Applications of Position Sensitive Detectors in Particle Physics and Pixel Detectors

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The 14th International Conference on Position Sensitive Detectors

3rd September 2026, QMUL, London

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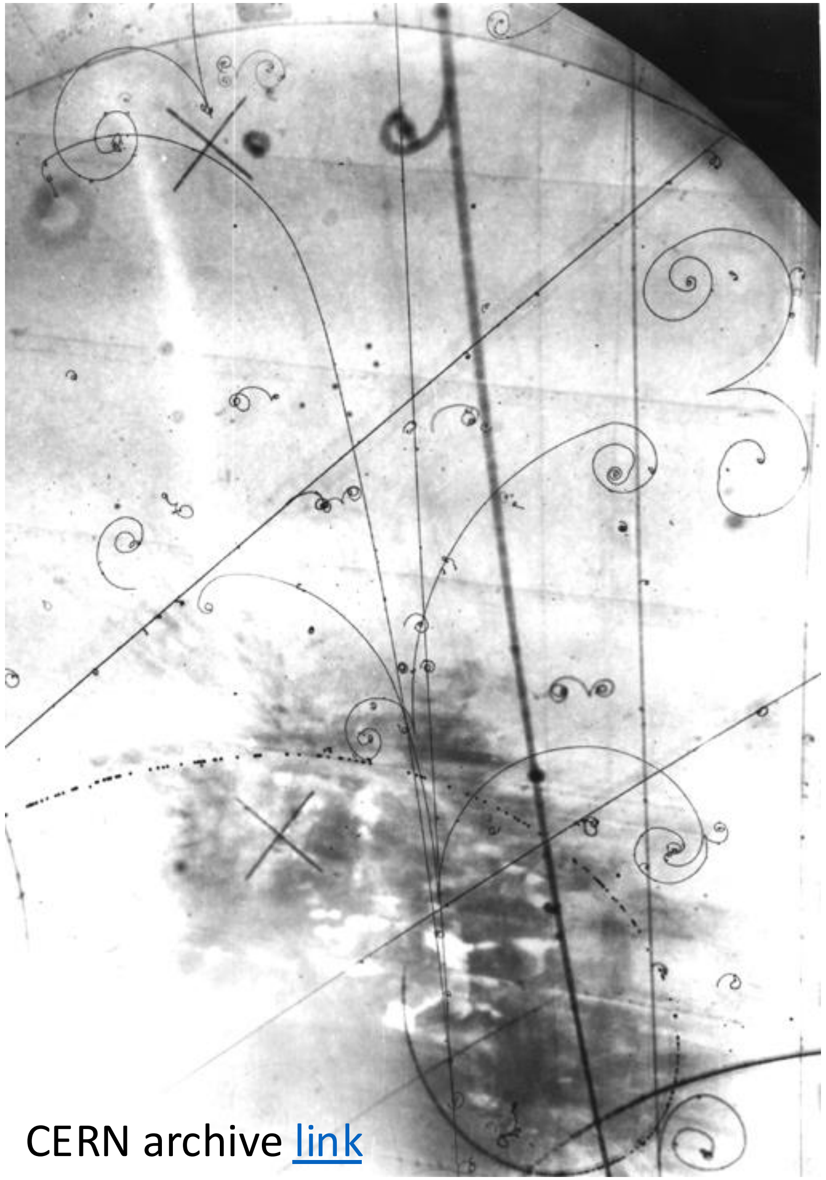
Position Sensitive Detectors in Particle Physics

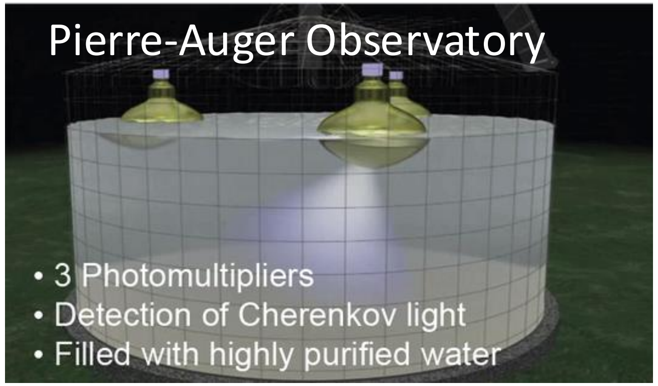
- Are used to reconstruct particle tracks:
  - Identify the interacting particles
  - Measure the energy of the particle
- Different applications and different technologies:
  - Neutrino and dark matter detection:
    - Light detection
    - Time projection chambers: Noble liquids-gas
    - CCD
  - Colliders:
    - Gas/liquid detectors to cover big volumes
    - Photo detectors: Scintillating
    - Silicon detectors for tracking and vertexing close to the interaction point

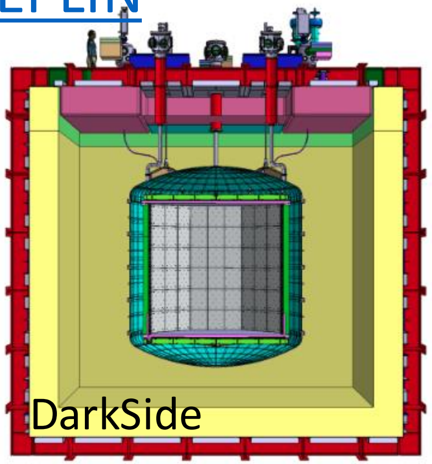


CERN archive link

Neutrino, DM and Astroparticle detectors

- Cherenkov Light detection:
  - Super-Kamiokande (50k tons of water) and Huge PMTs
  - Pierre Auger Observatory: 1600 tanks
- Time projection Chambers. Neutrino or dark matter particle interaction produce scintillation light, ionization or electroluminescence:
  - Dune, DarkSide
  - Xenon experiment, LUX-ZEPLIN
- Semiconductors for DM
  - Silicon CCDs in Damic
  - Ge in SuperCDMS





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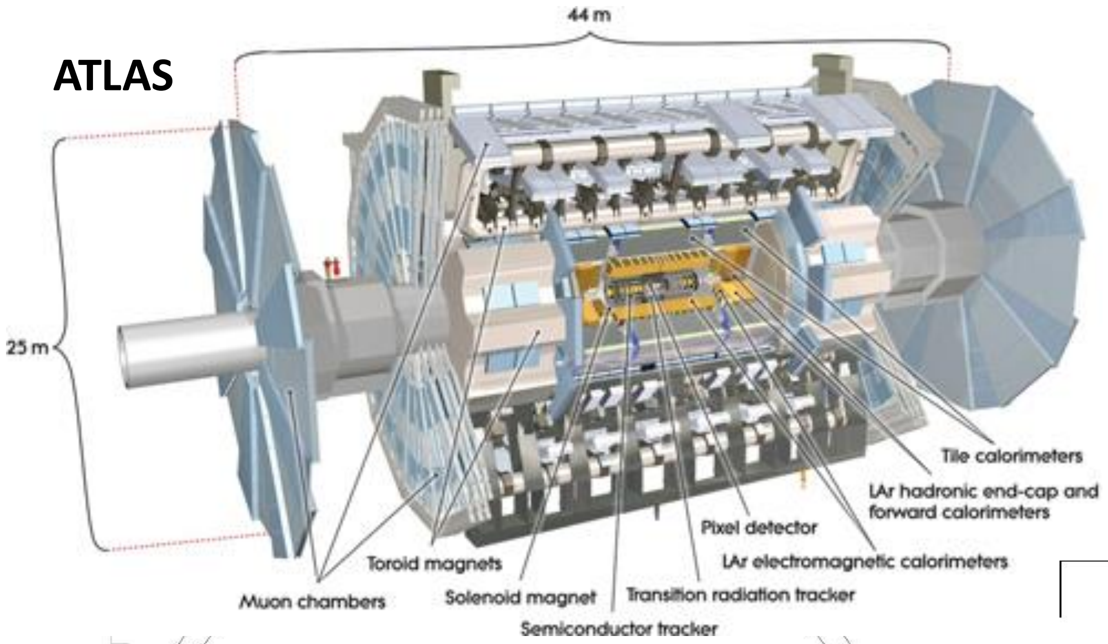
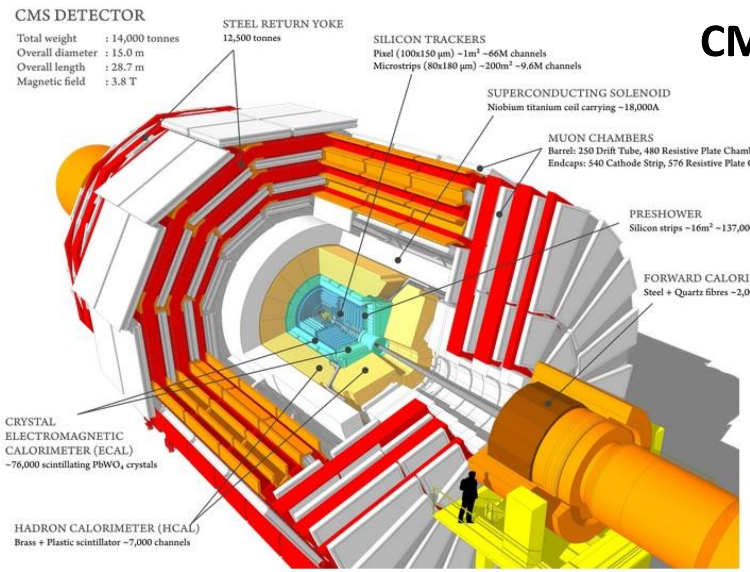
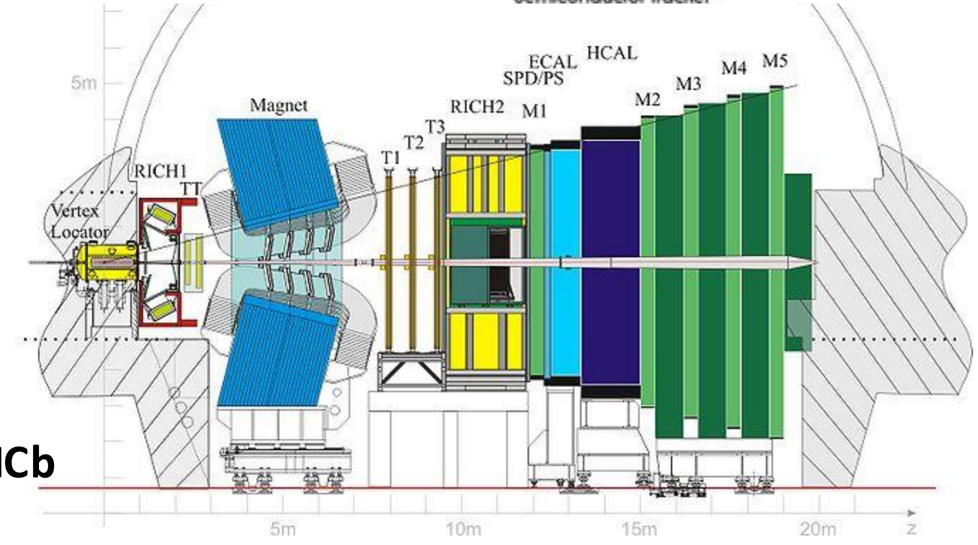
Collider experiments: onion structure

