Monte Carlo biasing techniques in Liquid Argon Dark Matter experiments

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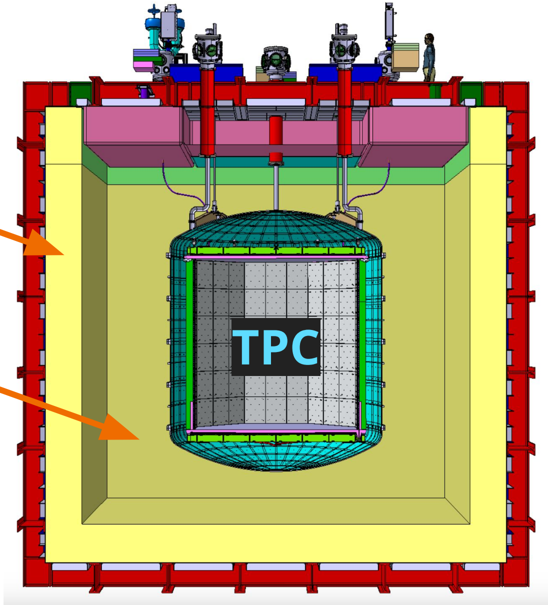
DarkSide-20k and neutrons

Directly detect **WIMPs** scattering
on liquid **Argon** nuclei

- TPC filled with 51 t of underground liquid Argon (20 t fiducial volume)
- Acrylic panels (**PMMA**) for **neutron tagging**
- **Membrane cryostat** filled with atmospheric liquid Argon

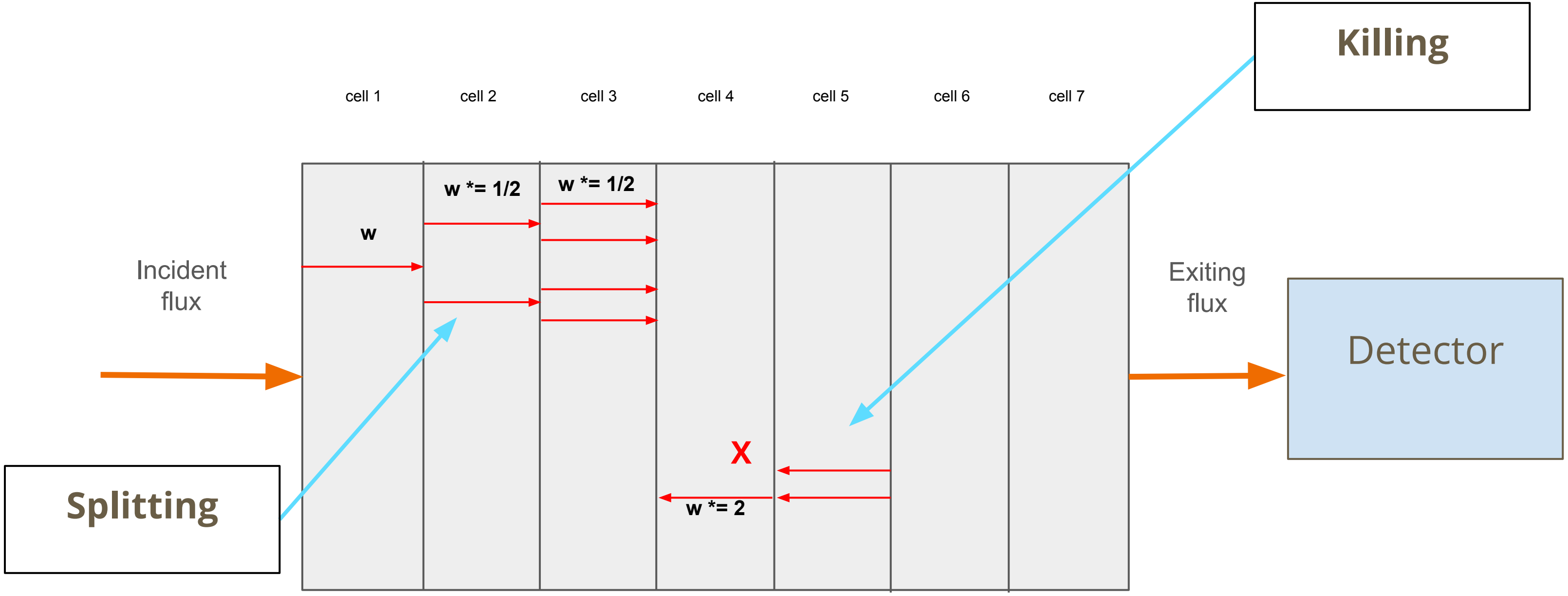


Neutrons can mimic a WIMP interaction in liquid Argon
⇒ Simulations of neutrons from Hall C ($\Phi = 10^{-6}$ n cm^{-2} s^{-1})

