Object-reconstruction optimisation at Muon Collider

Session B08: **Muon Collider Symposium I**

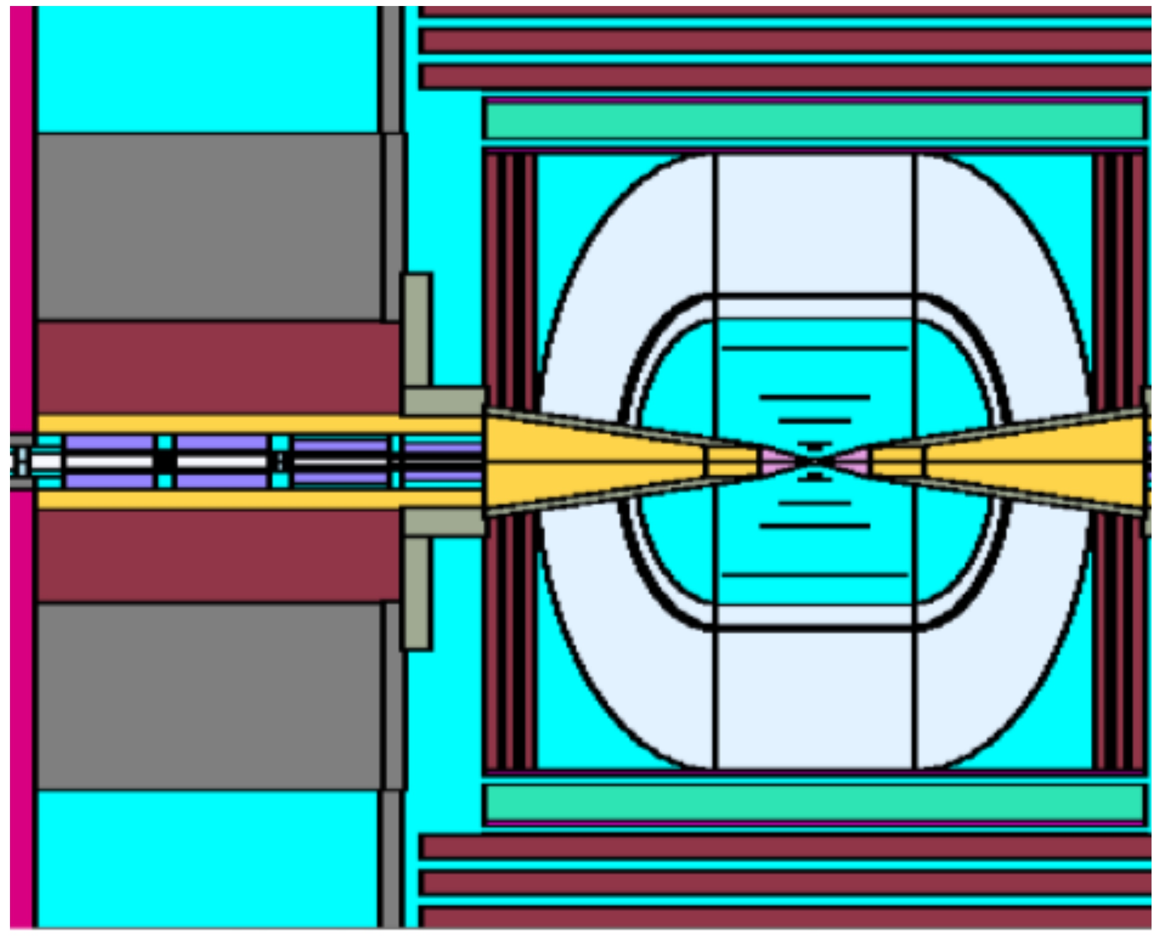
N. Bartosik

INFN Torino

on behalf of the

Muon Collider Detector and Physics Group

Beam Induced Background: $\sqrt{s}$ = 1.5 TeV



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

Essential component is the MDI: **tungsten nozzles** reduce the BIB rate by a factor ~500

Currently using a BIB sample simulated by **MAP** **with** ***MARS15*** for $\sqrt{s}$ = 1.5 TeV

↳ **soon to transition to the independent simulation** with ***FLUKA + FlukaLineBuilder***

see the talk by C. Curatolo

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

- collected at the outer surface of the detector and the MDI - - - - -
- 2 × 180M particles → full simulation needed for a realistic detector-performance estimation

Detector geometry based on the CLIC design [DD4hep]

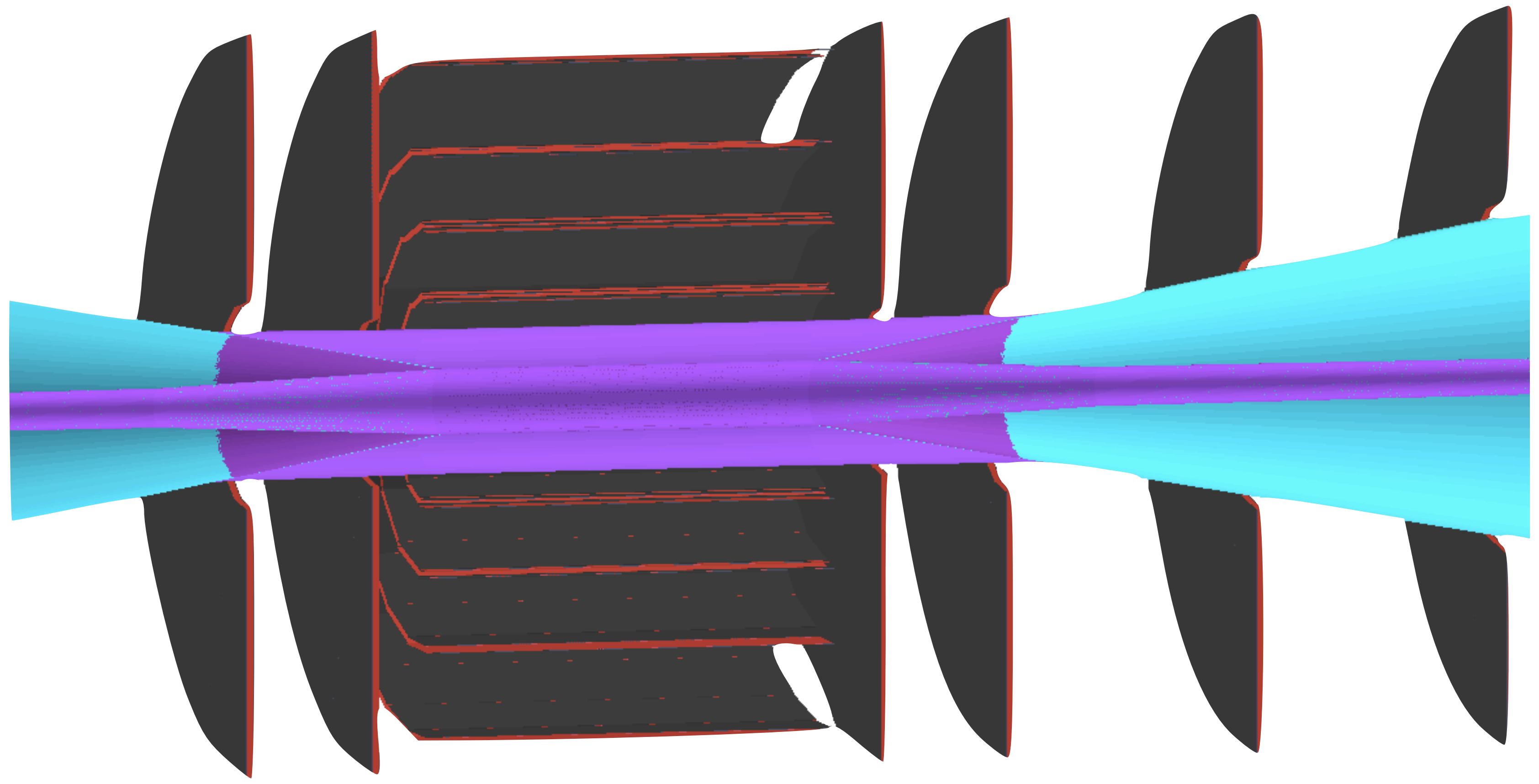
Tungsten nozzles: forward acceptance >10°

