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Tateyama, Japan

Tracking and vertexing challenges at a multi-TeV Muon Collider

VERTEX 2022

The 31st International Workshop on Vertex Detectors

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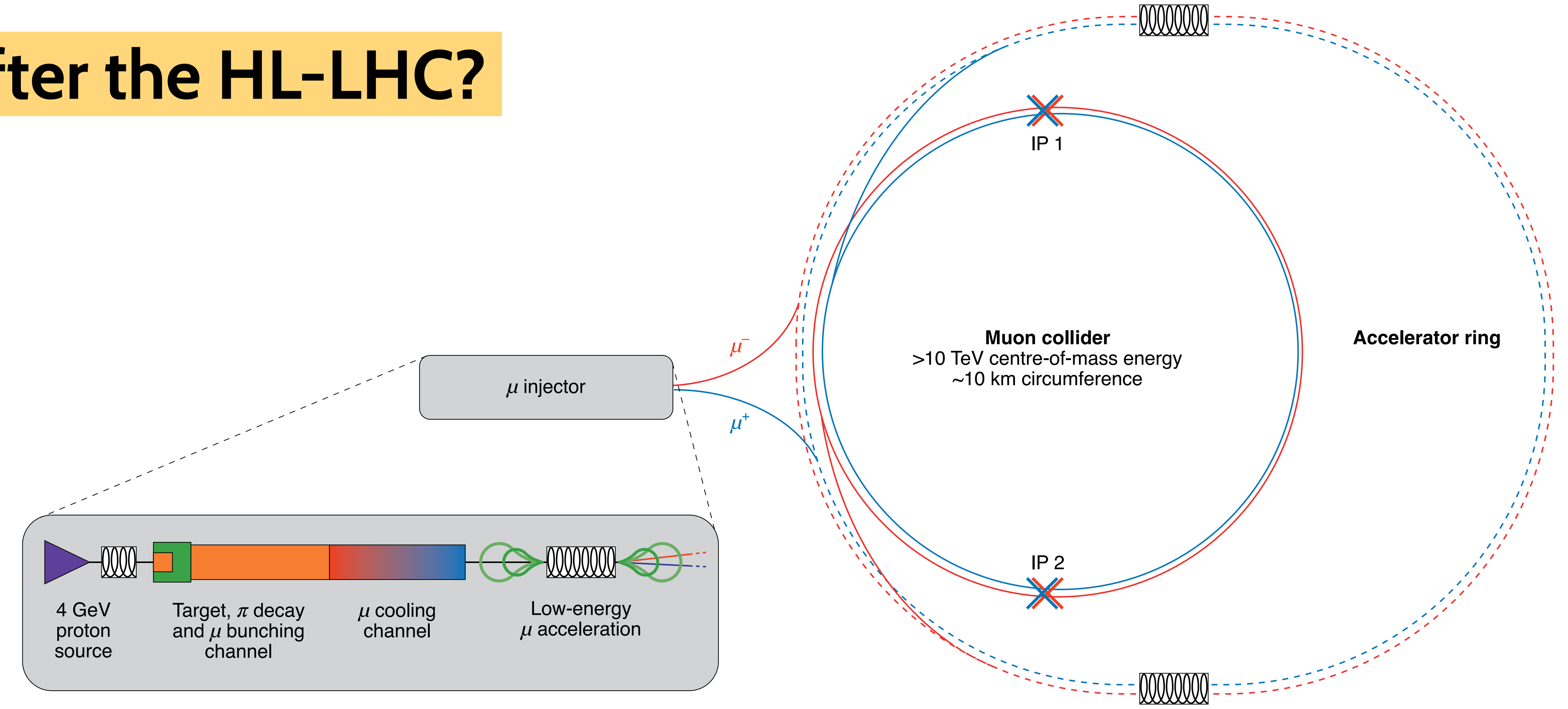
on behalf of the **Muon Collider Physics and Detector group**

(a) INFN Torino *(Italy)* (b) CERN *(Switzerland)*

Muon Collider: the dream machine

Big question for particle physics today: which collider to build after the HL-LHC?



Several important requirements have to be satisfied:

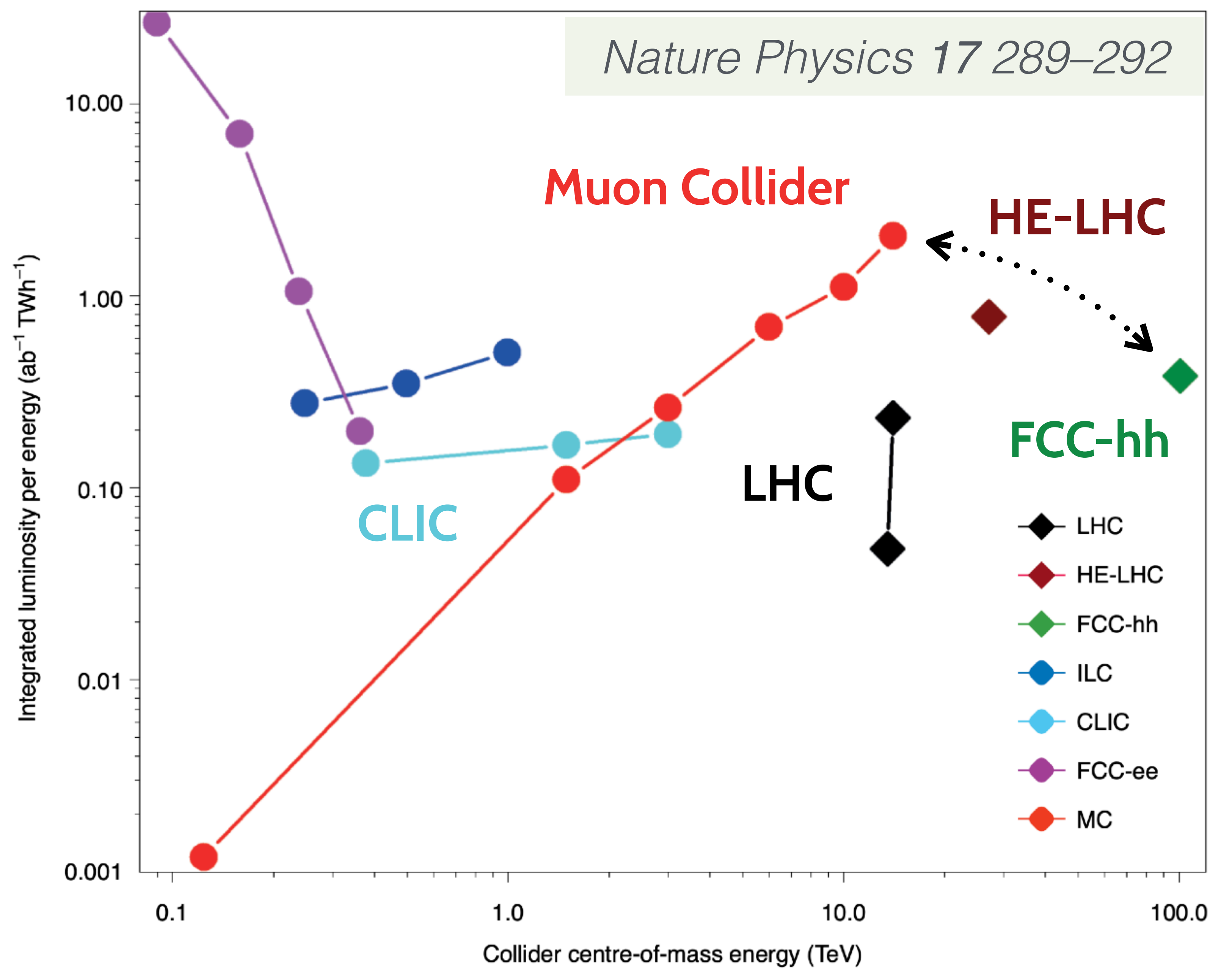
- energy reach exceeding the LHC by a large factor
- enable precision measurements of Standard Model
- have low construction cost → small size
- be sustainable in operation → energy efficient

Muon Collider combines the best features of the two classes of machines:

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

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

At $\sqrt{s} \geq 3$ TeV Muon Collider becomes the most energy efficient machine ▶



Rich physics program provided by $\mu^+\mu^-$ and VBF processes
with the discovery reach at $\sqrt{s}$=14 TeV comparable to FCC-hh at $\sqrt{s}$=100 TeV

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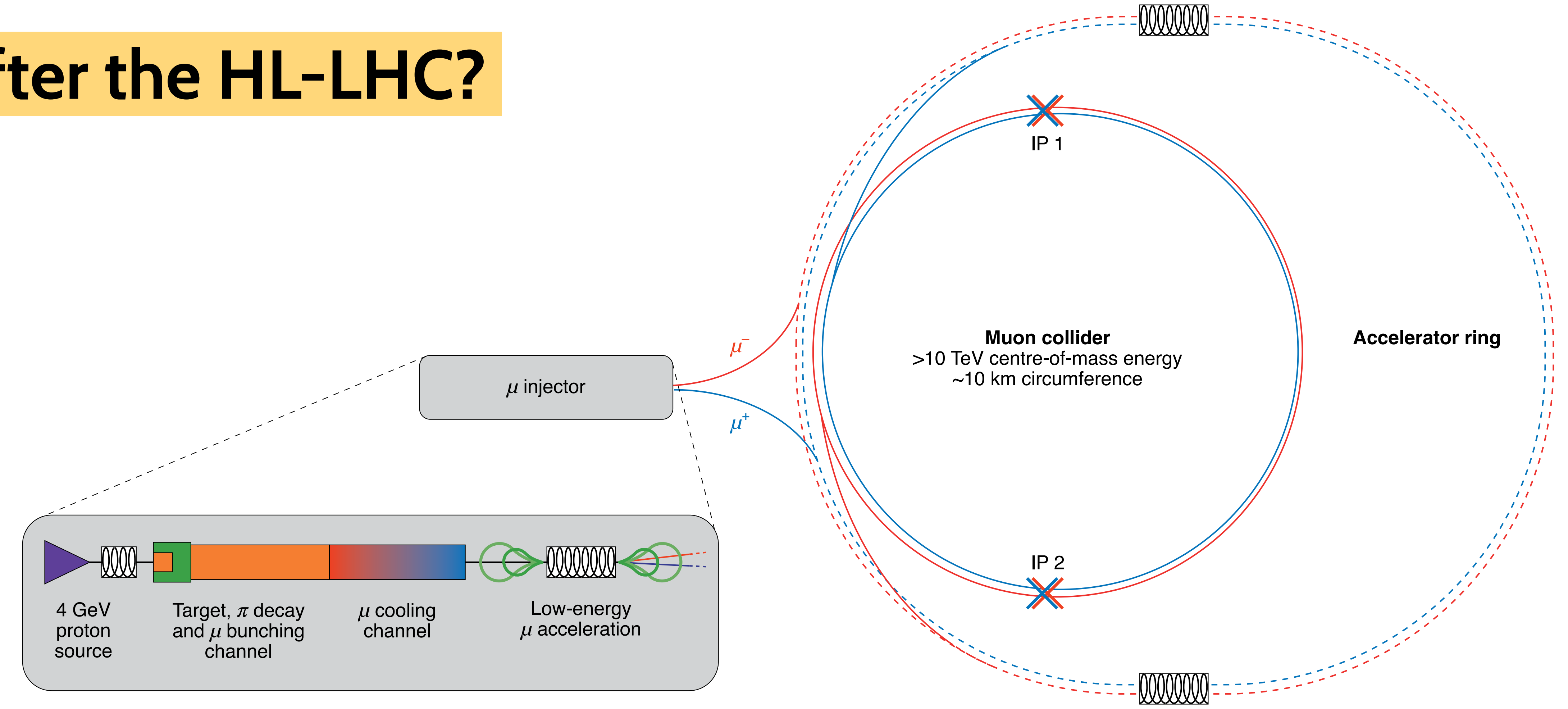

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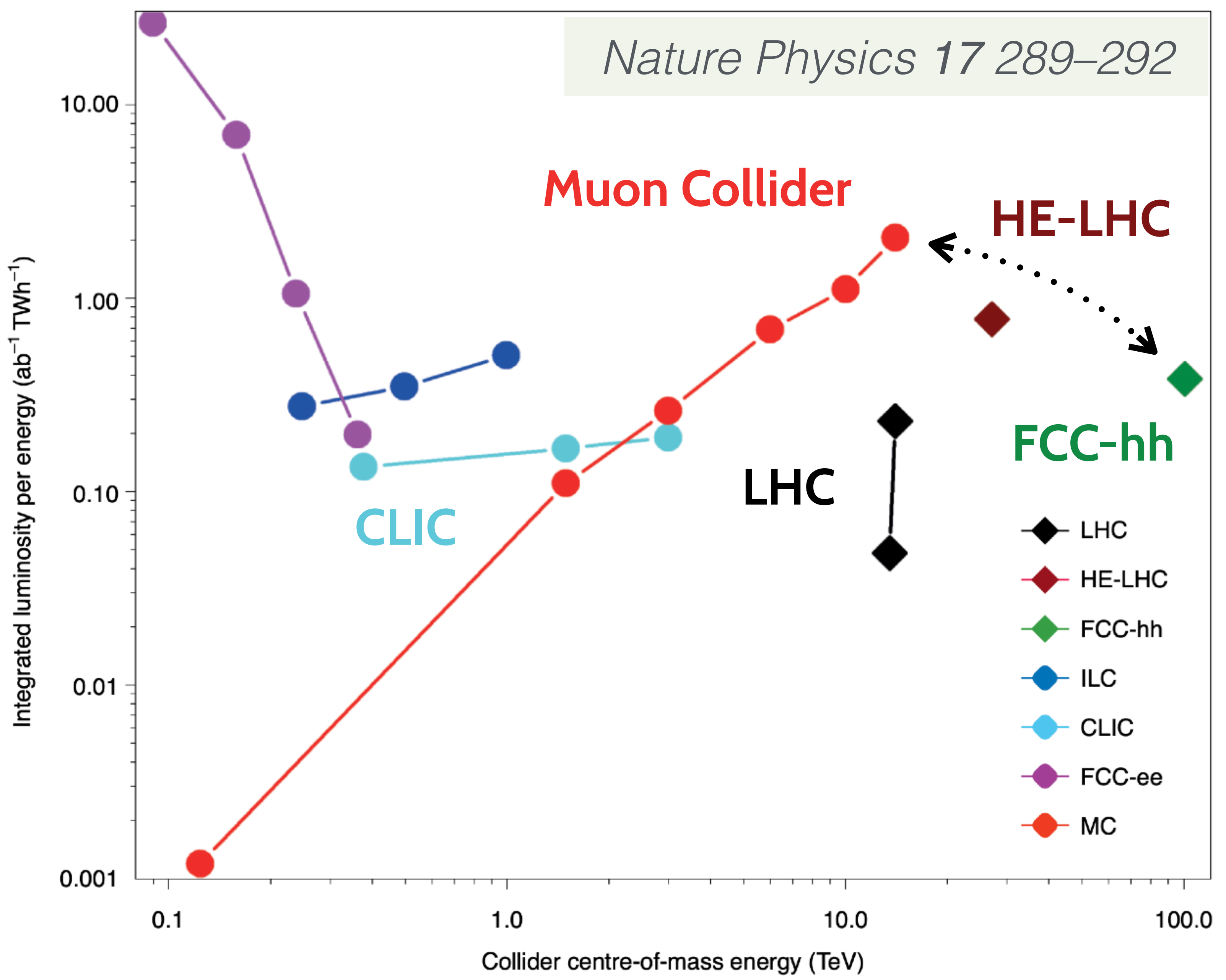