ATLAS



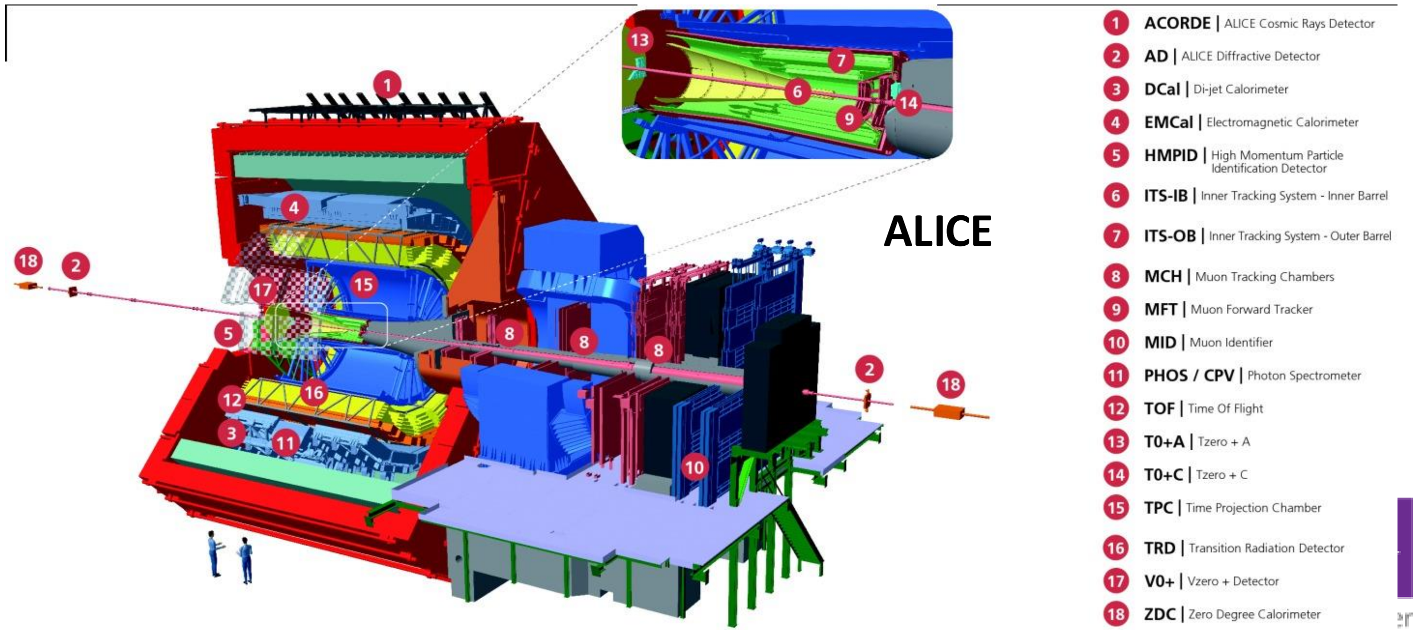
CMS





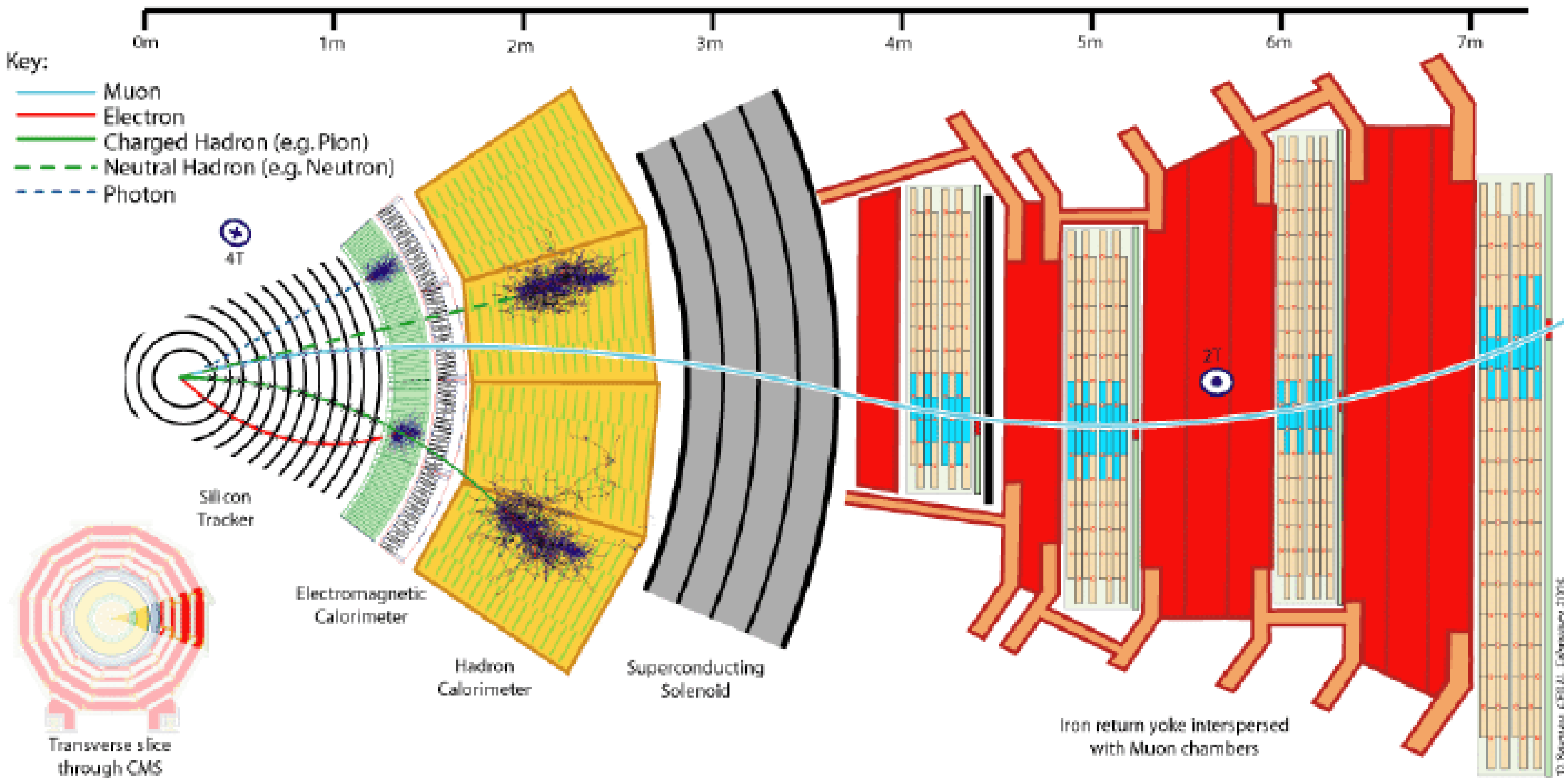
LHCb

ALICE



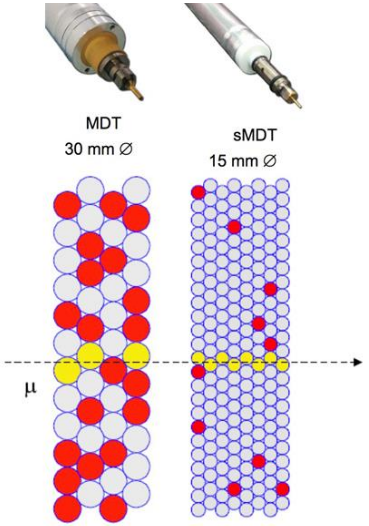
An example, CMS experiment

[CMS-PHO-GEN-2016-001](CMS-PHO-GEN-2016-001)

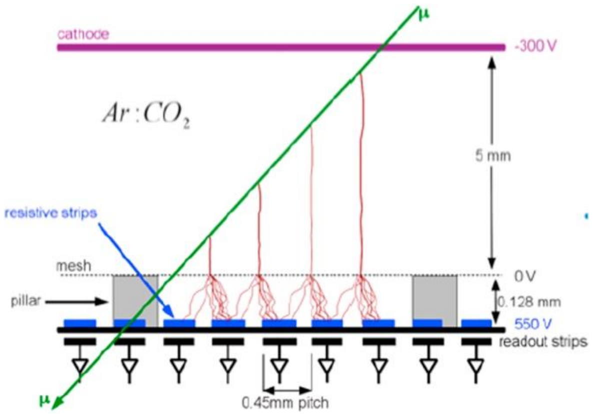


Muon chambers: Ionisation

- Gas detectors can cover big volumes cost-effectively.
  - Monitored Drift Tubes (MDT)
    - 3 cm diameter gas cylinders with a central wire: 5000 V
  - Resistive Plate Chambers (RPCs)
    - Parallel planes with a **Δ**V and filled with gas
  - Thin Gap Chambers (TGCs)
    - Parallel 50 um wires in gas
  - Micromegas: 800V
- High maintenance and high power



ATLAS MDT



ATLAS Micromega

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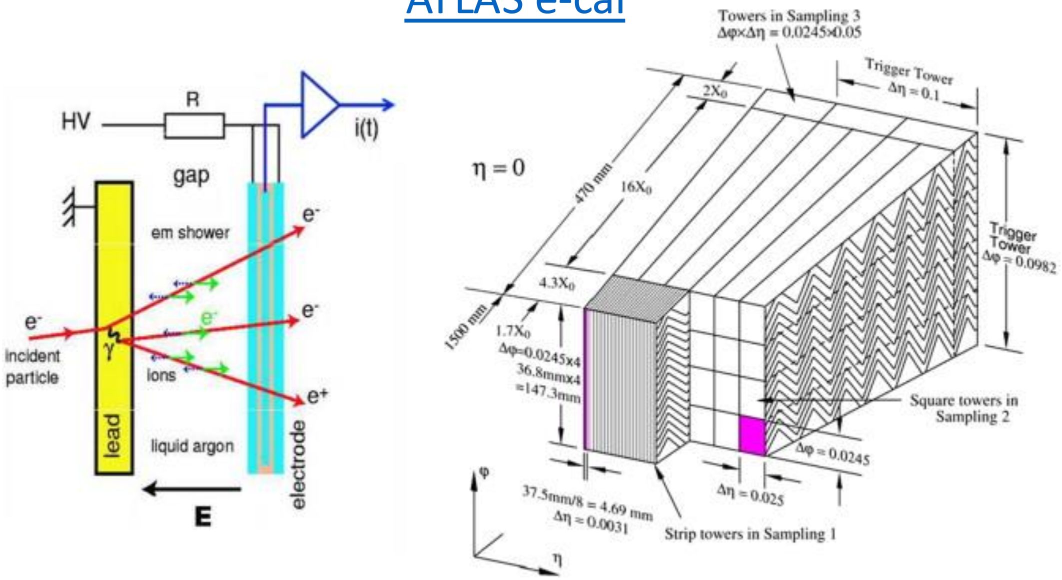
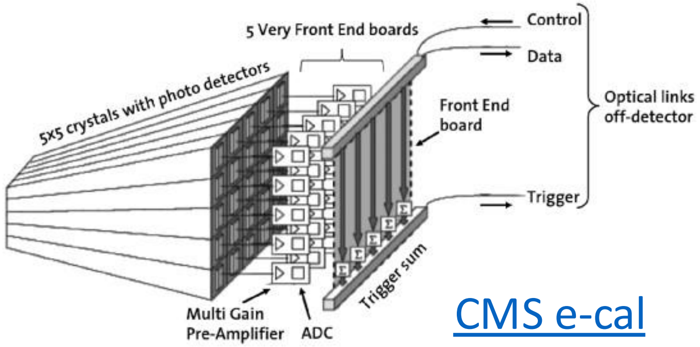
Calorimeters

