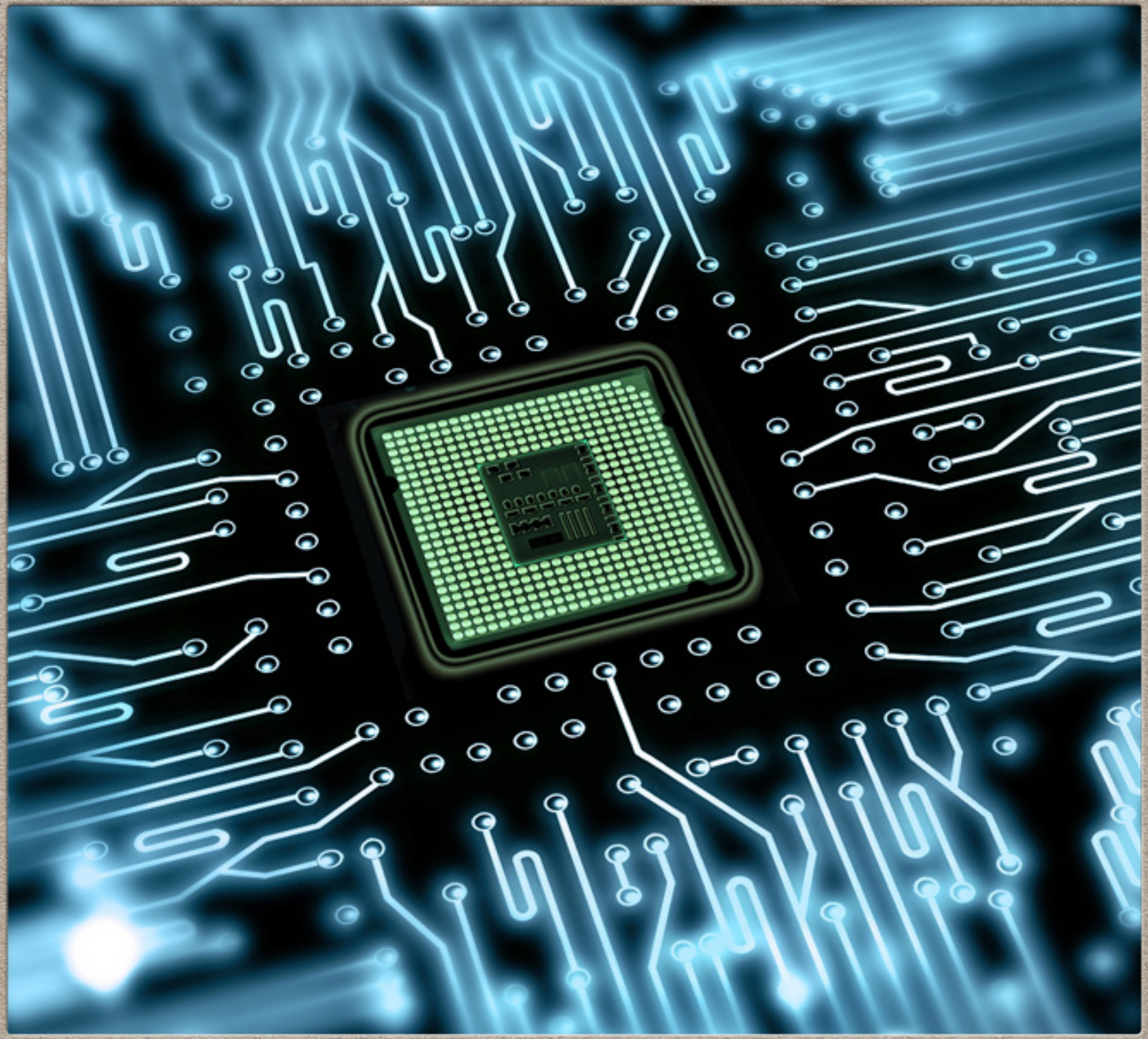
SEMICONDUCTOR DETECTORS

MARCO SCODEGGIO - ADVANCED DETECTION TECHNIQUES

OUTLINE:

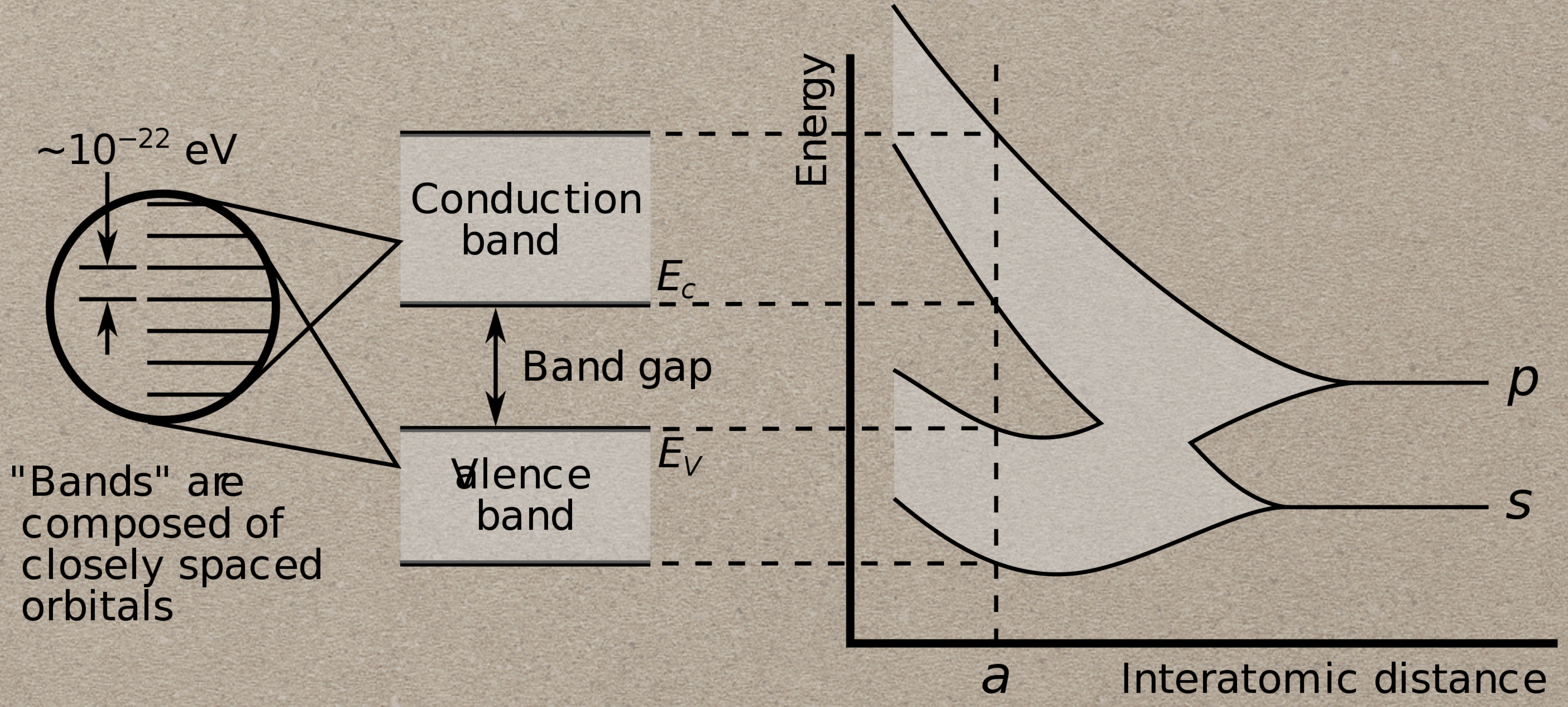
- Semiconductor detectors, working principles and features
- Case study: CMS Tracker
- What Next? FCC unfolding future



SEMICONDUCTORS
ELECTRONIC BAND STRUCTURE

Emergent feature in solids or many-atom systems

Overlap of many atomic/molecular orbitals



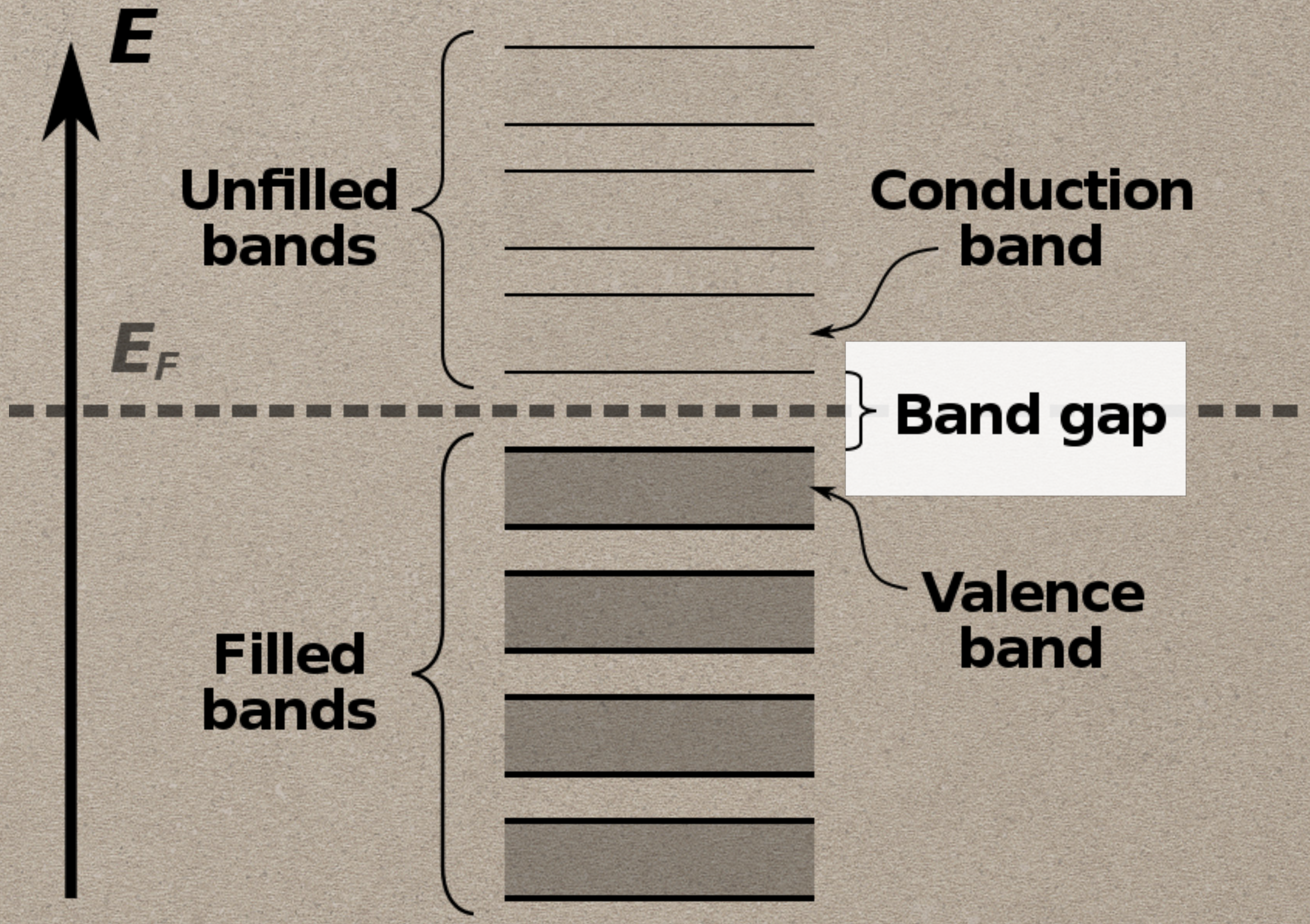
SEMICONDUCTORS
ELECTRONIC BAND STRUCTURE

Electrical features arise due to the position of the Fermi energy (E_F) wrt the bands:

Conductor: E_F is on top of a band

Semiconductor: E_F is between two bands, but these are divided by a relatively small band gap

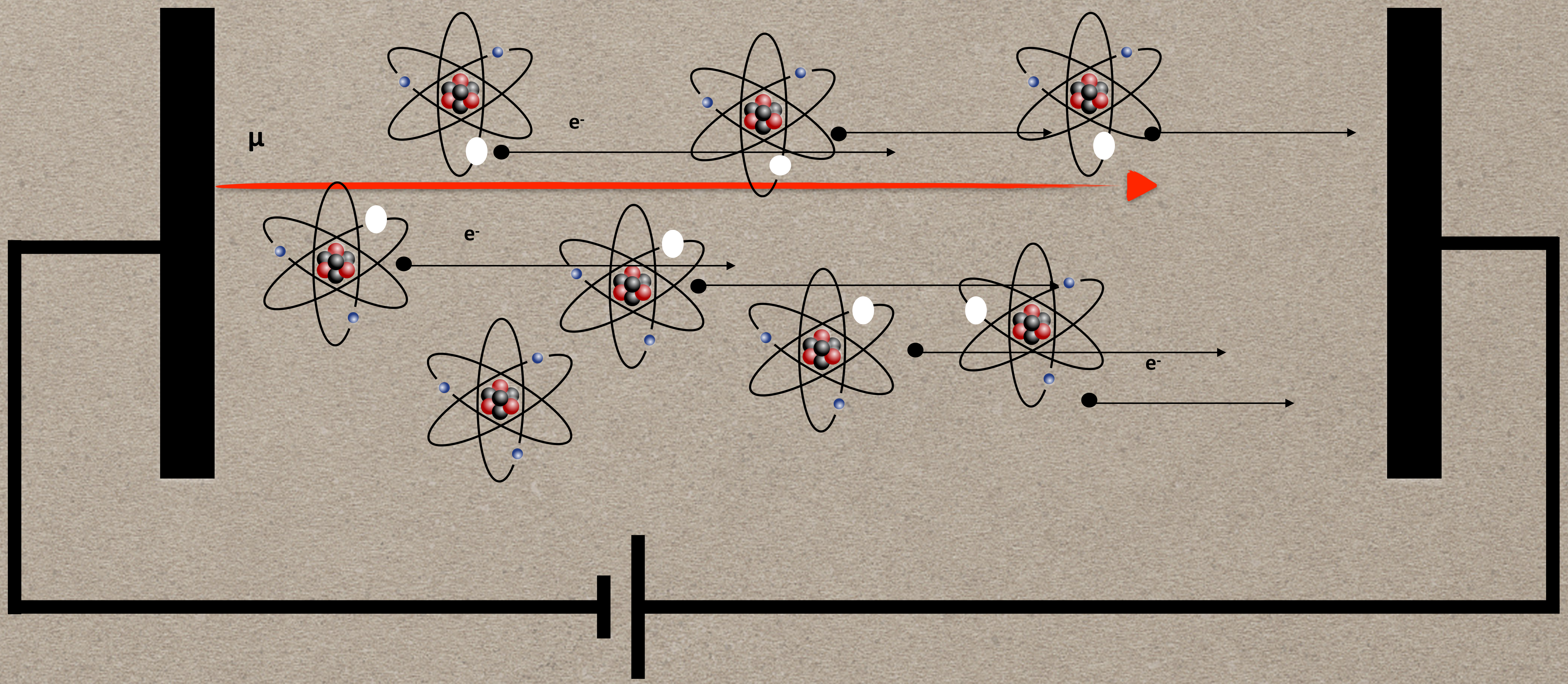
Insulator: E_F is between two bands, but these are divided by a big band gap



DETECTING A PARTICLE

Just as it happens in any other ionisation chamber, a charged particle passes through the semiconductor and creates electron - hole (e^- h) pairs

Via an electric field the e^- h pairs are separated collected in the electrodes



SO... ARE WE DONE?

