III. Physikalisches Institut A | RWTH AACHEN UNIVERSITY

Experimental Techniques in Particle Physics (WS 2020/2021)

Semiconductor Detectors (Part II)

Prof. Alexander Schmidt

15.12.2020

x-mas break information

- the official RWTH christmas break is

23.12.2020 - 05.01.2021

- the last lecture/exercise of the year is Tuesday 22.12.2020
- we continue in January with the GEANT and FPGA courses on Wednesday 06.01.2021
- the first lecture/exercises of the year will be Tuesday 12.01.2021

Principle of particle detection with silicon (see last lecture for details)

Through going charged particles create $e^- h^+$ pairs in the depletion zone (about 30.000 pairs in standard detector thickness). These charges drift to the electrodes. The drift (current) creates the signal which is amplified by an amplifier connected to each strip. From the signals on the individual strips the position of the through going particle is deduced.

A typical n-type Si strip detector:

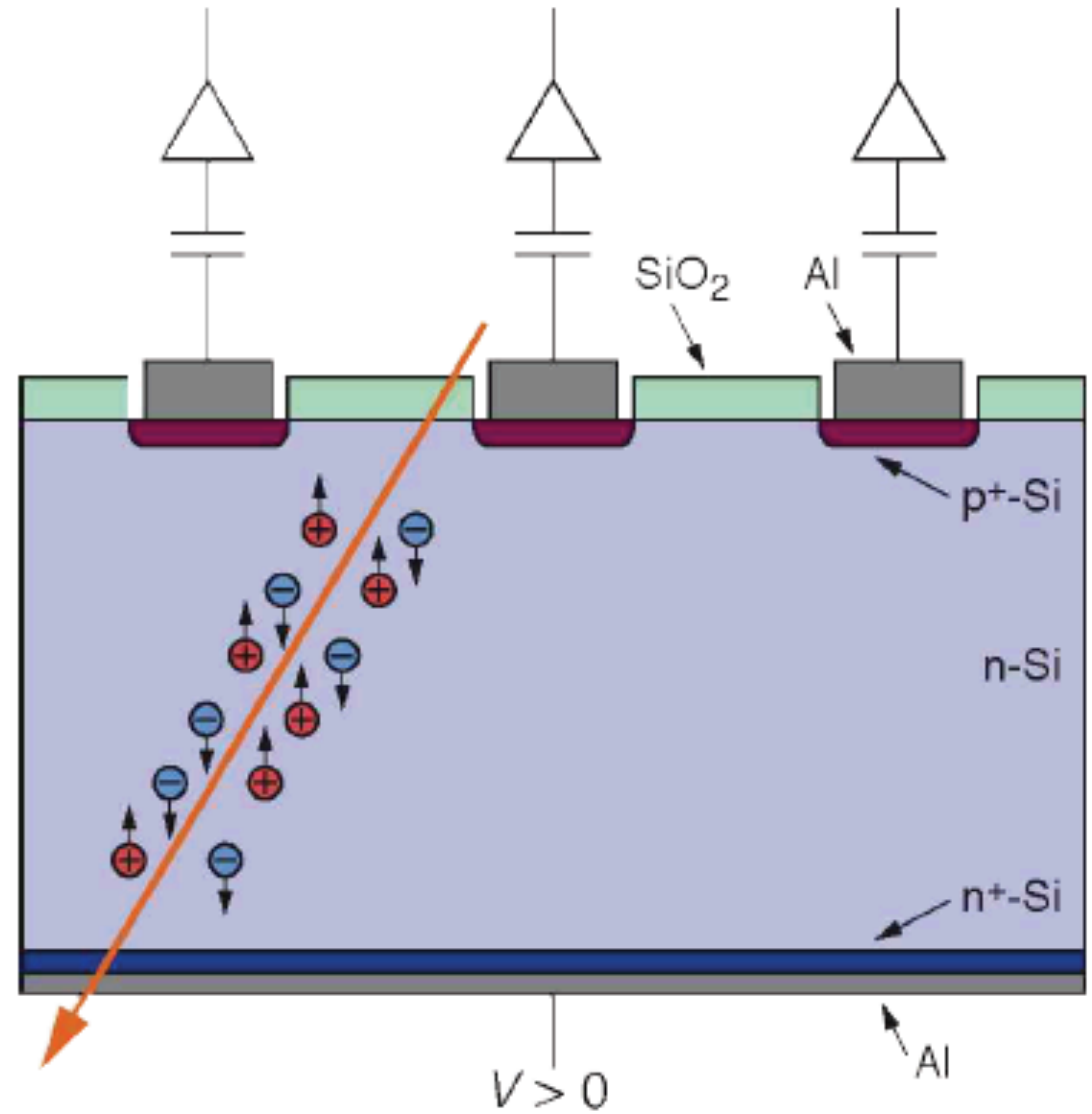
★ p^+n junction:
$N_a \approx 10^{15}$ cm^{-3}, $N_d \approx 1$–$5 \cdot 10^{12}$ cm^{-3}

★ n-type bulk: $\rho > 2$ kΩcm
➔ thickness 300 μm

★ Operating voltage < 200 V.

★ n^+ layer on backplane to improve ohmic contact

★ Aluminum metallization



Comparison (not exhaustive)

Advantages of silicon detectors over gas detectors:

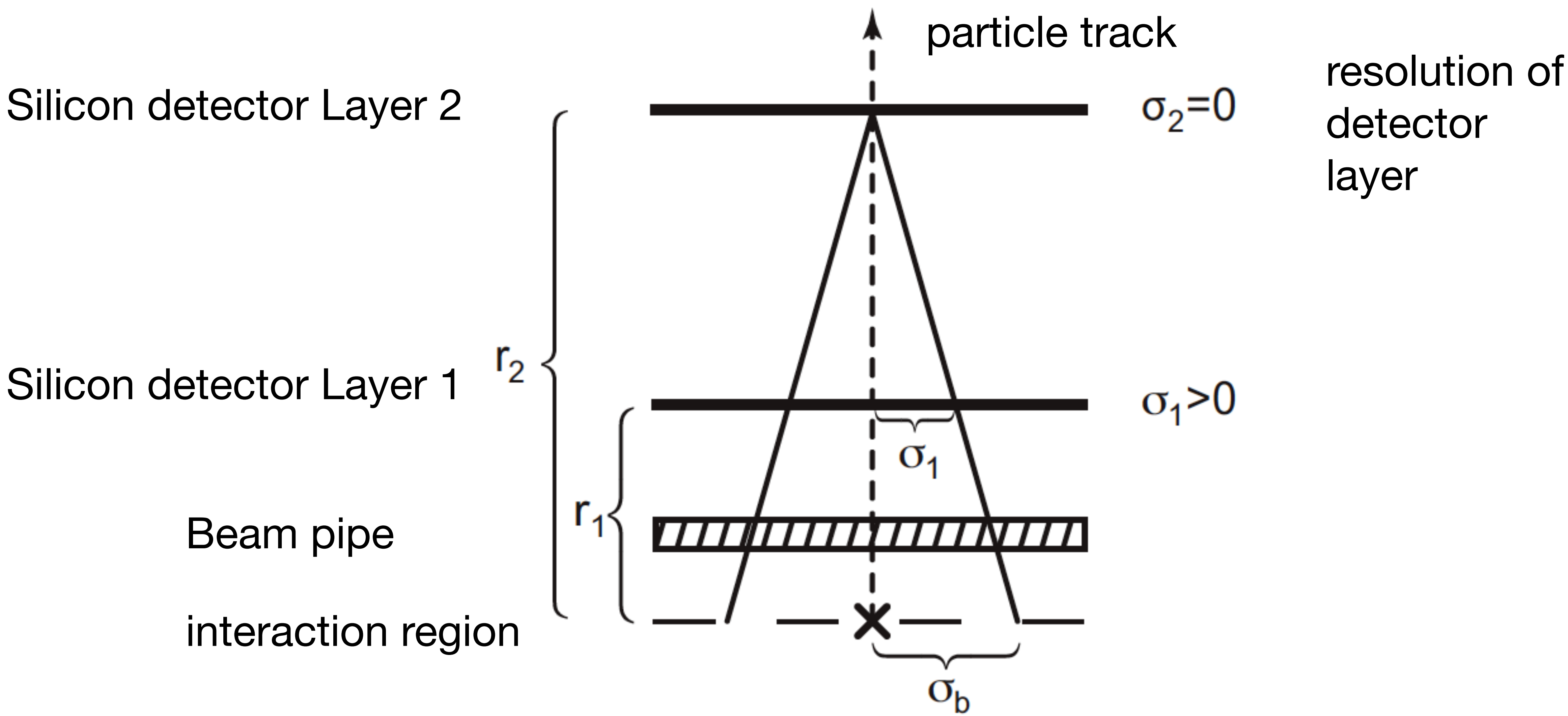
- faster response time (no long drift distances)
- higher occupancies possible
- can be placed closer to the interaction region
- no gas monitoring and handling necessary
- very high position resolution

Disadvantages:

- more material compared to gas (more material interactions)
- radiation hardness worse than gas

Lever arm

- **simple example:** idealized detector with perfect Layer 2

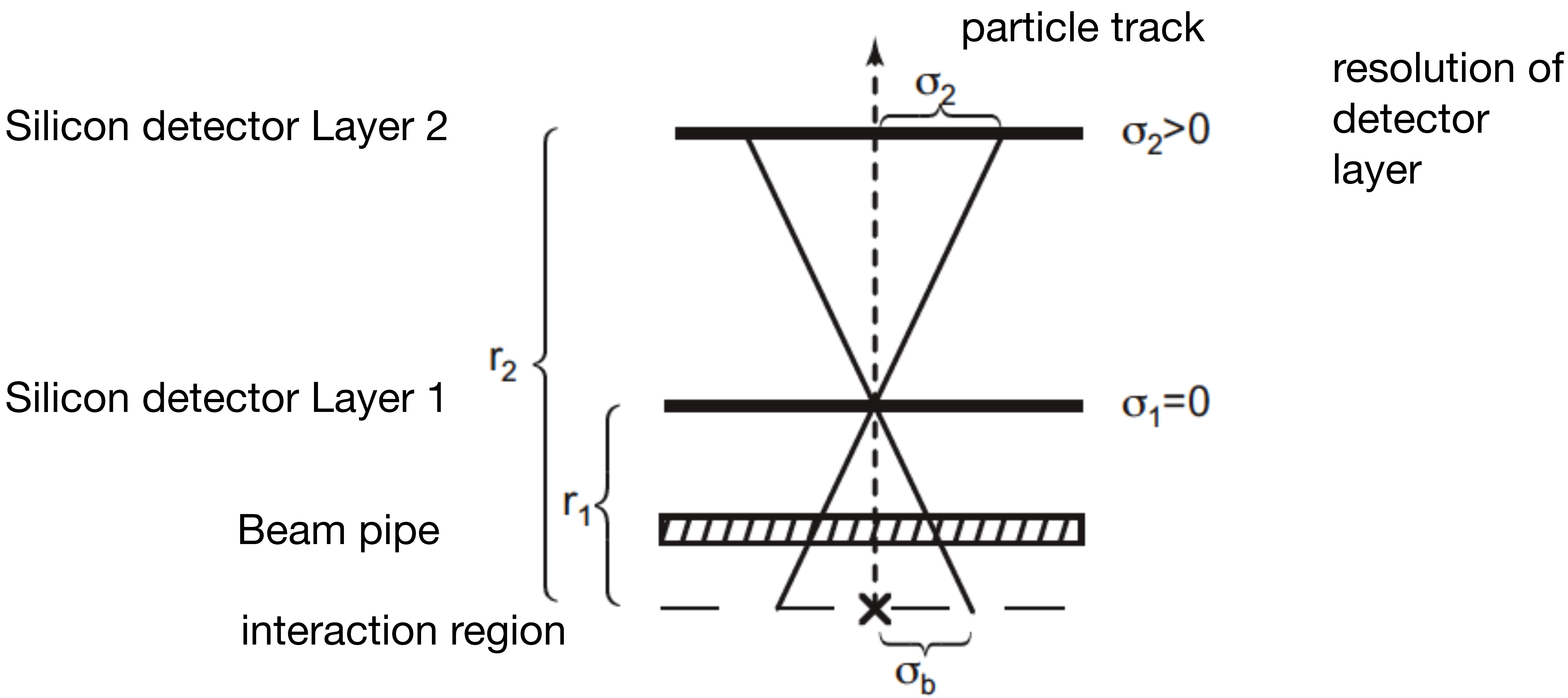


resolution of σ_b:

$$\frac{\sigma_b}{\sigma_1} = \frac{r_2}{r_2 - r_1}$$

Lever arm

- **next example:** idealized detector with perfect Layer 1



resolution of σ_b:

$$\frac{\sigma_b}{\sigma_2} = \frac{r_1}{r_2 - r_1}$$

Lever arm

- **combined resolution:** addition in squares

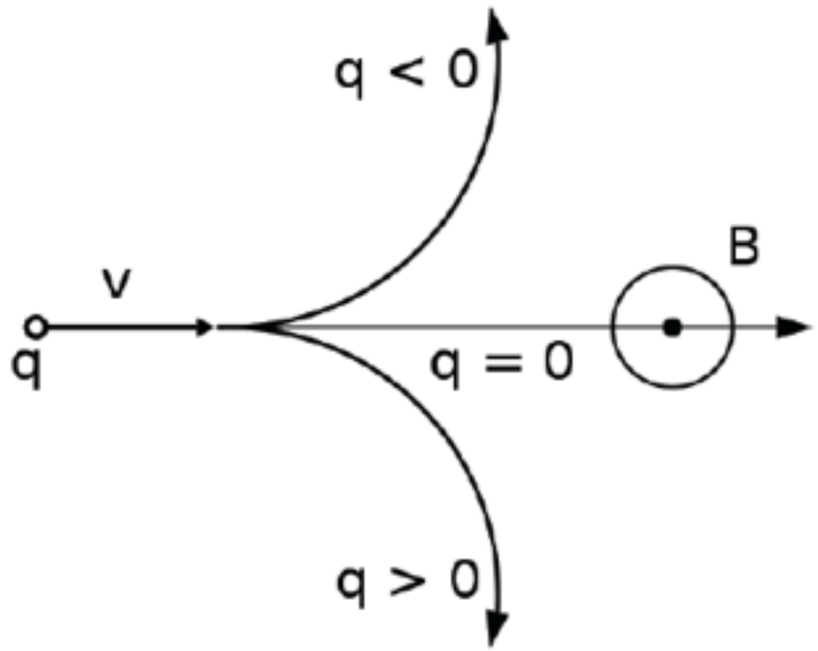
$$\sigma_b^2 = \left(\frac{r_1}{r_2 - r_1}\, \sigma_2 \right)^2 + \left(\frac{r_2}{r_2 - r_1}\, \sigma_1 \right)^2 + \sigma_{\text{ms}}^2$$

multiple scattering (see lecture on material interactions)

- **conclusions:**
  - σ_1 is dominant. Innermost detector should have best resolution
  - lever arm $r_2 - r_1$ should be as large as possible
  - innermost detector distance r_1 should be small (close to interaction point
  - amount of material should be small to keep multiple scattering to a minimum

