May 19, 2021

vCHEP 2021

INFN TORINO

Full detector simulation with unprecedented background occupancy at a Muon Collider

vCHEP 2021

25th International Conference on Computing in High-Energy and Nuclear Physics

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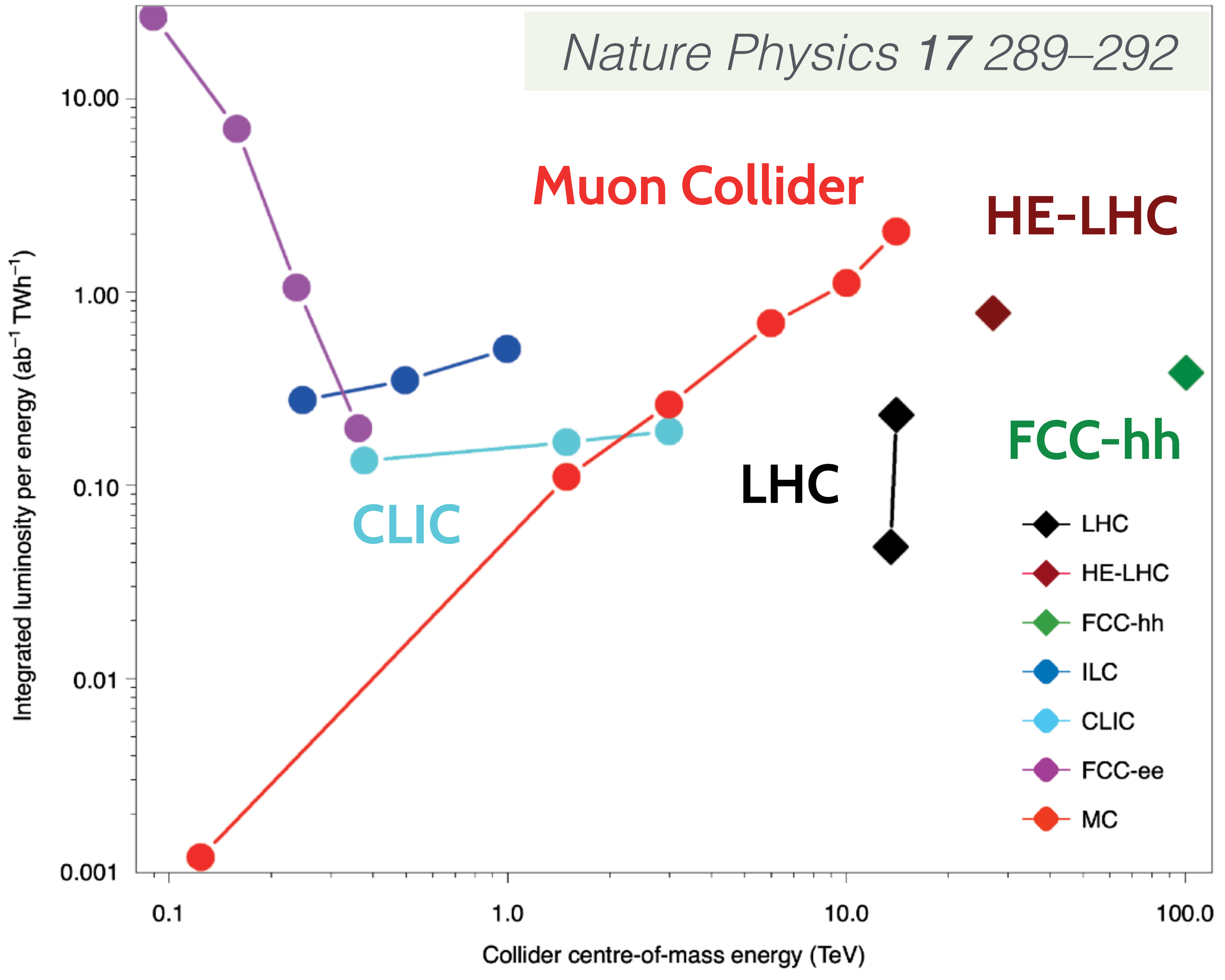
Muon Collider allows to combine in a single machine
high precision of e^+e^- colliders (CLIC, FCC-ee, ...)
and high energy reach of hadron colliders (LHC, HE-LHC, FCC-hh, ...)

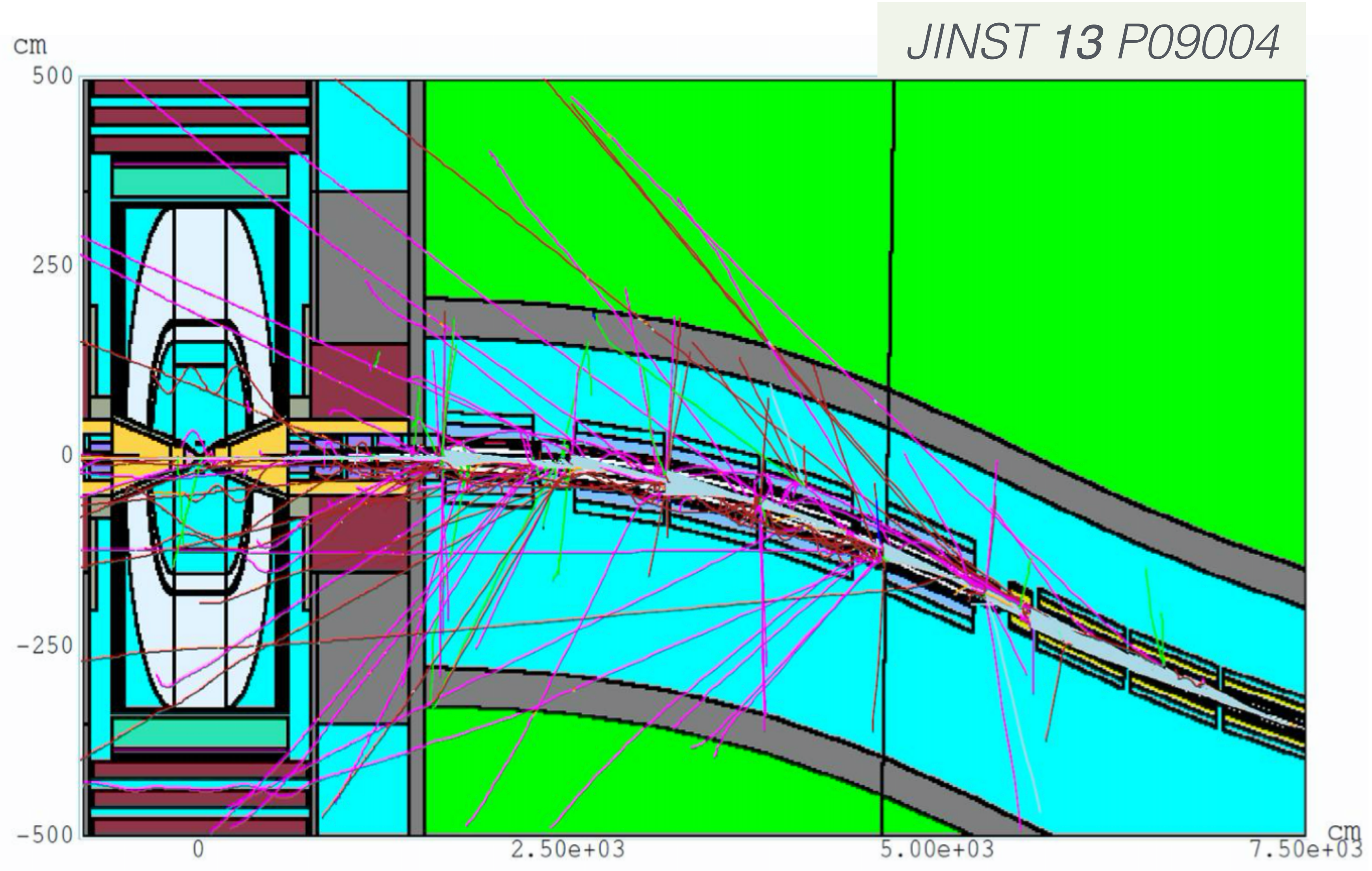
- muons are elementary particles, like e^+/e^-, creating "clean" collisions
- ×200 higher mass → ×10^4 less synchrotron radiation losses

At √s = 3 TeV (and higher) Muon Collider is the most energy efficient high-luminosity machine for discoveries and precision measurements ▶



Unique advantages come at a price of
challenging machine design (short muon lifetime)
and harsh Beam Induced Background (BIB)

↳ interactions of secondary/tertiary muon decay products with the accelerator lattice and the Machine-Detector Interface (MDI)



We start with √s = 1.5 TeV design that has been studied the most by the MAP program using *MARS15*: accelerator lattice + optimised MDI design ▶

New BIB simulation workflow at the finalising stage of development based on *FLUKA + FlukaLineBuilder* to study higher centre-of-mass energies

For 0.75 TeV beams at $2{\times}10^{12}$ μ/bunch → $4{\times}10^{5}$ muon decays/m in a single beam crossing

↳ **directly affecting the experiment:** radiation damage + occupancy in the detector

Essential component is the MDI: **tungsten nozzles** moderating the rate and energy of BIB particles reaching the detector volume

Result of a BIB simulation → **list of stable particles reaching the detector region in a single beam crossing** *(mostly soft photons, neutrons, electrons)*

- collected at the outer surface of the detector + MDI ▶
- 2 × 180M particles → further interactions with the detector simulated in GEANT4

Detector geometry largely based on the CLIC design [DD4hep description]

