Global studies of beyond the Standard Model theories: dark matter and supersymmetry

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Overview

1. Beyond the Standard Model
   - Dark Matter models
   - Supersymmetric models
2. Global fits
   - GAMBIT
3. Results
4. Conclusions

Outline

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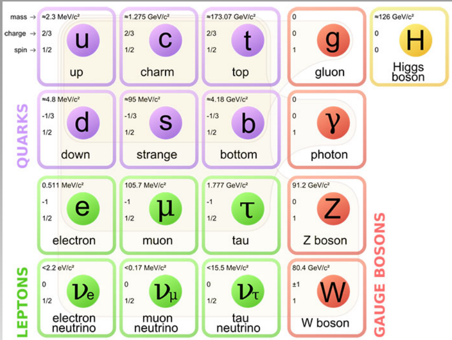
Beyond the SM

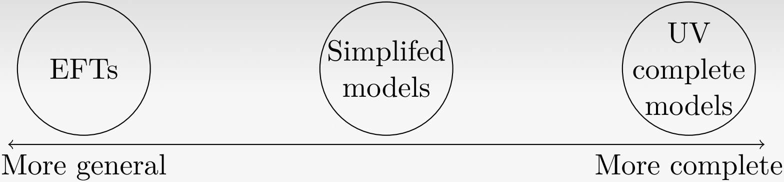
- SM must be extended
- Phenomenological issues
  - → Gravity
  - → Dark Matter & Dark Energy
  - → Neutrino masses
  - → Baryon asymmetry
  - → Precision measurements
- Theoretical issues
  - → Hierarchy problem
  - → Vacuum stability
  - → Charge quantisation
  - → ...



- BSM models attempt to resolve some of these issues
  - → UV complete models introduce new particles and new parameters
  - → Predictions must not contradict precise SM measurements
  - → Preference for simplified or effective models

Dark Matter models

- Plenty of evidence for DM from astrophysical sources
- 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
- So far no evidence that DM interacts with SM → constraints on DM models
- Understand the full set of constraints on multiple DM models



Dark Matter models

- UV complete (ish): Higgs portal models
  - → Scalar DM (S)

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

  - → Vector DM (V_μ)

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

  - → Fermionic DM (Dirac, ψ)

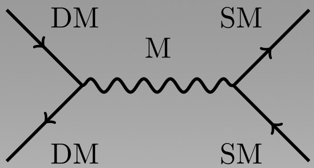
$$\mathcal{L}_\psi = \bar{\psi}(i\partial\!\!\!/ - \mu_\psi)\psi - \frac{\lambda_\psi}{\Lambda_\psi}(\cos\theta \bar{\psi}\psi + \sin\theta \bar{\psi} i\gamma_5 \psi) H^\dagger H$$

  - → Fermionic DM (Majorana, χ)

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

Dark Matter models

- Simplifed DM models
- Singlet DM candidate plus mediator that couples to SM particles
- E.g vector mediator V_μ that couples only to 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 vector (X_μ) or a fermion (ψ or χ)

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

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

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

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

Dark Matter models

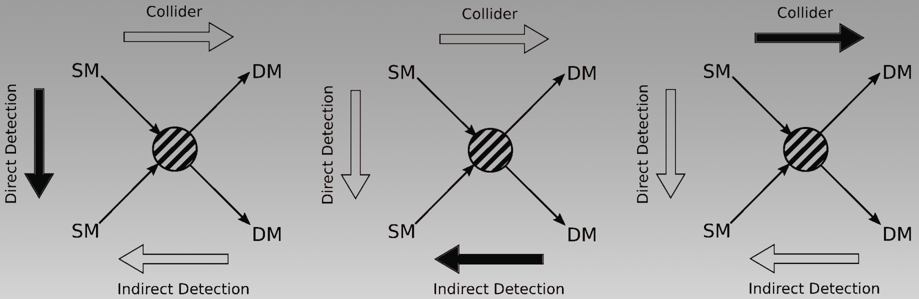
- Effective field theory of DM (DM EFT)
- Dirac fermionic DM χ: $\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm int} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi$
- Effective interactions (quarks/gluons): $\mathcal{L}_{\rm int} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}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

$$
\begin{aligned}
\mathcal{Q}_1^{(5)} &= \frac{e}{8\pi^2}(\overline{\chi}\sigma_{\mu\nu}\chi)F^{\mu\nu}\,, \\
\mathcal{Q}_2^{(5)} &= \frac{e}{8\pi^2}(\overline{\chi}i\sigma_{\mu\nu}\gamma_5\chi)F^{\mu\nu} \\
\mathcal{Q}_{1,q}^{(6)} &= (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)\,, \\
\mathcal{Q}_{2,q}^{(6)} &= (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu q)\,, \\
\mathcal{Q}_{3,q}^{(6)} &= (\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,, \\
\mathcal{Q}_{4,q}^{(6)} &= (\overline{\chi}\gamma_\mu\gamma_5\chi)(\overline{q}\gamma^\mu\gamma_5 q)\,. \\
\mathcal{Q}_1^{(7)} &= \frac{\alpha_s}{12\pi}(\overline{\chi}\chi)G^{a\mu\nu}G^a_{\mu\nu}\,, \\
\mathcal{Q}_2^{(7)} &= \frac{\alpha_s}{12\pi}(\overline{\chi}i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,
\end{aligned}
$$

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

Dark Matter models

- Three ways to look for DM interactions in particle physics



→ DM interacting with nuclei

→ LZ, XENON1T, PandaX,. . .

Relic density!

→ DM annihilates into SM particles

→ γ rays, νs, $\bar{p}$, . . .

→ Fermi-LAT, IceCube, AMS02

→ LHC searches for large $\not{E}_T$

→ Mono-X (jet, . . .)

