What is GAMBIT?

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Kavli Institute for Cosmology, Cambridge,
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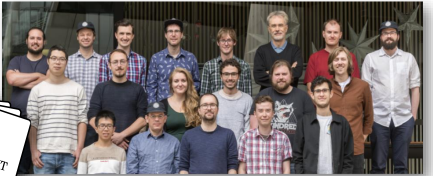
GAMBIT

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, SuperIso, 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

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What is GAMBIT for?

Beyond the SM

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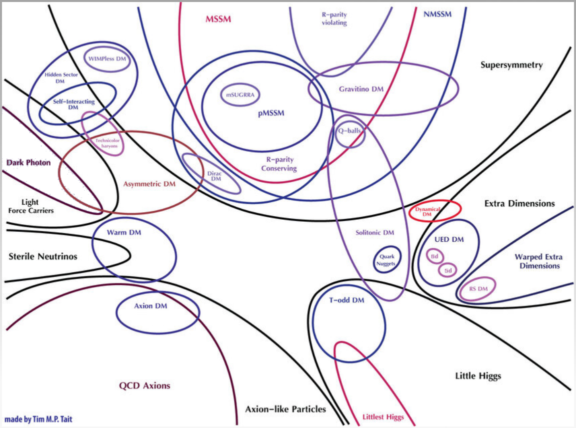
- Standard Model and ΛCDM can explain most phenomena
- Beyond SM and/or beyond ΛCDM required to fit many issues
- Landscape of BSM models is enormous
- Many new particles and many new parameters
- Constrained from multiple particle, astrophysical and cosmological sources
- Global studies only reliable way to explore BSM models

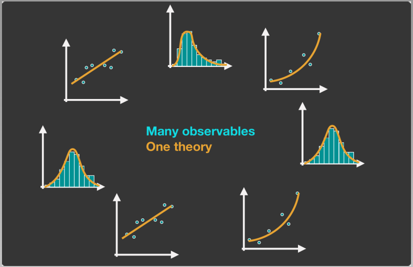


from Tim Tait

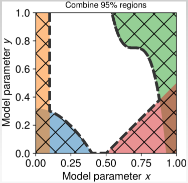
Global fits

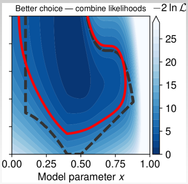
- Multitude of experimental observables for each model
- Theory predictions $f(x)$
- Experiments measure $\mathcal{L}(\theta)$
- One needs

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



from A.Kvellestad





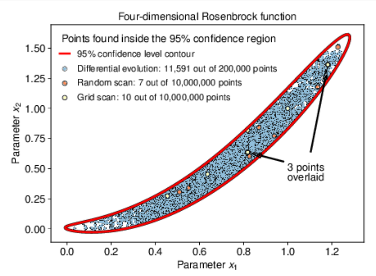
[Rept.Prog.Phys. 85 (2022) 5, 052201]

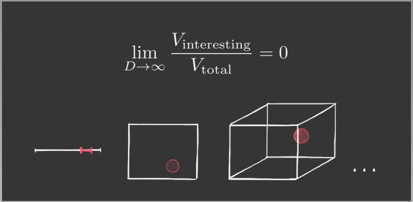
- Exclusion regions do not properly represent the model predictions
- Impossible to analyse signals
- Combine all constraints into a composite likelihood

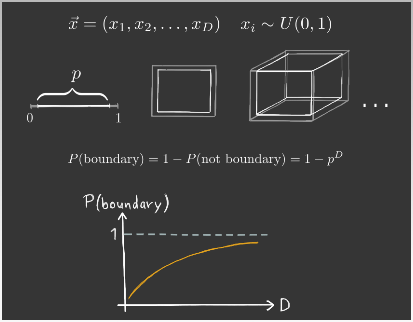
$$\mathcal{L} = \mathcal{L}_{Collider}\mathcal{L}_{Higgs}\mathcal{L}_{DM}\mathcal{L}_{Flavour}\cdots$$

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,...)







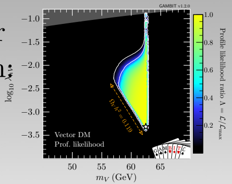
from A.Kvellestad

Global fits

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

Frequentist

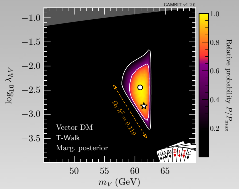
- How well does my model reproduce the data?
- Parameter estimation: profiling $\mathcal{L}/\mathcal{L}_{\text{max}}$



- 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 ⇝ GAMBIT

What is GAMBIT made of?

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 [Eur.Phys.J. C81 (2021) no 12, 1103]

Models

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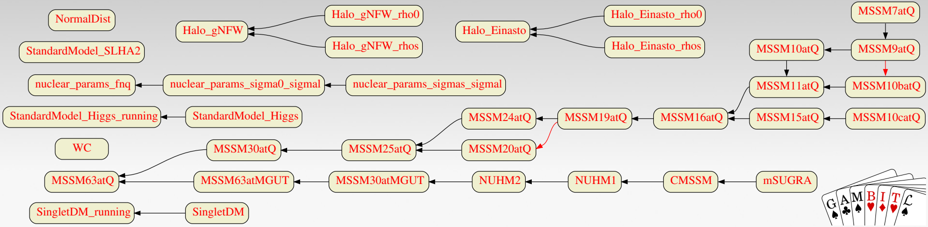
- Extensive model database

SUSY	DM	Cosmo	Others
CMSSM NUHM1,2 MSSM63 MSSM63+mG	S, F, V HP Singlet S, F, V Simplified Axions DMEFT	ΛCDM $\Delta N_{\rm eff}$ Power-law inflation	SM RH neutrinos WC nuisance models

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



Backends

CosmoBit
Acropolis 1.2.1
AlterBBN 2.2
DarkAges 1.2.0
MontePythonLike 3.5.0
MultiModeCode 2.0.0
classy 3.1.0
plc 3.0

