

Neutron efficiency optimization for the nHCal

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6/30/2026

Introduction

- Low energy neutrons are hard to detect efficiently
- The design of the nHCal is relatively flexible
- Optimization using AI within the available headroom?

Overview

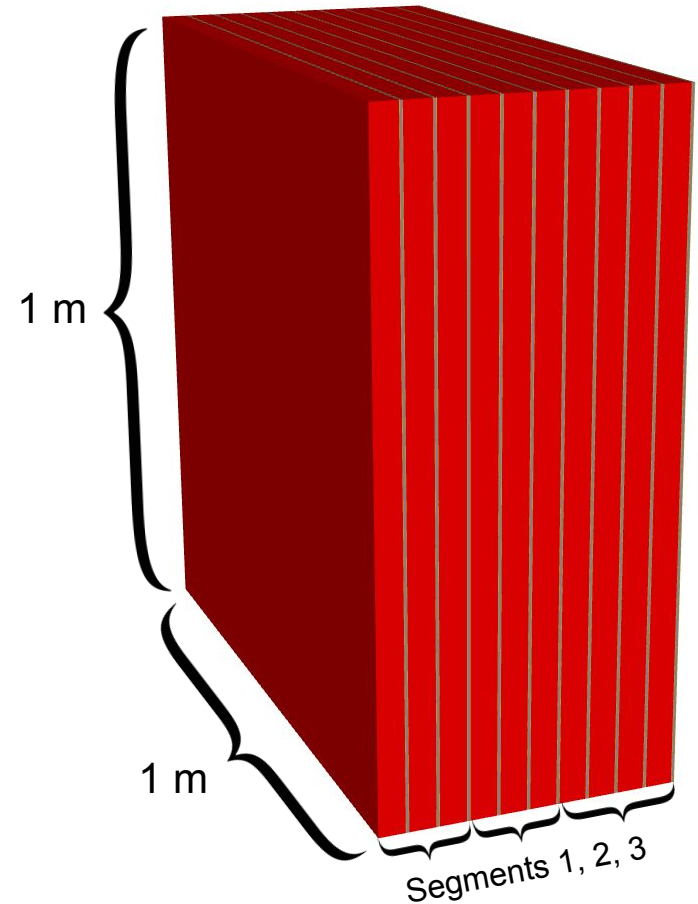
- Software Environment
- Detector & Design Space
- Beam Setup
- Thresholding and Hit Extraction
- Efficiency Metric
- Model Setup
- Uncertainties
- Results

