Input from IMCC

(International Muon Collider Collaboration)

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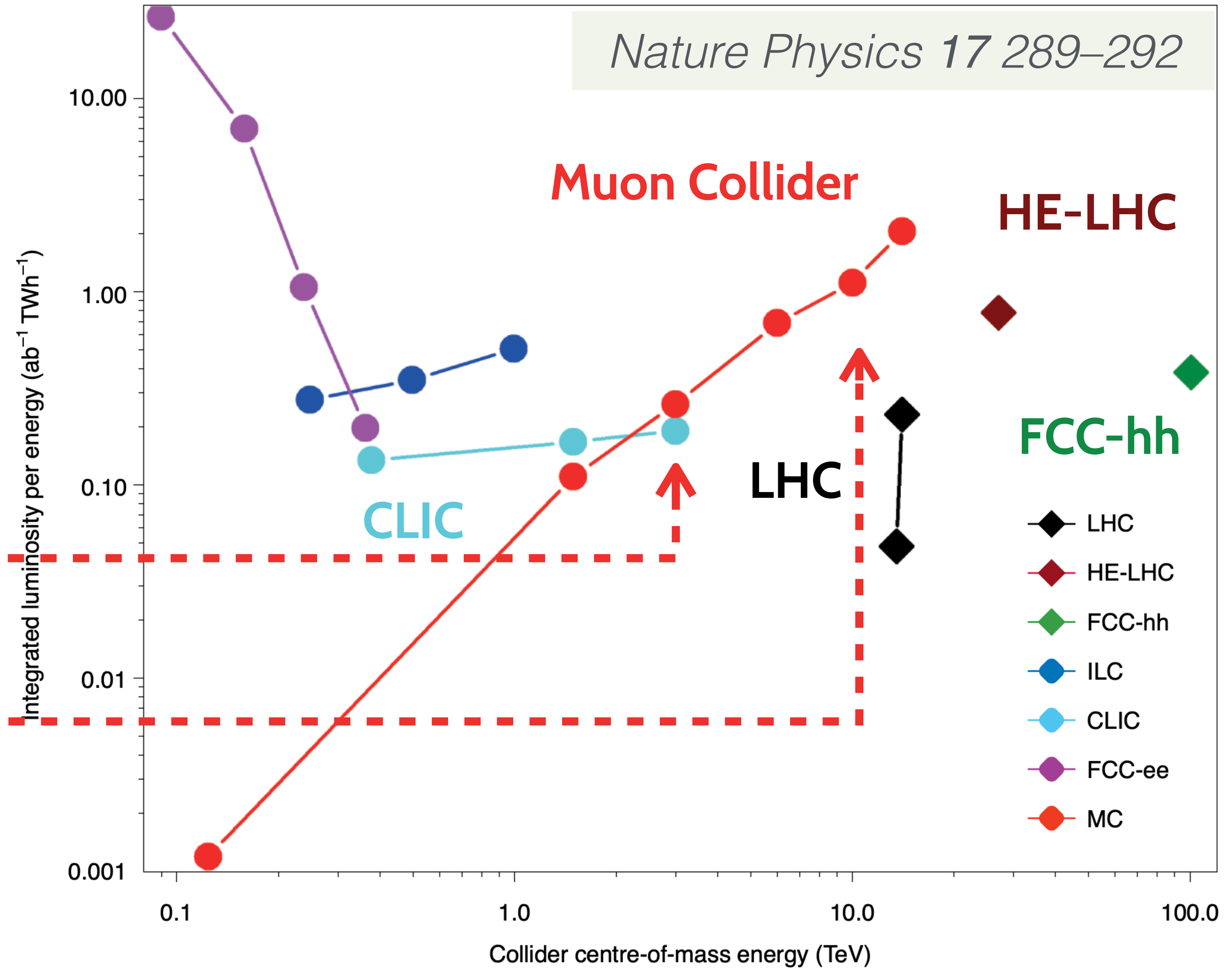
Muon Collider combines advantages of the two types of machines:

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

At √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: √s ≥ 10 TeV Muon Collider



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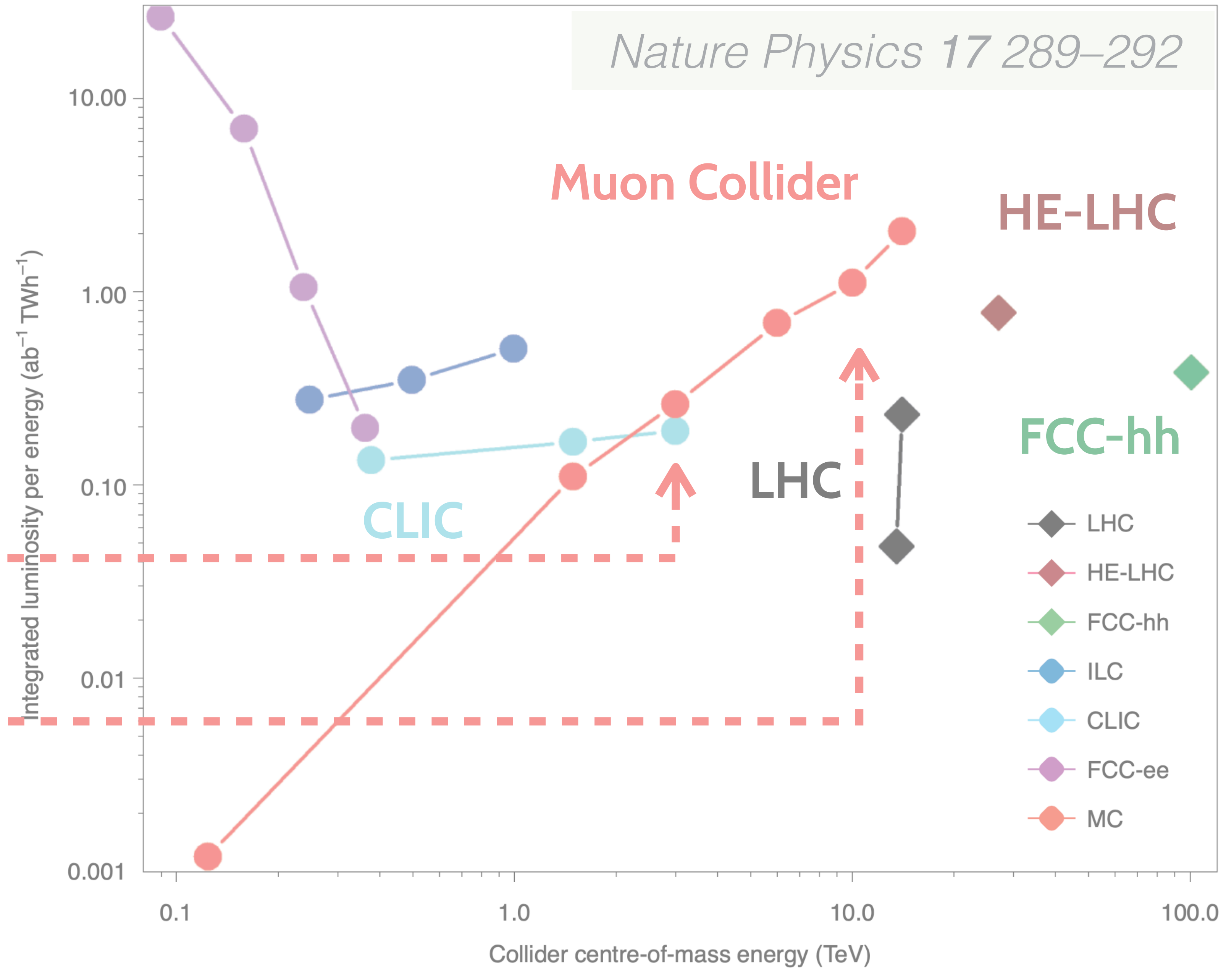
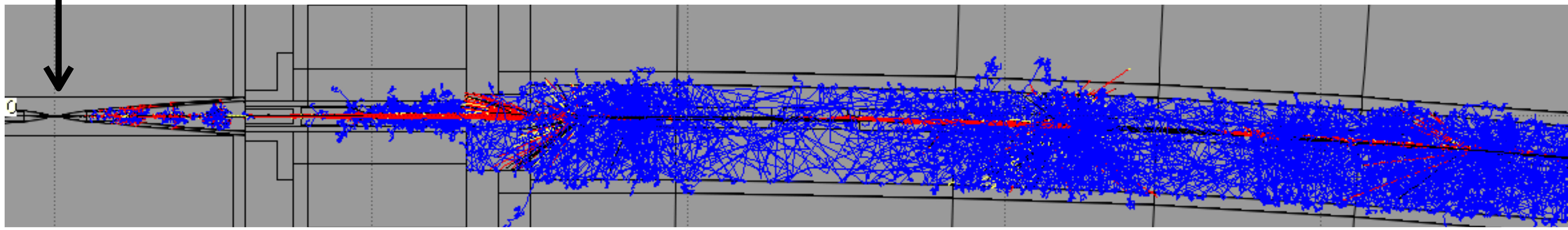


