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Cape Town, South Africa

Tracking-detector design for a multi-TeV Muon Collider

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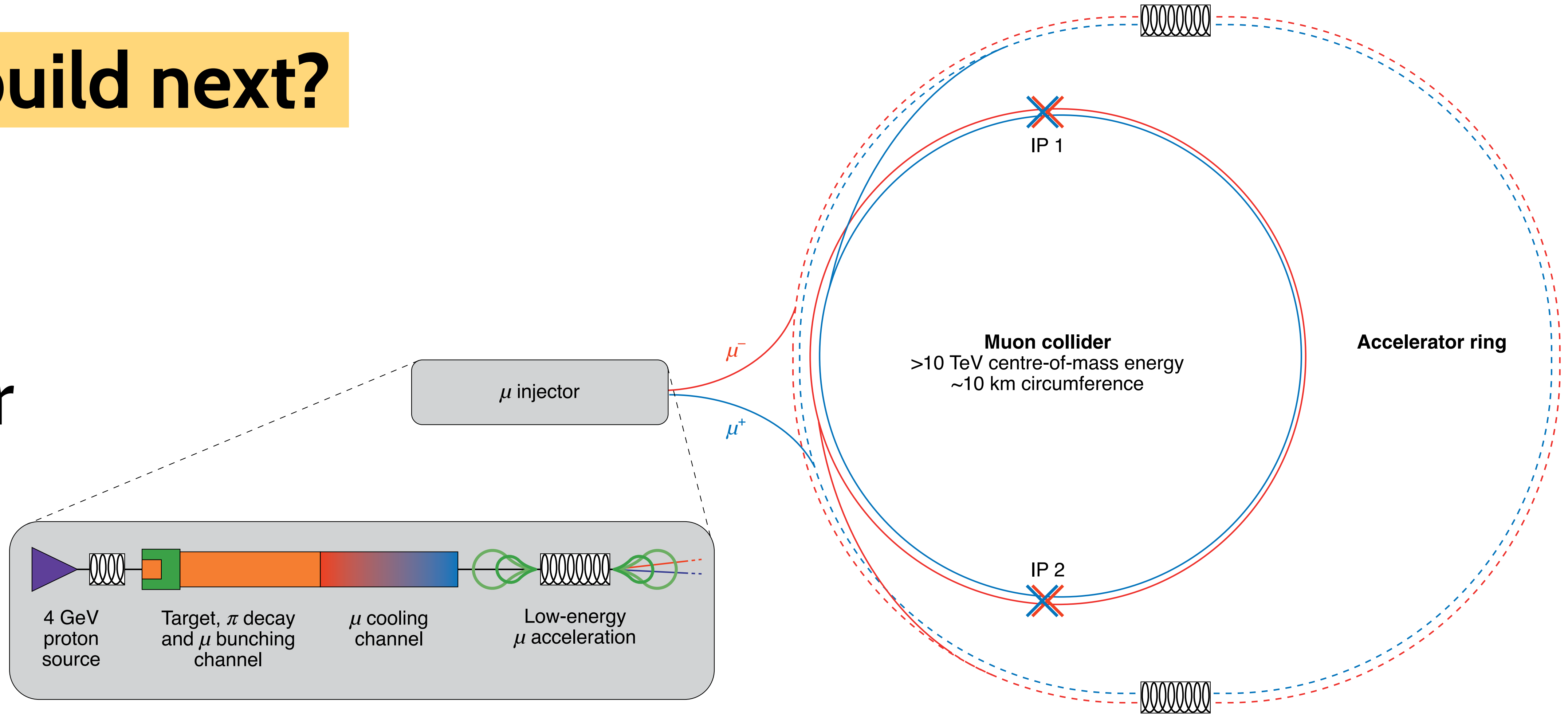
Muon Collider: a promising discovery machine

Big question for particle physics today: which collider to build next?



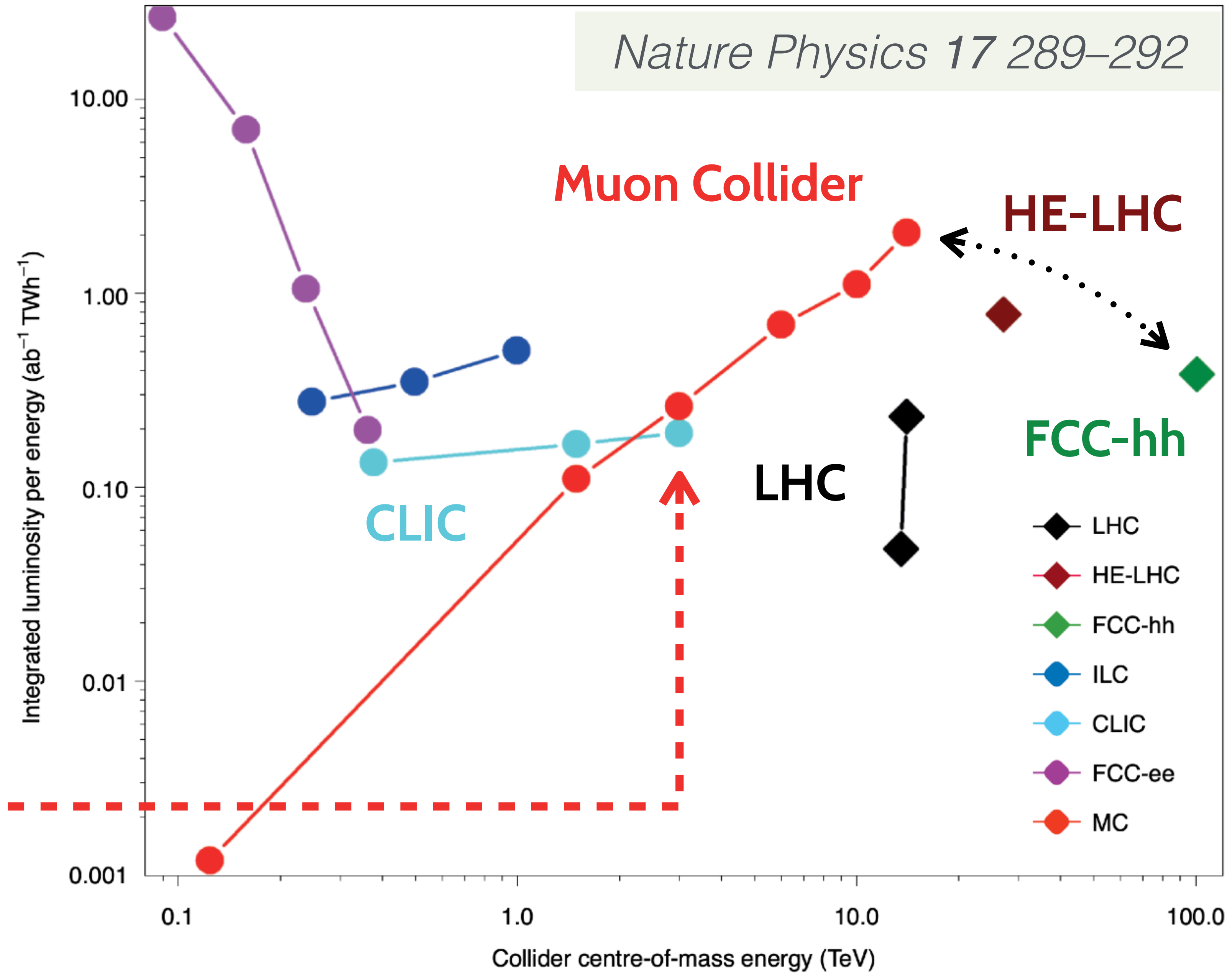
Several requirements have to be satisfied:

- energy reach exceeding that of the LHC by a large factor
- enable Standard Model precision measurements
- have small size → reduced construction cost
- low energy consumption → sustainable operation

Muon Collider combines advantages of the two types of machines:

high precision of *e⁺e⁻* colliders + **high energy reach** of *pp* colliders

- like e±, μ± 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 √s = 14 TeV)*



At √s ≥ 3 TeV Muon Collider is the most energy efficient machine
providing rich physics from μ⁺μ⁻ collisions and VBF processes

Beam Induced Background: the critical challenge

For the beam density of 2×10^{12} muons/bunch → **huge number of decays per metre of lattice**
e.g. 4.1 × 10^5 at $\sqrt{s}$ = 1.5 TeV

Secondary/tertiary particles interact with the lattice → **producing Beam Induced Background (BIB)**

BIB intensity and composition depend on:

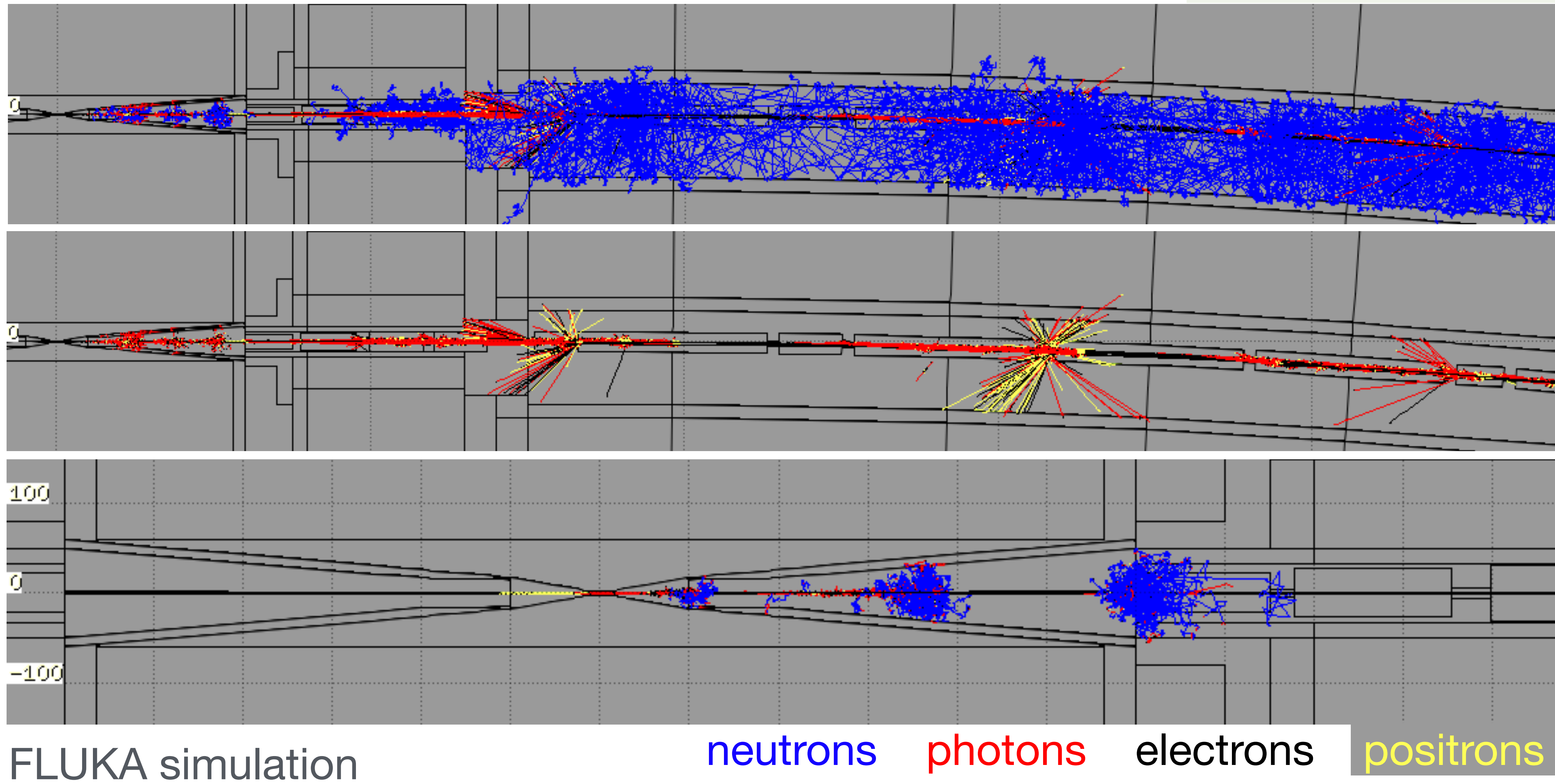
- **beam parameters** (energy, size, rate)
- **accelerator layout** (magnets, shielding)

Machine-Detector Interface (MDI) is crucial
for absorbing as much of BIB particles as possible

The most studied case uses $\sqrt{s}$ = 1.5 TeV design by MAP
now being iterated with FLUKA simulations ▶

- tungsten nozzles with BCH cladding
- 10° opening angle *(limiting the forward acceptance)*

arXiv:2203.07964



FLUKA simulation

↳ **new MDI designs are under development focusing on $\sqrt{s}$ = 3 TeV and $\sqrt{s}$ = 10 TeV**

BIB properties: overview

BIB has several characteristic features useful for its suppression

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

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

↳ conceptually different from pile-up contributions at the LHC

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

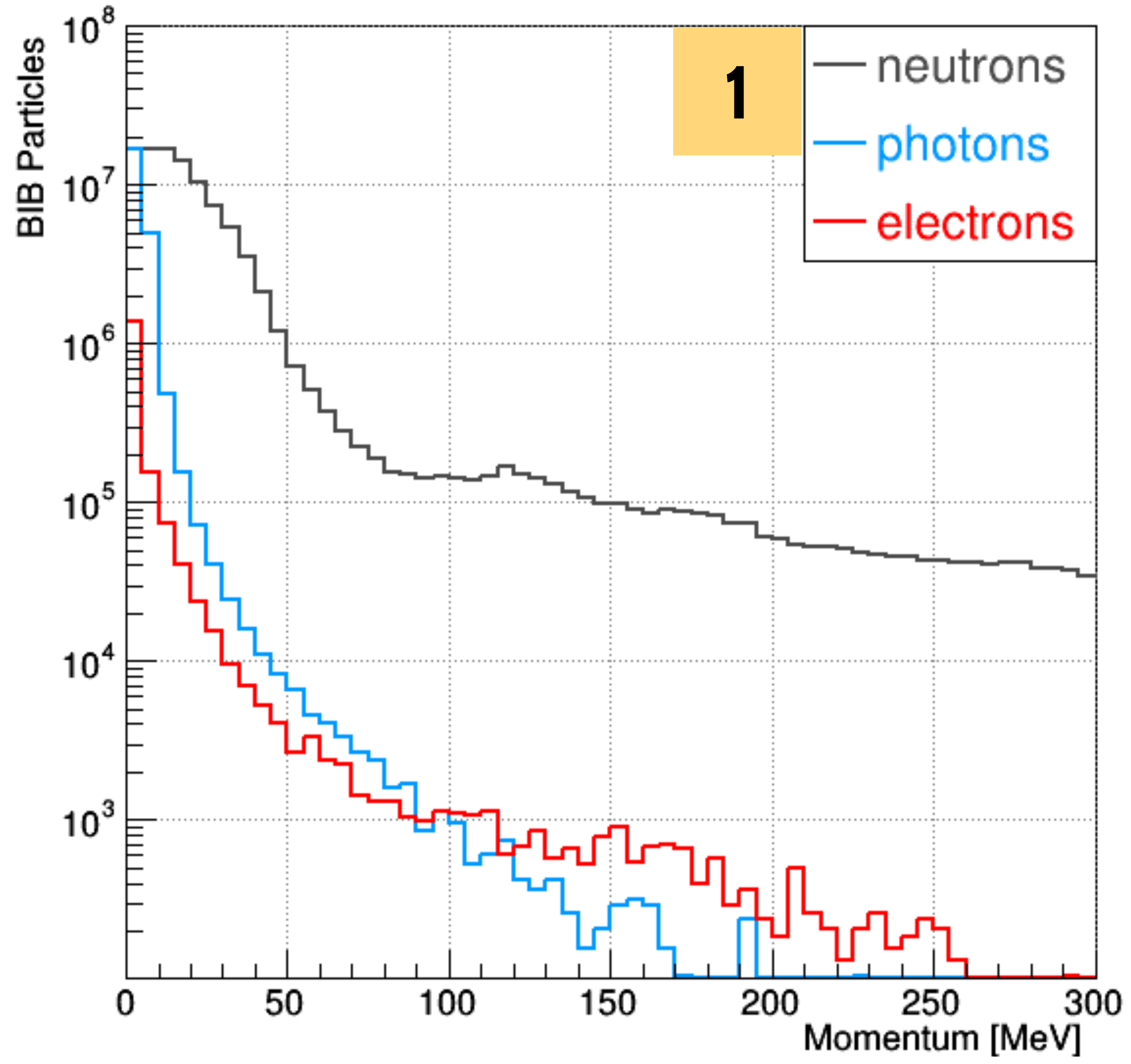
$\mu^+\mu^-$ collision time spread: 30ps at $\sqrt{s}$ = 1.5 TeV (≤20ps at $\sqrt{s}$ = 3 TeV)