DarkBit
CaptnGeneral 2.1
DDCalc 2.3.0
DarkSUSY 6.4.0
DirectDM 2.2.0
MicrOmegas 3.6.9.2
gamLike 1.0.1
nulike 1.0.9
pbarlike 1.0

ColliderBit
Contur 2.1.1
HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212
Rivet 3.1.5
nulike 1.0.9
phy 0.7

PrecisionBit
FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

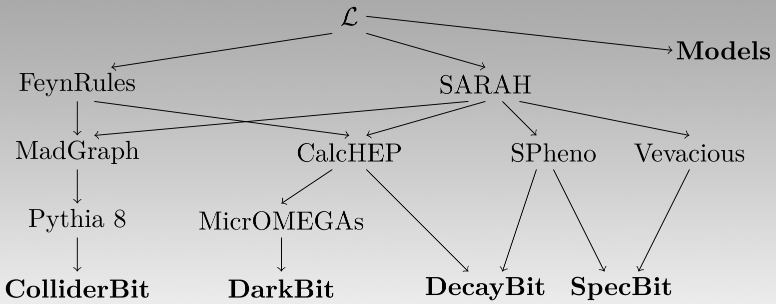
SpecBit
FlexibleSUSY 2.0.1
SPheno 4.0.3
Vevacious 1.0

FlavBit
HepLike 2.0
HepLikeData 1.4
SuperISO 3.6

DecayBit
CalcHEP 3.6.27
SUSY_HIT 1.5

GUM

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



- Autogenerates GAMBIT code for selected model

More about GAMBIT

- Want to know more about GAMBIT and how to use it?
  → **Tuesday 9:30am** ⇝ GAMBIT tutorial
  → Coding/breakout sessions all week

- Only care about specific working groups?
  → **Monday 2:00pm** ⇝ Flavour WG
  → **Tuesday 11:30am** ⇝ Neutrino WG
  → **Wednesday 9:30am** ⇝ Scanner WG
  → **Wednesday 2:00pm** ⇝ Core WG
  → **Thursday 9:30am** ⇝ Collider WG
  → **Thursday 2:00pm** ⇝ Dark Matter / Cosmo WG
  → **Friday 9:30am** ⇝ Precision WG

What has GAMBIT done?

GAMBIT results

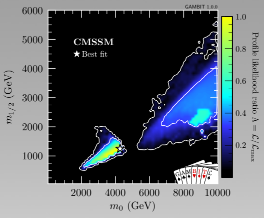
- 8 code papers: GAMBIT, ColliderBit, DarkBit, FlavBit, SDPBit, ScannerBit, CosmoBit, GUM
- 18 physics papers
  - → 4 SUSY papers [Eur.Phys.J.C 83 (2023) 6, 493, Eur. Phys. J. C 79 (2019) 395] [Eur. Phys. J. C 77 (2017) 879, Eur. Phys. J. C 77 (2017) 824]
  - → 9 DM papers [arXiv:2303.07362, arXiv:2303.08351] [Eur.Phys.J.C 83 (2023) 3, 249, Eur.Phys.J.C 81 (2021) 11, 992] [JHEP 05 (2021) 159, JHEP 03 (2019) 191, Eur. Phys. J. C 79 (2019) 38] [Eur. Phys. J. C 78 (2018) 830, Eur. Phys. J. C 77 (2017) 568]
  - → 2 Cosmo papers [JCAP 12 (2022) 027, Phys.Rev.D 103 (2021) 12, 123508]
  - → 2 Flavour papers [Eur. Phys. J. C 81 (2021)]
  - → 1 Right-handed neutrinos [Eur. Phys. J. C 80 (2020) 6, 569]
- 1 review [Progress in Particle and Nuclear Physics, 113 (2020) 103769]
- 20 conference proceedings [gambit-proceedings-20xx]

https://gambitbsm.org/community/publications/

Examples

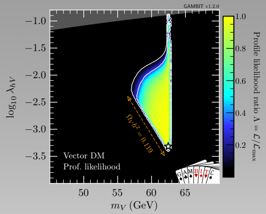
CMSSM

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



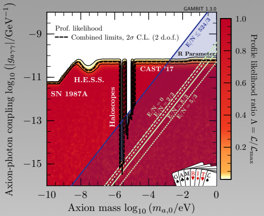
Higgs-portal DM

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



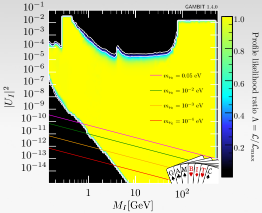
QCD axions

[JHEP 03 (2019) 191]