Let's make a quick calculation

Assume a MIP in Si (of 1 cm^2), we have:

$$\frac{dE}{dx} = 3.87 \frac{MeV}{cm}$$

$$I_0^{Si} = 3.62\, eV$$

$$n^{Si} \sim 1.45 \times 10^{10}\, cm^{-3}$$

$$\frac{N_{MIP}}{N_{intrinsic}} = \frac{\frac{dE}{dx}}{I_0^{Si}} \times \frac{1}{(N^{Si} \times 1cm^2)} \sim \boxed{10^{-4}}$$

Hence, a semiconductor by itself is not enough, we need a way to decrease the number of electrons

SEMICONDUCTORS
ELECTRONIC BAND STRUCTURE

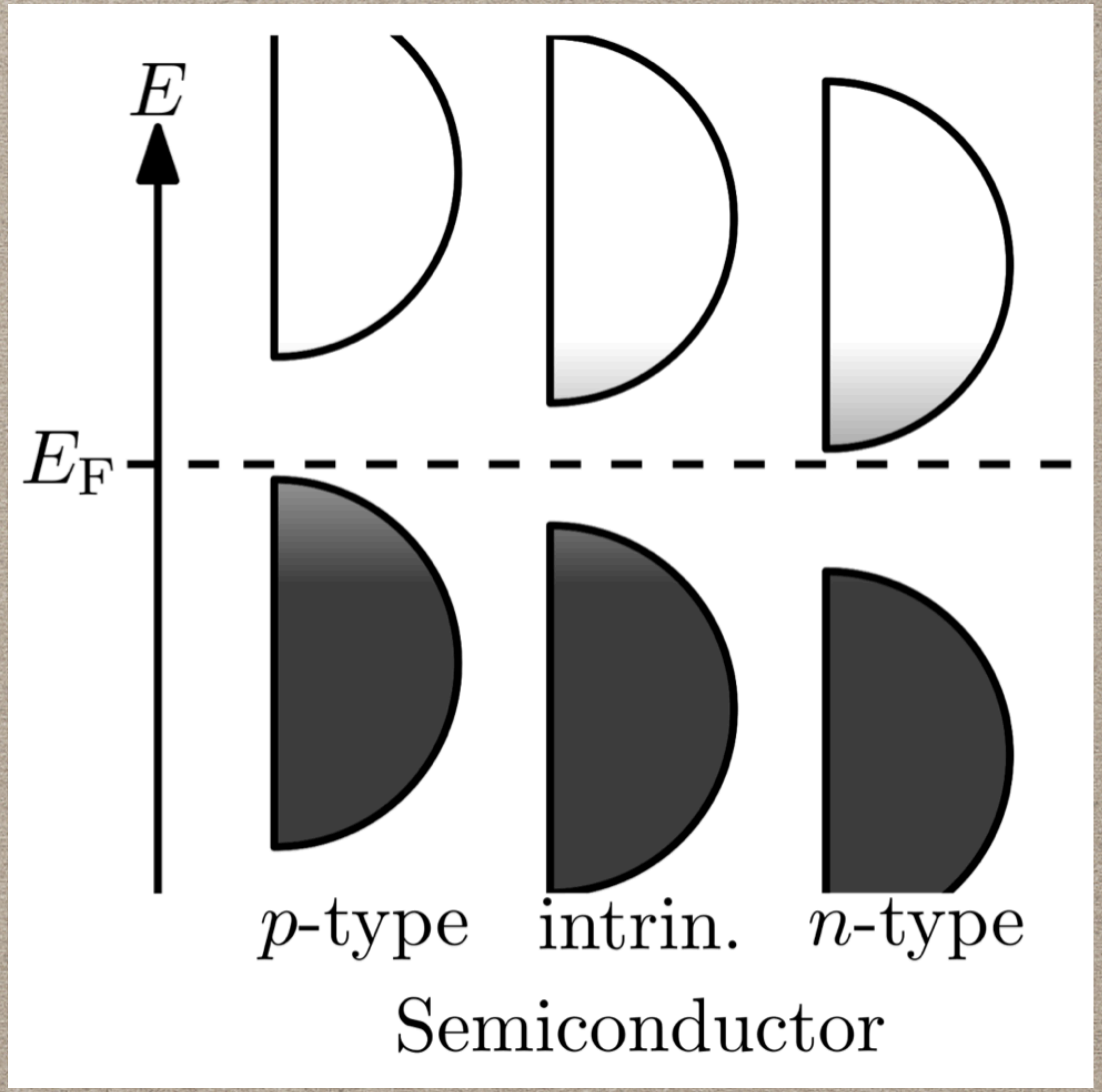
Semiconductor (sc): E_F is between two bands, but these are divided by a relatively small band gap

They can be…

intrinsic sc: number of holes and free electrons is equal

doped sc: created by adding a donor or acceptor element to the sc, with the scope of decreasing the band gap by adding single energy levels between bands

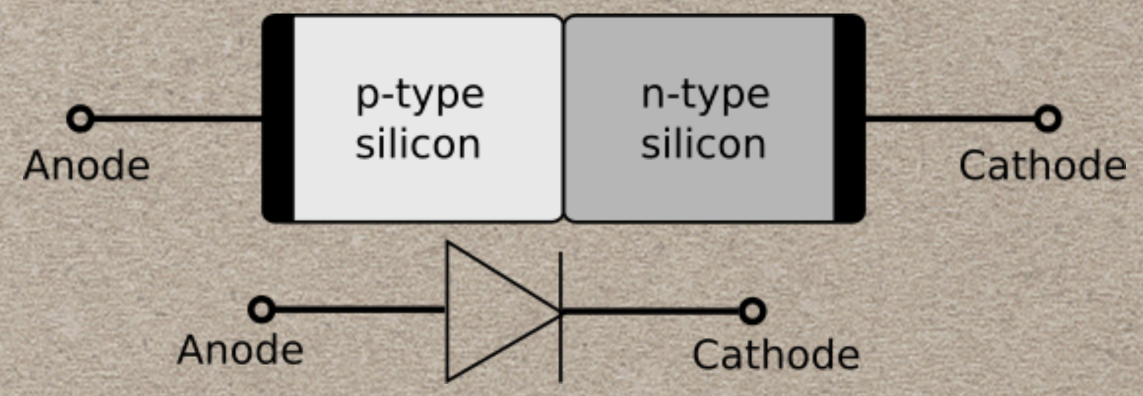
1. n-doped: added free electrons energy levels near the CB
2. p-doped: added hole energy levels near the VB



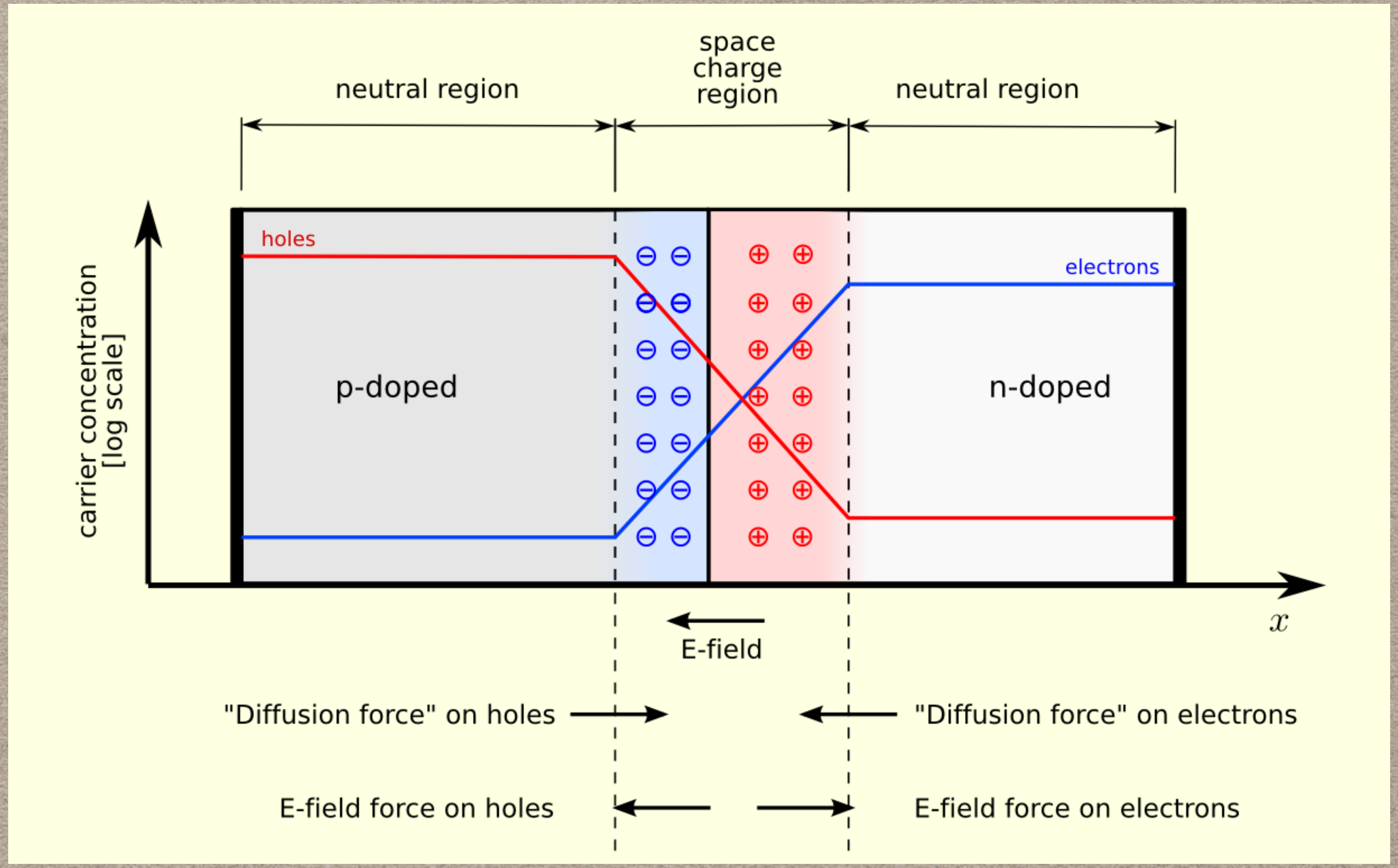
THE BUILDING BLOCK

p-n junction

p-n junction is just a volume that forms when a p and n semiconductors are put in contact



At the junction, without any potential difference applied, e^- from the n-type diffuse into the p-type towards the holes excess.
This process creates a positive (negative) region in the n-type (p-type), and a potential difference forms.

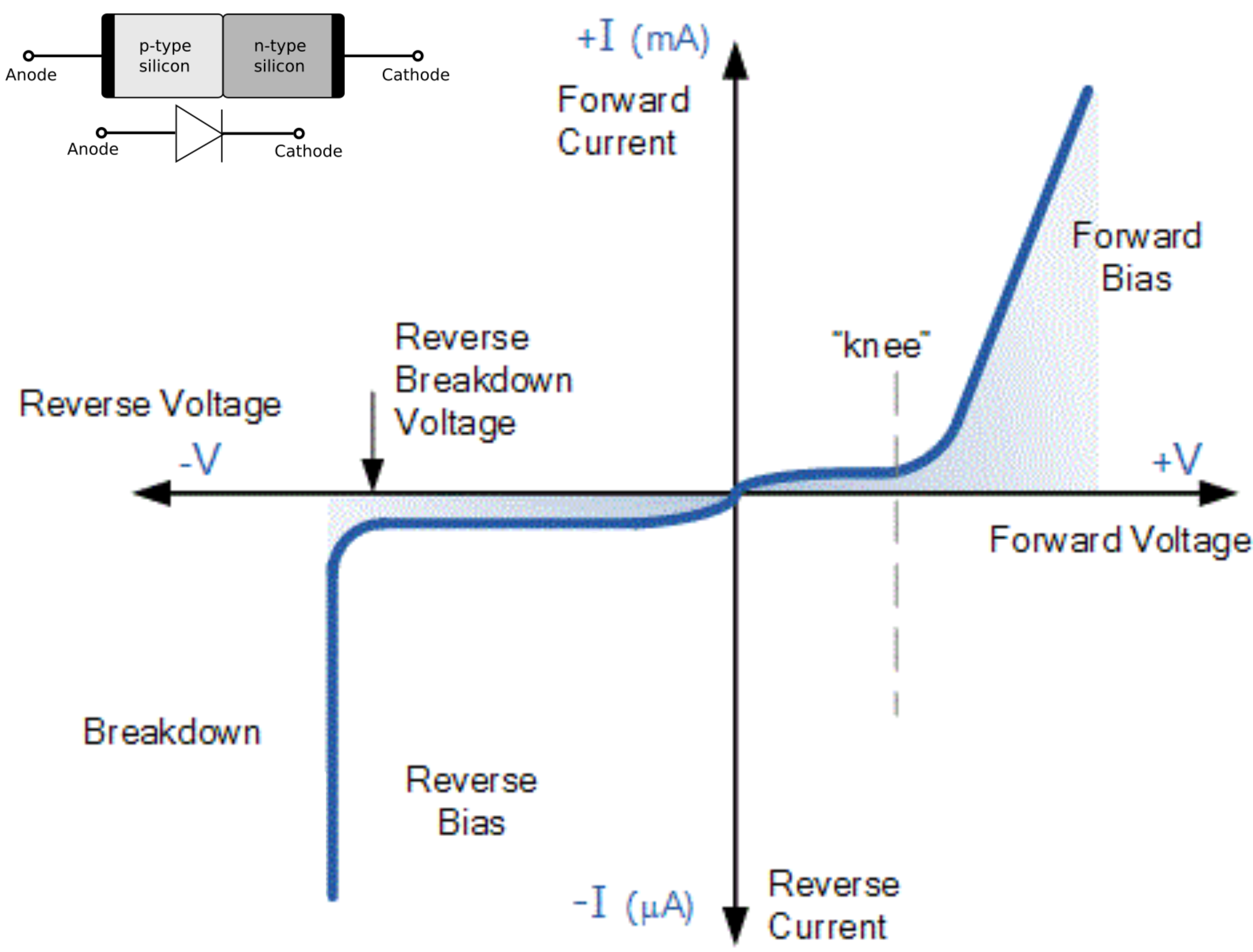


THE BUILDING BLOCK

p-n junction

From the equilibrium, one can:

- *forward bias*: injecting e$^-$ in the n-type and removed from the p-type, narrowing the depletion region
- ***reverse bias***: injecting e$^-$ in the p-type and removing them from the n-type, broadening the depletion region



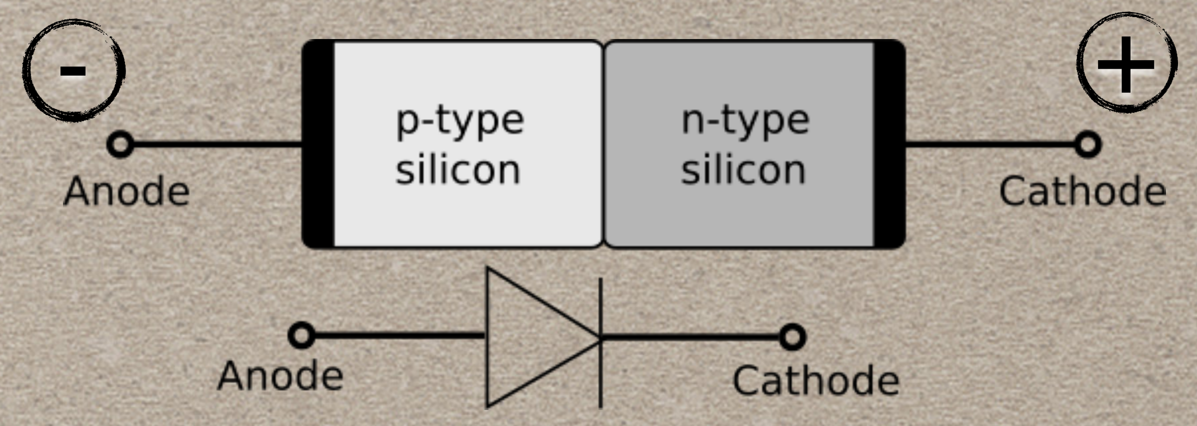
THE BUILDING BLOCK

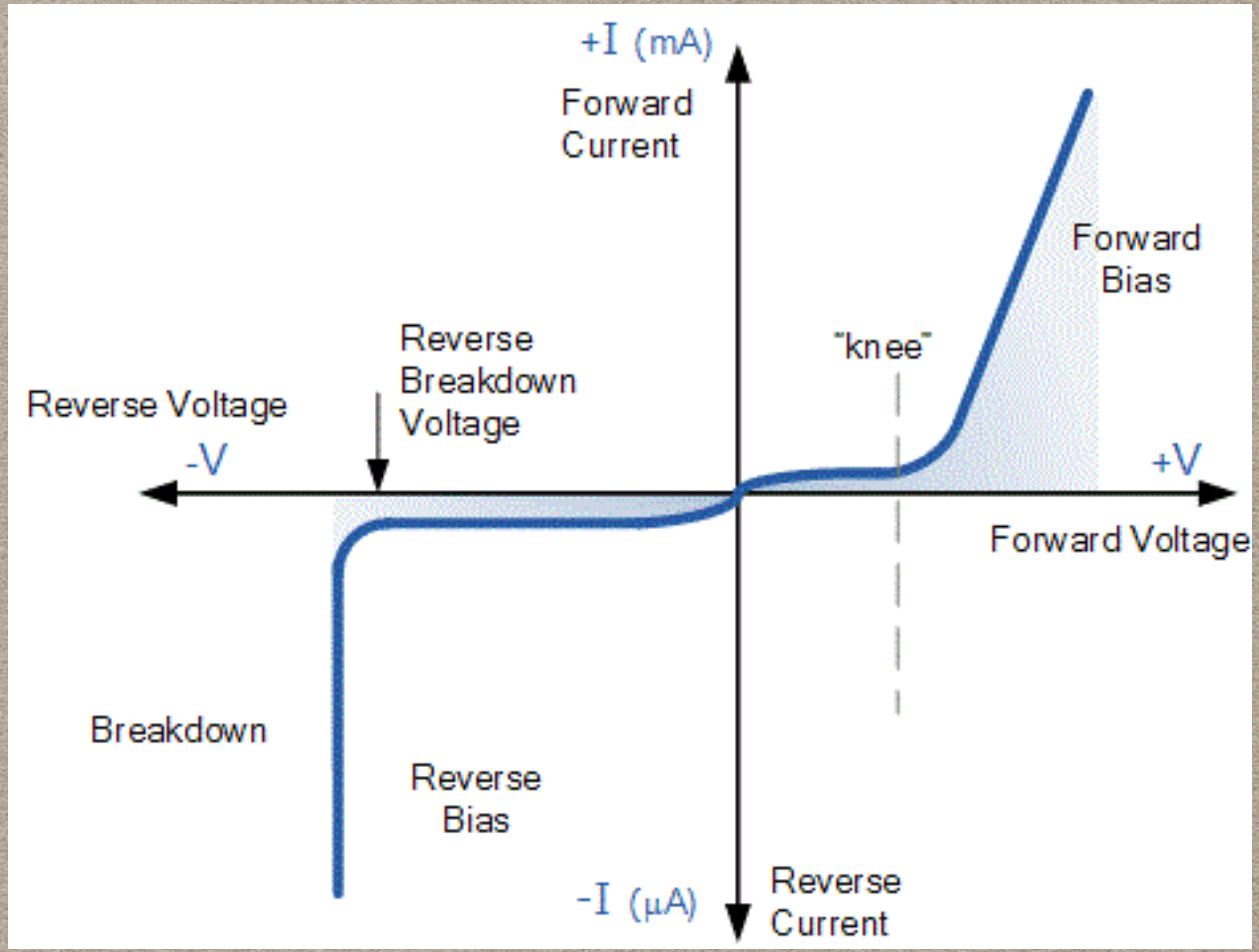
Reverse biasing a p-n junction

If we apply an external voltage V with the cathode to p and the anode to n, we pull away the majority carriers from the depletion zone