Software Environment

- DD4hep 1.37
- Geant4 11.4.1
- ROOT 6.38.04
- EDM4hep 1.0
- podio 1.7

Detector & Design Space

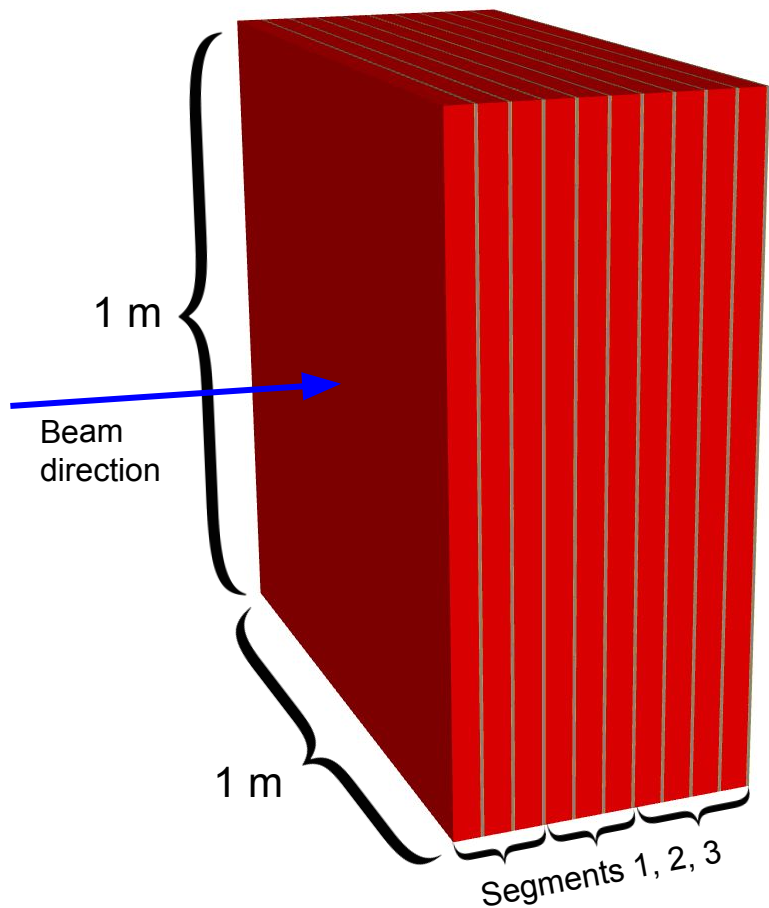
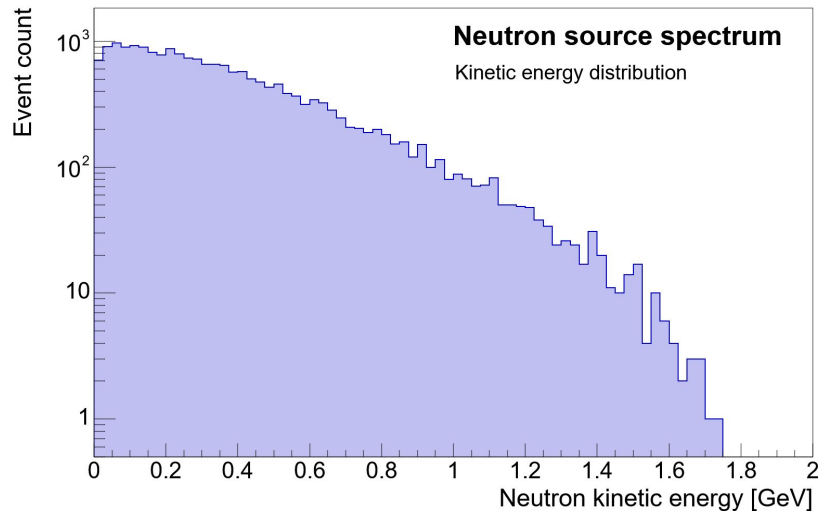
- Same materials as the nHCal.
- 1m by 1m transverse slab – lateral energy leakage $< \sim 2.5\%$.
- 10 cm by 10 cm cells
- 10 total layers divided into 3 longitudinal segments, absorber-to-scintillator ratio varies per segment.
- Total of 6 unique thicknesses from absorbers and scintillators across 3 segments \rightarrow 6D design space



Beam setup

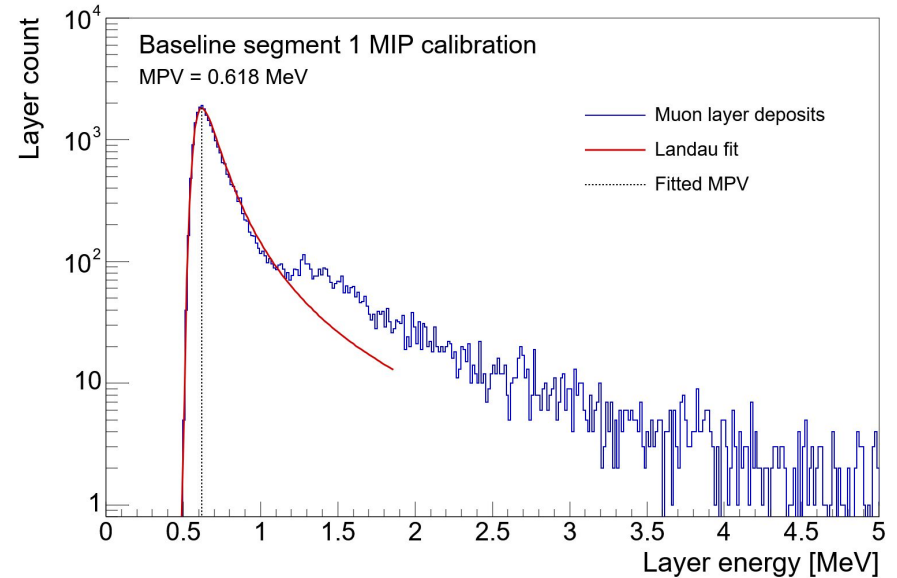
DDsim particle gun:

- Neutrons only
- 0.1-2.5 GeV/c
- Perpendicular to the face of the detector
- FTFP_BERT_HP



Thresholding and Hit Extraction

- **Threshold computation:**
 - Simulate 10,000 muon events in the baseline geometry
 - Sum deposited energy by layer for each event, then pool layers within each longitudinal segment.
 - Fit the segment energy distribution to extract the baseline MIP most probable value
 - Use $0.5 * \text{MIP}$ as the threshold
- A hit is a calorimeter cell whose 0-100 ns integrated energy exceeds the threshold for its longitudinal segment.



For additional geometries, the MIP value is scaled linearly according to the scintillator thickness.

Efficiency Metric

Detection efficiency is the fraction of simulated neutron events with usable truth information that have at least one calorimeter cell above threshold anywhere in the detector.

$$\epsilon_{\text{det}} = \frac{N_{\text{detected}}}{N_{\text{valid}}}$$

Model Setup

6 Input Features:

- Absorber 1
- Scintillator 1
- Absorber 2
- Scintillator 2
- Absorber 3
- Scintillator 3

$\text{thickness}_{\text{abs}} \in [3.5, 4.5] \text{ cm}$
 $\text{thickness}_{\text{scint}} \in [0.3, 0.6] \text{ cm}$



Model:

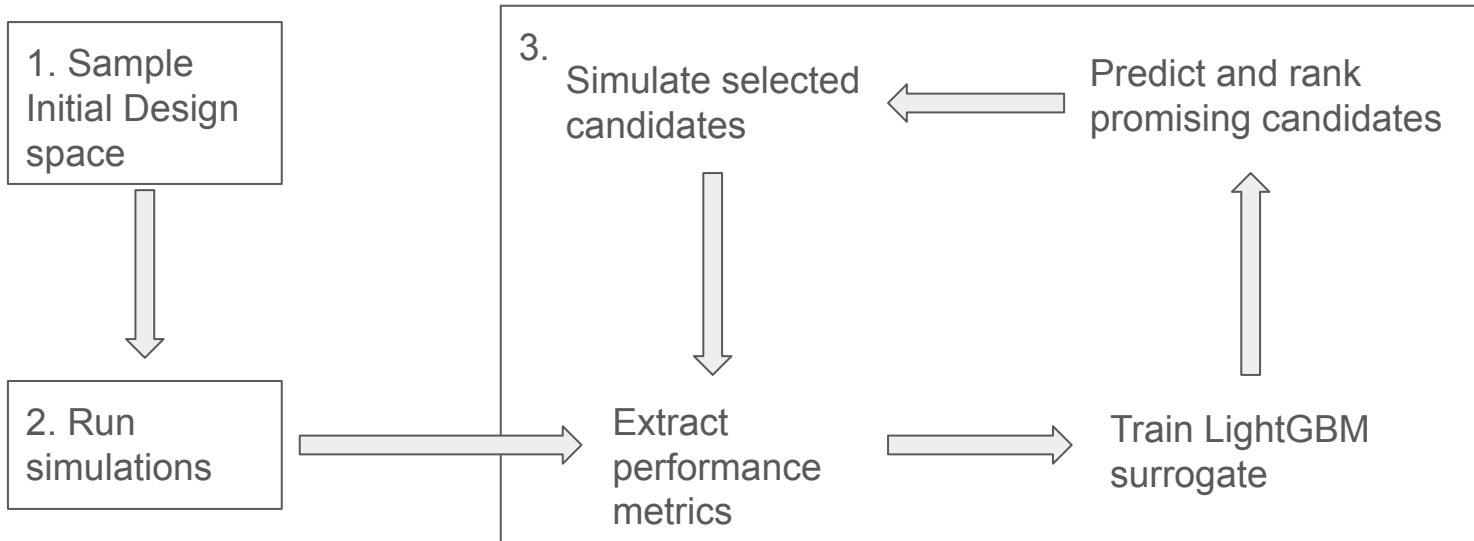
- Gradient-boosted decision trees via LightGBM



