# SuperCDMS Background Simulations using Geant4's Importance Biasing

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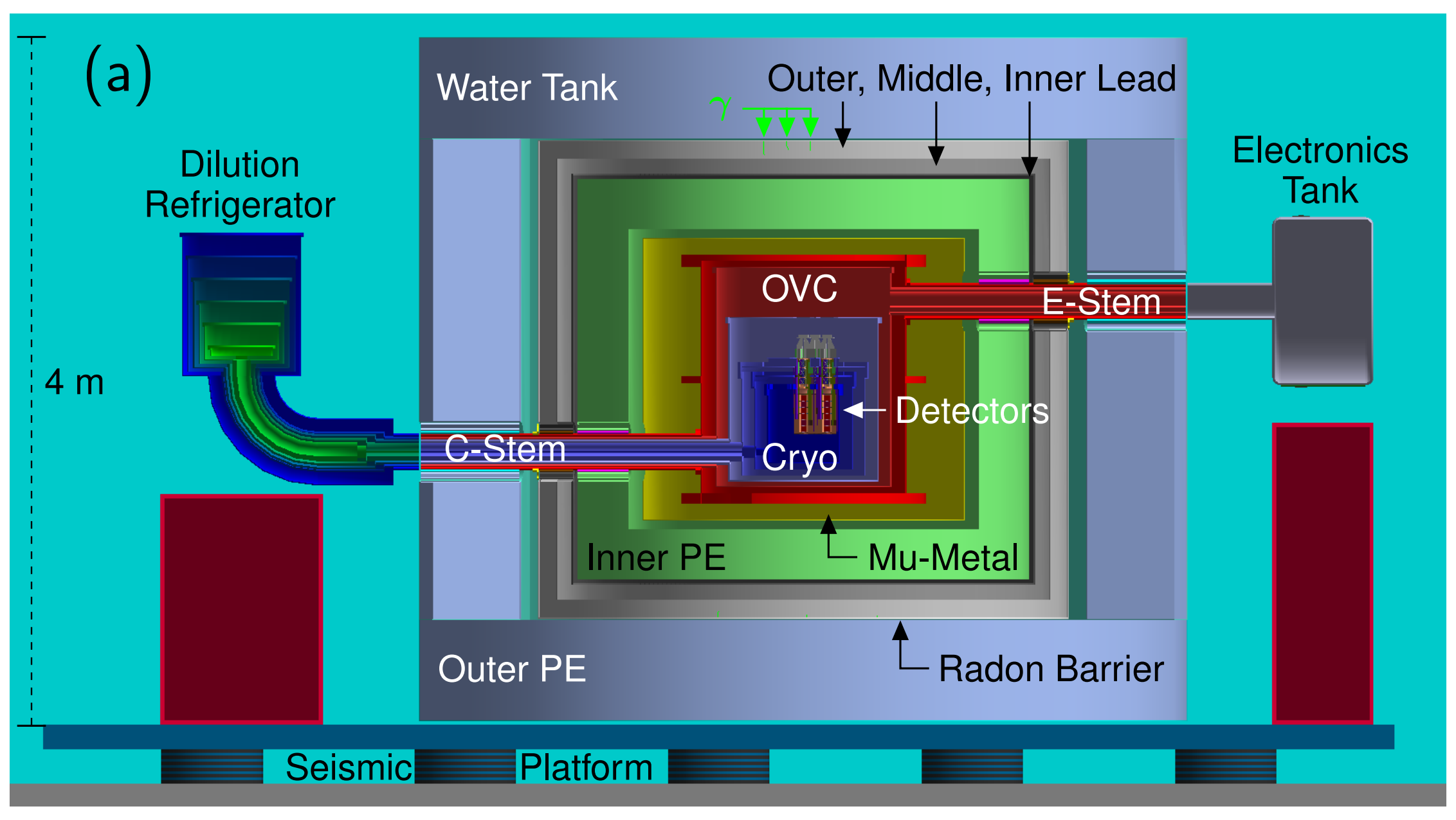
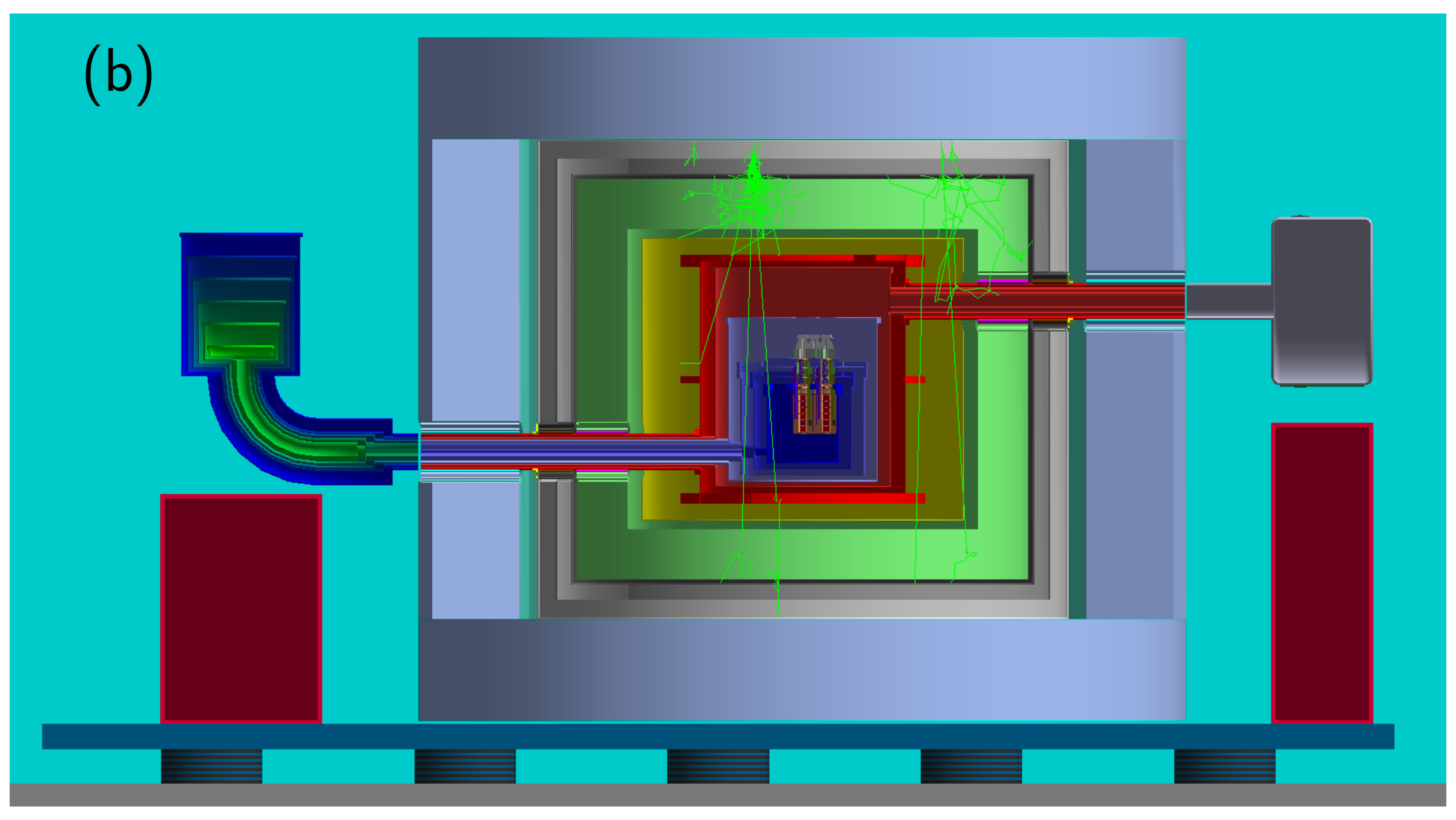
## SuperCDMS Background Simulations