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

→ H invisible width

Supersymmetric models

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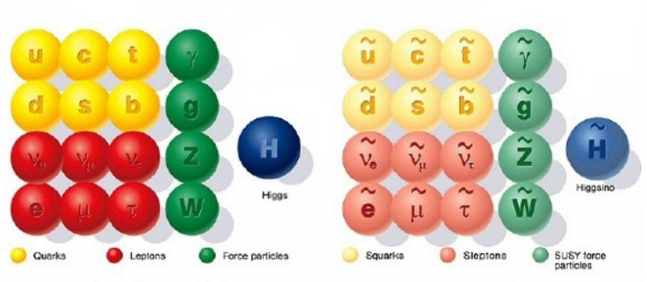
- Symmetry between fermions and bosons
- Predicts a whole new spectrum of supersymmetric partners



GOOD

→ Solves hierarchy problem

→ Provides DM candidate

→ Stabilises vacuum

BAD

→ Many new parameters $\mathcal{O}(100)$

→ No evidence at LHC or precision measurements

Supersymmetric models

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- Reduce number of parameters with simple SUSY models
  - → Unification at some high scale (GUT scale)

CMSSM	$\{m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$
NUHM1	$\{m_0, m_H, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$
NUHM2	$\{m_0, m_{H_u}, m_{H_d}, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$

  - → Simplified weak-scale SUSY

MSSM7	$\{A_t, A_b, m_{H_u}, m_{H_d}, m_{\tilde{f}}, M_2, \tan\beta\}$
MSSM11 (pMSSM)	$\{A_{(t,b,l)}, m_{H_{(u,d)}}, m_{(\tilde{q},\tilde{l})}, M_{(1,2,3)}, \tan\beta\}$

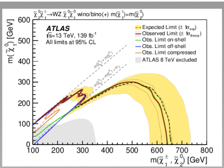
  - → Split SUSY models

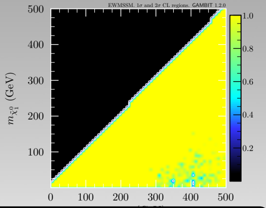
EWMSSM	$\{M_1, M_2, \mu, \tan\beta\}$
EWMSSM + $\tilde{G}$	$\{M_1, M_2, \mu, \tan\beta, m_{\tilde{G}}\}$

  - → Many many more

Supersymmetric models

- Reinterpretation of SUSY searches at the LHC
- LHC results often given in simplified models
  - → Production of lightest states
  - → Fixed branching ratios
  - → Sometimes misses interesting pheno
- Necessary to recast to complete models
  - → Availabily of analysis data (HEPData)
  - → Documentation of statisical models
  - → Reinterpretation Forum [arxiv:2003.07868]





HEP Software Foundation [arxiv:1712.06982]

Understanding the full implications of [experimental] searches requires the interpretation of the experimental results in the context of many more theoretical models than are currently explored at the time of publication.

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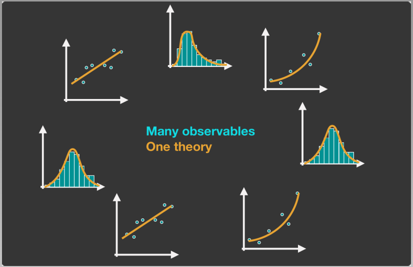
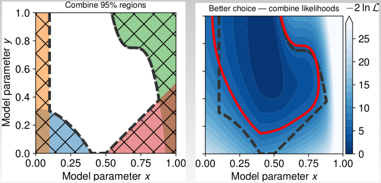
Global fits

- Multitude of experimental observables for each model
- Theory predictions $f(x)$
- Experiments measure $\mathcal{L}(\theta)$
- One needs

$$\mathcal{L}(x;\theta) = \frac{\mathcal{L}(\theta;x)\pi(x)}{\pi(\theta)}$$





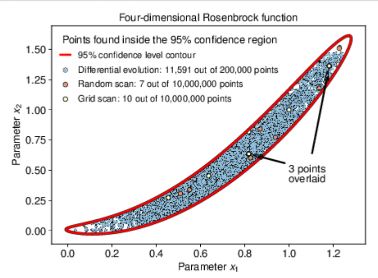
[Rept.Prog.Phys. 85 (2022) 5, 052201]

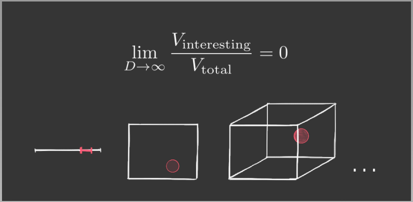
- Exclusion regions do not properly represent the model predictions
- Becomes impossible to analyse signals
- Combine all constraints into a composite likelihood

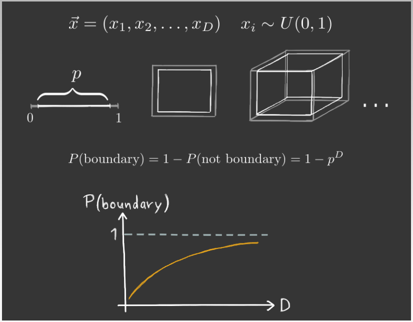
$$\mathcal{L} = \mathcal{L}_{Collider}\mathcal{L}_{Higgs}\mathcal{L}_{DM}\mathcal{L}_{Flavour}\cdots$$

Global fits

- Many BSM models come with many parameters
- Hard to find interesting regions
- Random methods are inefficient
- Mostly sample the boundary
- Need smart sampling strategies (differential, nested, genetic,...)





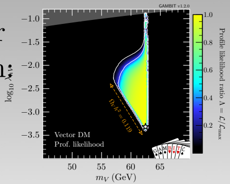


Global fits

- Assessment of validity of models should be done with rigorous statisical interpretations

Frequentist

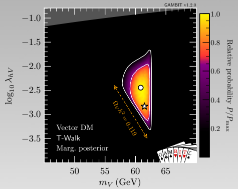
- How well does my model reproduce the data?
- Parameter estimation: profiling $\mathcal{L}/\mathcal{L}_{\max}$



- Goodness-of-fit: p-value
- Must include all tests, LEE

Bayesian

- How much I trust my model given the data?
- Parameter estimation: marginalising $P/P_{\max}$



- Model comparison: Bayes factors
- Prior dependence

- All of this comes with serious computational challenges $\rightsquigarrow$ `GAMBIT`

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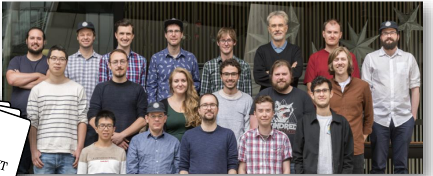
GAMBIT: The Global And Modular BSM Inference Tool

