October 12th, 2022

Muon Collider - Annual Meeting

Detector Design

using BIB simulation data

General principles and technical implementation

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on behalf of the

Muon Collider Physics and Detector + MDI groups

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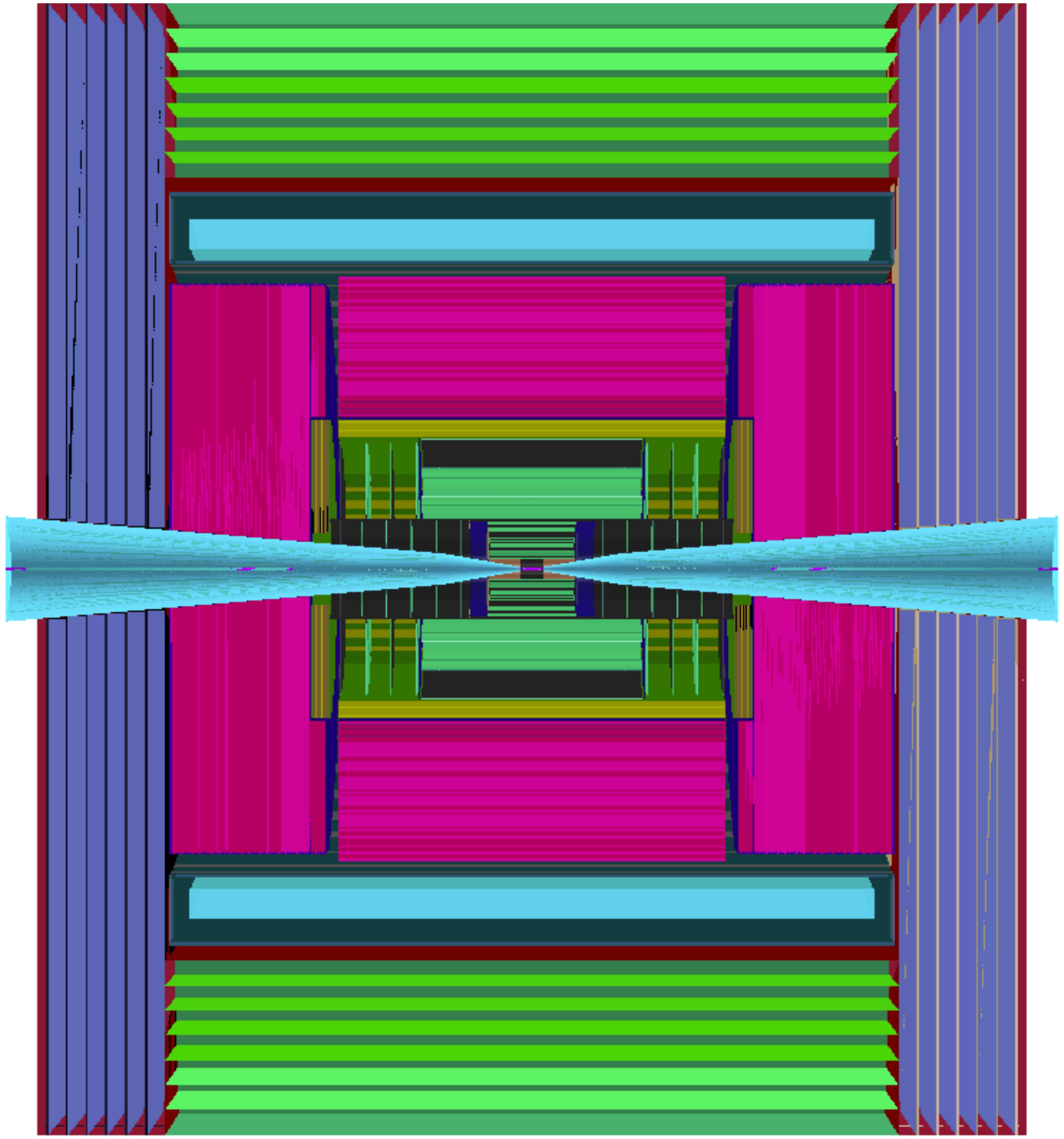
Detector design: main components



Muon Collider detector follows the typical layout of general-purpose collider experiments:

- **low-material-budget tracking detector (TRK)**
  ↳ Vertex Detector (VXD) + Inner Tracker + Outer Tracker
- **electromagnetic calorimeter (ECAL)**
- **hadronic calorimeter (HCAL)**
- **superconducting solenoid**
- **muon spectrometer**

Less typical part of the experiment:

- **large tungsten nozzles (MDI)** → machine-detector interface
  ↳ essential for absorbing beam-induced background (BIB) induced by muon decays inside the beam

Changes to the MDI design will impact the detector performance

↳ **MDI and detector have to be designed together**

Detector design: performance metrics

Each subdetector has its own key performance metrics → can be estimated "on paper"

- **Vertex Detector:** impact-parameter resolution for tracks
- **Inner/Outer Tracker:** track p_T + angle resolution
- **ECAL/HCAL:** energy + shower-shape resolution
- **muon spectrometer:** muon p_T resolution
- **magnet:** high-p_T resolution + low-p_T acceptance for tracks

Performance estimation becomes more complex at the level of actual reconstructed particles:

- **detection thresholds, noise, pile-up, particle misidentifications, etc.**
  ↳ **interplay of different subdetectors + variations in response to different particle types**
- **contribution from BIB particles can degrade performance of the detector tremendously**

Reliable design of a detector requires detailed simulation of all the technical aspects including all relevant effects from BIB particles → must be as realistic as reasonably possible

BIB effects: main aspects

We know several key features of BIB particles that are relevant for detector design

1. **Predominantly very soft particles** (~10 MeV) except for neutrons

   fairly uniform spatial distribution → no isolated signal-like energy deposits
   ↳ different kind of pile-up from what we are used to at the LHC

2. **Significant spread in time** (few ns + long tails up to a few μs)

   $\mu^+\mu^-$ collision time spread: 30ps at $\sqrt{s}$ = 1.5 TeV | ≤20ps at $\sqrt{s}$ = 3 TeV
   ↳ can be a strong handle on BIB with precise-enough timing

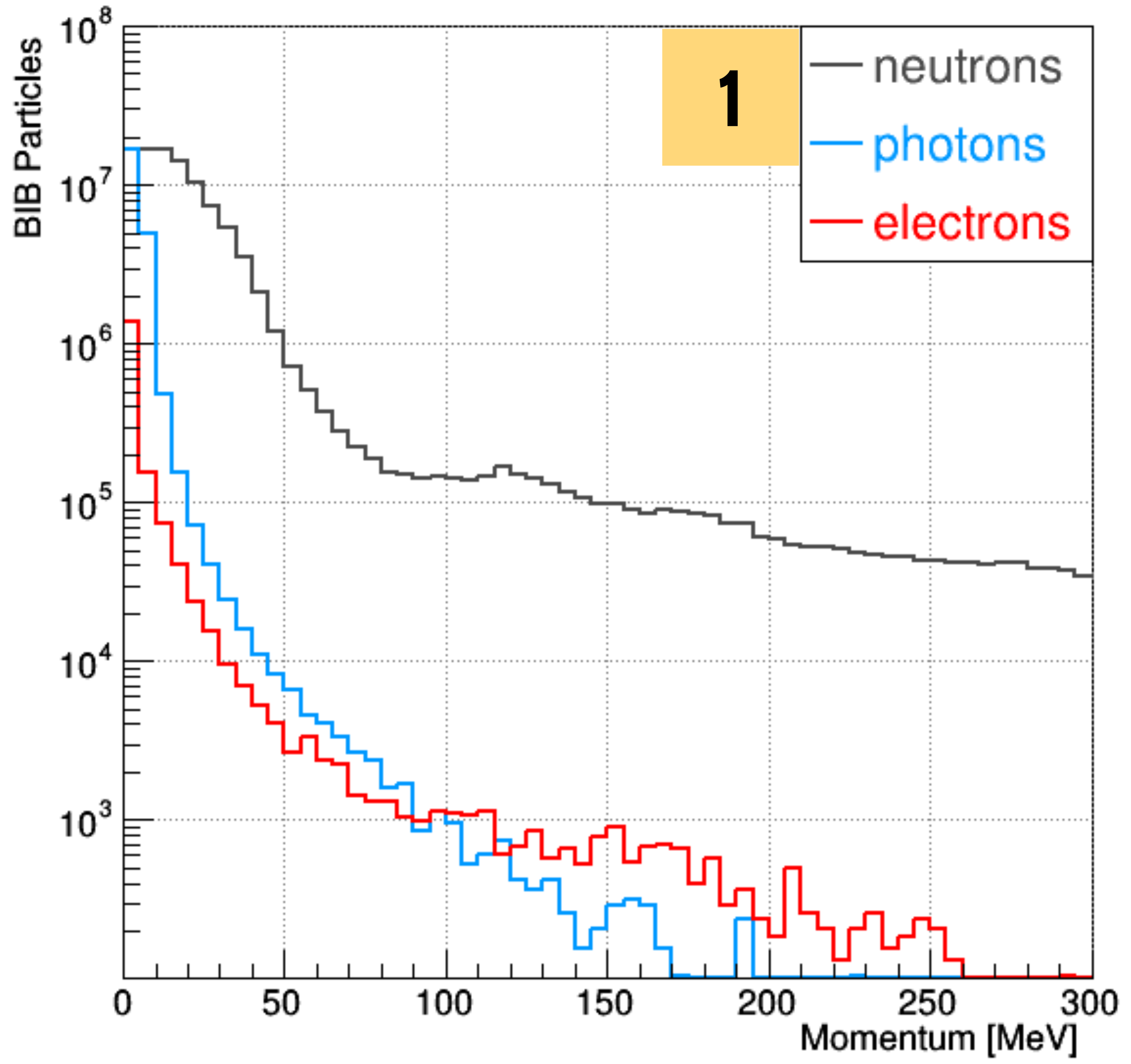
3. **Strongly displaced origin along the beam**

