Global fits of simplified dark matter models

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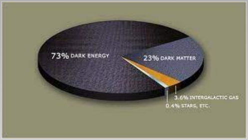
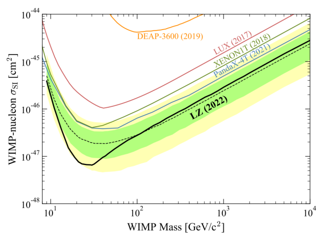
Dark Matter

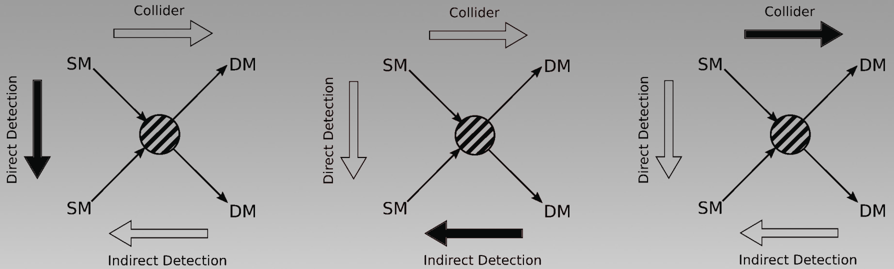
- Plenty of evidence for DM from astrophysics (e.g bullet cluster) and cosmology (e.g CMB)
- If DM is a particle and if interacts then we should be able to detect it
- Most popular DM models are WIMPs
  - → EW-scale mass, accesible at colliders
  - → Just right RD through freeze-out
  - → Form part of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





- No evidence 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

- 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 $\not{E}_T$

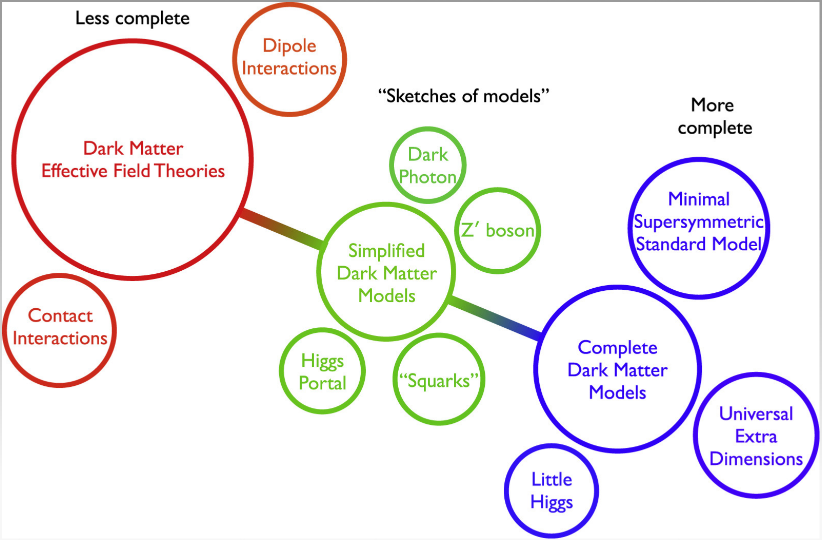
→ Mono-X (jet, ...)

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

→ H invisible width

- Relic abundance $\Omega_{\rm DM}h^2 = 0.120 \pm 0.001$

Dark Matter


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

Simplified DM models

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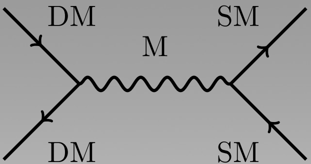
- Singlet DM candidate plus vector mediator that couples to SM particles (quarks)

$$\mathcal{L}_V = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m_M{}^2 V_\mu V^\mu + g_q V_\mu \bar{q}\gamma^\mu q$$



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

[C.Chang, P.Scott, TG, F.Kahlhoefer, A.Kvellestad, M.White, Eur.Phys.J.C 83 (2023) 3, 249]

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

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

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

[C.Chang, P.Scott, TG, F.Kahlhoefer, M.White, Eur.Phys.J.C 83 (2023) 8]

