LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

Fundação
para a Ciência
e a Tecnologia

Universidade do Minho
Escola de Ciências

Using Machine Learning to find new dark matter phenomenology in a scotogenic model

PASCOS 2025 - July 2025
Based on 2505.08862 - FAS, Miguel Crispim Romão, Nuno Filipe Castro and Werner Porod

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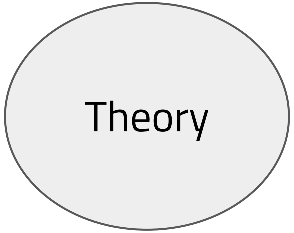
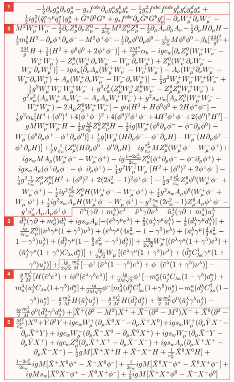
supported by

Beyond Standard Model Scans

BSM Parameter Spaces Scans

$$\mathcal{L}(\theta)$$

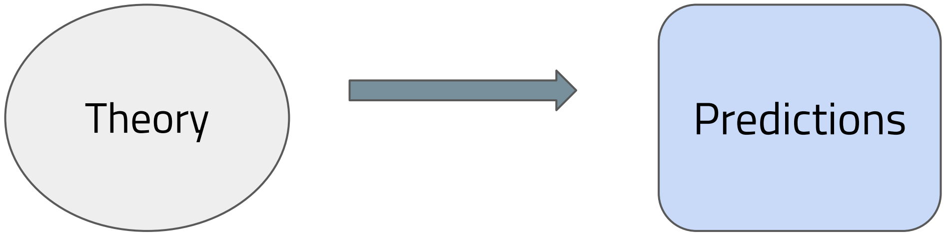


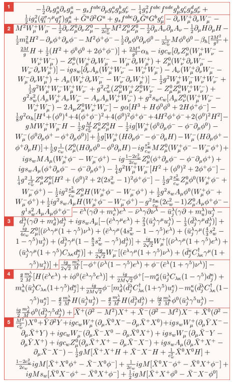


θ: Free parameters

BSM Parameter Spaces Scans

$\mathcal{L}(\theta)$ $\{\mathcal{O}_i(\theta)\}$

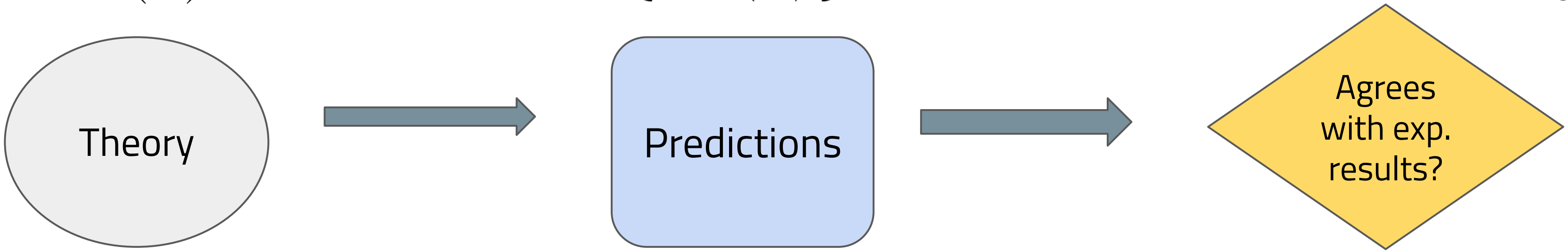


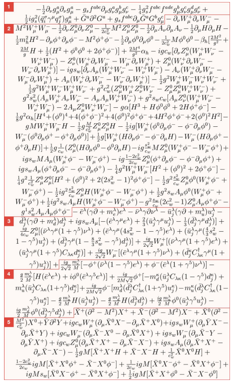


θ: Free parameters
O: Observable

BSM Parameter Spaces Scans

$\mathcal{L}(\theta)$ $\{\mathcal{O}_i(\theta)\}$ $\{\mathcal{O}^i_{\mathrm{LB}} \leq \mathcal{O}^i(\theta) \leq \mathcal{O}^i_{\mathrm{UB}}\}$





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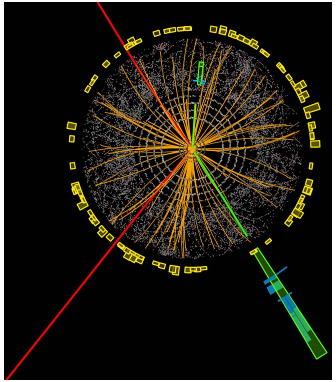


BSM Parameter Spaces Scans

$$\mathcal{L}(\theta)$$

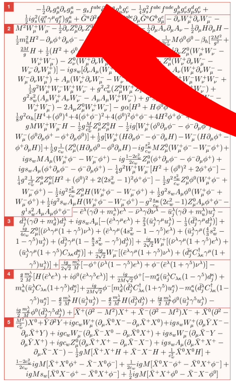
Theory

$$\{\mathcal{O}_i(\theta)\}$$

Predictions

$$\{\mathcal{O}^i_{\mathrm{LB}} \leq \mathcal{O}^i(\theta) \leq \mathcal{O}^i_{\mathrm{UB}}\}$$

Agrees with exp. results?



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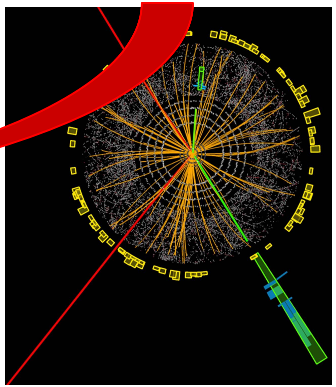
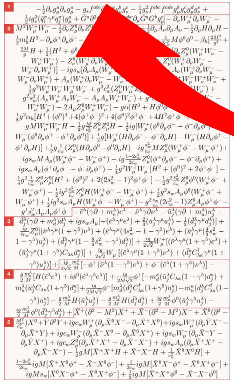


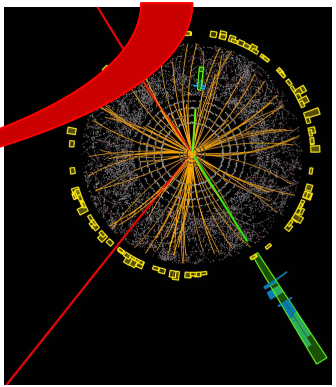
BSM Parameter Spaces Scans

$$\mathcal{L}(\theta) \qquad \{\mathcal{O}_i(\theta)\} \qquad \{\mathcal{O}^i_{\mathrm{LB}} \leq \mathcal{O}^i(\theta) \leq \mathcal{O}^i_{\mathrm{UB}}\}$$

Theory → Predictions → Agrees with exp. results?



θ: Free parameters
O: Observable



N(θ) ~ 10^2 **N(O) ~10^2**

BSM Parameter Spaces Scans

$$\mathcal{L}(\theta)$$

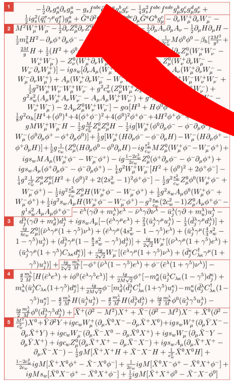
Theory

$$\{\mathcal{O}_i(\theta)\}$$

Predictions

$$\{\mathcal{O}^i_{\mathrm{LB}} \leq \mathcal{O}^i(\theta) \leq \mathcal{O}^i_{\mathrm{UB}}\}$$

Agrees with exp. results?



