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Muon Collider detector R&D: Tracking

RD_MUCOL meeting with referees

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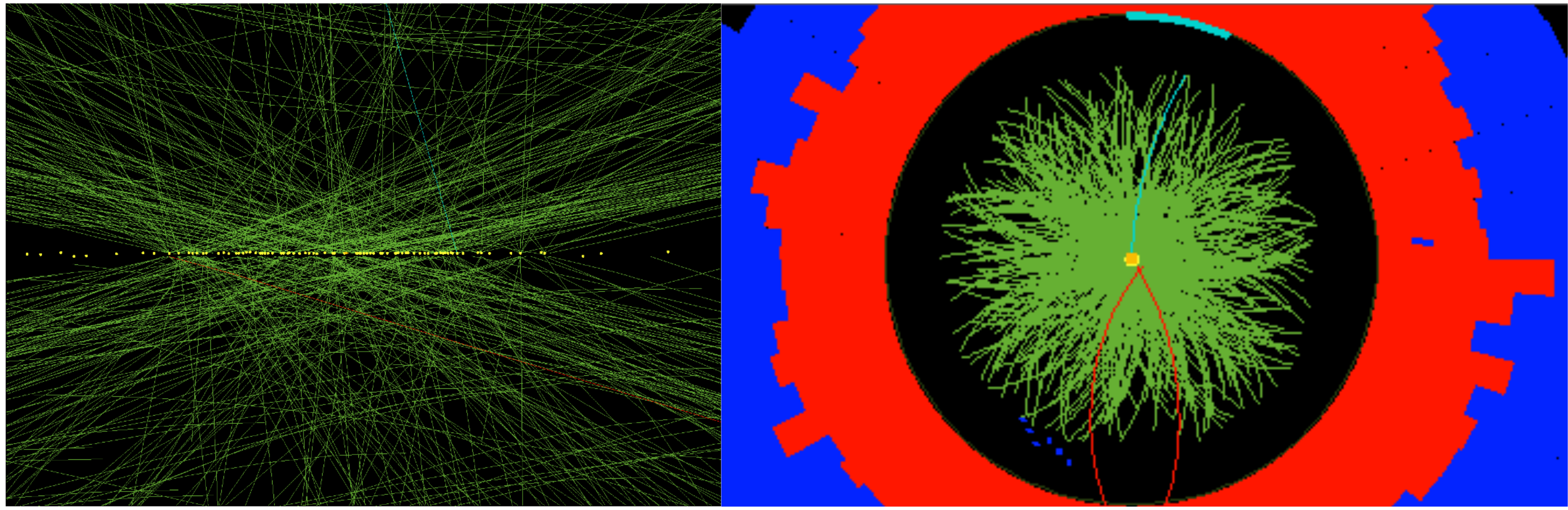
At the **LHC** we are used to backgrounds primarily from pile-up *pp* collisions

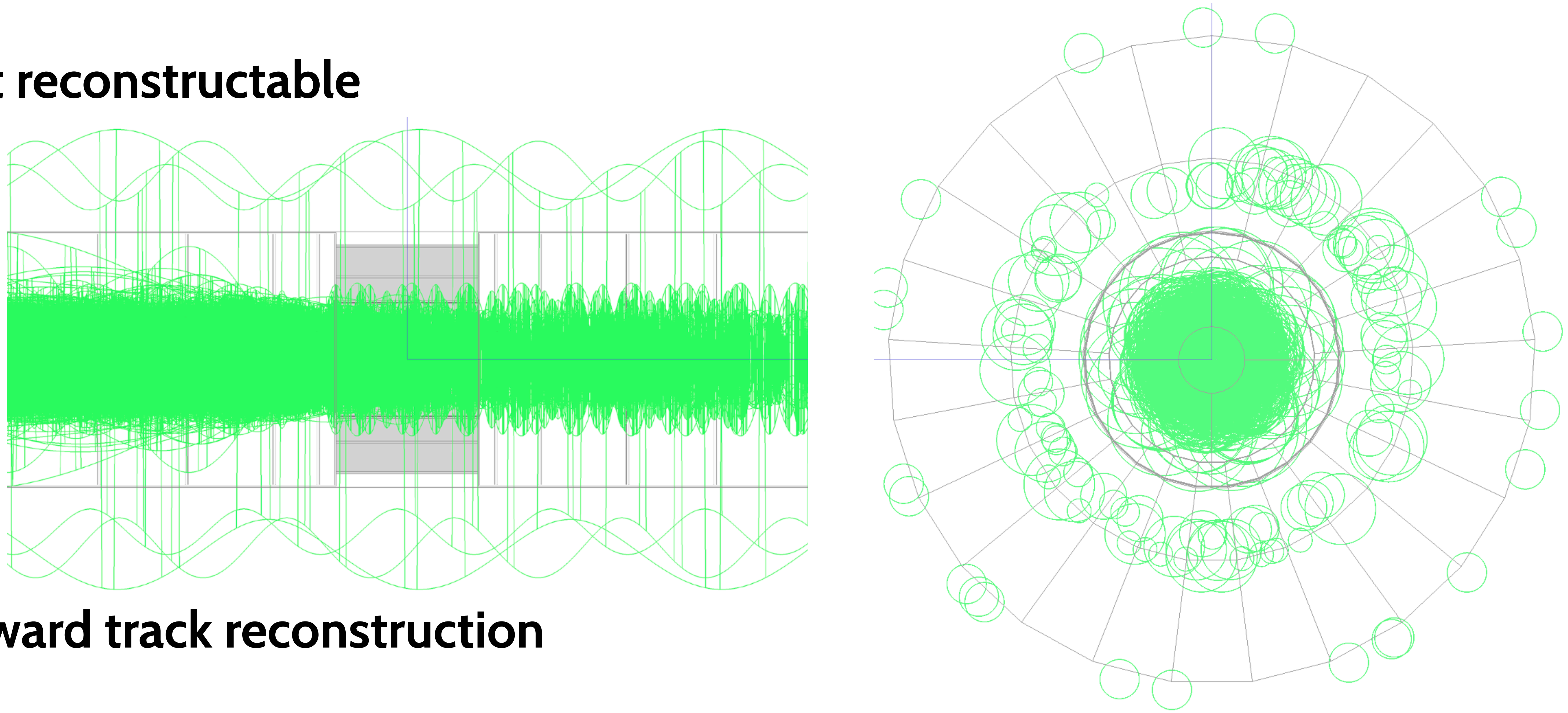
↳ distinctive tracks pointing at displaced vertices