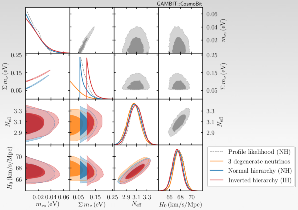
Right-Handed Neutrinos

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



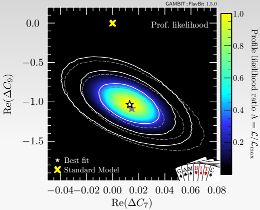
Neutrino Masses

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



Flavour EFT

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

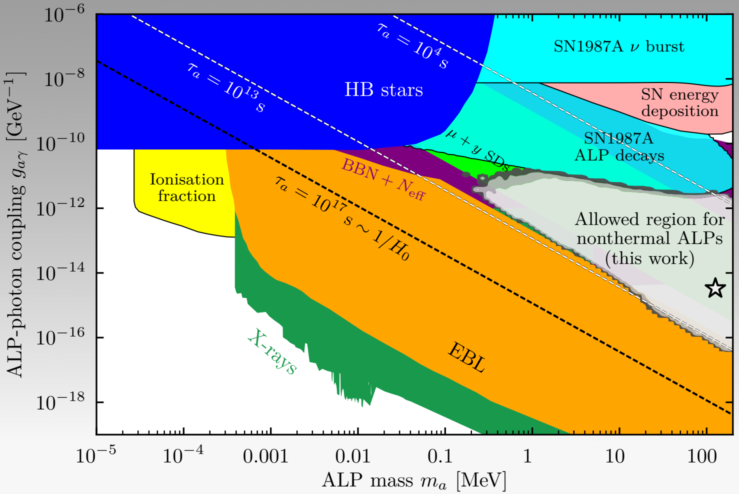


Decaying cosmological axion-like particles

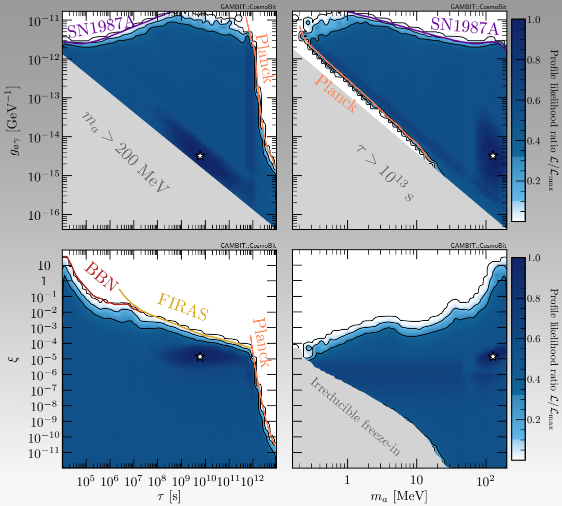
[JCAP 12 (2022) 027]

Cosmo ALP

- Axion-like particles decaying between BBN and CMB



Cosmo ALP



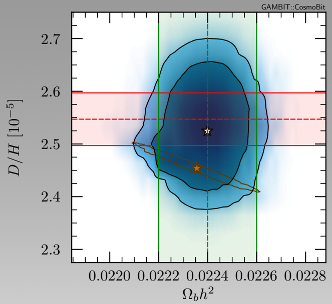
- Frequentist results
- Independent pars $\{m_a, \tau_a, \xi\}$
- Small abundance $\xi \ll 1$
- Mass lower bound $m_a > 300$ keV
- No effect from $N_{\rm eff}$, η_b or R parameter
- Mostly flat $\Delta\mathcal{L}$
- Small excess at

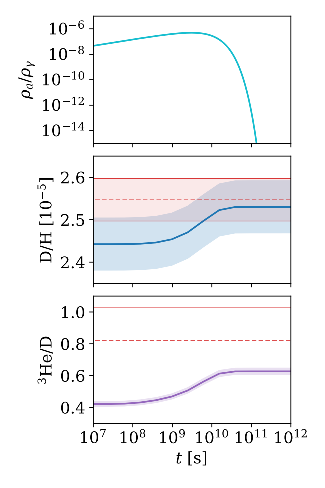
$$m_a = 126.1 \text{ MeV}$$

$$\tau_a = 6.04 \times 10^9 \text{ s}$$

$$\xi = 4.18 \times 10^{-5}$$

Cosmo ALP





- In ΛCDM there is a correlation between $\Omega_b h^2$ and D/H
- No correlation in ALP model because photodisintegration
- Improved fit to observations
- ΛCDM within 1σ of ALP model

Effective field theory of Dark Matter

[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

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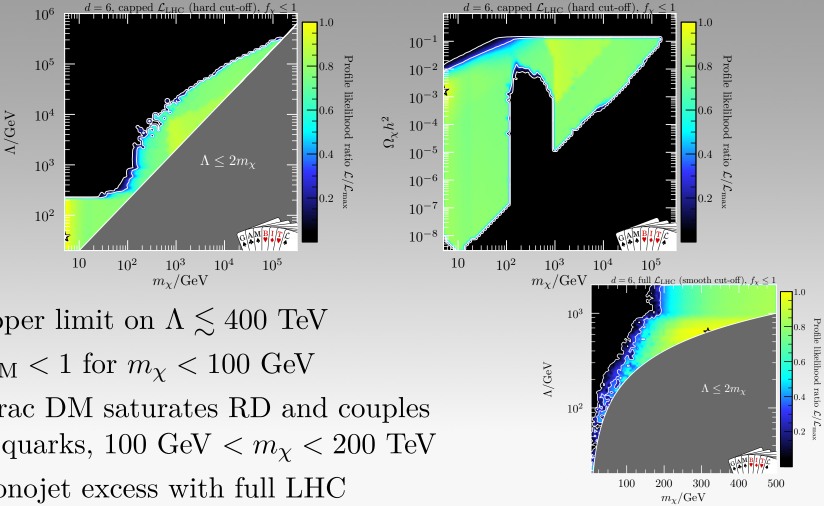
- Only 6-dim operators, $\Omega_{\rm DM}h^2$ upper limit, exclusion only LHC



→ Upper limit on $\Lambda \lesssim 400$ TeV

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

→ Dirac DM saturates RD and couples to quarks, 100 GeV $< m_\chi <$ 200 TeV

→ Monojet excess with full LHC

EW MSSM with light gravitino

[Eur.Phys.J.C 83 (2023) 6, 493]

EW MSSM + $\tilde{G}$

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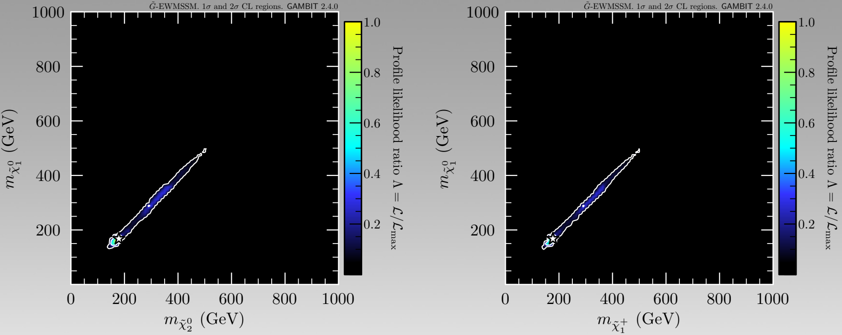
[GAMBIT, arXiv:2303.15527 [hep-ph]]

