Geant4 detector simulation at the Muon Collider

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Muon Collider combines advantages of the two types of machines:

high precision of e^+e^- colliders + **high energy reach** of *pp* colliders

- like $e^\pm$, $\mu^\pm$ are elementary particles → creating "*clean*" collisions
- × 200 higher mass → × 10^9 less synchrotron radiation losses
  ↳ can fit in a compact ring *(27 km circumference for $\sqrt{s}$ = 14 TeV)*

Introduction: Muon Collider

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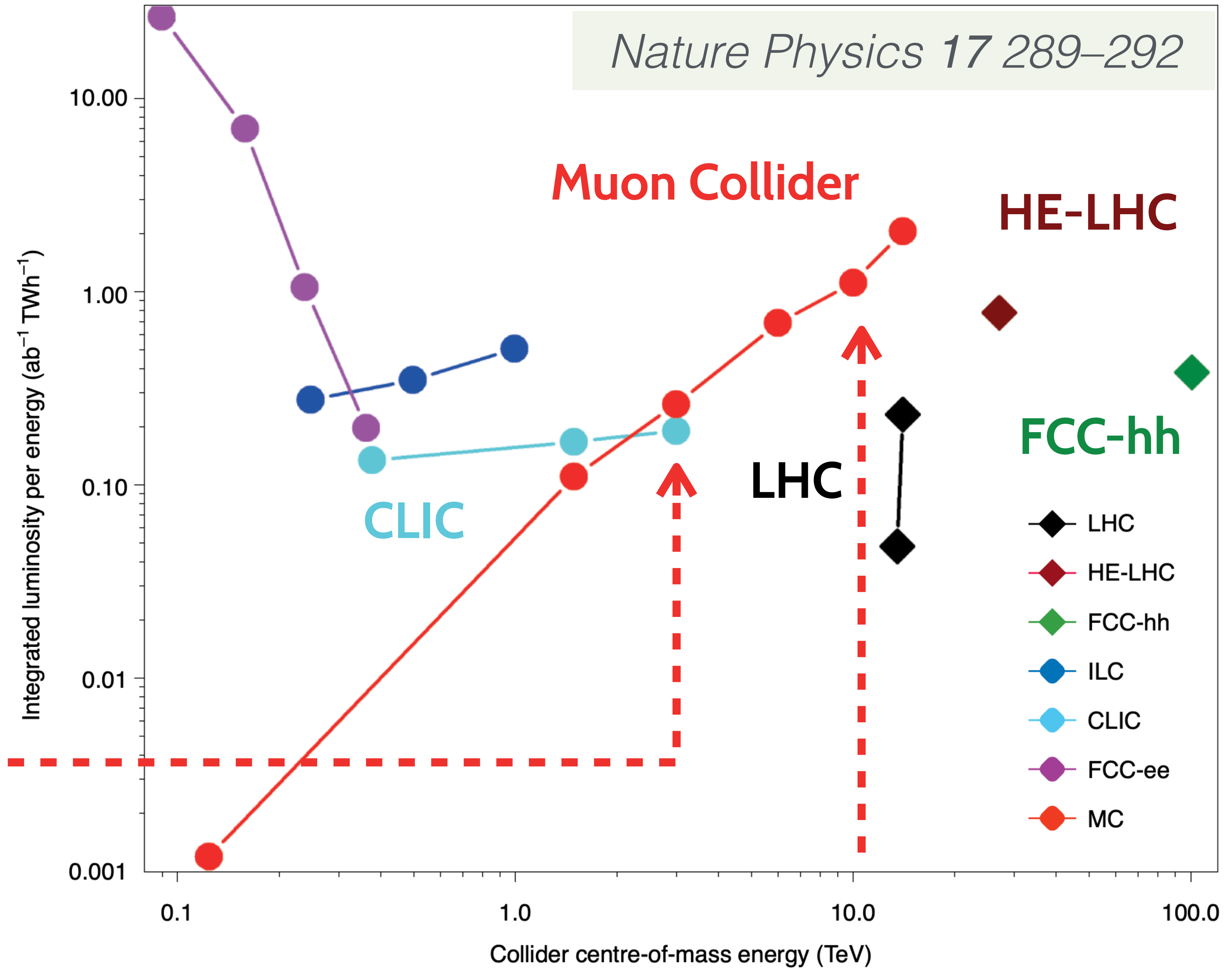

At $\sqrt{s}$ ≥ 3 TeV Muon Collider is the most energy efficient machine
providing rich physics from $\mu^+\mu^-$ collisions and VBF processes

Current target of our studies: $\sqrt{s}$ ≥ 10 TeV Muon Collider

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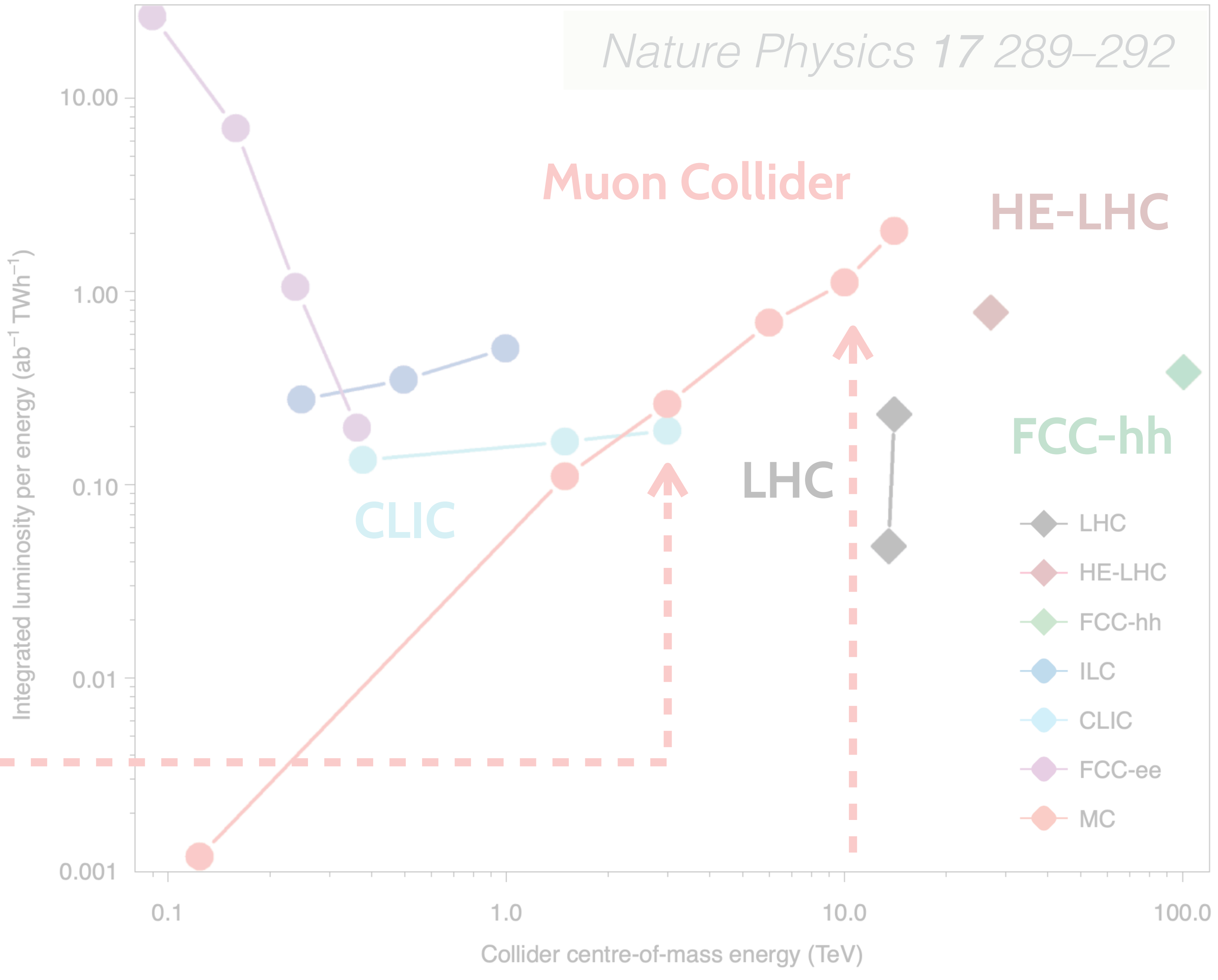