Tracking detectors

The determination of the momentum of charged particles can be performed by measuring the bending of a particle trajectory (track) in a magnetic field



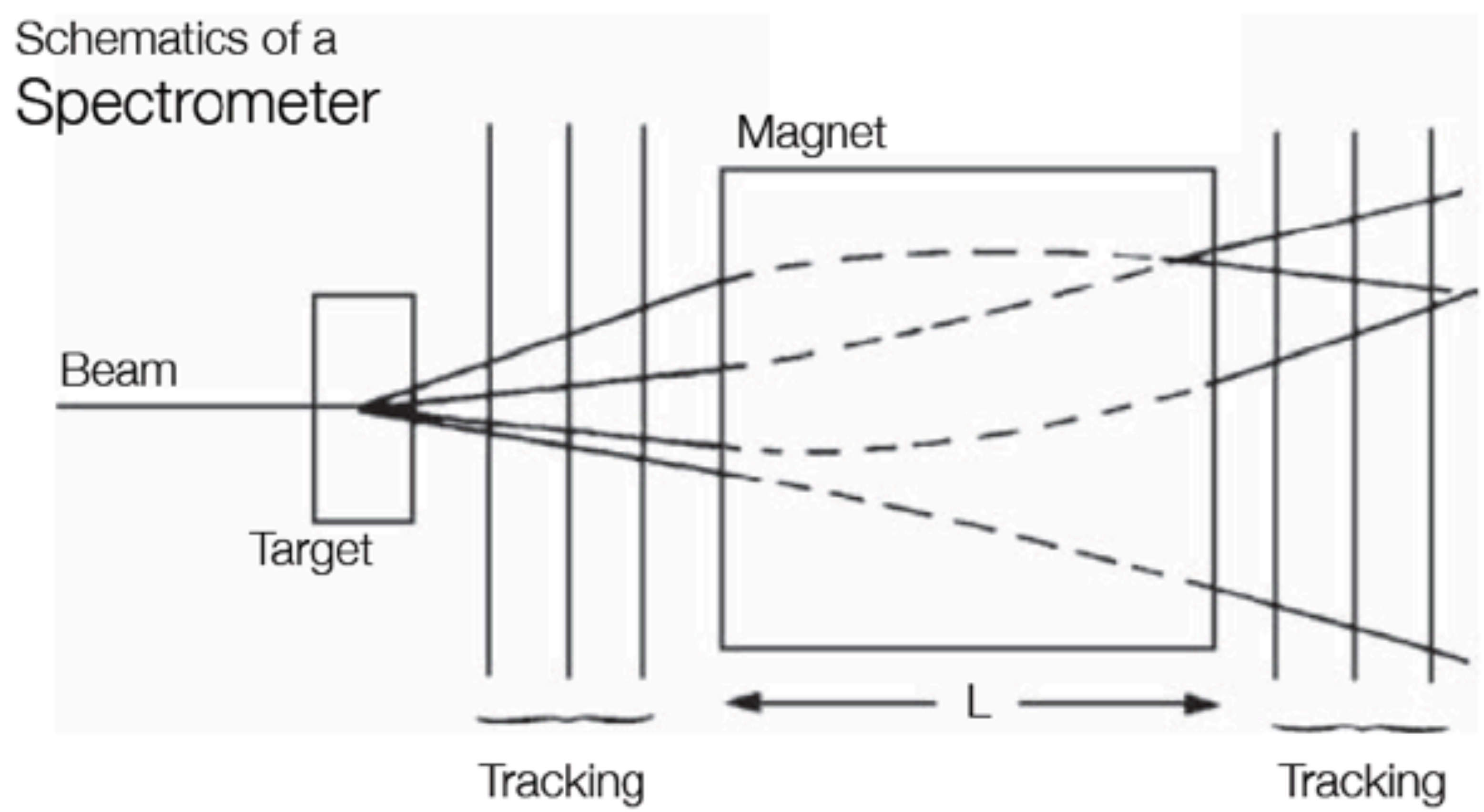
$$\vec{F} = q\vec{v} \times \vec{B}$$

Lorentz force: is the force on a point charge due to electromagnetic fields

$$\frac{mv^2}{r} = qvB$$

… for a particle in motion perpendicular to a constant B field

In practice:
- use layers of position sensitive detectors before and after (or inside) a magnetic field to measure a trajectory
- determine the bending radius

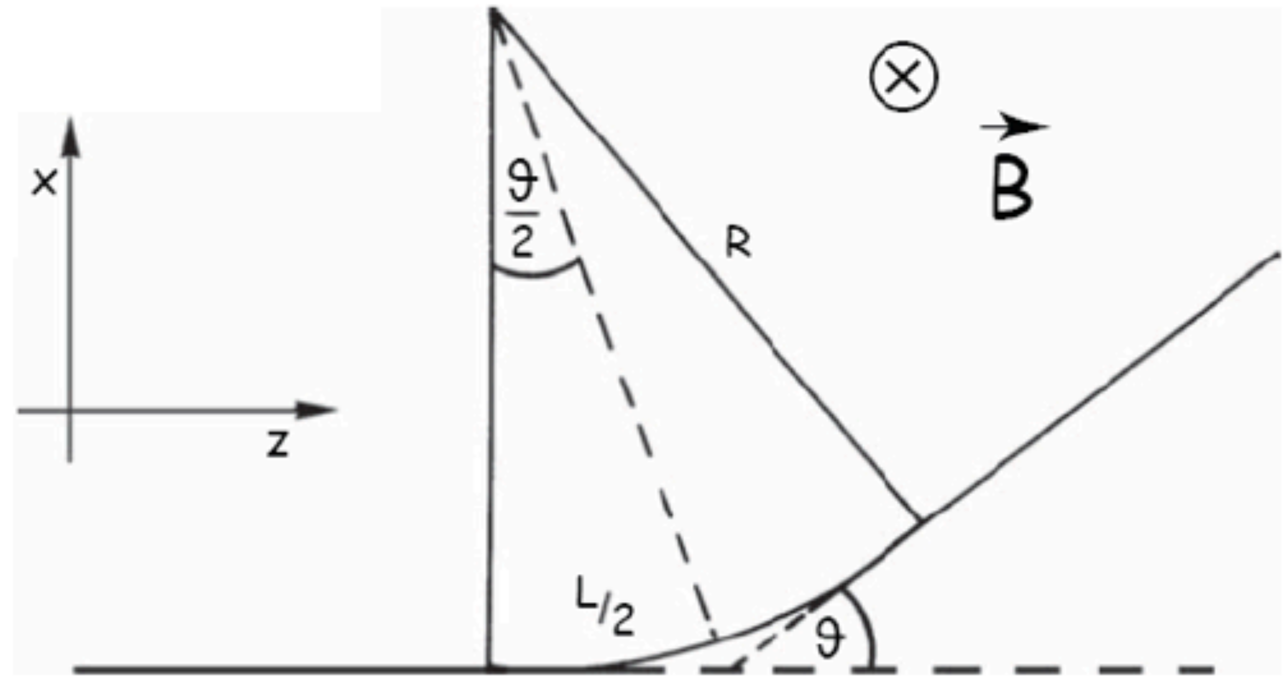


Tracking detectors

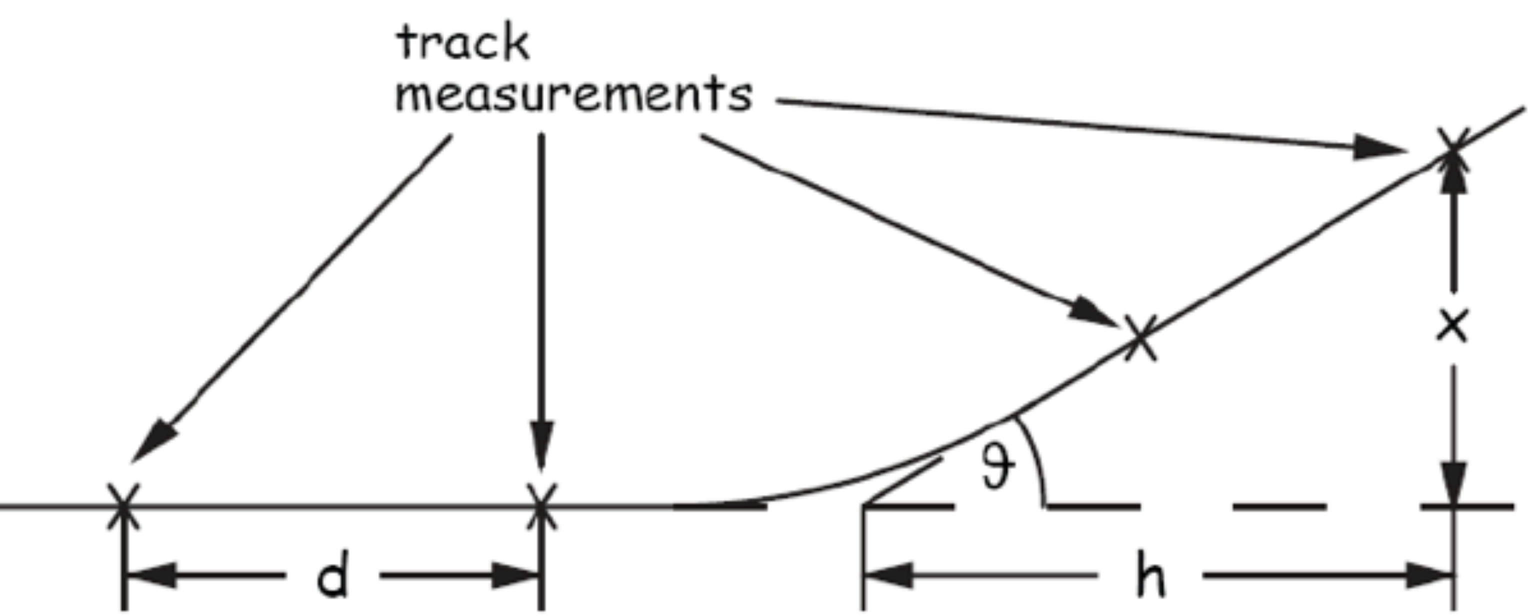
Momentum determination
in fixed target experiments ...

$$p = eRB \qquad \vartheta = {}^{L}\!/_{R} = {}^{L}\!/_{p} \cdot eB$$

$$p = eB \cdot {}^{L}\!/_{\vartheta}$$



Momentum resolution: $\rightarrow \quad \dfrac{\sigma_p}{p} = \dfrac{\sigma_\vartheta}{\vartheta}$ with $\sigma_\vartheta \sim \sigma_x$



Determination of σ_p/p:

$$\vartheta = \frac{x}{h} \qquad \sigma_\vartheta = \frac{\sigma_x}{h}$$

$$\frac{\sigma_p}{p} = \frac{\sigma_\vartheta}{\vartheta} = \frac{\sigma_x}{h} \cdot \frac{p}{eBL}$$

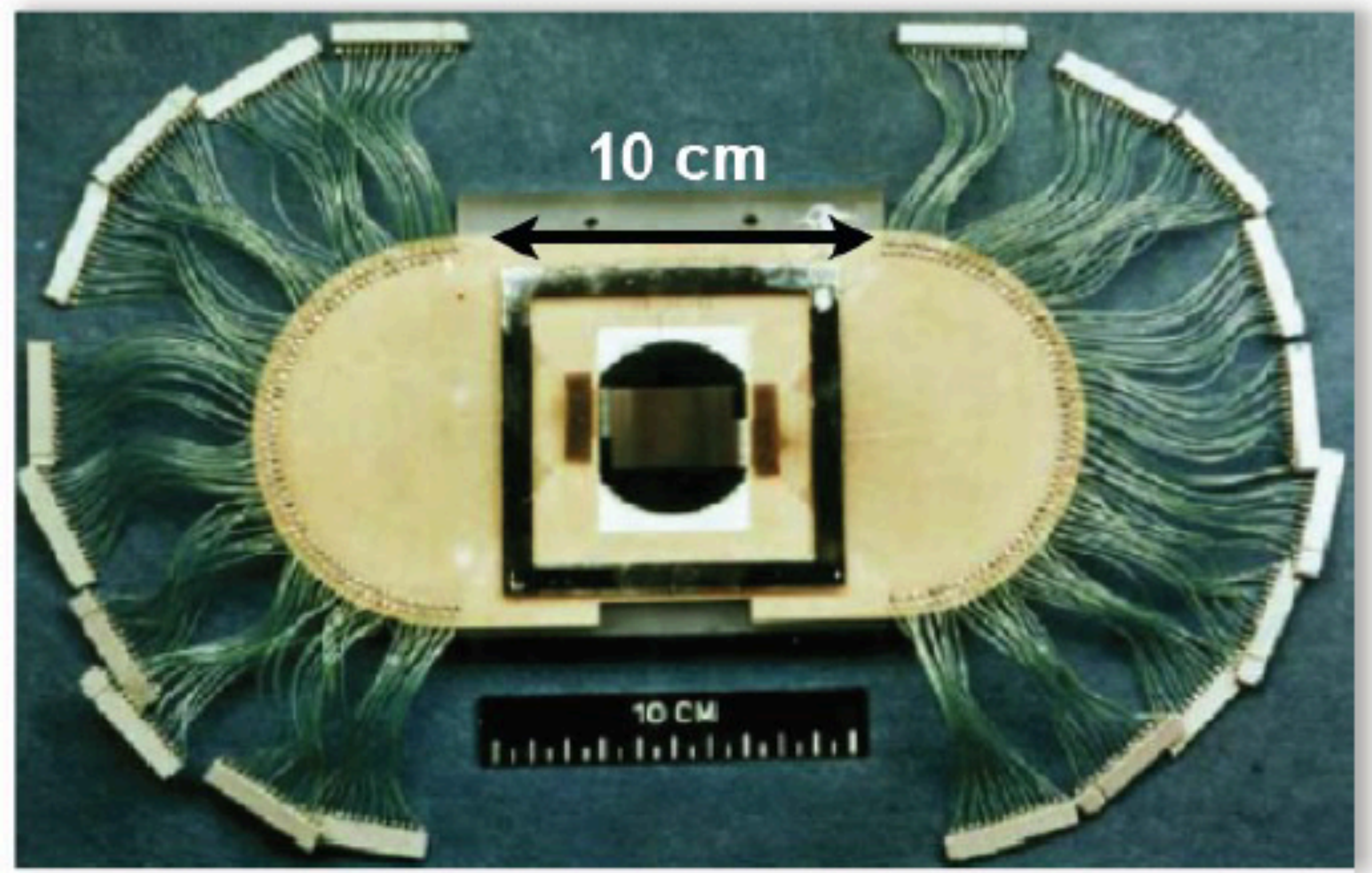
Long lever arm improves momentum resolution ...

