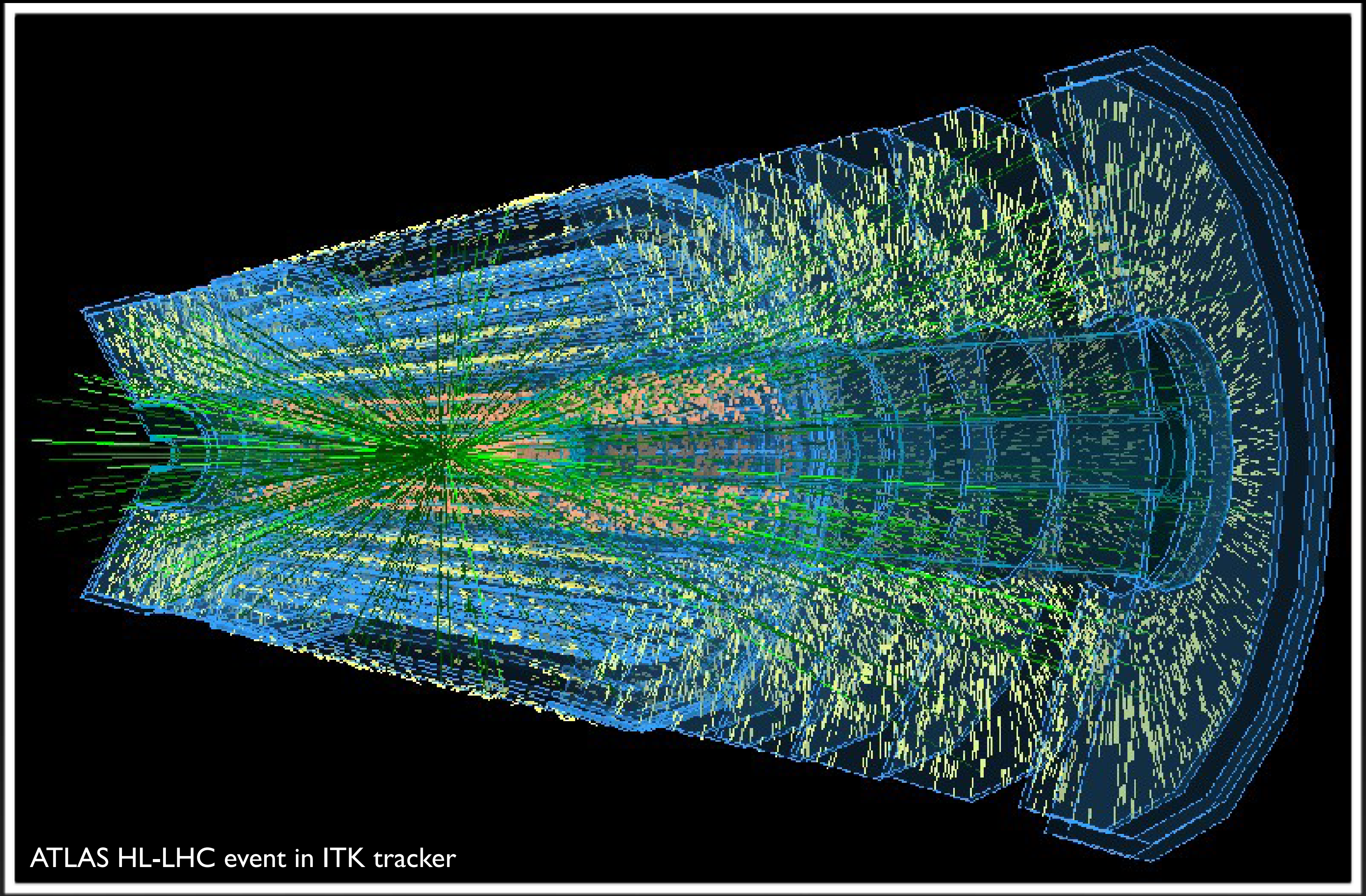
Markus Elsing

Tracking at the LHC (Part 2)

LHC Tracking Detectors



Introduction: LHC and Experiments

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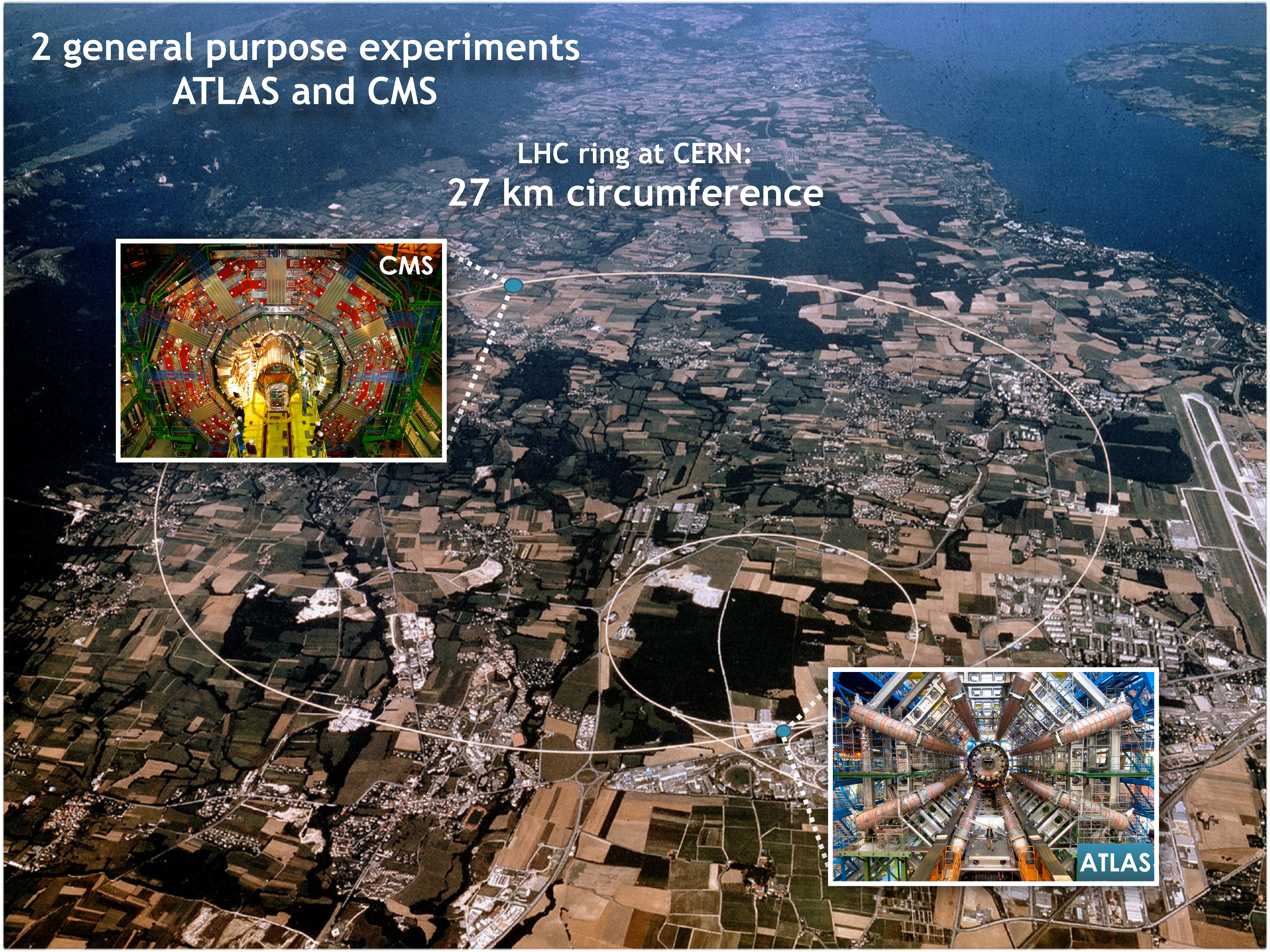

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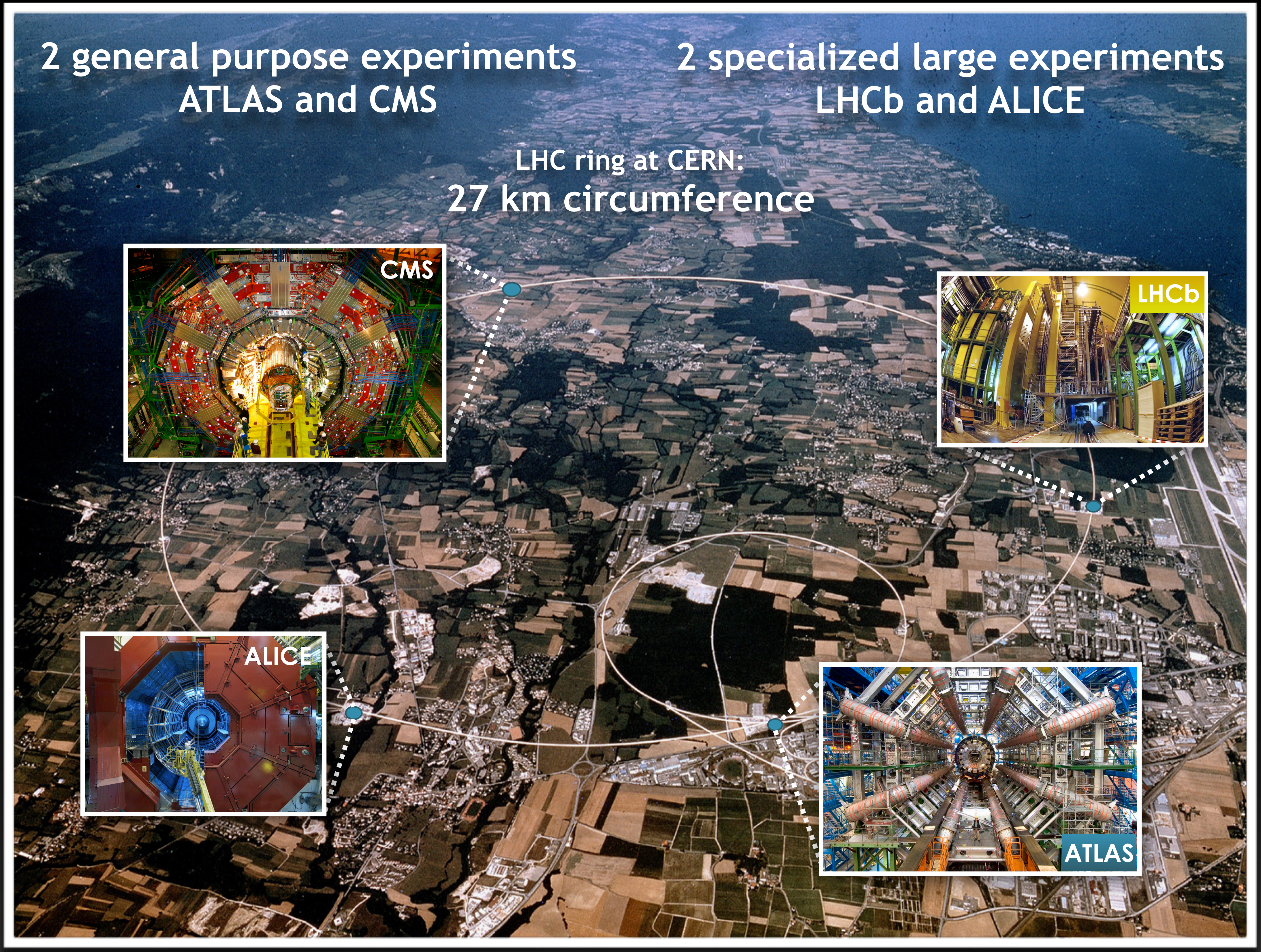
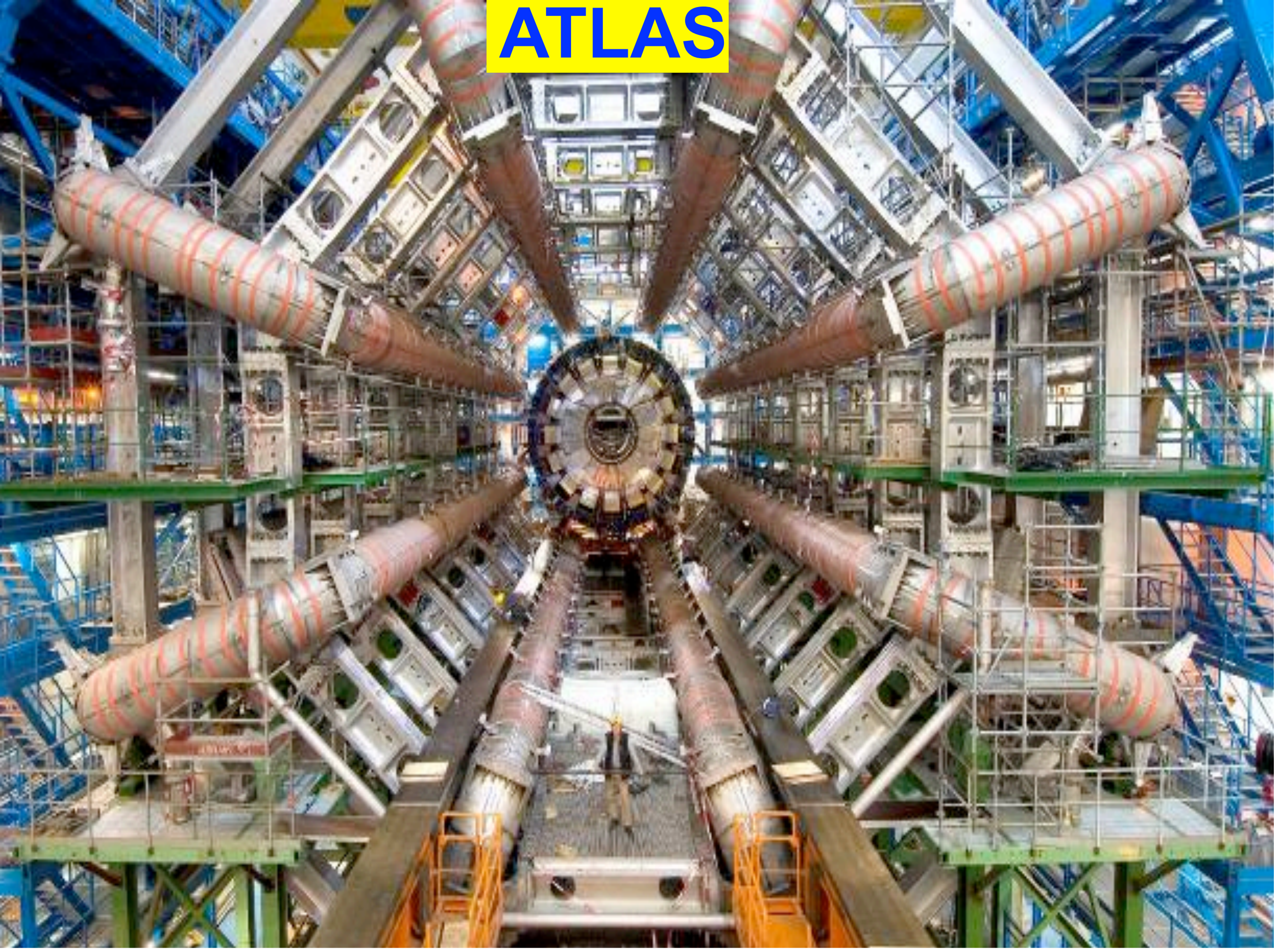
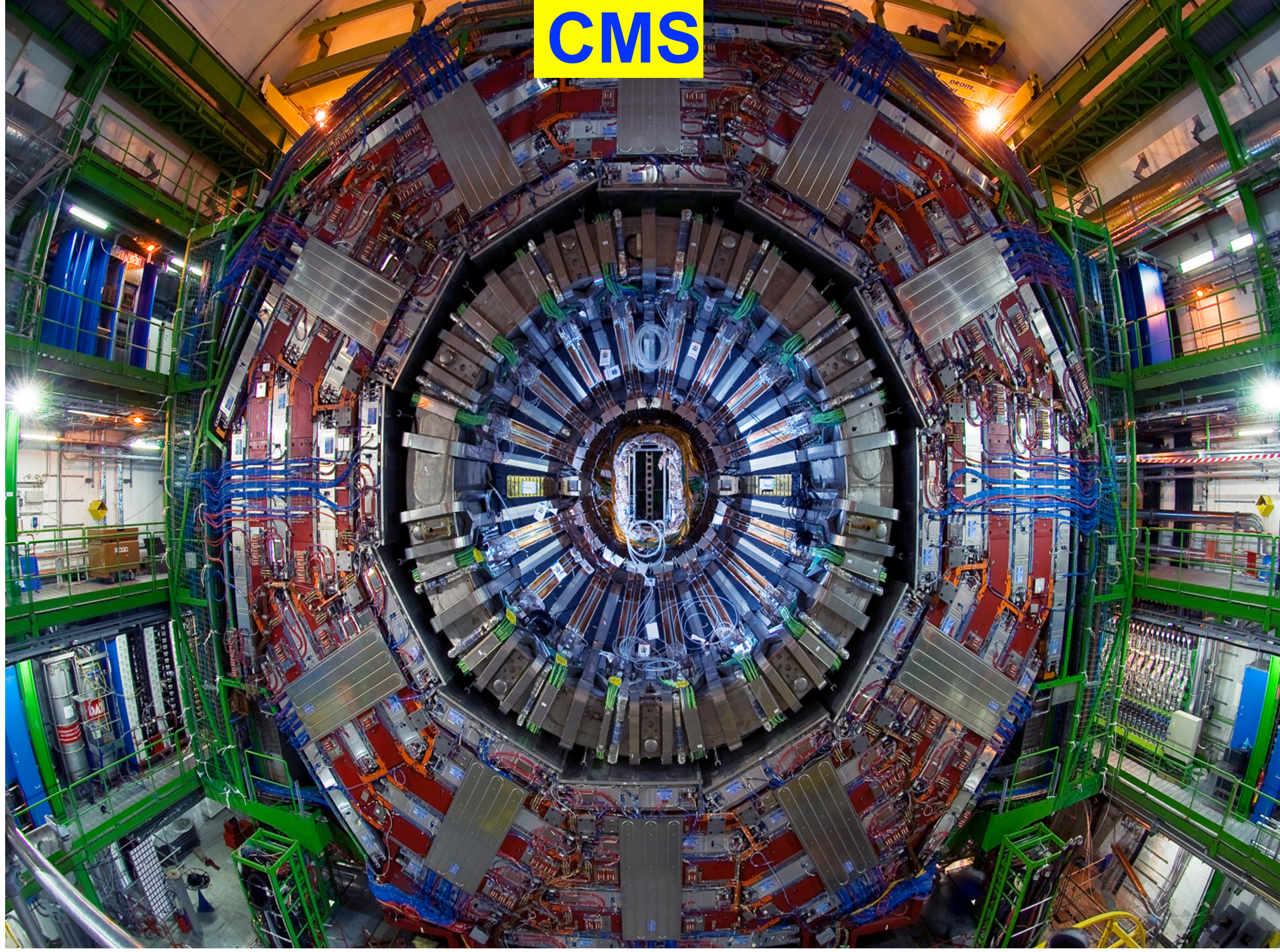



ATLAS


CMS


LHCb

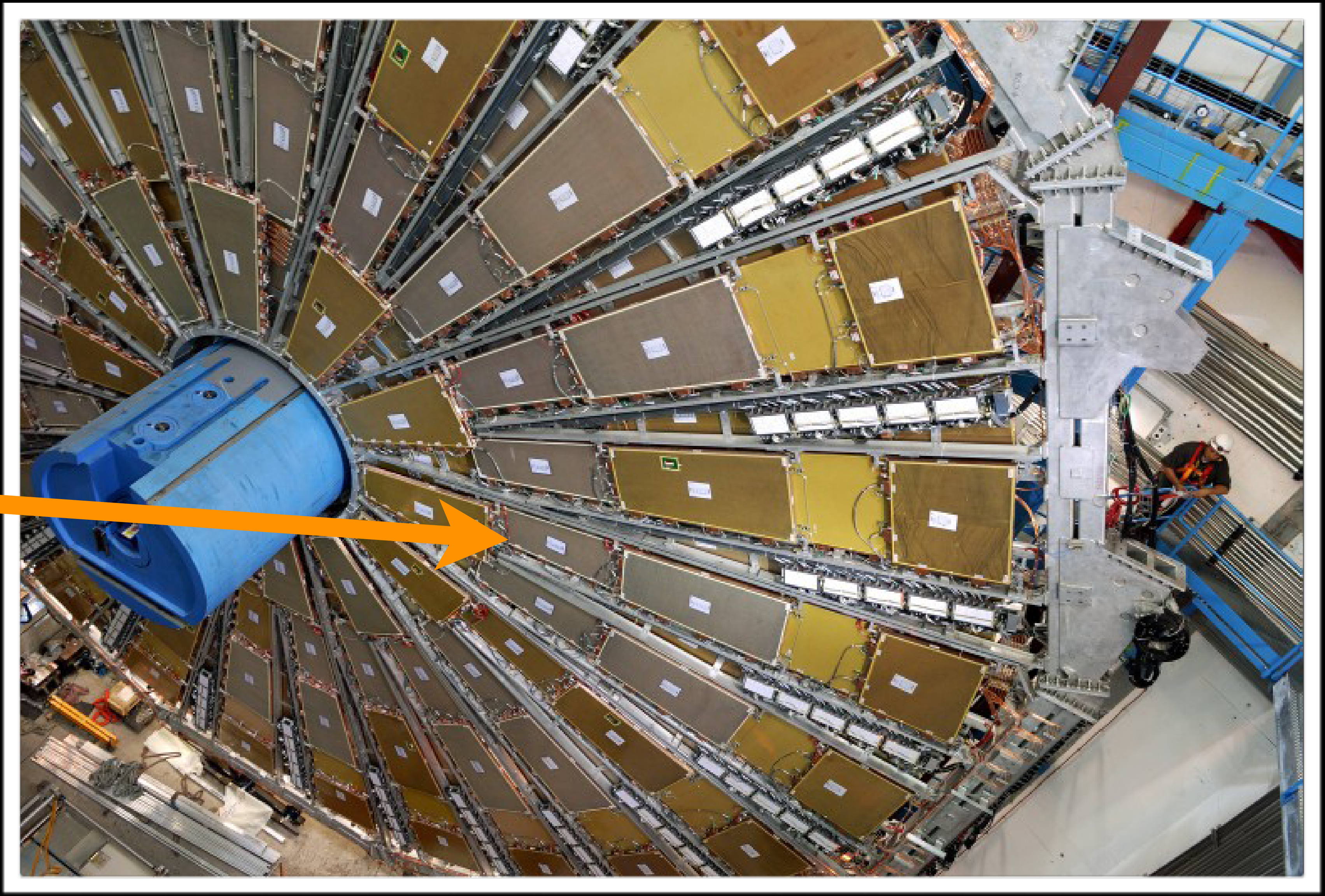

ALICE

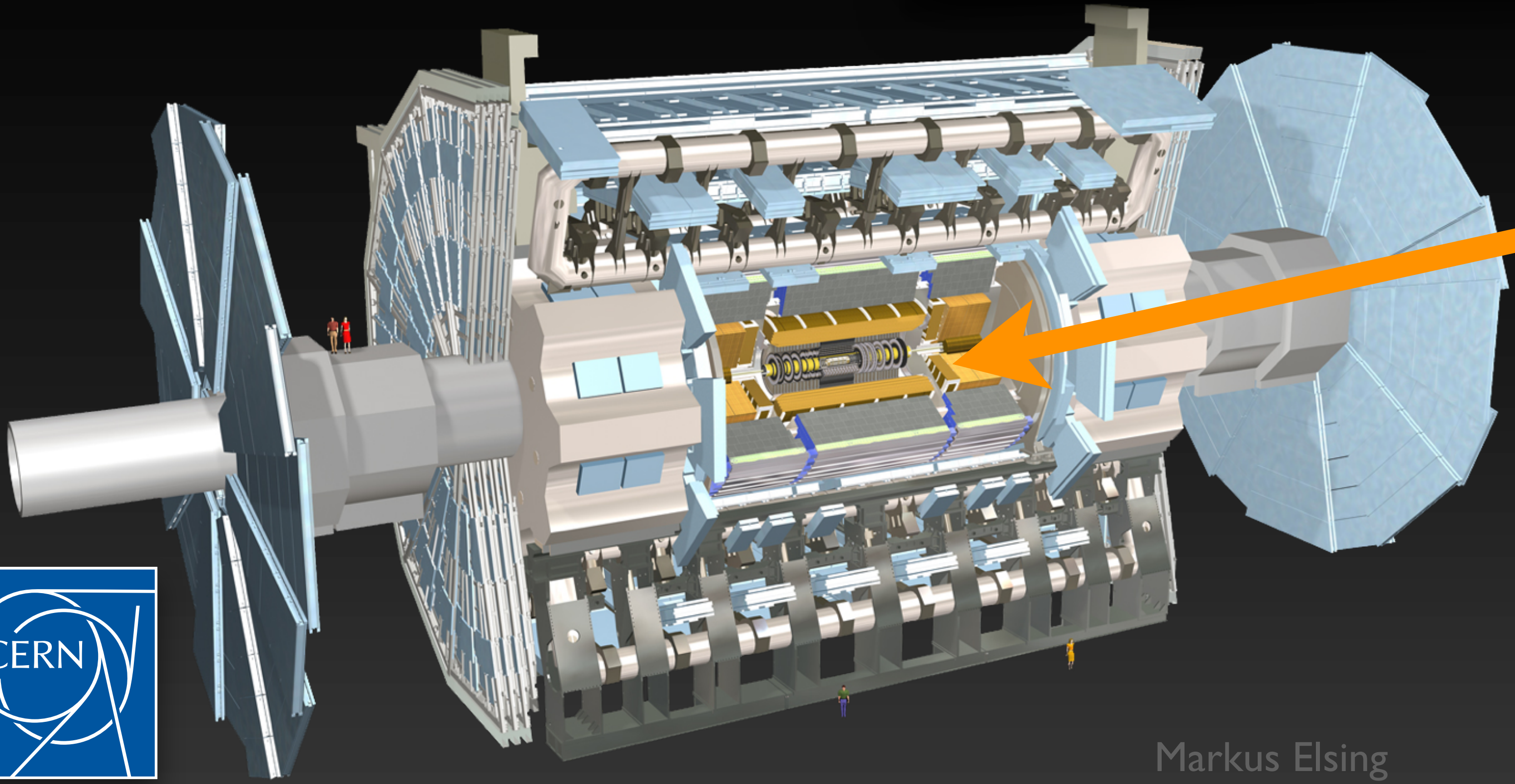
Outline of Part 2

- give an overview of the LHC detectors
  - ➡ inner tracking and as well some words on the muon systems
- tracking detectors
  - ➡ discuss constraints, roles and design choices
- a bit of detector technologies and their applications
  - ➡ semiconductor trackers
  - ➡ drift tube detectors