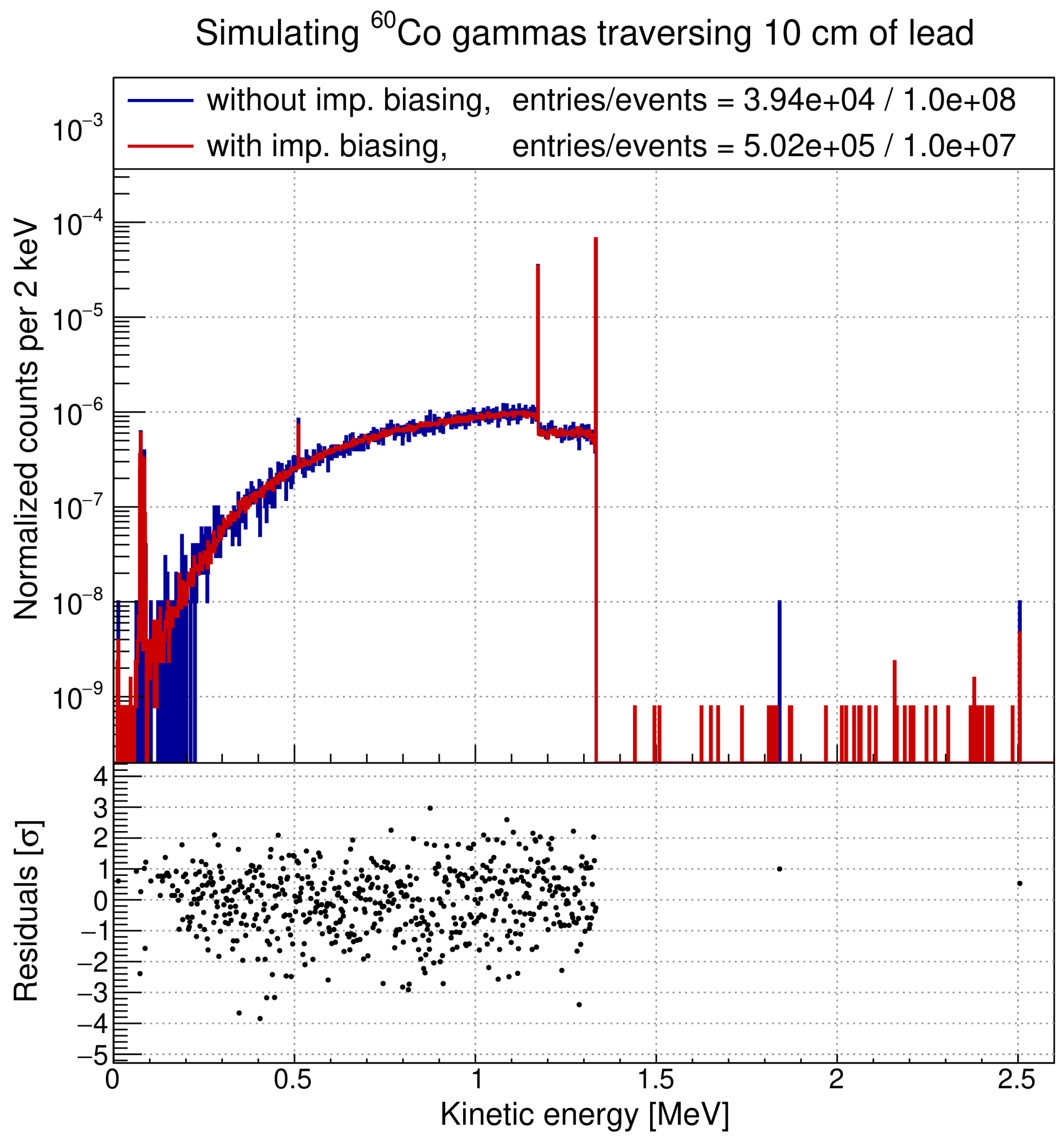
► SuperCDMS is a dark matter experiment which will operate cryogenic Ge and Si detectors 2 km underground at SNOLAB. The detectors are surrounded by several layers of ultra-clean materials to shield them from external gamma rays and neutrons originating from the rock cavern walls.
As the shielding is very effective, the majority of the propagated particles are absorbed when traversing the geometry. Consequently, corresponding **Geant4 simulations lack sufficient statistics** in terms of number of detector hits which impedes background simulation studies.