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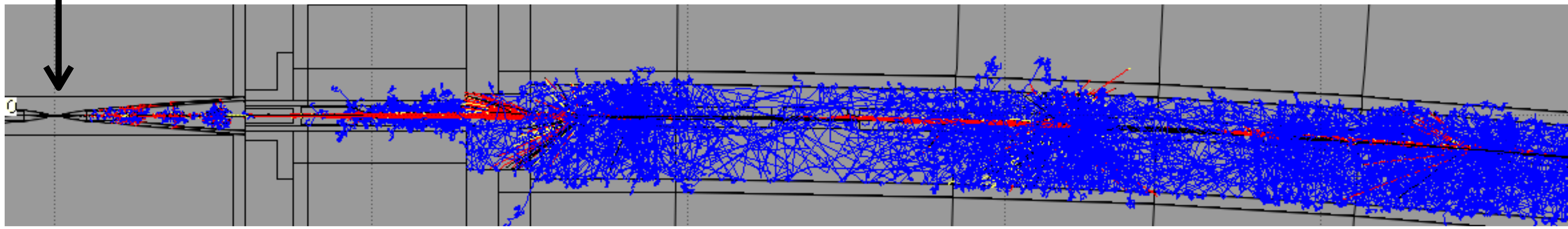
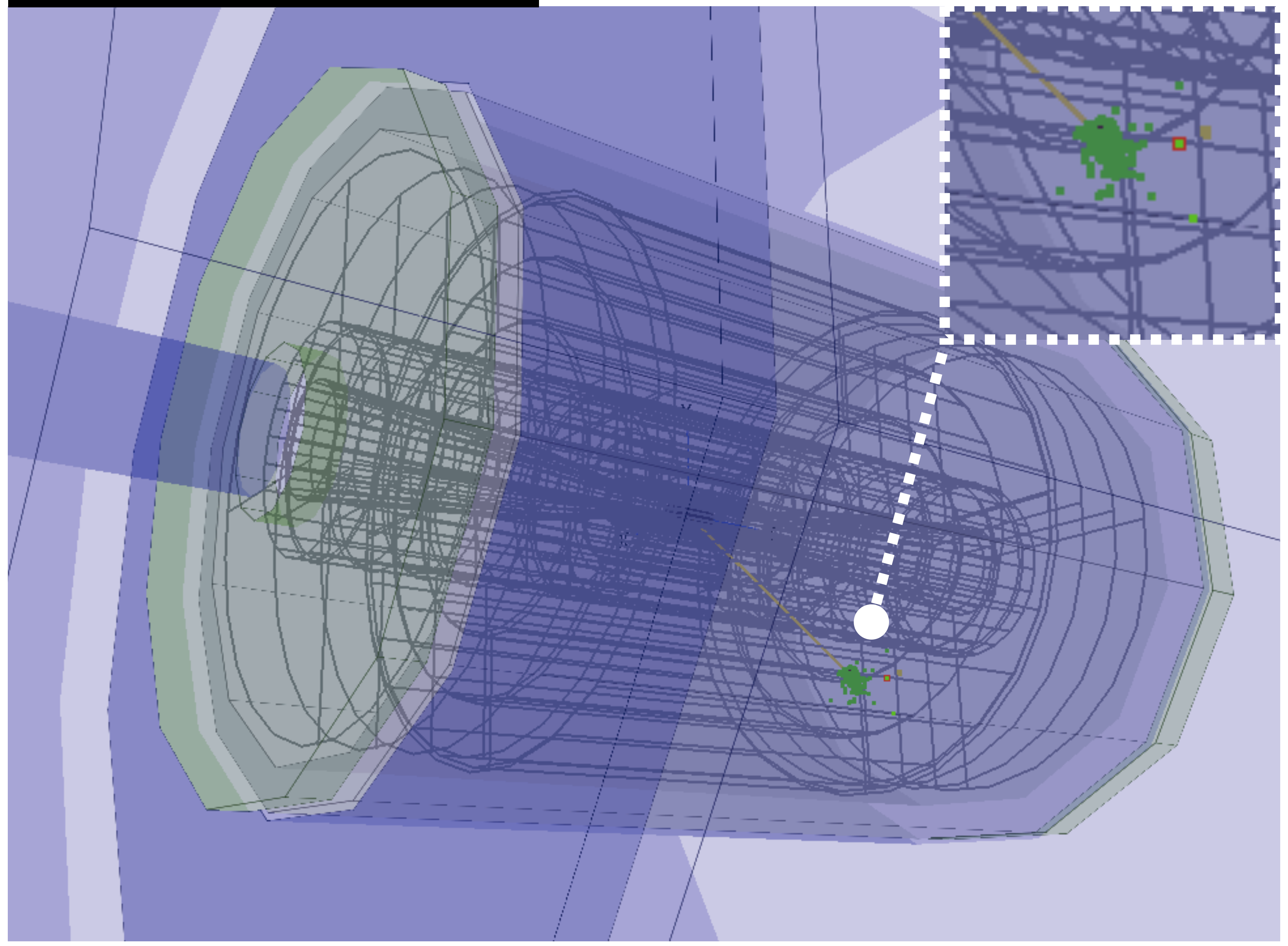
The greatest experimental challenge: mitigation of the Beam Induced Background (BIB)
part of the μ± decays reaching the detector

Propagation of μ± beams in the accelerator lattice ▶



We need to tune our detector design and reconstruction algorithms to cope with BIB

10 GeV photon in ECAL



The project started with very limited manpower

↳ focus on a simulation workflow that is fast to set up and easy to modify for different detector prototypes

Scope of the simulation

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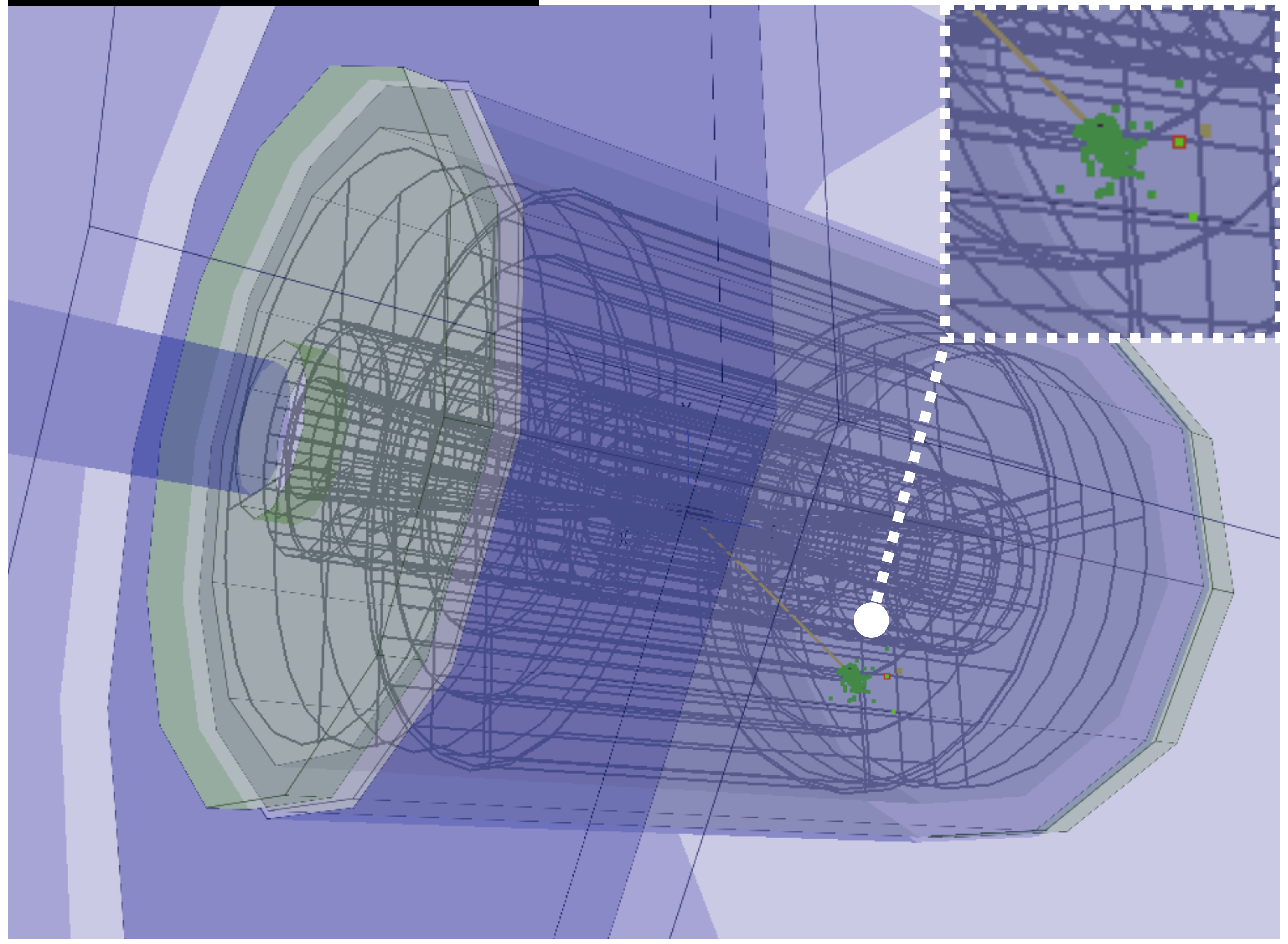
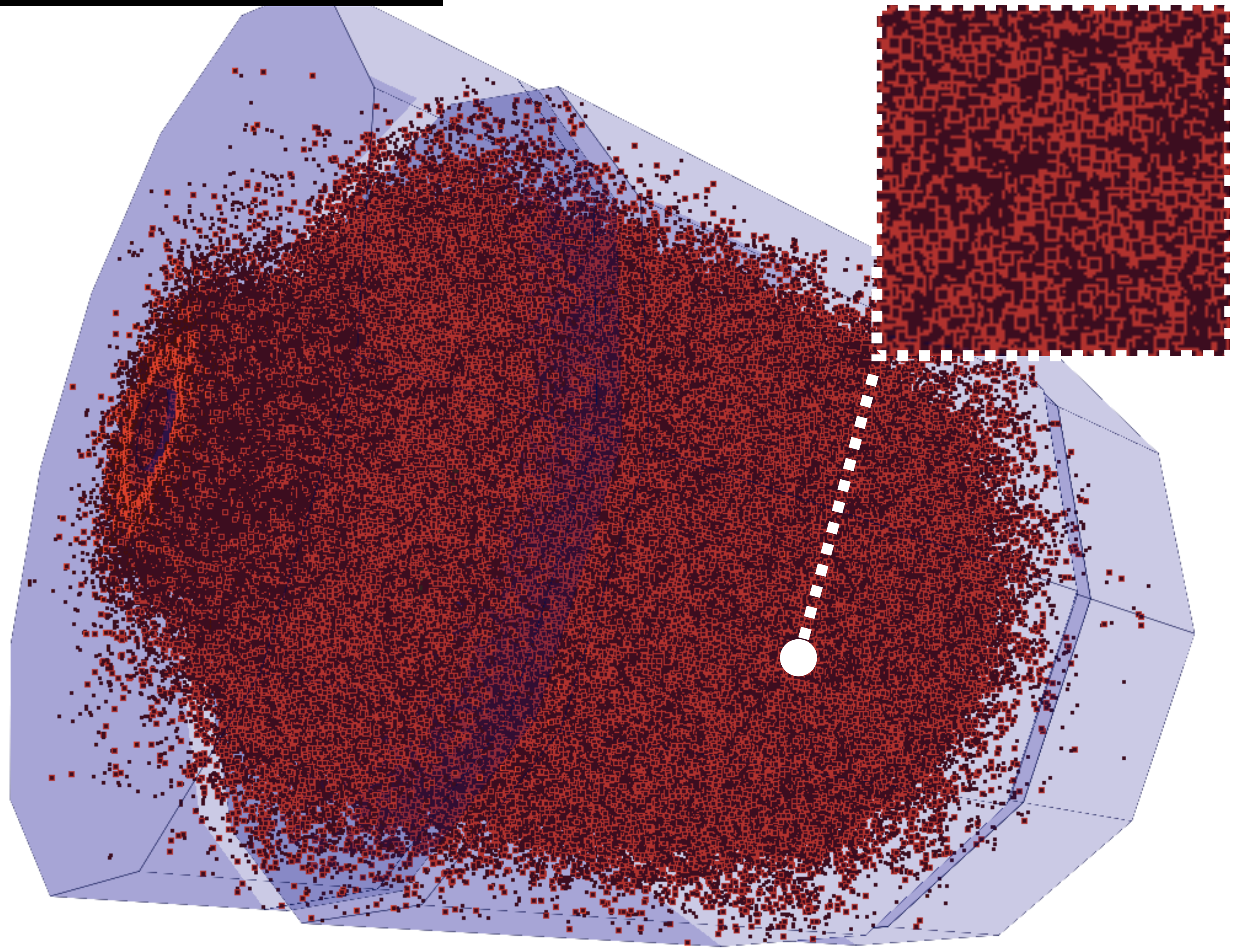