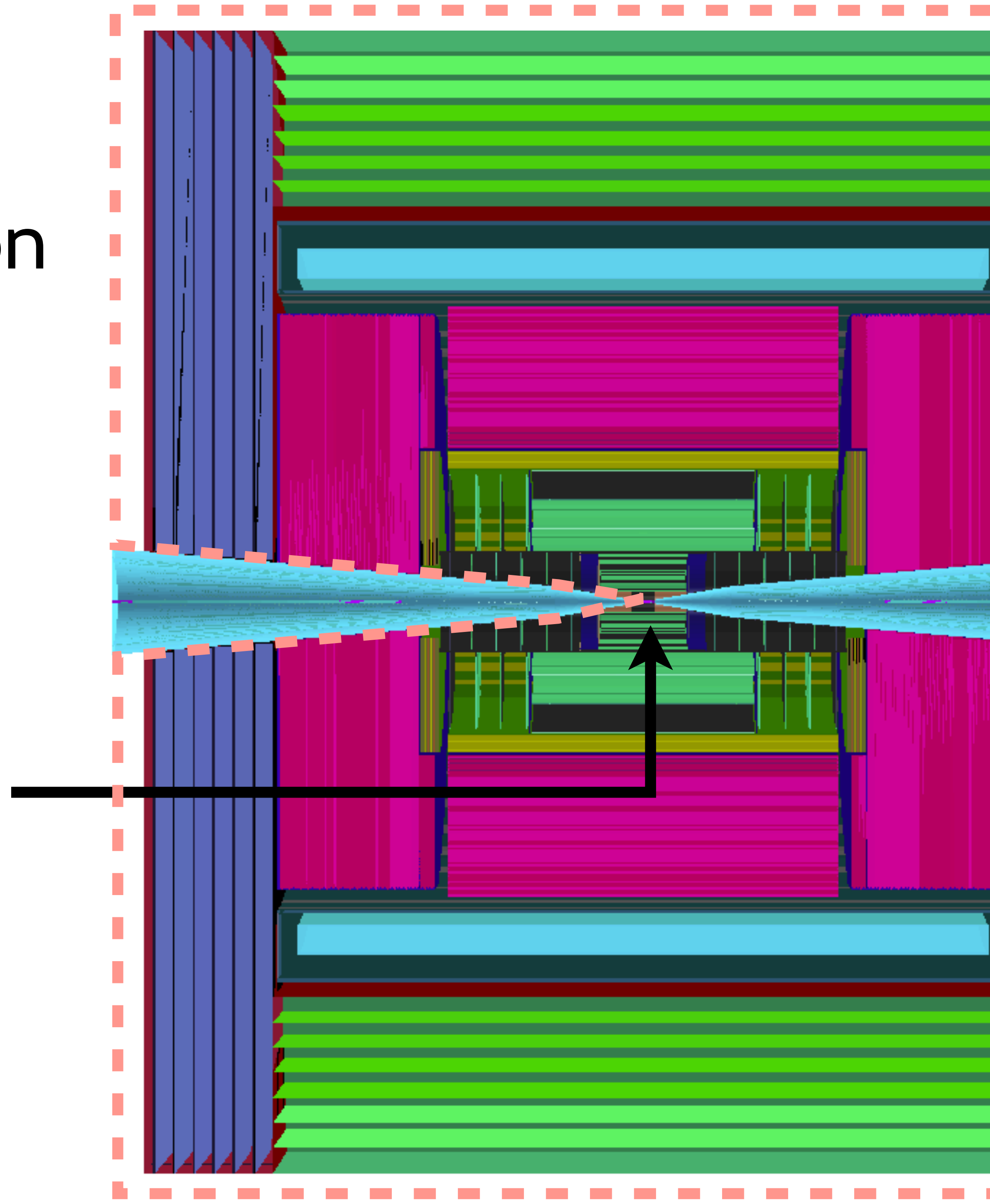
High-granularity calorimeter

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

All-silicon tracker: B = 3.57 T

- double-layer vertex detector



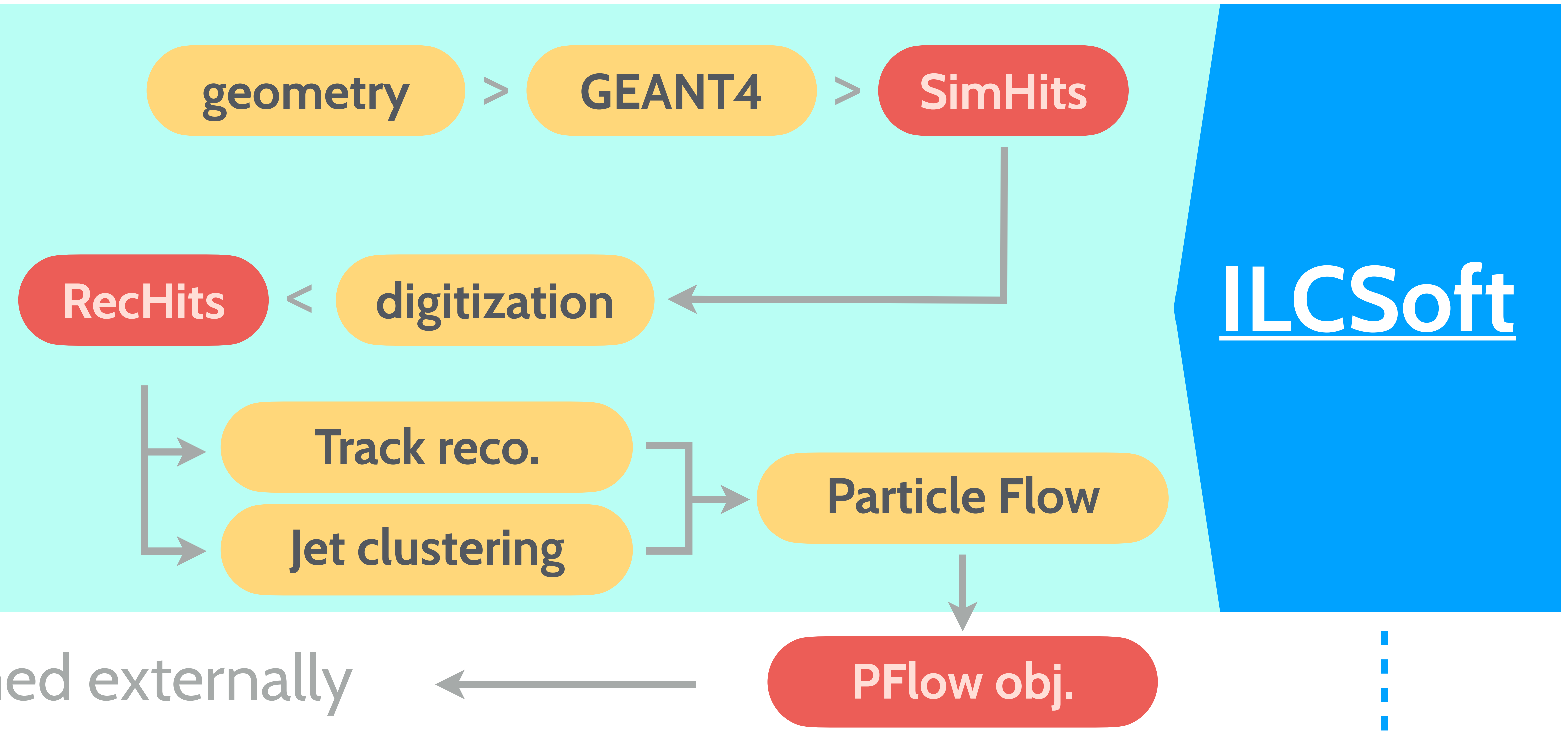


Simulation software tack: ILCSoft

Software framework of the CLIC experiment chosen as a starting point

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**
3. **conversion of simulated hits to reconstructed hits**
4. **reconstruction of tracks/jets/particles**
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](Key4HEP) **stack:** planning full transition in the future

Centralised software revisions distributed through Docker and Singularity containers + manual build instructions

Tutorial on the simulation software was organised recently: September 30, 2020

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)

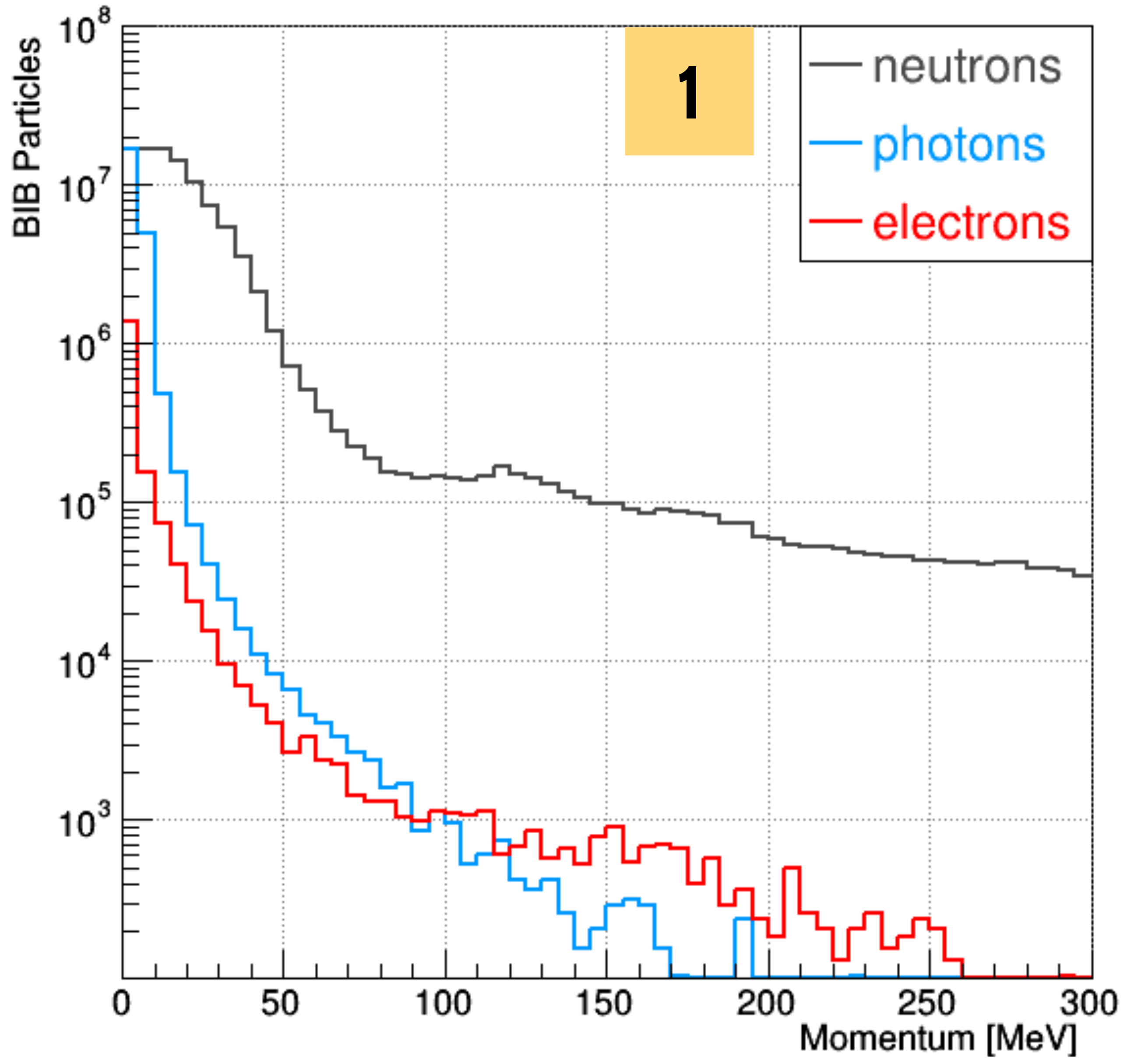
$\mu^+\mu^-$ collision time spread: ~30ps (defined by the muon-beam properties)
↳ strong handle on the BIB → requires state-of-the-art timing capabilities