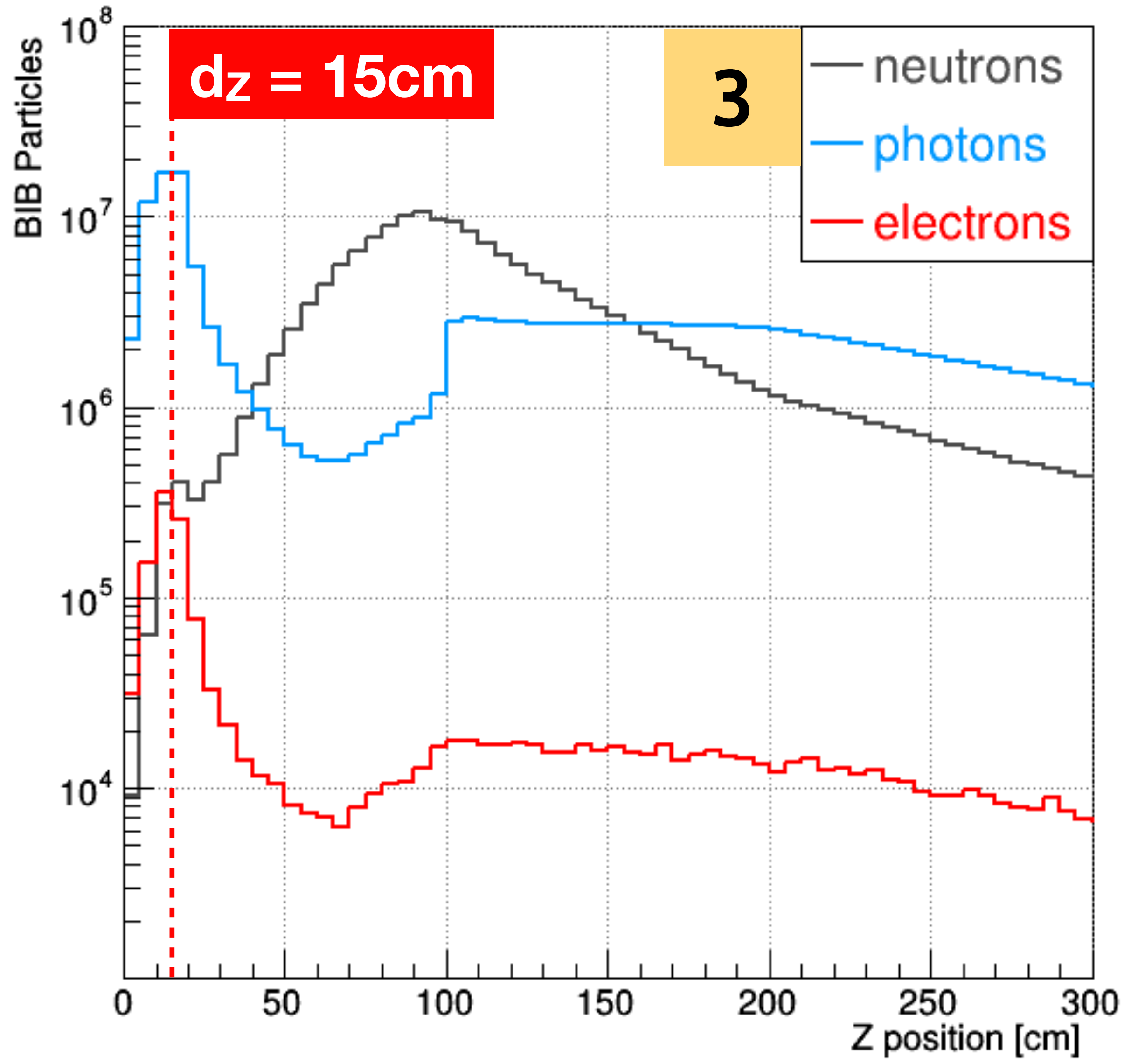
   crossing detector surface at a shallow angle
   ↳ affects charge distribution + time of flight

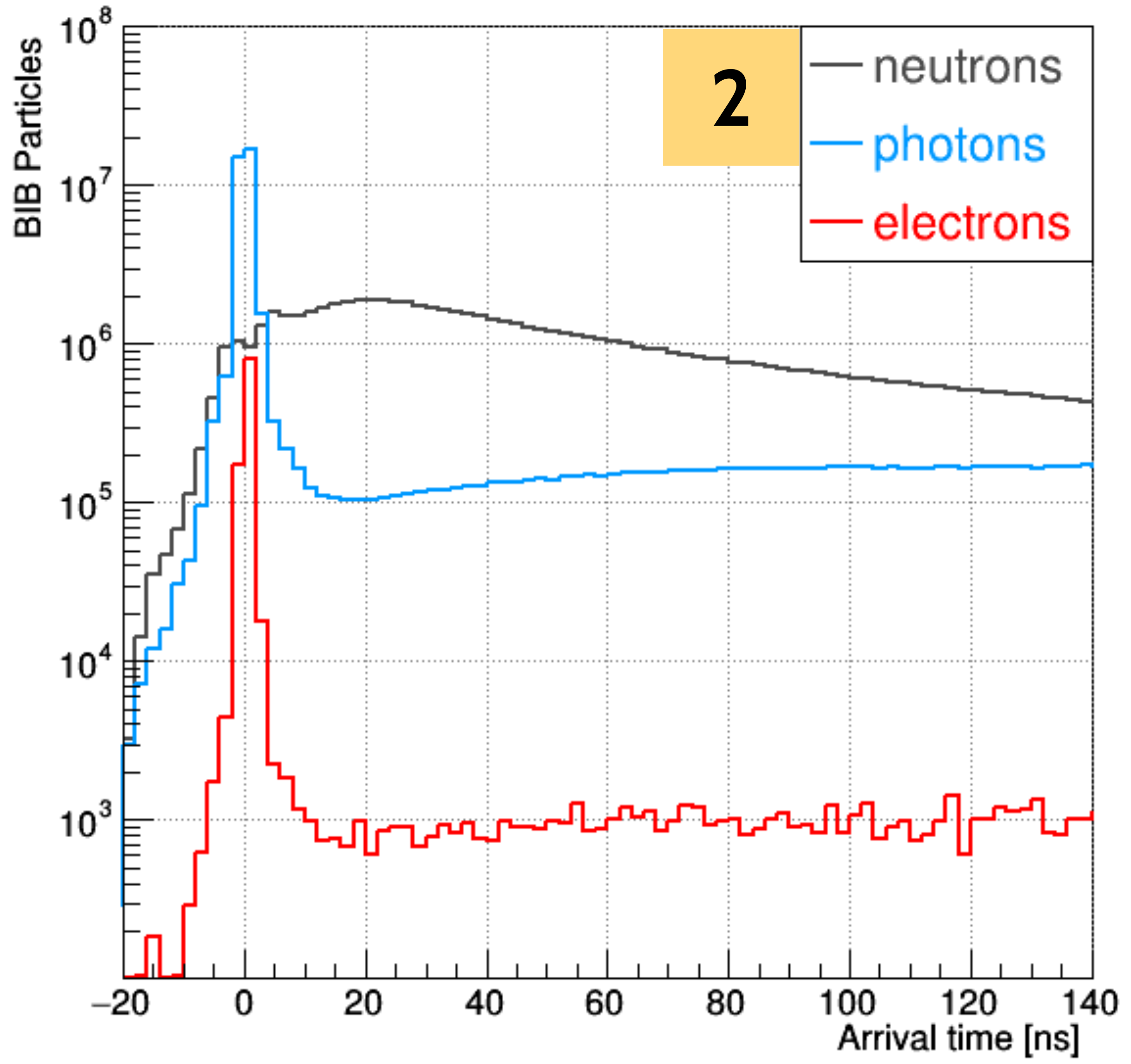
4. **Very high flux of photons + neutrons**

   significant radiation damage to the detector

Any of these features can change significantly during optimisation of the MDI







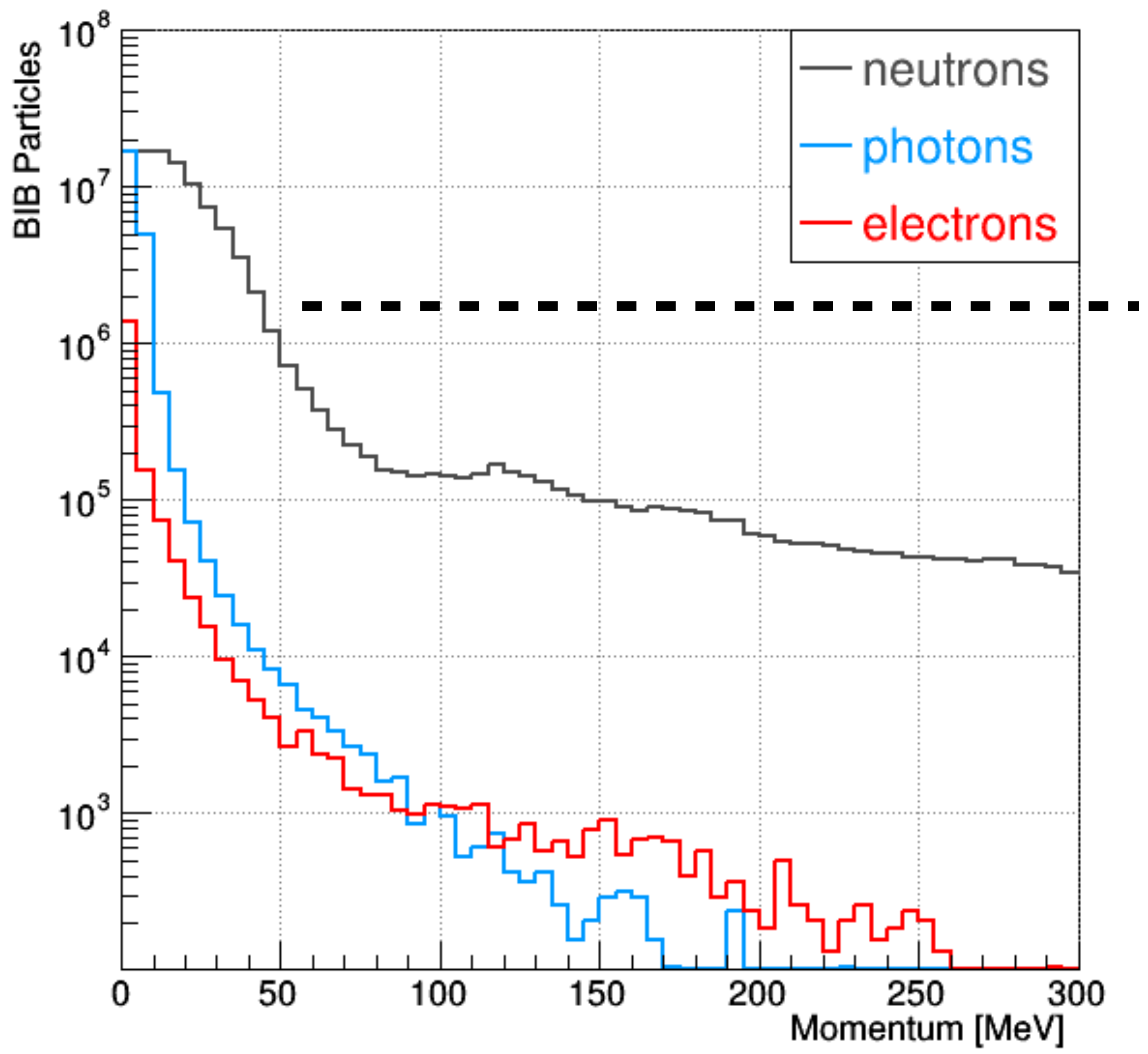
What does it mean to optimise the MDI?