ATLAS

- from the outside, all one sees are **muon chambers**
  ➡ tracking of muons in toroid field





➡ most particles are absorbed in the **calorimeters**, which measure their energy
➡ not subject of these lectures

ATLAS

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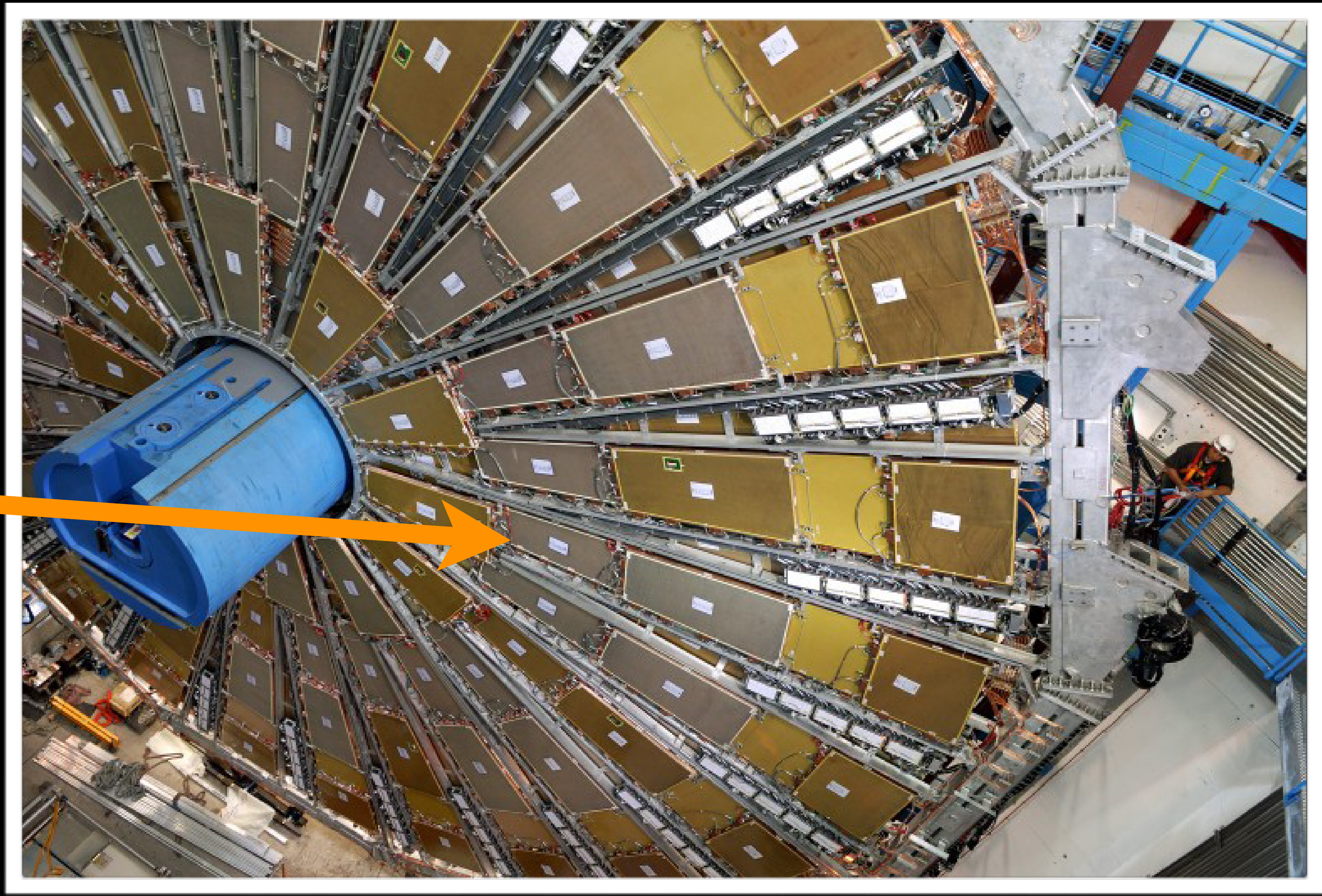

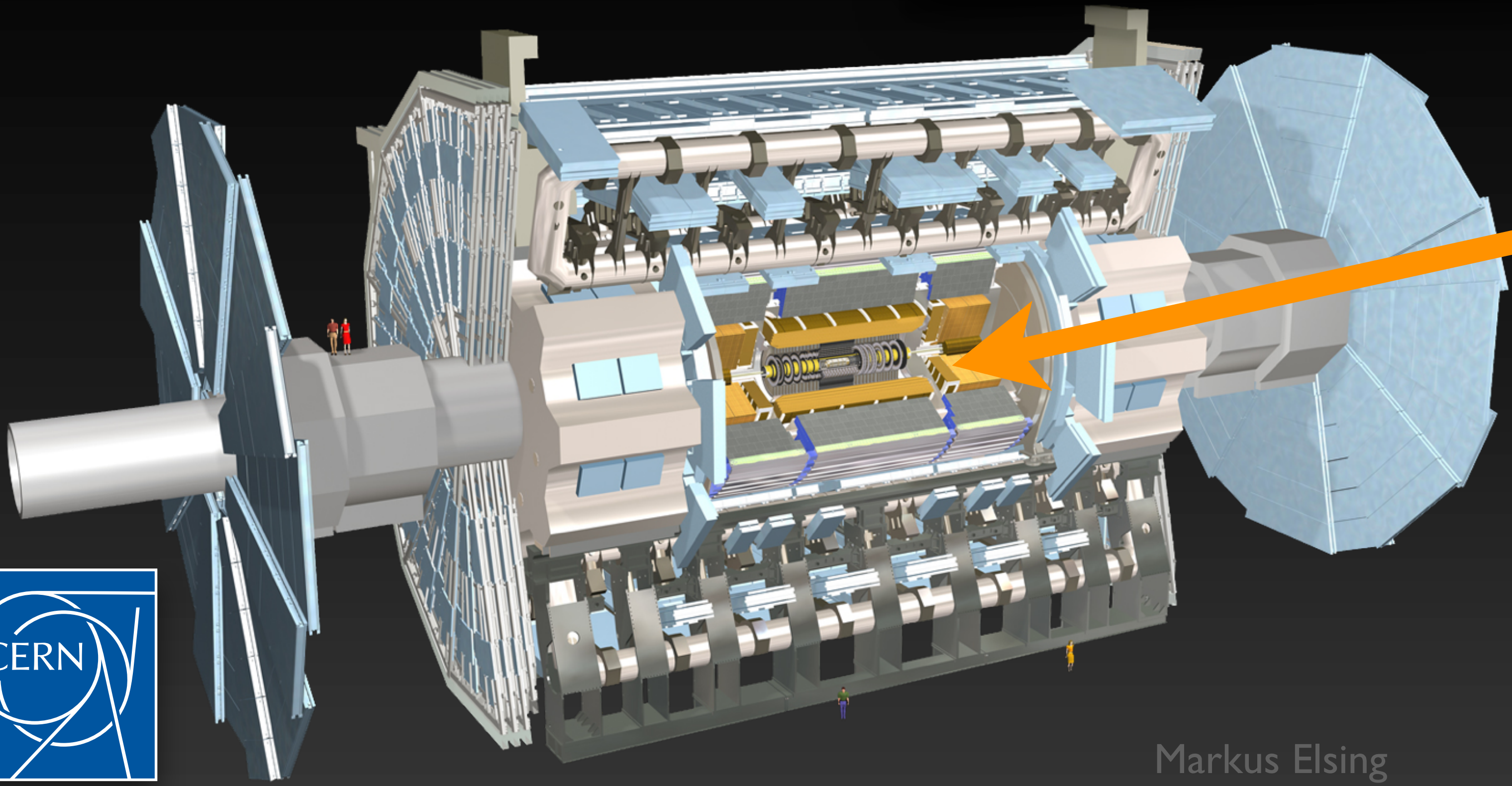

- ➡ most particles are absorbed in the **calorimeters**, which measure their energy
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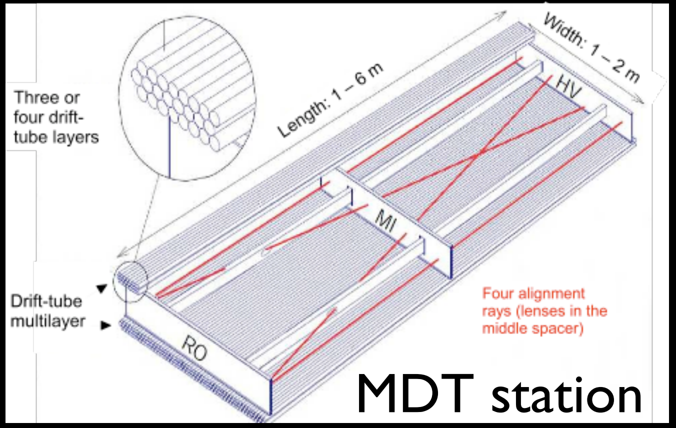
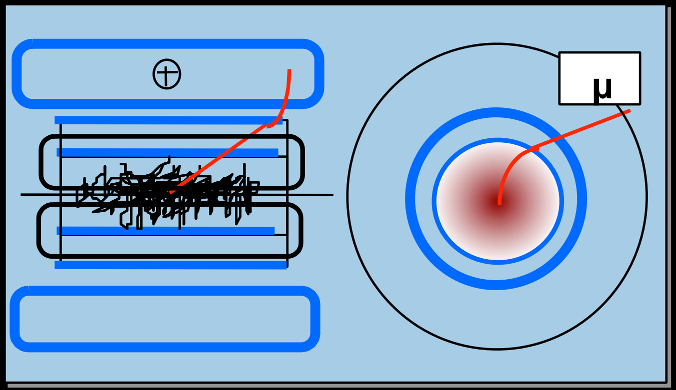
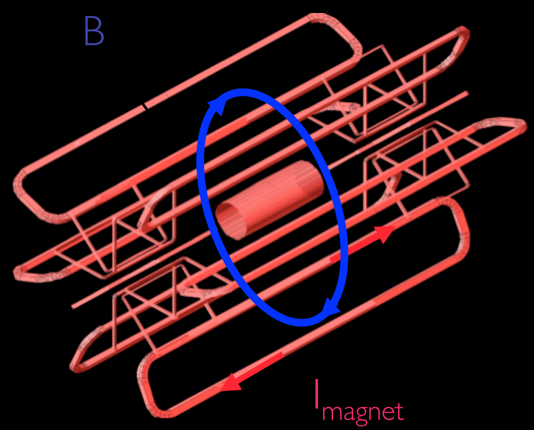
- let' have a brief look at the **muon systems**
  - ➡ ATLAS and CMS

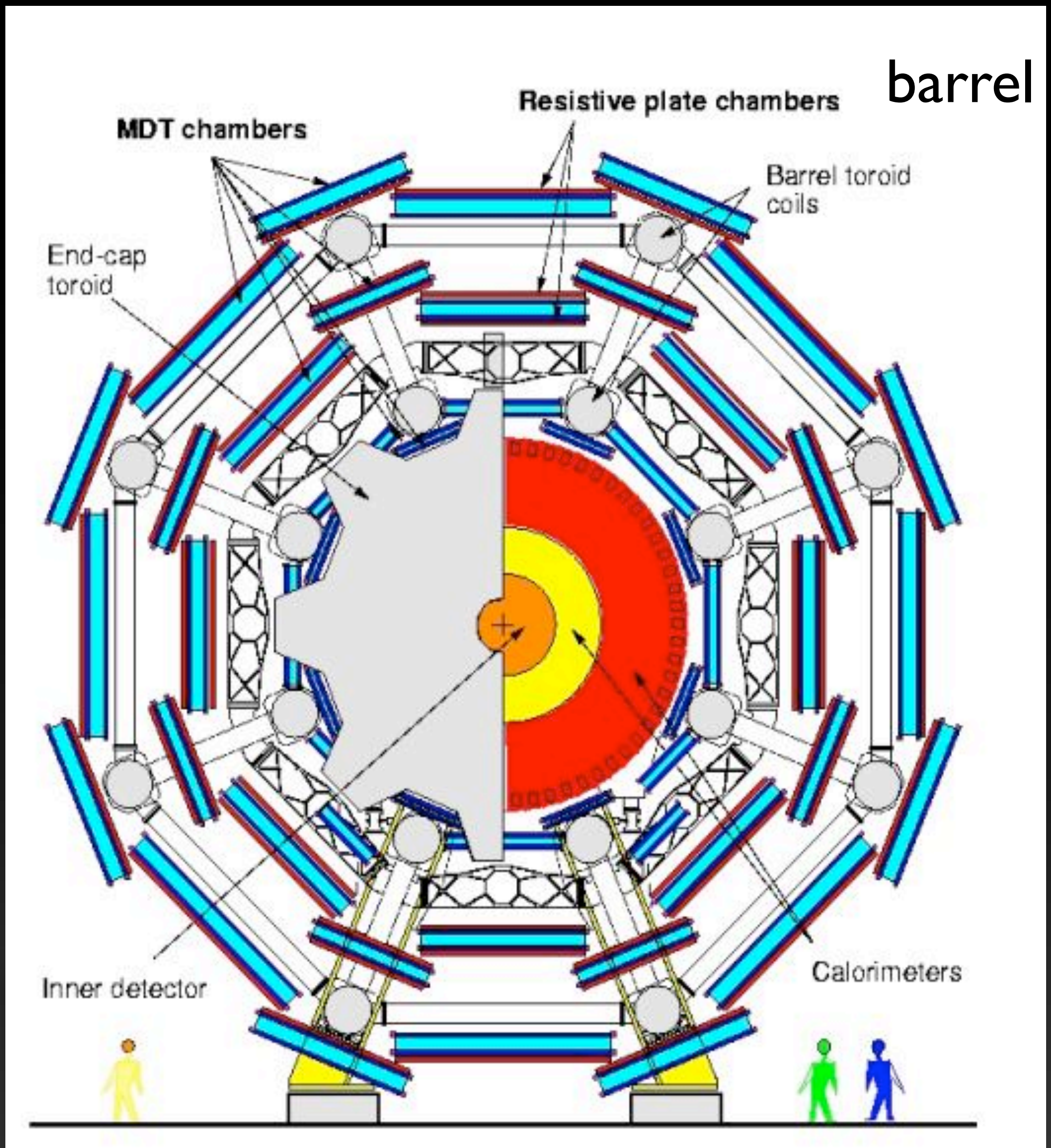
ATLAS Muon Spectrometer

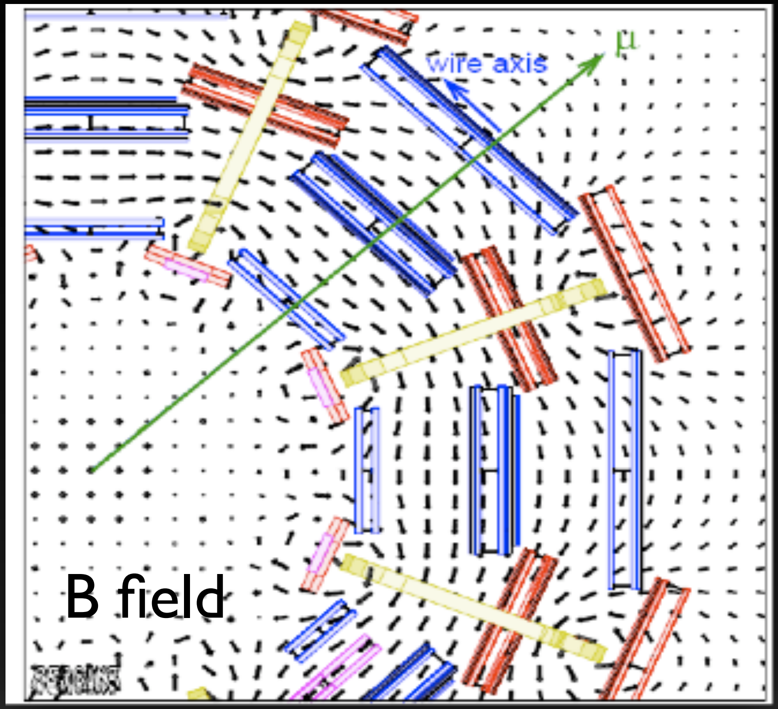


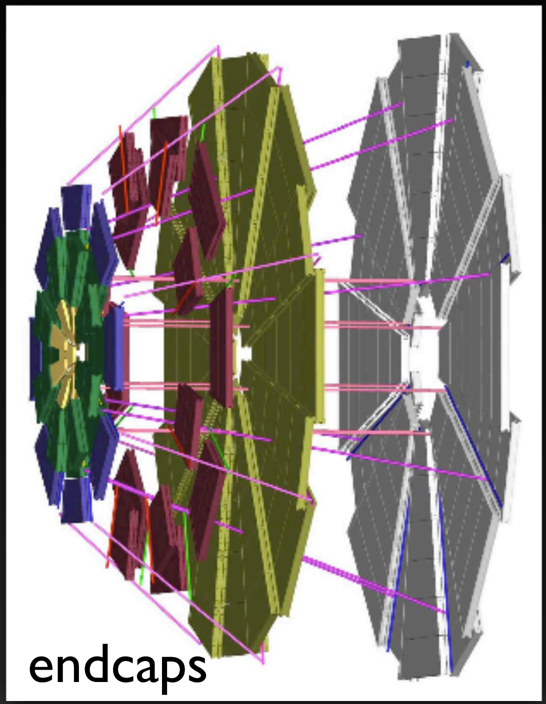




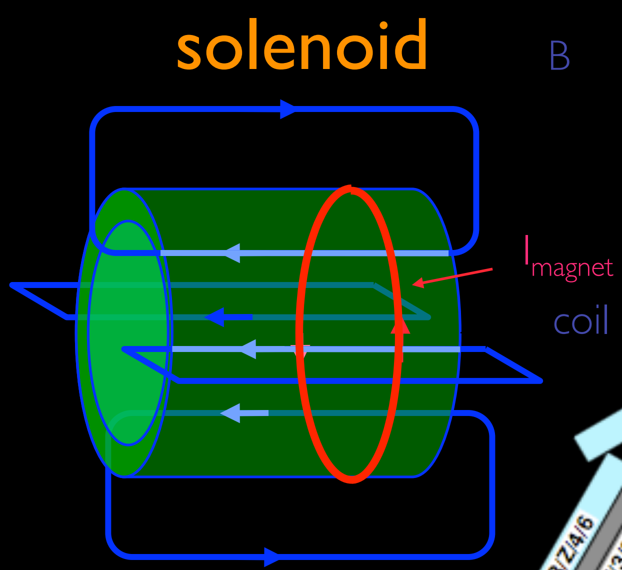
- a huge system
  - ➡ 4 different technologies (MDT,CSC,RPC,TGC)
  - ➡ large area (10.000 m²)
  - ➡ many channels (1 M)
- toroid field configuration
  - ➡ large magnetic field variations in toroid
  - ➡ field 4 Tesla near coils
- optical alignment system

