Study on Tracker Occupancy for a Muon Collider Experiment

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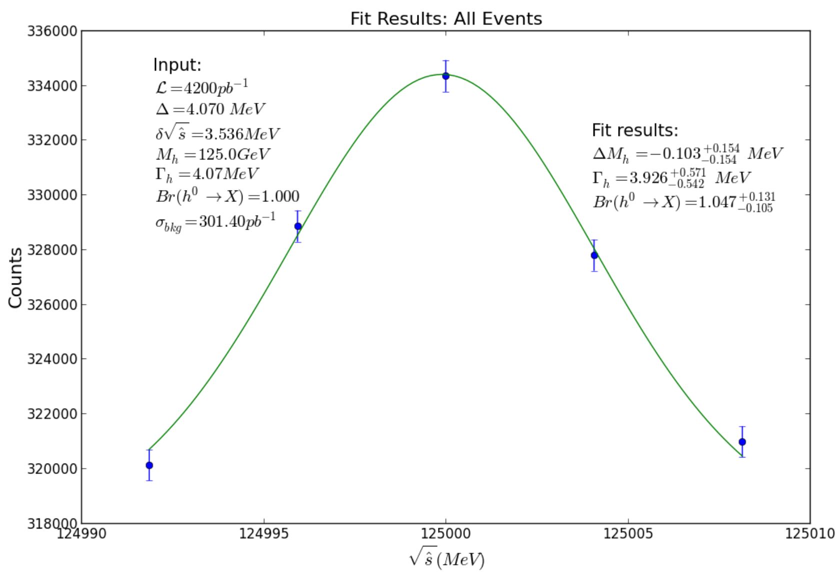
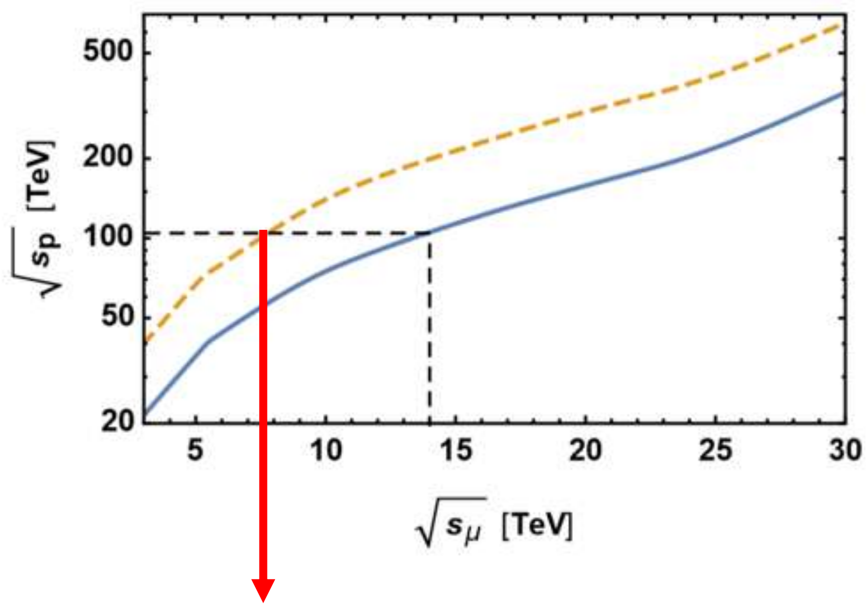
On behalf of the working group of **LoIs #234, 117, 228** (and also our collaborating European colleagues)

Why a muon collider experiment

- Muon colliders could be the future at the energy frontier:
  - Muon are fundamental particles → precision machine
  - Muons are ”heavy” → discovery machine.



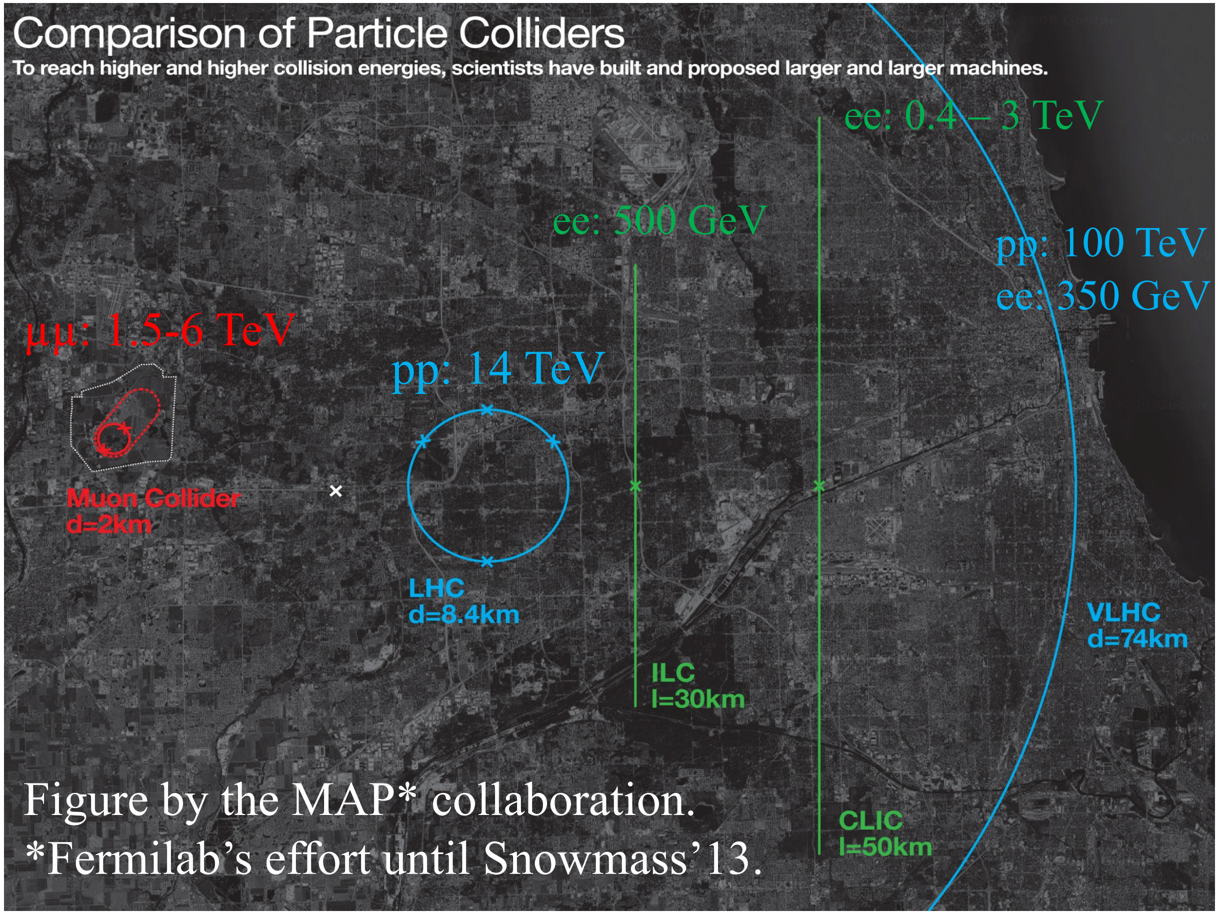


Higgs mass peak scan:
Higgs mass with a precision of **0.1 MeV**
Higgs width with **15%** precision
arXiv:1308.2143

For √s **≳ 7.5 TeV**, a muon collider will surpass a 100 TeV pp machine for electroweak physics.
arXiv:1901.06150

Why a muon collider experiment

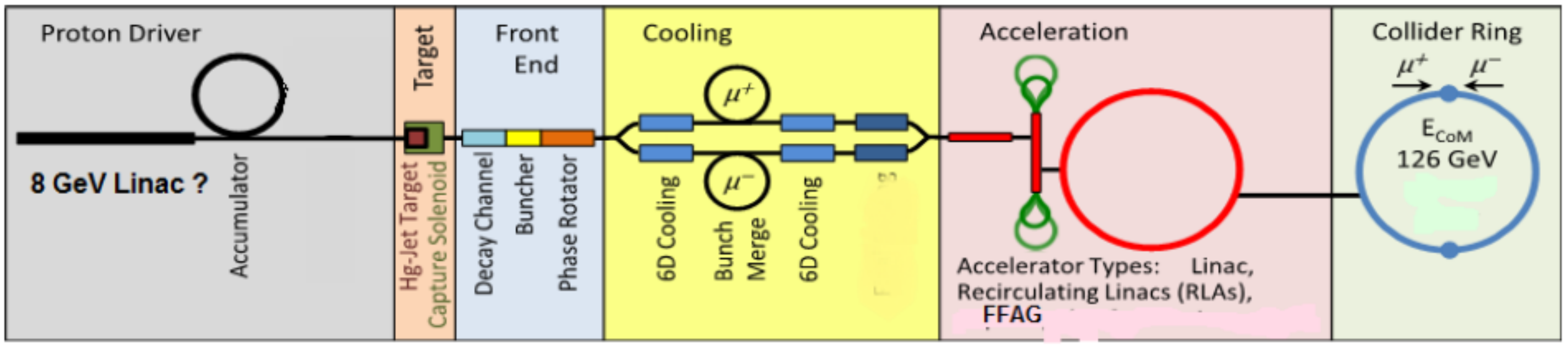
- Muons are fundamental and heavy → can build a multi-TeV collider on a small footprint.



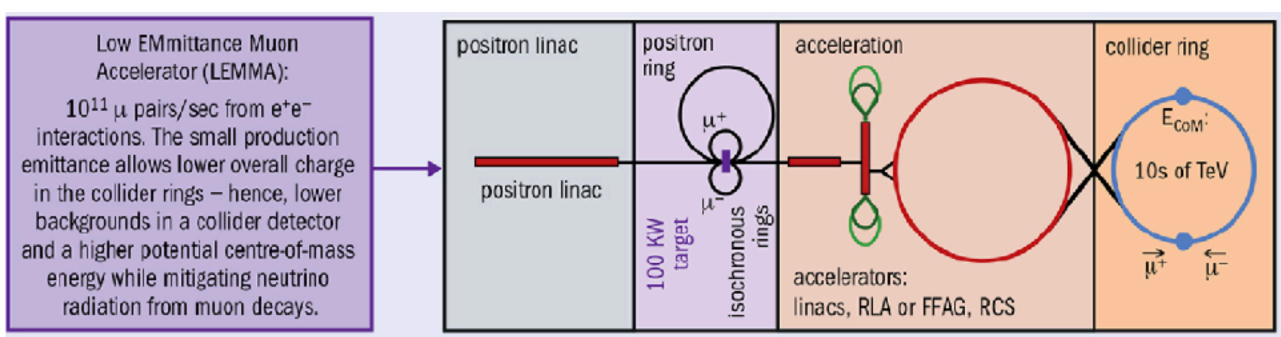
- Of course, a lot of R&D is needed to realize such a novel machine.

Muon collider technologies

- Until last Snowmass, Fermilab developed a muon collider concept using muon cooling (muon accelerator program (MAP)).



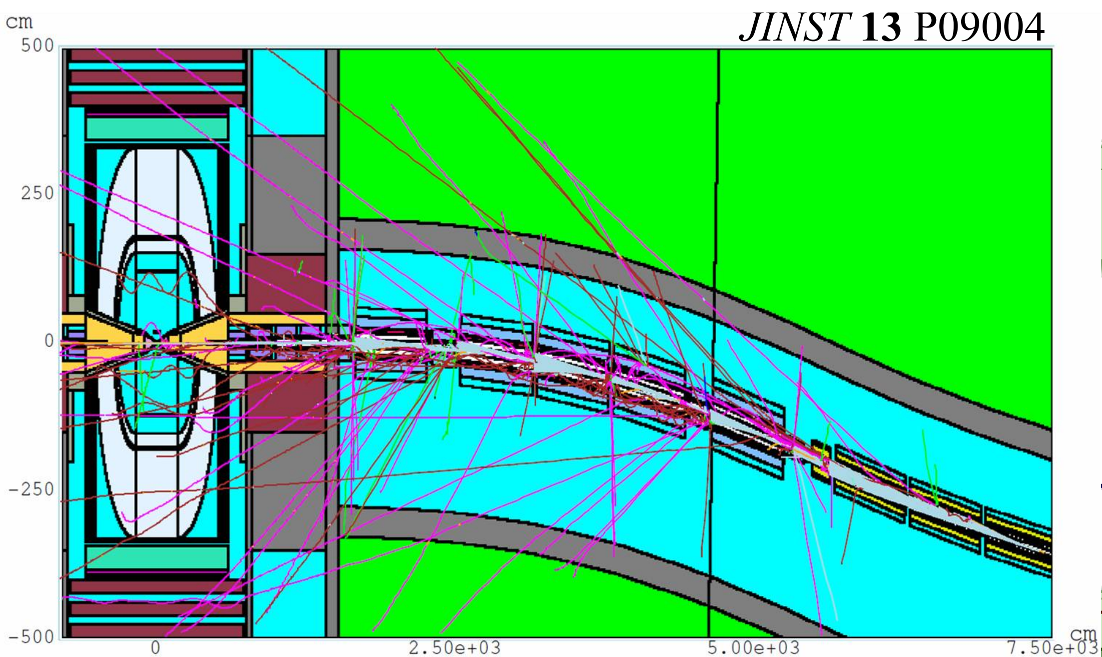
  - Produce muons from a high intensity proton source; after cooling 10^{12} μ/bunch
  - The starting point of our studies heavily rely on the work done by the MAP collaboration.
- Another muon collider concept emerged in the last year: LEMMA using production at threshold:

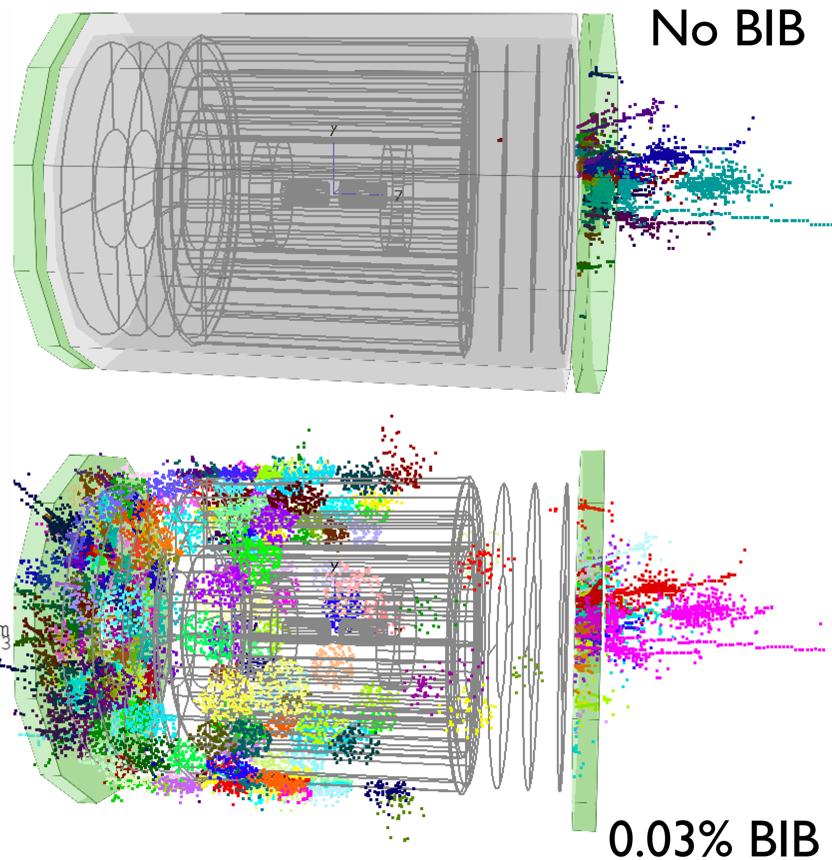


The challenge for a muon collider experiment

- Muons are unstable, and decay in-flight.
  - This plot is done with MARS simulation at $\sqrt{s} = 1.5$ TeV.