Early silicon detectors

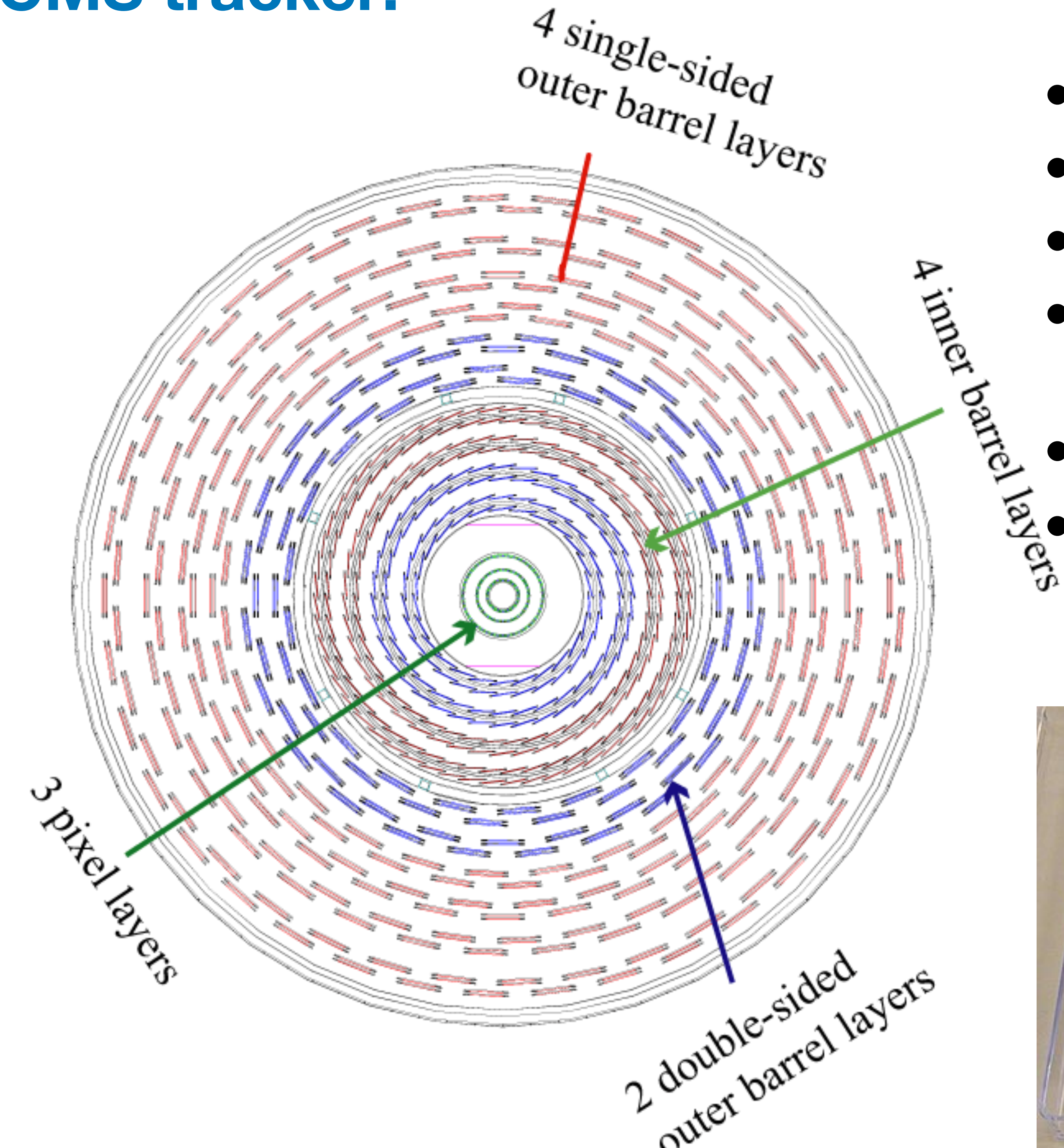
> NA11 at CERN

First use of a position-sensitive silicon detector in HEP experiment

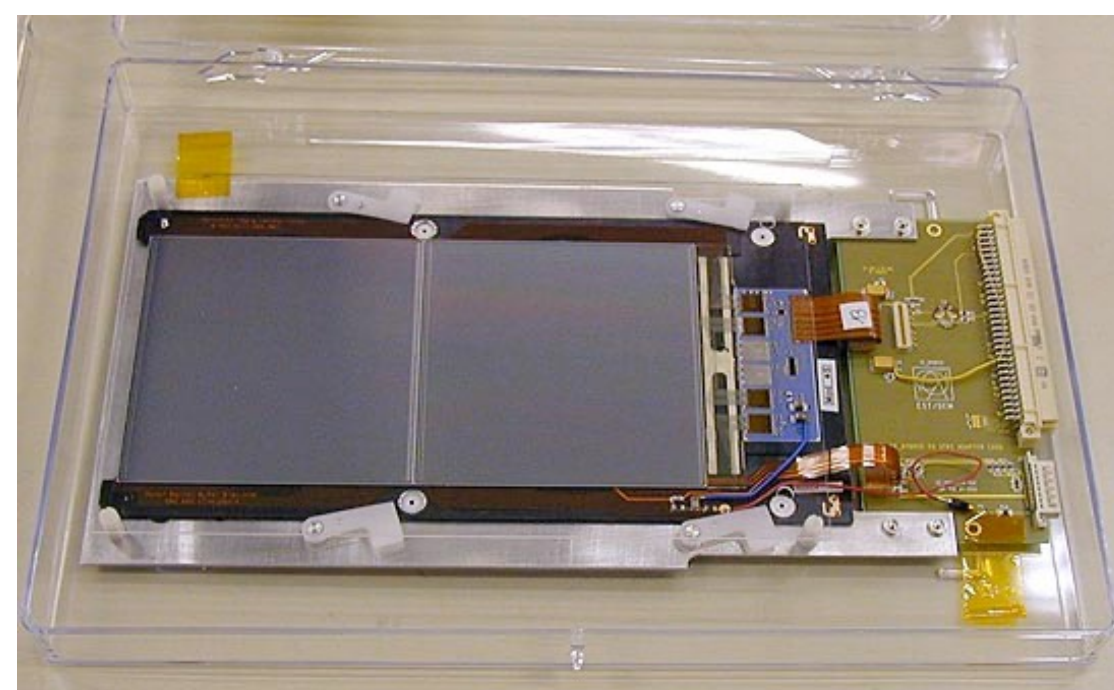
- Measurement of charm-quark lifetime
- 1200 diode strips on 24 x 36mm^2 active area
- 250-500 µm thick bulk material
- 4.5 µm resolution



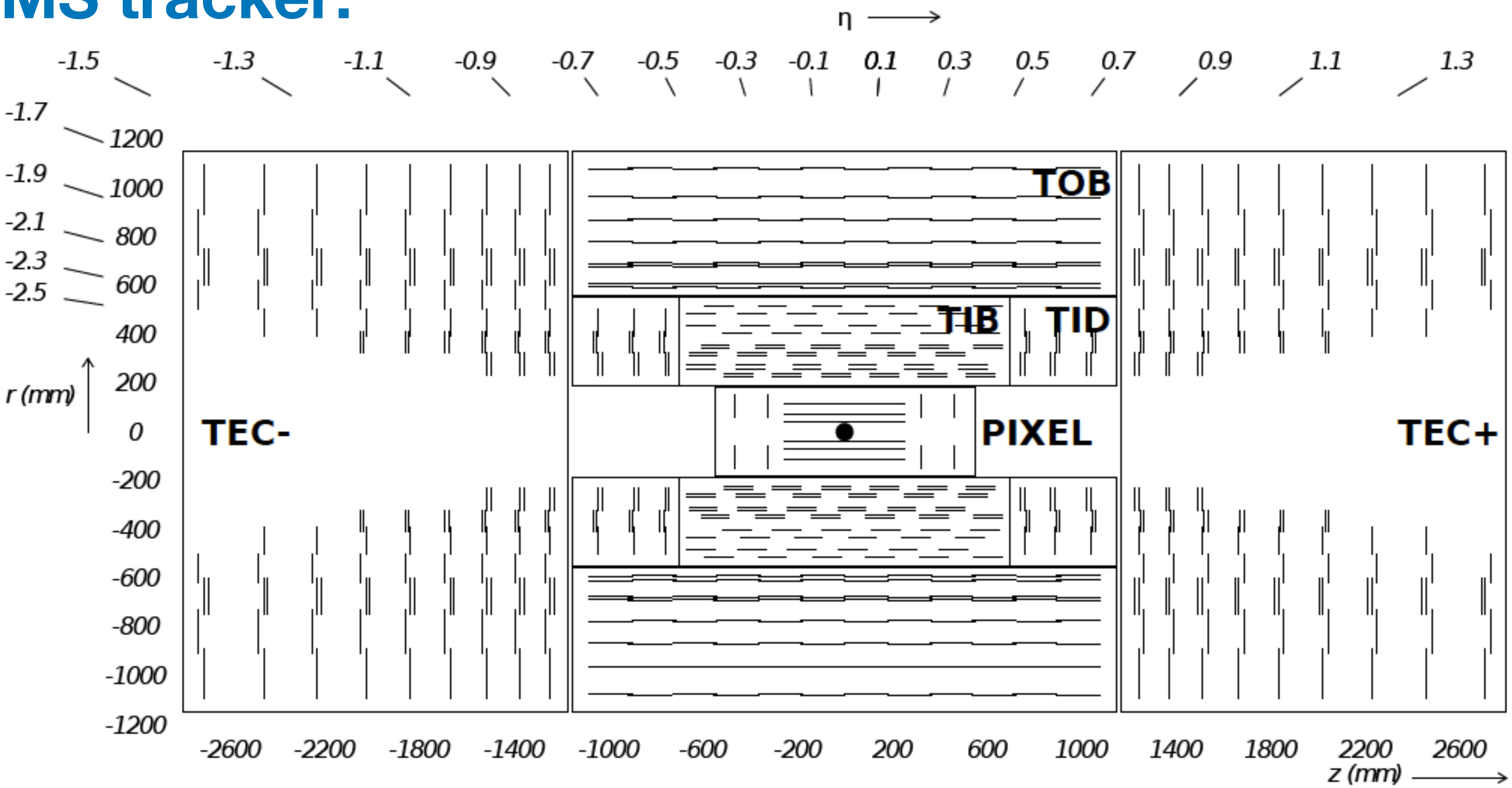
CMS tracker:



- 10 barrel layers
- 9+3 endcap layers (next slide)
- radius 1.1 m, length 5.8m
- 200 m^2 active silicon
  (largest silicon tracker ever built)
- acceptance up to $|\eta|<2.5$
- 500 people, 15 years design development and construction

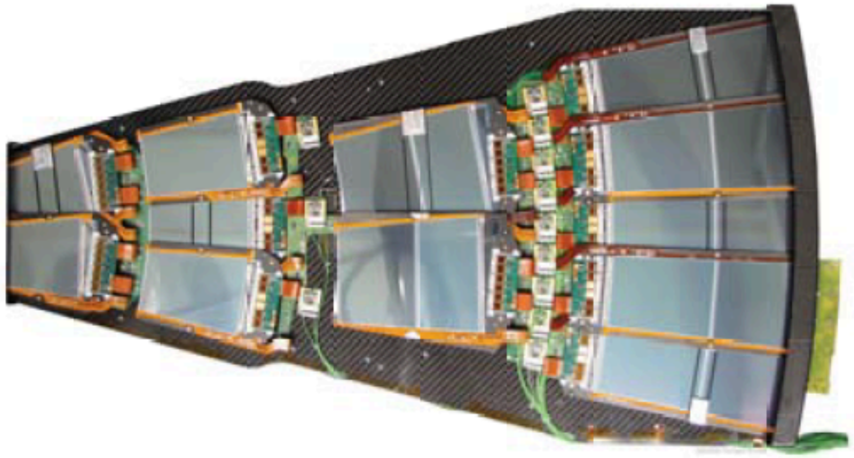


CMS tracker:



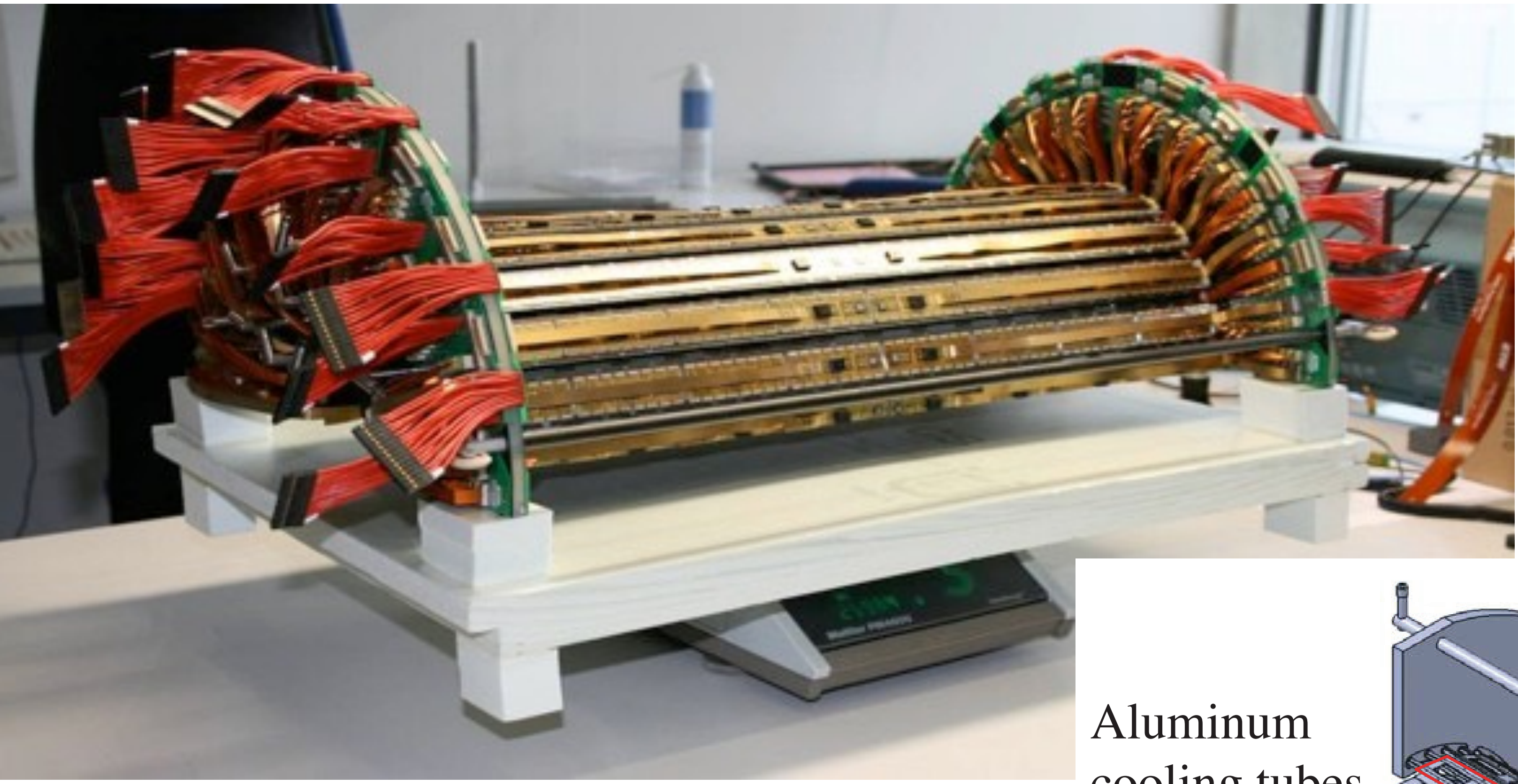
endcap (TEC) "petal"