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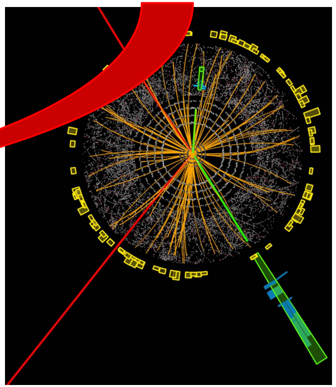


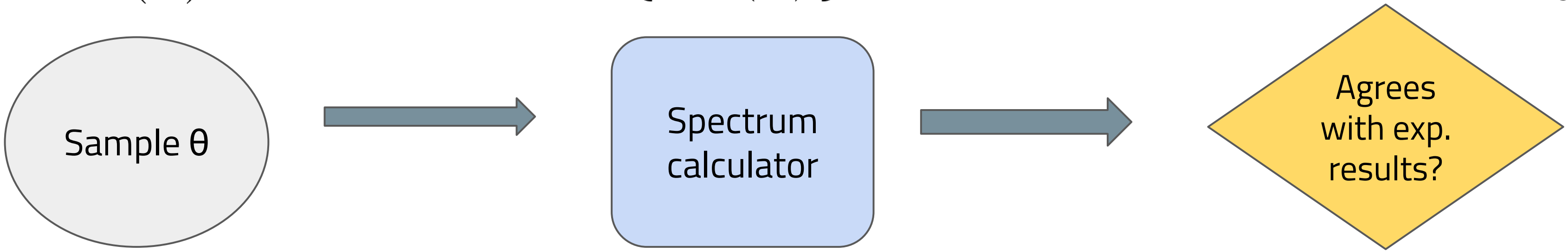
N(θ) ~ 10^2

N(O) ~10^2

Curse of dimensionality!

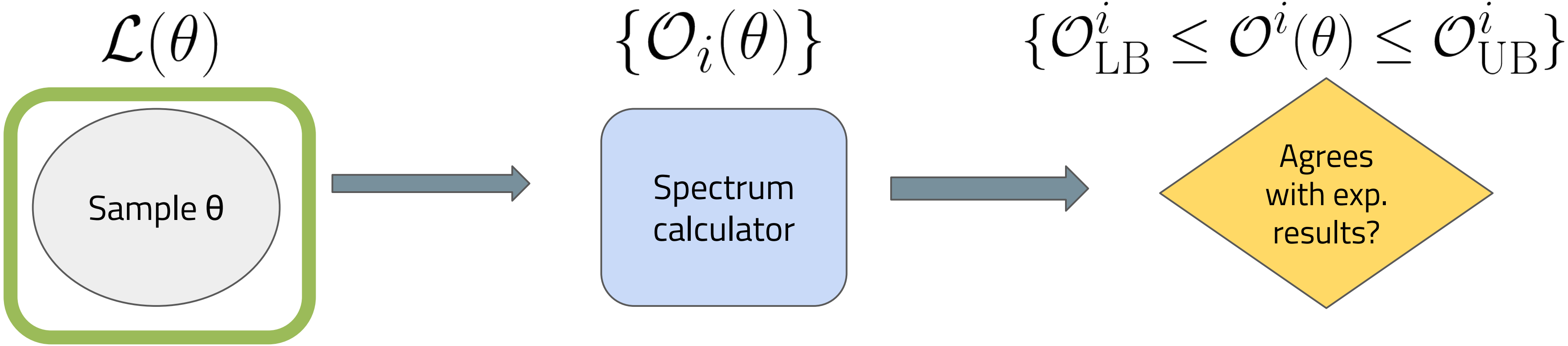
BSM Parameter Spaces Scans

$$\mathcal{L}(\theta) \qquad \{\mathcal{O}_i(\theta)\} \qquad \{\mathcal{O}^i_{\mathrm{LB}} \leq \mathcal{O}^i(\theta) \leq \mathcal{O}^i_{\mathrm{UB}}\}$$



θ: Free parameters
O: Observable

BSM Parameter Spaces Scans



θ: Free parameters
O: Observable

<u>Proposed solution</u>: Increase efficiency by modifying sampling

Methodology

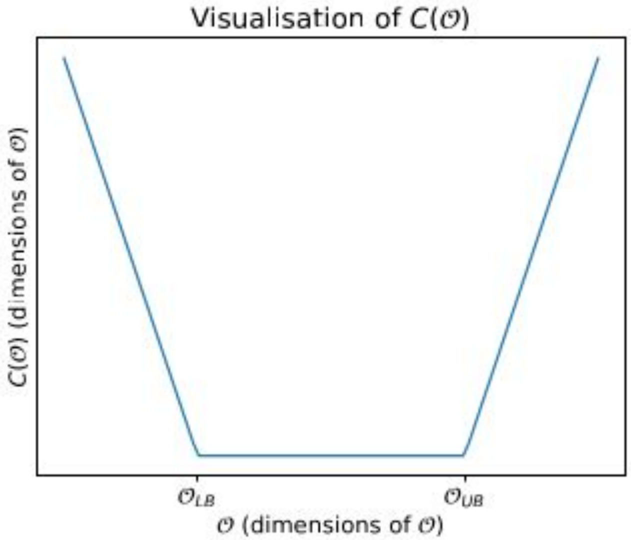
Parameter Spaces Scans
Black Box Optimisation

FAS, MCR, NFC, MN and WP
Phys. Rev. D 107, 035004
arXiV 2206.09223

- **How far** is the point from being valid
  - Cost function C(O)

- To find valid points is to minimise C(O)

→ **Optimisation** problem!



$$C(\mathcal{O}) = max(0, -\mathcal{O} + \mathcal{O}_{LB}, \mathcal{O} - \mathcal{O}_{UB})$$