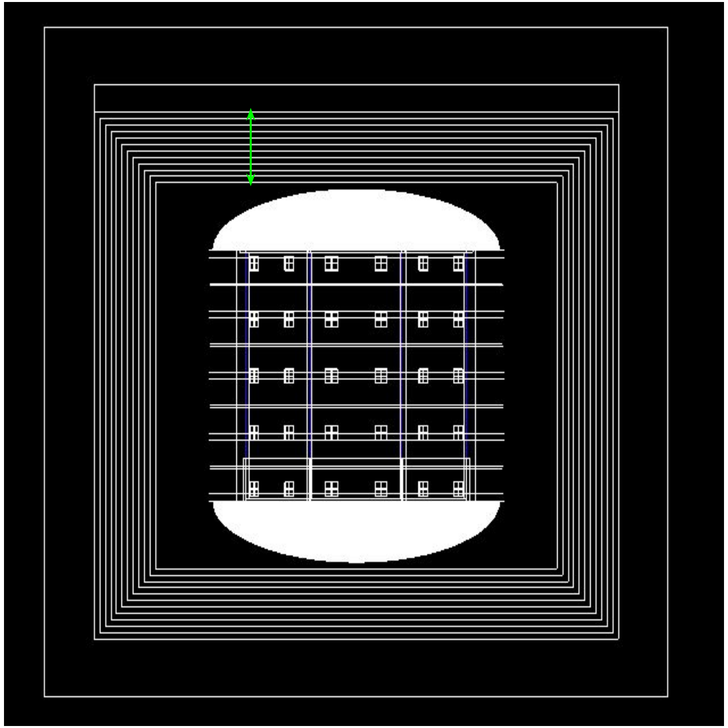
Standard Monte Carlo simulations are **inefficient when simulating shieldings** (cryostat foam and atmospheric liquid Argon): 10^{13} simulated neutrons from Hall C → 420 counts in the TPC in the ROI (5% stat. error)

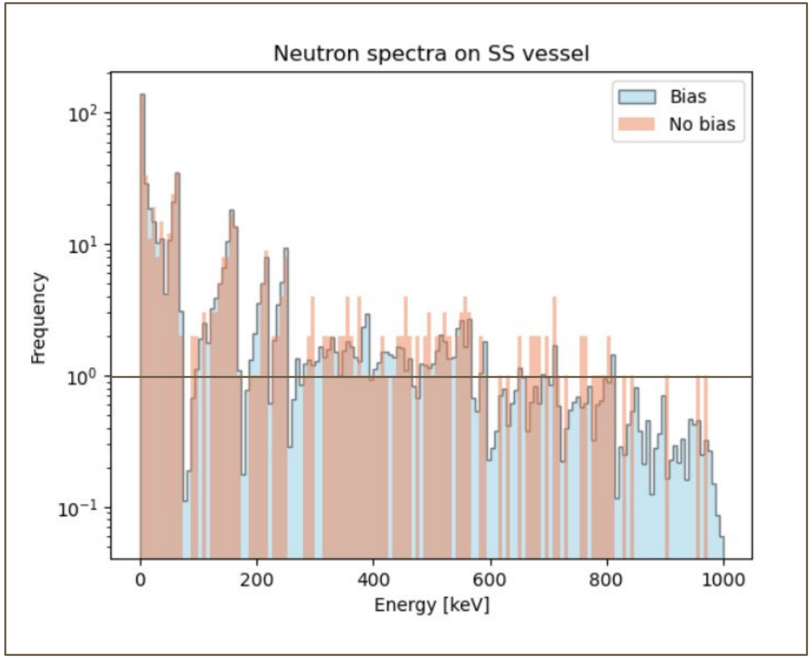
⇒ **Biased Monte Carlo simulation: save computing time** by sampling *less often* particles entering *less important regions*, and *more often* when entering *more important regions*