- Designed to entirely stop particles and to measure their energy
- Measure total charge, ionisation or scintillation light
- They can be:
    - Electromagnetic:
        - LAr-ATLAS → collecting charge
        - lead tungstate ($PbWO_4$) scintillation crystals - CMS
    - Hadronic:
        - interleaved steel plates and plastic scintillator tiles - ATLAS
        - layers of dense brass/steel absorbers and plastic scintillators – CMS

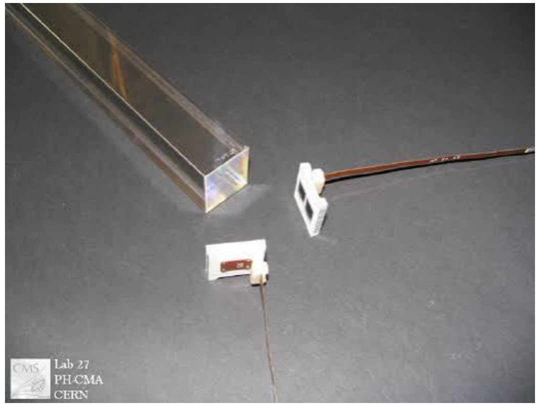
- Position resolution in Calorimeters is becoming highly important for future colliders and application of machine learning algorithm

ATLAS e-cal





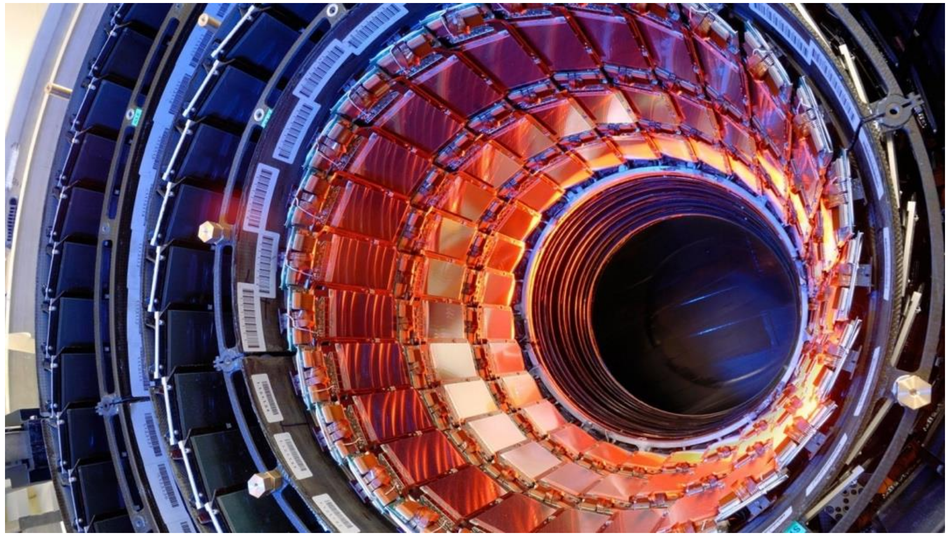
CMS e-cal



Trackers and pixel detectors

- Gas detector:
  - Straw tubes (ATLAS-TRT): >1500V
- Silicon strip detectors
  - Variable pitches depending on location
- Pixel detectors pitch
  - 100um x 150 um: CMS
  - 400 um x 50 um: ATLAS

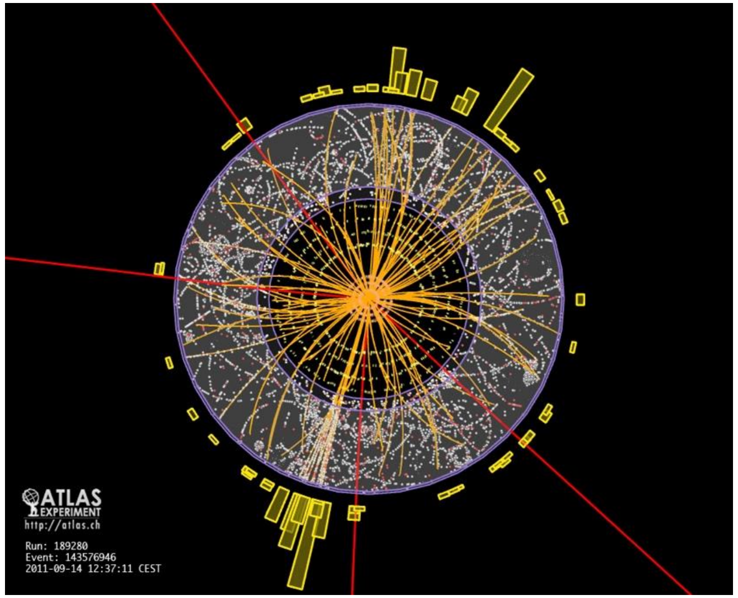
CMS tracker detector

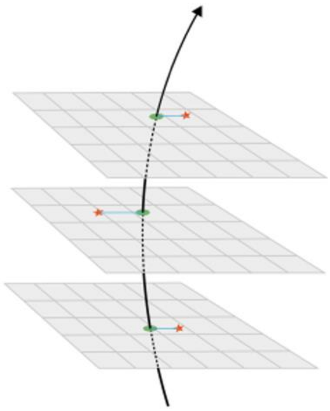


The ATLAS SCT

Tracking detectors

- Layers around the interaction point
- A track is the reconstructed trajectory of an ionising particle, connecting hits from different layers:
  - Pattern recognition is figuring out which hits go to what tracks
- Measure position and momentum of ionising particles
  - Position resolution. Distance between the real hit and the fitted track
  - Transverse momentum (Pt) From track curvature
  - Longitudinal (z_0) and transverse (R_0) track impact parameter resolution





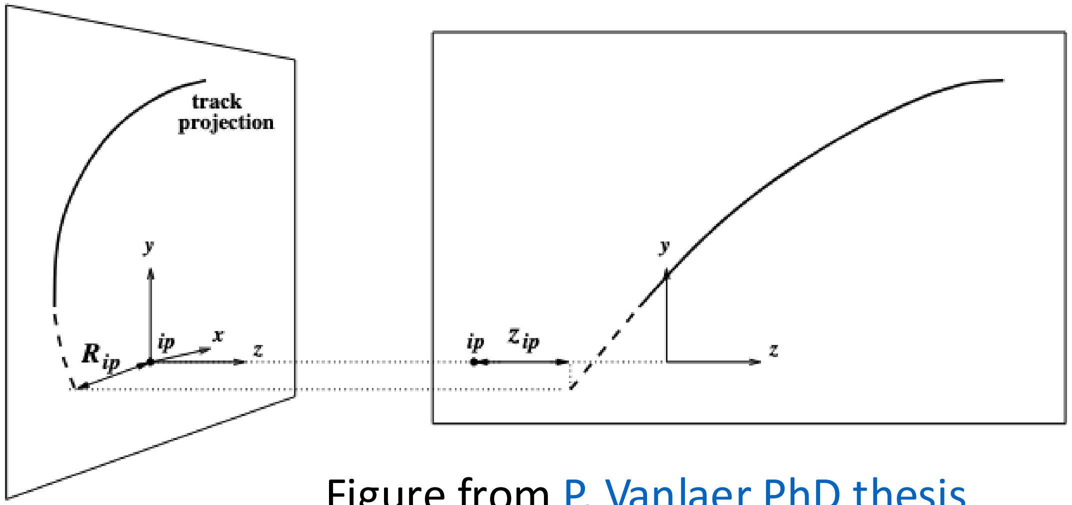
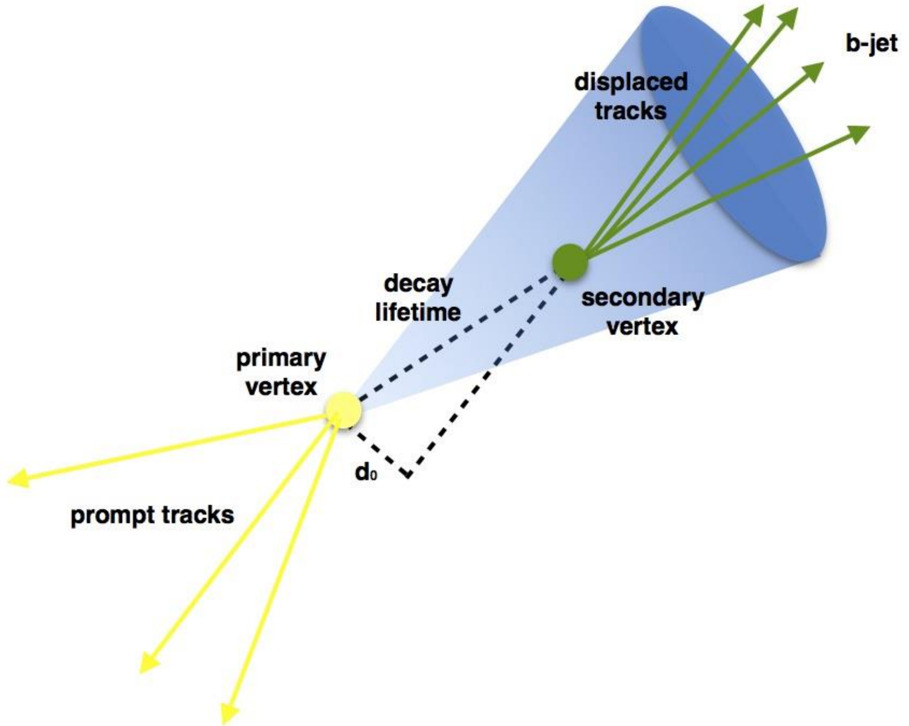
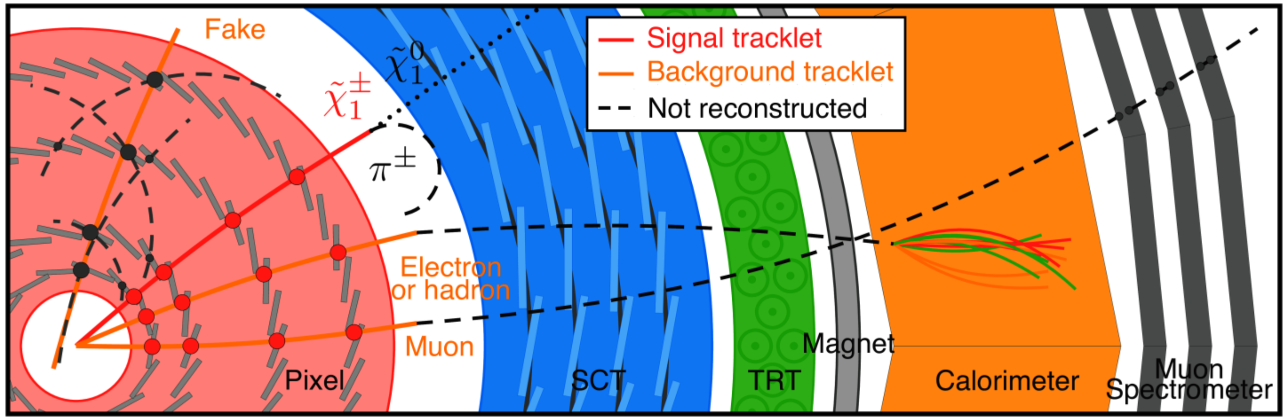