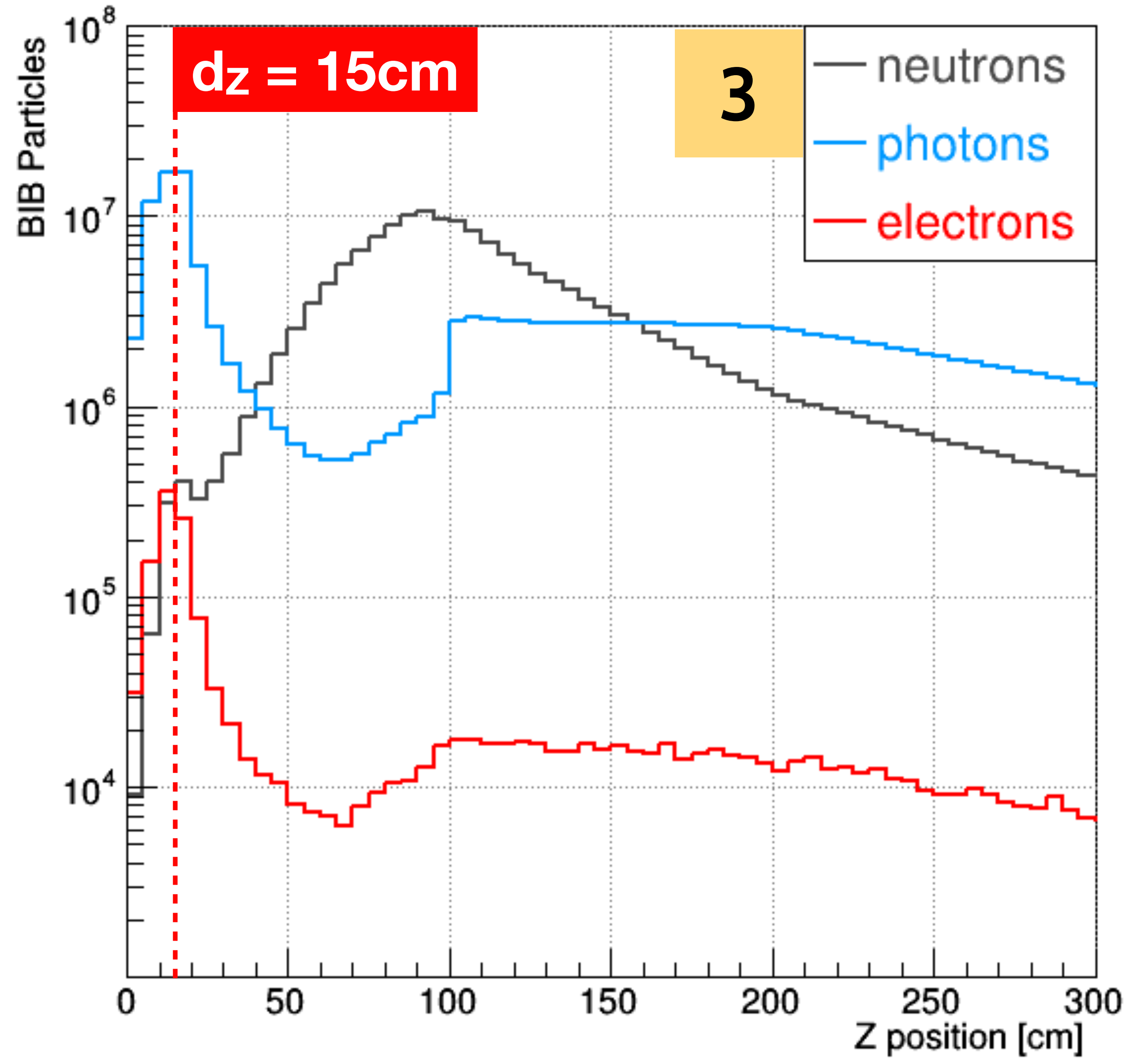
↳ allows out-of-time hit rejection

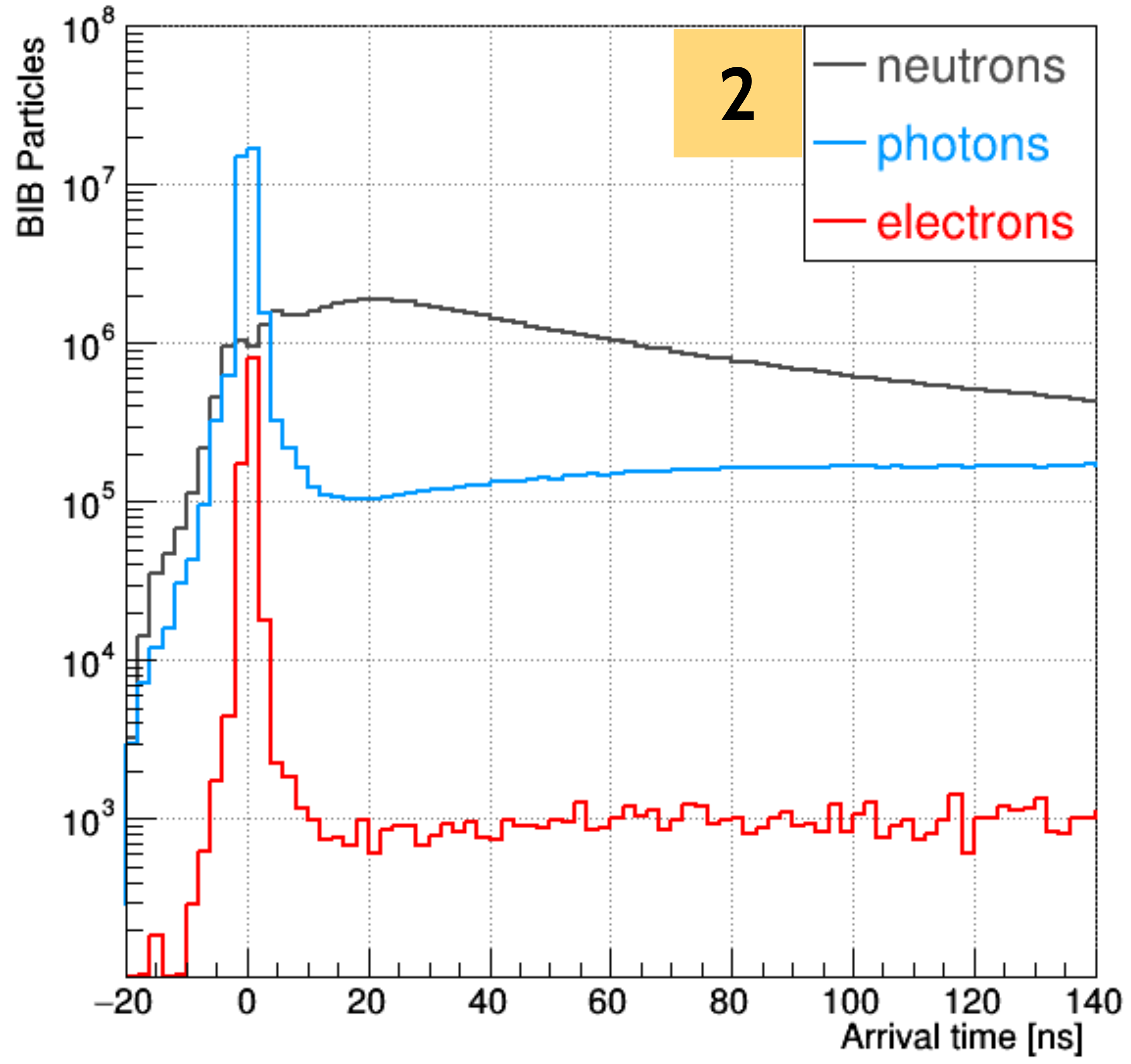
3. Strongly displaced origin along the beam

crossing detector surface at a shallow angle

↳ affects charge distribution + time of flight







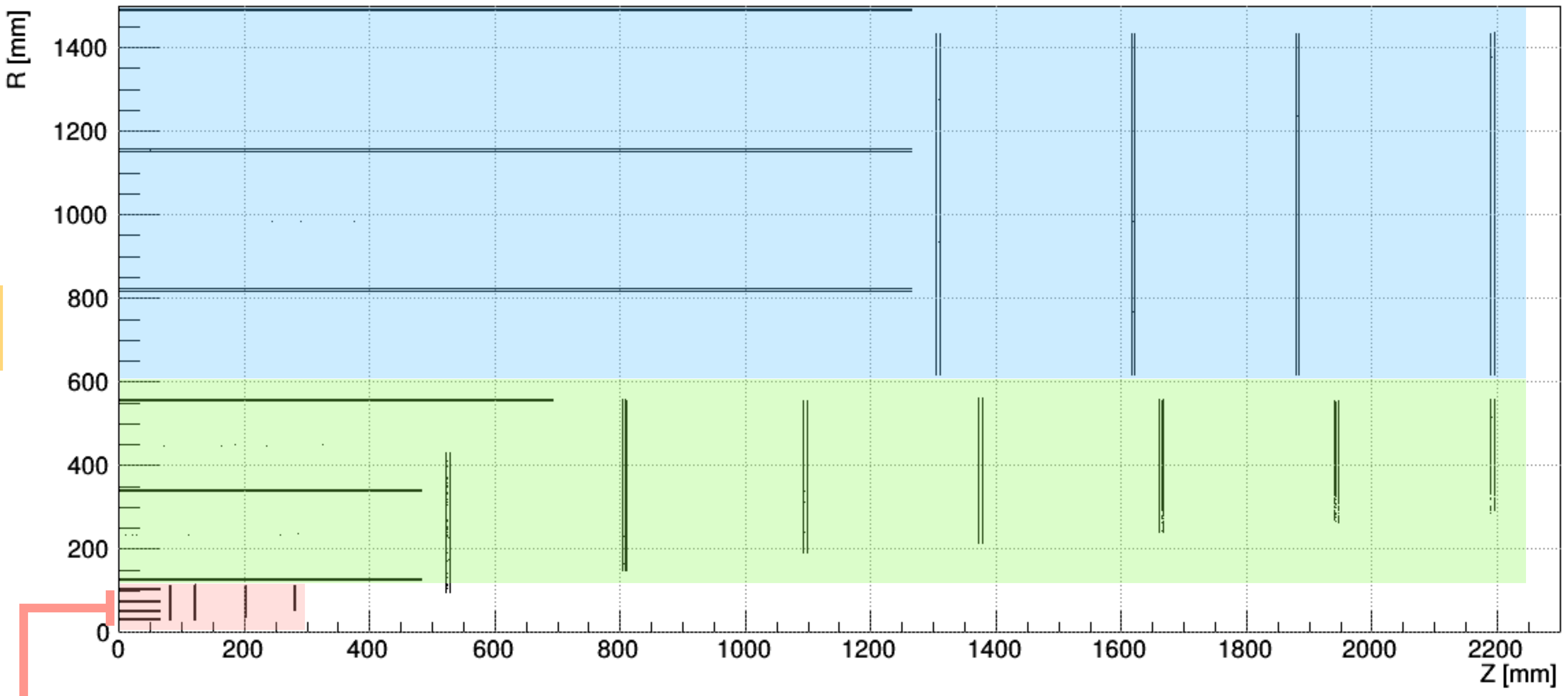
Dominant contributions in the Tracker:

- **neutrons** → radiation damage
- **photons** → creating secondary electrons
- **electrons** → creating background hits

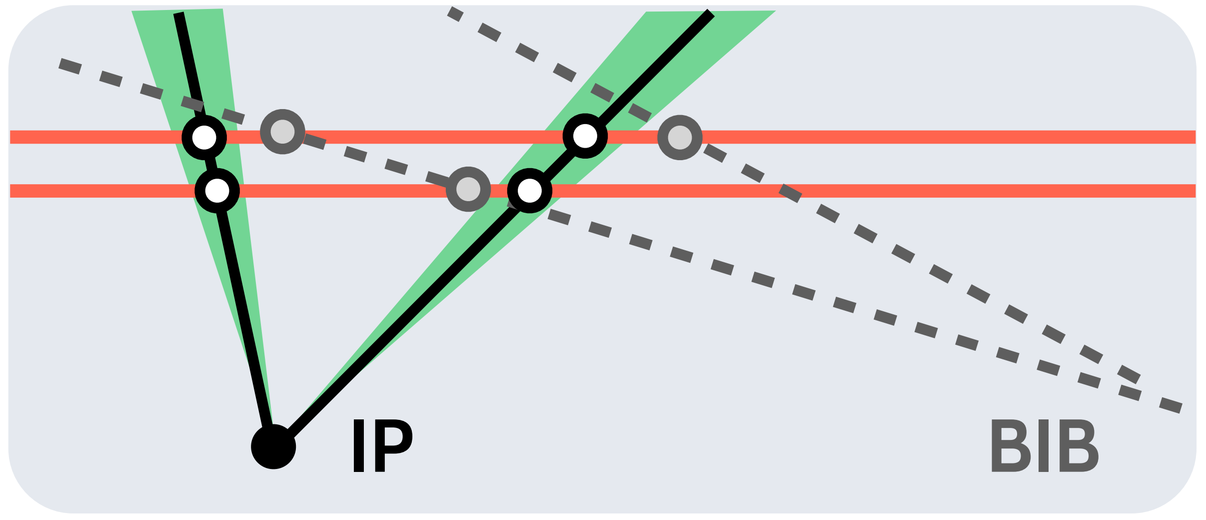
Current Tracker model based on the CLIC design
without specific technology implementations