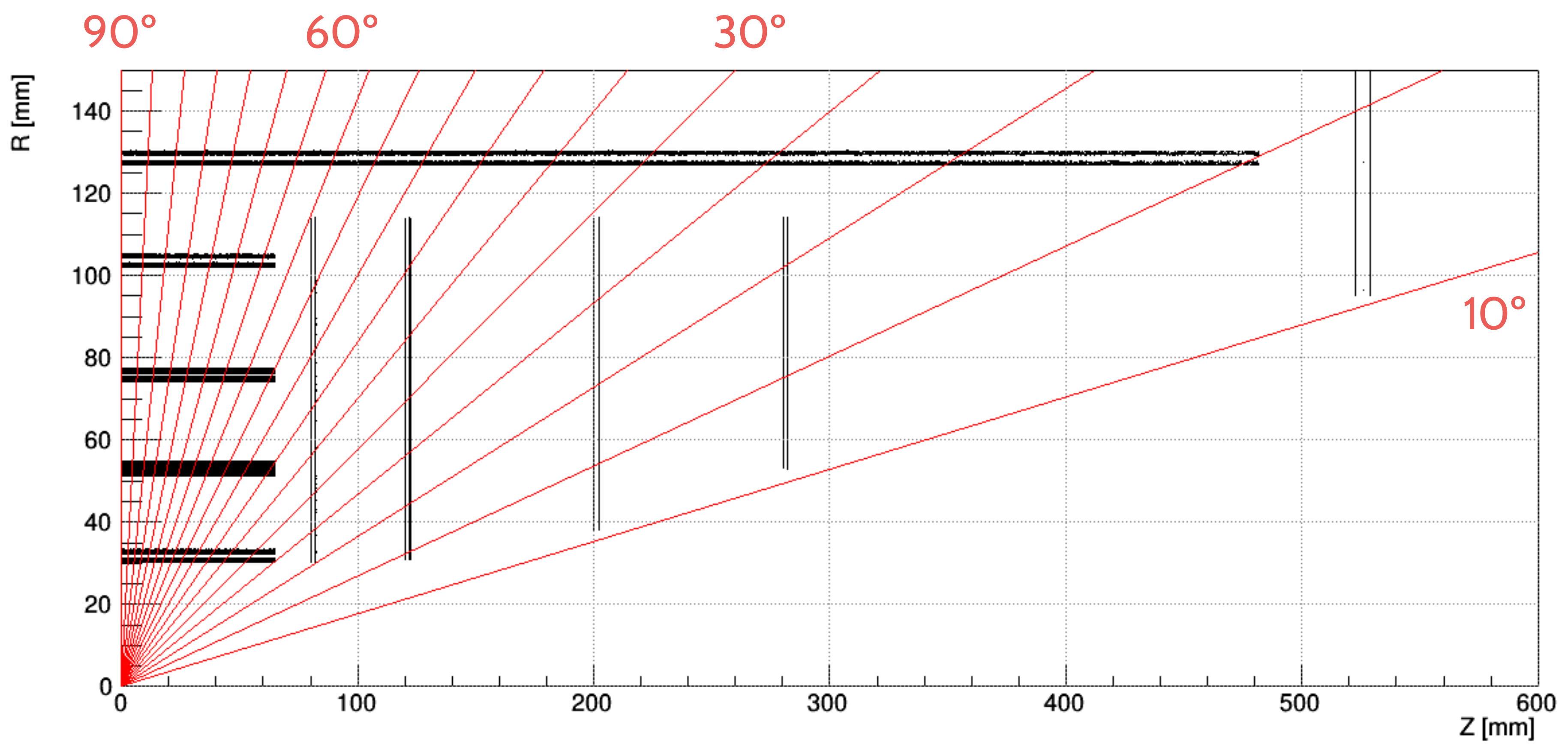
Tungsten nozzles: forward acceptance >10°

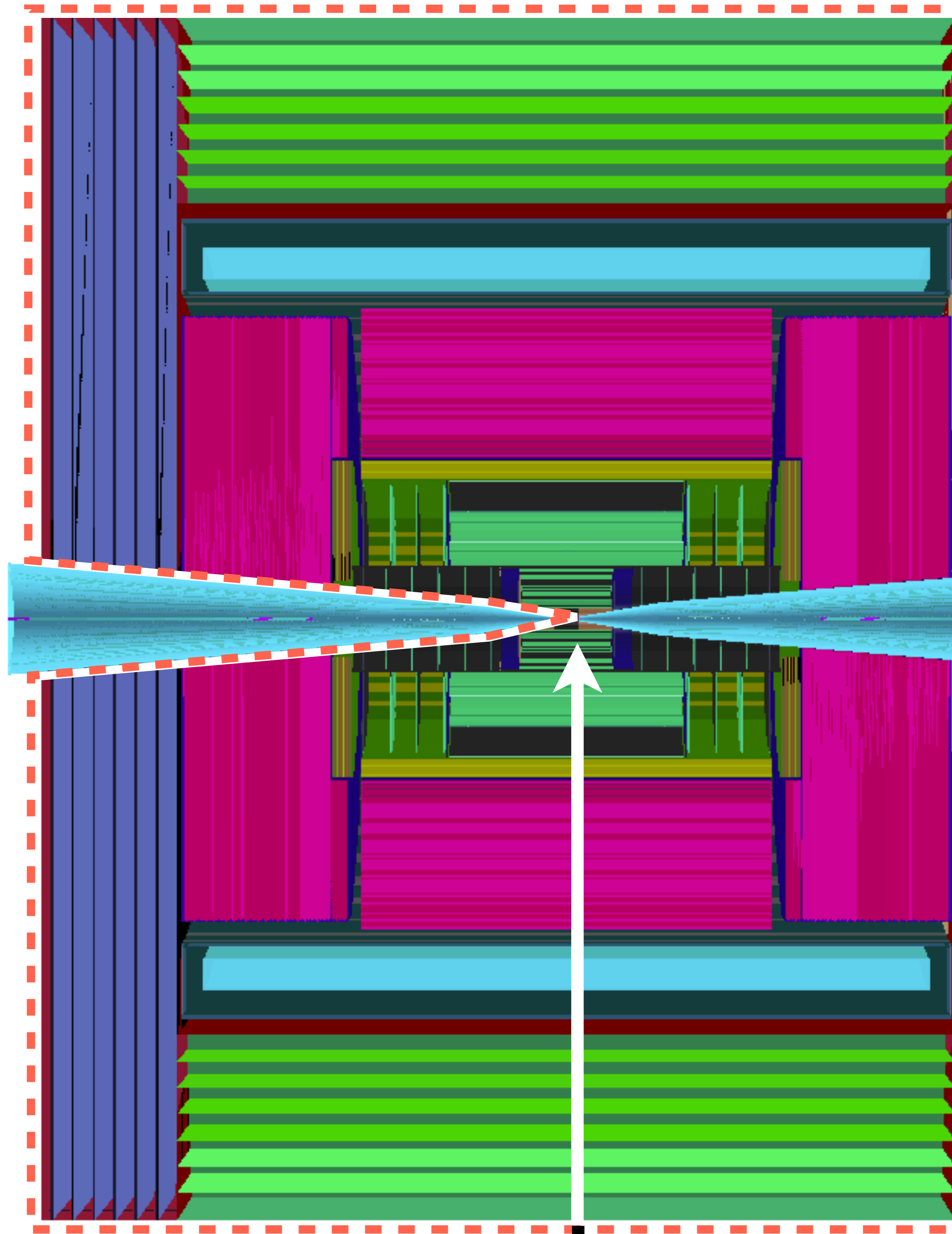
High-granularity sampling calorimeter

- **ECAL:** 40 layers of **W** + **Si**
- **HCAL:** 60 layers of **Fe** + **scintillator** + **SiPM**

All-silicon tracker: B = 3.57 T

- double-layer Vertex Detector ▶
  ↳ doublet selection: matching time + angle





Vertex Detector

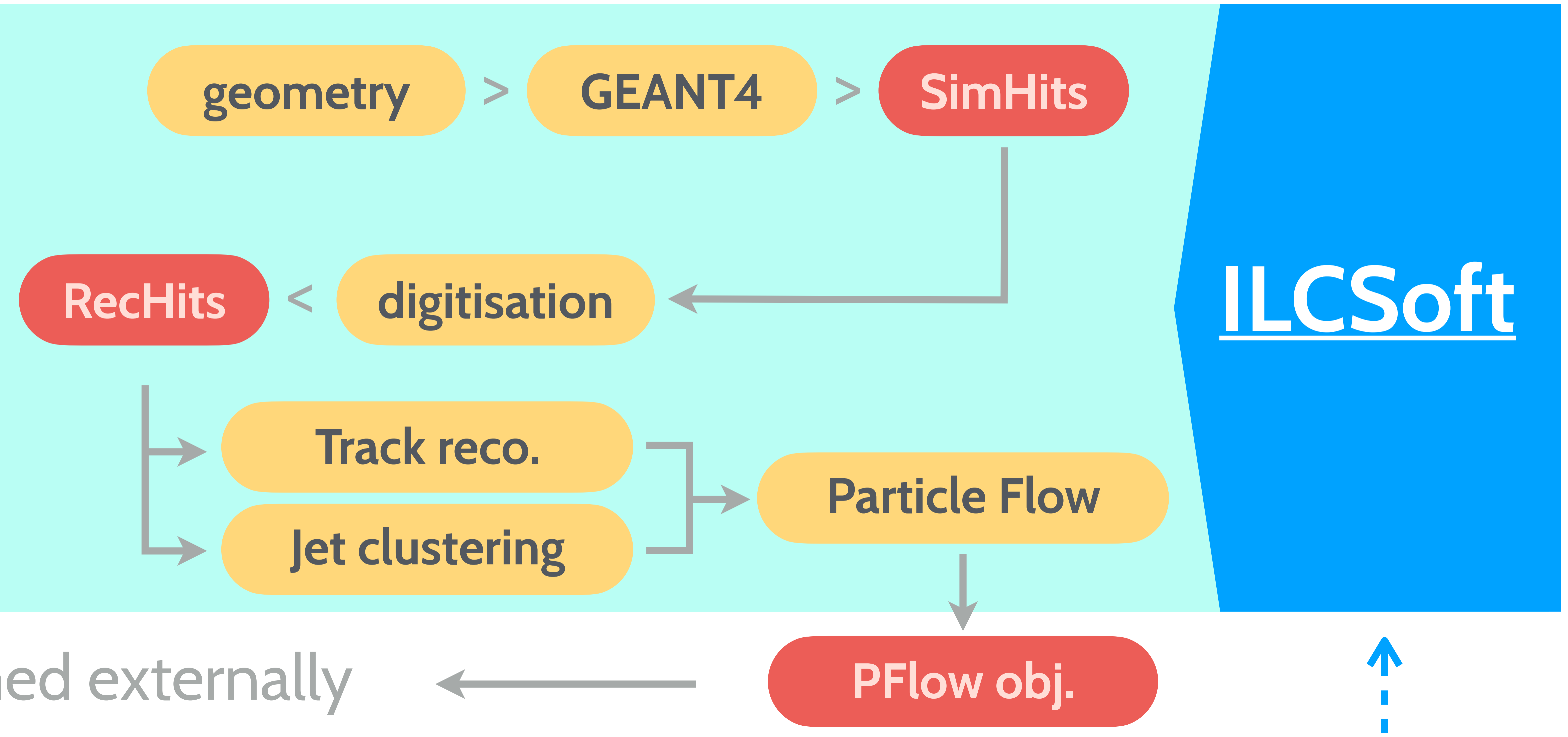
- closest to the BIB source
- extreme hit density up to 1K cm^{-2}