Event at the CMS experiment with 78 reconstructed vertices ▶



At the **Muon Collider** background tracks are not reconstructable

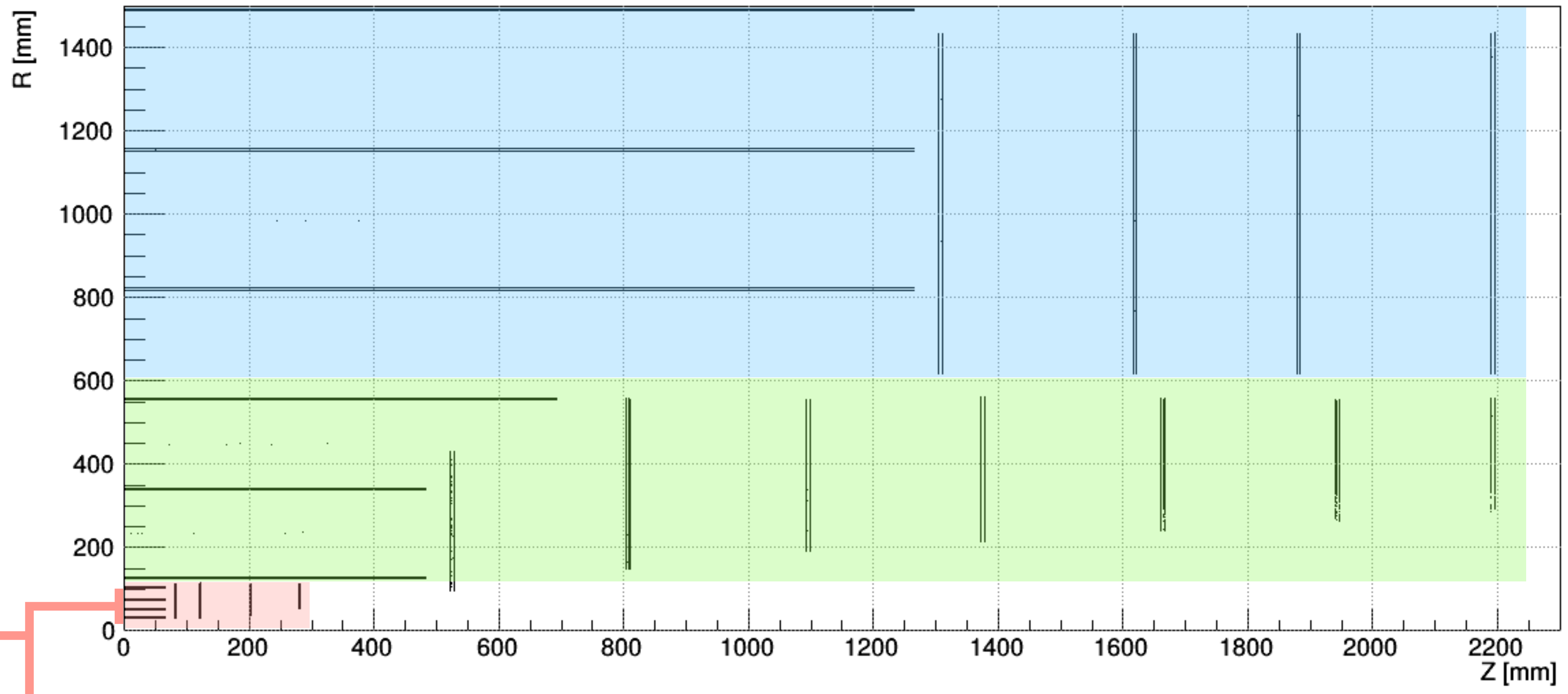
A cloud of looping tracks from soft electrons: $\langle p_T \rangle$ = 3.5 MeV ▶