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

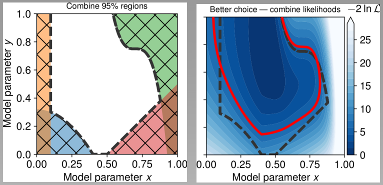
Simplified DM models

- 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, $\Gamma(m_M) \leq m_M$, $\Gamma(\sqrt{s}) \leq \sqrt{s}$

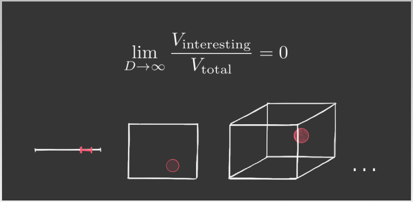
Global fits of DM models

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

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



[arXiv:2012.09874 [hep-ph]]



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

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

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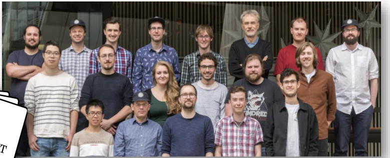
GAMBIT: The Global And Modular BSM Inference Tool

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

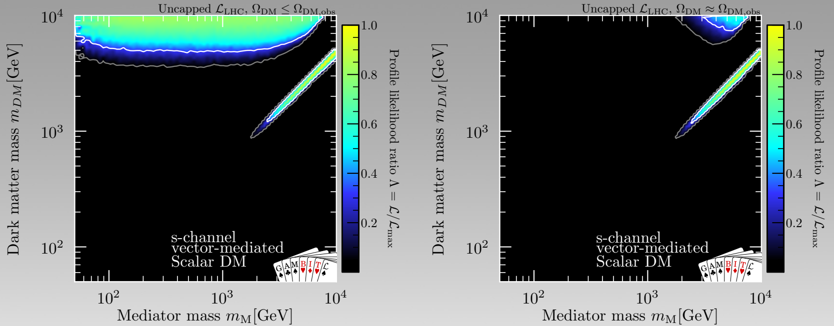
Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

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

Results

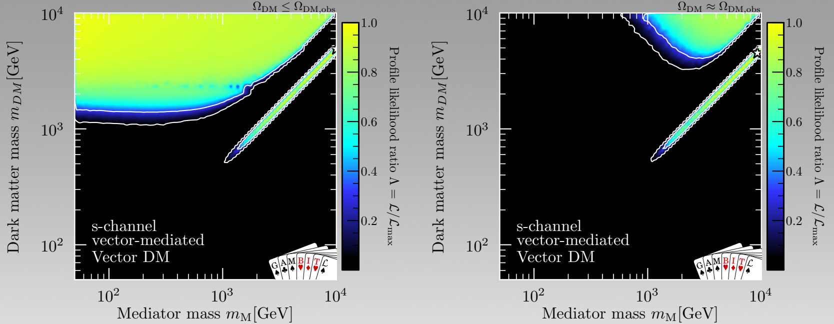
- Scalar DM



- Resonance region $m_{\rm M} \sim 2m_{\rm DM}$ still survives for $m_M \gtrsim 2$ TeV
- High $m_{\rm DM} \gtrsim 4$ TeV region valid for arbitrary m_M if $\Omega_{\rm DM} < \Omega_{\rm DM,obs}$
- For saturated RD, off resonance forced to high $m_M \gtrsim 3$ TeV

Results

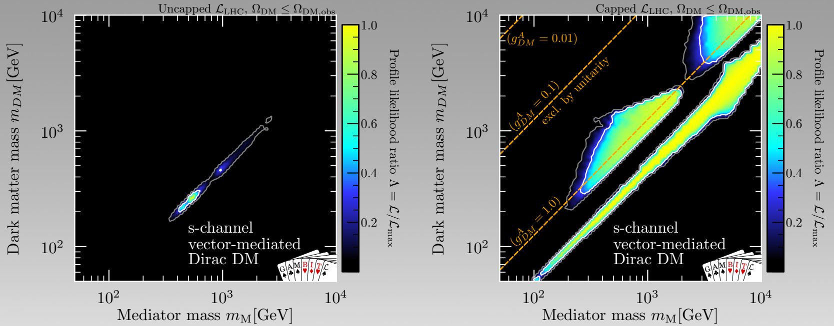
- Vector DM



- Very similar to scalar but looser DD constraints on high mass due to nature of interaction
- m_{DM} allowed all the way to 1 TeV for DM subcomponent and 2 TeV for saturated RD

