Optimising GEANT4 event biasing for underground rare-event searches

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Introduction

Rare-event searches, e.g. dark matter direct detection, are becoming **increasingly sensitive**:

- **Ultra-low backgrounds** (~0.01 cpd/kg/keV)
- **Low energy thresholds** and ROIs at **< keV-scale**

Simulation statistics constrained by **highly suppressive shielding**

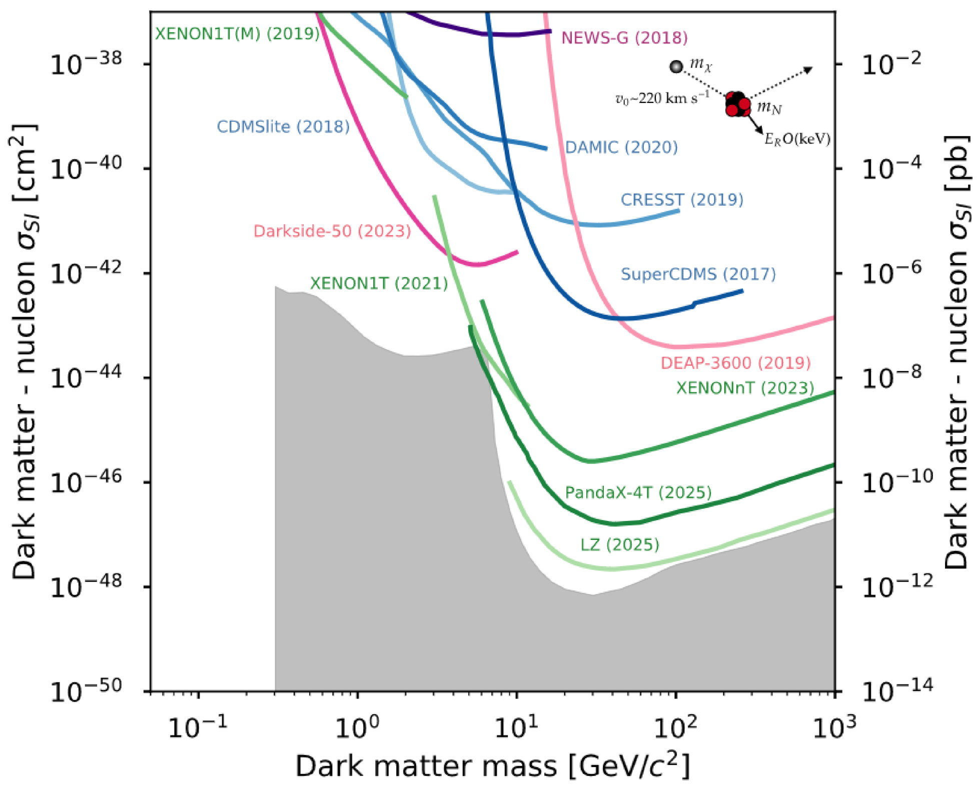
GEANT4 includes built-in biasing techniques:

- Statistically **weight biased particles** to maintain physics, reduce variance

Some implementation in rare-event searches, but unoptimized

Goal: Develop **rare-event search tailored guidance/approach to optimisation**

- Balance **computational effort with variance**

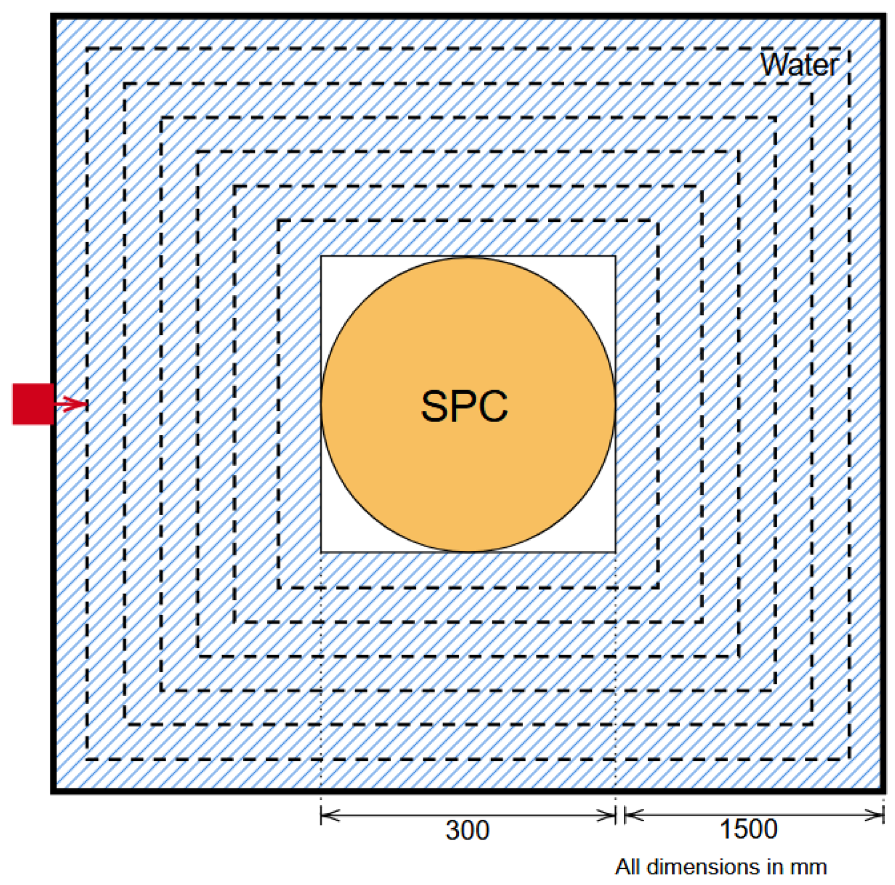


Importance Splitting & Russian Roulette Biasing and Geometry

Common biasing technique: **Importance Splitting & Russian Roulette**

- 'Splits' simulated particles **at non-physical boundaries between importance 'layers'**
- Particles assigned **reduced statistical weight**
- Number of particles split, weights, determined by **importance values assigned to layers**
- Backwards going particles killed probabilistically

$$N_{\mathrm{split}} = \frac{I_{\mathrm{post}}}{I_{\mathrm{pre}}} \quad w = \frac{1}{I_{\mathrm{post}}} \quad p_{\mathrm{kill}} = 1 - \frac{I_{\mathrm{post}}}{I_{\mathrm{pre}}}$$



$$t_{\mathrm{shield}} = M \times t_{\mathrm{layer}} \qquad I = 2^m$$

Methodology and Metrics

Range of simulations with:

- Range of layer counts
- Collected jobs of increasing number of primary events
- **DarkSPHERE-inspired shielding [1], 1.5 m thick** with spherical proportional counter (SPC)

Sum weights to get probability of interaction with SPC for each job in collection

- Mean (μ_P) and standard deviation (σ_P) extracted to find relative uncertainty (R):