It's impossible to get rid of BIB particles completely within the limited space available for MDI

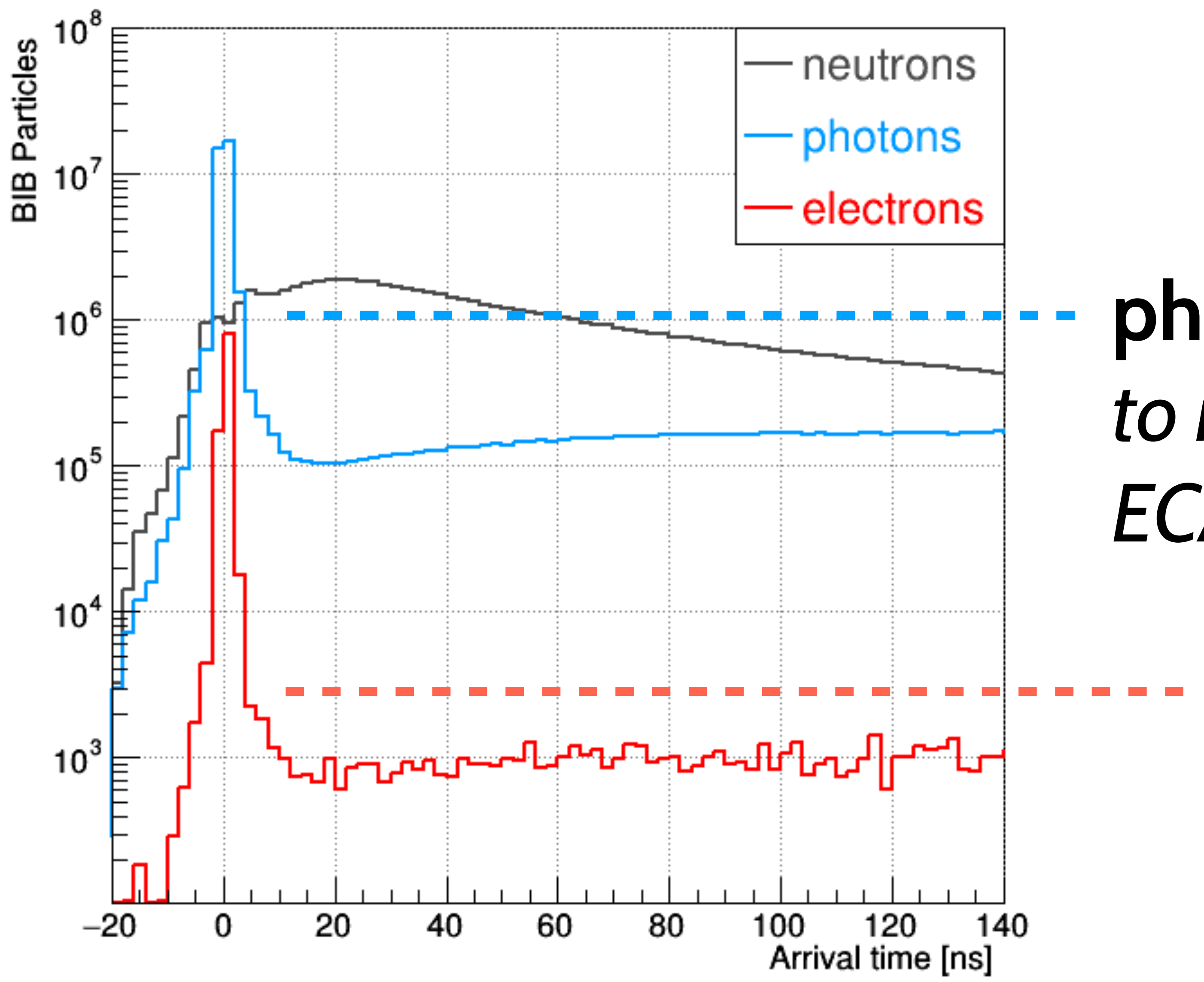
Geometry and composition of the MDI can be tuned for suppressing some parts of the BIB spectrum, but in most cases it will enhance some other parts of the spectrum

↳ optimal MDI is a compromise between "critical" and "tolerable" BIB contributions

Which part of the spectrum should we focus on?