Results

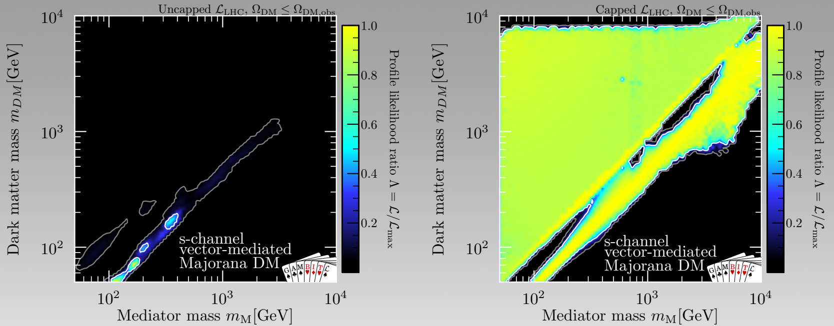
- Dirac fermion DM



- Dirac DM fits small excessed on CMS monojet searches ($\sim 2\sigma$)
- With *capped* $\mathcal{L}_{\rm LHC}$ resonance region allowed to $m_M \sim 100$ GeV
- Off-resonance region constrained by unitarity of $g^A_{\rm DM}$, RD and DD
- Restricting to exact RD, bounds $m_M \gtrsim 500$ GeV

Results

- Majorana fermion DM



- Majorana DM has pure axial-vector coupling $g^A_{\rm DM}$
- Also fits the monojet excess for lower masses $m_M \sim 100$ GeV
- No constrain from DD due to the axial-vector coupling
- Majorana DM can be subcomponent or full DM

Conclusions and outlook

- Bosonic DM is in trouble in simplified models
  - → Low DM masses only on resonance
  - → Heavy DM mostly for $\Omega_{DM} < \Omega_{DM,obs}$
- Fermionic DM way more promising due to suppressed DD
  - → Pure axial-vector interactions preferred
  - → Can exist for most range of masses as subcomponent or full DM
- Minor insignificant excesses
  - → CMS monojet excess in simplified likelihood prefers low DM masses
- Prospects for probing remaining regions
  - → DD or LHC will not signficantly tackle HP resonance region
  - → Monojet and dijet searches promising for bosonic DM
  - → Perhaps indirect searches (AMS-02?)

Thanks!

Backup

Effective model: DM EFT

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

DM EFT

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

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

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

DM EFT

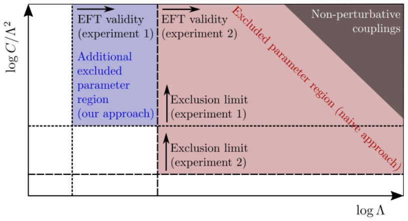
- Running and mixing
  - → For direct detection WCs are needed at $\mu = 2$ GeV (DirectDM)
  - → For $\Lambda > m_t(m_t)$:

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

$$\Delta\mathcal{C}_i^{(7)} = -\mathcal{C}_{i+4,q}^{(7)} \quad (i = 1,2)$$
$$\Delta\mathcal{C}_i^{(7)} = \mathcal{C}_{i+4,q}^{(7)} \quad (i = 3,4)$$

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

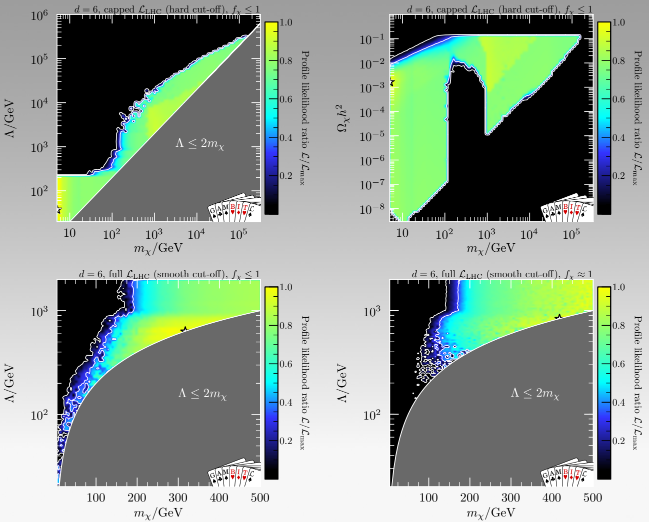
$$\Lambda < \not{E}_T \quad \begin{cases} \dfrac{d\sigma}{d\not{E}_T} = 0 \\ \dfrac{d\sigma}{d\not{E}_T} \to \dfrac{d\sigma}{d\not{E}_T}\left(\dfrac{\not{E}_T}{\Lambda}\right)^{-a} \end{cases}$$