$$\mathcal{R} = \frac{\sigma_P}{\mu_P}$$

***R* compared against average execution time (μ_t) of sims**

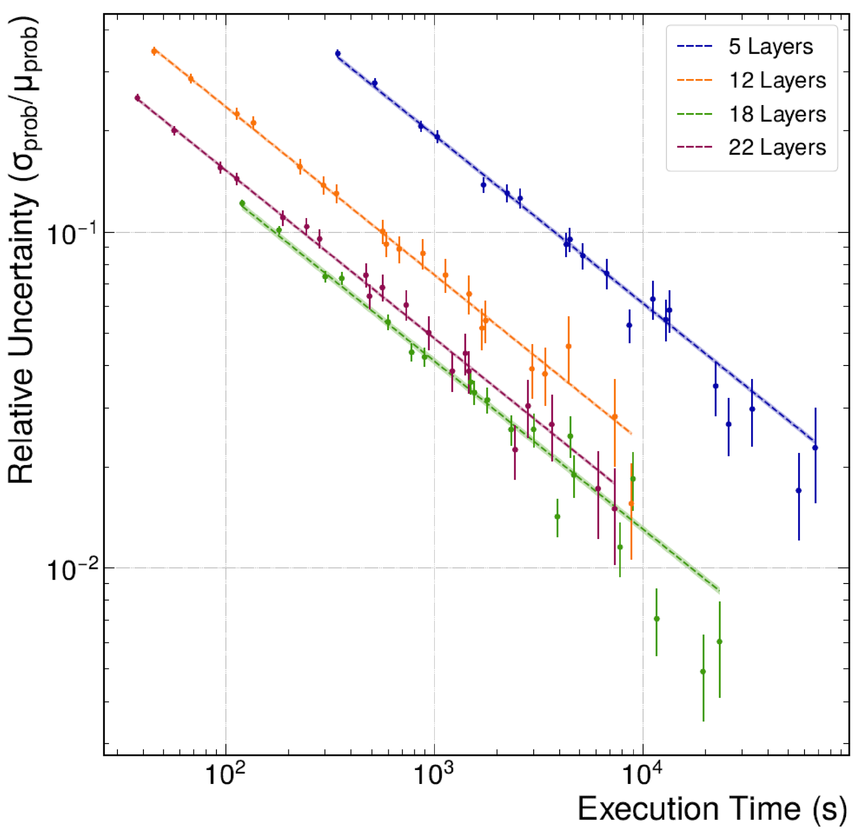
Results: Photons and Neutrons

Study performed for two particle types

- Gammas at 2750 keV and 1461 keV
- Neutrons at 10 MeV and 5 MeV

Relative uncertainty vs. execution time plotted for different numbers of layers

- **Fit with power law: $A \times t^{-1/2}$**



Time slices are chosen, with ***R* plotted against number of layers for each time slice**

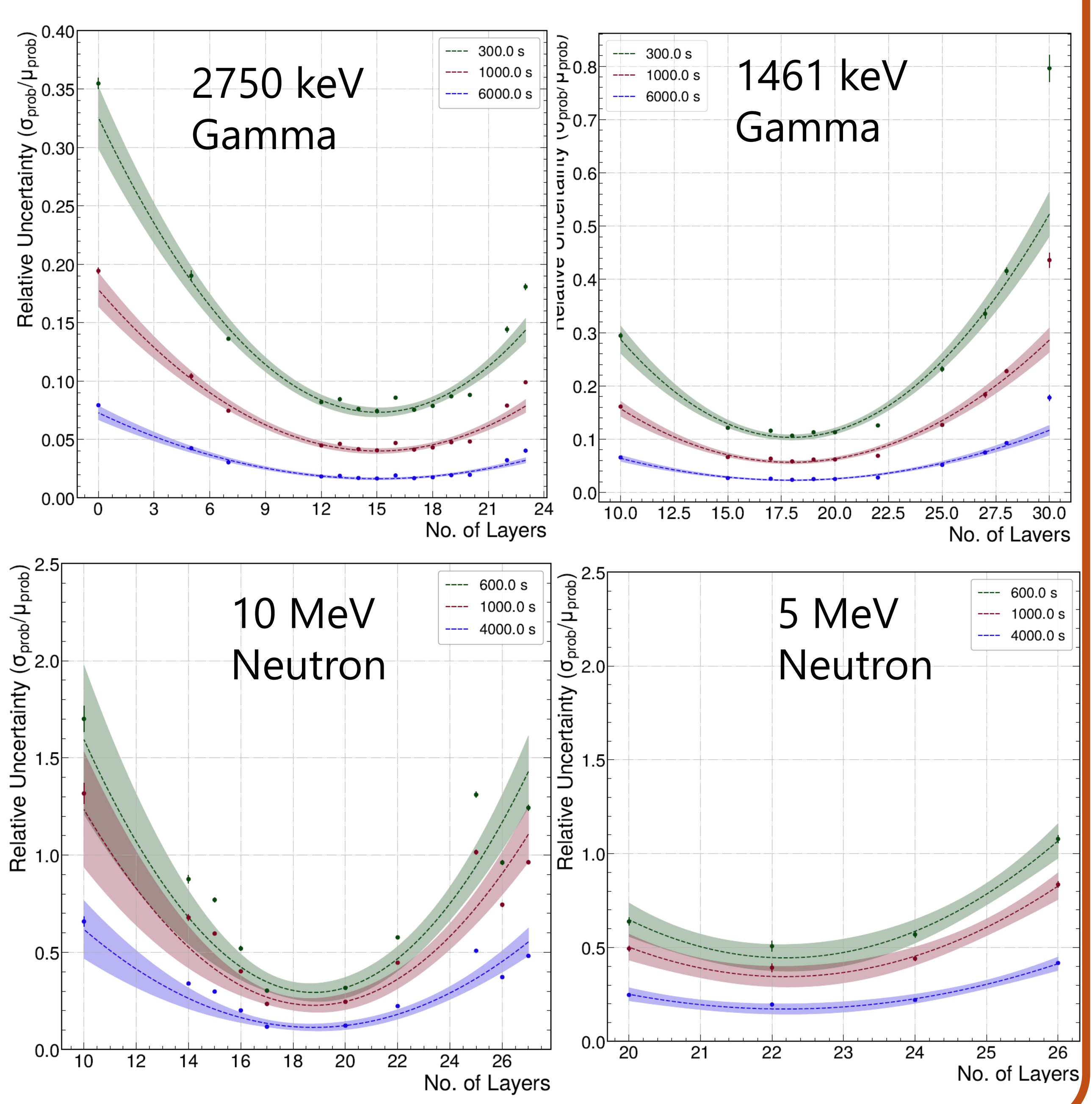
- **Parabolic shape. Minima:** most optimal layer number