3 Target Outputs:

- Detection efficiency
- Average fired-tile count
- Average fired-layer count

Optimization Loop



Uncertainties

1. Main uncertainty: MC statistical fluctuations between geometry evaluations.
 - a. Initial scan uses 5k events/geometry, so near-top candidates may be misranked
 - b. High-performing geometries were rerun with 20k events to reduce fluctuations
 - c. 50,000 events for the final baseline-optimum comparison
2. Efficiency values use binomial error.
3. Tile Mean and Layer Mean use standard error on the mean.

Results

Metric	Value
$t_{\text{abs},1}$	4.0000
$t_{\text{scin},1}$	0.4000
$t_{\text{abs},2}$	4.0000
$t_{\text{scin},2}$	0.4000
$t_{\text{abs},3}$	4.0000
$t_{\text{scin},3}$	0.4000
Efficiency	0.53168 ± 0.00223
Tiles Mean	1.09176 ± 0.00659
Layers Mean	0.97714 ± 0.00566

Table 1: *Baseline geometry.*

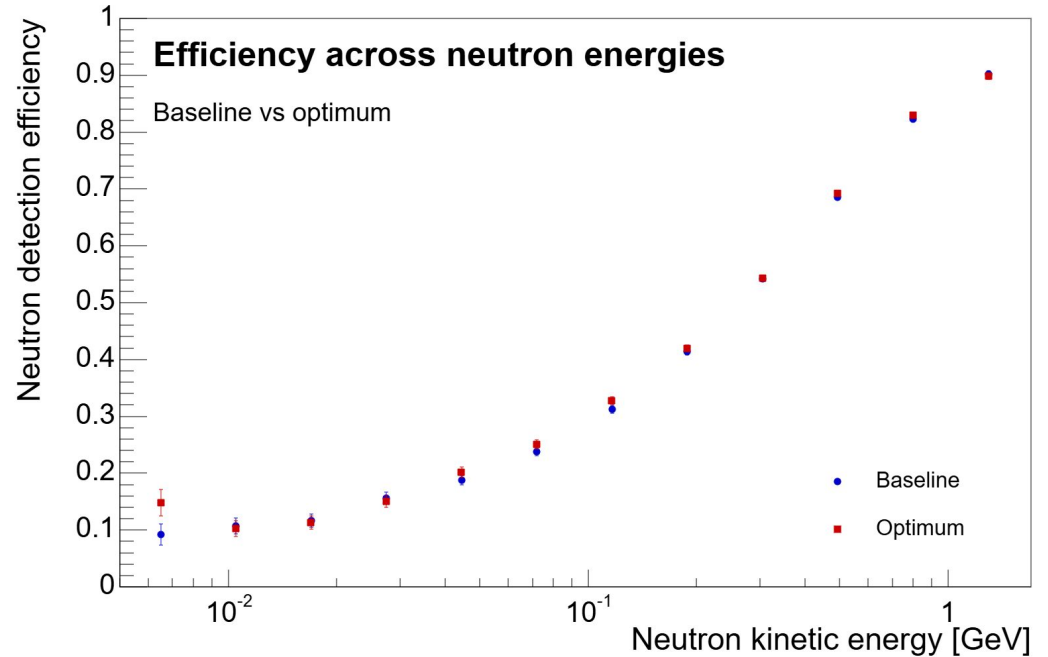
Metric	Value
$t_{\text{abs},1}$	3.5894
$t_{\text{scin},1}$	0.3793
$t_{\text{abs},2}$	3.9174
$t_{\text{scin},2}$	0.4802
$t_{\text{abs},3}$	4.4785
$t_{\text{scin},3}$	0.4348
Efficiency	0.53666 ± 0.00223
Tiles Mean	1.10520 ± 0.00661
Layers Mean	0.98940 ± 0.00569