DM EFT

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

DM EFT


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

Likelihoods

- Direct Detection

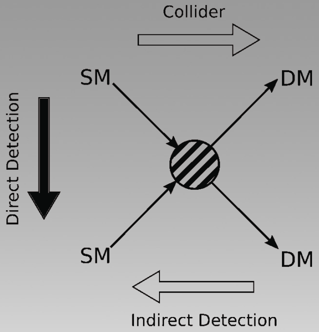
$$\frac{\mathrm{d}R}{\mathrm{d}E_\mathrm{R}} = \frac{\rho}{m_T\, m_\chi} \int_{v_\mathrm{min}}^{\infty} v f(v) \frac{\mathrm{d}\sigma}{\mathrm{d}E_\mathrm{R}} \mathrm{d}^3 v$$

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

→ Non-relativistic operators

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

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



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

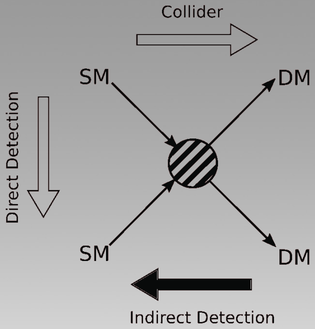
  → Planck 2018: $\Omega_\mathrm{DM} h^2 \leq 0.120 \pm 0.001$

Likelihoods

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

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

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



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

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

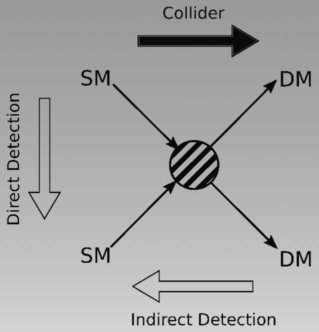
Likelihoods

- Collider constraints
  - → Many signatures for DM searches

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

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

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



- → ATLAS 139fb^{-1} mono-jet
  - ⇝ SR with best significance
  - ⇝ $\mathcal{L}_{\text{ATLAS}}(s_i) \equiv \mathcal{L}_{\text{ATLAS}}(s_i, \hat{\hat{\gamma}}_i)$
- → CMS 36fb^{-1} mono-jet
  - ⇝ Profile over systematics
  - ⇝ $\mathcal{L}_{\text{CMS}}(\mathbf{s}) \equiv \mathcal{L}_{\text{CMS}}(\mathbf{s}, \hat{\hat{\gamma}})$
- → *Capped* likelihood

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

Scan framework

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- Model parameters

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

- Nuisance parameters

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

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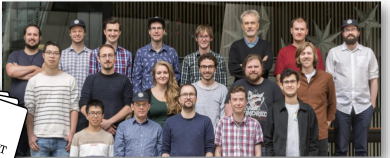