The potential barrier increases and diffusion is suppressed

On the other hand, a small drift current (*leakage*) across the junction is due to thermal e^- h pair and this needs to be accounted for





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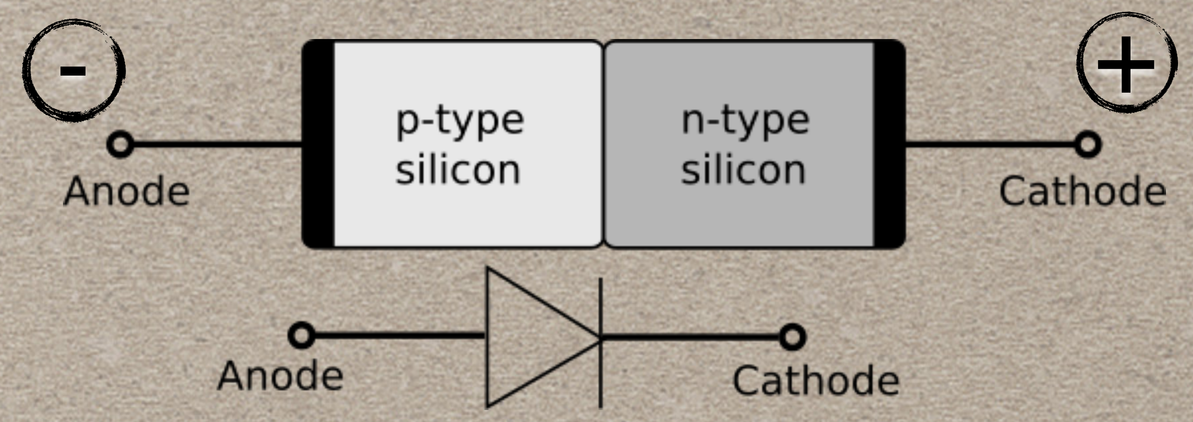


Finally, due to the reverse biasing the number of free carriers decrease (usually a depletion zone as big as the semiconductor itself is obtained) and the current flow diminish

Now we can use this as an ionisation chamber

SEMICONDUCTOR DETECTOR FEATURES

Energy Resolution

We know that the resolution is defined as

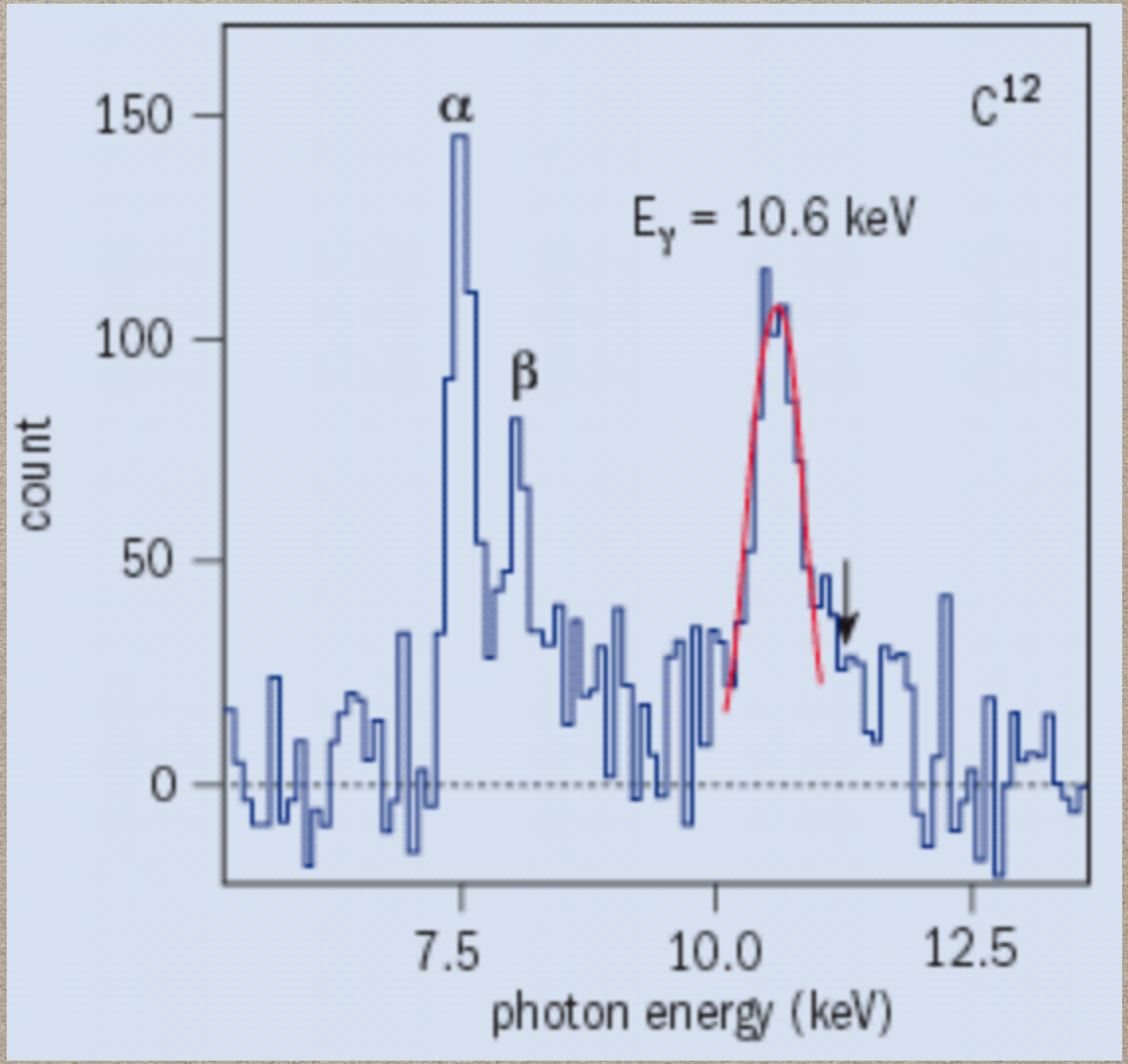
$$\sigma = \frac{\Delta E}{E}$$

Given the number of e$^-$ h pair created by a particle with energy E

$$N_{e-h} = \frac{E}{E_0}$$

We can work the resolution out by doing

$$\left.\begin{aligned} E &\propto N_{e-h} \\ \Delta E &\propto \sqrt{N_{e-h}} \end{aligned}\right\} \sigma \sim \frac{1}{\sqrt{E}}$$



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Given two a priori hypotheses:

1. Poisson distribution with many counts (i.e. gaussian peak)
2. Energy loss is not purely stochastic (discrete electron shells!) → Introducing an empirical term, the Fano factor (~0.1)

the theoretical limit is…

$$\sigma = 2\sqrt{2\ln 2}\sqrt{\frac{FE_0}{E}}$$

SEMICONDUCTOR DETECTOR FEATURES

Position Resolution

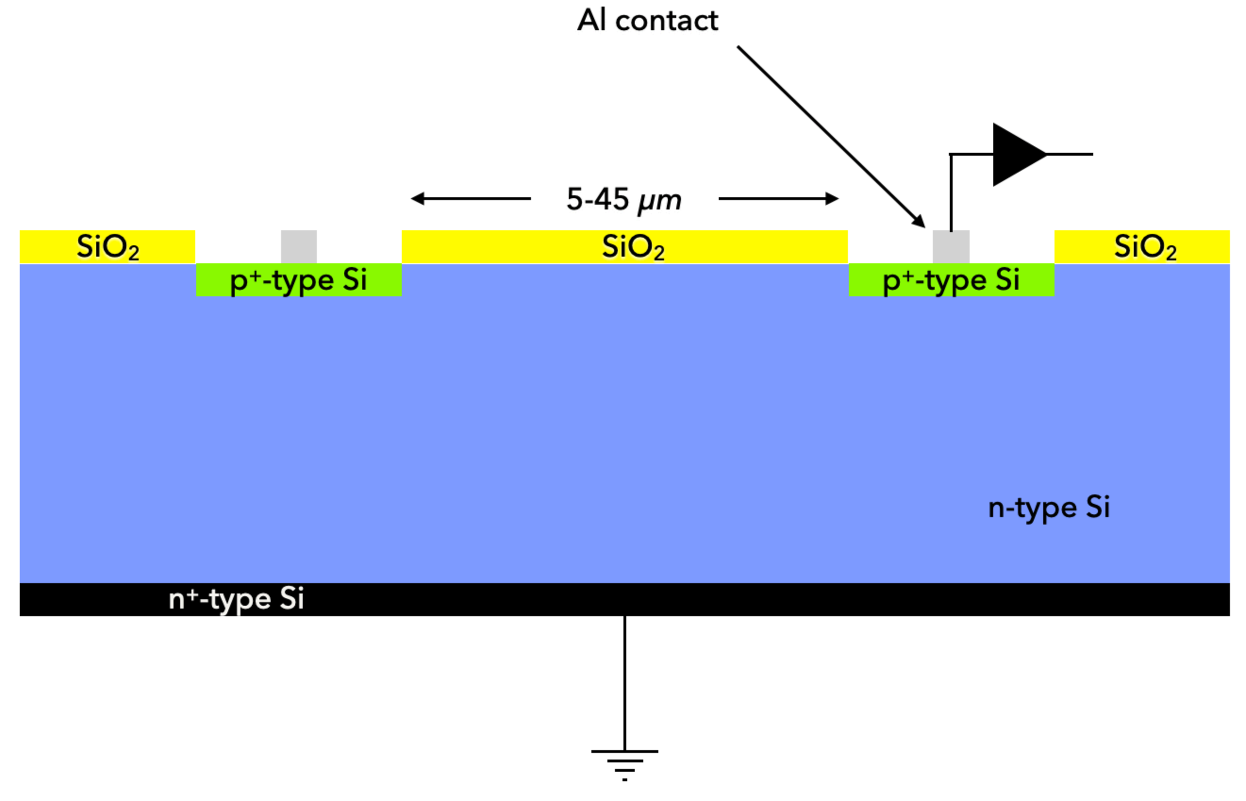
It depends on both the physics of the involved process and the detector parameters

1. Simplest estimation → strip pitch/pixel dimension → uniform distribution

$$\sigma_{dim} = \frac{dim}{\sqrt{12}} \sim 5 - 45\,\mu m$$

2. Charge centroid estimation

$$\sigma_{cc} \propto \frac{dim}{\left[\frac{S}{N}\right]} \sim 3 - 4\,\mu m$$



Limitations can come from:

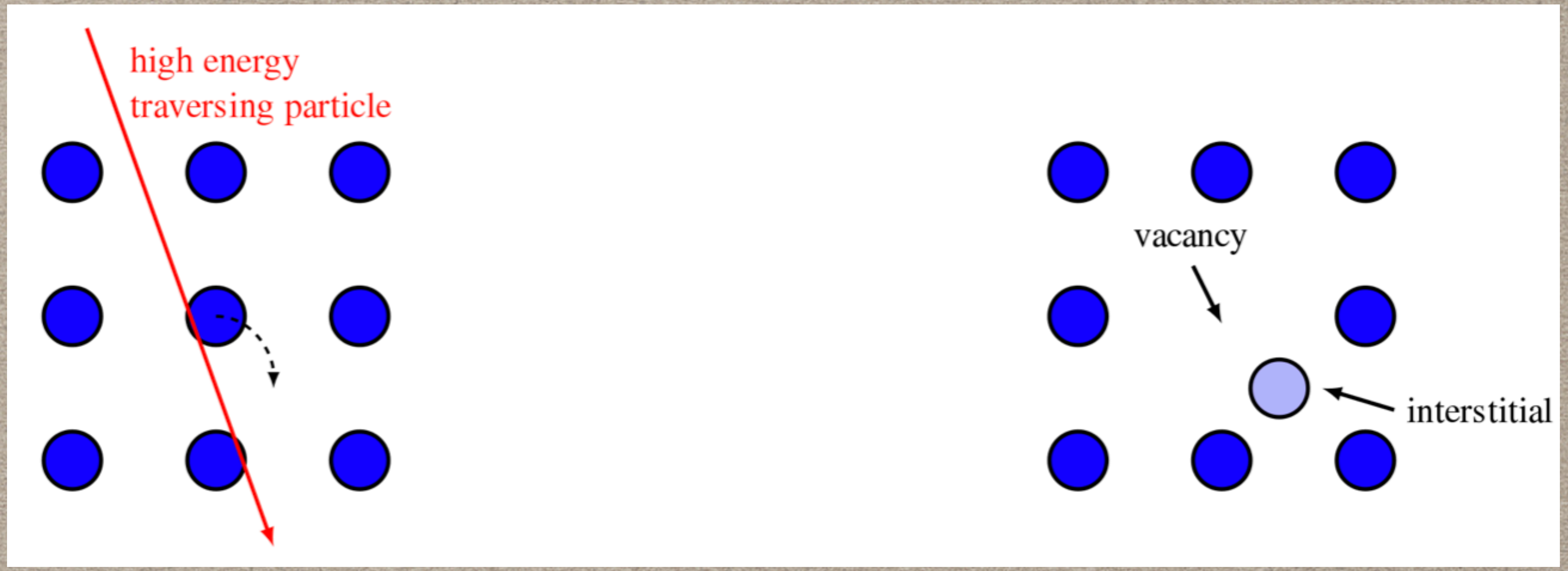
1. Smearing of the charge distribution due to $\vec{B}$ (Lorentz force)
2. The δ-rays, which worsen the resolution by spreading the signal distribution $\rightarrow \propto \left(\frac{N_\delta}{N_{tot}}\right) \times r_\delta$
3. Diffusion phenomena, the e^- h cloud widens as the carriers drift towards the electrodes $\propto \sqrt{t_{coll}}$, where the proportionality is ~ 10^{-2} m^2s^{-1}

SEMICONDUCTOR DETECTOR FEATURES

Radiation hardness

When particles interact with the lattice Si-nuclei, it can permanently damage the bulk itself by knocking the nuclei themselves away (*Bulk defect*)

Also the "inactive" surface (*Surface defects*) can suffer from radiation, HEPs can in fact change the dielectric properties of the metal contact, of the SiO_2 cover…