How biasing works



Biasing implemented in DarkSide-20k





Biased vs standard simulations

Standard simulations with highest statistics:

Primary neutrons	Counts in ROI in TPC	Relative error
10^{13}	420	**5%**

Using biasing techniques, **8%** error is achieved simulating **2×10^{10}** primary neutrons

→ **a factor 500 less particles simulated, almost same statistical error**

$$G = \frac{N_{biased}}{N_{std}}$$

$$N = N_{hits} \times w$$

$$\varepsilon_N = \sqrt{\sum_{i=1}^{N'} w_i^2} = \frac{\sqrt{N}}{\sqrt{G}}$$

Error on N reduced by a factor **15** if **G = 200**

More information: https://hdl.handle.net/11567/1165135

Glen Cowan. Error analysis with weighted events
Glen Cowan. Statistical tests with weighted Monte Carlo events

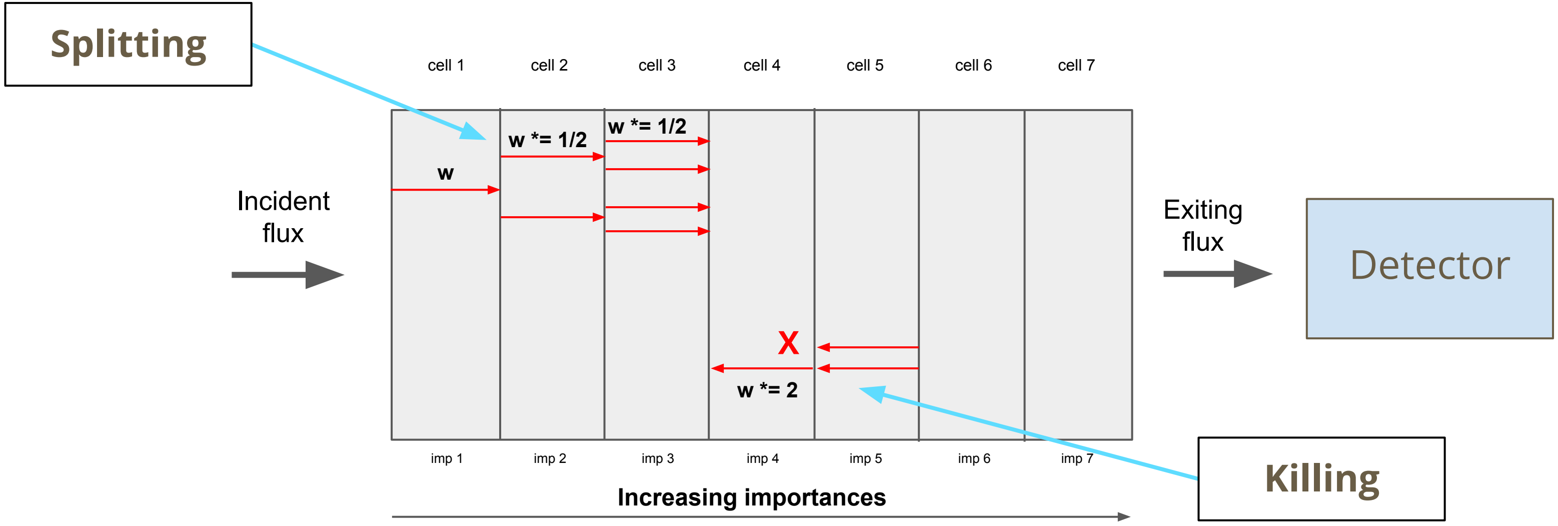
Backup

How importance sampling works: an example

Maintain a **uniform particle population**, **compensating for attenuation** due to absorption or distance

1. Divide the region of interest in **cells**
2. Define the **importance** of each cell (*relative importance*)

E.g. relative importance = 2 $\dfrac{\text{imp }2}{\text{imp }1} = 2\,,\ \dfrac{\text{imp }3}{\text{imp }2} = 2\,, \ldots$