Figure from [P. Vanlaer PhD thesis]

Vertices and fake tracks



- Vertices
  - Primary: Location of the collisions
  - Secondary/tertiary
    - decay of particles with a lifetime (b, c-hadrons)
    - Scattering (interaction with matter)
- Fake tracks
  - Merging of two or more tracks
  - Mis-assigning some hits
  - Random combination
- Fakes can impact the reconstruction

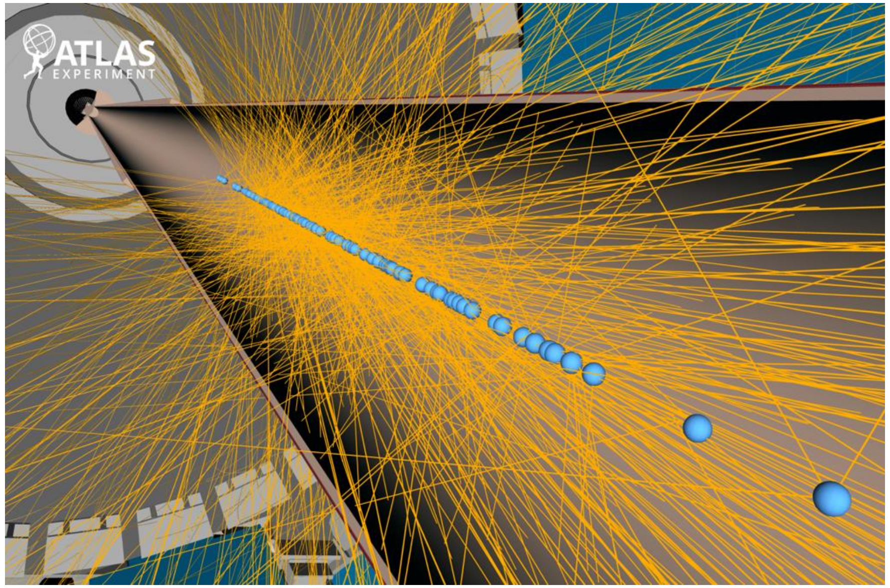


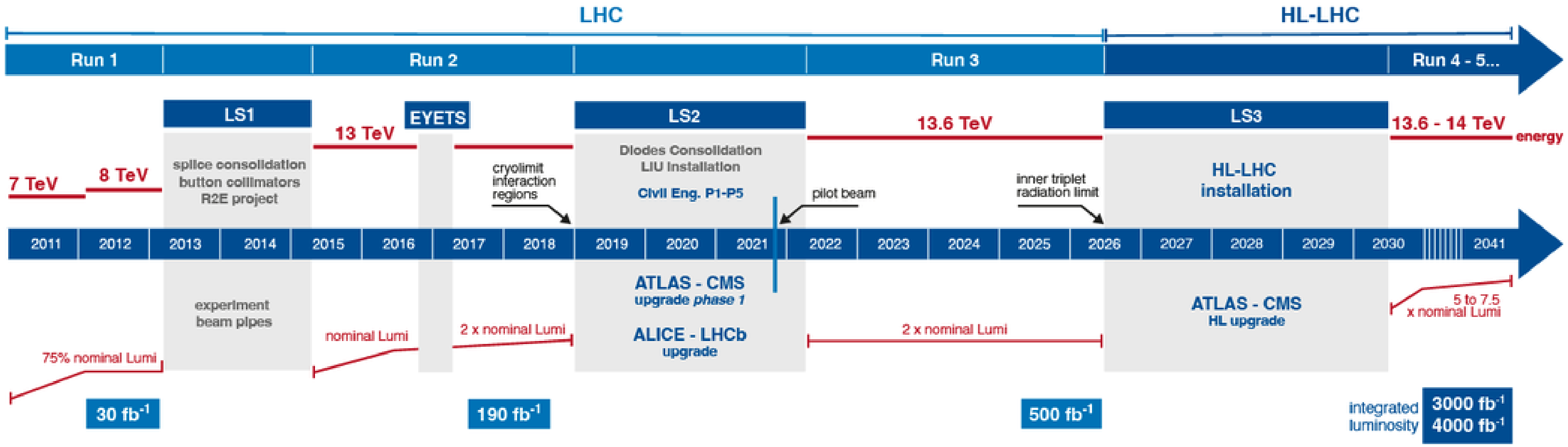
[Moriond conference 2021]

The LHC upgrade: HiLumi LHC

HiLumi

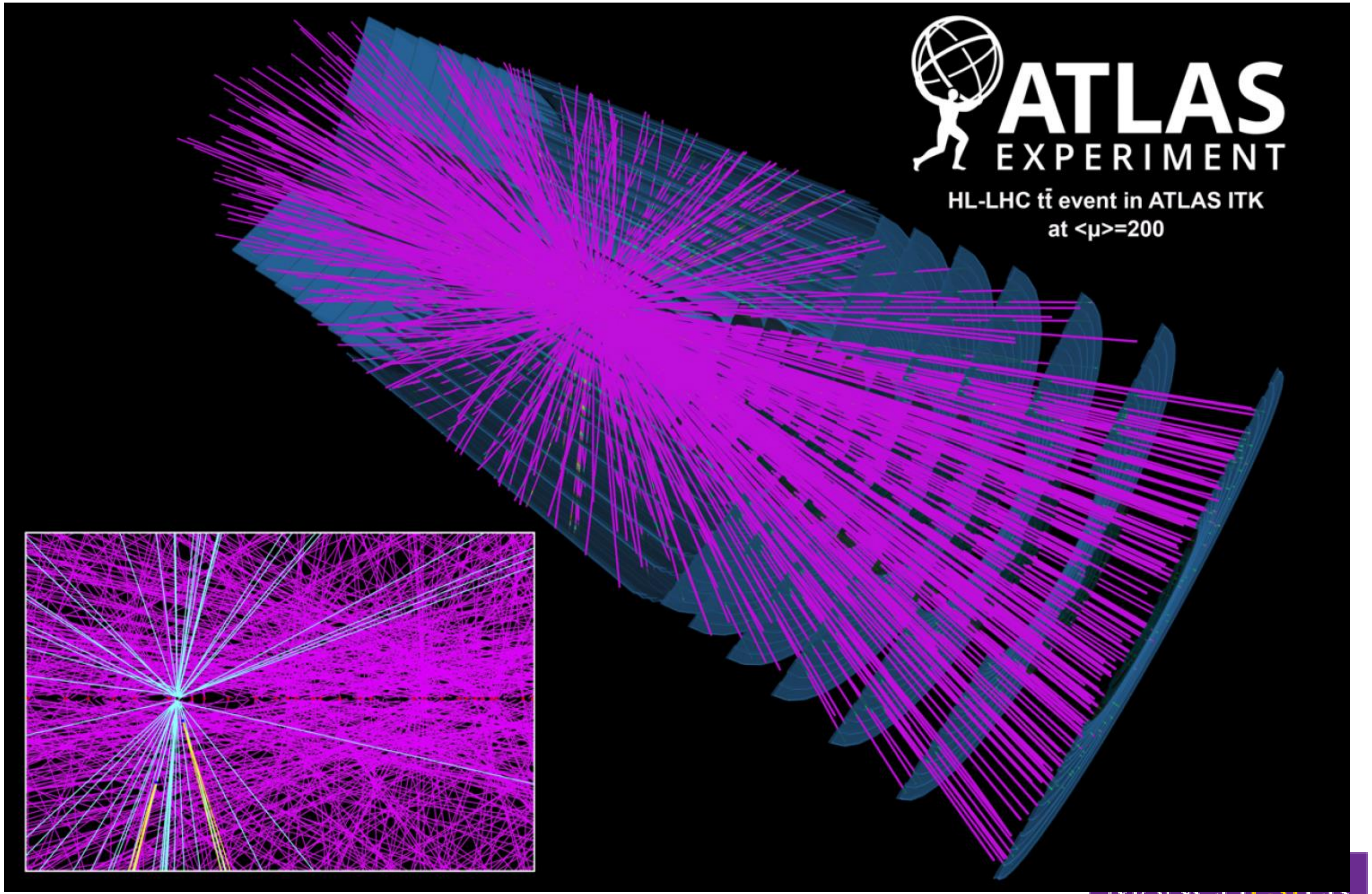
- Produce 380 millions of Higgs bosons
- Luminosity Increase:
  - $L \sim 7x\ 10^{34}\ cm^{-2}s^{-1}$
  - $L_{int} \sim 4000fb^{-1}$.
- 200 pile up events (~ 3.3 x LHC)
- Radiation fluence:
  - $\phi_{HL\text{-}LHC} \sim 10 \times \phi_{LHC} = 2 \times 10^{16}\ n_{eq}/cm^2$.





