

Higgs portal DMd

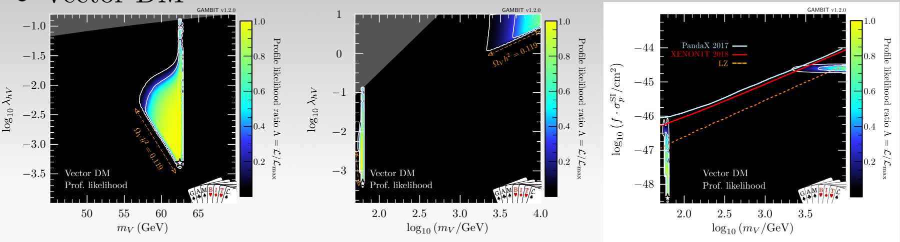
- Direct Detection DDCalc
  - → XENON1T, LUX 2016, PandaX 2016-17, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017, and DarkSide-50
- Relic abundance DarkSUSY, plc
  - → Planck 2015: $\Omega_{\rm DM} h^2 \leq 0.1188 \pm 0.0010$
- Indirect detection with γ-rays gamLike
  - → Pass-8 combined of 15 dSphs from *Fermi*-LAT data
- ID with neutrinos Capt'n General, nulike
  - → 79-string IceCube search
- Higgs invisible width
  - → $\mathrm{BR}_{\rm inv}(h- > \bar{X}X) < 19\%$ (2σ)
- Theoretical constraints
  - → Perturbative unitarity $0 \leq \lambda_{hV} \leq \frac{2m_V^2}{v_0^2}$
  - → EFT validity $\frac{\lambda_{hX}}{\Lambda_X} \geq \frac{4\pi}{2m_X}$

Higgs portal DM

- Scalar DM

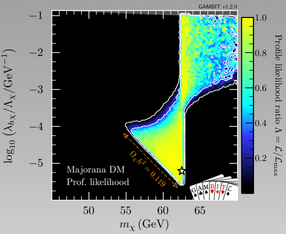


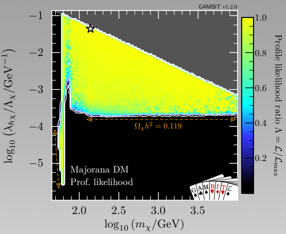
- Vector DM

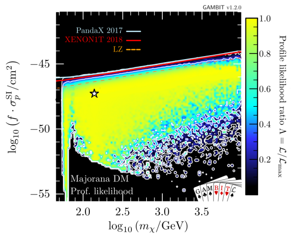


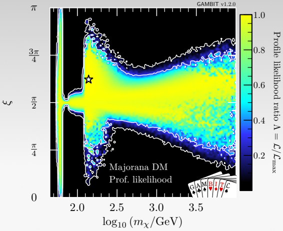
Higgs portal DM

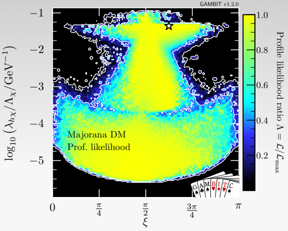
- Majorana fermion DM (≈ identical to Dirac DM)











Effective model: DM EFT

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

DM EFT

- Dirac fermionic DM χ: $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm int} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi$
- Effective interactions (quarks/gluons): $\mathcal{L}_{\rm int} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$

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

DM EFT

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

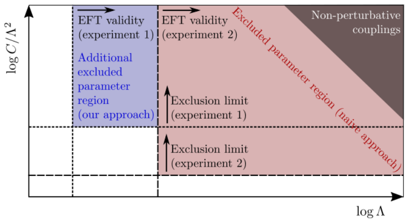
$$\mathcal{C}_{1,2}^{(5)} = -4\frac{m_t(m_t)^2}{\Lambda^2}\log\frac{\Lambda^2}{m_t(m_t)^2}\mathcal{C}_{9,10}^{(7)}$$