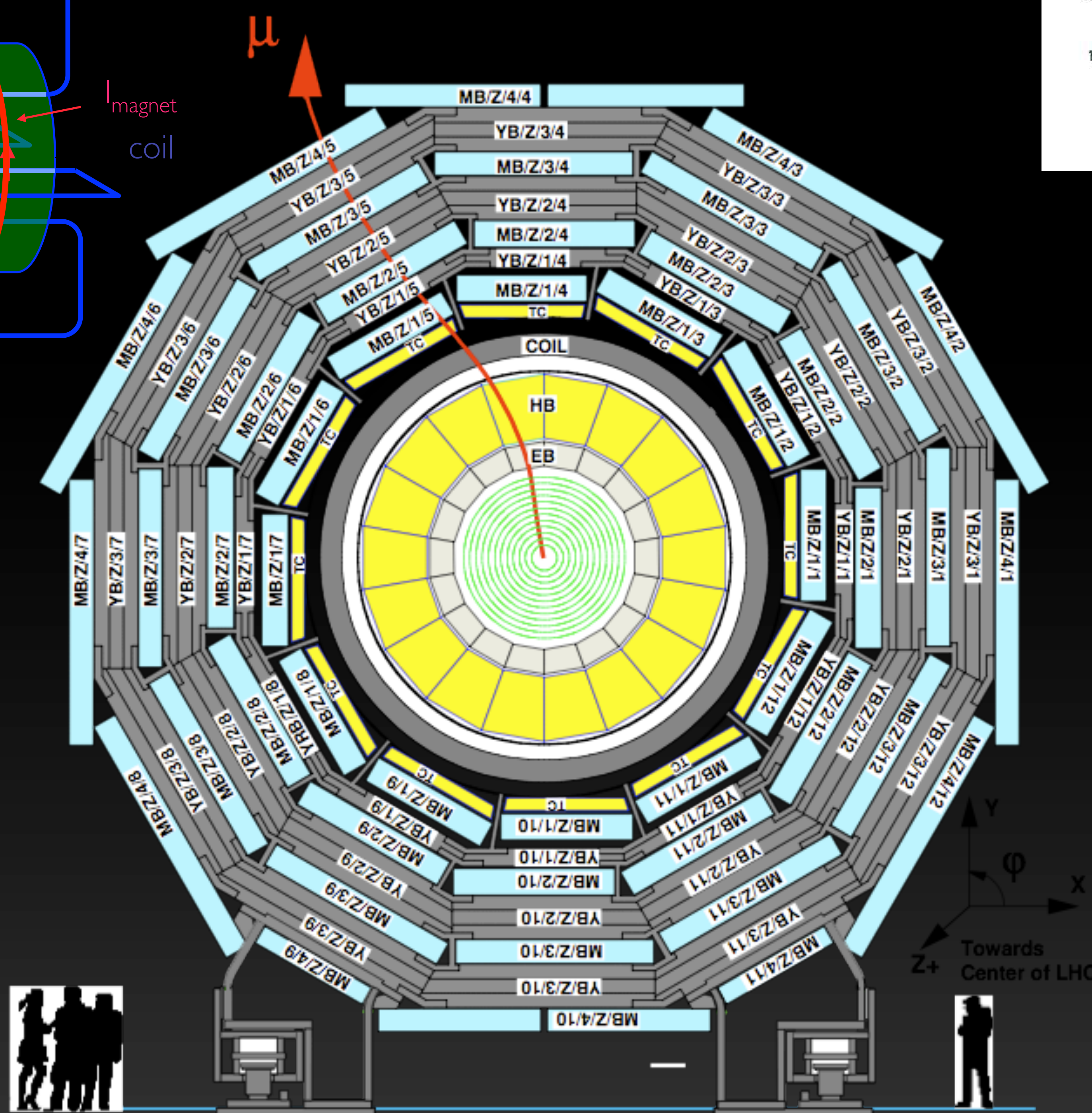


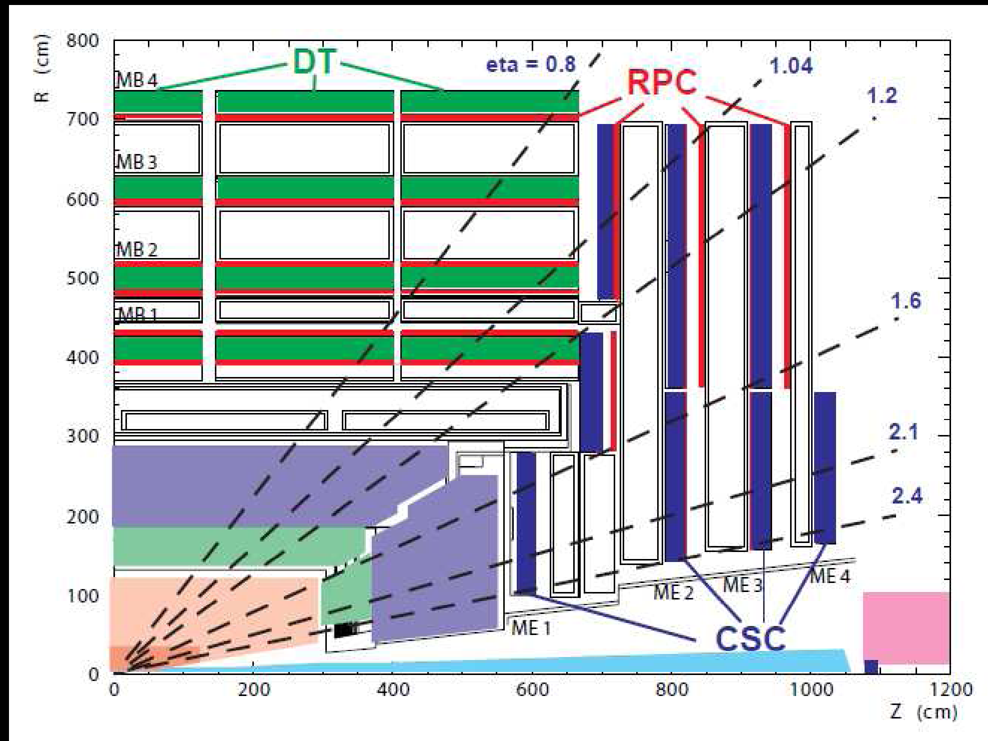




CMS Muon System

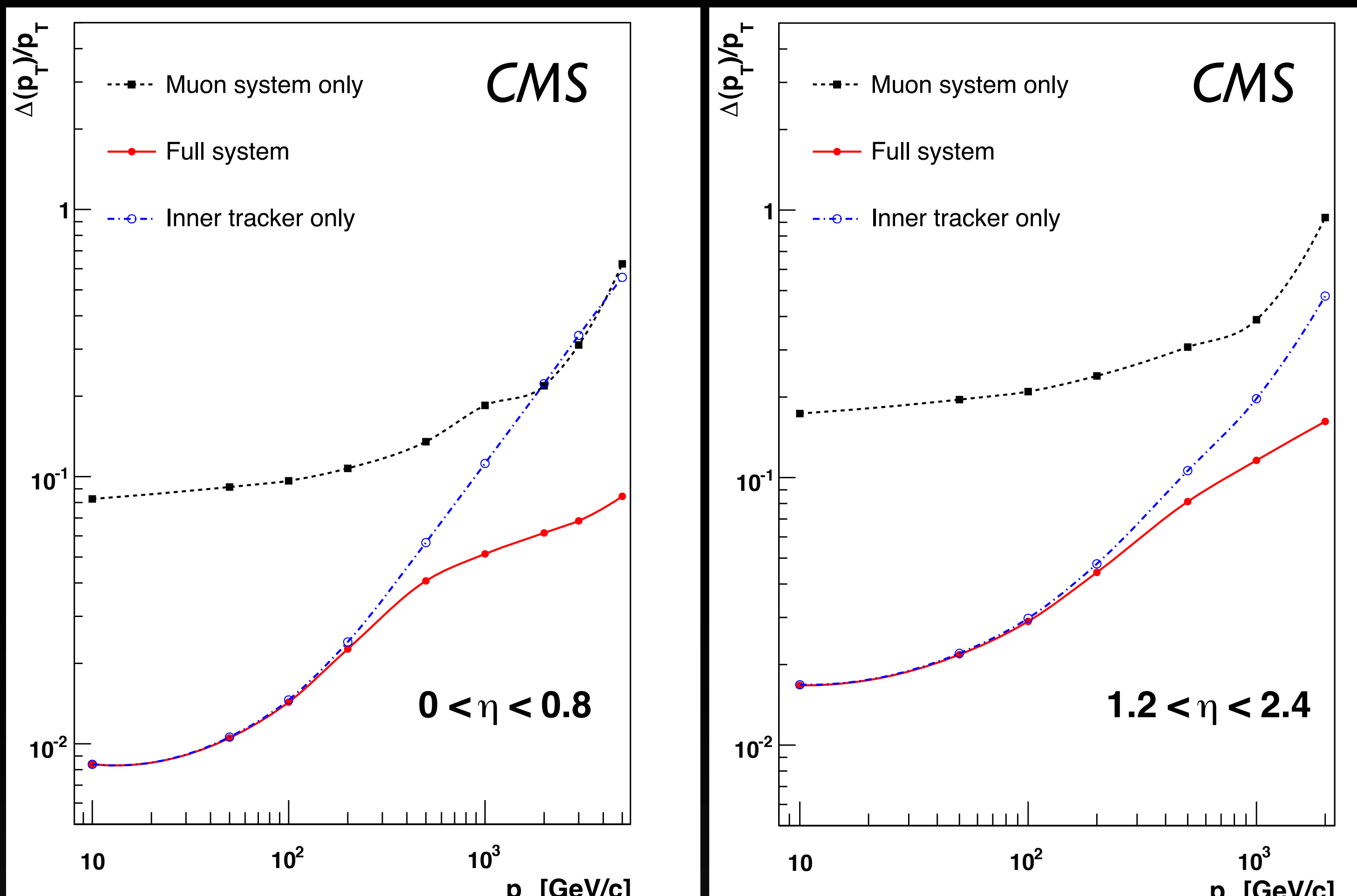


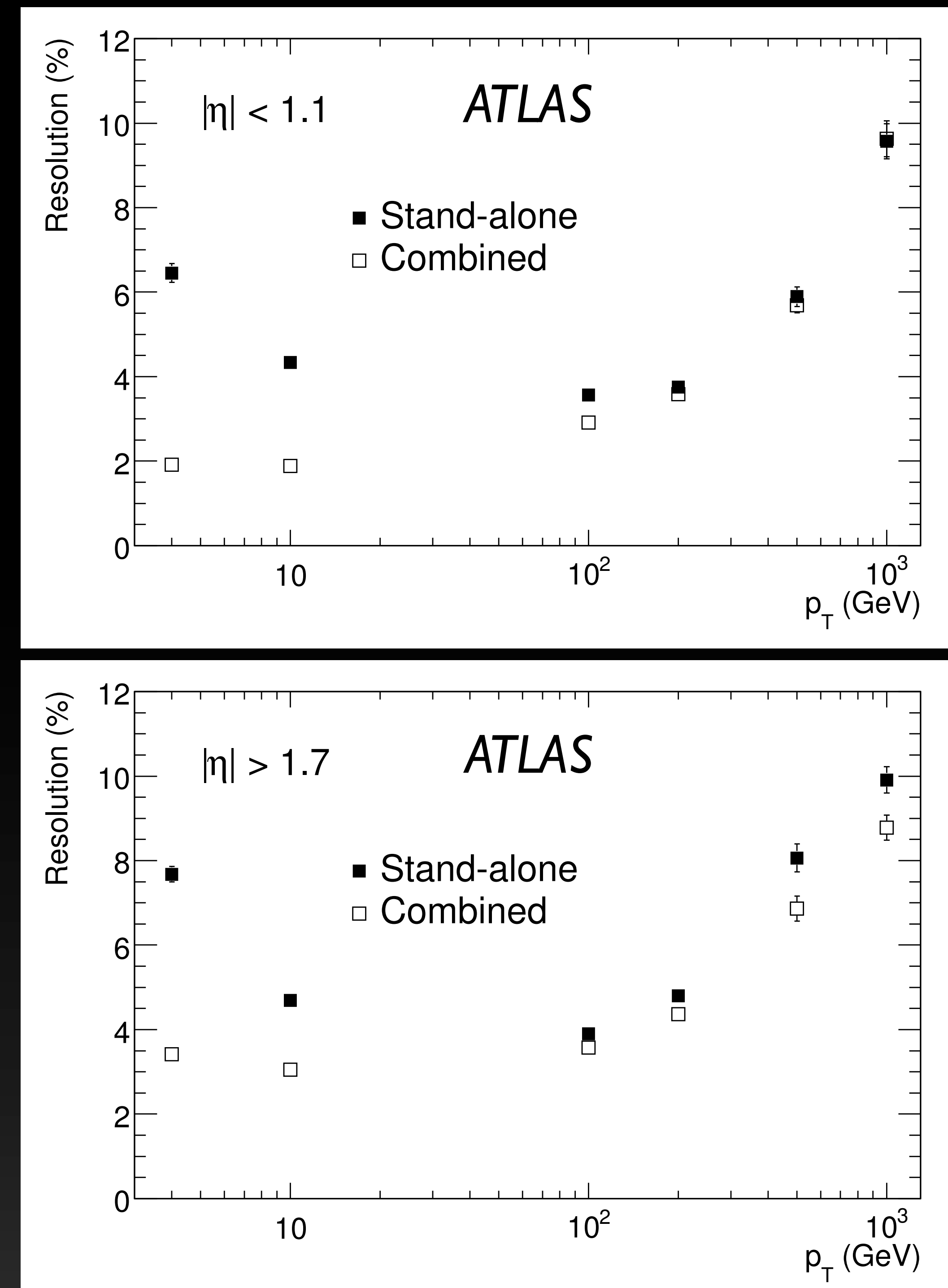




- Muon Drift Tubes
  - ➡ magnetic field return in iron yoke of solenoid
  - ➡ combine with precise p_T measurement in Tracker
- Cathode Strip Chambers
  - ➡ in the endcaps
- Resistive Plate Chambers

Expected Momentum Resolution

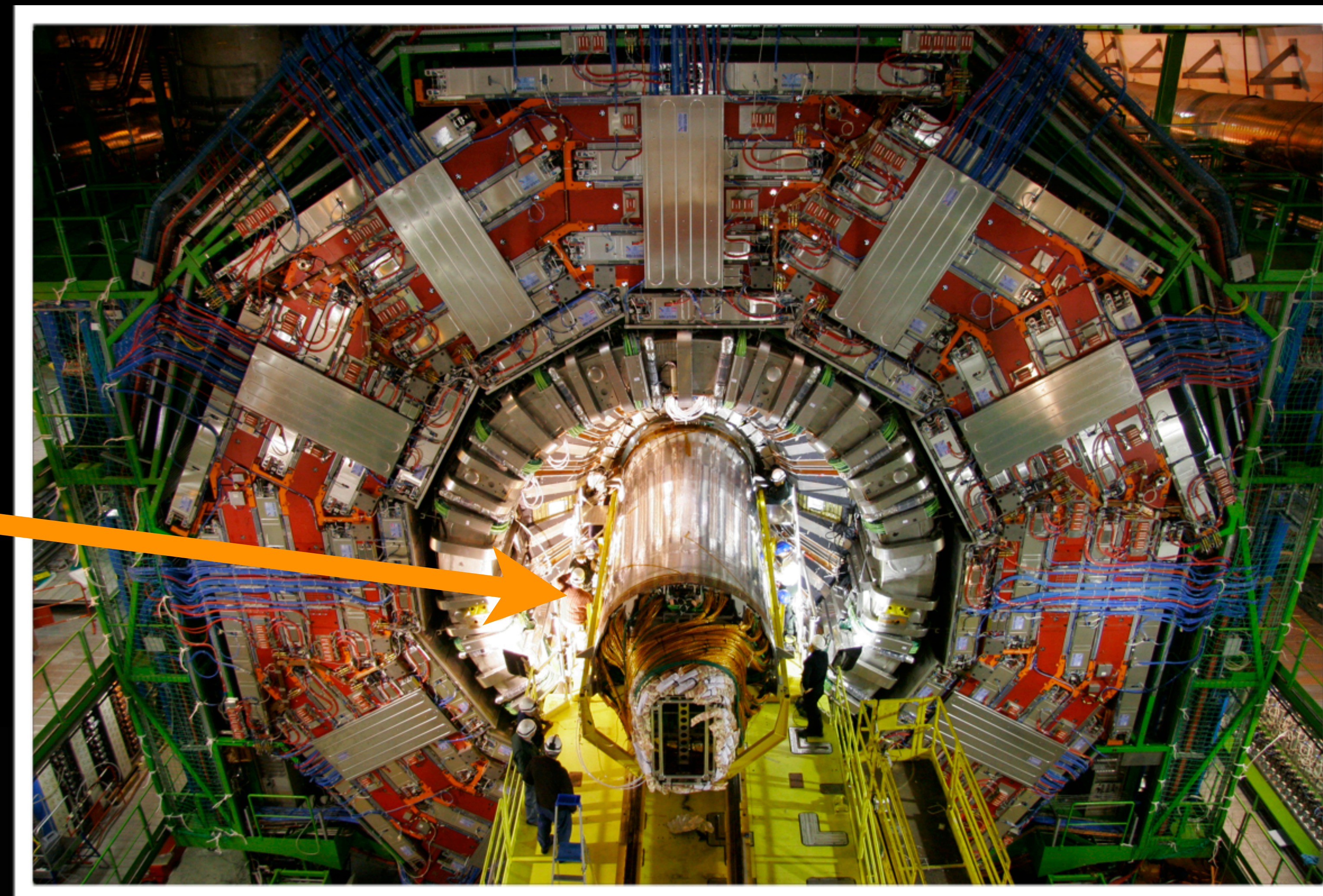


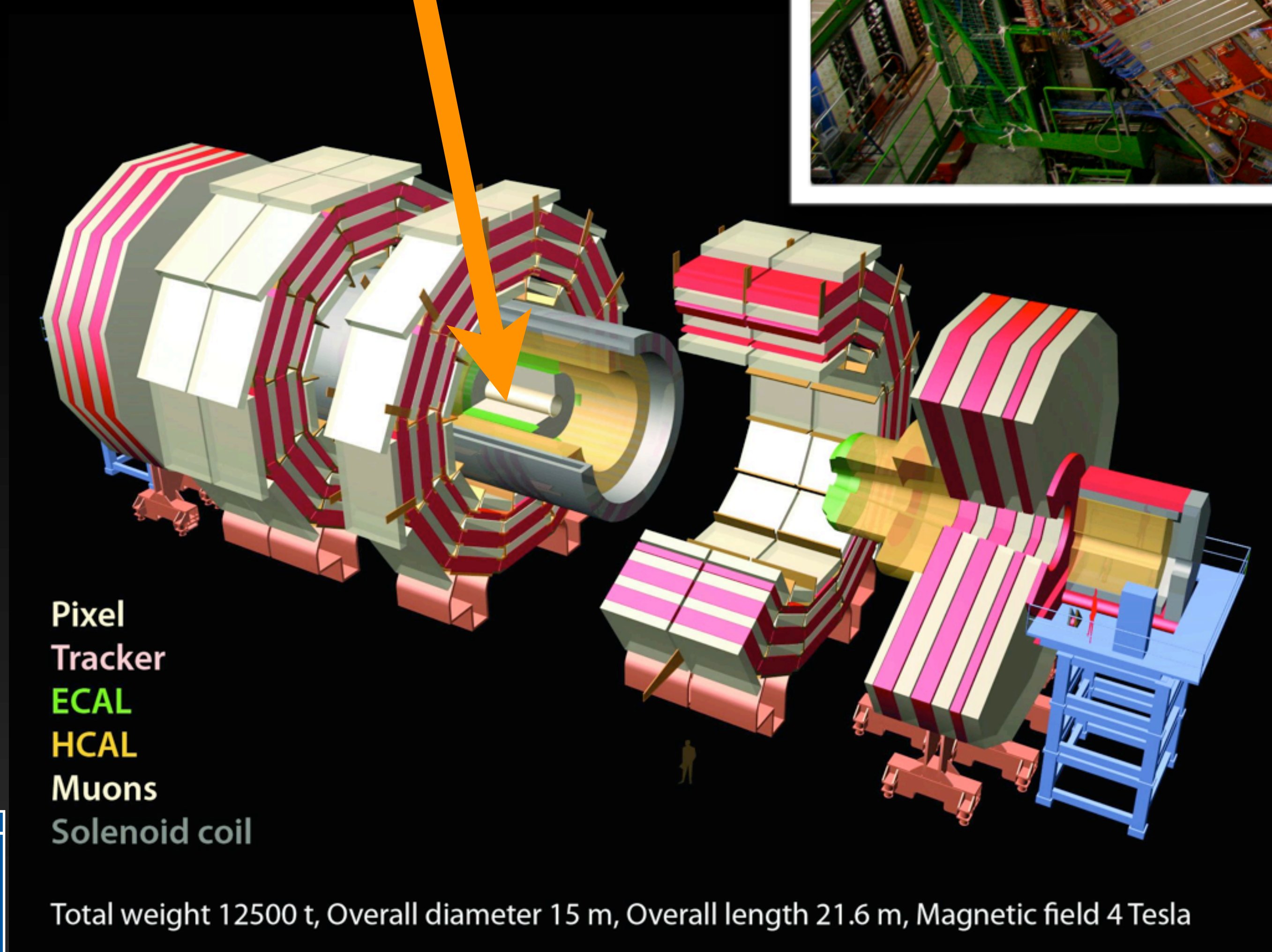


- comparable performance
  - ➡ CMS benefits from good Inner Tracker resolution
  - ➡ in ATLAS Muon Spectrometer dominates at high p_T
  - ➡ ATLAS has slightly larger η coverage

CMS

- in the following will concentrate on the central trackers





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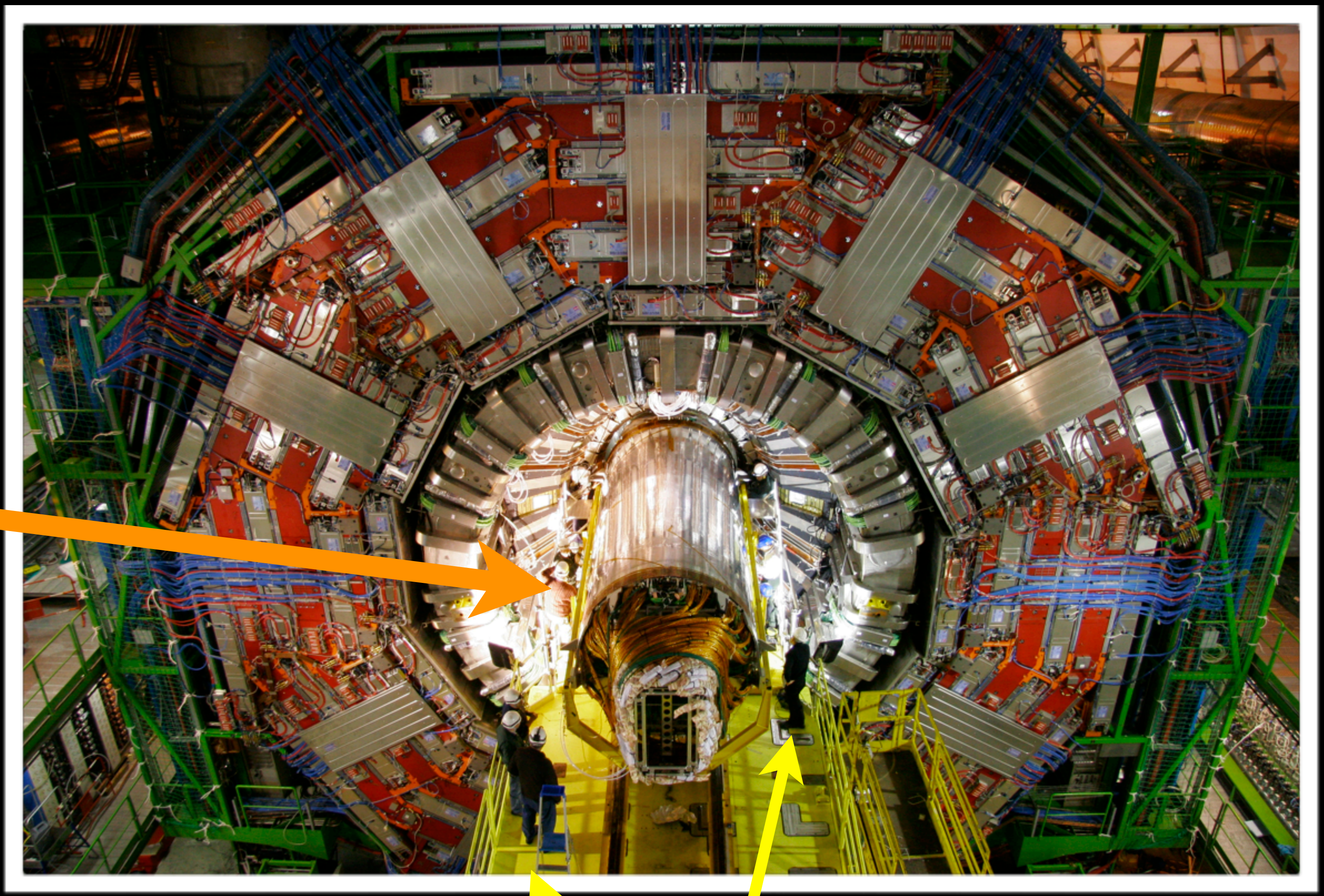
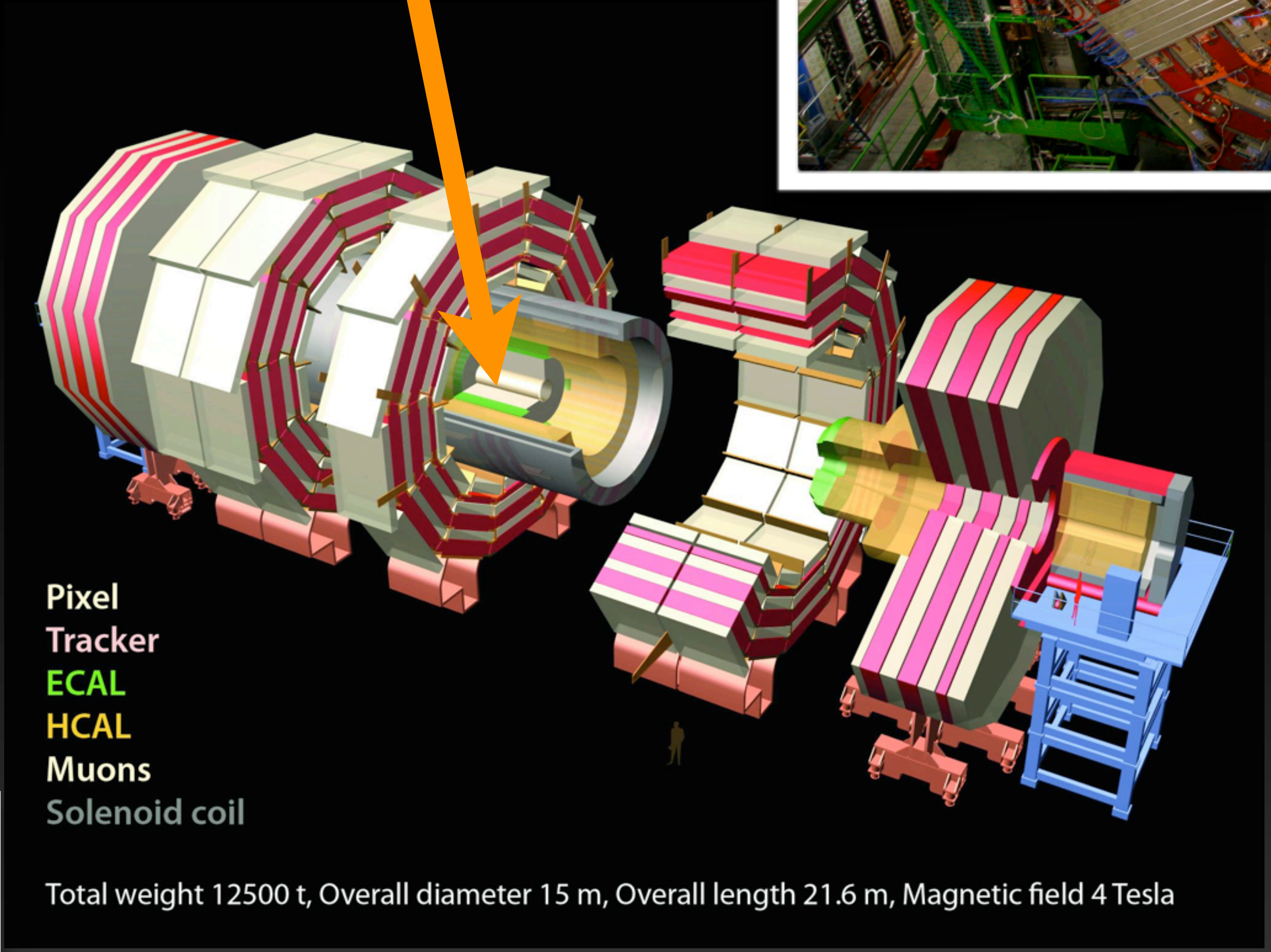




...like for sure they did as well

Constraints on Tracking Detectors

- high occupancy, high radiation dose, high data rate
  - ➡ at full design luminosity more than **20 interactions** per p-p bunch crossing
    - more than a **1000 charged particles** in tracker, every 25ns.
  - ➡ even higher multiplicity in **central Pb-Pb collisions**
    - with >10000 charged particles in trackers
  - ➡ design for **10^{15} neq** (neutron equivalent) for innermost layers (10 year lifetime)
- tension...
  - ➡ **minimize material** for most precise measurements and to minimize interactions before the calorimeter
  - ➡ increasing **sensor granularity** to reduce occupancy
    - increase number of electronics channels and heat load
    - more material
- technology choices
  - ➡ **silicon detectors**, usually pixels for vertexing, and strips for tracking
    - good spatial resolution, high granularity, fast signal response
    - thin detector gives a large signal
  - ➡ can be complemented by **gas detectors** further away from vertex