M. Swiatlowski

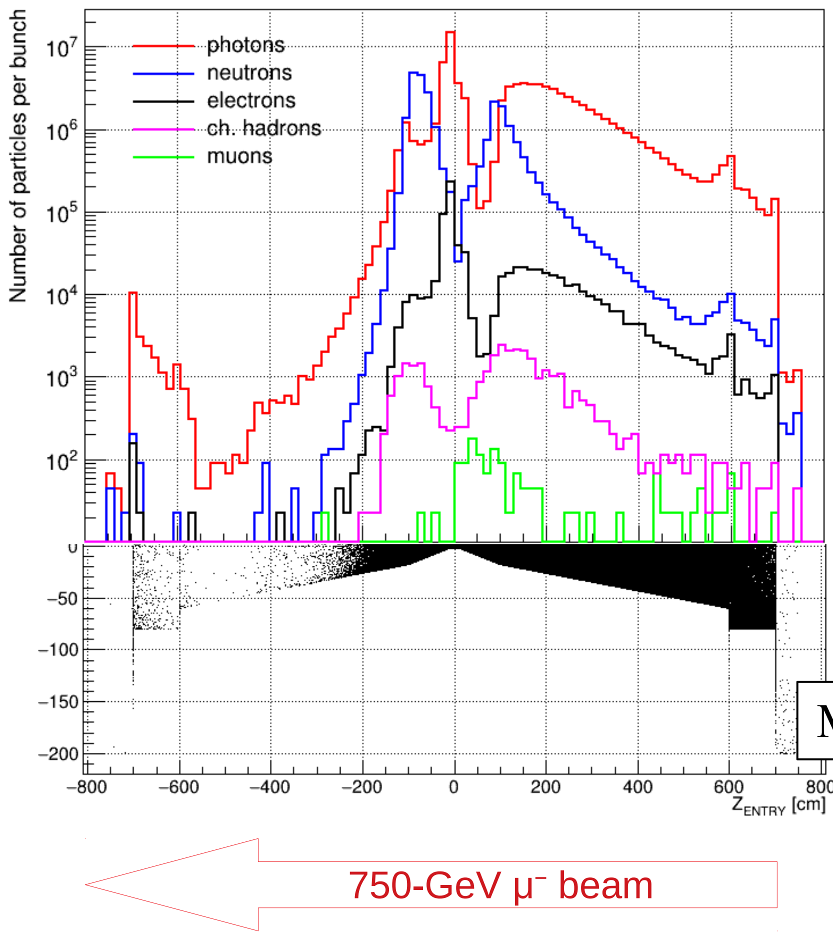


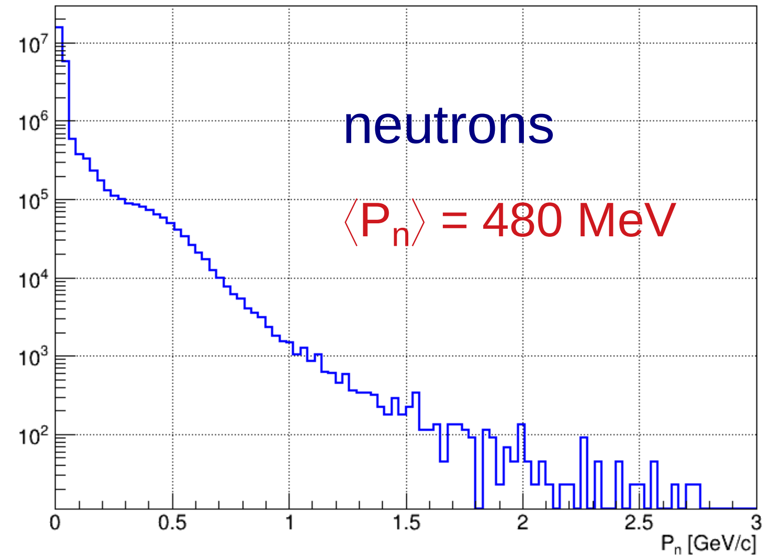


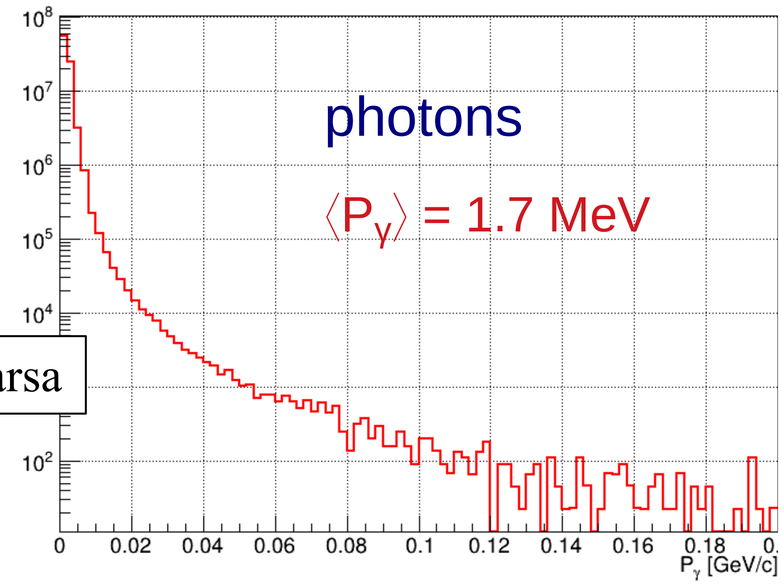
- The beam-induced background (BIB) needs to be handled by all subdetectors.

The challenge for a muon collider experiment

- Muons are unstable, and decay in-flight.
  - The detector is bombarded by (soft) particles.







M. Casarsa

The Tracker Occupancy Study

Why study the tracker occupancy?

- In order to be able to perform tracking at a muon collider experiment, we need to require a decently low tracker occupancy.
  - This might be challenging because of the presence of the BIB.

  - Study how space and time segmentation of the tracker compare for BIB rejection.

- Take a BIB event file and test what per pixel occupancy can be achieved for different assumption on pixel size and time resolution.
  - Note: number of particles from BIB >> number of particles from hard scatter, so studying BIB only file should be sufficient.
  - BIB only for $\sqrt{s}$ = 1.5 TeV configuration obtained using MARS.
  - The BIB file was provided to us by our Italian colleagues (special thanks to Massimo Casarsa and Nazar Bartosik).

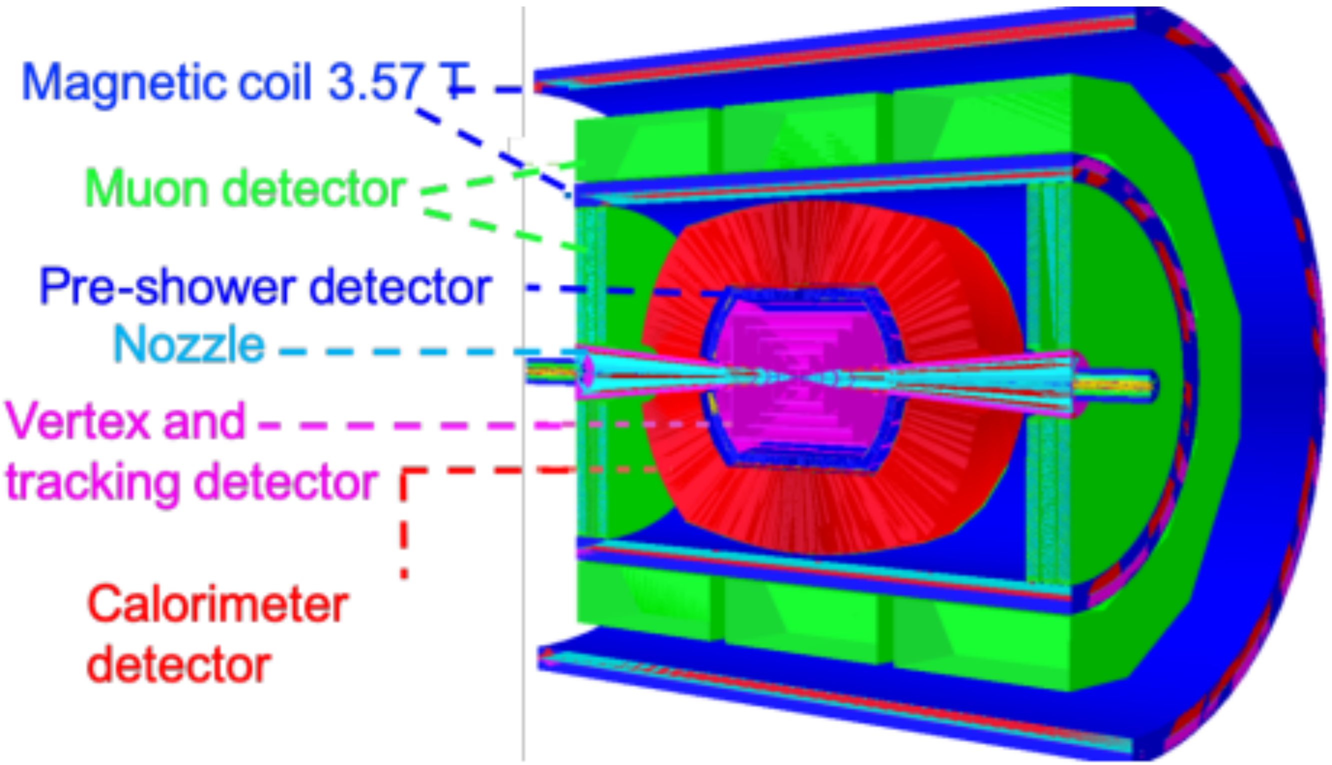
The idea of the study

- Study how space and time segmentation of the tracker compare for BIB rejection.

- My goal was to see if we can get a per pixel occupancy of about 1% or lower.
  - This is a very simple study. I only take the hit properties (position/time) and assume certain pixel sizes and time resolutions to see what an ideal detector occupancy might be.
  - No digitization model is included. I just smeared simulated hits.

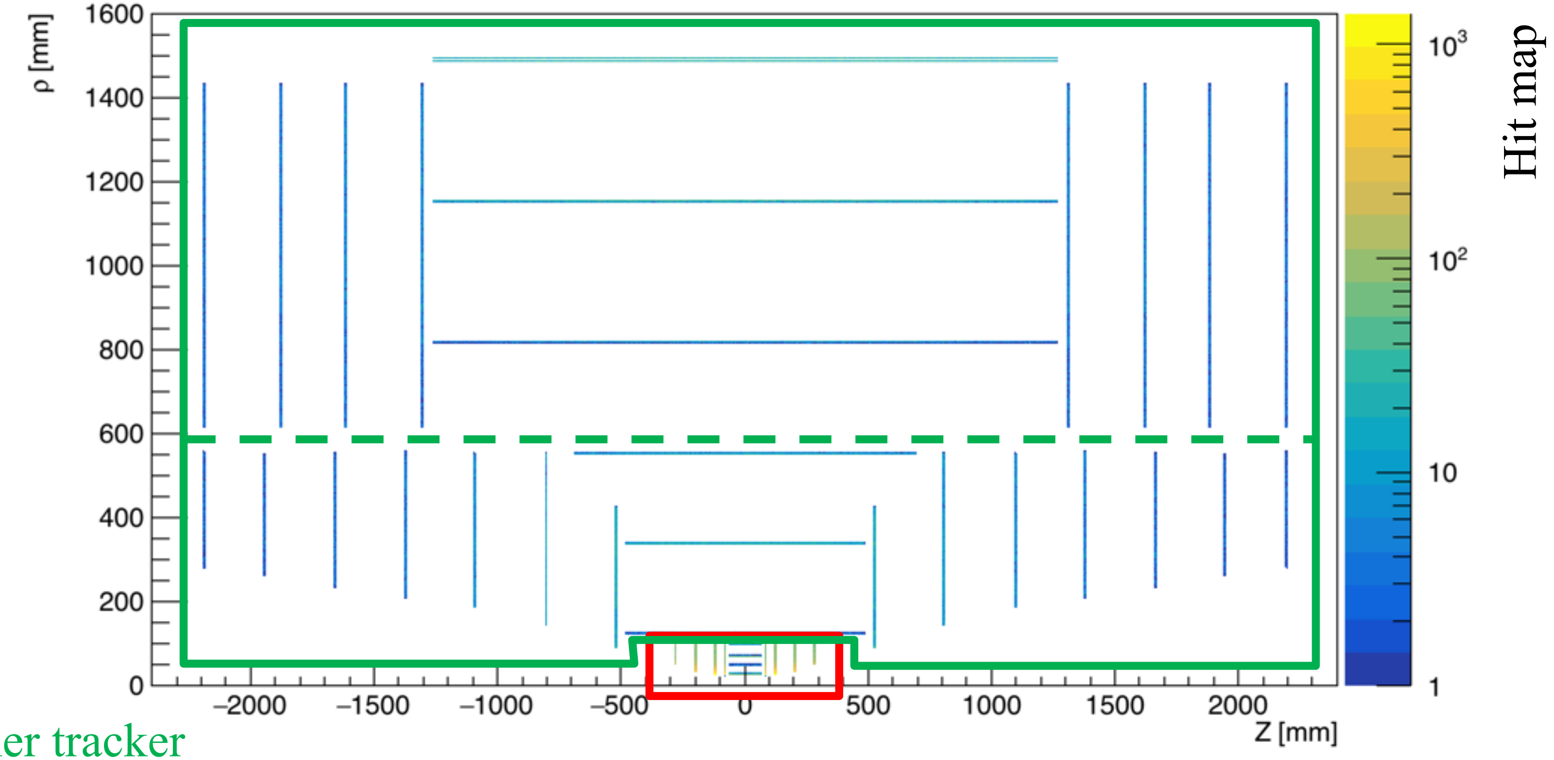
- Disclaimer: This study has nothing to do with the technology used for the tracking detector.

The muon collider experiment



The muon collider tracker

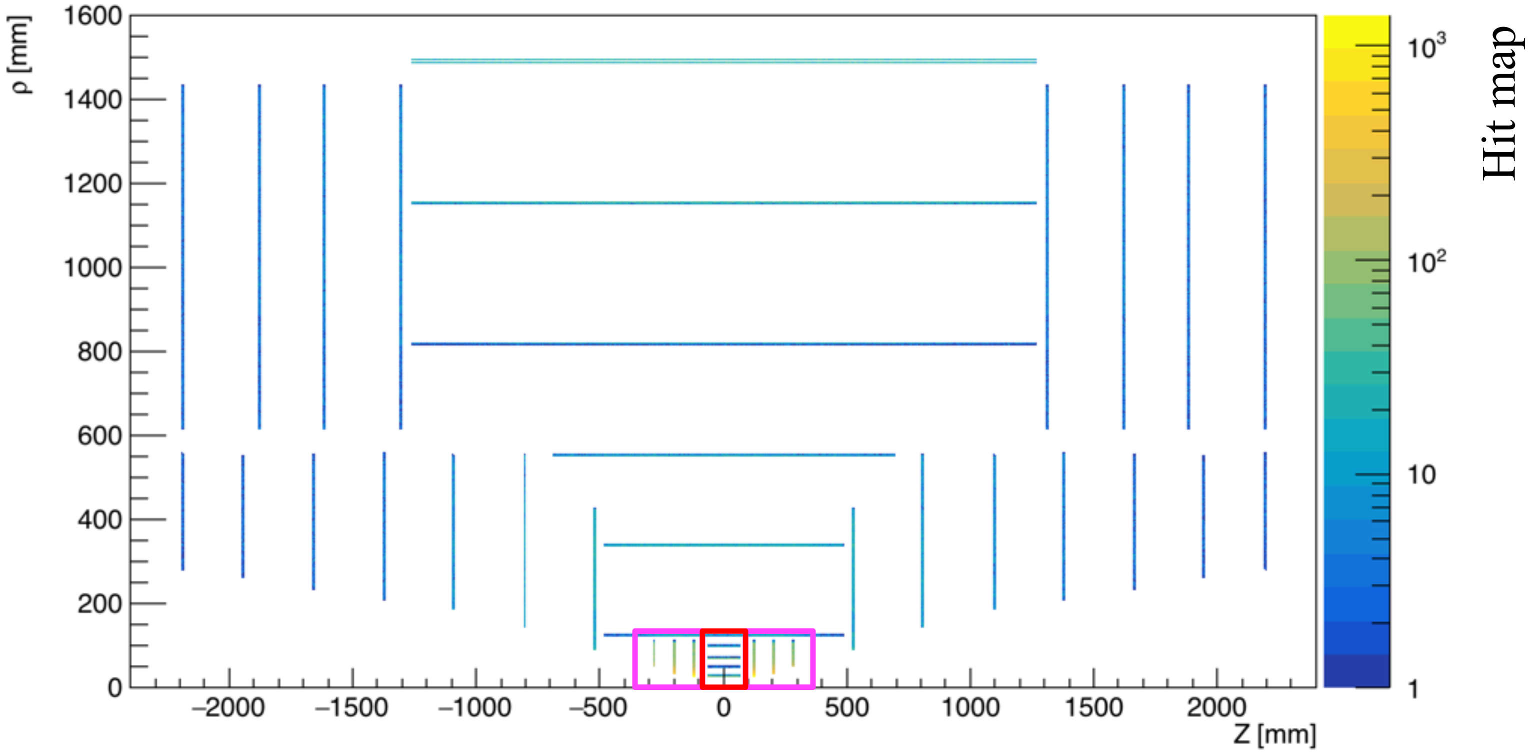
- The vertex tracker consist of 4 (4) double layer, the outer+inner tracker of 6 (7/4) single/double layers in barrel (endcap) region (based on CLIC's layout) but modified for muon collider environment (making space for the nozzle).