Simulation software

Software framework of the CLIC experiment chosen as a starting point: designed for e^+e^- colliders

Key components of the full-simulation physics analysis:

1. **generation of the main process (ME + PS)** ← done externally (Whizard/Madgraph+Pythia)
2. **simulation of the detector response to the incoming particles** (DD4hep interface)
3. **simulation of detector effects**
   efficiency, electronics noise + thresholds, ...
4. **reconstruction of higher-level objects**
   photons, tracks, jets, particle identification
5. **higher-level analysis** ← can be performed externally



All the simulation and reconstruction done within a single framework

Most of custom packages specific to the Muon Collider maintained in the public Muon Collider Software repository

Large overlap with the Key4HEP software stack: planning full transition in the future

Unique properties of BIB at the Muon Collider require a number of changes and optimisations in this workflow for the efficient simulation of millions of such events

Detector simulation workflow

Full simulated event obtained via three distinct stages:

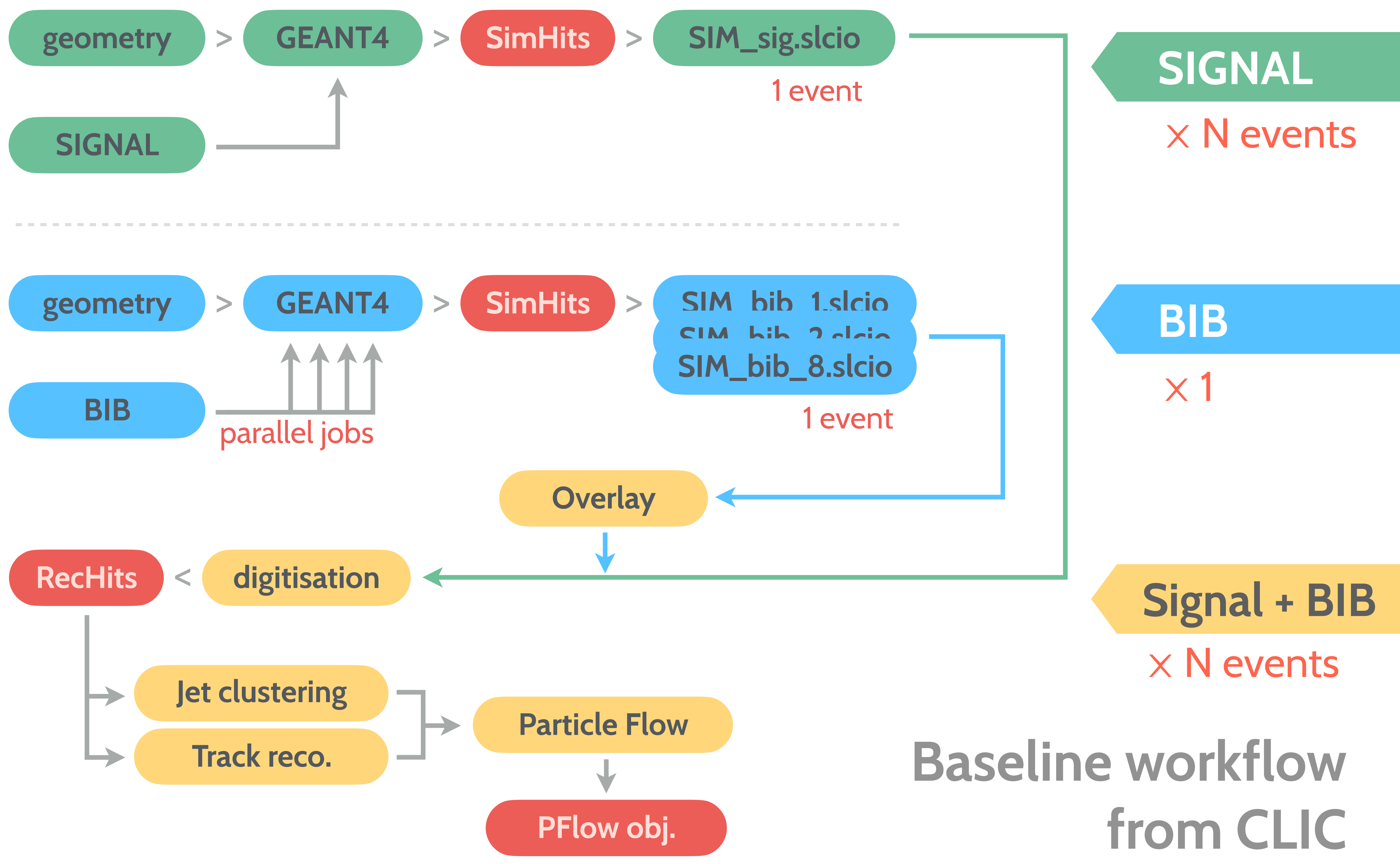
GEANT4 simulation of Signal: straightforward and fast

GEANT4 simulation of BIB: ~10^8 particles/event
↳ **extremely slow** → need a pool of reusable events

Overlay of BIB: performed in each event before digitisation
↳ sensitive to the # of BIB SimHits and merging logics

Reconstruction speed of higher-level objects strongly depends on the amount of input RecHits from BIB

- especially relevant for track reconstruction *(combinatorics)*
- BIB contribution has to be suppressed as early as possible



Baseline workflow from CLIC

BIB contribution creates tremendous amount of data → every step requires careful treatment of computing resources

DISK STORAGE | DISK I/O | CPU TIME | RAM USAGE | DISTRIBUTION

Properties of the BIB contribution

BIB has several characteristic features → **crucial for its effective suppression**

1. Predominantly very soft particles (p << 250 MeV) except for neutrons

fairly uniform distribution in the detector → no isolated signal-like deposits

↳ conceptually different from pile-up contributions at the LHC

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

$\mu^+\mu^-$ collision time spread: 30ps (defined by the muon-beam properties)

↳ strong handle on the BIB → requires state-of-the-art timing detectors

3. Large spread of the origin along the beam

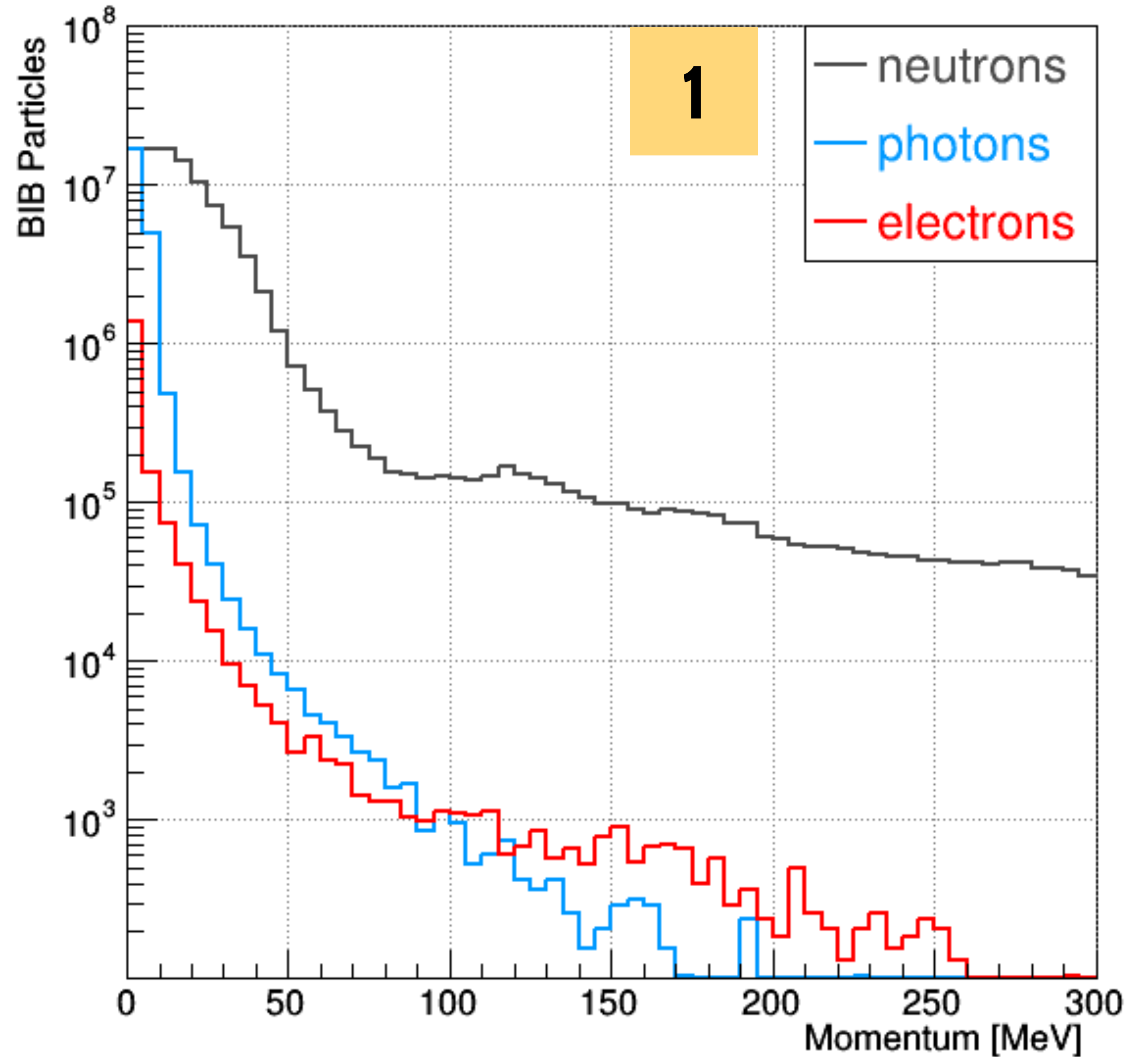
different azimuthal angle wrt the detector surface