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Scan framework

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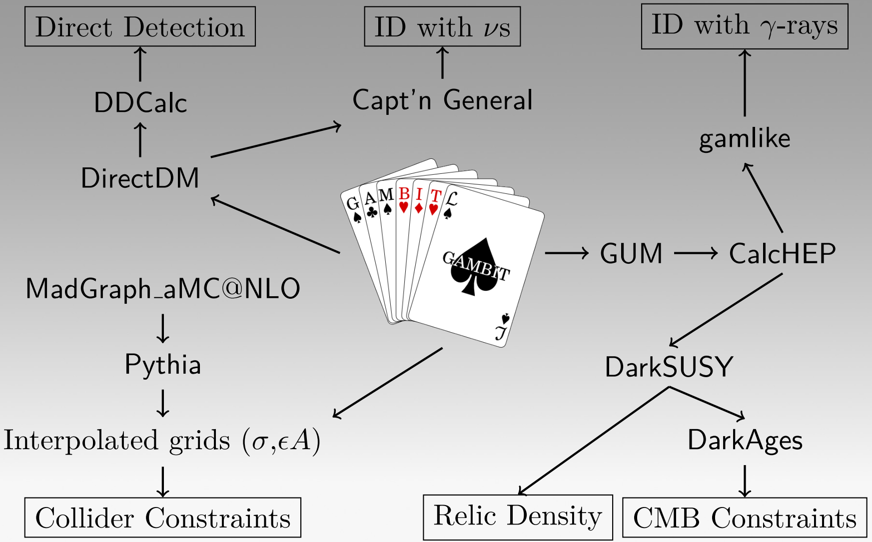
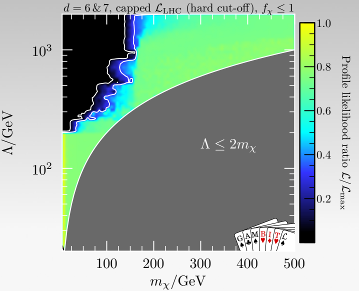
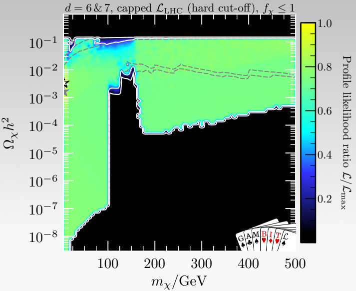


Results

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





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]

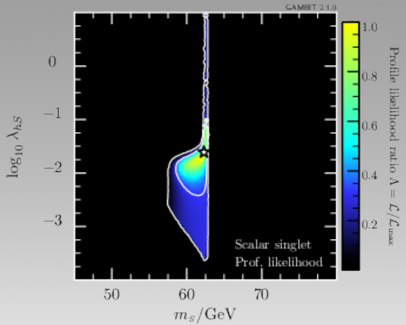
$$\mathcal{L}_\chi = \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi - \frac{1}{2}\frac{\lambda_{h\chi}}{\Lambda_\chi}(\cos\xi \bar{\chi}\chi + \sin\xi \bar{\chi} i\gamma_5 \chi)(vh + \frac{1}{2}h^2)$$

Higgs portal DM

- 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**
  ⇝ Sowmiya Balan's talk, Wed 16:16
- Higgs invisible width
  → $\text{BR}_{\text{inv}}(h \to \bar{X}X) < 14\%$ (95% CL) ($\sim 6\%$)
- Perturbative unitarity and EFT validity

Higgs portal DM

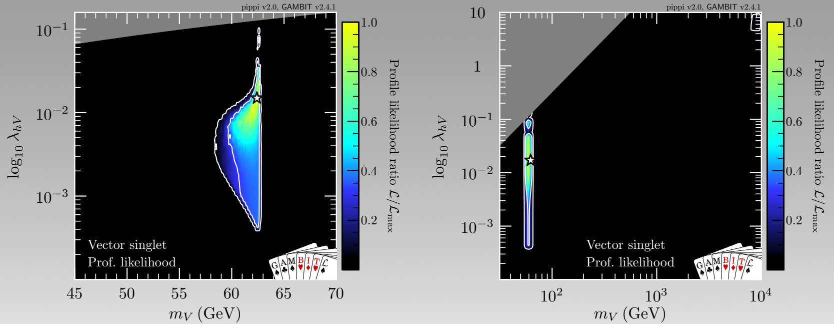
- Scalar DM



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

Higgs portal DM

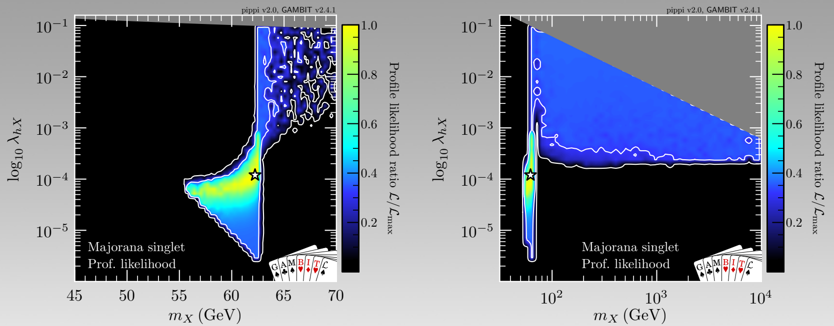
- Vector DM



- Only resonance region $m_s \sim m_h/2$ survive
- Intermediate mass killed by unitarity bound
- Recent DD constraints (LZ) destroys high mass
- Small excess in Higgs invisible decay $\mathrm{BR}_{\mathrm{inv}} = 0.06$