The greatest experimental challenge: **mitigation of the Beam Induced Background (BIB)**
part of the $\mu^\pm$ decays reaching the detector

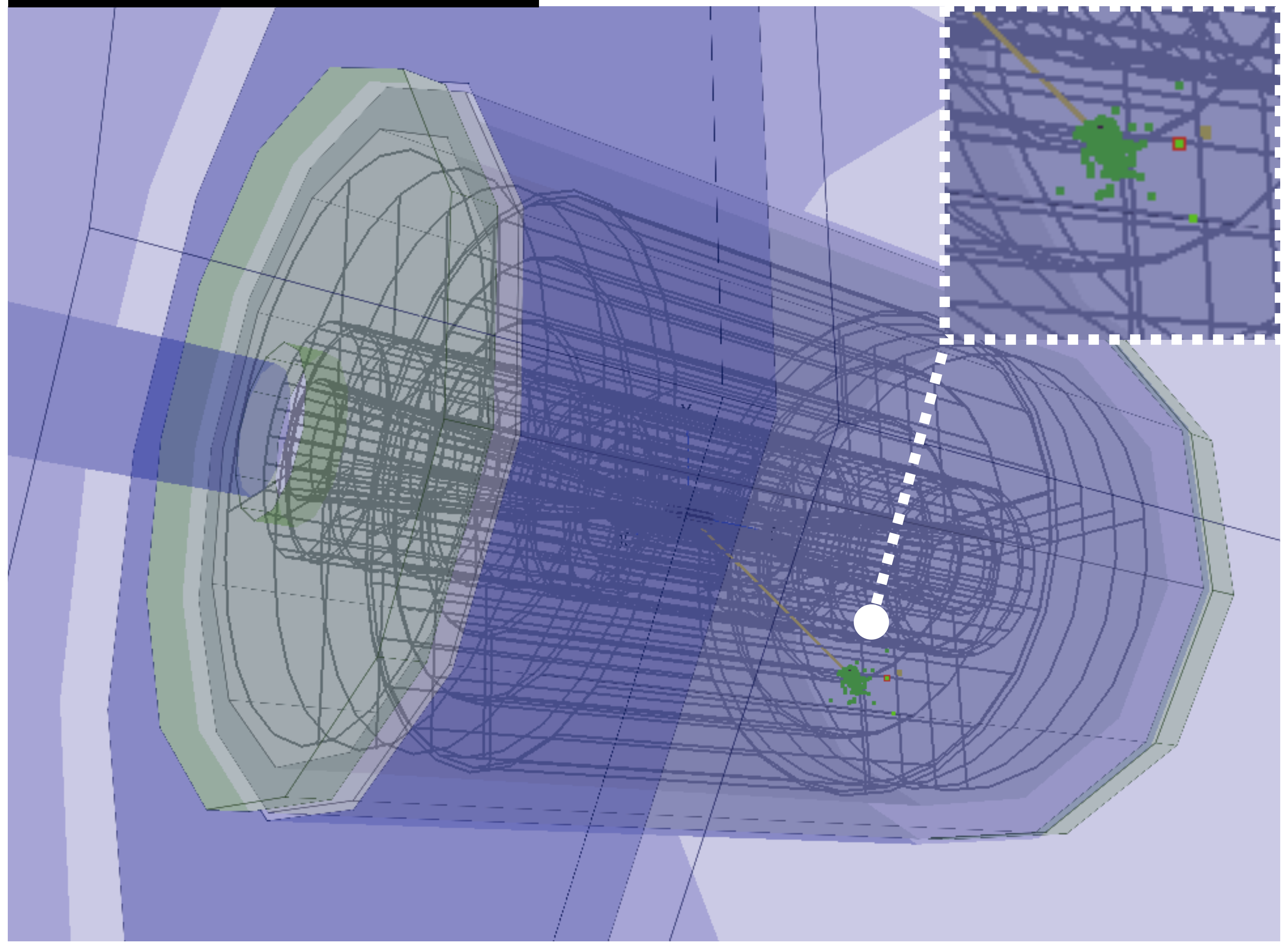
Propagation of μ± beams in the accelerator lattice simulated in FLUKA ▶