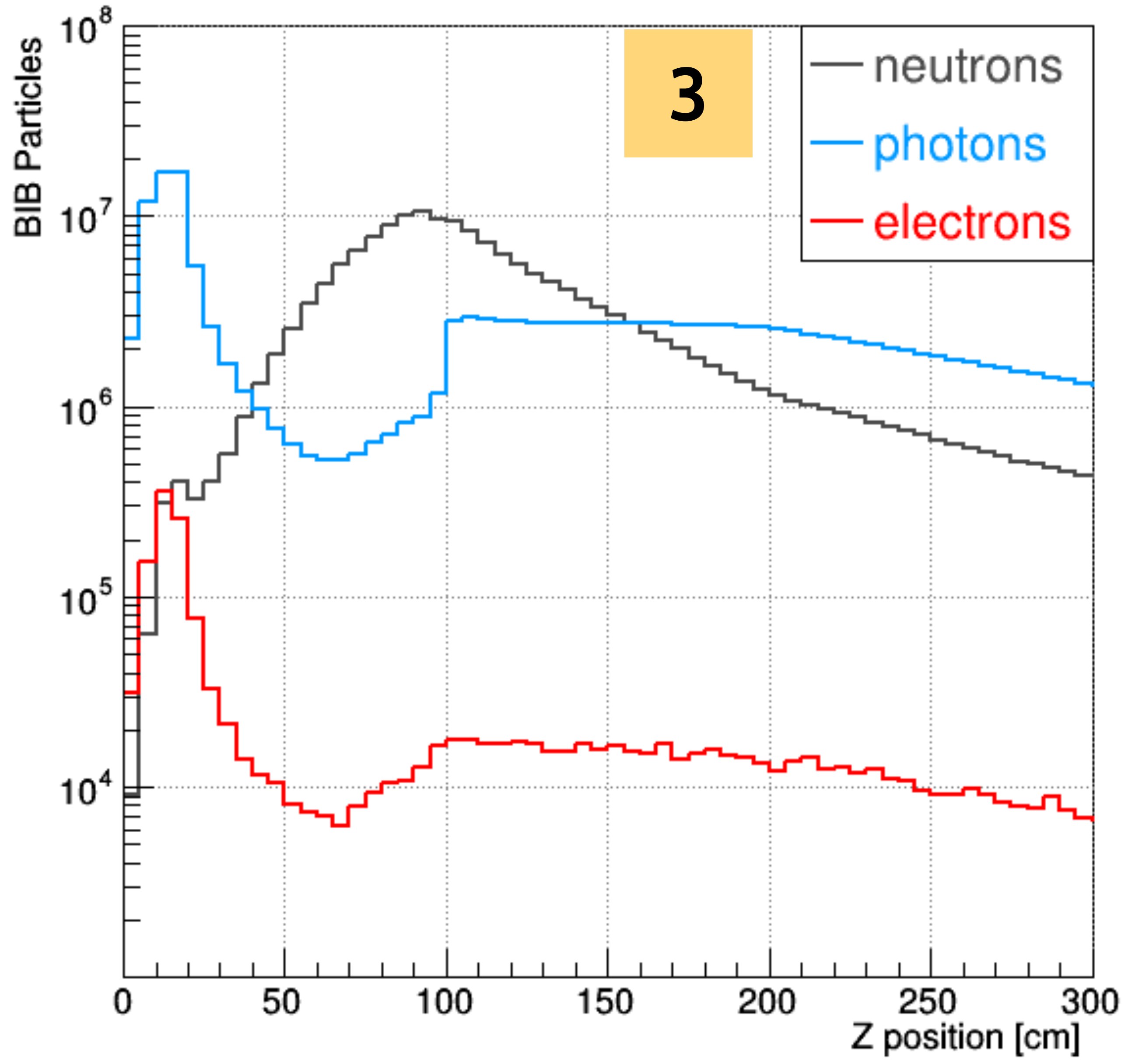
+ affecting the time of flight to the detector

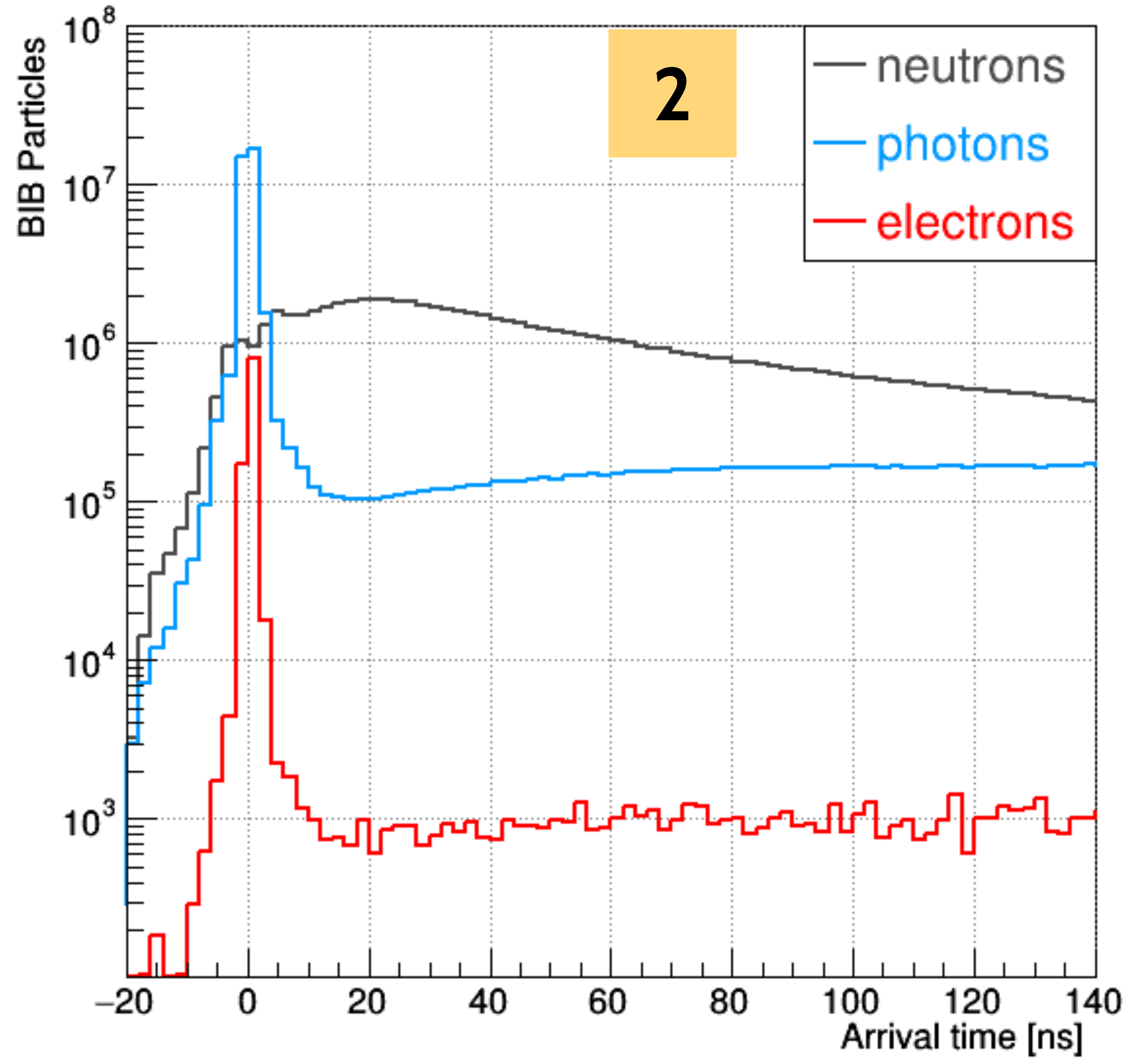
↳ relevant for position-sensitive detectors

Sophisticated detector technologies and event-reconstruction strategies required to exploit these features of the BIB