neutrons?
to minimise the radiation damage

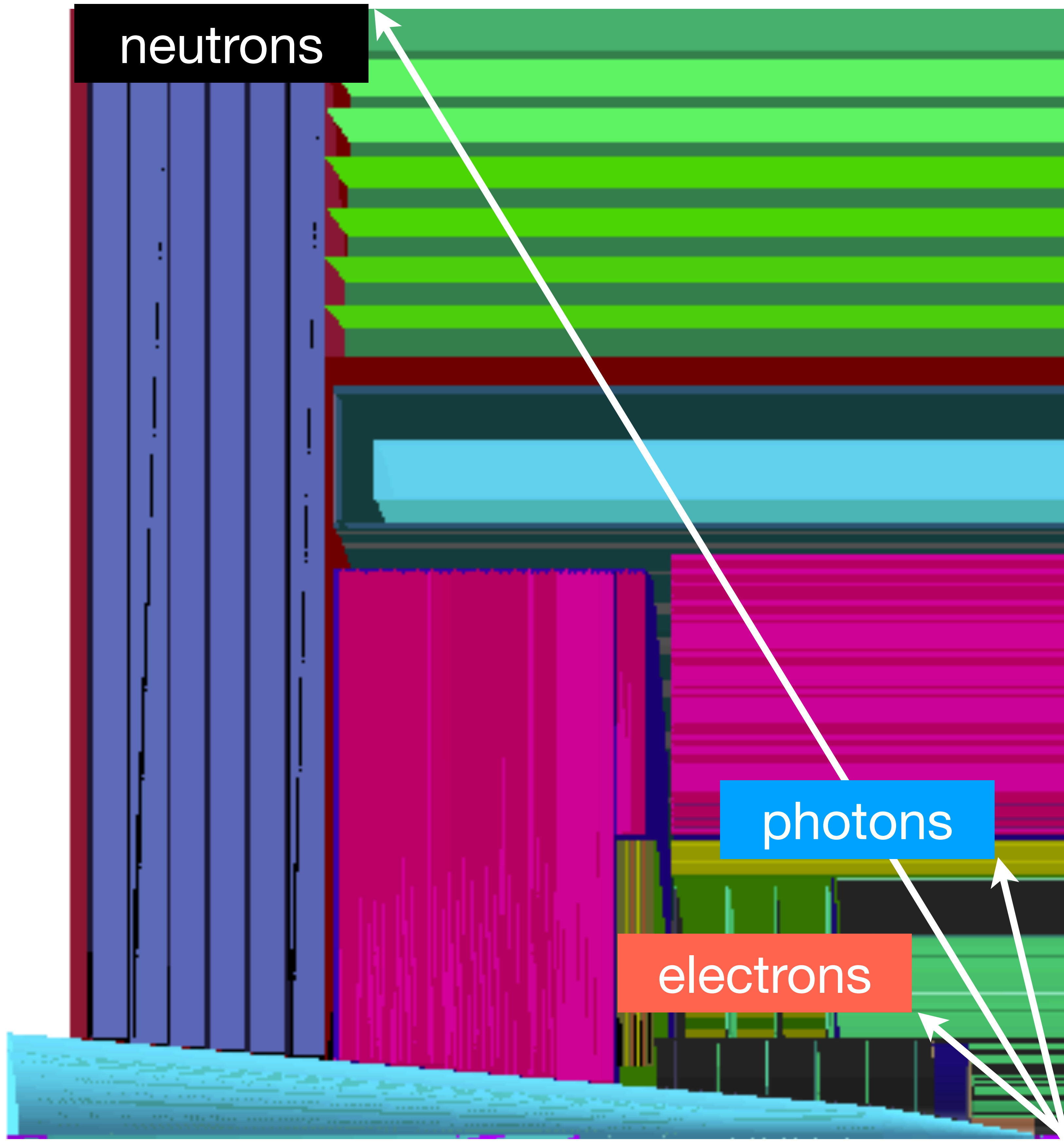


photons?
to minimise the ECAL occupancy

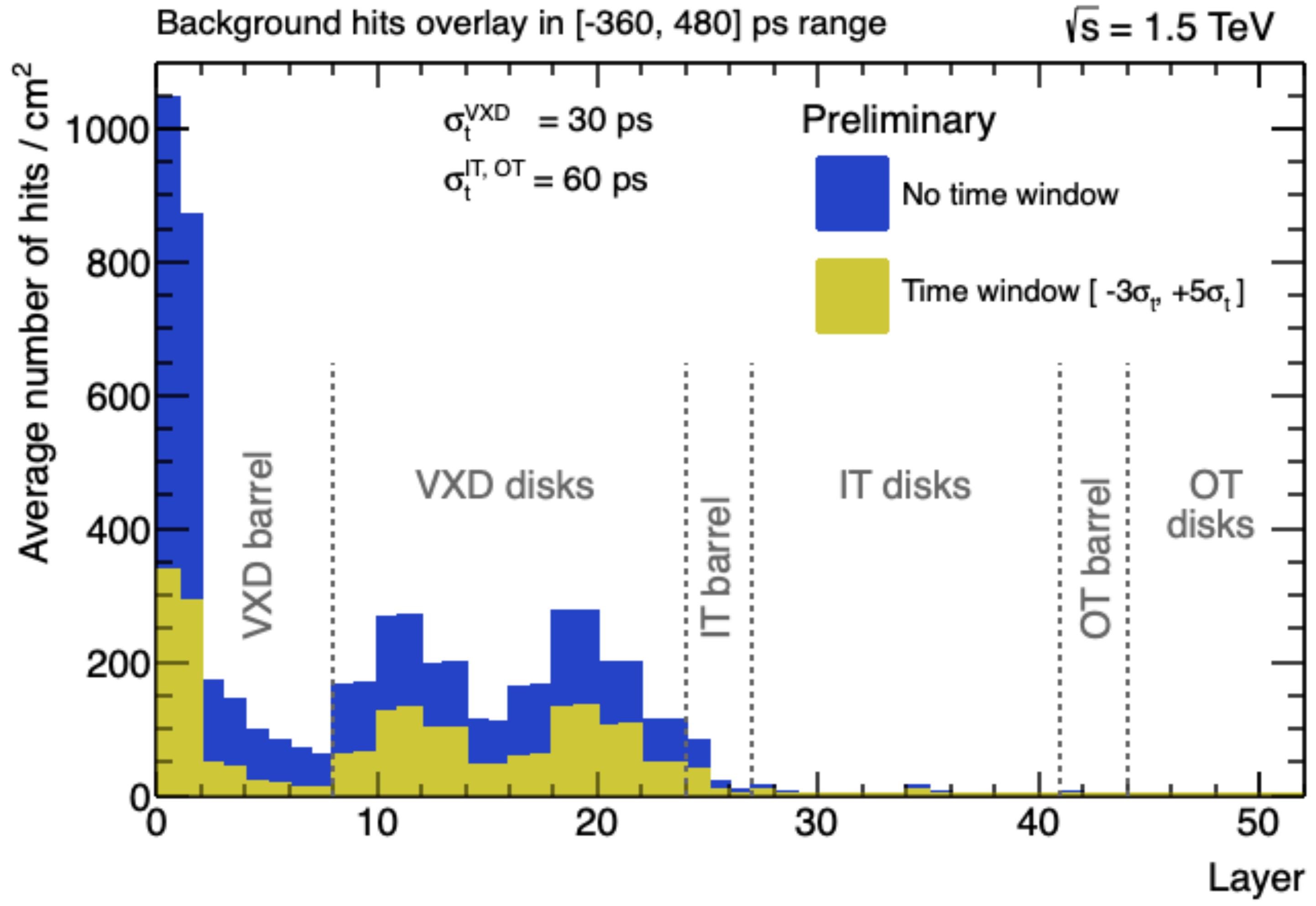
electrons?
to minimise the TRK occupancy

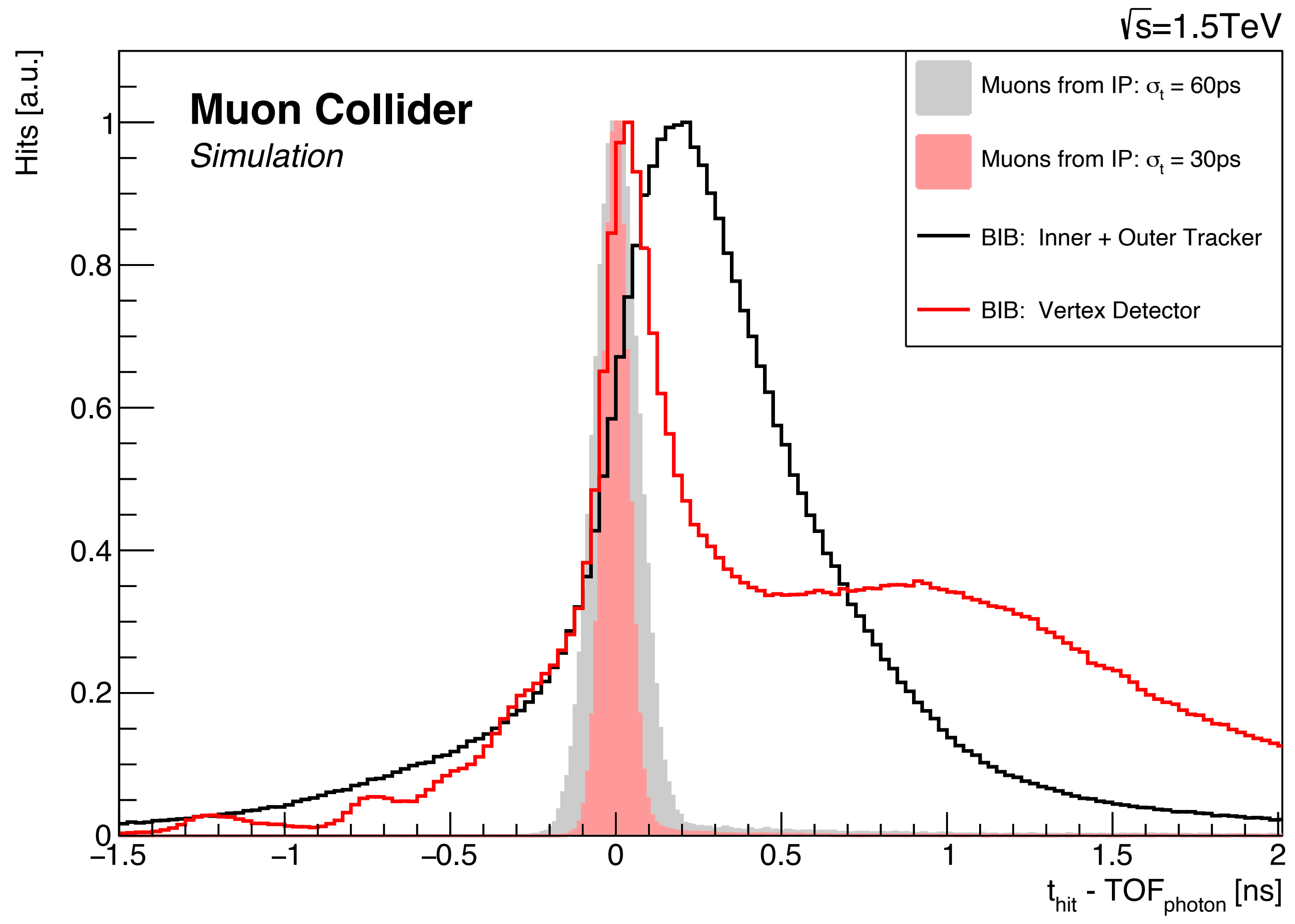
Different subdetectors are mostly affected by different types of particles

1. **electrons** — **stay within the Tracking Detector**
   low-p_T loopers → multiple hits/particle
2. **photons** — **primarily absorbed in ECAL**
   adding background energy deposits
3. **neutrons** — **mostly depositing energy to HCAL**
   + radiation damage across the whole detector volume
   especially thermal neutrons → multiple scatterings/particle



Signals from electrons can be suppressed with precise timing detectors





← **detected time corrected for the time-of-flight from the centre** assuming photon's path

We are using two separate and independent software packages for simulating BIB effects:

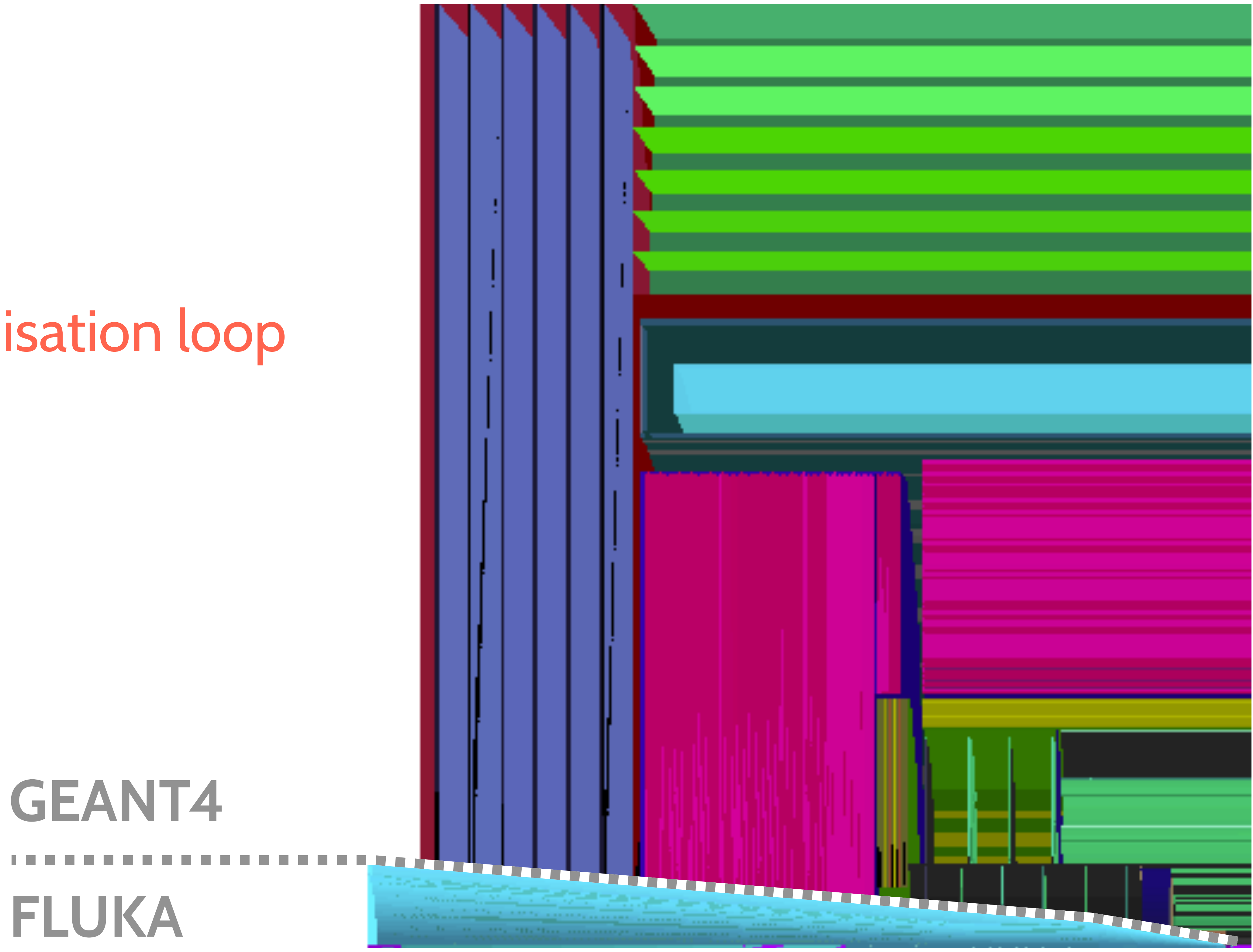
1. **production of BIB particles in the accelerator lattice + interaction with the MDI** (all passive material)
   ↳ using FLUKA + LineBuilder
2. **interaction of BIB particles with the detector + conversion to realistic signals** (passive + active materials)
   ↳ using GEANT4 within the ILCSoft framework