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Beam Induced Background: the critical challenge

Assuming the beam density of 2×10¹² muons/bunch → **large number of decays in the collider ring**
e.g. for $\sqrt{s}$ = 1.5 TeV: 4.1 × 10⁵ decays per metre of lattice

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

- depends on the beam parameters *(energy, size, rate)*
- depends on the accelerator layout *(magnets, shields)*

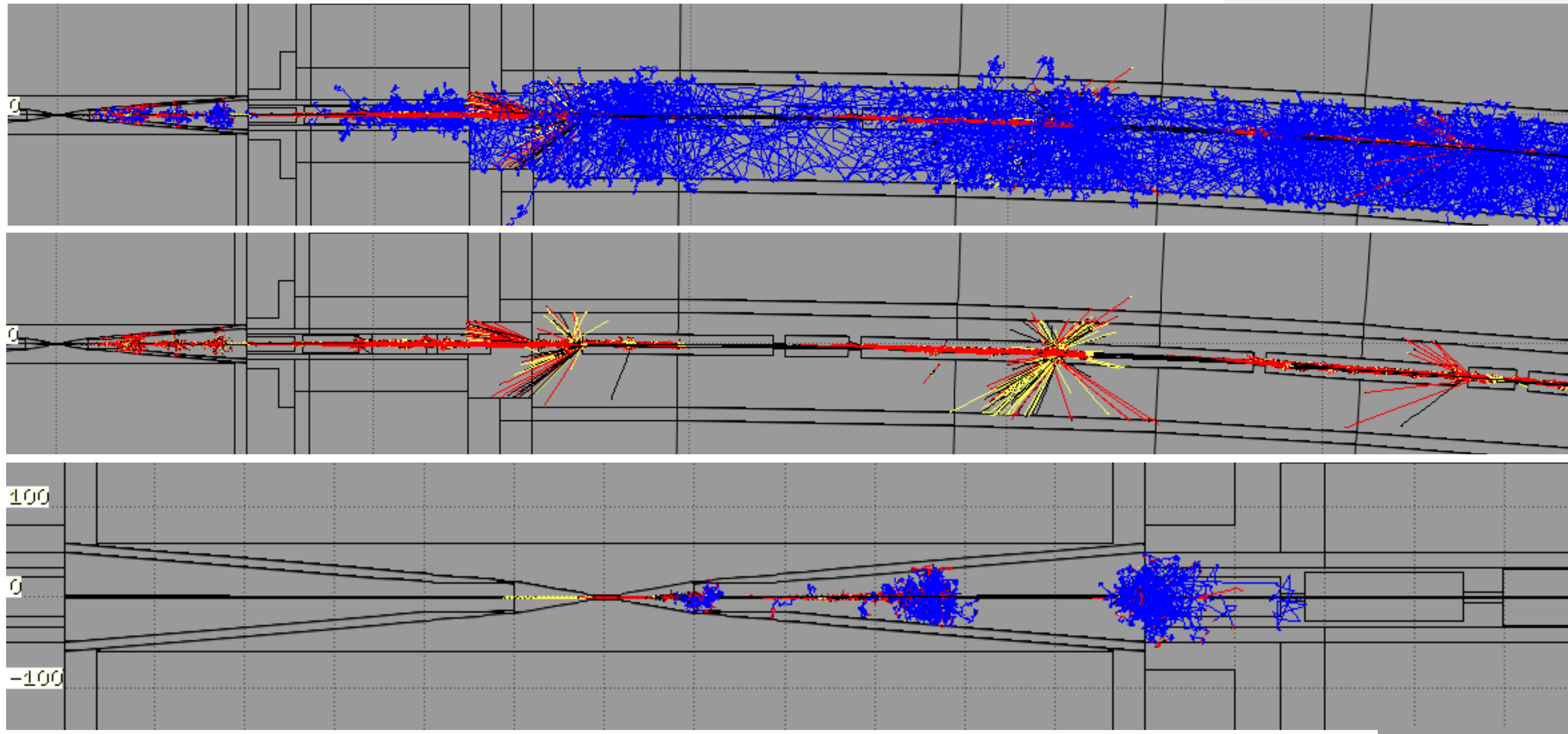
Machine-Detector Interface (MDI) is crucial
for absorbing as much of BIB particles as possible

Dedicated MDI for a $\sqrt{s}$ = 1.5 TeV Muon Collider designed by the Muon Accelerator Program (MAP) ▶

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

↳ **reduces the flux and energy of BIB particles reaching the detector by 2-3 orders of magnitude**

arXiv:2203.07964



FLUKA simulation — neutrons, photons, electrons, positrons

The remaining BIB particles still pose serious experimental challenges for the detector design + event reconstruction

BIB properties: $\sqrt{s}$ = 1.5 TeV

BIB has several characteristic features to be exploited in the detector design

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

fairly uniform spatial distribution → no isolated signal-like energy deposits

↳ conceptually different from pile-up contributions at the LHC

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

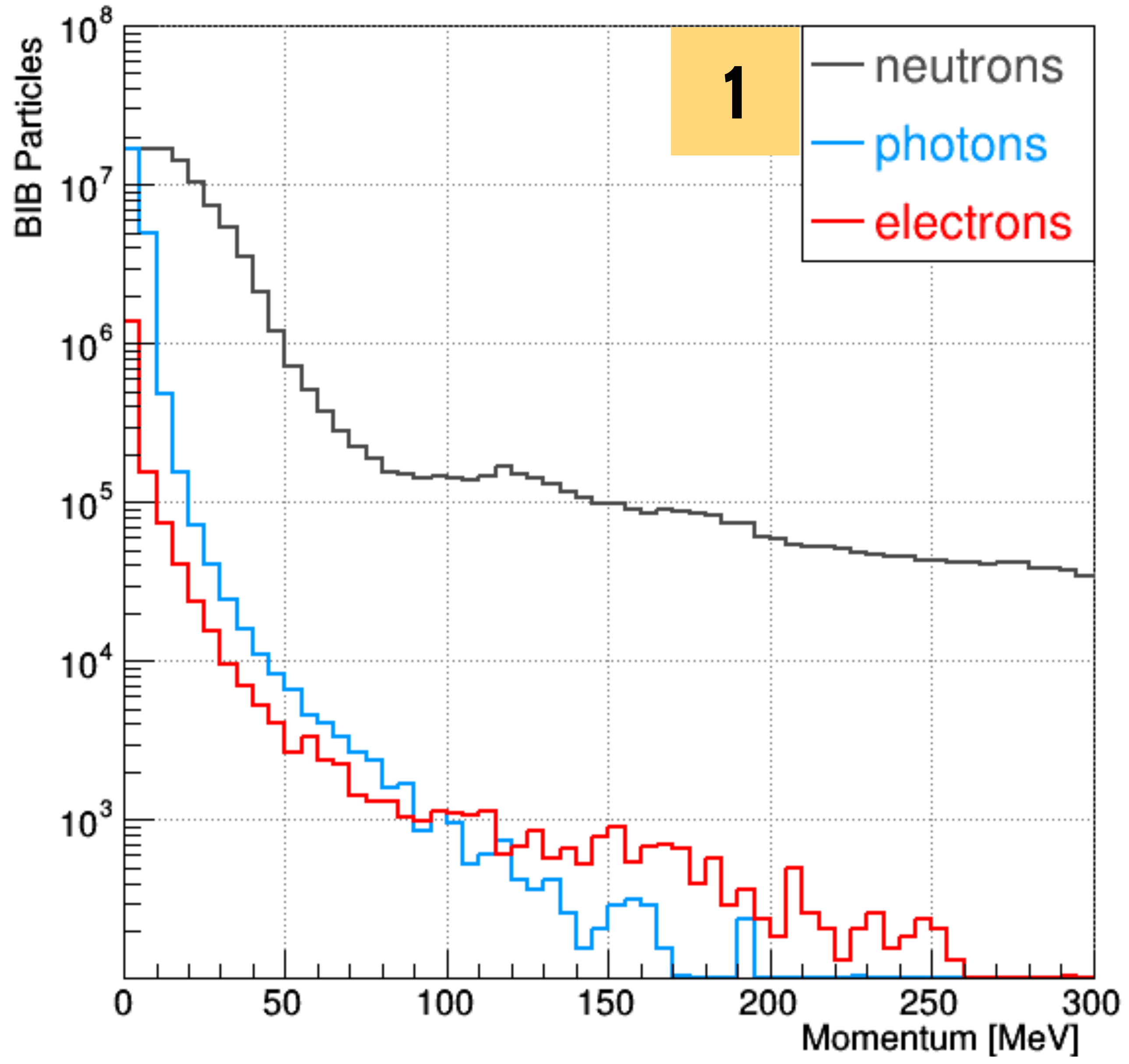
$\mu^+\mu^-$ collision time spread: 30ps at $\sqrt{s}$ = 1.5 TeV | ≤20ps at $\sqrt{s}$ = 3 TeV

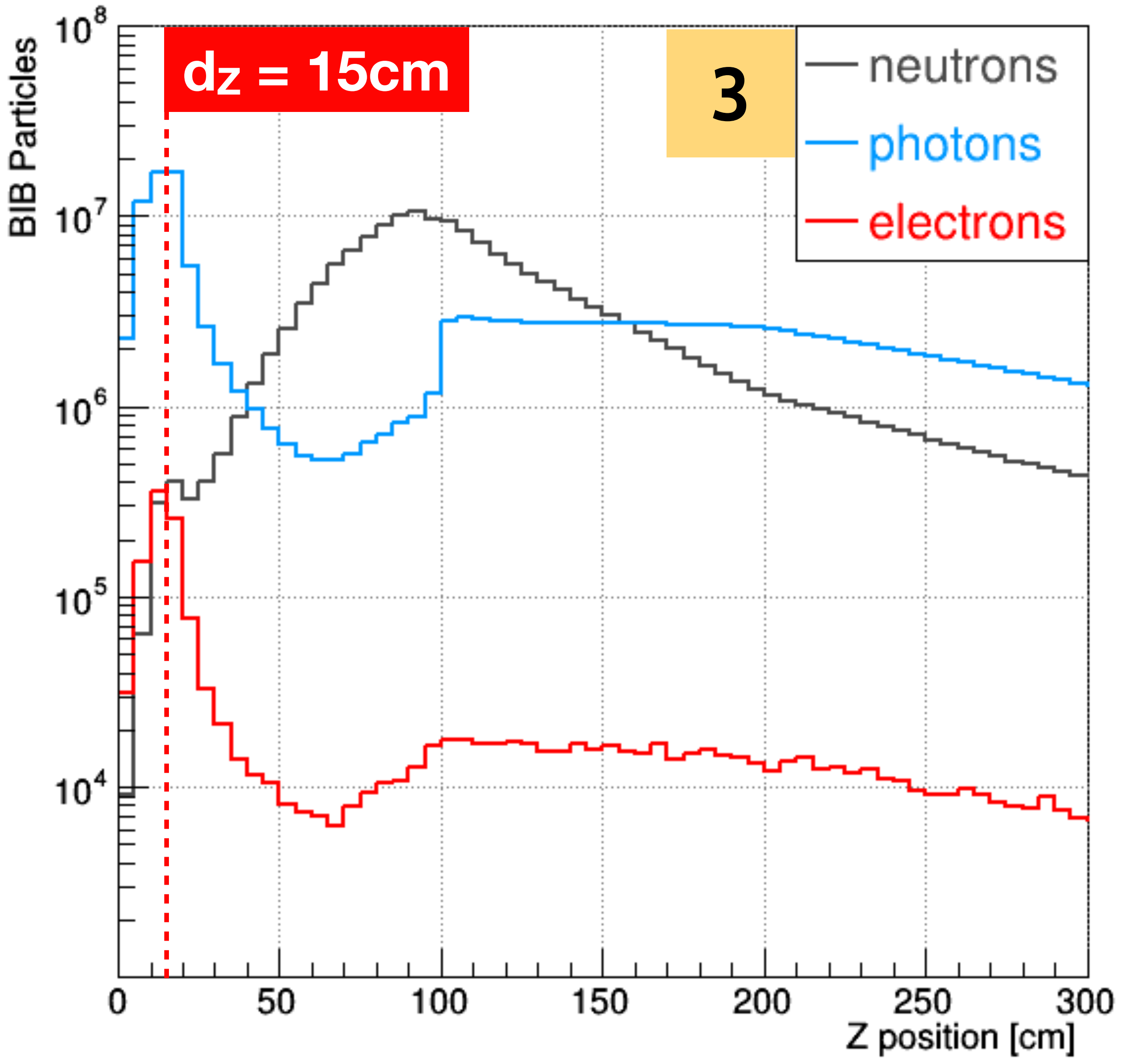
↳ strong handle on the BIB → requires state-of-the-art timing detectors