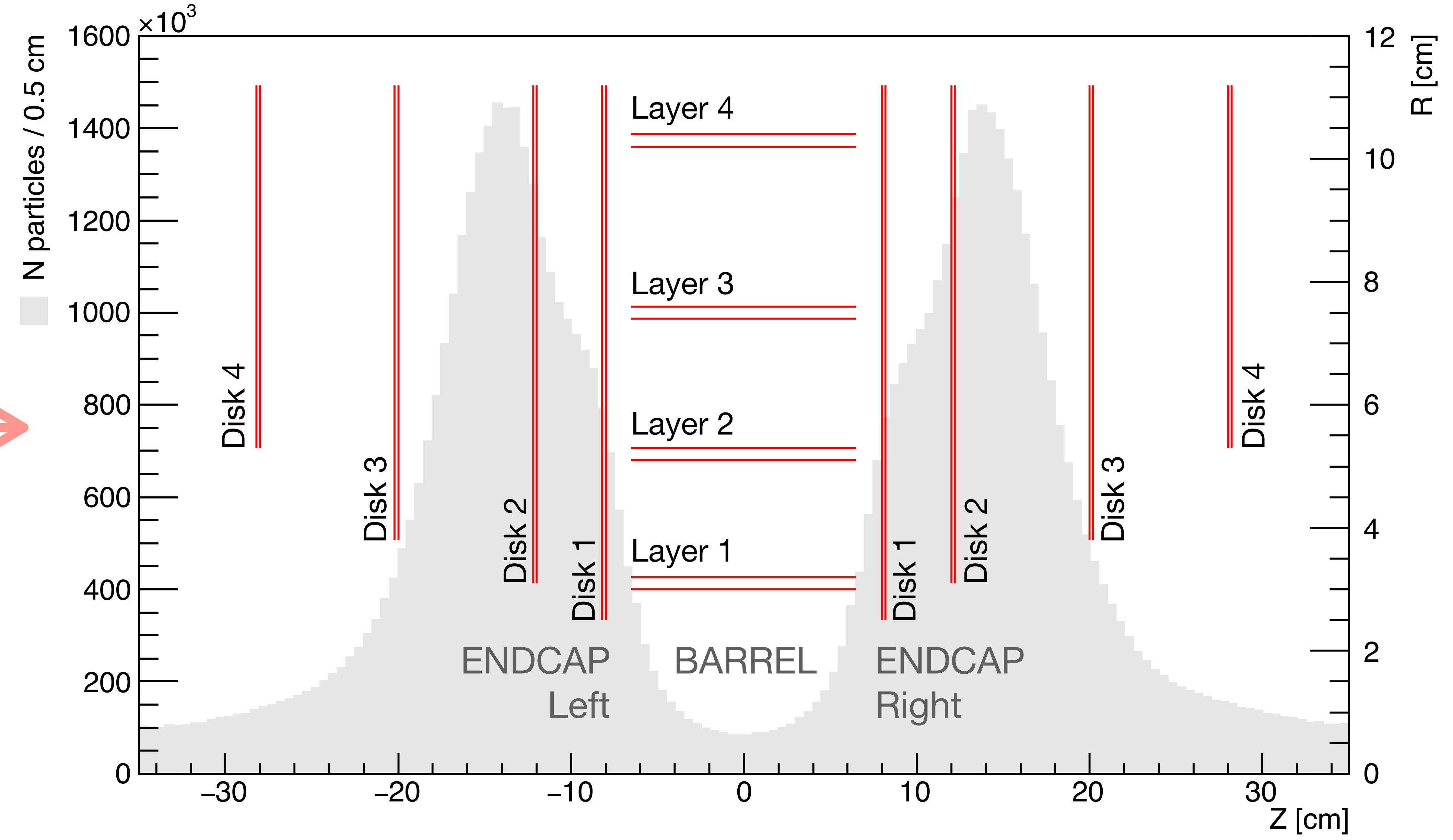
Silicon sensors with high spatial and timing resolution

- **Outer Tracker** 50 µm × 10 mm σ_t = 60 ps
- **Inner Tracker** 50 µm × 1 mm σ_t = 60 ps
- **Vertex Detector** 50 µm × 50 µm σ_t = 30 ps
  ↳ σ_{UV} = 5 µm × 5 µm



Double layers ▶
in the Vertex Detector
for BIB rejection
using stub filtering



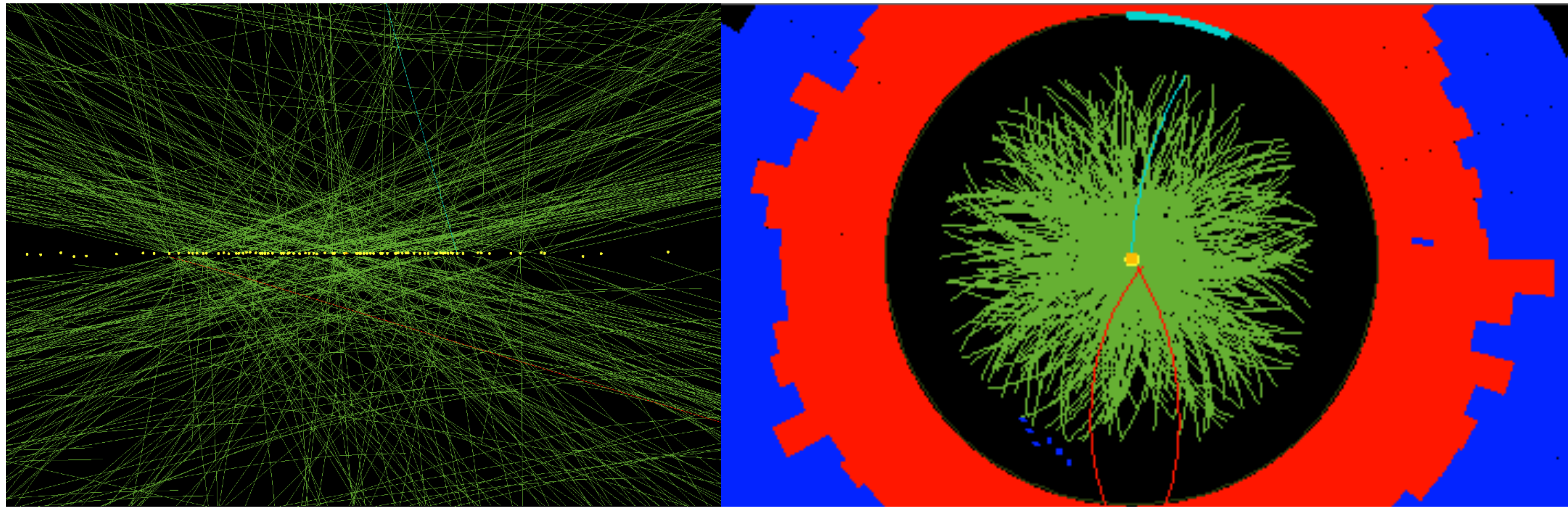


Magnetic field: B = 3.57 T → optimised for √s= 1.5 TeV
↳ expected to change for higher centre-of-mass energies

At the LHC we are used to backgrounds primarily from pile-up *pp* collisions

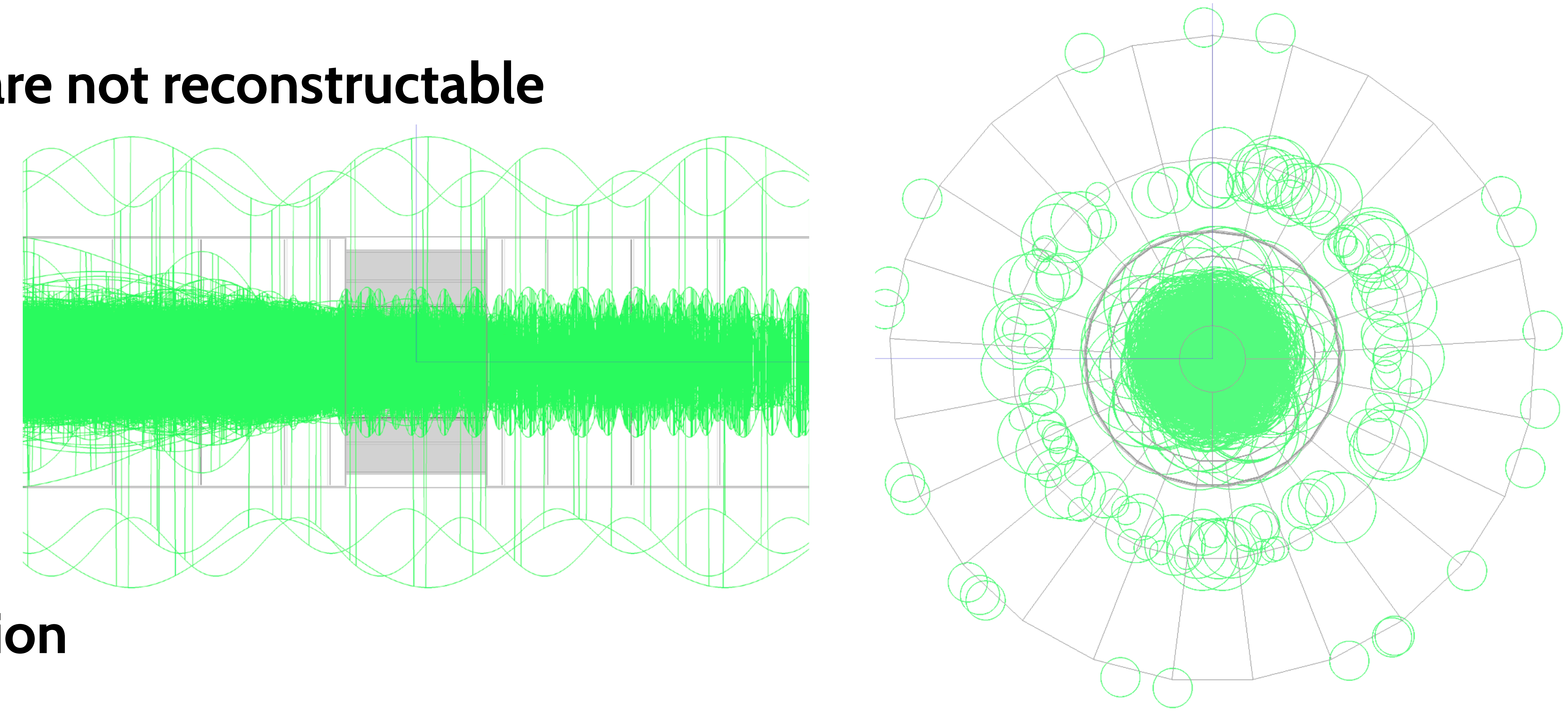
↳ **real tracks pointing at displaced vertices**

Event at the CMS experiment with 78 reconstructed vertices ▶



At the Muon Collider background tracks are not reconstructable

A cloud of looping tracks from soft electrons: <p_T> = 3.5 MeV ▶



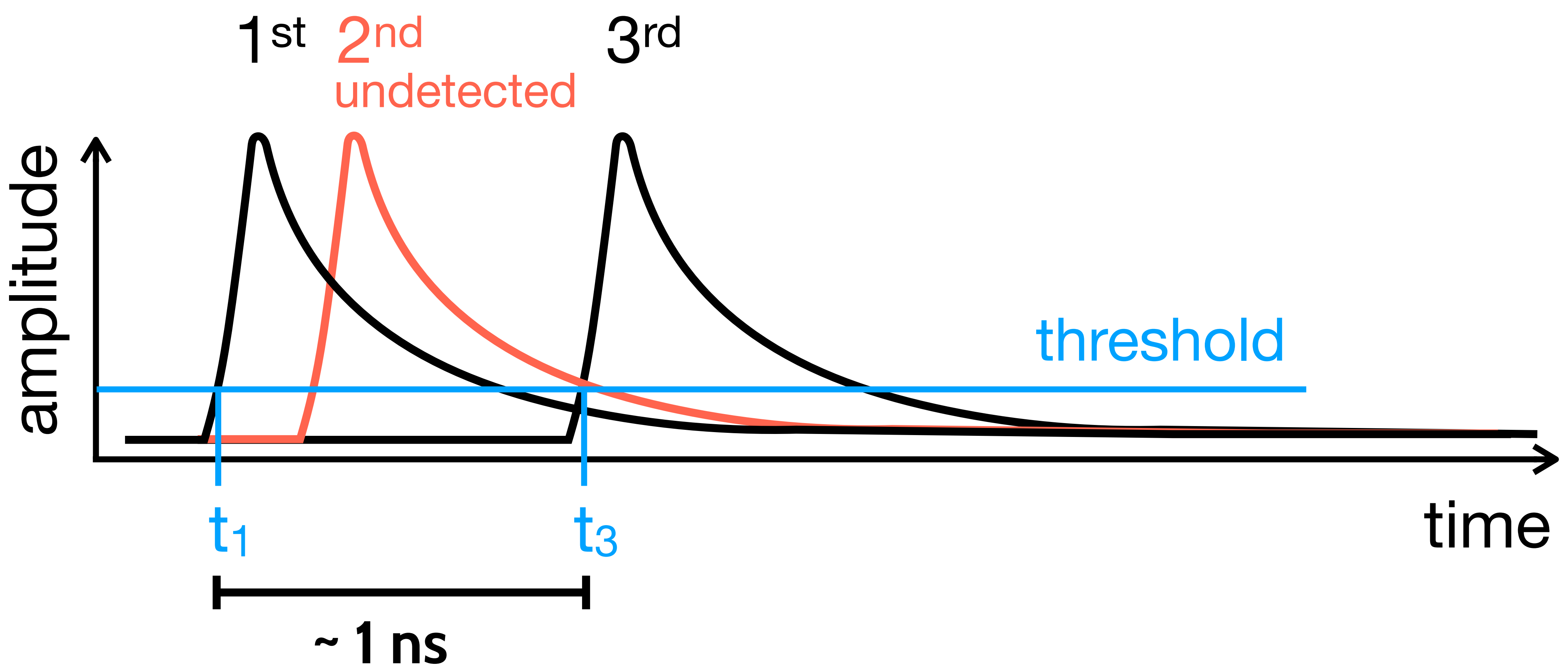
Creates tremendous combinatorics for the classical outward track reconstruction