Scope of the simulation

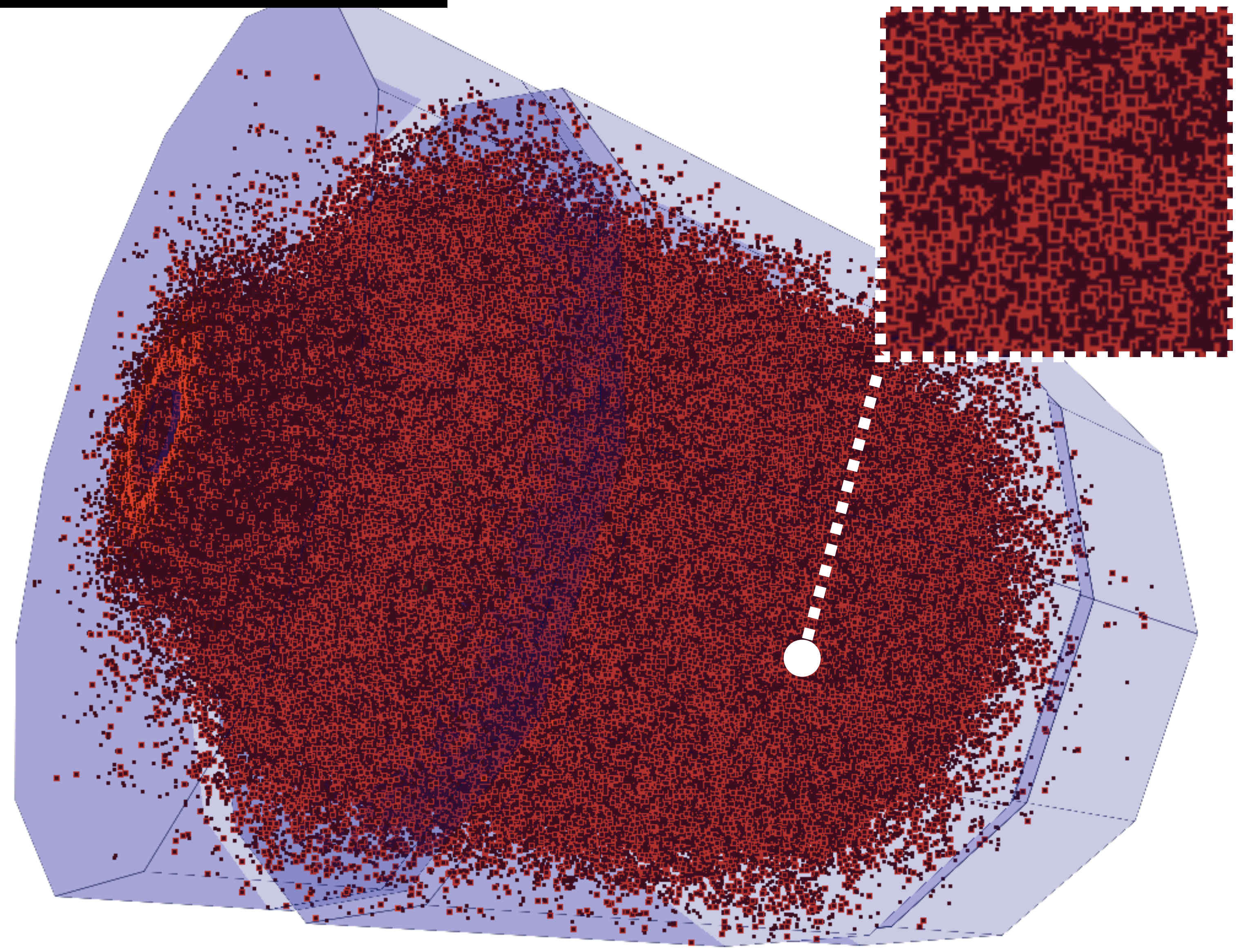
We need to tune our detector design and reconstruction algorithms to **cope with BIB**

10 GeV photon in ECAL



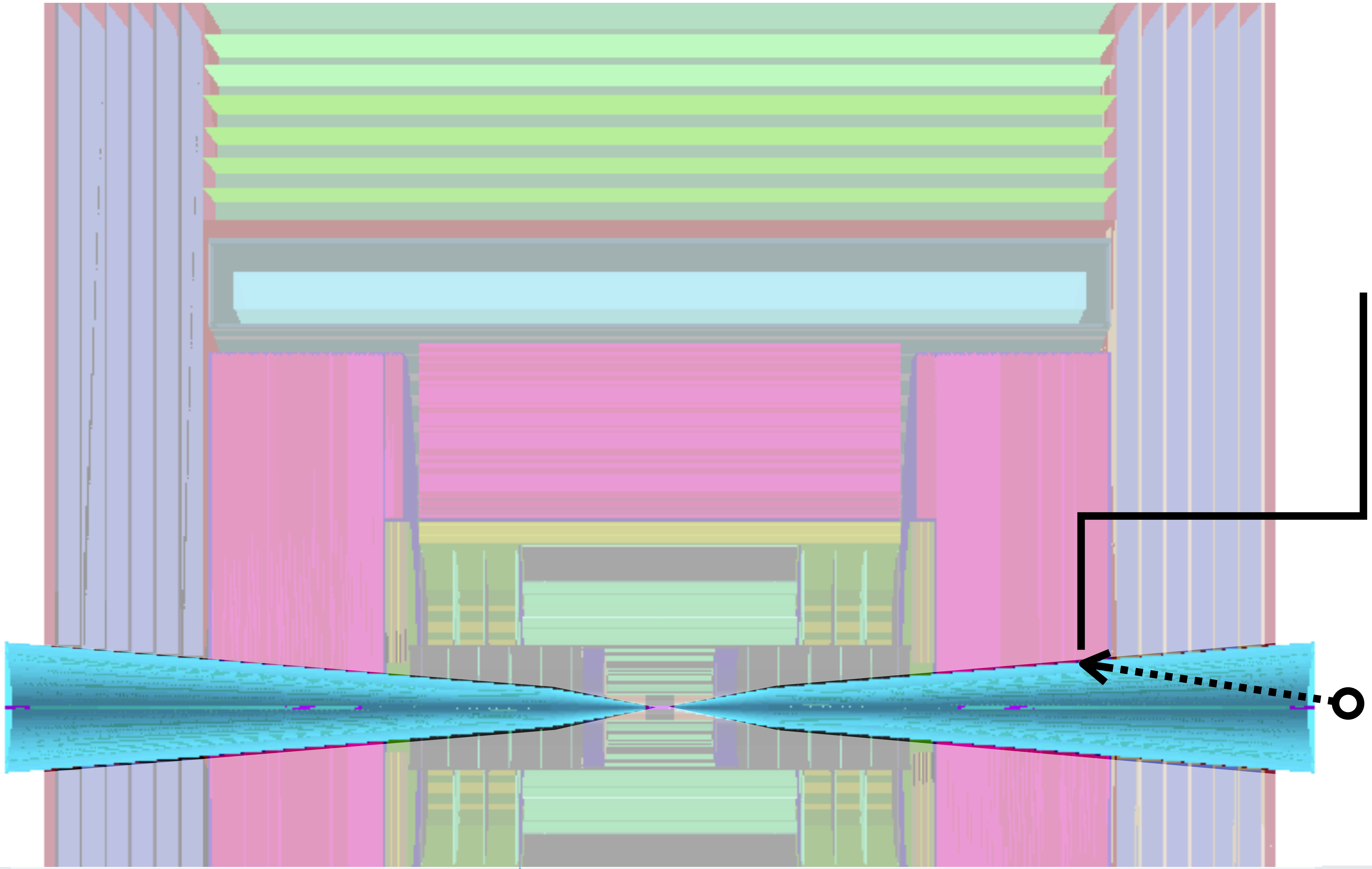
Adding **SimHits** from **BIB particles**