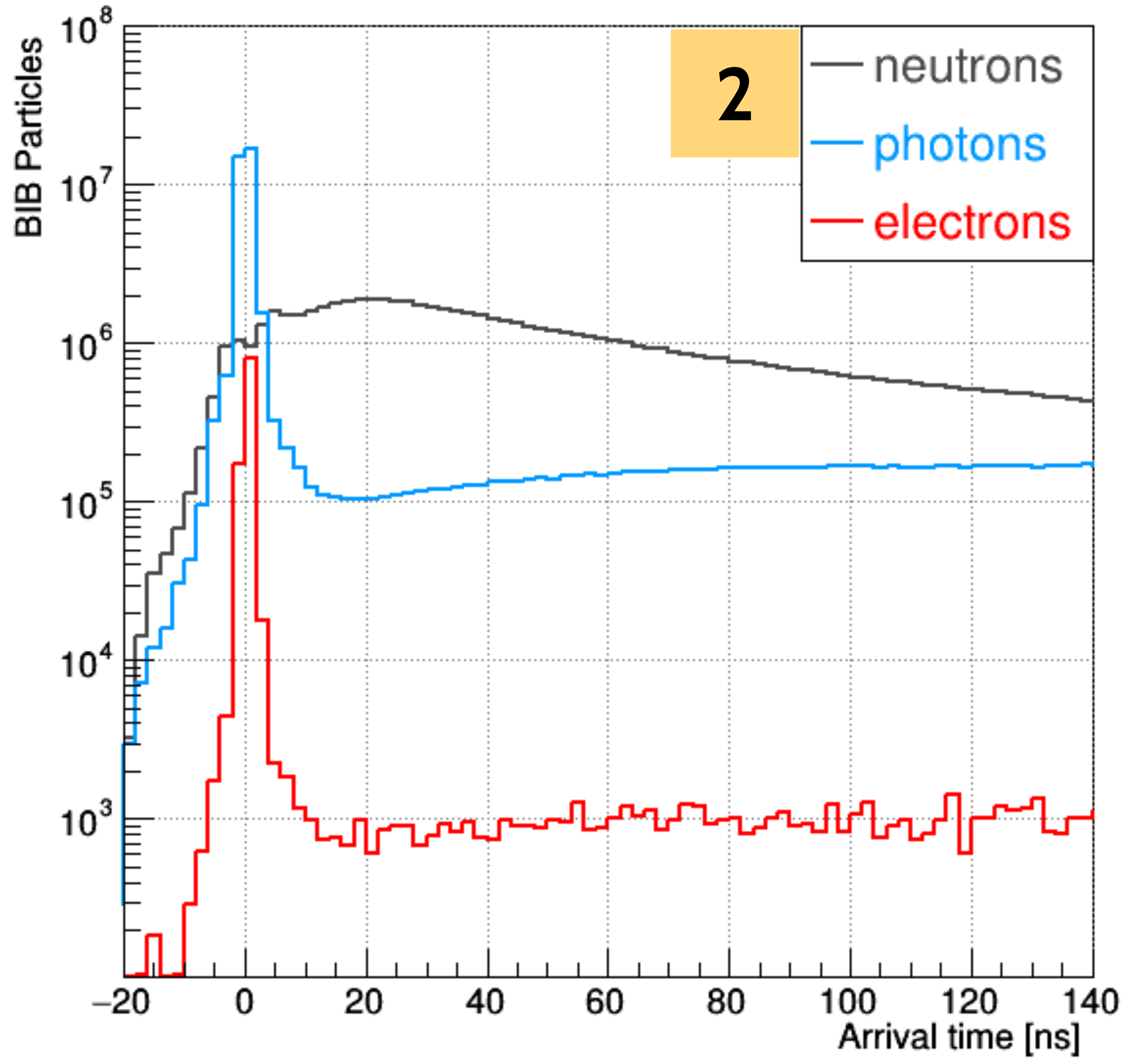
3. Strongly displaced origin along the beam

crossing detector surface at a shallow angle

↳ affects charge distribution + time of flight







Main BIB contributions in the tracking detector:

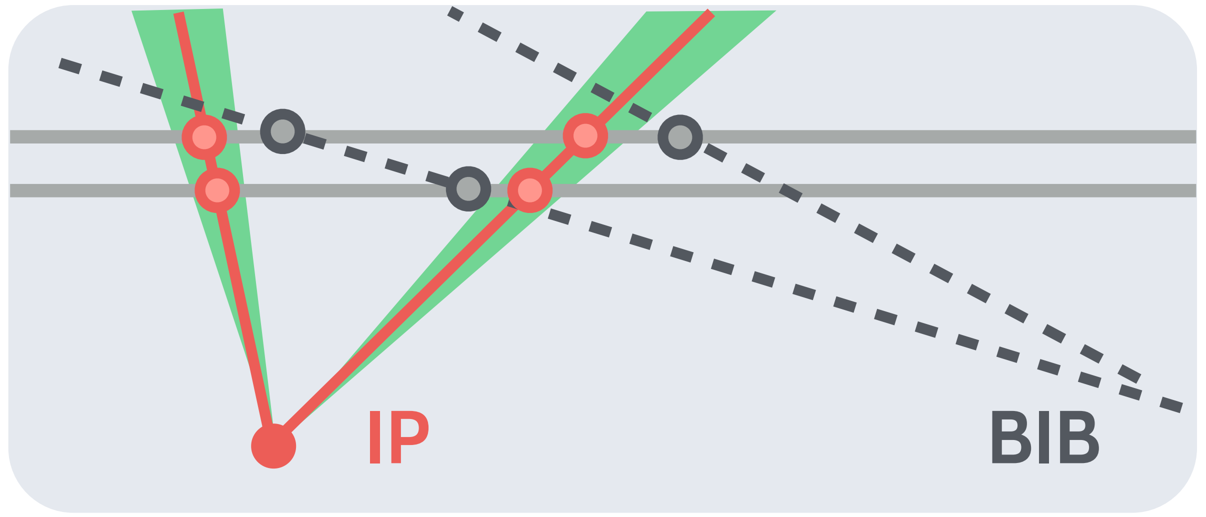
- **electrons** → directly producing tracker hits
- **neutrons** → radiation damage to Si + electronics
- **photons** → creating secondary electrons by absorption in the tracker

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

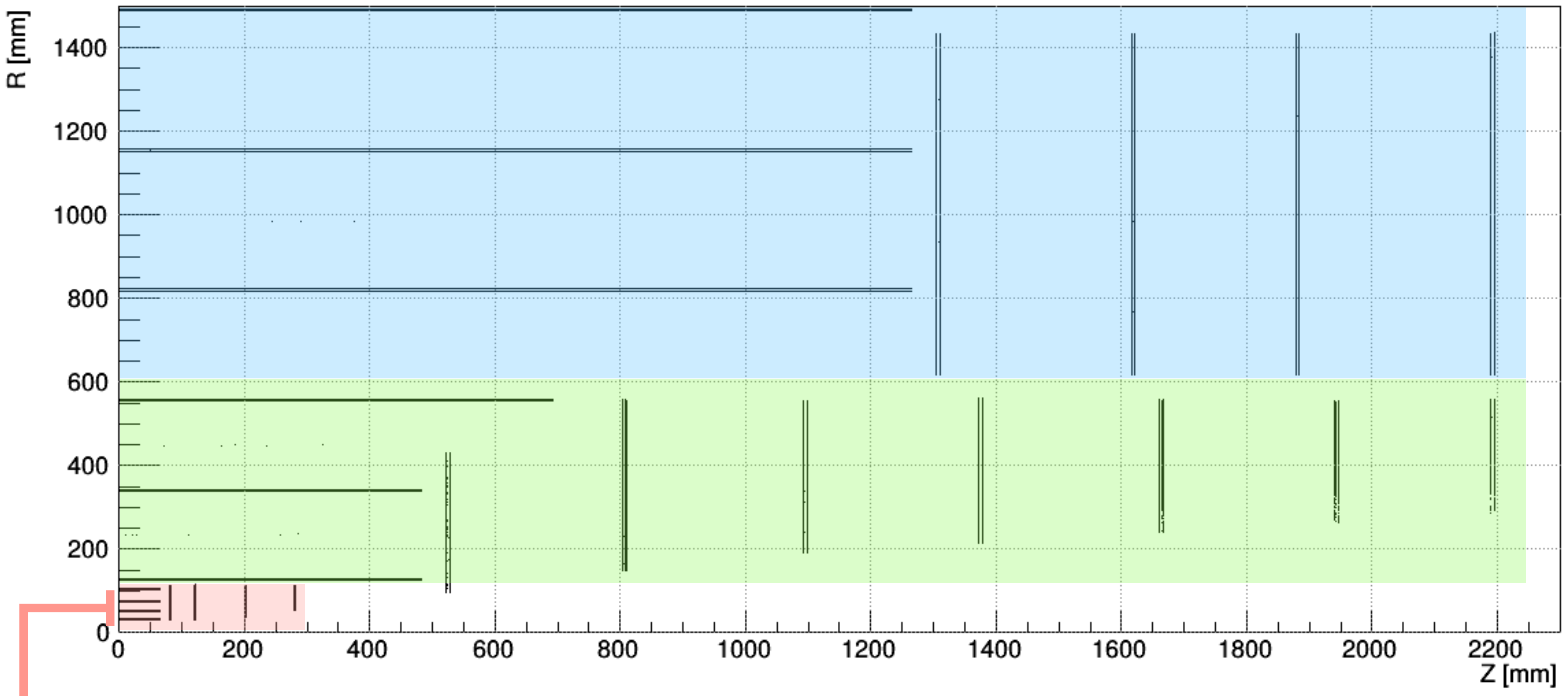
Silicon sensors with high spatial and timing resolution

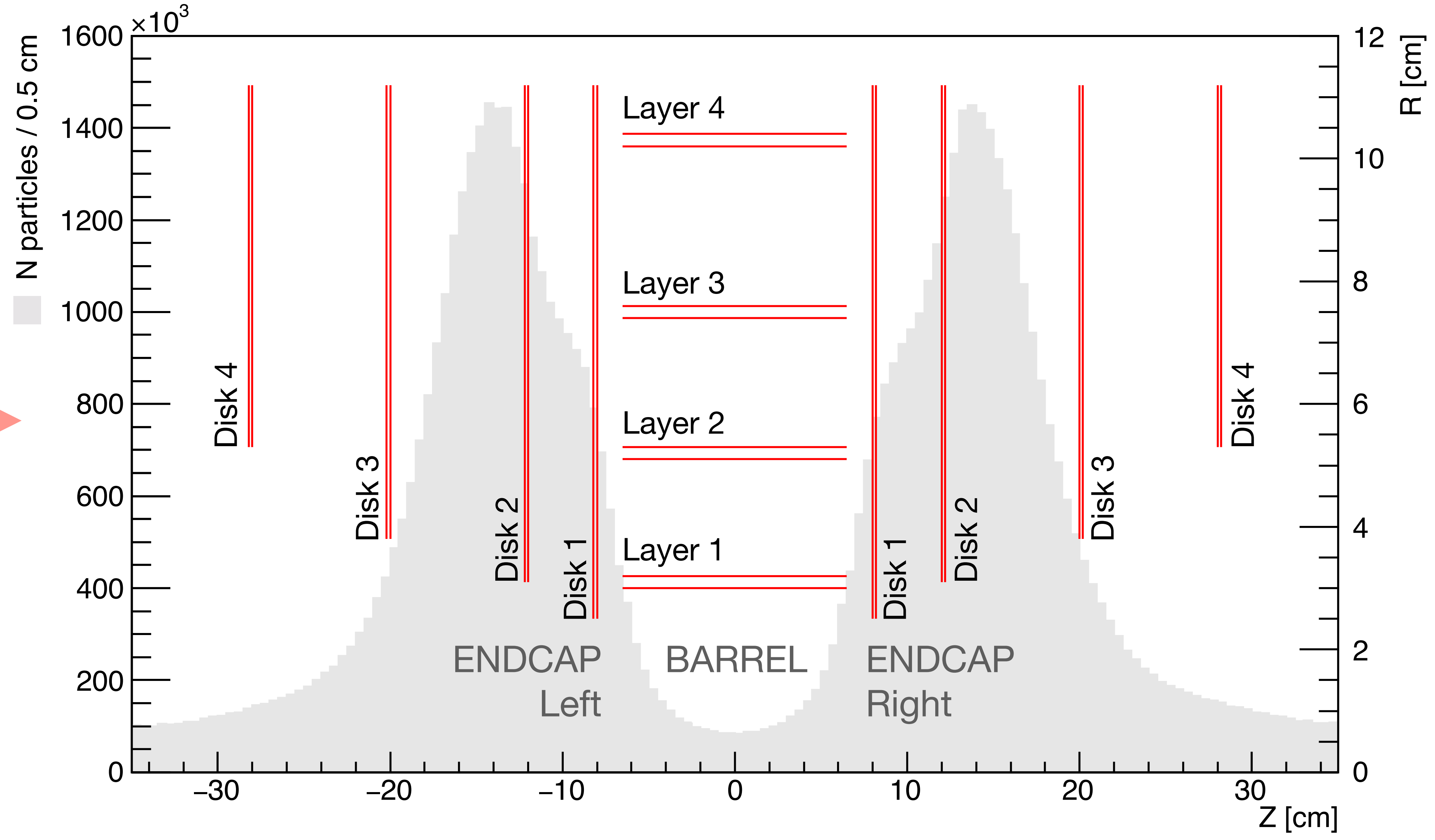
- **Outer Tracker** 50µm × 10mm σ_t = 60ps
- **Inner Tracker** 50µm × 1mm σ_t = 60ps
- **Vertex Detector** 50µm × 50µm σ_t = 30ps
  ↳ σ_{UV} = 5µm × 5µm
  - forward disks placed outside of the regions with highest BIB flux to minimize occupancy