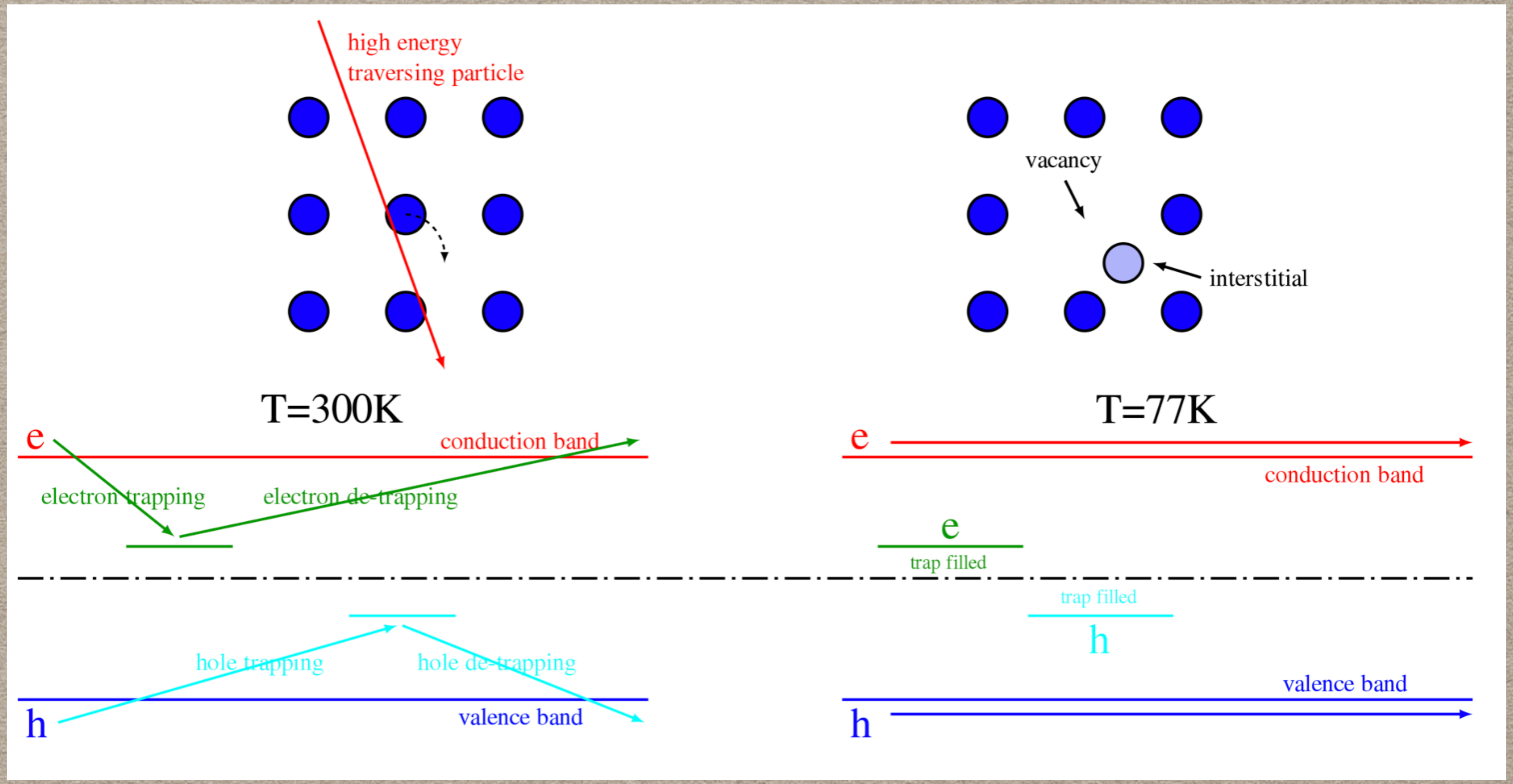
SEMICONDUCTOR DETECTOR FEATURES

Radiation hardness

When particles interact with the lattice Si-nuclei, it can permanently damage the bulk itself by knocking the nuclei themselves away (*Bulk defect*)

@300 K the defects temporarily trap e^- h pairs and re-emit them in a time longer than the read-out time, worsening the signal strength

@ < 100 K a e^-/h, trapped in a local defect, remains trapped due to the very low phonon interactions. This fills up the defect and allows the signal to be restored (Lazarus effect → future applications?)

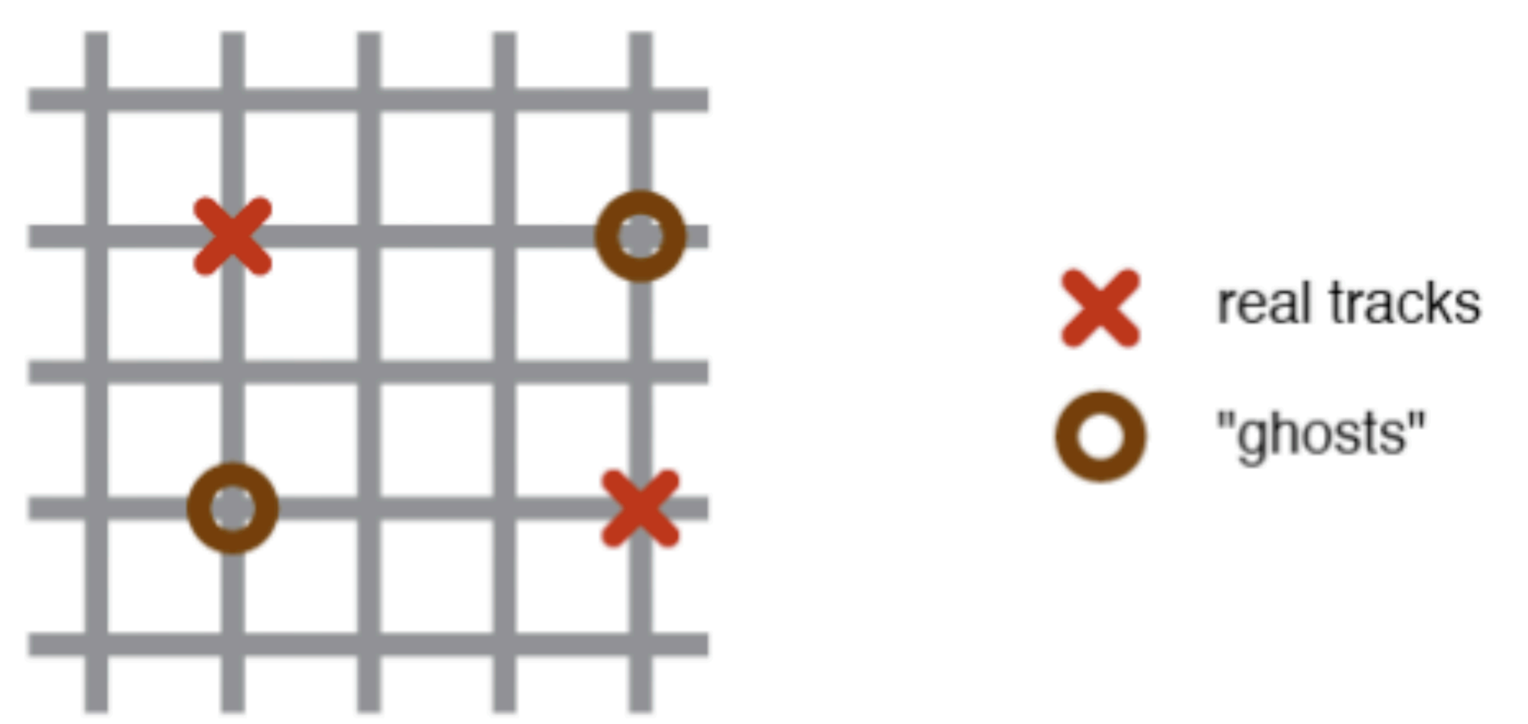


STRIP DETECTORS

1 dimensional segmentation
that runs through the Si wafer

A strip measures 1 coordinate only, hence 2 orthogonal sets of strips are needed to obtain a 2D position

If 2 or more particles hit the strips, ghost hits appear

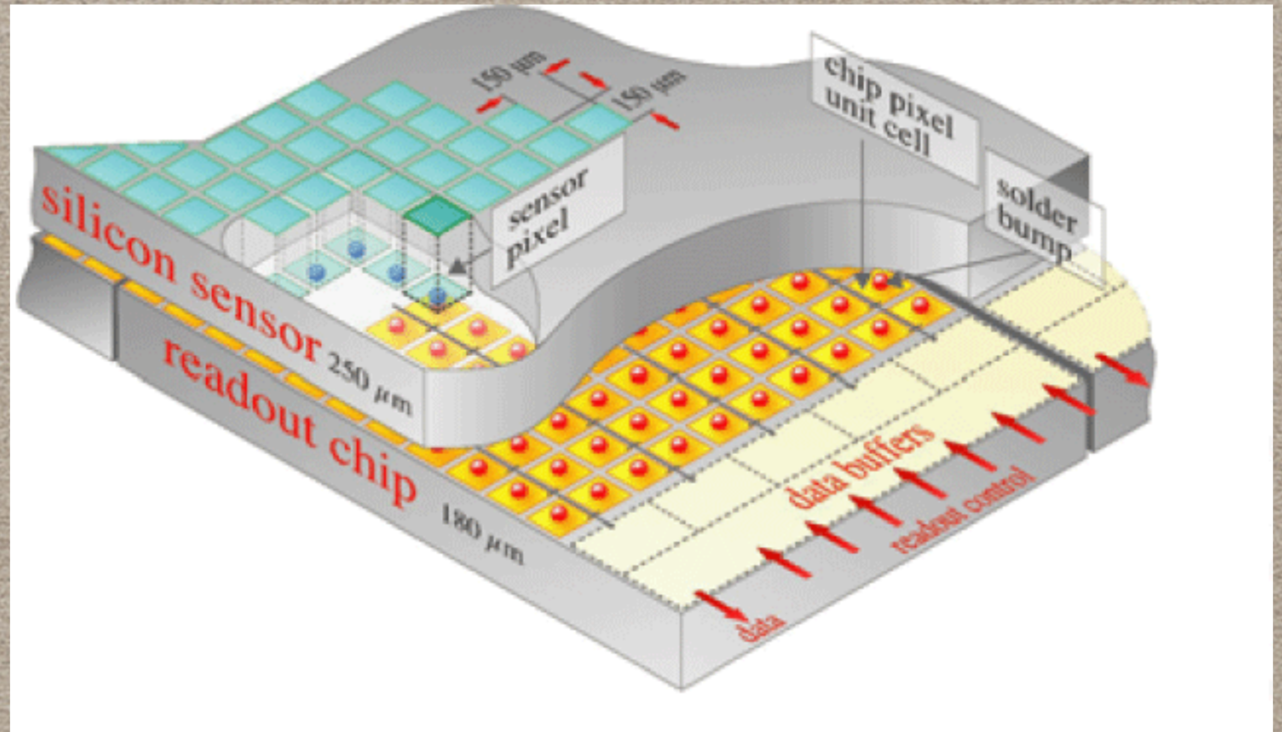


PIXEL DETECTORS

2 dimensional segmentation

pixels can provide xy position information of the passage of the ionising particle, without ambiguous ghost hits

Main disadvantages are related to the high number of readout channels, which force to have inbuilt electronics connected via bump bonding



STRIP DETECTORS

1 dimensional segmentation
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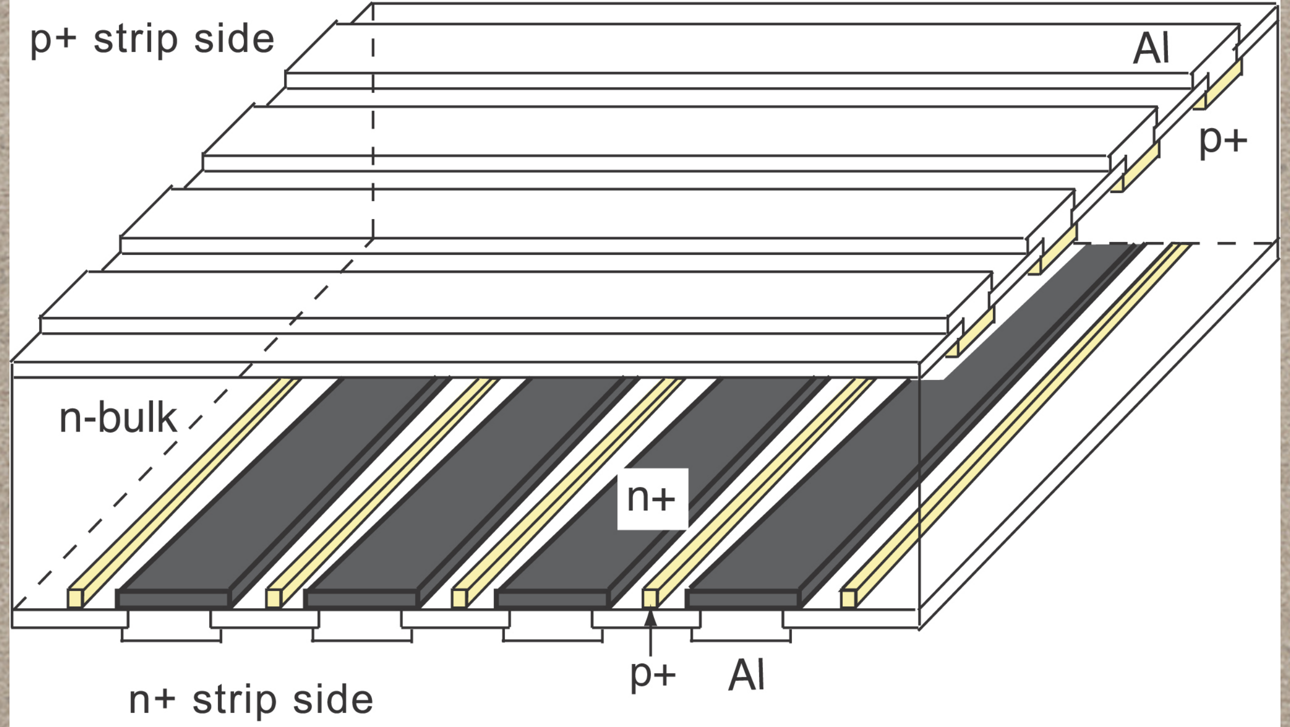
A strip measures 1 coordinate only, hence 2 orthogonal sets of strips are needed to obtain a 2D position

If 2 or more particles hit the strips, ghost hits appear → double-sided strip detectors



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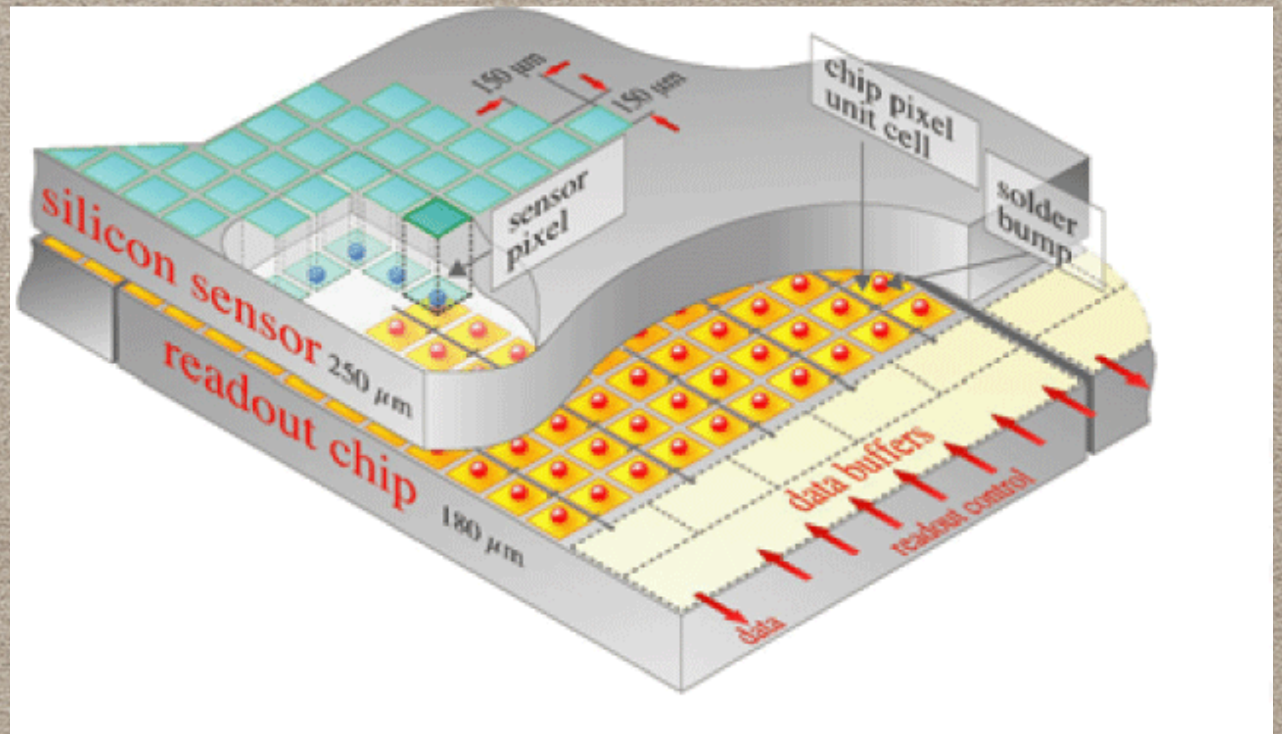


THE CASE STUDY: CMS TRACKER

Phase-0 Tracker (Up to mid Run 2)