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 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: V Ananyev, P Athron, N Avis-Kozar, C Balázs, A Beniwal, S Bloor, LL Braseth, T Bringmann, A Buckley, J Butterworth, 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, M Lecroq, P Jackson, D Jacob, C Lin, FN Mahmoudi, G Martinez, H Pacey, MT Prim, T Procter, F Rajec, A Raklev, JJ Renk, R Ruiz, A Scaffidi, P Scott, N Serra, P Stöcker, W. Su, J Van den Abeele, A Vincent, C Weniger, A Woodcock, M White, Y Zhang ++

80+ participants in many experiments and numerous major theory codes

Modules (Bits)

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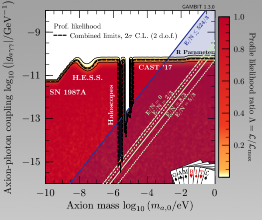
- Physics Modules
  - → **ColliderBit**: collider searches [Eur.Phys.J. C77 (2017) no.11, 795]
  - → **DarkBit**: relic density, dd,... [Eur.Phys.J. C77 (2017) no.12, 831]
  - → **FlavBit**: flavour observables [Eur.Phys.J. C77 (2017) no.11, 786]
  - → **SpecBit**: spectra, RGE running [Eur.Phys.J. C78 (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 [Eur.Phys.J. C81 (2021) no 12, 1103]

Examples

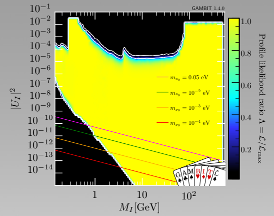
QCD axions

[JHEP 03 (2019) 191]



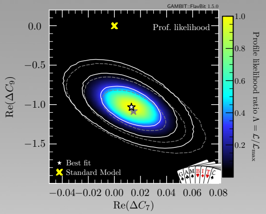
Right-Handed Neutrinos

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



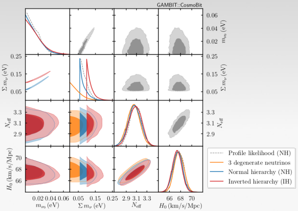
Flavour EFT

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



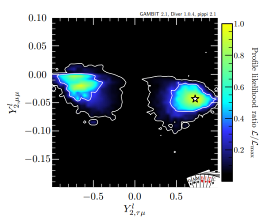
Neutrino Masses

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



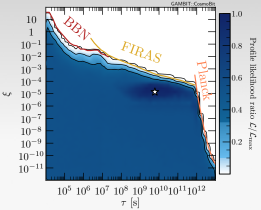
THDM-III

[JHEP 01 (2022) 037]



Cosmo ALPs

[JCAP 12 (2022) 027]



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Results

- $\rightsquigarrow$ Higgs portal DM
- $\rightsquigarrow$ Simplified DM models
- $\rightsquigarrow$ DM EFT
- $\rightsquigarrow$ ~~GUT scale SUSY~~
- $\rightsquigarrow$ EW MSSM + $\tilde{G}$

Higgs portal DM

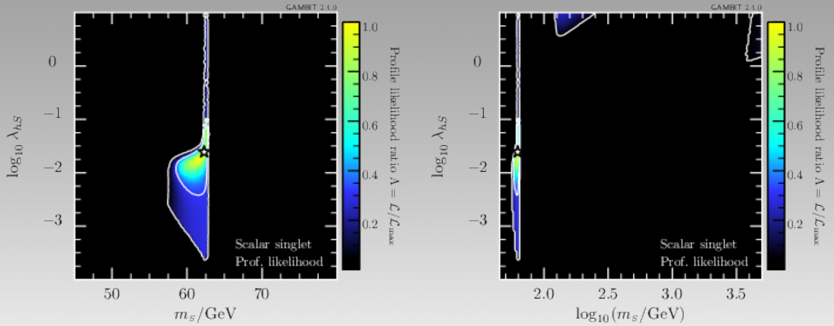
- Direct Detection — DDCalc
  - → XENON1T, LUX 2016, PandaX 2016, 17 & **4T**, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017 & **2019**, DarkSide-50, **LZ 2022**
- Relic abundance — DarkSUSY, plc
  - → Planck 2015: $\Omega_{\rm DM} h^2 \leq 0.1188 \pm 0.0010$
- Indirect detection with γ-rays — gamLike
  - → Pass-8 combined of 15 dSphs from *Fermi*-LAT data
- Indirect detection with neutrinos — Capt'n General, nulike
  - → 79-string IceCube search
- **Indirect detection with antiprotons** — pbarlike
  - → **AMS-02 using the INJ.BRK+vA propagation model**
- Higgs invisible width
  - → $\mathrm{BR_{inv}}(h \to \bar{X}X) < 19\%$ (2σ) [< **14% (95% CL)**]
- Theoretical constraints
  - → Perturbative unitarity and EFT validity

Higgs portal DM

- Scalar DM

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

[S.Balan et al, arXiv:2303.07362 [hep-ph]]



- Disconnected regions: along resonance $m_s \sim m_h/2$ and high mass
- High mass almost completely excluded by DD, ID and RD
- Small excess in Higgs invisible decay $\text{BR}_{\text{inv}} = 0.06$

Higgs portal DM

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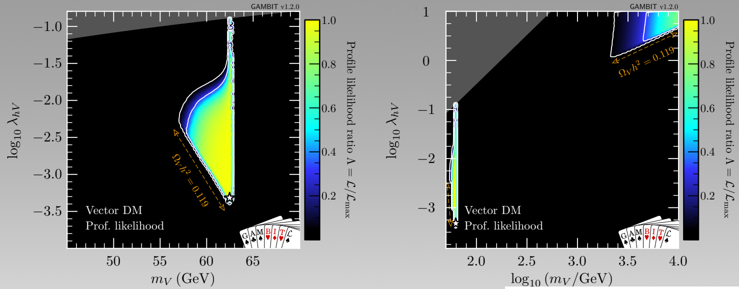
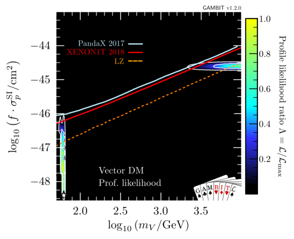
- Vector DM