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

EW MSSM + $\tilde{G}$

- 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

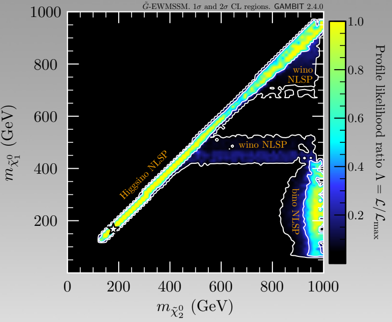
→ Dominant channels are $\tilde{\chi}_1^0 \to h\tilde{G}$, $\tilde{\chi}_1^0 \to Z\tilde{G}$

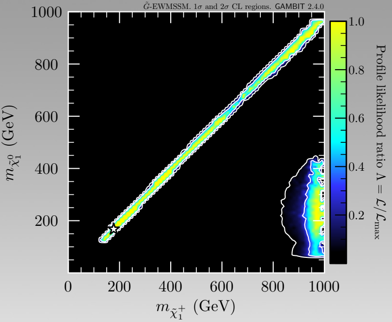
→ Fits excess is leptons + $E_T^{\rm miss}$and b-jets + $E_T^{\rm miss}$searches

→ Simultaneous fit to multi-lepton and multi-b signal regions

EW MSSM + $\tilde{G}$

- "Capped" likelihood (exclusion-only)





→ 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

→ SM cross section measurements kill lowest masses

What will GAMBIT do next?

Current "nearly done$^{\text{TMMW}}$" projects

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- Flavour WG:
  - → global studies of the THDM-I, THDM-II, THDM-III and IDM
    - ⇝ flavour constraints from LHCb and Belle (II)
    - ⇝ collider searches for heavy H and SM measurements
- Cosmo / DM WG:
  - → Sub-GeV DM with a dark photon **Thursday 3:00pm**
    - ⇝ Cosmological and astrophysical constraints
    - ⇝ Direct detection, collider and beam dump experiments
  - → Annual modulation of DM
    - ⇝ disentangling the DAMA signal with ANAIS and COSINE
- Neutrino WG:
  - → global fit of the oscillations of three neutrinos **Tuesday 11:30am**
    - ⇝ solar, atmospheric, reactor and accelerator experiments
- Collider WG:
  - → ColliderBit Solo: standalone tool for recasting of LHC searches

Next targets

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- Long author (full community) projects: **Thursday 11:30am**
  - → Flavour and collider study of light leptoquarks
    - ⇝ what models to focus on now that $R_{K^{(*)}}$ is gone?
    - ⇝ recasting of collider searches for leptoquarks
  - → Status of SUSY after Run 2 of the LHC
    - ⇝ where do popular SUSY models (e.g. CMSSM) stand after Run 2?
    - ⇝ recasting of SUSY searches
- Other WG or short papers
  - → Cosmo / DM WG:
    - ⇝ Gravitational waves (Nanograv, etc) **Tuesday 2:00pm**
  - → Precision WG:
    - ⇝ SMEFT fit
    - ⇝ MW in the MSSM
  - → Core WG:
    - ⇝ GAMBIT-light **Wednesday 4:00pm**

Conclusions

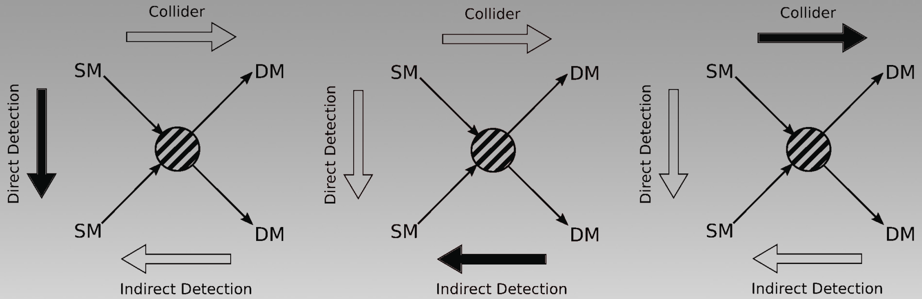
Conclusions

- BSM models with many parameters and constraints ⇝ global fits
  - → Likelihood combination, smart sampling, statisical interpretation
  - → GAMBIT is the most complete and flexible framework for global fits
- GAMBIT is made of modules for each physics sector
  - → ColliderBit, DarkBit, CosmoBit, etc
  - → Interfaced to state-of-the art external tools
  - → Autogeneration of GAMBIT code with GUM
- GAMBIT has done 18 studies of BSM models in SUSY, DM, Cosmo, flavour and neutrino physics
- Many interesting projects ongoing and more to come

Backup

Dark Matter

- Three ways to look for DM interactions in particle physics



→ DM interacting with nuclei

→ LZ, XENON1T, PandaX,. . .

→ 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

Relic density!