Double layers for angle-based BIB rejection ▶ in the Vertex Detector



Magnetic field: B = 3.57 T → *inherited from pre-existing MDI design*

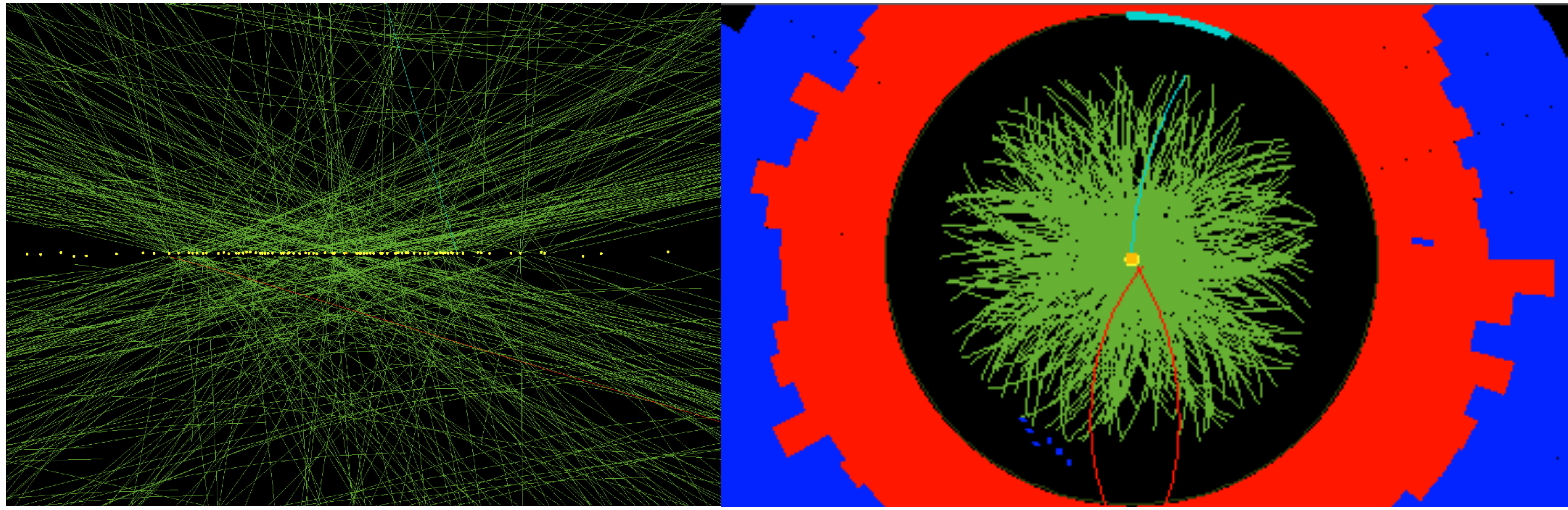




At the **LHC** we are used to backgrounds primarily from pile-up *pp* collisions

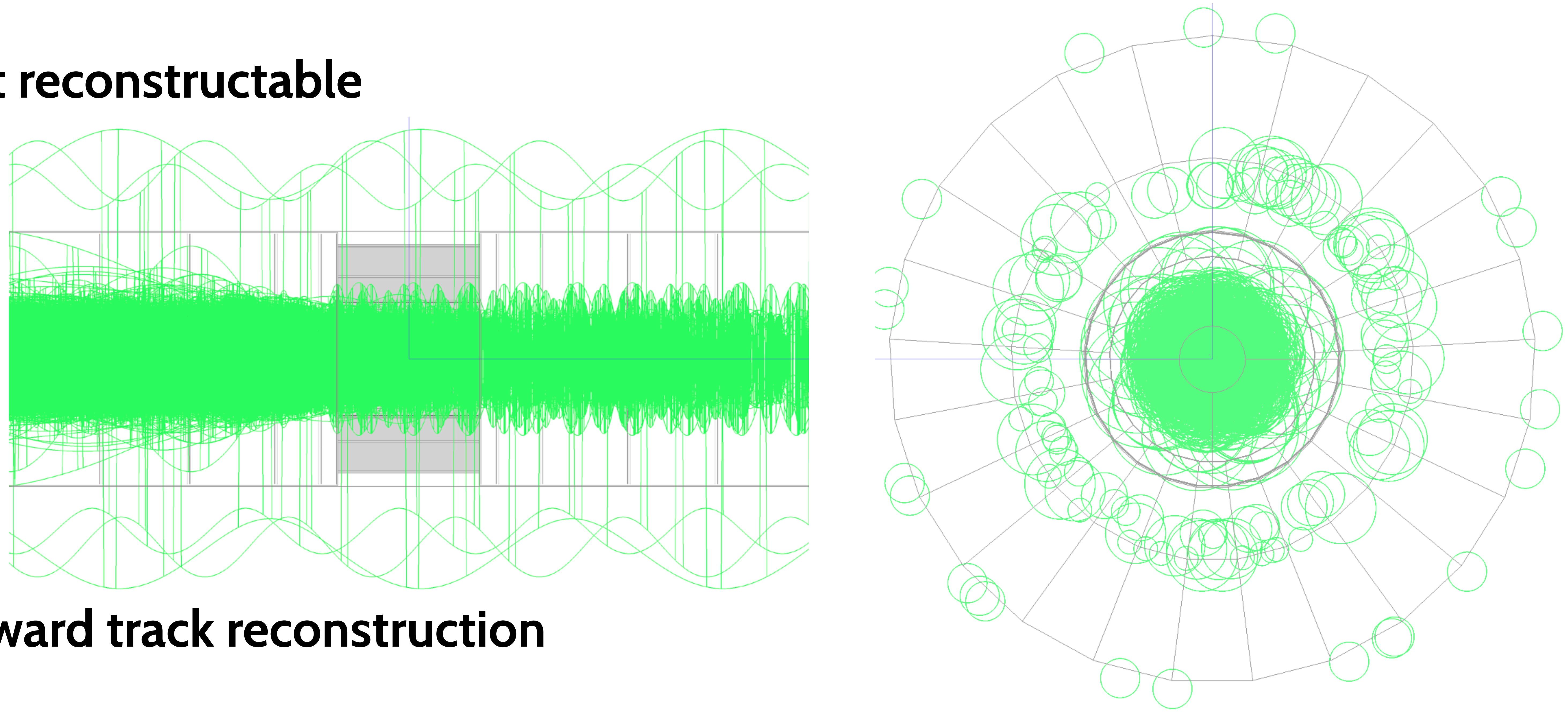
↳ real tracks pointing at displaced vertices

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 ▶

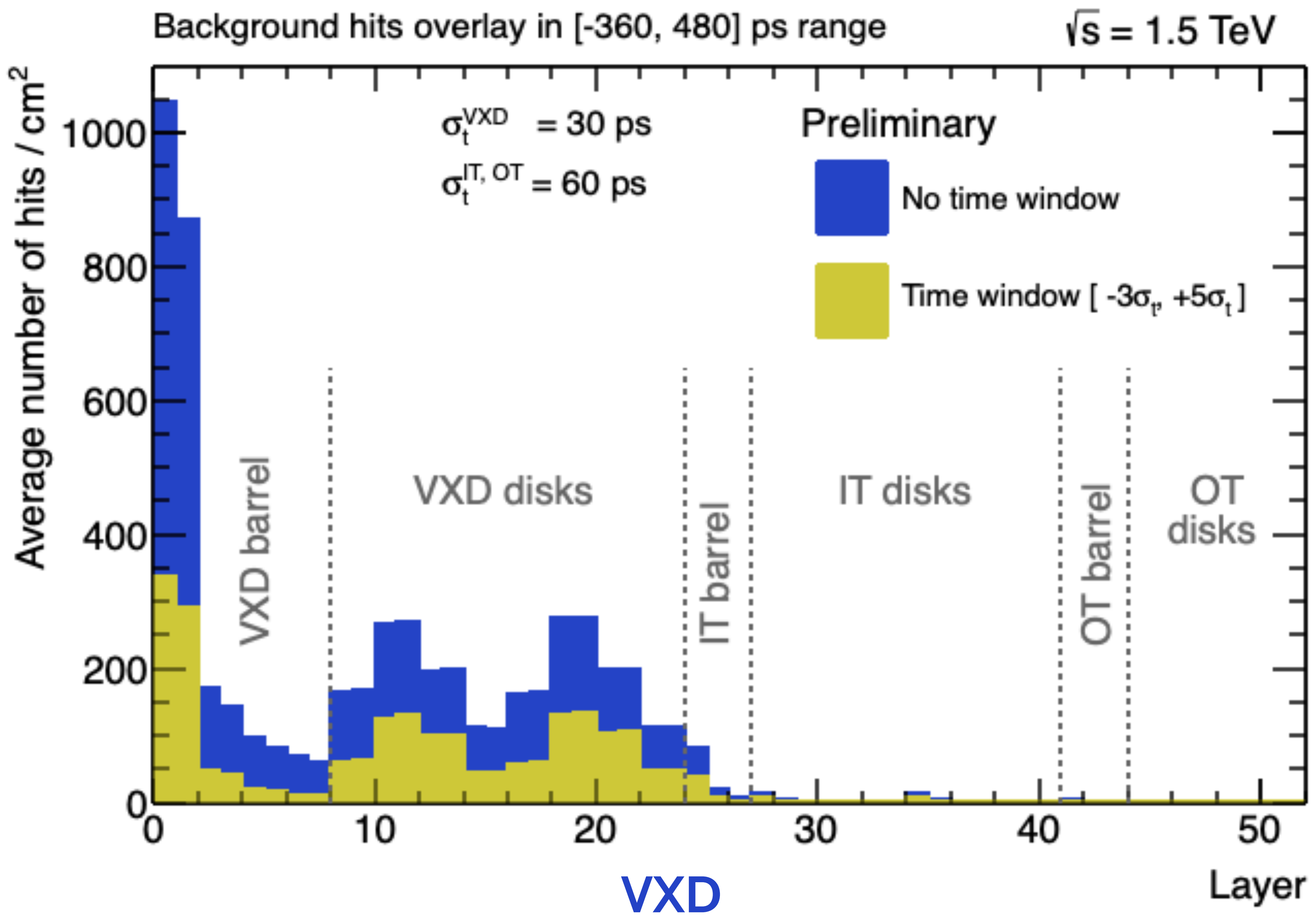


Tremendous combinatorics for the classical outward track reconstruction

Raw hit density in the Vertex Detector is unsustainable

↳ up to ≤ 1K hits/cm² in a narrow ±0.5 ns time-integration window

Occupancy is reduced by ≥50% with even narrower time windows ▶
assuming state-of-the-art time resolution for single hits

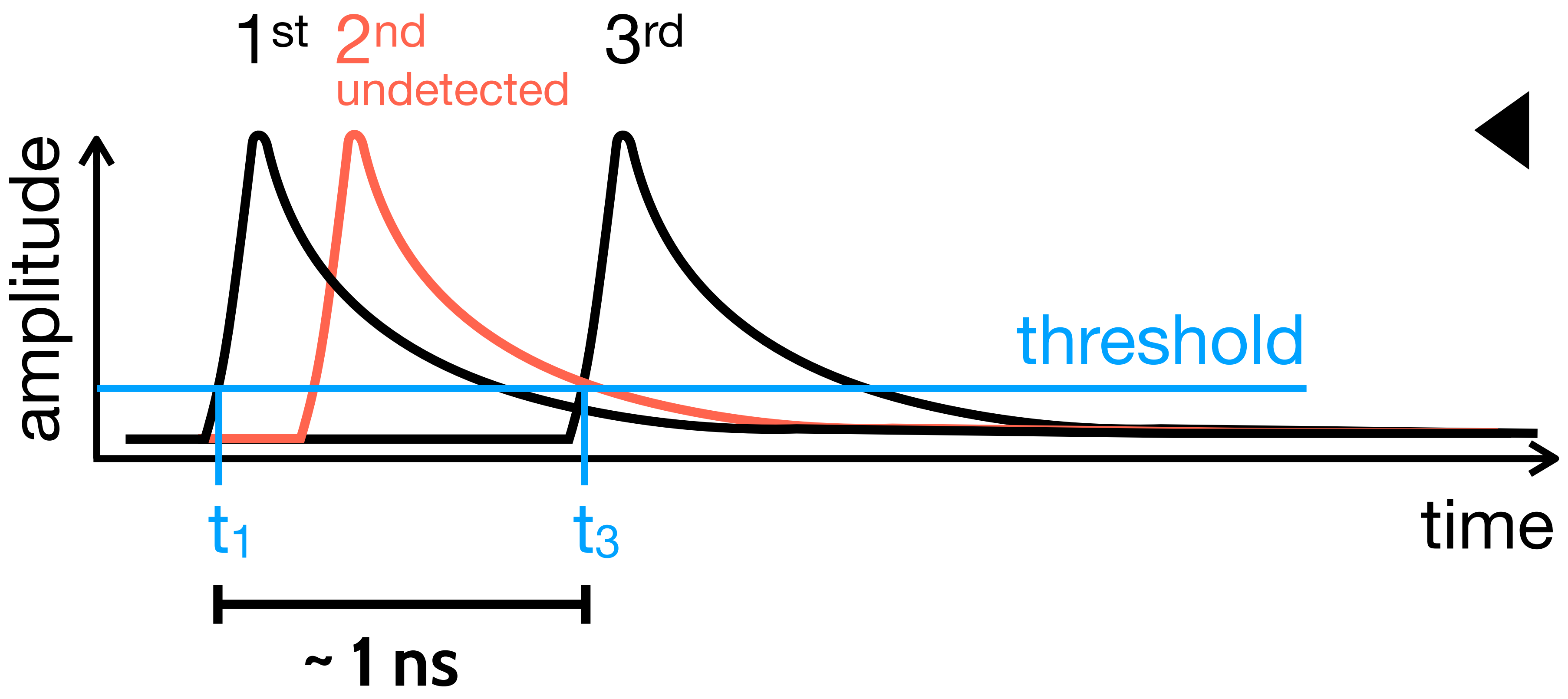


The narrow time window defined around the expected arrival from the IP
subtracting a photon's time of flight (TOF_{photon}) at the hit position

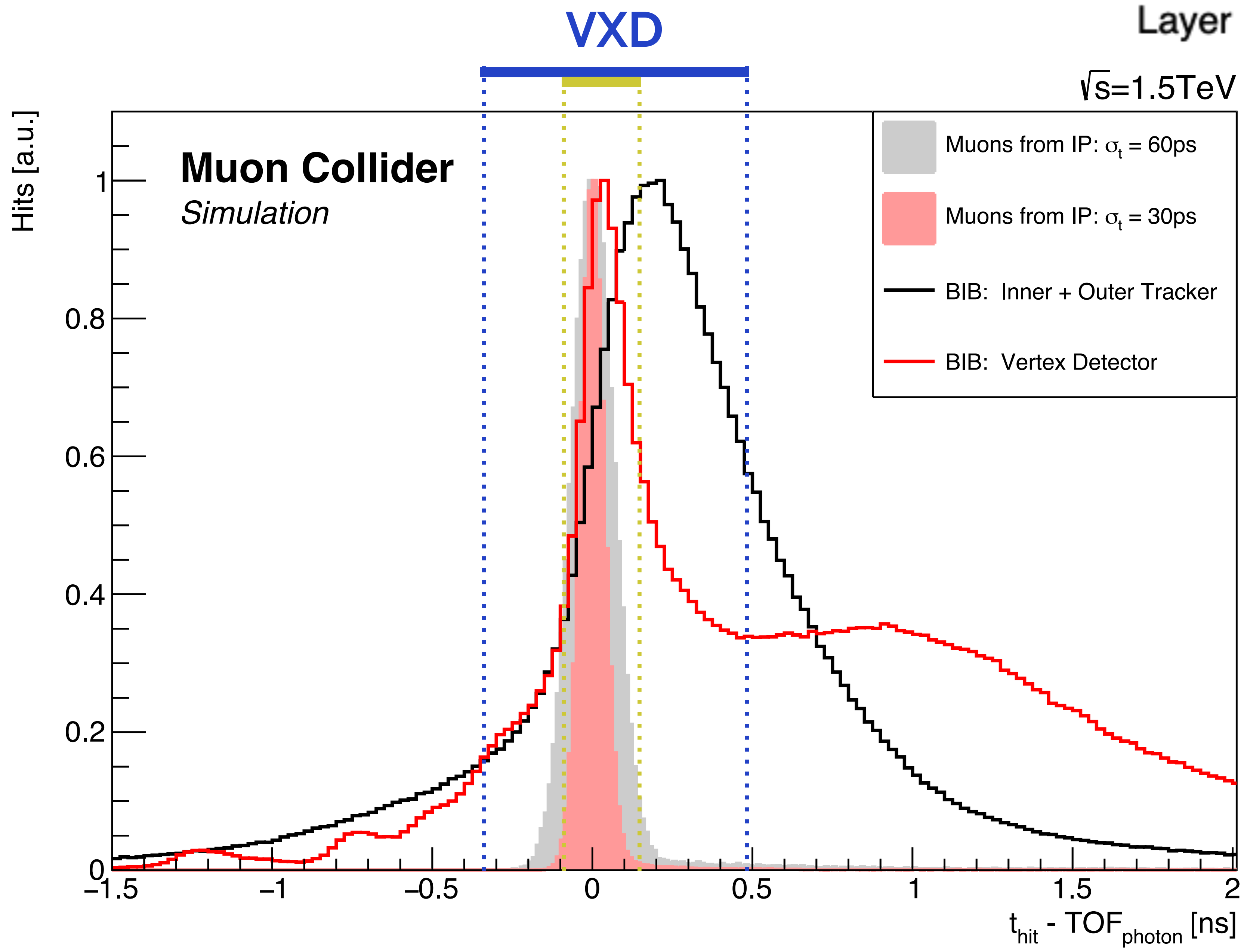
↳ absolute time windows vary with the module's position in θ angle