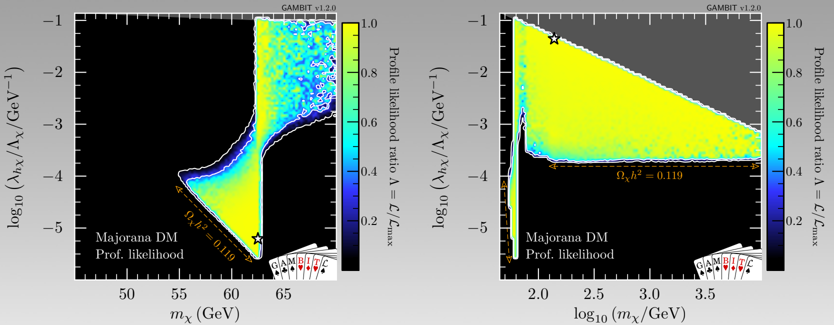
[GAMBIT. Eur.Phys.J.C 79 (2019) 1, 38]



- Resonance region and highest mass region survive
- Intermediate mass killed by unitarity bound
- Inclusion of recent DD constraints may kill high mass



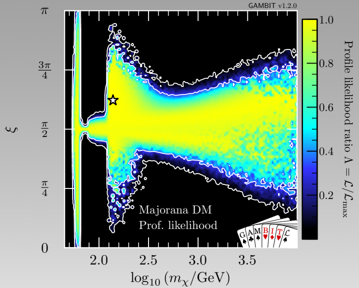
- Majorana fermion DM (≈ Dirac DM) [GAMBIT. Eur.Phys.J.C 79 (2019) 1, 38]

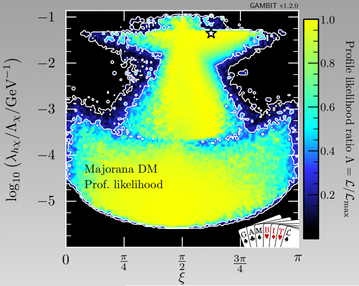


- Resonance and high mass regions connected
- Looser constraints from DD due to pseudoscalar interactions

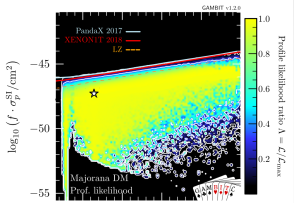
Higgs portal DM

- Additional parameter CP phase ξ





- Preferred pseudoscalar interactions
- Pure scalar not allowed at high masses
- Due to suppression of DD signals, no significant change with LZ & PandaX 4T



Simplified DM models

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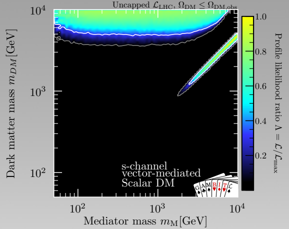
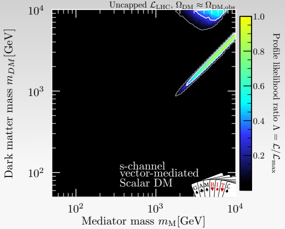
- Direct Detection — DirectDM, DDCalc
  - → XENON1T, LUX 2016, PandaX 2016-17 & **4T**, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017-19, DarkSide-50 and LZ 2022
- Relic abundance — CalcHEP, DarkSUSY, plc
  - → Planck 2018: $\Omega_{\rm DM} h^2 \leq 0.120 \pm 0.001$
- ID with γ-rays — CalcHEP, gamLike
  - → Pass-8 combined of 15 dSphs from *Fermi*-LAT data
- Collider constraints — MadGraph_aMC@NLO, Pythia
  - → ATLAS 139fb^{-1} mono-jet search
  - → CMS 137fb^{-1} mono-jet search
  - → ATLAS & CMS dijet resonance searches
- Unitary violation $s \lesssim \frac{\sqrt{48\pi} m_{\rm DM}^2}{g_{\rm DM}}$
- Perturbativity of decay widths, $\Gamma(m_M) \leq m_M$, $\Gamma(\sqrt{s}) \leq \sqrt{s}$

Simplified DM models

- Scalar DM

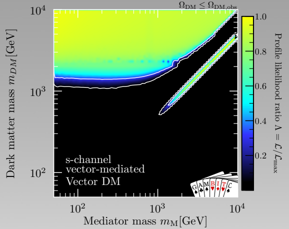
[C.Chang et al, Eur.Phys.J.C 83 (2023) 3, 249]

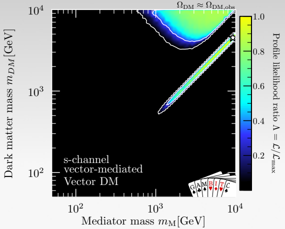




- Vector DM

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

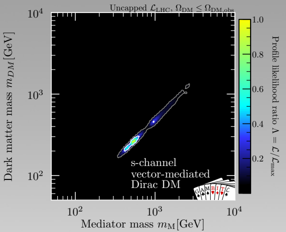


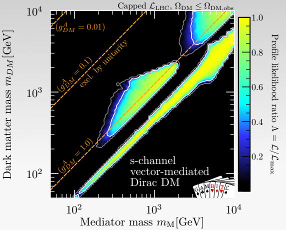


Simplified DM models

- Dirac fermion DM

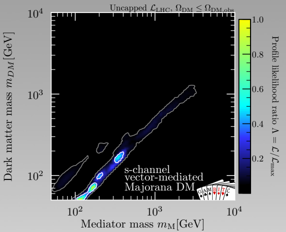
[C.Chang et al, Eur.Phys.J.C 83 (2023) 3, 249]

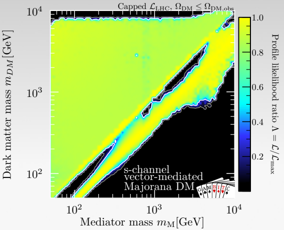




- Majorana fermion DM

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





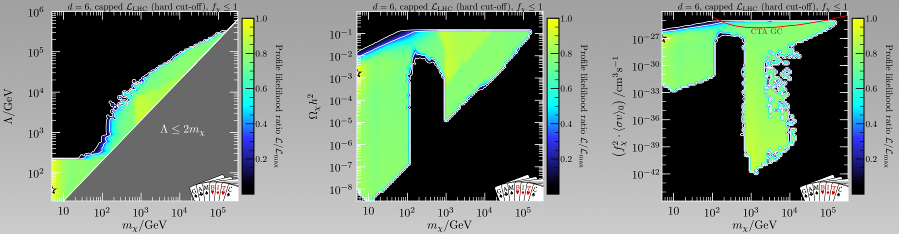
DM EFT

- 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: $\Omega_{\rm DM} h^2 \leq 0.120 \pm 0.001$
- ID 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 $139 {\rm fb}^{-1}$ mono-jet
  → CMS $36 {\rm fb}^{-1}$ mono-jet

