STUDY ON TRACKER OCCUPANCY

Hannsjörg Weber (Fermilab)

The idea of the study

- The study is aimed to understand how space and time segmentation of the tracker compare for BIB rejection.

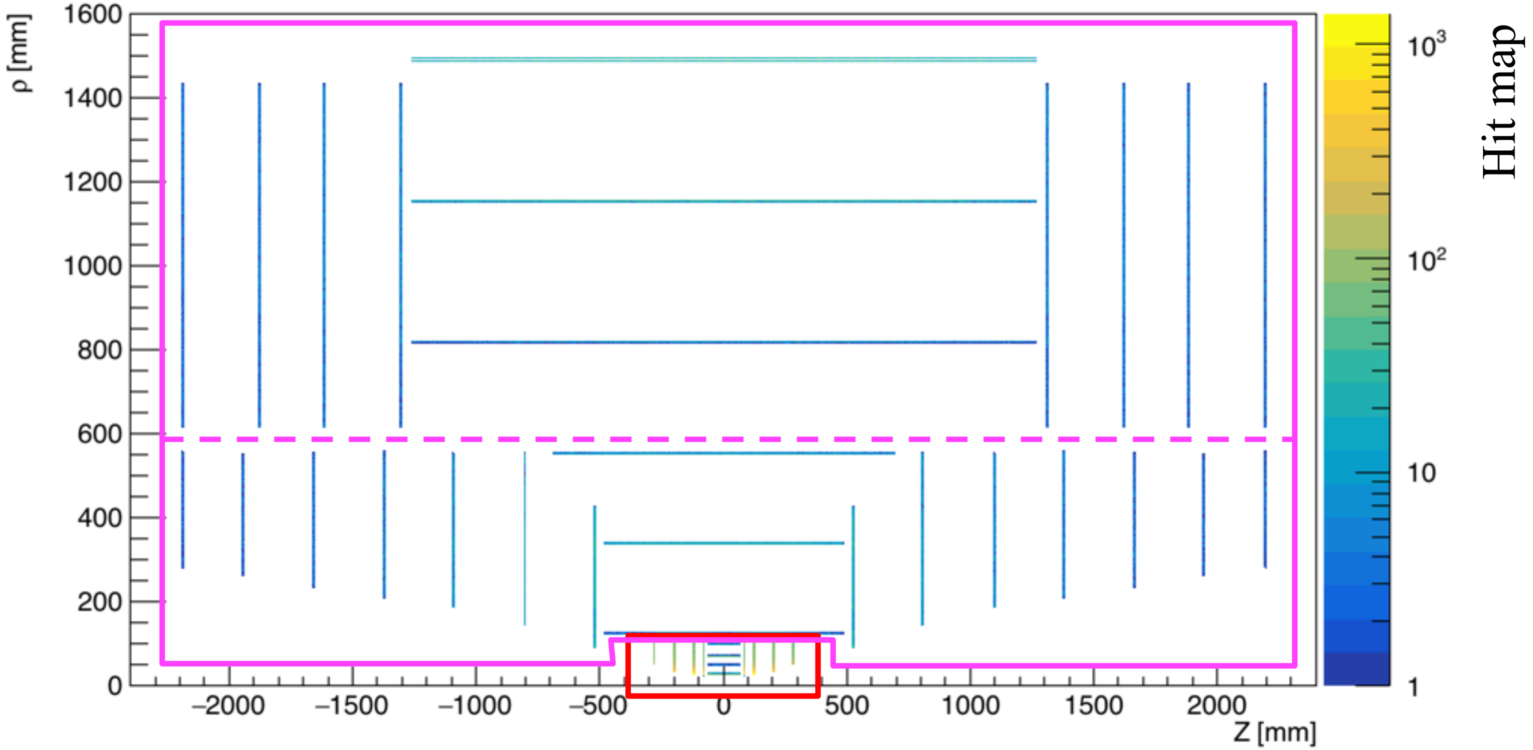
- Take a BIB event file and test what per pixel occupancy can be achieved for different assumption on pixel size and time resolution.
  - BIB only for $\sqrt{s}$ = 1.5 TeV configuration obtained using MARS.
  - I got a root ntuple and a simple macro from Massimo Casarsa telling me how to read it out (Thanks!).

- My goal was to see if we can get a per pixel occupancy of 1% or lower (number motivated what CLIC has set as its goal.
  - Note: number of particles from BIB >> number of particles from hard scatter, so studying BIB only file should be sufficient.
  - Also note, 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.

The muon collider tracker

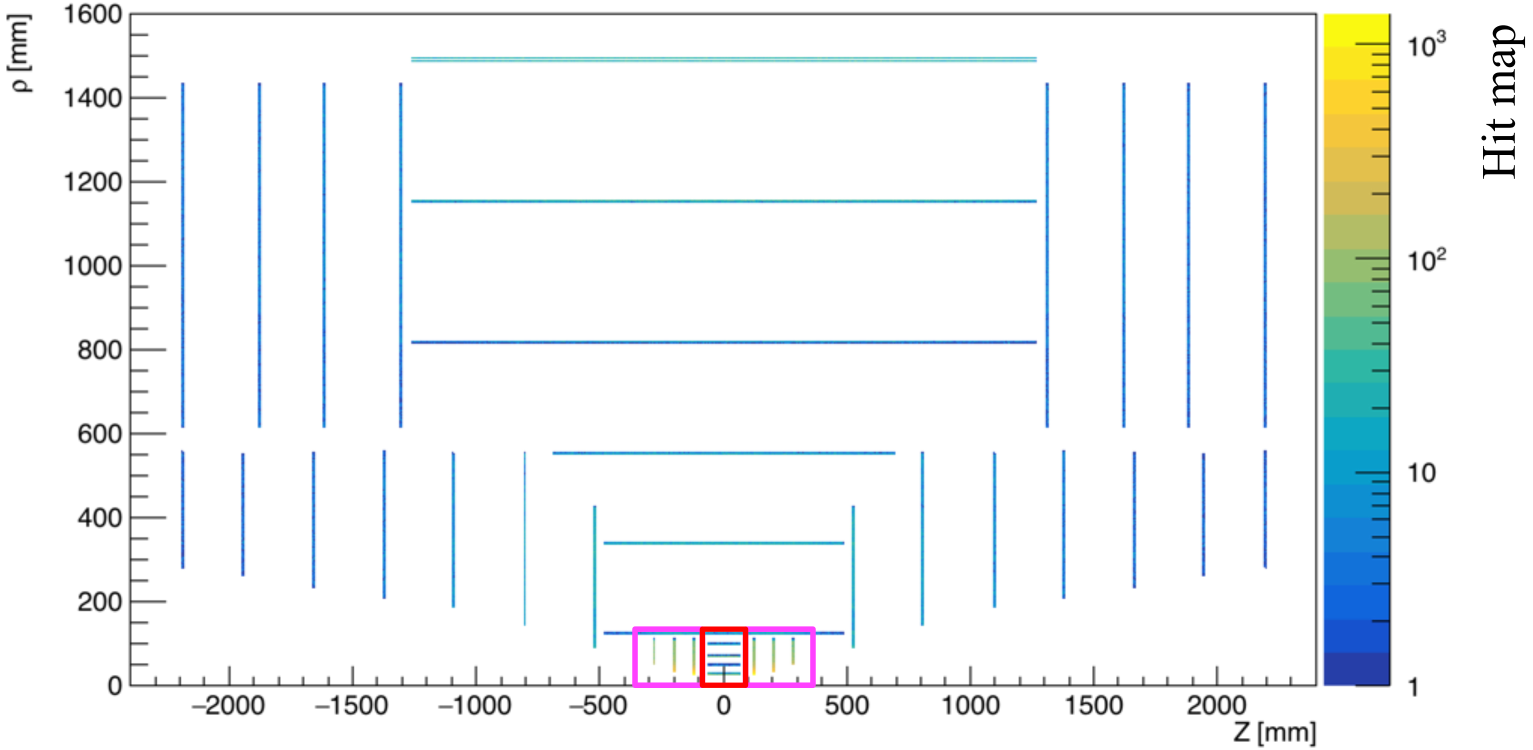
- The vertex tracker consist of 4 (4) double layer, the outer+inner tracker of 6 (7/4) single/double layers in barrel (endcap) region.