Dark Matter

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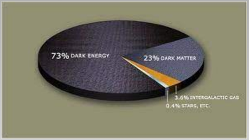
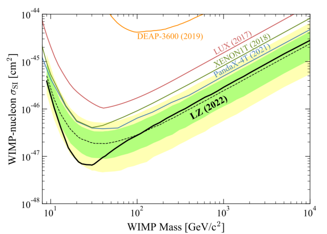
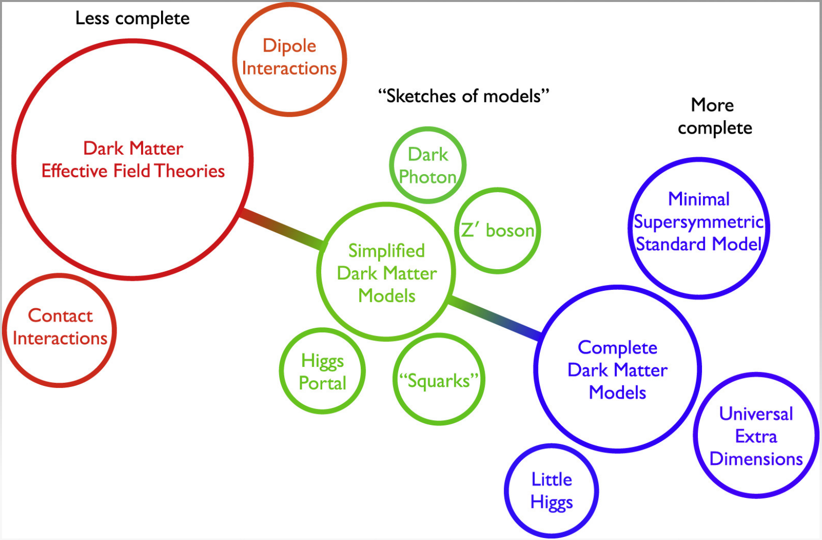
- Plenty of evidence for DM from astrophysics (e.g bullet cluster) and cosmology (e.g CMB)
- If DM is a particle and if interacts then we should be able to detect it
- Most popular DM models are WIMPs
  - → EW-scale mass, accesible at colliders
  - → Just right RD through freeze-out
  - → Form part of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





- No evidence that DM interacts with SM
- 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


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

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

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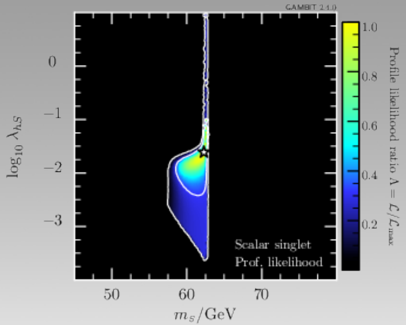
- Direct Detection — DDCalc
  - → XENON1T, LUX 2016, PandaX 2016, 17 & **4T**, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017 & **2019**, DarkSide-50, **LZ 2022**
- Relic abundance — DarkSUSY, plc
  - → Planck 2015: $\Omega_{\rm DM} h^2 \leq 0.1188 \pm 0.0010$
- Indirect detection with γ-rays — gamLike
  - → 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
  - → $\text{BR}_{\rm inv}(h \to \bar{X} X) < 19\%$ (2σ) [< **14% (95% CL)**]
- Theoretical constraints
  - → Perturbative unitarity and EFT validity

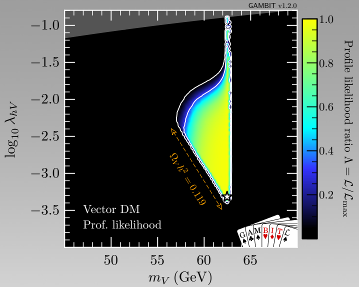
- Scalar DM

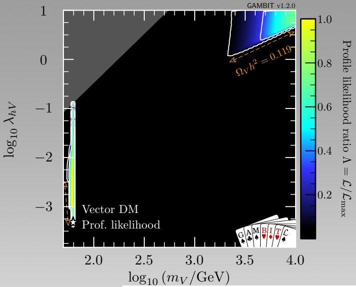


- Disconnected regions: along resonance $m_s \sim m_h/2$ and high mass
- High mass almost completely excluded by DD, ID and RD
- Small excess in Higgs invisible decay $\mathrm{BR}_{\mathrm{inv}} = 0.06$

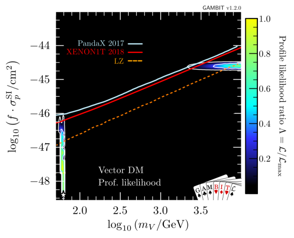
Higgs portal DM

- Vector DM

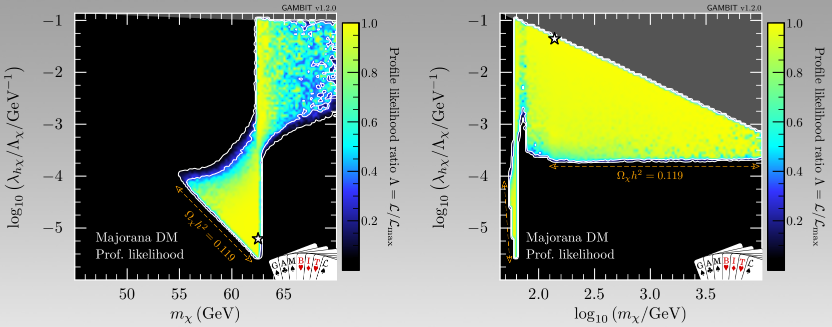




- Resonance region and highest mass region survive
- Intermediate mass killed by unitarity bound
- Inclusion of recent DD constraints may kill high mass



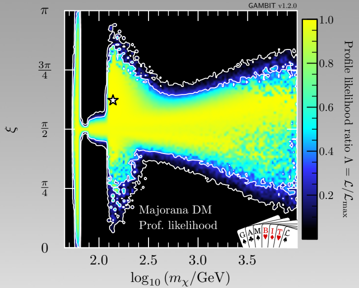
- Majorana fermion DM (≈ Dirac DM)

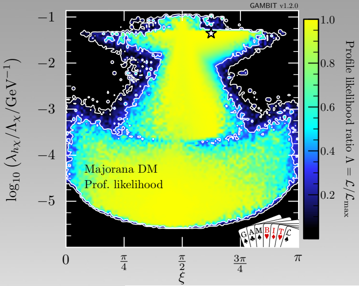


- Resonance and high mass regions connected
- Looser constraints from DD due to pseudoscalar interactions

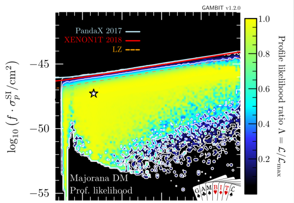
Higgs portal DM

- 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



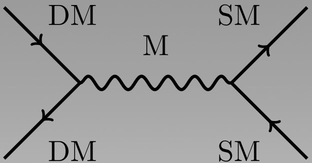
DM EFT

- 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 139fb^{-1} mono-jet
  - → CMS 36fb^{-1} mono-jet