Additional Roles of Tracker at LHC

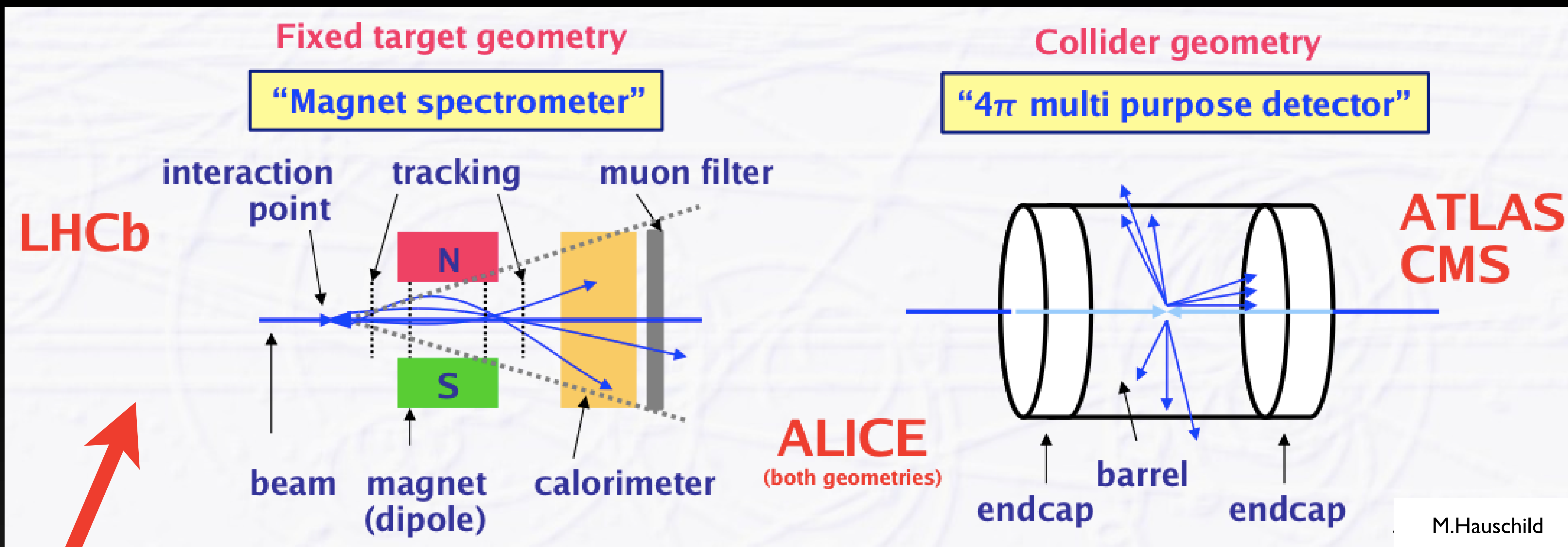
- tracker also contribute to particle identification (PID)
  - ➡ use dedicated detectors to distinguish different particle types
    - Transition Radiation detectors also contribute to tracking
    - Ring Imaging Cherenkov detectors
    - time of flight
- match tracks with showers in the calorimeter
  - ➡ identify electrons from characteristic shower shape
- match central tracks with muon chamber segments
  - ➡ muon chamber information improves muon momentum measurement

Overall Design Choices

- **ATLAS and CMS** are general purpose detectors
  - ➡ central tracker covers $|\eta|<2.5$
    (polar angle expressed as pseudorapidity: $\eta = -\ln \tan (\Theta/2)$)
- **ALICE** - optimized for heavy ions, high occupancy
  - ➡ tracker restricted to $|\eta|<0.9$, plus forward muons
- all three are symmetric about the interaction point
  - ➡ solenoid magnet providing uniform magnetic field parallel to the beam direction
  - ➡ ATLAS Muon Spectrometer is in field of 3 toroid magnets
- **LHCb** - beauty-hadron production in forward direction
  - ➡ despite the different geometry, design is driven by the same principles to give optimal performance
  - ➡ tracker is not in a magnetic field, tracks are measured before and after a dipole magnet

Overall Design Choices

- layout of the tracking detectors
  - ➡ follow the typical geometry of fix target and collider experiments



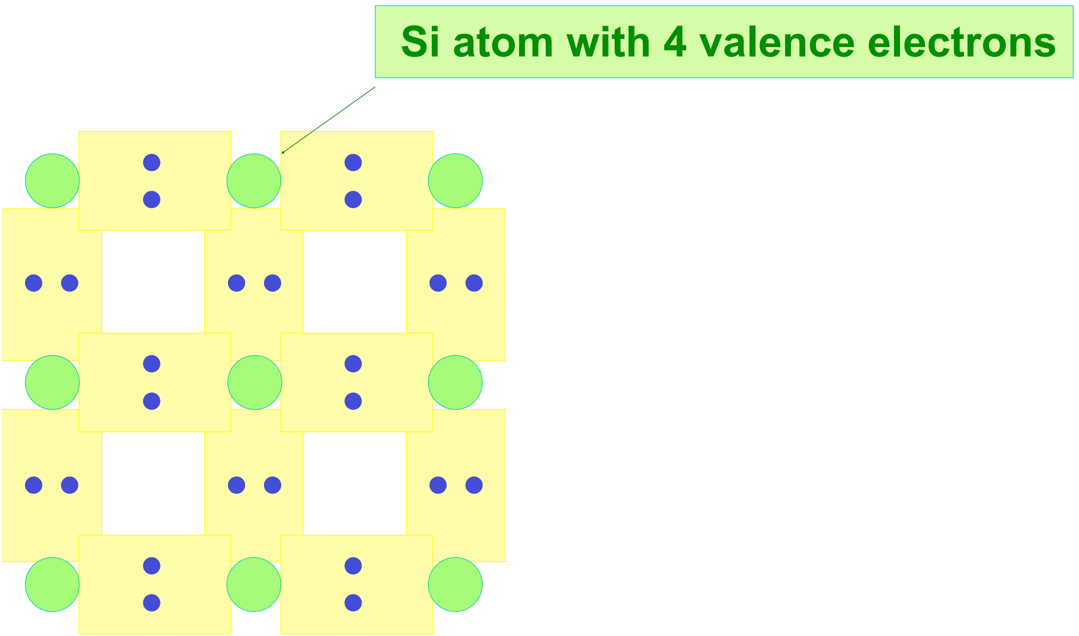
ATLAS
(muon spectrometer)

Semiconductor Trackers

Semiconductors

Semiconductors

- doping of silicon crystal semiconductors:



Semiconductors

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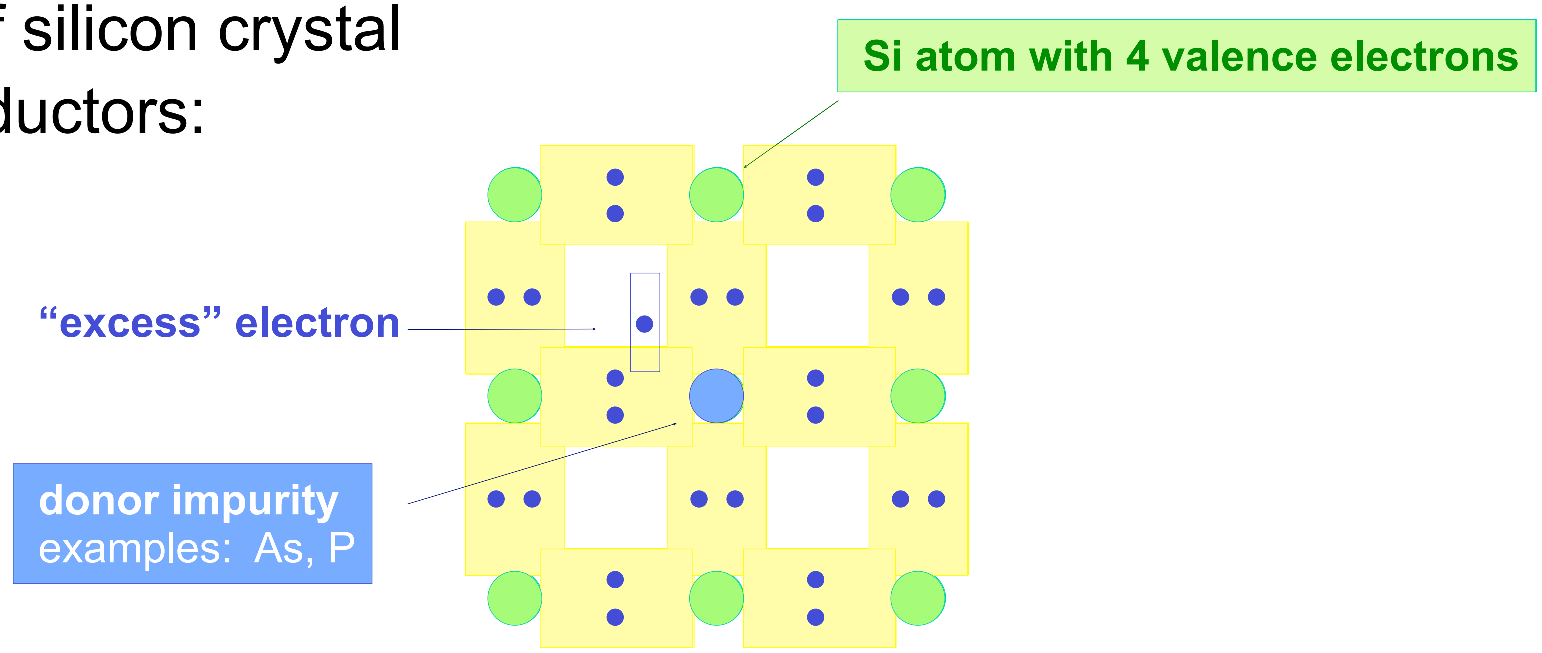

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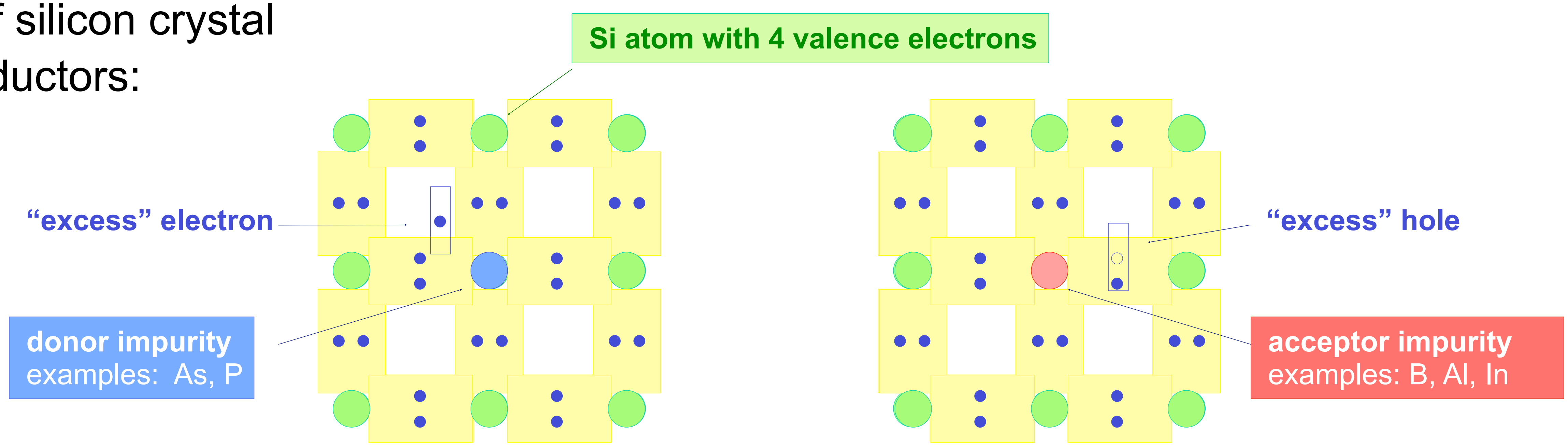

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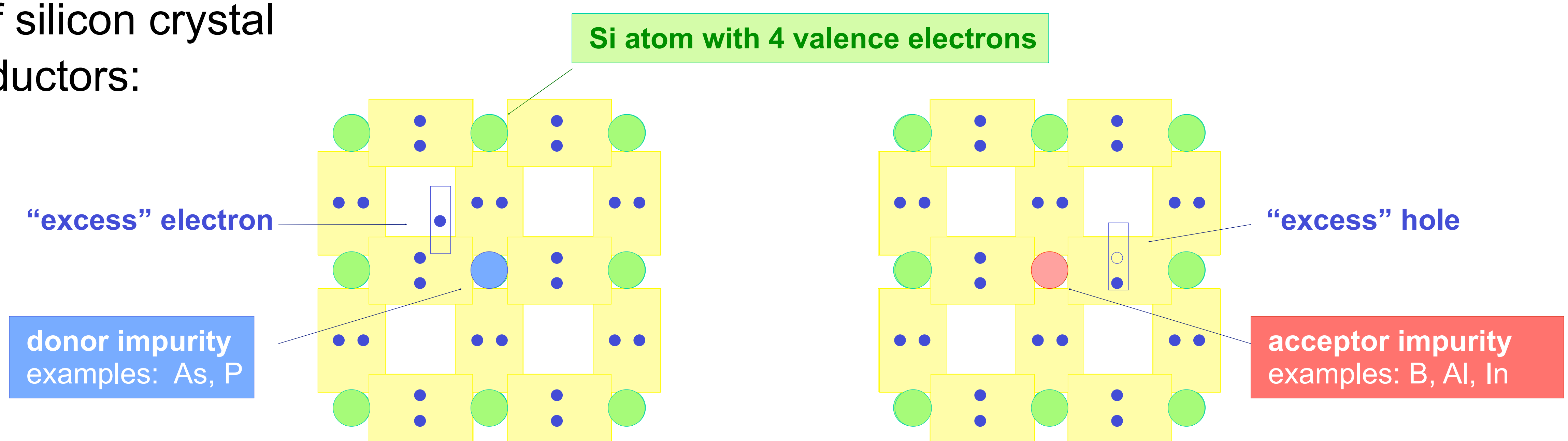
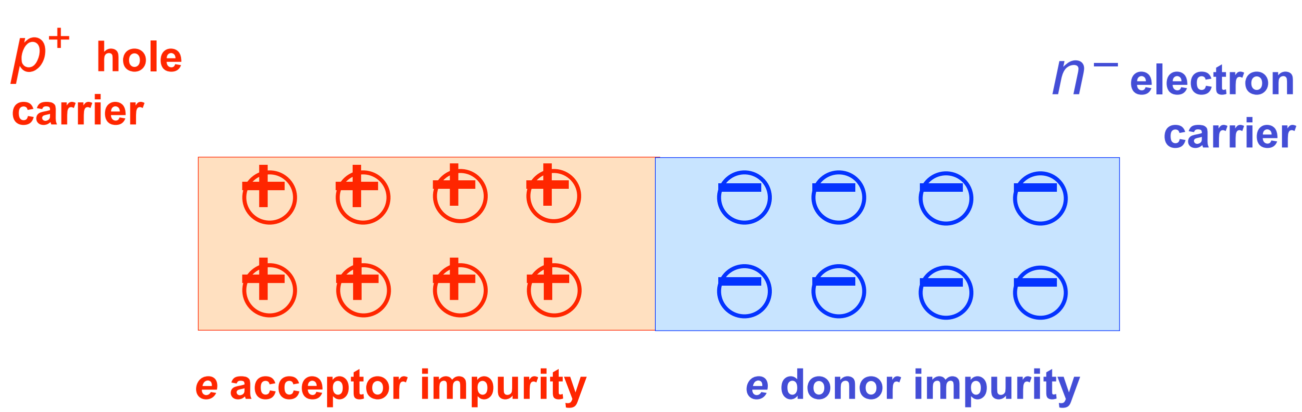


p–*n* junction



- *p* doping adds electro-phile atoms
- *n* doping adds electro-phobe atoms

Semiconductors

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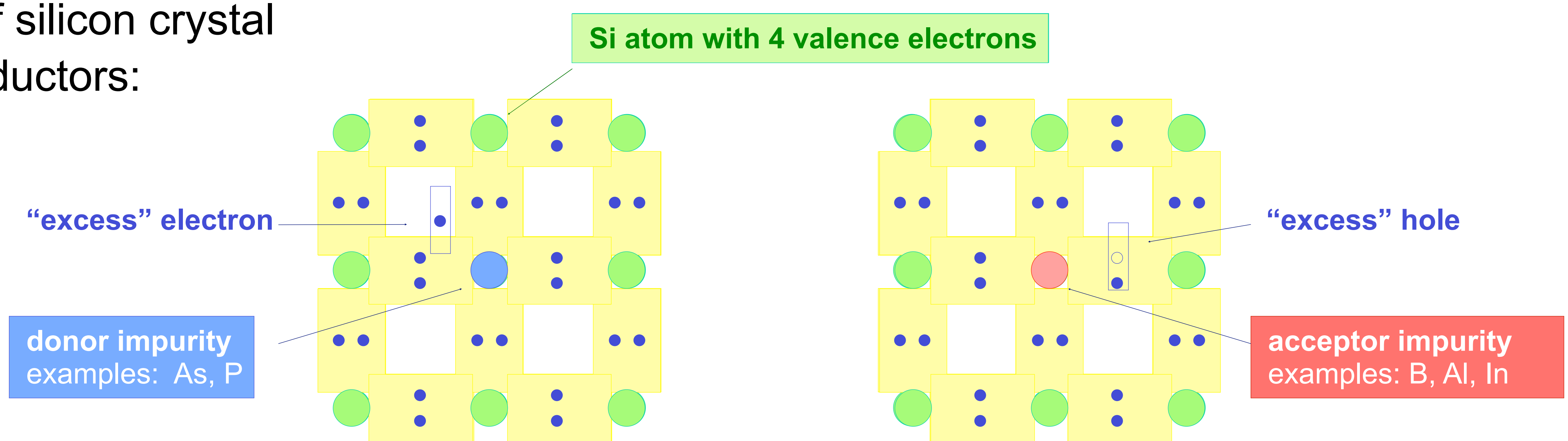

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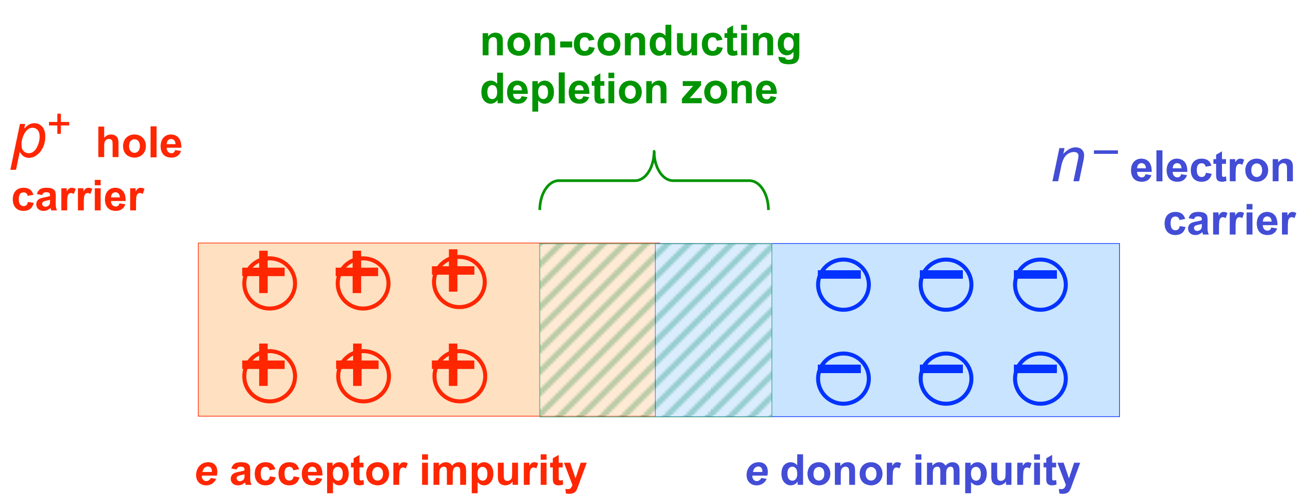

- in the junction zone, electron-hole pairs recombine creating depletion
- the potential barrier in the junction counter-weighs the doping potential

Semiconductors

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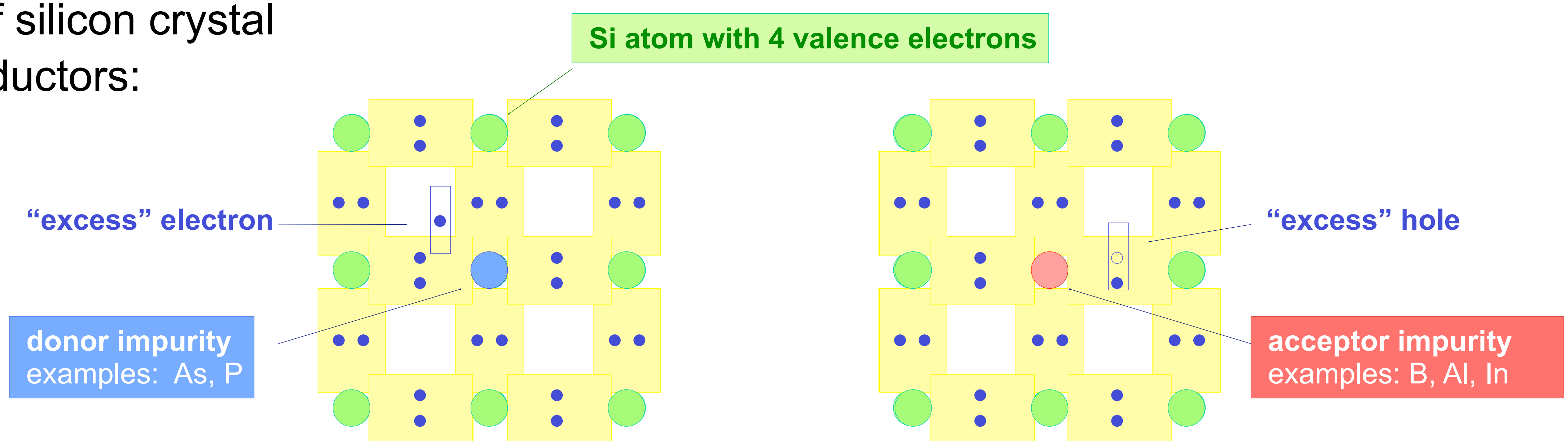
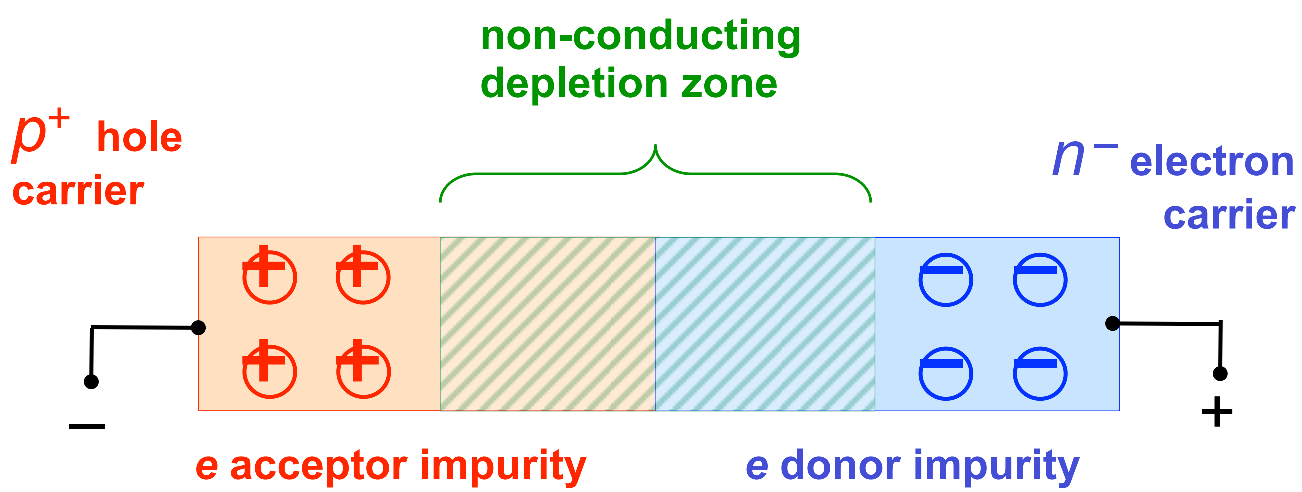
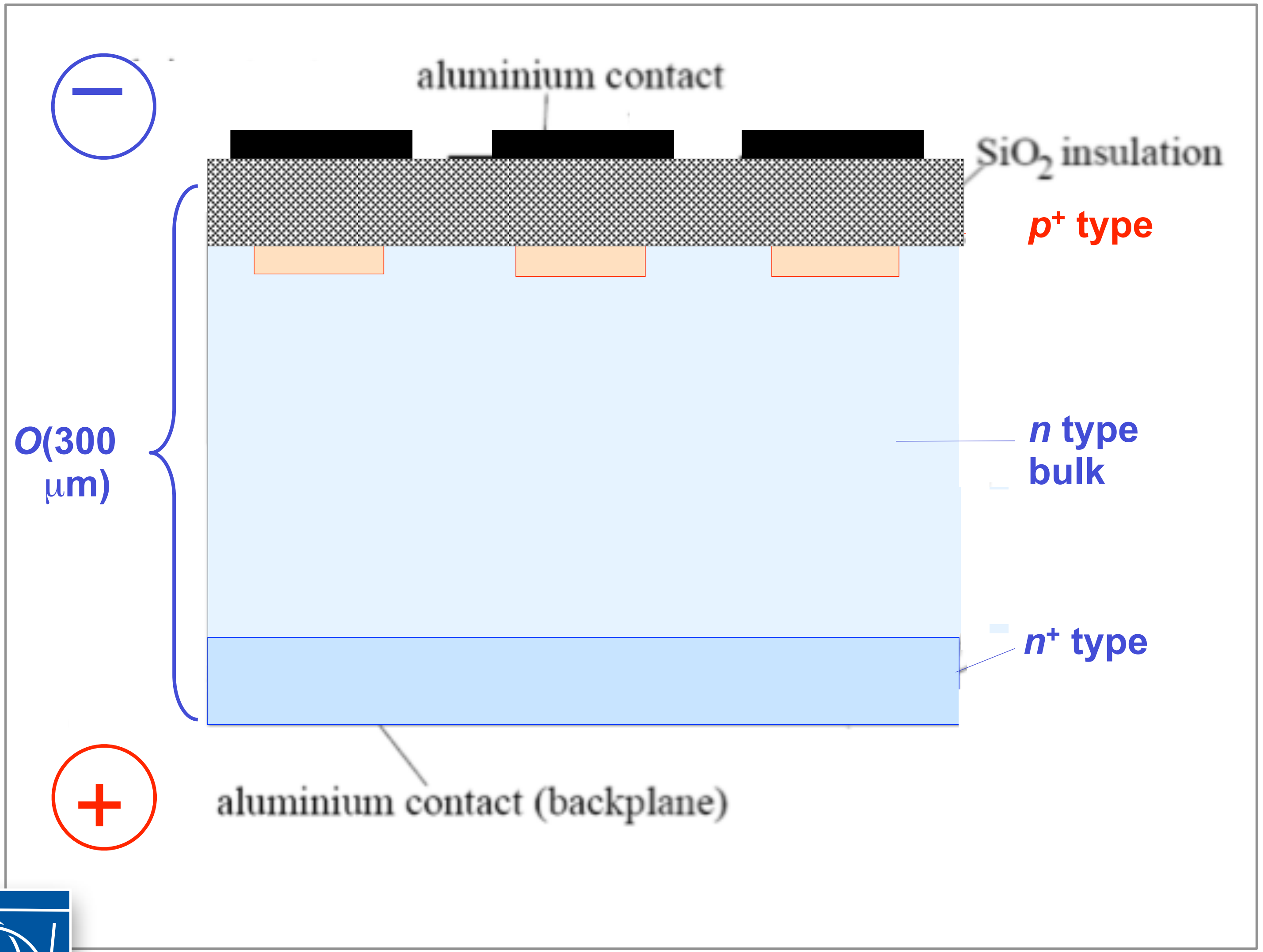