Outer+inner tracker



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

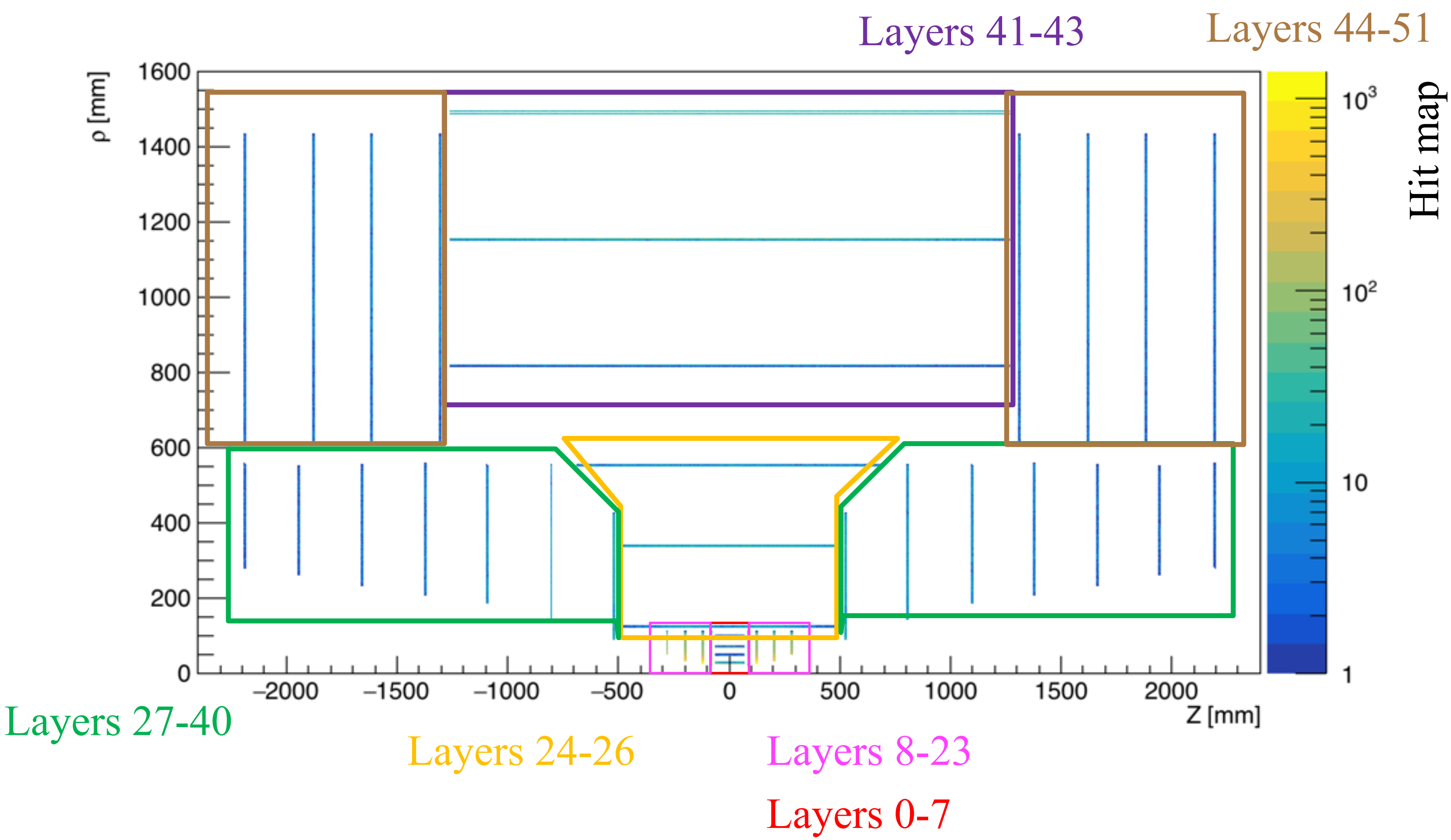
The muon collider tracker labeling



Layers 8-23

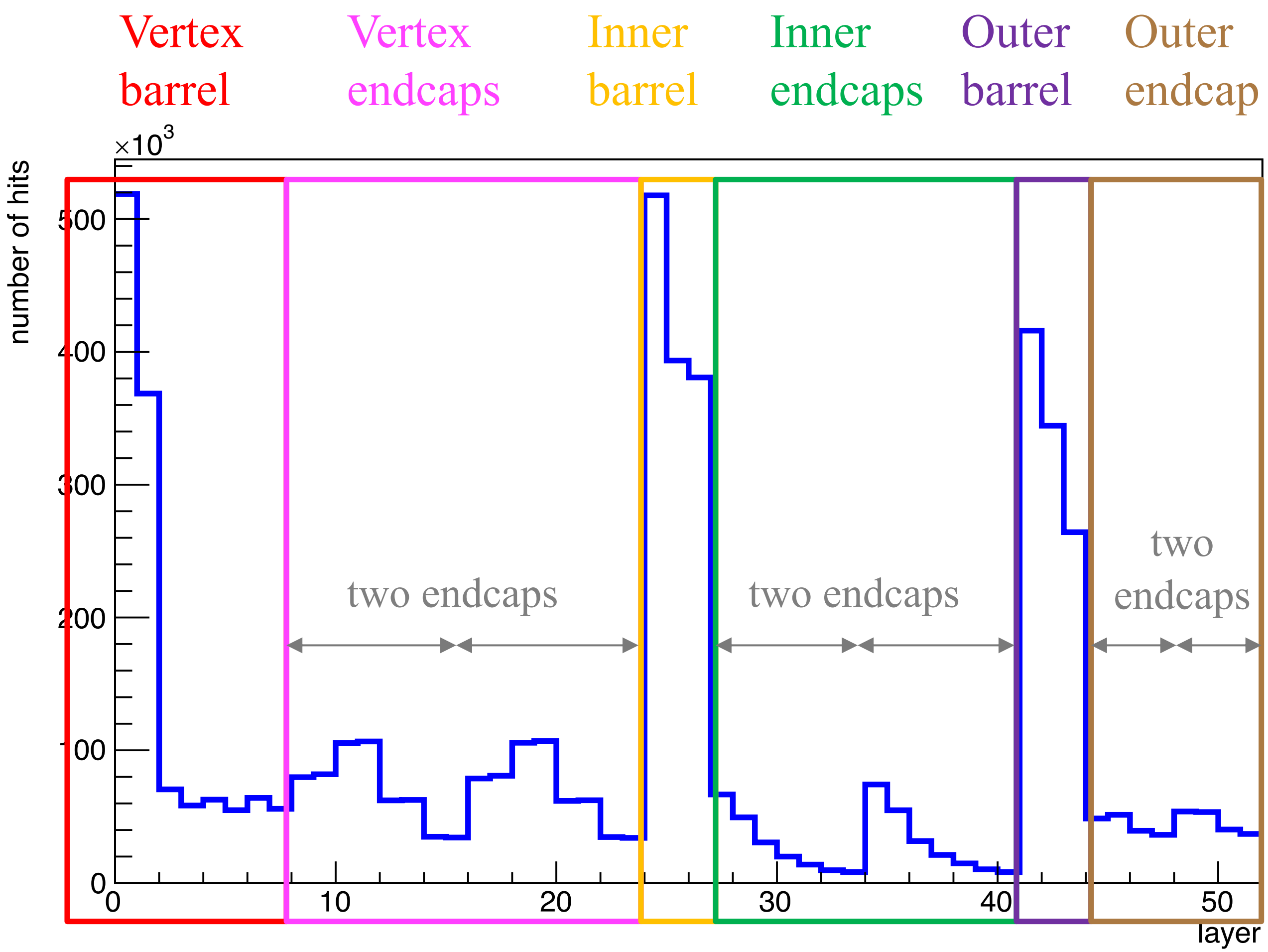
Layers 0-7

The muon collider tracker labeling



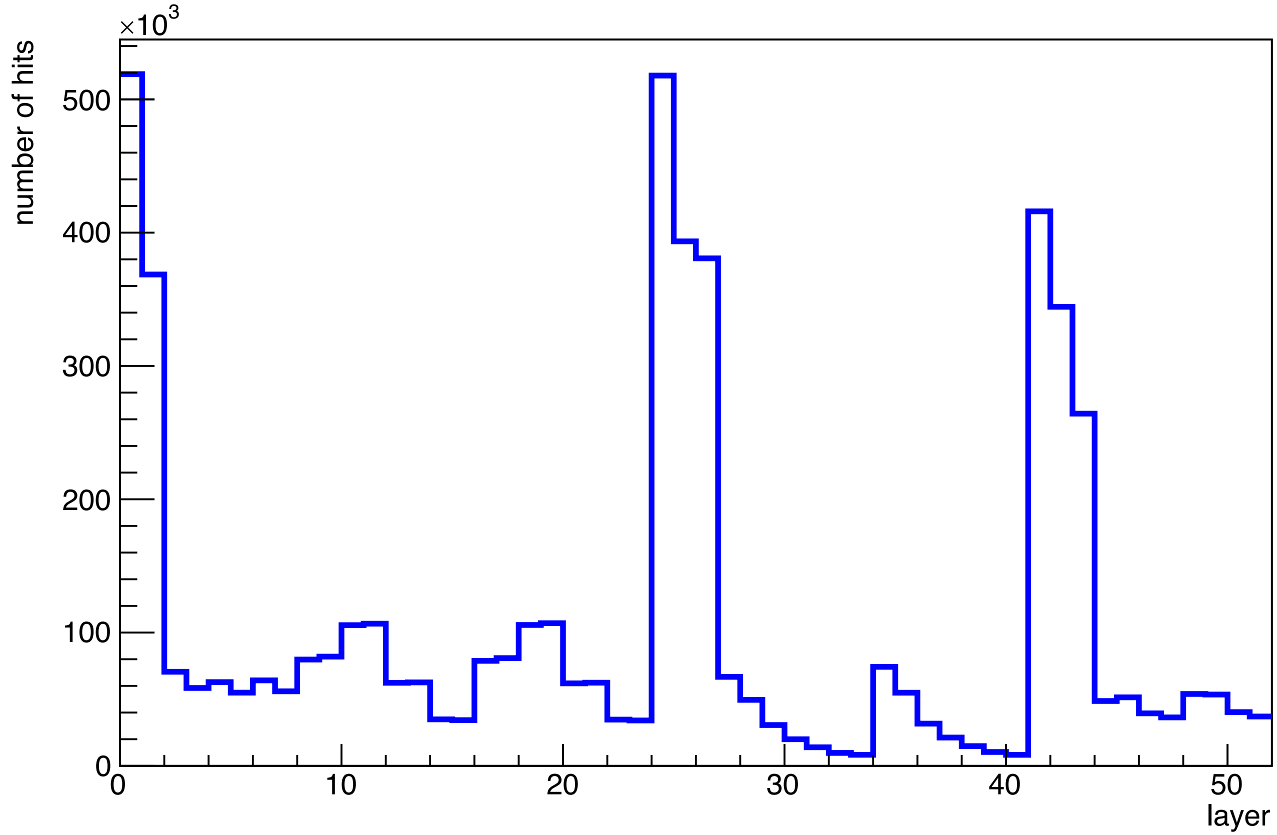
The muon collider tracker labeling

- Reminder of how layers are labeled.



Defining occupancy

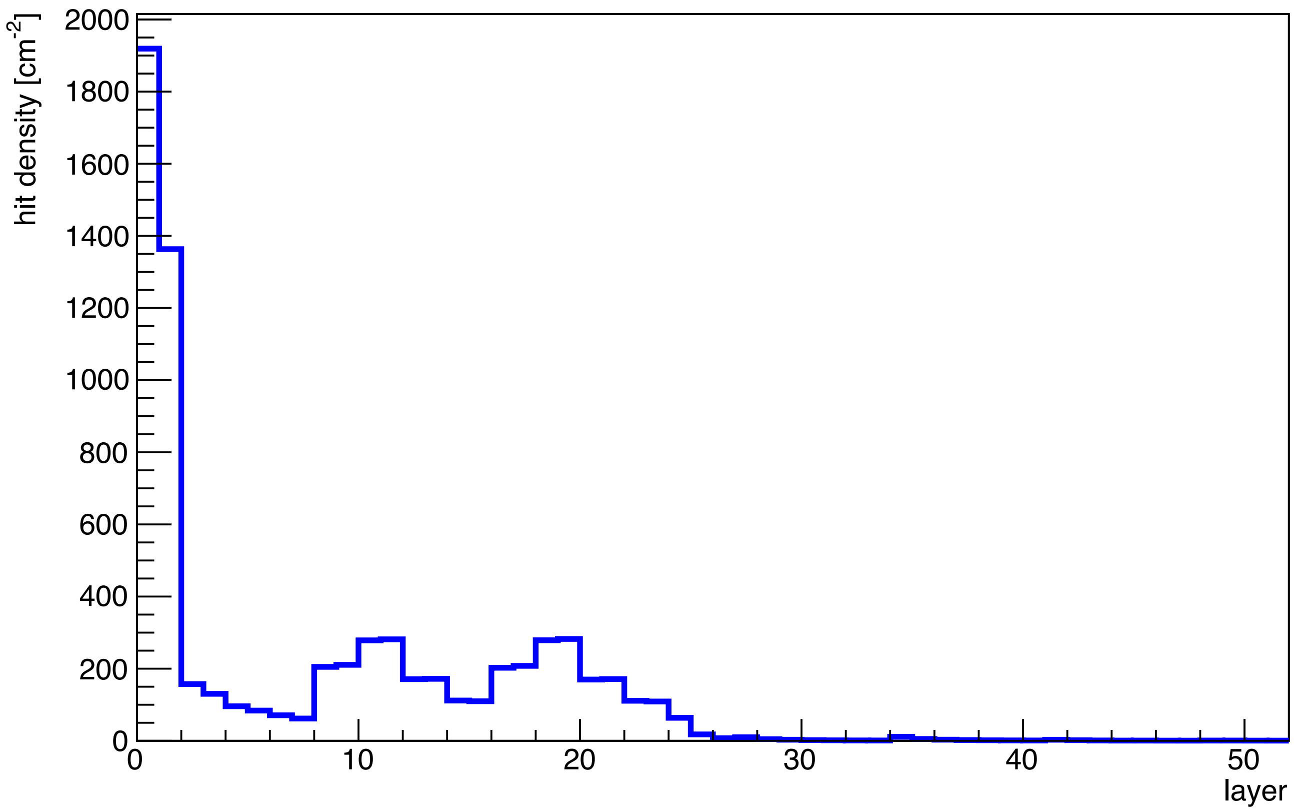
- Occupancy of a layer: Number of reconstruct(able) hits per layer: count every crossing through layer (so no detector reconstruction efficiency factored in), but count all crossing within a single pixel as one obviously



Up to half a million hits in one layer.

Defining occupancy

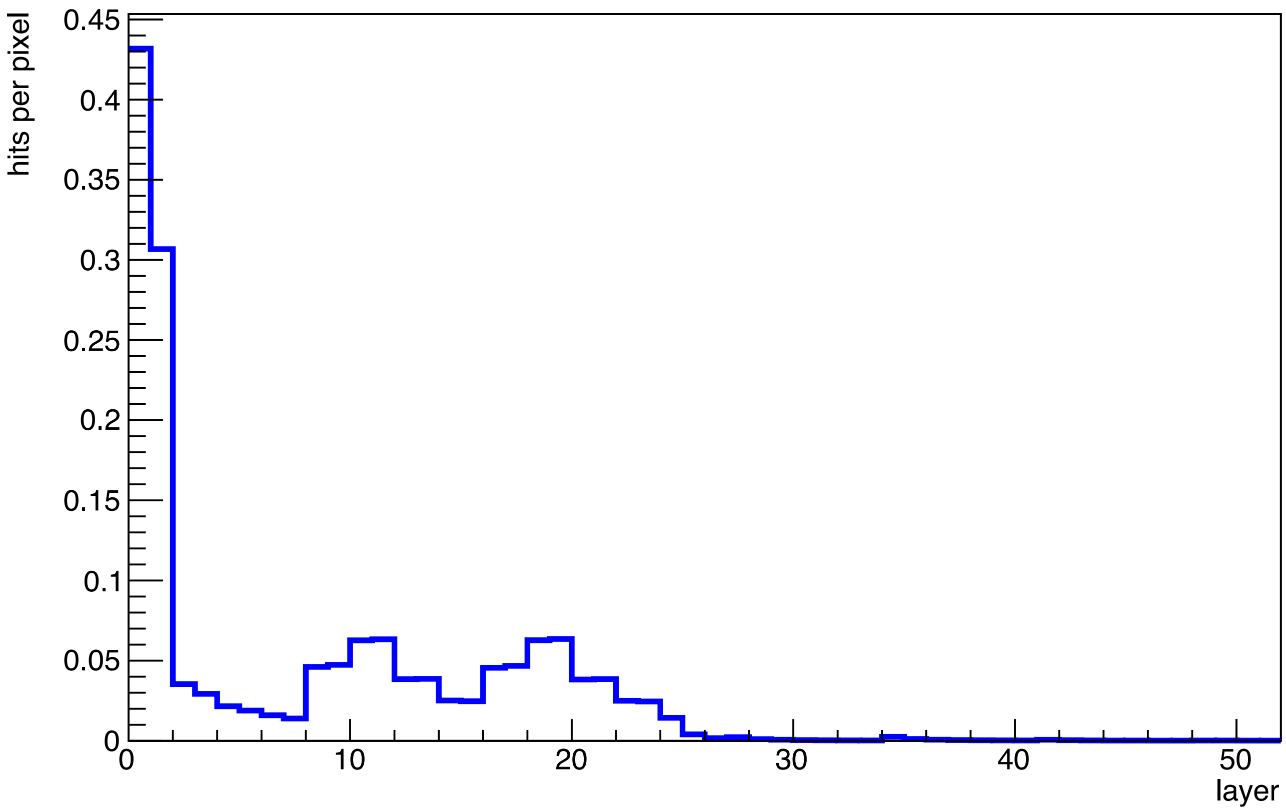
- Occupancy: Normalize that number by area of each layer



Up to 2000 hits per cm^2 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, no time resolution (but timing cut of 1 ns).