+ detailed simulation needed to properly evaluate their potential





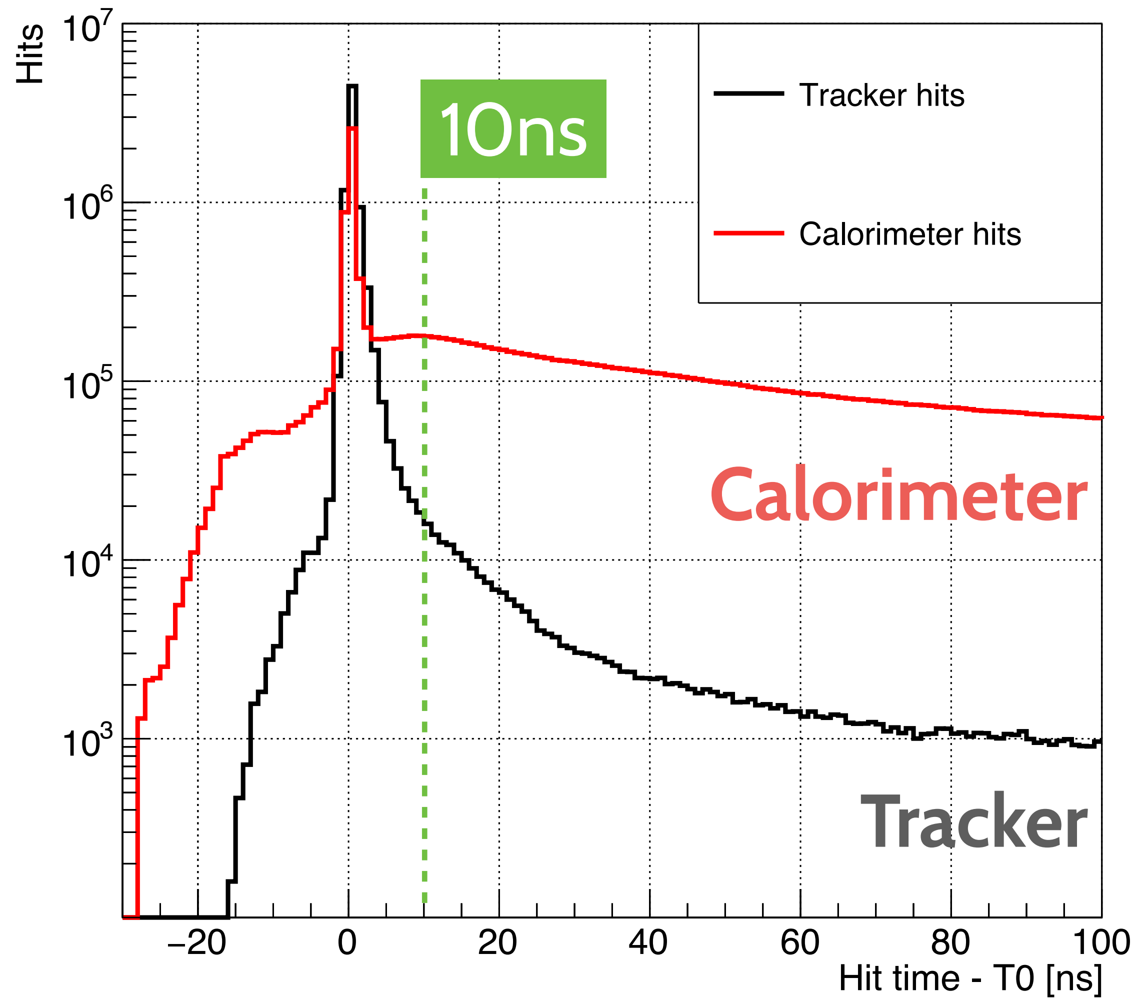


Optimisation I: GEANT4

Not all of the ~10^8 BIB particles arriving to the detector are relevant for its performance in a real experiment
↳ **detectors have finite readout time windows → only a subset of particles relevant for the event reconstruction**

1. No GEANT4 simulation of particles arriving too late ×6 less CPU

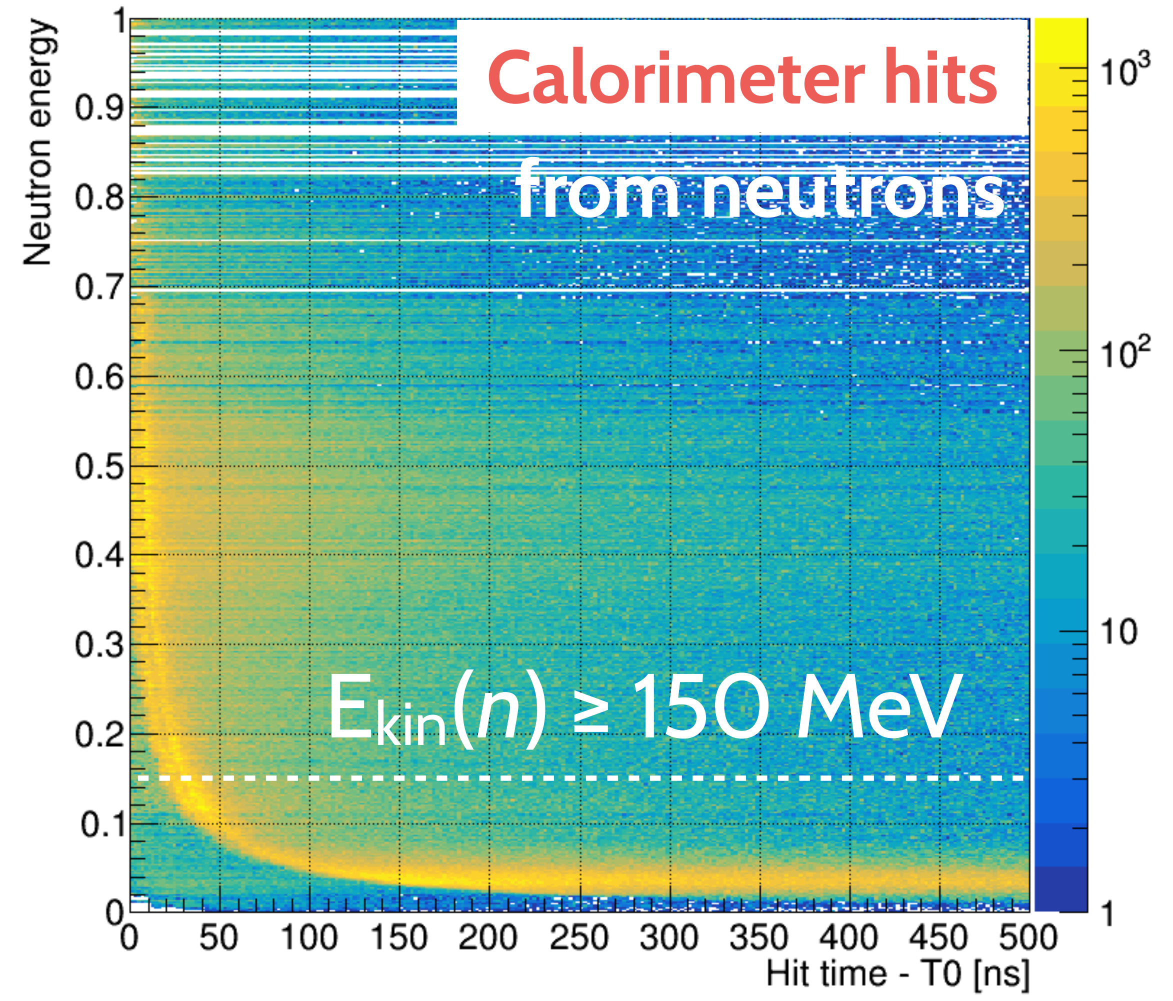
hits at t > 10ns will be outside of the realistic readout time windows
↳ all particles with t > 25ns at the MDI surface are discarded *(accounting for TOF)*



1

2. No GEANT4 simulation of low-energy neutrons ×20 less CPU

high-precision neutron model required for accurate simulation: `QGSP_BERT_HP`
but they are slow → arrive to the detector with a significant delay
↳ neutrons with E_{kin} < 150 MeV can be safely excluded + faster model: `QGSP_BERT`



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GEANT4 simulation of a single BIB event improved from 127 days → 1 day
↳ ~10-100 reusable events can be generated in several days *(parallelisation)*

3. Russian roulette sampling can be used for the most abundant particles *(used in CMS)*

individual neutrons and photons from BIB are not reconstructable → only combined energy deposits in calorimeters are relevant for digitisation/reconstruction
↳ simulate a fraction (1/f) of particles with a weight (f) → less CPU/RAM/DISK

Digitisation logics

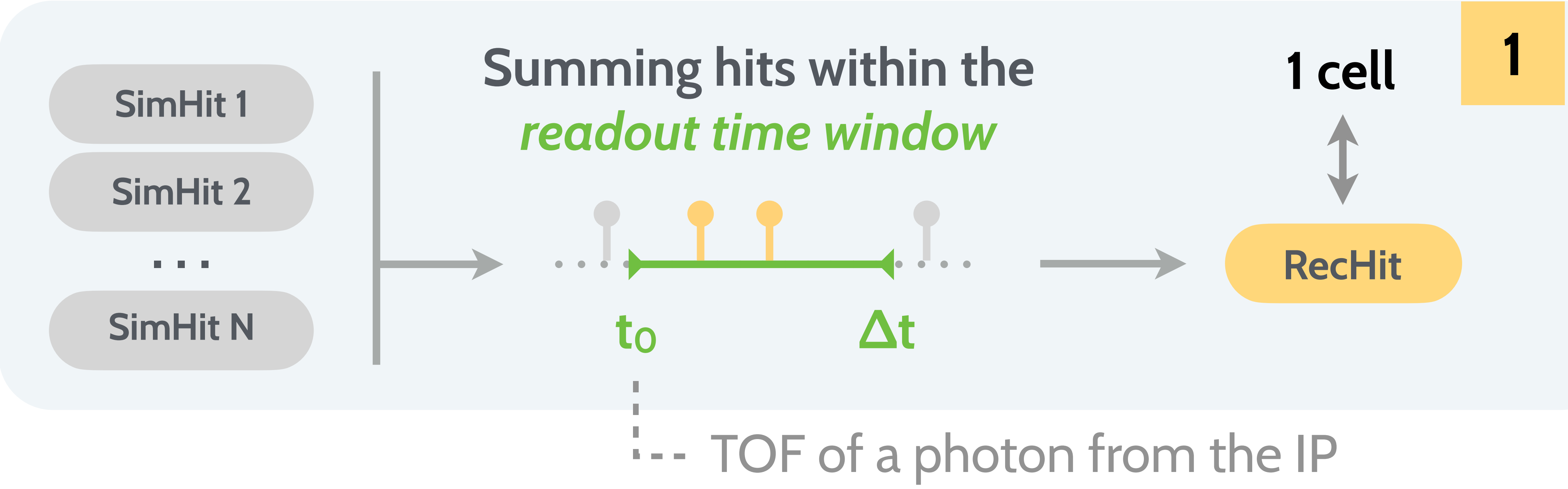
GEANT4 hits produced separately for Signal and BIB → merging + detector effects added during digitisation

↳ **two distinct classes of hits: CalorimeterHit** (ECAL, HCAL, Muon detector) + **TrackerHit** (Tracking detector)

1. Calorimeter hits: cell ID + E_{dep} + timestamp

large cells (0.5×0.5 - 3×3 cm) → manageable # of cells

↳ hits merged within a fixed readout time window *(0-10ns)*



2. TrackerHits: sensor ID + 2D position + time *and more*

small pixels (50×50 μm) to macro-pixels (0.05×10 mm)