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

Results

- Only 6-dim operators, $\Omega_{\rm DM}h^2$ upper limit, LHC loglike *capped*



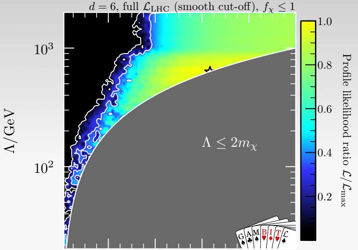
→ LHC constrains large Λ - small m_χ, absent for $\Lambda < 250$ GeV

→ *Fermi*-LAT data ($m_\chi \approx 5$ GeV)

→ $f_{\rm DM} < 1$ for $m_\chi < 100$ GeV

→ Monojet excess with full LHC

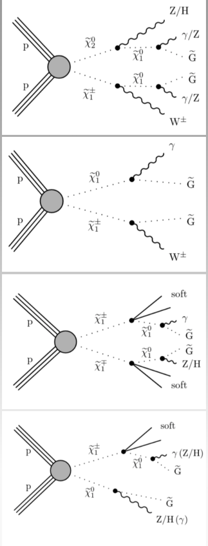
→ Upper limit on Λ



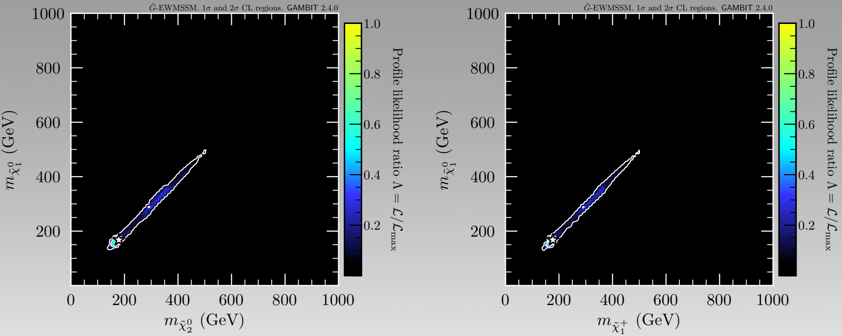
EW MSSM + $\tilde{G}$

[GAMBIT, arXiv:2303.15527 [hep-ph]]

- LHC SUSY searches
  - $\rightarrow$ 15 ATLAS and 12 CMS Run 2
  - $\rightarrow$ $\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 2/3/4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 0/1/2 leptons + $\tilde{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 2/3 b-jets + 0/1 lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ multiple jets + $E_{\mathrm{T}}^{\mathrm{miss}}$
- LHC "SM" xsec measurements
  - $\rightarrow$ 22 pools with 45 ATLAS, CMS and LHCb measurements
  - $\rightarrow$ $pp \rightarrow ZZ \rightarrow 4l$
  - $\rightarrow$ $pp \rightarrow W^+W^- \rightarrow ll'(j) + E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ $pp \rightarrow Z\gamma \rightarrow ll\gamma$
- LEP xsection constraints
  - $\rightarrow$ $\chi^{\pm} \rightarrow \mathrm{SM} + \tilde{G}$
  - $\rightarrow$ L3 search $\chi^0 \rightarrow \gamma + \tilde{G}$



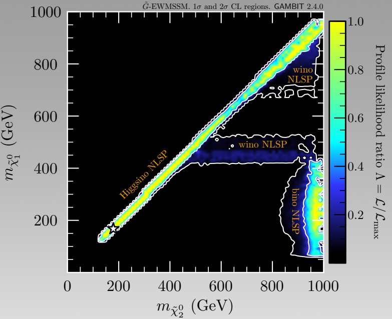
- Profile likelihoods for neutralinos and charginos

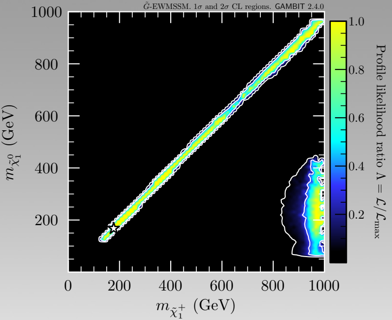


→ Preferred scenario are Higgsino-like, i.e. $\mu < M_1, M_2$
→ At 2σ, $\mu < 0, \tan\beta \sim 1$, $\Rightarrow$ 140 GeV $< \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_1^\pm <$ 500 GeV
→ Dominant channels are $\tilde{\chi}_1^0 \to h\tilde{G}$, $\tilde{\chi}_1^0 \to Z\tilde{G}$
→ Fits excess is leptons + $E_{\rm T}^{\rm miss}$ and b-jets + $E_{\rm T}^{\rm miss}$ searches
→ Simultaneous fit to multi-lepton and multi-b signal regions

EW MSSM + $\tilde{G}$

- "Capped" likelihood (exclusion-only)



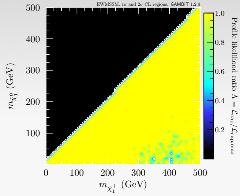


→ Stronger constraining power c.f. EWMSSM

→ Largest suriving region Higgsino NSLP

→ γ + MET searches exclude binos < 800 GeV

→ l + MET excludes wino except at > 600 GeV and ∼ 450 GeV due to excesses



Outline

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1. Beyond the Standard Model
   - Dark Matter models
   - Supersymmetric models
2. Global fits
   - GAMBIT
3. Results
4. Conclusions

Conclusions

- Beyond the SM theories are necessary to complement the SM
- Hard to explore due to the large number of parameters and constraints
- Global fits are an efficicent methodology to study BSM theories with statistical rigour
- GAMBIT provides a flexible and modular framework for global fits
- **Dark Matter models**
  - → Most WIMP models in a lot of trouble (HP)
  - → Resonant annhilitation survives consistently (HP, SDM)
  - → Fermion DM less excluded due to suppression of DD (HP, SDM)
  - → Upper limit on the scale of new physics (DMEFT)
- **Supersymmetric models**
  - → Very strongly constrained by LHC searches
  - → Only compressed Higgsino scenario remaining at low masses
  - → Small combined excesses fit better SUSY than SM