Table 2: *Optimum geometry.*

Results

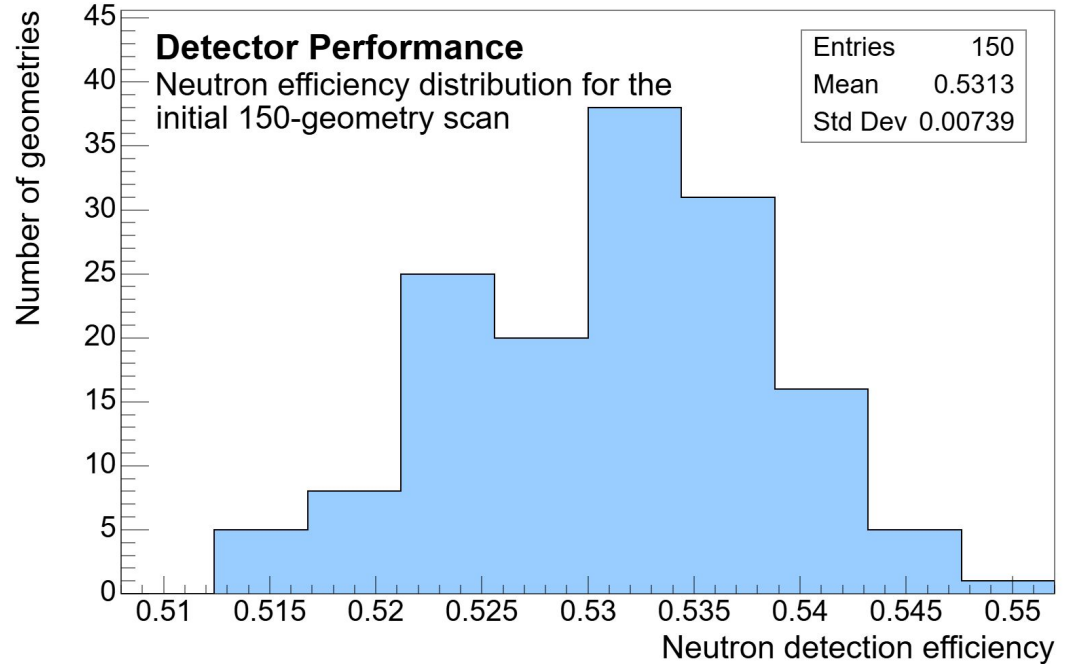
Most gains occur at the lowest energy bin and intermediate energy bins.

- ~60% relative increase in efficiency in the first bin
- ~5% relative increase in efficiency in intermediate bins (~1/3 of all events)



Results

- The initial scan showed a narrow efficiency range of about 0.51-0.55.
- 80%+ of surrogate proposals followed the same depth pattern within this landscape.



Conclusion

- Thickness tuning has limited impact in this setup
- Surrogate search tested structure in the constrained design space
- Efficiency response is shallow across the scanned range

Limitations / Future work

Limitations

- Hit-level truth study
- Results depend heavily on threshold
- Performance differences are small and sensitive to MC stats