Outer+inner tracker

Vertex tracker: closest to the beam line → largest BIB contribution

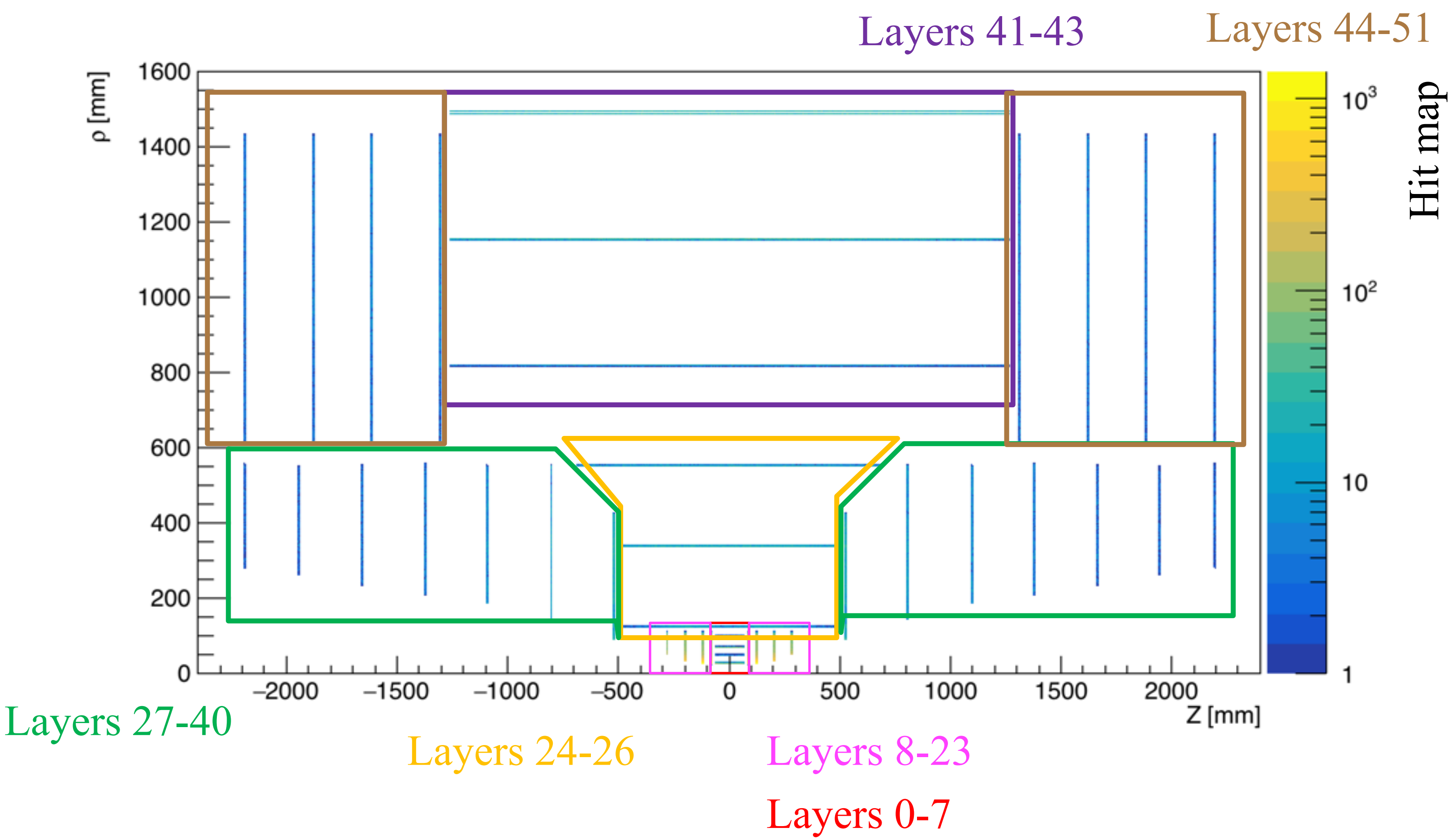
The muon collider tracker labeling



Layers 8-23

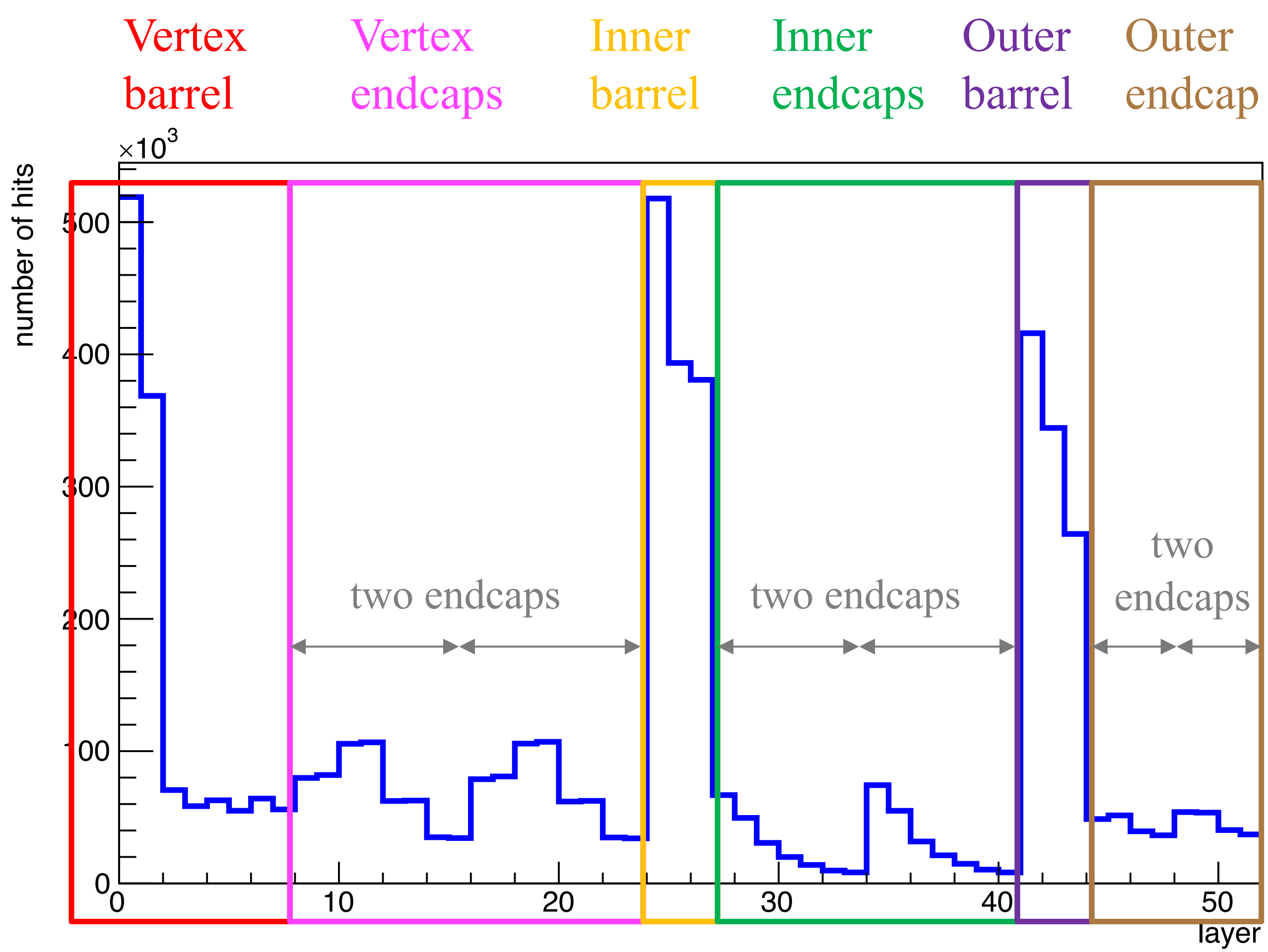
Layers 0-7

The muon collider tracker labeling



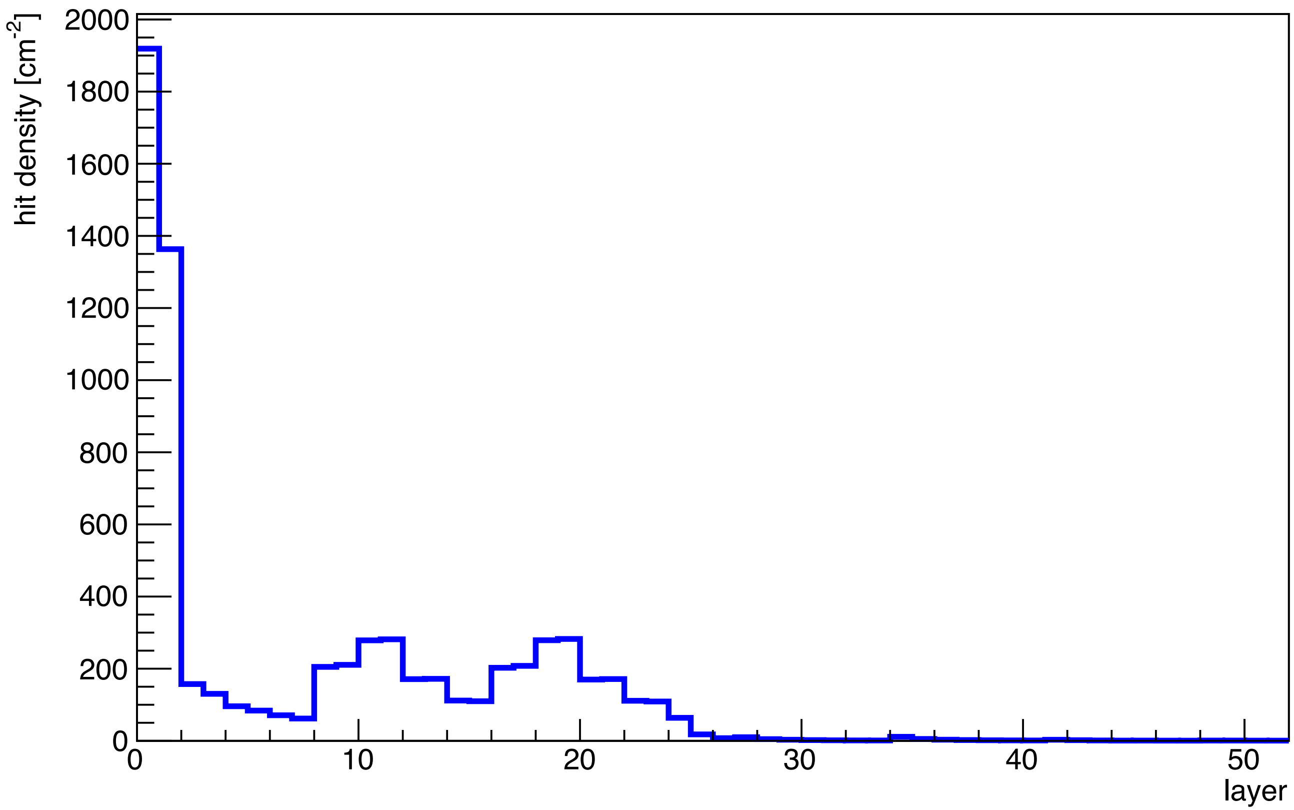
The muon collider tracker labeling

- Reminder of how layers are labeled.



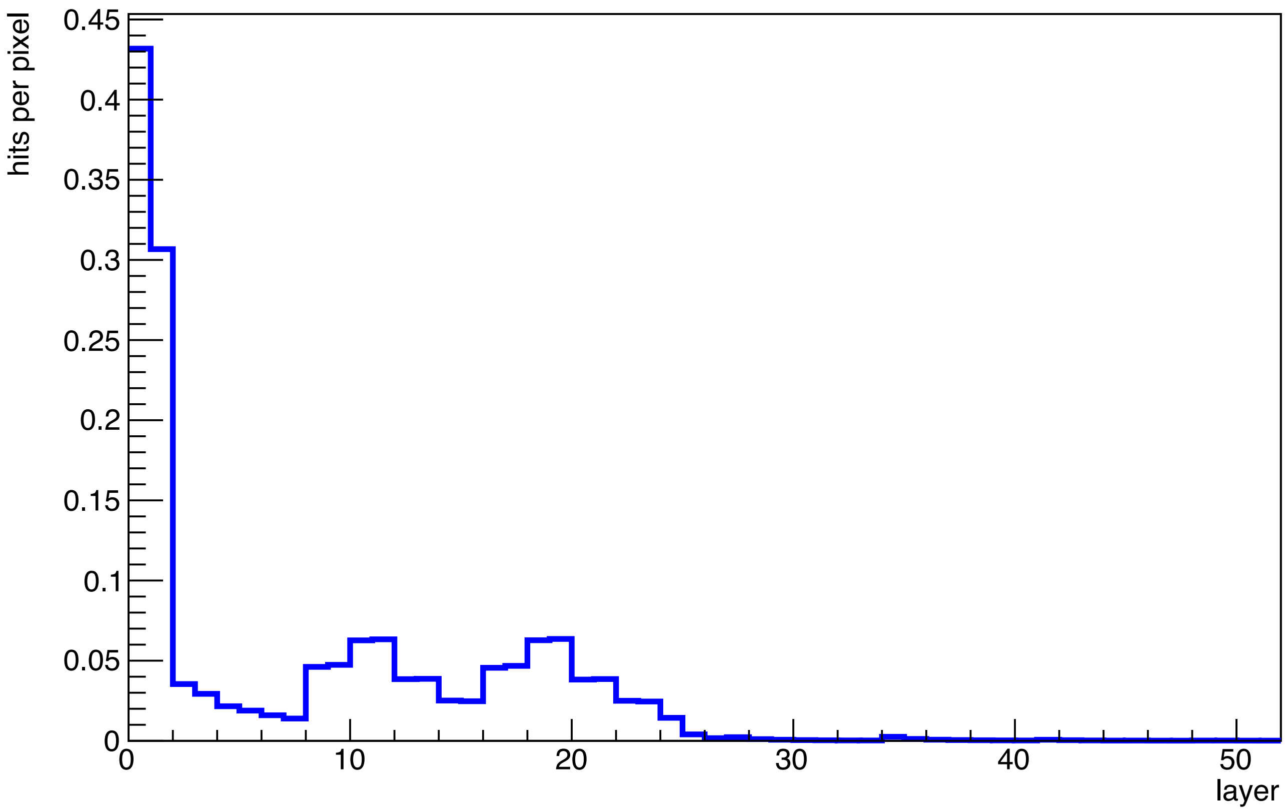
Defining occupancy

- Usually the occupancy is given as hits per cm^2.
  - For a muon collider experiment with a $\pm$1ns cut on hits, see up to 2000 hits per cm^2 per event in two innermost layers.



Defining occupancy

- Pixel* occupancy: Normalize that number by number of pixels per cm^2.
  - i.e. this is the fraction of pixel that light up.
  - The goal is to get this number down to 1%.



This plot is for 150×150 μm^2, with a time cut of 1 ns.

*When I say pixel, I also mean strips.

The two parameters of the study

- This study is a simplified occupancy study by playing with 2 parameters.