10 GeV photon + **BIB** in ECAL



Roughly 4 × 10⁸ particles from μ± decays arriving to the detector in a single bunch crossing (BX)

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**

$\mu^{\pm}$ decays in the beam lattice simulated with FLUKA
until the MDI-detector border

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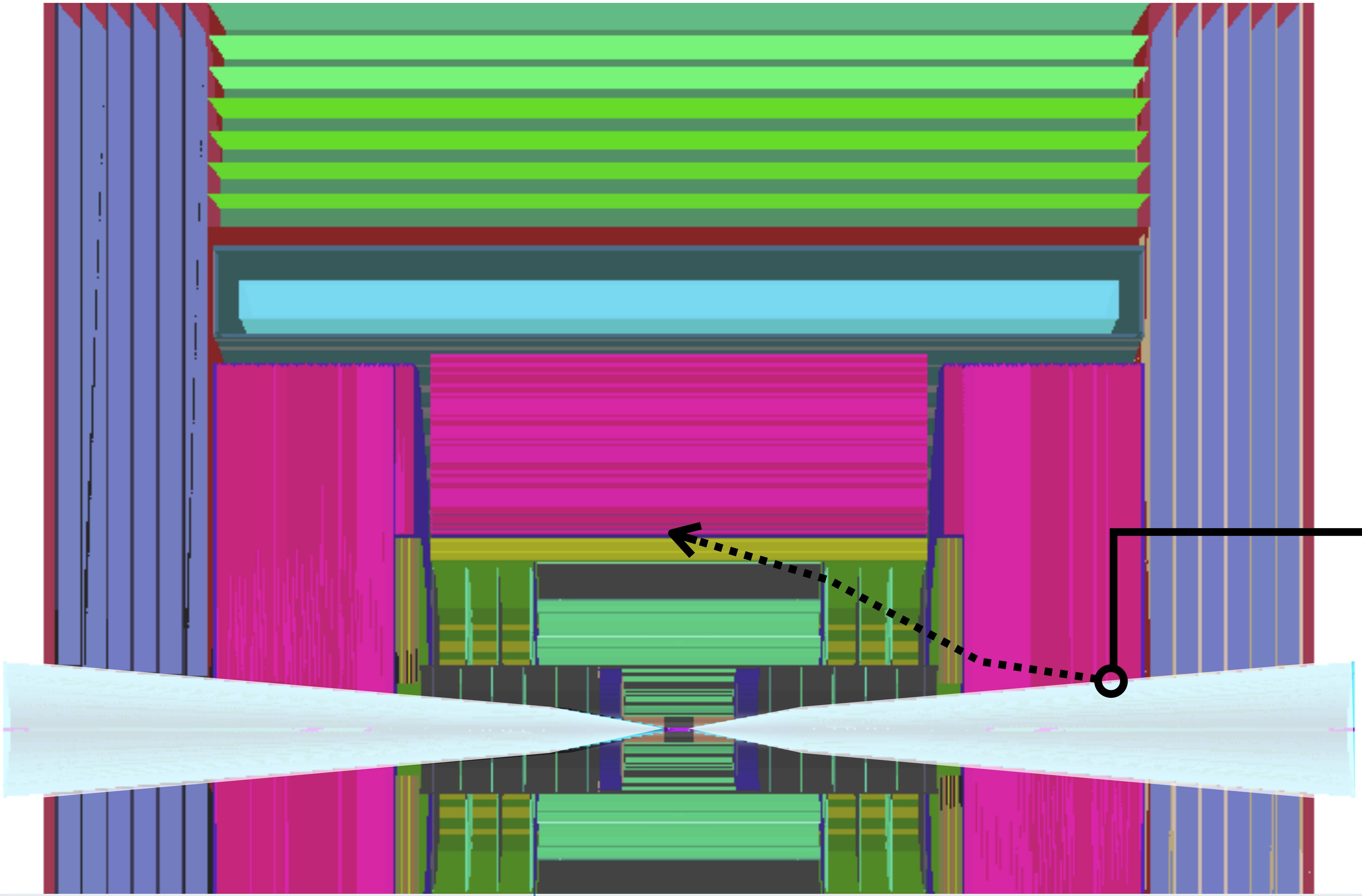
separated by the outer surface of the MDI