Higgs portal DM

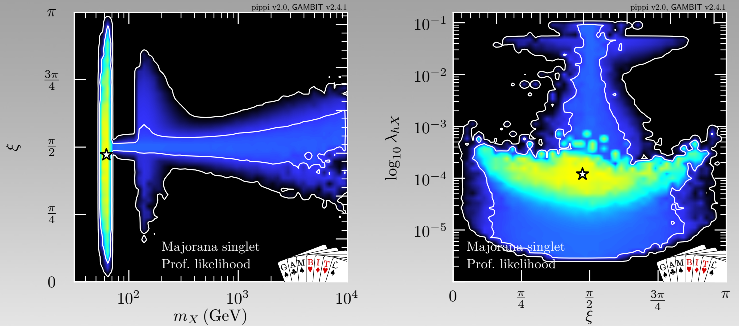
- Majorana fermion DM ($\approx$ Dirac DM)



- Resonance and high mass regions connected
- Looser constraints from DD due to pseudoscalar interactions (ξ)
- Higgs invisible decay excess prefers resonance region

Higgs portal DM

- Additional parameter CP phase ξ



- Mild preference for pseudoscalar interactions $\xi \sim \pi/2$
- Pure scalar not allowed at high masses (at 2σ)
- Only viable HP candidate outside resonance

Global fits

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

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

- Perform an extensive **parameter scan**

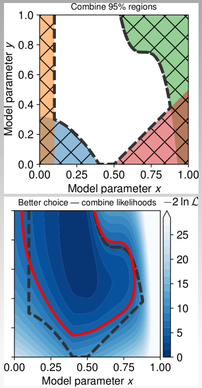
→ Old-school sampling methods (random, grid) are inefficient

→ Harder to make statement about statistics

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

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

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



[arXiv:2012.09874 [hep-ph]]

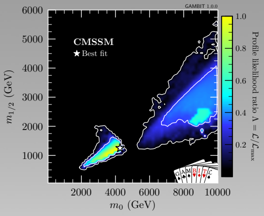
Modules (Bits)

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

Examples

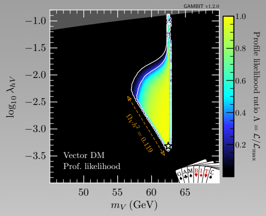
CMSSM

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



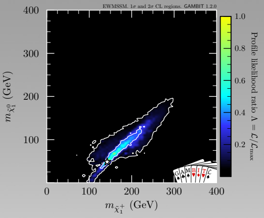
Higgs-portal DM

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



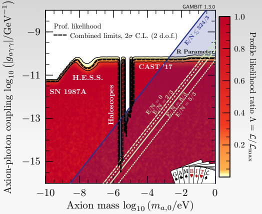
MSSM-EW

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



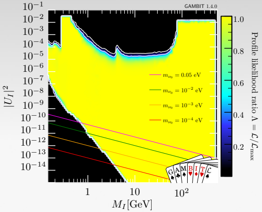
QCD axions

[JHEP 03 (2019) 191]



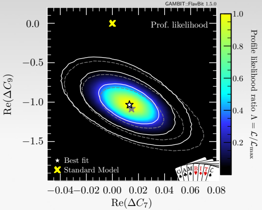
Right-Handed Neutrinos

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



Flavour EFT

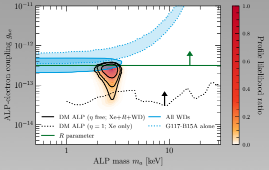
[Eur.Phys.J.C 81 (2021)12,1076]



Examples

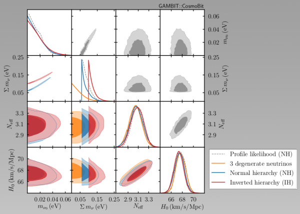
DM ALPs

[JHEP 05 (2021) 159]