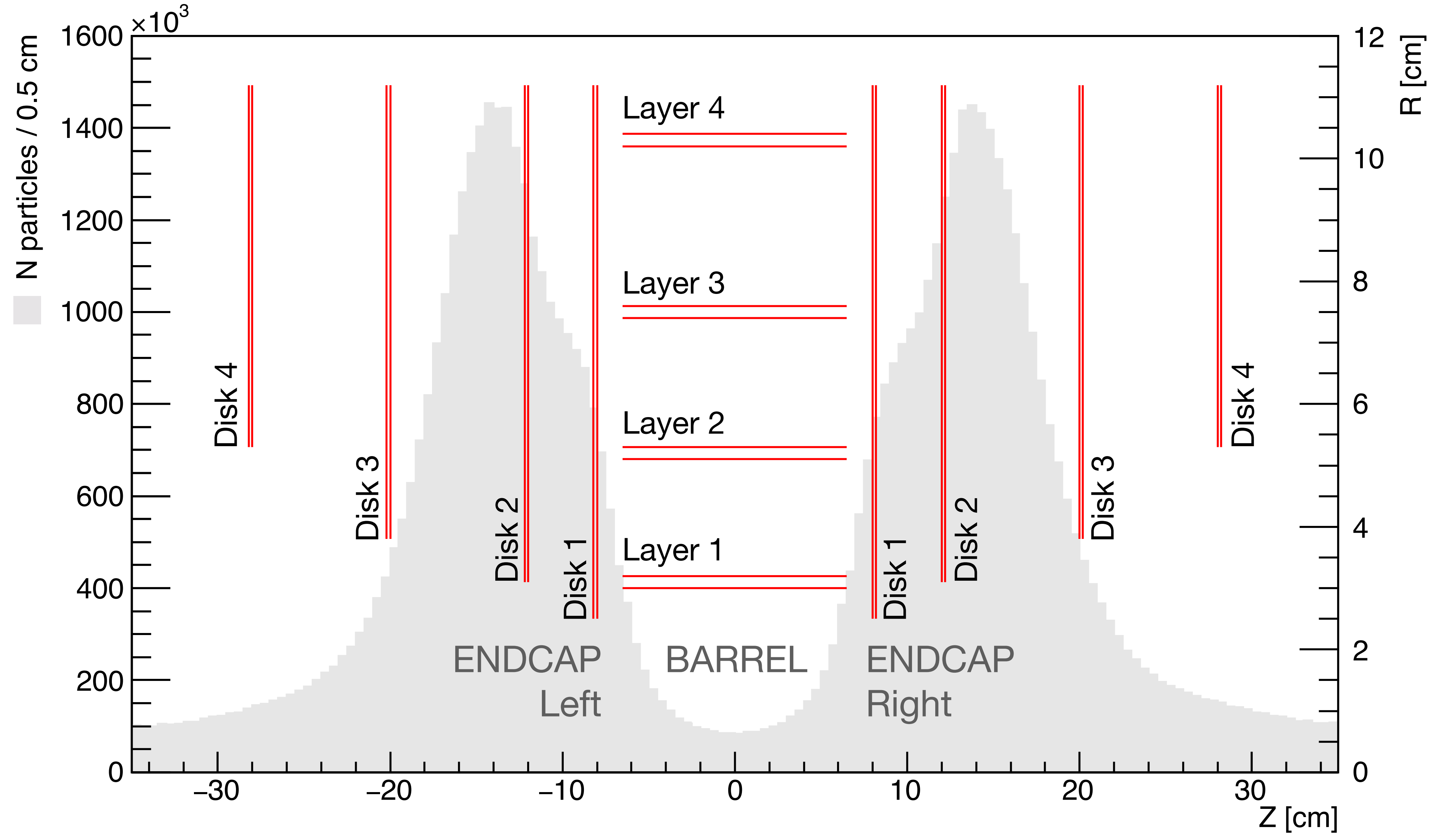


Tremendous combinatorics for the classical outward track reconstruction

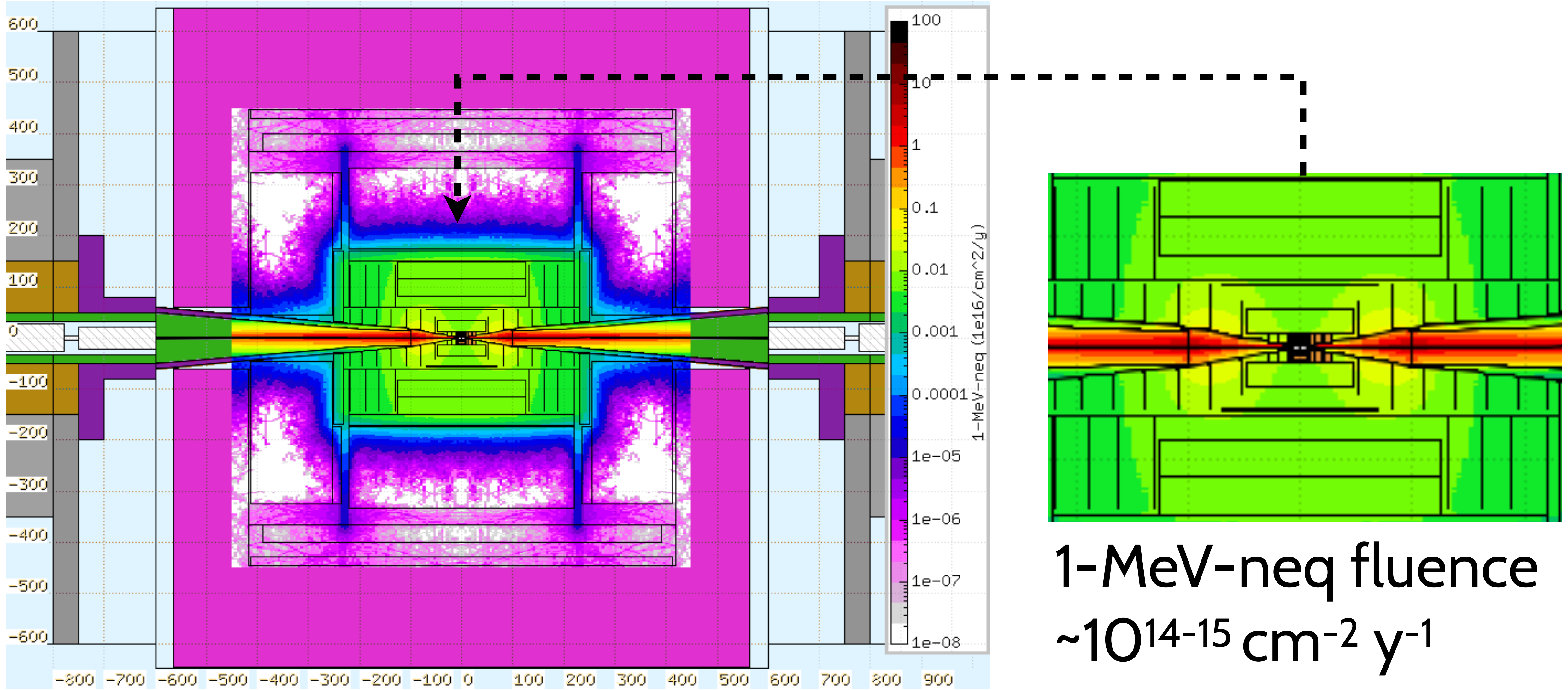
Silicon sensors with high spatial and timing resolution