reverse bias *p*–*n* junction



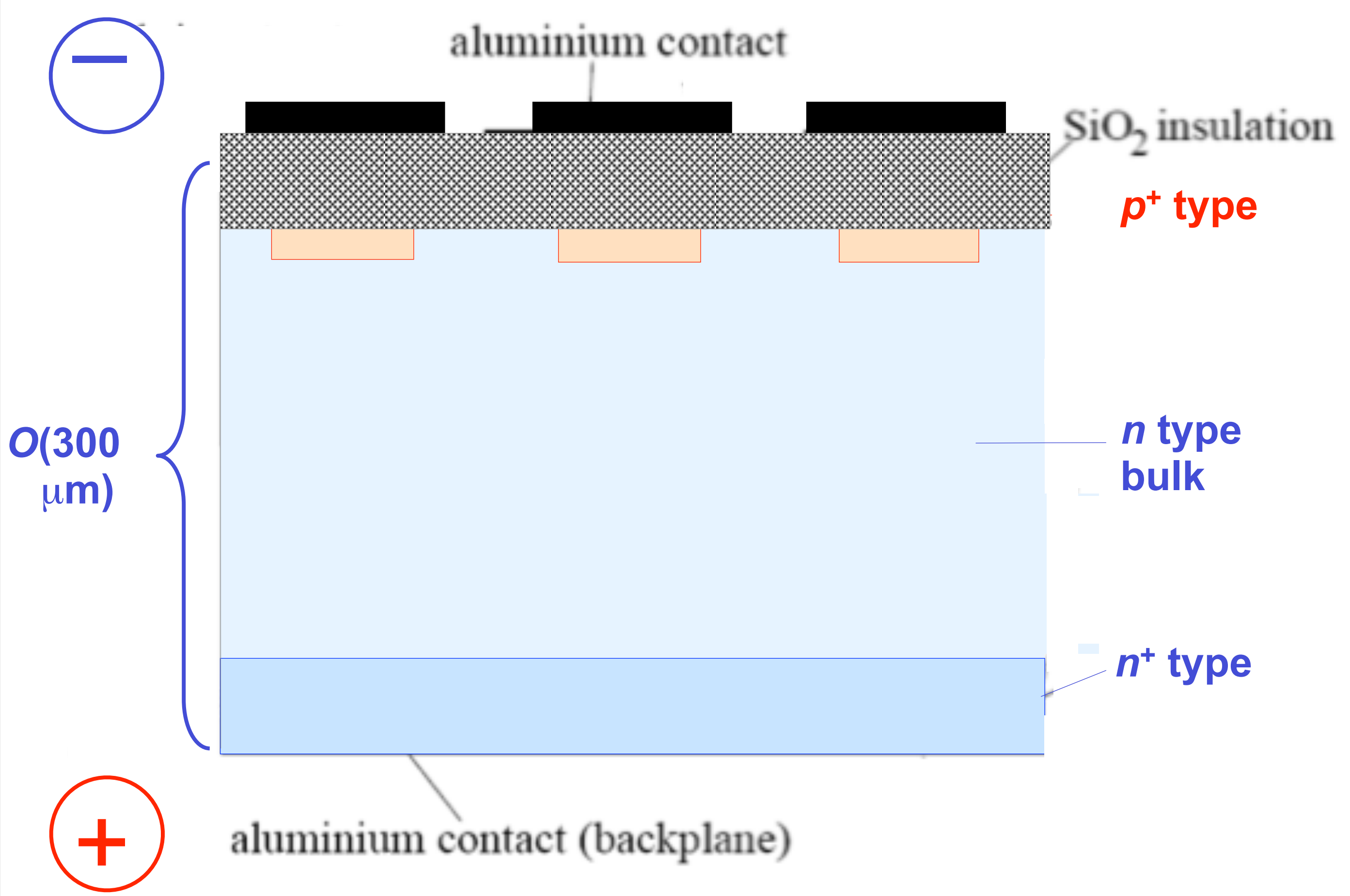
- the reversed bias voltage increases the potential barrier in the depletion zone, enhancing its resistance
- minimal current across the junction

The *p–n* Junction as a Tracking Detector



The *p–n* Junction as a Tracking Detector

- thin (~μm), highly doped p^+ (~10^{19} cm^{-3}) layer on lightly doped *n* (~10^{12} cm^{-3}) substrate
- high mobility of charge carriers in Si allows fast charge collection (~5 ns for electron)
- high Si density & low electron–hole creation potential (3.6 eV compared to ~36 eV for gaseous ionization) allows use of very thin detectors with reasonable signal



schema of silicon microstrip sensor

- reverse bias: backplane set to positive voltage (< 500 V)
- a traversing charged particle ionizes silicon, creating conduction electrons and holes that induce a measurable current by drifting to electrodes
- metal-semiconductor transition forms charge (Schottky) barrier similar to *p–n* junction. Highly doped n^+ layer reduces width of potential barrier and hence resistance

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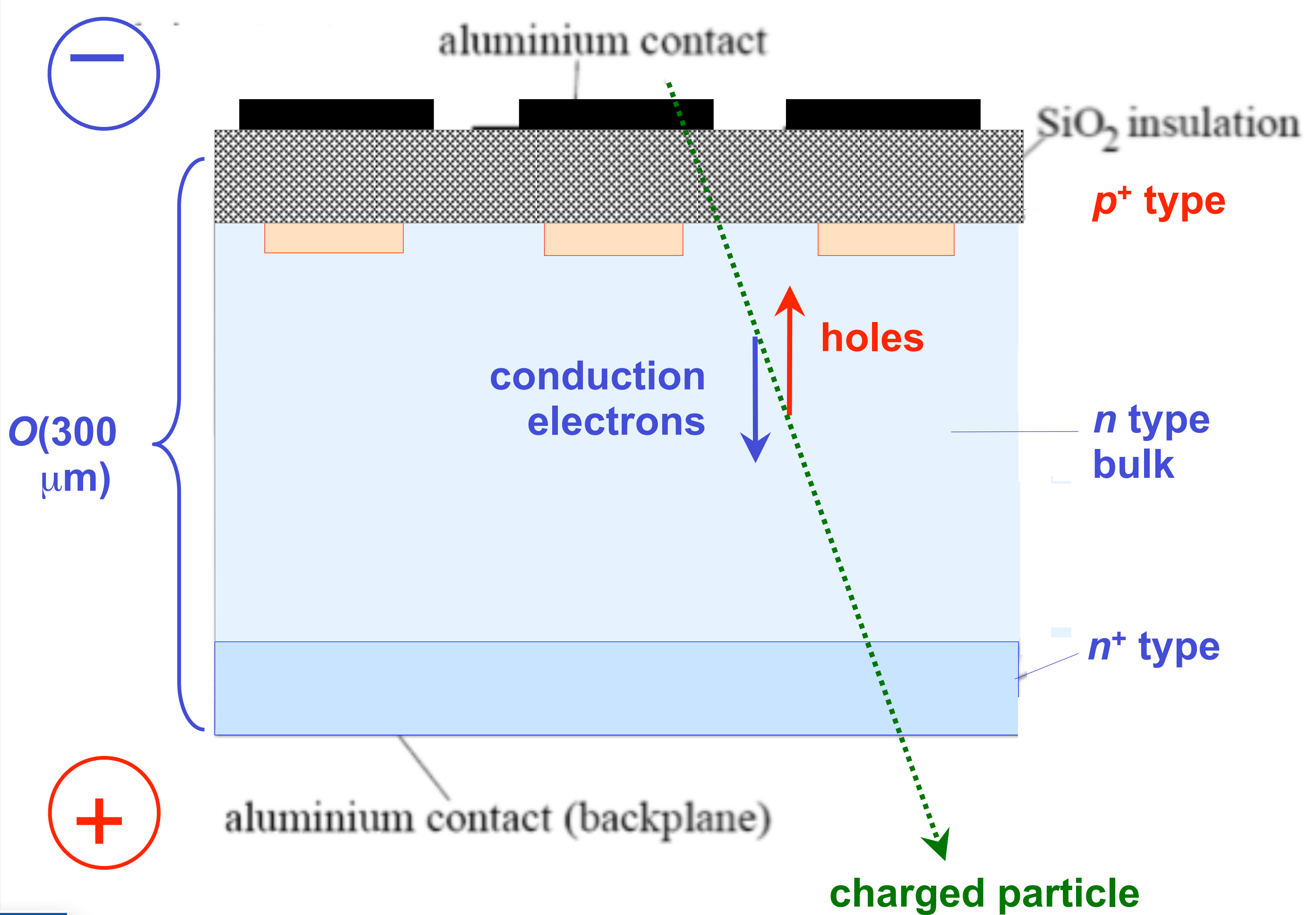

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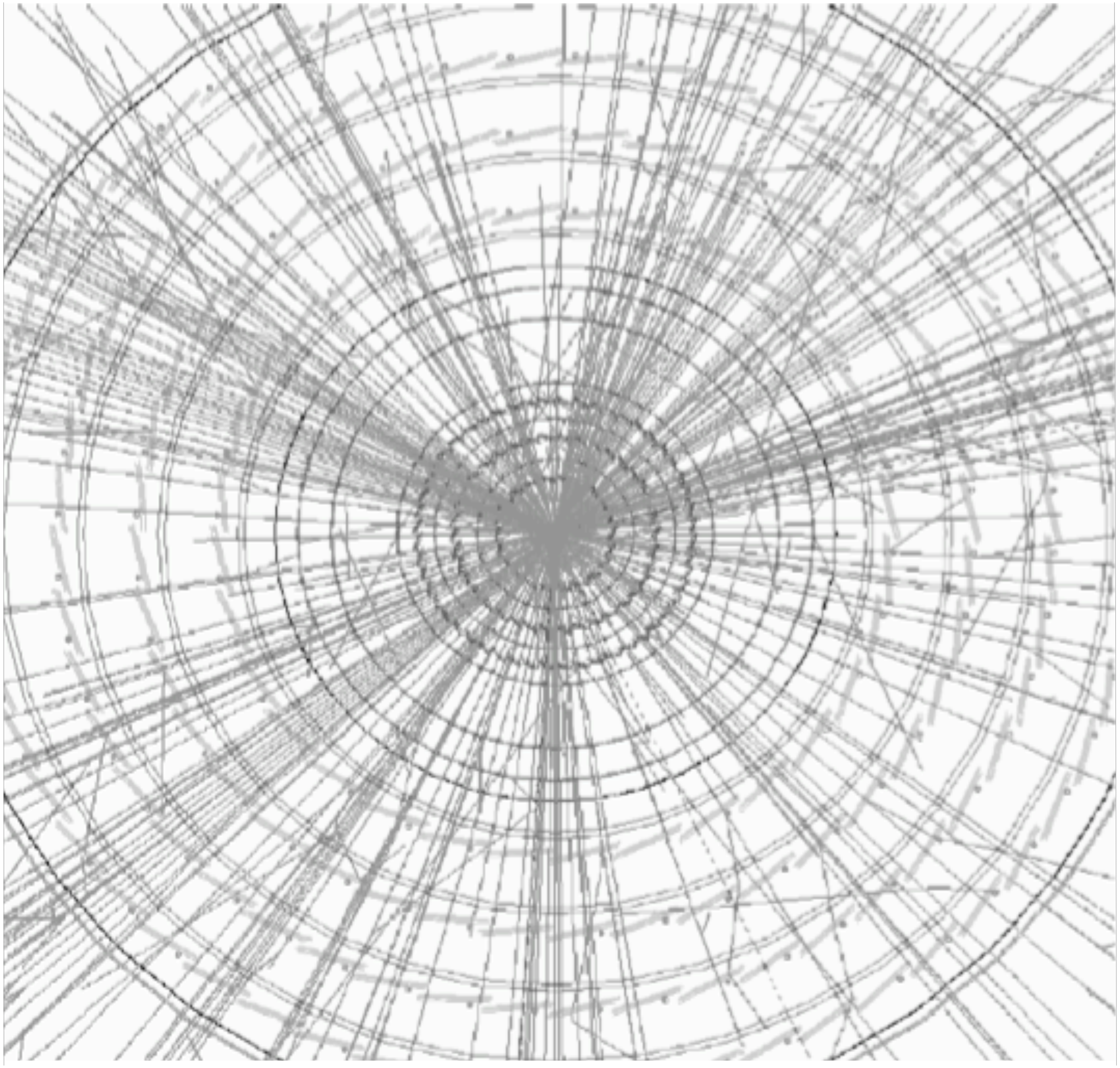
Lorentz Angle Measurement



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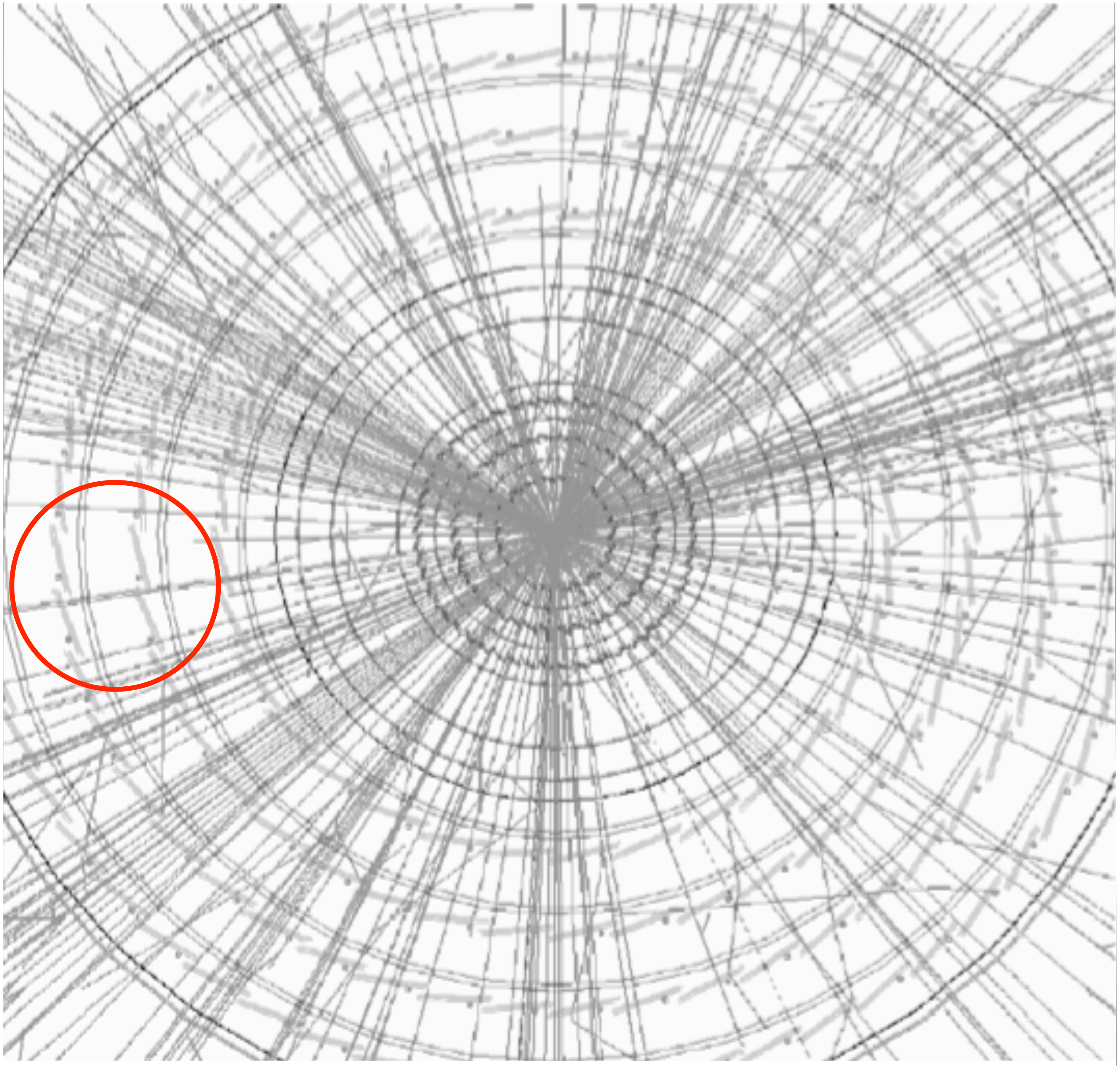

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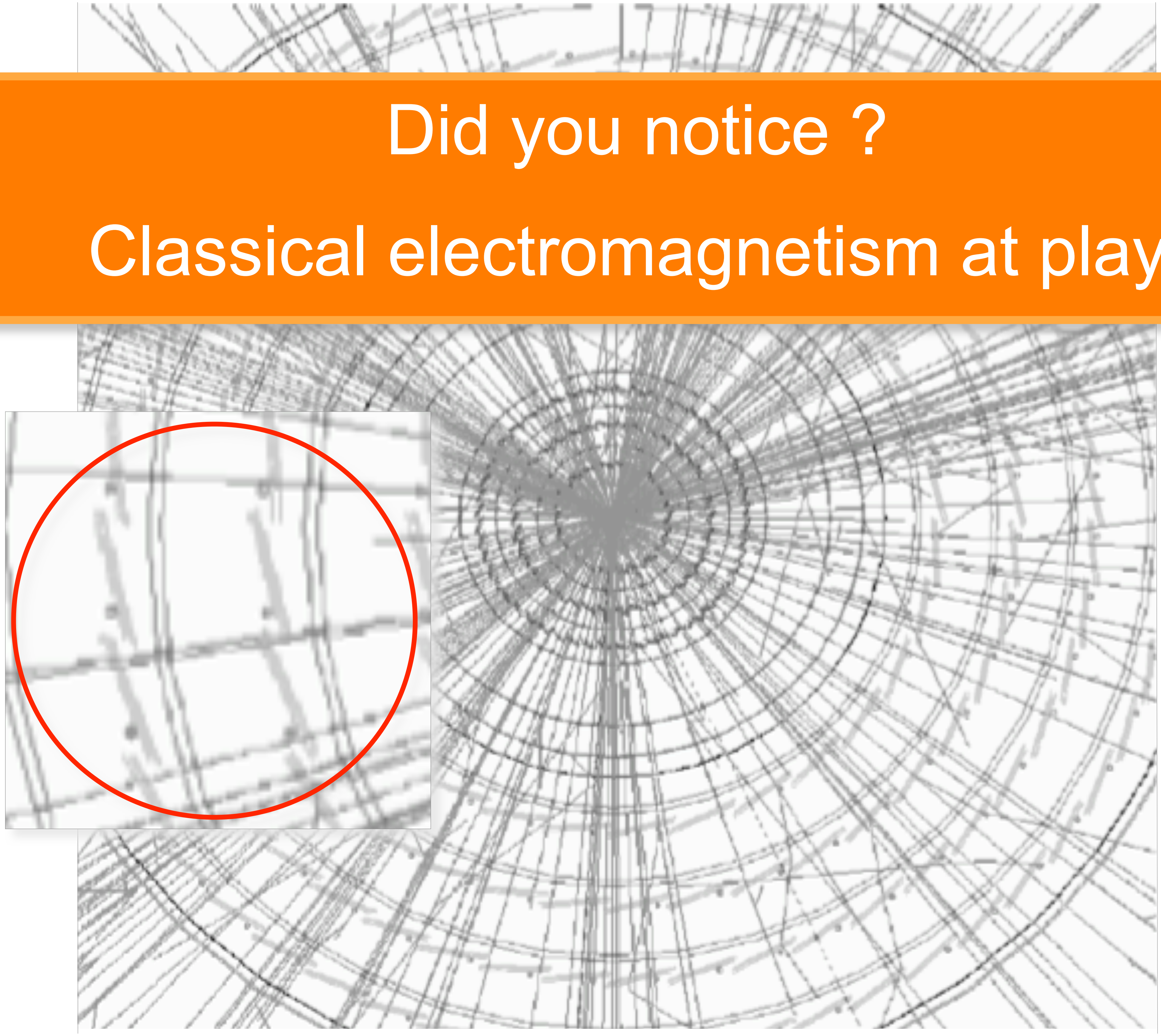
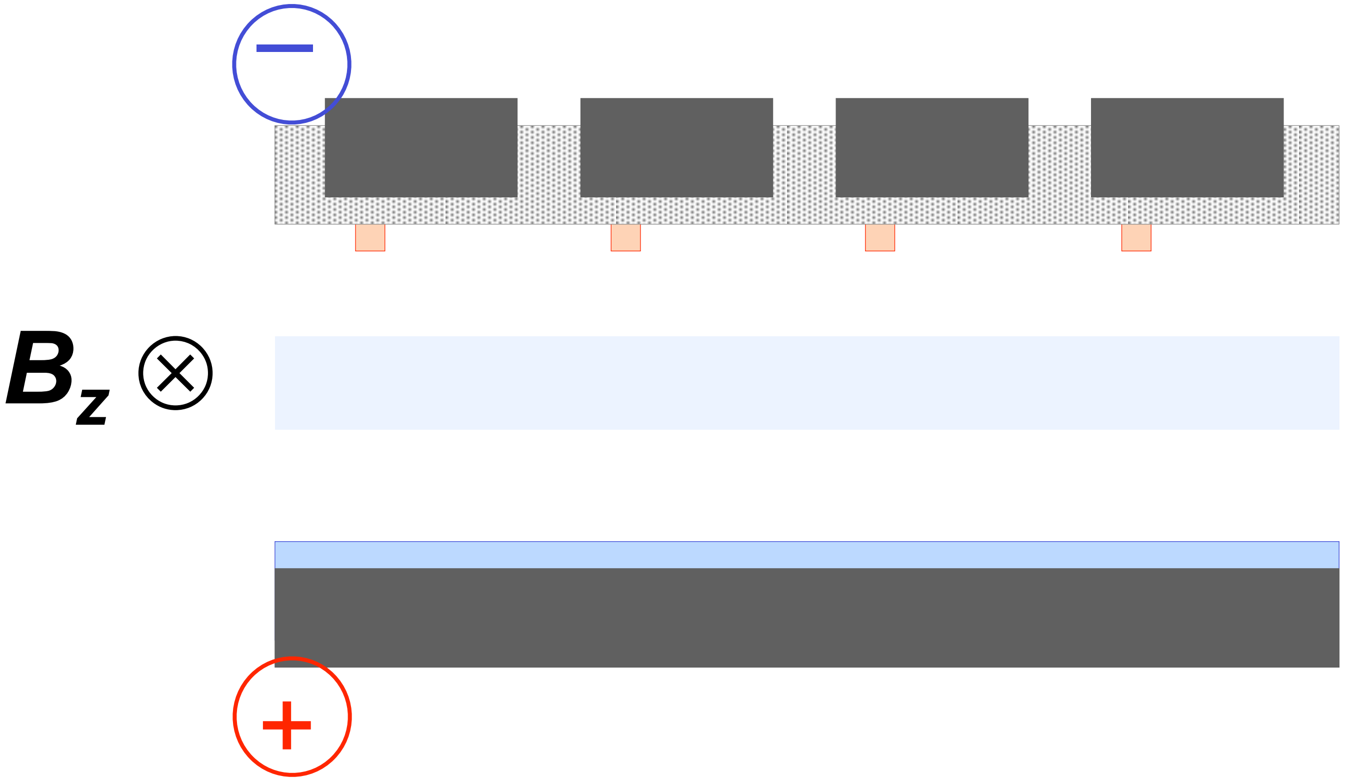


Did you notice ?

Classical electromagnetism at play!