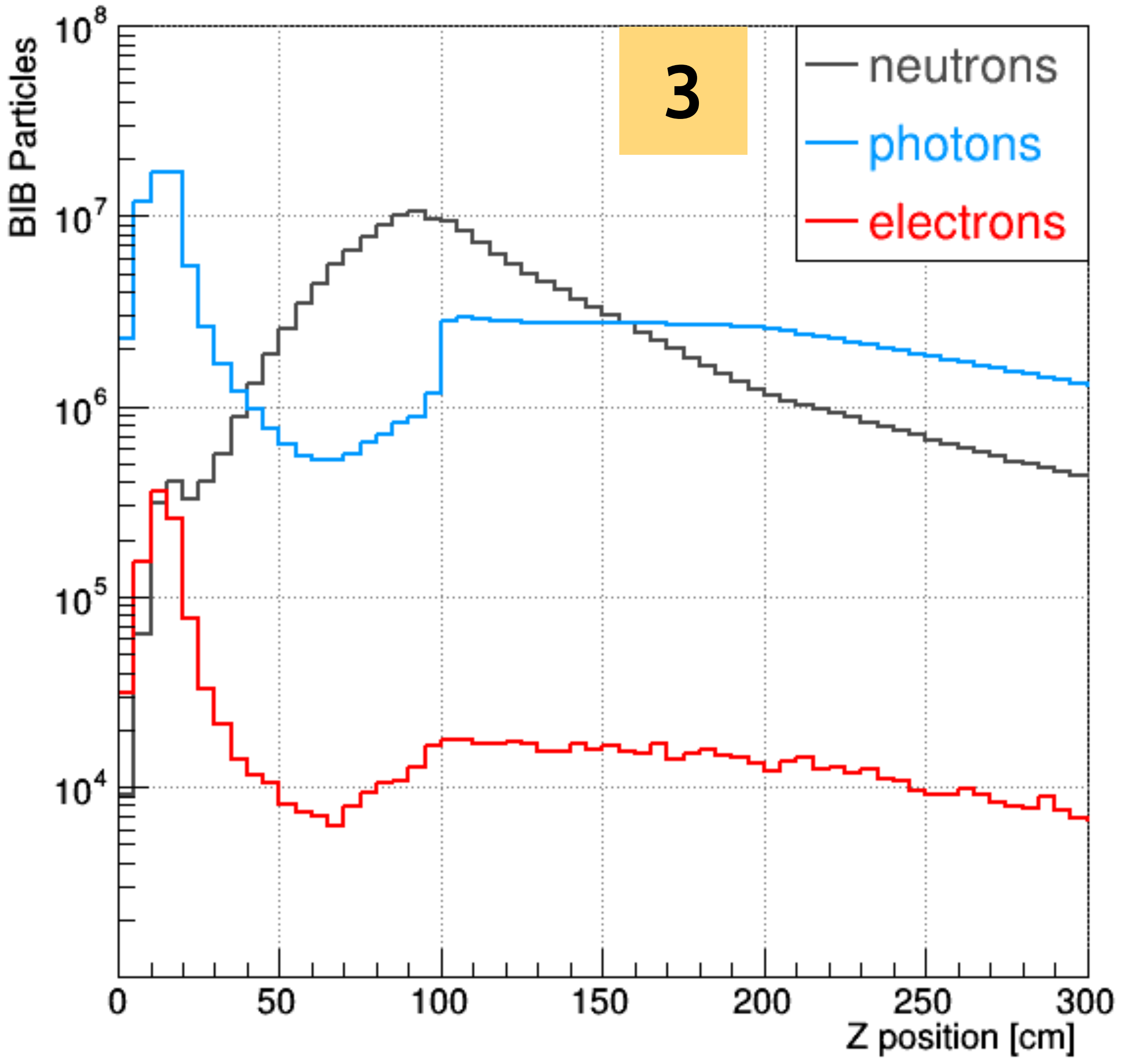
3. Large spread of the origin along the beam

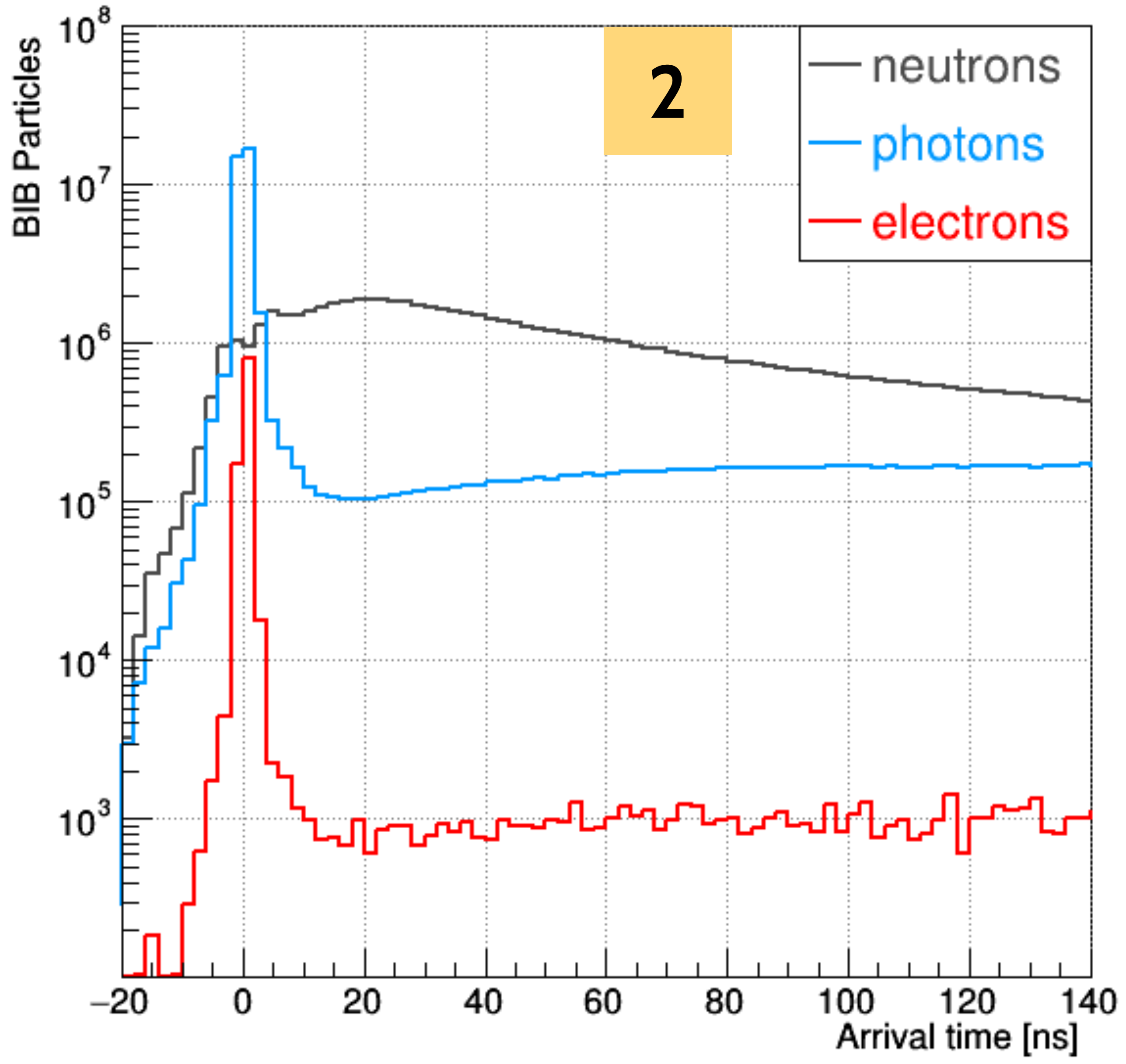
different azimuthal angle wrt the detector surface
+ affecting the time of flight to the detector

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

4D coordinates of the Interaction Point (IP) define the reference to 2 and 3







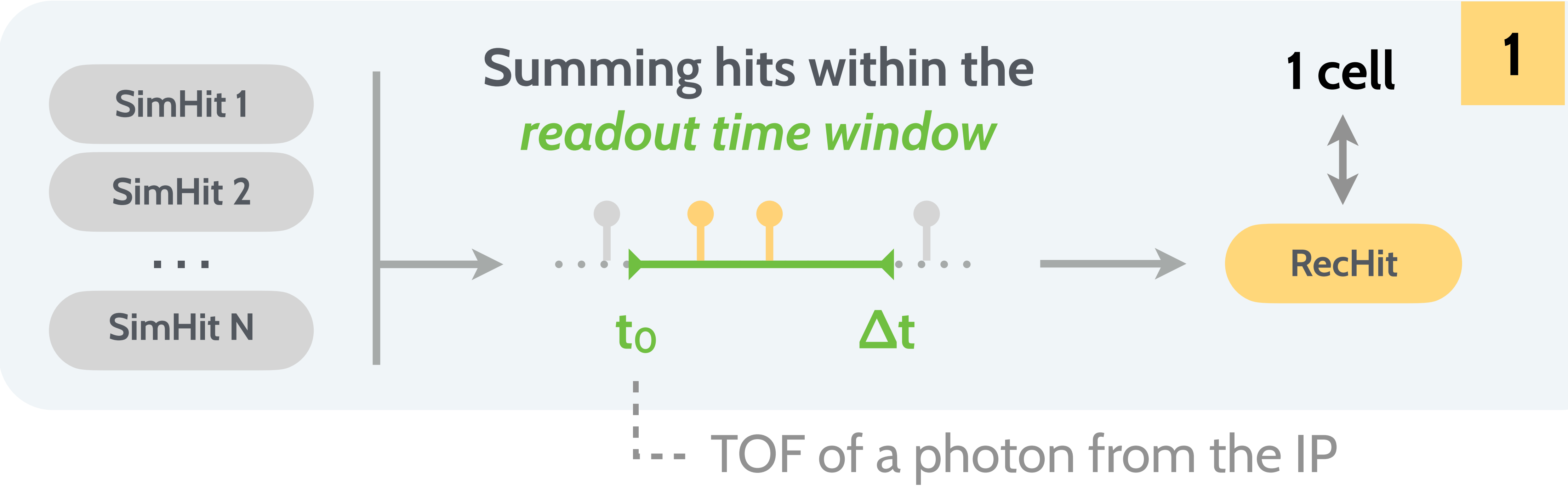
GEANT4 hits produced separately for signal and BIB → merging + detector effects added during digitisation