front

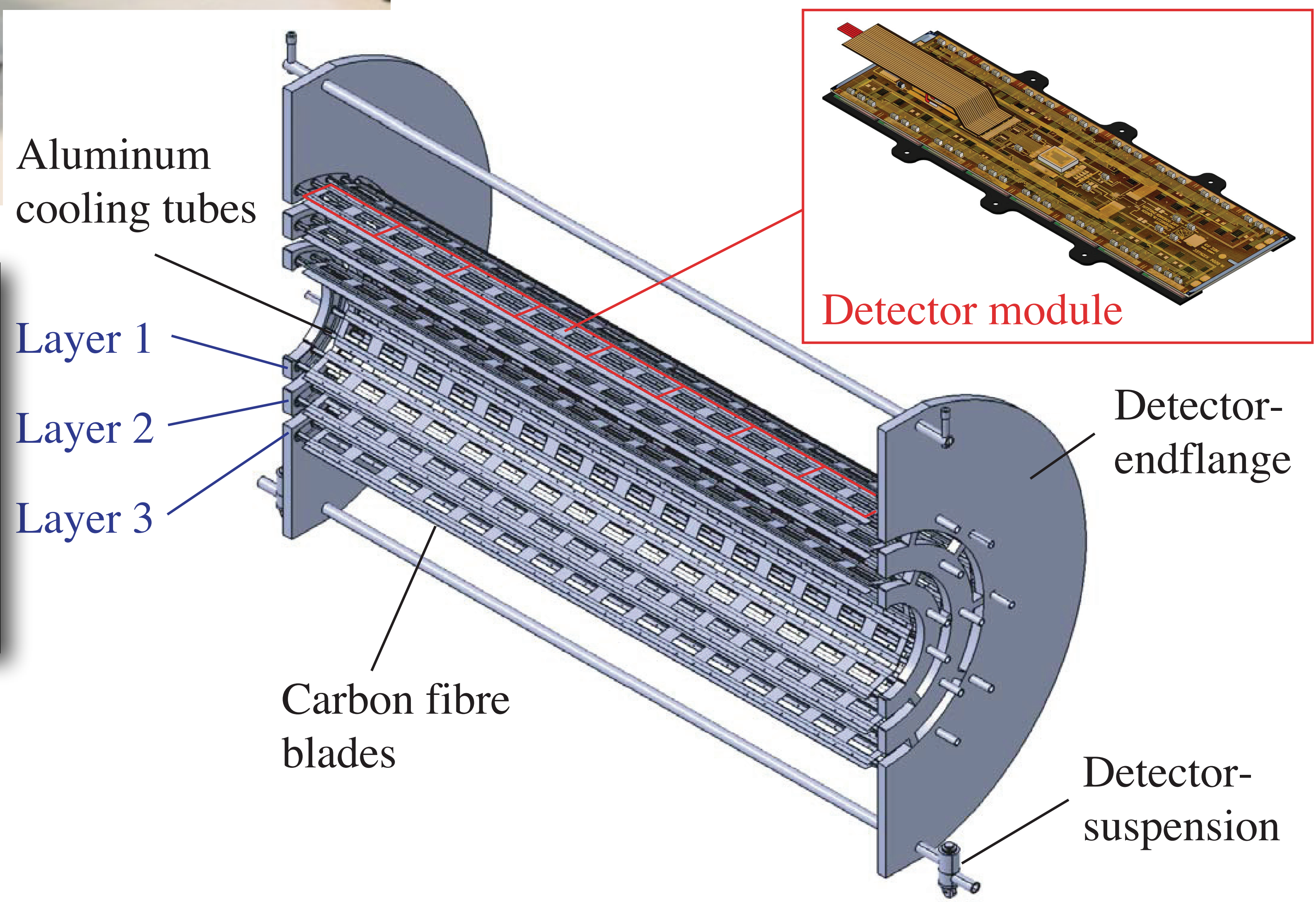


back

CMS pixel detector (first one):



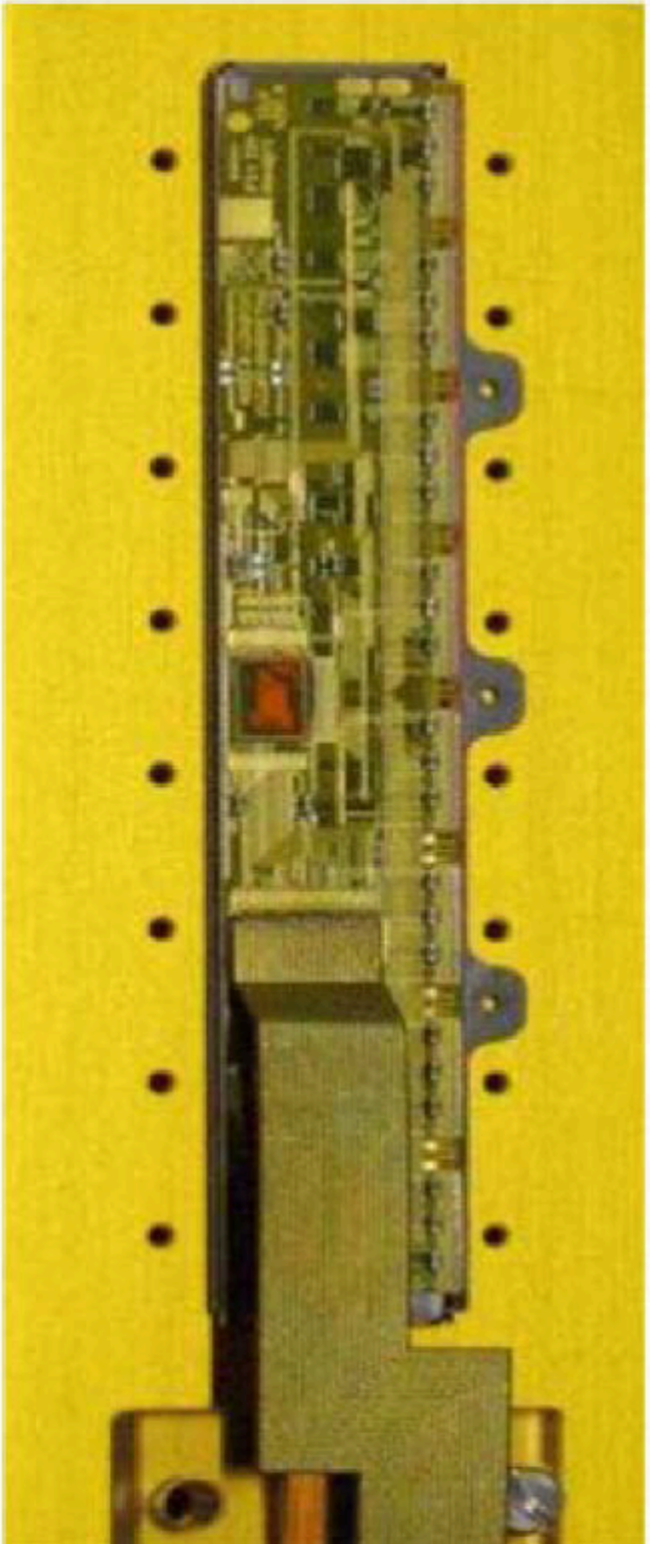
672 modules
of size 6.6 x 2.6 cm
each containing 66 560 pixels
of size 150 x 100 μm



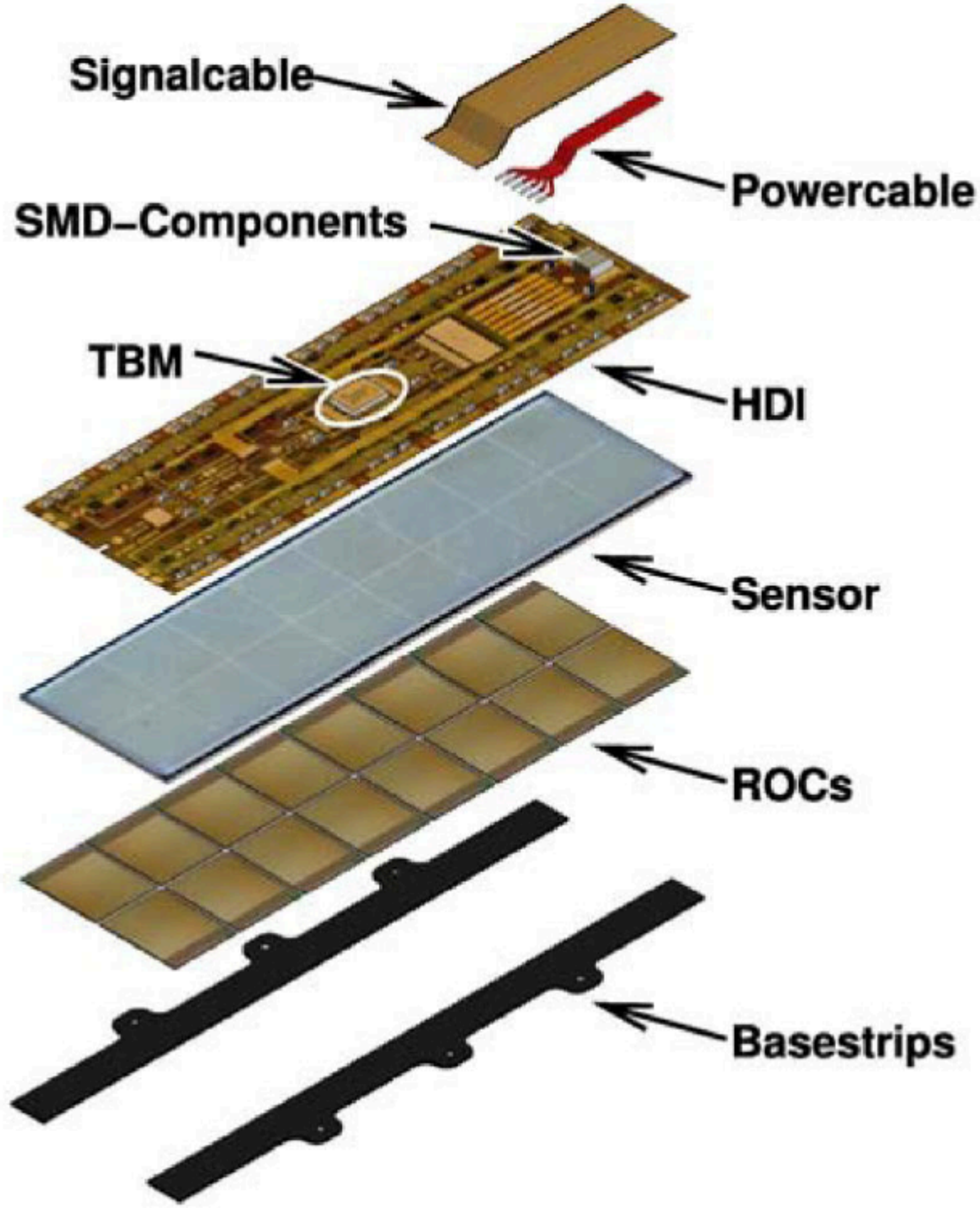
- 48 million read-out channels
- analog charge readout
- hit resolution of 15-20μm
- 3 layers at radii 4.4cm, 7.4cm and 10.2cm

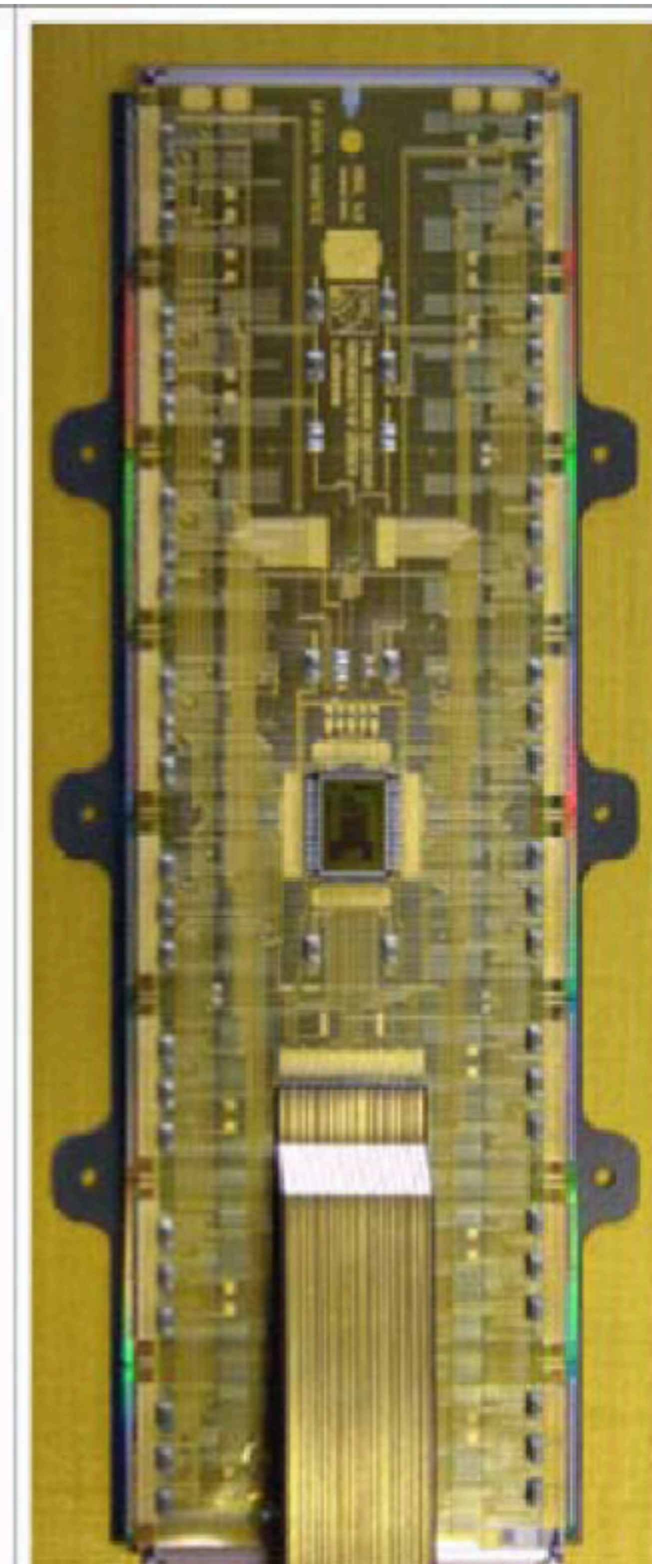
reconstructs tracks and vertices close to the interaction region

CMS pixel module (first one):