Physical predictability through **layer thickness in terms of mean free path ($t_{Layer} = c \times \lambda_{H2O}^{\gamma\backslash n}$)**

Multiple (c) of $\lambda_{H2O}^{\gamma\backslash n}$ in optimal layer thickness is:

- **Particle dependent**
- **Energy independent**
- **Generalisable to shielding thickness and material**

Primary Particle	Energy [keV]	Layers $[\lambda_{\mathrm{H_2O}}^{\gamma/n}]$	Optimal t_{layer} $[\lambda_{\mathrm{H_2O}}^{\gamma/n}]$	t_{layer} Range $[\lambda_{\mathrm{H_2O}}^{\gamma/n}]$
γ-ray	2750	15 (15.10)	(0.42 ± 0.03)	$[0.30, 0.69]$
	1461	18 (18.07)	(0.49 ± 0.02)	$[0.38, 0.63]$
Neutron	10000	19 (18.75)	(0.84 ± 0.05)	$[0.73, 0.99]$
	5000	22 (22.18)	(0.96 ± 0.04)	$[0.88, 1.04]$



Improved Efficiency and Computing Emissions

Gains in computational efficiency to reach required R

- **Fix R**, and **compare execution time for different amounts of layers**

Apply to 2750 keV gammas, considering:

- **Optimal** (15 layers), **Under-biased** (5 layers), **Over-biased** (23 layers), **Unbiased**

The optimal scenario is found to have large gains over the other scenarios

Translates to a **reduction in computing-related emissions**

- These emissions can contribute ~10% of the average particle physicists carbon footprint [2]

Biasing Level	Execution Time [s]	Footprint [gCO_2e]	Factor Increase on Optimal
Optimal (15L)	300.00	0.135	-
Under-biased (5L)	1966.53	0.890	6.6
Over-biased (23L)	1776.26	0.804	5.0
Unbiased	6844.21	3.099	23.0

Summary

- Rare-event searches **are pushing both low threshold and ultra-low background frontiers**
- With this comes **highly suppressive shielding**
- **Precise simulations require prohibitively large amounts of computing resources**
- Presented an optimisation study of the importance splitting/Russian roulette technique, to offer guidance for its implementation
- **Main outcome: A generalisable, optimal layer thickness is obtained in terms a particle's mean free path in shielding**
  - It is **particle dependent, energy independent, and generalisable to shielding thickness and material**
  - It **yields significant improvement** in **computational efficiency, variance reduction**, reduced **computing related emissions**

arxiv.org/abs/2609.03822
arxiv.org/abs/2609.07523

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[1] NEWS-G Collaboration, Exploring light dark matter with the DarkSPHERE spherical proportional counter electroformed underground at the Boulby Underground Laboratory, doi:10.1103/PhysRevD.108.112006.
[2] V. S. Lang, et al., Know your footprint – Eval-uation of the professional carbon footprint for individual researchers in high energy physics and related fields, doi:10.1038/s44168-025-00232-7.