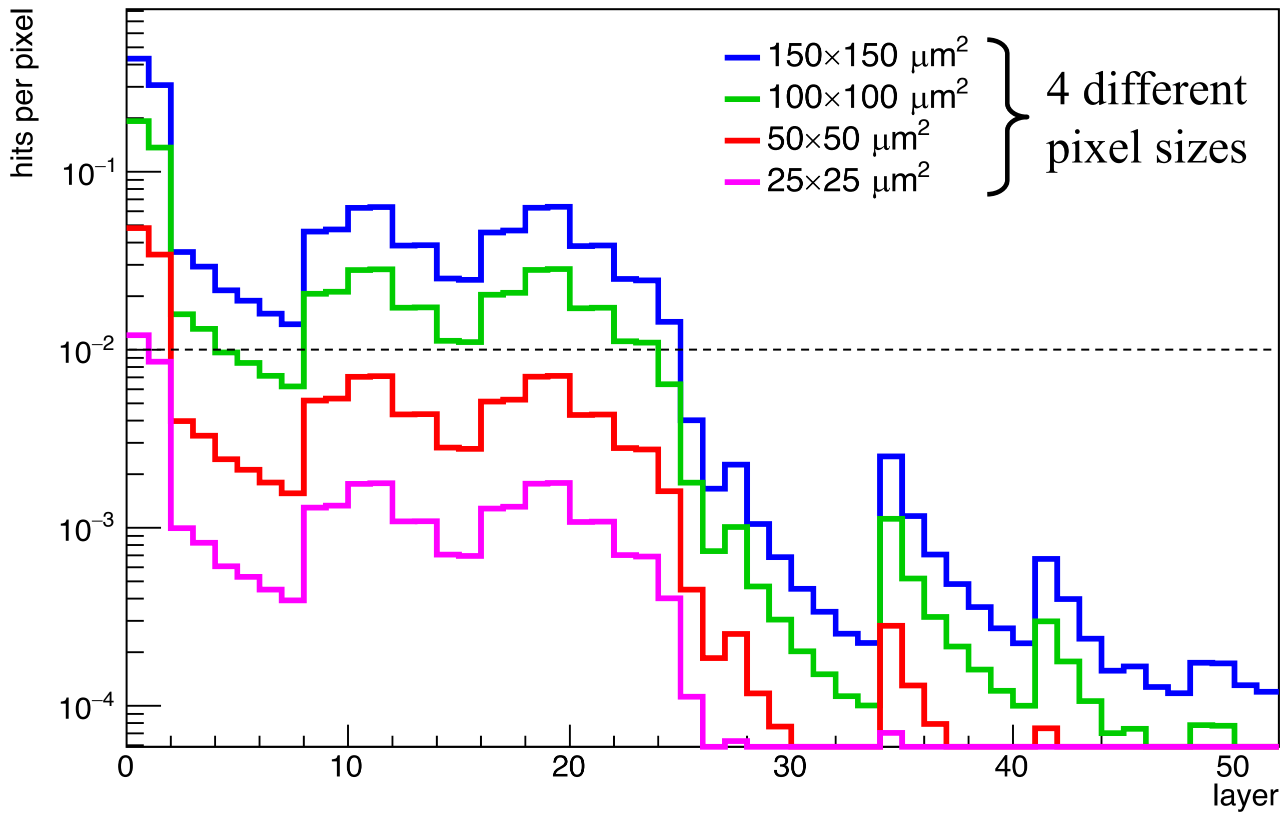
1. **Position resolution:**
   - If 2 hits have distance is smaller than the pixel dimension, count 1 hit, else as 2 hits.
     - Note that I do not create a pixelated tracker. Usually my number is correct, but for high occupancies, the number will be a bit optimistic (but by less than $\times 2$).

2. **Time resolution:**
   - For every assumed time resolution σ_t of the tracker, smear arrival time by a Gaussian of that resolution. Cut on arrival times $> 3\sqrt{\sigma_t^2 + \sigma_b^2}$, where σ_b is the timing spread due to the beams (assumed as 25 ps).

   - If any particle within the same pixel/strip hit (see 1.) arrives within the timing window, count the hit, else the hit is disgarded.

Playing with position resolution only.

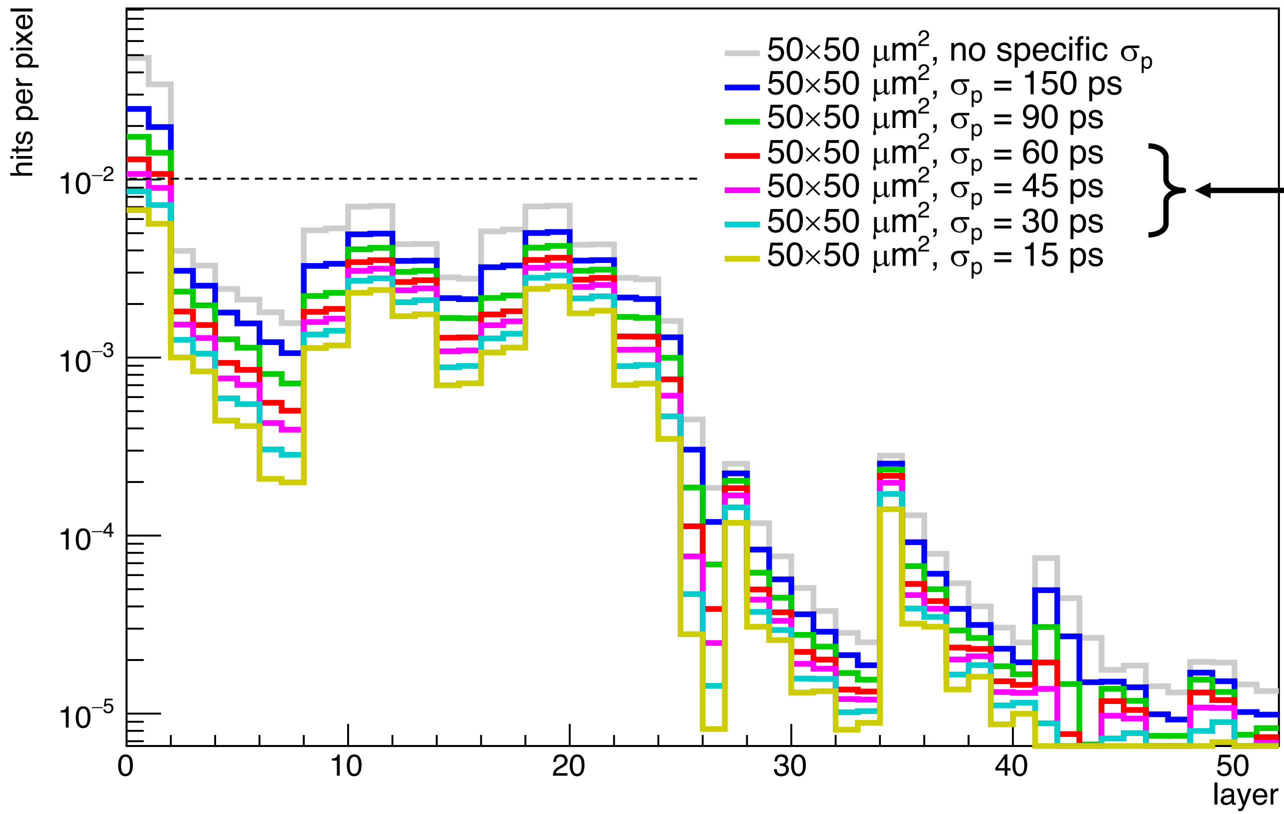
- Use ntuples where a 1ns time of arrival cut is applied, i.e. effective $\sigma_p \approx 300$ ps.
  - If we had “no” access to timing, we could achieve low occupancy with 25×25 µm².



Vertex (25×25 µm²): 4.6 billion pixels
Inner (150×150 µm²): 0.9 billion pixels
Outer (150×150 µm²): 5.1 billion pixels

Add timing dimension – for 50×50 μm^2

- Even ”modest” timing can reduce occupancy by a large factor.
  - With good timing, these pixels would work.
  - Additional benefit: all of these hits are BIB – i.e. hits we don’t care about. Cutting them out will relieve the DAQ, tracking reconstruction, etc. by a lot.



For inner tracker, any timing works. For innermost vertex layer need good timing.

Testing tracker configurations

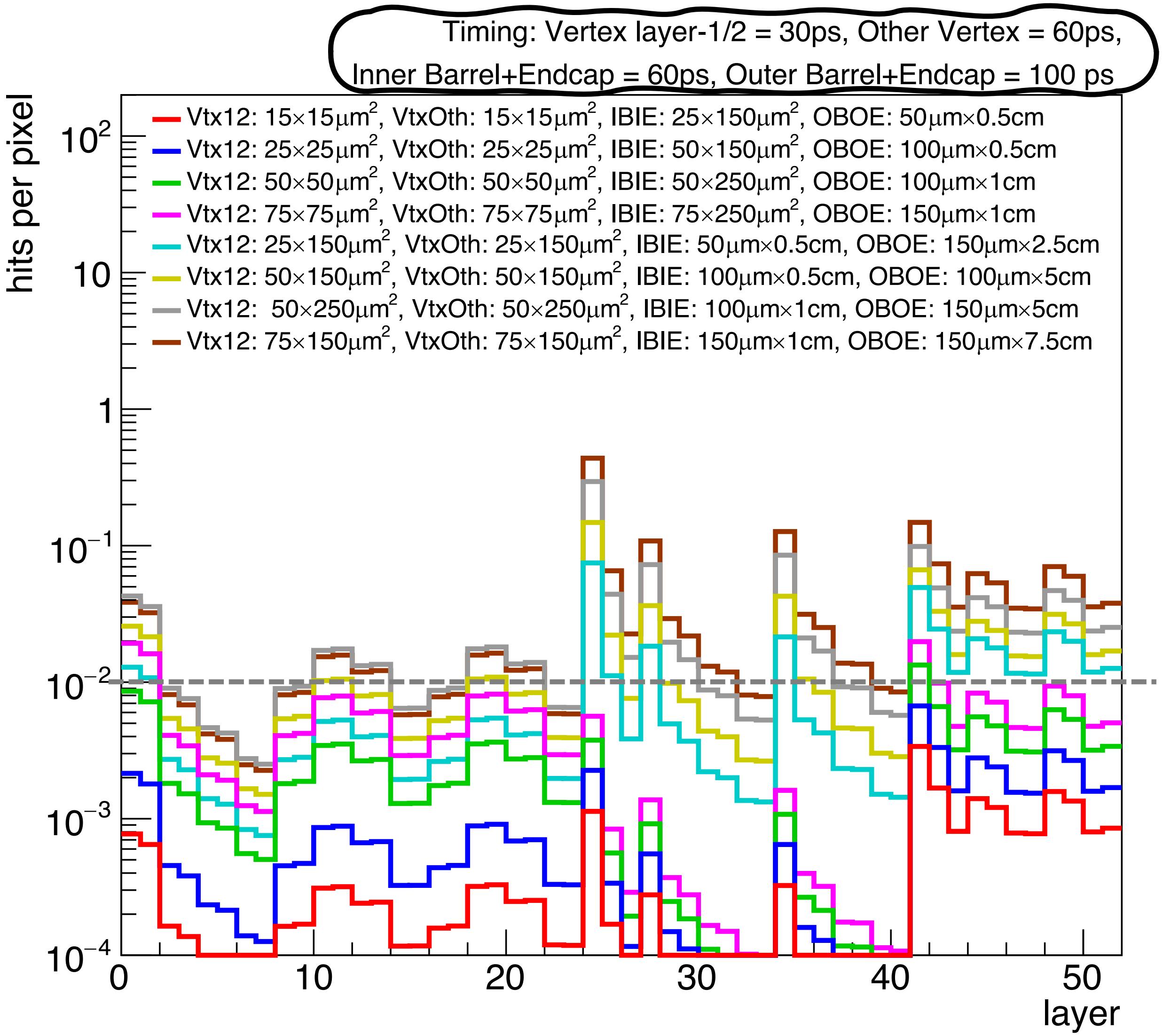
- I will not show all the ways I studied the combination of these two parameters, but only show you two figures.

- In the first, I fix a timing to a reasonable assumption I derived at and vary pixel size:
  - The timing assumed is 30ps / 60 ps / 100 ps for innermost layers / inner tracker / outer tracker.
  - Using square/asymmetric pixels for vertex tracker.
  - Using asymmetric/macro pixels for inner tracker (long side ≤ few mm).
  - Using strips for outer tracker (few mm up to few cm).

- In the second plot, I fix the pixel/strip dimension and vary timing cut.
  - Pixel dimension is $50 \times 50\ \mu m^2$ up to $100\ \mu m \times 2$ cm.
  - Vary timing resolution from 200 ps down to 5 ps.

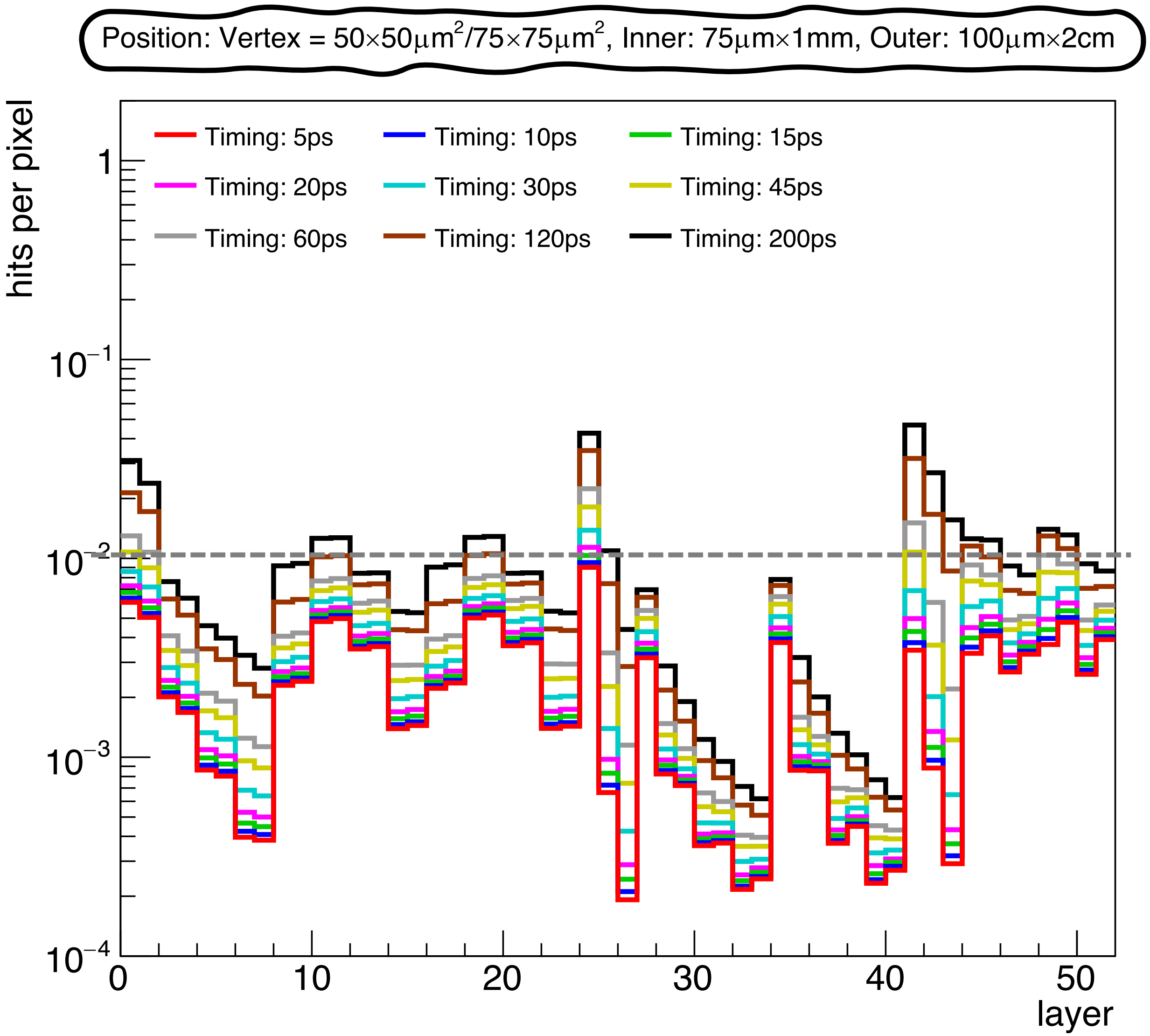
- In the backup, I show more scenarios.