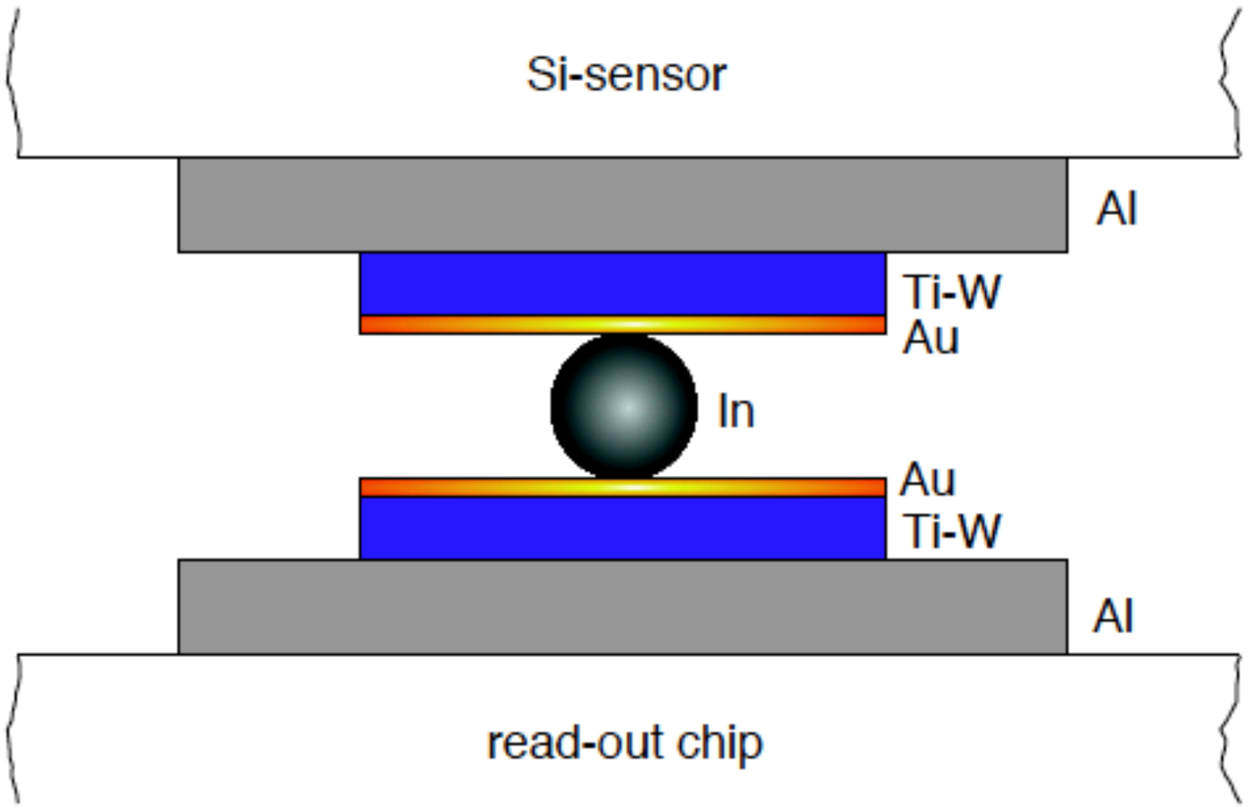
half–module ≙ 8 ROCs

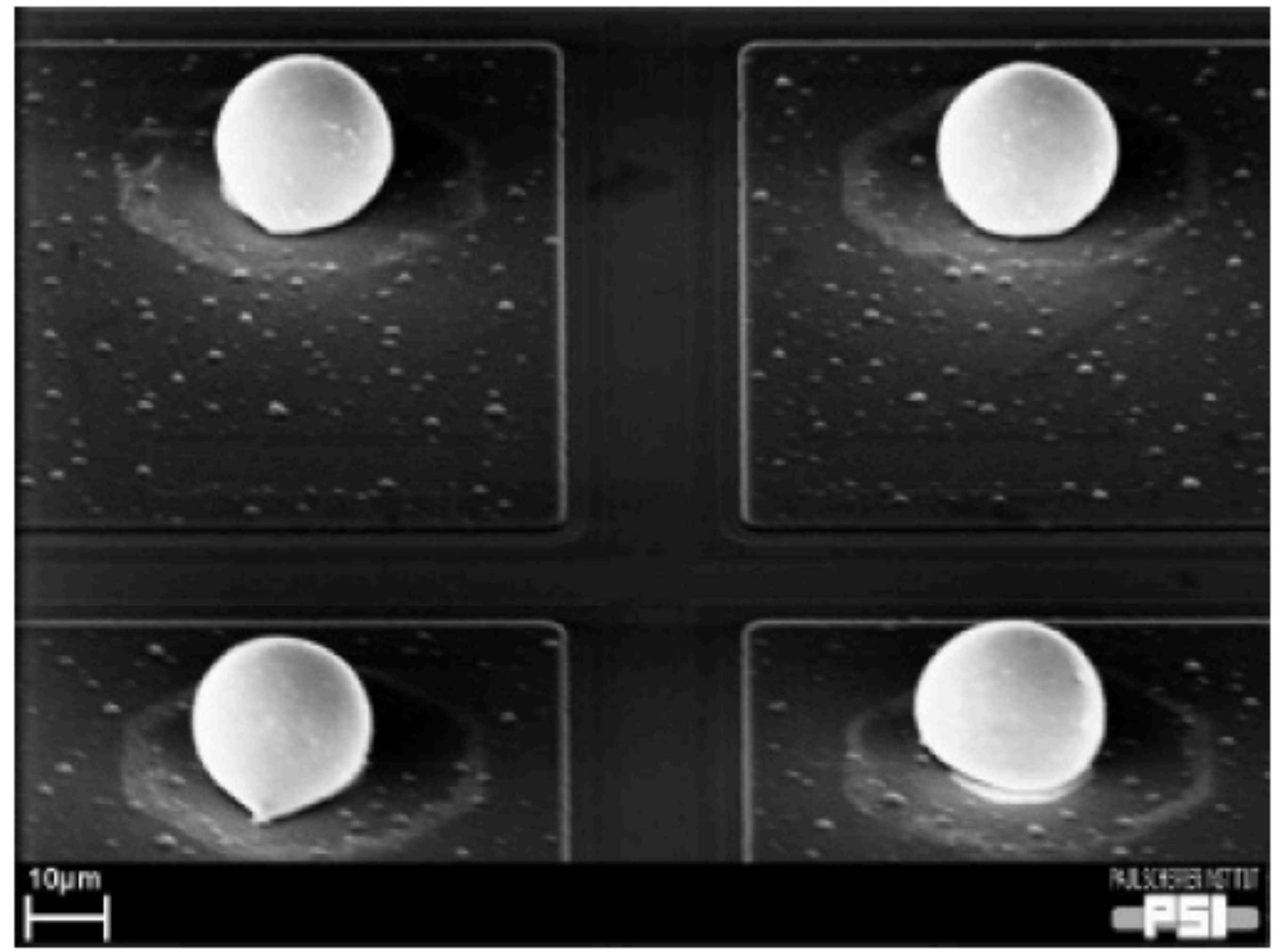




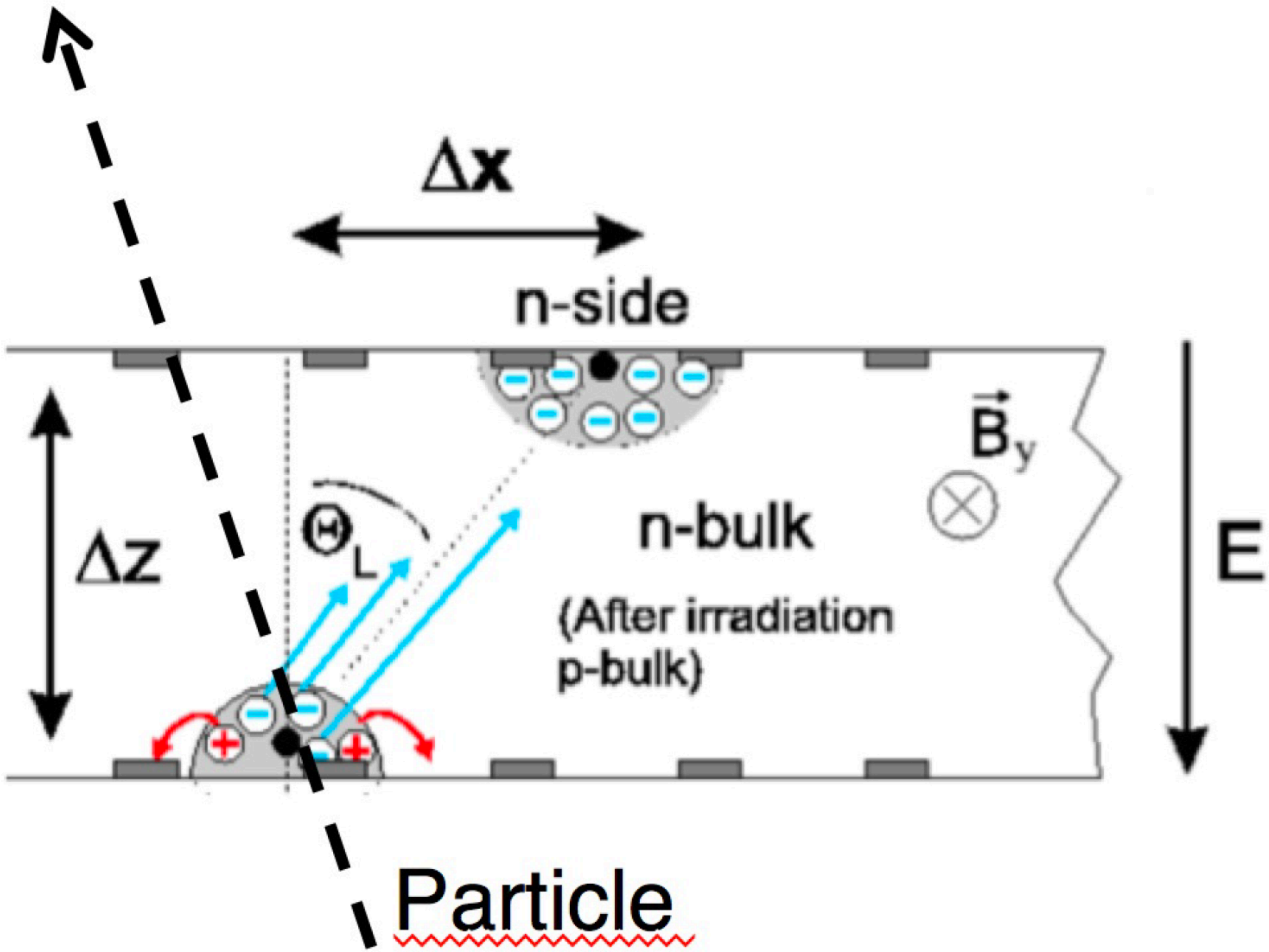
full–module ≙ 16 ROCs

CMS pixel sensor:
“bump-bonding to readout chip”





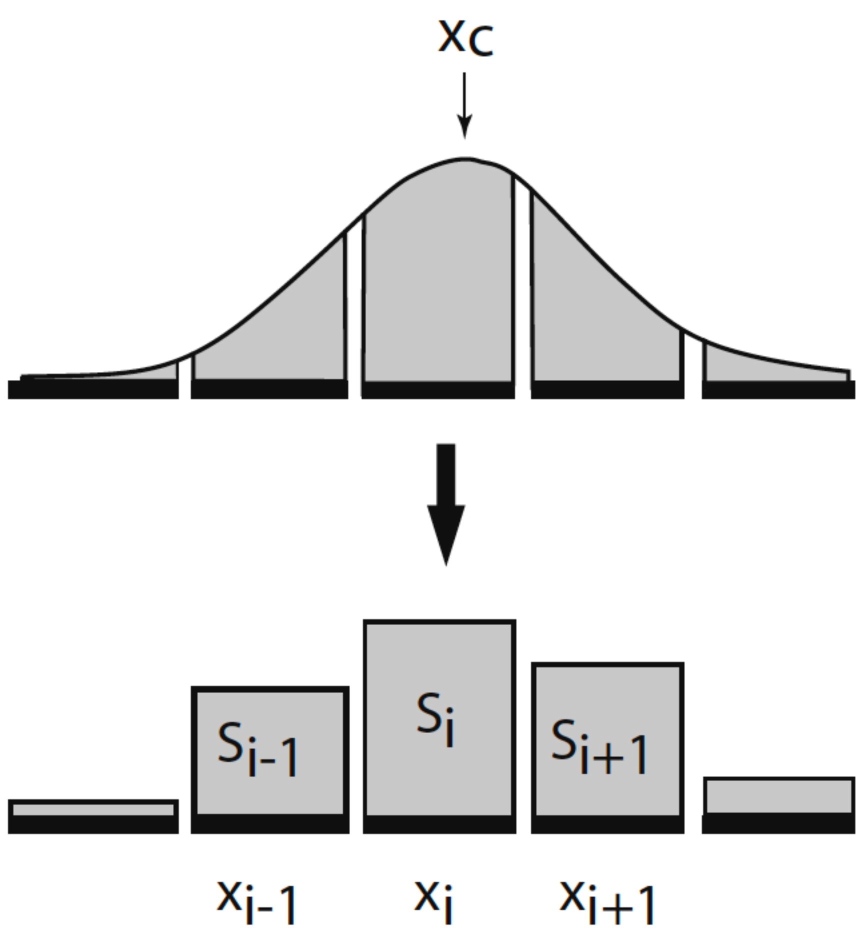
Lorentz drift:



Pixel charge clusters:

charge sharing:

- one detector “hit” induces charge in many nearby readout pixels
- the resulting position “resolution” is better than the size of a pixel



$$x = x_c = \frac{\sum S_i \, x_i}{\sum S_i}$$

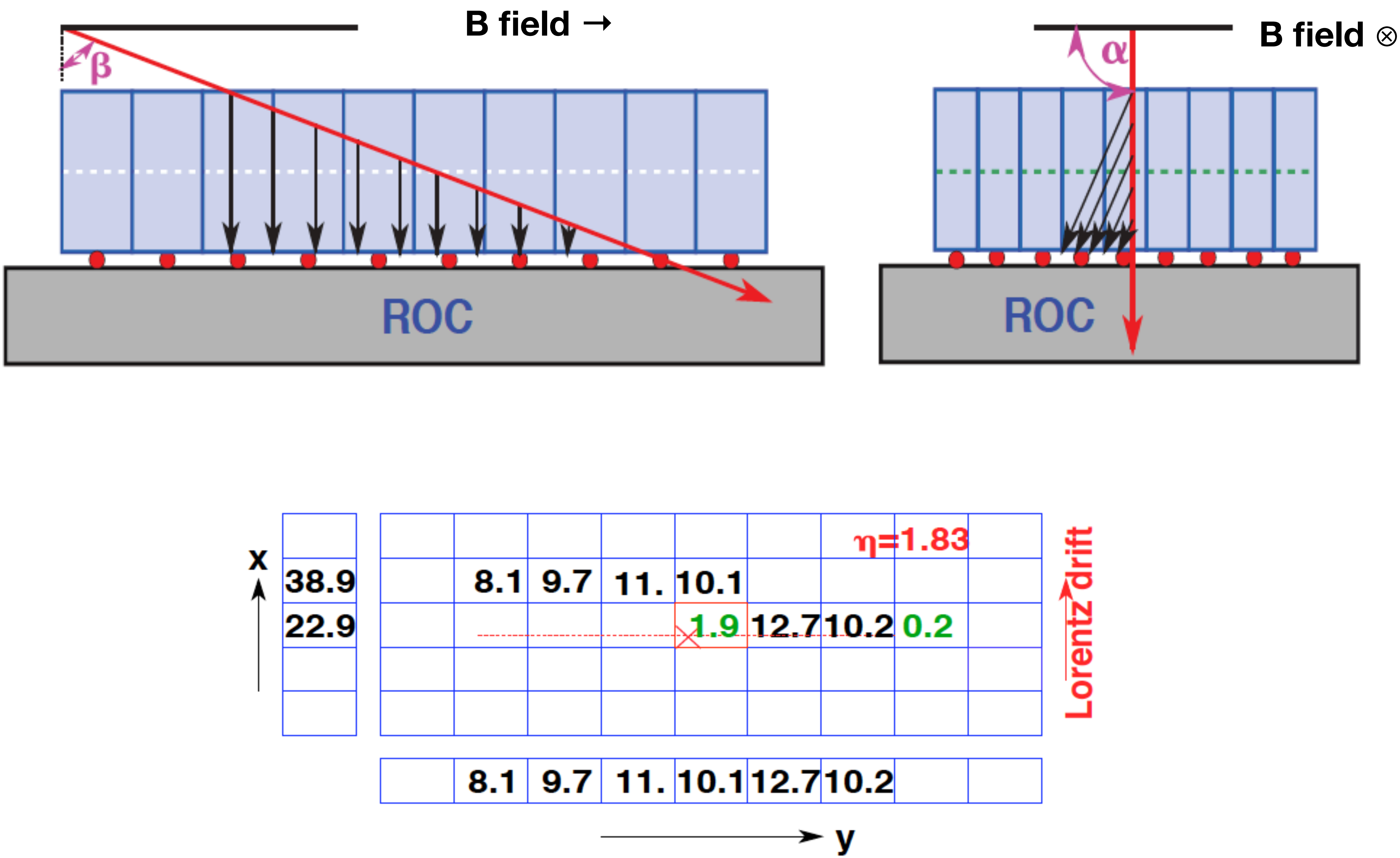
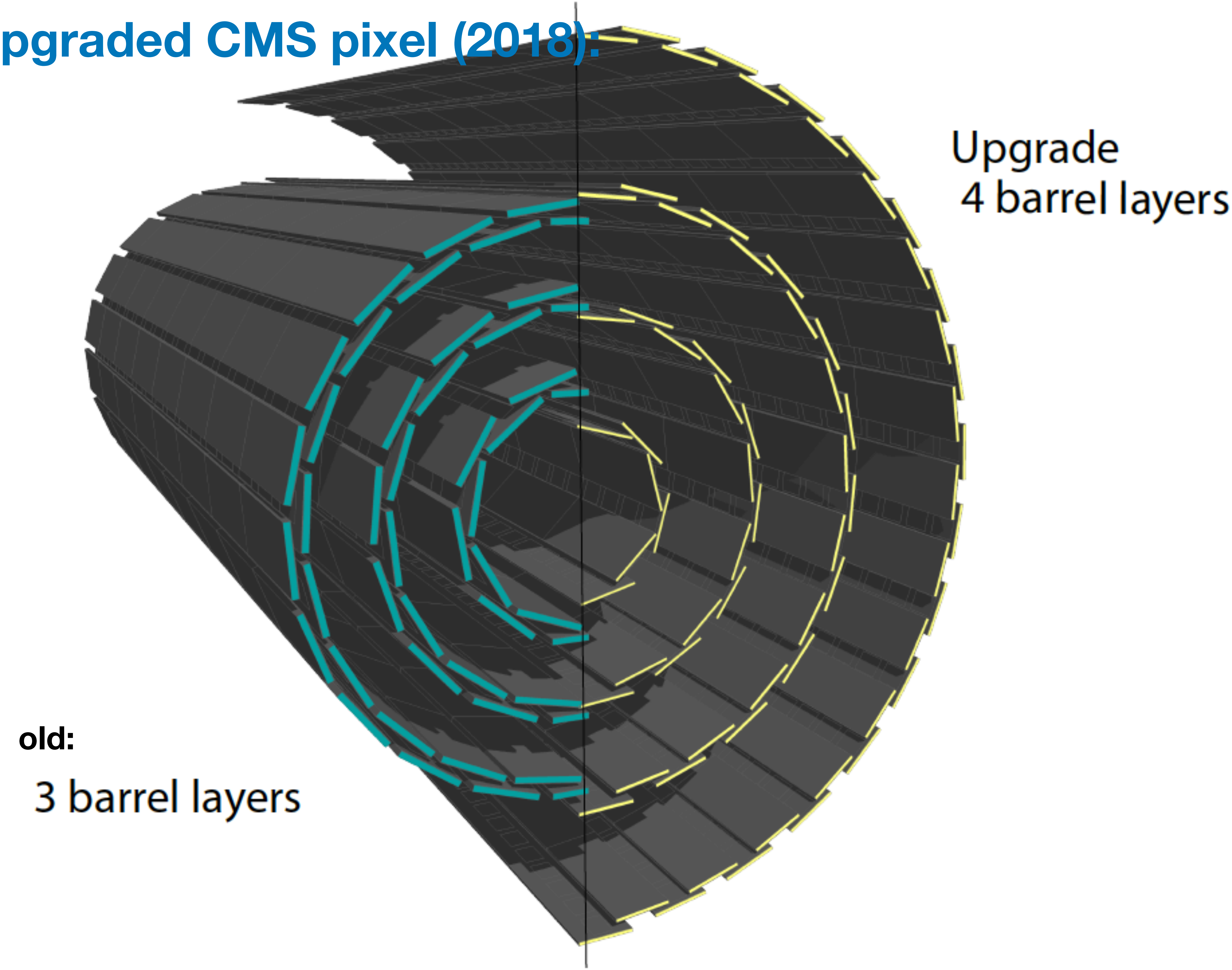
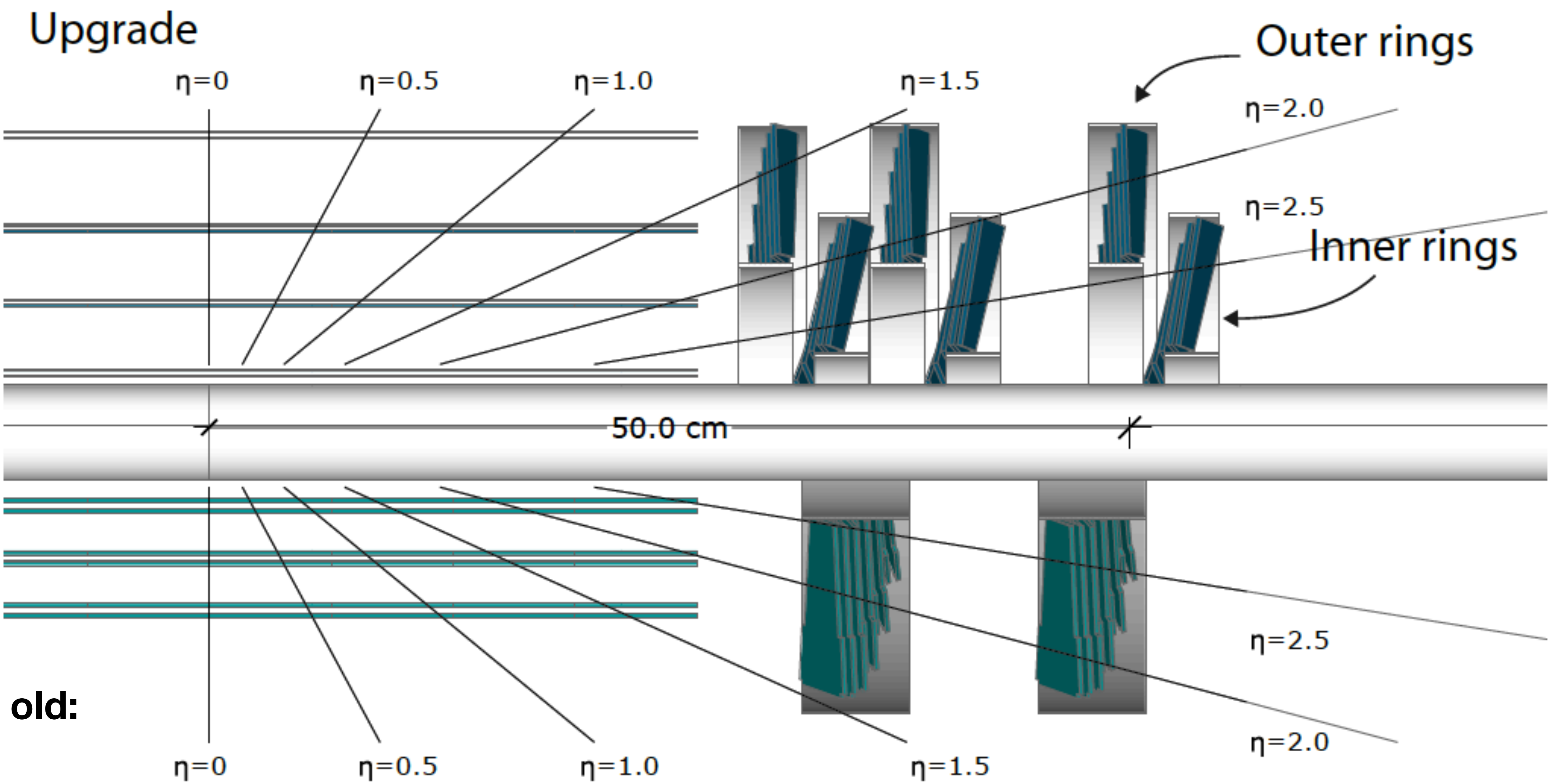


Figure 4.11 Charge deposition by a particle track ($\eta = 1.83$ or $\beta = 20°$). The signals in each pixel are in kiloelectrons. Signals below threshold are in green. The red cross is the geometrical center of the track and dashed red line represents the track projection.

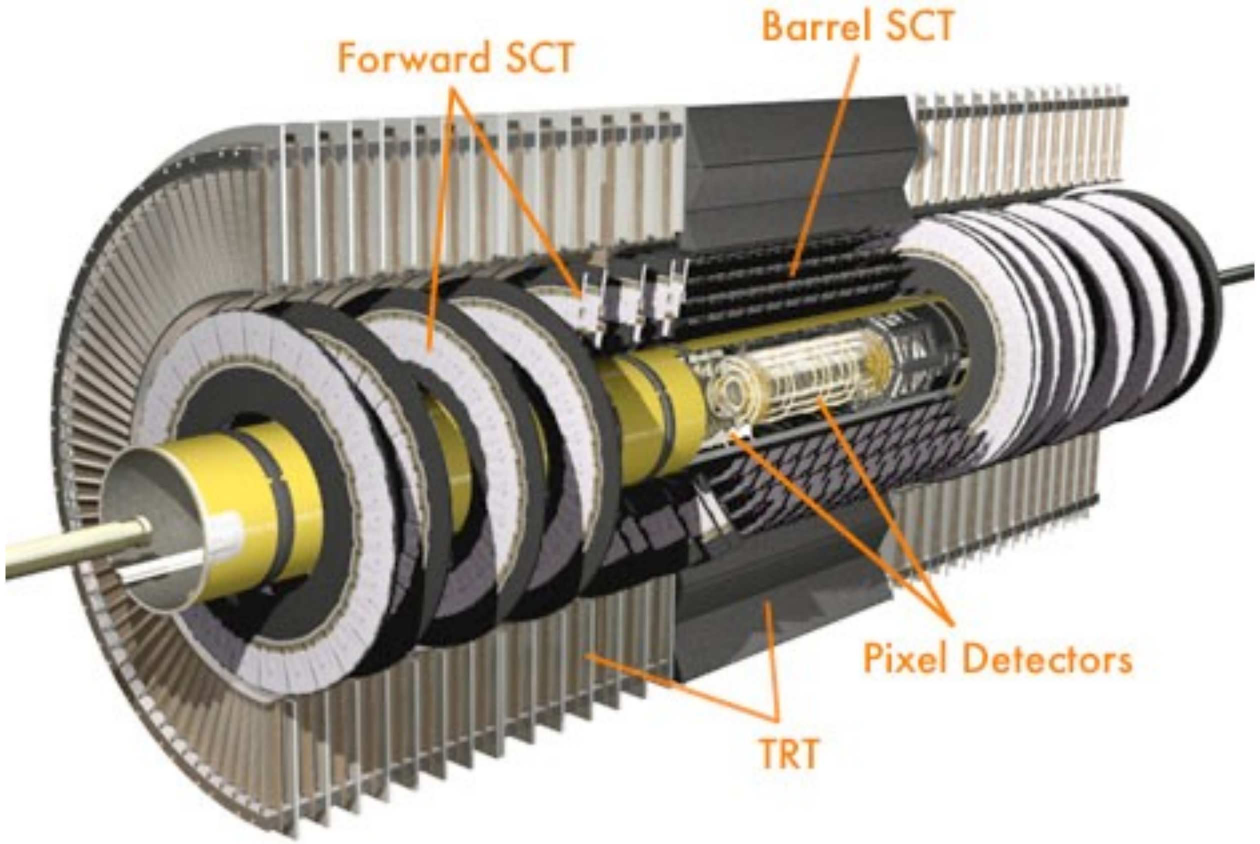
Upgraded CMS pixel (2018):



Upgraded CMS pixel (2018):