How importance sampling works: details

In general, when crossing from a cell m with importance imp(m) to a cell n with importance imp(n):

$$r = \frac{\mathrm{imp(n)}}{\mathrm{imp(m)}} \quad \begin{cases} r > 1 & \text{splitting} & w_n = w_m \times \frac{1}{r}\ ,\ N_n = N_m \times r \\ r < 1 & \text{killing} & P(\mathrm{kill}) = 1 - r,\ w_n = w_m \times \frac{1}{r} \\ r = 1 & \text{continue tracking} & \end{cases}$$

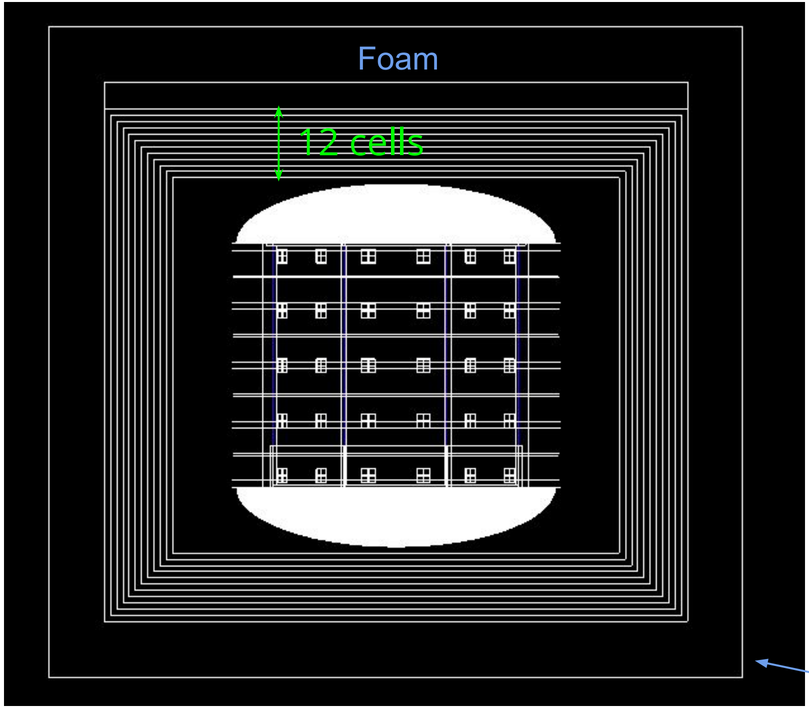
If r is not an integer, the algorithm for splitting (r > 1) is:

$$N_n = N_m \times [\mathrm{int}(r) + 1] \text{ with } P = r - \mathrm{int}(r)$$

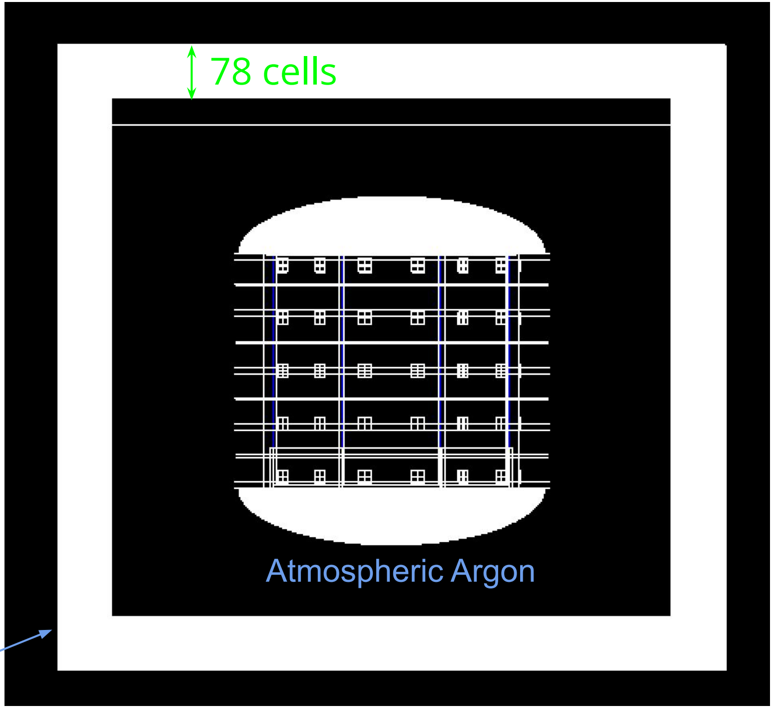
$$N_n = N_m \times \mathrm{int}(r) \text{ with } P = 1 + \mathrm{int}(r) - r$$