↳ **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

↳ merge hits within the fixed readout time window



2. TrackerHits: sensor ID + E_{dep} + position + time *and more*

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

↳ too many channels to treat them individually

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

simple and fast → the present baseline

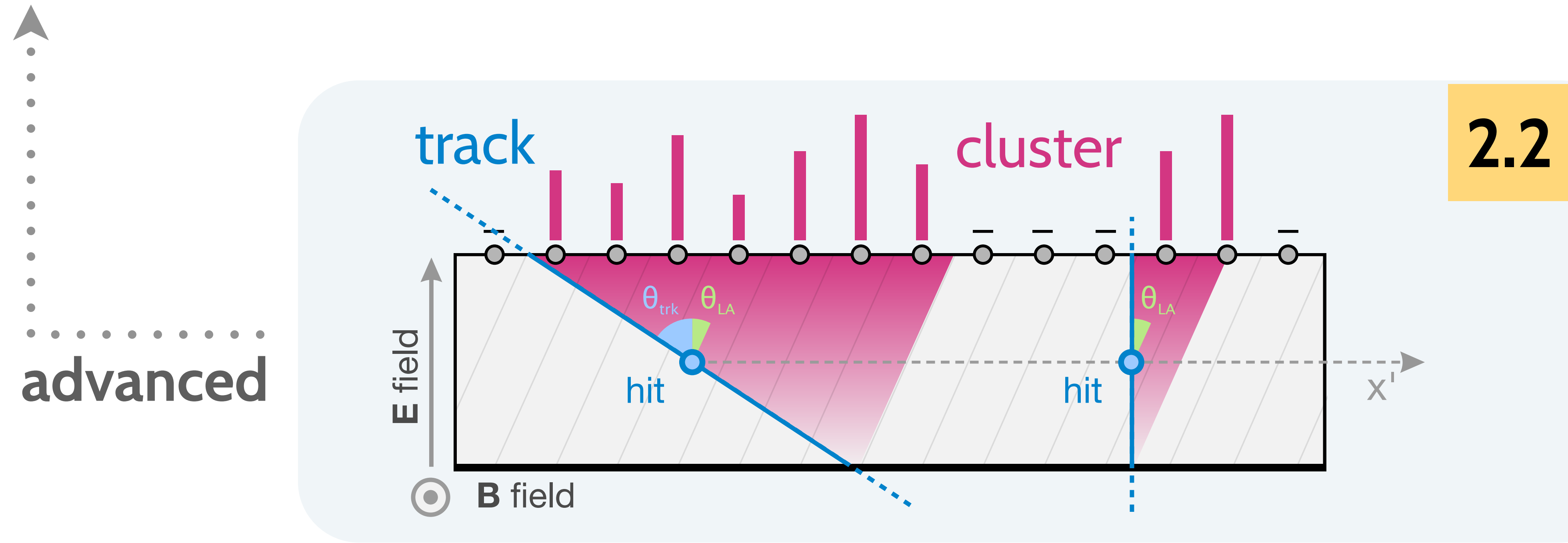
NO charge sharing, pile-up and electronics effects

2.2. Realistic simulation of sensor + readout-chip response

slower → in the development-testing stage

allows cluster-shape analysis for further BIB suppression

effects of readout-electronics properly taken into accounts



BIB introduces ~10^8 particles in a single event → a tremendous computation load: CPU, RAM, disk space
↳ **contributions not relevant for the end result have to be excluded from the chain as early as possible**

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

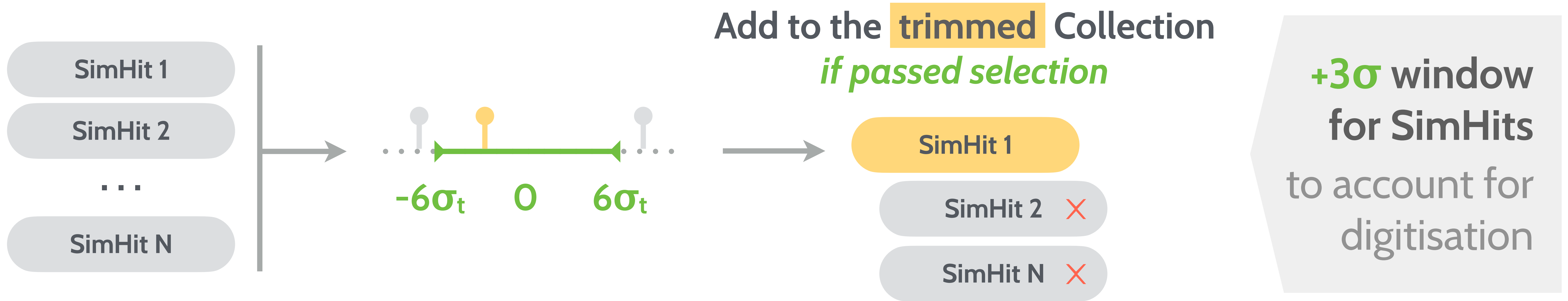
hits at t > 10ns will be outside the realistic readout time windows
↳ accounting for TOF: particles with t > 25ns at MDI are ignored

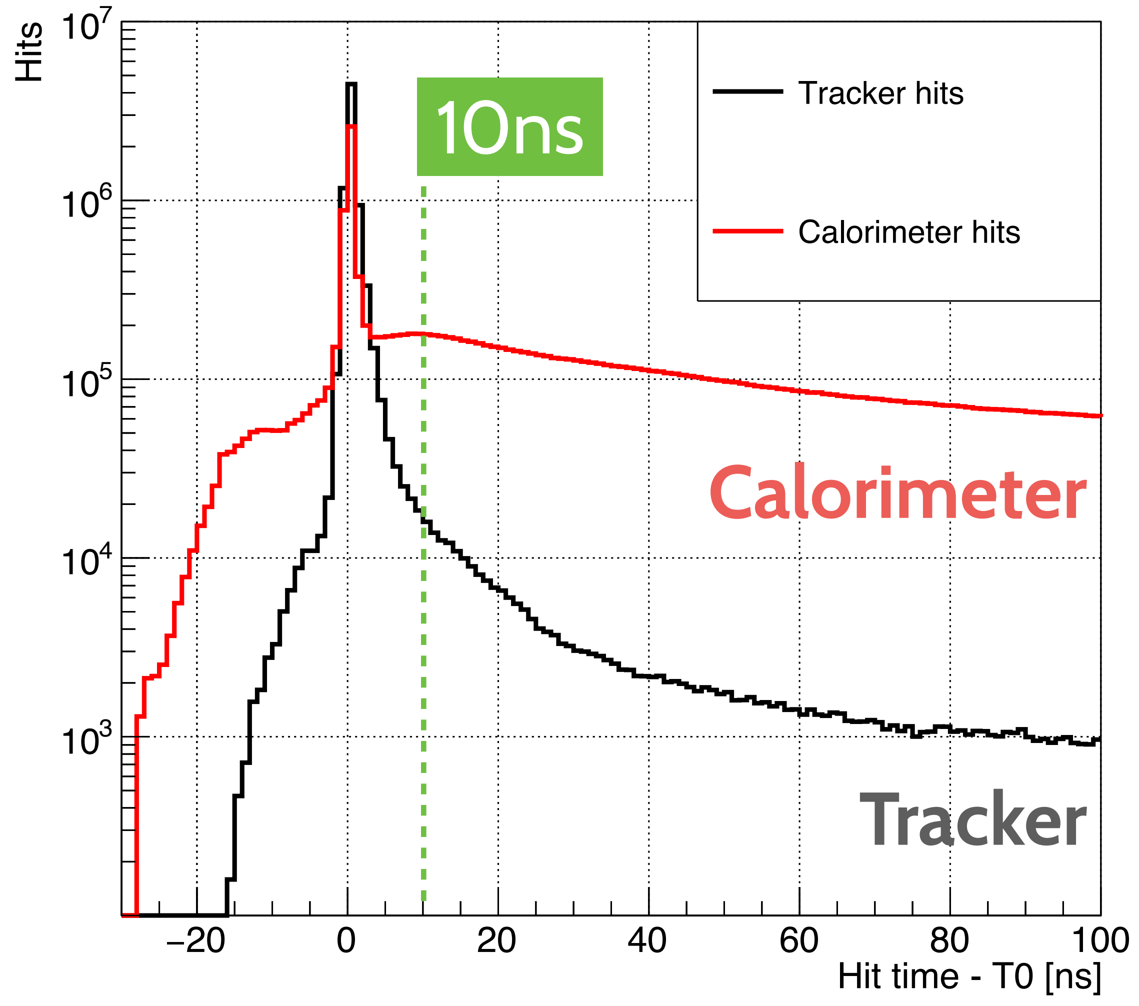
2. No GEANT4 simulation of slow neutrons ×20 less CPU

low-energy neutrons reach the calorimeter too late
↳ neutrons with E_{kin} < 150 MeV can be safely excluded

3. Trimming of SimHits before digitisation ×10 less RAM

many SimHits don't pass the readout timing cuts during digitisation
↳ storing trimmed SimHit collections → less processing during digitisation





