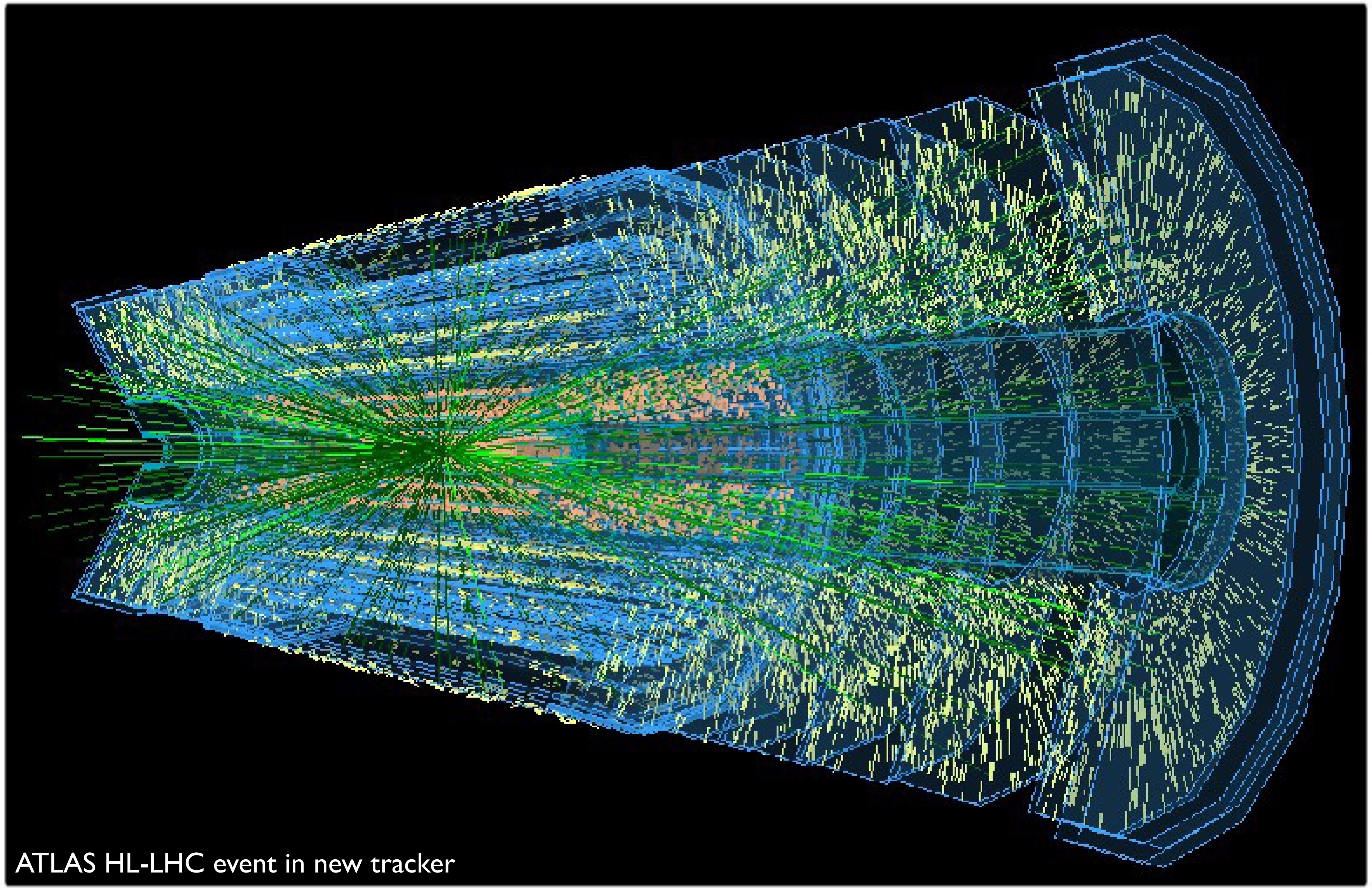
Tracking at the LHC (Part 2):
Brief Overview of LHC Tracking Detectors