Non-neligible fraction of BIB hits arriving earlier than TOF_{photon}

↳ rejected during hit clustering → not used in track reconstruction
but contribute to the sensor occupancy

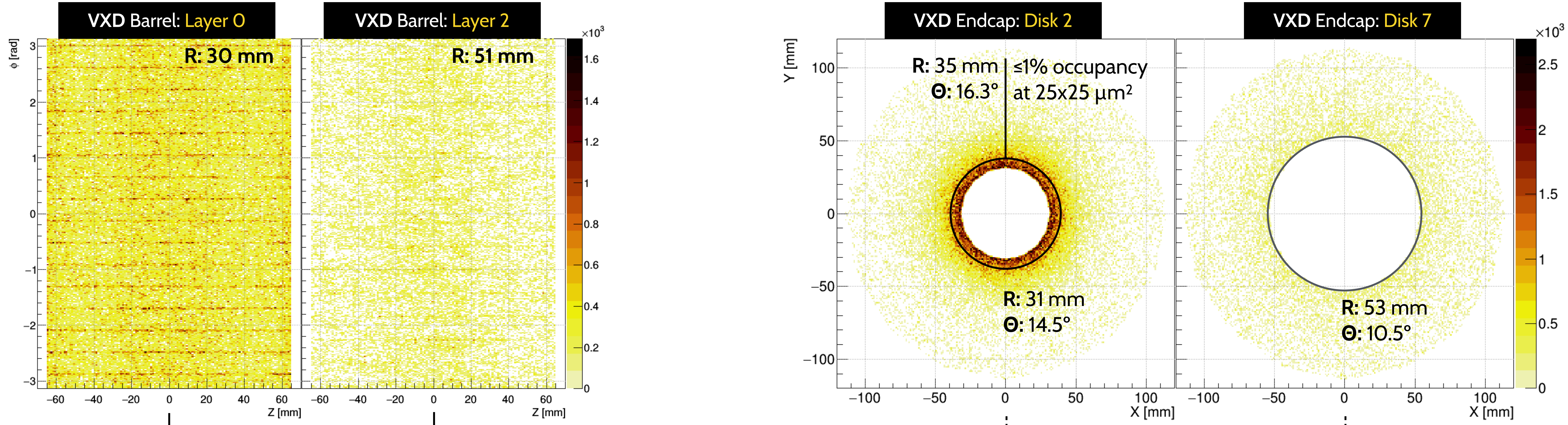


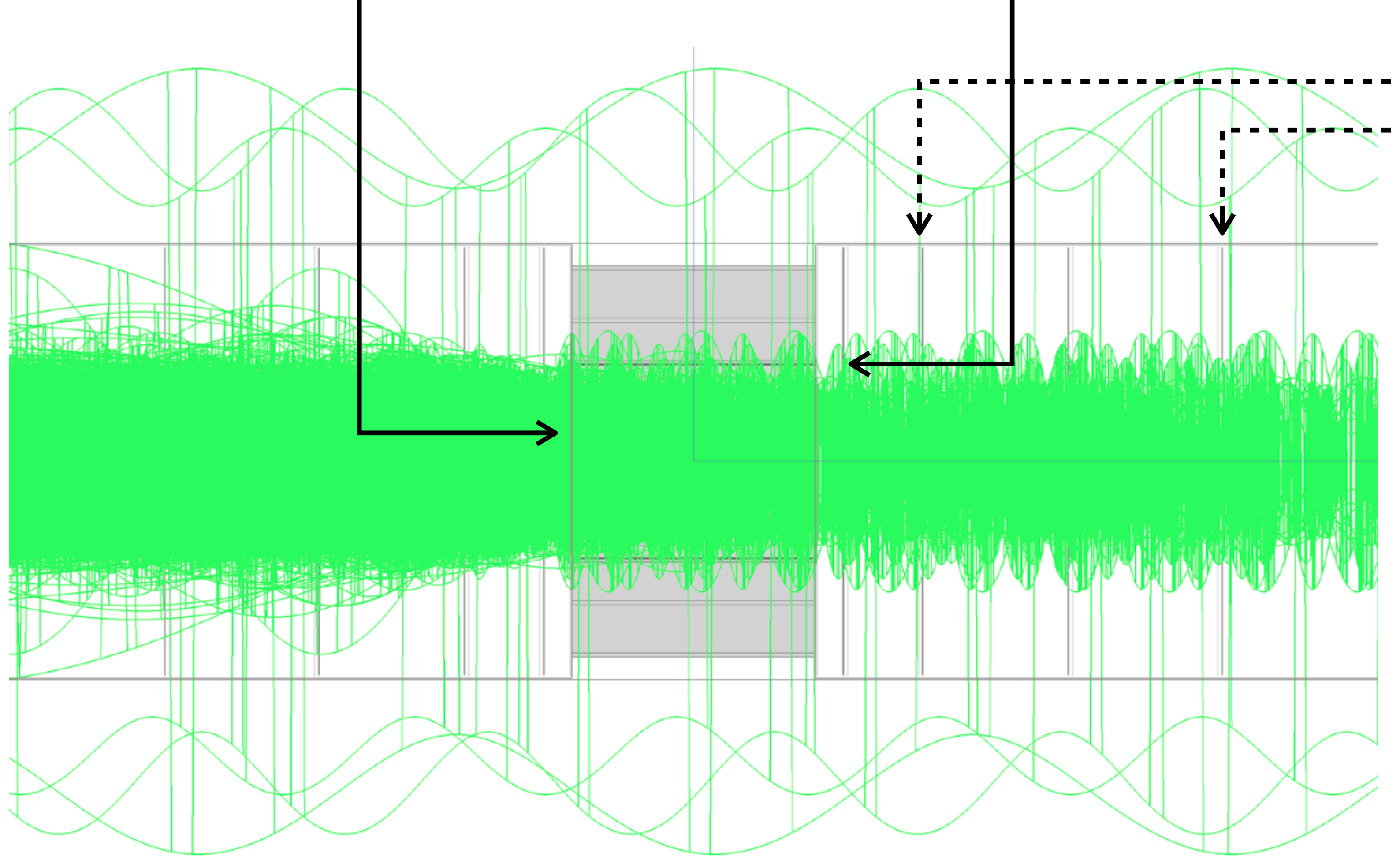
◀ A hit from an early BIB particle would make the pixel blind to the potential signal particle



Pixel granularity: occupancy

Particle density is not uniform → highest close to the tungsten nozzles (within the $-3\sigma_t < t < 5\sigma_t$ window)





Pixel pitch must be optimised separately for each region

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

Choice of detector technologies must be very careful

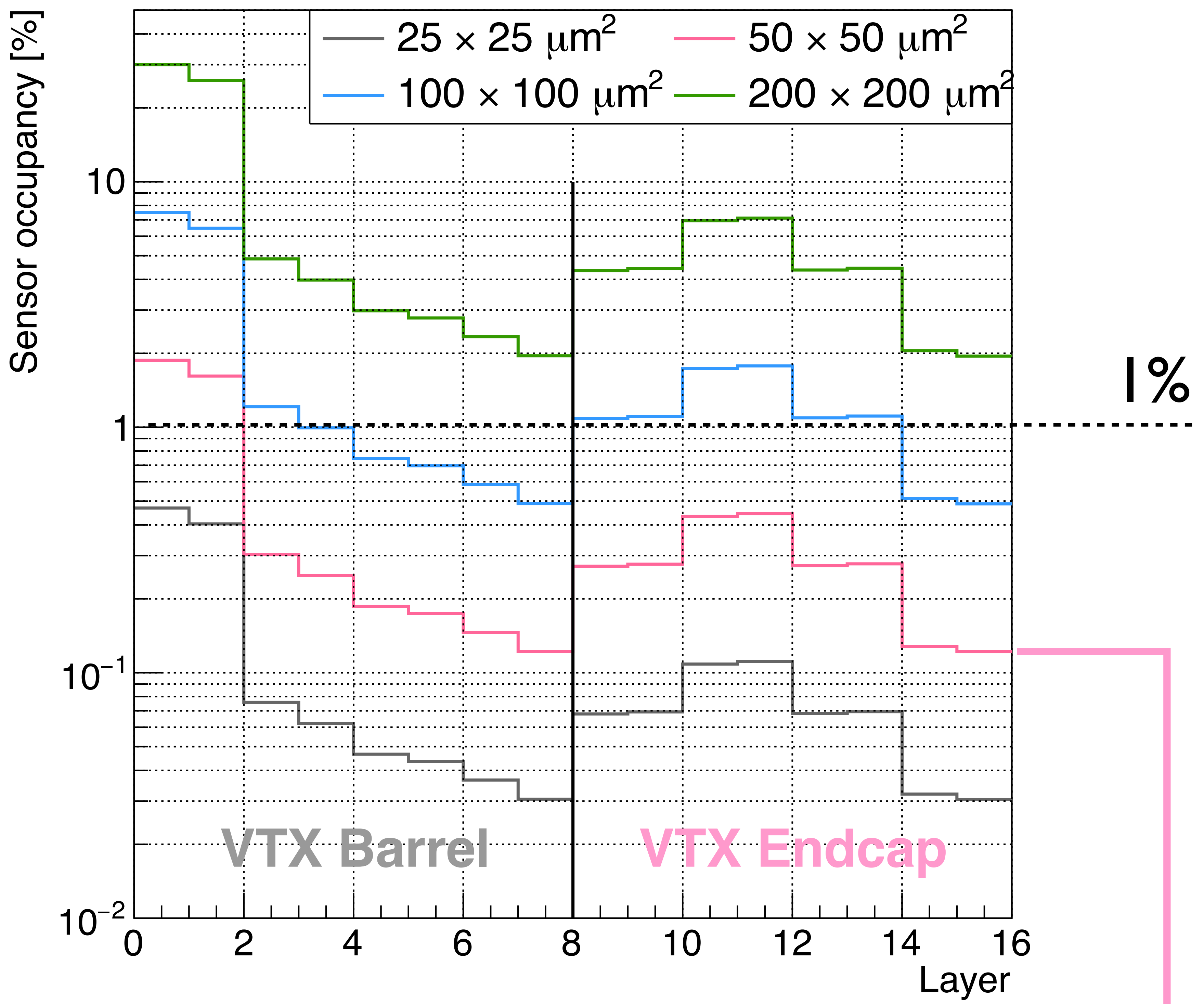
Current state-of-the-art Silicon pixel sensors can deliver the nevessary timing resolution → potentially even better in ~10 years from now

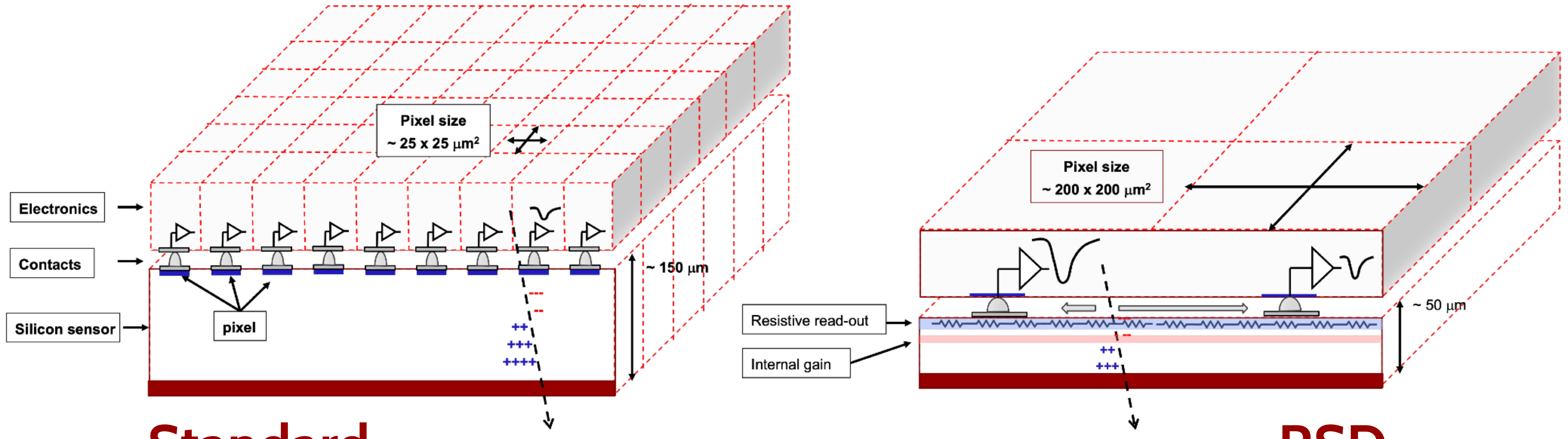
One of the candidate technologies considered for the major part of the Tracking Detector → Resistive Silicon Detectors (RSD)