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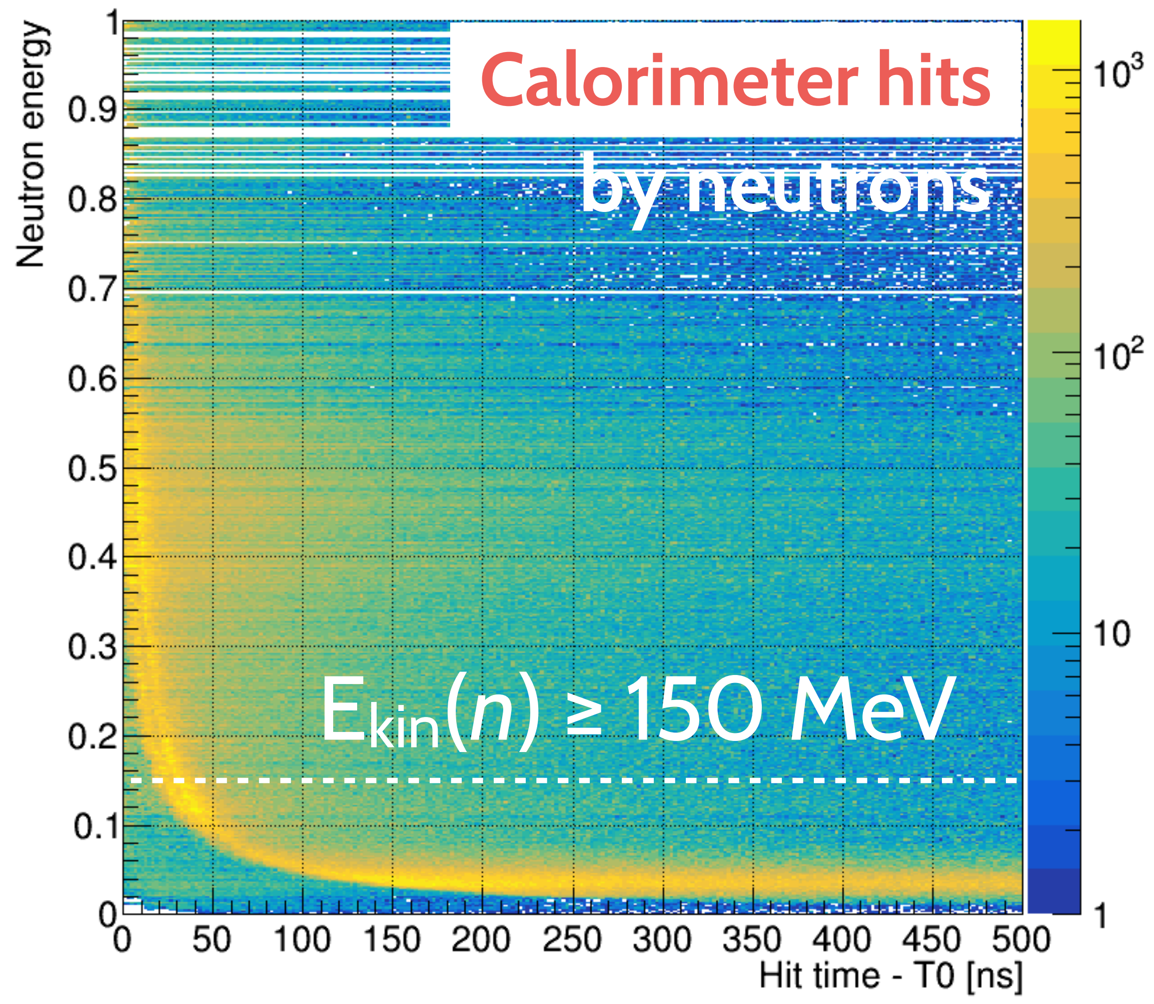
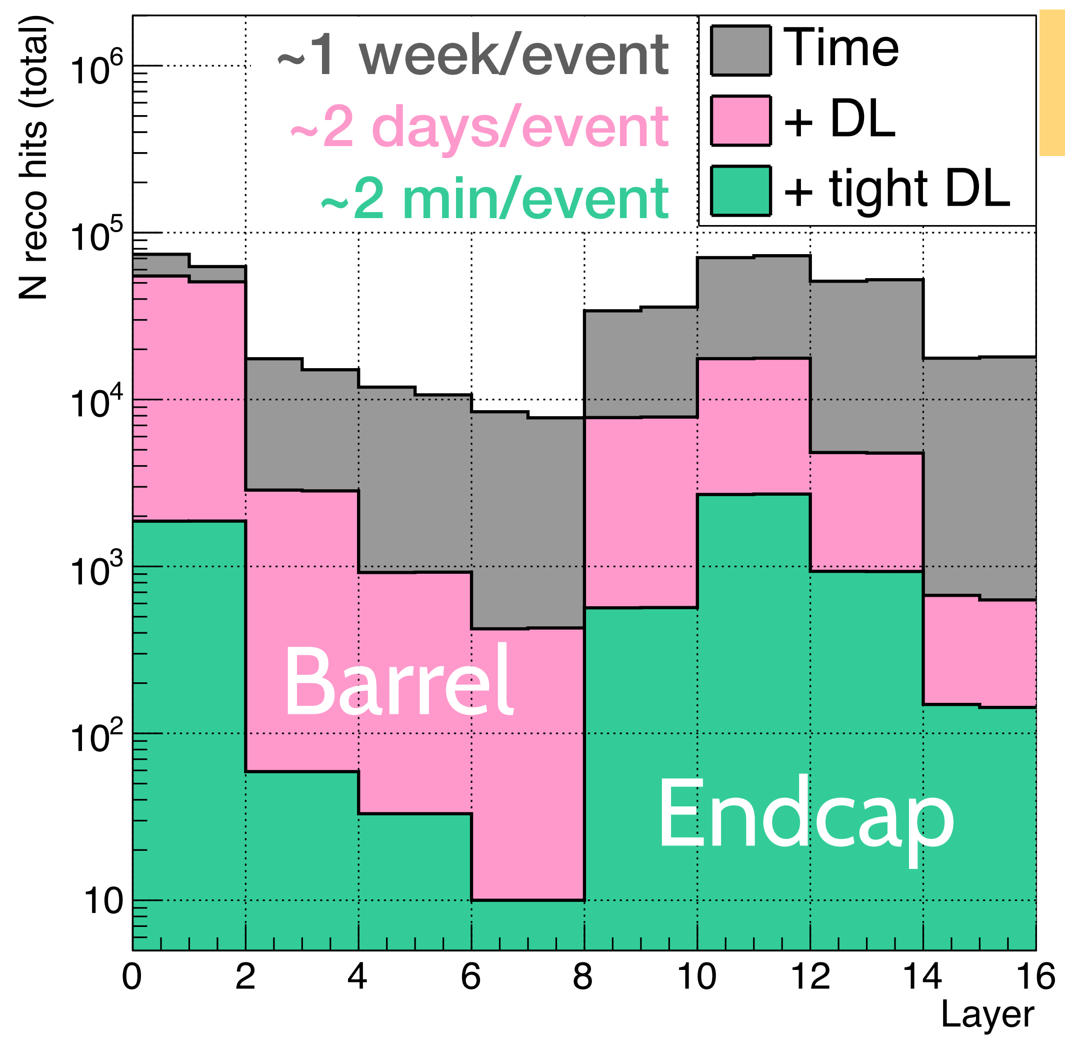


2

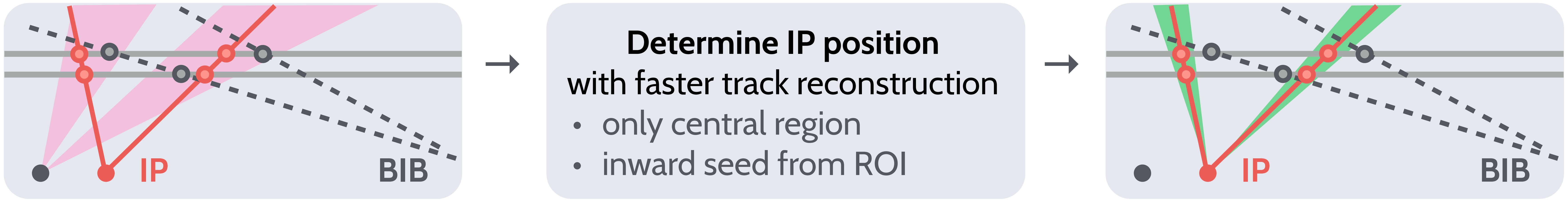
Reconstruction of tracks suffers from large combinatorial background
↳ **suppression of BIB hits is crucial to reconstruct events in reasonable time**