Lectures given at the University of Freiburg
Markus Elsing, 12-13.April 2016



ATLAS HL-LHC event in new tracker

Introduction: LHC and Experiments

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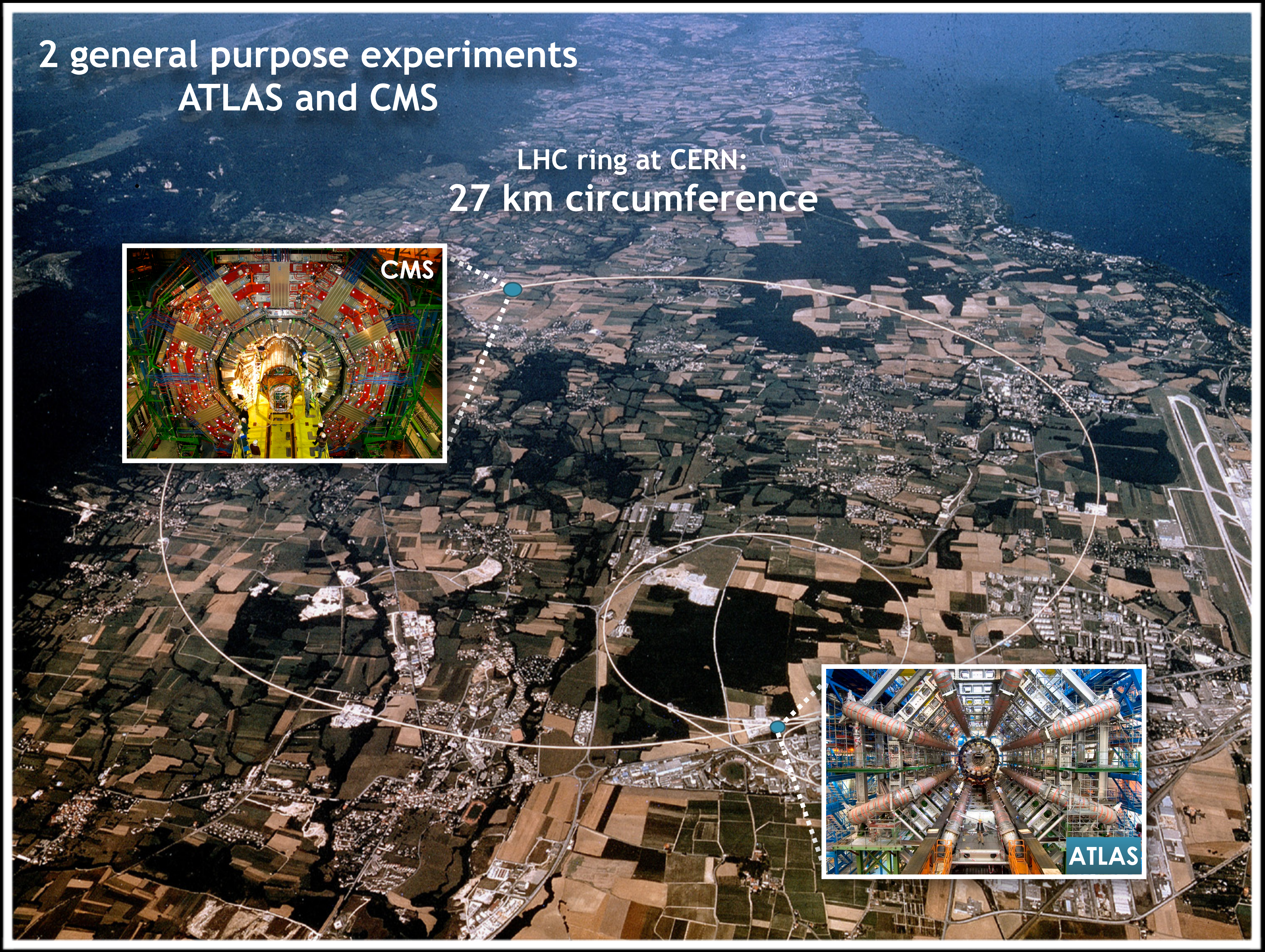