↳ **$\sigma_t \geq 20ps$ $\sigma_{UV} \geq 4\mu m$ pitch ≥ 50µm** → low number of channels

- high spatial resolution 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





Standard **RSD**

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

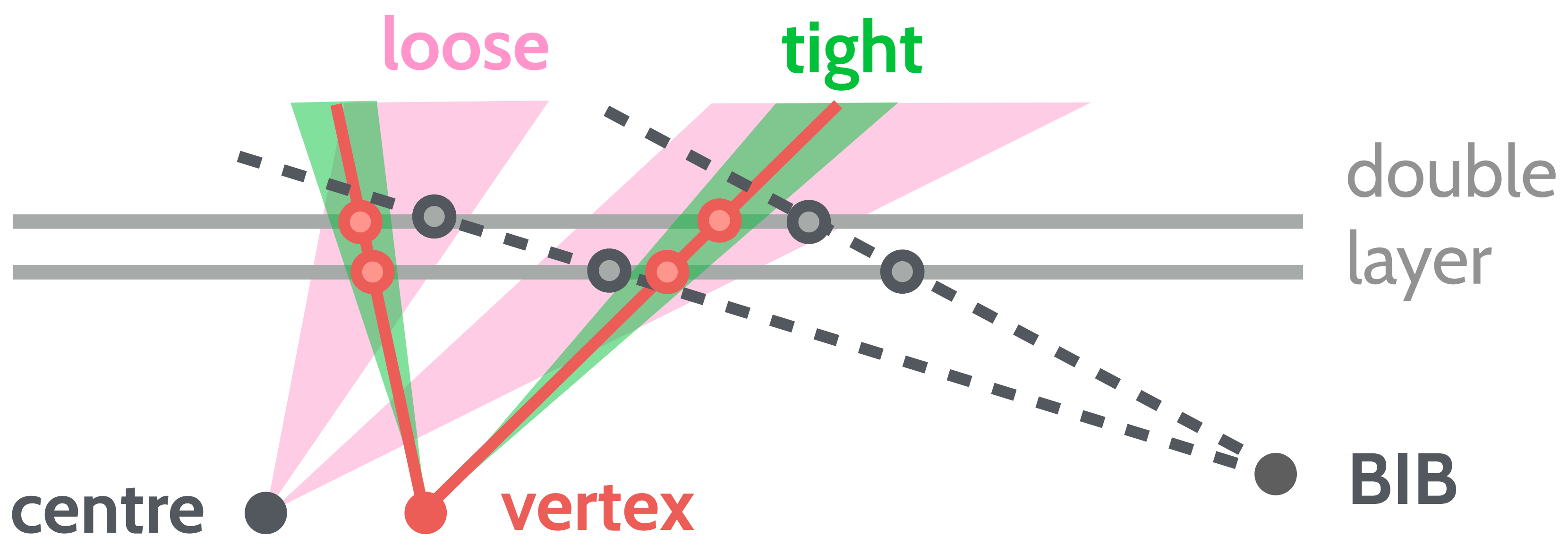
↳ more traditional design required for VTX e.g. Trench Isolated LGAD

Particle density in the innermost barrel layer too high for track seeding → extreme combinatorics

↳ can be used only for matching to already reconstructed tracks → improving impact-parameter resolution

Angular filtering: combinatorics

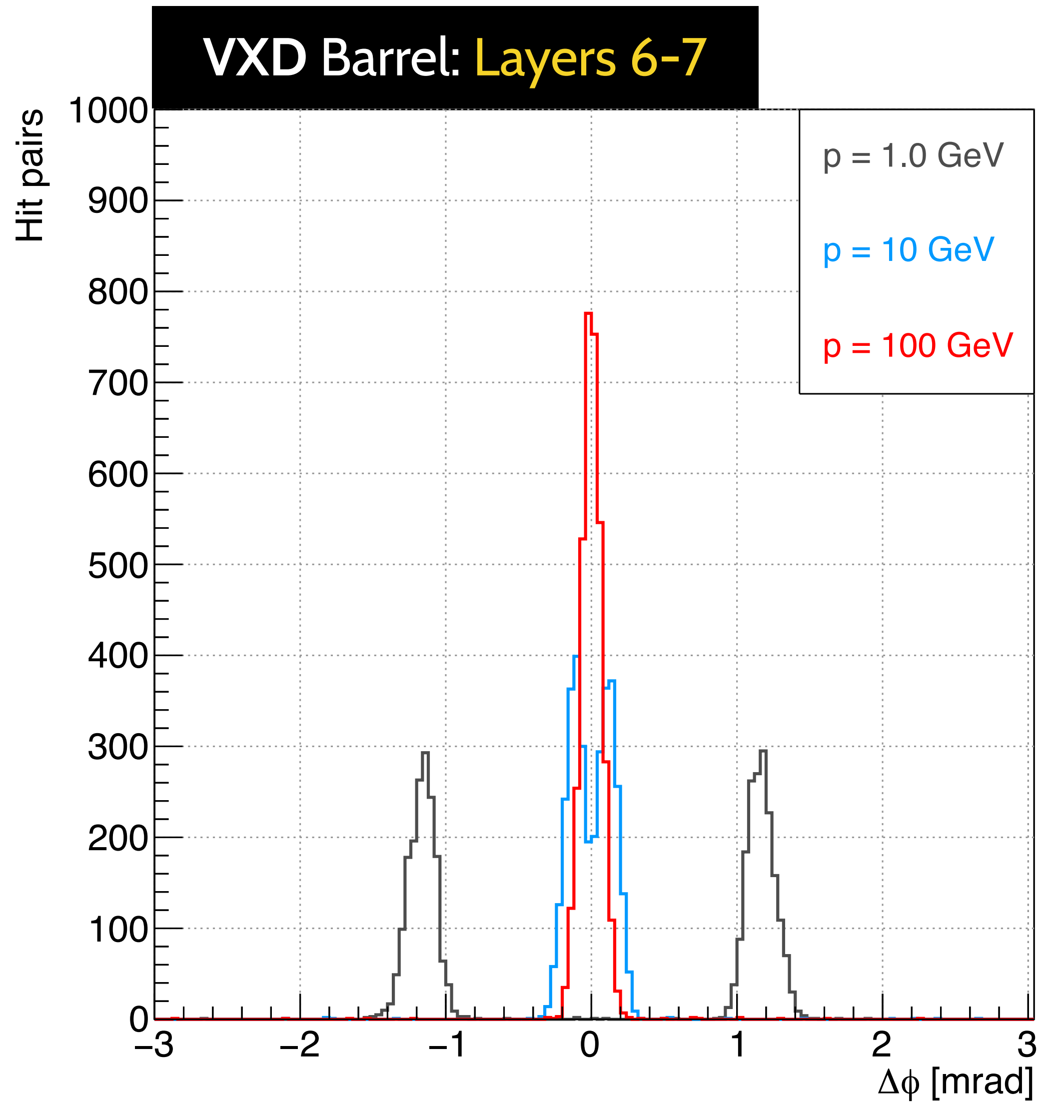
After reading out so many hits → how do we reconstruct actual tracks?
↳ BIB tracks are not reconstructable, but combinatorics is huge

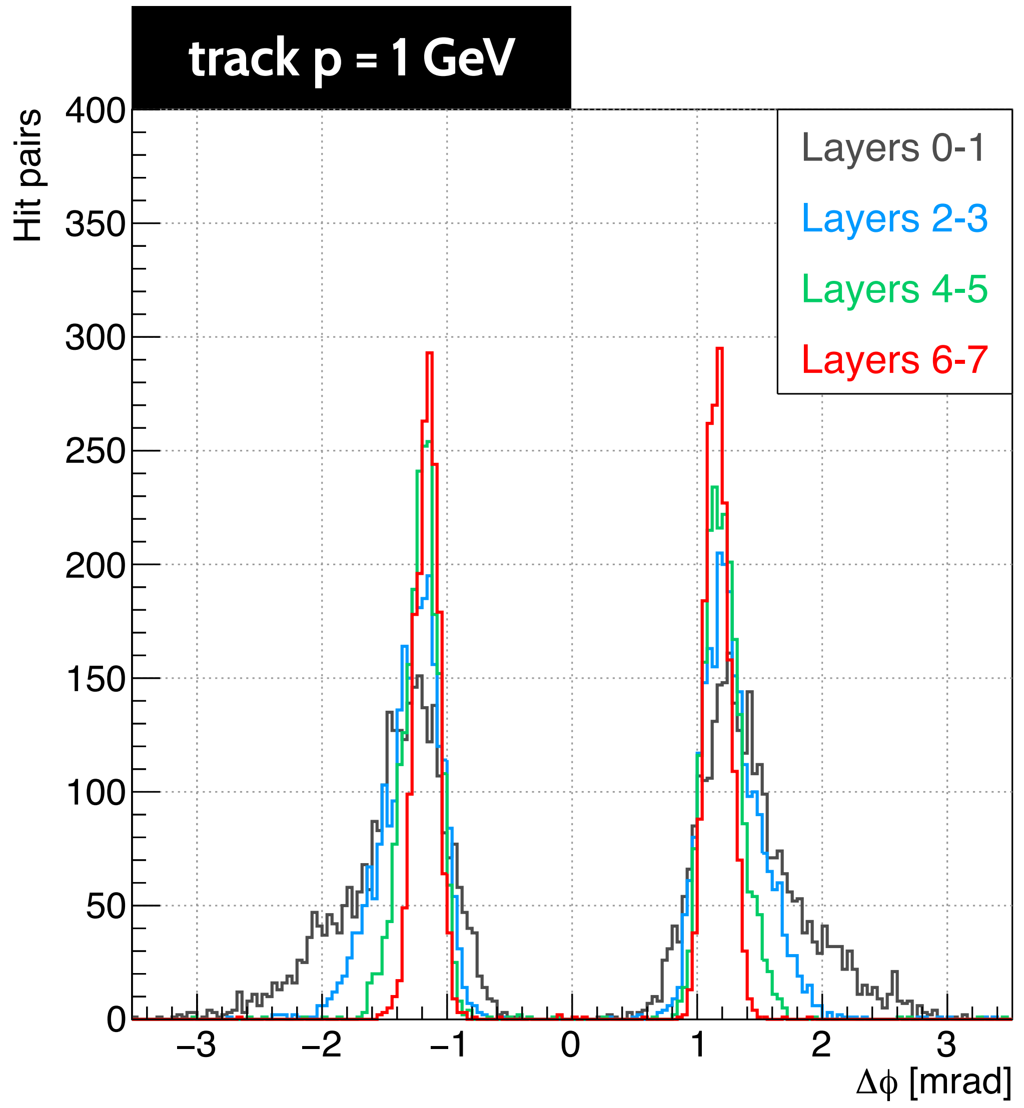


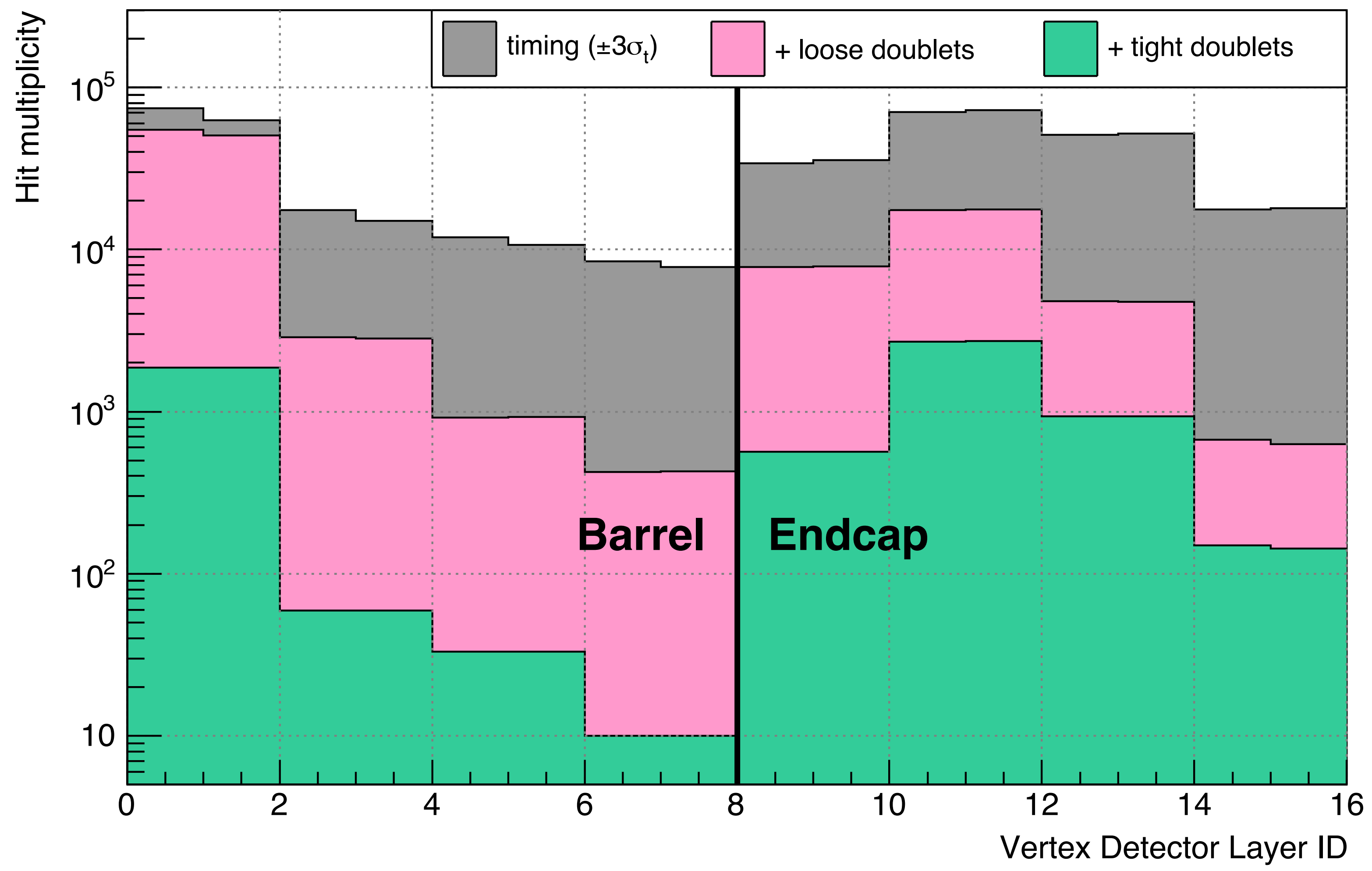
Combinatorics can be reduced dramatically by exploiting hit directionality
selecting stubs from double layers pointing towards the interaction point