↳ too many channels to treat them individually in GEANT4

2.1. Simple 4D smearing by σ_U | σ_V | σ_t

simple and fast → the present baseline

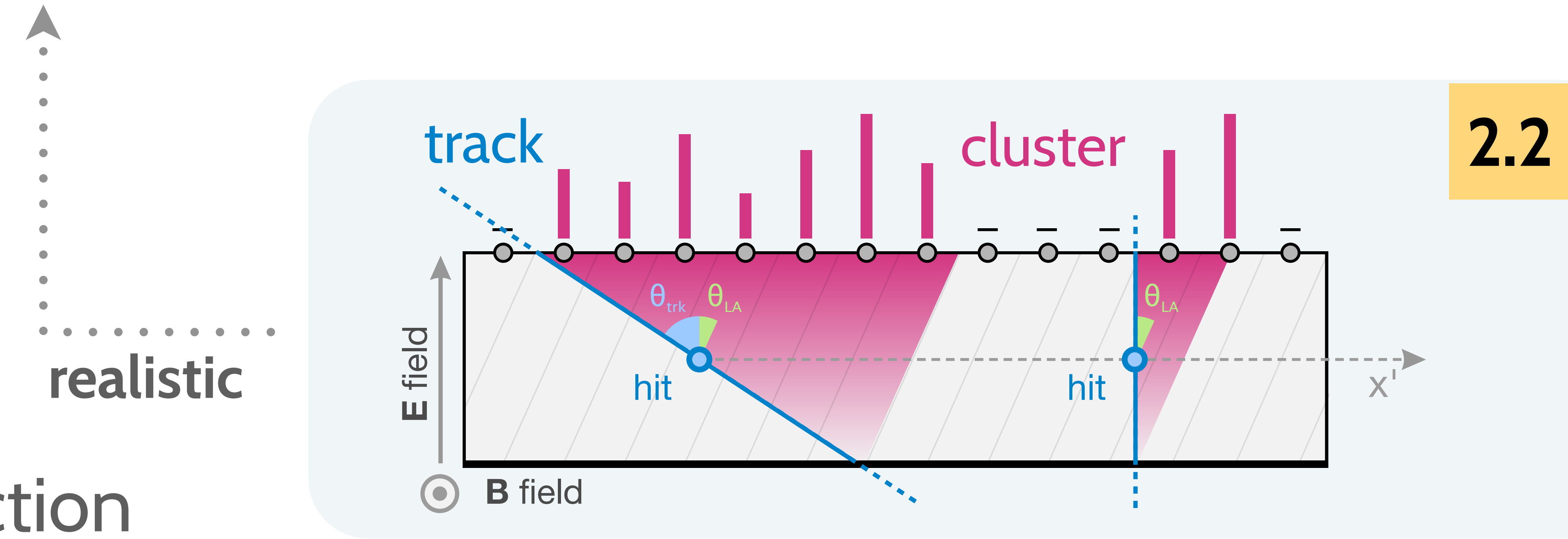
NO charge sharing, pile-up, electronics effects, etc.

2.2. Realistic simulation of sensor + readout-chip response

complex and slower → in the development-testing stage

allows cluster-shape analysis for further BIB suppression

↳ more expensive digitisation → great savings in track reconstruction



Optimisation 2: digitisation

Tracker hits

Individual BIB particles have to be simulated

- **very small pixel size,** down to 50×50 μm
- **cluster-shape** → particle type/angle is important
- **precise timing** → pile-up effects are important

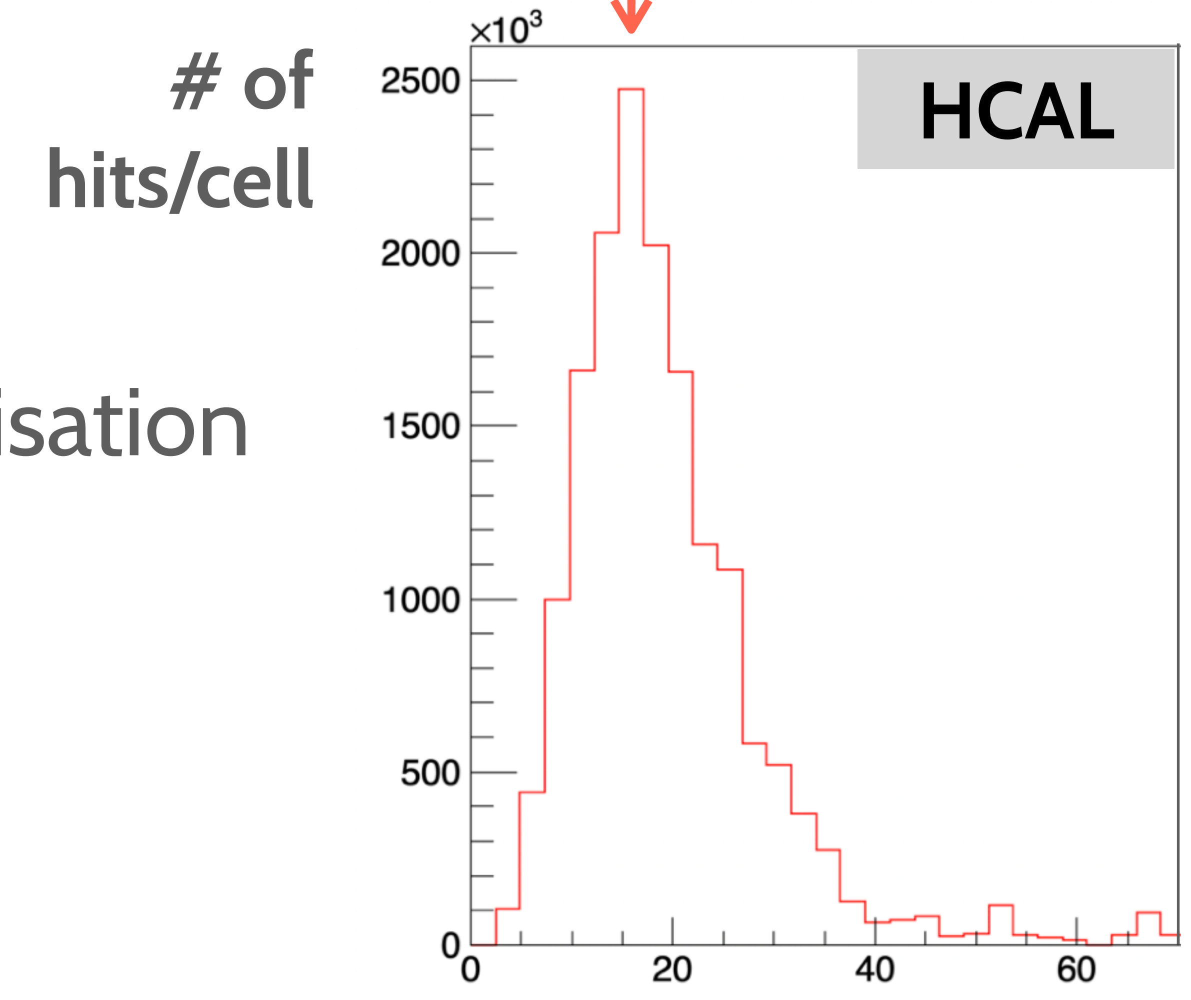
Hits created much later than the readout window will be discarded after digitisation anyway

Calorimeter hits

Only combined energy deposit in a single cell is relevant

- **large cell size,** at least 5×5 mm
- **less precise timing,** order of 100ps - 1ns
- **spatial distribution is fairly uniform**

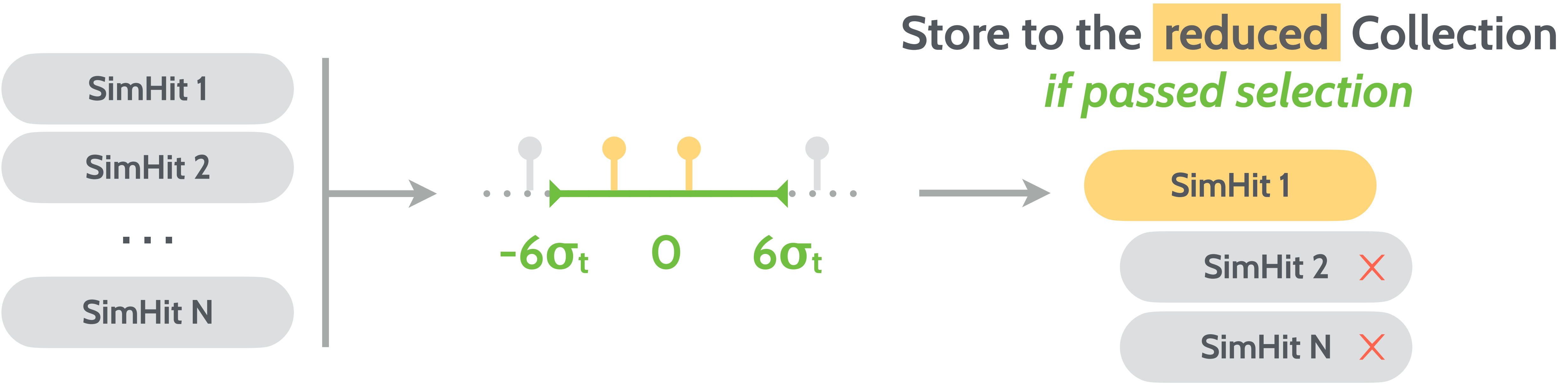
Individual contributions in each cell occupy extra space
on average ×15 more than needed



Reducing SimHit collections before digitisation

×10 less DISK/RAM

many SimHits don't pass the readout cuts after digitisation
↳ store trimmed/merged SimHit collections to disk → only detector effects added at digitisation