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

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

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

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



DM EFT

- Direct Detection — DirectDM, DDCalc
  - → XENON1T, LUX 2016, PandaX 2016-17, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017-19, and DarkSide-50
- Relic abundance — CalcHEP, DarkSUSY, plc
  - → Planck 2018: $\Omega_{\rm DM} h^2 \leq 0.120 \pm 0.001$
- Indirect detection with γ-rays — CalcHEP, gamLike
  - → Pass-8 combined of 15 dSphs from *Fermi*-LAT data
- ID with neutrinos — DirectDM, Capt'n General, nulike
  - → 79-string IceCube search
- ID constraints from CMB — CalcHEP, DarkSUSY, DarkAges
  - → 95% CL limit on energy deposition efficiency $f_{\rm eff}$
- Collider constraints — MadGraph_aMC@NLO, Pythia
  - → ATLAS 139fb^{-1} mono-jet
  - → CMS 36fb^{-1} mono-jet

DM EFT

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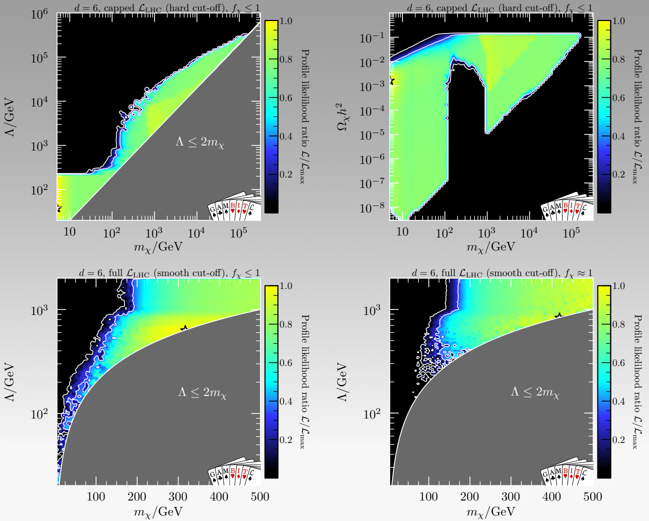


Conclusions and Outlook

- Conclusions
  - → WIMP scenarios alive and kicking
  - → Scalar & Vector DM in trouble
  - → Fermionic HP DM prefers pseudoscalar interactions
  - → EFT of DM hints a upper limit on Λ
  - → Light DM cannot saturate relic abundance
- Outlook
  - → Next generation DD experiments can constrain very severely HP models
  - → Very interesting next few years for WIMPs
  - → WIMPs not the only DM candidate
  - → See Chris' talk on simplified DM models

Thanks!

Backup

- Direct Detection

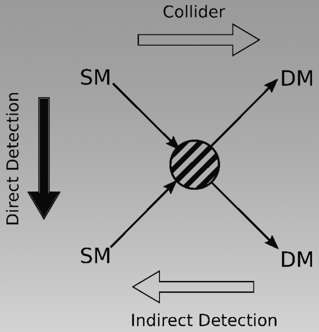
$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{R}} = \frac{\rho}{m_T\, m_\chi} \int_{v_\mathrm{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{R}} \mathrm{d}^3 v$$

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

→ Non-relativistic operators

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

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



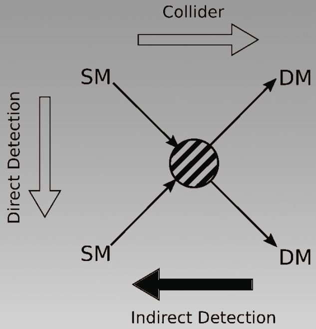
- Relic abundance $\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v_\mathrm{rel}\rangle \left(n_\chi n_{\bar\chi} - n_{\chi,\mathrm{eq}} n_{\bar\chi,\mathrm{eq}}\right)$
  → Planck 2018: $\Omega_\mathrm{DM} h^2 \leq 0.120 \pm 0.001$

Likelihoods

- 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

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

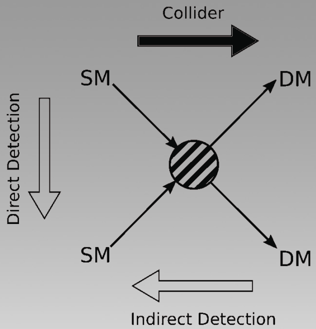
Likelihoods

- 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

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- Model parameters

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

- Nuisance parameters

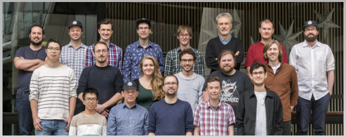
Local DM density	ρ_0
Most probable speed	v_{peak}
Galactic escape speed	v_{esc}
Running top mass ($\overline{\mathrm{MS}}$ scheme)	$m_t(m_t)$
Pion-nucleon sigma term	$\sigma_{\pi N}$
s-quark contrib. to nucleon spin	Δs
s-quark nuclear tensor charge	g_T^s
s-quark charge radius of the proton	r_s^2