Hit pairing done in two angular dimensions: Δϕ + Δθ

- **Δθ limited by the length of the interaction-region**
  σ_Z = 10 mm at $\sqrt{s}$ = 1.5 TeV → **σ_Z = 1.5 mm** at $\sqrt{s}$ = 10 TeV
  ↳ even larger when including strongly displaced vertices
- **Δϕ limited by the lowest track p_T + distance from the IP** ▶







~1 week/event
~2 days/event
~2 min/event

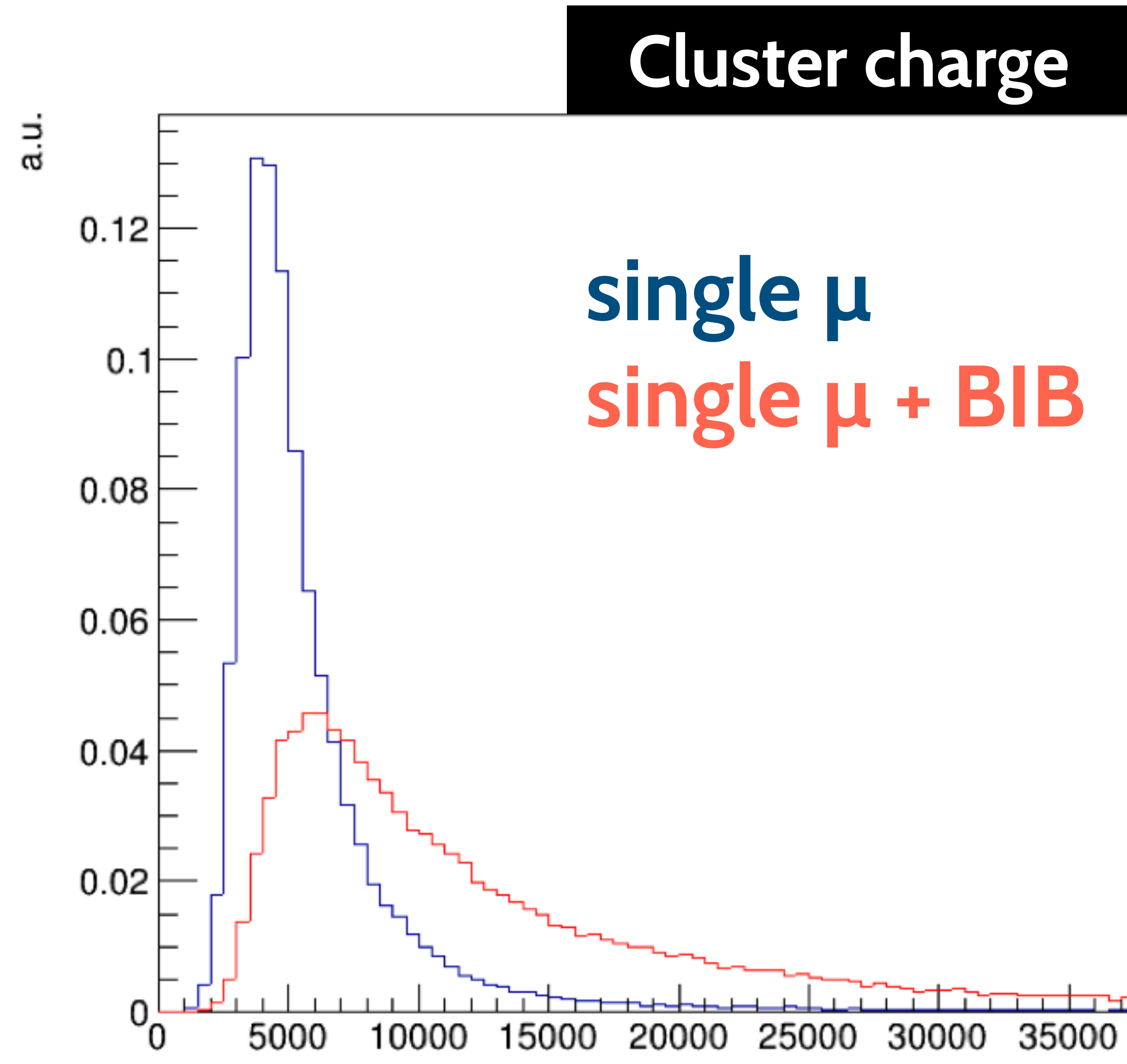
◀ **Number of input hits for track reconstruction significantly reduced**
after loose angular filtering compatible with a σ_Z = 10 mm beamspot

Further reduction of hit multiplicity by an order of magnitude possible
when the vertex position is precisely known *(before full track reconstruction)*

A number of developments are ongoing to explore additional means for occupancy reduction

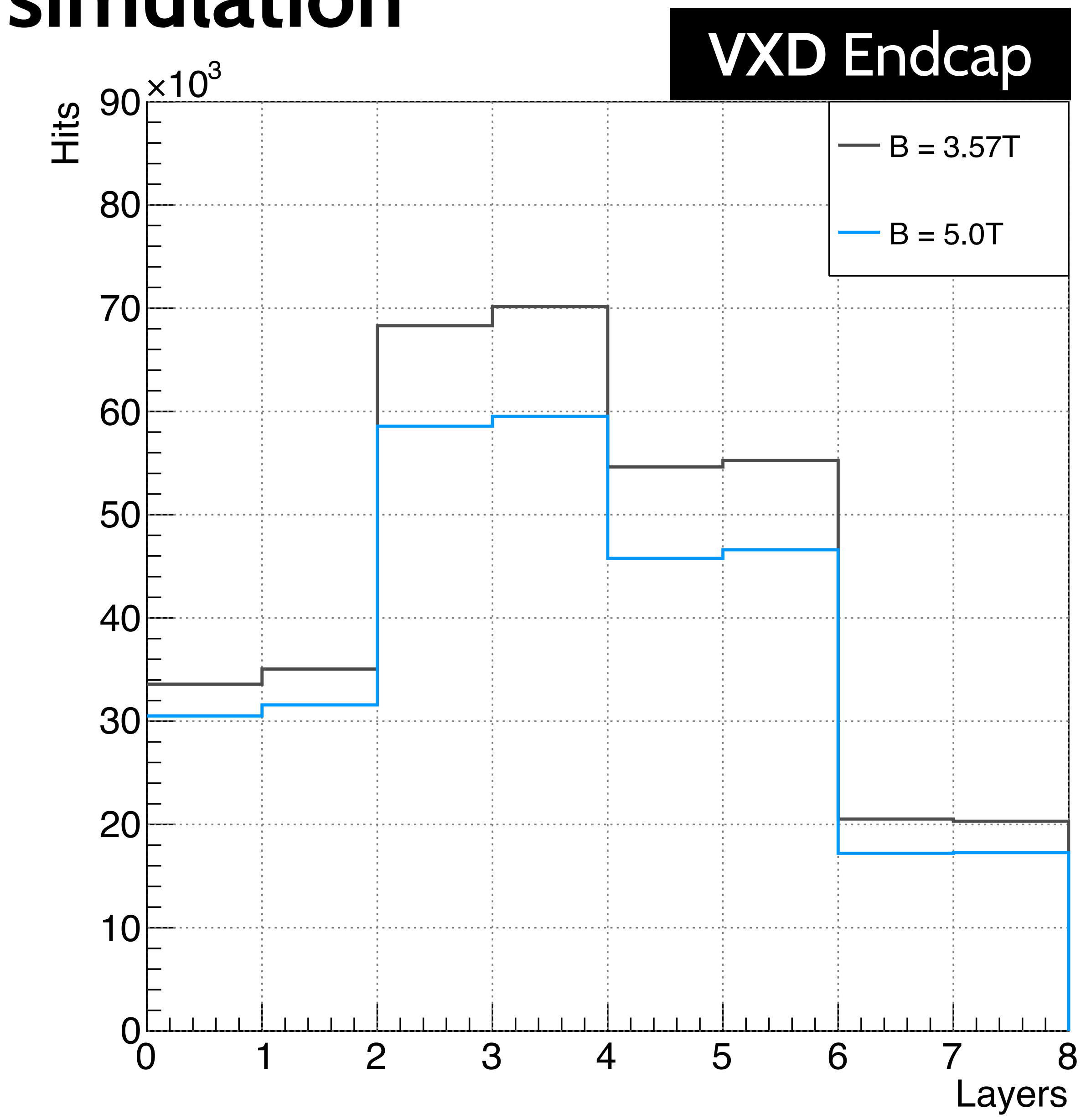
Realistic digitisation of pixel sensors to exploit cluster shapes for BIB rejection ▶

↳ BIB particles crossing sensors at shallow angles → wider clusters → more charge



Increasing strength of the magnetic field in the GEANT4 simulation

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



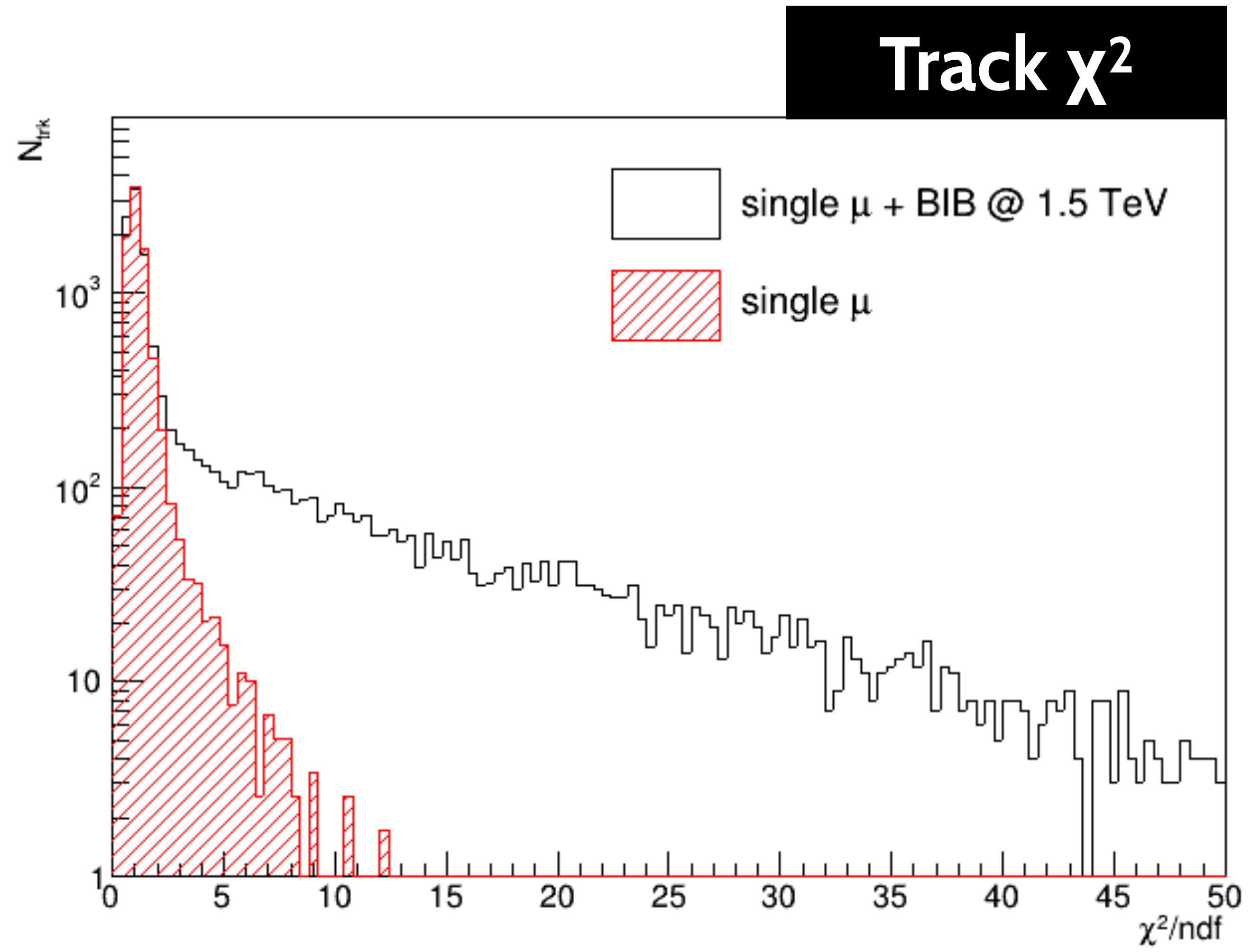
Integrating critical surfaces of the Vertex Detector into the MDI-optimisation workflow in FLUKA

↳ shape + composition can be fine-tuned to reduce occupancy in specific regions and time windows instead of integrated number of arriving particles

Adopting the ACTS tracking software for faster computational performance

↳ targeting full 4D track reconstruction in the future

↳ great potential for early rejection of fake track candidates based on bad χ^2 ▶



Summary

Muon Collider is a unique machine for both discoveries and precision measurements
gaining a lot of attention from the theoretical and experimental communities

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

Beam Induced Background introduces unprecedent occupancy in the Vertex Detector
making generic readout and track-reconstruction schemes highly inefficient

State-of-the-art timing resolution combined with fine spatial granularity are necessary
well inline with ongoing R&D towards HL-LHC

Novel approaches to track reconstruction are very much needed
e.g. 4D track-reconstruction, track-less vertex identification, computing optimisations