Lorentz Angle Measurement

- the sensors are tilted relative to the pointing axis: SCT (11°) and Pixel (-20°) (*)
  - the charges traveling through the Si substrate are deviated by 2T B field (Hall effect)



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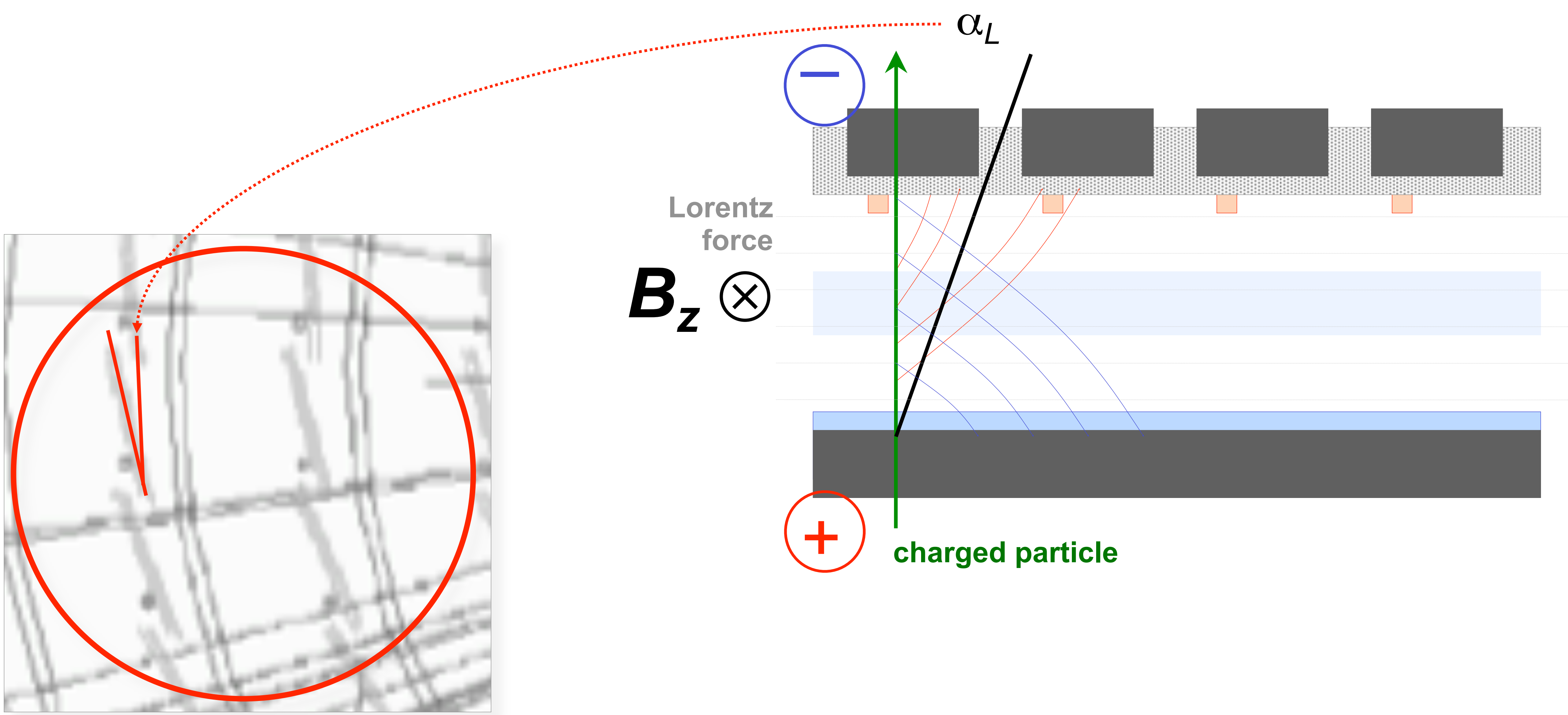

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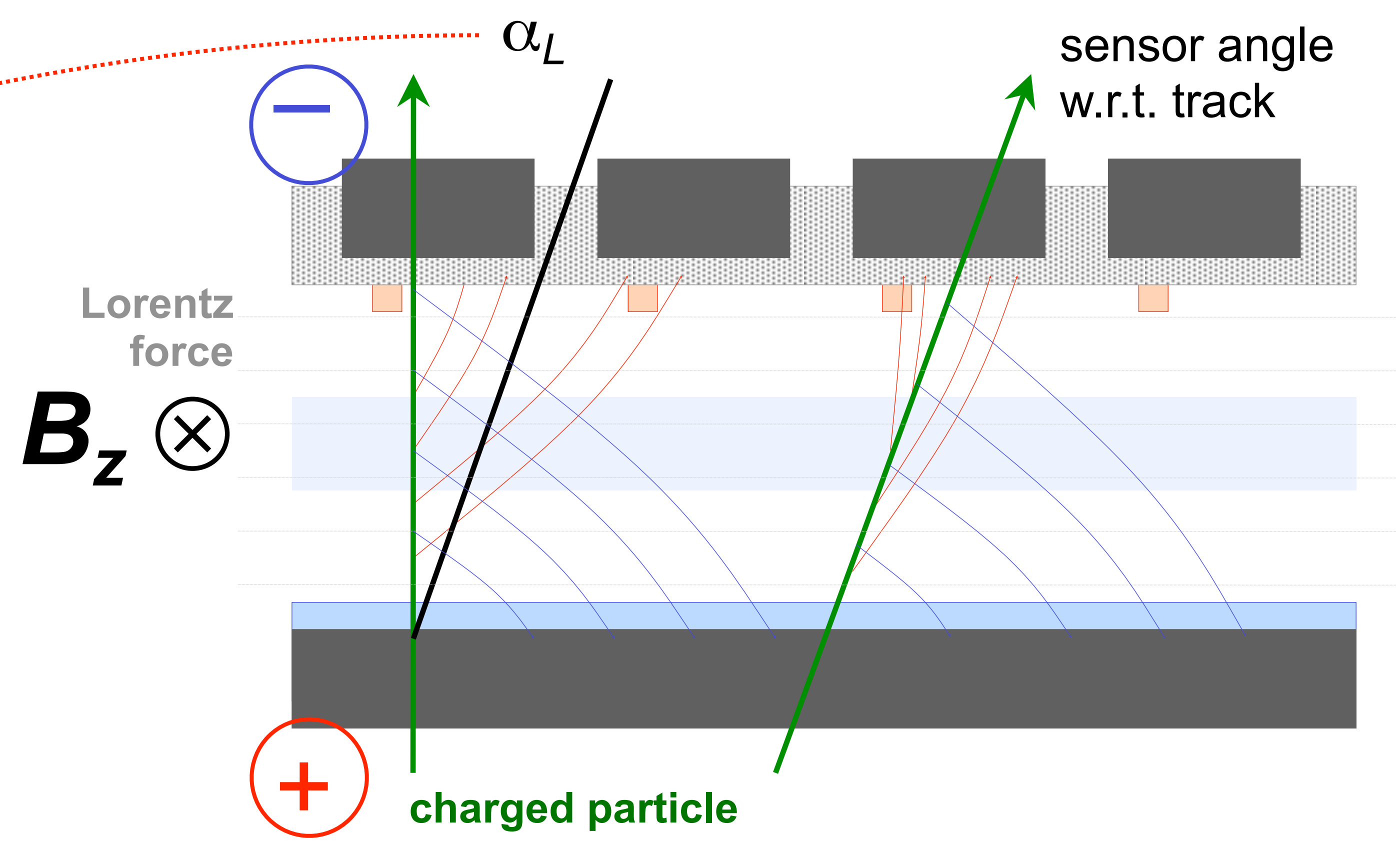

- Lorentz angle determined empirically in test beam by minimizing cluster size
- $\alpha_L = f(V_{depl})$ → as bias voltage increases to cope with irradiation, α_L decreases

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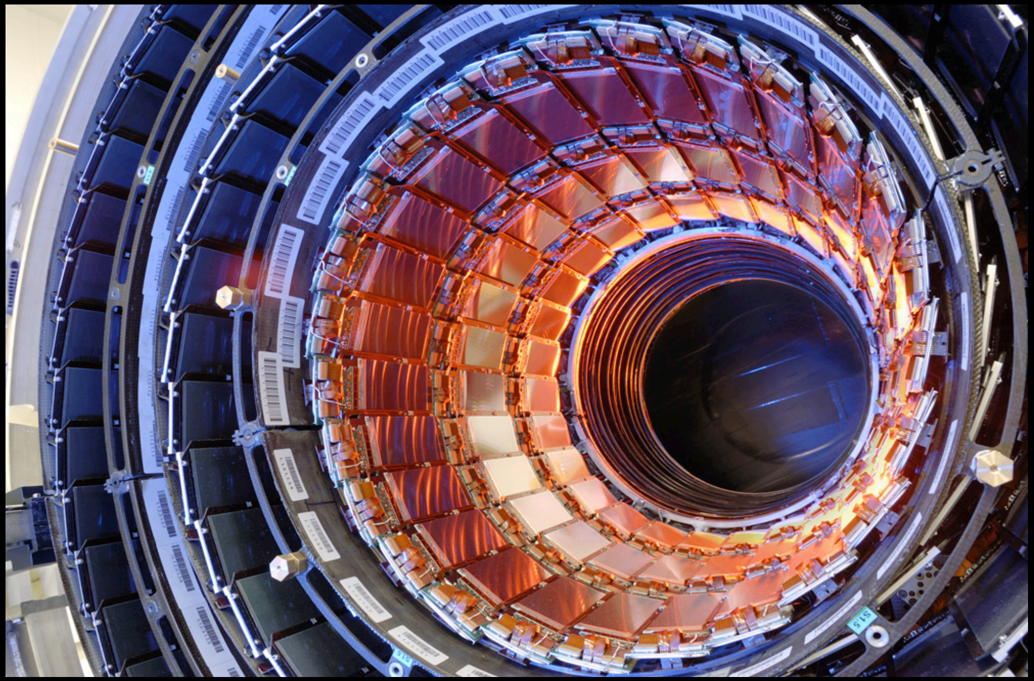
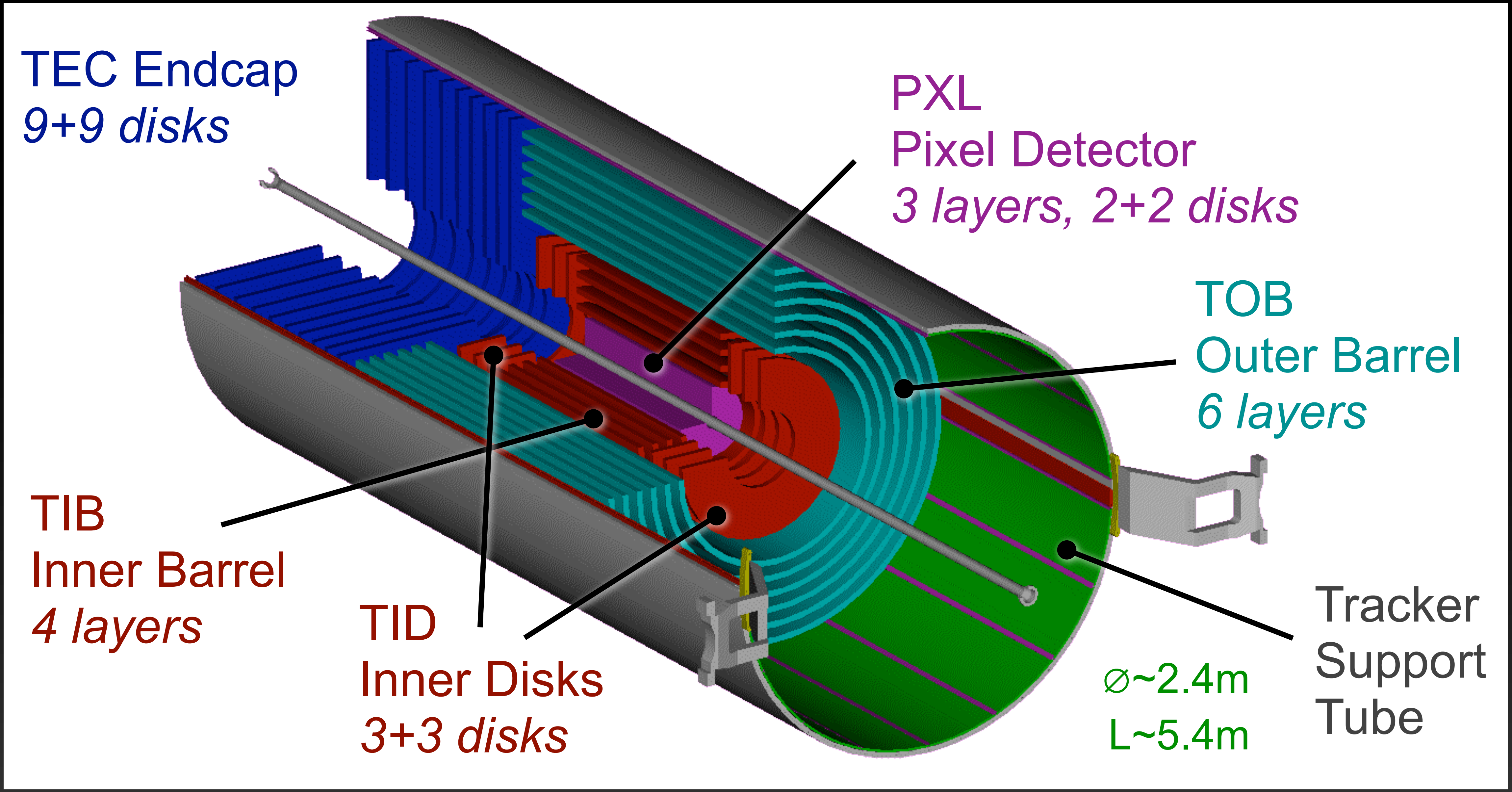
CMS Tracker

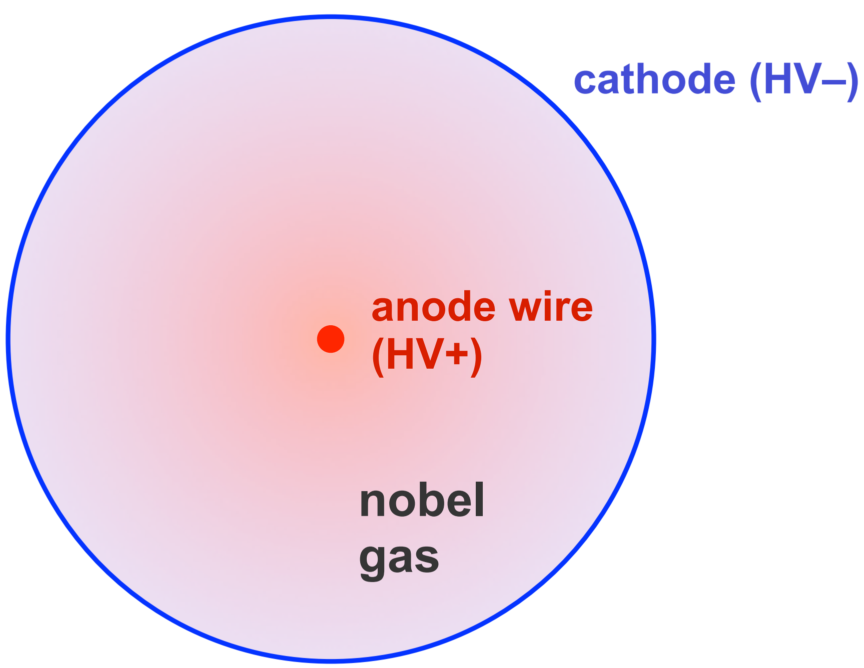
- largest silicon tracker ever built
  - ➡ **Pixels:** 66M channels, 100x150 μm² Pixel
  - ➡ **Si-Strip detector:** ~23m³, 210m² of Si area, 10.7M channels





Drift Tubes in ATLAS: Inner Detector and Muon Spectrometer

- classical detection technique for charged particles based on gas ionization and drift time measurement



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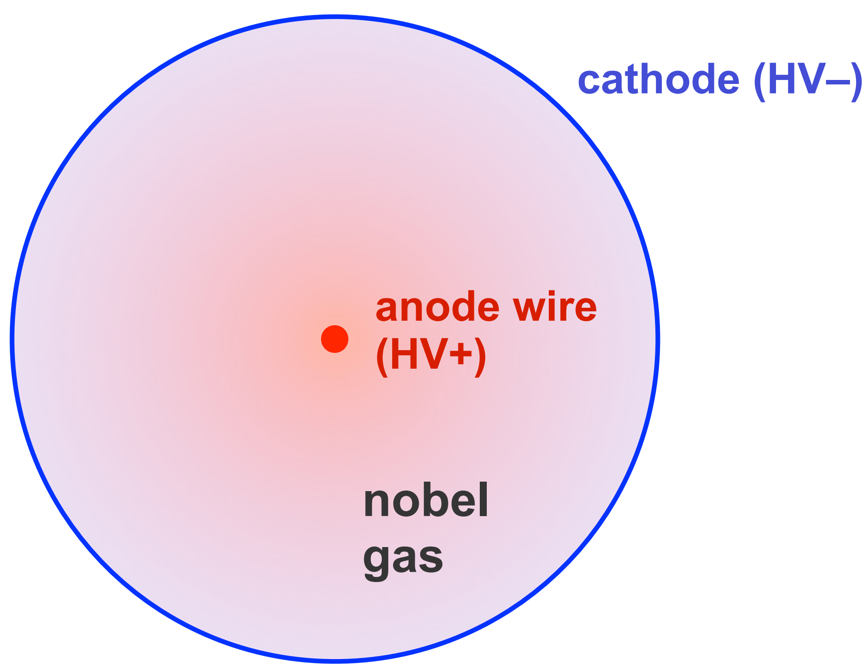

- drift tubes used in muon systems and ATLAS TRT
- primary electrons drift towards thin anode wire
- charge amplification during drift (~10^4) in high E-field in vicinity of wire: $E(r) \sim U_0 / r$
- signal rises with number of primary e's (dE/dx) [signal dominated by ions]
- macroscopic drift time: $v_D / c \sim 10^{-4} \rightarrow \sim 30$ ns/mm
- determine v_D from difference between signal peaking time and expected particle passage
- spatial resolution of $O(100\ \mu\text{m})$

TRT: Kapton tubes, ∅ = 4 mm
MDT: Aluminium tubes, ∅ = 30 mm

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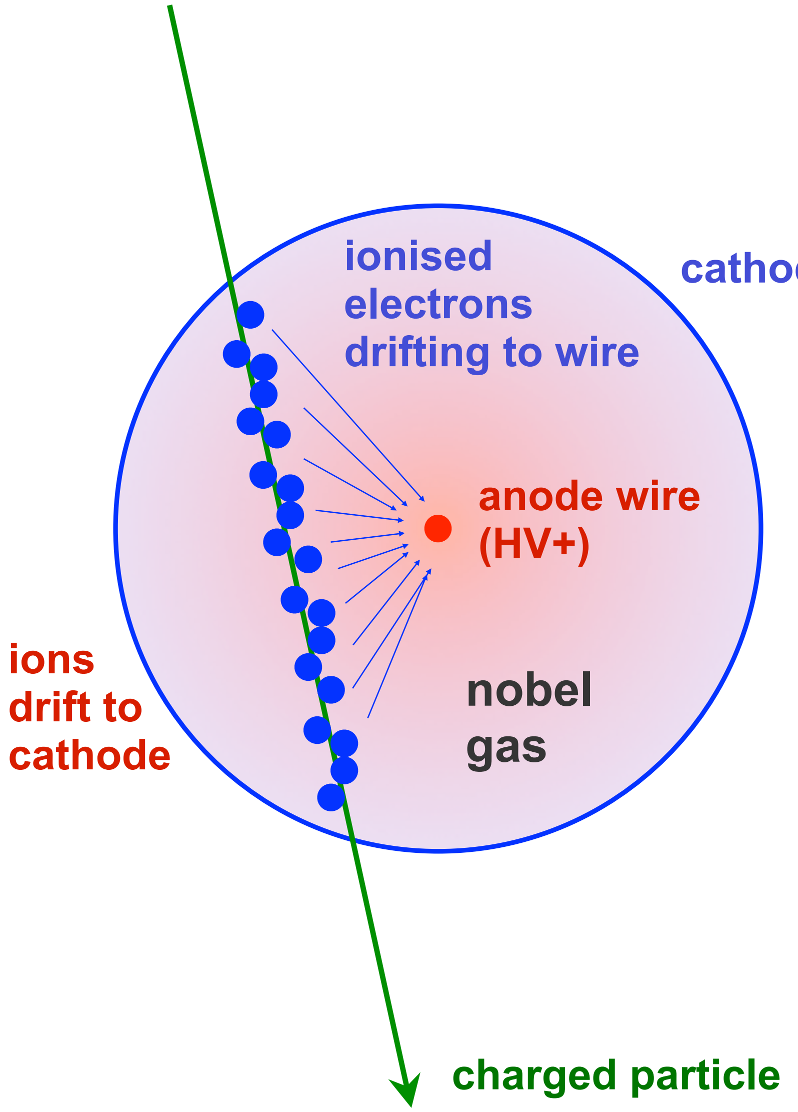

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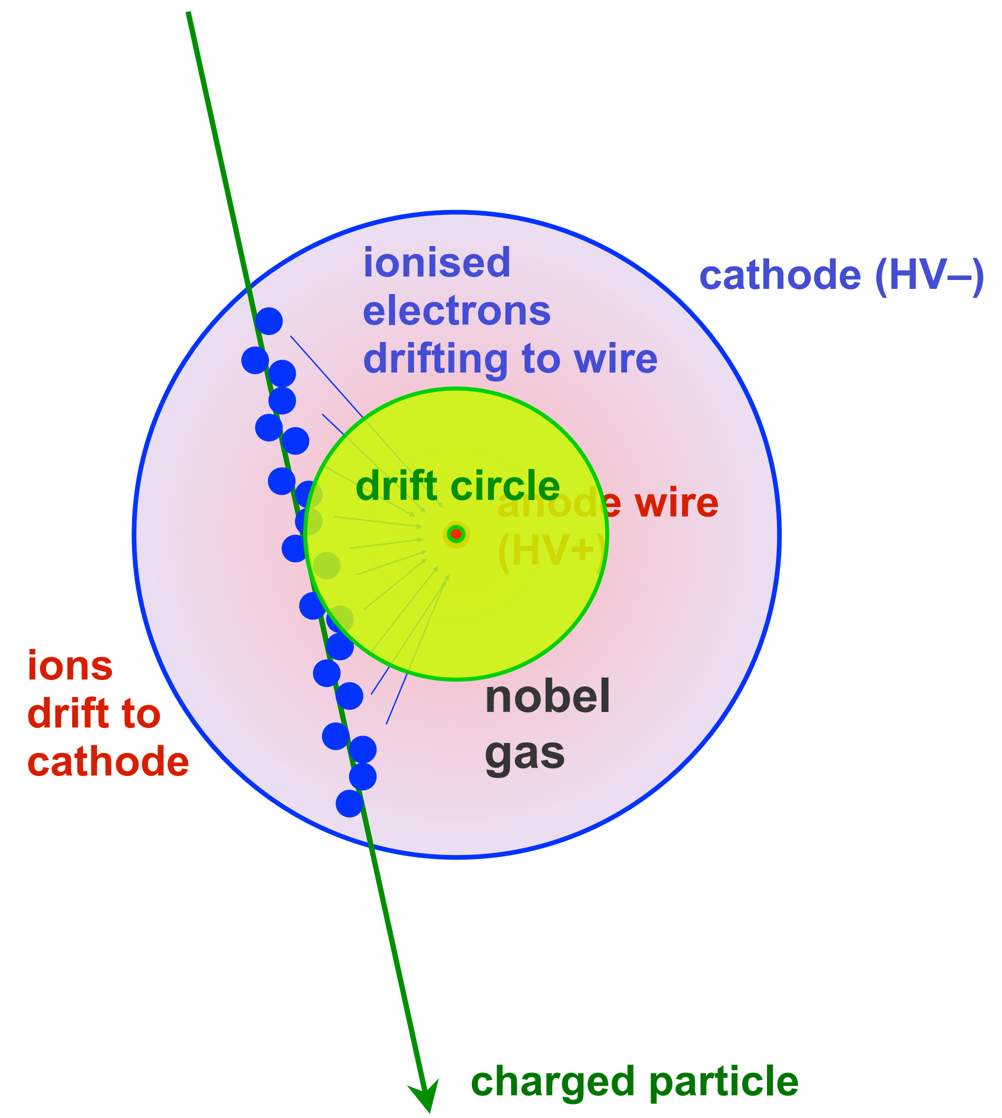