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

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



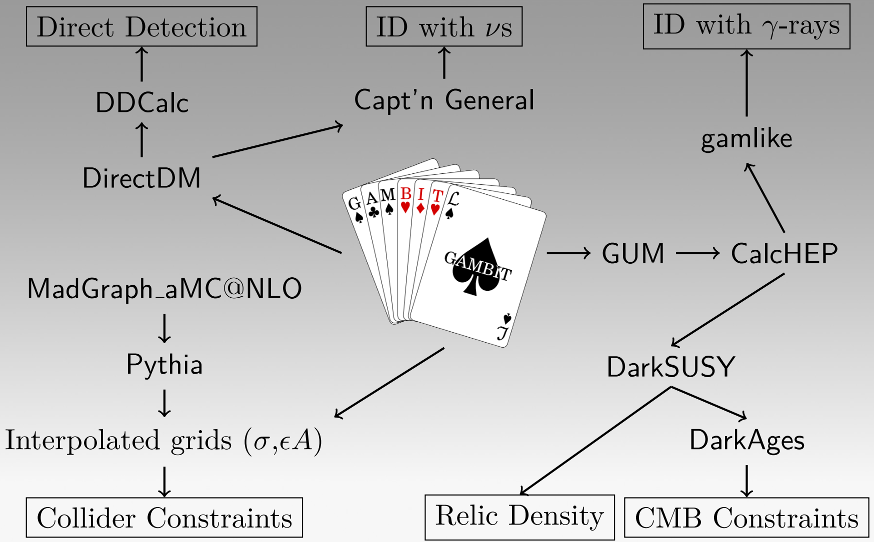
Members of:
ATLAS, Belle-II, CLiC, CMS, CTA, *Fermi*-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

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

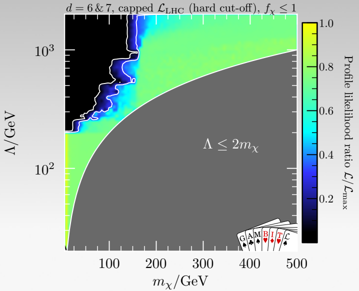
70+ participants in 11 experiments and 14 major theory codes

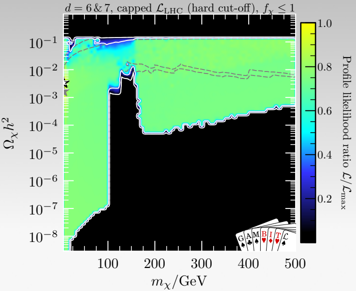
Scan framework



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**

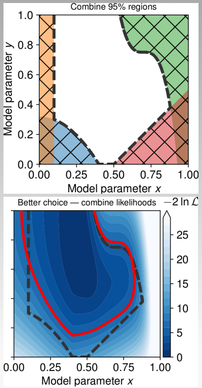
→ Old-school sampling methods (random, grid) are inefficient

→ 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]]

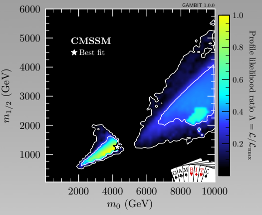
Modules (Bits)

- 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

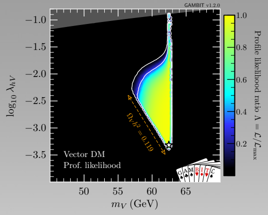
CMSSM

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



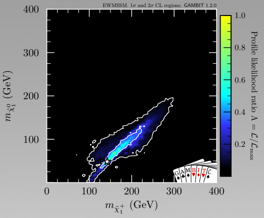
Higgs-portal DM

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



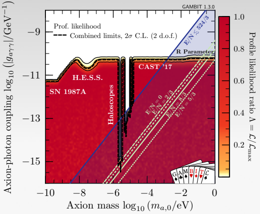
MSSM-EW

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



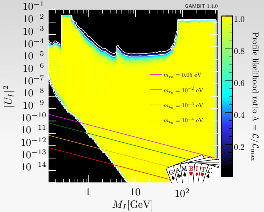
QCD axions

[JHEP 03 (2019) 191]