Reminder how I did the study

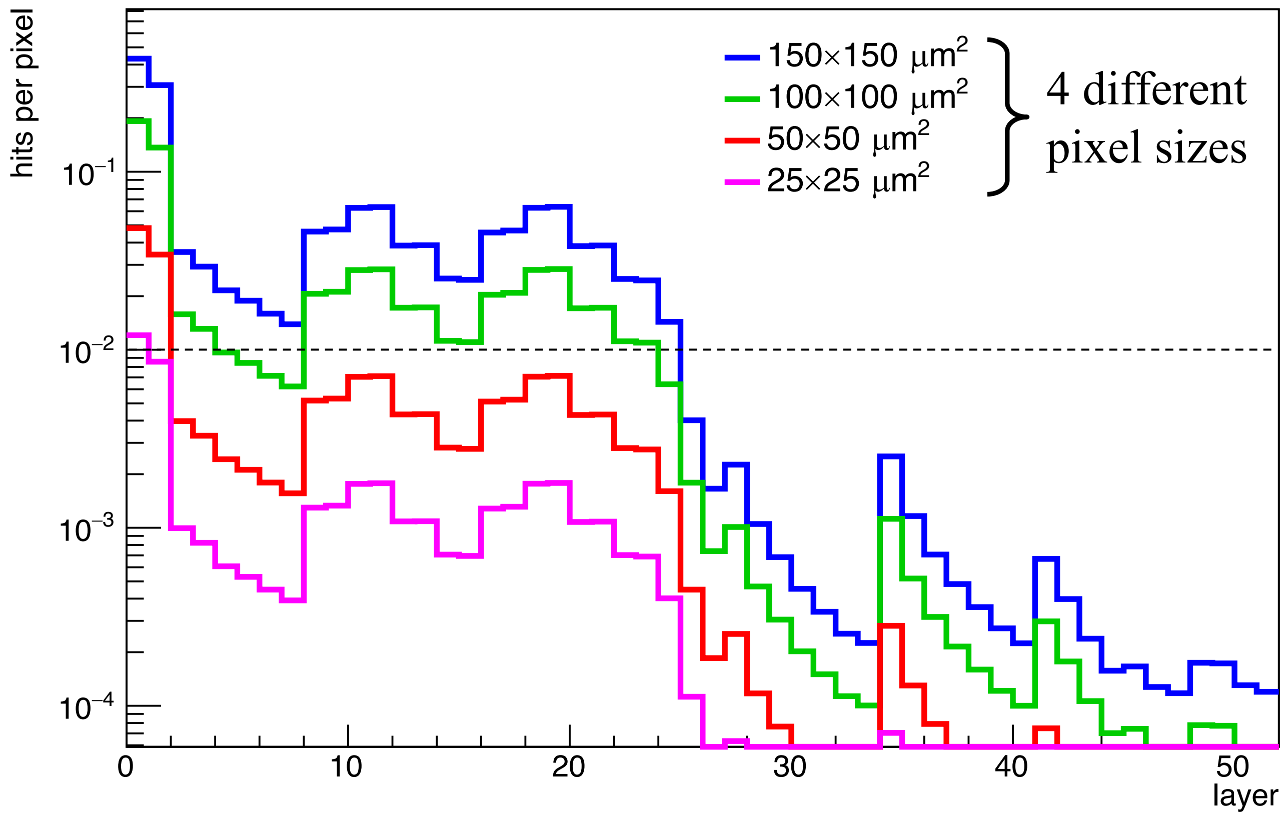
- This study is a simplified occupancy study by playing with 2 parameters.

1. Position resolution:
   - If two hits have distance is smaller than the pixel dimension, count one hit. Else, count as two hits.
     - This will lead in slightly too optimistic number (less than ×2), so number will be in the right ballpark.
     - I am using square or asymmetric pixels and/or strips, but in the first step I only consider square pixels.

2. Time resolution:
   - For every assumed time resolution σ_p of a pixel, smear arrival time by a Gaussian of that resolution. Cut on arrival times $> 3\sqrt{\sigma_p^2 + \sigma_b^2}$, where σ_b is the timing spread due to the beams (assumed as 25 ps).
     - I had a small bug here, but that one had a minor impact.
   - If any hit within the same pixel (see 1.) arrives within the timing window, count the hit, else the hit is disgarded.

Pixel hit density with no timing*

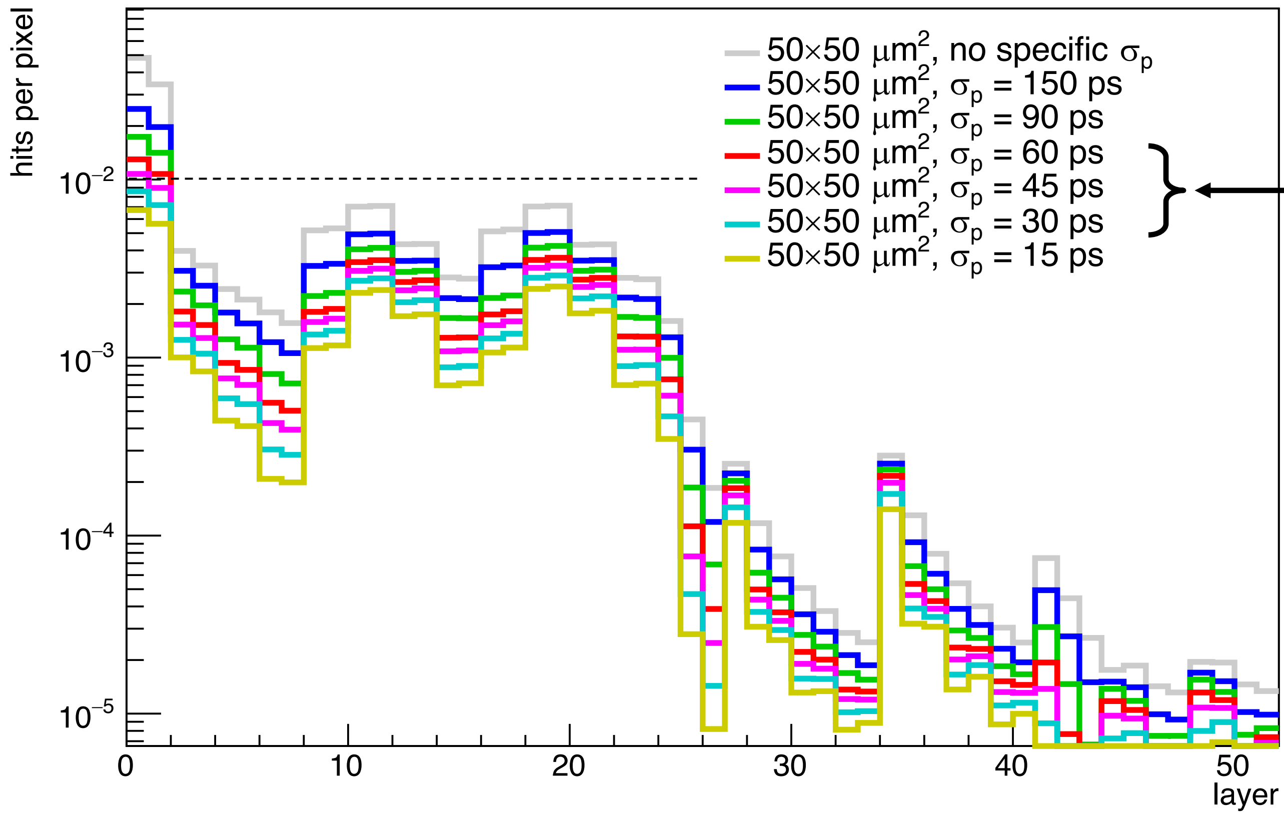
- * No timing means still that 1ns cut from ntuples is applied, i.e. effective $\sigma_p \approx 300$ ps.
  - If we had "no" access to timing, we could achieve low occupancy with 25×25 μm².



Vertex (25×25 μm²): 4.6 billion pixels
Inner (50×50 μm²): 8.3 billion pixels
Outer (150×150 μm²): 5.1 billion pixels

Add timing – for 50×50 µm²

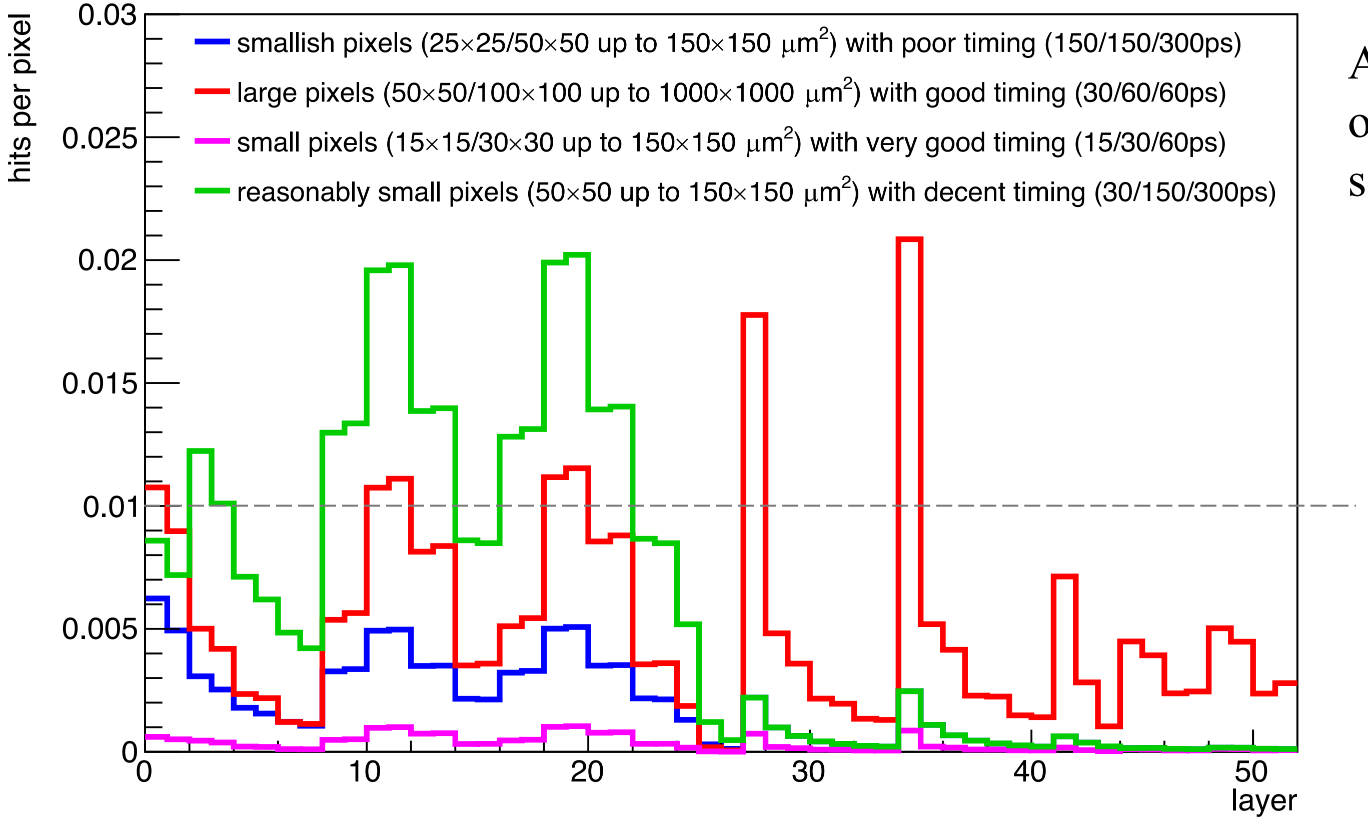
- Even ”modest” timing can reduce occupancy by a large factor.
  - With good timing, these pixels would work.



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

Possible configurations

	#pixels	Time L12	Res L12	Time V+IB	Res V+IB	Time IE+O	Res IE+O
Blue	9 bill	150 ps	$(25\ \mu m)^2$	150 ps	$(50\ \mu m)^2$	300 ps	$(150\ \mu m)^2$
Red	1 bill	45 ps	$(50\ \mu m)^2$	30 ps	$(100\ \mu m)^2$	60 ps	$(500\text{-}1000\ \mu m)^2$
Pink	17 bill	15 ps	$(15\ \mu m)^2$	30 ps	$(30\ \mu m)^2$	60 ps	$(100\text{-}150\ \mu m)^2$
Green	6 bill	30 ps	$(50\ \mu m)^2$	150 ps	$(100\ \mu m)^2$	300 ps	$(150\ \mu m)^2$



At this stage, I only considered square pixel.

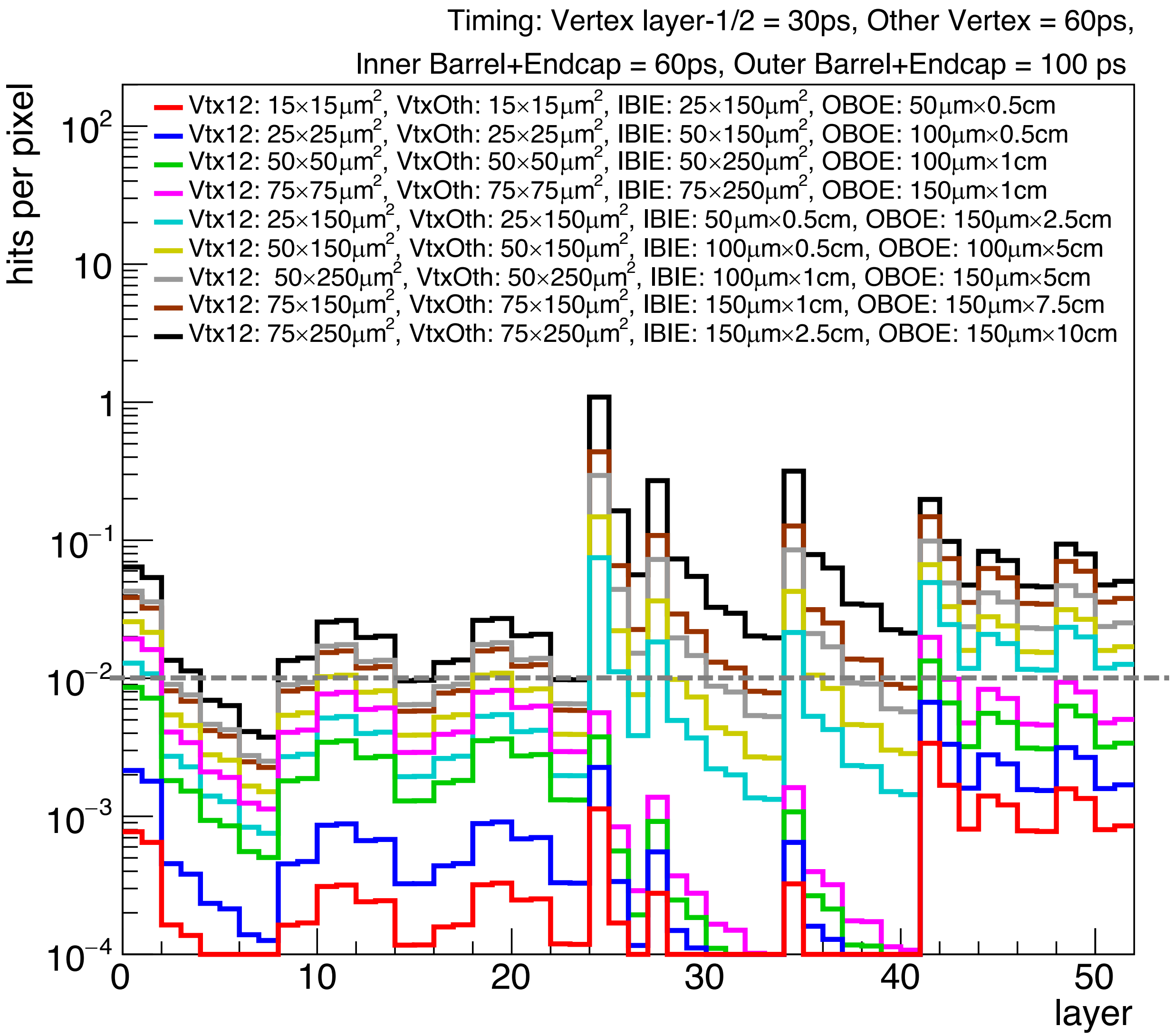
Target is 1-3%.