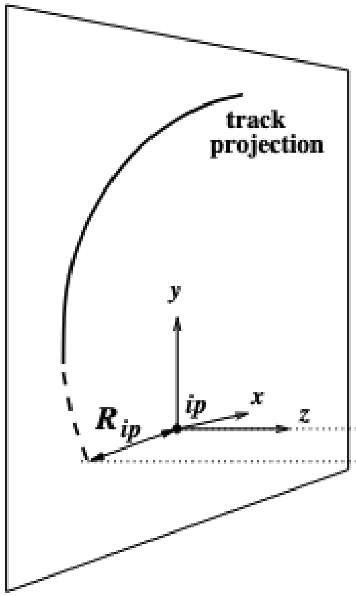
Tracker ad pixel detectors at HiLumi

- Extremely high density of Tracks and vertices
- 4D detection
  - Space granularity
  - Time granularity
    - Adding timing layers
- Higher granularity, closer to the IP



Time resolution

- Longitudinal (z_0) and transverse (R_0) track impact parameter resolution
- Collisions (interactions) spread in time (180 ps) can help to reduce the pile-up
- Achieving time resolution ~ 30 ps allows going from μ ∽ 200 to 40
- Impact on the physics analysis
- Factor 5 to 10x improvement on vertex merging rate
- Factor 3 to 5x reduction of false positive on track to vertex association
- Timing information:
  - Per Track → 1 timing layer (HL-LHC)



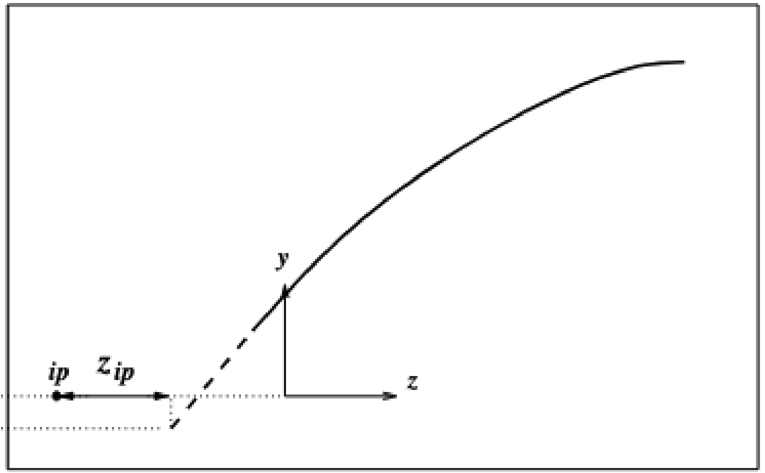


Figure from P. Vanlaer PhD thesis

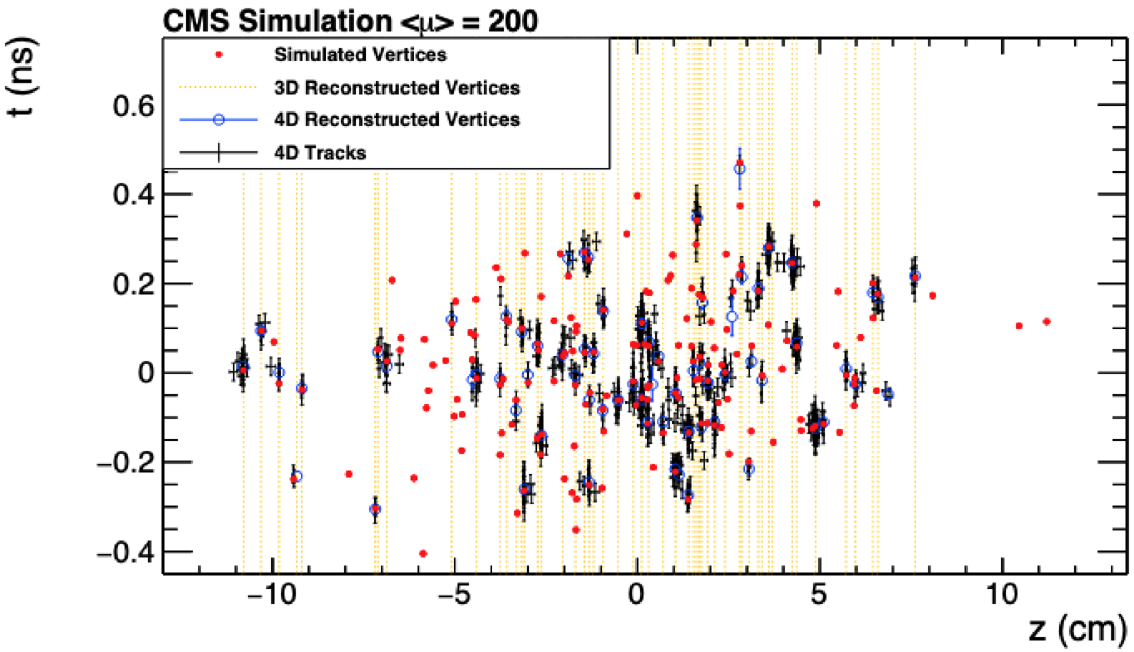


Figure from L. Gray "4 Dimensional trackers" contribution to Connecting the Dots workshop 2017

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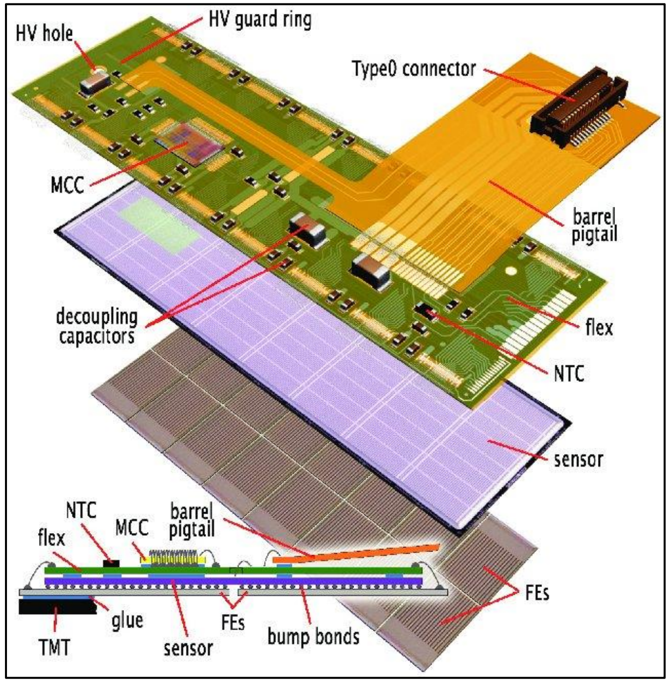
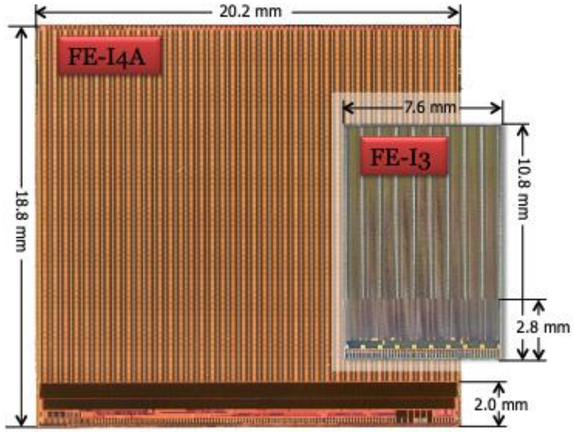
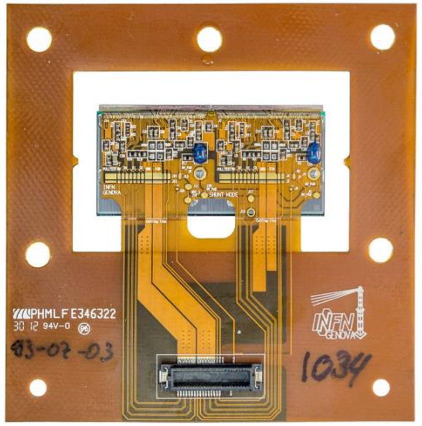
Pixel detectors developments.

- Pixel detectors are in the innermost layers:
  - Smaller areas to cover up and higher resolution requested
  - Pixel detectors are more expensive
- The developments have been/will be on:
  - Thinning sensors
  - Smaller pixel size
  - Interconnection yield (bump bonding)
  - Getting closer to the beam pipe
  - Bigger area ROC (and thinner)
  - fast
  - Radiation Hardness

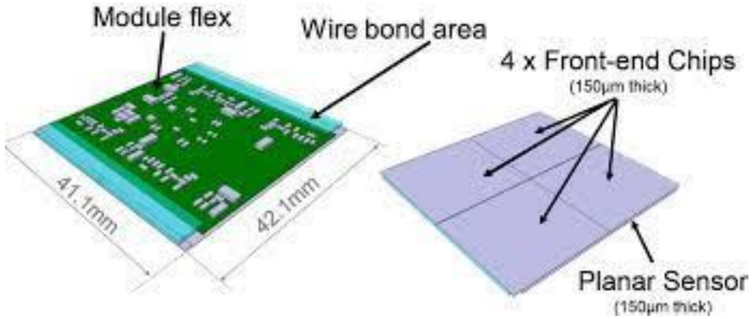
ATLAS ID – pixel module (50 x 400 um^2)







ATLAS IBL – pixel dual- module (50 x 250 um^2)



ATLAS ITk – QUAD module (50 x 50 um^2)
Triplet (25 x 100 um^2)

Summary

- Particle physics needs position sensitive detectors for many different applications compromising:
  - Volume vs cost
  - Coverage and hermeticity vs services
  - Resolution vs cost and services
  - Mass vs resolution
  - Cost vs Power
  - …. And all possible combinations
- Pixel detectors starting a new Era: FCC
  - High granularity (**σ** <10 um)
  - Extremely Low mass
    - 40 um thickness sensors
    - optical data
    - Monolithic
  - Timing layers (~30 ps)
  - Radiation hardness (most important for hadron)