Point is valid when **C(O) = 0**

Parameter Spaces Scans
Black Box Optimisation

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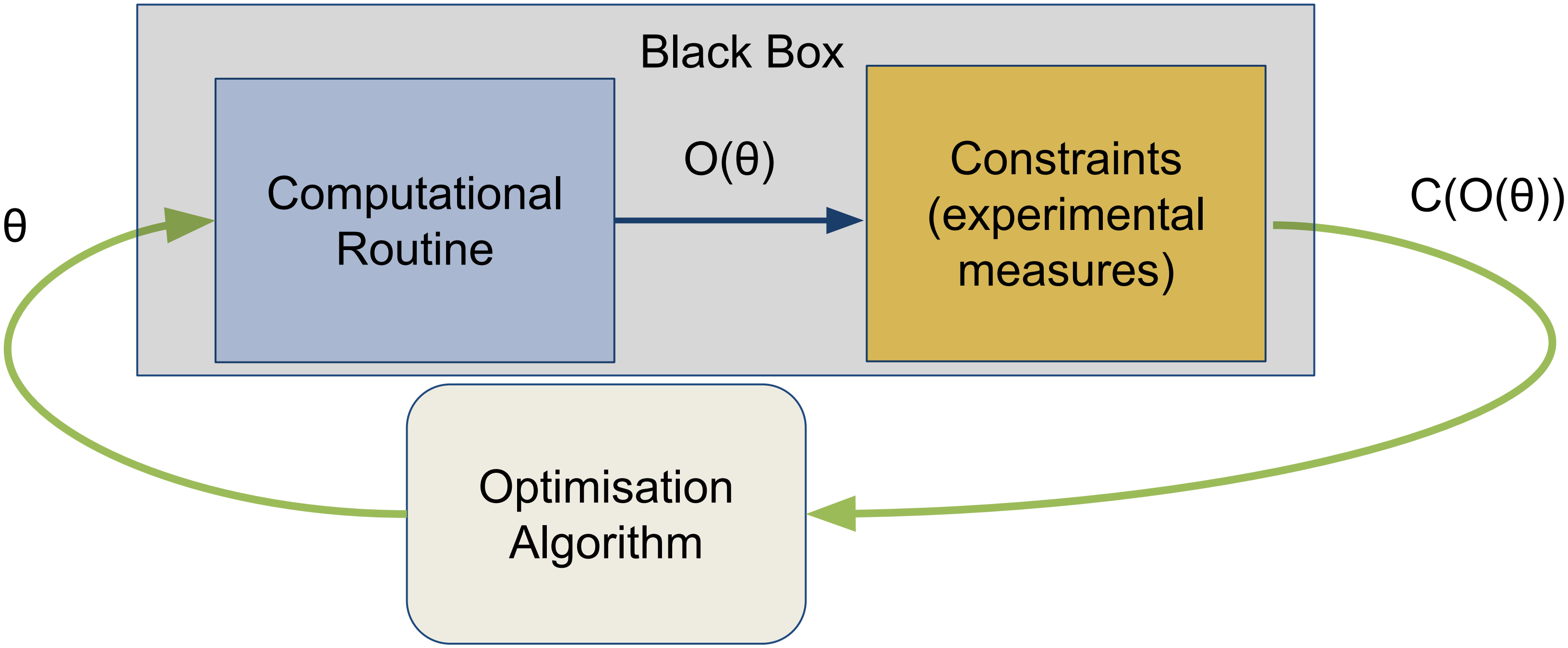


Black Box Optimization Scans

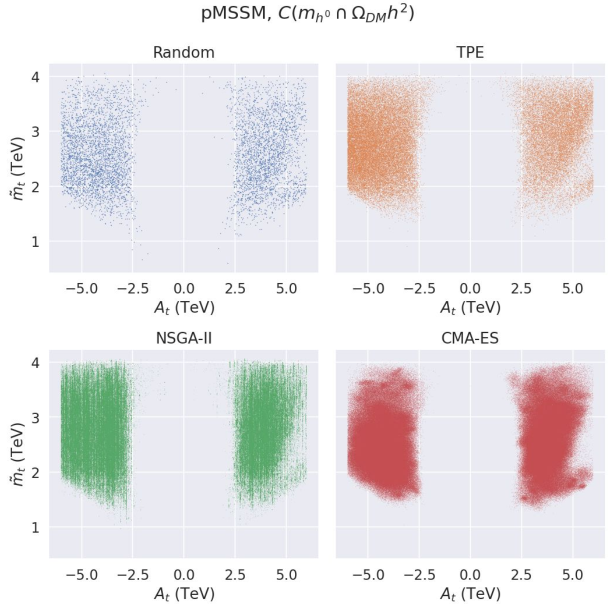
First case study

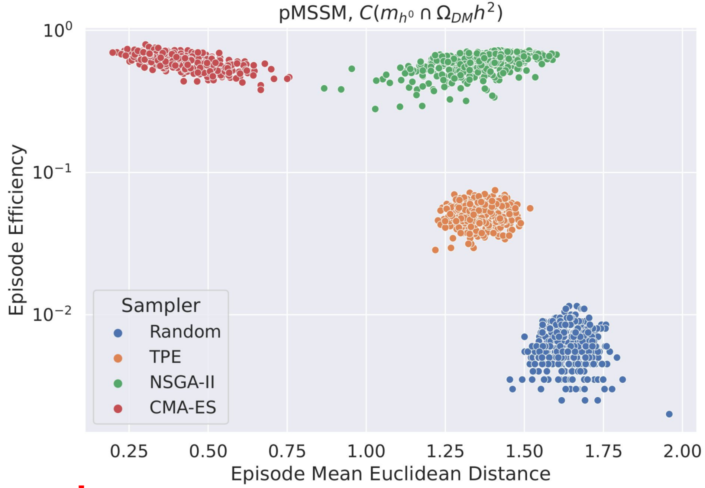
FAS, MCR, NFC, MN and WP
Phys. Rev. D 107, 035004
arXiV 2206.09223

- Physics cases: **Supersymmetry** constrained by **Higgs mass** and **Dark Matter Relic Density**
  - **cMSSM**: 4 free parameters
  - **pMSSM**: 19 free parameters

Optimisation Algorithms

Bayesian:	**TPE**	⇒	Best **coverage**
Evolutionary:	**CMA-ES**	⇒	Best **efficiency**
Genetic:	**NSGA-II**	⇒	In between

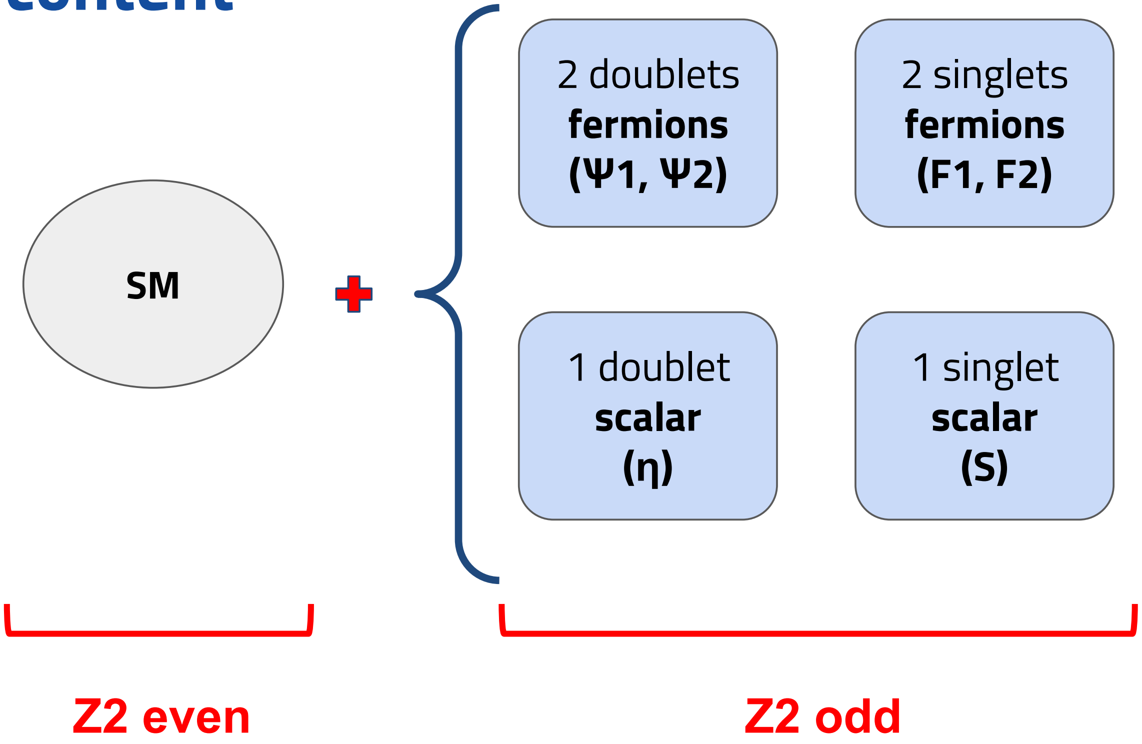




Gain of ~ 100x in efficiency!