Backup

DM EFT

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

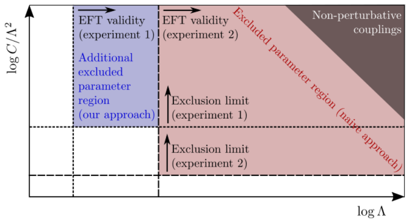
$$\mathcal{C}^{(5)}_{1,2} = -4\frac{m_t(m_t)^2}{\Lambda^2}\log\frac{\Lambda^2}{m_t(m_t)^2}\mathcal{C}^{(7)}_{9,10}$$

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

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

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

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



Likelihoods

- Direct Detection

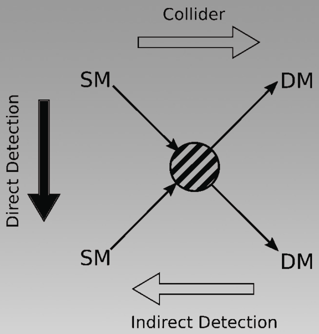
$$\frac{\mathrm{d}R}{\mathrm{d}E_{\mathrm{R}}} = \frac{\rho}{m_T\, m_\chi} \int_{v_{\min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_{\mathrm{R}}} \mathrm{d}^3 v$$

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

$\rightarrow$ Non-relativistic operators

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

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



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

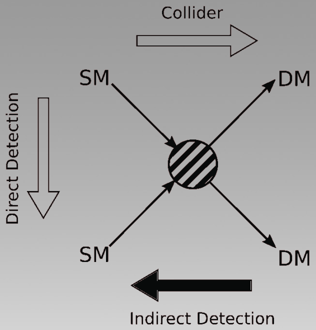
  $\rightarrow$ Planck 2018: $\Omega_{\mathrm{DM}} h^2 \leq 0.120 \pm 0.001$

Likelihoods

- Indirect detection with γ-rays
  - $\rightarrow$ γ-rays from DM annihilation in dSphs

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

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



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

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

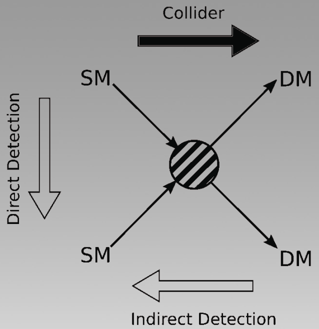
Likelihoods

- 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

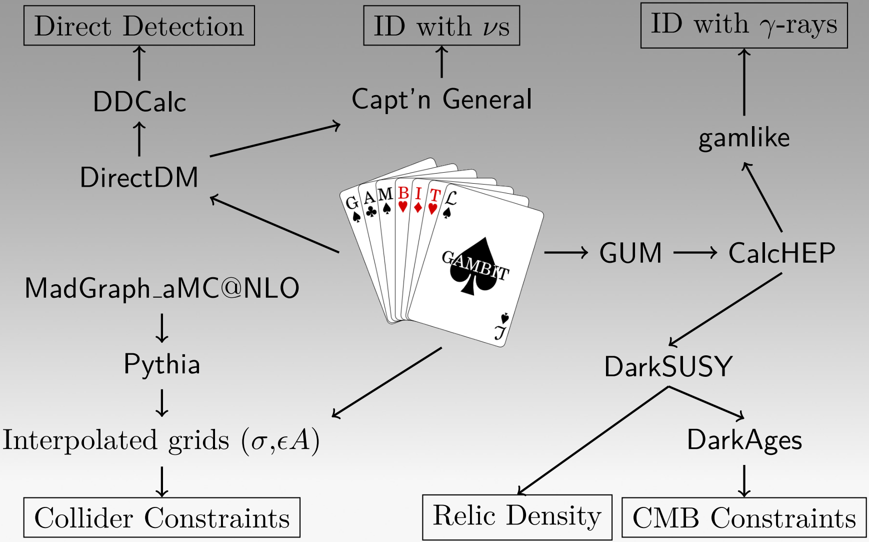
DM mass	m_χ
New physics scale	Λ
Wilson coefficients	$\mathcal{C}_a^{(d)}$

- Nuisance parameters

Local DM density	ρ_0
Most probable speed	$v_{\rm peak}$
Galactic escape speed	$v_{\rm esc}$
Running top mass ($\overline{\rm MS}$ 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



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

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]

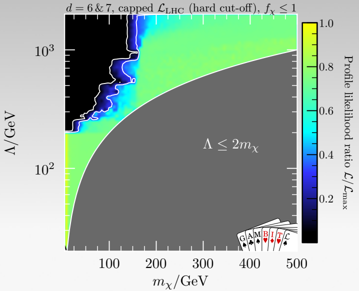
[1][F. Bishara et. al., JHEP 11 (2017) 059] [2][PDG 2020] [3][A. Crivellin et. al., Phys. Rev. D 89 (2014) 054021] [4][D. Djukanovic et. al., Phys. Rev. Lett. 123 (2019) 212001, R. S. Sufian et. al.., Phys. Rev. Lett. 118 (2017) 042001] [5][R. Gupta, et. al., Phys. Rev. D 98 (2018) 091501] [6][S. Aoki 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.]

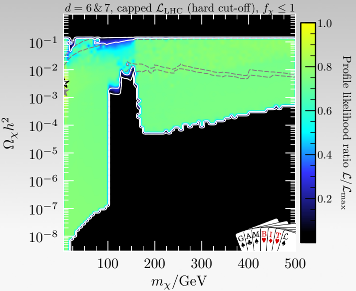
Nuisance parameters

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) $\mathrm{GeV^{-2}}$

DM EFT

- Include dim-7 operators, $\Omega_{\rm DM}h^2$ upper limit, LHC loglike *capped*
  - $\rightarrow$ No change on large Λ - small m_χ region
  - $\rightarrow$ Neither $\mathcal{Q}^{(7)}_{1-4}$ (LHC) nor $\mathcal{Q}^{(7)}_{5-10,q}$ (suppressed) contribute to ann xsec
  - $\rightarrow$ However, RD can be saturated for $m_\chi < 100$ GeV (and small Λ)
  - $\rightarrow$ $\mathcal{Q}^{(7)}_{3}$ and $\mathcal{Q}^{(7)}_{7,q}$ give unconstrained signals in DD and ID
  - $\rightarrow$ Similar fits to LHC excesses, even when dim-6 ops are zero