- **Outer Tracker** 50µm × 1mm σ_t = 60ps
- **Inner Tracker** 50µm × 10mm σ_t = 60ps
- **Vertex Detector** 25µm × 25µm σ_t = 30ps
  - double layers with 2mm spacing
  - forward disks placed outside of the regions with highest BIB flux to minimize occupancy





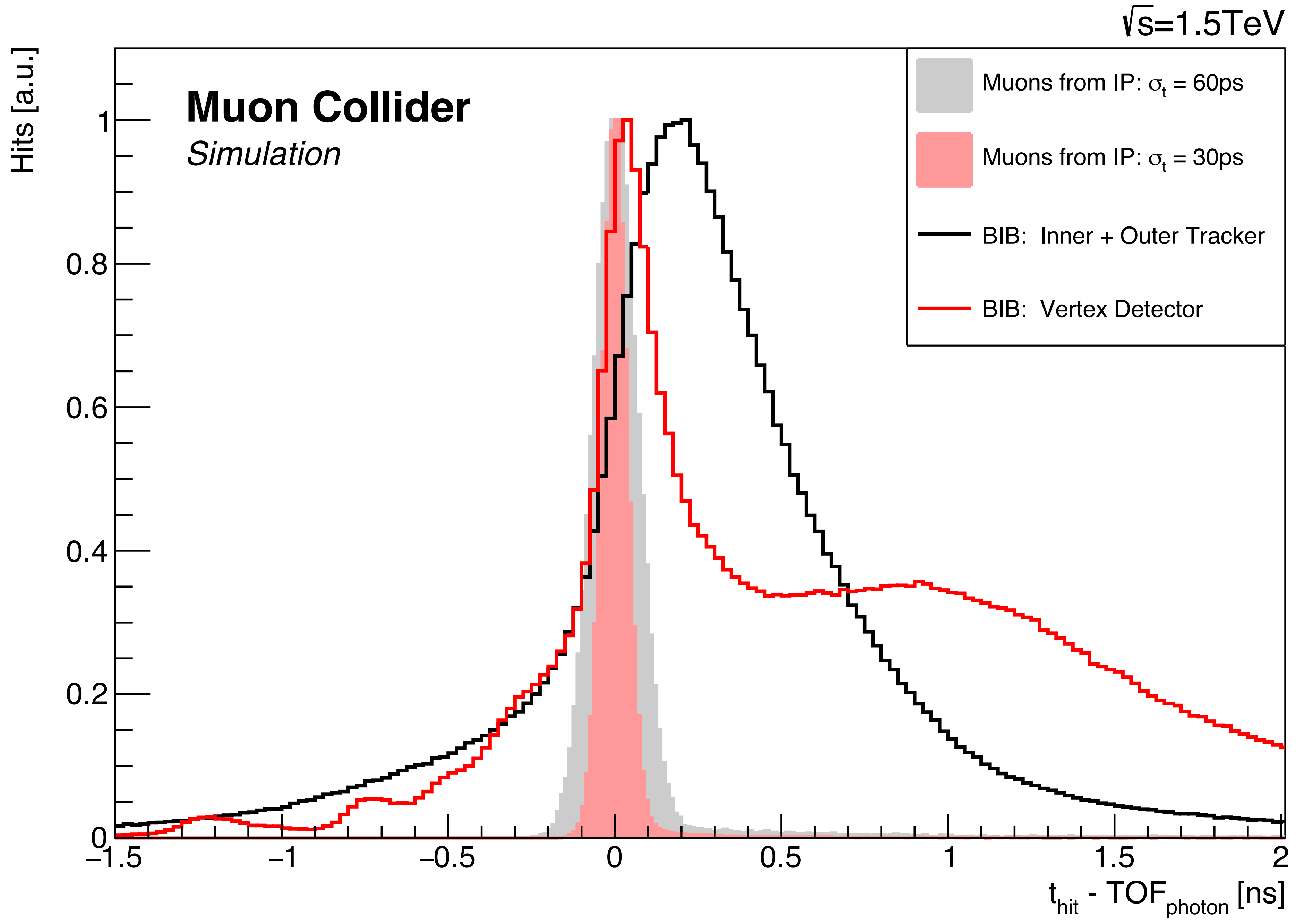
Radiation hardness comparable to HL-LHC requirements