Scotogenic Model

Scotogenic Model
Particle content



Scotogenic Model
Particle content

	Fermions				Scalars	
	Ψ_1	Ψ_2	F_1	F_2	η	S
$SU(2)_L$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	-1	1	0	0	1	0

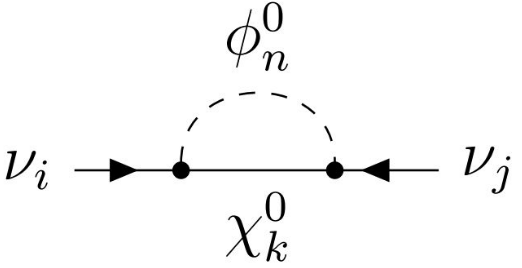
- **Neutrino masses at 1-loop level**
- **DM candidates**
- **LFV**
- **(g - 2)μ**

- 46 free **parameters**
- 31 (experimental / theoretical) **constraints**

Scotogenic Model
Fermion sector

$$\begin{aligned}\mathcal{L}_{\text{fermion}} \supset & -\frac{1}{2}M_{F_{ij}}F_iF_j - M_\Psi\Psi_1\Psi_2 \\ & - y_{1i}\Psi_1 H F_i - y_{2i}\Psi_2\tilde{H}F_i \\ & - \underbrace{\underbrace{g_\Psi^k\Psi_2 L_k S} - \underbrace{g_{F_j}^k \eta L_k F_j}}_{\text{Neutrino masses at 1-loop level}} - g_R^k e_k^c \tilde{\eta}\Psi_1 + \text{h.c.}\end{aligned}$$

Scotogenic Model
Neutrino masses



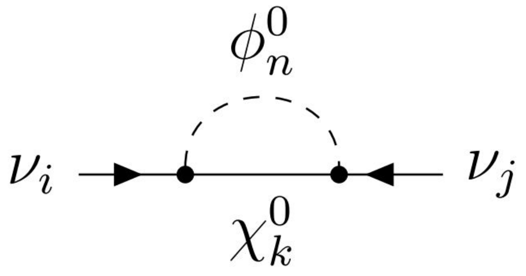
$$\equiv \quad \overline{\nu_j^c}\left(\mathcal{M}_\nu\right)_{ji}\nu_i$$

$$\boxed{\mathcal{G} \;=\; \begin{pmatrix} g_\Psi^1 & g_\Psi^2 & g_\Psi^3 \\ g_{F_1}^1 & g_{F_1}^2 & g_{F_1}^3 \\ g_{F_2}^1 & g_{F_2}^2 & g_{F_2}^3 \end{pmatrix}}$$

$$\boxed{\mathcal{M}_\nu \;=\; \mathcal{G}^T\, M_L\, \mathcal{G}}$$

Scotogenic Model
Neutrino masses

$$\mathcal{G} = \begin{pmatrix} g^1_\Psi & g^2_\Psi & g^3_\Psi \\ g^1_{F_1} & g^2_{F_1} & g^3_{F_1} \\ g^1_{F_2} & g^2_{F_2} & g^3_{F_2} \end{pmatrix}$$



$$\equiv \quad \overline{\nu^c_j}\,\left(\mathcal{M}_\nu\right)_{ji}\,\nu_i$$

$$\mathcal{M}_\nu = \mathcal{G}^T\, M_L\, \mathcal{G}$$

$$|U^{ij}_{\mathrm{PMNS}}| \sim 1 \quad \Longrightarrow \quad \begin{cases} |g^1_\Psi| \sim |g^2_\Psi| \sim |g^3_\Psi| \\ |g^1_{F_k}| \sim |g^2_{F_k}| \sim |g^3_{F_k}| \end{cases}$$

Scotogenic Model
Mass basis

- Scalar sector

$$\left(\phi_1^0, \phi_2^0, A^0\right)^T = U_\phi \left(S, \eta^0, A^0\right)^T$$

- Fermion sector

$$\left(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0\right)^T = U_\chi \left(F_1, F_2, \Psi_1^0, \Psi_2^0\right)^T$$

Scotogenic Model
Mass basis

- Scalar sector

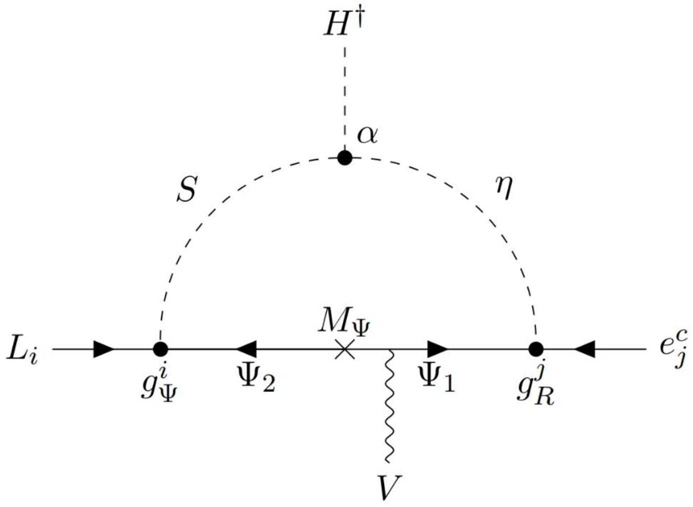
$$\left(\boxed{\phi_1^0}, \phi_2^0, \boxed{A^0}\right)^T = U_\phi \left(S, \eta^0, A^0\right)^T$$

DM candidates

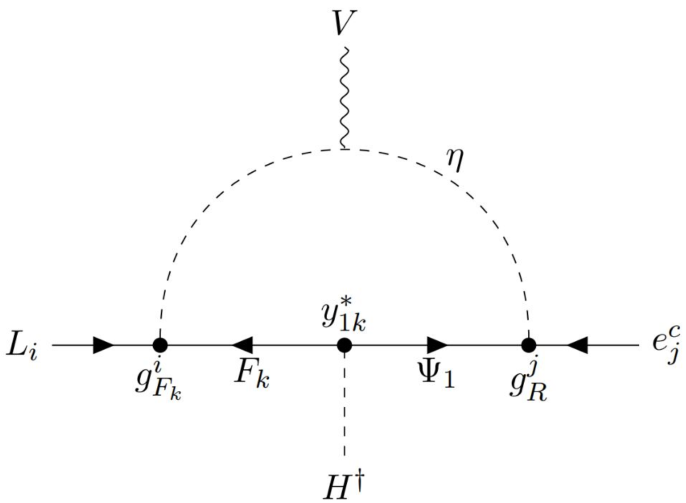
- Fermion sector

$$\left(\boxed{\chi_1^0}, \chi_2^0, \chi_3^0, \chi_4^0\right)^T = U_\chi \left(F_1, F_2, \Psi_1^0, \Psi_2^0\right)^T$$