Added configuration

- When I started the study, I only used square pixels. Especially in the outer tracker, those are not needed.
- So, I added the option to use strips, etc.
    - Asymmetric pixels: long side of few 100µm.
    - Macropixels: long side being of order millimeters.
    - Short strips: long side of order of centimeters, $\leq$2.5cm.
    - Long strips: up to 15cm.

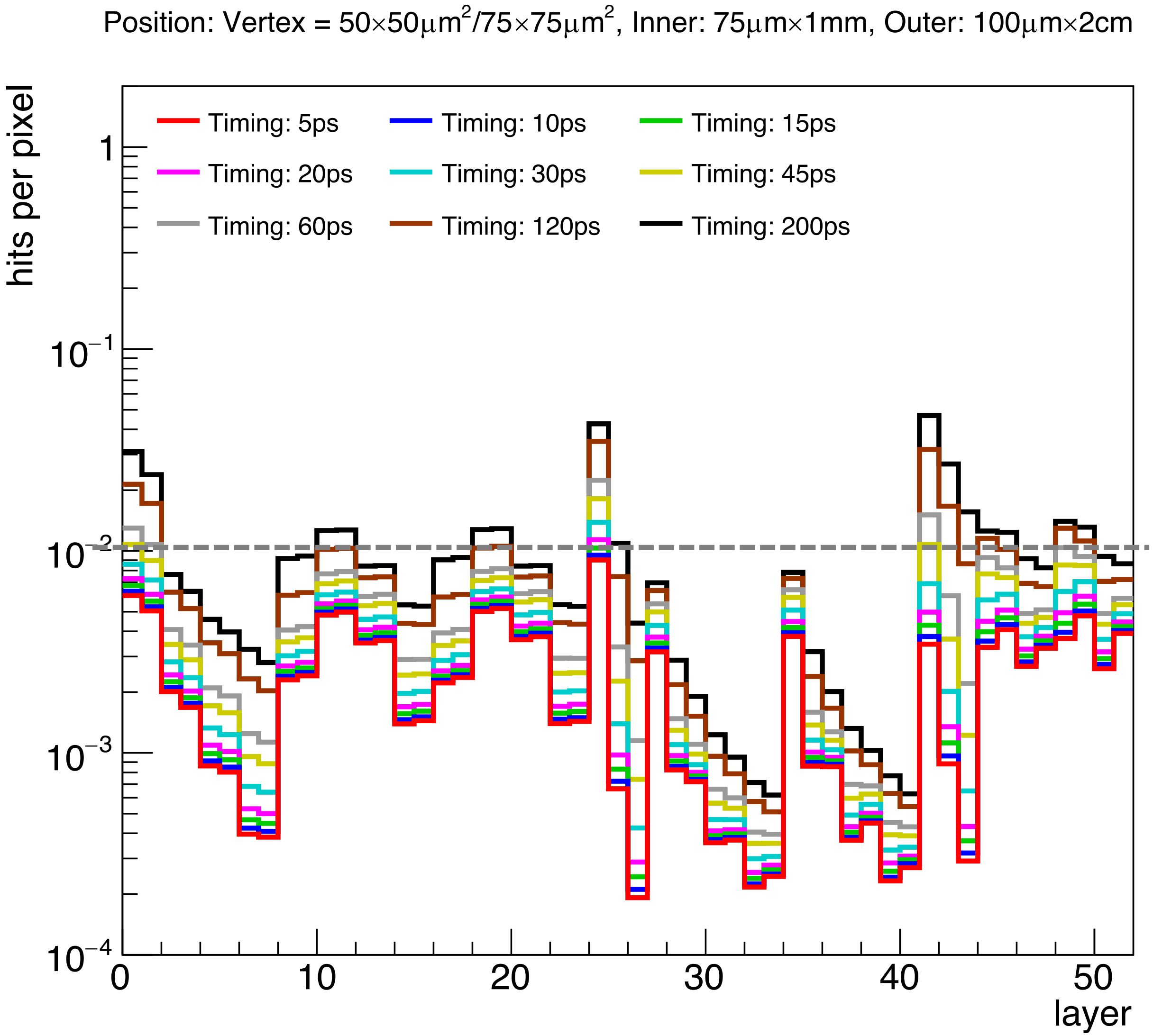
- In the backup, I show several scenarios, but here I show only 2 plots:
    - Fix timing, and play with pixel/strip size.
    - Fix pixel/strip size, play with timing.

Pixel occupancy for nominal timing configuration



- We find that even with good timing, we still need short strips O(100 μm × 1 cm) in the outer tracker (i.e. cannot use long strips).
- For the inner endcaps, we can use macropixels O(100 μm × 1 mm) , possibly shorter for innermost barrel layer.
- We can have LHC-sized pixels for the vertex detector.

Pixel occupancy with flipped legend



- 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 need better timing of 20-30ps.
- For pixels/strip larger, of course tighter timing requirements are needed.

Summary

- I did an extremely simple study, studying how many hits can be reconstructed depending on the pixel size and pixel time resolution.
  - I extended that study to allow for asymmetric pixels/macropixels and short/long strips.

- 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 2cm).
- We cannot use long strips anywhere in the detector, even with good timing.
  - Assuming this type of configuration with good timing, the detector would have about 1.5 billion pixels (≤ number of pixels for CMS phase-2).
- Modest timing is needed for outer and inner tracker, good timing for the vertex tracker (and preferable for barrel throughout).

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

Added configuration

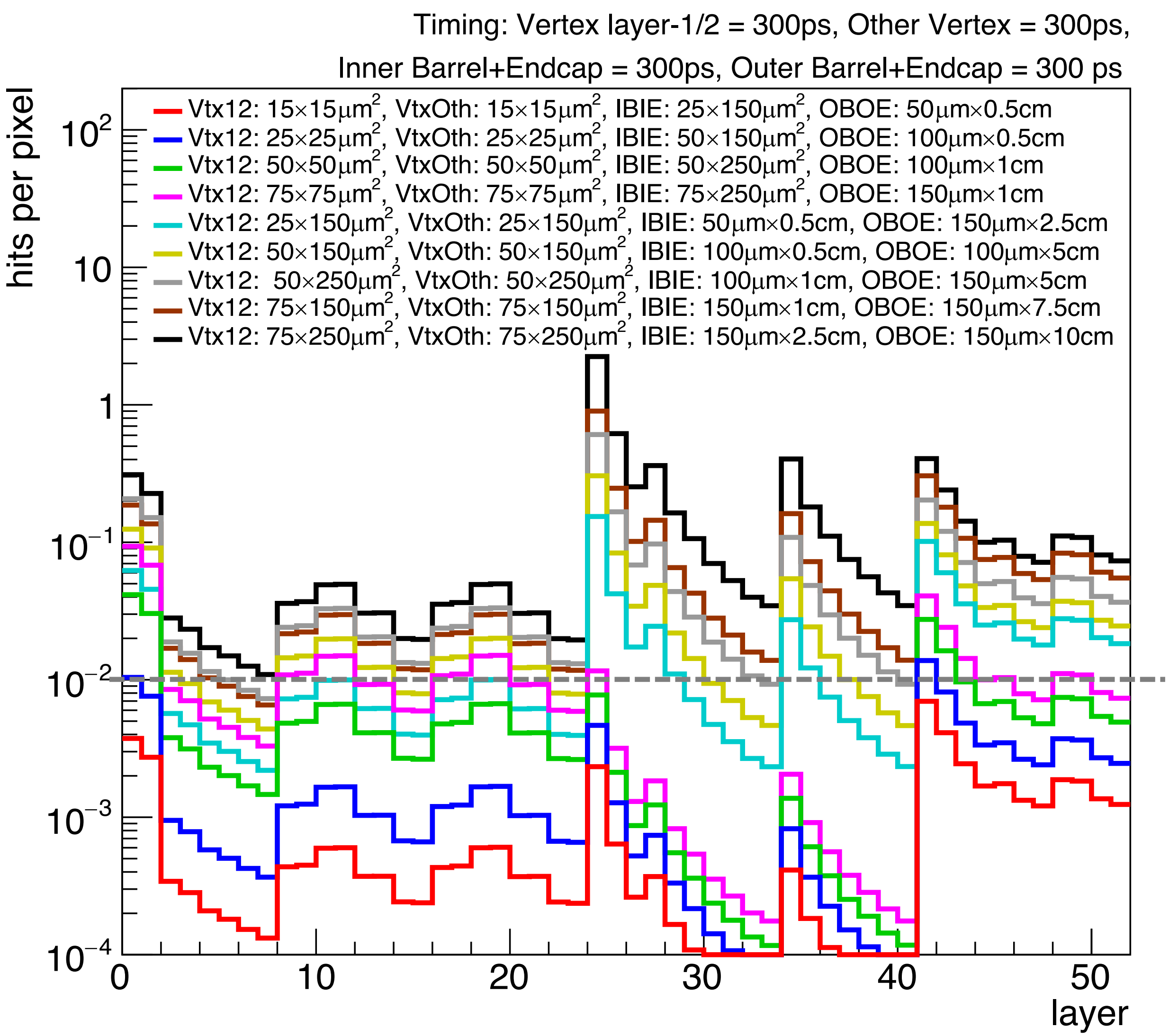
- When I started the study, I only used square pixels. Especially in the outer tracker, those are not needed.
- So, I added the option to use strips, etc.
  - Asymmetric pixels: long side of few 100μm
  - Macropixels: long side being of order mm.
  - Short strips: long side of order of cm, ≤2.5cm.
  - 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

*In backup is a version where Inner barrel is treated the same as Other vertex detector instead.

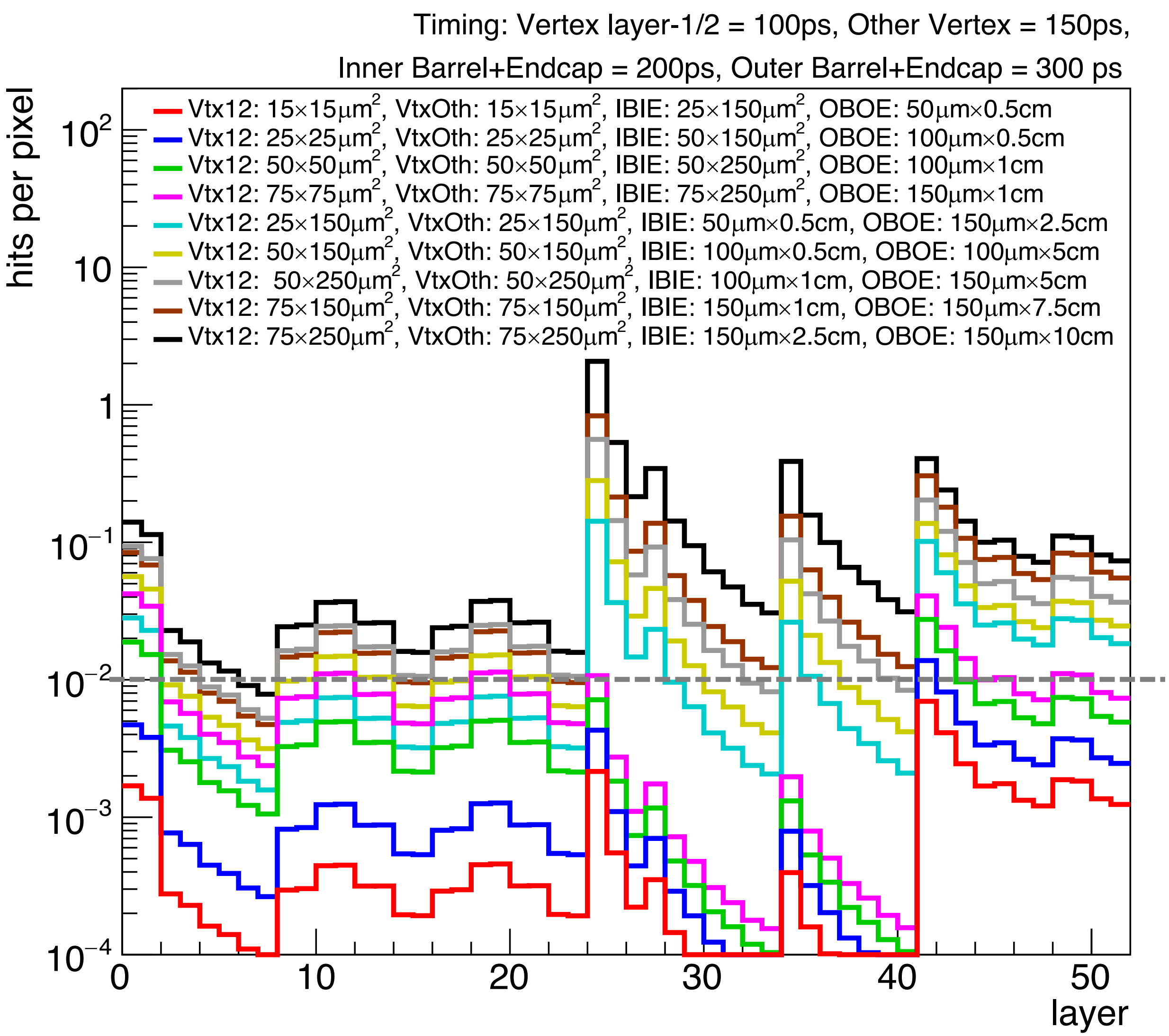
Targets: in next slides, other timings in backup