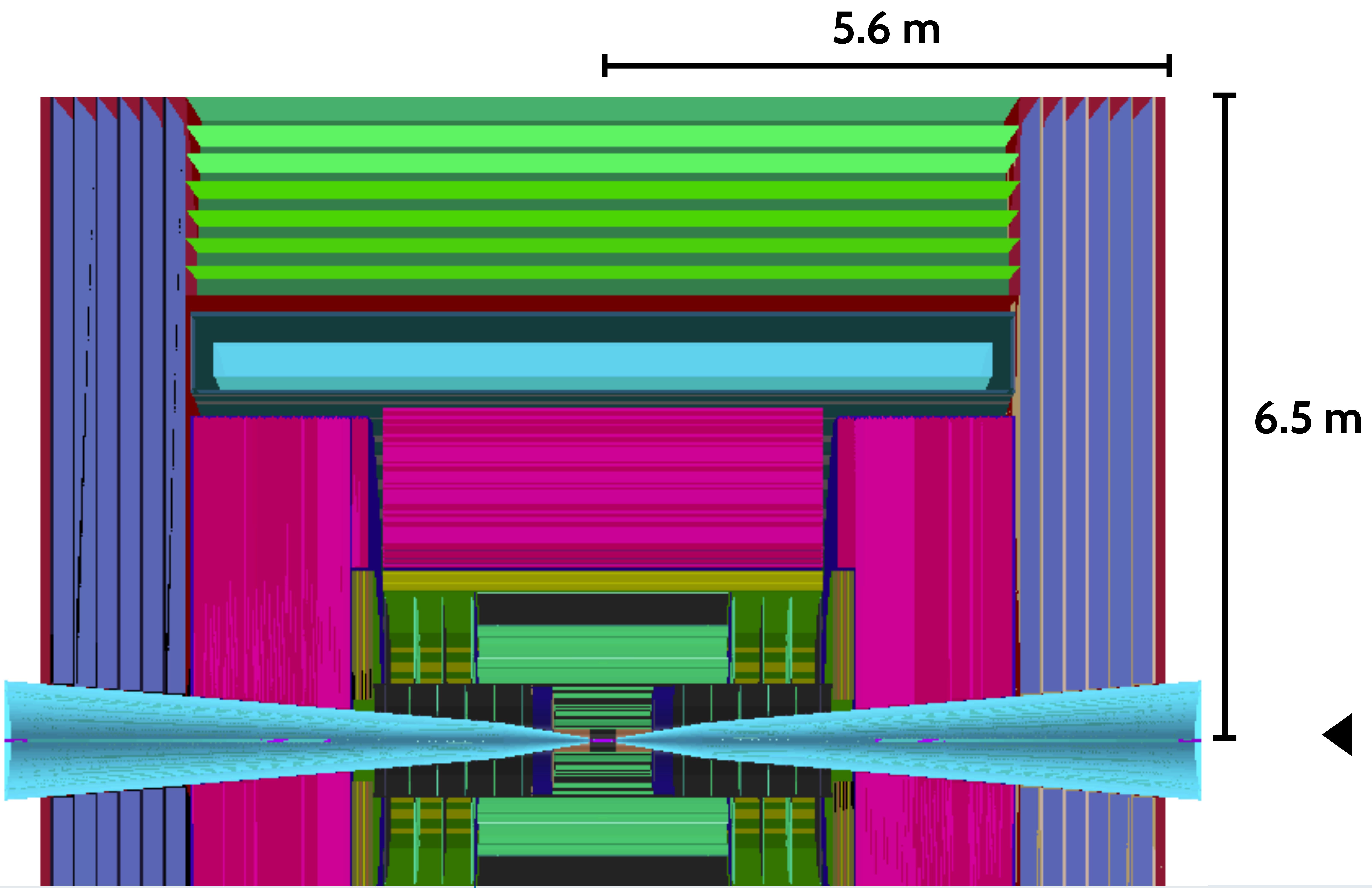
10 GeV photon + **BIB** in ECAL



Adding **SimHits** from **BIB particles**

Roughly 4×10^8 particles from $\mu^\pm$ decays arriving to the detector in a single bunch crossing (BX)

We have 2 detector proposals with dimensions similar to that of the CLIC detector
with main differences in the magnet layout and calorimeter technologies

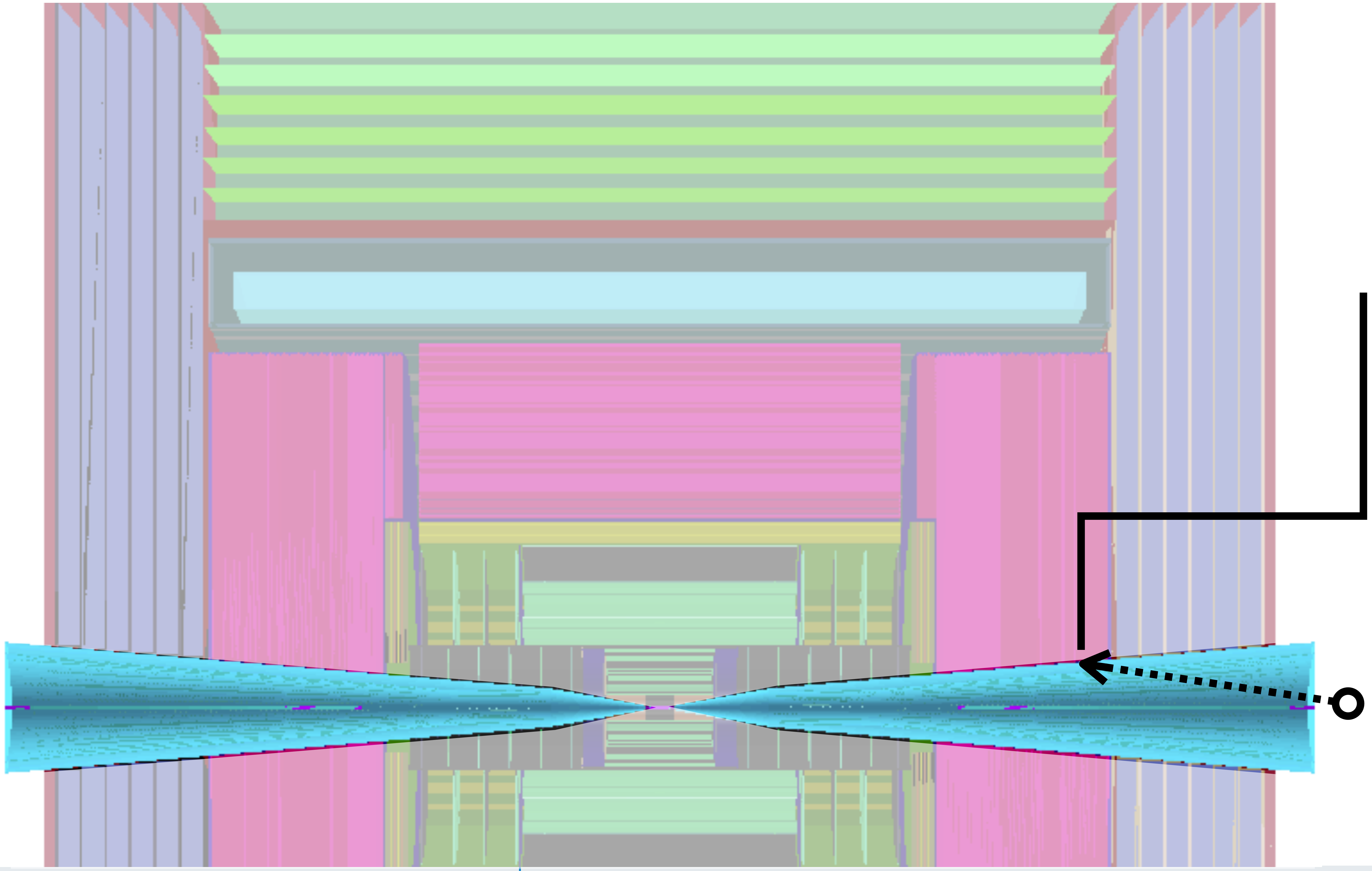


Using DD4hep framework
for geometry description and interfacing to GEANT4

Tungsten nozzles (MDI)
protecting the detector from BIB particles

BIB simulation stages

BIB simulation is performed in two distinctive steps
separated by the outer surface of the MDI