Scotogenic Model
LFV and (g-2)μ



$\sim \alpha\, g_\Psi\, g_R$



$\sim y_1\, g_F\, g_R$

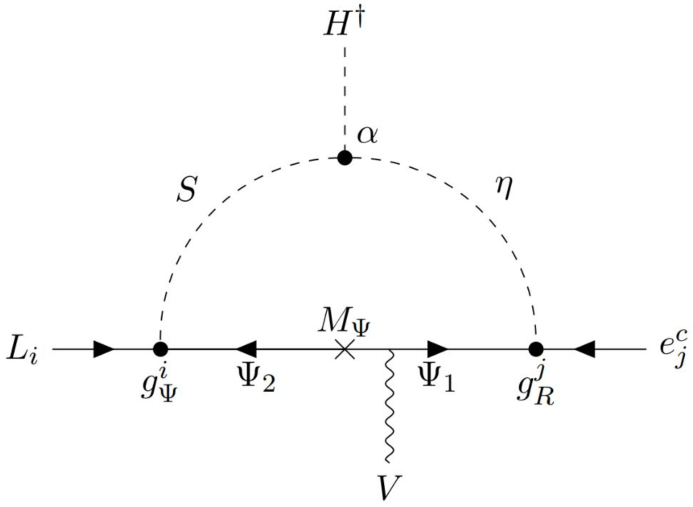
Scotogenic Model
LFV and (g-2)μ

$$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13} \quad \Rightarrow \quad |g_F^2|, |g_\Psi^2|, |g_R^2|$$

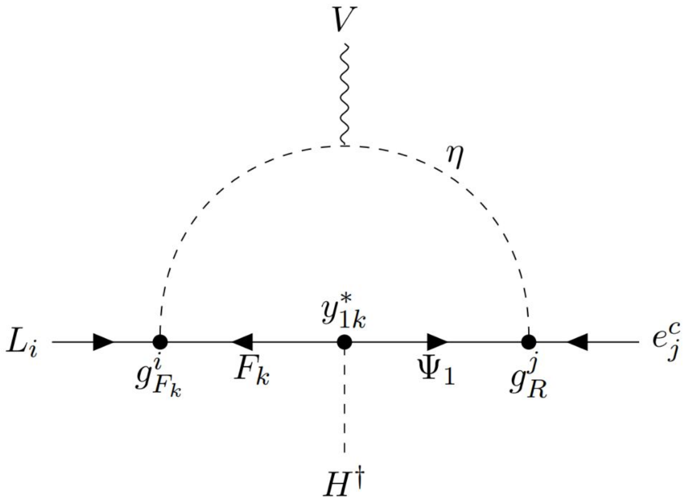
small

$$a_\mu^{\mathrm{BSM}} = (251 \pm 59) \times 10^{-11} \quad \Rightarrow \quad |g_F^2|, |g_\Psi^2|, |g_R^2|$$

large



$$\sim \alpha\, g_\Psi\, g_R$$



$$\sim y_1\, g_F\, g_R$$

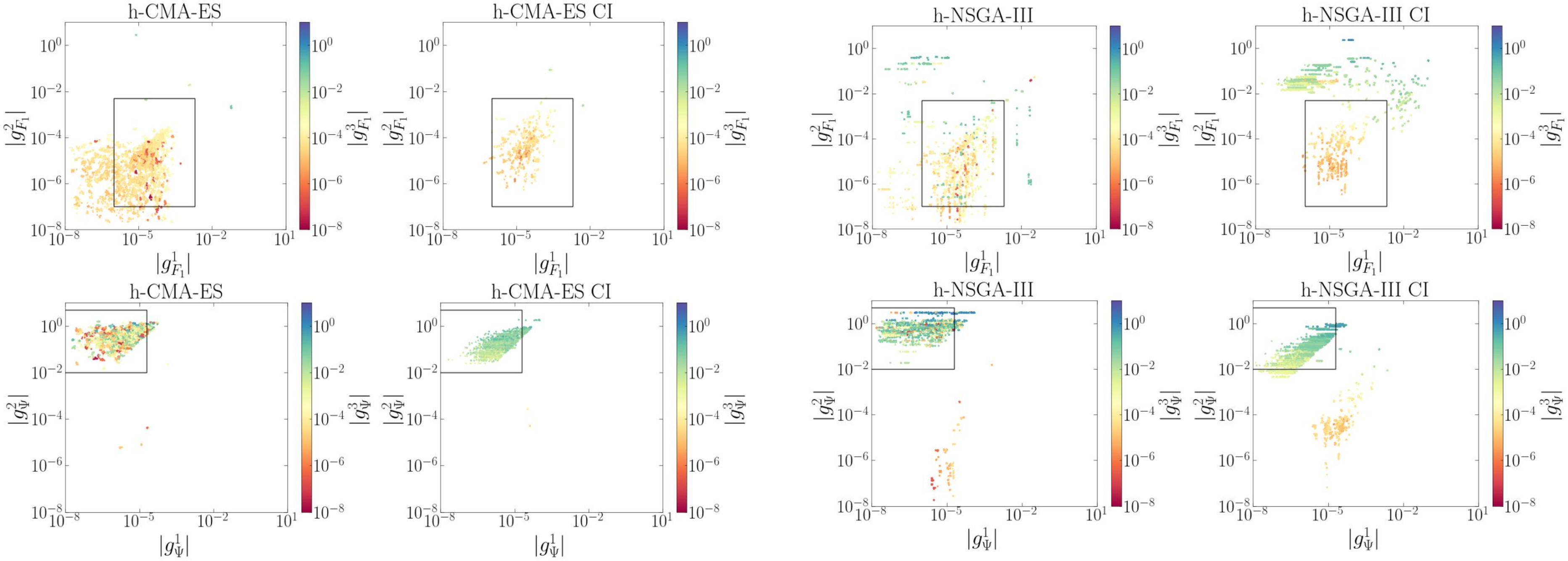
Results

FAS, MCR, NFC and WP
arXiV 2505.08862

Scotogenic Model
Results - parameters

Optimisation Algorithms

Single-objective: **CMA-ES** → **local** exploration
Multi-objective: **NSGA-III** → **global** exploration



boxes show range of points found with MCMC in 2301.08485

FAS, MCR, NFC and WP
arXiV 2505.08862

Scotogenic Model
Results - parameters

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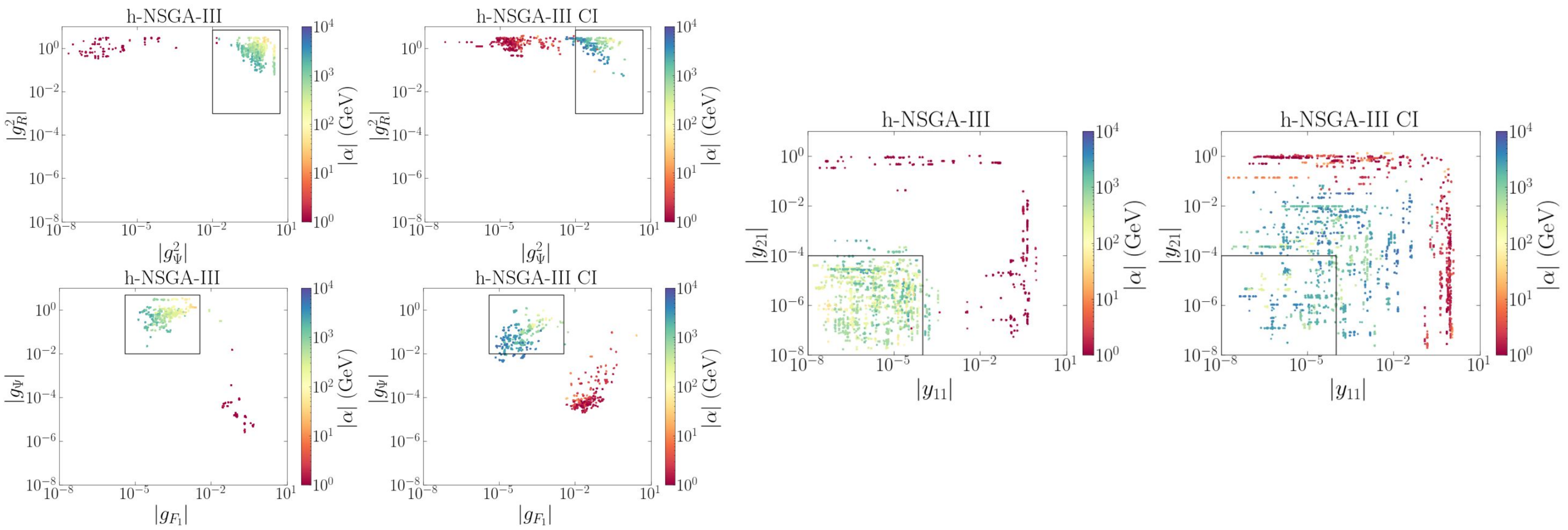