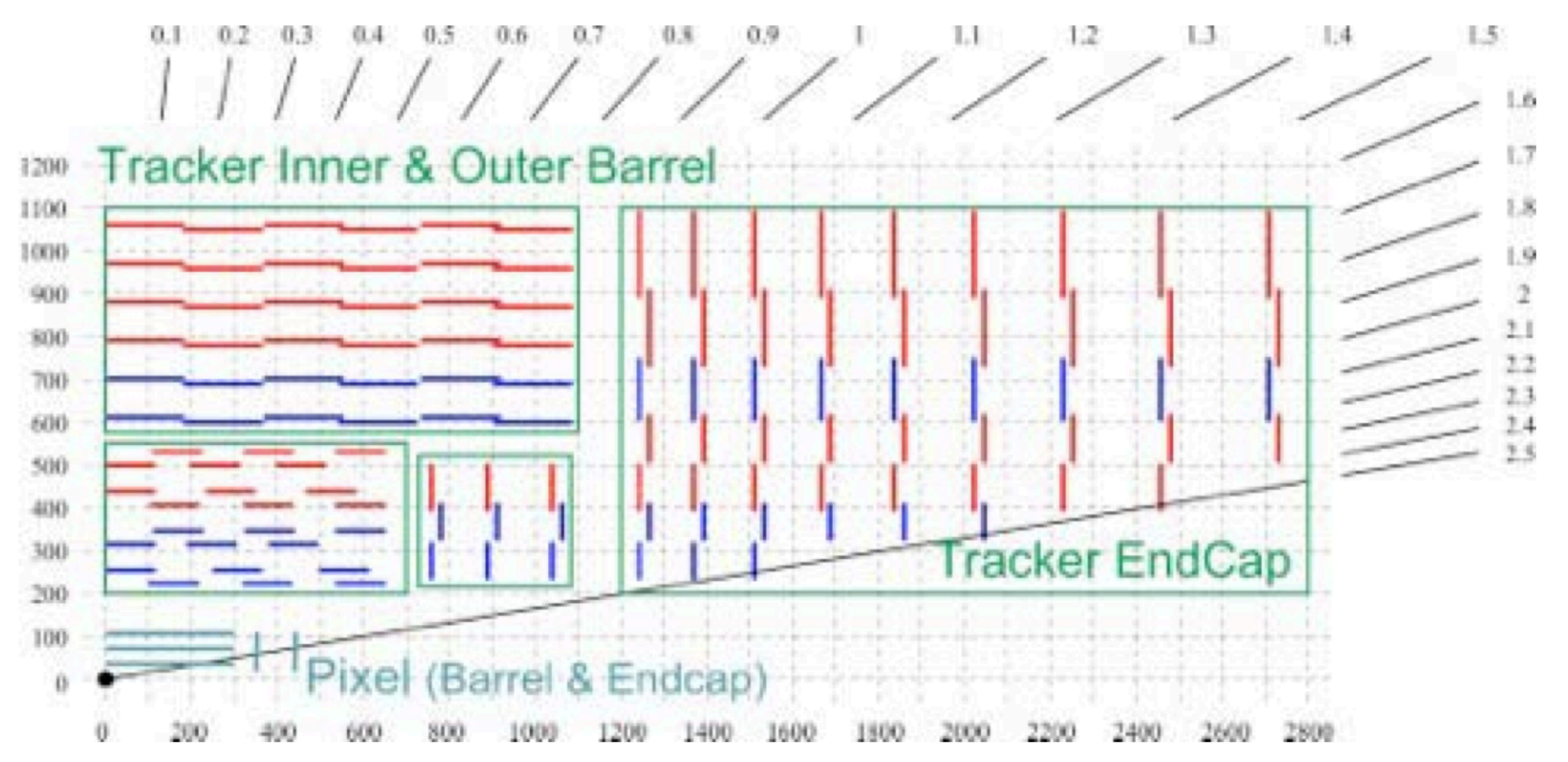
Inner Pixel Detector

66 milions pixels (~16k ROCs) covering 1.1 m^2 area

n^+-n-p pixels of (rφ *x* z) 100x150x285 μm^3

Barrel: 3 layers from 4 cm to 10 cm wrt beam pipe

End-caps: 2 disks on each side



Outer Strip Detector

9.6 milions strips covering 200 m^2 area

p^+-n-n strips of 320 (500 outer barrel) μm thick

Barrel: 4 + 6 layers from 25 cm wrt beam pipe

End-caps: 3 + 9 disks on each side

Blue layers equipped with stereo module for 2D measurements (i.e. 2 Si strip sensors back to back tiled aligned at 100 mrad)

THE CASE STUDY: CMS TRACKER

Phase-0 Tracker (Up to mid Run 2)

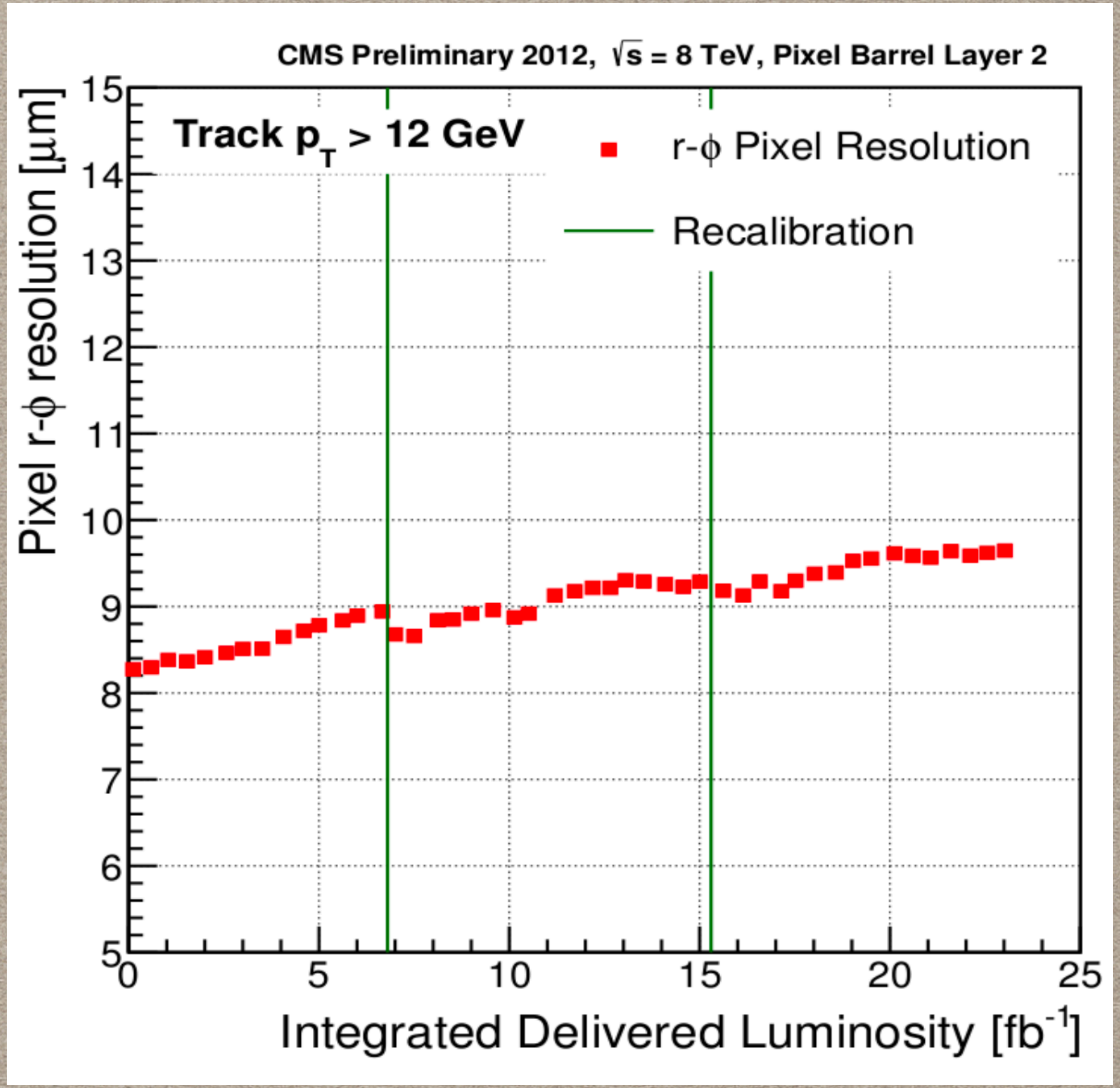
Problems with the Pixel Detector

Occupancy scales linearly with pile-up

Higher occupancy means higher power consumption and overflow in the ROCs

Radiation induced effects are ~~irreversible~~

Lorentz angle was found to increase with irradiation, but higher occupancy meant also higher thresholds → constant net worsening of resolution



THE CASE STUDY: CMS TRACKER

Phase-1 Tracker (up to LS 2024)

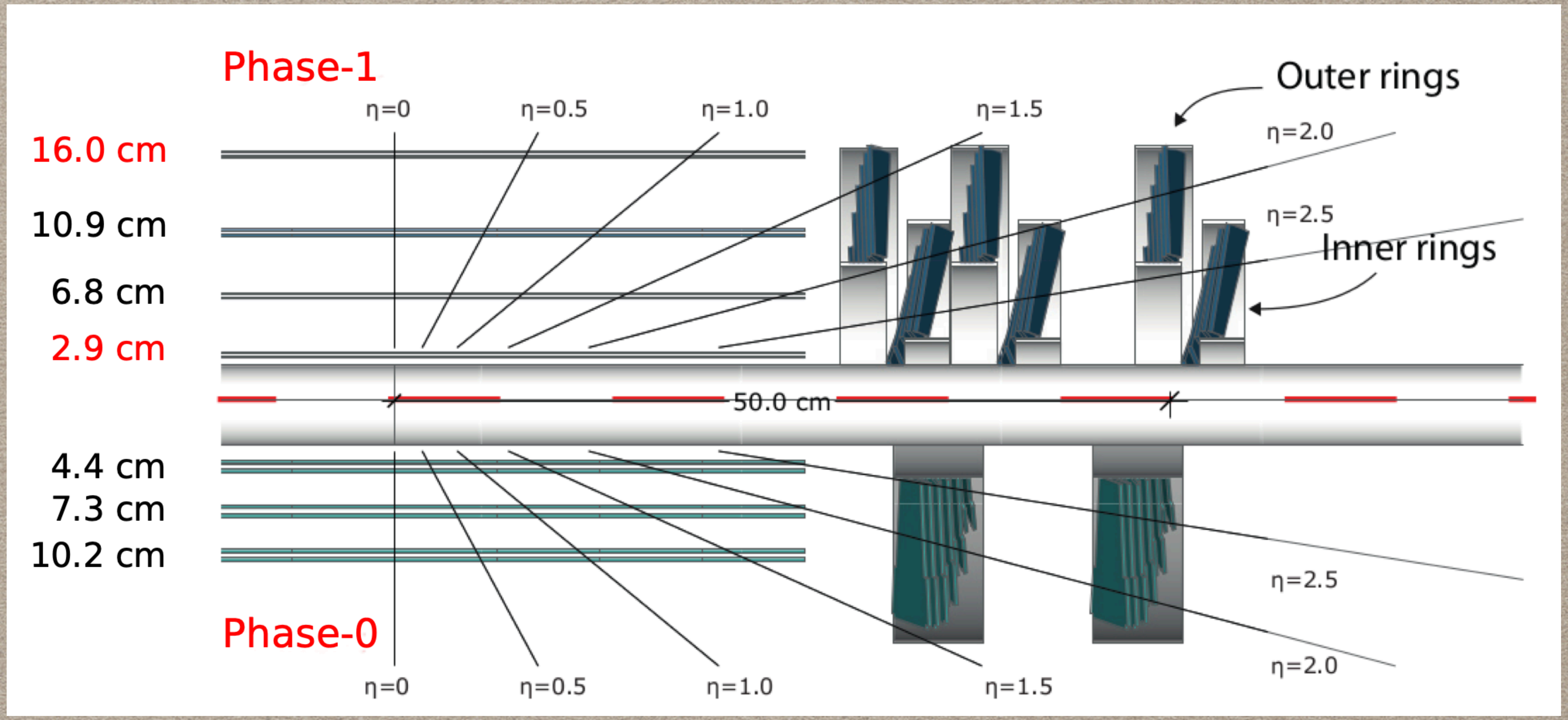
Inner Pixel Detector

4-hit coverage for $|\eta| < 2.5$

n^+-n-p 2x pixels of 100x150x285 μm^3 (2 m^2)

Barrel: 4 layers from 3 cm to 16 cm wrt beam pipe

End-caps: 3 jagged disks on each side



THE CASE STUDY: CMS TRACKER

Phase-1 Tracker (up to LS 2024)

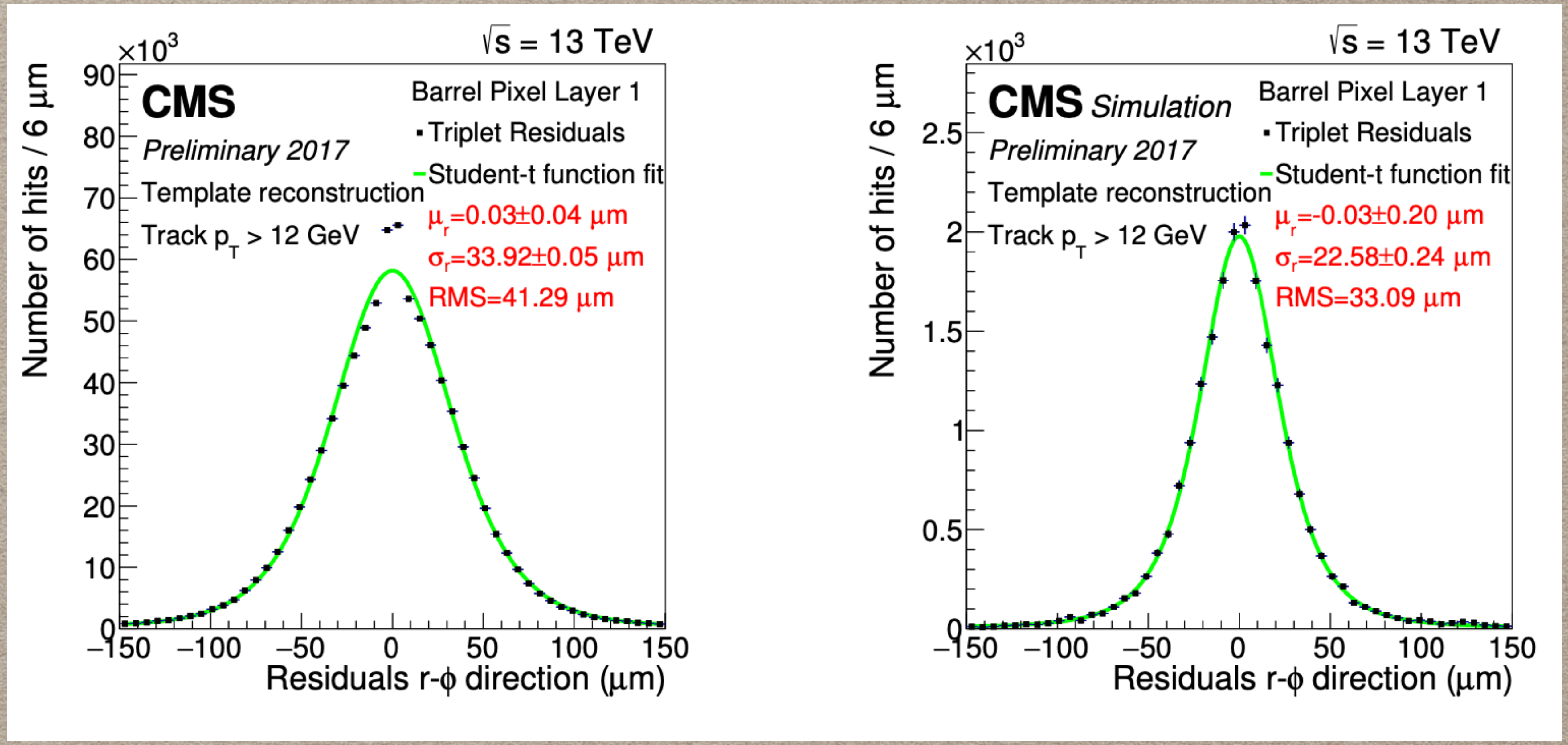
Inner Pixel Detector

Two phase CO_2 cooling system (up to -20 °C)

First layer too near to beam pipe (4 times more hit than L4!) to single pixels ROCs, the bump-bonded chip reads 2x2 clusters

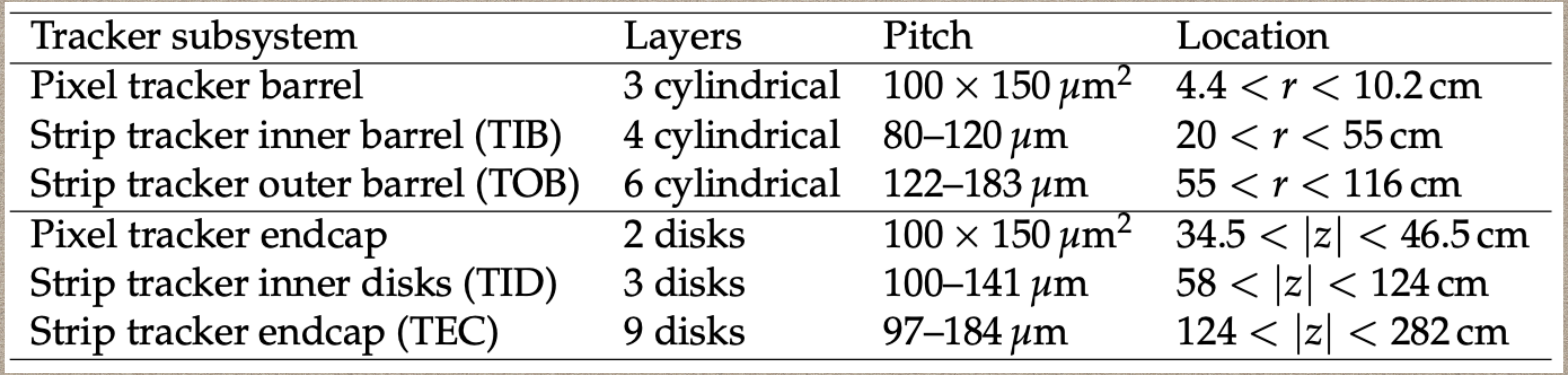
Efficiency of 98 % @580 MHzcm^{-2} (i.e. 2x10^{34} cm^{-2}s^{-2})