STEP 1

Particles reaching the border are stopped and killed

→ **MCParticles** → **FILE**

μ± decays in the beam lattice simulated with FLUKA
until the MDI-detector border

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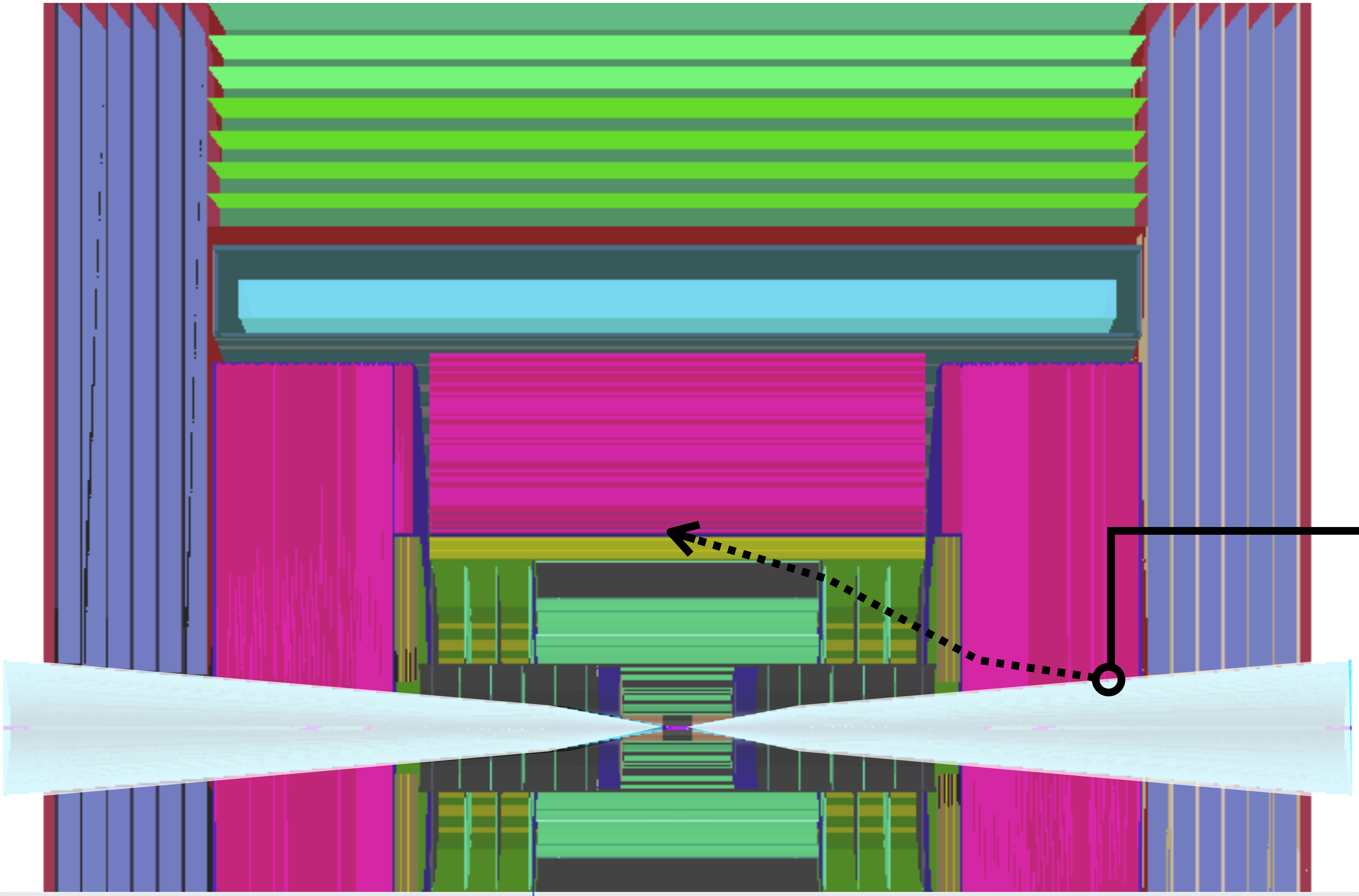


STEP 2

MCParticles ← FILE

Particles are propagated through the detector in GEANT4

SimHits → FILE

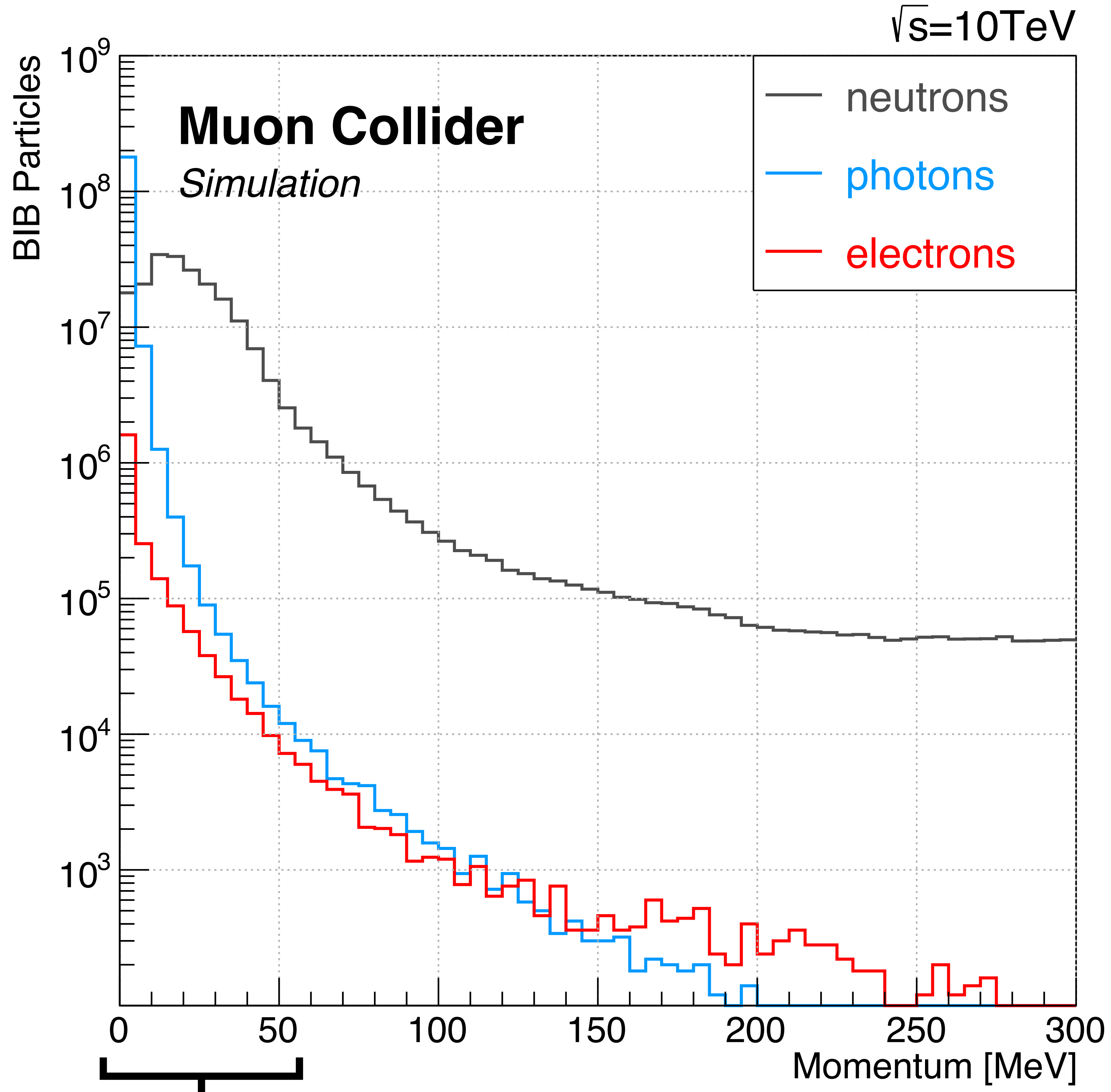
Overlay with signal SimHits
before digitization + reconstruction