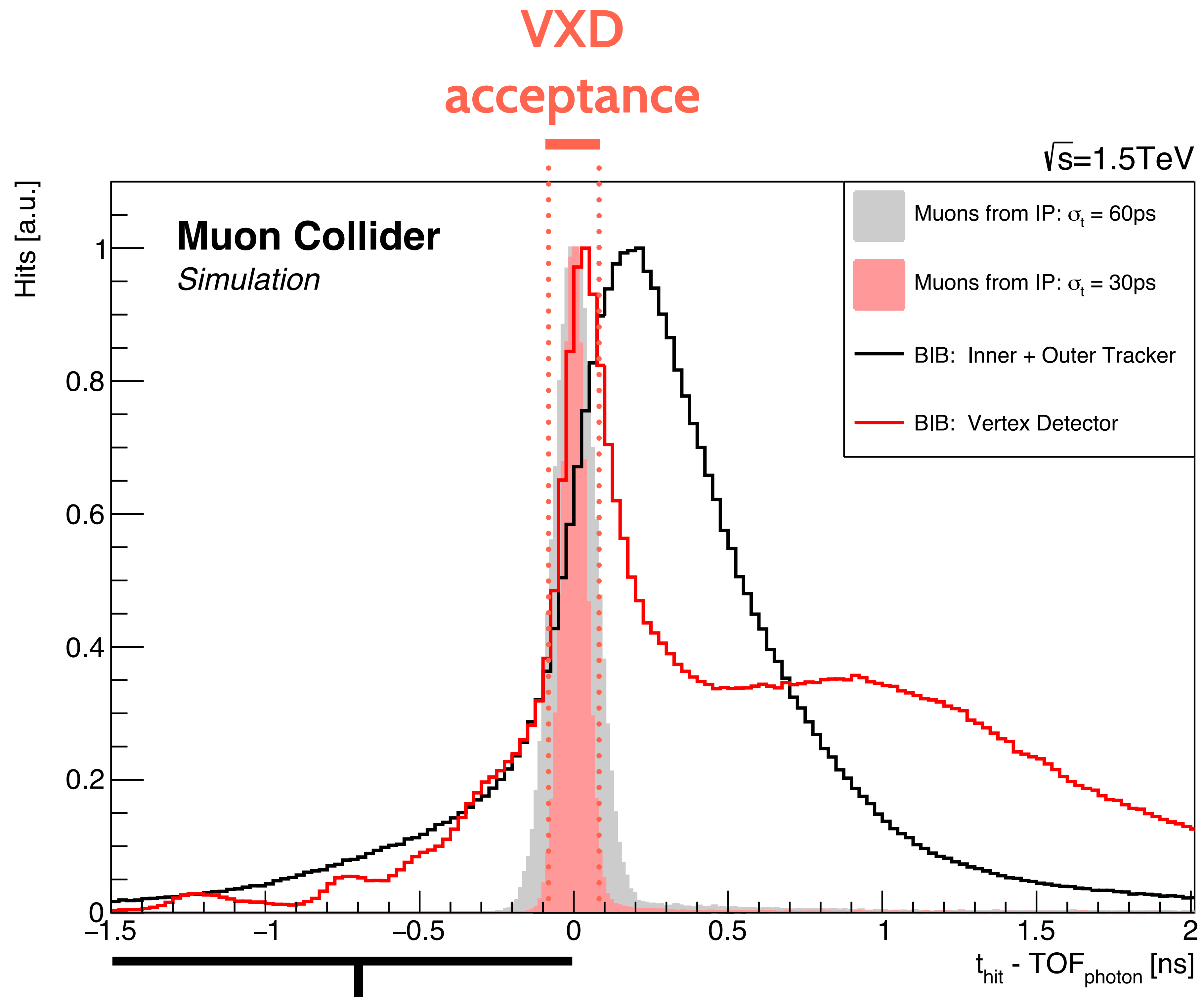
Raw hit density in the Vertex Detector is unsustainable
↳ up to 5K hits/cm² in a 15 ns time-integration window

State-of-the-art time resolution enables narrow time windows
comparable to the time spread of the beam crossing

Exact time windows tailored to the sensor's position ▶
subtracting a photon's time of flight (TOF_{photon}) from IP

Substantial number of BIB hits arriving earlier than TOF_{photon}
created by particles exiting from the nozzle close to the sensor

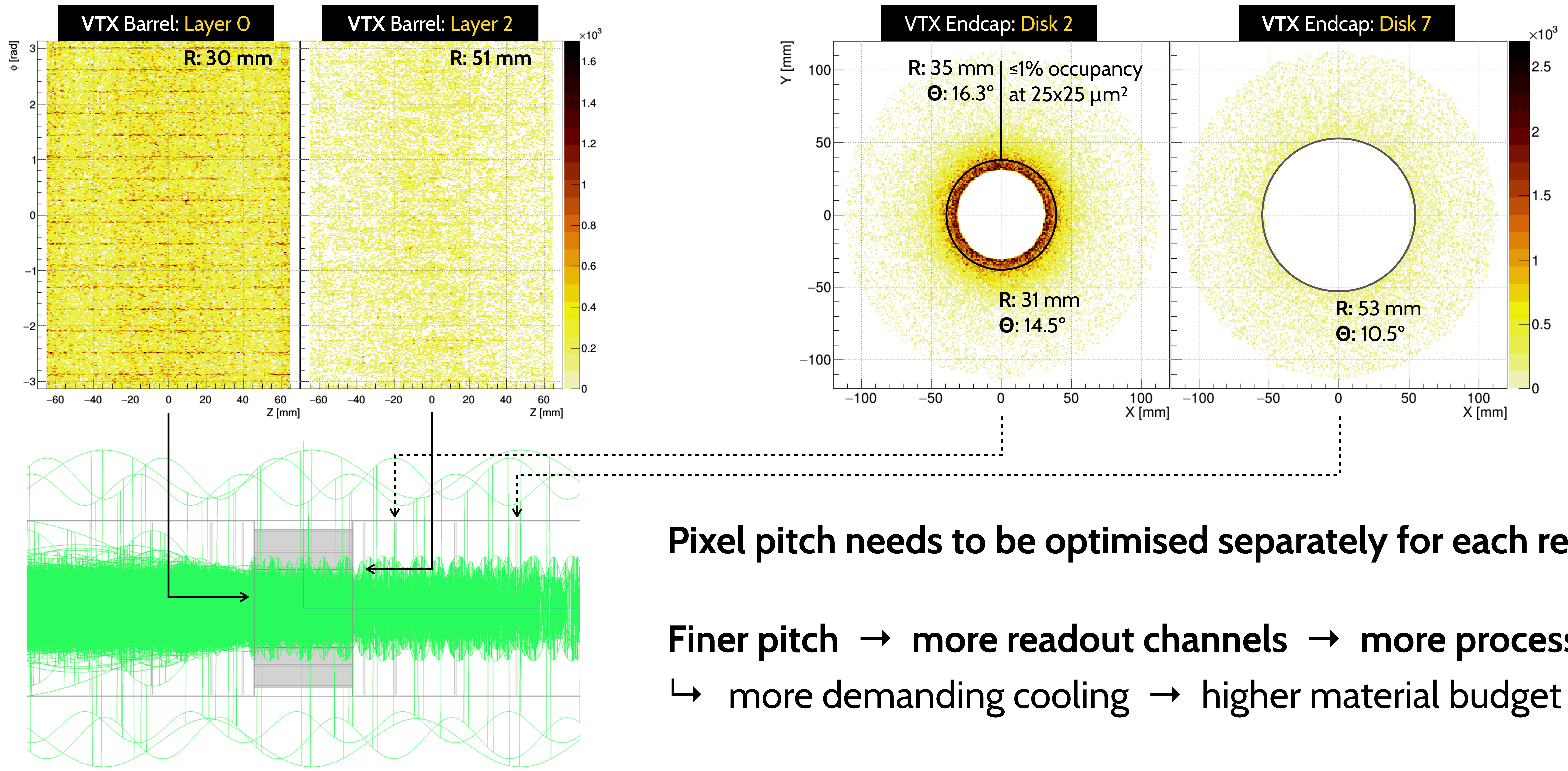




A hit from an early BIB particle would make the pixel blind
to the potential signal particle

Hit density: spatial distribution

Background density varies across the tracker → highest close to the tungsten nozzles (after time filtering)



Pixel pitch needs to be optimised separately for each region

Finer pitch → more readout channels → more processing
↳ more demanding cooling → higher material budget

Majority of the hits (up to 90%) **created by primary electrons** coming from the MDI outer surface

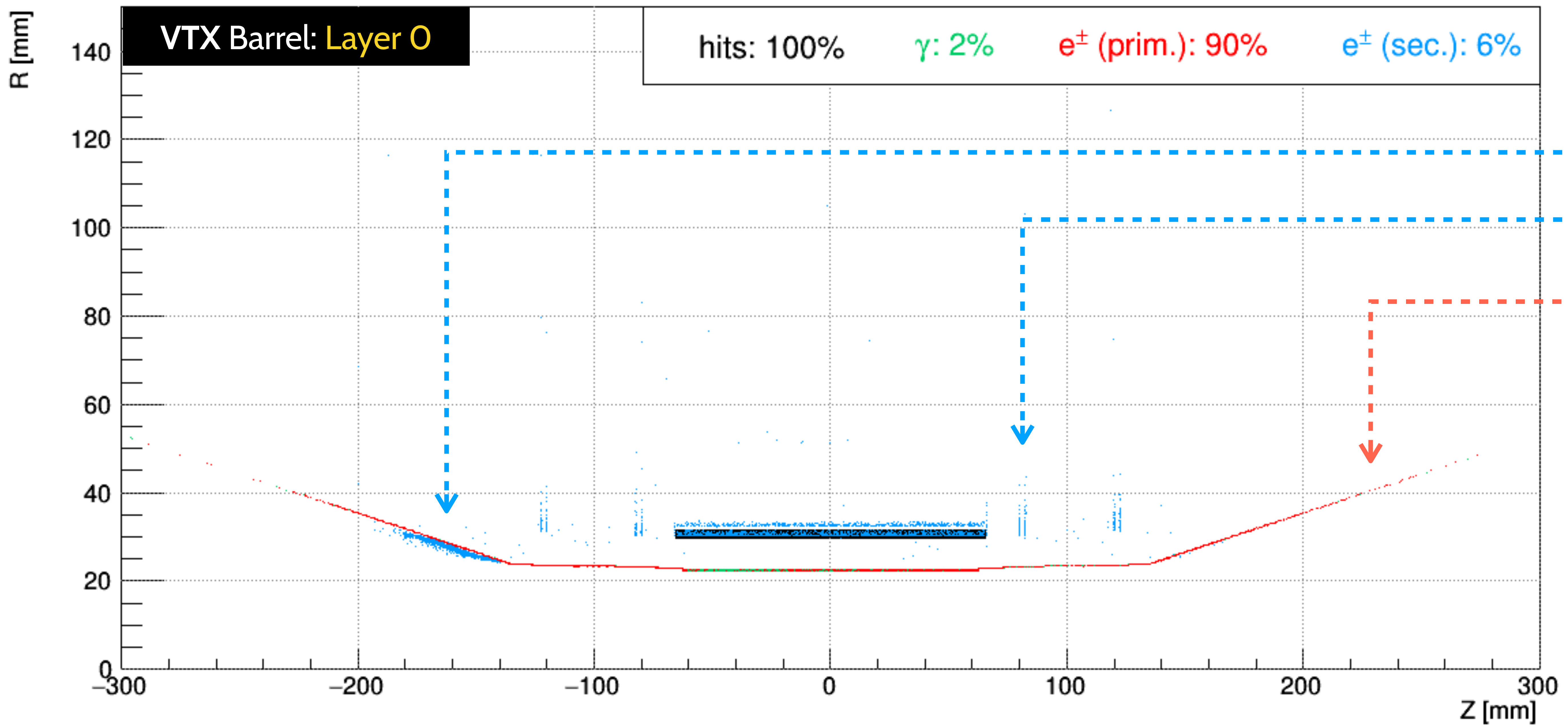
Primary electrons

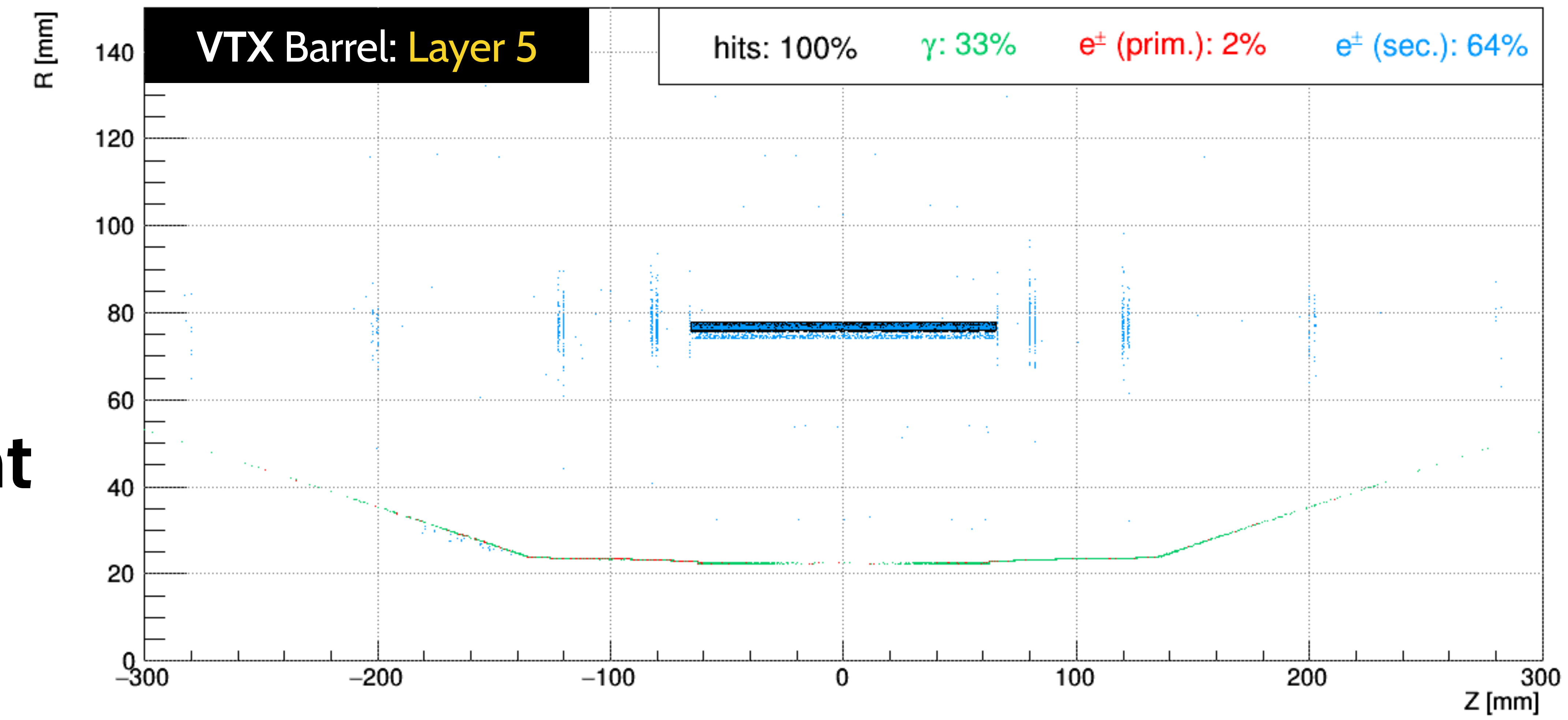
Primary photons

Secondary electrons

created by interaction of primary photons with:

- MDI material
- detector material





Further away from IP secondary electrons become dominant

Slight adjustments in MDI design can have great impact

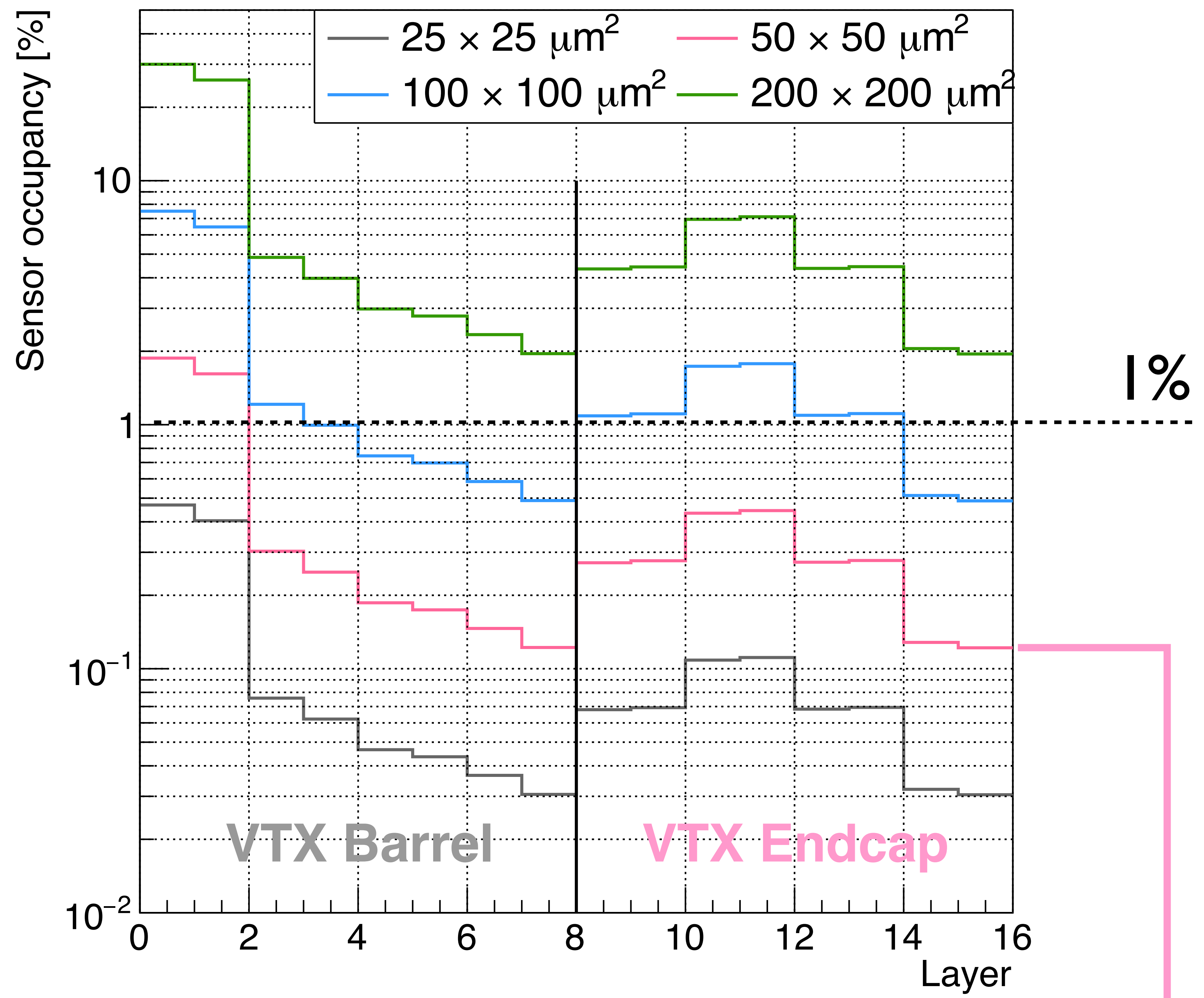
One of the candidate technologies for the major part of the Tracker

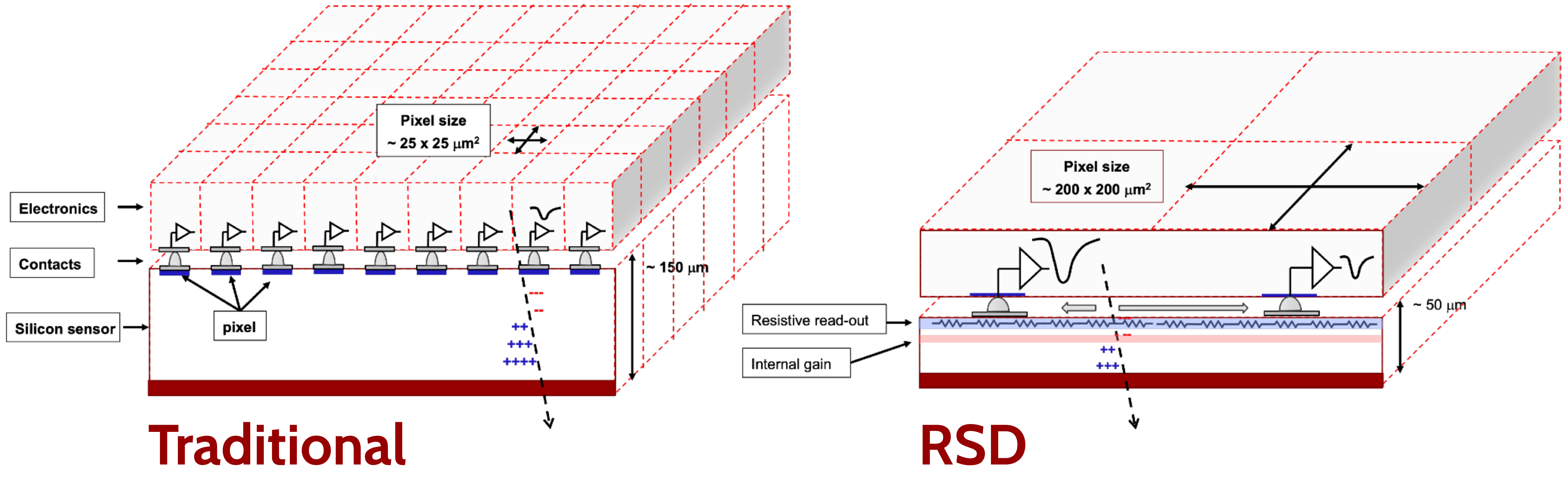
↳ **Resistive Silicon Detectors (RSD)**

$\sigma_t \geq 20\text{ps}$ $\sigma_{UV} \geq 4\ \mu m$ pitch $\geq 50\ \mu m$

Unusually high spatial resolution for such a large pitch
provided by charge sharing across multiple pads

↳ **low occupancy must be ensured to avoid pile-up effects ▶**
50×50 μm pads would be sufficient for most of the VTX





◀ **Effective area used for readout of a single hit is 3×3 pads → 150×150 μm²**

↳ more traditional design required for VTX
e.g. Trench Isolated LGAD

Total material budget must be kept as low as possible: sensor + readout + cooling + support

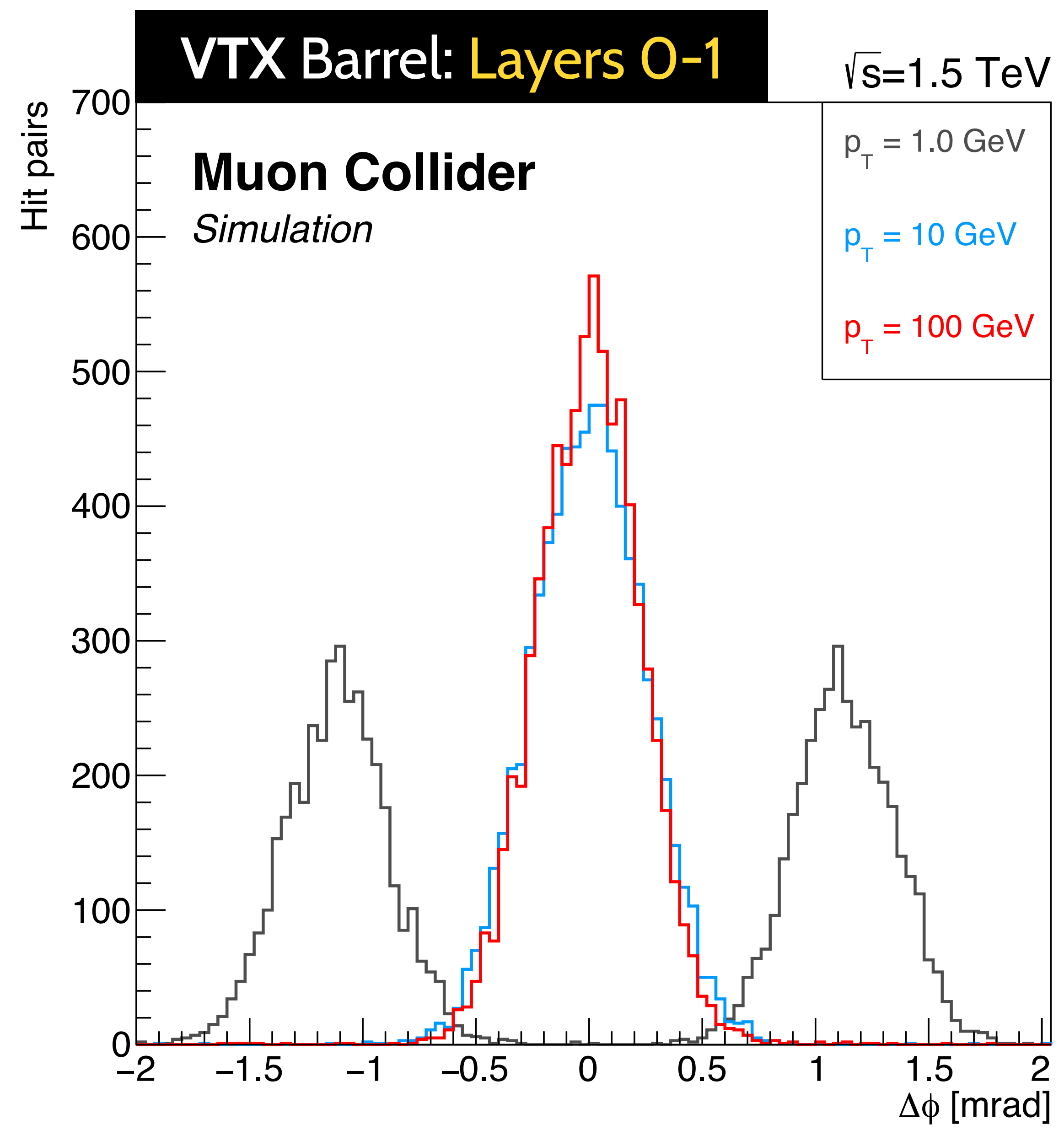
Angular filtering: combinatorics

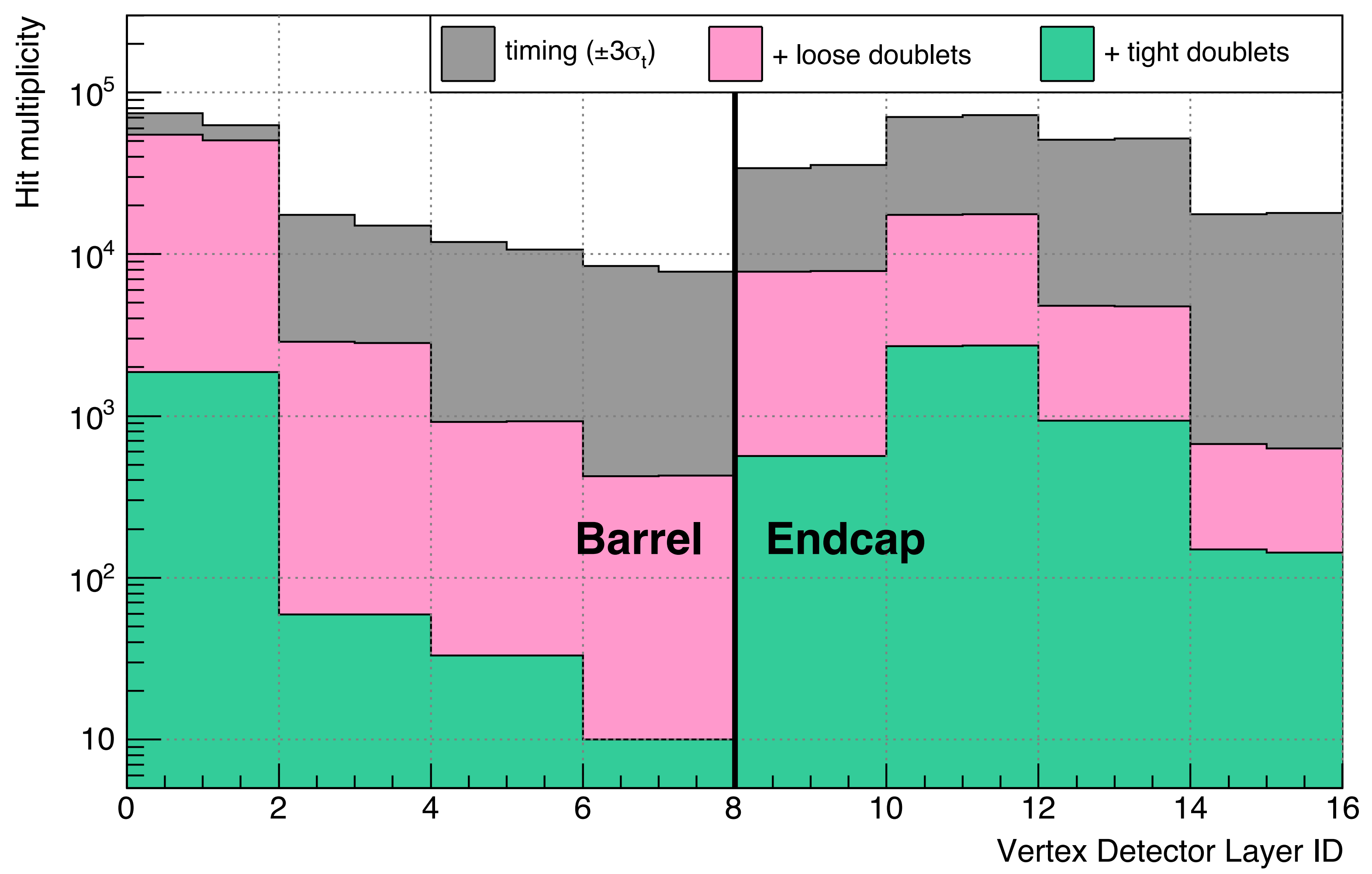
After reading out so many hits → how do we reconstruct actual tracks?
↳ BIB tracks are not reconstructable, but combinatorics is huge

Combinatorics can be reduced dramatically by exploiting hit directionality
selecting stubs from double layers pointing towards the interaction point

Hit pairing done in two angular dimensions:

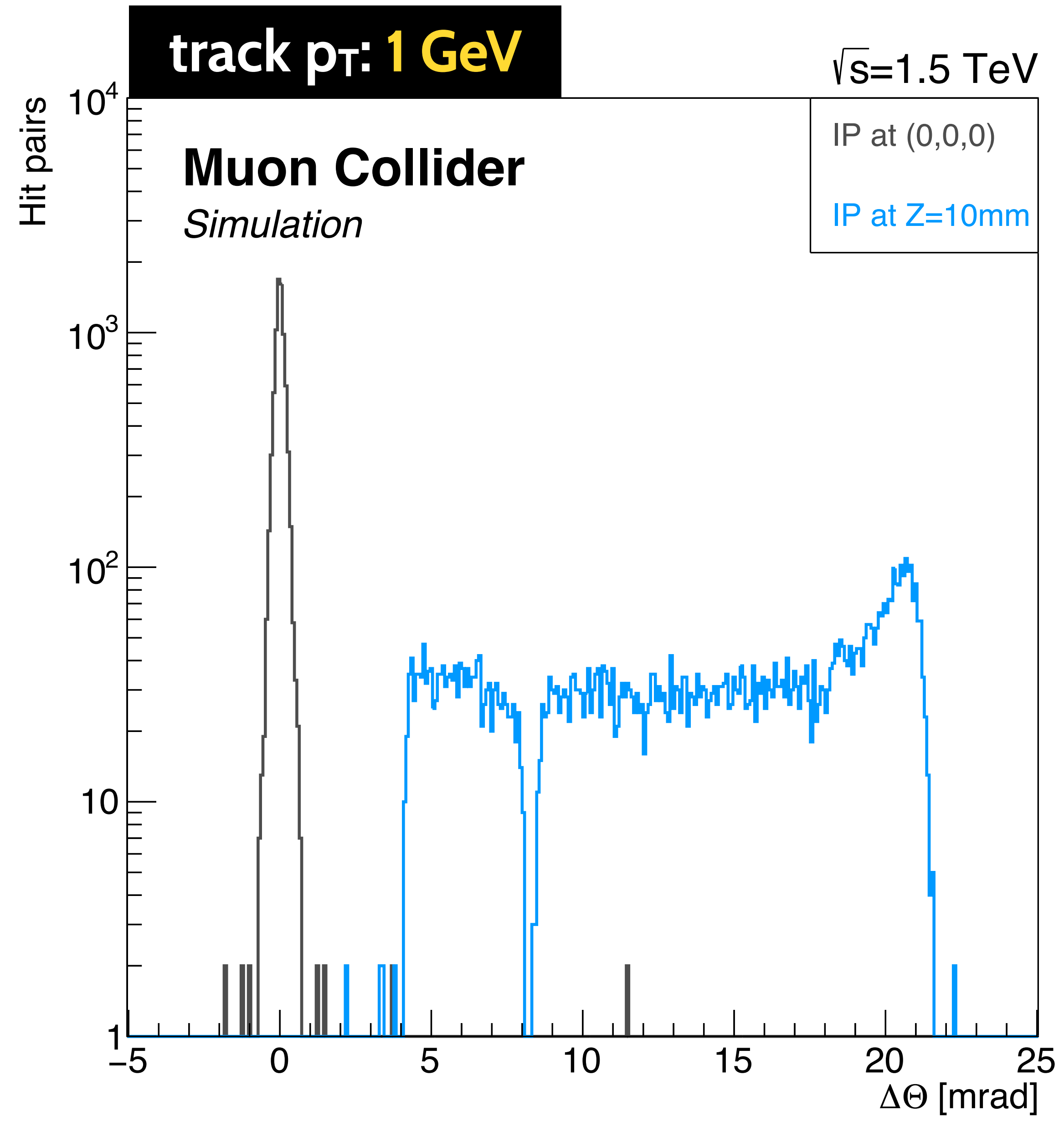
- **$\Delta\theta$ limited by the length of the interaction-region + vertex displacement**
  σ_Z = 10 mm at $\sqrt{s}$ = 1.5 TeV → **1.5 mm** at $\sqrt{s}$ = 10 TeV
- **$\Delta\phi$ limited by the lowest track p_T**





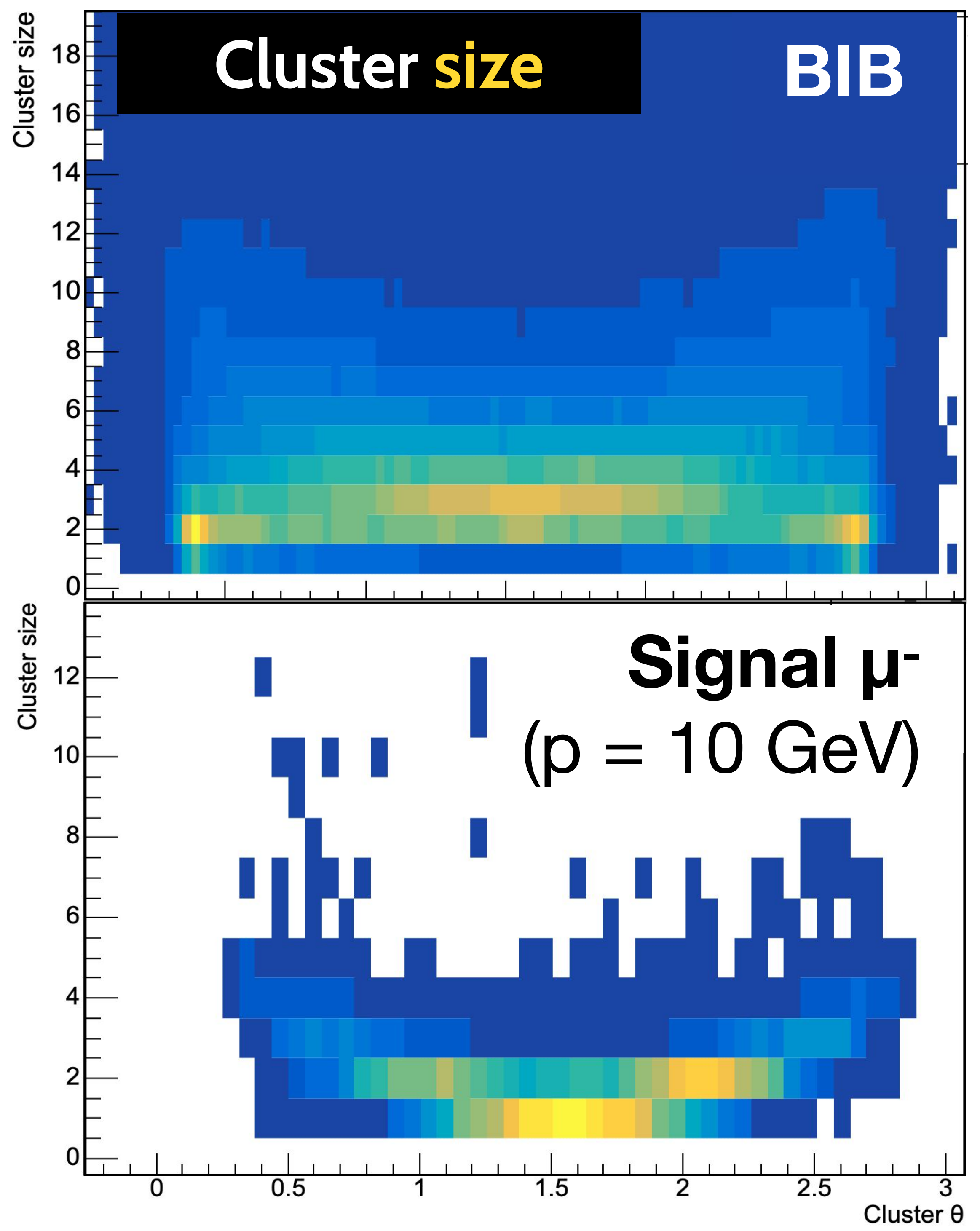
~1 week/event
~2 days/event → σ_Z = 10 mm beamstop
~2 min/event → precisely known vertex position

◀ **Reduction of combinatorics has a huge impact on the event-reconstruction speed**



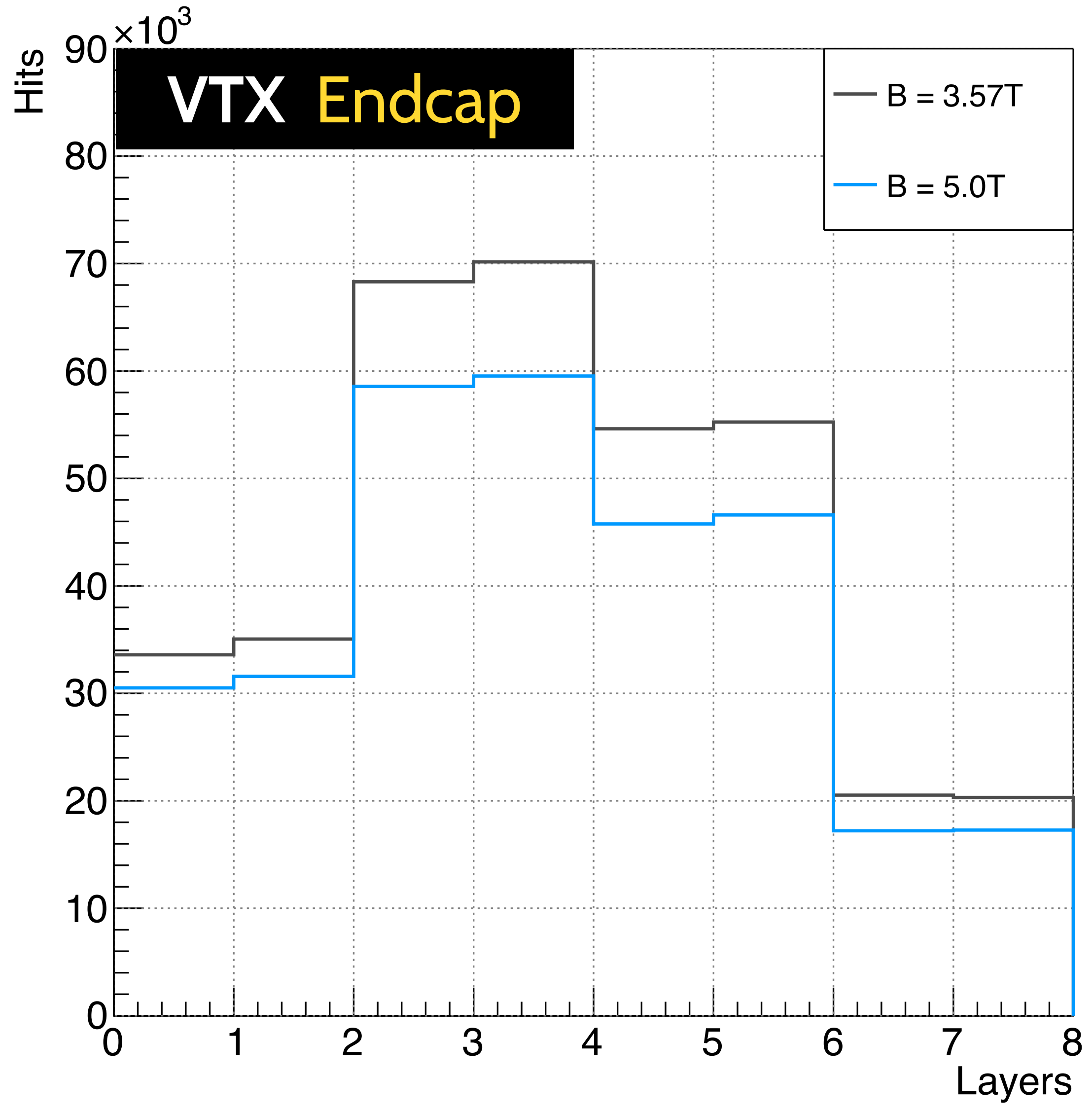
Realistic digitisation of pixel sensors to study cluster-based BIB rejection

↳ BIB particles crossing sensors at shallow angles → larger clusters ▶



Increasing strength of the magnetic field

- low-p_T BIB tracks contained in a smaller radius ▶
- enhanced rejection of BIB stubs in $\Delta\phi$

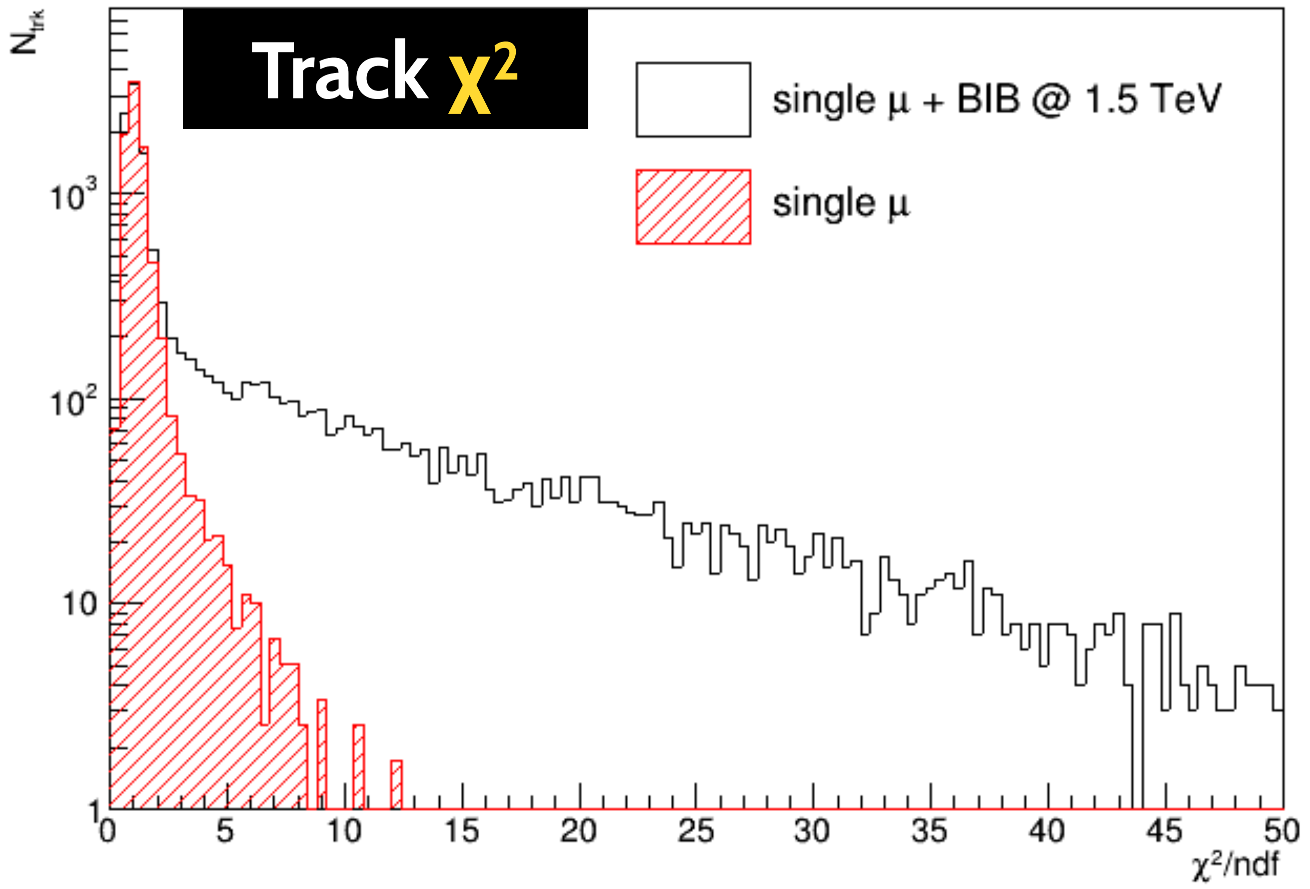


Further MDI-optimisation using full simulation with realistic digitisation for fast feedback