Single hit resolution < 7 μm



THE CASE STUDY: CMS TRACKER

Features Phase-1 Tracker (up to LS 2024)



Tracker subsystem	Layers	Pitch	Location
Pixel tracker barrel	3 cylindrical	$100 \times 150\,\mu m^2$	$4.4 < r < 10.2\,cm$
Strip tracker inner barrel (TIB)	4 cylindrical	80–120 μm	$20 < r < 55\,cm$
Strip tracker outer barrel (TOB)	6 cylindrical	122–183 μm	$55 < r < 116\,cm$
Pixel tracker endcap	2 disks	$100 \times 150\,\mu m^2$	$34.5 < \lvert z \rvert < 46.5\,cm$
Strip tracker inner disks (TID)	3 disks	100–141 μm	$58 < \lvert z \rvert < 124\,cm$
Strip tracker endcap (TEC)	9 disks	97–184 μm	$124 < \lvert z \rvert < 282\,cm$

Outer Strip Detector

Resolution Inner barrel (rφ): 13-38 μm
Resolution Outer barrel (rφ): 18-47 μm

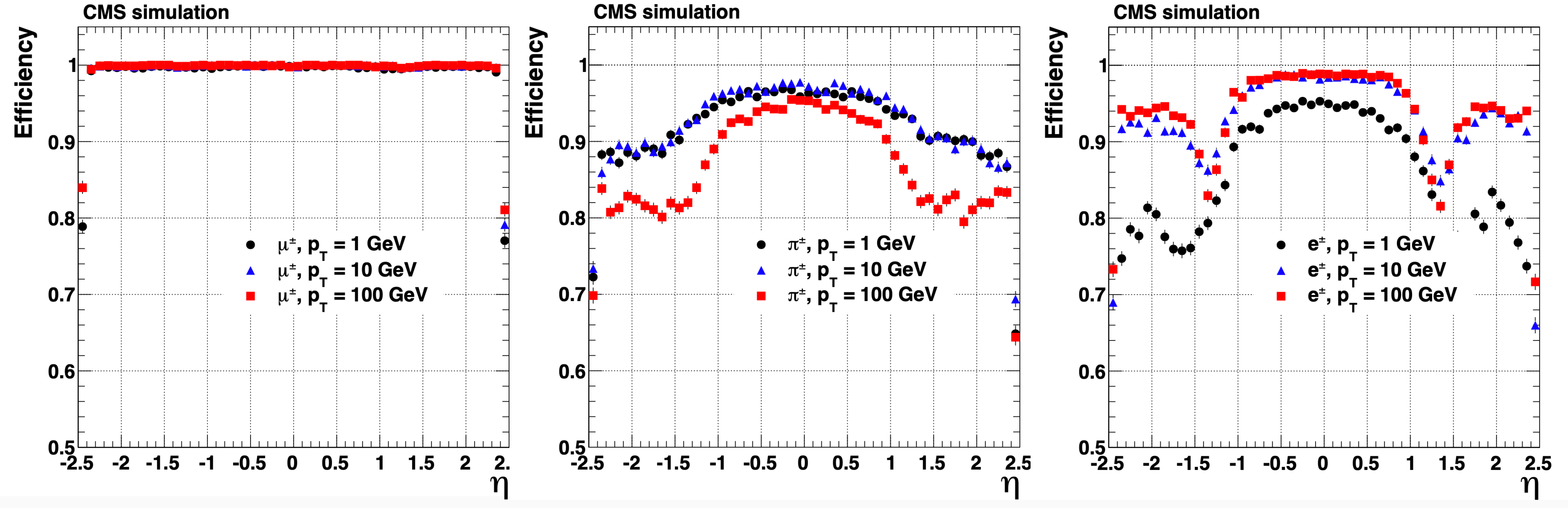
Typically, along *z* one has a x10 factor

Inner Pixel Detector

Resolution (rφ *x* z): 10 x 30 μm

THE CASE STUDY: CMS TRACKER

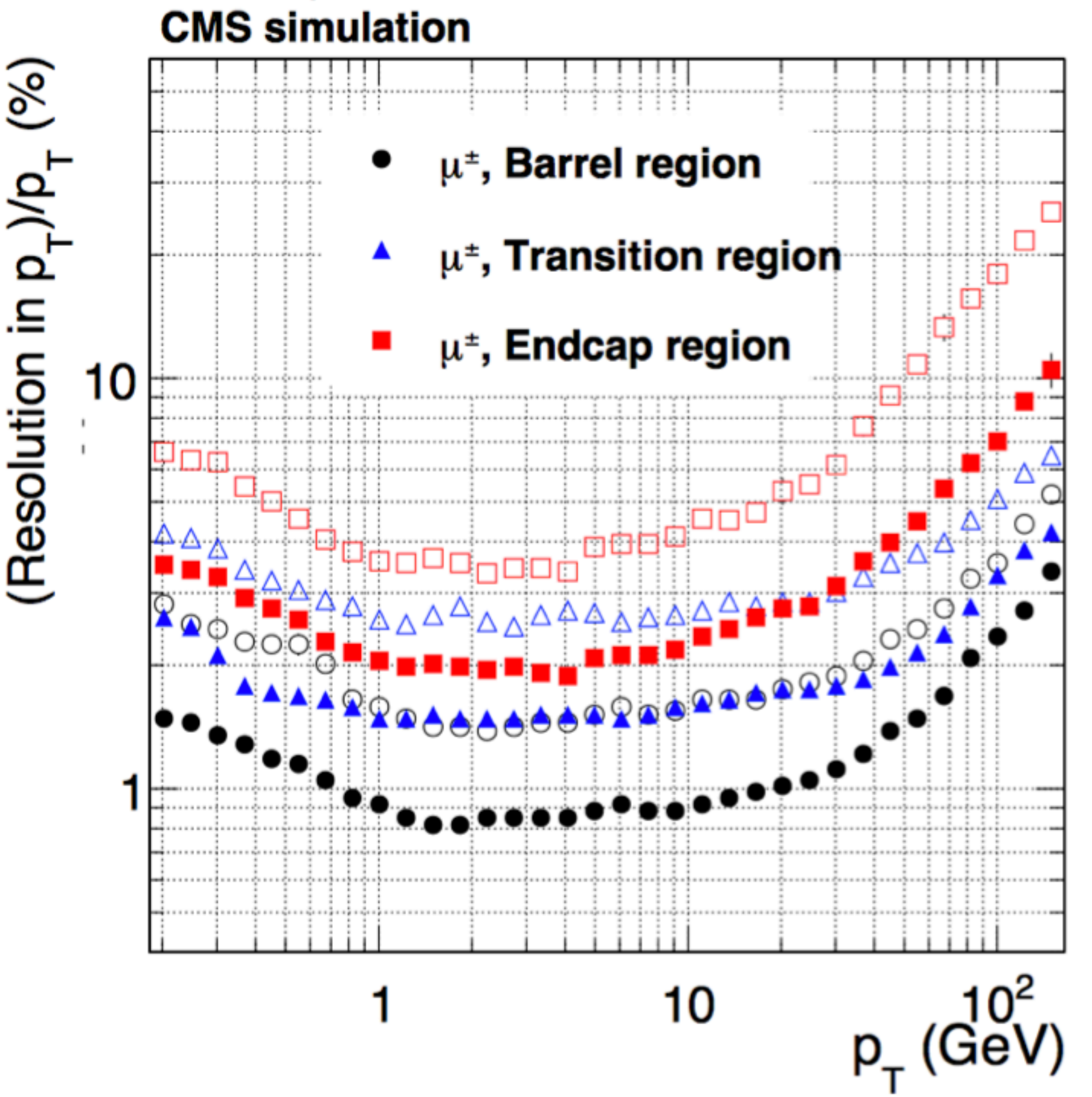
Features Phase-1 Tracker (up to LS 2024)

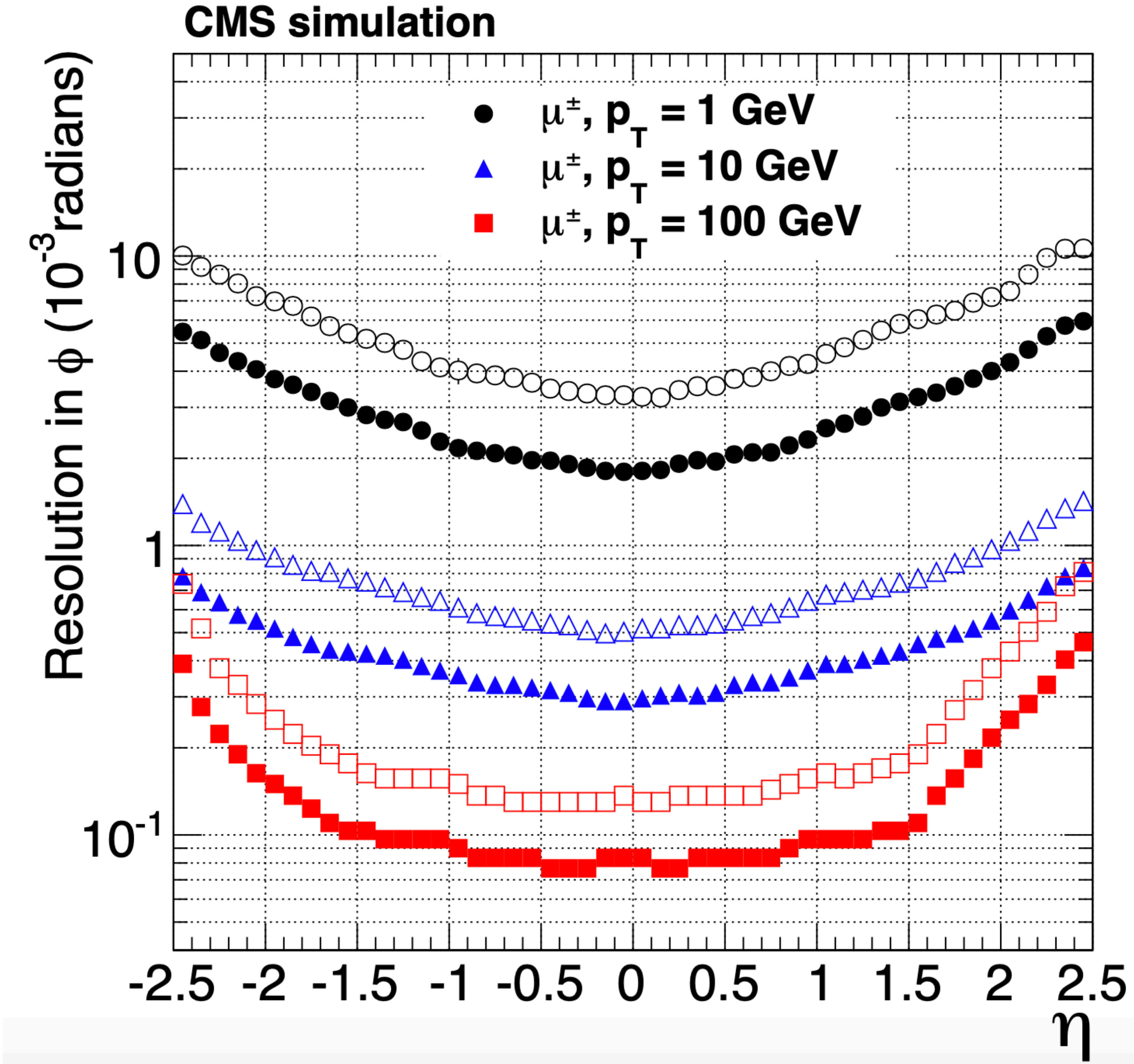


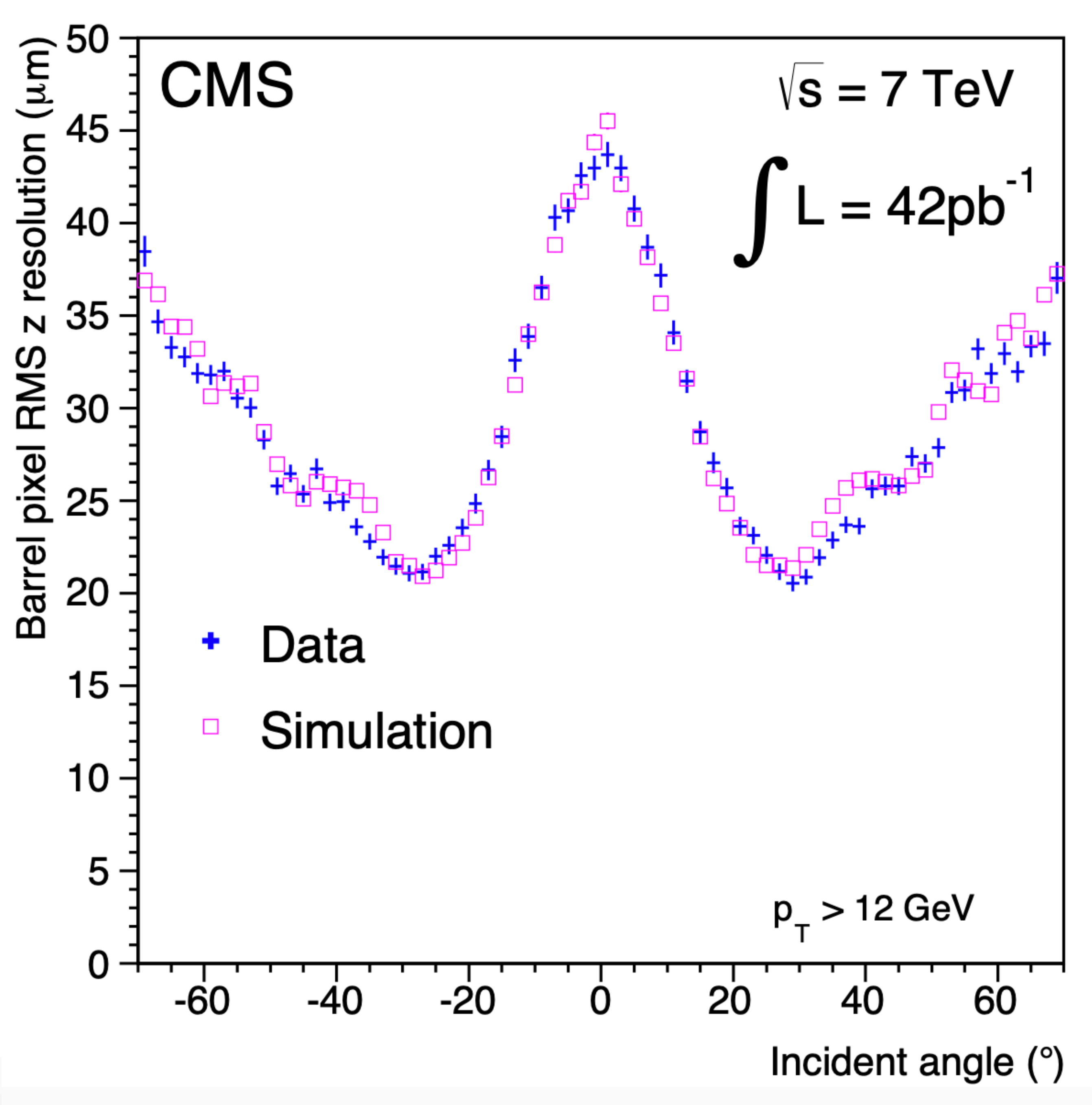
Efficiency: 94% for of $|\eta| < 0.9$ and 85% for $0.9 < |\eta| < 2.5$ @$p_T > 0.9$ GeV,
while for iso-μ efficiency is essentially 100%

THE CASE STUDY: CMS TRACKER

Features Phase-1 Tracker (up to LS 2024)