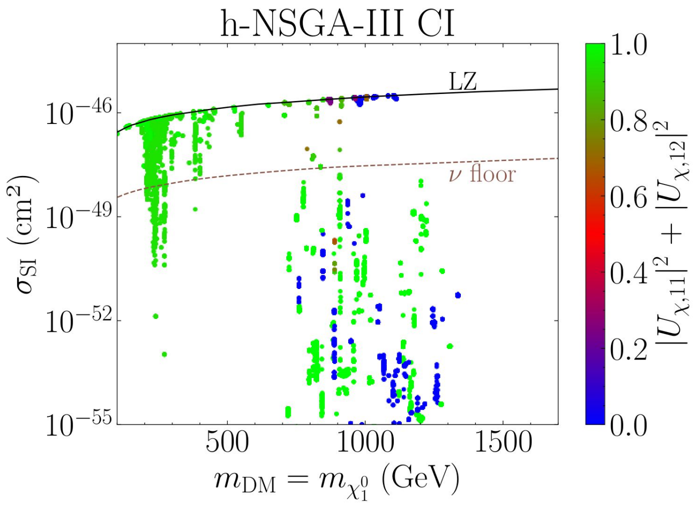
boxes show range of points found with MCMC in 2301.08485

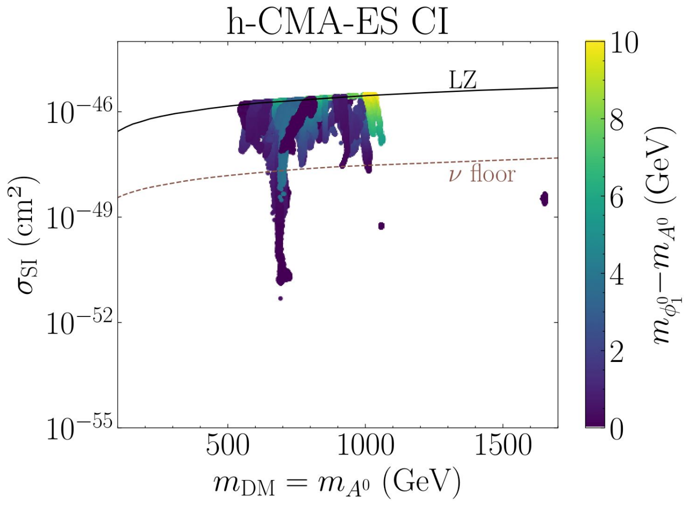
FAS, MCR, NFC and WP
arXiV 2505.08862

Parameter Spaces Scan
Results - Dark Matter

Optimisation Algorithms

Single-objective: **CMA-ES** ⇒ **local** exploration
Multi-objective: **NSGA-III** ⇒ **global** exploration





New phenomenology:

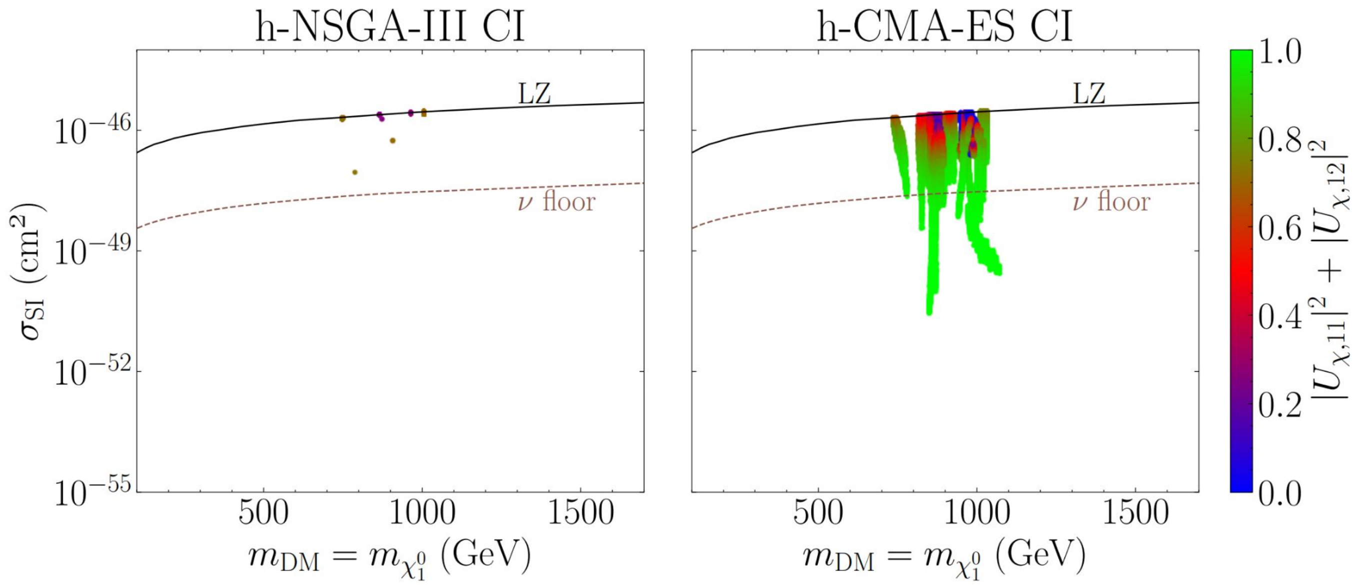
- **Fermionic dark matter above neutrino floor**
- **Axial dark matter**

FAS, MCR, NFC and WP
arXiV 2505.08862

JCR, MCR
arXiV 22402.07661
Phys. Rev. D 109, 095040

Parameter Spaces Scan
Novelty detection

- Exploration is enhanced with a **novelty detection** (ND) reward.
- ND can be applied to **parameter space** and/or **observable space**.
- ND in **observable space** can explore **new phenomenology**.