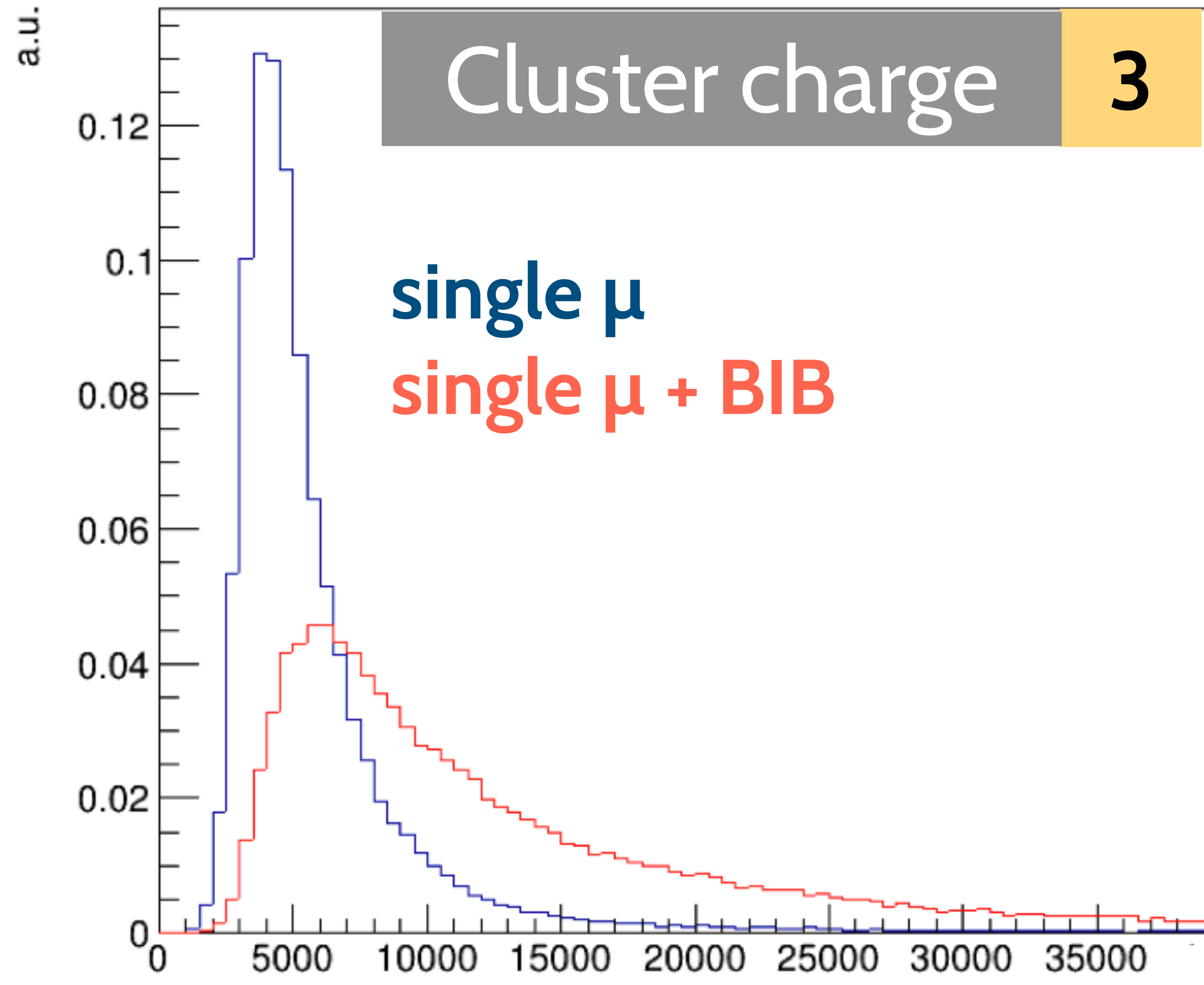
2



1. Selection of hits in the narrow time window tailored to the sensor position
↳ limited by the tracker time resolution + acceptance for slow particles

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





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

All these strategies require a challenging detector design
↳ **high spatial and time resolution + low occupancy** ← *more in the talk by* ***H. Weber***

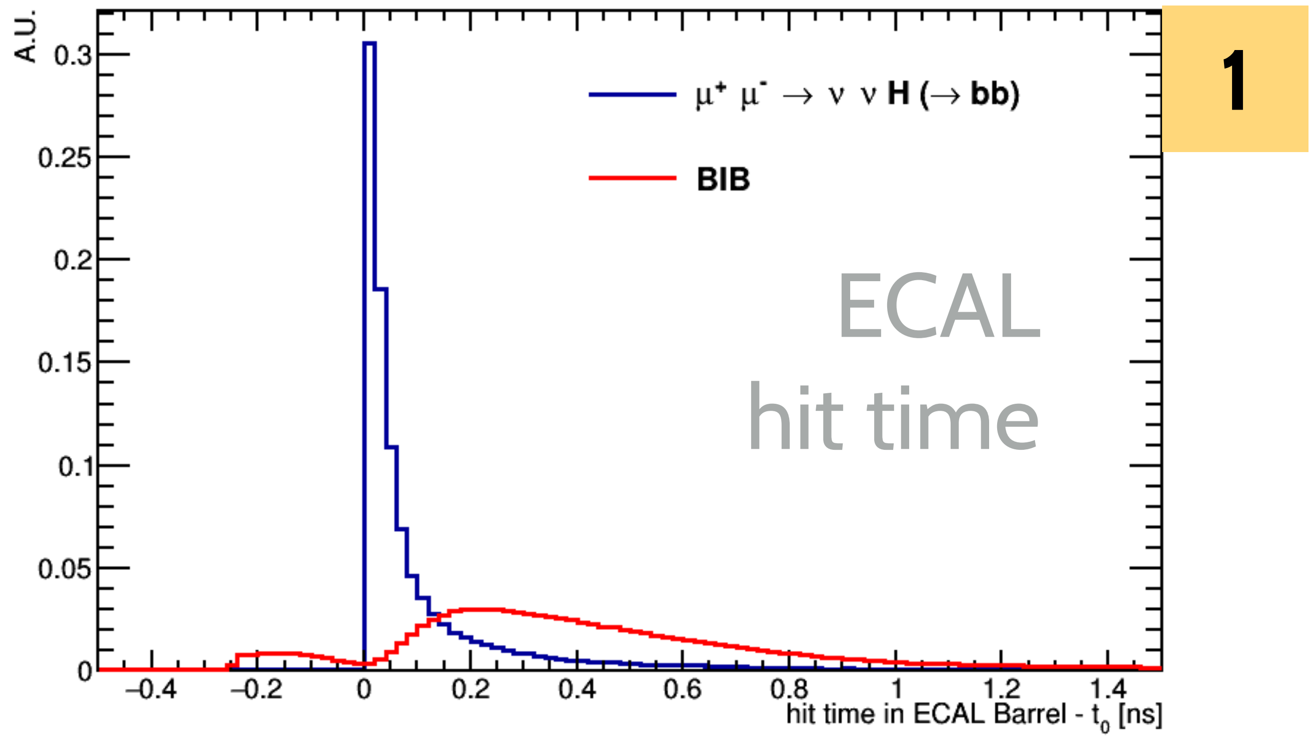
Currently using Conformal Tracking with state-of-the-art timing detectors ← *more in the talk by* ***M. Casarsa***

Potential performance boost with ACTS tracking software ← *more in the talk by* ***K. Krizka***

About 6 TeV (2.5 TeV) of energy deposited in ECAL (HCAL) by BIB
↳ effective BIB subtraction necessary for jet reconstruction