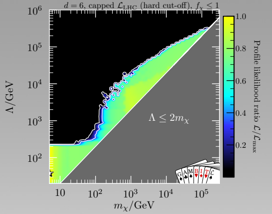
Neutrino Masses

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



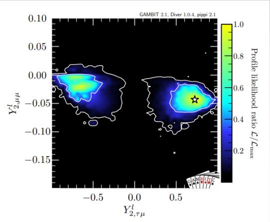
DMEFT

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



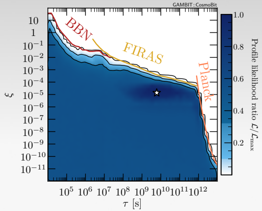
THDM-III

[JHEP 01 (2022) 037]



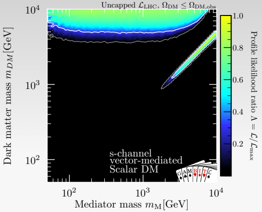
Cosmo ALPs

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



S-channel DM

[arXiv:2209.13266 [hep-ph]]



Core

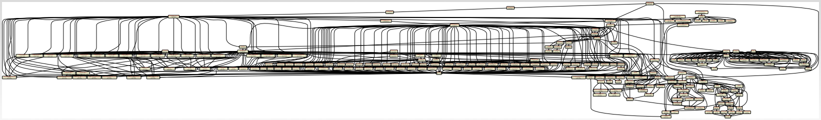
- Each module contains a collection of module functions
- Module functions provide a *capability*
- They have dependencies and backend requirements
- Allowed for specific models
- At run time a dependency tree is generated and resolved