Collider Likelihoods

- ATLAS, Poisson loglike marginalised over nuisance ξ = 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

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

DM EFT

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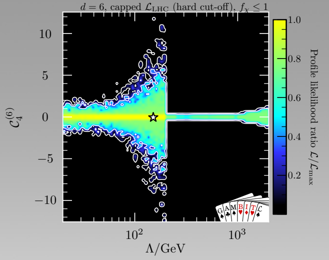
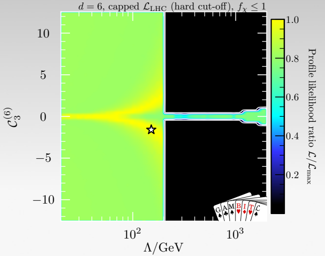
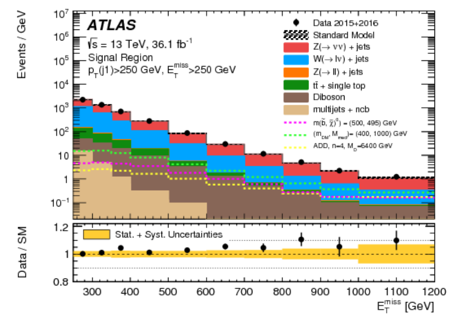
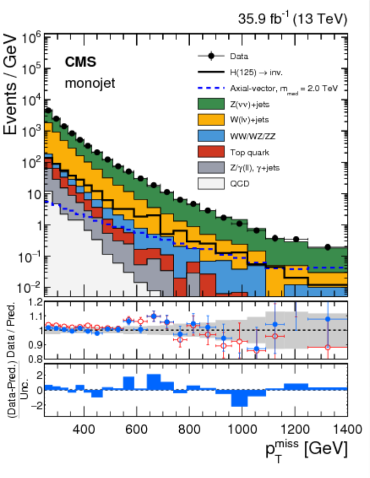
- $\mathcal{C}_1^{(6)}$
  - $\rightarrow$ spin-independent scattering
  - $\rightarrow$ strongly constrained $\rightsquigarrow$ very small
- $\mathcal{C}_2^{(6)}$
  - $\rightarrow$ momentum-dependent scattering
  - $\rightarrow$ $\Lambda < 250$ GeV DD constrained
  - $\rightarrow$ $\Lambda > 250$ GeV 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 $\mathcal{C}_2^{(6)}$





DMEFT


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]

EW MSSM + $\tilde{G}$

Name	Spin	Gauge ES	Mass ES	Param
Higgs bosons	0	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h\ H\ A\ H^\pm$	-
squarks	0	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	-	-
		$\tilde{c}_L\ \tilde{c}_R\ \tilde{s}_L\ \tilde{s}_R$	-	-
		$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_R\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$	-
sleptons	0	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	-	-
		$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	-	-
		$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$	-
neutralino	1/2	$\tilde{B}\ \tilde{W}^3\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{\chi}_1^0\ \tilde{\chi}_2^0\ \tilde{\chi}_3^0\ \tilde{\chi}_4^0$	$M_1, M_2, \mu, \tan\beta$
chargino	1/2	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{\chi}_1^\pm\ \tilde{\chi}_2^\pm$	$\mu, M_2, \tan\beta$
gluino	1/2	$\tilde{g}$	-	-
gravitino	3/2	$\tilde{G}$	-	$m_{\tilde{G}} = 1$ eV

- Only 7 SUSY particles below 1 TeV, other decoupled
- 4D theory parameter space: $M_1, M_2, \mu, \tan\beta$
- Light gravitino for prompt decay of lightest neutralino/chargino

Scan framework

- GAMBIT modules used for the scan
  - → SpecBit ⇝ one-loop spectrum with FlexibleSUSY
  - → DecayBit ⇝ $\tilde{\chi}^{0,\pm} \to \tilde{\chi}^{0,\pm}$ decays with SUSY-HIT
    $\chi^{0,\pm} \to \tilde{G}$ decays native
  - → ColliderBit ⇝ MC event generation with Pythia 8
    detector simulation with BuckFast
    LHC search emulation native
    SM measurements with Rivet and Contur
  - → ScannerBit ⇝ sampling using diver

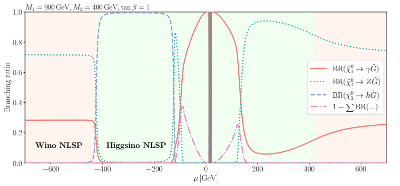
- Parameter ranges

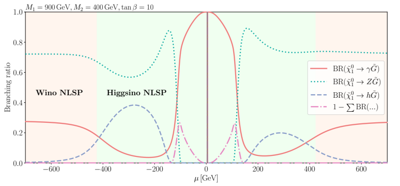
$M_1(Q)$	$[-1, 1]$ TeV	hybrid, flat
$M_2(Q)$	$[0, 1]$ TeV	hybrid, flat
$\mu(Q)$	$[-1, 1]$ TeV	hybrid, flat
$\tan\beta(m_Z)$	$[1, 70]$	log, flat
$m_{\tilde{G}}$	1 eV	fixed

- Scan details
  - → diver 1.0.4 self-adaptive rand/1/bin evolution
  - → 16M MC events for LHC searches
  - → 100k MC events for measurements
  - → 3.1×10^5 parameter samples

EW MSSM + $\tilde{G}$

- Three phenomenological scenarios
  - $\rightarrow$ Wino NLSP: $M_2 < M_1, \mu \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \rightarrow \{Z,\gamma\}\tilde{G}, \; \tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$
  - $\rightarrow$ Higgsino NLSP: $\mu < M_1, M_2 \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \rightarrow \{Z,h\}\tilde{G}, \; \tilde{\chi}_2^0, \tilde{\chi}_1^\pm \rightarrow f^\pm f^{\pm,0} \tilde{\chi}_1^0$
  - $\rightarrow$ Bino NLSP: $M_1 < M_2, \mu \quad \rightsquigarrow \quad \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
- Heavier $\tilde{\chi}_i^0/\tilde{\chi}_i^\pm$ decay to NLSP with multiple $\{Z, W^\pm, h\}$
- Chargino NLSP extremely rare