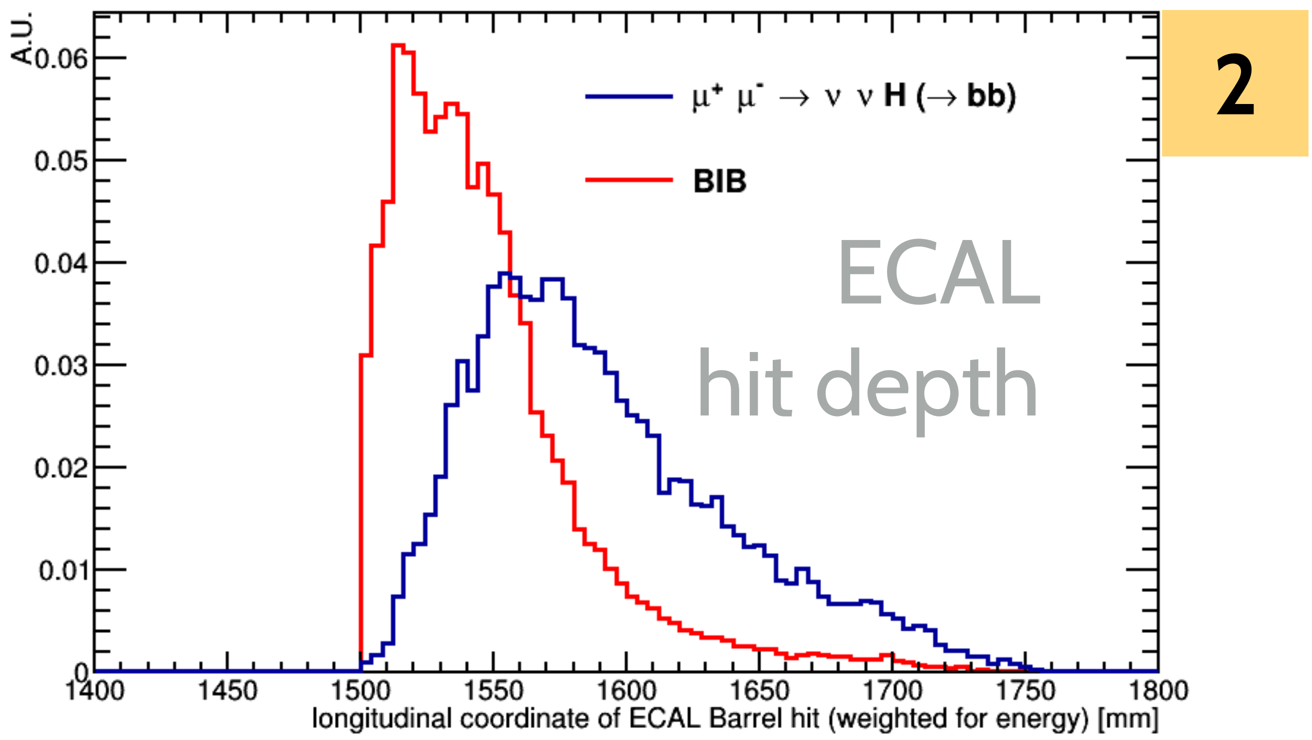
1. Timing can be exploited

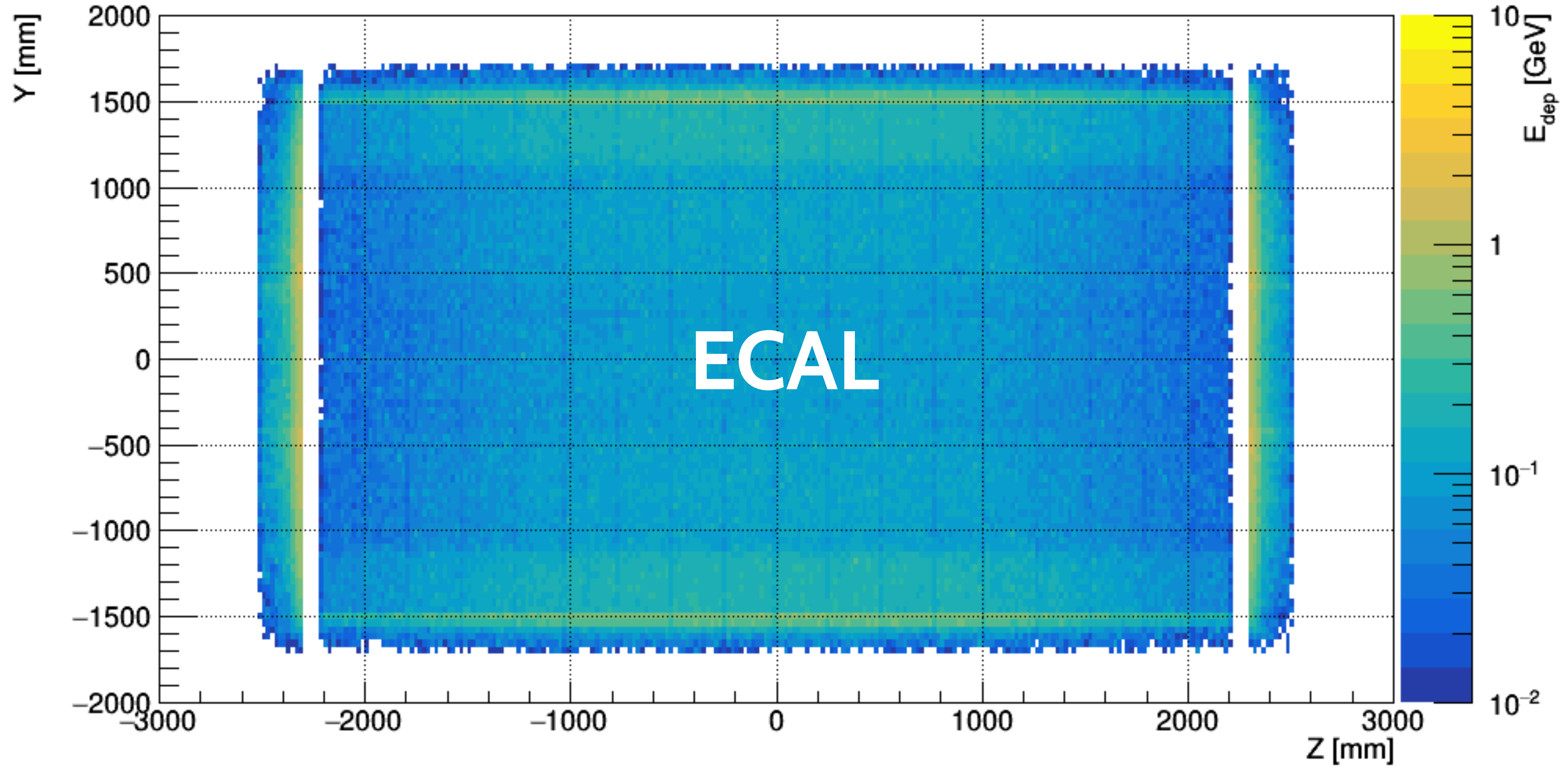
BIB particles arrive later,
but shower development takes time
↳ sharp time cut is not the best solution

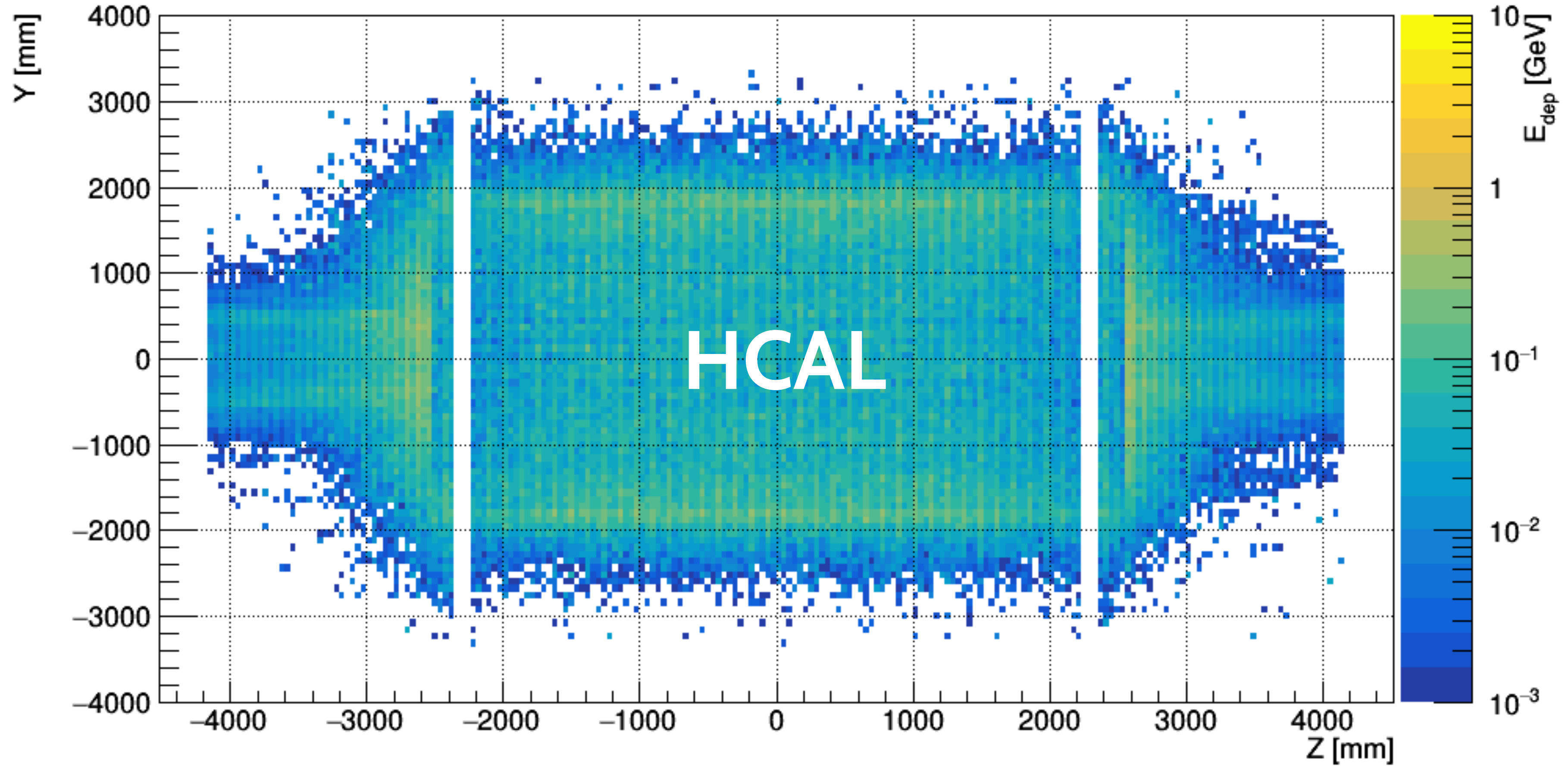


2. Depth profile is different

BIB particles are stopped earlier
inside the calorimeter
↳ longitudinal segmentation is crucial







Optimal BIB suppression achievable with multivariate analysis techniques

Currently average BIB contribution is parameterised as a function of the azimuthal angle and depth → subtracted from the total deposition ← *more in the talk by* [L. Sestini]

Muon reconstruction: PANDORA particle flow

Fraction of muons in the the BIB is fairly small
↳ **so serious issues with muon reconstruction**