Pixel occupancy for ntuple timing configuration



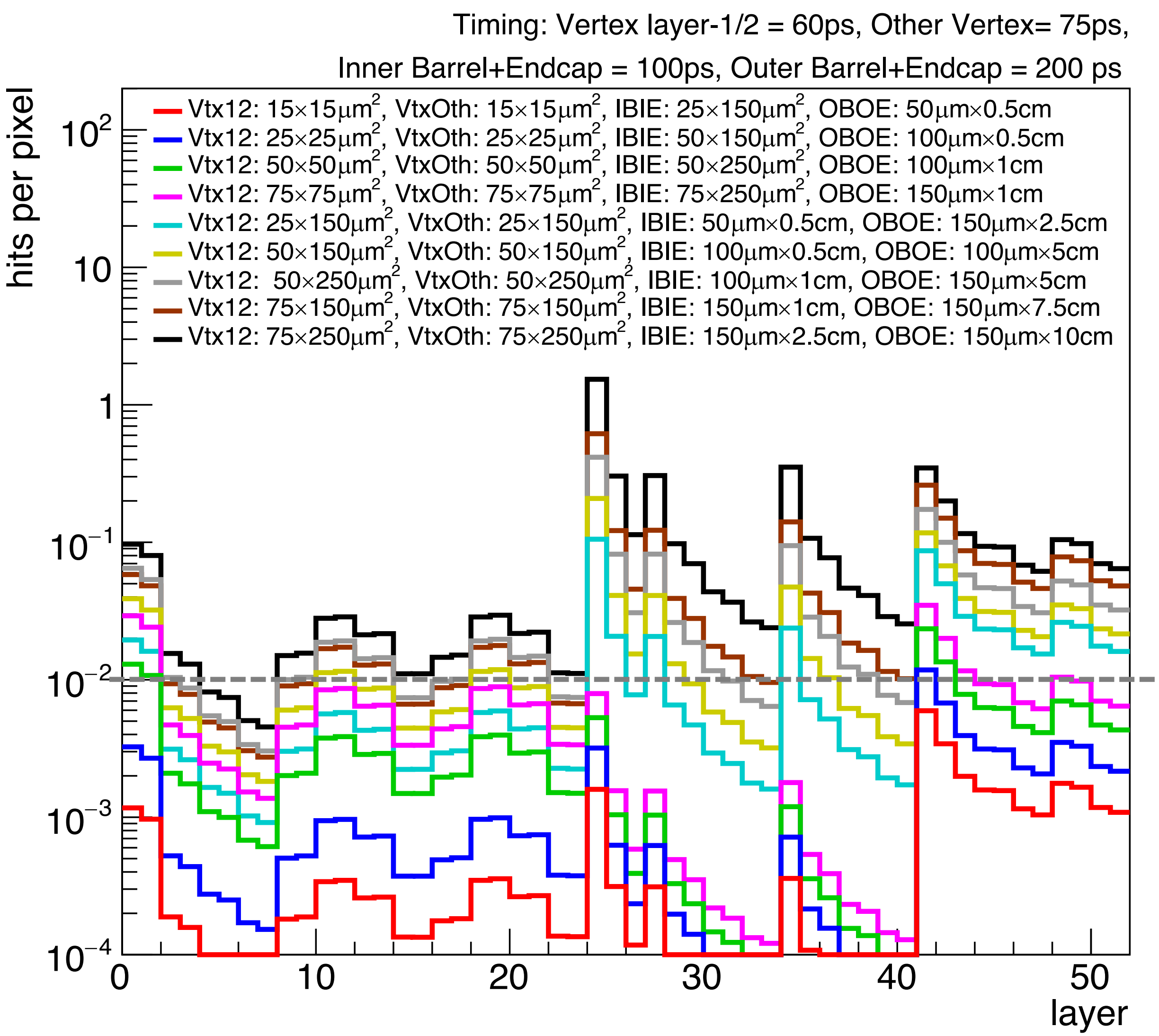
- If we cannot build good timing tracker, we really need macropixels in the outer detector.
- For the inner tracker, we can have asymmetric pixels throughout, but macropixels are too large.
- Vertex tracker needs small pixels.

Pixel occupancy for bad timing configuration



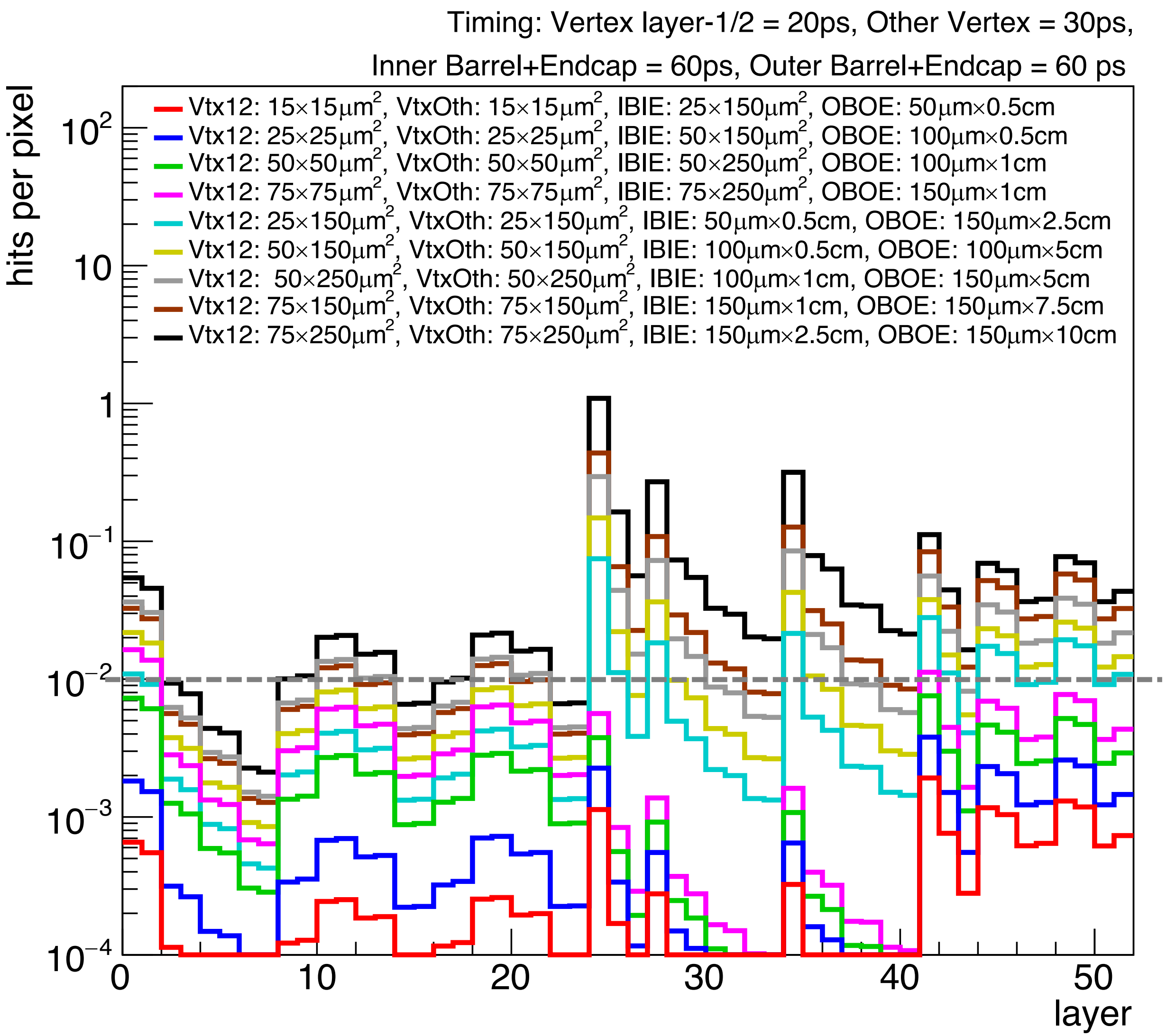
- If we cannot build good timing tracker, we really need macropixels in the outer detector.
- For the inner tracker, we can have asymmetric pixels throughout , but macropixels are too large.
- Vertex tracker needs small pixels.

Pixel occupancy for conservative timing configuration



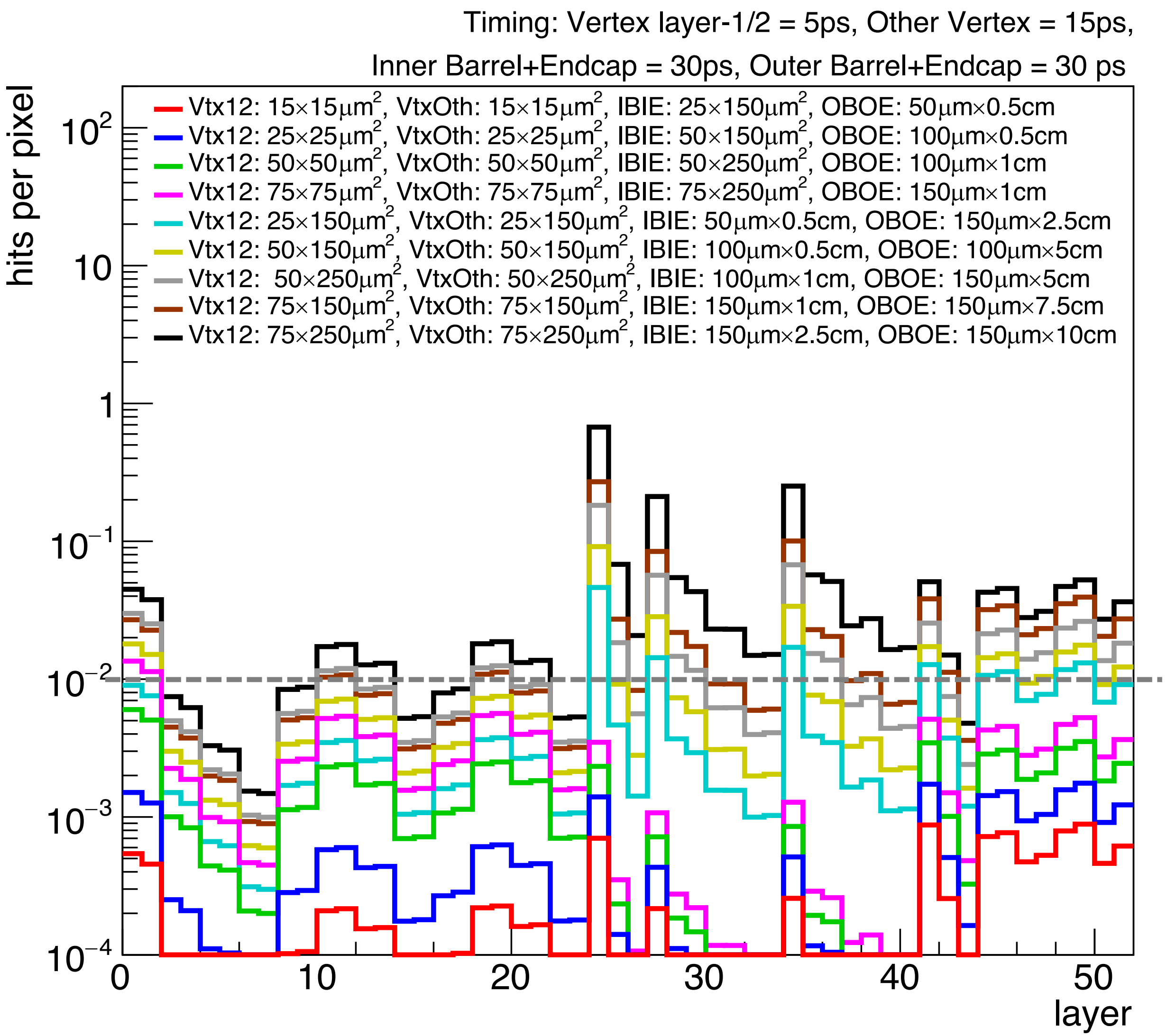
- For conservative timing, we need very short strips in the outer tracker.
- For the inner endcaps, we can use macropixels, we still need (asymmetric) pixels in the inner barrel.
- We can have LHC-sized pixels for the vertex detector, potentially smaller for the two innermost layers.