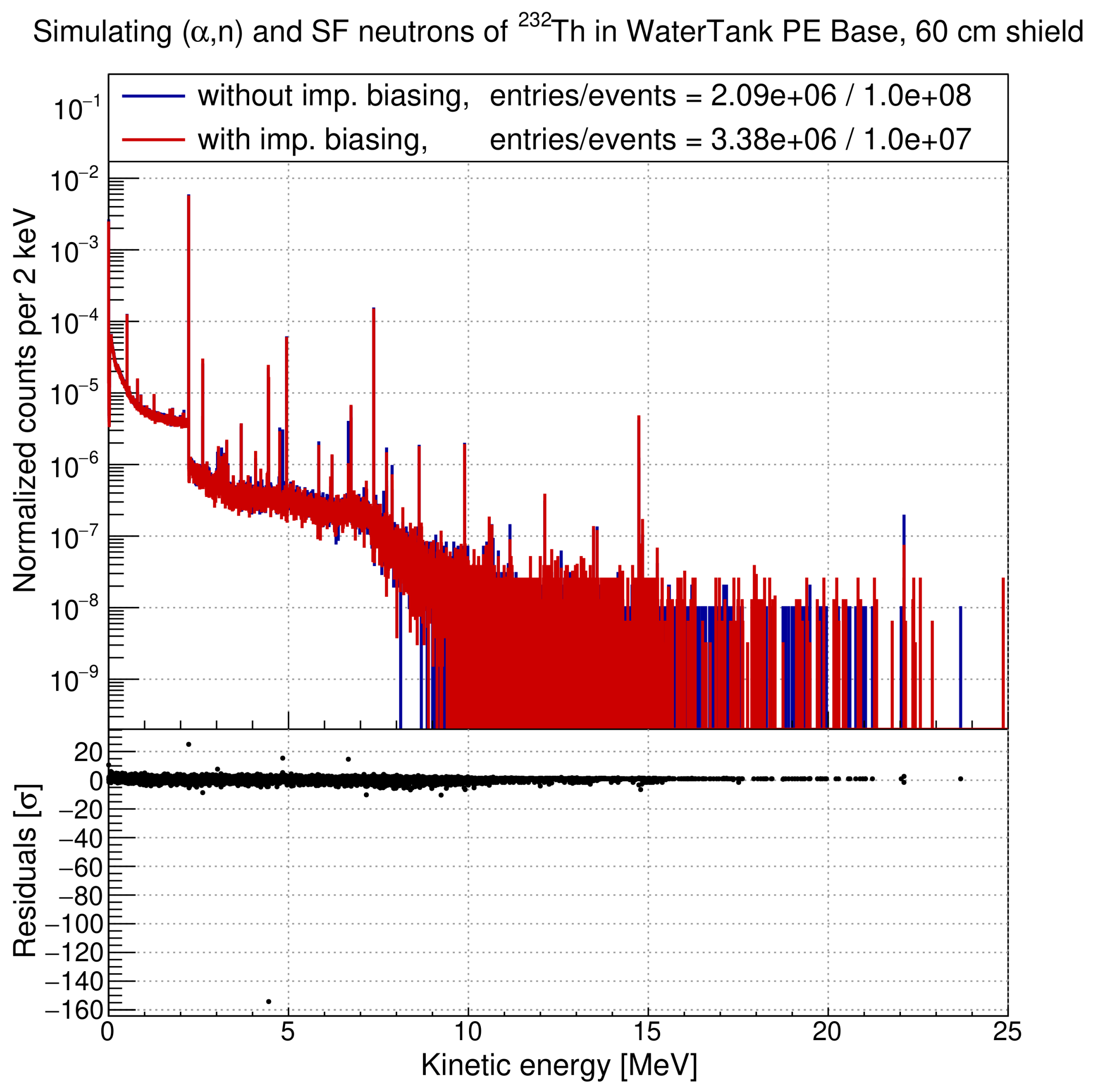
Gammas ($\gamma$) propagating through the Lead Shield without importance biasing (a) and with importance biasing (b).