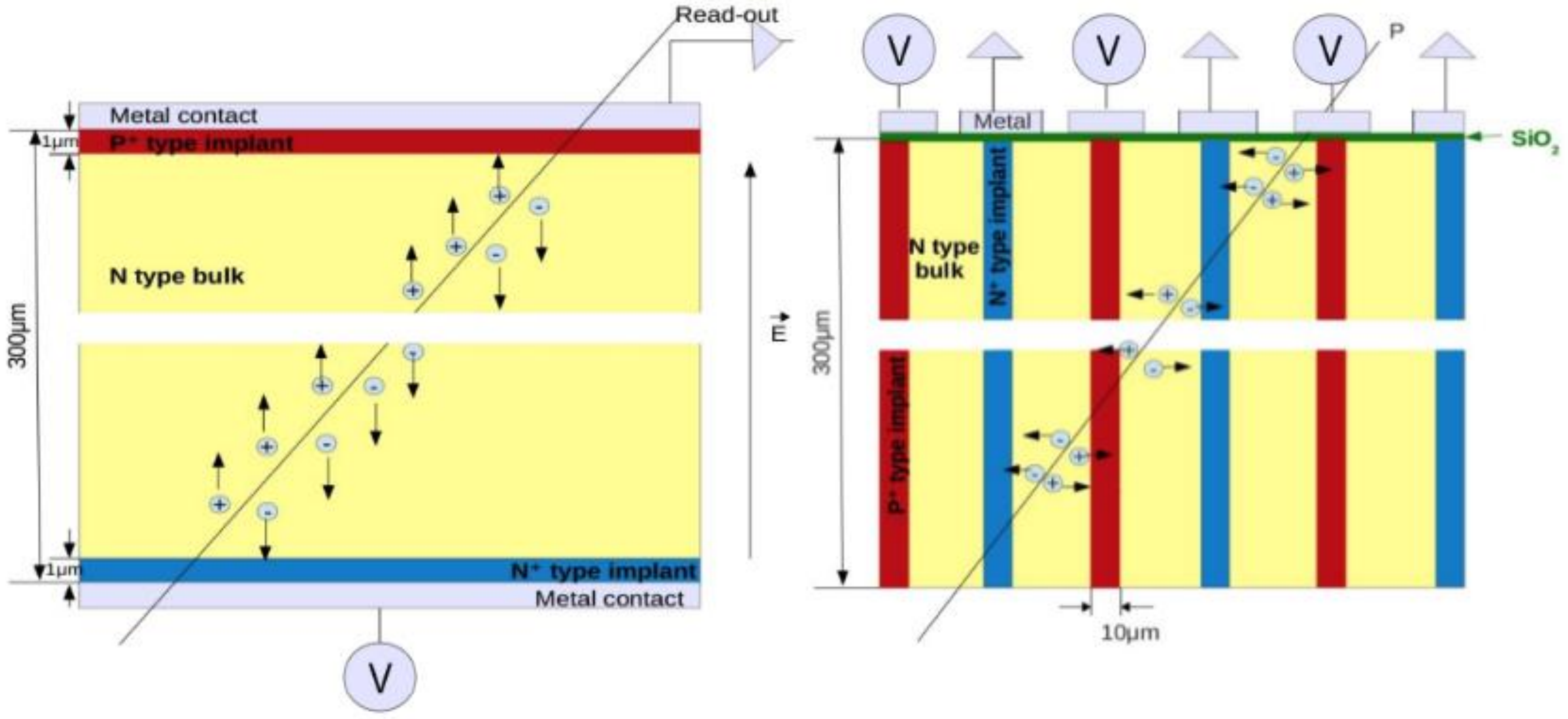
A. Macchiolo talk: [“Future directions for pixel detectors: timing and pixel size performance”]

Thank you very much for your attention.
Questions?

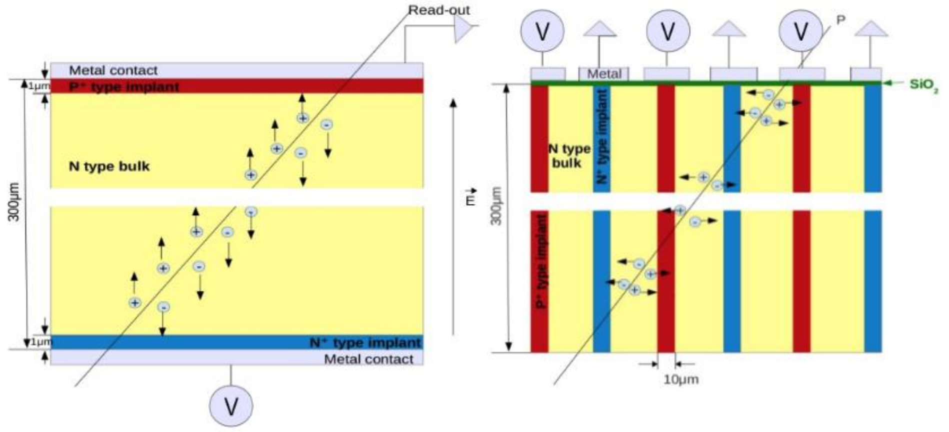
Backup

Devices structures

- Electrode position: Planar vs 3D (surface or embedded)
  - 3D sensors were proposed by S. Parker in 1997 [4]
  - They can be strip or pixel sensors



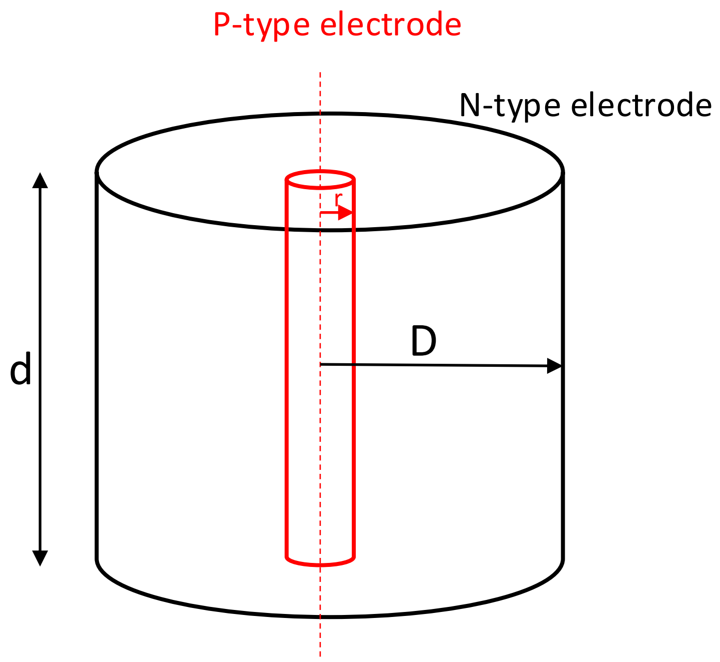
3D structures characteristics



- In 3D devices, distance between electrodes no more limited by the sensor thickness.
- Full depletion voltage now is given by the coaxial approximation [11]:

$$V_{FD} = \frac{qN_{eff}}{2\epsilon_0\epsilon_{Si}}\left(D^2\left[ln(\frac{D}{r} - 0.5)\right] + 0.5r^2\right)$$

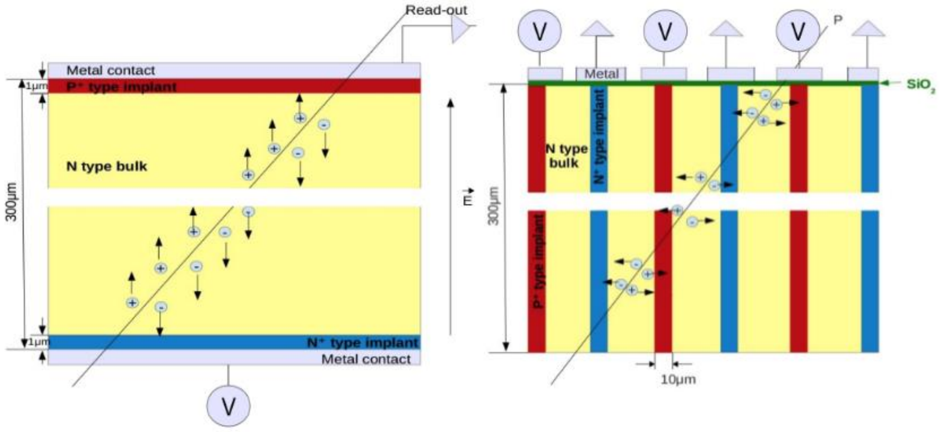
D = Electrode distance
r = column radii



- Smaller V_{FD}
- Shorter distances to travel for carriers
- Input capacitance is higher than in planar → challenging for ROC

$$C = \frac{2\pi\varepsilon_0 d}{ln\left(\frac{D}{r}\right)}$$

- short collection distances, fast collection times and low depletion voltages



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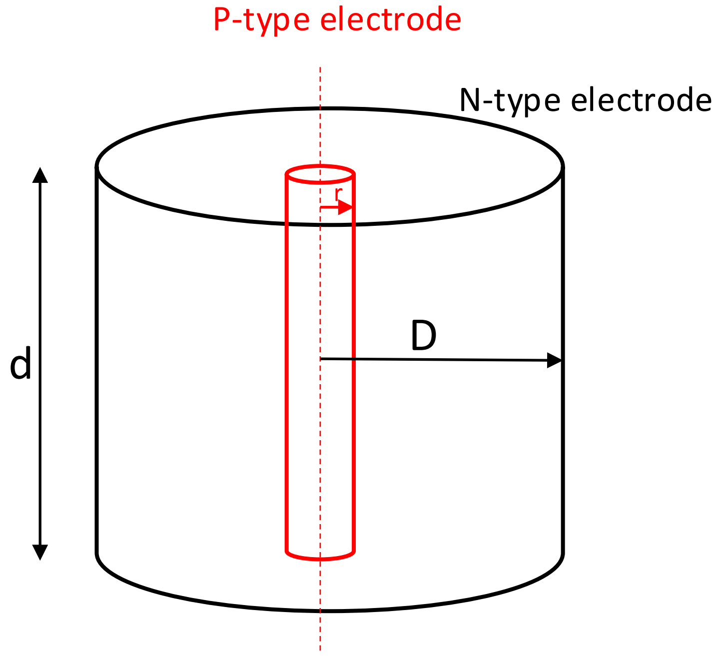

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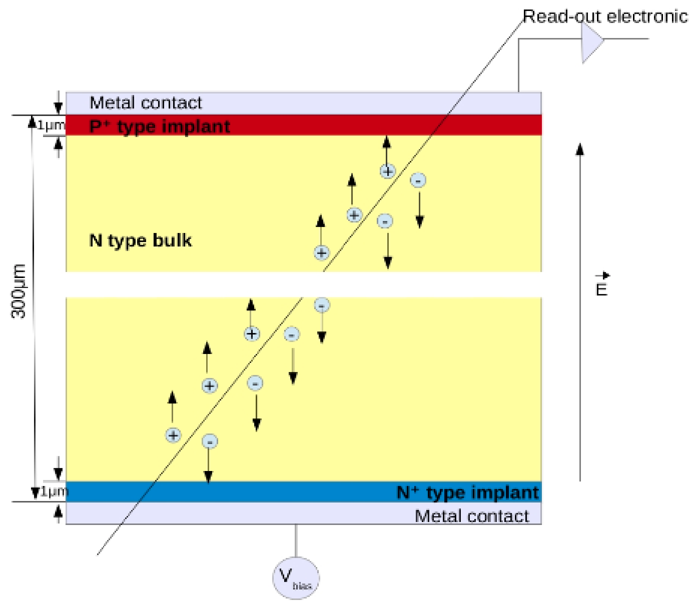
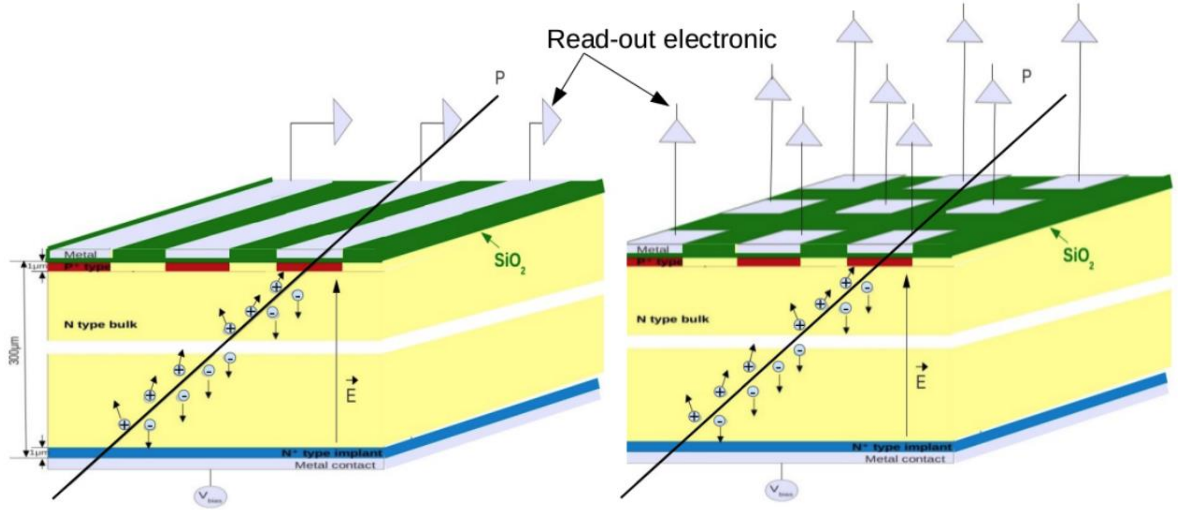
Position resolution