EW MSSM + $\tilde{G}$

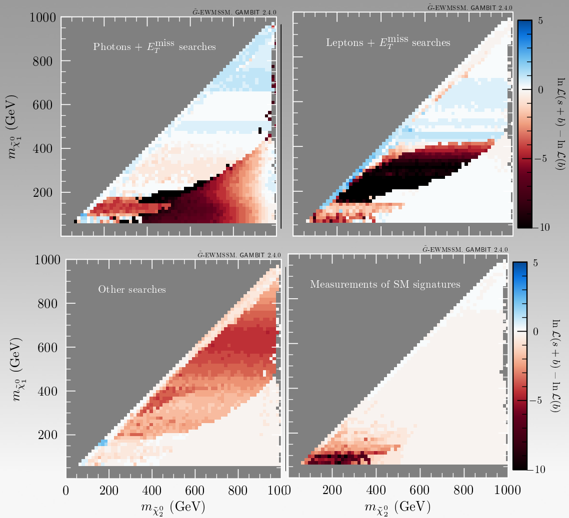
- Impact of searches and measurements

→ Photon searches exclude low mass binos

→ Lepton searches exclude low mass winos

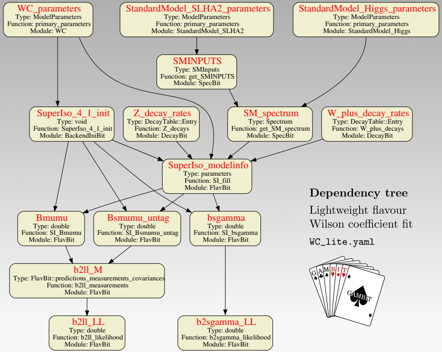
→ Boosted boson searches exclude high mass winos

→ Measurements exclude low mass Higgsino and winos



Module functions

- **Module functions** are the building blocks of GAMBIT
- Module functions provide a **capability**
- They have **dependencies** on other capabilities
- They have **backend requirements**
- Can be allowed for specific **models**
- Module functions are wrapped in functors
- GAMBIT resolves the dependeny graph at runtime



Dependency tree
Lightweight flavour
Wilson coefficient fit
`WC_lite.yaml`

Core

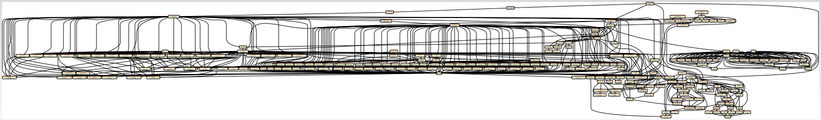
- Each module contains a collection of module functions
- Module functions provide a *capability*
- They have dependencies and backend requirements
- Allowed for specific models
- At run time a dependency tree is generated and resolved

```
// 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
```



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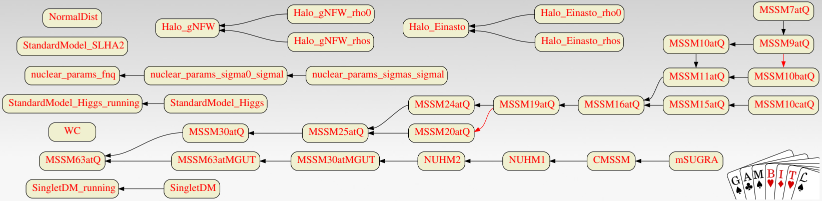
- Extensive model database

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

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



Backends

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- External tools used to compute some physical quantity
- Interfaced with GAMBIT dynamically
- 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

DarkBit

CaptnGeneral 1.0
DDCalc 2.2.0
DarkSUSY 6.2.2
MicrOmegas 3.6.9.2
gamLike 1.0.1

ColliderBit

HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212

FlavBit

SuperISO 3.6

PrecisionBit

FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

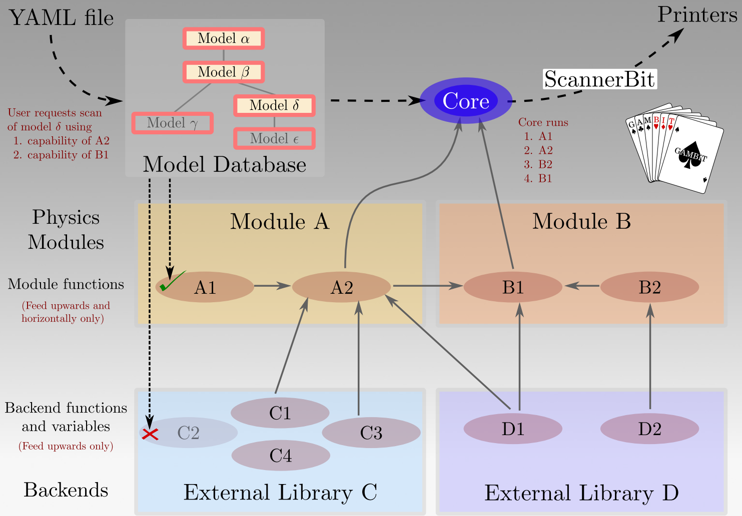
SpecBit

FlexibleSUSY 2.0.1
SPheno 4.0.3

DecayBit

SUSY_HIT 1.5

An example run



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

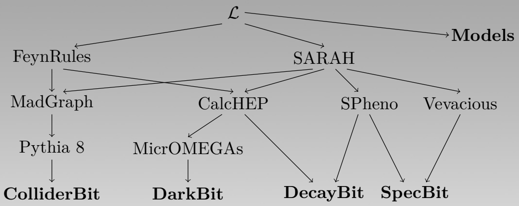
```
#define MODULE FlavBit                              // A tasty GAMBIT module.
START_MODULE

  #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

GUM

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

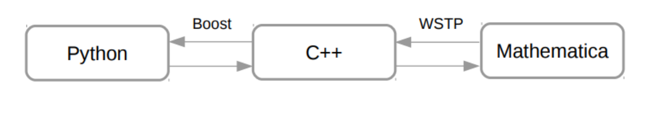


- GAMBIT-compatible outputs from GUM

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 release with GAMBIT 2.0

An example

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- Majorana DM χ with scalar mediator Y

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

```
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
```