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

Simplifed 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)

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

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

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

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

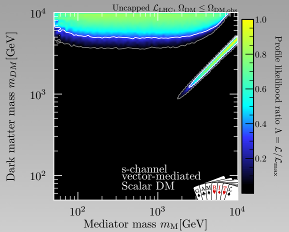
Simplified DM models

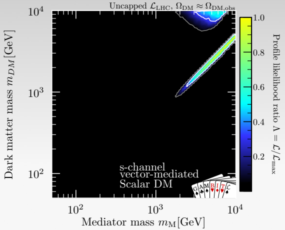
- Direct Detection — DirectDM, DDCalc
  - → XENON1T, LUX 2016, PandaX 2016-17 & **4T**, CDMSlite, CRESST-II, CRESST-III, PICO-60 2017-19, DarkSide-50 and LZ 2022
- Relic abundance — CalcHEP, DarkSUSY, plc
  - → Planck 2018: $\Omega_{\rm DM}h^2 \leq 0.120 \pm 0.001$
- ID with γ-rays — CalcHEP, gamLike
  - → 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

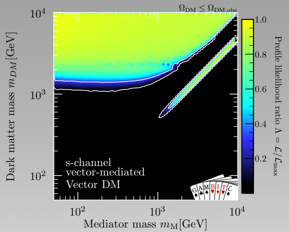
[C.Chang et al, Eur.Phys.J.C 83 (2023) 3, 249]

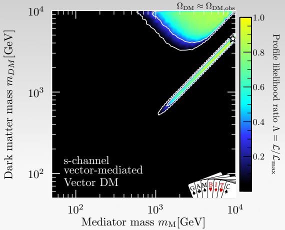




- Vector DM

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





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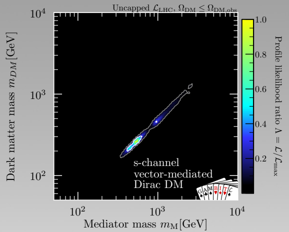
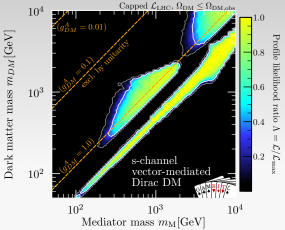
- Dirac fermion DM

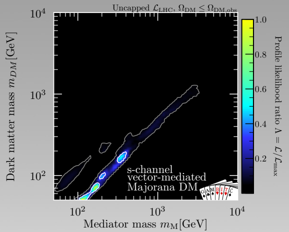
[C.Chang et al, Eur.Phys.J.C 83 (2023) 3, 249]

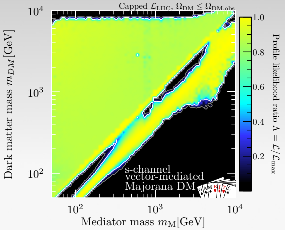




- Majorana fermion DM

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





DM EFT

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

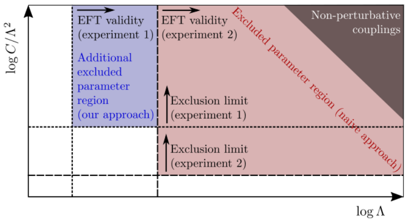
$$\mathcal{C}^{(5)}_{1,2} = -4\frac{m_t(m_t)^2}{\Lambda^2}\log\frac{\Lambda^2}{m_t(m_t)^2}\,\mathcal{C}^{(7)}_{9,10}$$

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

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

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

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



Likelihoods

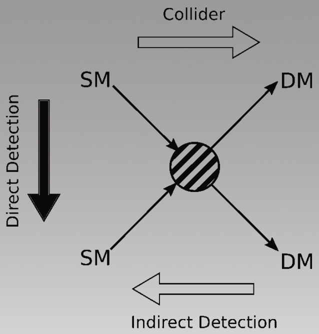
- Direct Detection

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

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

$\rightarrow$ Non-relativistic operators

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



$$\sigma_\mathrm{SI}^V = \frac{\mu_N \lambda_{hV}^2 f_N^2 M_N^2}{4\pi m_V^2 m_h^4}, \quad \frac{d\sigma_\mathrm{SI}^X}{dq^2} = \frac{1}{v^2}\left(\frac{\lambda_{hX}}{\Lambda_X}\right)^2 \frac{A^2F^2(E)f_N^2 m_N^2}{4\pi m_h^4}\left(\cos^2\xi + \frac{q^2}{4m_X^2}\sin^2\xi\right)$$

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

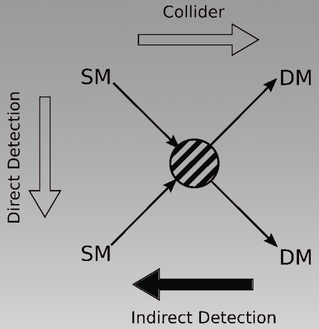
  $\rightarrow$ Planck 2018: $\Omega_\mathrm{DM}h^2 \leq 0.120 \pm 0.001$

Likelihoods

- Indirect detection with γ-rays
  - → 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