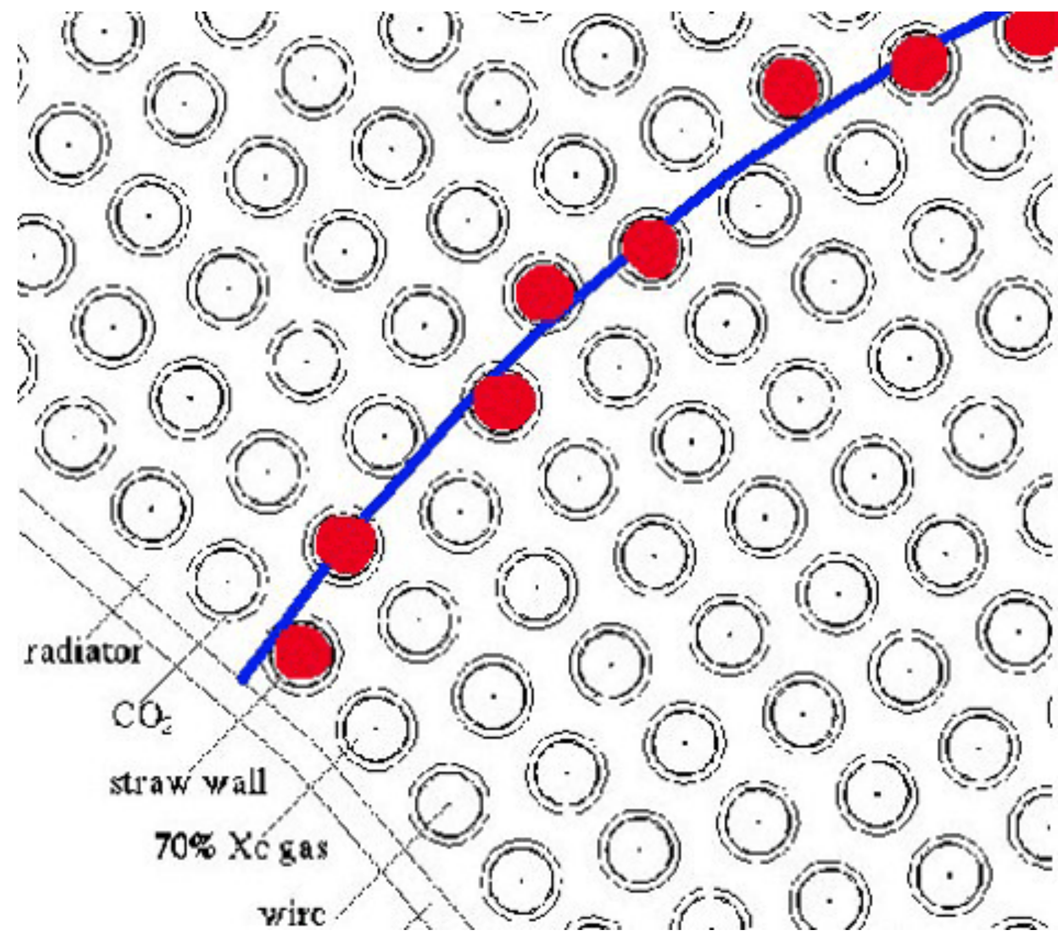


ATLAS Tracking Detector

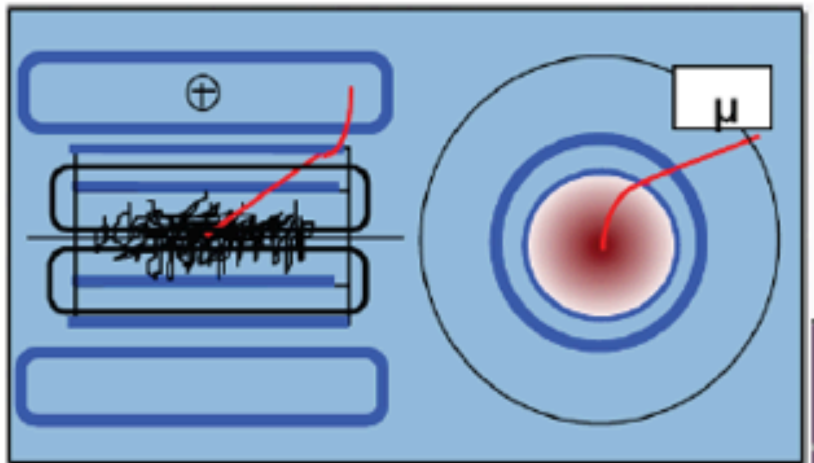


- radius 1.3 m, length 7m
- 3 pixel barrel + 3 endcap layers
- 50 x 400 μm pixels (80M readout channels)
- Semi Conductor Tracker (SCT) consists of silicon strip modules in 4 barrel layers and 9 endcap

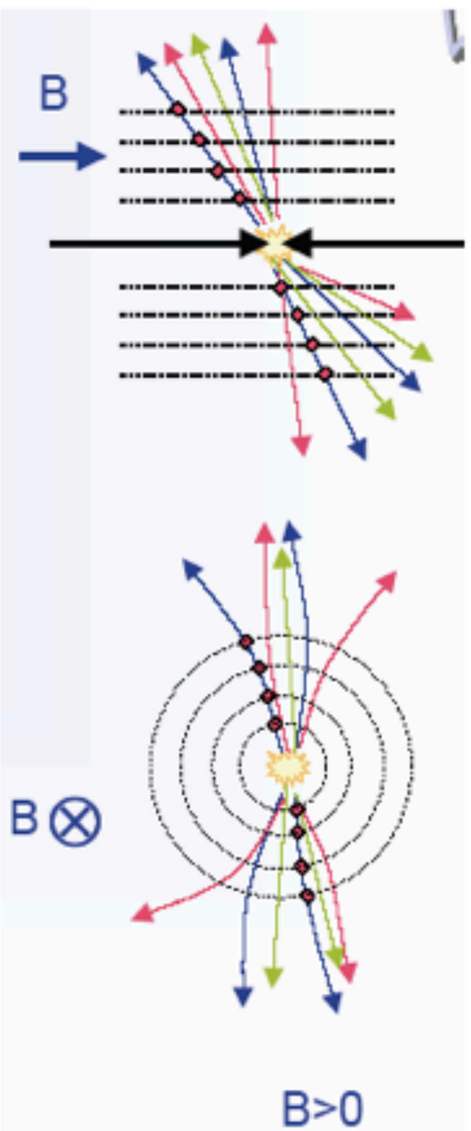
- Transition Radiation Tracker (TRT) is outermost part
- 420000 drift tubes (straws) filled with gas and a wire (ionization)
- interleaved with a radiator emitting x-rays when electrons pass through
  → **electron identification**

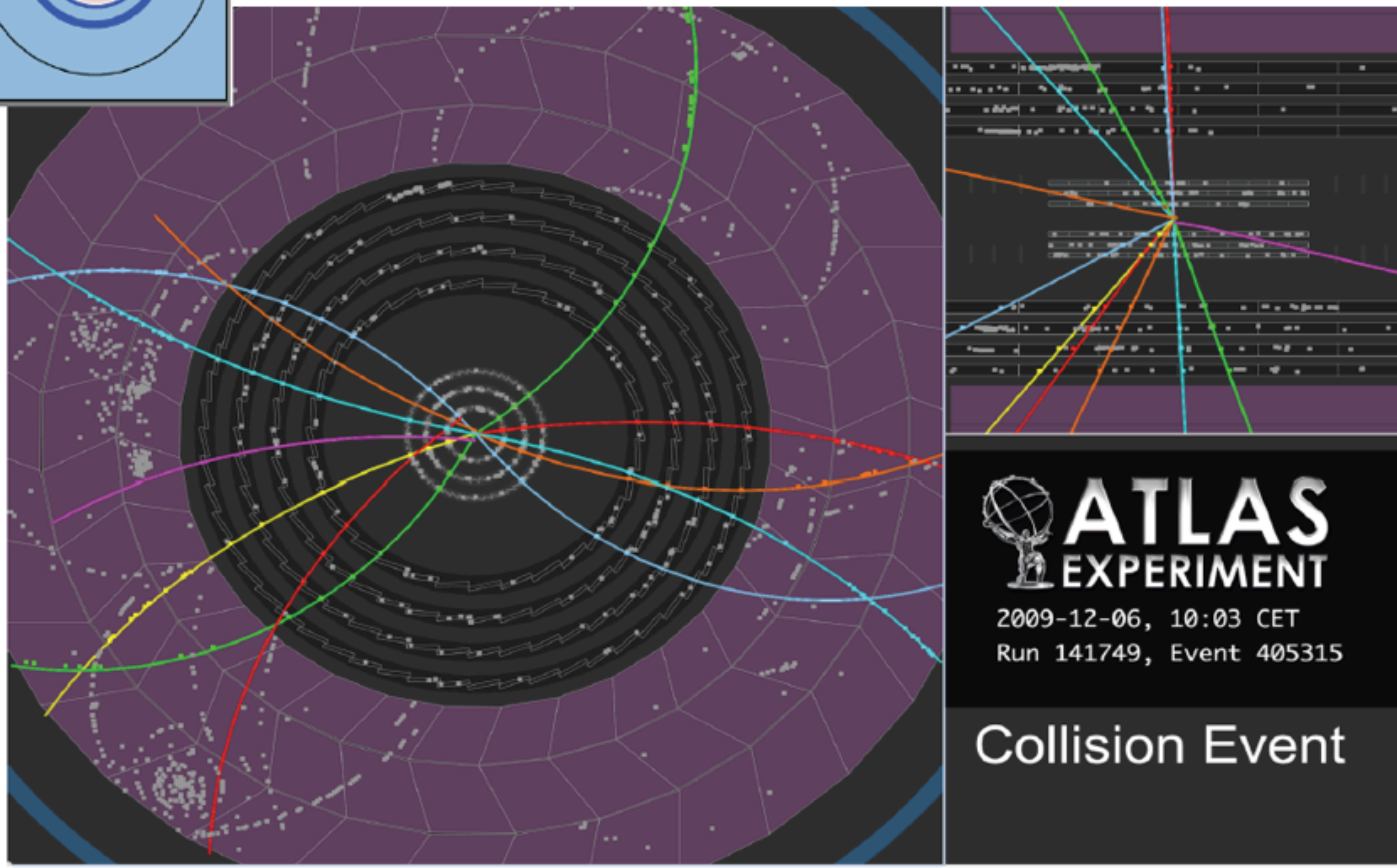


Tracking inside a magnetic field



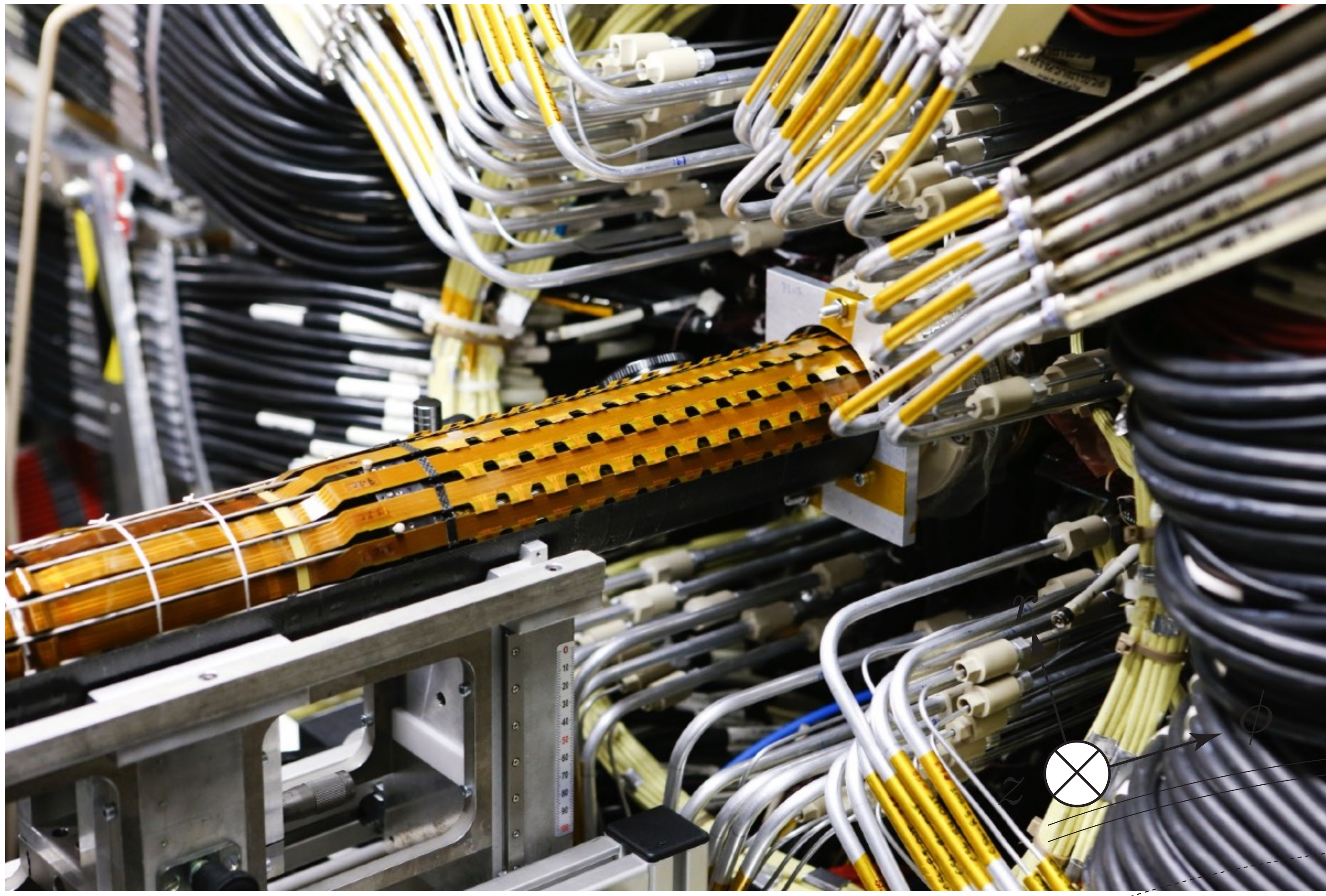
ATLAS: (air-core) toroid magnet
+ inner solenoid