Pixel occupancy with fixed timing



- We find that we need:
  - Small square pixel in innermost layers.
  - Macropixels O(50 µm × 1 mm) for the inner tracker.
  - Short strips O(100 µm × 1 cm) for the outer tracker.

Pixel occupancy with fixed pixel size



- If we can afford small pixels/strips, most of the detector can use "modest" timing resolution if ~60ps.
- For innermost vertex/inner barrel layer, we will benefit for better timing of 20-30ps.
- However, as all hits shown here are unwanted hits, a very good timing would be very beneficial.

Current tracker configuration for muon collider physics studies

- Based on these and other studies, we fixed the tracker configuration for the snowmass physics studies. For more details, see this presentation by Massimo Casarsa.

		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	729M
	E	25 µm × 25 µm pixels	50 µm	30 ps	5 µm × 5 µm	462M
IT	B	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	164M
	E	50 µm × 1 mm macropixels	100 µm	60 ps	7 µm × 90 µm	127M
OT	B	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	117M
	E	50 µm × 10 mm microstrips	100 µm	60 ps	7 µm × 90 µm	56M

Sum: 1.6B

Summary

- I showed a simple study, studying how many hits can be reconstructed depending on the pixel size and pixel time resolution.

- Assuming a per-pixel occupancy goal of ~1%, we need good timing and small pixels for the innermost layers.
- For the inner tracker, we will need macropixels (length of about 1mm).
- For the outer tracker, we need short strips (length about 1-2cm).
  - We cannot use long strips anywhere in the detector, even with good timing.

- Modest timing is needed for outer and inner tracker, good timing for the vertex tracker.
  - Preferable to have good timing everywhere so that we can reduce the number of unwanted hits that will relieve the system (DAQ, reconstruction) as much as possible.

- Further improvements can be possible, for example using hit correlations of two close parallel silicon layers (p_T modules). This could be potentially a big factor.

- Assuming this type of configuration with good timing, the detector would have about 1.6 billion pixels ($\leq$ number of pixels for CMS phase-2 tracker).

What does this mean for IF

- Having a silicon sensor of $25\times25\ \mu m^2$ with a 30 ps resolution is a technological challenge.
  - Must be able to get good timing resolution of small-pitch pixels?
  - What does this mean for power consumption / thermal properties?
  - We still will have plenty of BIB hits (even after timing cuts and/or p_T modules), how can the DAQ handle the data volume?
  - How does such a sensor behave under irradiation?

Backup

Size of a detector

K: thousand (Kilo)
M: million (Mega)
G: billion (Giga)

- Taking plots from slide 9-11:

Color	2 innermost layers	Other Vertex	Inner Tracker	Outer Tracker	Total
red	240 M	4.35 G	5.57 G	460 M	10.6 G
blue	86 M	1.57 G	2.78 G	230 M	4.76 G
green	**22 M**	390 M	1.67 G	110 M	2.19 G
pink	9.6 M	170 M	**1.11 G**	**76 M**	1.37 G
cyan	14 M	260 M	**83 M**	**30 M**	390 M
yellow	7.2 M	**130 M**	42 M	29 M	210 M
gray	4.3 M	78 M	21 M	15 M	118 M
brown	4.8 M	87 M	14 M	10 M	116 M
black	2.9 M	52 M	5.6 M	7.6 M	68 M

- Compare to slide 7: blue: 9G, red: 1G, green: 6G, pink: 17G

Timing configuration tested

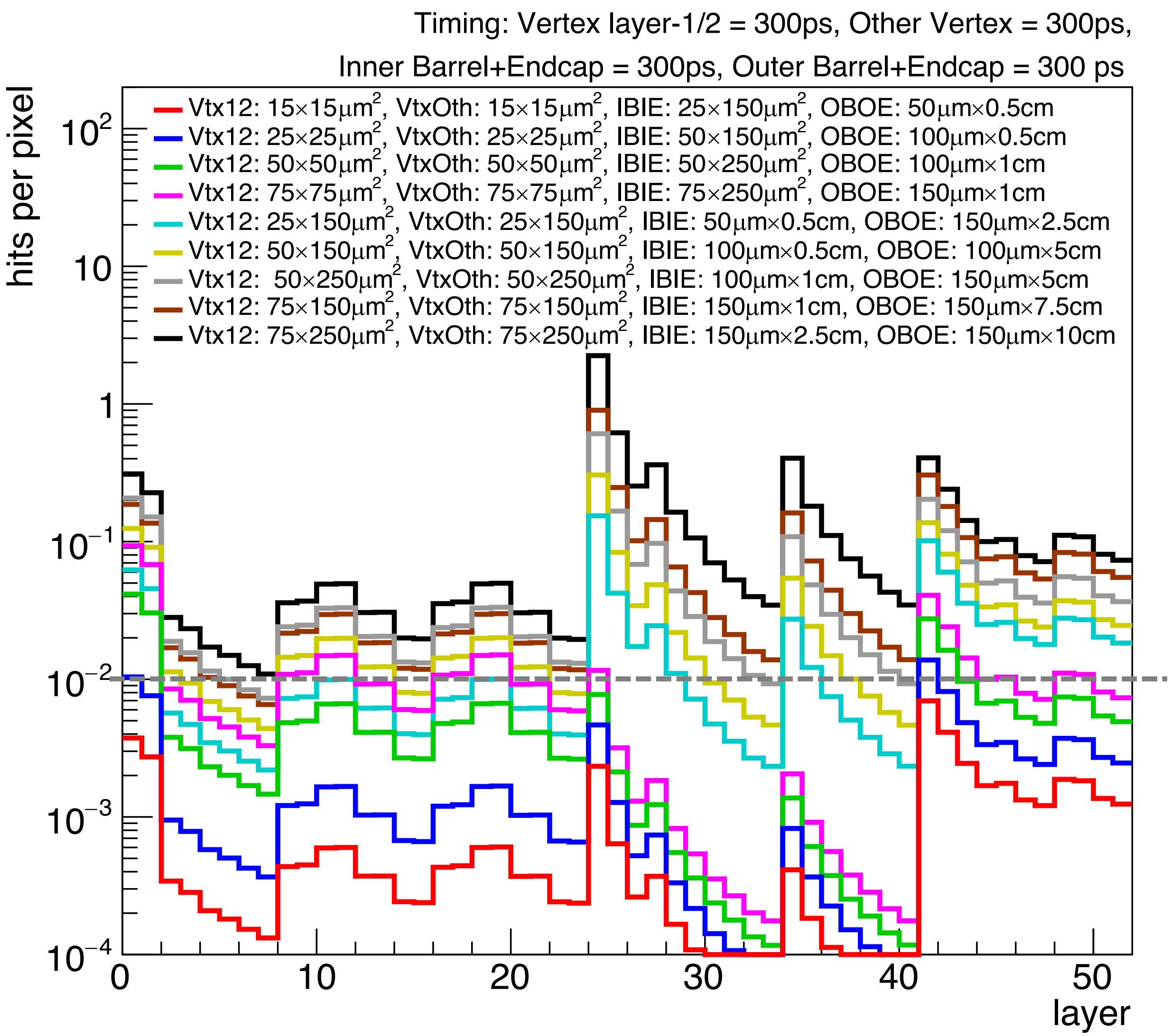
- So, I studied following "pixel" sizes:
  - Square pixels: long side up to 150µm
  - Asymmetric pixels: long side of few 100µm
  - Macropixels: long side being of order mm.
  - Short strips: long side of order of cm, ≤2.5cm.
  - Long strips: up to 15cm.

Configuration	Ntuple timing	Bad timing	Conserva-tive timing	Nominal(?) timing	Achievable timing	Superb timing
2 innermost layers	300ps	100ps	60ps	30ps	20ps	5ps
Other vertex detector	300ps	150ps	75ps	60ps	30ps	15ps
Inner barrel*+endcap	300ps	200ps	100ps	60ps	60ps	30ps
Outer barrel + endcap	300ps	300ps	200ps	100ps	60ps	30ps

*I also have versions where Inner barrel is treated the same as Other vertex detector instead.

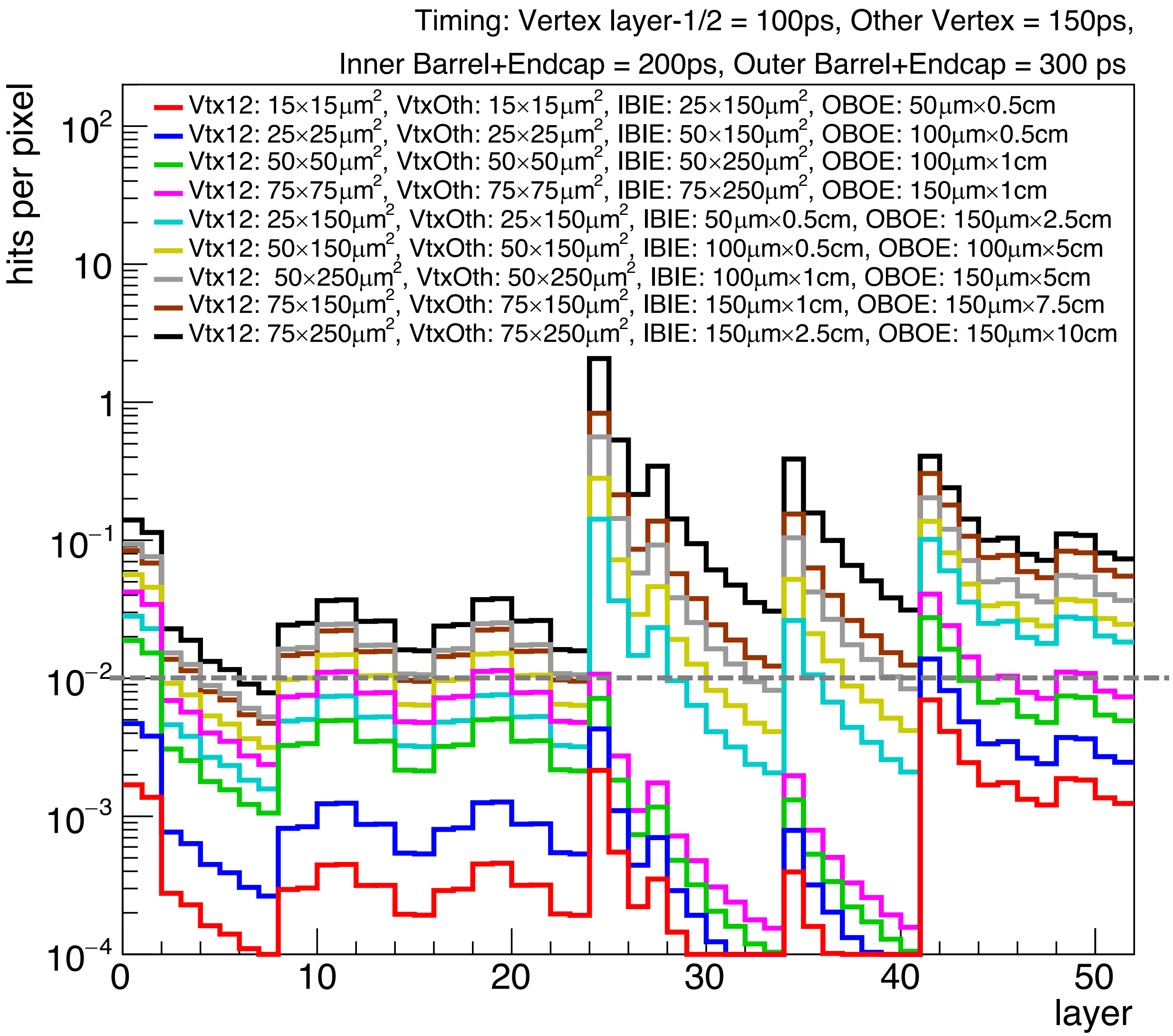
Targets: in next slides, other timings in backup

Pixel occupancy for ntuple timing configuration



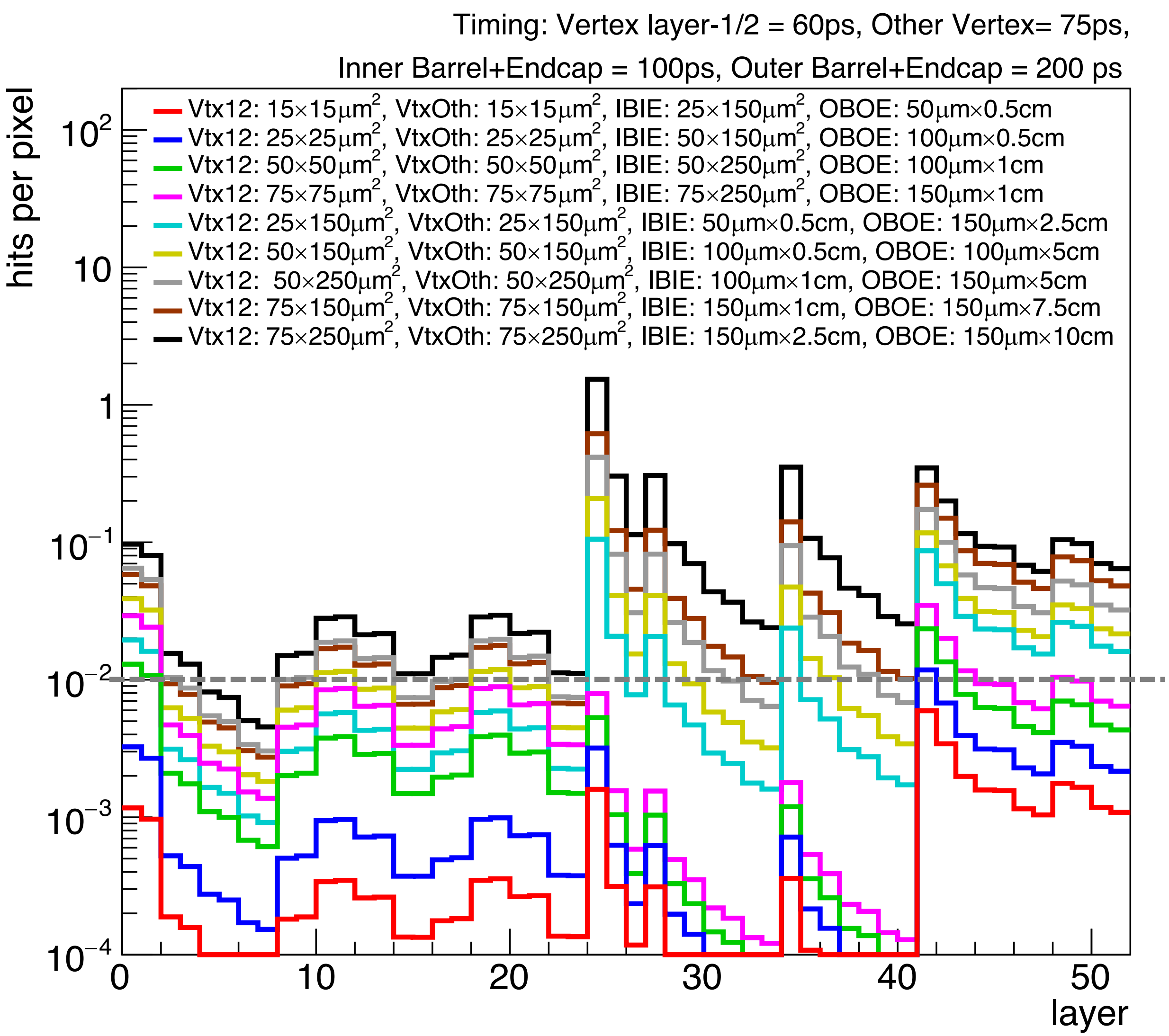
- If we cannot build good timing tracker, we really need macropixels in the outer detector.
- For the inner tracker, we can have asymmetric pixels throughout, but macropixels are too large.
- Vertex tracker needs small pixels.