STEP 2

MCParticles ← **FILE**

Particles are propagated through the detector in GEANT4

SimHits → **FILE**

Overlay with signal SimHits
before digitization + reconstruction

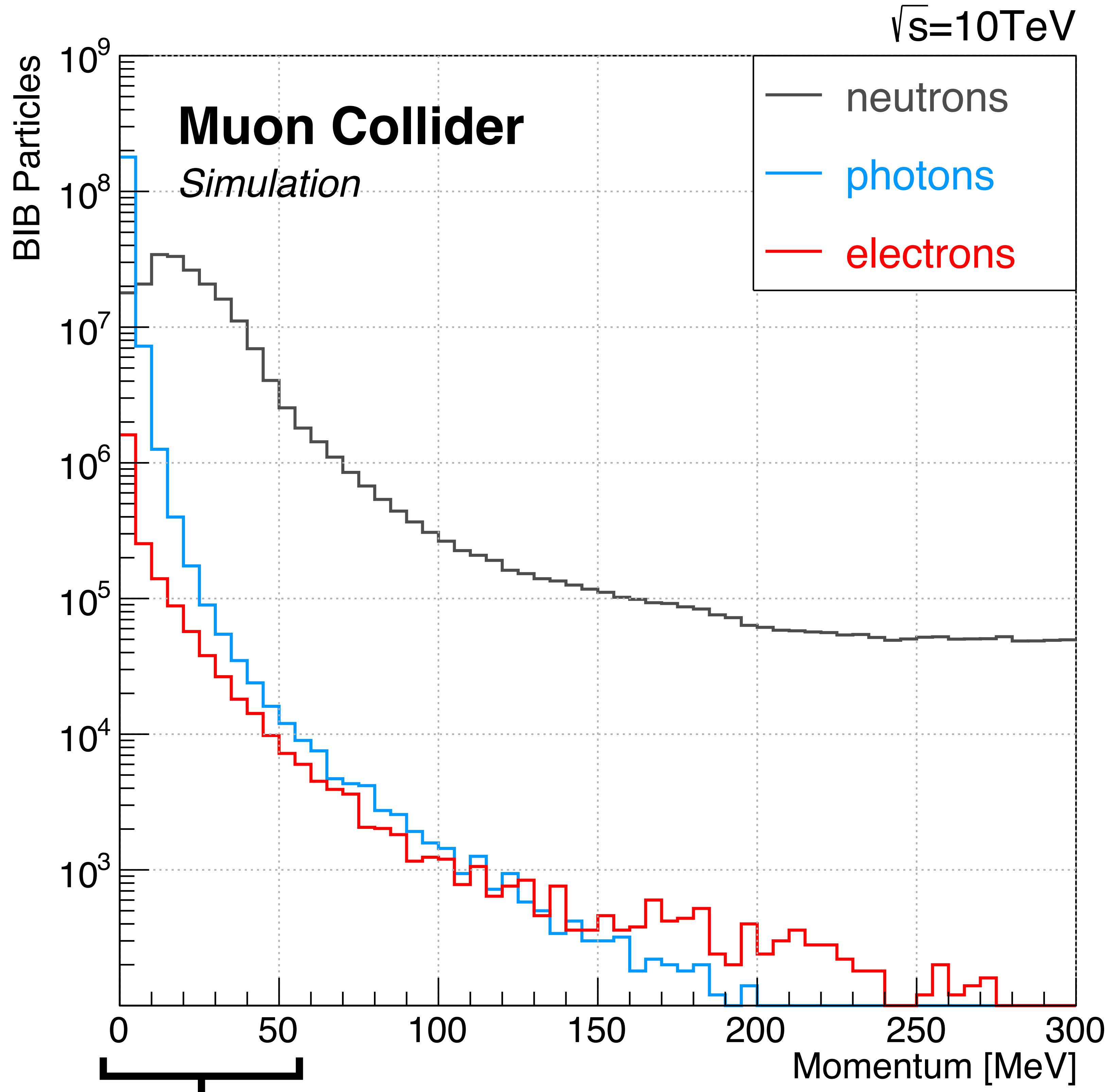
BIB properties

BIB particles have several **characteristic features**

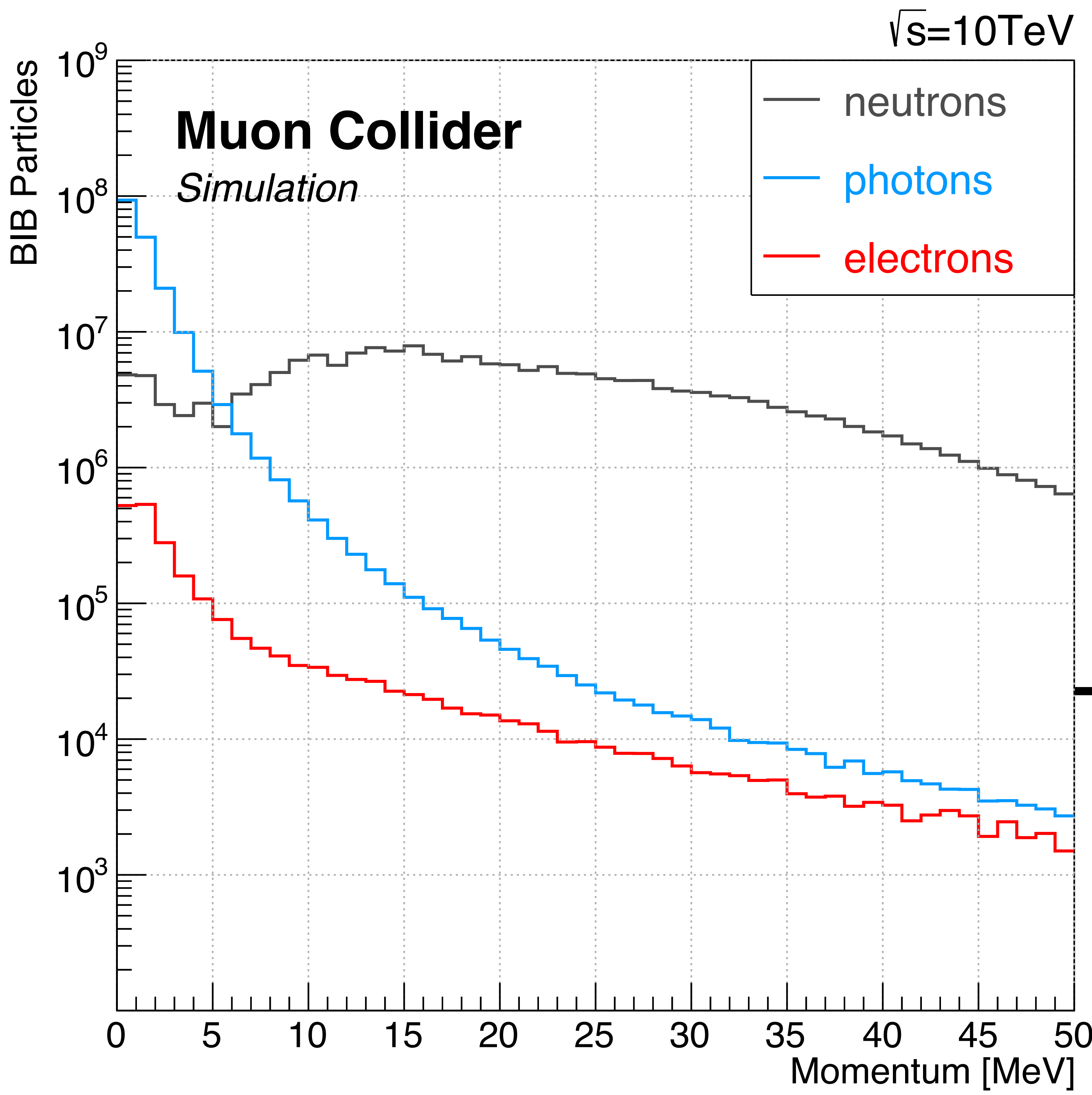
1. Predominantly very soft particles

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