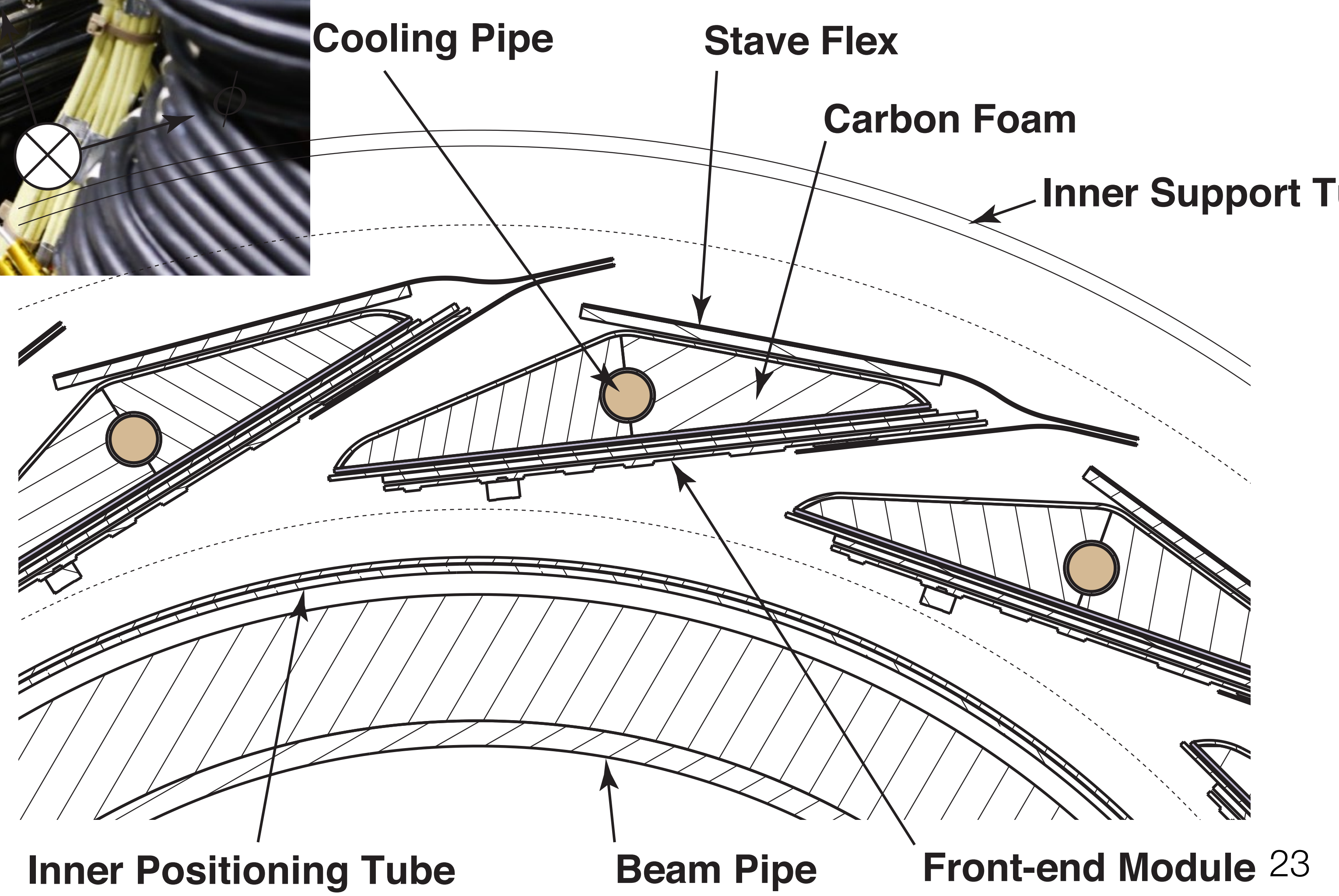




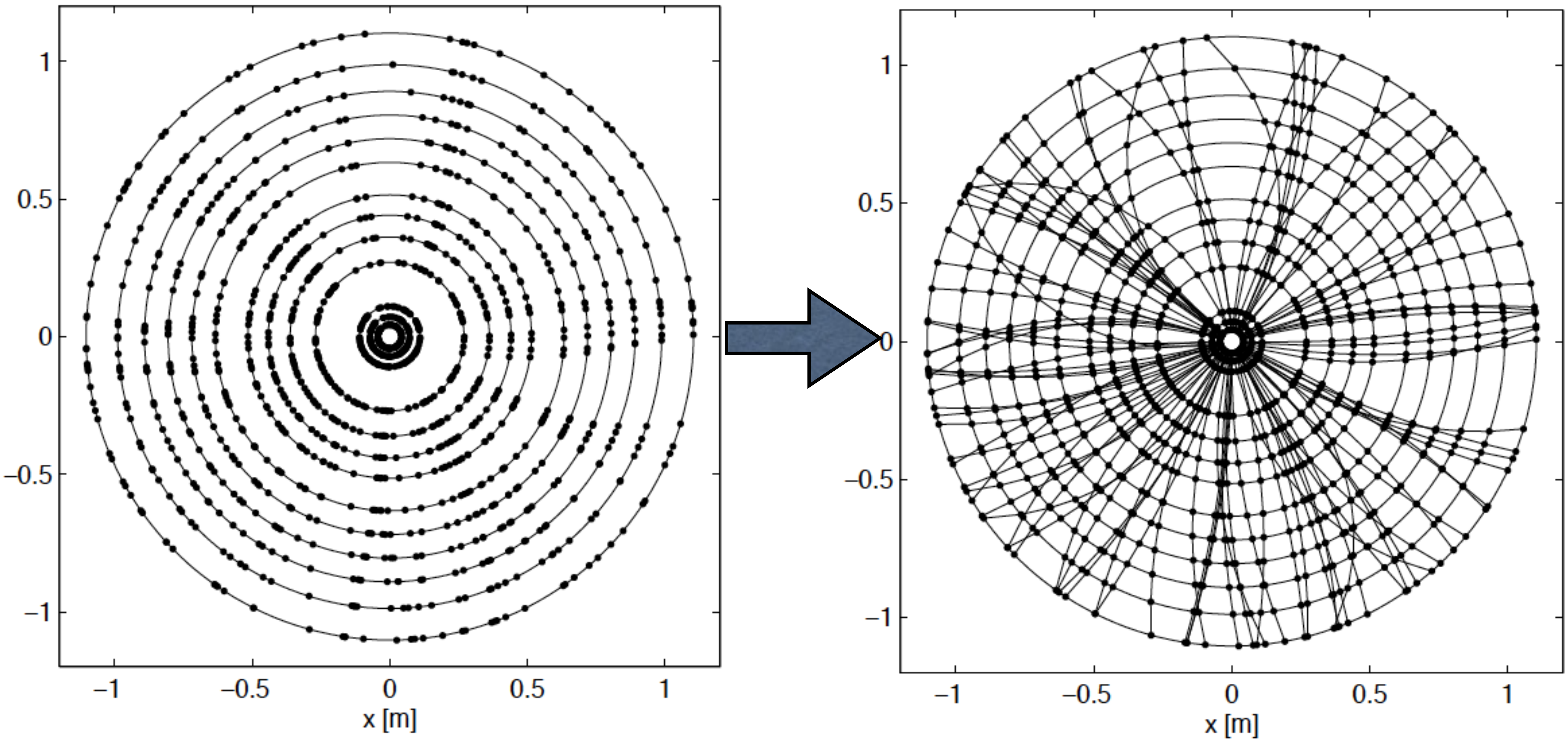
http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html

ATLAS new inner pixel detector layer (IBL)



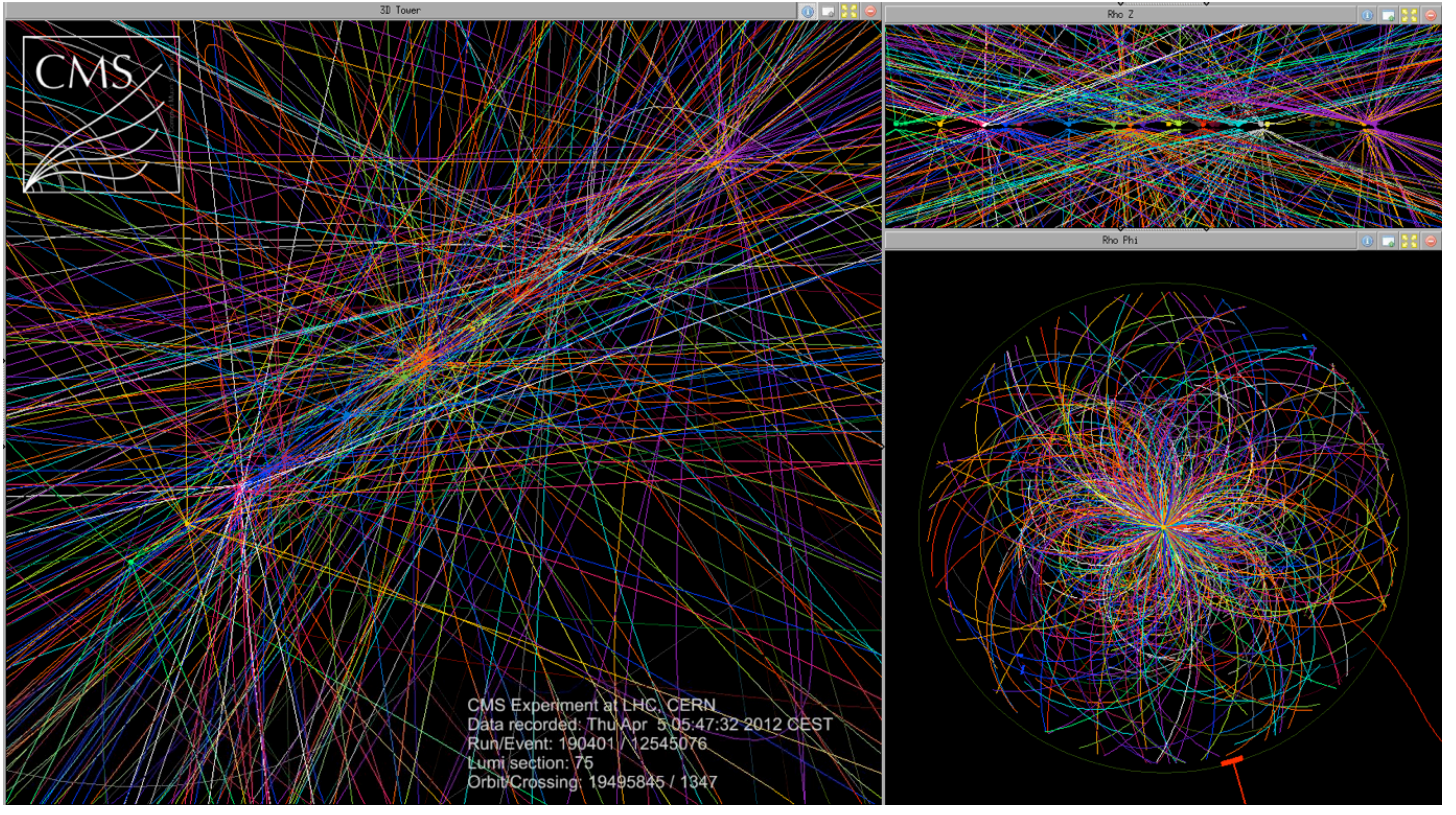


Track reconstruction



- classification or pattern recognition problem
- multiple ambiguous hypotheses possible
- supposed to be conservative (discarded hypothesis cannot be recovered later)

Track reconstruction



Example for track finding approaches (global):

- conformal mapping:
  - ★ circles (tracks) through the origin in a 2D x-y-coordinate system map to straight lines in u-v system by the transformation

    $$u = \frac{x}{x^2 + y^2}, \quad v = \frac{y}{x^2 + y^2}$$

    where the circle equation is given by $(x-a)^2 + (y-b)^2 = r^2 = a^2 + b^2$
  - ★ the straight lines are then $v = \frac{1}{2b} - u\frac{a}{b}$
  - ★ scan along azimuthal angle to find accumulation of hits along the straight line (peaks in the histogram indicate tracks)
  - ★ works for high-p_T tracks passing close to the origin

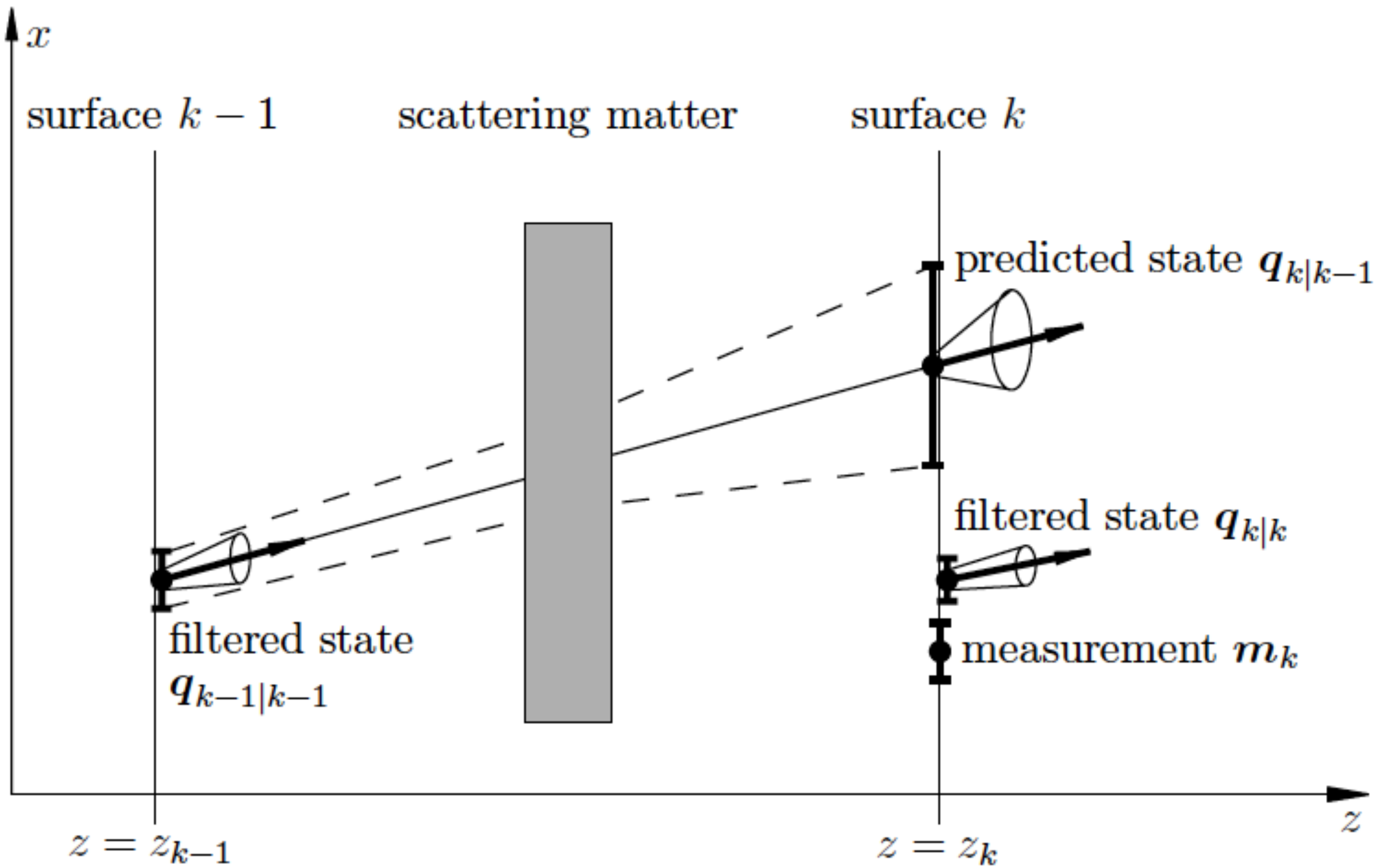
- slightly extended: Hough and Legendre transform
  - ★ allows for a wider range of momenta by introducing an additional straight line transformation (see literature for details, e.g. A.Strandlie, R.Frühwirth, "Track and vertex reconstruction")

Example for track finding approaches (local):

- track road:
  - ★initiated with a set of measurements that could come from the same particle
  - ★use a model (shape of the trajectory) to interpolate between the measurements and create a "road" around the trajectory
  - ★measurements inside the road boundaries constitute the track candidate
  - ★subsequent track fit can evaluate the correctness

- track following:
  - ★from a "seed" the track is extrapolated (based on the model) to the next detector layer containing a measurement
  - ★closest measurement point is included in the track candidate
  - ★iterate until last detector layer or no hits found anymore

Kalman filter algorithm, see details in Exercise



Tracking Performance

- a helix is fully defined with **5 parameters**. At LHC the parameters are chosen for practical reasons as:
  - transverse momentum: **p_t**
  - azimuthal angle: **ϕ**
  - polar angle: **$\cot(\theta)$**
  - transverse impact parameter at the point of closest approach to PV: **d_0**
  - longitudinal impact parameter: **z_0**