Cells in AAr and cryostat foam

Cells in AAr



Cells in the foam



Cryostat external wall

Cells importances

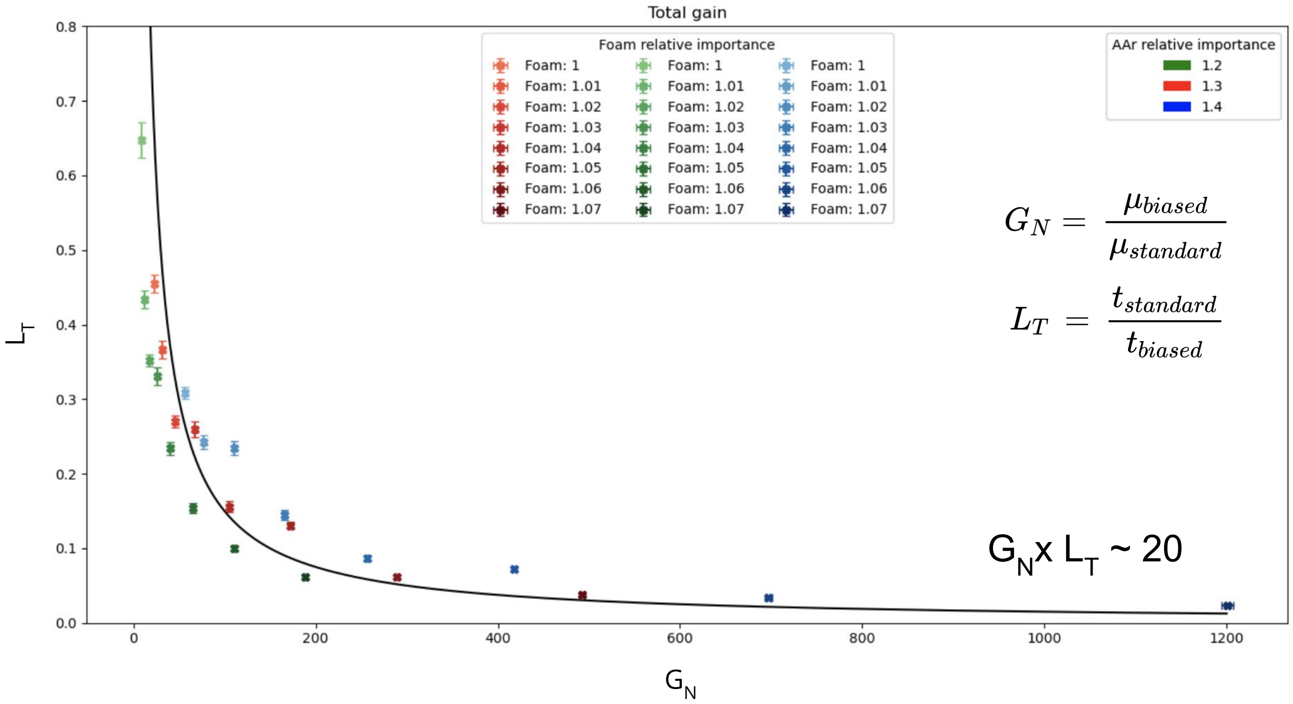
$$\boxed{\text{hits(standard) = hits(biasing) x w(on hit)}}$$

For each importance in the scan, **150 simulations**, **200k neutrons each** (so that **1‰ error on counts**)

- Rescale (***debiasing***) the counts multiplying by their weight
- Calculate **mean** and the **SE** on the 150 simulations
- **Compare** with standard result:
    - **G_N**: gain in number of counts $$G_N = \frac{\mu_{biased}}{\mu_{standard}}$$
    - **L_T**: loss of time $$L_T = \frac{t_{standard}}{t_{biased}}$$
    - Agreement debiased/standard: $$\sigma_{\text{comp}} = \frac{|\mu_{debiased} - \mu_{standard}|}{\sqrt{SE^2_{debiased} + SE^2_{standard}}}$$