BIB particles have several **characteristic features**

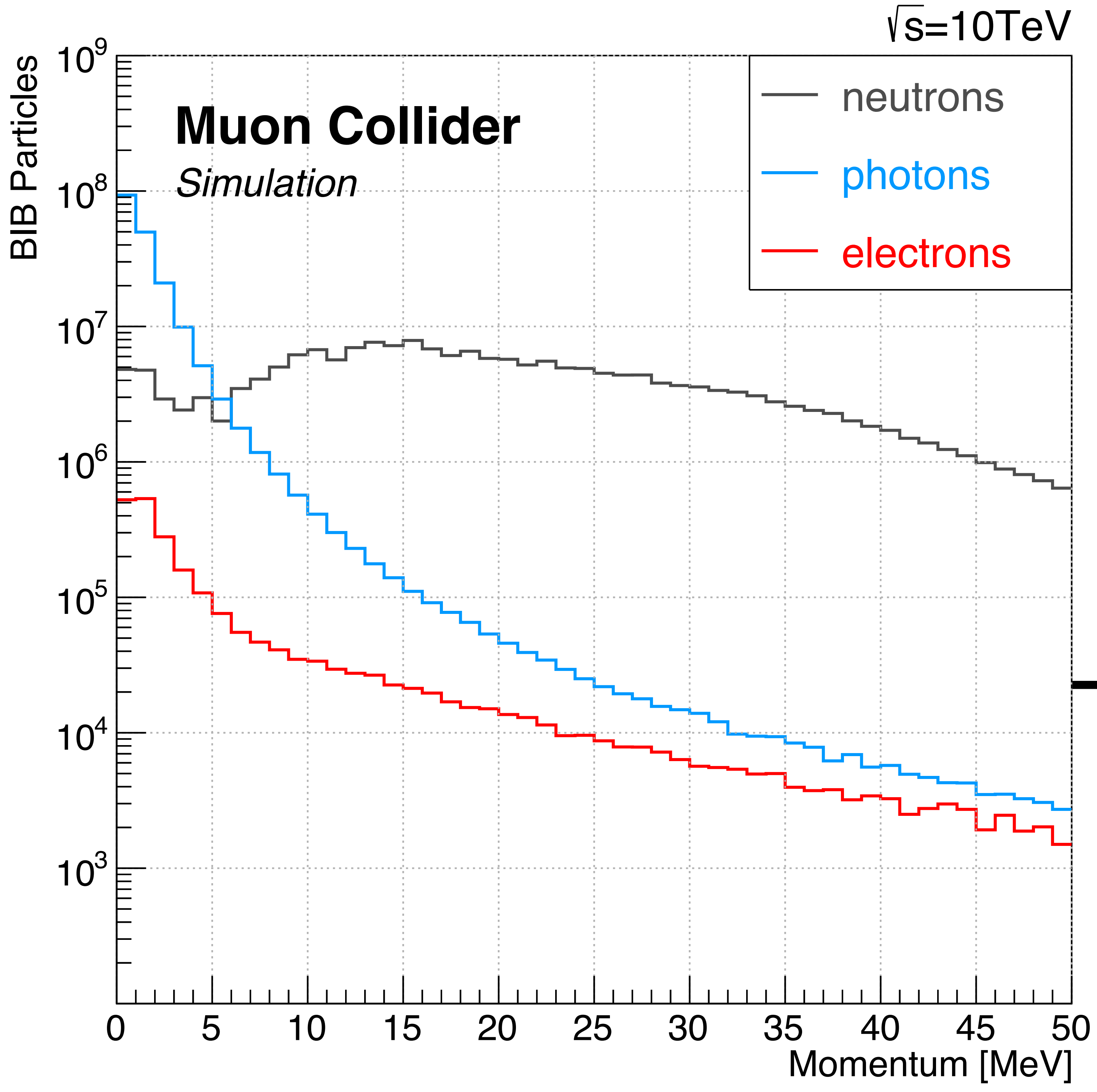
1. Predominantly very soft particles

uniformly distributed in space → not like signal-like tracks or jets

↳ conceptually different from pile-up contributions at the LHC



QGSP_BERT_HP
model should be used ▶
to properly describe
all the particle interactions



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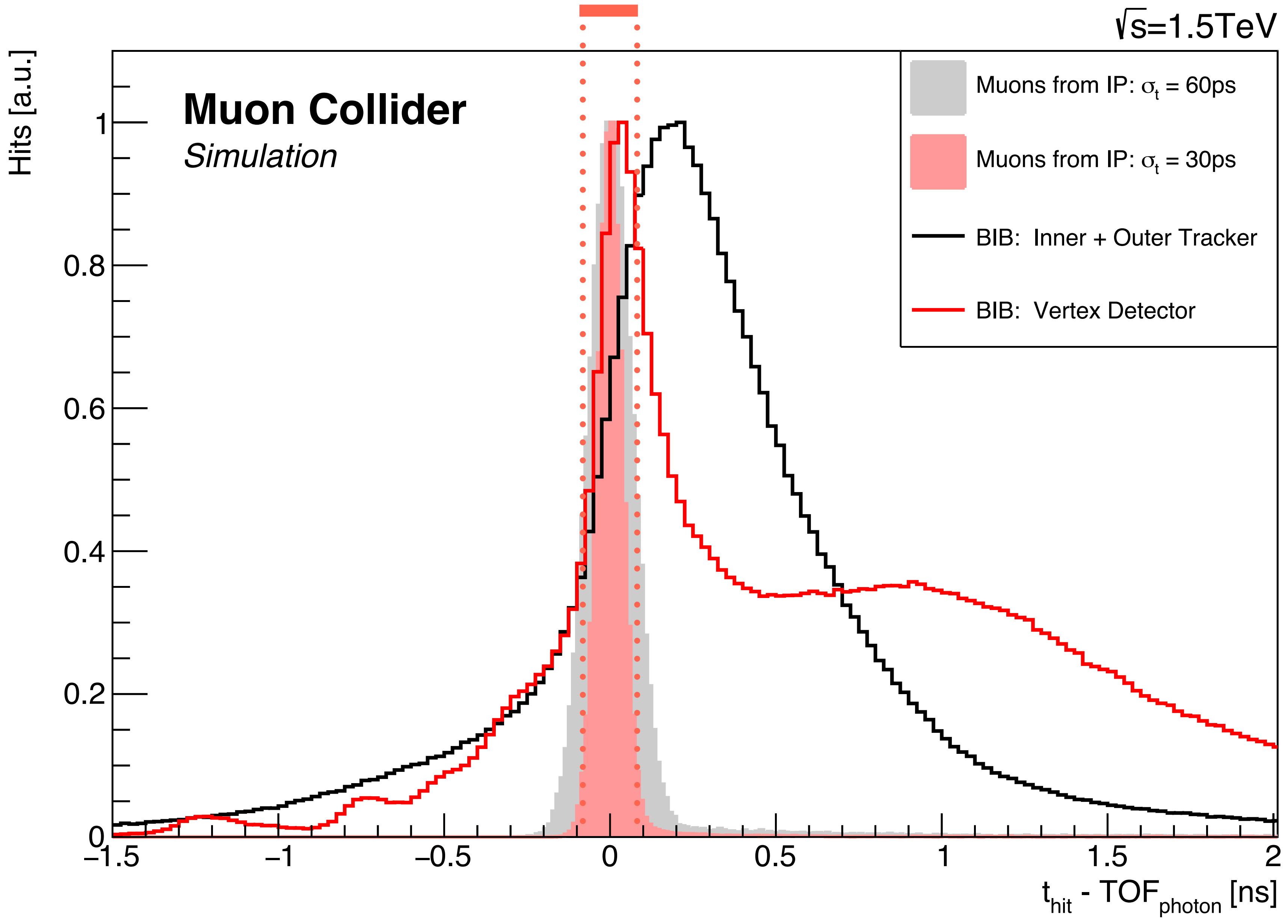
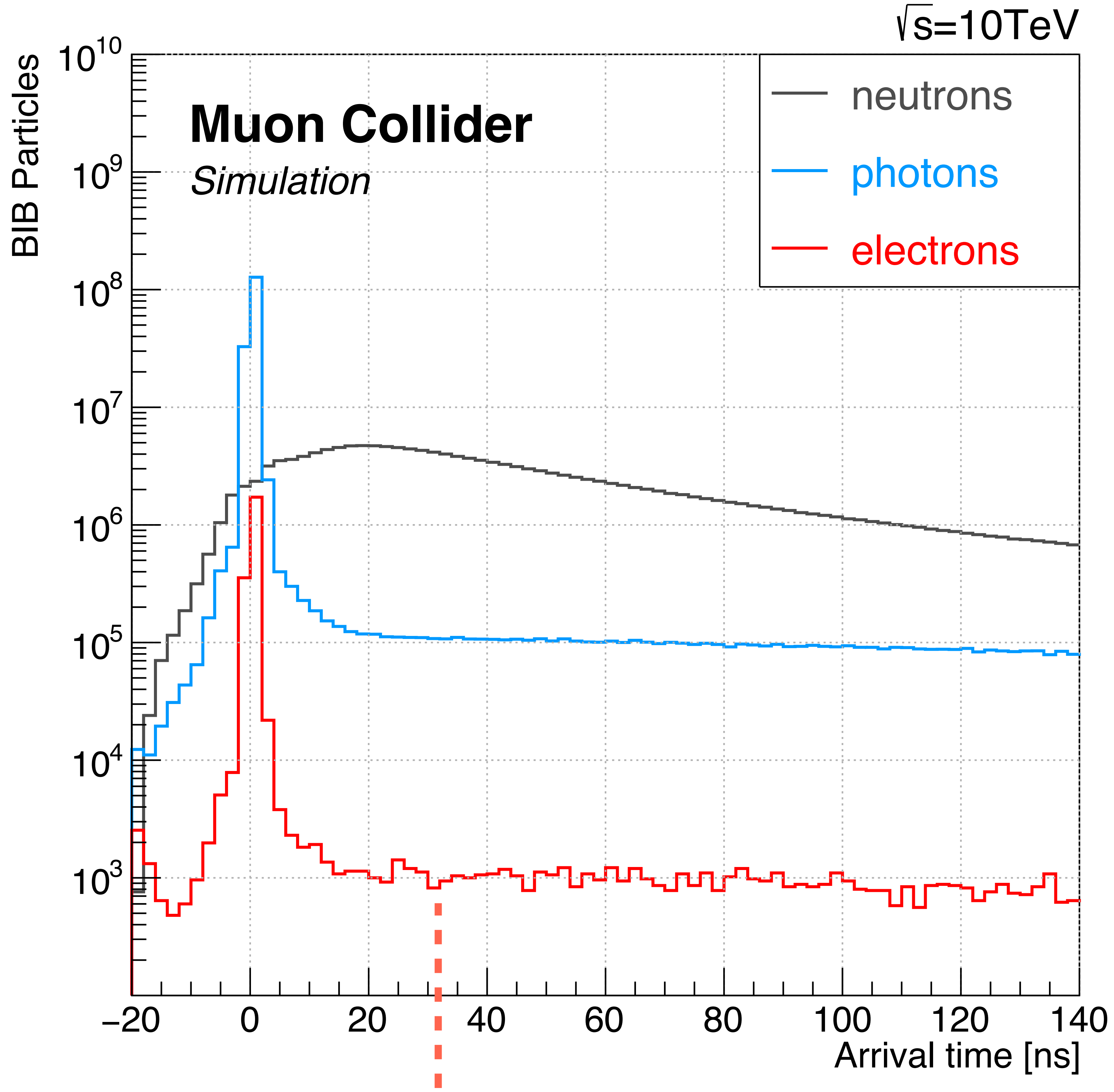
2. **Significant spread in time** (few ns + long tails up to a few μs)