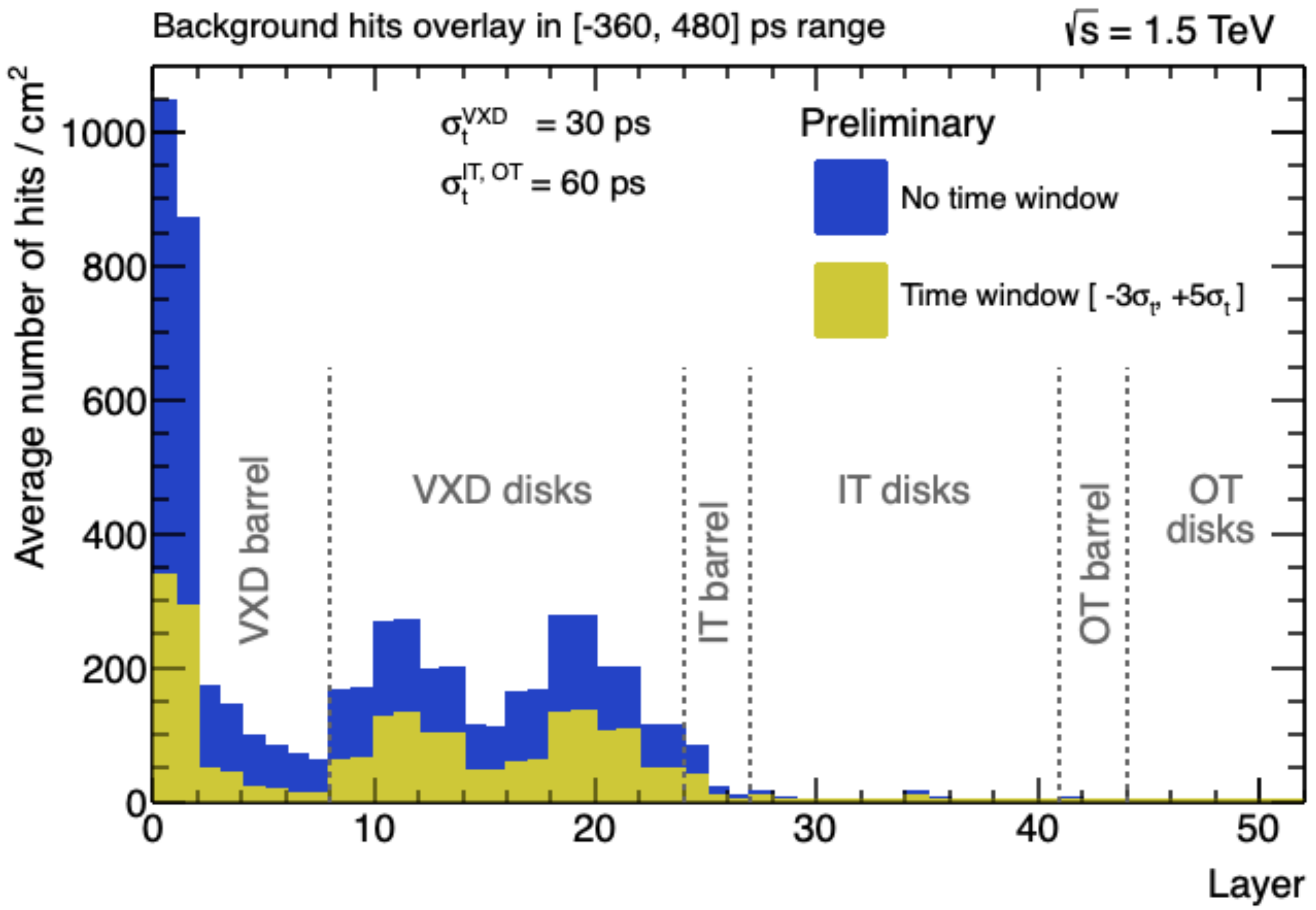


1-MeV-neq fluence
~$10^{14\text{-}15}$ cm^{-2} y^{-1}

Precise timing enables very narrow readout time windows tailored to the sensor position + expected time-of-flight

↳ the easiest way to reject BIB hits on detector → lower bandwidth + less combinatorics during track reconstruction





Most critical in the Vertex Detector (up to 1K hits/cm²)

↳ closest to the interaction point → highest hit density → biggest impact on combinatorics during track seeding

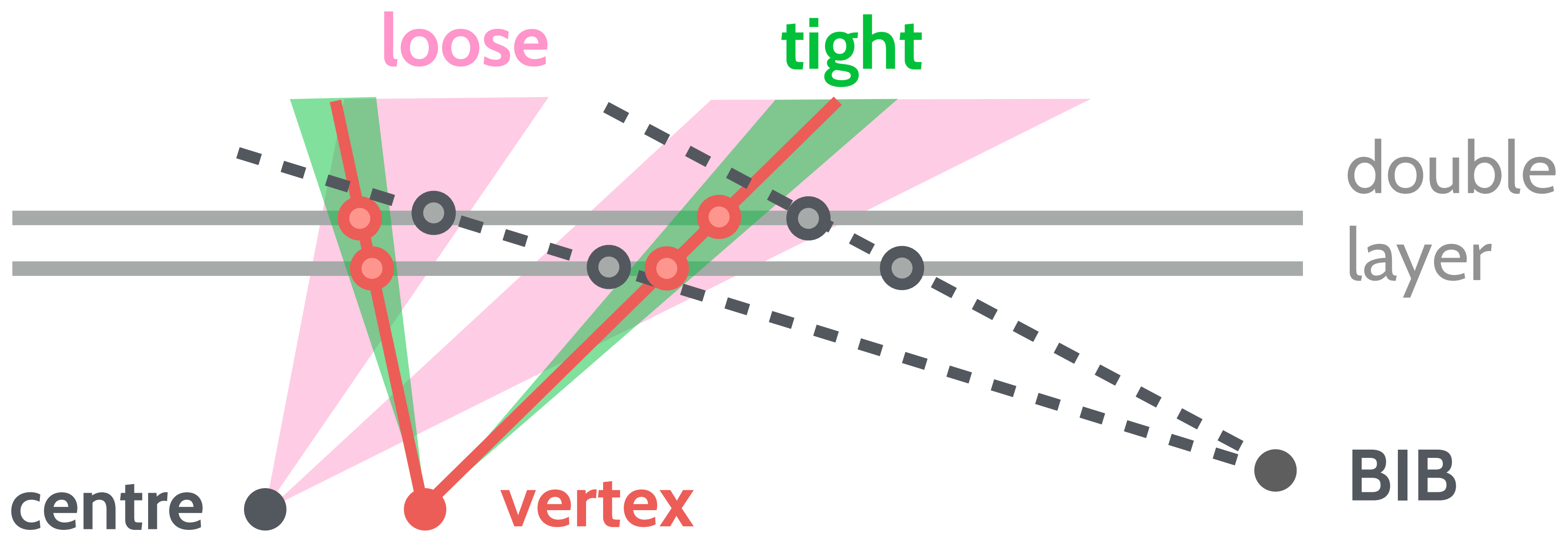
σ_t = 30 ps is comparable to the the $\mu^+\mu^-$ collision-time uncertainty