↳ potentially reducing TID and occupancy

Adopting ACTS tracking software for faster computational performance

↳ targeting full 4D track reconstruction with hit time in the Kalman filter for early rejection of fake track candidates



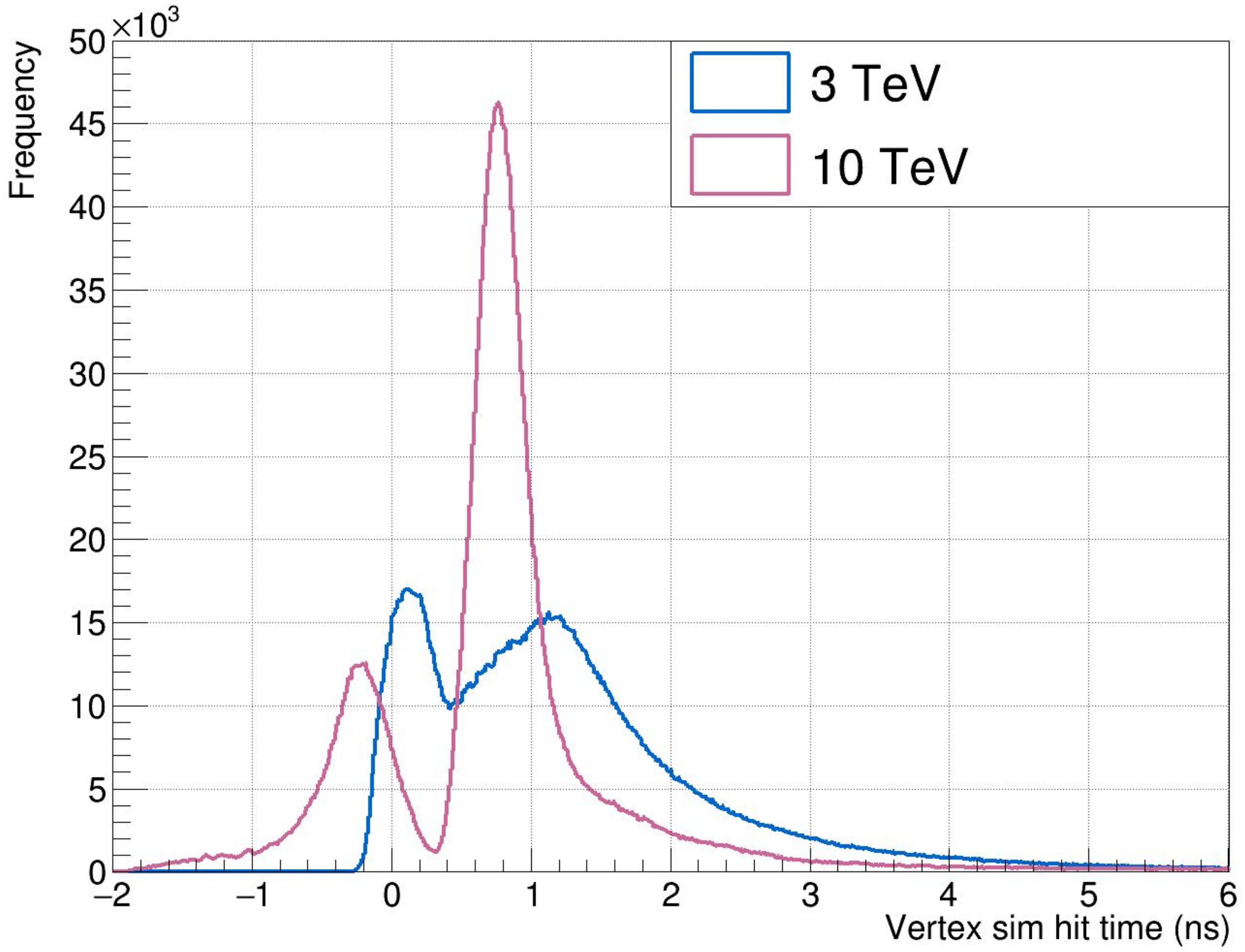
Most of the fake tracks already suppressed using conventional methods ▶

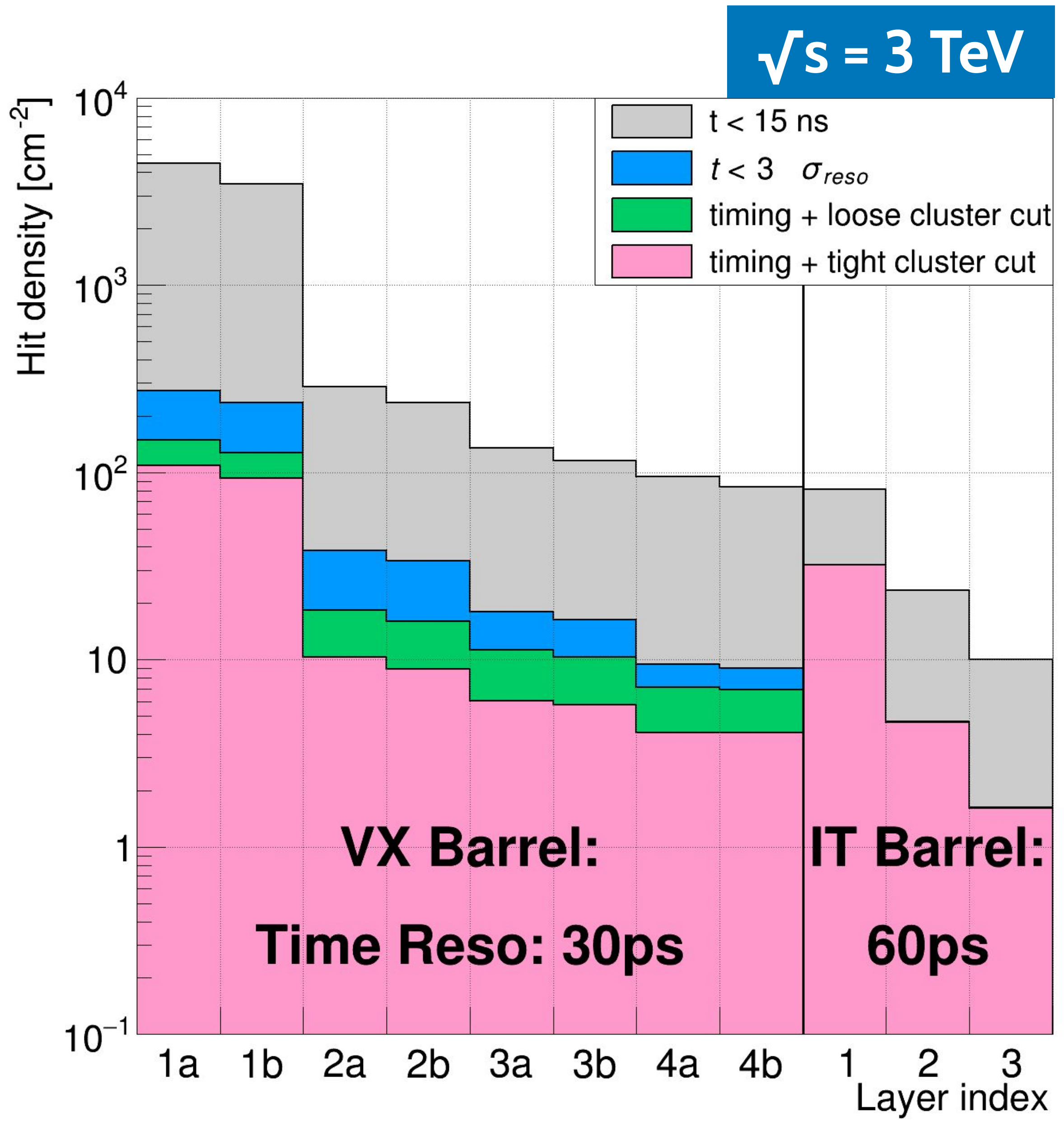
↳ sufficient physics performance, but too slow at the moment

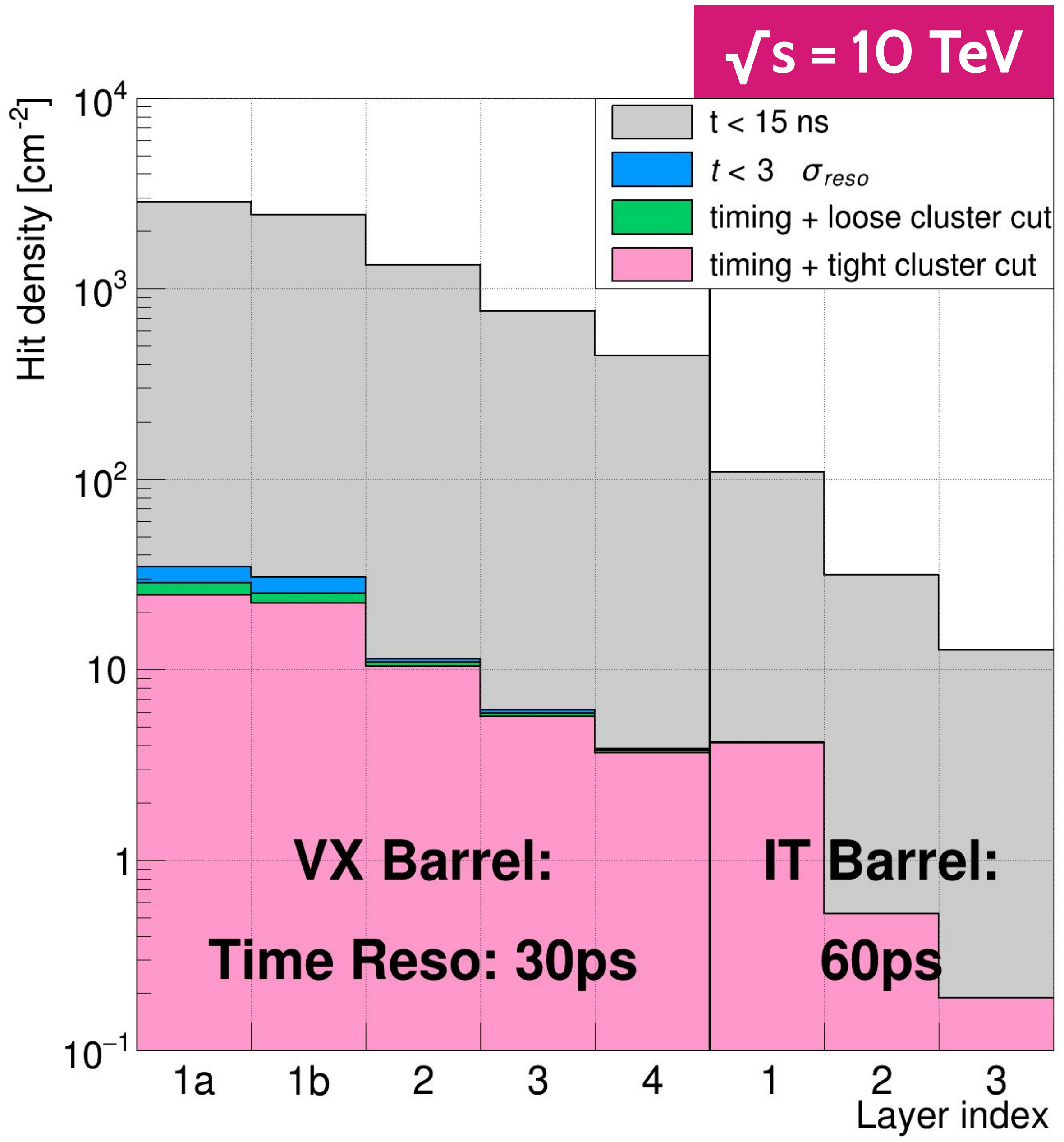
Towards $\sqrt{s}$ = 3-10 TeV: ongoing studies

Comprehensive experiment designs are being developed for $\sqrt{s}$ = 3TeV and 10 TeV
with optimisation studies of the MDI + detector happenning together

Example: cluster-shape filtering less effective at $\sqrt{s}$ = 10 TeV (BIB is more central)
BUT time filtering is more effective (different time structure of BIB hits)







Expecting further improvement with a dedicated MDI design

↳ establishing fast feedback loop from the full detector simulation in GEANT4 for MDI studies

Summary

Extensive simulation studies ongoing for a Muon Collider program at $\sqrt{s}$ = 1.5 / 3 / 10 TeV
with a coordinated effort between the machine-detector-interface and detector groups

Tracking Detector is a crucial component for nearly any physics analysis
with the most challenging requirements in the Vertex Detector

Beam Induced Background (BIB) introduces unprecedent hit density
making generic readout and track-reconstruction schemes highly inefficient

State-of-the-art timing resolution combined with fine spatial granularity are necessary
for efficient on-detector BIB rejection

Overall material budget in the Tracker region must be minimised
to limit the production of secondary soft electrons

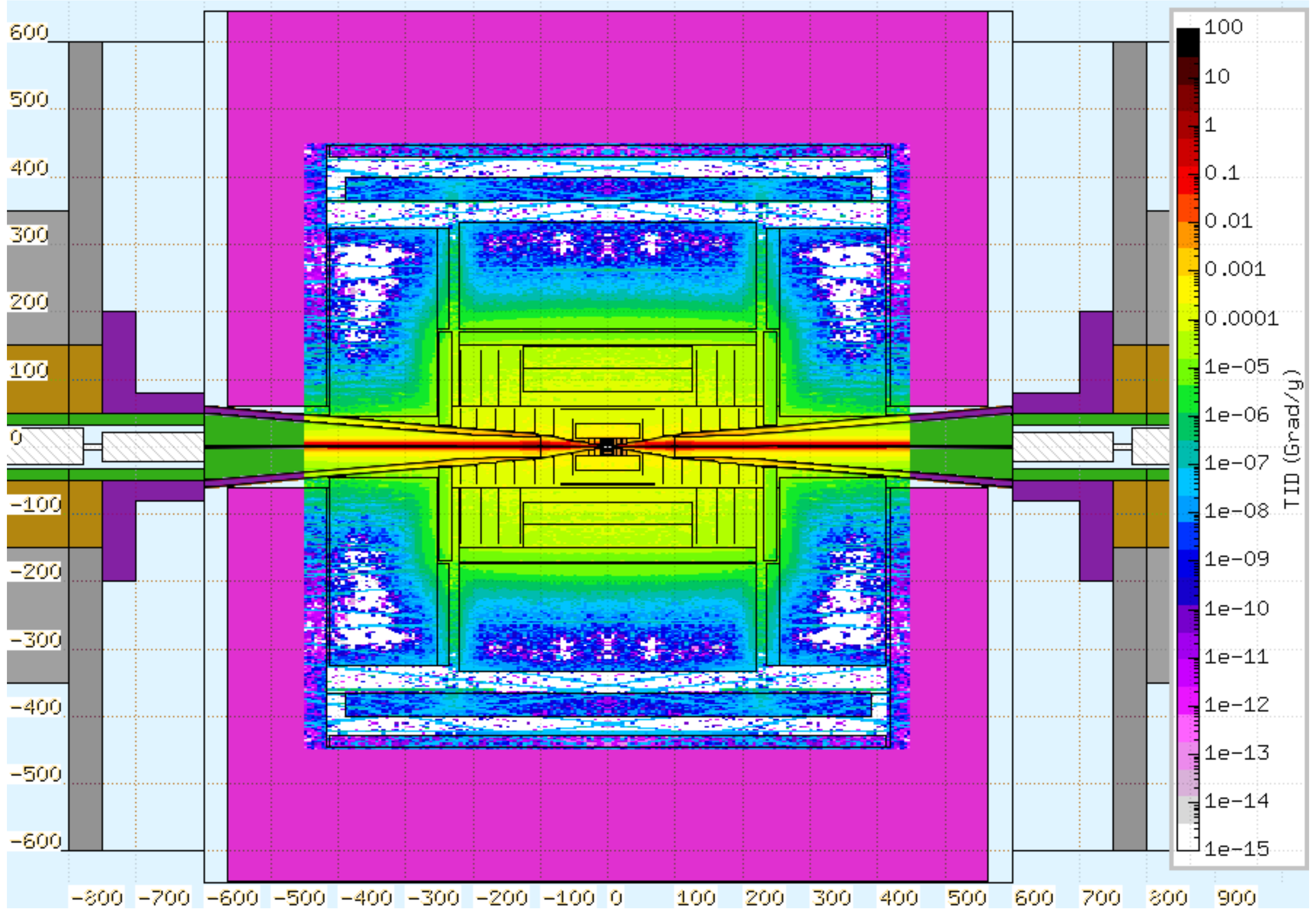
R&D of many relevant technologies are ongoing under ECFA DRD program
outlined in the dedicated note: arXiv:2203.07224