- Position resolution is given by the size of the electrode (to first order):
  - Electrode size is also limited by:
    - Wafer size
    - Electronics bonding (interconnection technique)
  - Electrodes are segmented into strips or pixels ('strixels' also exist)
    - Sensors remains 100% efficient despite the gaps (field lines remain parallel until near the surface) provided:
      - $V_{bias} > V_{FD}$
      - Un-irradiated sensors
  - Connection to the readout electronics





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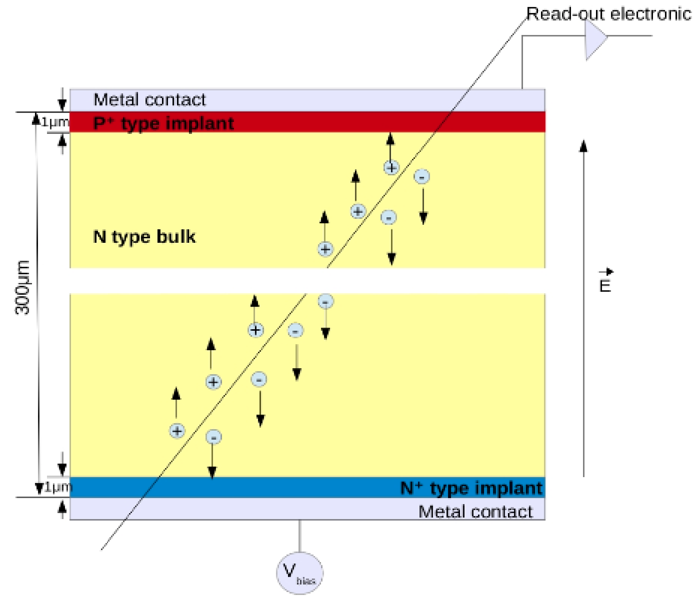
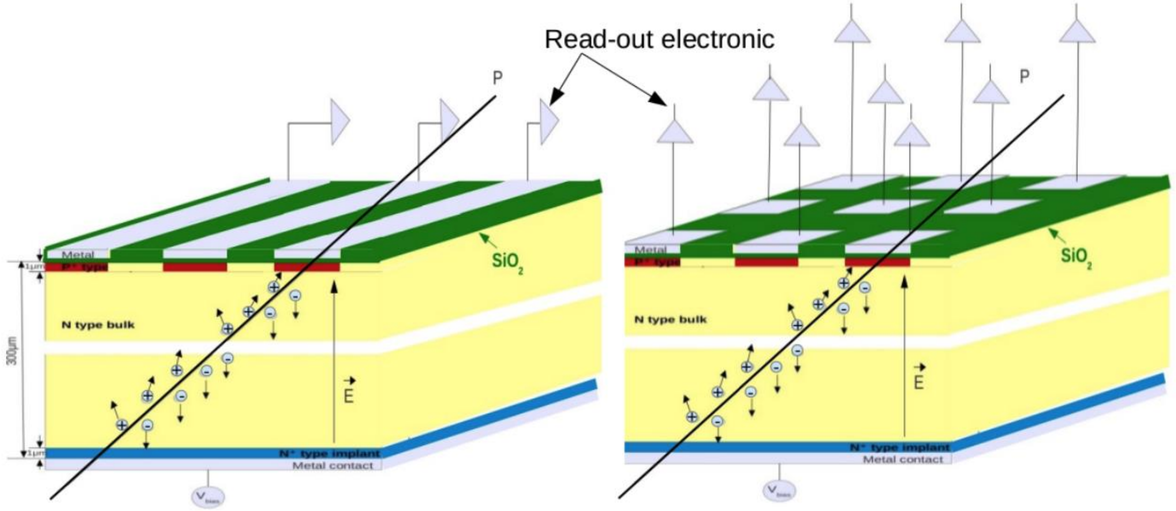
Position resolution in semiconductors

- Position resolution is given by the size of the electrode (to first order):
  - Electrode size is also limited by:
    - Wafer size
    - Electronics bonding (interconnection technique)
  - Electrodes are segmented into strips or pixels (‘strixels’ also exist)
    - Sensors remains 100% efficient despite the gaps (field lines remain parallel until near the surface) provided:
      - $V_{bias} > V_{FD}$
      - Un-irradiated sensors
  - Segmentation in the junction side or the ohmic side





Position resolution

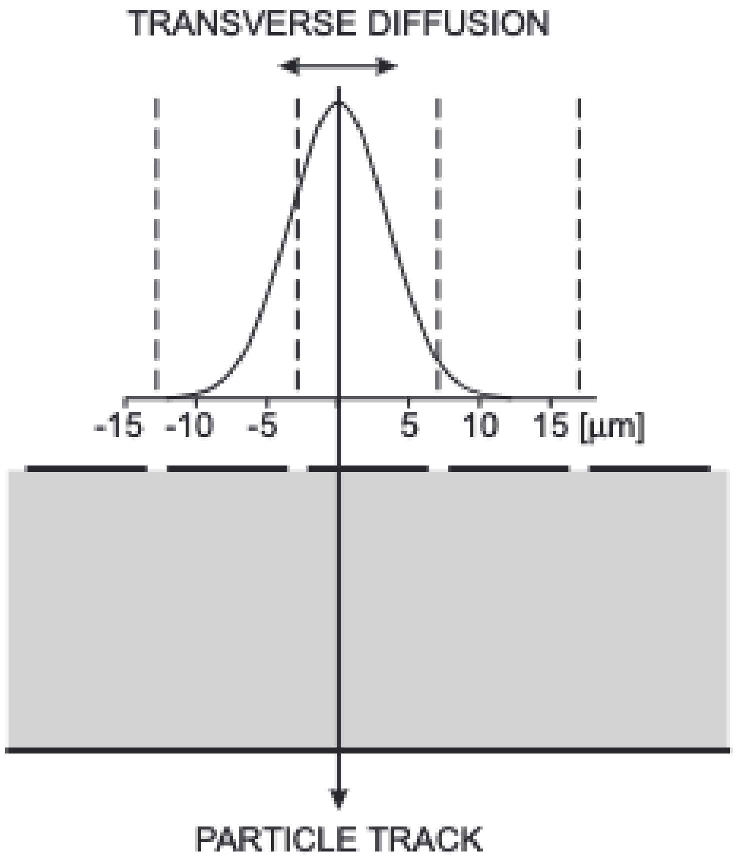
- Position resolution:
  - Diode → Pitch 'p'
  - Strip or pixel detector. Tracks randomly aligned with the strip, the difference between the measured and the real position have a gaussian distribution with the standard deviation:

$$\sigma^2 = \int_{-p/2}^{p/2} \frac{x^2}{p} dx = \frac{p^2}{12} ,$$

  - Transverse diffusion (the phenomenon), thermal spread of the charges with an RMS width σ^2 = 2Dt:
    - D is the diffusion constant, proportional to the carrier's mobility (=kTμ/e)
    - Using the average field approximation: $\boldsymbol{E}$ = V/d
    - t is the collection time, inversely proportional to the mobility t ~d/v =d/($\mu\boldsymbol{E}$) = $d^2/(\mu V)$
    - The transverse diffusion is independent of the carrier

$$\sigma_y = \sqrt{2Dt} \approx \sqrt{2\frac{kT}{e}\frac{d^2}{V_b}}$$

  - Charge sharing between electrodes (the effect).



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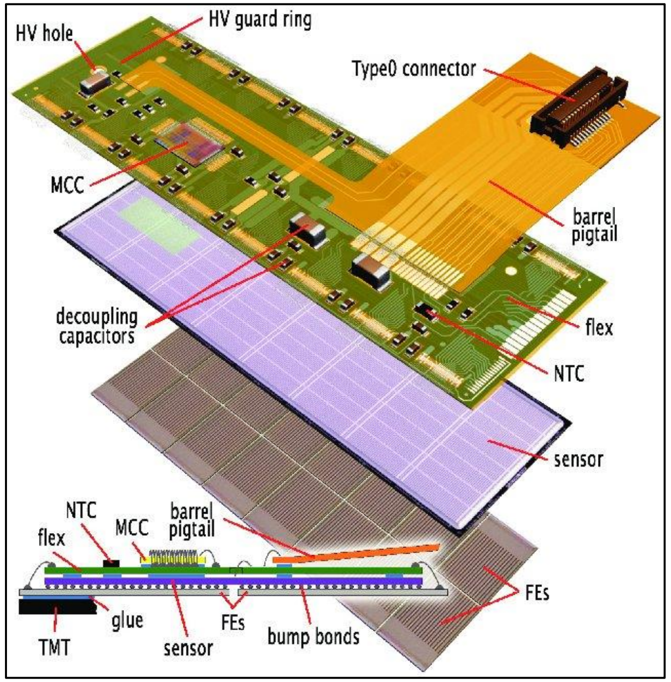
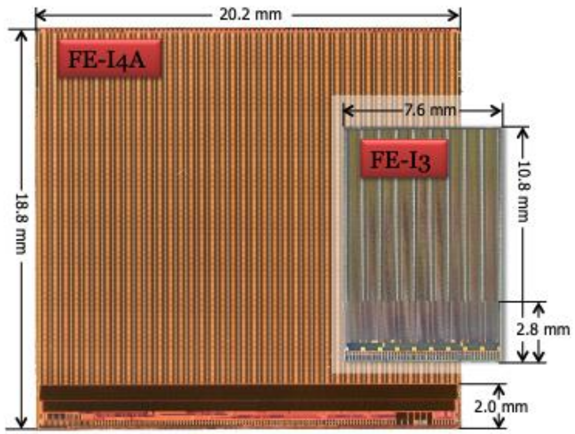
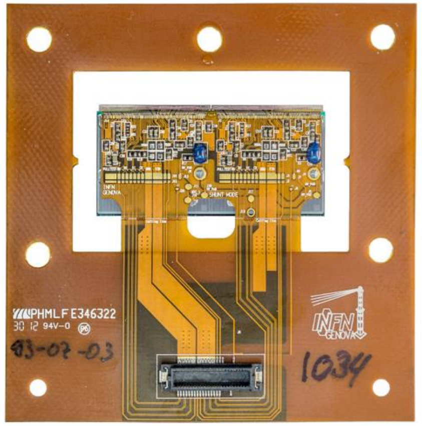
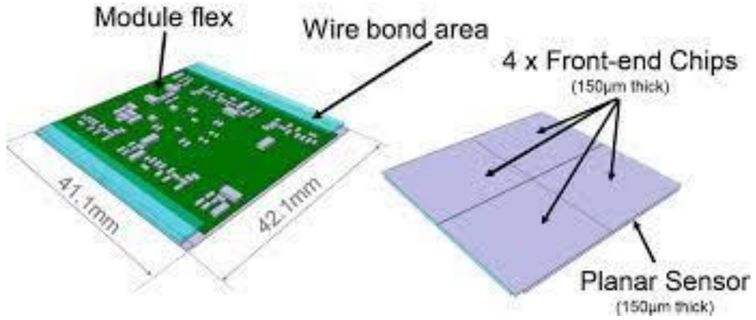
ATLAS ID – pixel module (50 x 400 um^2)