↳ even better resolution can still be beneficial for 4D tracking, but can't be used for on-detector hit filtering

On-detector identification of hits from shallow-angle tracks is extremely powerful for BIB suppression

↳ most BIB hits in the Tracker created by electrons crossing sensors at shallow angles

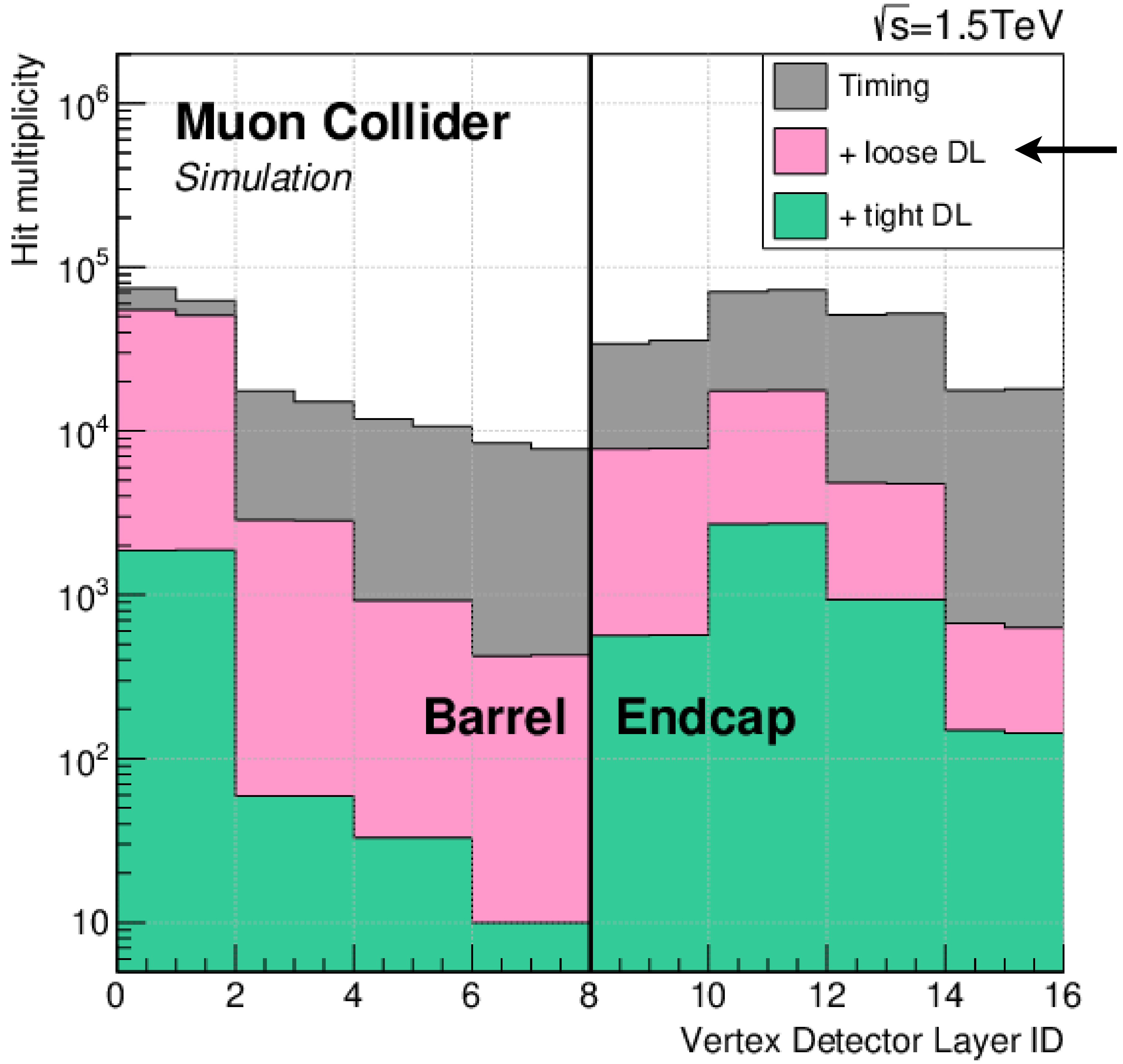
Double-layer arrangement in the Vertex Detector allows to select hits in pairs (stubs) **aligned with the interaction point**



Tighter angular filtering requires the vertex position to be known in advance ▶

↳ not easily applicable to displaced tracks but reduces combinatorial background tremendously *(by factor 20-1000)*

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



for σ_z = 10mm beamspot

will be smaller at $\sqrt{s}$ = 10 TeV
↳ **σ_z = 1.5 mm**

Angular sensitivity from single hits might be possible with cluster-shape or pulse-shape analysis