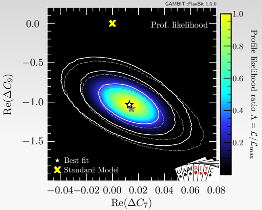
Right-Handed Neutrinos

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



Flavour EFT

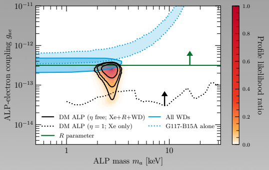
[Eur.Phys.J.C 81 (2021)12,1076]



Examples

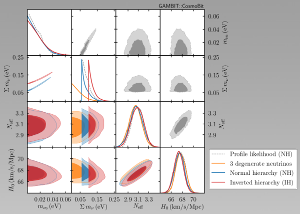
DM ALPs

[JHEP 05 (2021) 159]



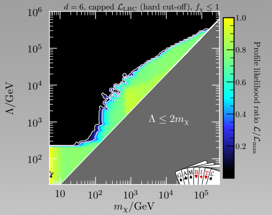
Neutrino Masses

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



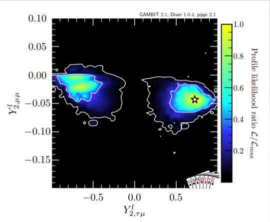
DMEFT

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



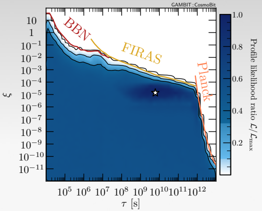
THDM-III

[JHEP 01 (2022) 037]



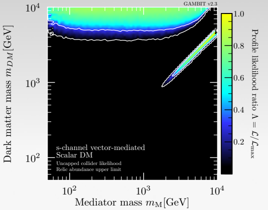
Cosmo ALPs

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



S-channel DM

[arXiv:2209.13266 [hep-ph]]