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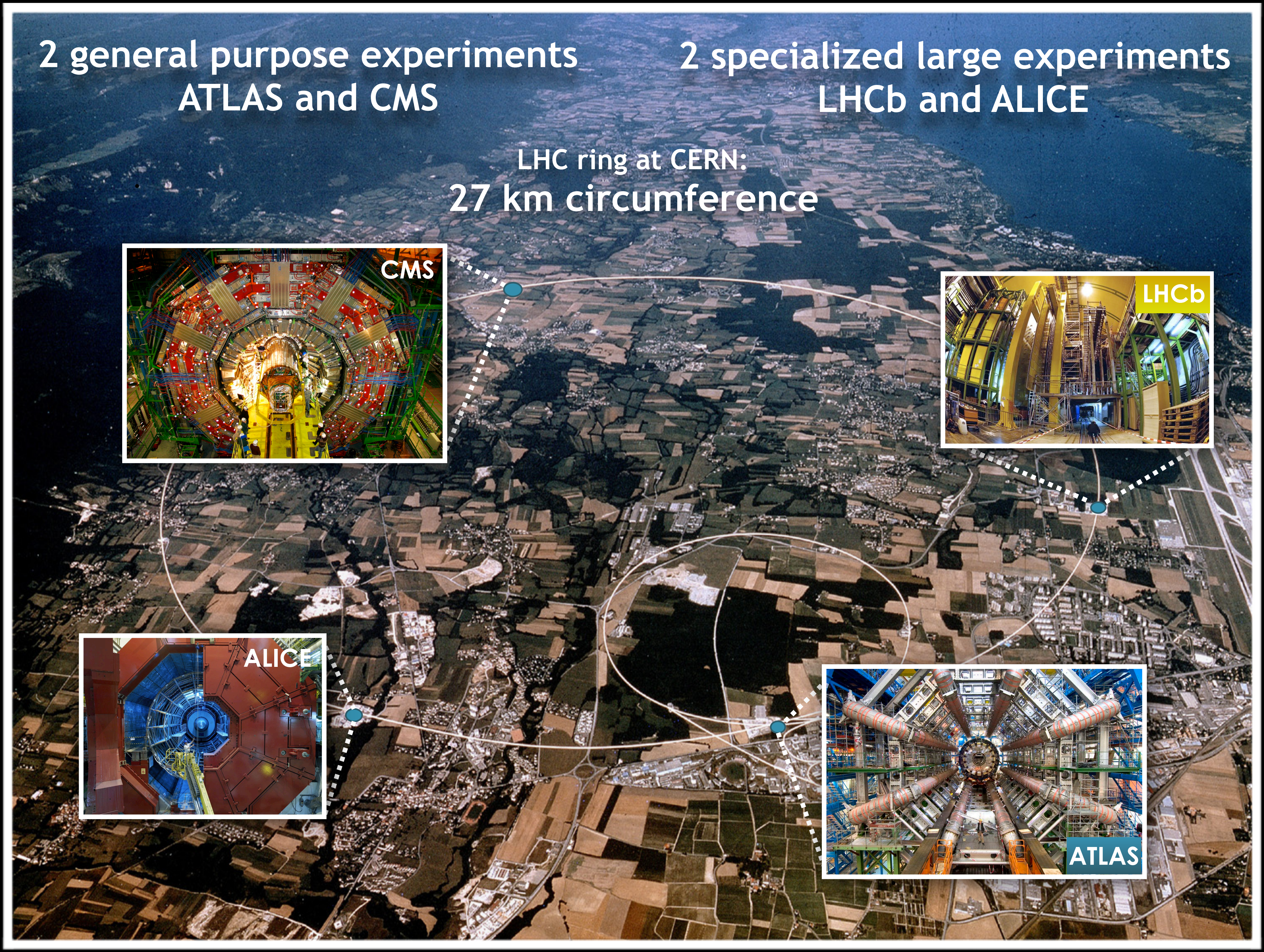