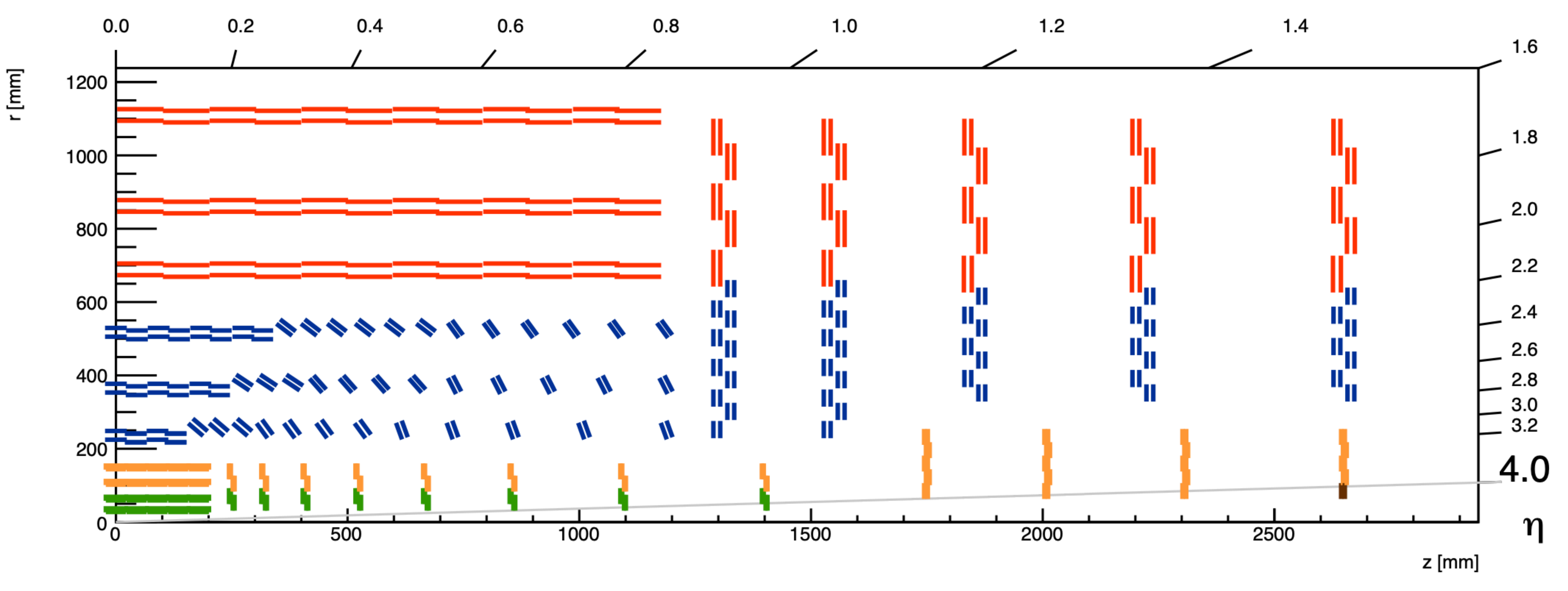


Resolution: For iso-μ of p_T = 100 GeV (|η| < 1.4), 2.8% in p_T, and 10 (30) μm in rφ (z)

Primary vertex resolution is 10 – 12 μm with an efficiency of ~1

THE CASE STUDY: CMS TRACKER

Phase-2 Tracker (HL-LHC)



Still in R&D

Will be installed from the LS 2024, with 2028 as the goal

It will need to be used for ~10 years @7.5×10^{34} $cm^{-2}s^{-2}$ (200 simultaneous pp collisions)

Expected 4-hit coverage up to |η| = 4.0 (2° !)

The OT will be part of the L1 trigger and some of its end-cap disks will be used for luminosity measurements

THE CASE STUDY: CMS TRACKER

Phase-2 Inner Pixel (IP) Tracker

Pixel Detector

2 billions of pixels bump-bombed on 2 or 4 ROCs

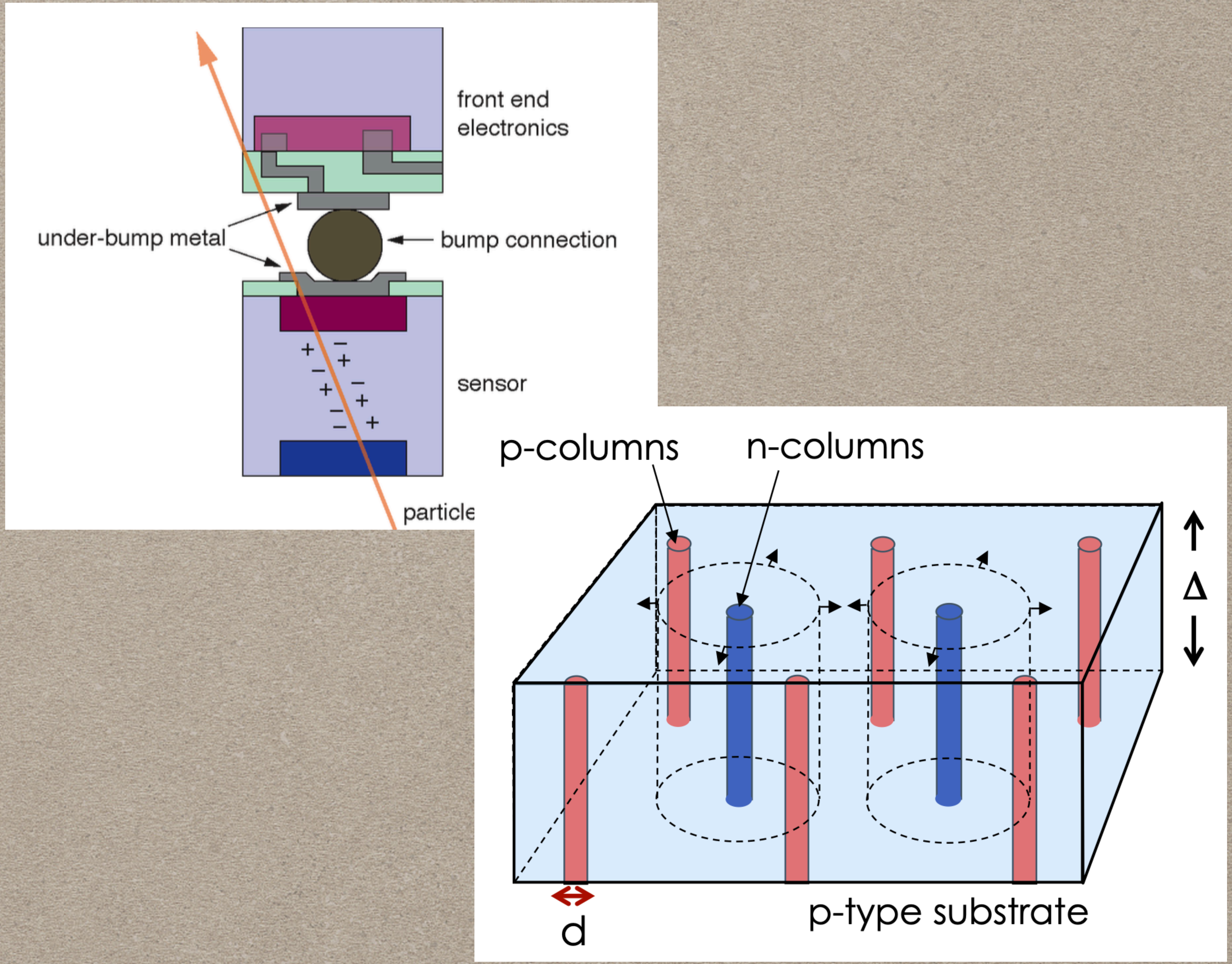
Barrel: 4 layers from 3 cm wrt beam pipe

n-p planar hybrid option: (50x50) or (25x100) x (100-150) μm^3

3D sensor option for barrel and small disks (100-150 μm thick)

Occupancy below 0.1%

Power provided in series of 12 modules, with separate chains for 2 and 4 ROCs



THE CASE STUDY: CMS TRACKER

Phase-2 Inner Pixel (IP) Tracker

Strip Detector

Similar number of modules, but x4 factor of strips than Phase-1

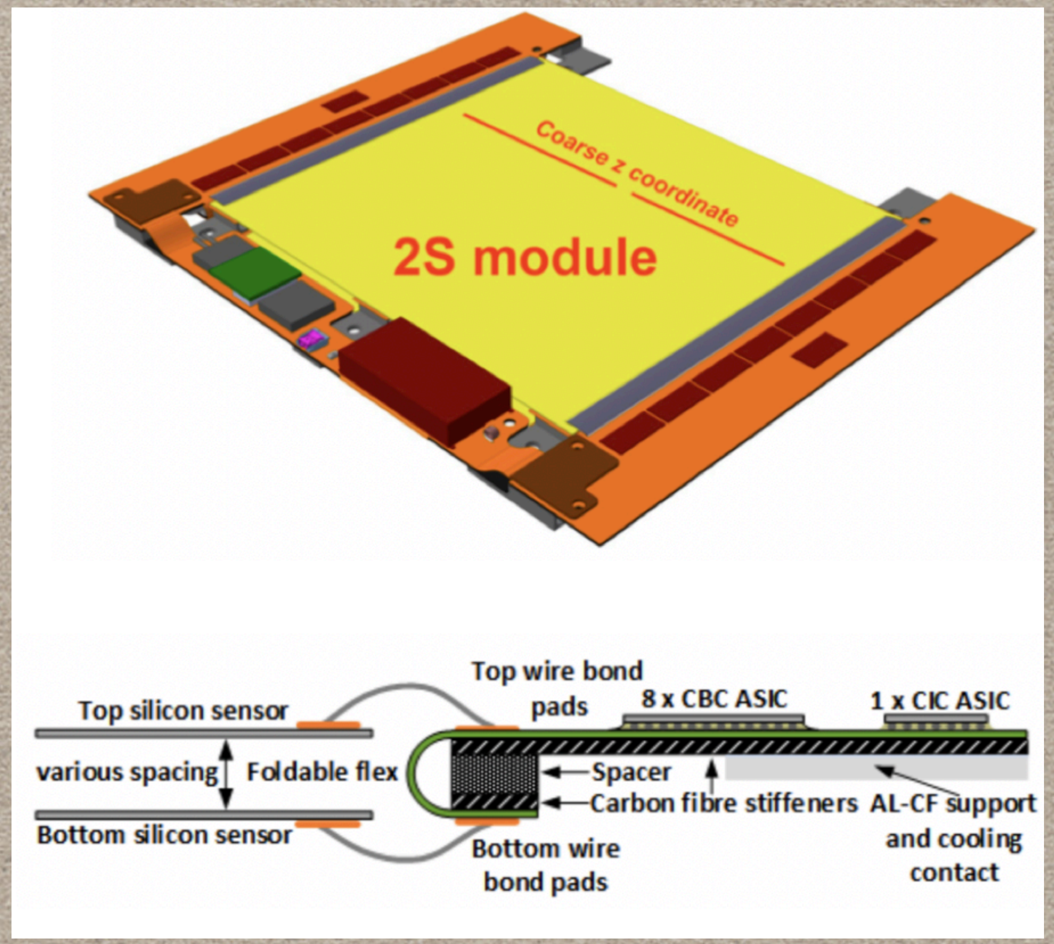
Occupancy < 1%

2S (Strip - Strip) modules: two Si strip sensors

PS (macroPixel - Strip) modules: Si strip sensor on top of a pixel (bump-bonded) one on the beam pipe side

For the L1 trigger a FPGA-based *track finder* will be implemented to reject low p_T tracks

Each module (13296) will be power supplied individually

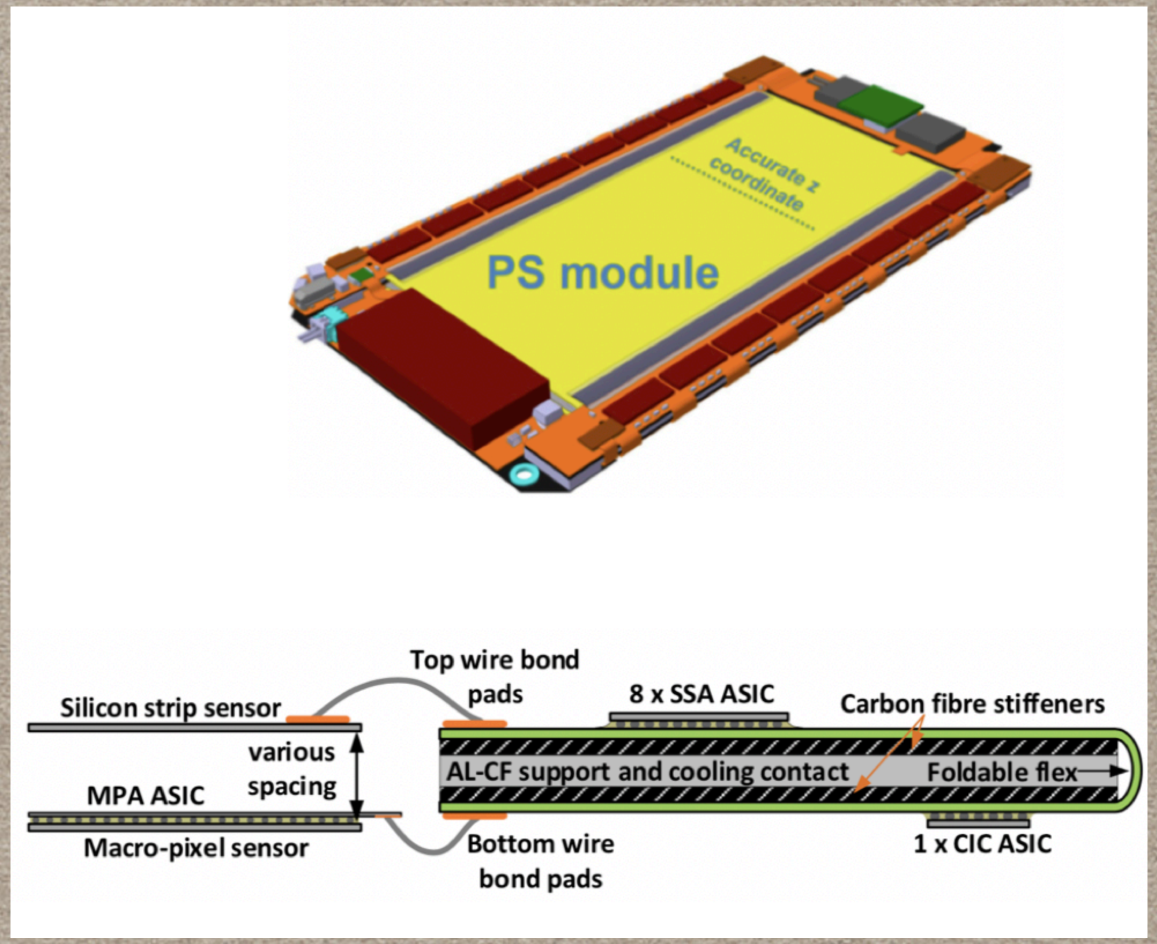


2S modules

2 row of 1016 strips 5 cm long with 90 μm pitch

PS modules

2 row of 960 strips 2.4 cm long with 100 μm pitch 32 rows of 960 pixels (1.5 mm x 100 μm)



WHAT NEXT? FCC UNFOLDING FUTURE

Main challenges

At FCC trackers will face a harsher environment that the one encountered in HL-HLC
(x5 factor in instantaneous luminosity with n_{eq} ~10^{16} - 10^{18} @30 ab^{-1})