Pixel occupancy for achievable timing configuration



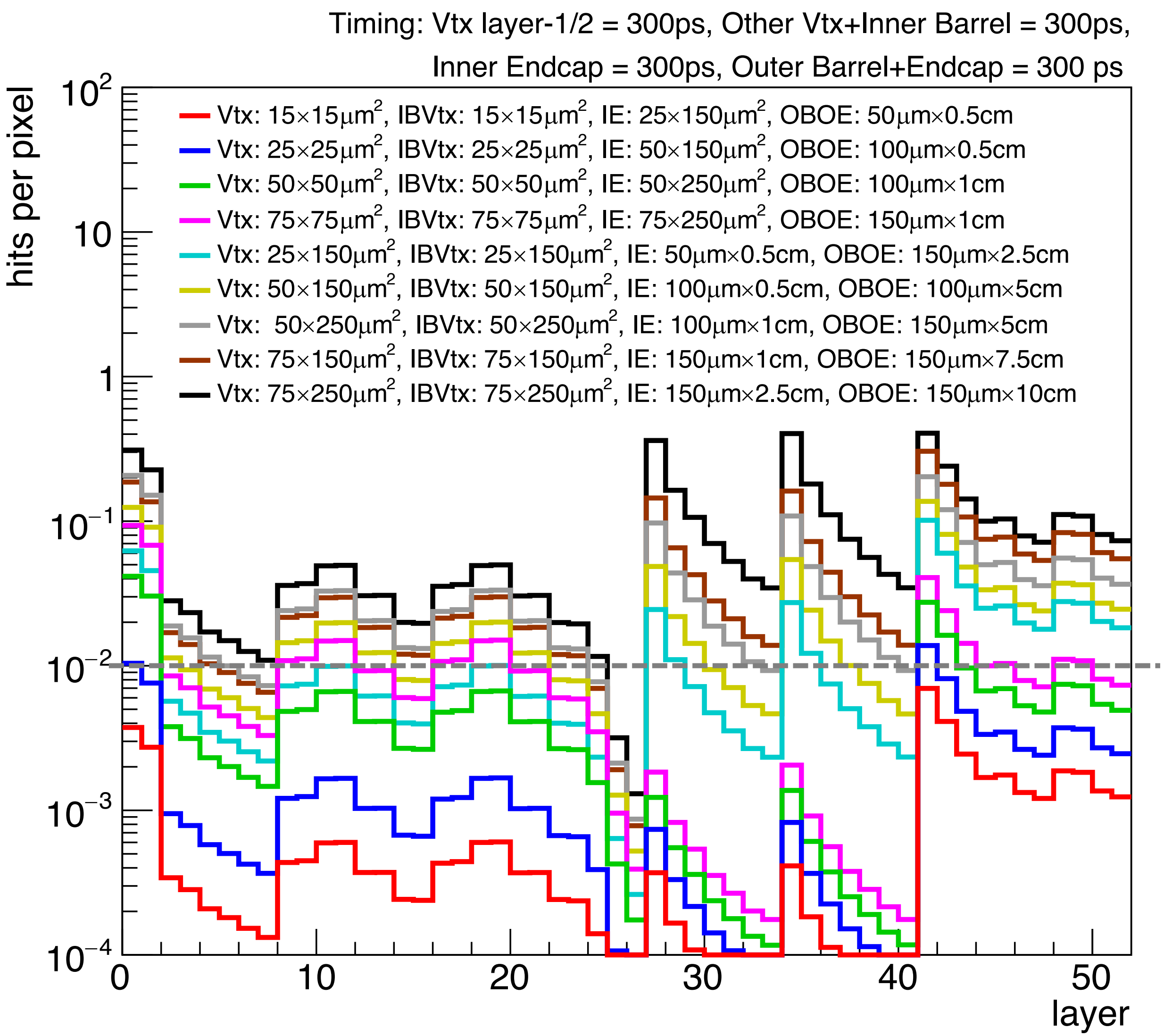
- These timing values were suggested by Artur Apresyan.
- It seems we need something like
  - $50\times50\ \mu m^2$ (2 innermost layers)
  - $75\times75\ \mu m^2$ (rest of vertex tracker)
  - $75\ \mu m \times 1$ mm (inner tracker)
  - $100\ \mu m \times 2$ cm

Pixel occupancy for aggressive timing configuration



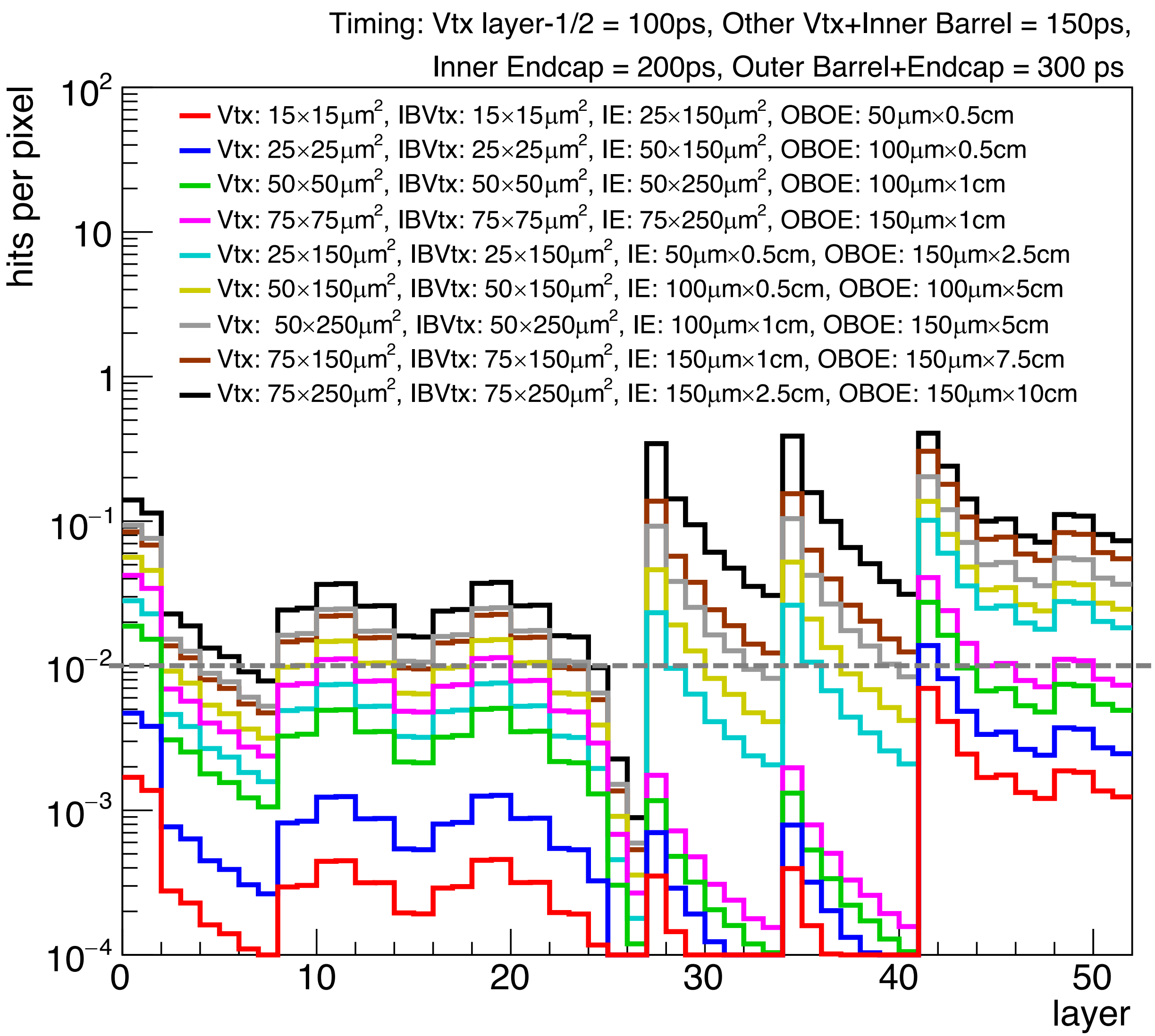
- This plot is overly optimistic.

Pixel occupancy for ntuple timing configuration



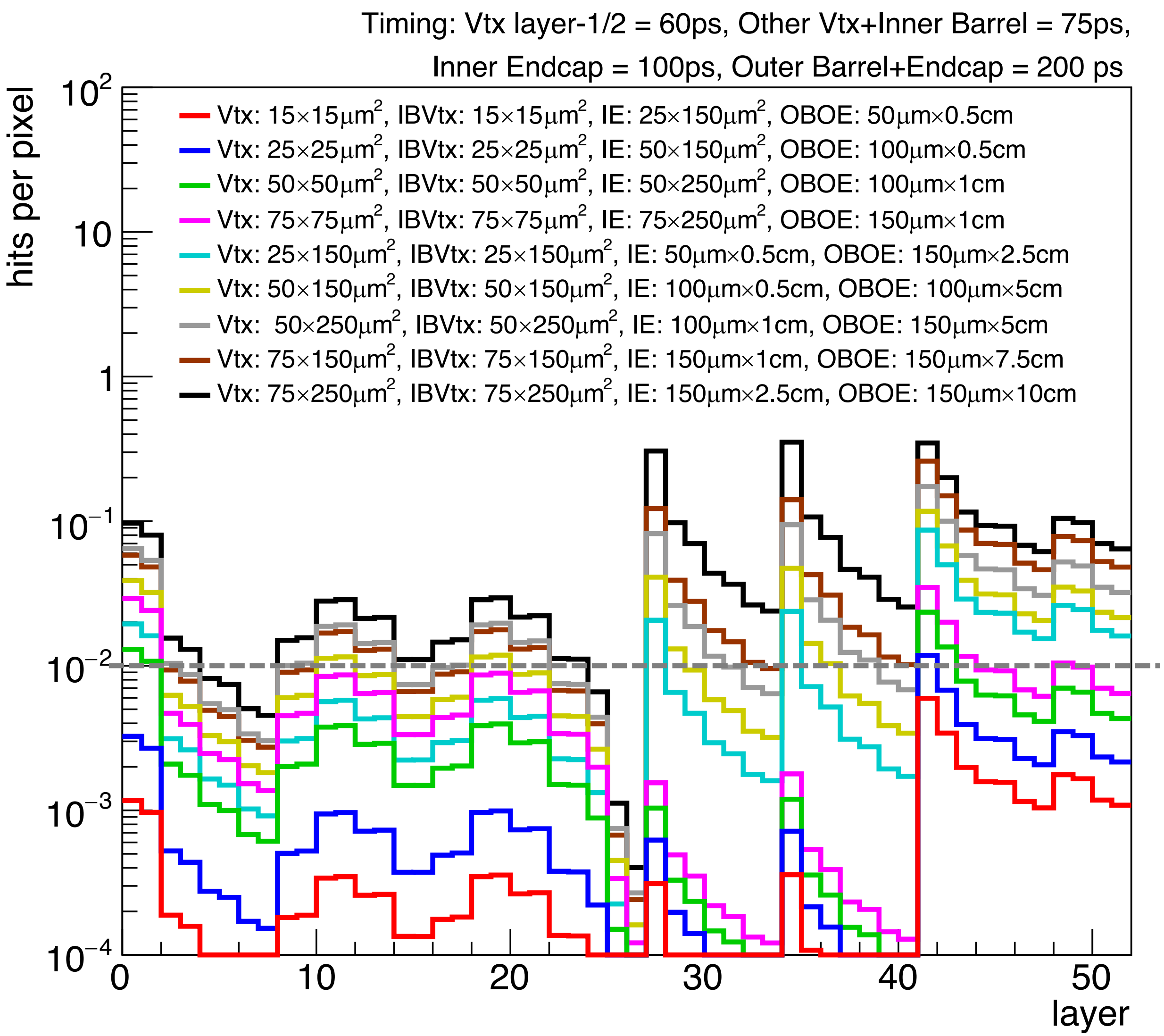
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for bad timing configuration



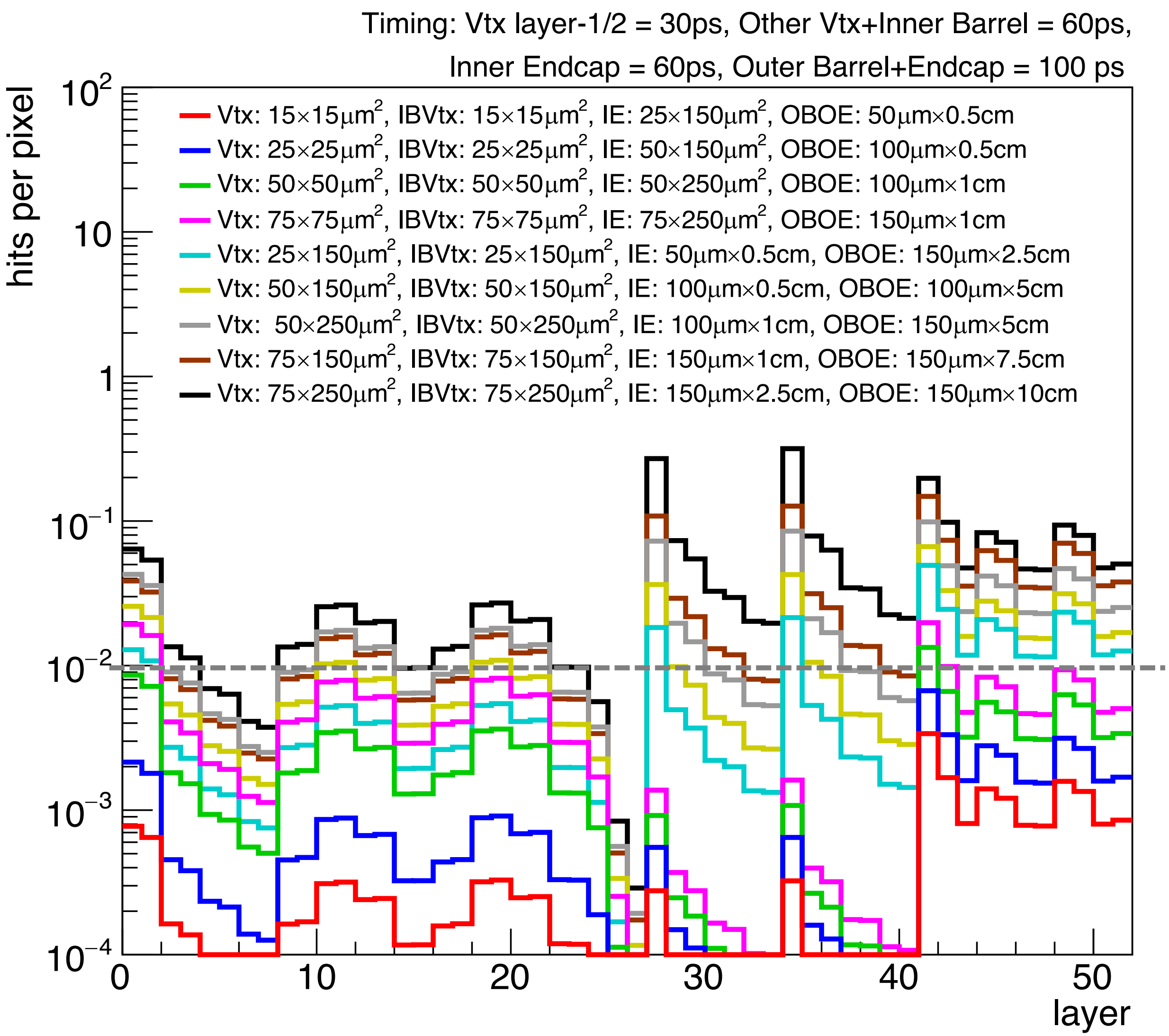
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for conservative timing configuration