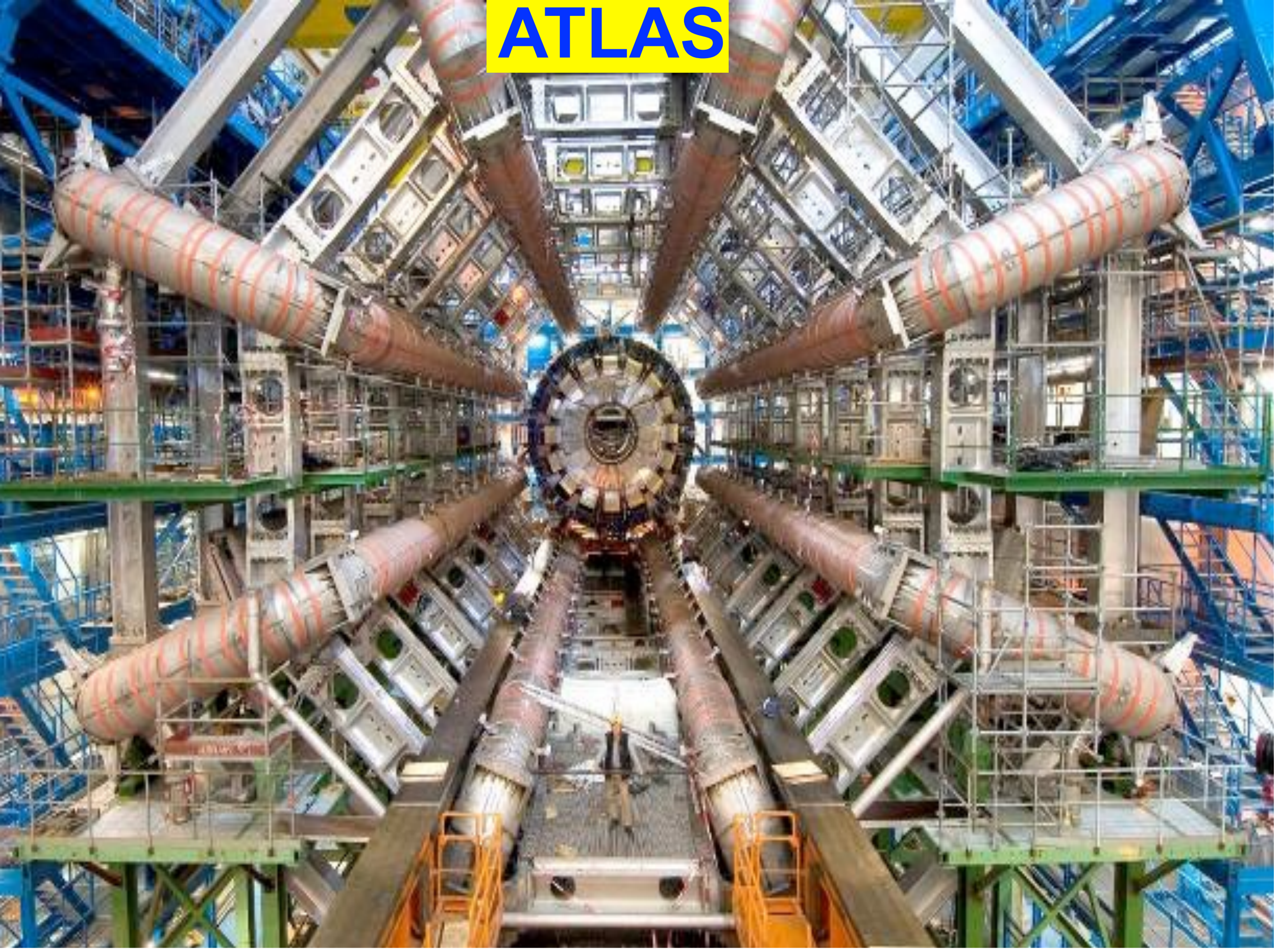
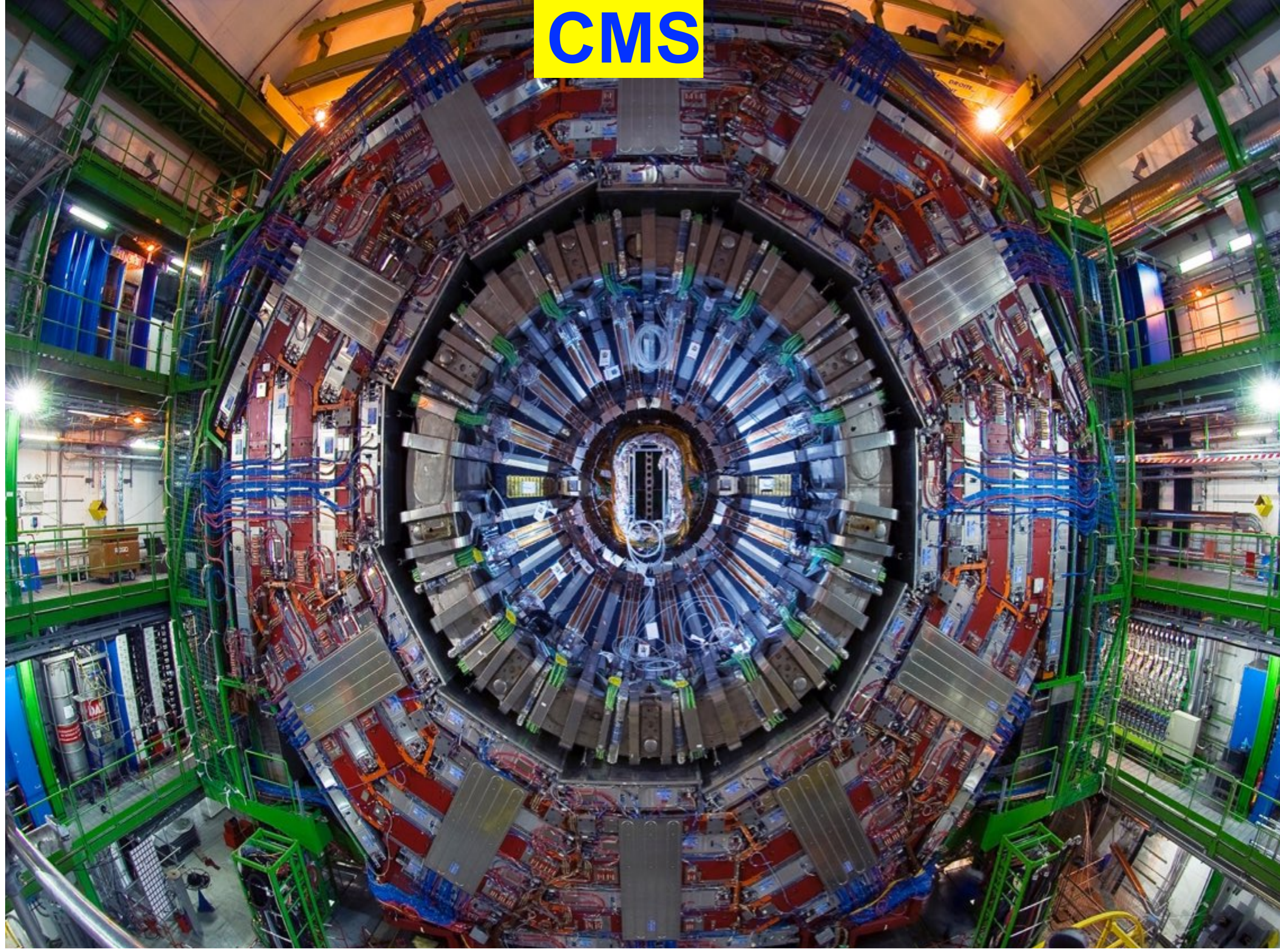



ATLAS


CMS


LHCb