Pile-up 1000 will produce 170 µm and < 1ps spaced vertices

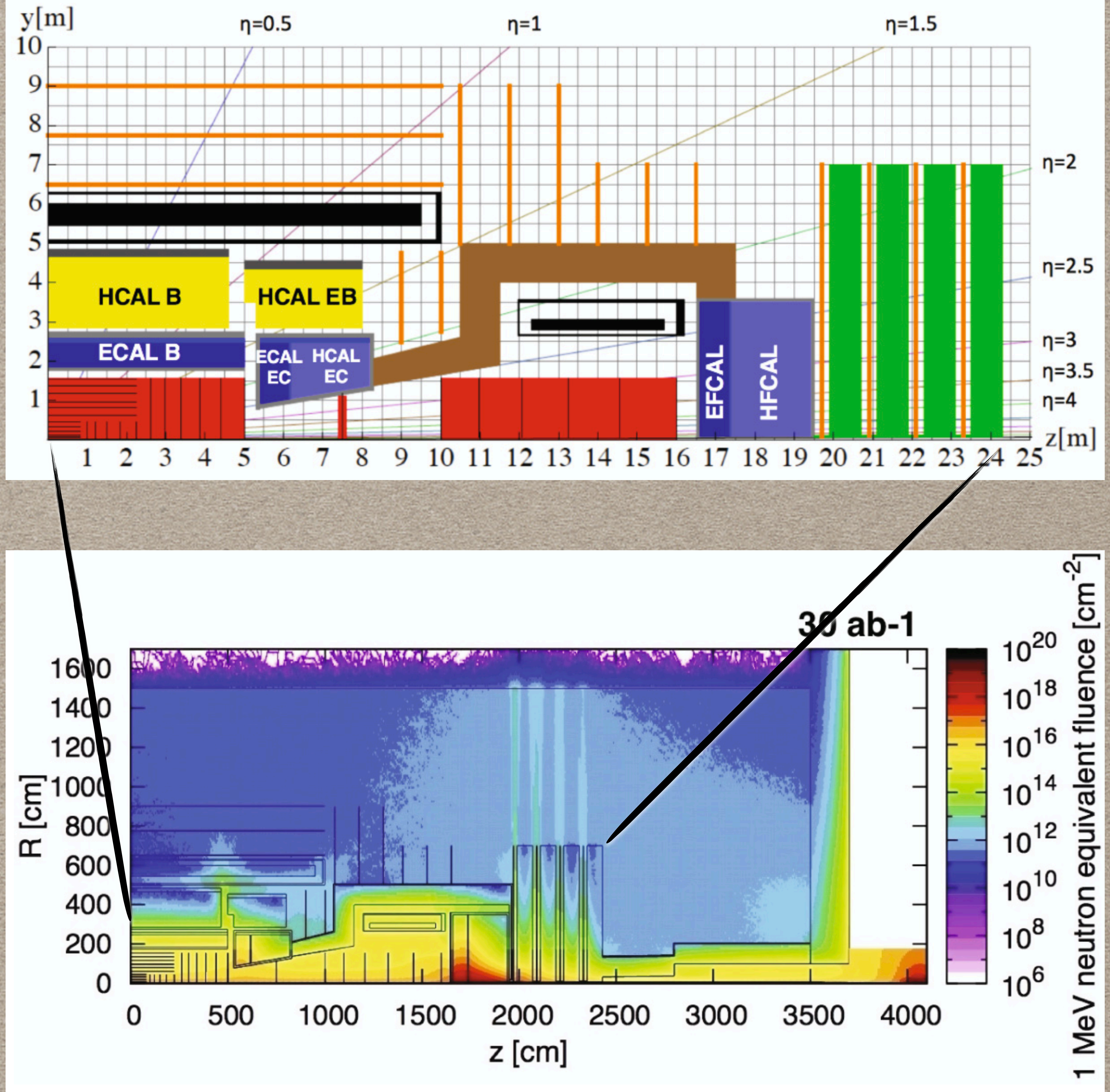
At these conditions correct vertex assignment can happen with good timing information → 4D measurement

$\delta p_T/p_T = 15\%$ @p_T = 10 TeV & single hit resolution < 5 µm

Good track coverage up to |η| = 6.0

Time stamp order of tenth of ns

All of this maintaining low power consumption and low material budget (< 0.3% X_0) in an area of O(100)m^2



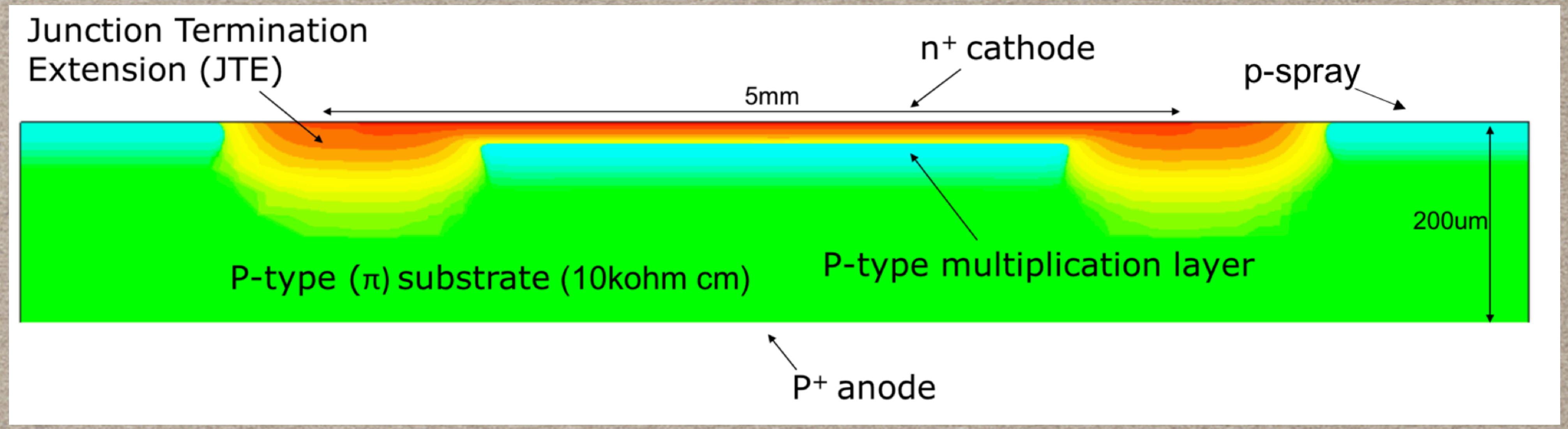
WHAT NEXT? FCC UNFOLDING FUTURE

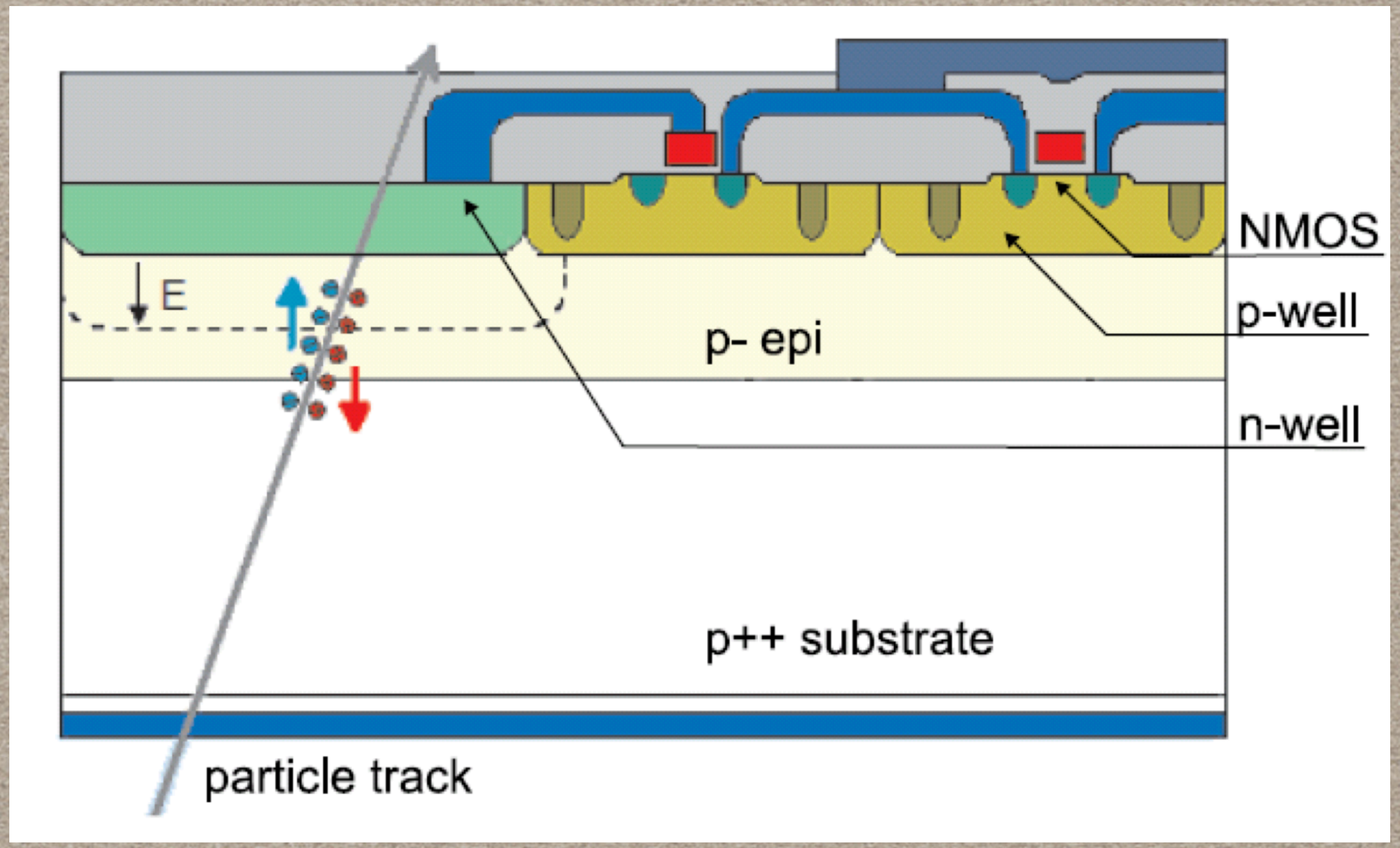
Technologies

Ultra fast Si detectors based on LGAD will allow a 4D measurement. With internal avalanche, thanks to an highly doped layer, these sensors will allow sub-ns (even tenth of ps) measurement

Decreasing the thickness of hybrid sensors or introducing different paradigms (no bump-bonding, but capacitative coupling via a thin layer of glue)

Monolithic sensors, CMOS devices in which the sensitive volume and the ROC are combined in a single piece of Si (20x20x50 μm^3)





WHAT NEXT? FCC UNFOLDING FUTURE

Pure Si Tracker - CLD

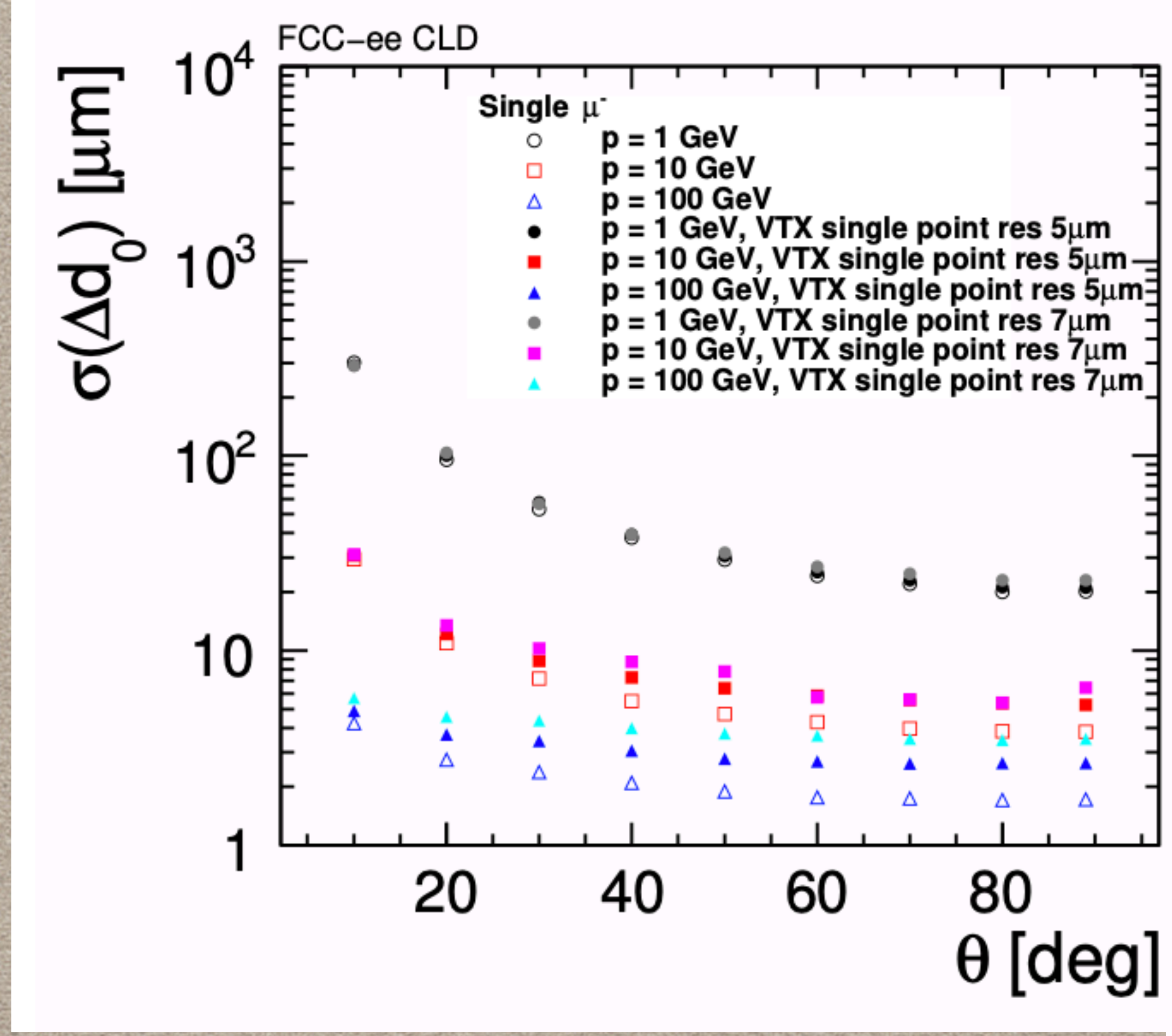
Vertex detector 25x25x50 μm³ pixel sensor

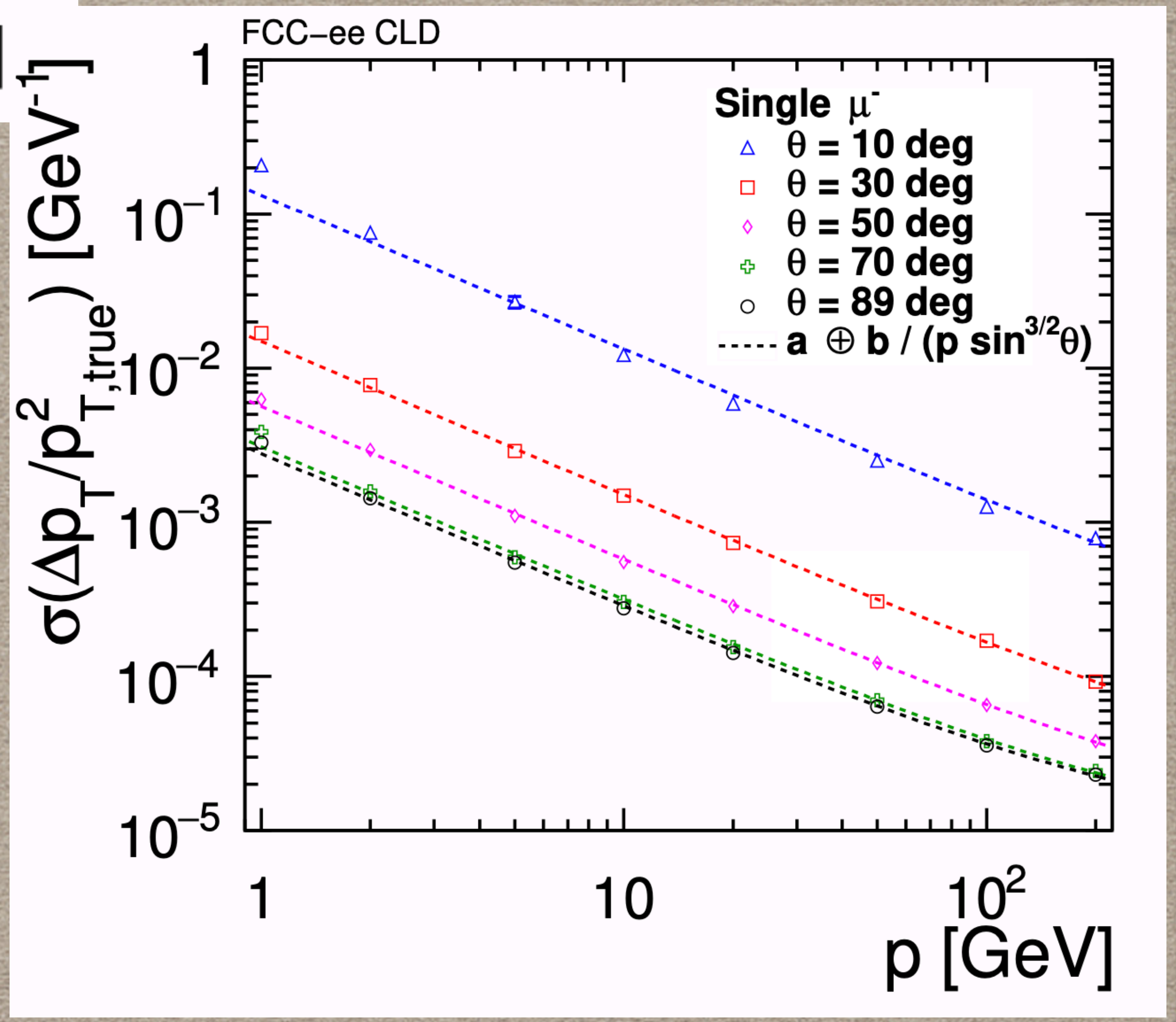
Tracker detector 25x25x500 μm³ in a monolithic structure

Single point resolution:

- vertex: 3 μm × 3 μm
- tracker barrel and discs: 7 μm × 90 μm
- outer tracker barrel and discs: 7 μm × 90 μm

p_T resolution of 3.5x10^{-5} GeV^{-1} @100 GeV in barrel





Many Thanks

For

Your Attention

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Ordered in a random fashion and many apologies if I missed some…

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