## Validation Spectra



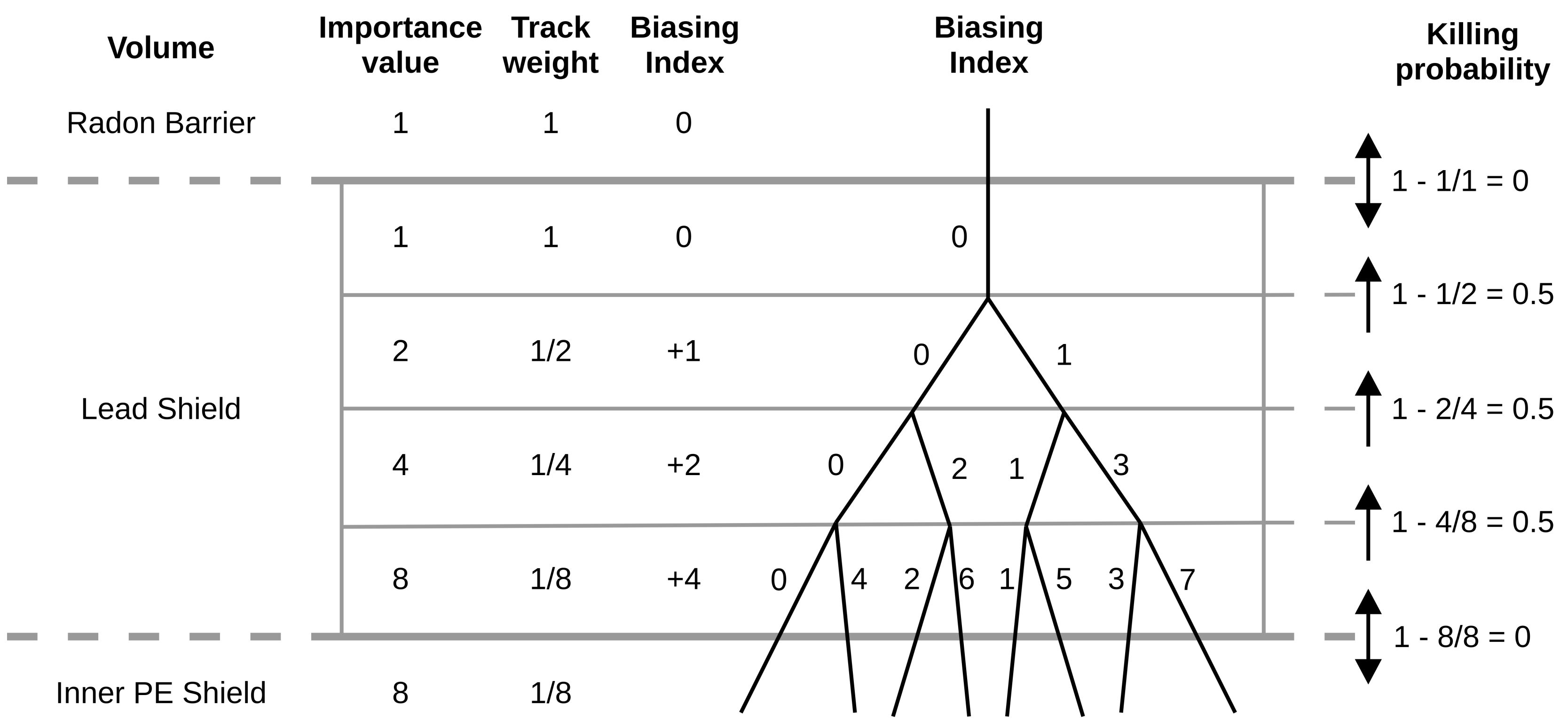
◄ Simulations were run with and without importance biasing for each isotope, decay chain and neutron spectrum which are simulated to model SuperCDMS' background.
Particles are propagated through the importance layers which cover the lead shield (isotopes) or all shielding layers (neutrons). After the innermost importance layer, all particles, their energy and track weight are recorded and the resulting spectra are constructed taking into account the biasing index.



◄ The peak features in the neutron simulations are gammas with discrete energies produced in neutron captures $(n, \gamma)$ and neutron inelastic scattering $(n, n')$ in the different shielding materials as well as gammas emitted during the decay of activated isotopes from these processes. Depending on the specific process, these gammas or gamma cascades can have higher kinetic energies than the initial neutron.