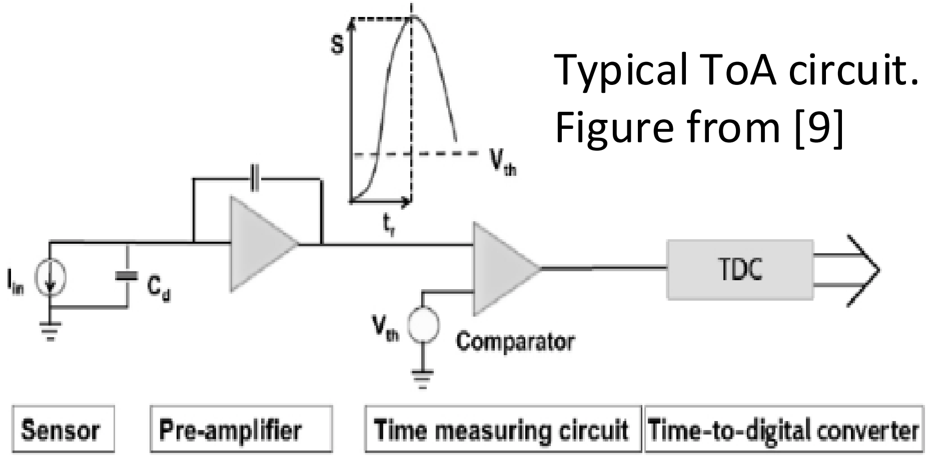


ATLAS IBL – pixel dual- module (50 x 250 um^2)



ATLAS ITk – QUAD module (50 x 50 um^2)
Triplet (25 x 100 um^2)

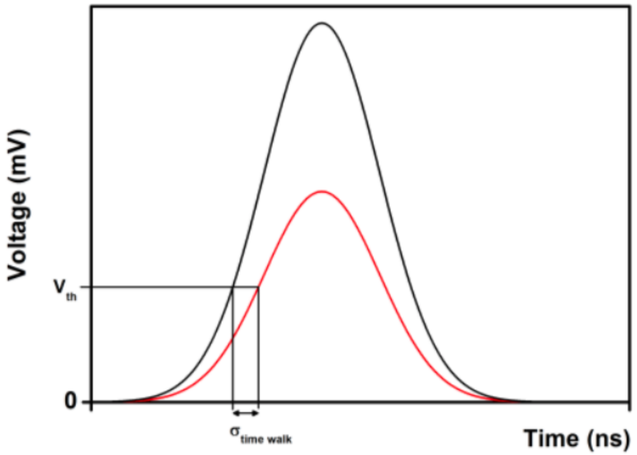
Time resolution



Typical ToA circuit. Figure from [9]

- All the components that change the shape of the signal introduce uncertainties
- Time resolution is:

$$\sigma_t^2 = \sigma_{time\ walk}^2 + \sigma_{Landau\ noise}^2 + \sigma_{jitter}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2$$



$$\sigma_{time\ walk} = [t_d]_{RMS} = \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS} \propto \left[\frac{N \cdot \sigma_N}{dV/dt}\right]_{RMS}$$

$\sigma_{Landau\ noise}$: Variations on the energy deposited. Thinned sensors → smaller variations

σ_{jitter} : Uncertainties on the Time of Arrival (ToA) for constant pulses. Signal level is modulated by noise, the time of threshold varies accordingly.

$$\sigma_t = \frac{\sigma_n}{(dV/dt)_{V_{th}}} \approx \frac{1}{S/N} t_r$$

$\sigma_{distortion}$: due to the sensor geometry, field as homogeneous as possible

σ_{TDC} : time info is digitized into a bin of width Δt. $\sigma_{TDC} = \Delta t/\sqrt{12}$

M. Carulla Areste PhD Thesis : "Thin LGAD timing detectors for the ATLAS experiment", 2019

Position Sensitive detectors in Particle Physics

- Particle interaction with matter:
  - Ionisation by charged particles:
    - Detect charge in electrodes
  - Excitation of electrons and de-excitation emitting light
    - Detect photons with light detector
  - Tiny neutral interactions:
    - Detect Phonons with cryo-technologies

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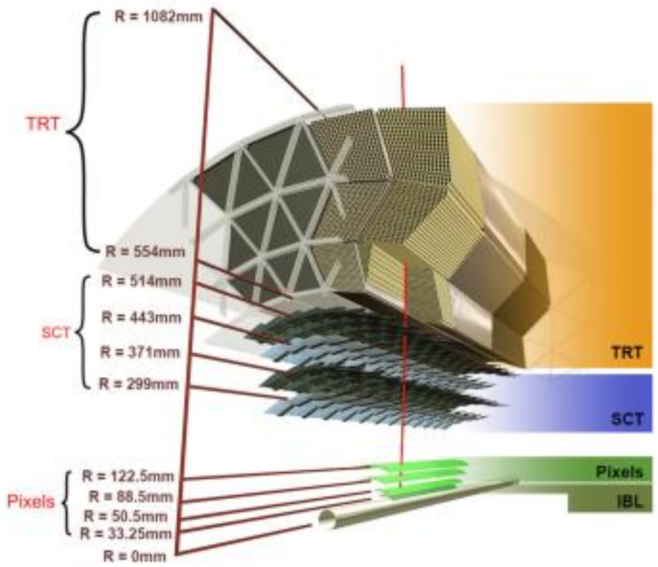
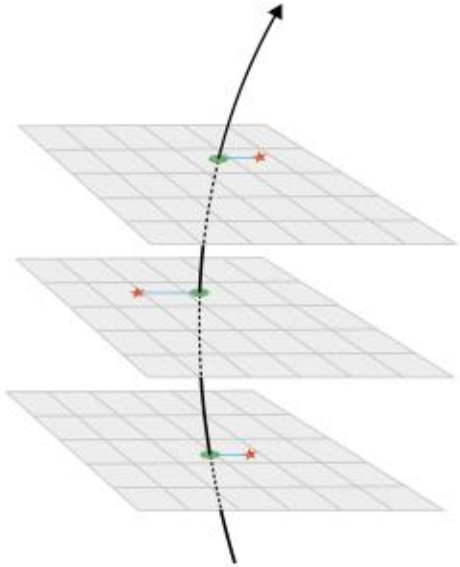
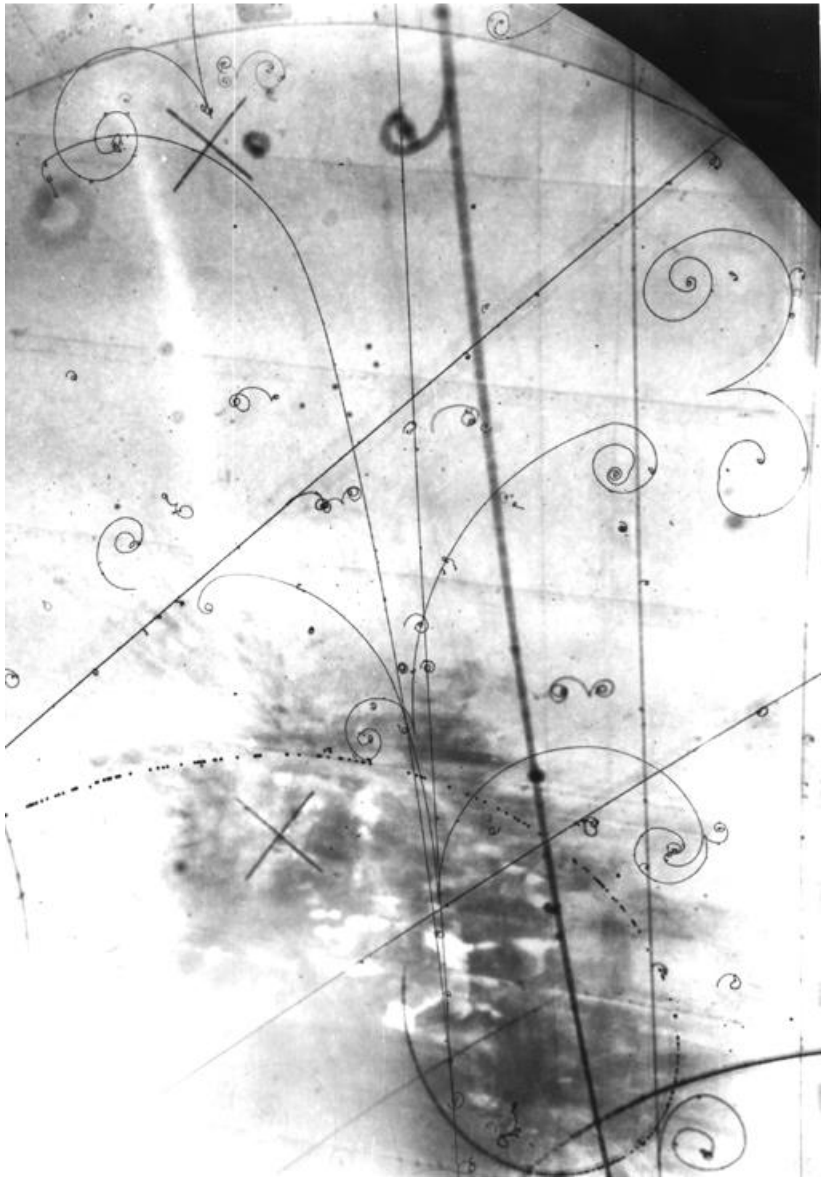
Position Resolution

- Distance between the real hit and the fitted track







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