Pixel occupancy for bad timing configuration



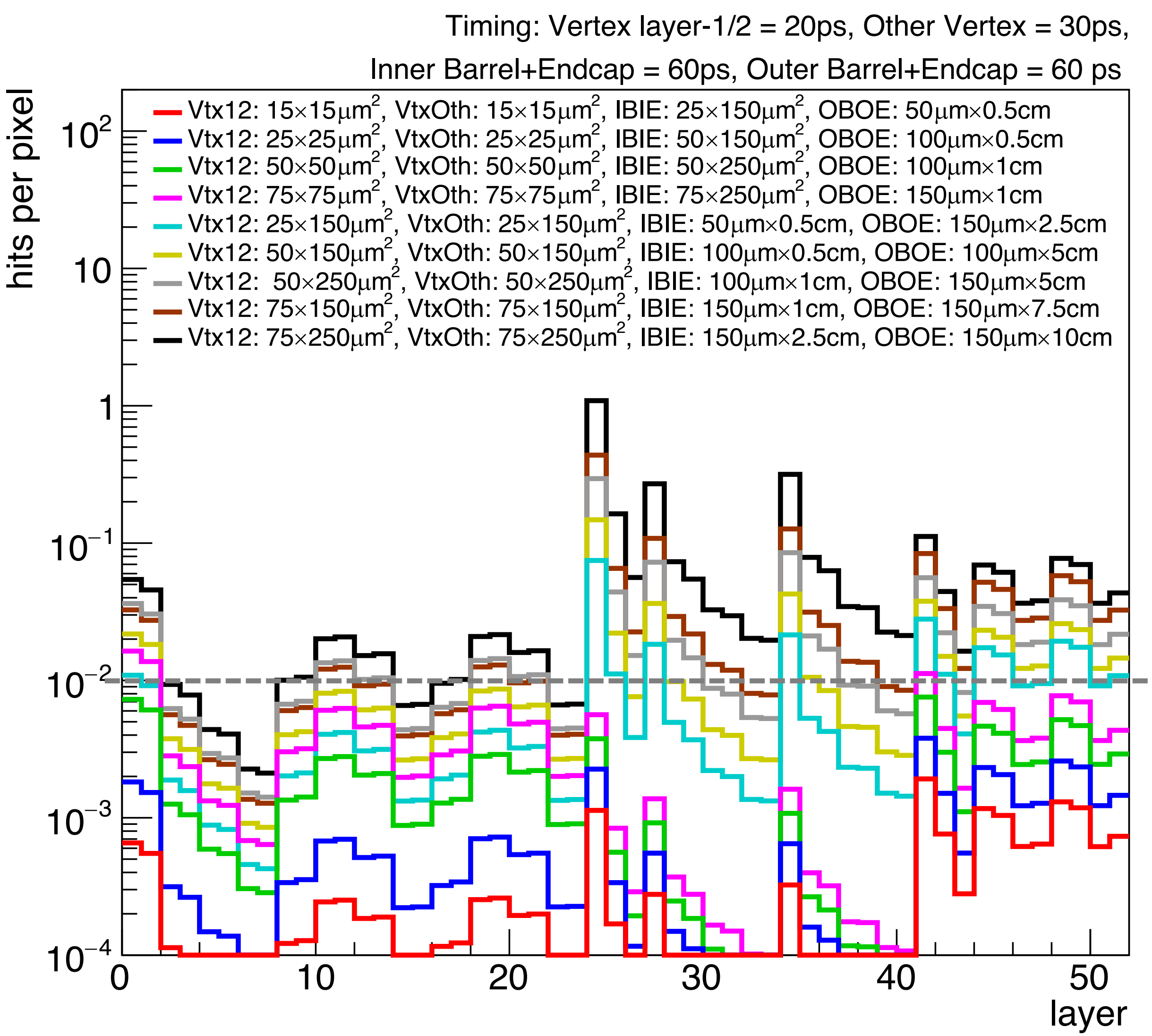
- If we cannot build good timing tracker, we really need macropixels in the outer detector.
- For the inner tracker, we can have asymmetric pixels throughout , but macropixels are too large.
- Vertex tracker needs small pixels.

Pixel occupancy for conservative timing configuration



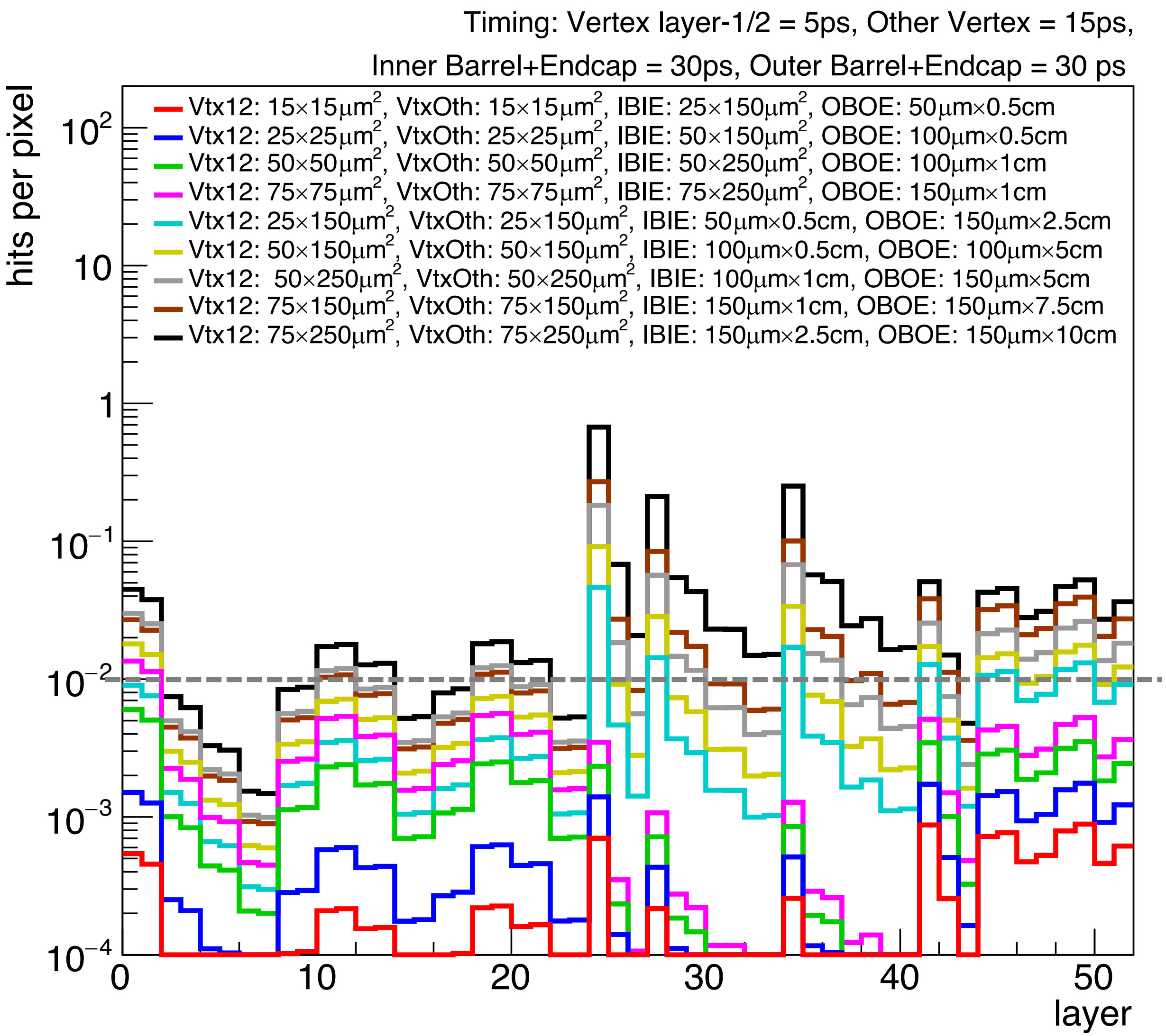
- For conservative timing, we need very short strips in the outer tracker.
- For the inner endcaps, we can use macropixels, we still need (asymmetric) pixels in the inner barrel.
- We can have LHC-sized pixels for the vertex detector, potentially smaller for the two innermost layers.

Pixel occupancy for achievable timing configuration



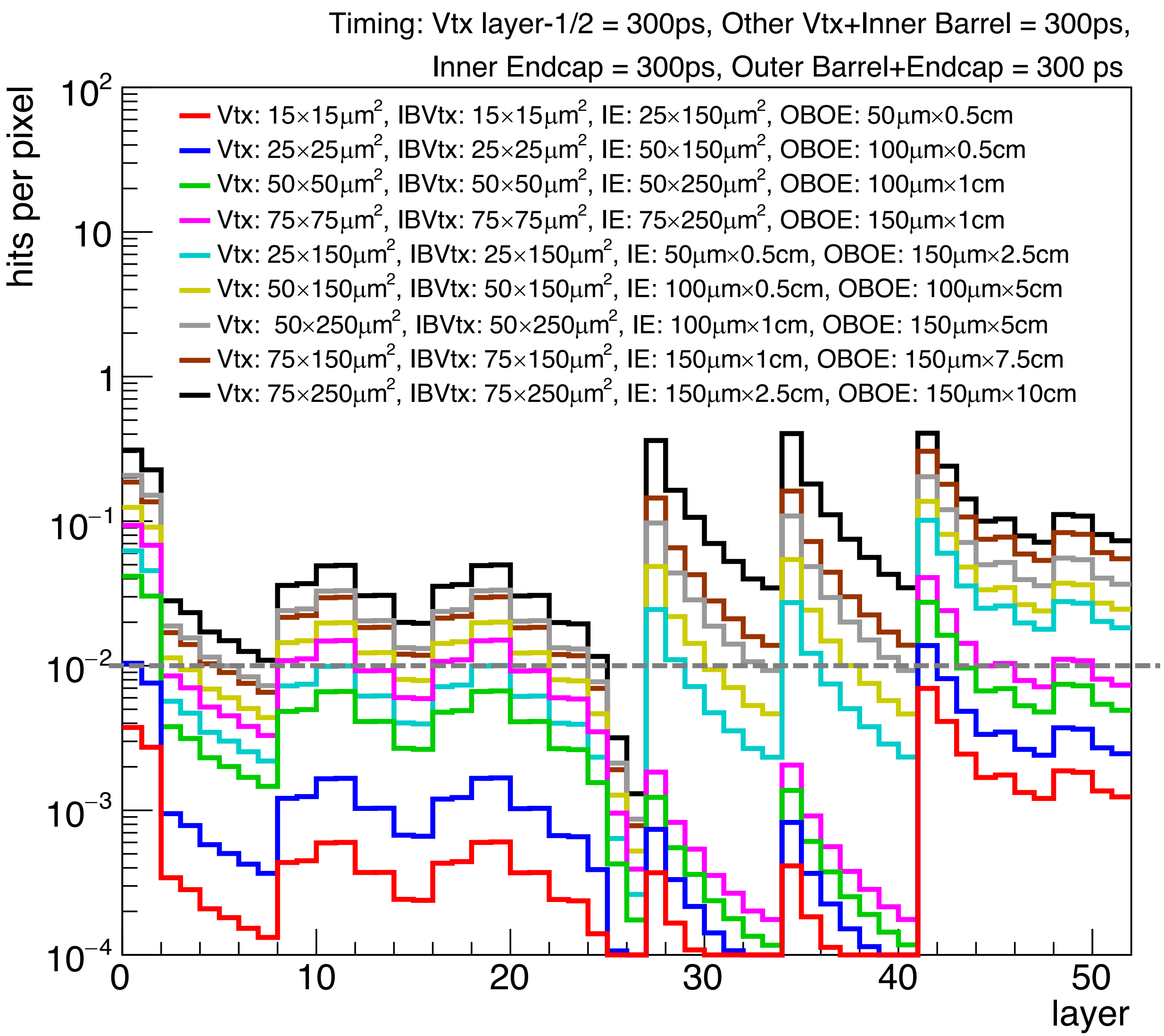
- These timing values were suggested by Artur Apresyan.
- It seems we need something like
  - $50\times50\ \mu m^2$ (2 innermost layers)
  - $75\times75\ \mu m^2$ (rest of vertex tracker)
  - $75\ \mu m \times 1$ mm (inner tracker)
  - $100\ \mu m \times 2$ cm

Pixel occupancy for aggressive timing configuration



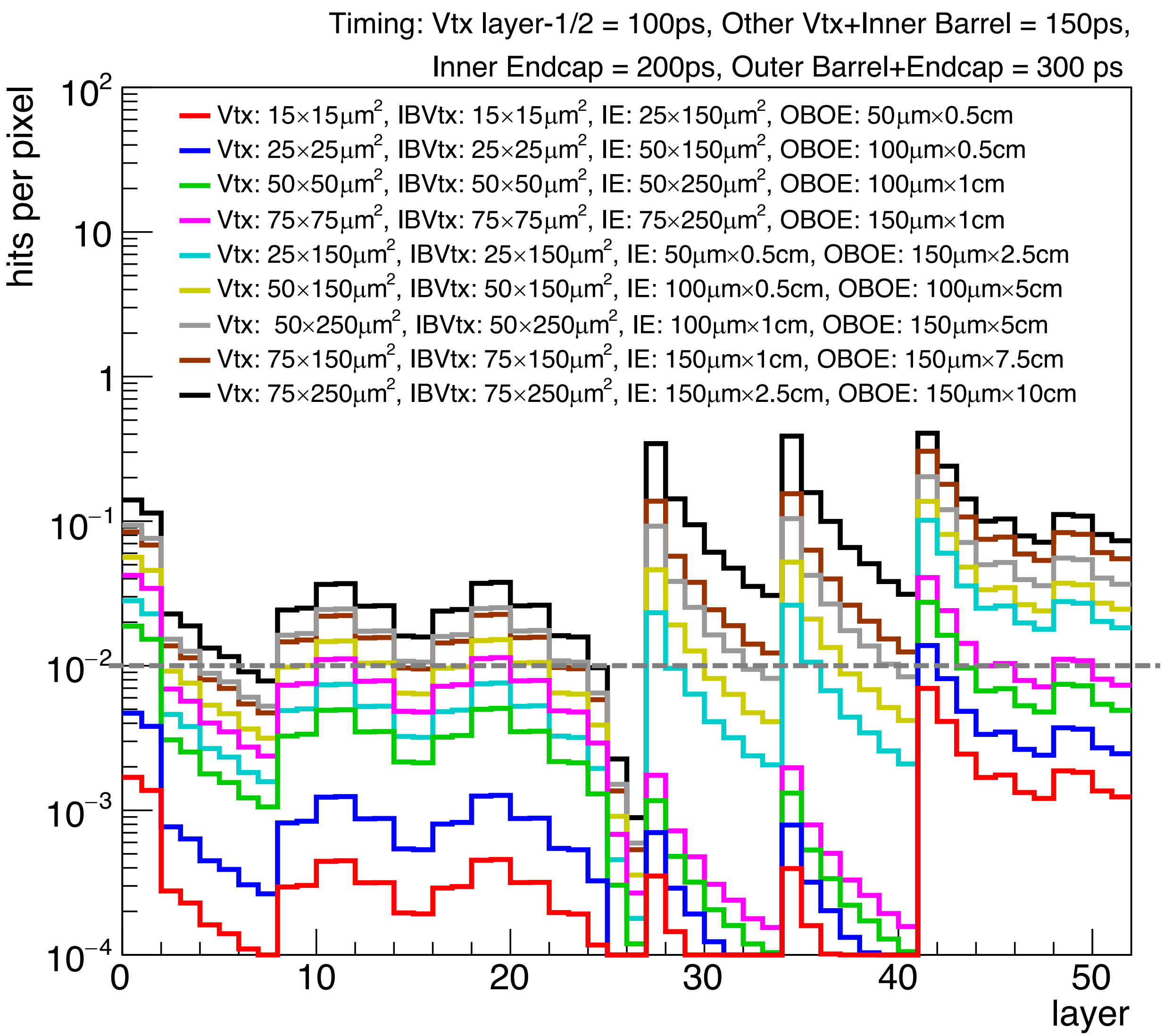
- This plot is overly optimistic.