↳ conceptually different from pile-up contributions at the LHC



Highly dispersed signals in every sub-detector ▶



↳ **Good candidates for fast simulation with generative AI**

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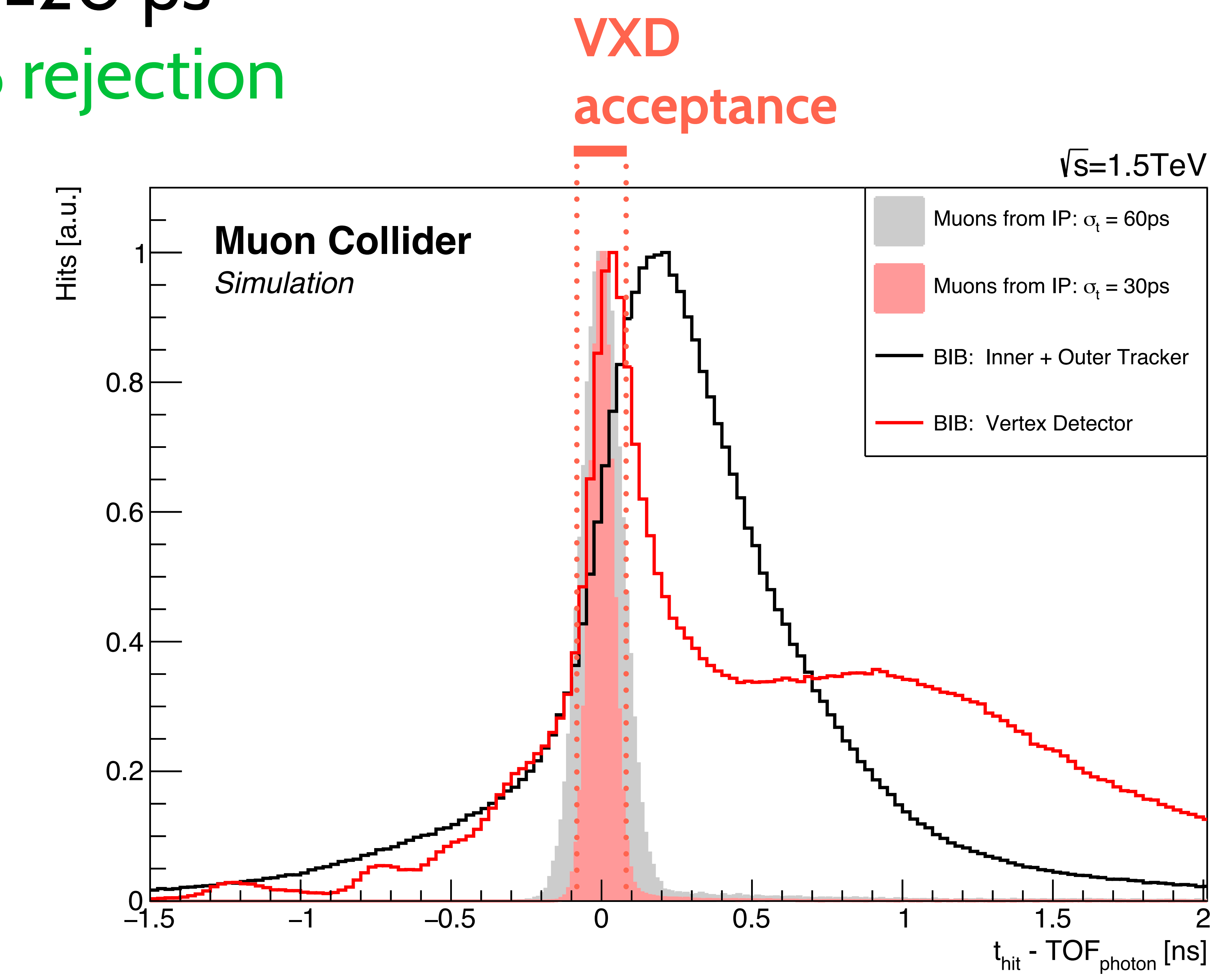
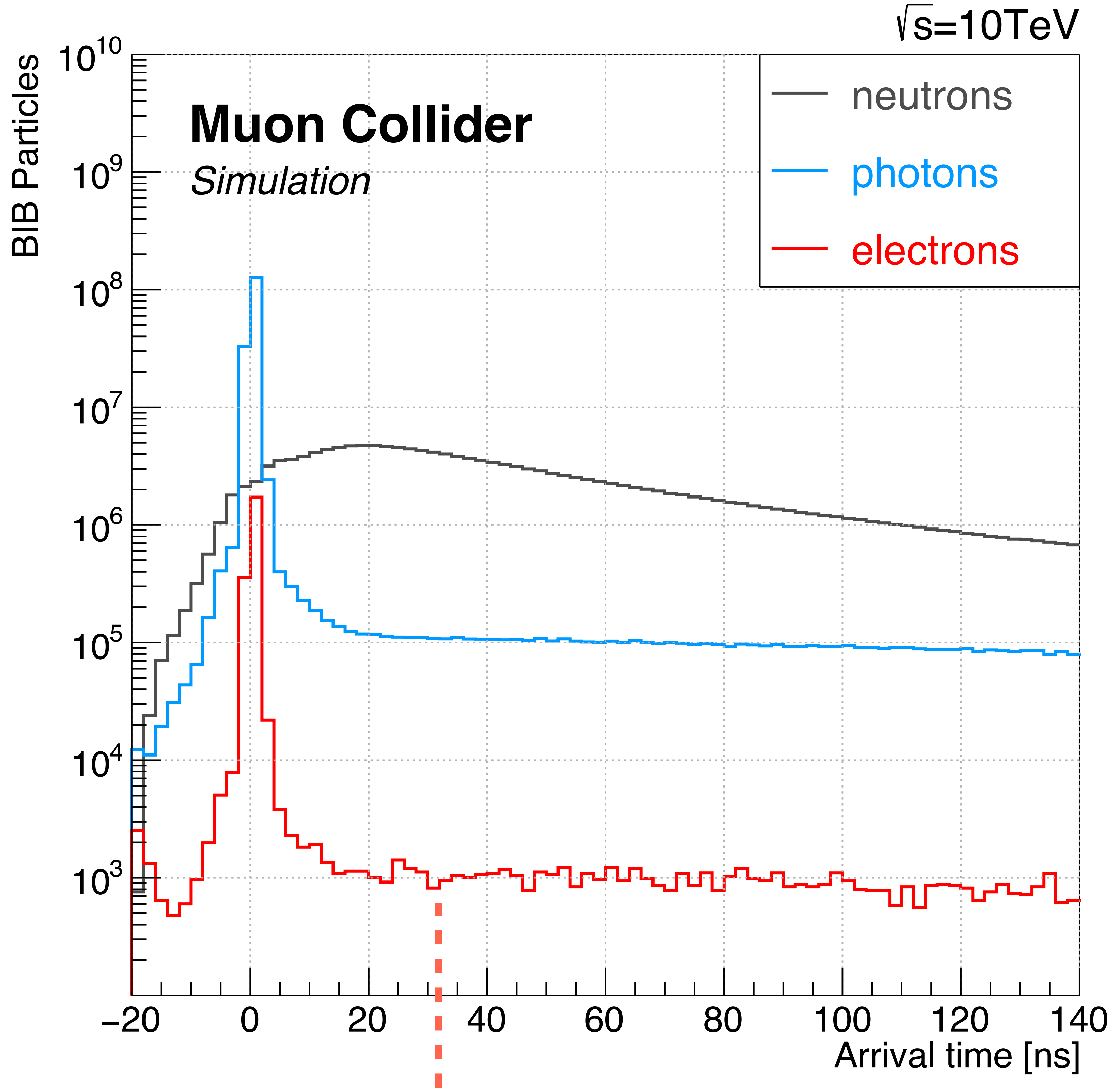
2. **Significant spread in time** (few ns + long tails up to a few μs)