## Importance Biasing Working Principle

▼ **Importance biasing introduces importance layers**, which are virtual geometries overlaid on the SuperCDMS lead shield geometry. Each importance layer $L$ has an importance value $V$, increasing from outside to inside with $V = 2^L$.
Each time a biased particle crosses the boundary between two importance layers, for which the importance value ratio between the next and the previous layer is 2, the particle is duplicated, keeping the same energy, momentum direction, position, etc. The track weight of both particles is divided by 2, i.e. the total track weight is conserved.
If a biased particle crosses the boundary between two importance layers where the ratio between the next and the previous layer is 0.5, there is a 50% probability that the particle track is killed. In the case the particle survives, its track weight is multiplied by 2.



▲ For $L = 4$ importance layers, there can be up to $2^{L-1} = 8$ different track topologies. The **Biasing Index** is introduced to **distinguish between different track topologies**. Without this distinction, one could observe non-physical energy collection due to interactions from different kinds of track topologies within the same Geant4 event.
Each time a particle is duplicated, the original particle keeps its biasing index, while the copied particle gets a new value. In all other physics processes which create secondary particles, the biasing index and track weight are inherited from the parent particle.
Importance biasing achieves that **more particles are being tracked which are traveling towards the detectors**, and fewer particles being tracked which are moving away. This increases the number of detector hits, and saves computing time by not tracking particles which have a geometrically low probability to reach the detectors.

## Efficiency Boost

► Simulations run with importance biasing can be significantly more efficient than unbiased simulations, but this strongly depends on the number of importance layers and the importance layer thickness.
The optimal parameters depend on the biased particle type, its energy and the traversed material(s). The efficiency boost is calculated comparing the particles which reached the innermost importance layer.

| Primary | Layers | Thickness | Efficiency boost |
|---|---|---|---|
| $^{26}$Al | 16 | 1.25 cm | $(16.4 \pm 0.8) \cdot 10^3$ |
| $^{40}$K | 16 | 1.25 cm | $(22.7 \pm 6.3) \cdot 10^3$ |
| $^{60}$Co | 16 | 1.25 cm | $(49.8 \pm 7.6) \cdot 10^3$ |
| $^{226}$Ra | 16 | 1.25 cm | $(21.1 \pm 0.2) \cdot 10^3$ |
| $^{232}$Th | 16 | 1.25 cm | $(17.2 \pm 0.8) \cdot 10^3$ |
| $^{235}$U | 16 | 1.25 cm | $> 17.9 \cdot 10^3$ |
| $^{238}$U | 16 | 1.25 cm | $(28 \pm 14) \cdot 10^3$ |
| $^{210}$Pb | 20 | 1.00 cm | $> 2.8 \cdot 10^3$ |
| $n\,(^{232}$Th) | 16 | 7.50 cm | $26.58 \pm 0.06$ |

▼ The importance biased simulation propagates up to several orders of magnitude more tracks, hence on a per-event basis it also runs much longer than the unbiased simulation. But even with orders of magnitude fewer primary particles, **significantly more detector hits** are observed in the importance biased simulation.
Concluding, with importance biasing, future background simulations for SuperCDMS will consume **orders of magnitude less computing time**, while achieving the statistics requirements for the detected energy spectra to develop a proper background model.

| Primary | Simulated events | | Detector hits | | Runtime [h] | | Efficiency boost |
|---|---|---|---|---|---|---|---|
| | imp. bias. | no bias | imp. bias. | no bias | imp. bias. | no bias | $[10^3]$ |
| $^{40}$K | $10^7$ | $2 \cdot 10^{10}$ | 35 | 4 | 2.6 | 3454 | $12.4 \pm 6.5$ |
| $^{60}$Co | $10^7$ | $10^{10}$ | 175 | 10 | 14.4 | 5900 | $7.5 \pm 2.4$ |
| $^{232}$Th | $10^7$ | $10^{10}$ | 2063 | 75 | 27.1 | 12123 | $13.7 \pm 1.6$ |

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