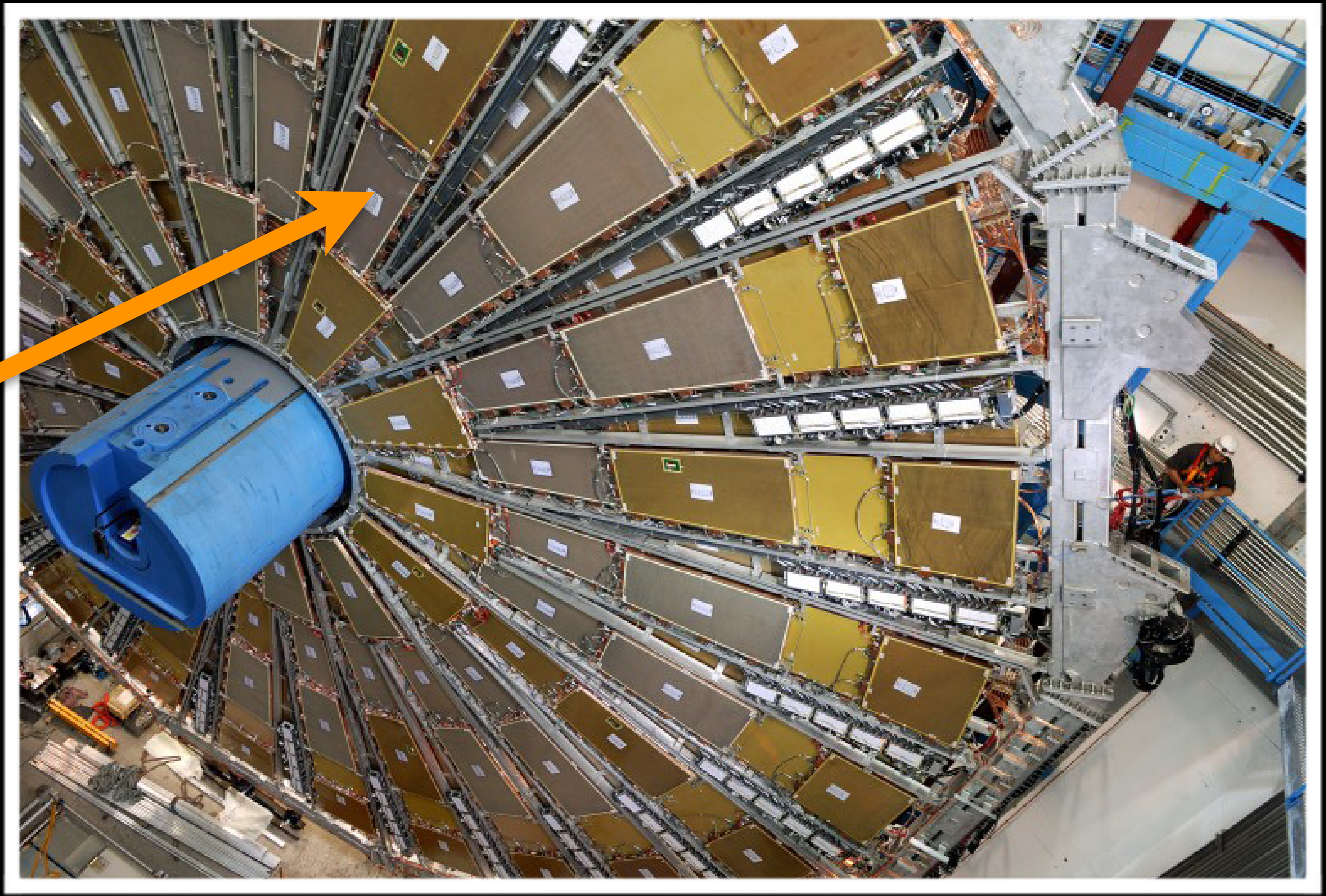

ALICE

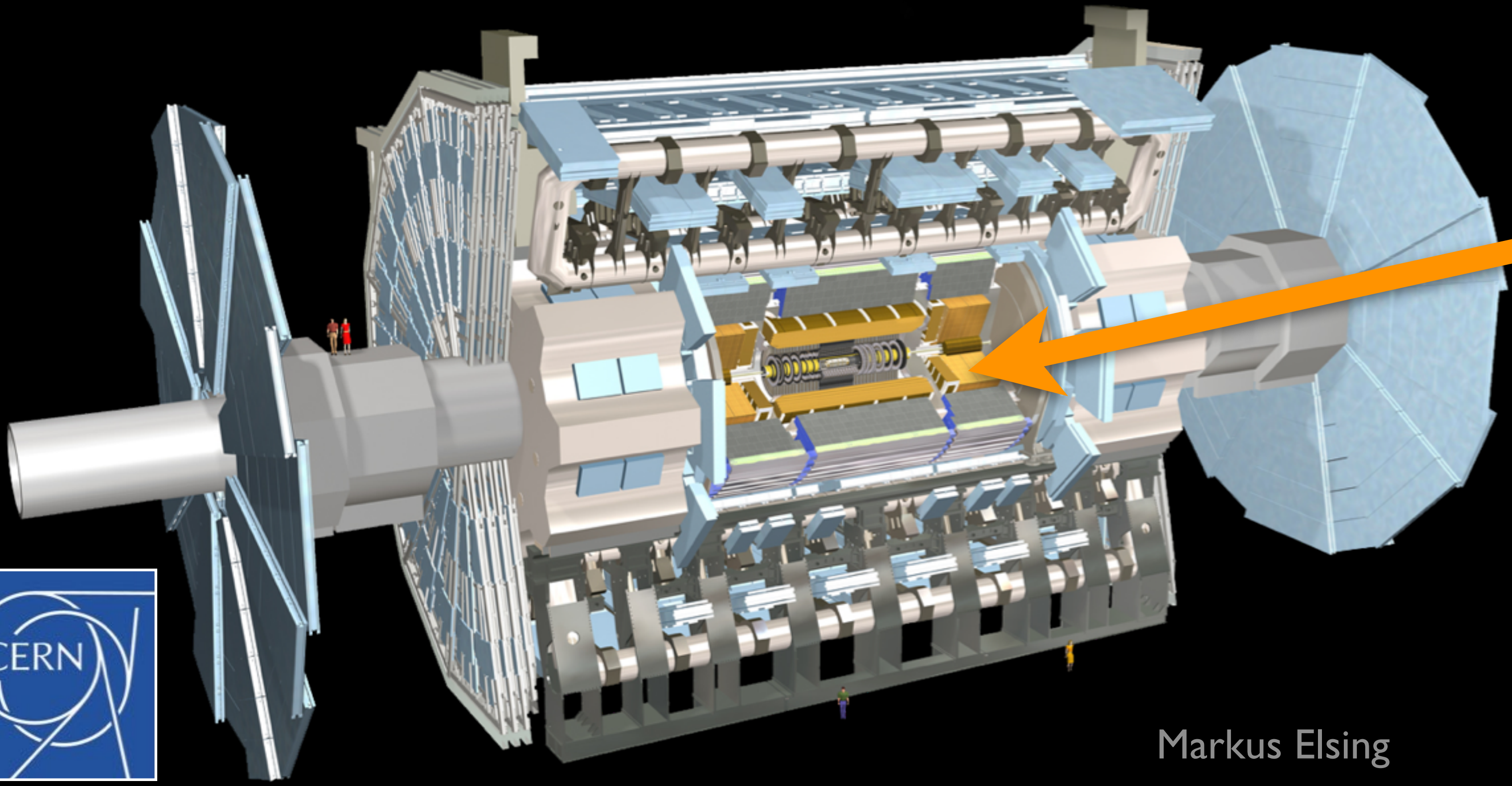
Outline of Part 2