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

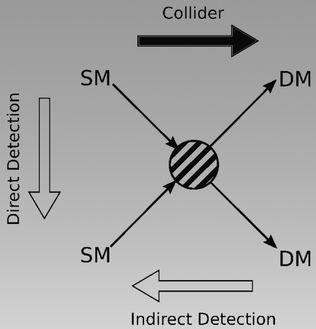
Likelihoods

- 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

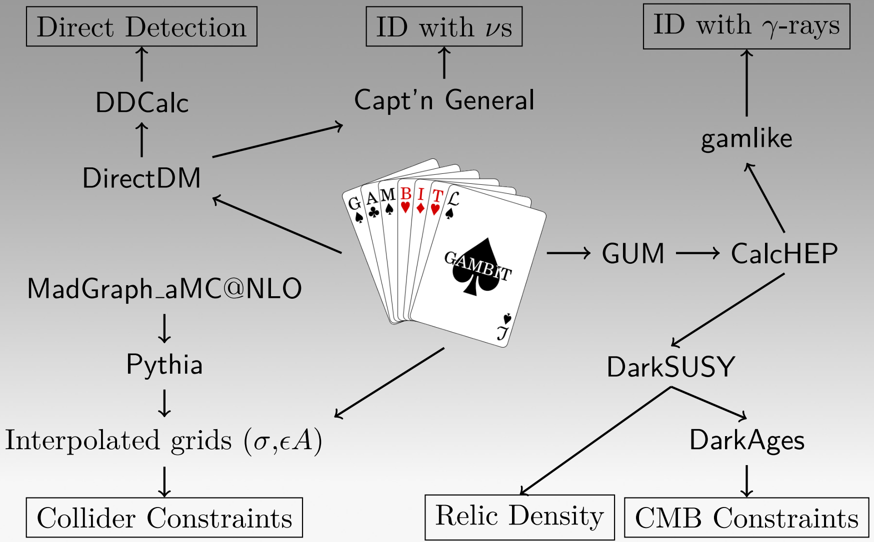
DM mass	m_χ
New physics scale	Λ
Wilson coefficients	$\mathcal{C}_a^{(d)}$

- Nuisance parameters

Local DM density	ρ_0
Most probable speed	$v_{\rm peak}$
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

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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

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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

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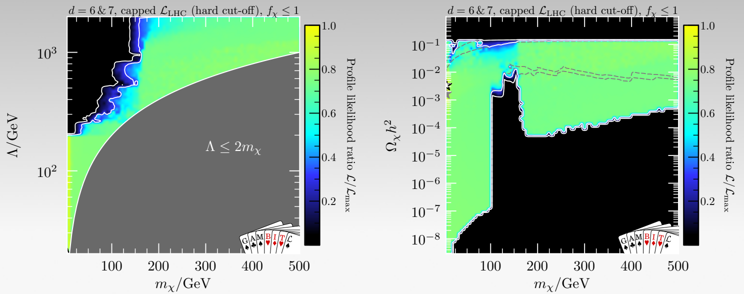
Nuisance parameter		Value ($\pm 3\sigma$ range)
Local DM density	ρ_0	0.2–0.8 GeV cm^{-3}
Most probable speed	v_{peak}	240 (24) km s^{-1}
Galactic escape speed	v_{esc}	528 (75) km s^{-1}
Running top mass ($\overline{\text{MS}}$ scheme)	$m_t(m_t)$	162.9 (6.0) GeV
Pion-nucleon sigma term	$\sigma_{\pi N}$	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}

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 $\xi =$ relative signal/bkg uncertainties

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

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

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

DM EFT

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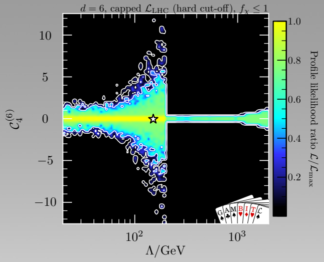
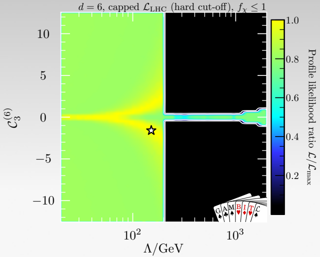
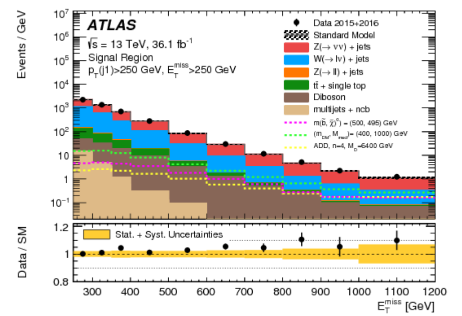
- $\mathcal{C}_1^{(6)}$
  - $\rightarrow$ spin-independent scattering
  - $\rightarrow$ strongly constrained $\rightsquigarrow$ very small
- $\mathcal{C}_2^{(6)}$
  - $\rightarrow$ momentum-dependent scattering
  - $\rightarrow$ $\Lambda < 250$ GeV DD constrained
  - $\rightarrow$ $\Lambda > 250$ GeV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

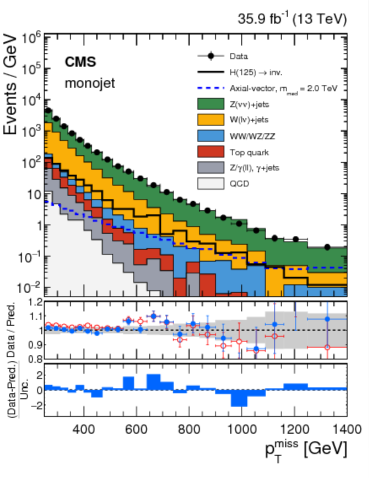




DMEFT



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
ADD, n=4, MD=6400 GeV
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]

Scan framework

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- 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