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

SimHits in the tracking detector ▶

Careful treatment of timing information is crucial





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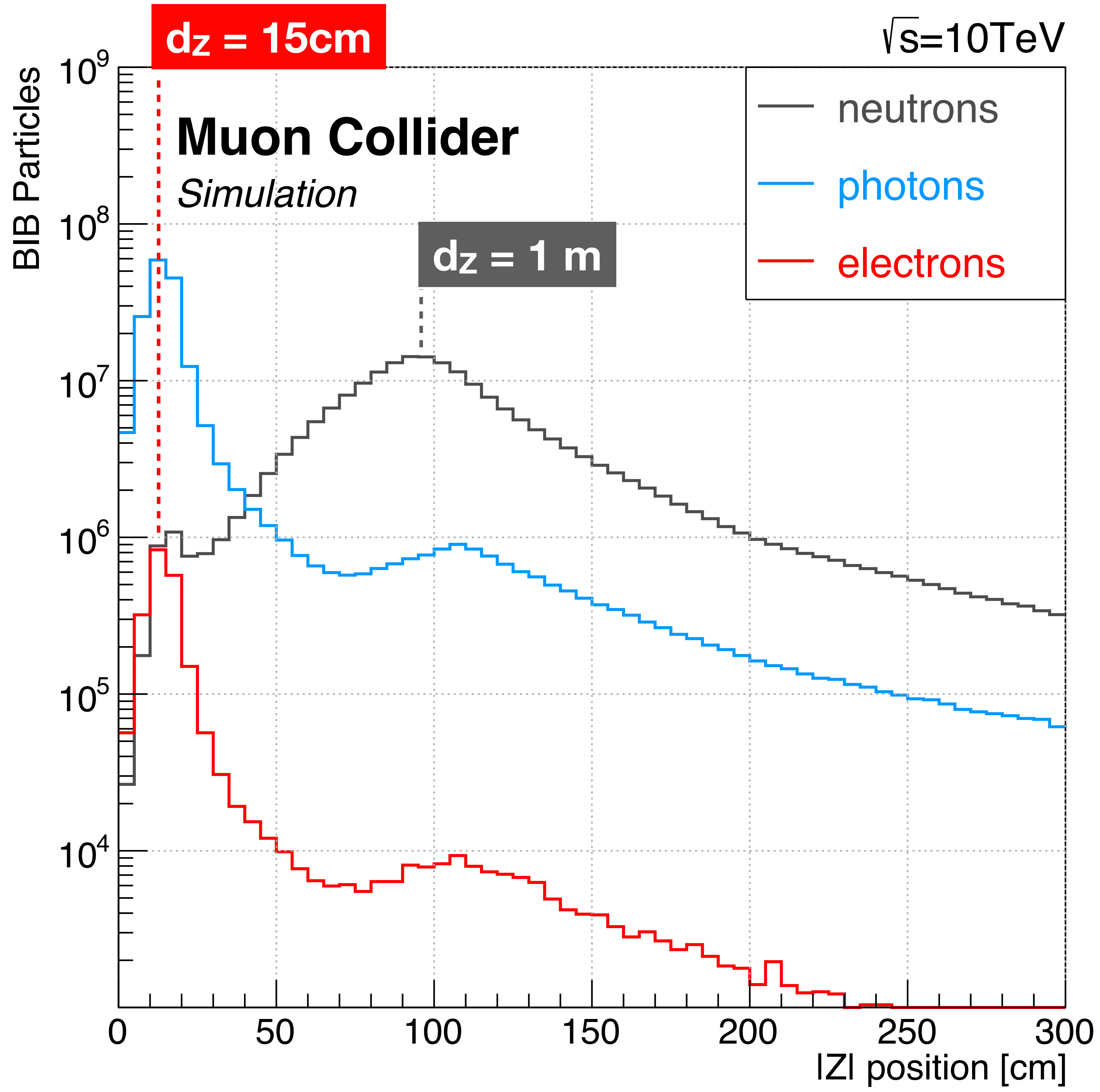
3. Strongly displaced origin along the beam line