↳ can be applied on detector → reduced bandwidth

Candidate technologies

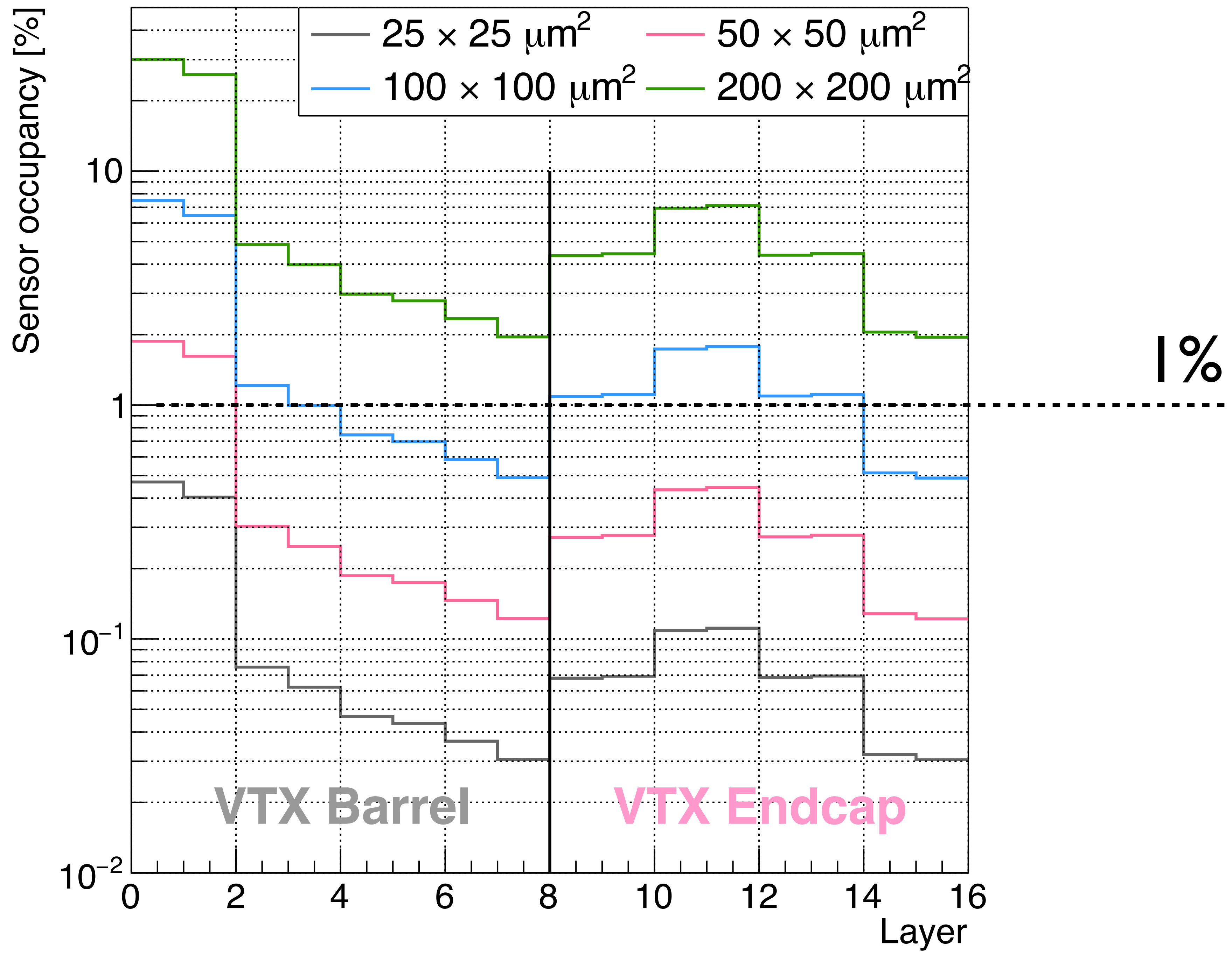
Tracking detector must combine three crucial parameters:

- **high time resolution** → to apply time-based hit filtering by on-detector electronics + 4D tracking to reduce combinatorics
- **high spatial resolution** → to enable angle-based hit filtering before track reconstruction
- **low material budget** → to offset extra material from advanced on-detector electronics + cooling

Currently state-of-the-art Silicon sensors can provide time resolutions of up to ~20ps:

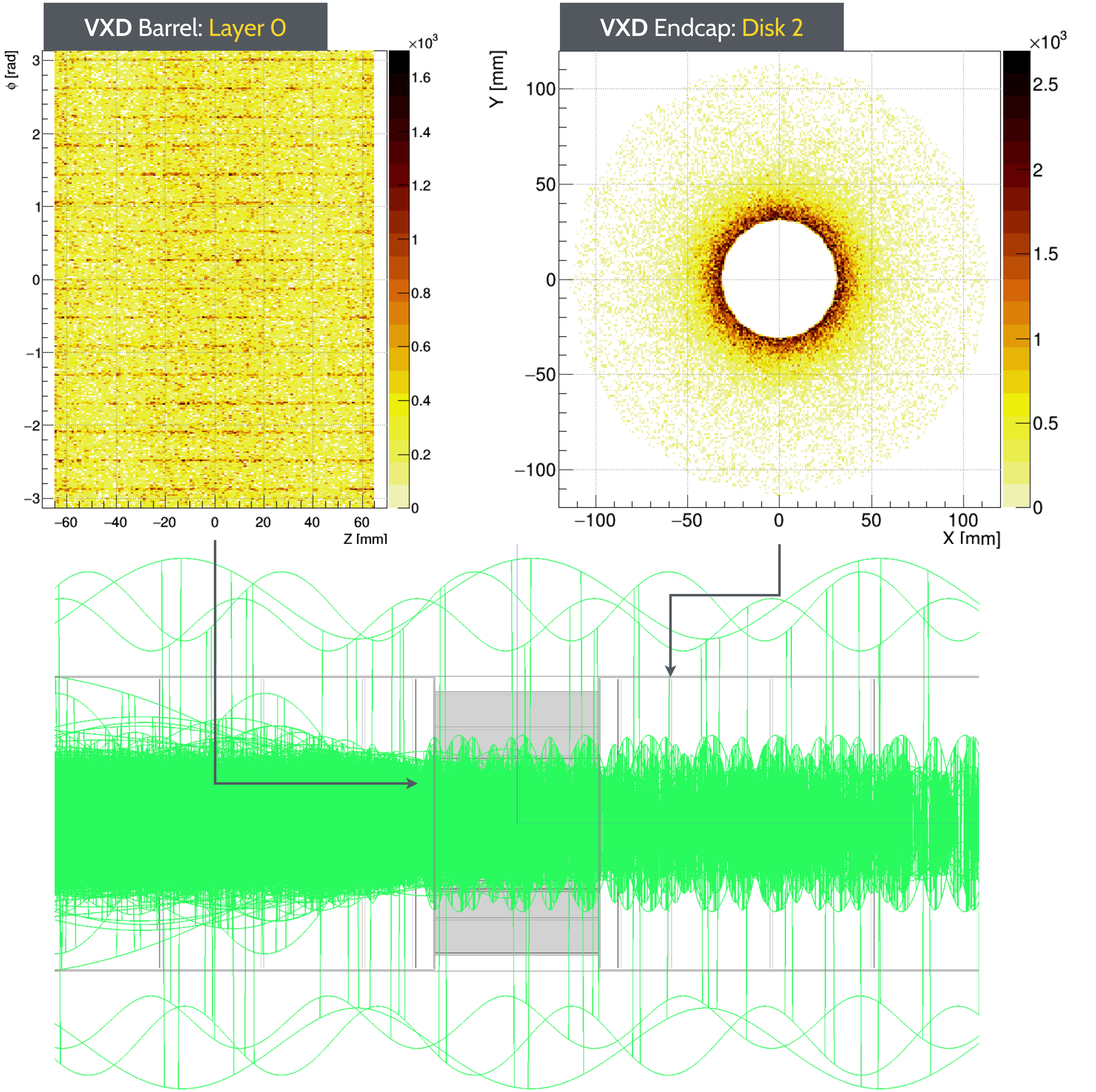
- **3D trenched sensors: σ_t ~ 20ps σ_x ~ 10µm d ~ 300µm**
  - high material budget, early stage technology
- **UFSD: σ_t ~ 30ps σ_x ~ 30µm d ~ 50µm**
  - low fill factor, limited spatial resolution (pixel size ≥ 50×50 µm²)
- **RSD: σ_t ~ 20ps σ_x ~ 4µm d ~ 50µm**
  - low material budget, high time and spatial resolution, low channel count
  - 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