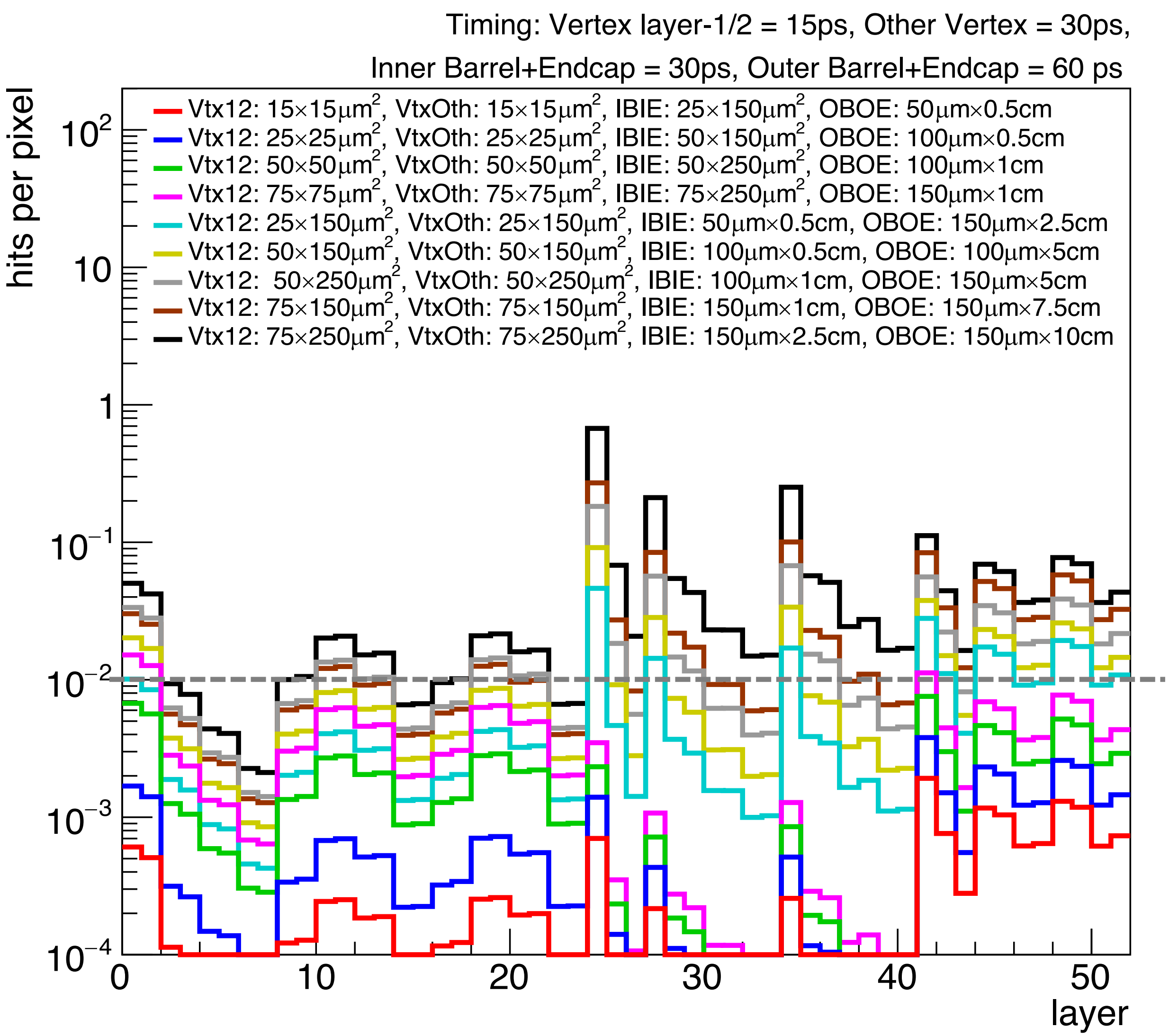
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for good timing configuration



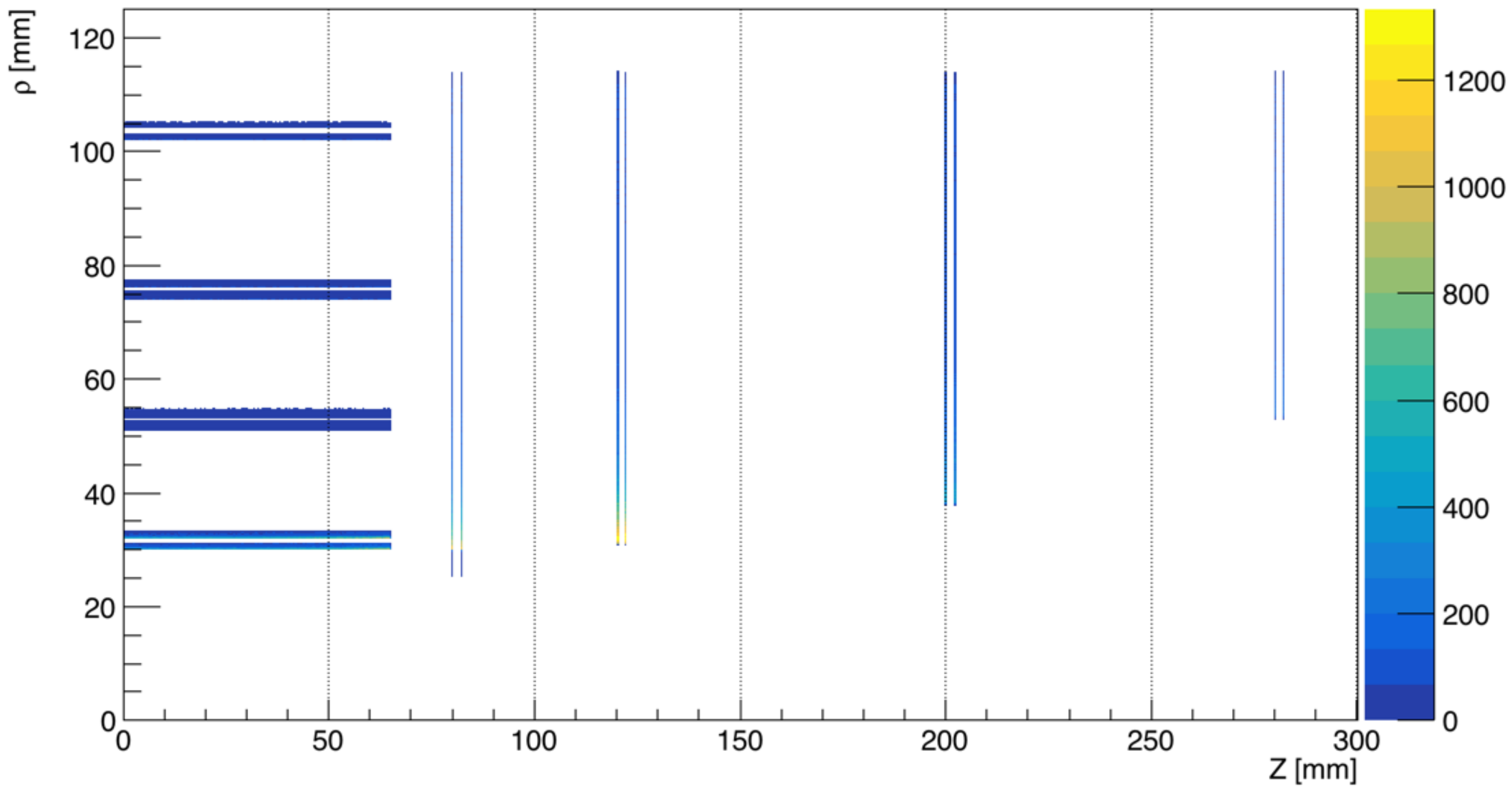
- Same plot as in main body but put Inner barrel into Vertex category.

Pixel occupancy for aggressive timing configuration

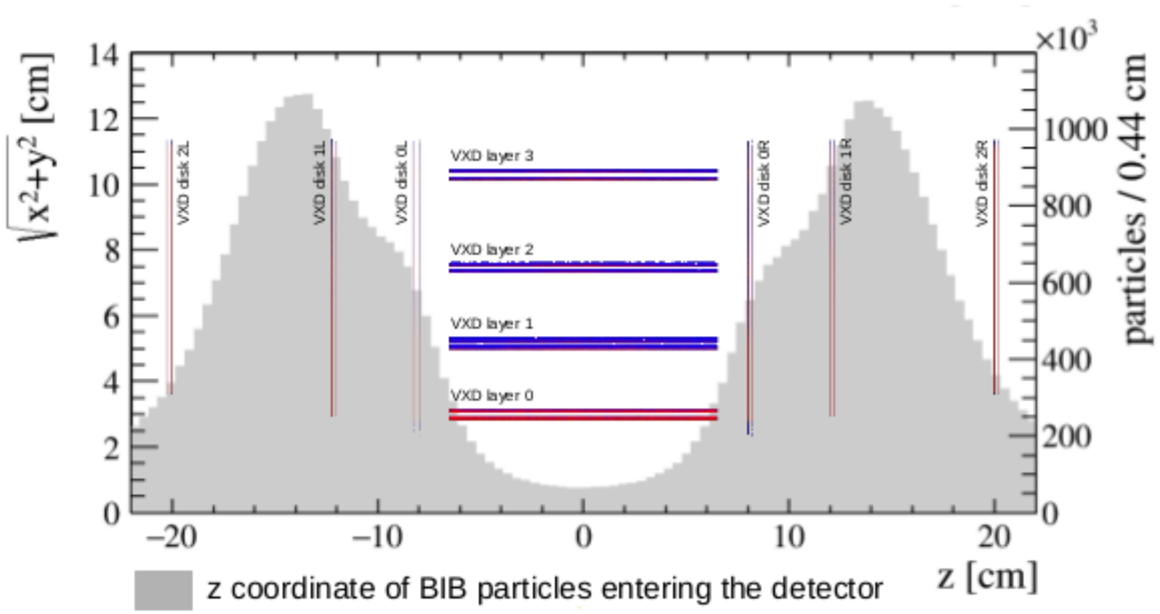


- If we can build a tracker with very good timing, the strips for the outer tracker can be of size up to ~2.5 cm.
- For the inner tracker, we can use macropixels. For innermost layer, LHC-style macropixels (100μm×1.5mm) should work.
- We can have LHC-sized pixels for the vertex detector.