Up to now most studies performed on the $\sqrt{s}$ = 1.5 TeV case
for a connection with the previous MAP studies

Realistic Muon Collider designs foresee $\sqrt{s}$ = 3 TeV and $\sqrt{s} \geq$ 10 TeV
but no dramatic changes in BIB characteristics are expected

Muon Collider will operate at ~100 KHz bunch-crossing rate
leaving plenty of time for data-processing (10μs)

Radiation levels do not exceed those at HL-LHC
~1 MRad/year TID + ~10^{15}/year 1 MeV n. eq. fluence in the tracker



Dedicated publications on physics and detector prepared as part of the Snowmass '21 process:

- Muon Collider Physics Summary | [arXiv:2203.07256]
- Simulated Detector Performance at the Muon Collider | [arXiv:2203.07964]
- Promising Technologies and R&D Directions for the Future Muon Collider Detectors | [arXiv:2203.07224]

Technical side of detector simulations for the Muon Collider | [Comput.Softw.Big Sci. 5 (2021) 1, 21]

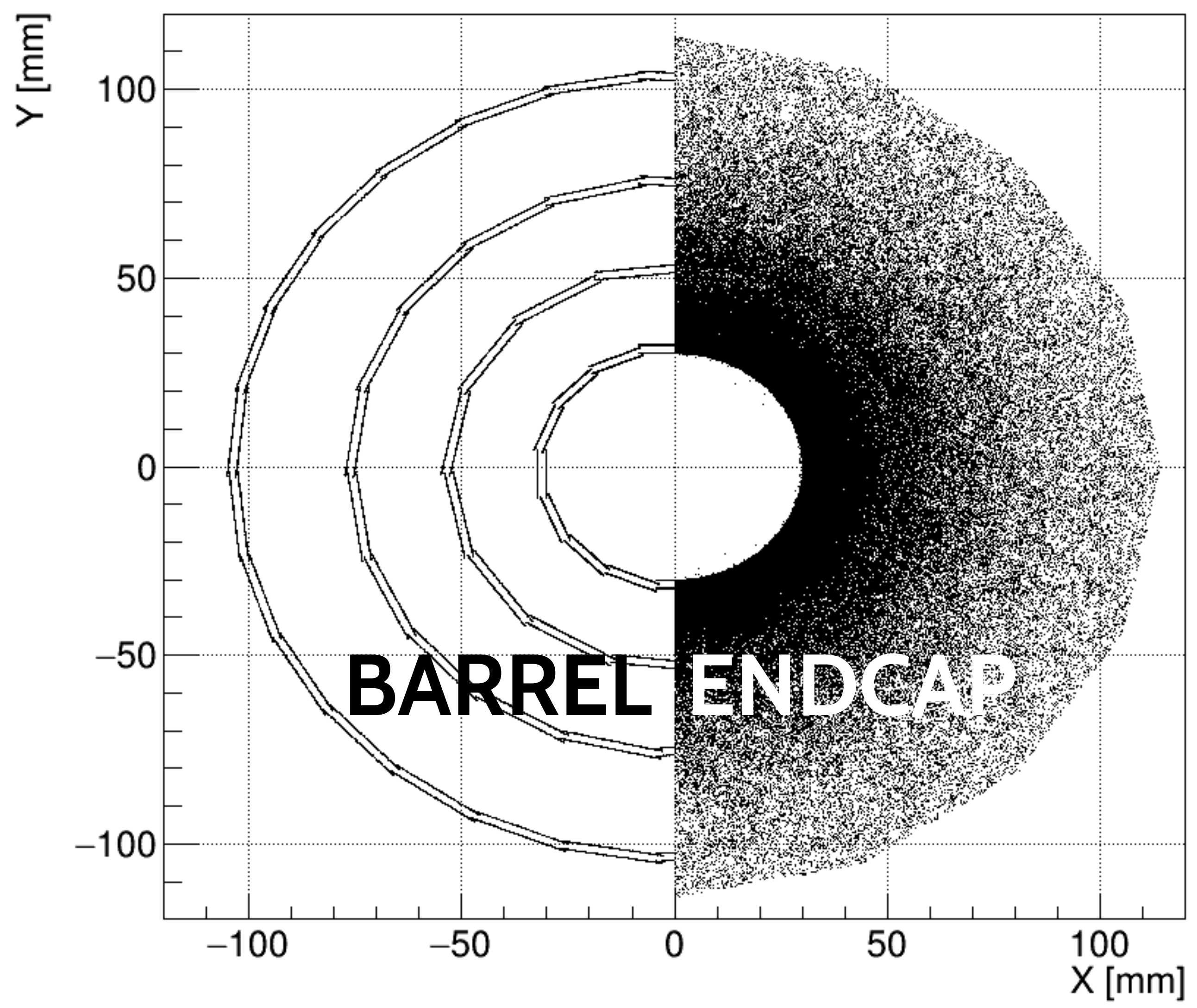
Special [JINST issue] on Muon Accelerators for Particle Physics

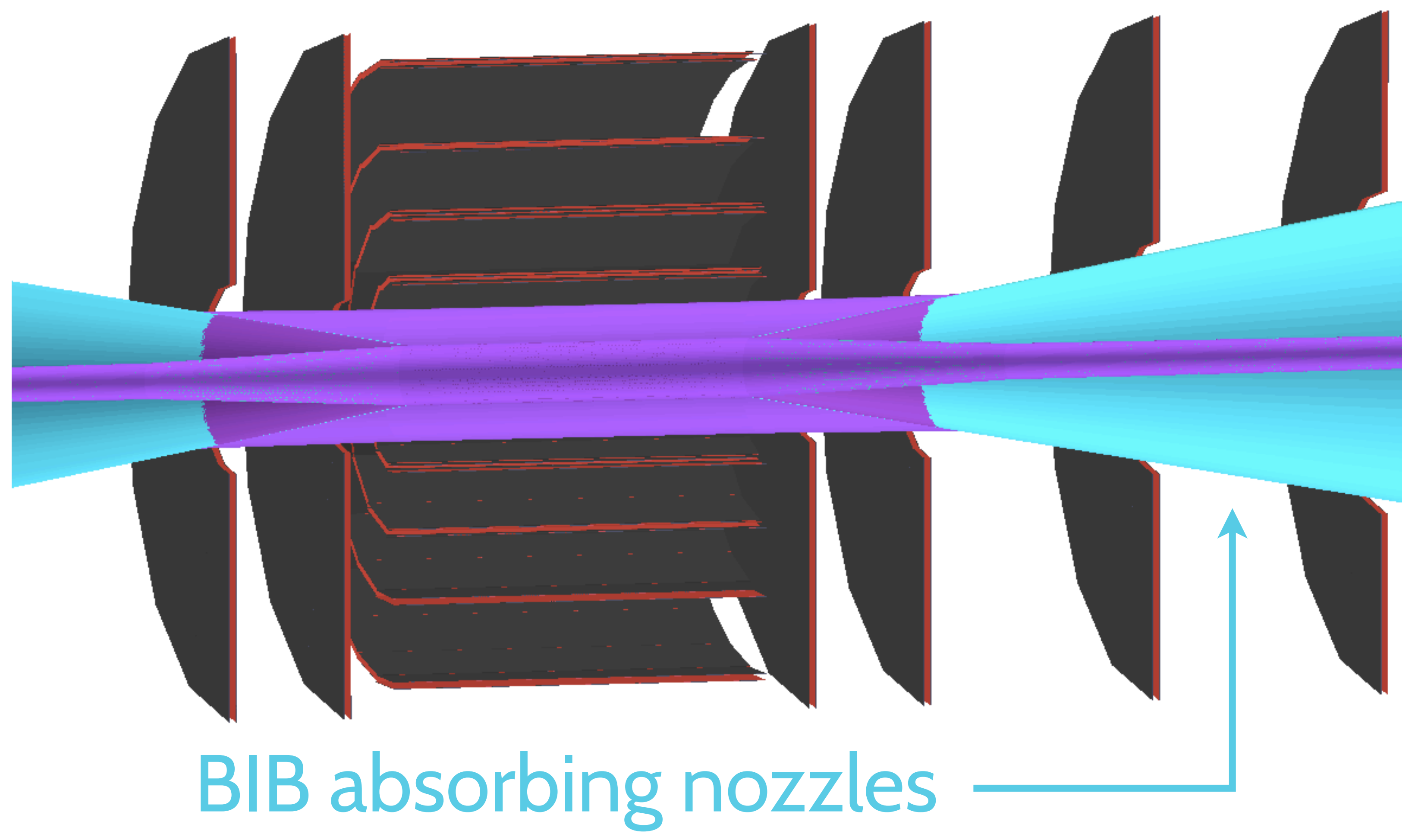
Muon Collider accelerator parameters

Parameter	$\sqrt{s} = 1.5$ TeV	$\sqrt{s} = 3$ TeV	$\sqrt{s} = 10$ TeV
Beam momentum [GeV]	750	1500	5000
Beam momentum spread [%]	0.1	0.1	0.1
Bunch intensity	$2 \cdot 10^{12}$	$2.2 \cdot 10^{12}$	$1.8 \cdot 10^{12}$
$\beta^*_{x,y}$ [cm]	1	0.5	0.15
ϵ_{TN} normalised transverse emittance [π μm rad]	25	25	25
ϵ_{LN} normalised longitudinal emittance [MeV m]	7.5	7.5	7.5
$\sigma_{x,y}$ beam size [μm]	6	3	0.9
σ_z beam size [mm]	10	5	1.5

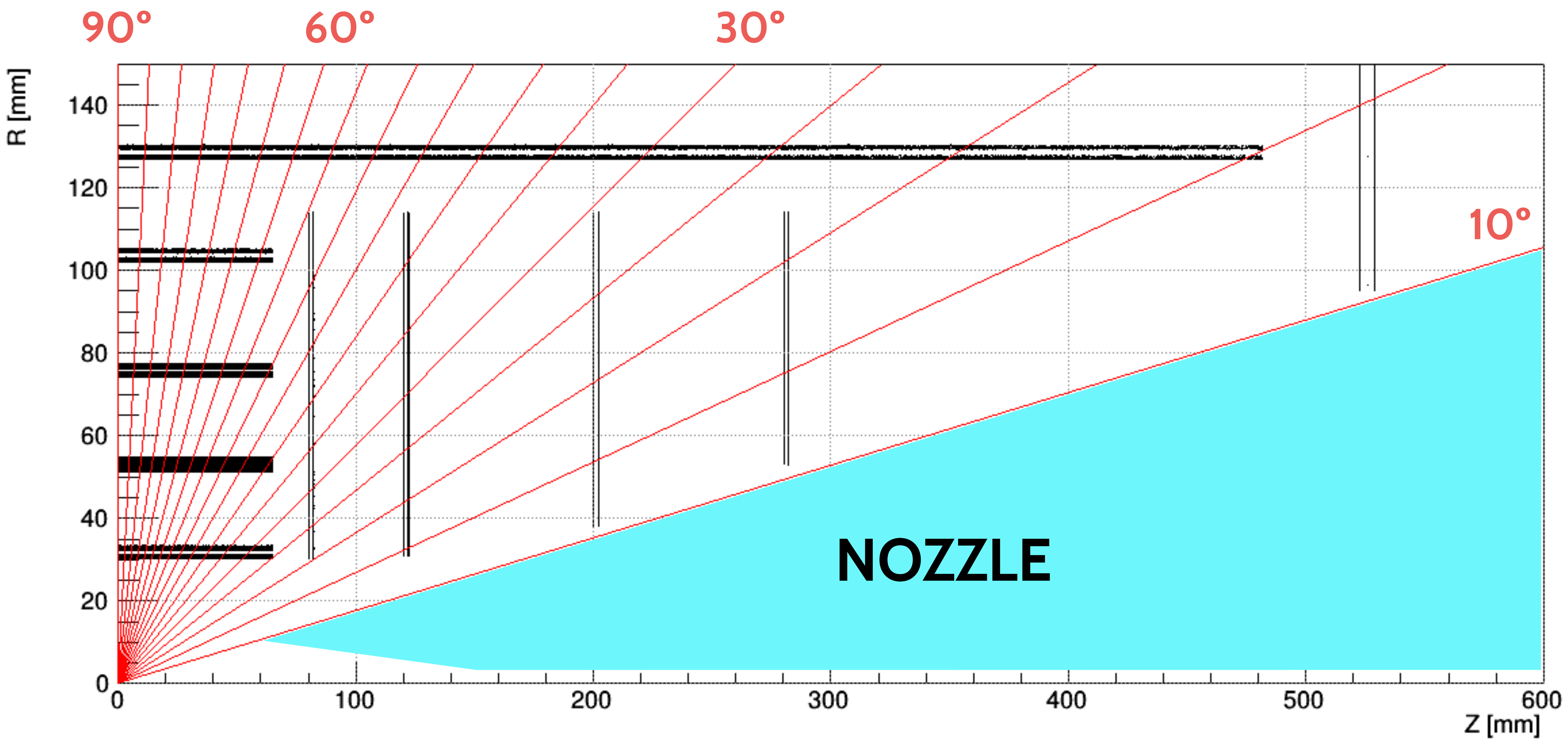
Integrated luminosity targets: 10 ab^{-1} at $\sqrt{s}$ = 10 TeV + potentially 1 ab^{-1} at $\sqrt{s}$ = 3 TeV
with instantaneous luminosity of ~10^{34} - 10^{35} cm^{-2} s^{-1}

Vertex Detector geometry in 3D





Angular layout of the VTX layers



Effect of the stronger magnetic field on occupancy