$\mu^+\mu^-$ collision time spread: ≤20 ps
↳ allows out-of-time BIB rejection

SimHits in the tracking detector ▶

VXD acceptance





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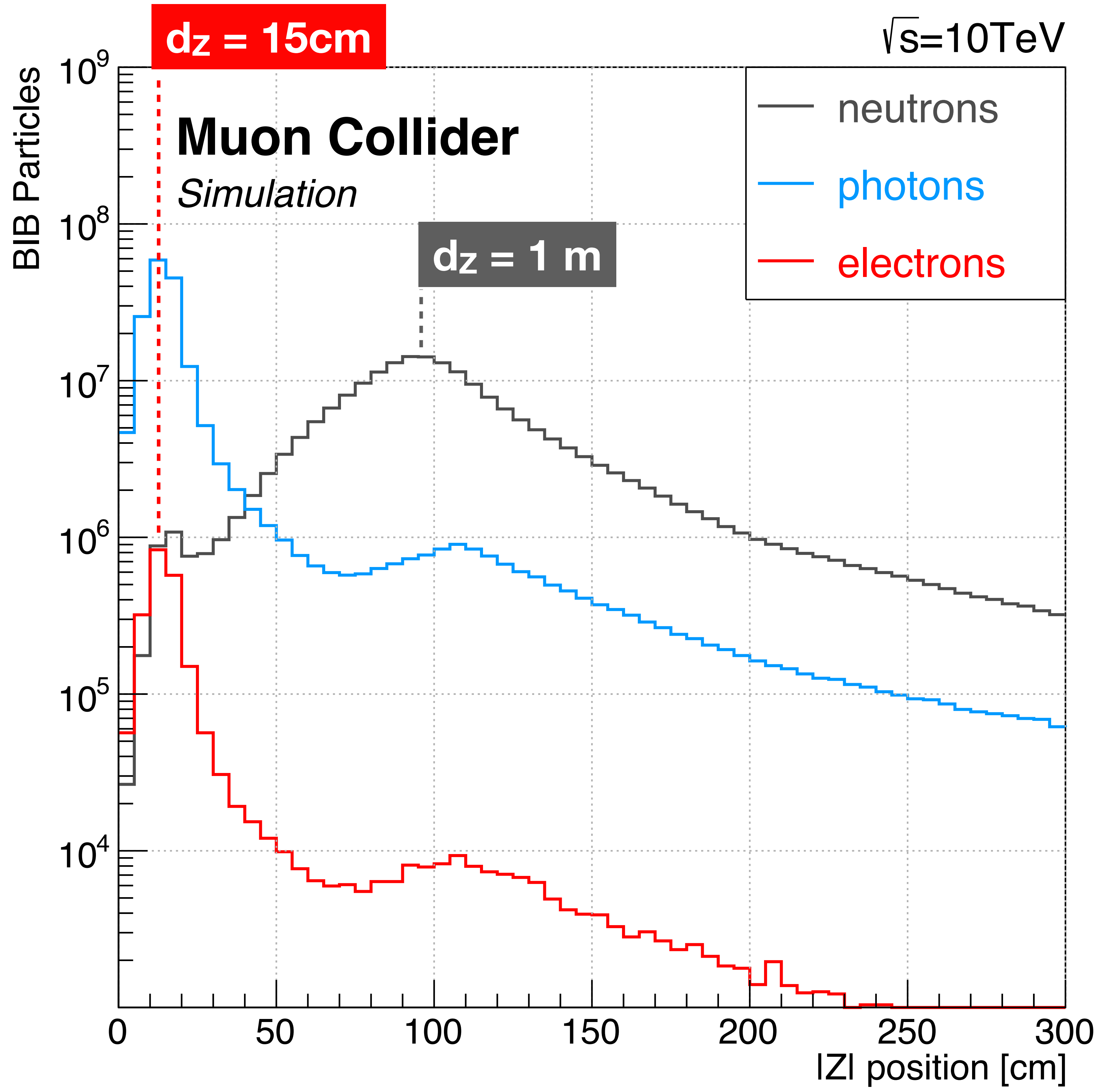
3. **Strongly displaced origin along the beam line**