Conclusions

- The methodology allows for efficiently exploration of **parameter** and **phenomenological spaces** without the need of simplifying assumptions

- Algorithms show an **exploration-exploitation trade-off** which can be combined for a more powerful search strategy

- Use of **Multi-objective optimization** and the introduction of **hierarchy** in **single-objective optimization** show promising results

- Scotogenic new phenomenology:
  - **Fermionic DM above neutrino floor**
  - **Axial DM**

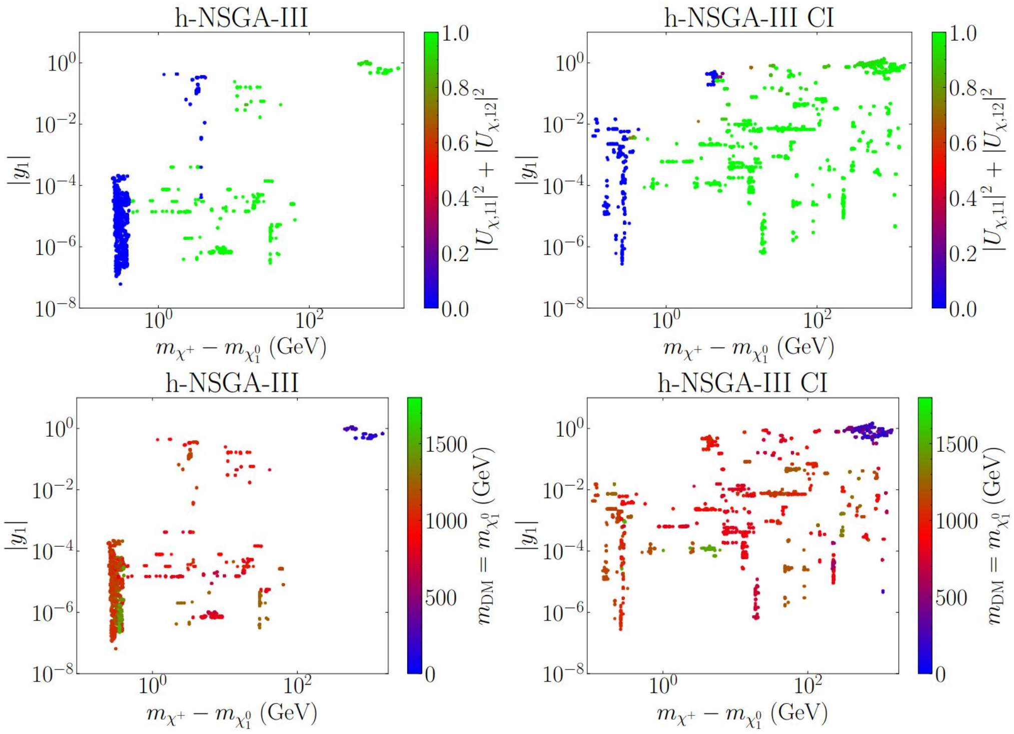
Backup

FAS, MCR, NFC and WP
arXiV 2505.08862

Parameter Spaces Scan
Results - Dark Matter

Optimisation Algorithms

Single-objective: **CMA-ES** → **local** exploration
Multi-objective: **NSGA-III** → **global** exploration



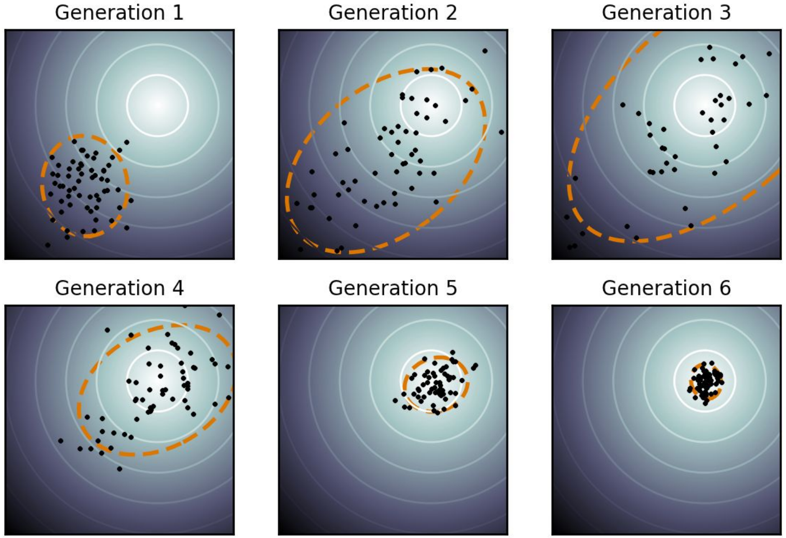
Parameter	Interval	Parametrisation	Mapping
λ_H	$[0.1,\ 0.3]$	Both	linear
$\lambda_{4S},\ \lambda_{4\eta}$	$[10^{-8},\ 1]$	Both	log
$\lambda_{S\eta},\ \lambda_S,\ \lambda_\eta,\ \lambda'_\eta,\ \lambda''_\eta$	$\pm[10^{-8},\ 1]$	Both	symlog
α (GeV)	$\pm[1,\ 10^4]$	Both	symlog
$M_S^2,\ M_\eta^2$ (GeV^2)	$5\times[10^5,\ 0^6]$	Both	linear
$M_1,\ M_2$ (GeV)	$[100,\ 2000]$	Both	linear
M_Ψ (GeV)	$[700,\ 2000]$	Both	linear
$\Re(y_{ij}),\ (i,j=1,2)$	$\pm[10^{-8},\ 3]$	Both	symlog
$\Im(y_{ij}),\ (i,j=1,2)$	$\pm[10^{-8},\ 3]$	Both	symlog
$\Re(g_R^k),\ (k=1,2,3)$	$\pm[10^{-8},\ 3]$	Both	symlog
$\Im(g_R^k),\ (k=1,2,3)$	$\pm[10^{-8},\ 3]$	Both	symlog
$\Re(g_\Psi^k),\ (k=1,2,3)$	$\pm[10^{-8},\ 3]$	Non CI	symlog
$\Im(g_\Psi^k),\ (k=1,2,3)$	$\pm[10^{-8},\ 3]$	Non CI	symlog
$\Re(g_{F_j}^k),,\ (k=1,2,3),\ (j=1,2)$	$\pm[10^{-8},\ 3]$	Non CI	symlog
$\Im(g_{F_j}^k),\ (k=1,2,3),\ (j=1,2)$	$\pm[10^{-8},\ 3]$	Non CI	symlog
m_{ν_1}	$[10^{-16},\ 10^{-10}]$	CI	log
m_{ν_2}	$[\sqrt{m_{\nu_1}^2+6.82\times10^{-23}},\ \sqrt{m_{\nu_1}^2+8.04\times10^{-23}}]$	CI	linear
m_{ν_3}	$[\sqrt{m_{\nu_1}^2+2.435\times10^{-21}},\ \sqrt{m_{\nu_1}^2+2.598\times10^{-21}}]$	CI	linear
$\theta_{12}^{\rm PMNS}$	$[31.27,\ 35.86]\frac{\pi}{180}$	CI	linear
$\theta_{13}^{\rm PMNS}$	$[8.20,\ 8.93]\frac{\pi}{180}$	CI	linear
$\theta_{23}^{\rm PMNS}$	$[40.1,\ 51.7]\frac{\pi}{180}$	CI	linear
$\delta_{\rm CP}$	$[120,\ 369]\frac{\pi}{180}$	CI	linear
$\Re(\theta_k^{\rm R}),\ (k=1,2,3)$	$[0,\ 2\pi]$	CI	linear
$\Im(\theta_k^{\rm R}),\ (k=1,2,3)$	$\pm[10^{-8},\ 3]$	CI	symlog