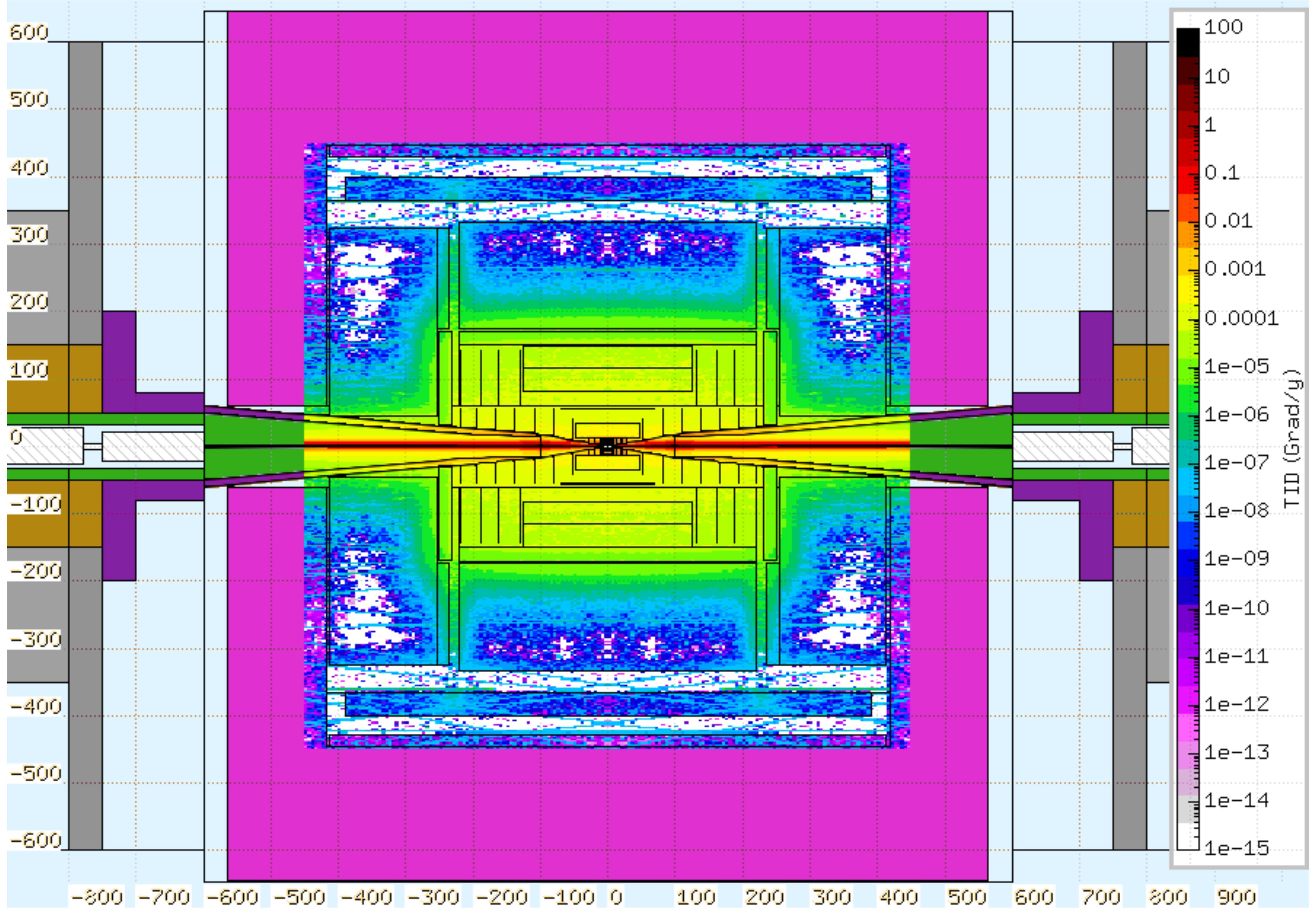
Plenty of work to do before seeing "clean" $\mu^+\mu^-$ collision events
but looks perfectly feasible within the next decade

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

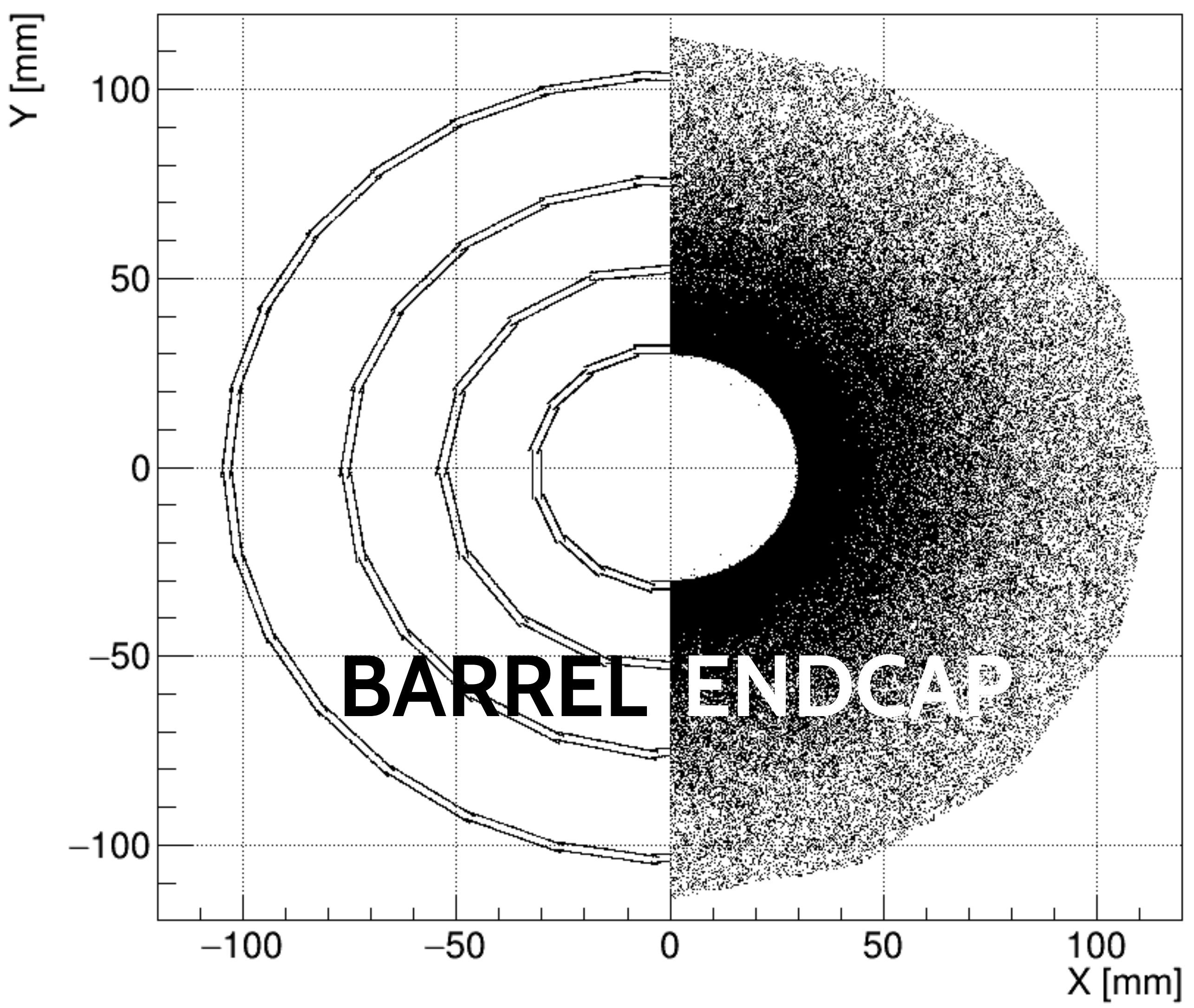
Special JINST issue on Muon Accelerators for Particle Physics

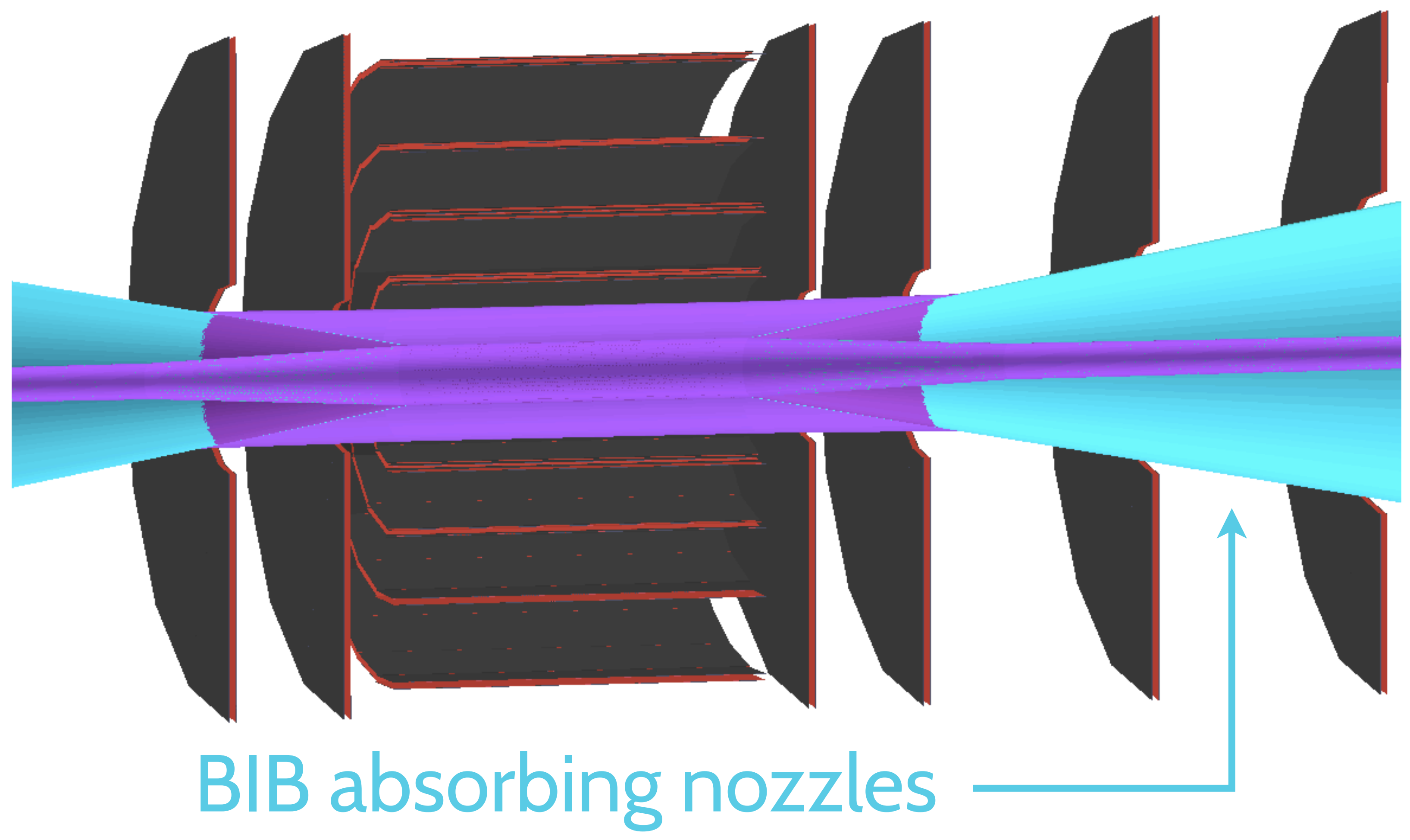
Muon Collider accelerator parameters

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

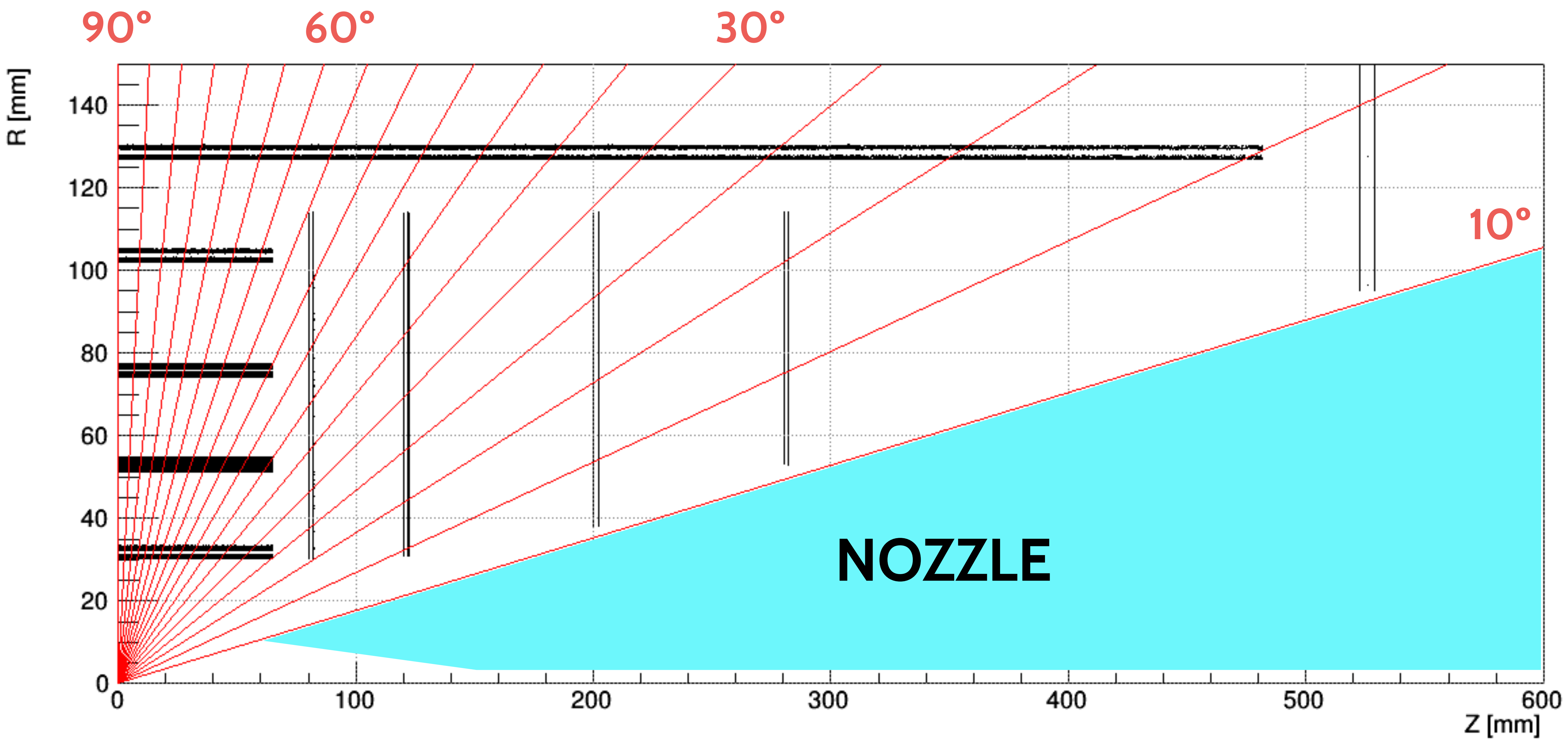
Integrated luminosity targets: 10 ab^{-1} at $\sqrt{s}$ = 10 TeV + potentially 1 ab^{-1} at $\sqrt{s}$ = 3 TeV
with instantaneous luminosity of ~10^{34} - 10^{35} cm^{-2} s^{-1}

Vertex Detector geometry in 3D





Angular layout of the VXD layers



Backup: Magnetic Field effect

Effect of the stronger magnetic field on occupancy