The most straighforward approach is to fully separate the two stages
stopping particles at the outer MDI surface and passing them to GEANT4

↳ FLUKA → GEANT4 → performance plots — simplest optimisation loop
adjust MDI + detector

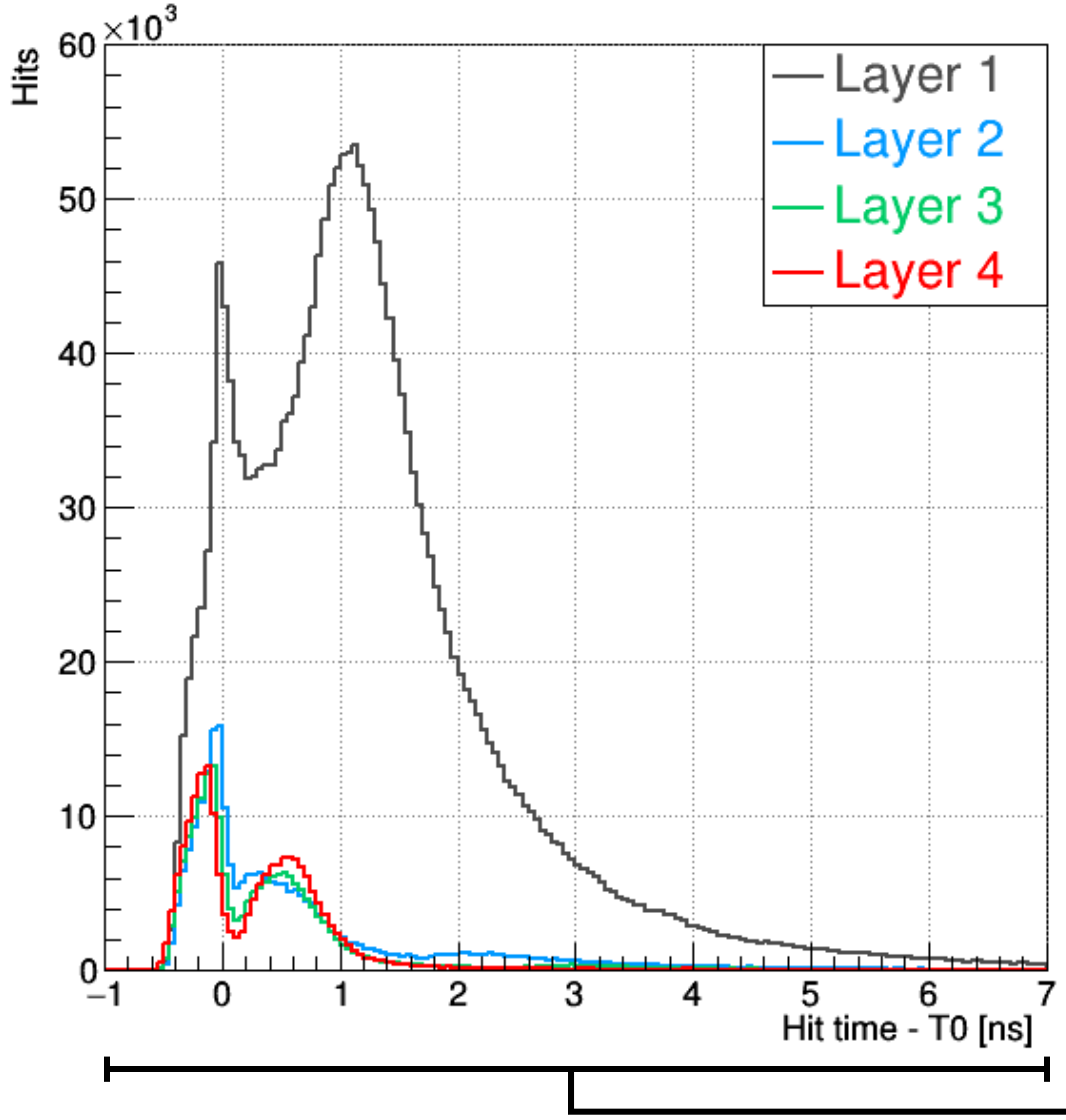
BIB particles produced by FLUKA → ~10^8 particles/BX
↳ simulating all of them in GEANT4 is impractical

Only a small fraction of these particles would contribute to actual reconstructed events
↳ particle arriving within a specific readout time interval
+ having sufficient energy to produce a hit



We can define two main metrics relevant for detector-performance optimisation

Using hits in the Vertex Detector (Barrel) as an example: 1 particle = 1 hit → we can count # of particles / cm²



1

Radiation damage to the sensitive materials of the detector
i.e. TID + 1 MeV n. eq. fluence delivered to each element

Particles arriving to the detector at any time are relevant
↳ full range of time must be integrated

Backscaterring of BIB particles from the detector must be taken into account

Small-scale details of the geometry are less relevant
↳ simplified detector geometry is implemented directly in FLUKA (dimensions + average material composition)

Realistic radiation maps of the detector can be obtained in the fastest way possible

Relevant for determining the materials and technologies to be used in different regions of the detector

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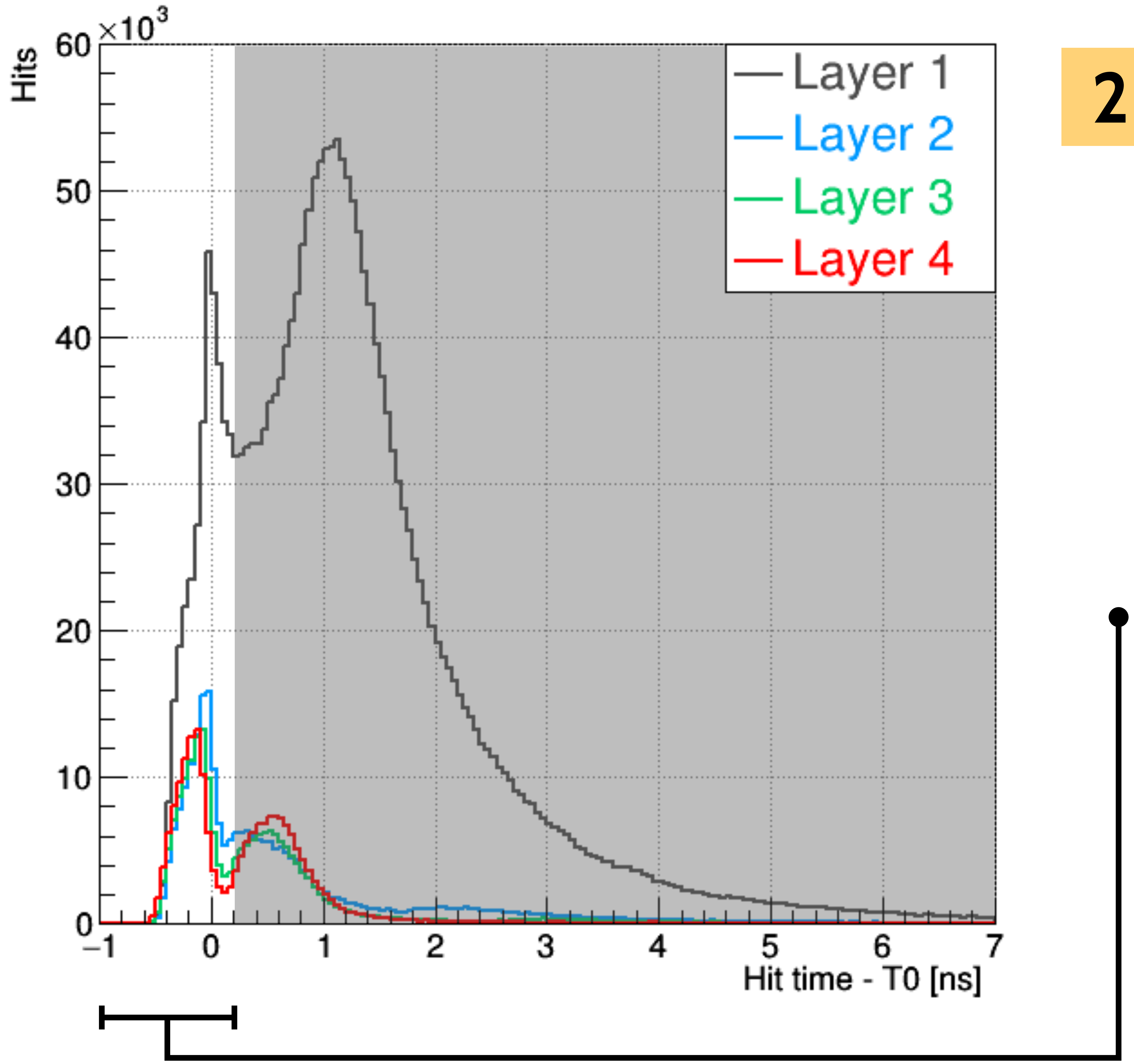
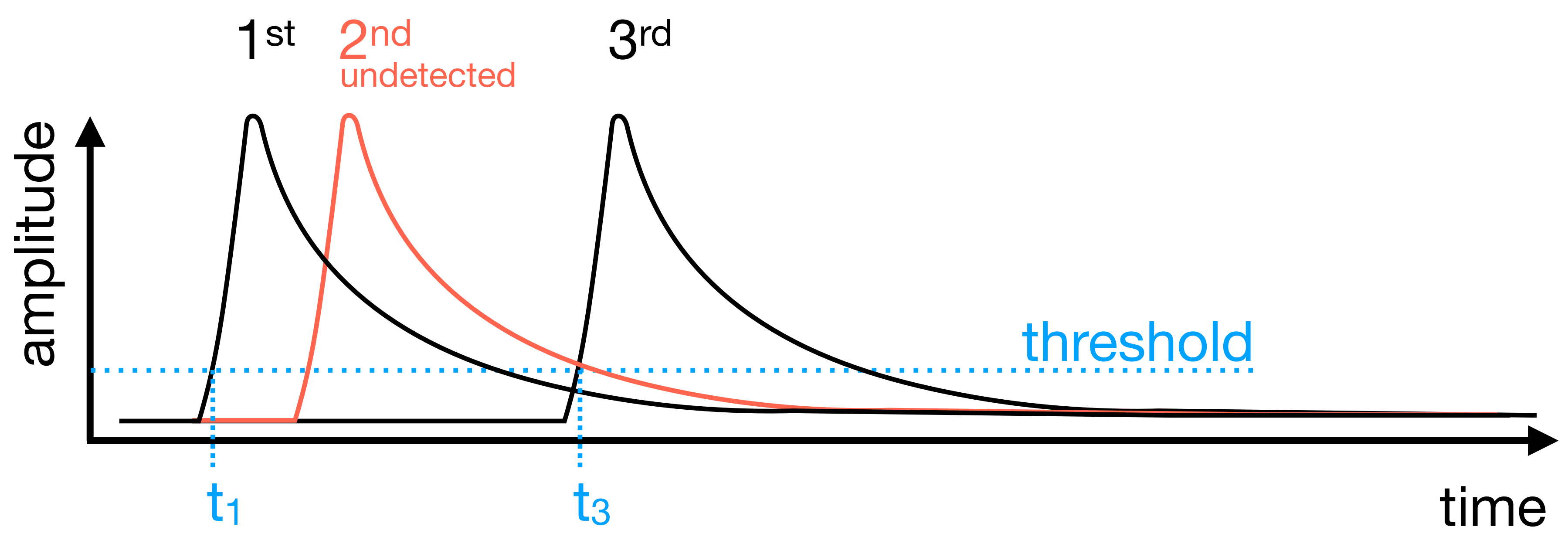