entering detector at a shallower angle

↳ affects hit-cluster shapes + time of flight

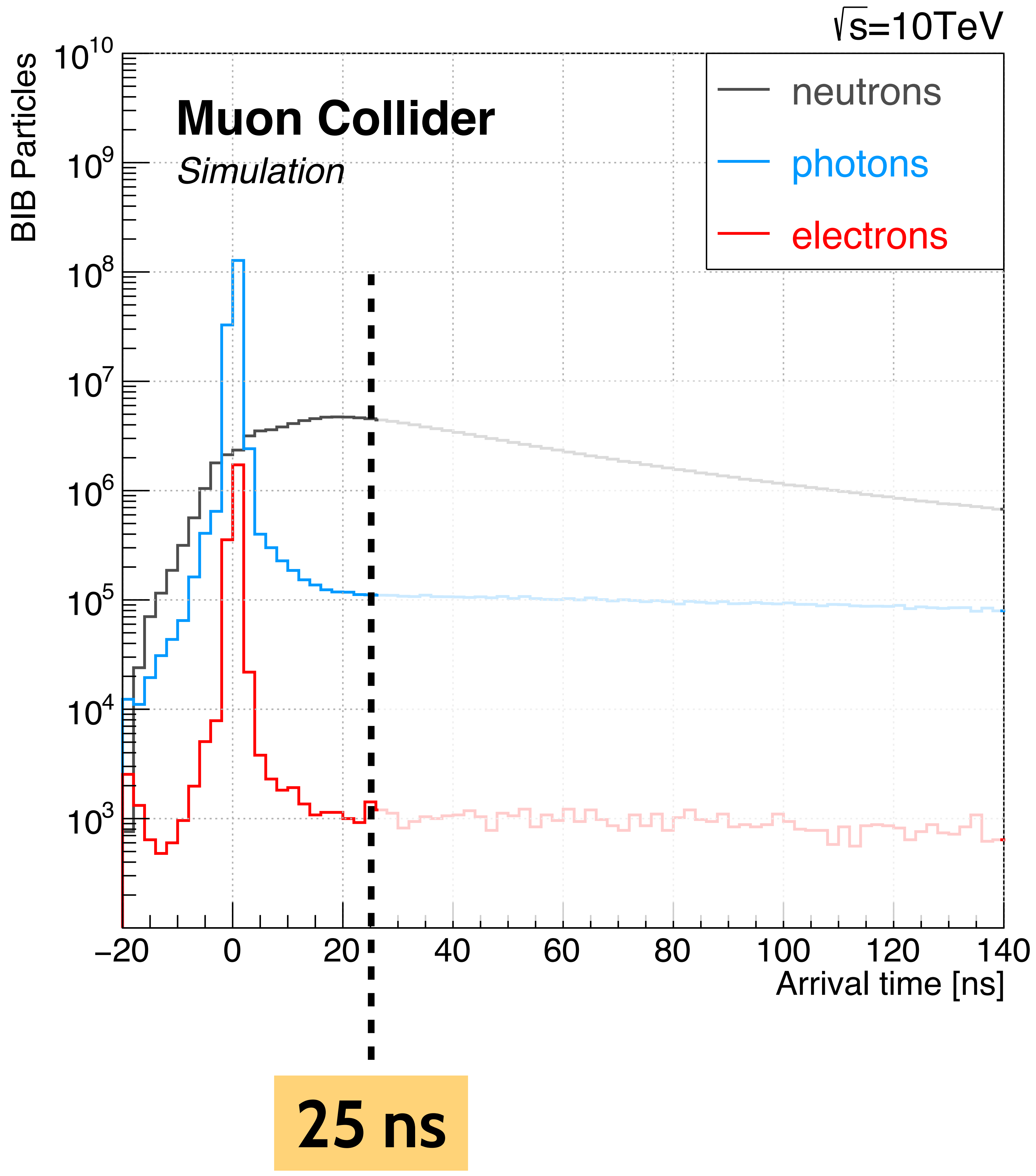


The fastest simulation is the one that is not run at all

1. Discard BIB particles with arrival time ≥ 25 ns

typical integration times in readout electronics: ~ 1-10 ns

↳ hits created by such particles would not contribute to the digitized signal



Computing-load reduction

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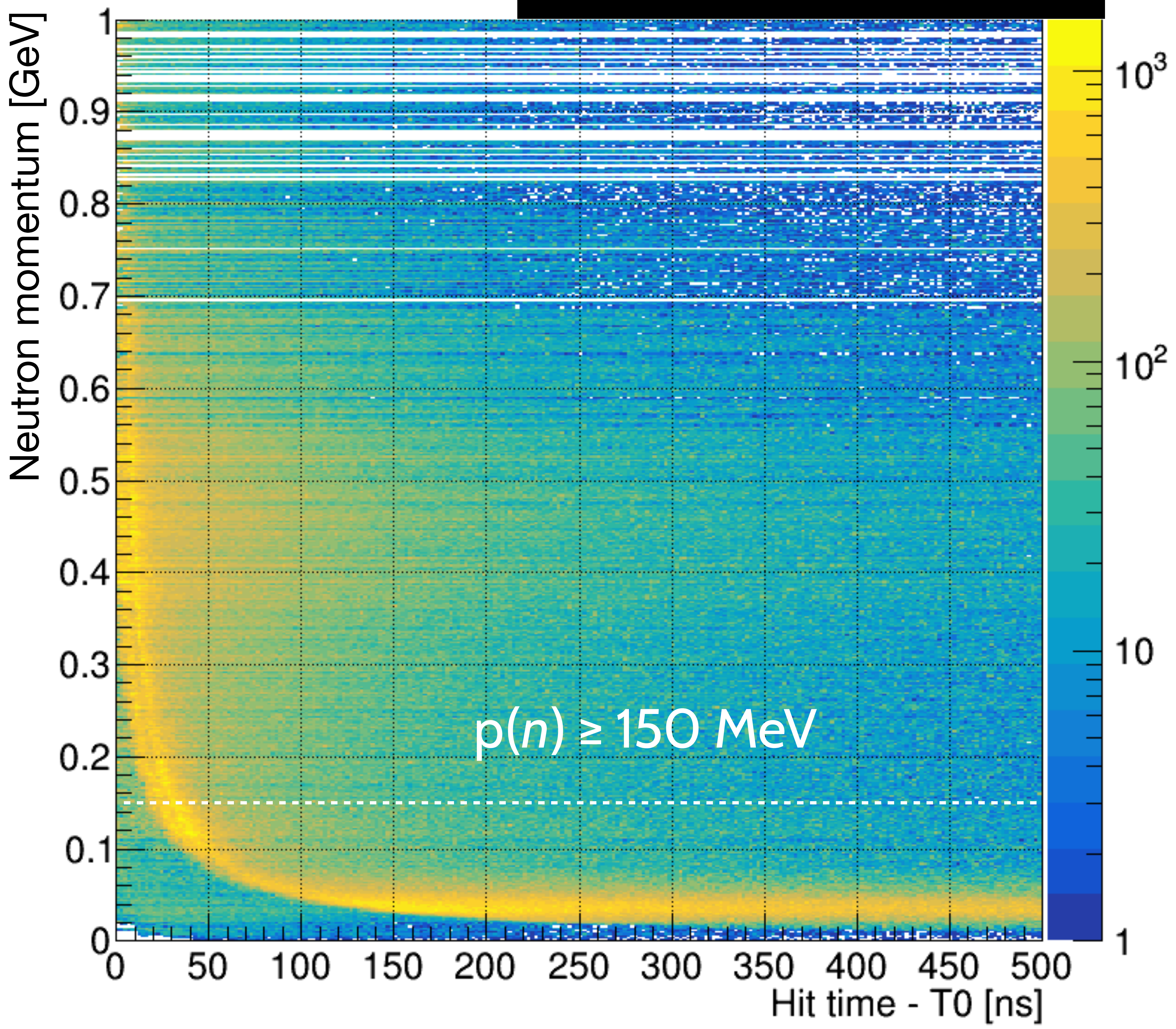
2. Discard neutrons with momentum ≤ 150 MeV

they are too slow to reach calorimeter cells within the typical readout time window of ~10 ns

↳ we can safely use the faster **`QGSP_BERT`** model

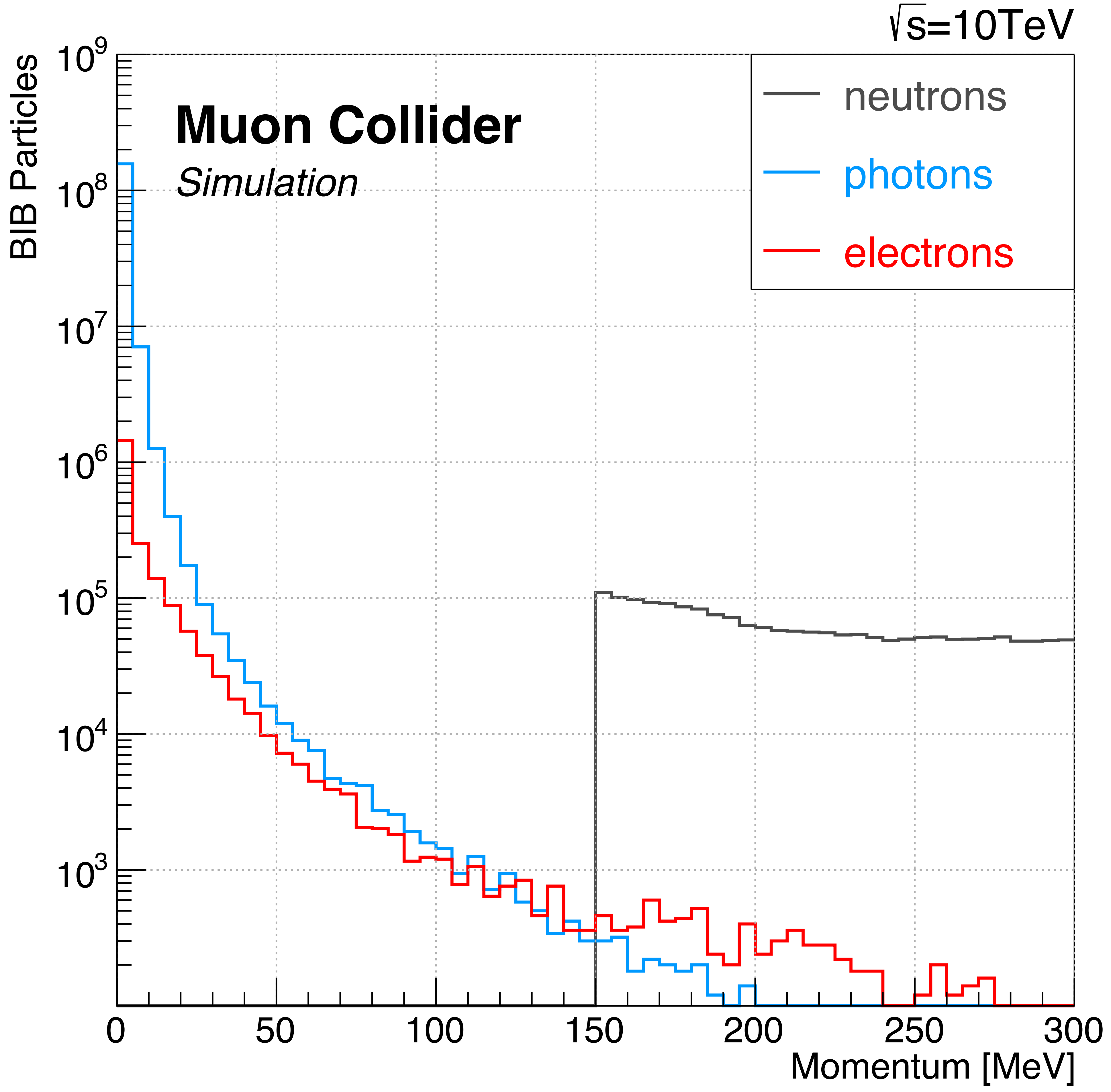
Calorimeter hits



Computing-load reduction

The actual spectrum of 2×10^8 particles entering our Geant4 simulation

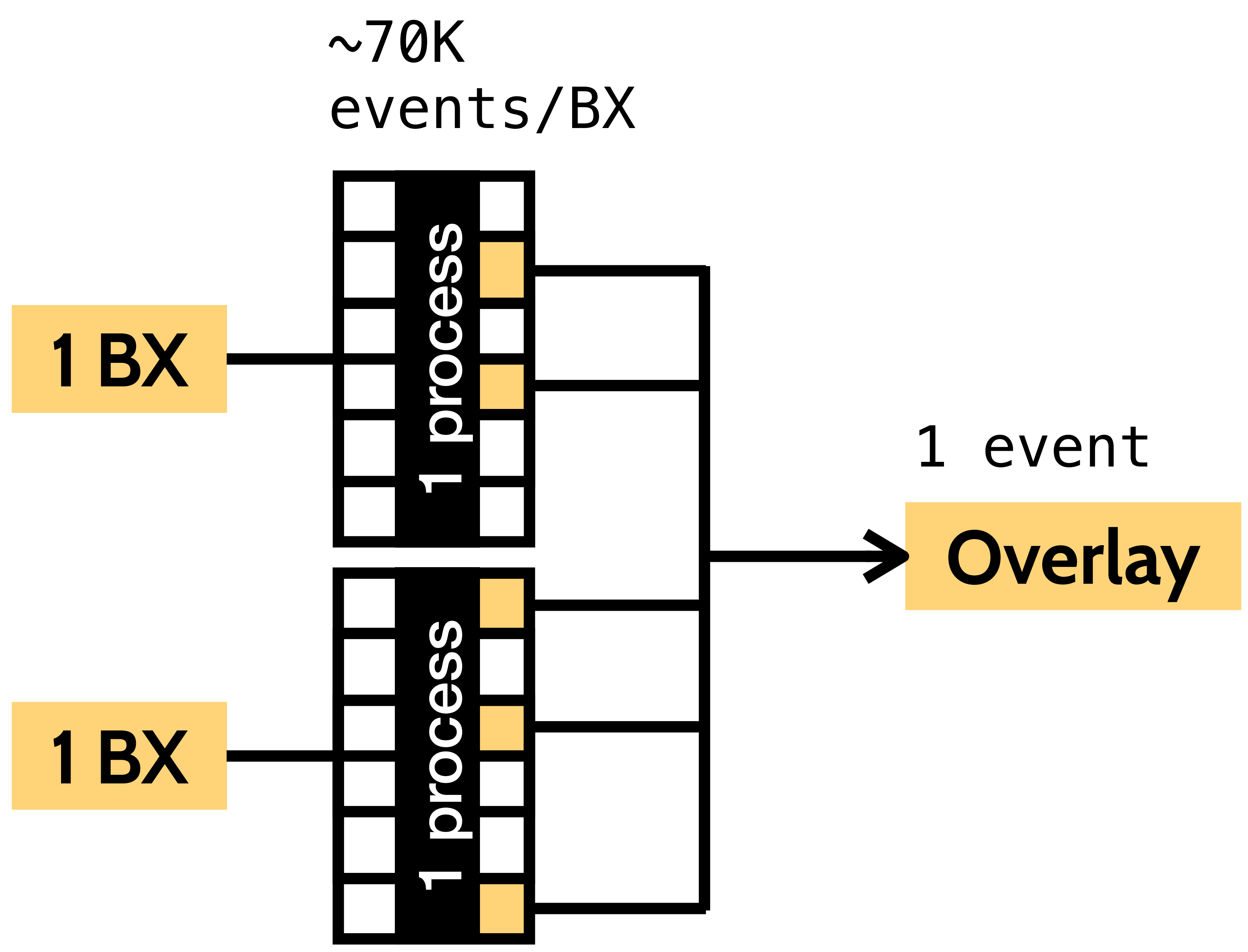
~50X less CPU-time



We don't run Geant4 directly. We interface it via DD4hep

↳ only single-threaded mode is available

We parallelize by splitting 1 BX into multiple sub-events and randomly mixing sub-events before overlay