Future work

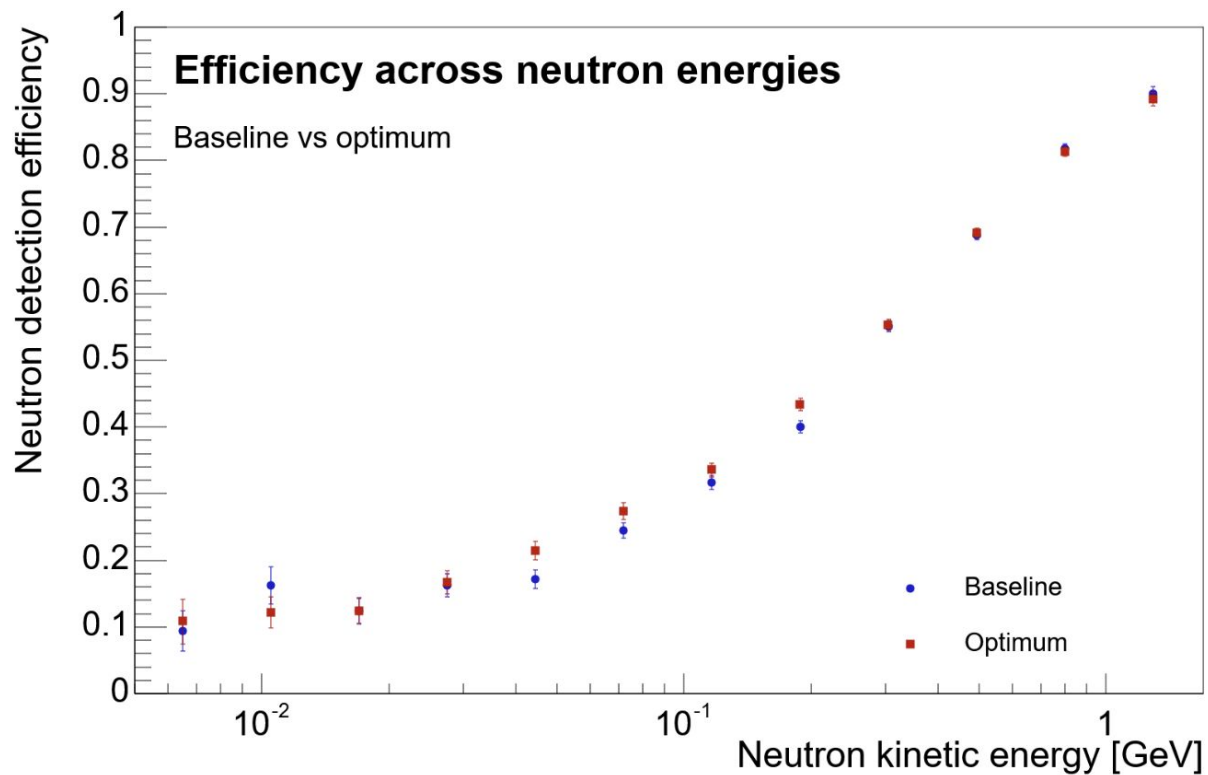
- More statistics
- Other neutral hadrons
- Reconstruction-level studies
- Different materials

Summary

- Small integrated neutron-efficiency gain
 - Shallow efficiency landscape overall
- Repeatable longitudinal trend across optimized candidates
 - Depth segmentation may affect neutron visibility systematically
- Nearby geometries may help optimize other neutral hadrons with little compromise to neutron efficiency

Extra slides

Efficiency vs KE (FTFP_BERT)



Run summary

1. Initial sample: 150 geometries, 5,000 events each
2. Optimization loop: 3 iterations, 5 proposed geometries per iteration
3. High performing geometries validated with 20k events
4. Leading contender geometries were compared against the baseline using five independent 10,000-event runs with different random seeds.
5. Final comparison plots: one 50,000-event run for each geometry

~ 1 million simulated neutron events in total

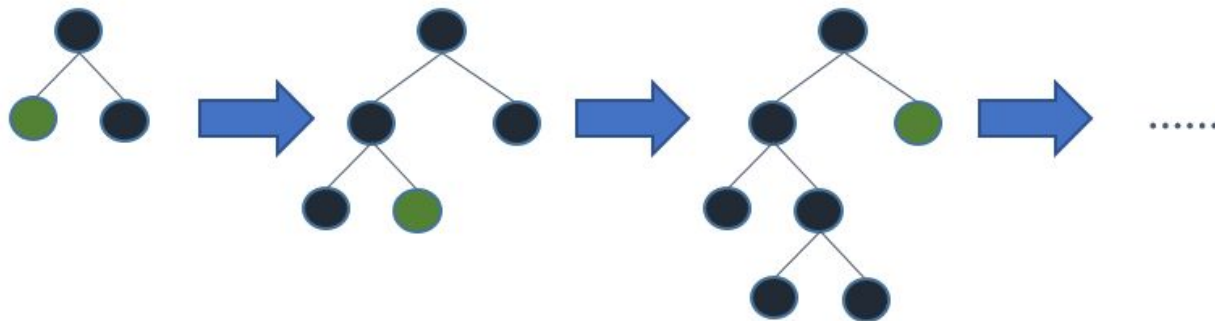
LightGBM

1. Decision Tree

- Ask if-then questions about input features
- At each split, choose the question that minimizes prediction error

2. Gradient Boosting

- Build many small trees in sequence
- Each tree focuses on correcting errors made by the previous trees



Leaf-wise tree growth