2 Detector occupancy – determines the chance of a pile-up signal in the same readout channel: typically should be ≤ 1%



Dead time can be much larger than the time resolution

↳ all BIB particles arriving even before the BX must be included up to the end of the readout time window

Relevant for determining the necessary spatial granularity in different regions of the detector

↳ balancing physics performance vs cost vs data rates

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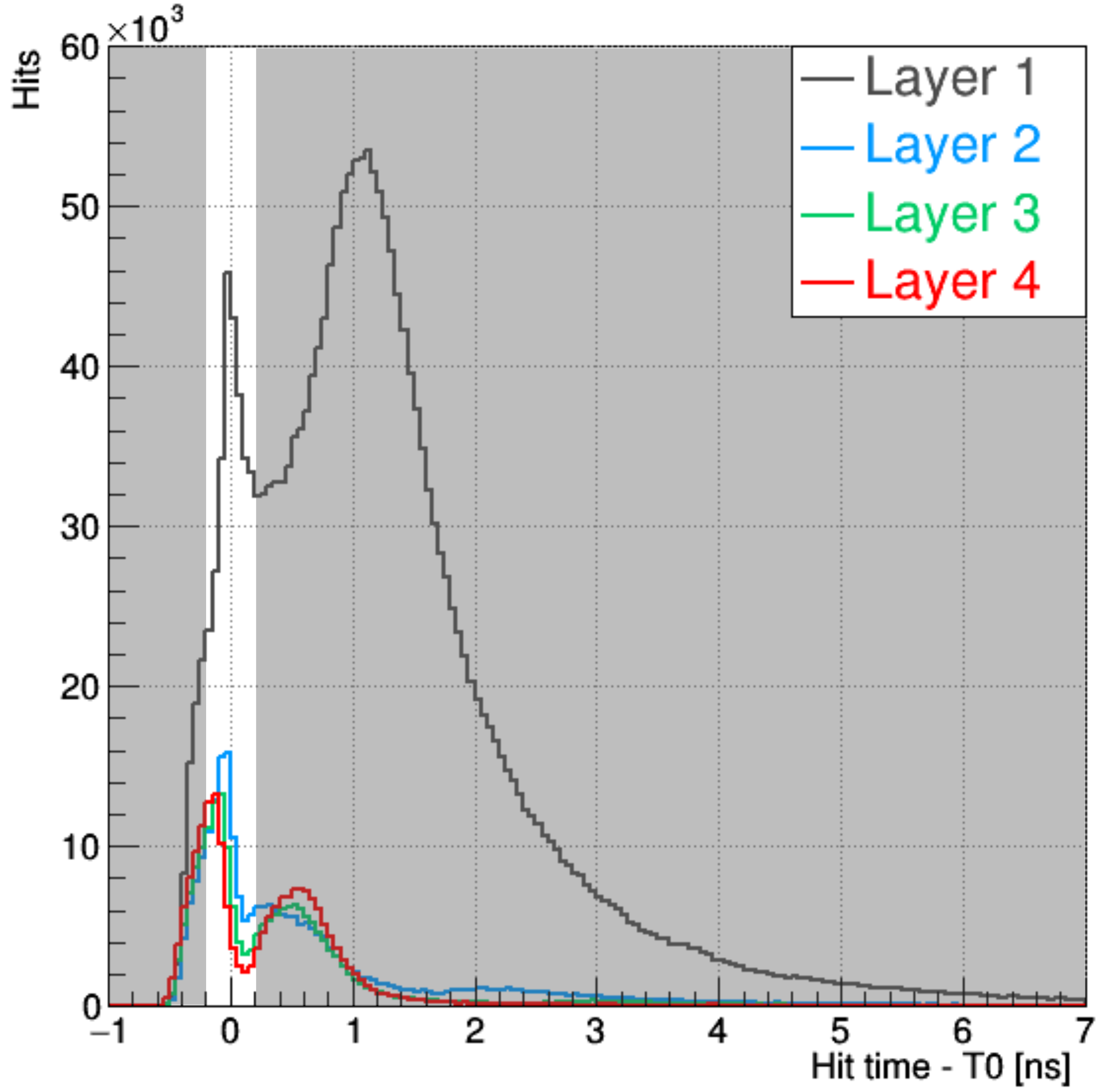
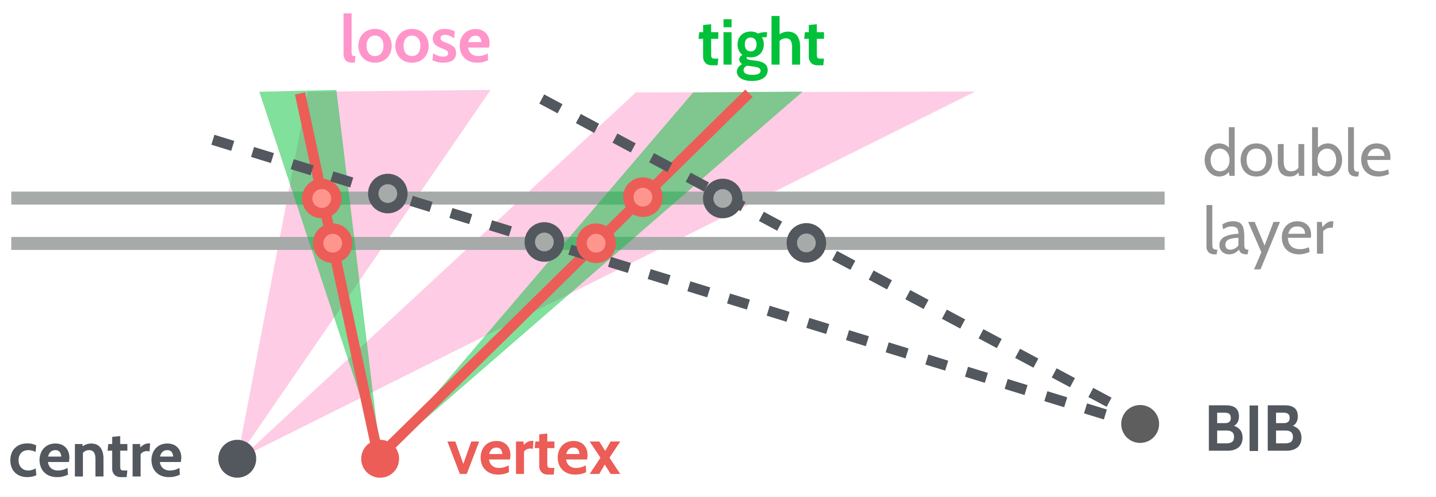


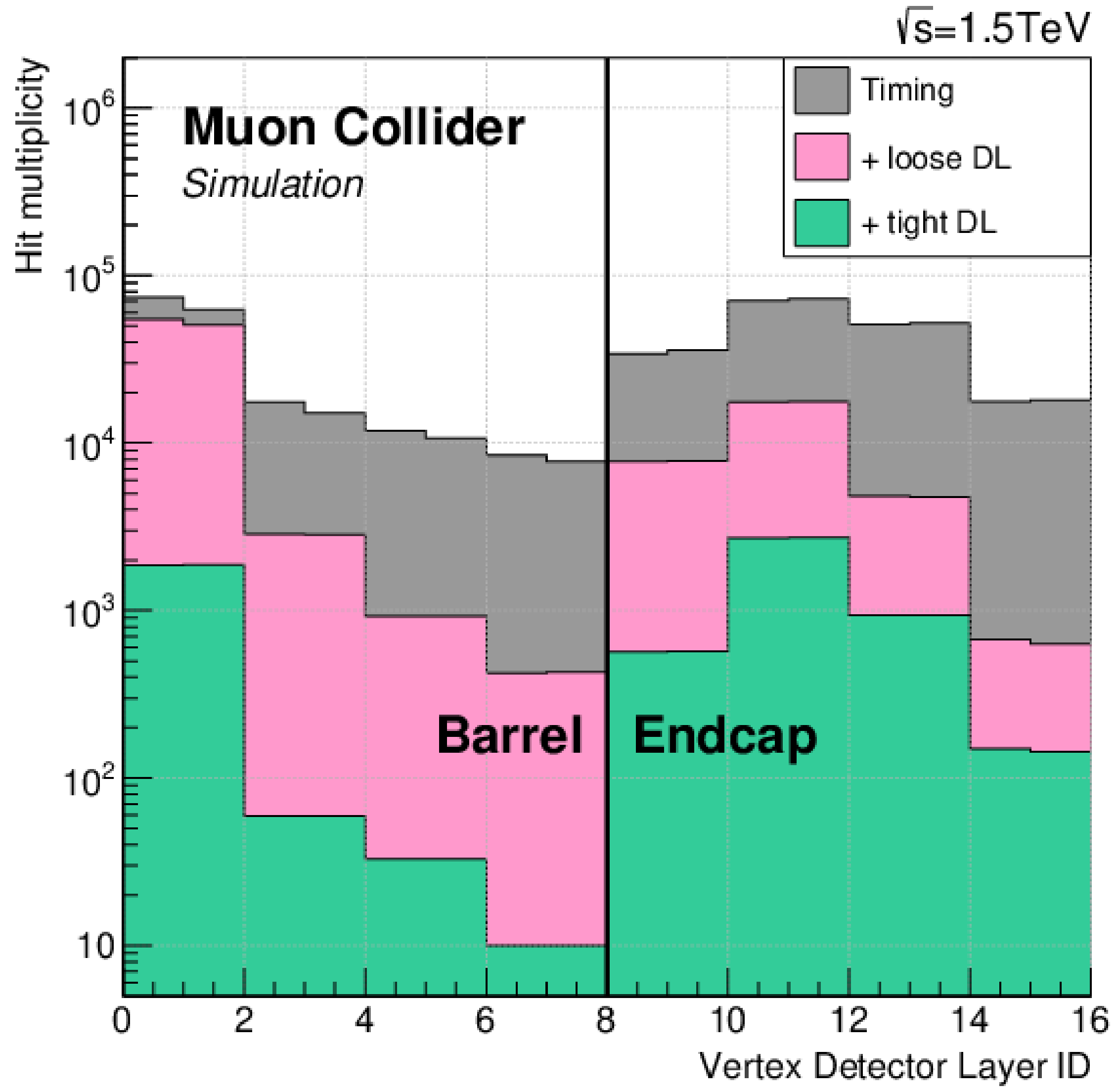
3 Total hit multiplicity → determines reconstruction complexity