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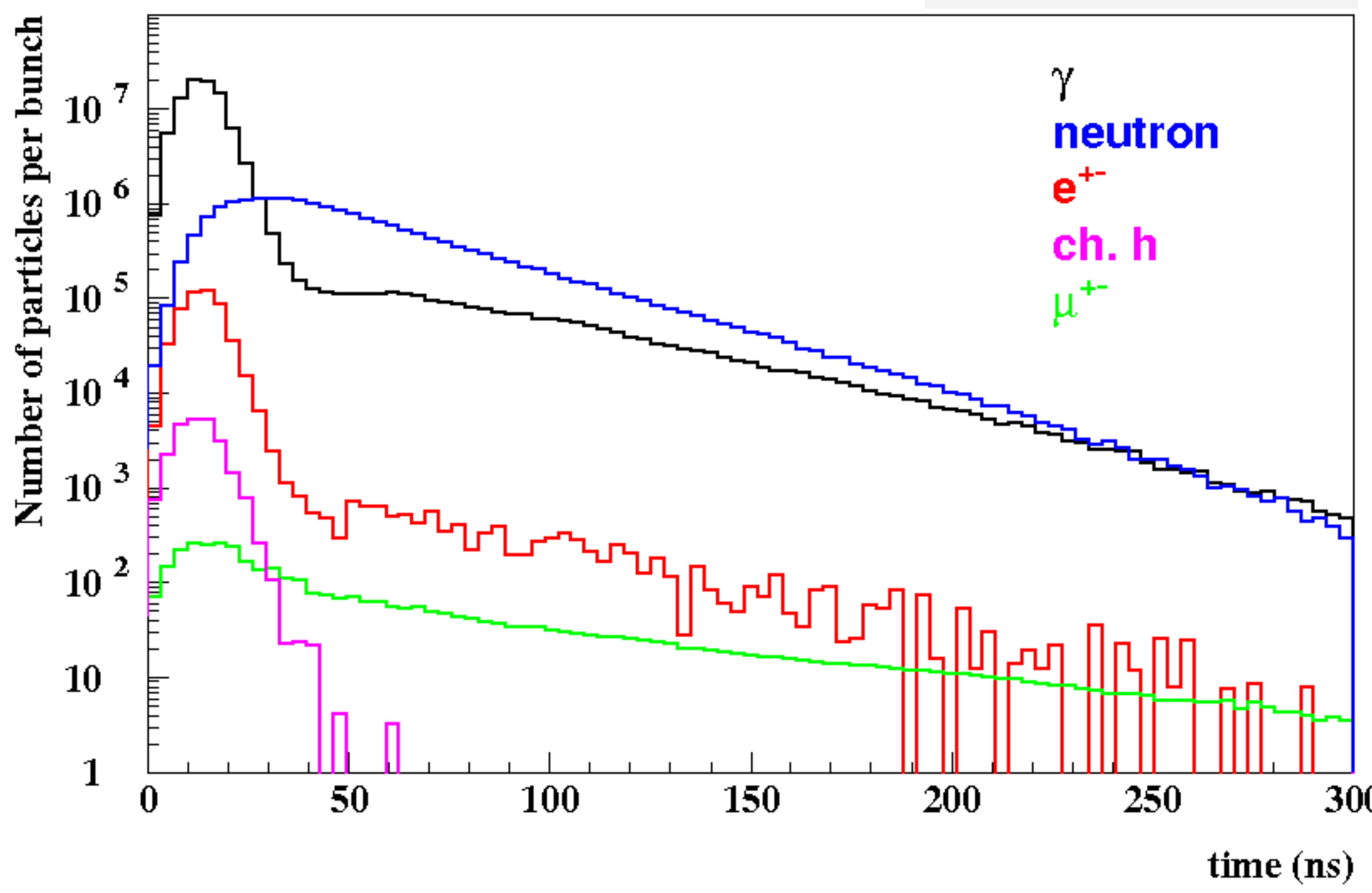
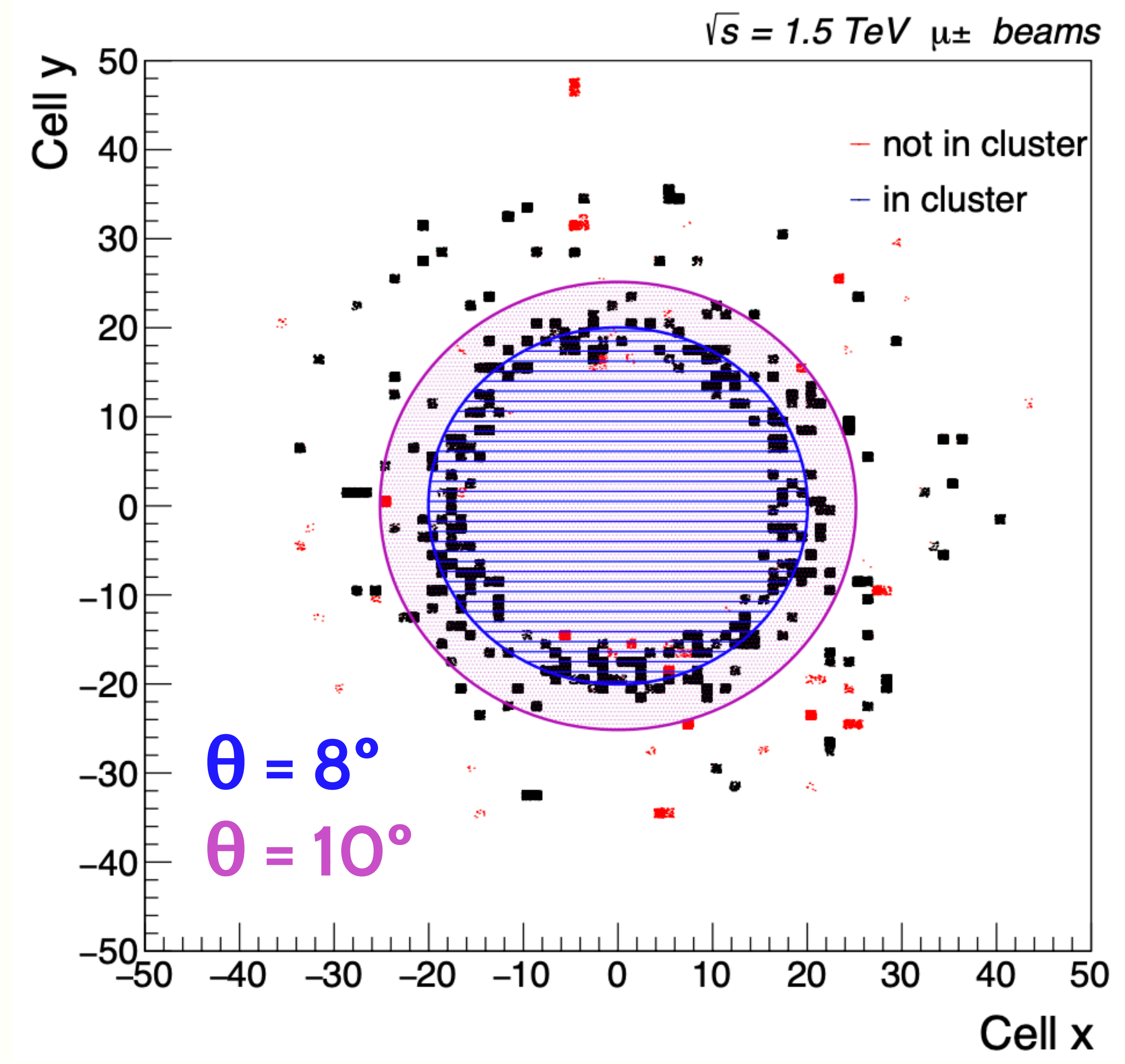
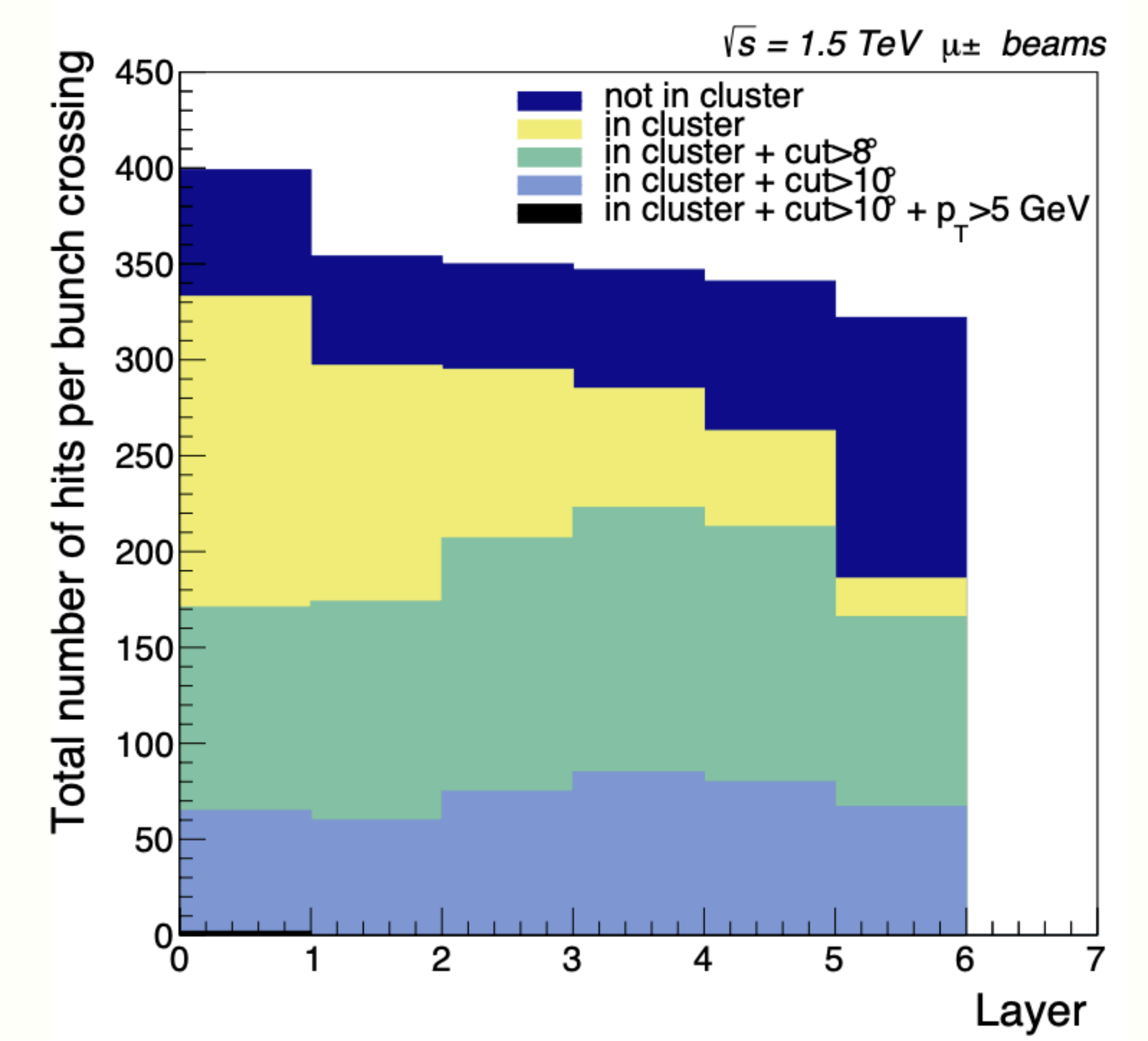


Sizeable BIB contribution only in the very forward region: θ < 10°

- fully suppressed by cluster selection and p_T > 5 GeV threshold
- using the PANDORA PFA framework to build clusters





← *more in the poster by C. Aimè*

Seeding from muon clusters required for efficient muon-track reconstruction

- planning to extend tracking algorithms to support seeding from extrapolated muon clusters

Summary

Beam-induced background poses significant computational challenges at Muon Collider

Current simulation studies are based on the iLCSoft framework

- planned transition to Key4HEP in the future

BIB suppression crucial at every step of event simulation and reconstruction

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

- intelligent solutions for making it more efficient are under development

Innovative object-reconstruction strategies are necessary that consistently use data from multiple subdetectors

Maximum coherence between detector technologies and the corresponding reconstruction algorithms is crucial for the optimal performance of the experiment