Core

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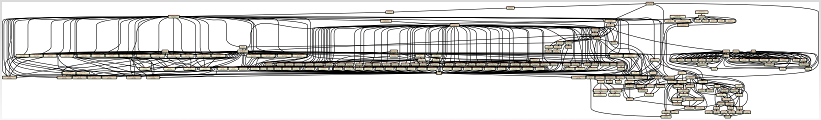
- Each module contains a collection of module functions
- Module functions provide a *capability*
- They have dependencies and backend requirements
- Allowed for specific models
- At run time a dependency tree is generated and resolved

```
// 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

- Extensive model database

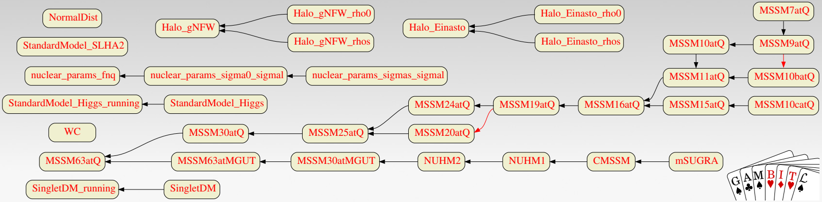
SUSY
CMSSM
NUHM1,2
MSSM63atQ

DM
Scalar Singlet
Fermionic Singlet
Vector Singlet
Axions

Cosmo
ΛCDM
ΔN_{eff}
Power-law
inflation

Others
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

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

ColliderBit

HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212
nulike 1.0.9

FlavBit

SuperISO 3.6

PrecisionBit

FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

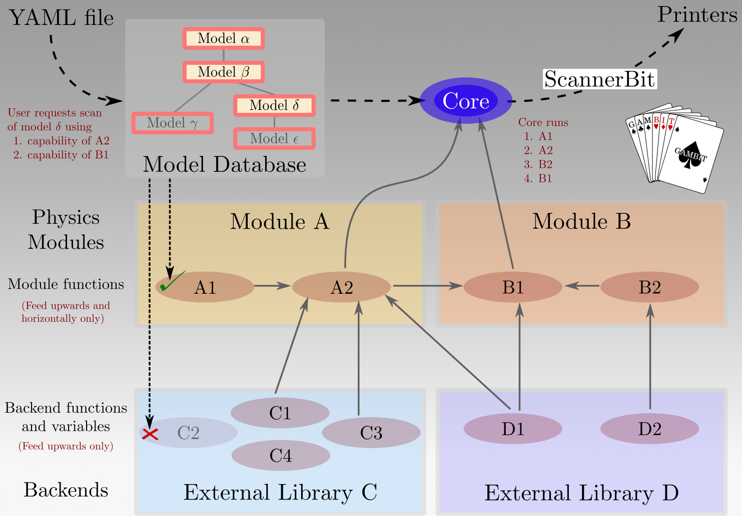
SpecBit

FlexibleSUSY 2.0.1
SPheno 4.0.3

DecayBit

SUSY_HIT 1.5

An example run



Operators

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	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

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

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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}

Collider Likelihoods

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- ATLAS, Poisson loglike marginalised over nuisance ξ = relative signal/bkg uncertainties

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

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

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

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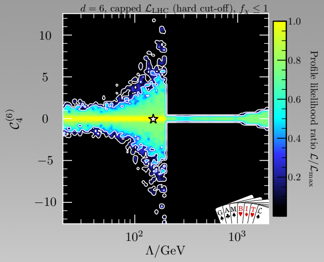
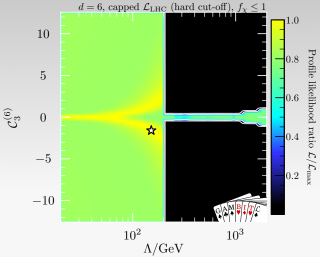
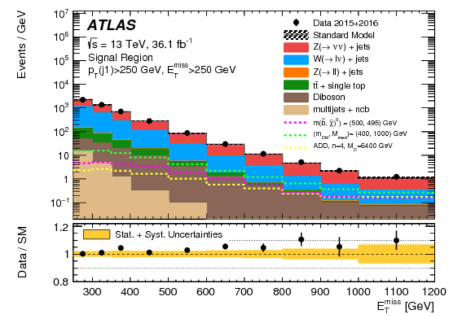
Results

- $\mathcal{C}_1^{(6)}$
  - $\rightarrow$ 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 $\mathcal{C}_2^{(6)}$

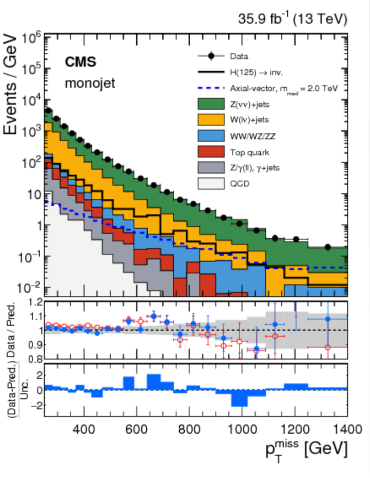




Results



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Signal Region
p_T(j1)>250 GeV, E_T^miss>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
E_T^miss [GeV]



35.9 fb⁻¹ (13 TeV)
CMS
monojet
Data
H(125) → inv.
Axial-vector, m_med = 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.
p_T^miss [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)

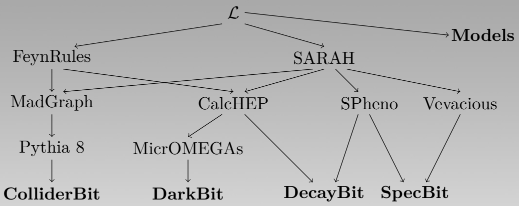
from P.Scott

Solution

The GAMBIT Universal Model Machine

GUM

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

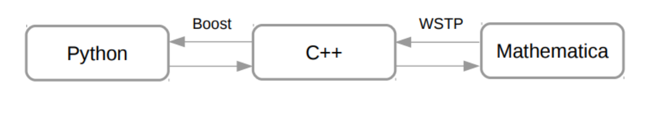


- GAMBIT-compatible outputs from GUM

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

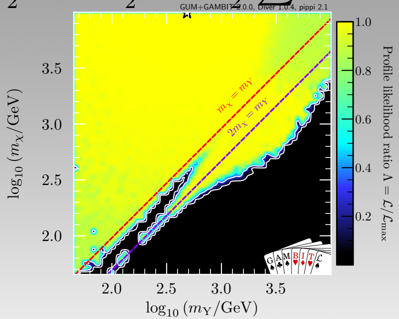
- Majorana DM χ with scalar mediator Y

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

```
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