↳ mostly relevant for track reconstruction (combinatorics)

Particle density affects the performance of other techniques

↳ e.g. angular selection of hit pairs pointing towards the vertex

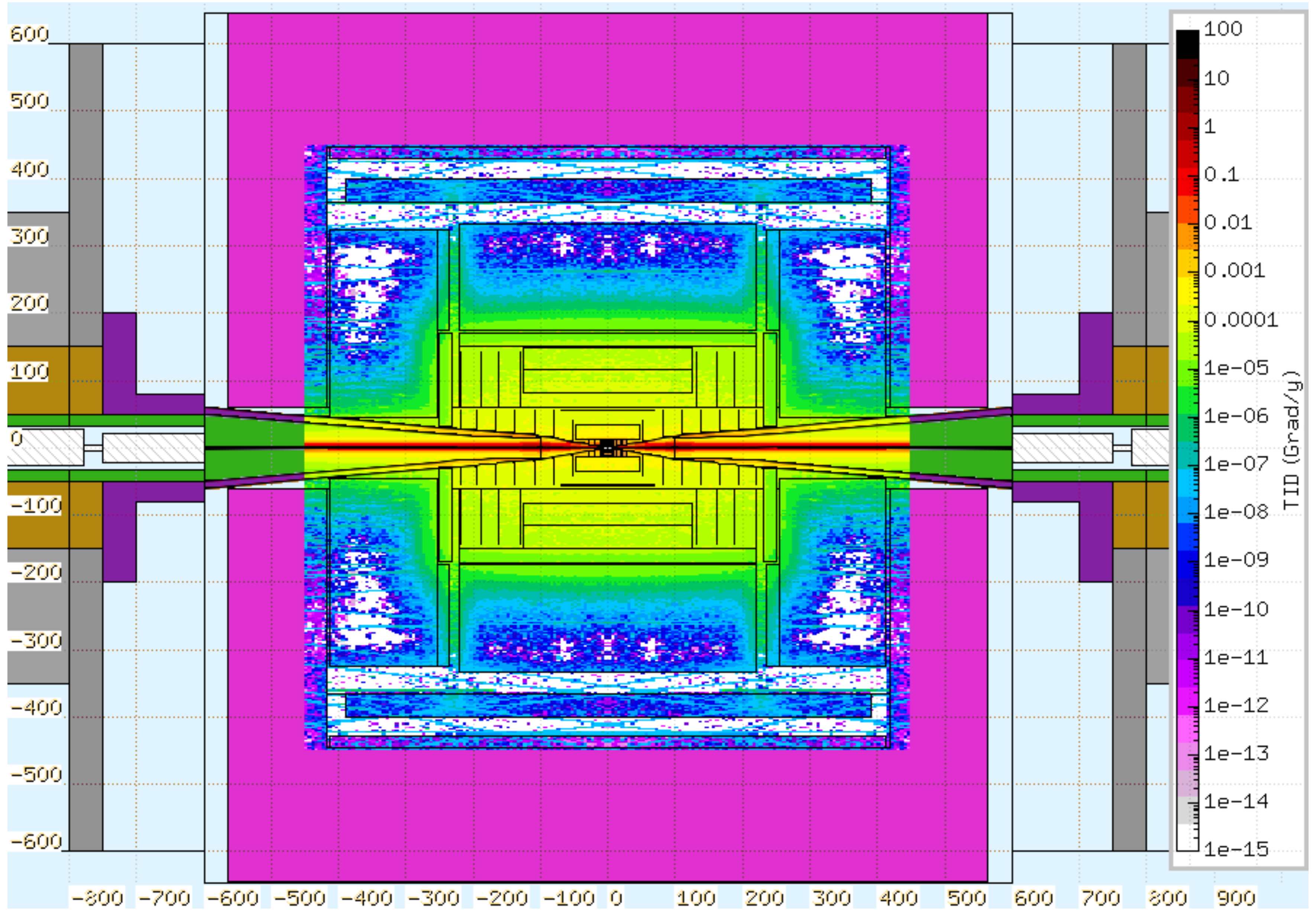




Relevant for determining optimal BIB-suppression algorithms + fine-tuning geometry for such algorithms

↳ double-layer sensor arrangements *(angular hit-pair filtering)*, spatial granularity *(cluster shape analysis)*

BIB simulation in FLUKA has two setups now:



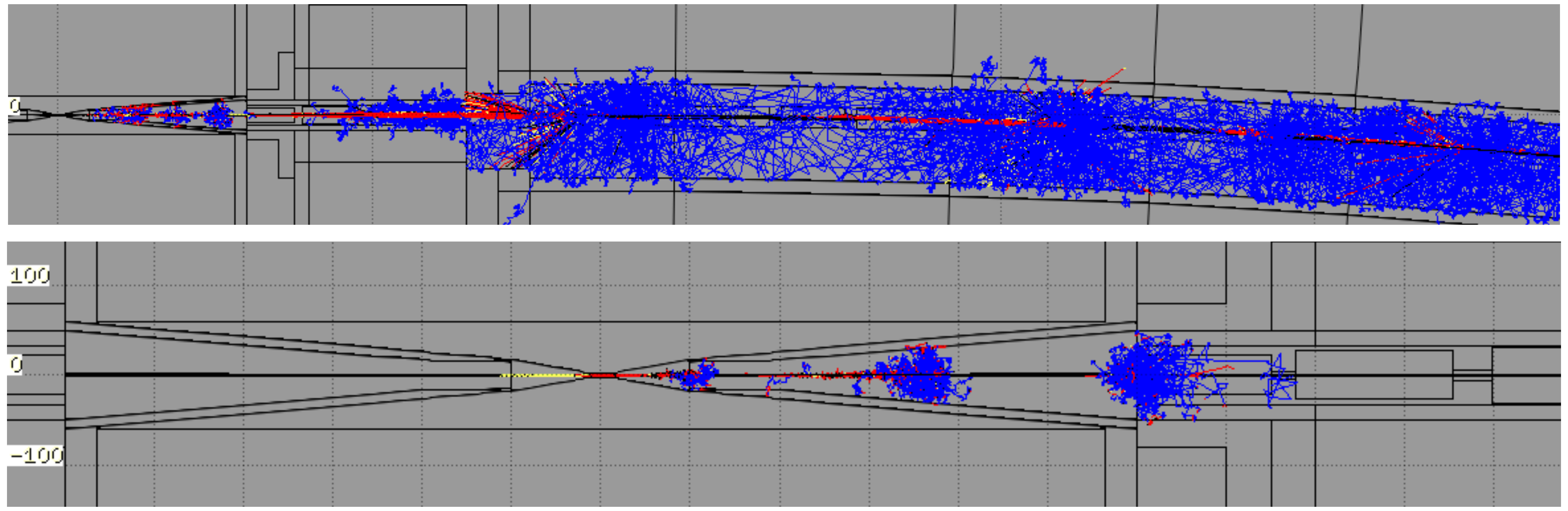
1 **MDI + approximate detector geometry**
↳ particles collected at several predefined surfaces

Particles collected at each surface and saved to file
↳ fast analysis to see particle densities at each surface

Approximate detector layout is known
↳ iterating through MDI designs to optimise the metrics

2 **Just the MDI + detector outer box**
↳ particles stopped at the border and saved to file

Particles passed to GEANT4 for detector simulation
↳ optimising detector geometry and parameters
+ fine-tuning reconstruction algorithms