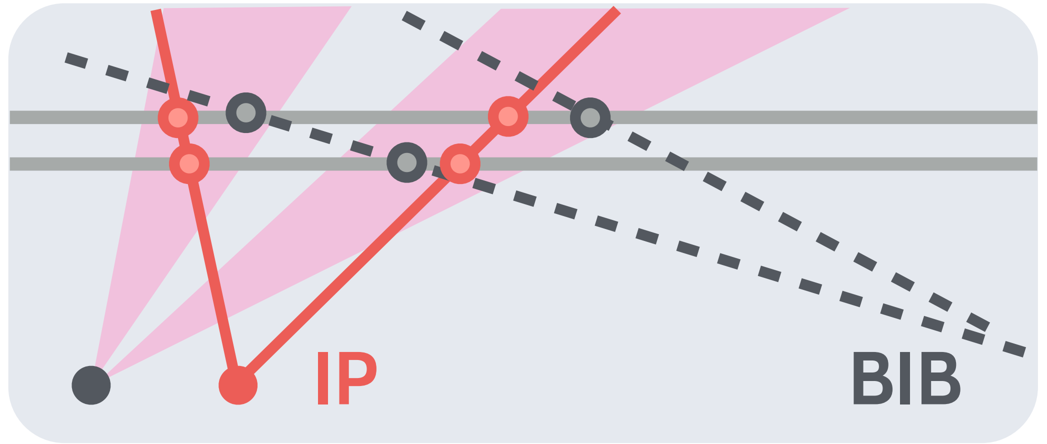
+3σ window for SimHits

to account for extra spread at digitisation

Reconstruction of tracks suffers from large combinatorial background
↳ **need suppression of BIB hits + efficient tracking strategies/algorithms**

1. Selection of hits in the narrow time window tailored to the sensor position
↳ limited by the time resolution + beamspot time spread + slow-particle TOF

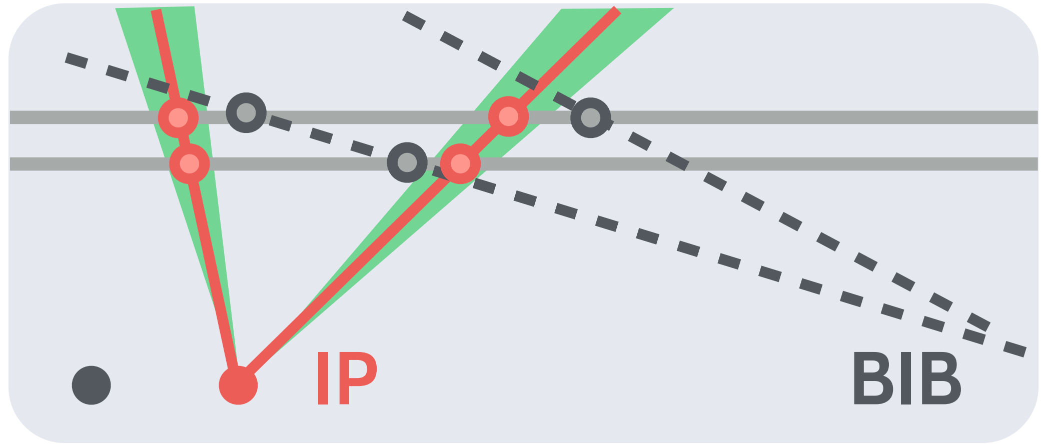
2. Selection of hit doublets aligned with the IP (double layers in the Vertex Detector)
↳ limited by the IP position resolution → requires multi-stage tracking strategy



→

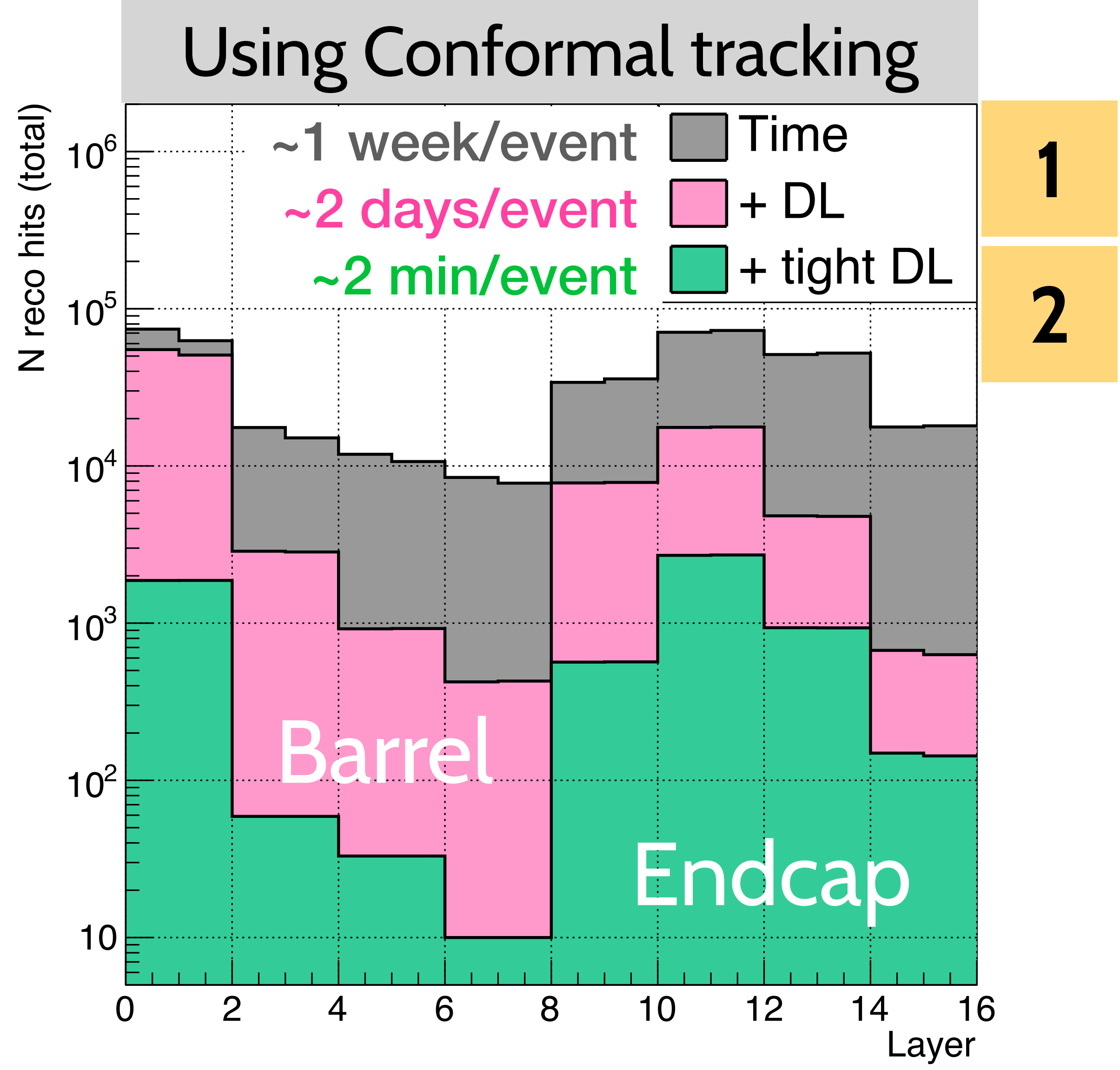
Determine IP position
with faster track reconstruction
- only central region
- inward search from ROI

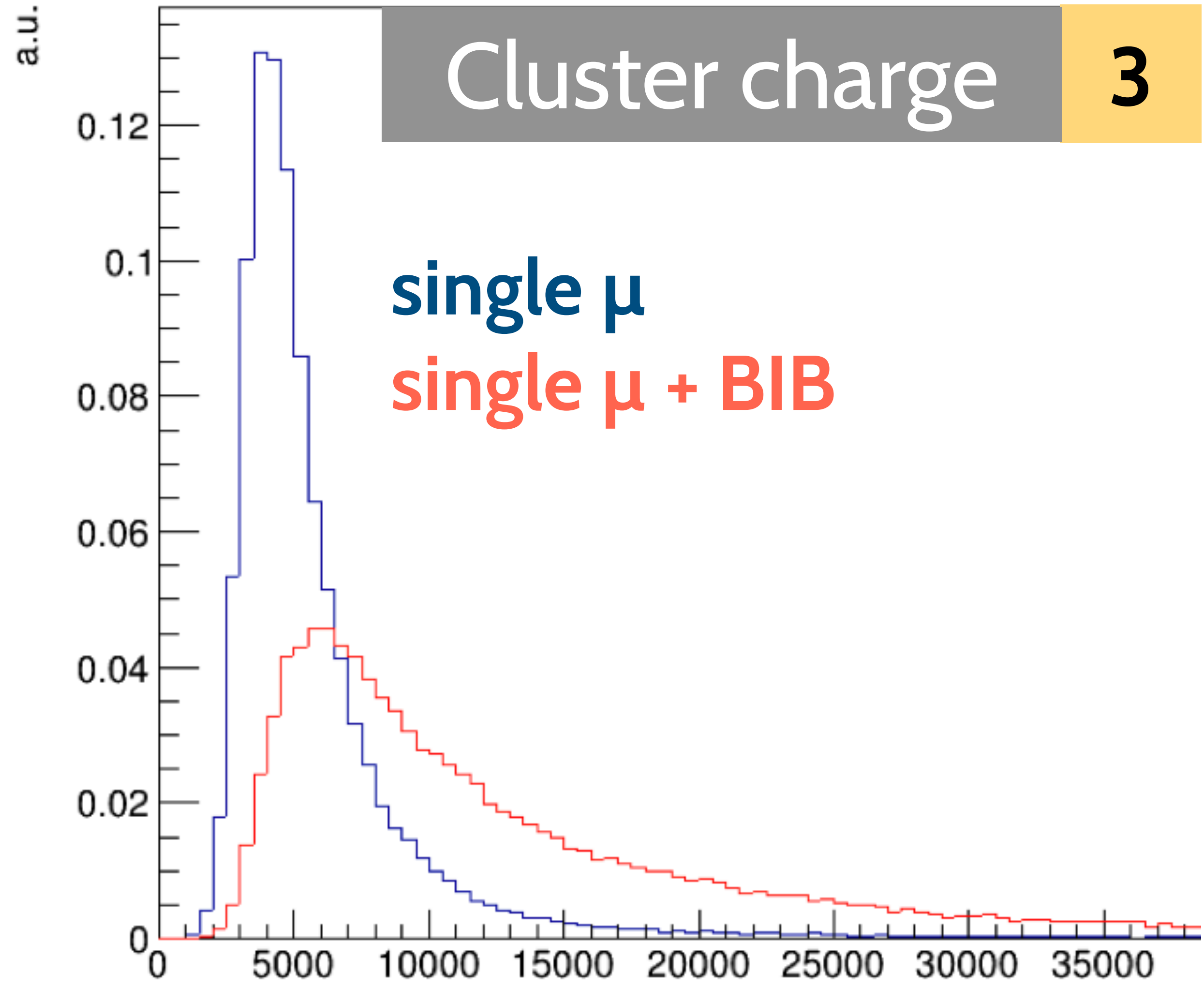
→



3. Cluster-based BIB suppression (shape and charge of hit clusters)
sensitivity to the particle direction/type in a single layer → requires realistic digitisation