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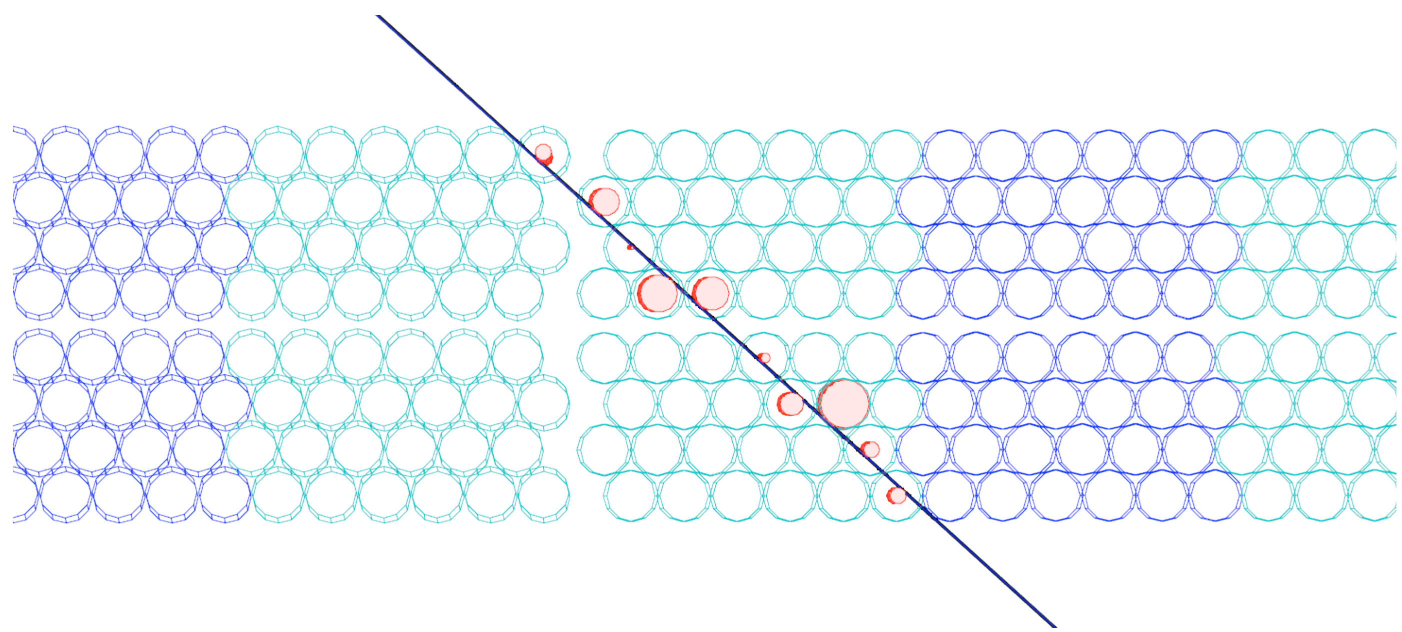
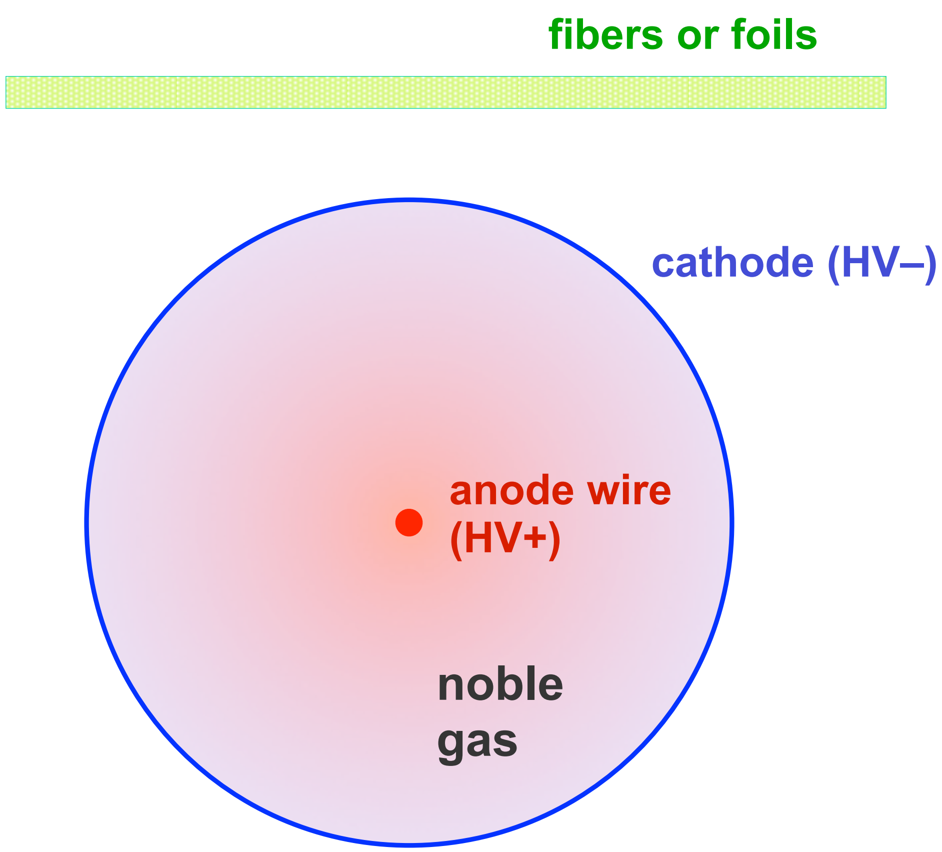
example: segment in muon drift tubes reconstruction from measured drift circles (left-right ambiguity)



Combining Tracking with PID: the ATLAS TRT

- *e*/π separation via transition radiation: polymer (PP) fibers/foils interleaved with drift tubes



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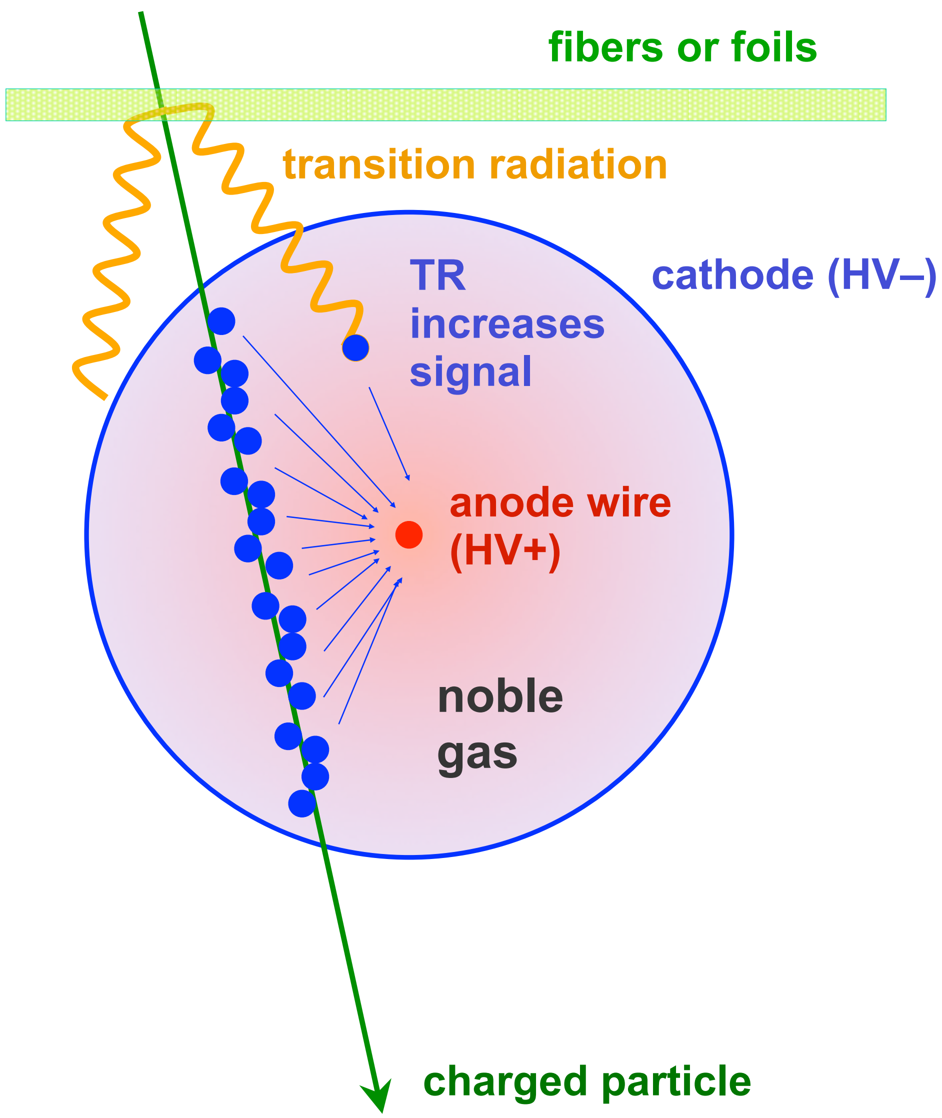

electrons radiate → higher signal
PID info by counting
high-threshold hits

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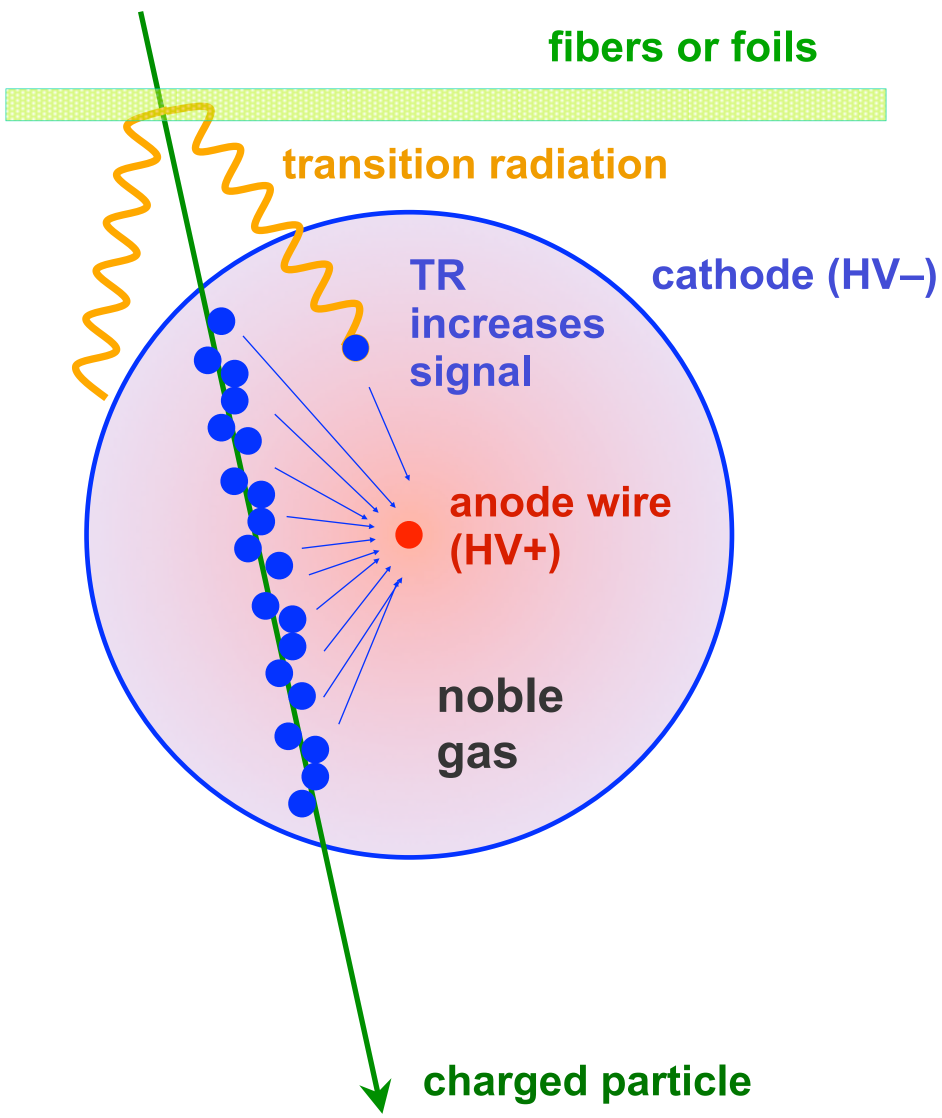
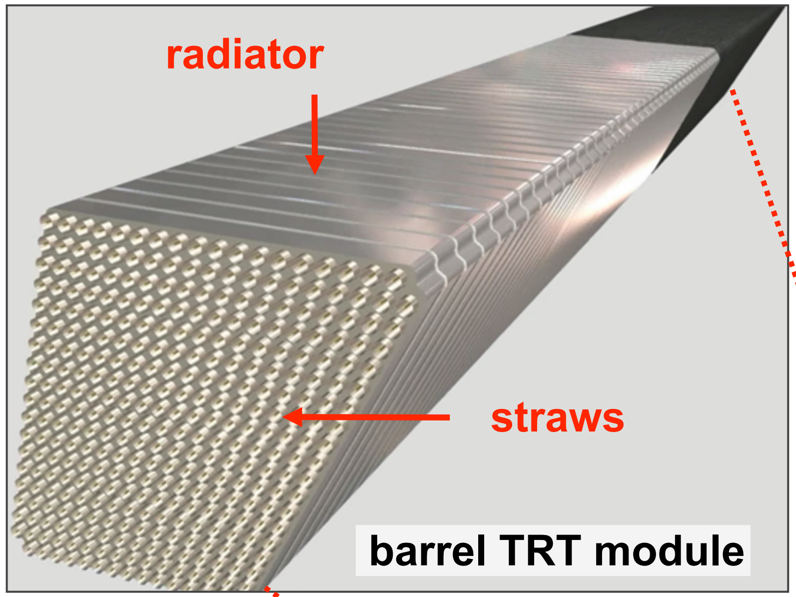
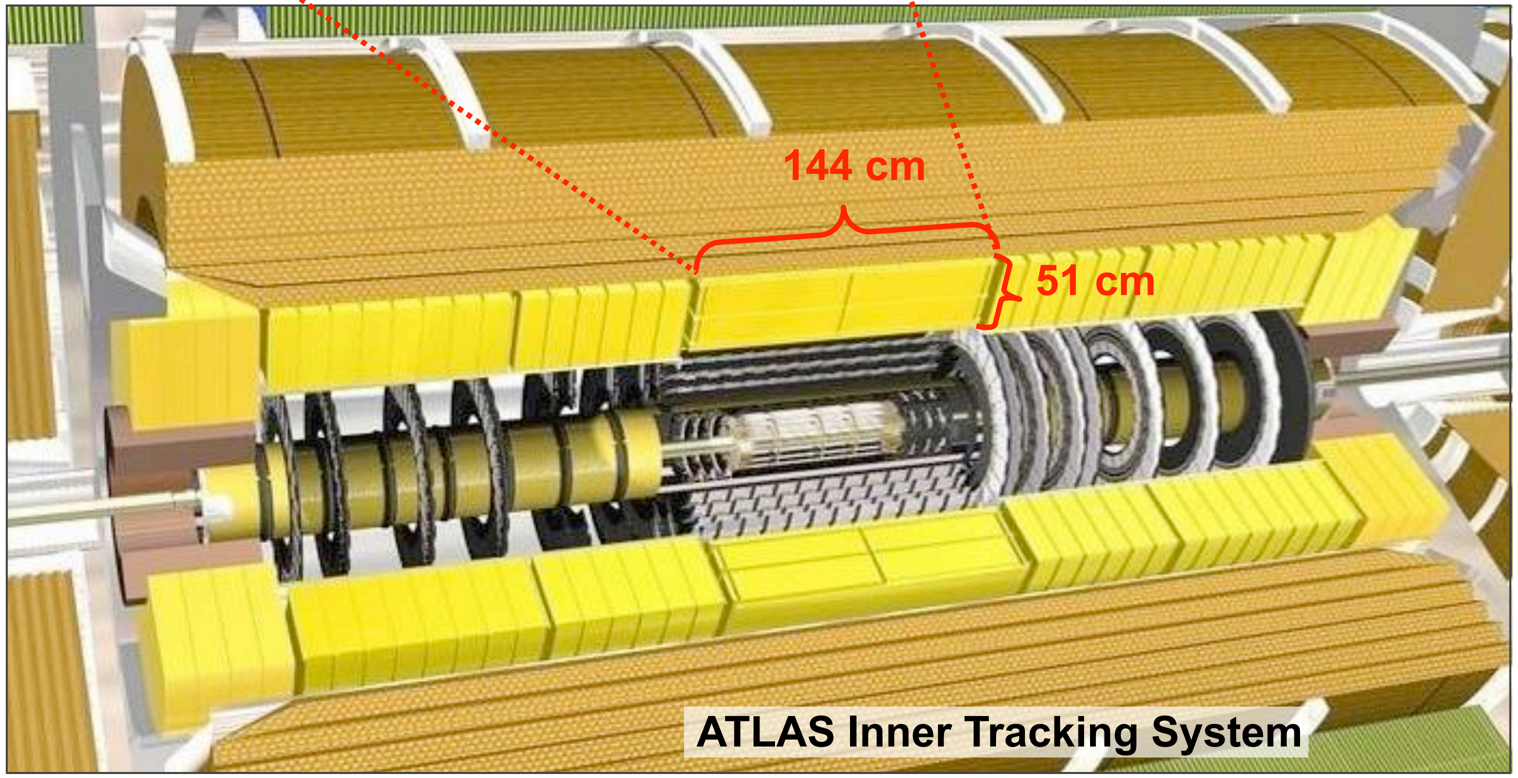




total: 370k straws

barrel ($|\eta| < 0.7$):
36 r-ϕ measurements / track
resolution ~130 μm / straw

14 end-cap wheels ($|\eta| < 2.1$):
40 or less z-ϕ points



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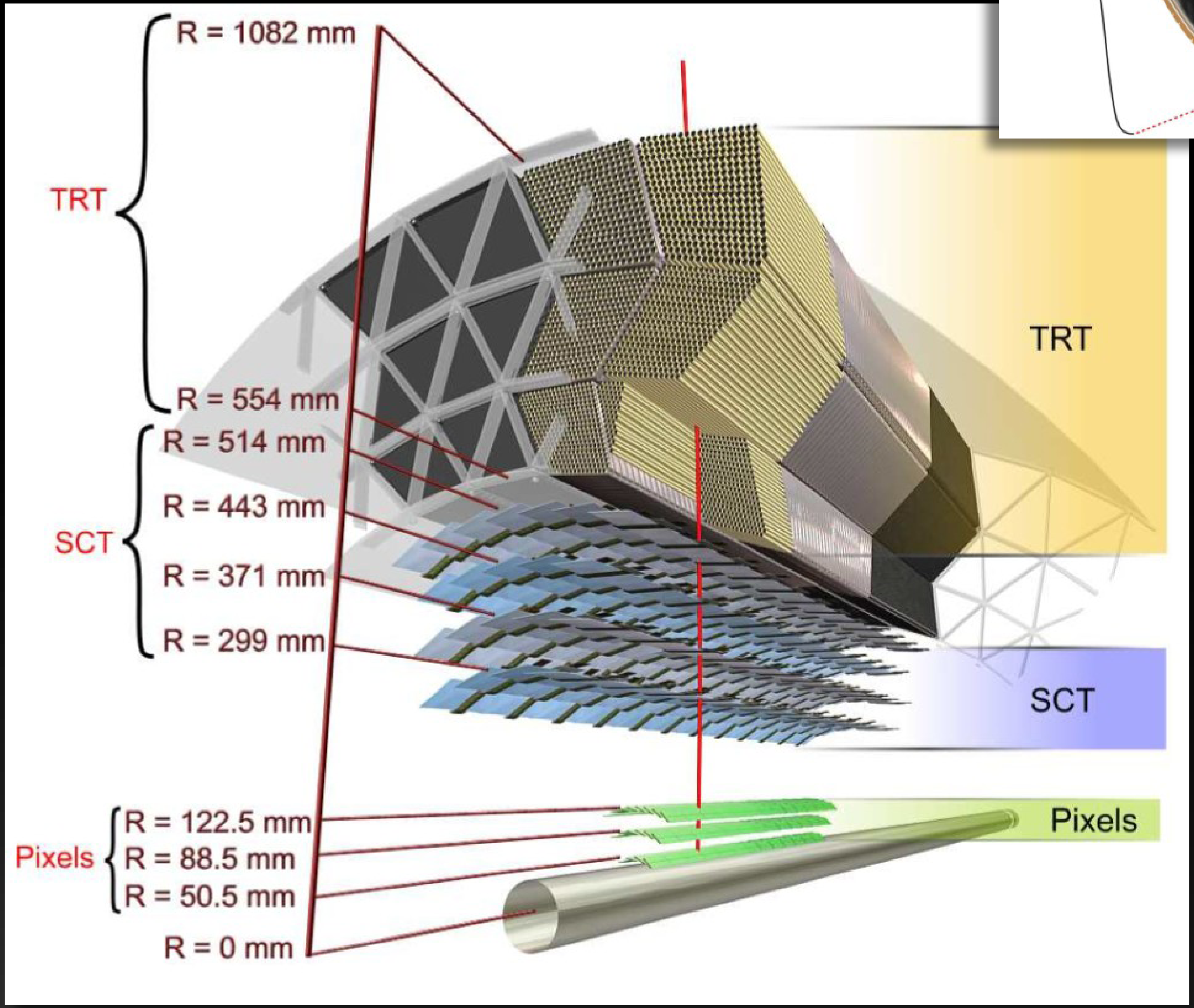
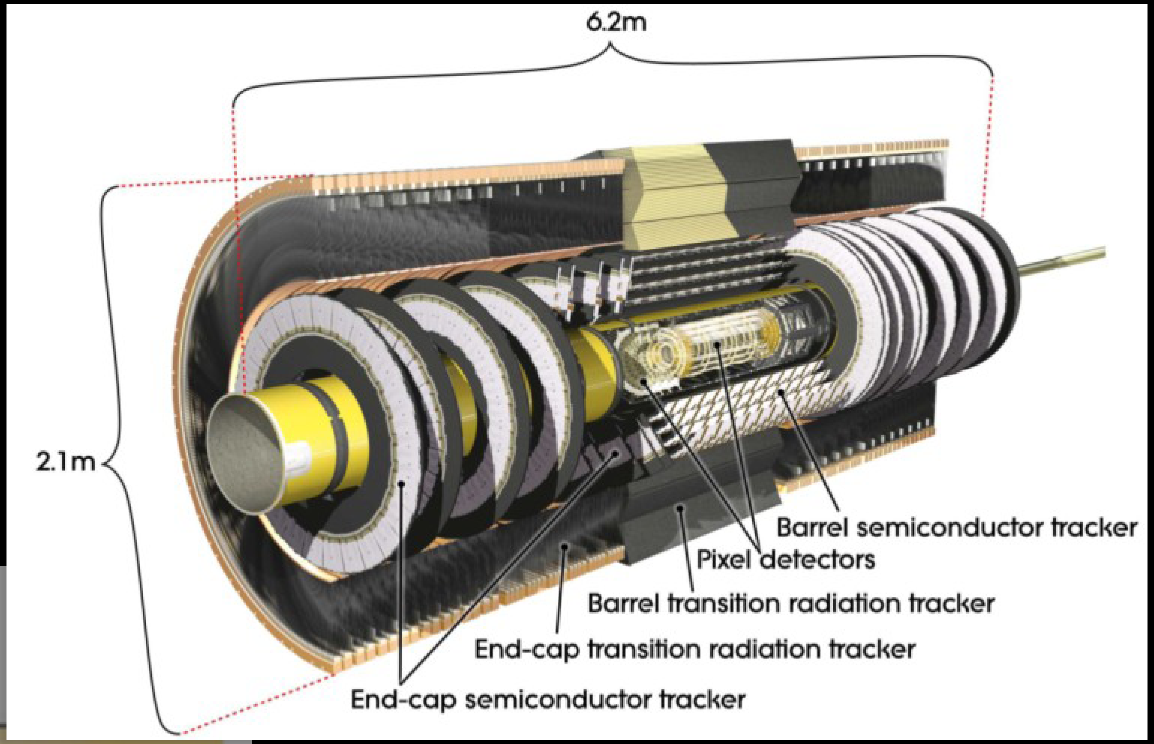
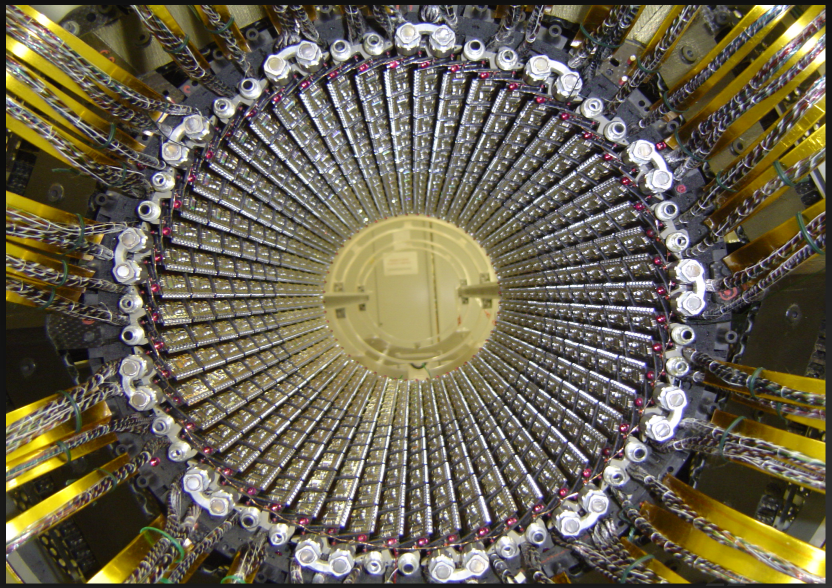
ATLAS Inner Detector