Relative importance scan

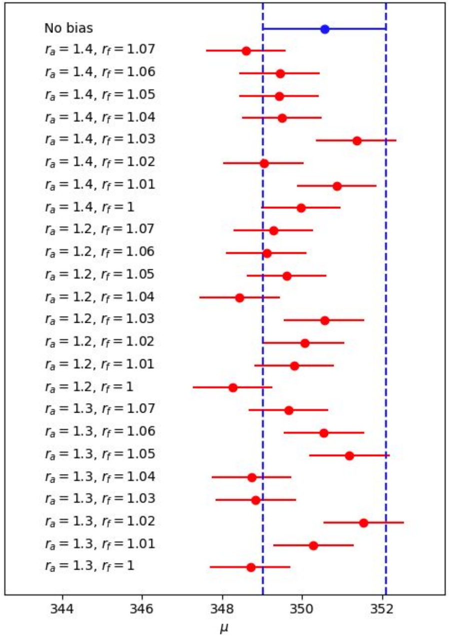
- Neutrons generated randomly inside the foam
- Counts on the SS vessel + debiasing



$$G_N = \frac{\mu_{biased}}{\mu_{standard}}$$

$$L_T = \frac{t_{standard}}{t_{biased}}$$

$G_N x L_T \sim 20$

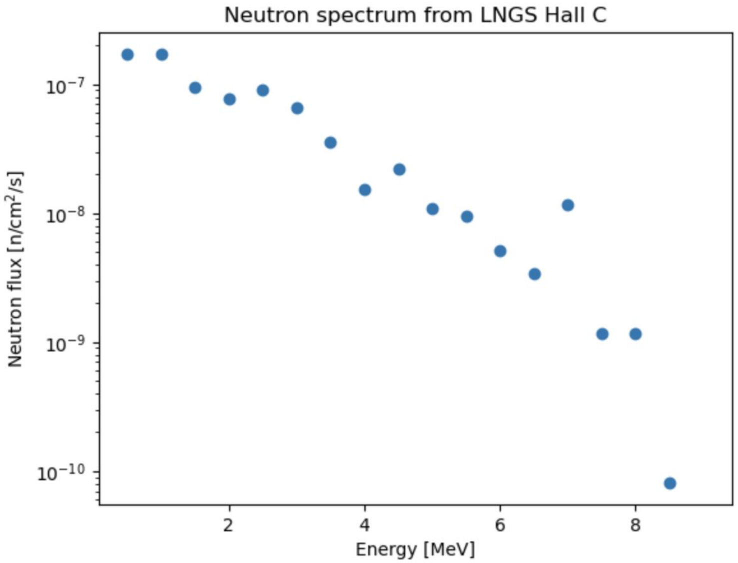


Agreement standard vs biasing simulations **< 1.2σ**, with **1‰ relative error** on the counts

High statistic simulations

- Primary neutrons from spherical surface, external to the cryostat
- Spectrum from LNGS Hall C
- Atmospheric Argon relative importance = 1.3
- Cryostat foam relative importance = 1.03

$$\boxed{G_N = 230,\ L_T = 0.2 \ \rightarrow G_{tot} = 50}$$



H. Wulandari et al. Neutron flux at the Gran Sasso underground laboratory revisited.

Results of biased simulations

Evaluate the computing efficiency by considering both the computing **time** and the **precision** achieved:

$$\boxed{FOM = \frac{1}{R^2 T}} \quad \text{where} \quad R = \frac{\sigma}{\bar{x}\sqrt{N}}$$

M. Dressel. Geometrical importance sampling in Geant4: From design to verification

Then evaluate the ratio of the FOM obtained with biased and standard simulations:

$$G = \frac{FOM_{bias}}{FOM_{std}} \Rightarrow$$ **G = 18.5**

G can be interpreted as an estimate of the factor of time the standard simulation would have to run longer than the biased one to achieve the same precision measured by the variance

High statistic simulations - results

Subset of 10^5 primary neutrons from sphere to SS vessel