4. Further promising optimisations are being explored:
- **faster code → integration of ACTS is in progress** *(vectorised calculations, GPUs)*
- **optimised track seeding → regions of interest** *(muons, calorimeters)*



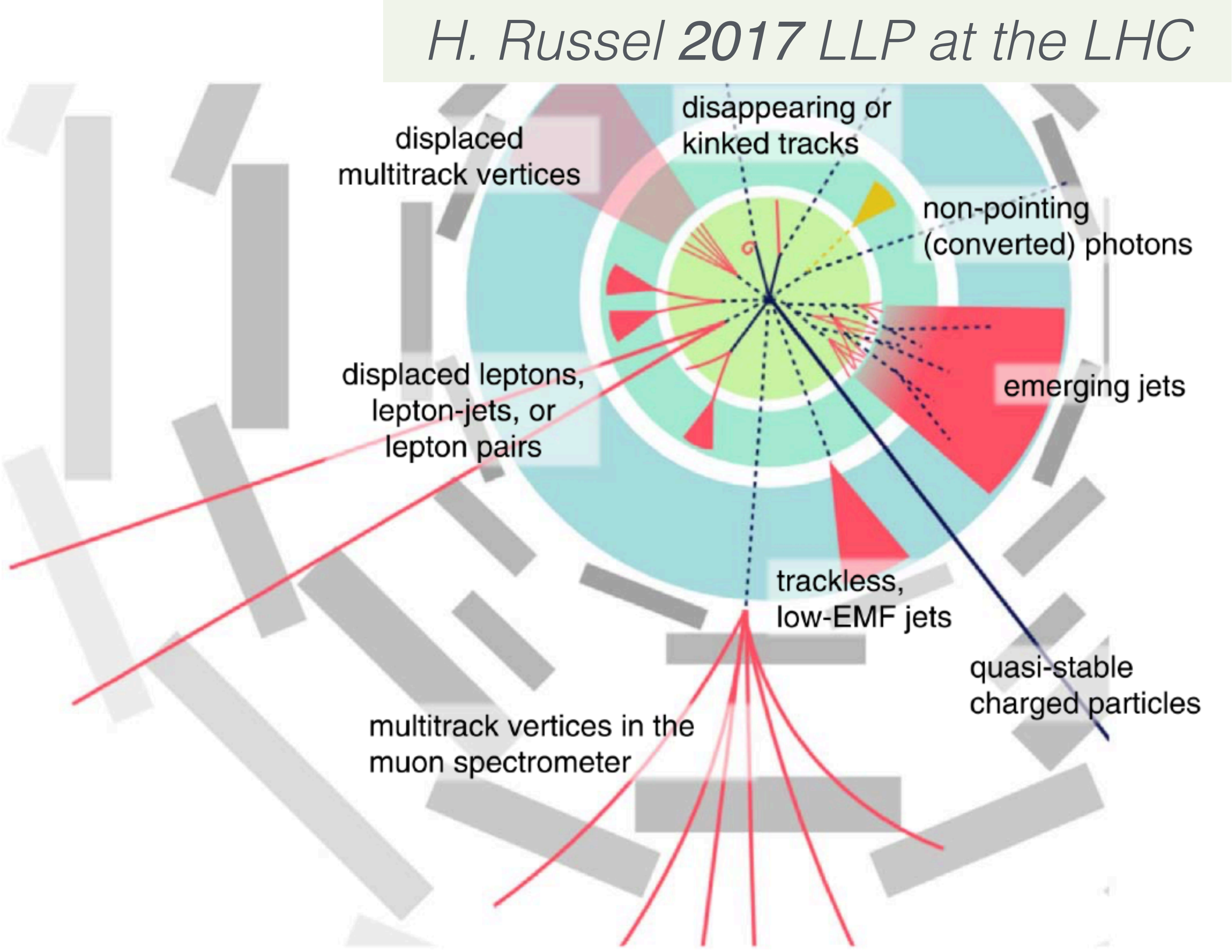


Optimisation 4: new tracking concepts

Extreme hit density calls for very tight selection: time, angle, cluster shape, etc.

But the great power of Muon Collider is in its discovery potential

↳ **exotic signatures can be missed with tight selections** (e.g. long-lived particles) ▶



1. Precise timing can be used in a smarter way

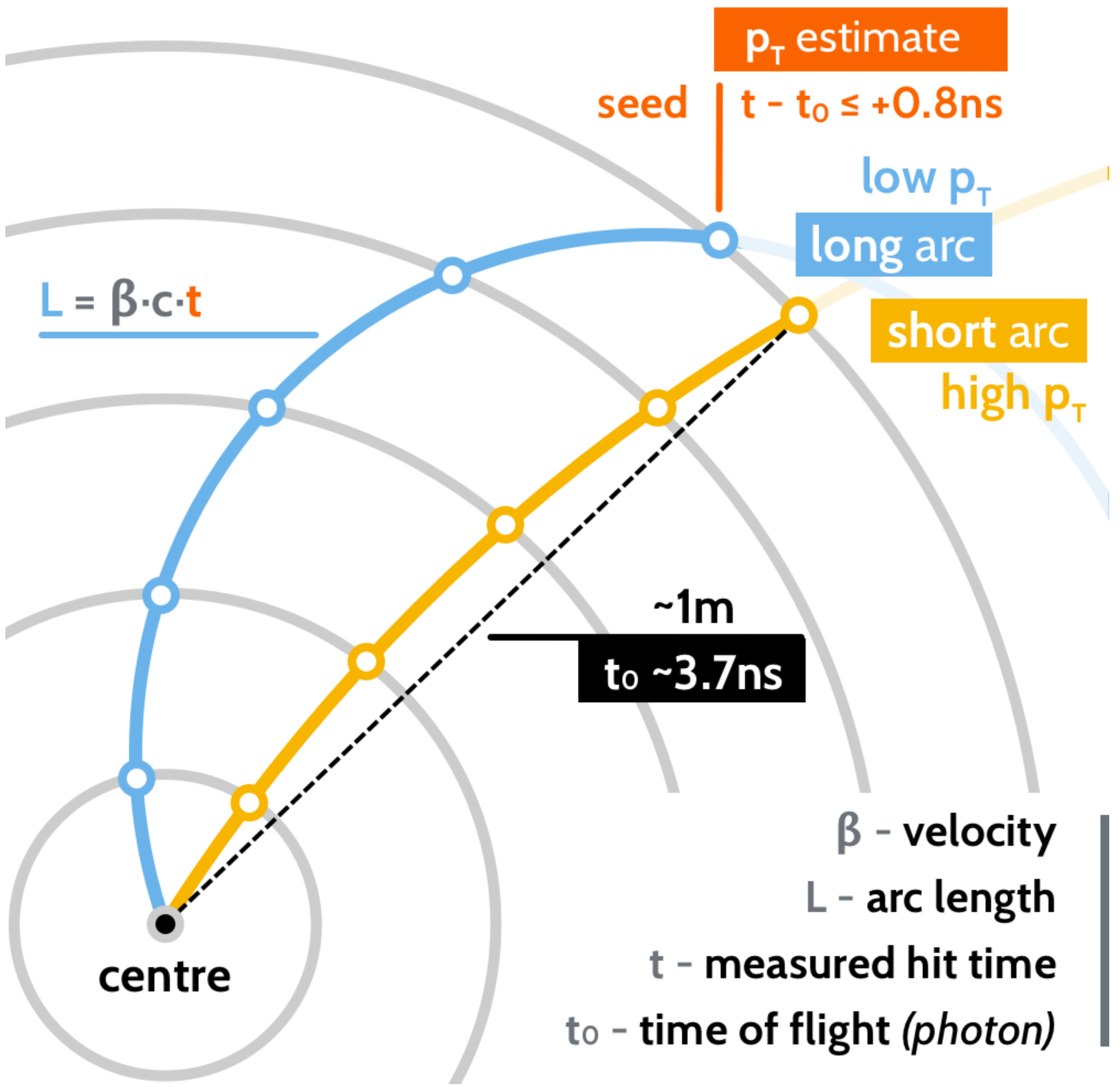
↳ full-featured 4D tracking → including time in the Kalman Filter

2. Generic single-pass tracking approach will be too inefficient

↳ need a staged approach optimised for specific track topologies

1. **high p_T, high velocity, small displacement** ▶
2. **low p_T, high velocity, small displacement** ▶
3. **lower velocities** *(massive particles: muons, pions, kaons, ...)*
4. **larger displacements** *(long-lived particles)*

Every track topology can use a dedicated seeding strategy
to minimise combinatorics



3. A single hit collection might be too heavy to handle

↳ can be split in subsets relevant for specific groups of track topologies

Summary

Muon Collider is a unique machine for discoveries and precision measurements

Beam Induced Background (BIB) poses tremendous computational challenges throughout the detector simulation workflow

Current simulation studies are based on the iLCSoft framework with limited computing resources

BIB suppression is crucial at every step of event simulation and reconstruction
to minimise the usage of disk storage, I/O, RAM and CPU on irrelevant computations

- storage and RAM are particularly important to make such studies widely accessible
many researchers don't have access to large-scale computing infrastructures at this stage

Track reconstruction is by far the most CPU-intensive and time consuming component

- intelligent solutions for making it more efficient are under development

A great progress has already been made, but another factor 10+ improvement is needed to enable realistic large-scale studies and we know how to get there