Vertex detector hit map



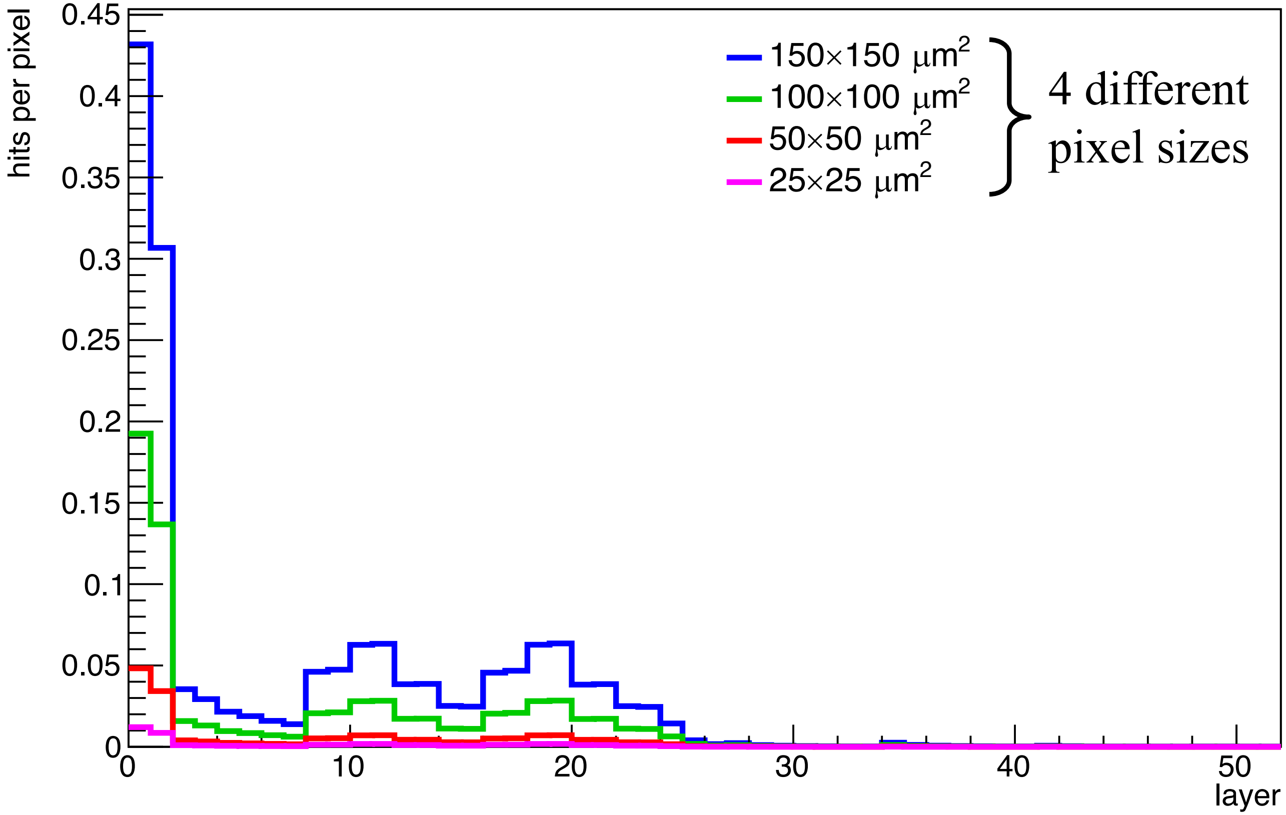
Vertex detector BIB distribution



Plot given to me by Massimo Casarsa

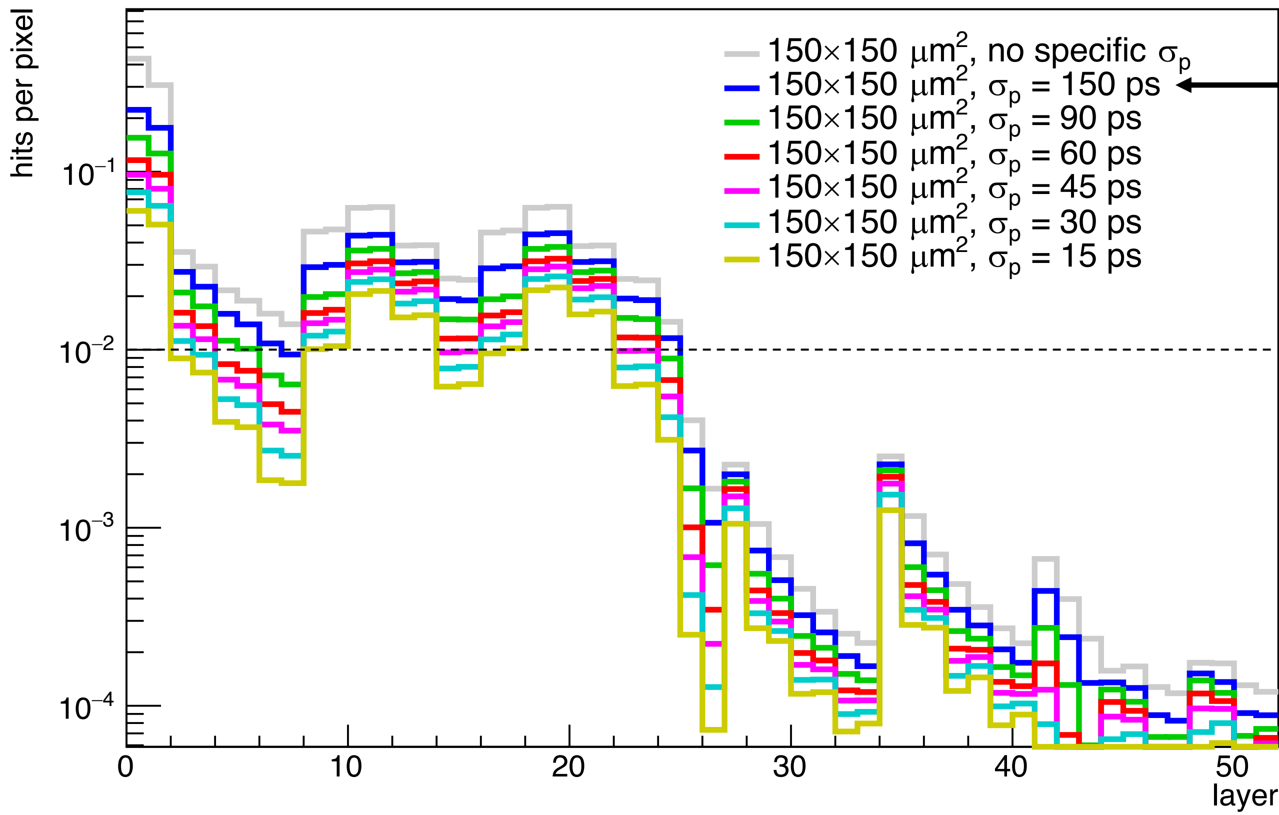
Pixel hit density with no timing*

- * No timing means still that 1ns cut from ntuples is applied.



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.

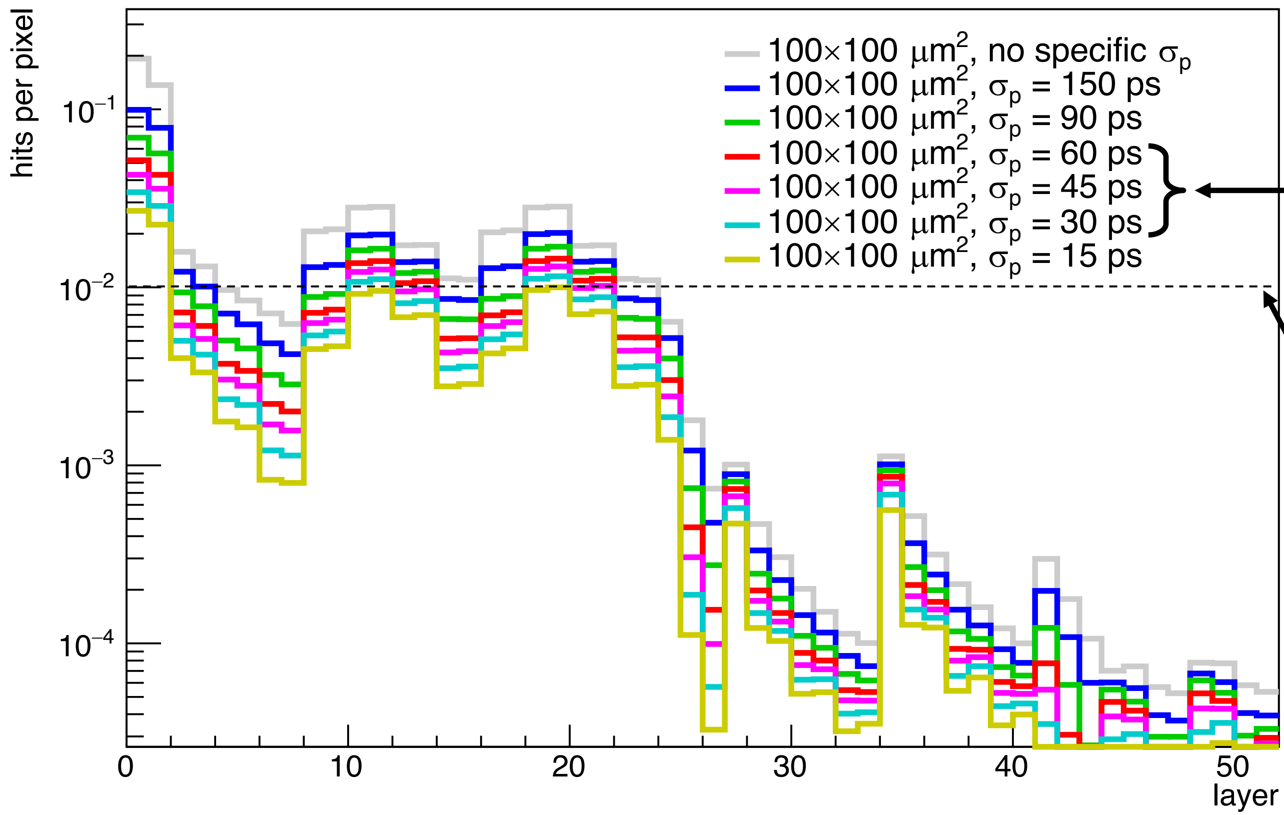


Even 150 ps reduces occupancy by ½ in innermost layers

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.

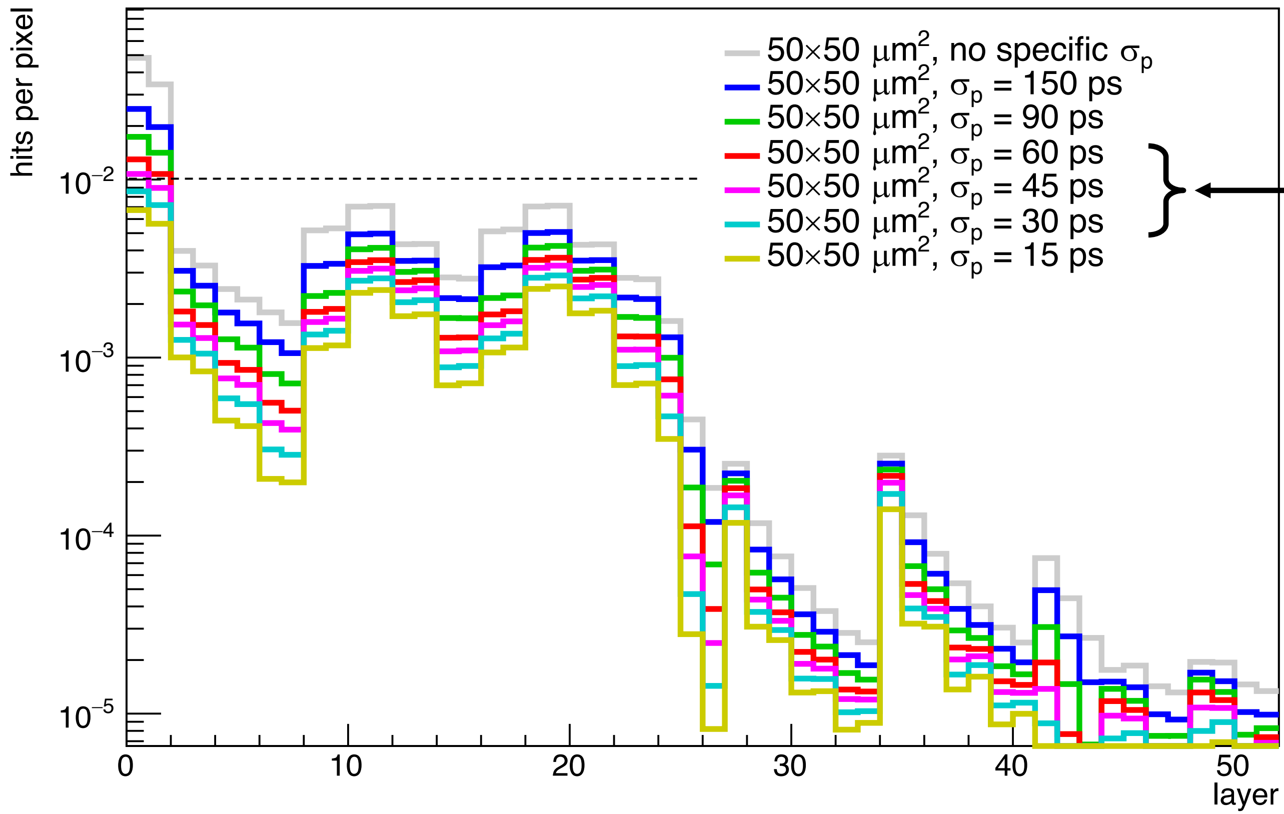


For inner tracker, need good timing (or smaller pixels)

But not good enough for two innermost layers.

Add timing – for 50×50 μm^2

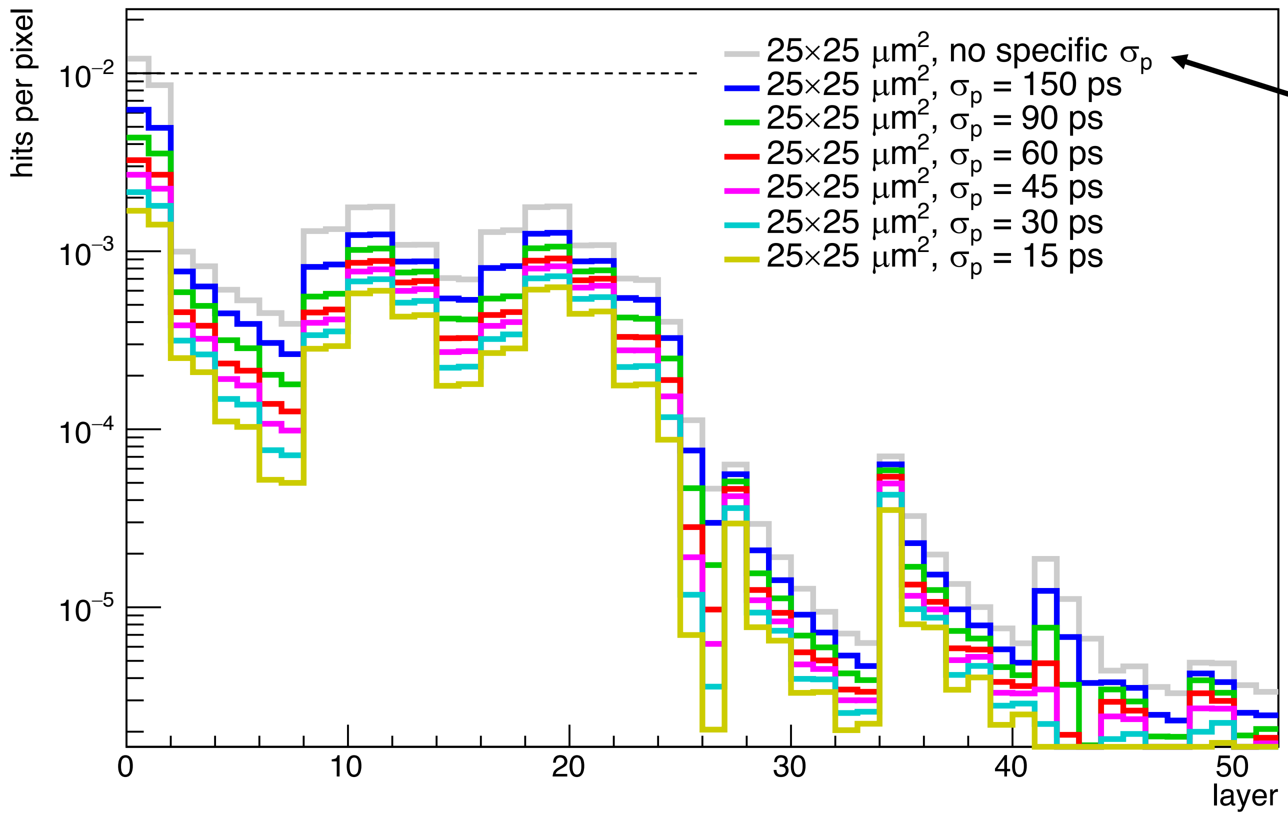
- Even ”modest” timing can reduce occupancy by a large factor.
  - With good timing, these pixels would work.



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

Add timing – for 25×25 μm²

- 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.