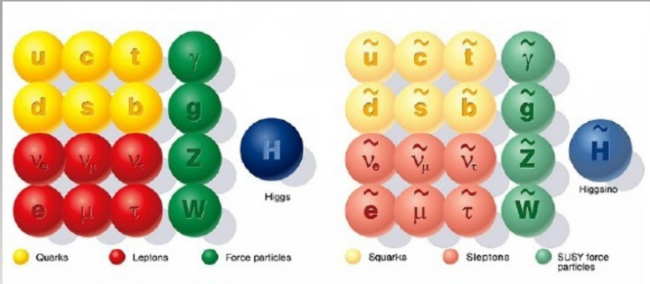
- Parameter ranges

$M_1(Q)$	$[-1, 1]$ 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

Supersymmetry

- 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

Supersymmetry

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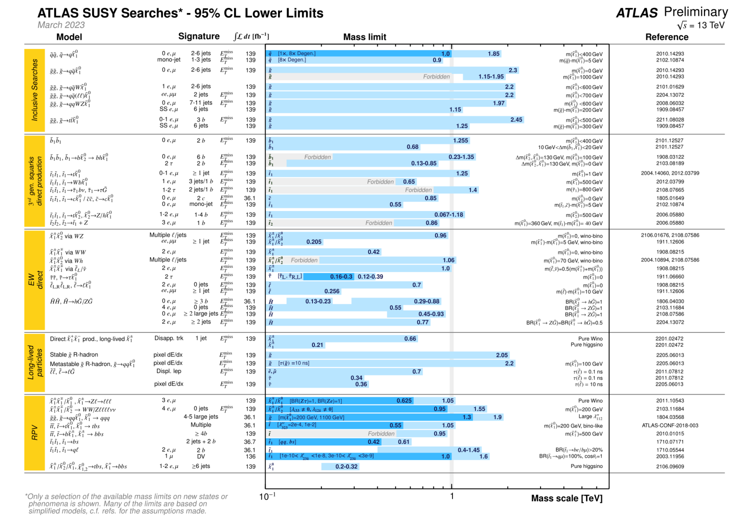

Supersymmetry

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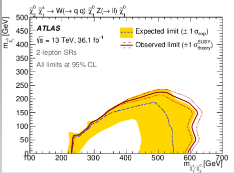
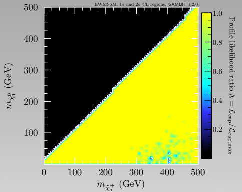
- Many of the limits are based on simplified models
  - → Production of lightest states
  - → Degenerate mass eigenstates
  - → Fixed branching ratios

  } ⇒ Reinterpretation

[RIF, SciPost Phys. 9 (2020) 2, 022]





[ATLAS, Phys.Rev.D 98 (2018) 9, 092012] [GAMBIT, Eur.Phys.J.C 79 (2019) 5, 395]

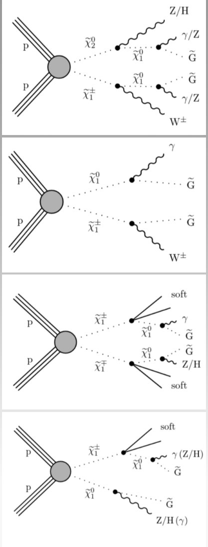
HEP Software Foundation

[Comput Softw Big Sci (2019) 3, 7]

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.

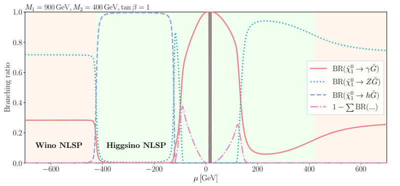
EW MSSM + $\tilde{G}$

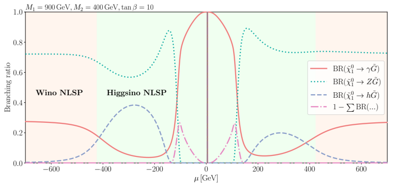
- LHC SUSY searches
  - $\rightarrow$ 15 ATLAS and 12 CMS Run 2
  - $\rightarrow$ $\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 2/3/4 leptons + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 0/1/2 leptons + $\tilde{t}$ + $E_{\mathrm{T}}^{\mathrm{miss}}$
  - $\rightarrow$ 2/3 b-jets + 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 $\chi^0 \rightarrow \gamma + \tilde{G}$



EW MSSM + $\tilde{G}$

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





EW MSSM + $\tilde{G}$

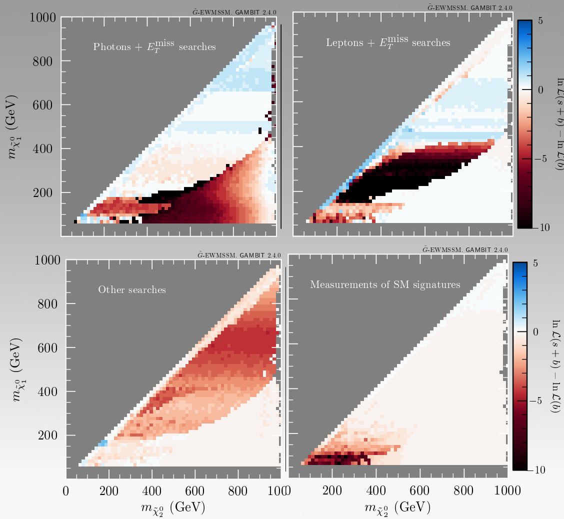
- Impact of searches and measurements

$\rightarrow$ Photon searches exclude low mass binos

$\rightarrow$ Lepton searches exclude low mass winos

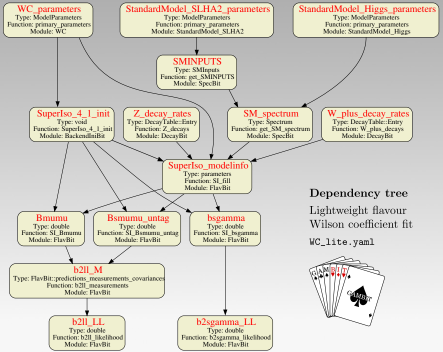
$\rightarrow$ Boosted boson searches exclude high mass winos

$\rightarrow$ 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

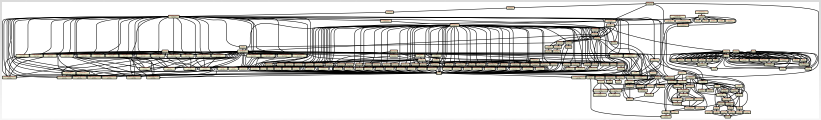
```
// SM-like Higgs mass with theoretical uncertainties
#define CAPABILITY prec_mh
START_CAPABILITY

  #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
```

- At run time a dependency tree is generated and resolved



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

An example

- Majorana DM χ with scalar mediator Y

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

```
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
```