- expanded view of barrel

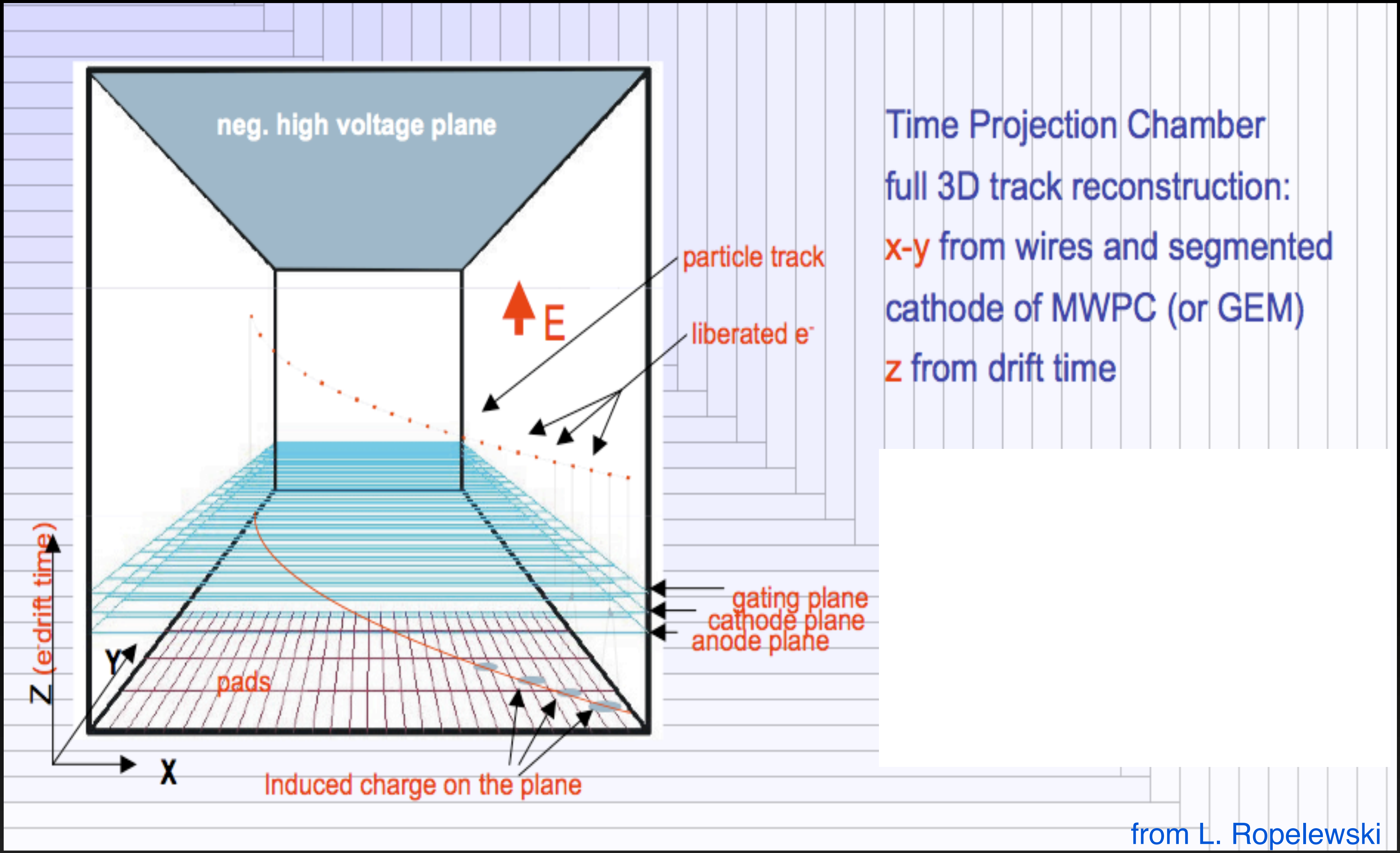




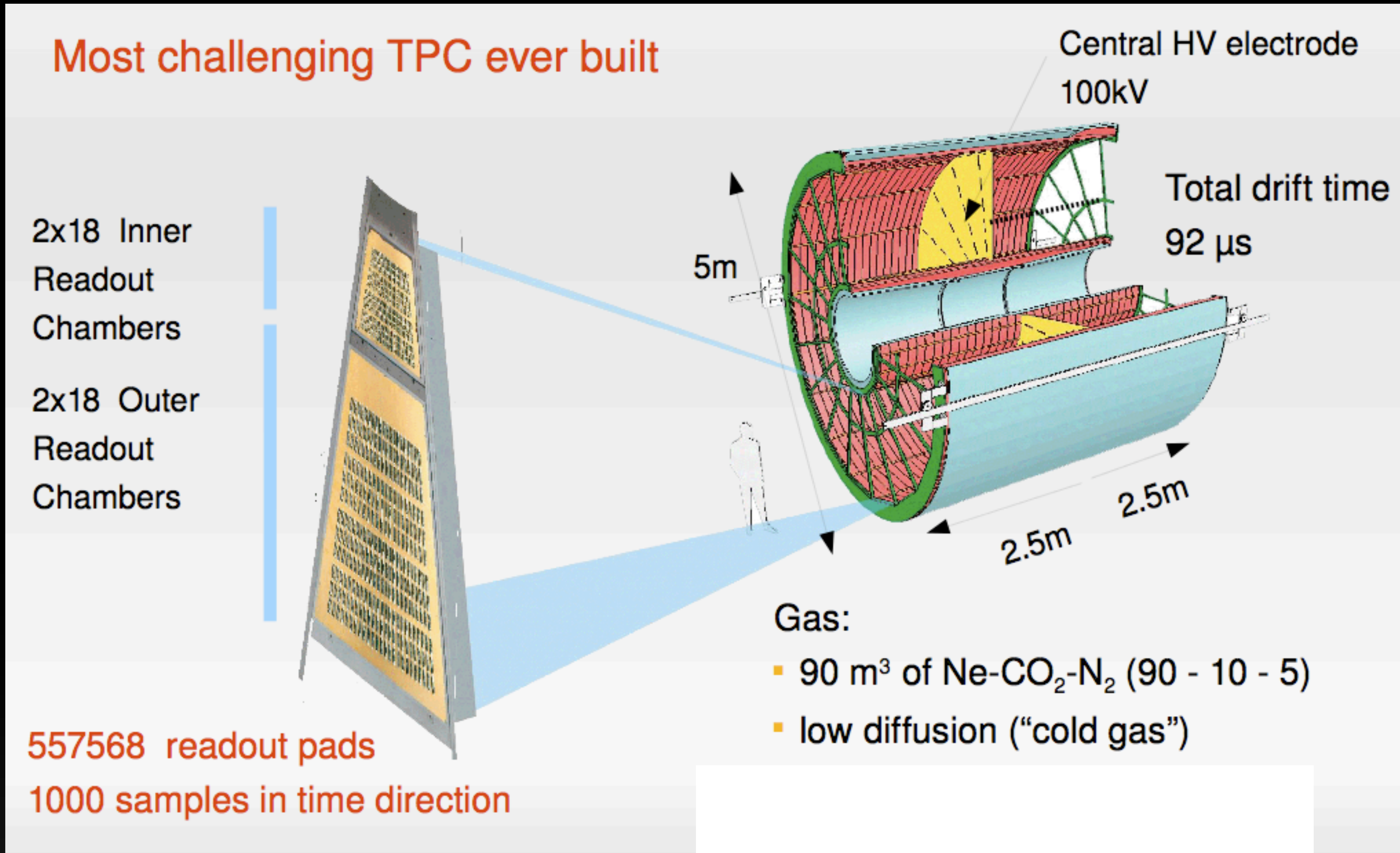
- barrel track passes:
  - ➡ ~36 TRT 4mm straws
  - ➡ 4x2 Si strips on stereo modules12cm x 80 mm, 285mm thick
  - ➡ 3 pixel layers, 250mm thick



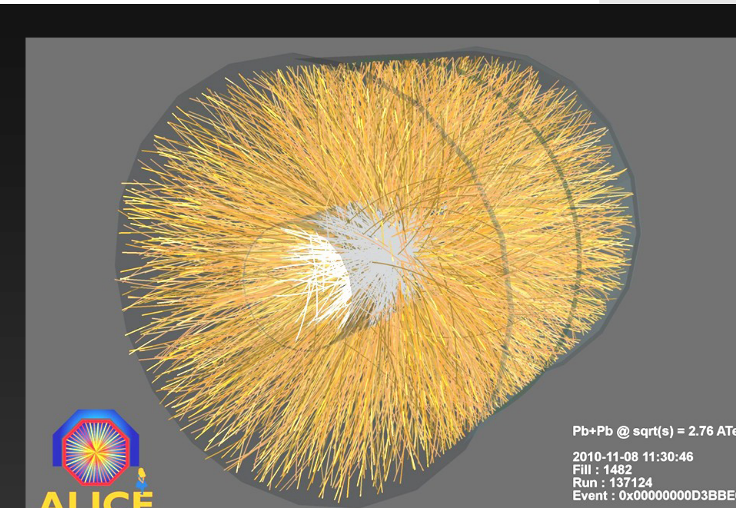
Time Projection Chambers (TPC)



- ➡ developed by D. Nygren in the 70's.
- ➡ long drift times (≈ 40 μs), thus rate limitations and very good gas quality required



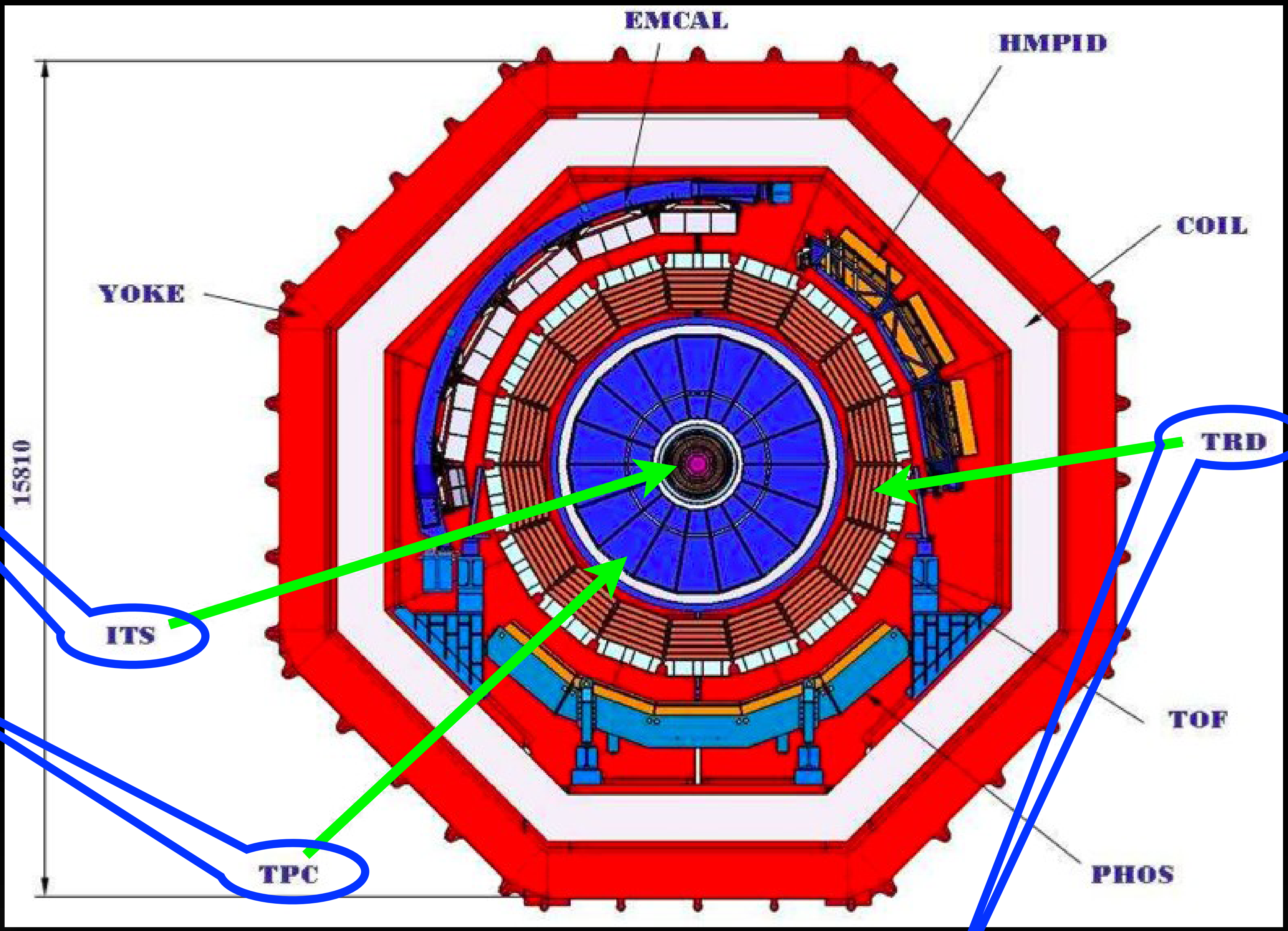
- ➡ ALICE data taking rate 1 kHz in pp
- ➡ few 100 Hz in Pb Pb



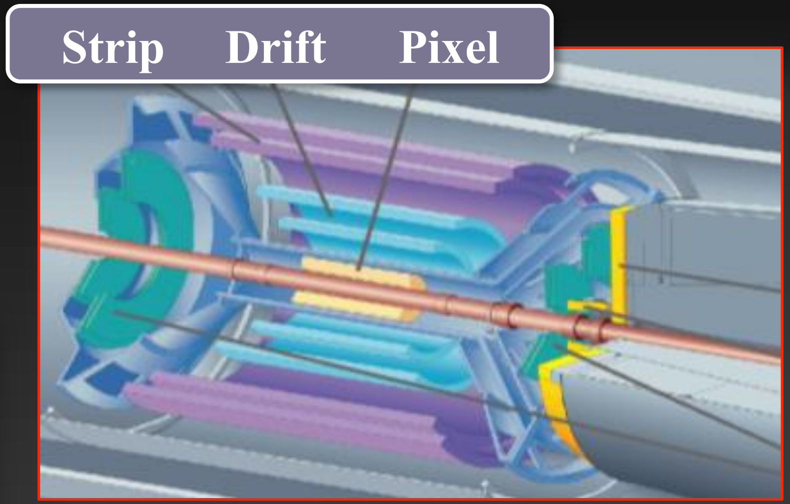
ALICE Tracking

➡ ITS : 6 layers
- 2 Pixels
- 2 silicon drift detectors
- 2 double sided strips

➡ Time Projection Chamber
- large volume gas detector with central electrode
- MWPC with cathode pad readout in end plates
- very good two-track resolution
- very low material in active region



ITS: 3 different silicon detector technologies



➡ Transition Radiation Detector
- electron ID, and improves momentum resolution
- outer radius 3.7m

➡ installed in L3 magnet
- lower B field (0.5 T) , larger R

Comparison of Barrel Tracker Layouts

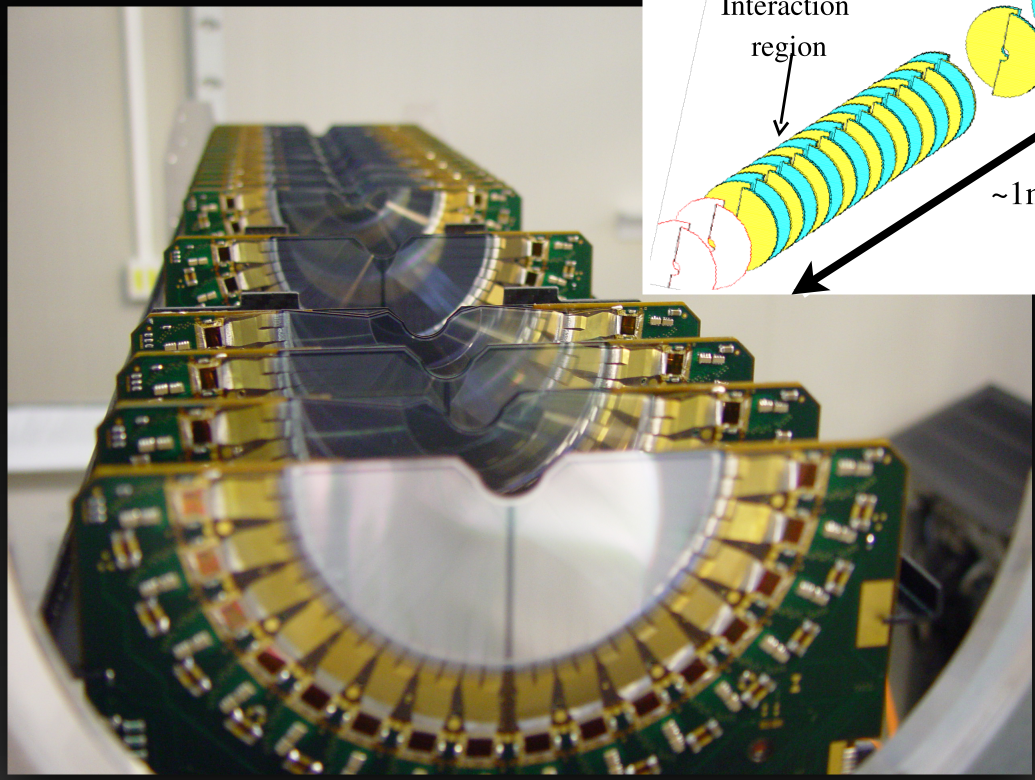
P.Wells	ALICE	ATLAS	CMS
R inner	3.9 cm	5.0 cm	4.4 cm
R outer	3.7 m	1.1 m	1.1 m
Length	5 m	5.4 m	5.8 m
$\|\eta\|$ range	0.9	2.5	2.5
B field	0.5 T	2 T	4 T
Total X_0 near η=0	0.08 (ITS) + 0.035 (TPC) + 0.234 (TRD)	0.3	0.4
Power	6 kW (ITS)	70 kW	60 kW
$r\phi$ resolution near outer radius	~ 800 μm TPC ~ 500 μm TRD	130 μm per TRT straw	35 μm per strip layer
p_T resolution at 1GeV and at 100 GeV	0.7% 3% (in pp)	1.3% 3.8%	0.7% 1.5%

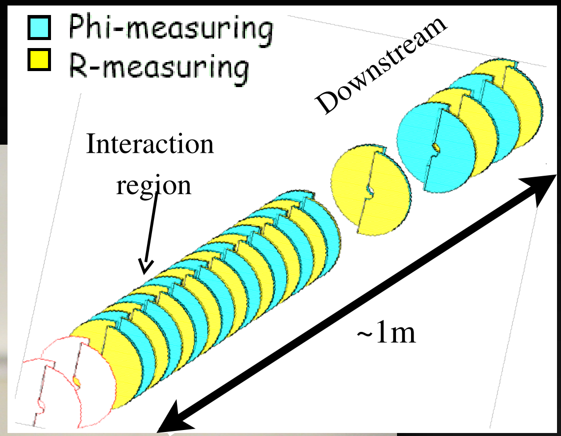
- LHCb is a spectrometer designed for B-physics
  - ➡ p_T resolution is 0.35% at 1 GeV, 0.55% at 100 GeV for good mass resolution

Summary of Pixel Barrel Layouts

P.Wells	ALICE	ATLAS	CMS
Radii (mm)	39 – 76	50.5 – 88.5 – 122.5	44 – 73 – 102
Pixel size $r\phi$ x z (μm^2)	50 x 425	40 x 400	100 x 150
Thickness (μm)	200	250	285
Resolution $r\phi$ / z (μm)	12 / 100	10 / 115	~15-20
Channels (million)	9.8	80.4	66
Area (m^2)	0.2	1.8	1

- LHCb VELO
  - ➡ forward geometry strip detector with 42 stations along, inner radius of 7 mm
  - ➡ moves close to beam when conditions are stable





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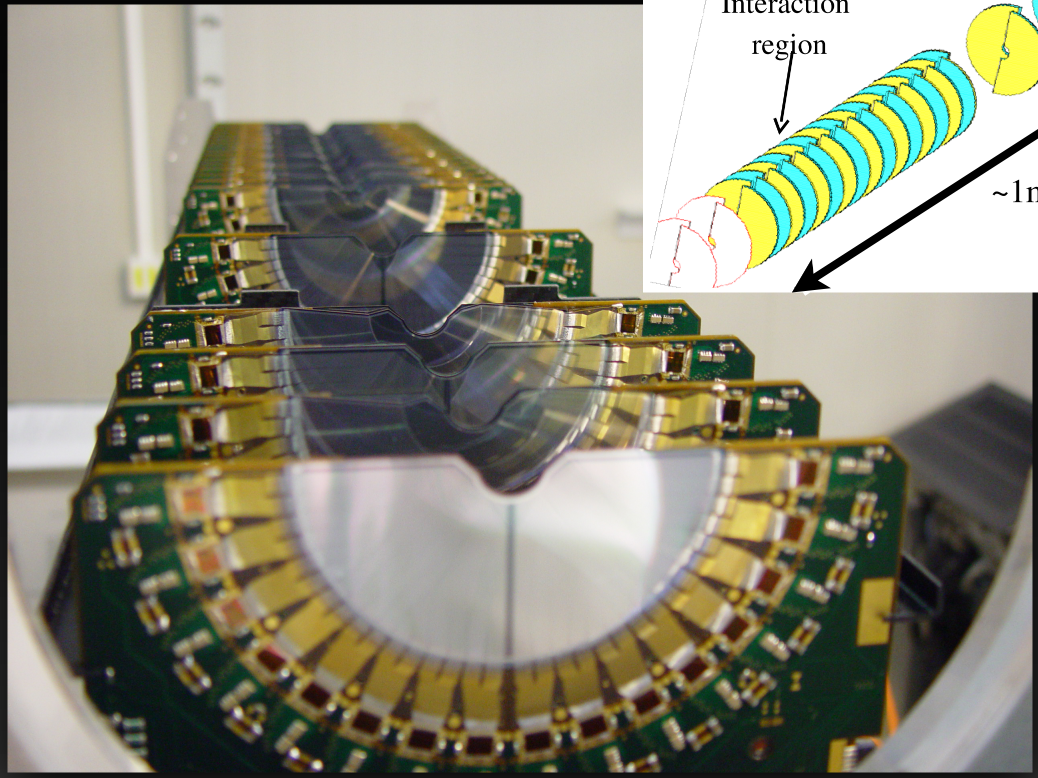
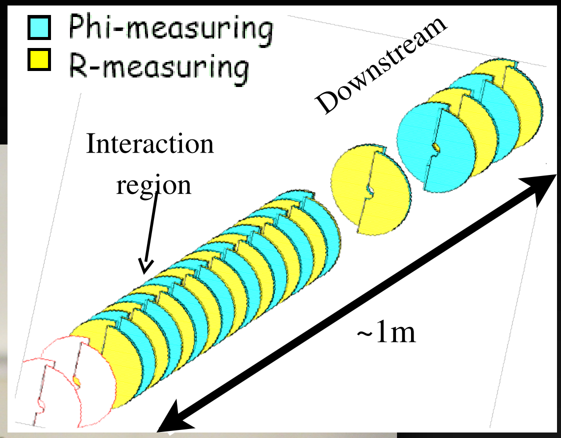
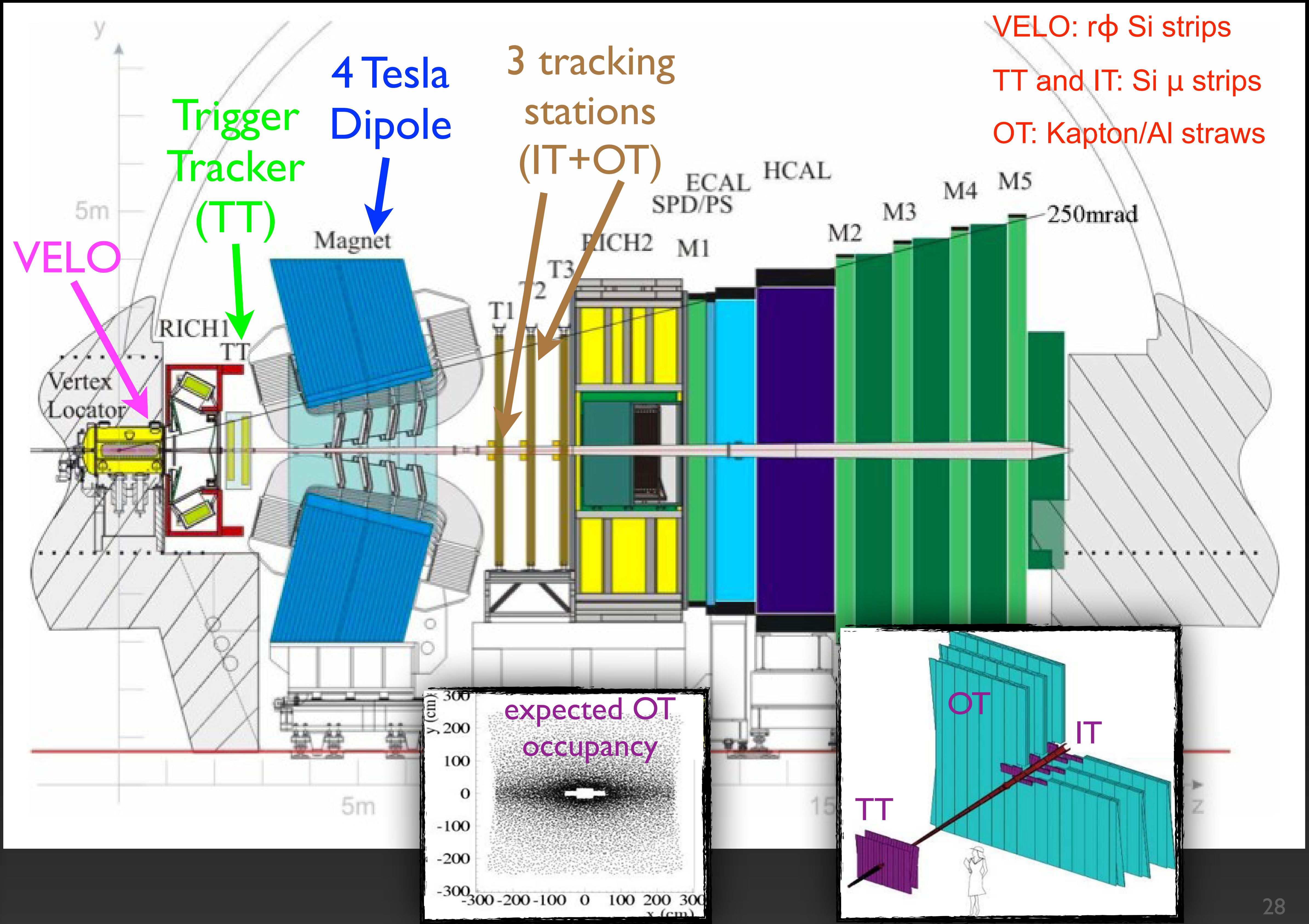




LHCb Tracking



Let's Summarize

- discussed physics of particles in material
- in this lecture I discussed tracking detectors
  - ➡ main design choices and constraints
  - ➡ silicon and drift tube detectors
  - ➡ LHC tracking detector layouts
- next I will discuss track reconstruction