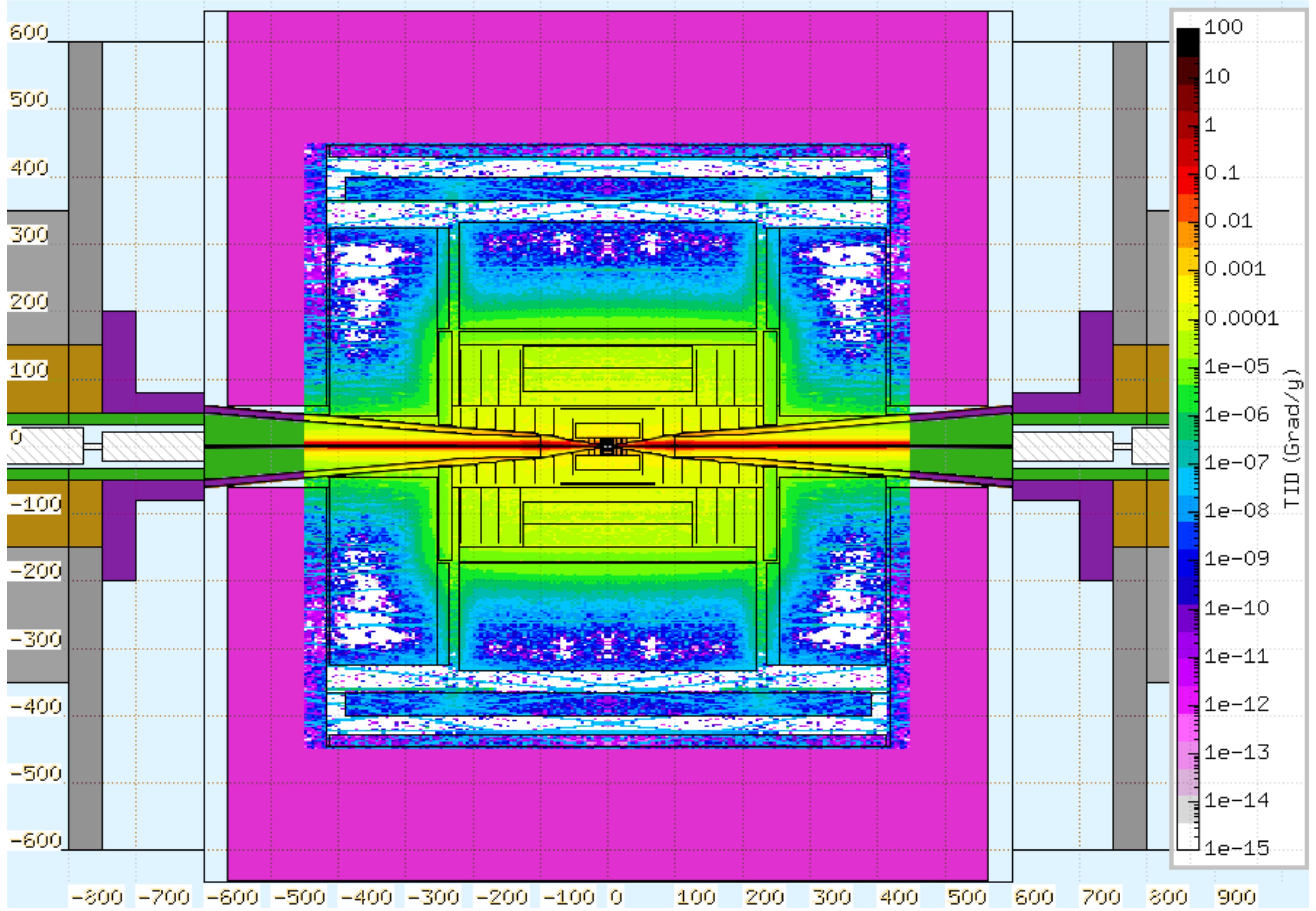
Vertex Detector occupancy is rather uniform within Barrel layers, but not in the Endcap disks

↳ occupancy increases at smaller radii



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 ▶



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}

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