Pixel occupancy for ntuple timing configuration



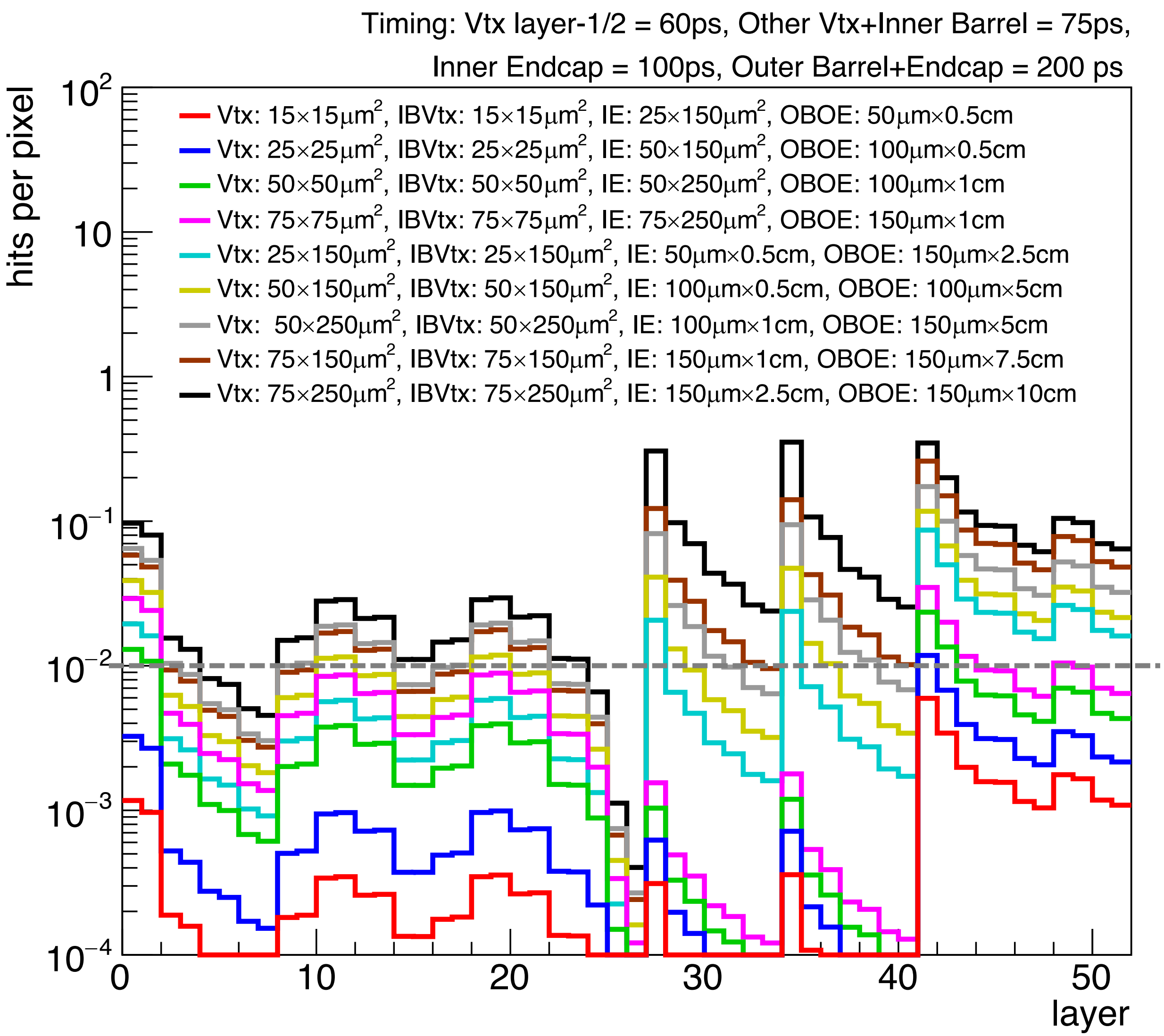
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for bad timing configuration



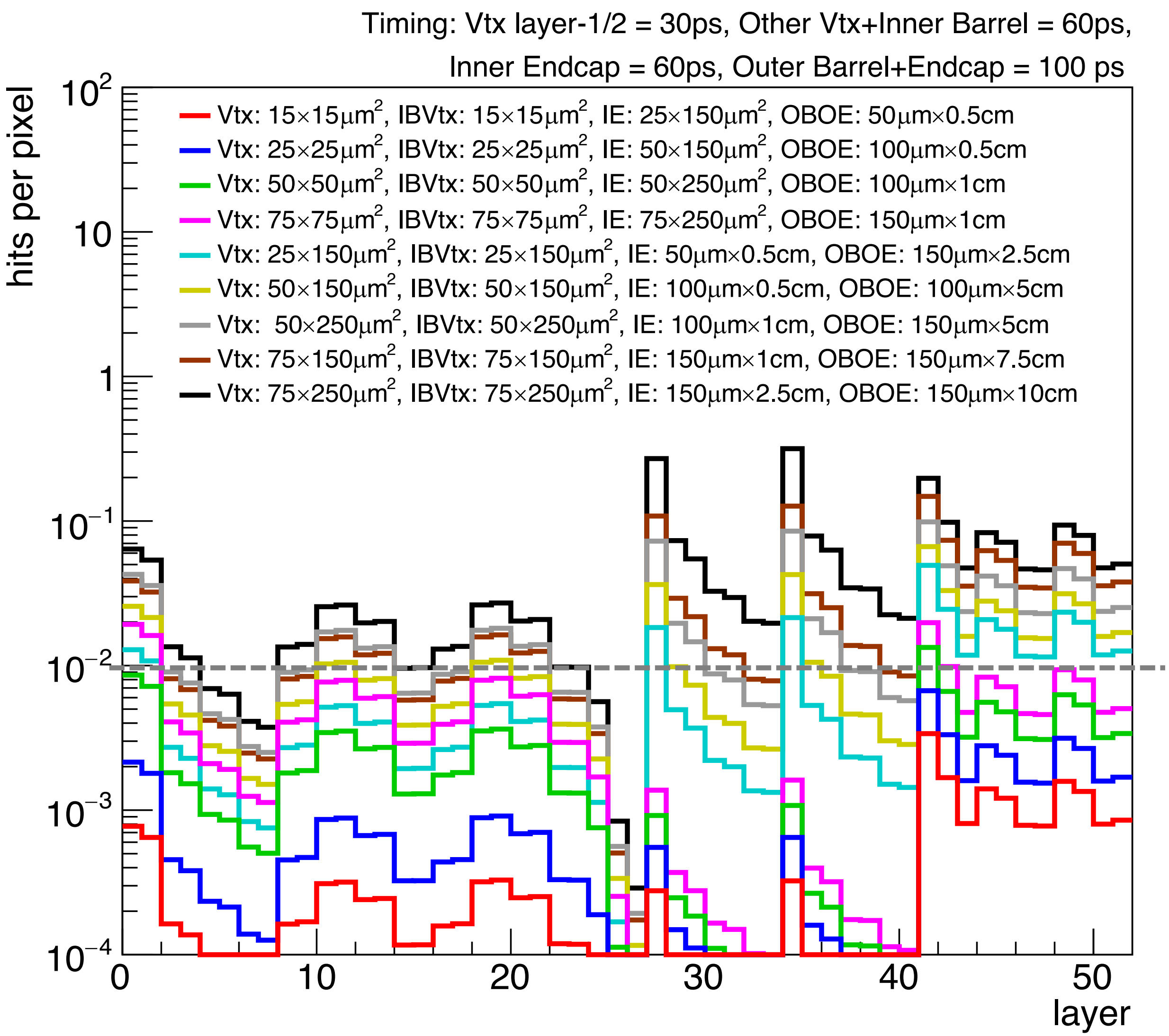
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for conservative timing configuration



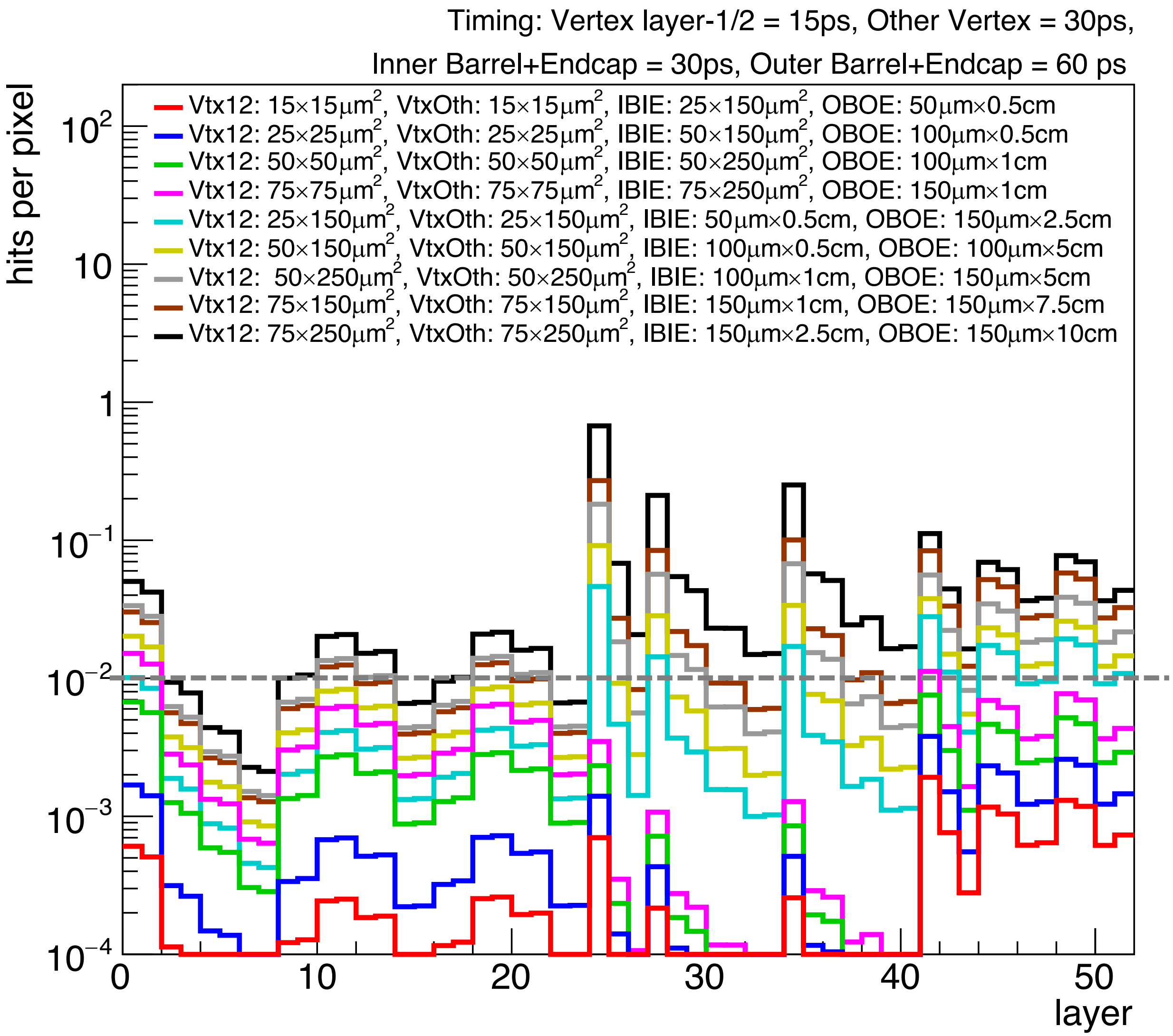
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for good timing configuration



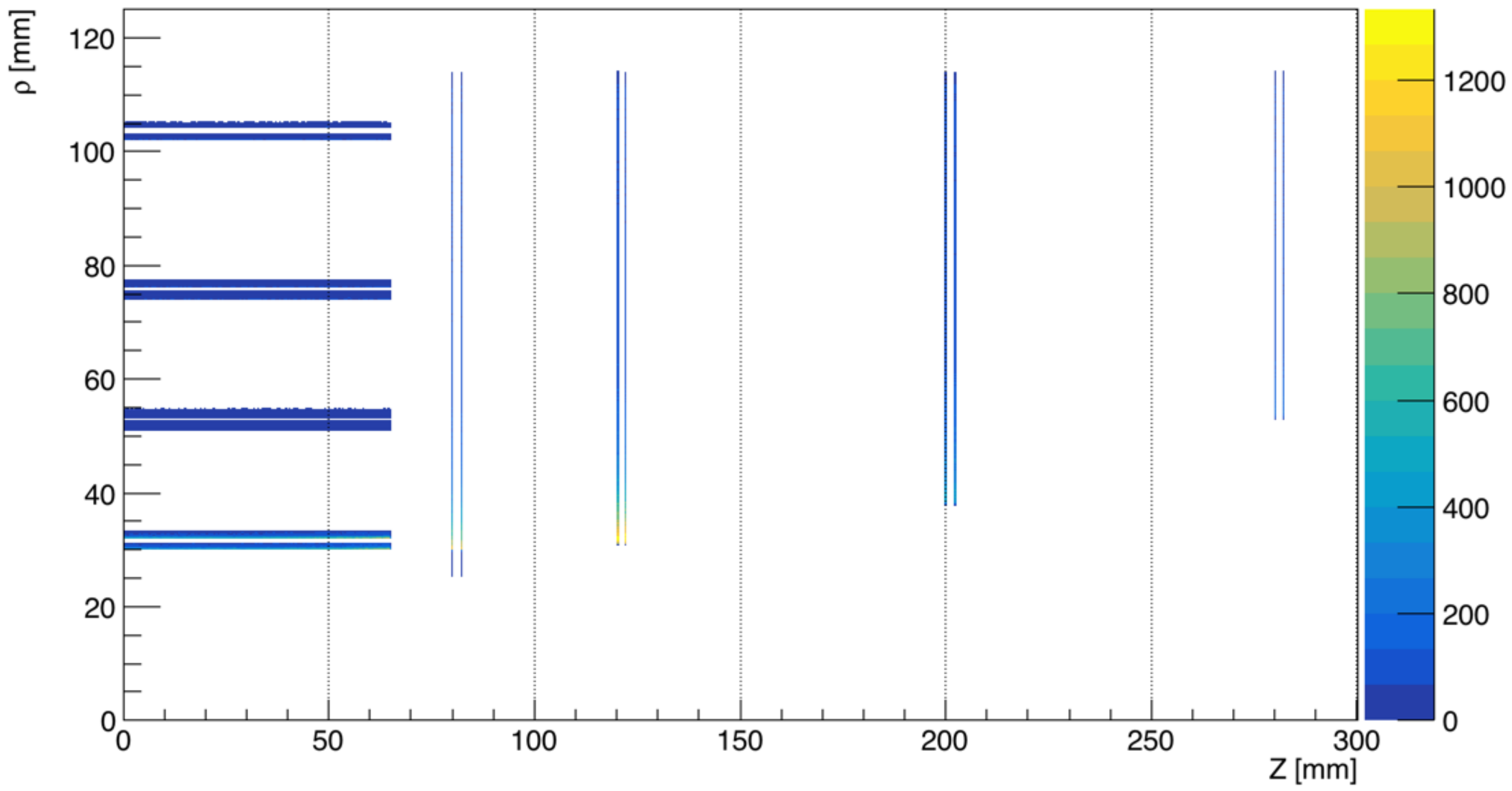
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for aggressive timing configuration

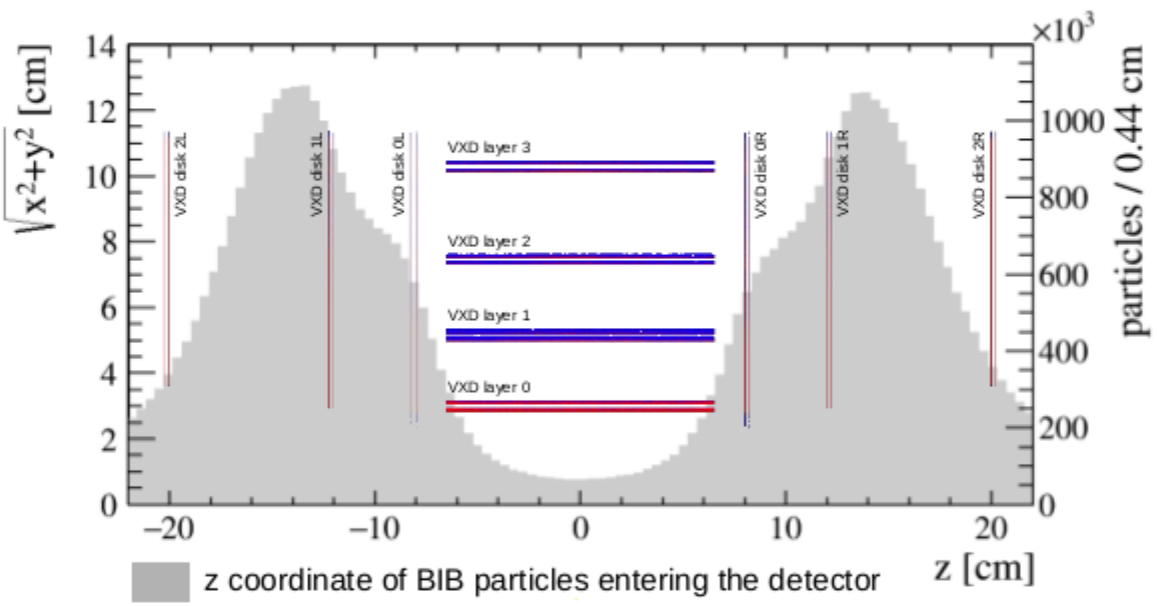


- If we can build a tracker with very good timing, the strips for the outer tracker can be of size up to ~2.5 cm.
- For the inner tracker, we can use macropixels. For innermost layer, LHC-style macropixels (100μm×1.5mm) should work.
- We can have LHC-sized pixels for the vertex detector.