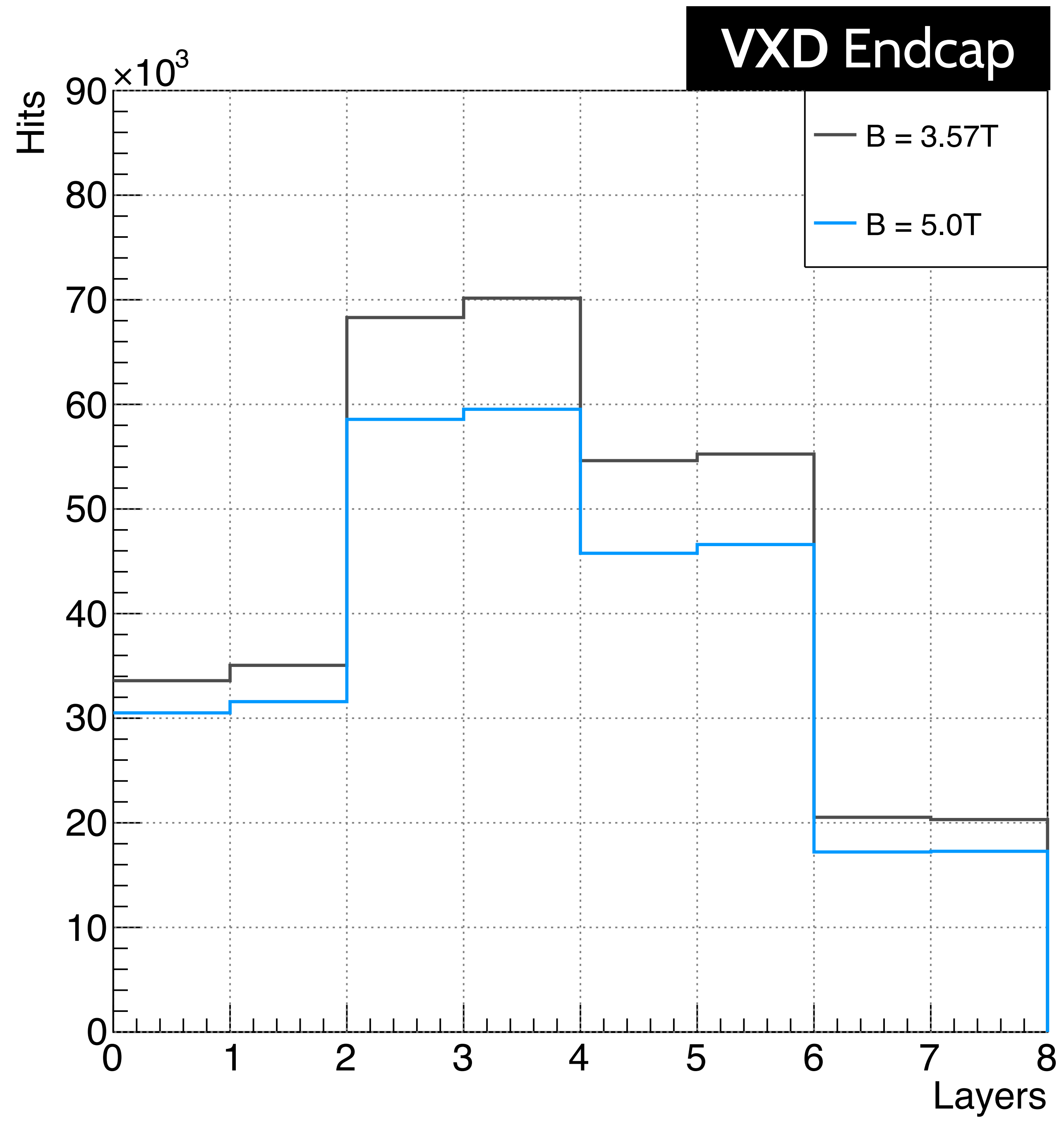


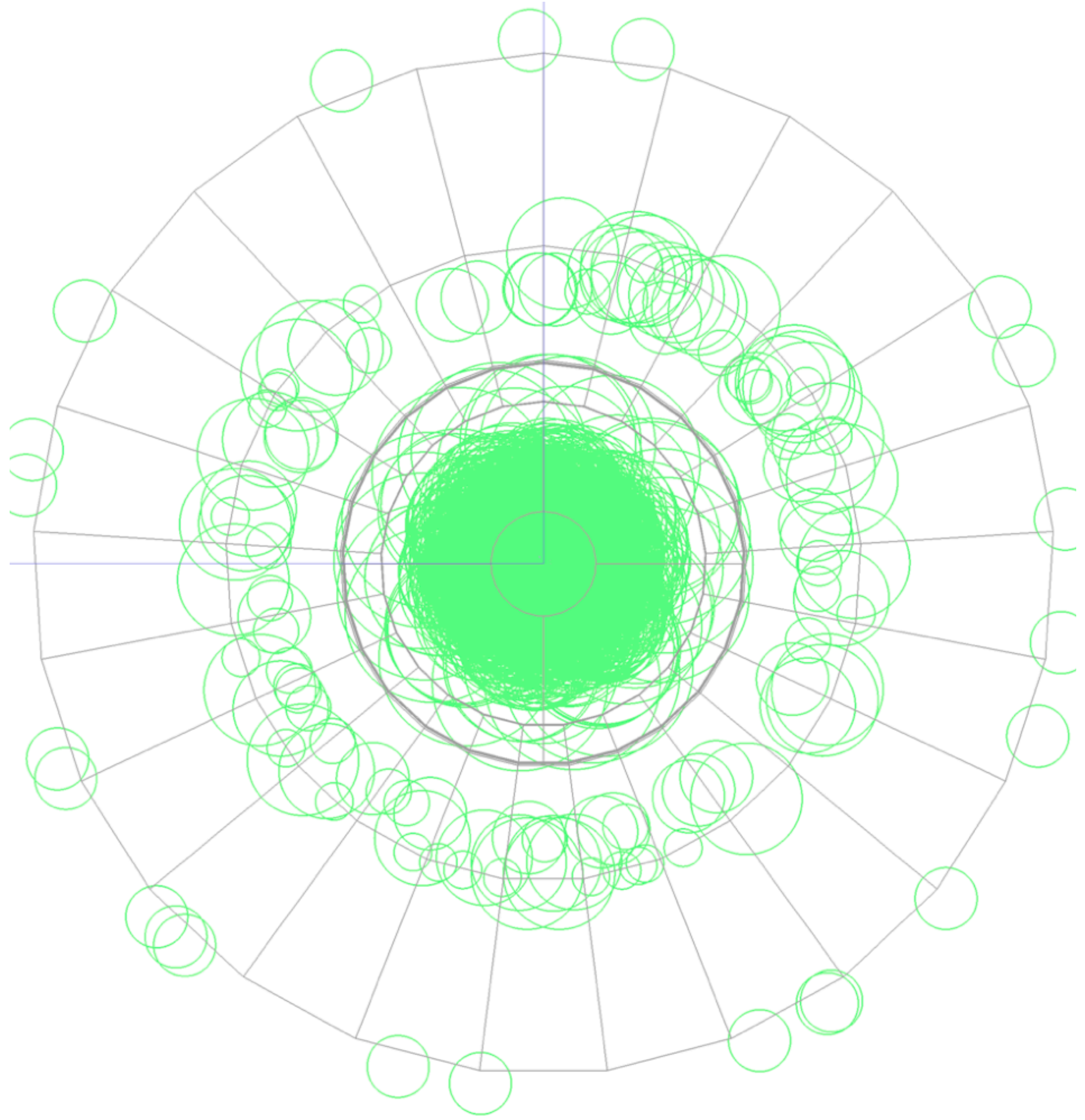
All relevant information stored for each BIB particle: pdgId, energy, momentum, position, absolute time
↳ allows flexible filtering of BIB particles that are passed to the MDI analysis or to GEANT4 simulation

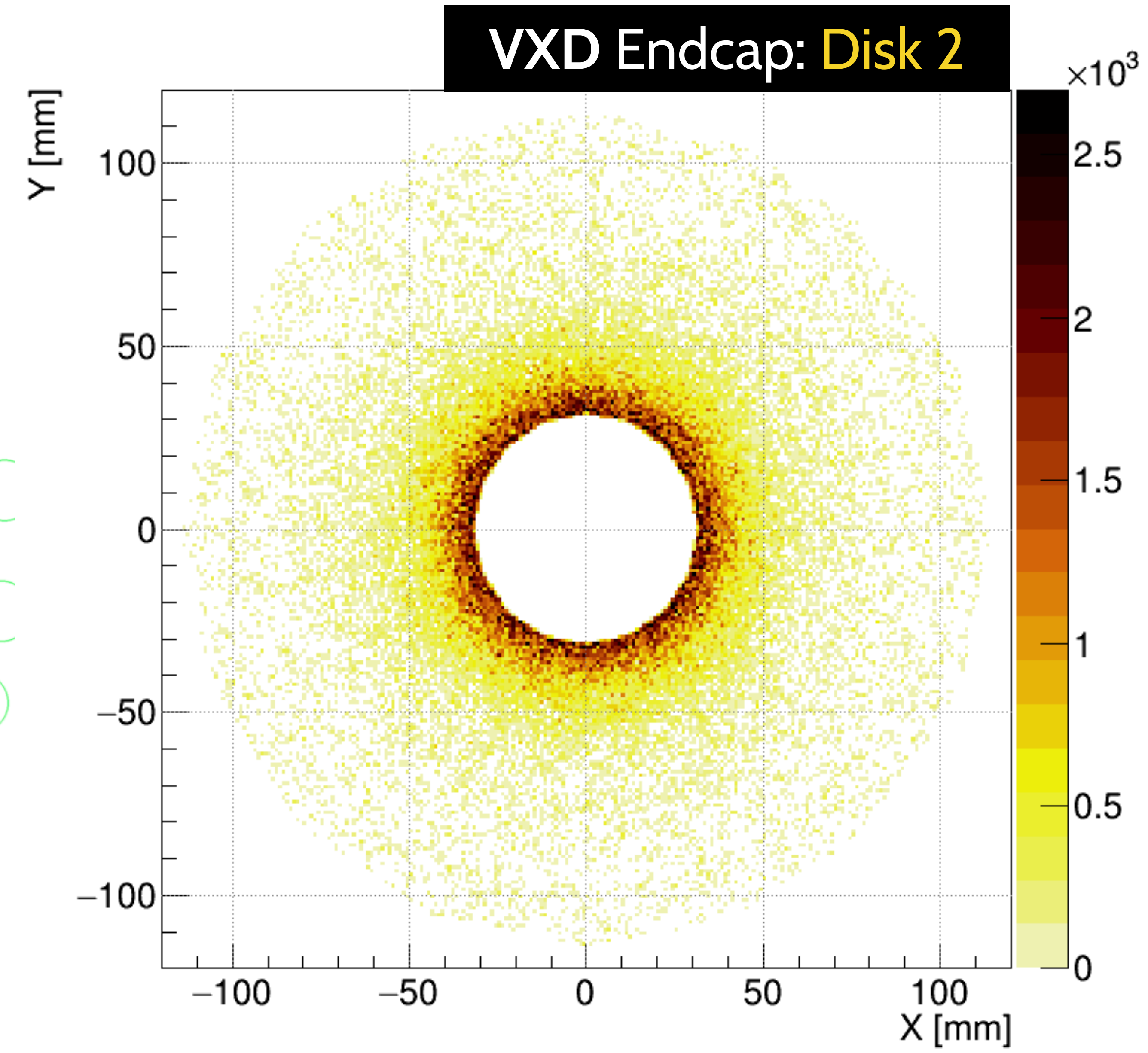
Example case: Vertex Detector

Most of BIB hits in the Vertex Detector are caused by very soft looping electrons (multiple hits/particle)

Increasing magnetic field (3.57 T → 5.0 T) showed significant reduction in hit multiplicity







← **magnetic field modified only in GEANT4 detector model**
but not in FLUKA → path of electrons within MDI is wrong

With the new approach occupancy in the Vertex Detector can be evaluated for several B-field values directly in FLUKA
↳ choice of the optimal MDI geometry + B-field can be much faster → tuning of hit-filtering algorithms in GEANT4

Summary

Simulation of BIB particles involves two independent packages: FLUKA and GEANT4

Part of detector-specific simulations are being implemented on the FLUKA side
for faster MDI-optimisation turnaround

Fine-tuning of the detector layout, response parametes and algorithm implementations in GEANT4
for detailed simulation of the actual physics performance

Plenty of detector-specific algorithms implemented in ILCSoft for each subdetector
covered by next talks in the *Physics and Detectors* session