Simulation metrics

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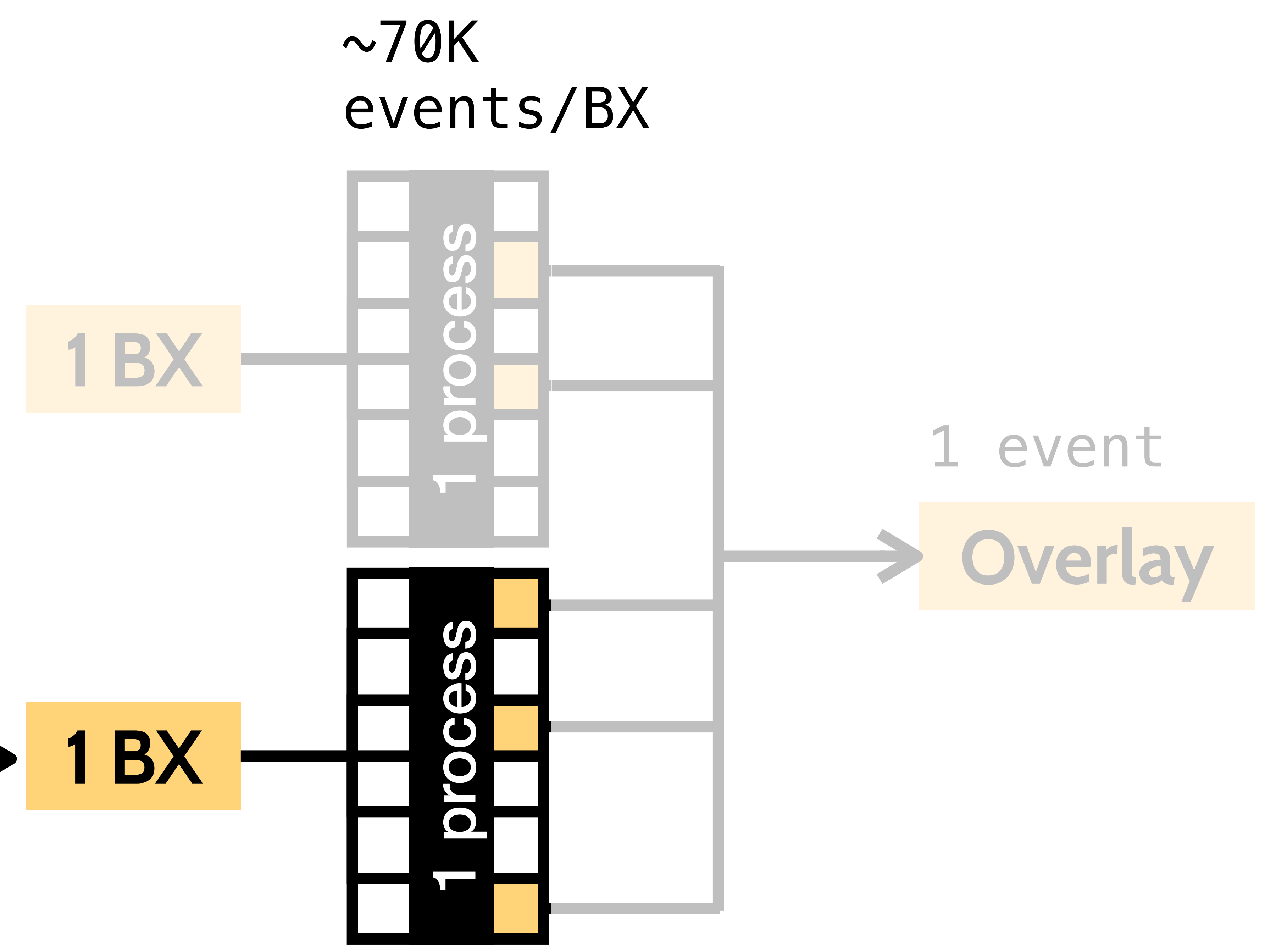

DD4hep (v1.29) → Geant4 (v11.2.0)

Simulation of 1 BX on a single thread	
Total events	70K
Particles/event	3K
Total CPU time	22 h
RAM	1.4 GB

Intel Xeon 2.1 GHz

261 logical volumes → 27 552 volume placements

↳ 5 threads can run in parallel on a machine with 8 GB of RAM

Shortcomings

Our current setup works well at the current prototyping stage
but will become inefficient in larger-scale simulations in the future

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   would become a limiting factor in simulations of much larger statistics

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2. **Splitting in many sub-events introduces lots of slow I/O during Overlay**
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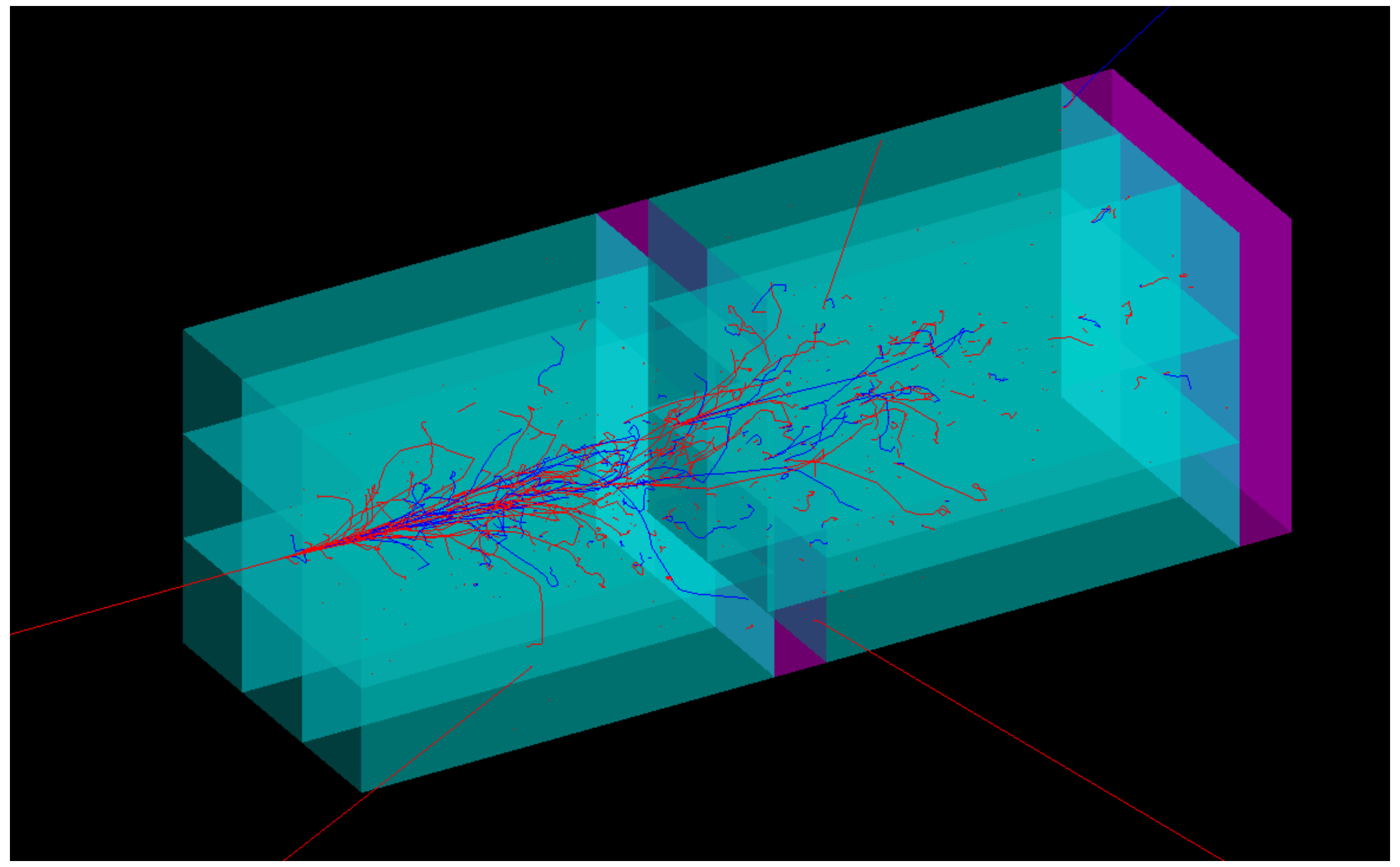
3. **Optical-photon propagation is completely ignored in calorimeters for the moment**
   would require hardware acceleration to be feasible for detailed readout simulation



◀ **e^- shower in Cherenkov 5×5 mm^2 crystals of the Crilin ECAL prototype**

Summary

At Muon Collider we deal with extreme numbers of particles
order of 10^8 particles/event

We use Geant4 via DD4hep framework
for flexible geometry definition that is directly reused in reconstruction

We care about timing at the level of ~10 ps

We obtain statistically independent events
by splitting and random mixing of simulated sub-events

Significant performance improvements will be needed in the future
for larger statistics and more accurate detector description