Vertex detector hit map



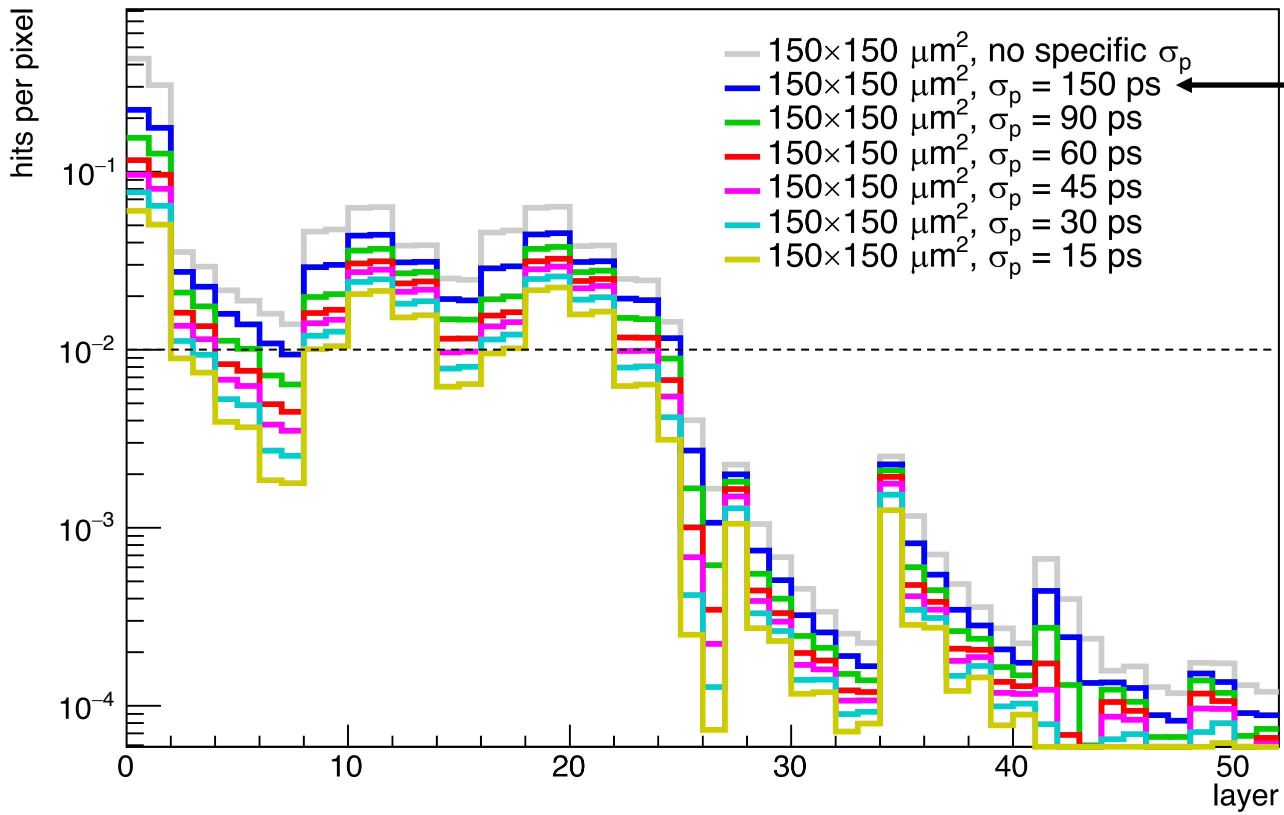
Vertex detector BIB distribution



Plot given to me by Massimo Casarsa

Add timing – for 150×150 μm²

- Even ”modest” timing can reduce occupancy by a large factor.
  - However, even a timing resolution better than the beam-intrinsic timing resolution will not be good enough for the innermost layer if pixels are too big.

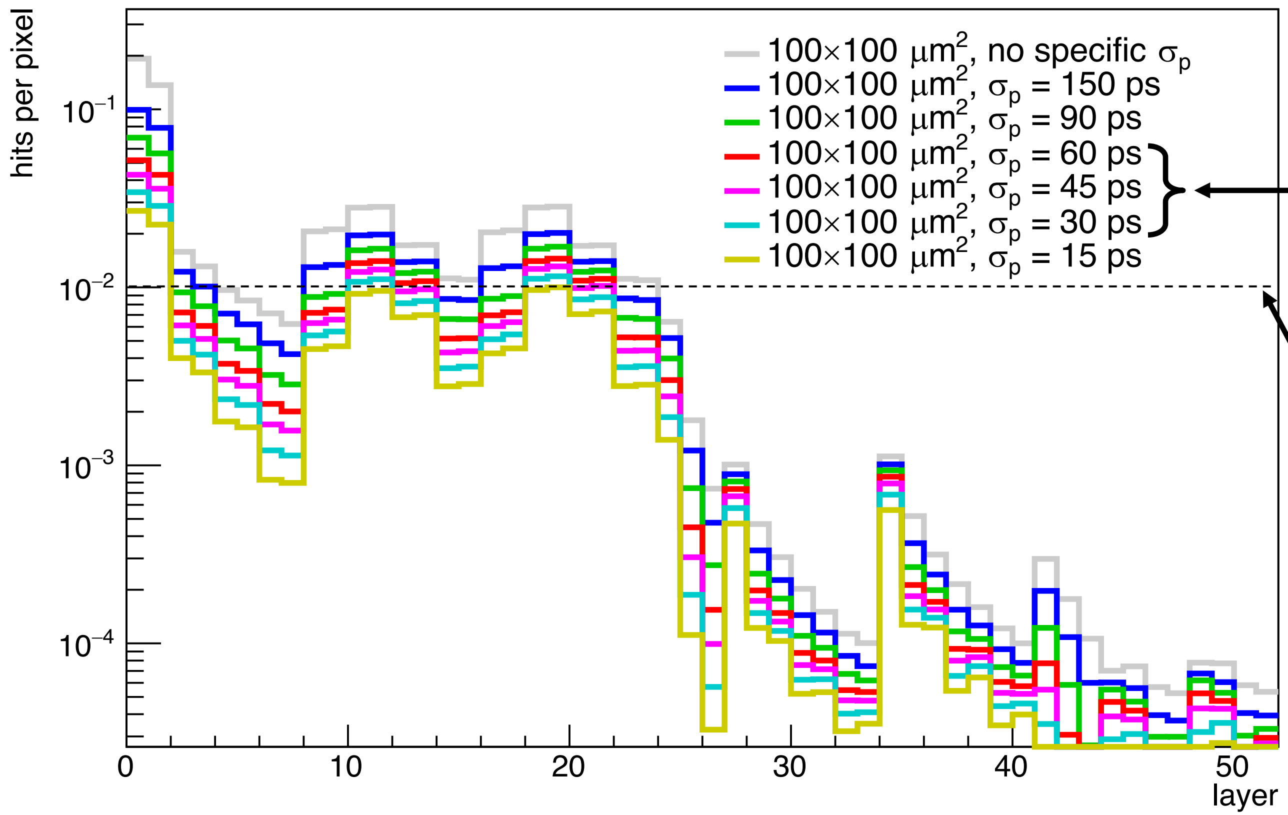


Even 150 ps reduces occupancy by ½ in innermost layers

But with pixels of the size of current CMS/ATLAS pixels, timing alone won’t help.

Add timing – for 100×100 μm²

- Even ”modest” timing can reduce occupancy by a large factor.
  - Good timing can work for all but two innermost layers.

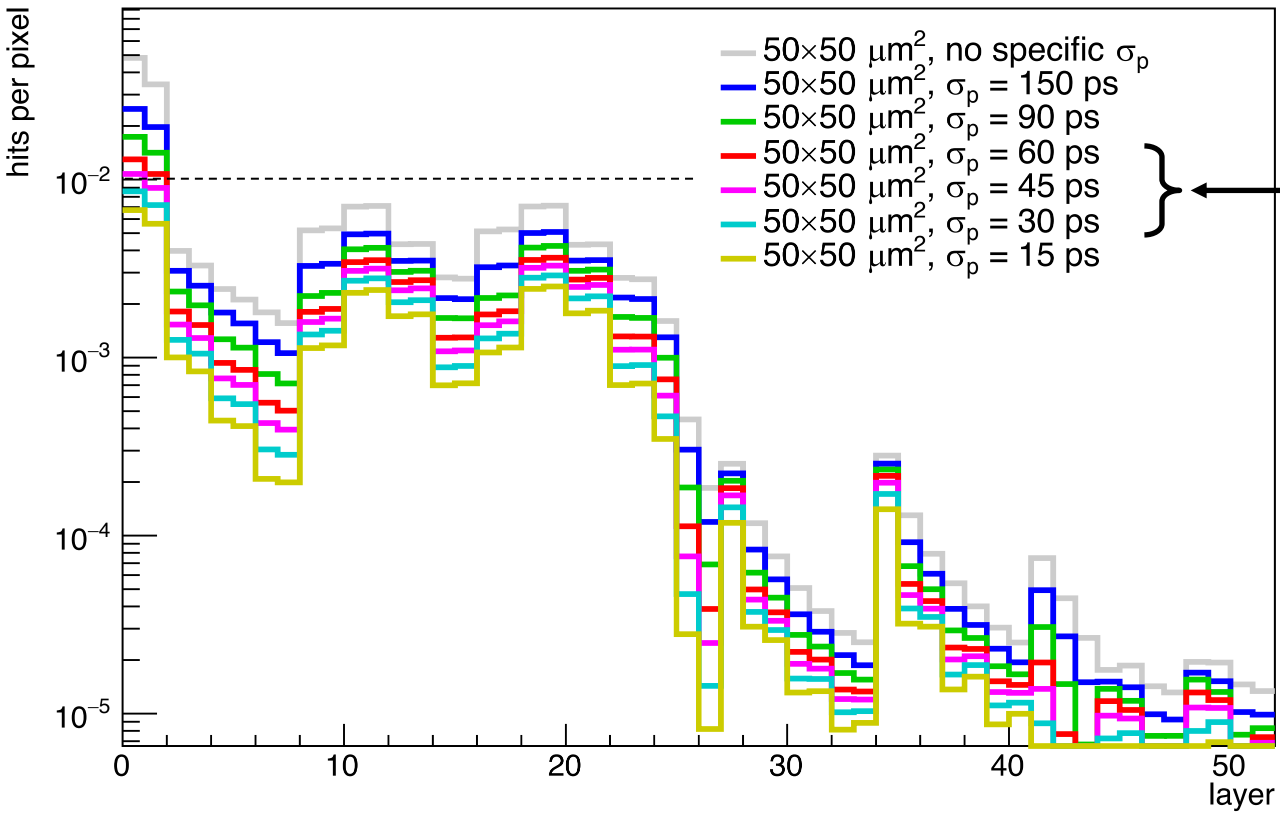


For inner tracker, need good timing (or smaller pixels)

But not good enough for two innermost layers.

Add timing – for 50×50 μm^2

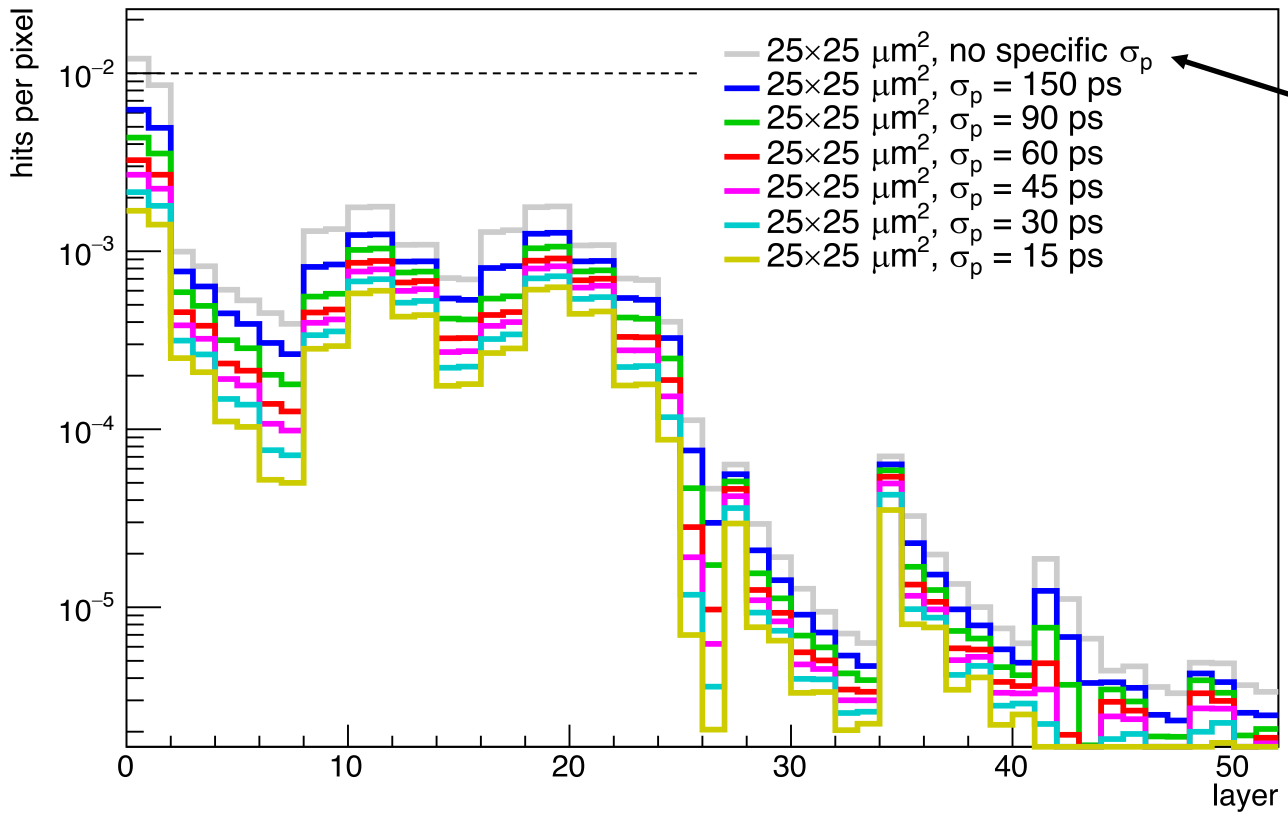
- Even ”modest” timing can reduce occupancy by a large factor.
  - With good timing, these pixels would work.



For inner tracker, any timing works. For innermost vertex layer need good timing.

Add timing – for 25×25 μm^2

- Even ”modest” timing can reduce occupancy by a large factor.
  - Smallest size pixels work even with ”poor timing”.



The 300ps timing required from ntuples is good enough for small pixel sizes.