entering tracking sensors at a shallower angle

↳ affects hit-cluster shapes + time of flight

↳ **Realistic digitization is important**
timing + cluster shapes



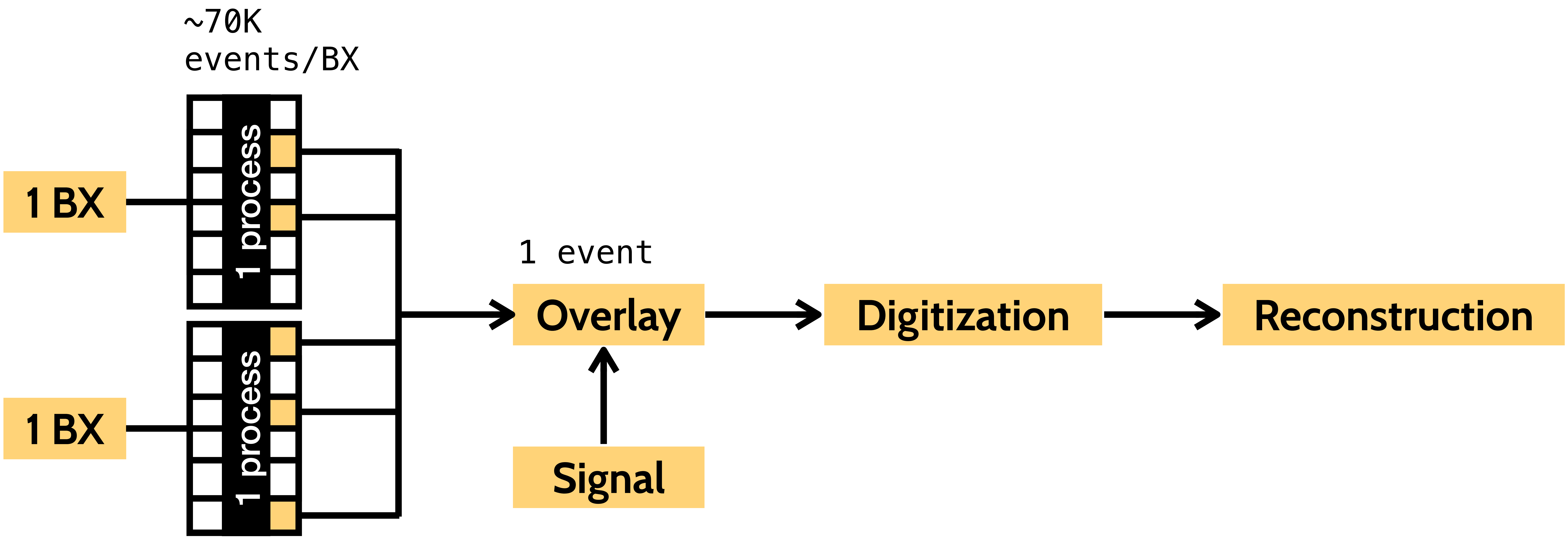
BIB parallelization

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

↳ only single-threaded mode is currently available

Full support of multithreading
necessary for RAM optimization

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



Simulation accuracy

In general we need to support simulation for two separate use cases:

Detector R&D

No need for high-statistics MC samples

Simulation must be as realistic and detailed as possible

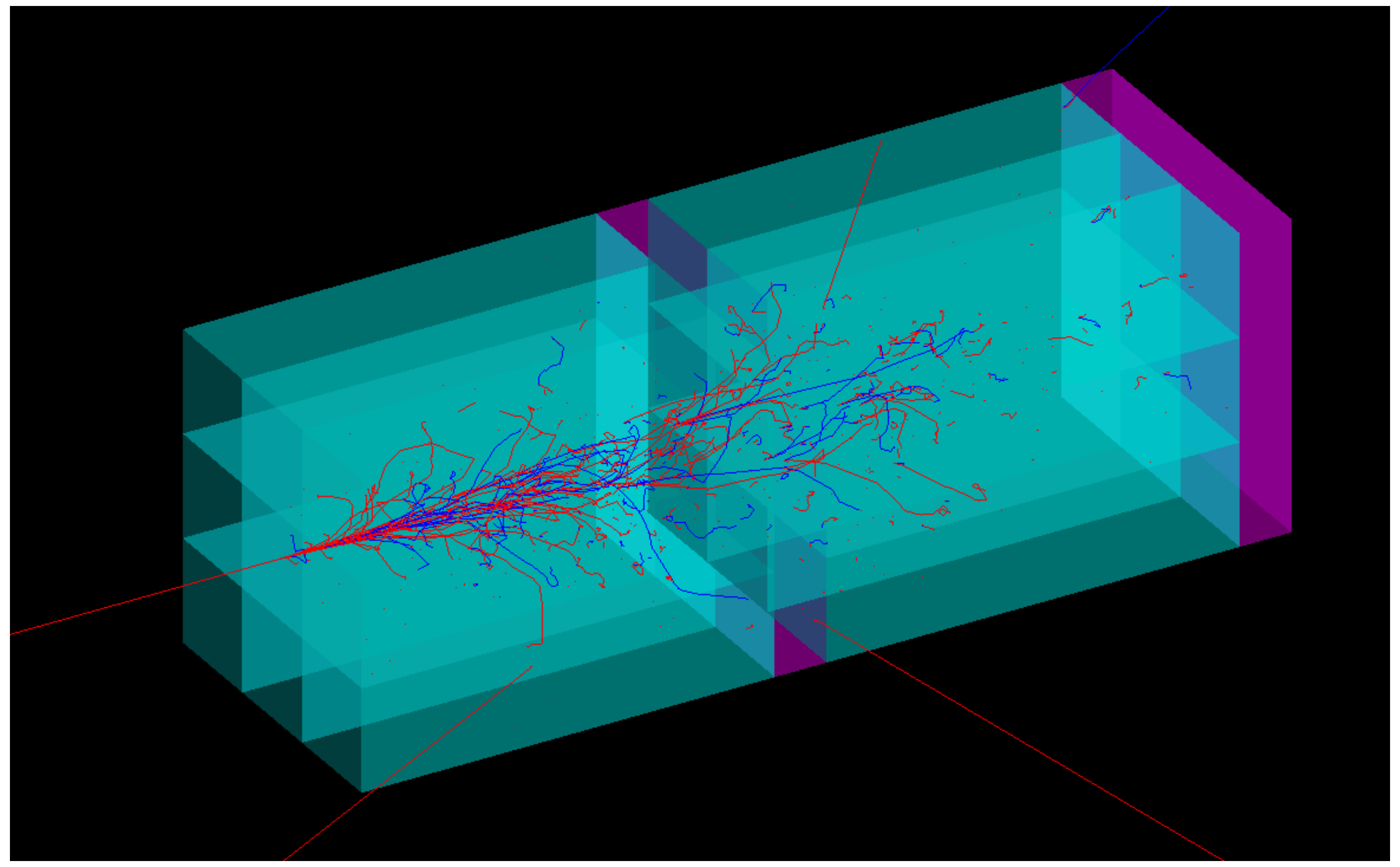
Full simulation is needed

Physics analyses

High-statistics samples are necessary

Any possibility for computing optimization must be exploited

Fast simulation is acceptable



FullSim example:

e^- shower in Cherenkov 5×5 mm^2 crystals of the Crilin ECAL prototype with ~20 ps resolution

Accurate propagation of optical photons is necessary
↳ need GPU acceleration

Outstanding issues

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

1. **Inefficient use of memory in the single-threaded mode of DD4hep**
   would become a limiting factor in simulations of high-statistics samples
2. **Splitting in many sub-events introduces lots of slow I/O during Overlay**
   in particular for calorimeter hits, where contributions in the same cell need to be merged
3. **Optical-photon propagation is completely ignored in calorimeters for the moment**
   would require hardware acceleration to be feasible for detailed readout simulation
4. **Use of precise timing information during track reconstruction** (we use ACTS)
   crucial for reducing combinatorics as early in the chain as possible
5. **Modern experiment-agnostic particle-flow reconstruction algorithm**
   we find PANDORA too outdated and hard to adapt to our needs

Less critical items

Some other minor inconveniences could improve the overall simulation experience

1. **Coherent software distribution on various computing platforms**
   so far Docker container is the common denominator → still suboptimal in certain cases
2. **Modern event display for visual presentations and simulation debugging**
3. **Continuity of Key4hep development effort**
   good idea that seems to lack confidence in its long-term support