Observable	Allowed Values	Parametrisation
m_h	$[124.25, 126.25]$ GeV	Both
$a_\mu^{\rm BSM}$	$[74,\ 428]\times10^{-11}$	Both
$\Omega_{\rm DM}h^2$	$[0.11,\ 0.13]$	Both
BR($\mu^-\to e^-\gamma$)	$<4.2\times10^{-13}$	Both
BR($\tau^-\to e^-\gamma$)	$<3.3\times10^{-8}$	Both
BR($\tau^-\to \mu^-\gamma$)	$<4.2\times10^{-8}$	Both
BR($\mu^-\to e^-e^+e^-$)	$<1.0\times10^{-12}$	Both
BR($\tau^-\to e^-e^+e^-$)	$<2.7\times10^{-8}$	Both
BR($\tau^-\to \mu^-\mu^+\mu^-$)	$<2.1\times10^{-8}$	Both
BR($\tau^-\to e^-\mu^+\mu^-$)	$<2.7\times10^{-8}$	Both
BR($\tau^-\to \mu^-e^+e^-$)	$<1.8\times10^{-8}$	Both
BR($\tau^-\to \mu^-e^+\mu^-$)	$<1.7\times10^{-8}$	Both
BR($\tau^-\to \mu^+e^-e^-$)	$<1.5\times10^{-8}$	Both
BR($\tau^-\to e^-\pi$)	$<8.0\times10^{-8}$	Both
BR($\tau^-\to e^-\eta$)	$<9.2\times10^{-8}$	Both
BR($\tau^-\to e^-\eta'$)	$<1.6\times10^{-7}$	Both
BR($\tau^-\to \mu^-\pi$)	$<1.1\times10^{-7}$	Both
BR($\tau^-\to \mu^-\eta$)	$<6.5\times10^{-8}$	Both
BR($\tau^-\to \mu^-\eta'$)	$<1.3\times10^{-7}$	Both
${\rm CR}_{\mu\to e}$(Ti)	$<4.3\times10^{-12}$	Both
${\rm CR}_{\mu\to e}$(Pb)	$<4.3\times10^{-11}$	Both
${\rm CR}_{\mu\to e}$(Au)	$<7.0\times10^{-13}$	Both
BR($Z^0\to e^\pm\mu^\mp$)	$<7.5\times10^{-7}$	Both
BR($Z^0\to e^\pm\tau^\mp$)	$<5.0\times10^{-6}$	Both
BR($Z^0\to \mu^\pm\tau^\mp$)	$<6.5\times10^{-6}$	Both
$\sigma_{\rm SI}^{\rm DM}$	LZ bounds	Both
Δm_{21}^2	$[6.82,\ 8.04]\times10^{-5}{\rm eV}^2$	Non CI
Δm_{31}^2	$[2.435,\ 2.598]\times10^{-3}{\rm eV}^2$	Non CI
$\sin^2(\theta_{12})$	$[0.269,\ 0.343]$	Non CI
$\sin^2(\theta_{13})$	$[0.02032,\ 0.02410]$	Non CI
$\sin^2(\theta_{23})$	$[0.415,\ 0.616]$	Non CI
$\delta_{\rm CP}$	$[120,\ 369]\times\frac{2\pi}{360}$	Non CI
$\lvert g_{F_j}^k\rvert,\ (k=1,2,3),\ (j=1,2)$	$[0,\ 4\pi]$	CI
$\lvert g_\Psi^k\rvert,\ (k=1,2,3)$	$[0,\ 4\pi]$	CI

Algorithms

Covariance matrix adaptation evolution strategy (CMA-ES)

[https://en.wikipedia.org/wiki/CMA-ES]

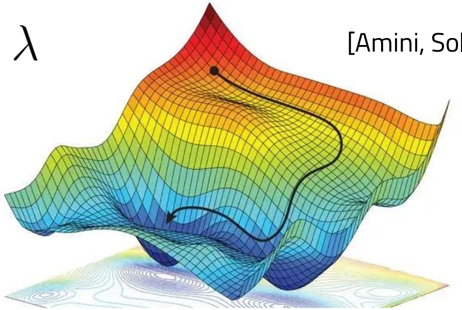


- Non genetic evolutionary algorithm
- Normal multivariate distribution
  - Mean: evolution direction
  - Covariance matrix: adapted iteratively

$$\theta_i^{(g+1)} \sim m^{(g)} + \sigma^{(g)} \mathcal{N}(0, \mathcal{C}^{(g)}) \quad \text{for} \quad i = 1, \cdots, \lambda$$

- Similar to a *gradient descent*

$$\mathbf{x}_{n+1} = \mathbf{x}_n - \gamma \nabla F(\mathbf{x}_n)$$

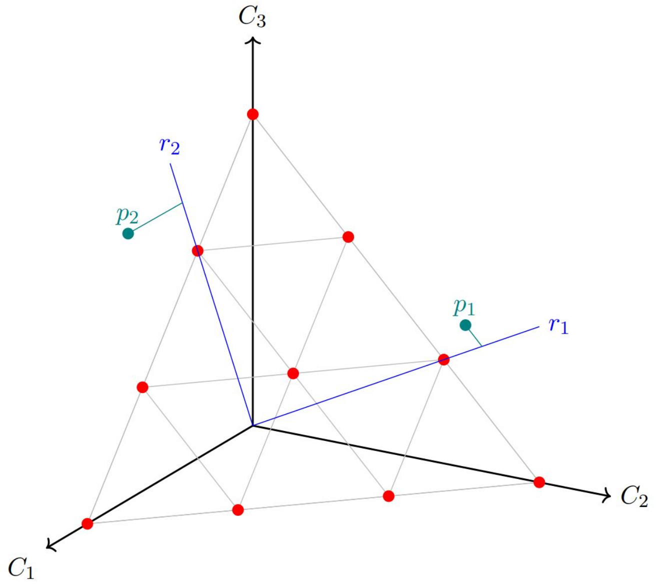


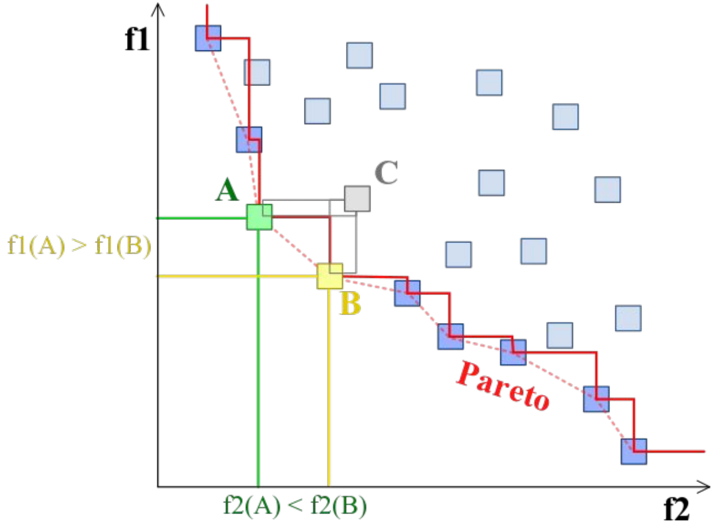
[Amini, Soleimany, Karaman, Rus, 2019]

Algorithms

Non-dominated Sorting Genetic Algorithm - III (NSGA-III)

- Multi-objective genetic algorithm
- Uses reference lines to increase diversity of solutions





[https://en.wikipedia.org/wiki/Pareto_front]

Algorithms

Non-dominated Sorting Genetic Algorithm - III (NSGA-III)

Hyperparameter	Value	Description	Algorithm
$\sigma^{(0)}$	1.0	Initial step size	CMA-ES
N	1000	Maximum number of generations	CMA-ES
N	2000	Maximum number of generations	NSGA-III
μ	400	Population size	NSGA-III
P_{cx}	0.9	Crossover probability	NSGA-III
η_{cx}	30	Crossover crowding factor	NSGA-III
P_{mut}	0.5	Mutation probability	NSGA-III
η_{mut}	40	Mutation crowding factor	NSGA-III
P_{ind}	$\frac{4}{N_{\text{dim}}}$	Independent mutation probability	NSGA-III