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

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

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

#undef CAPABILITY
```



Models

- Extensive model database

SUSY

CMSSM
NUHM1,2
MSSM63atQ

DM

Scalar Singlet
Fermionic Singlet
Vector Singlet
Axions

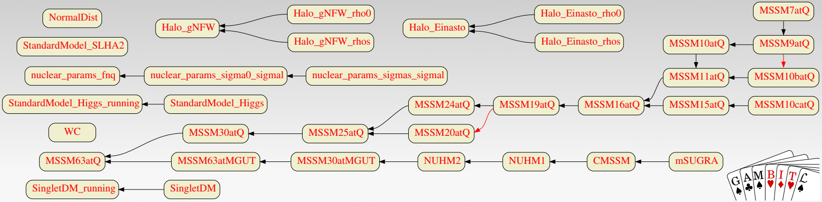
Cosmo

ΛCDM
ΔN_{eff}
Power-law
inflation

Others

SM
RH neutrinos
WC
nuisance models

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



Backends

Karlsruher Institut für Technologie

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

CosmoBit

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

DarkBit

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

ColliderBit

HiggsBounds 4.3.1
HiggsSignals 1.4
Pythia 8.212
nulike 1.0.9

FlavBit

SuperISO 3.6

PrecisionBit

FeynHiggs 2.12.0
SUSYHD 1.0.2
gm2calc 1.3.0

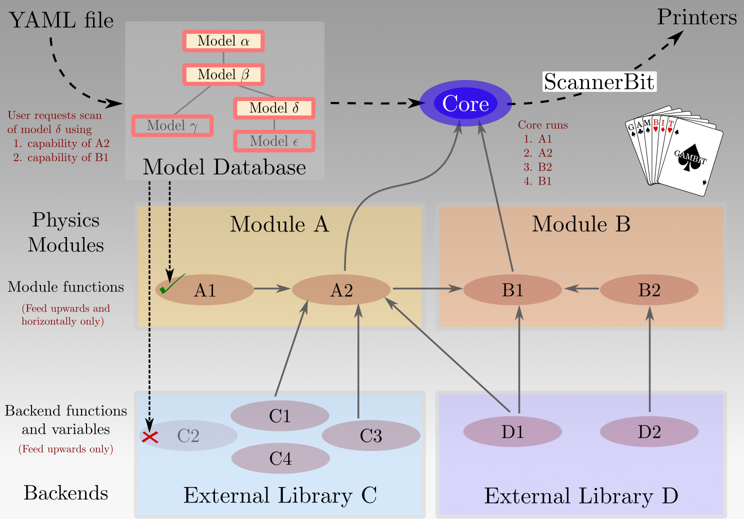
SpecBit

FlexibleSUSY 2.0.1
SPheno 4.0.3

DecayBit

SUSY_HIT 1.5

An example run



Operators

	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 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 ($\overline{\mathrm{MS}}$ 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) GeV^{-2}

Collider Likelihoods

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

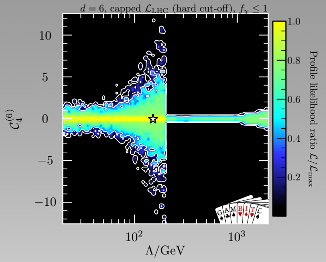
$$\mathcal{L}_{\text{marg}}(n|p) = \int_0^\infty \frac{[\xi p]^n \, e^{-\xi p}}{n!} \times \frac{1}{\sqrt{2\pi}\sigma_\xi} \frac{1}{\xi} \exp\left[-\frac{1}{2}\left(\frac{\ln \xi}{\sigma_\xi}\right)^2\right] \mathrm{d}\xi \, .$$

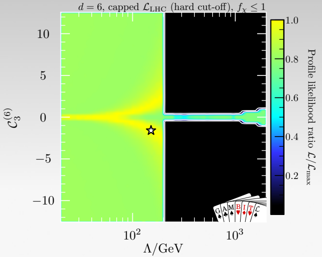
- CMS, convolved Poisson-Gaussian, profiled over systematic uncertainties γ on expected background yields with covariance matrix Σ

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

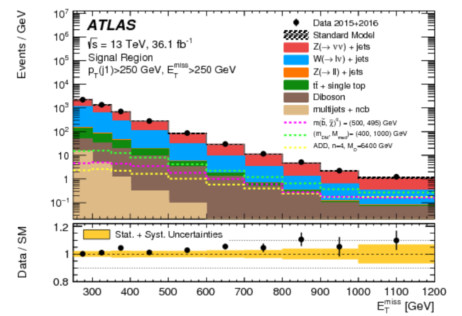
Results

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

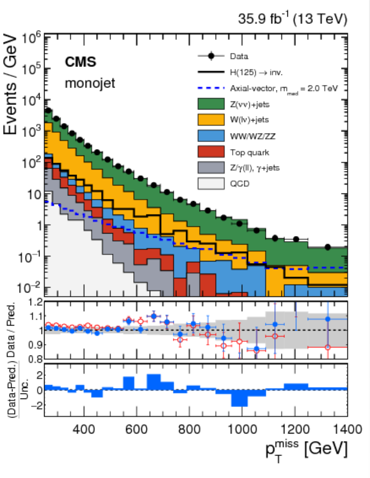




Results



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



35.9 fb⁻¹ (13 TeV)
CMS
monojet
Data
H(125) → inv.
Z(νν)+jets
W(lν)+jets
WW/WZ/ZZ
Top quark
Z/γ(ll), γ+jets
QCD
Events / GeV
Data / Pred.
(Data-Pred.) Unc.
p_T^miss [GeV]

But...

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

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

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

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

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

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

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

Adding a new module function is easy:

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

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

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

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

from P.Scott

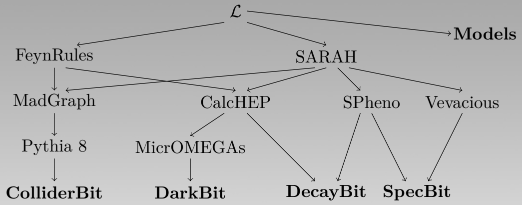
Solution

Karlsruher Institut für Technologie

The GAMBIT Universal Model Machine

GUM

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

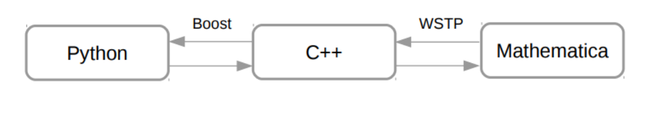


- GAMBIT-compatible outputs from GUM

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

GUM

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



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

An example

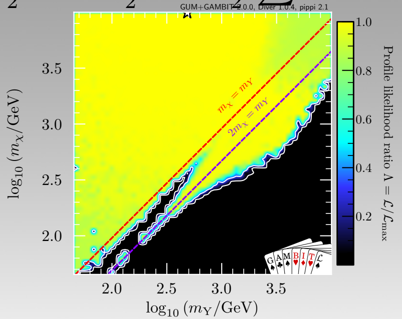
- Majorana DM χ with scalar mediator Y

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

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

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

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



$\rightsquigarrow$ Follow Sanjay's tutorial 3pm Room A