- 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





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- ➡ not subject of these lectures

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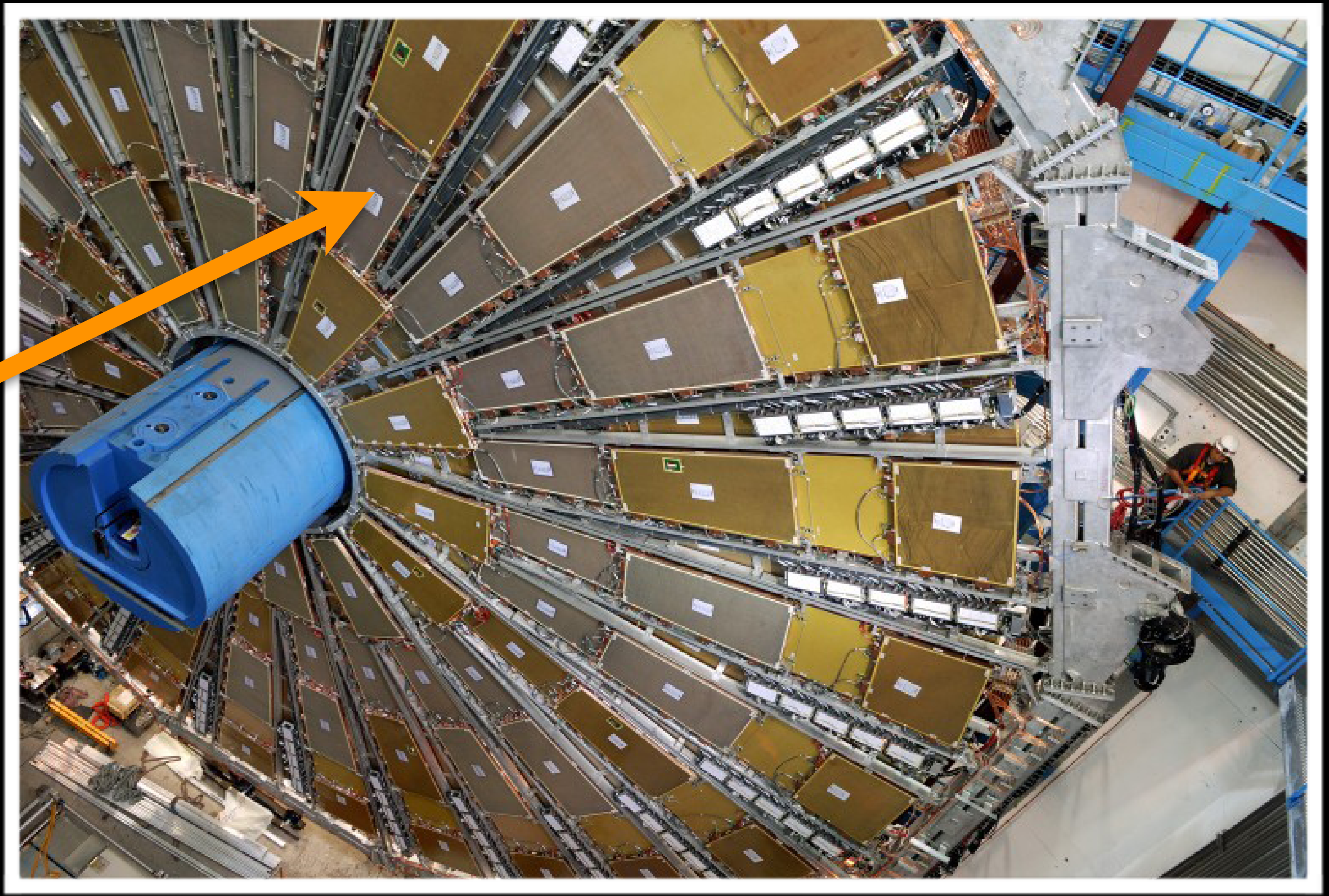

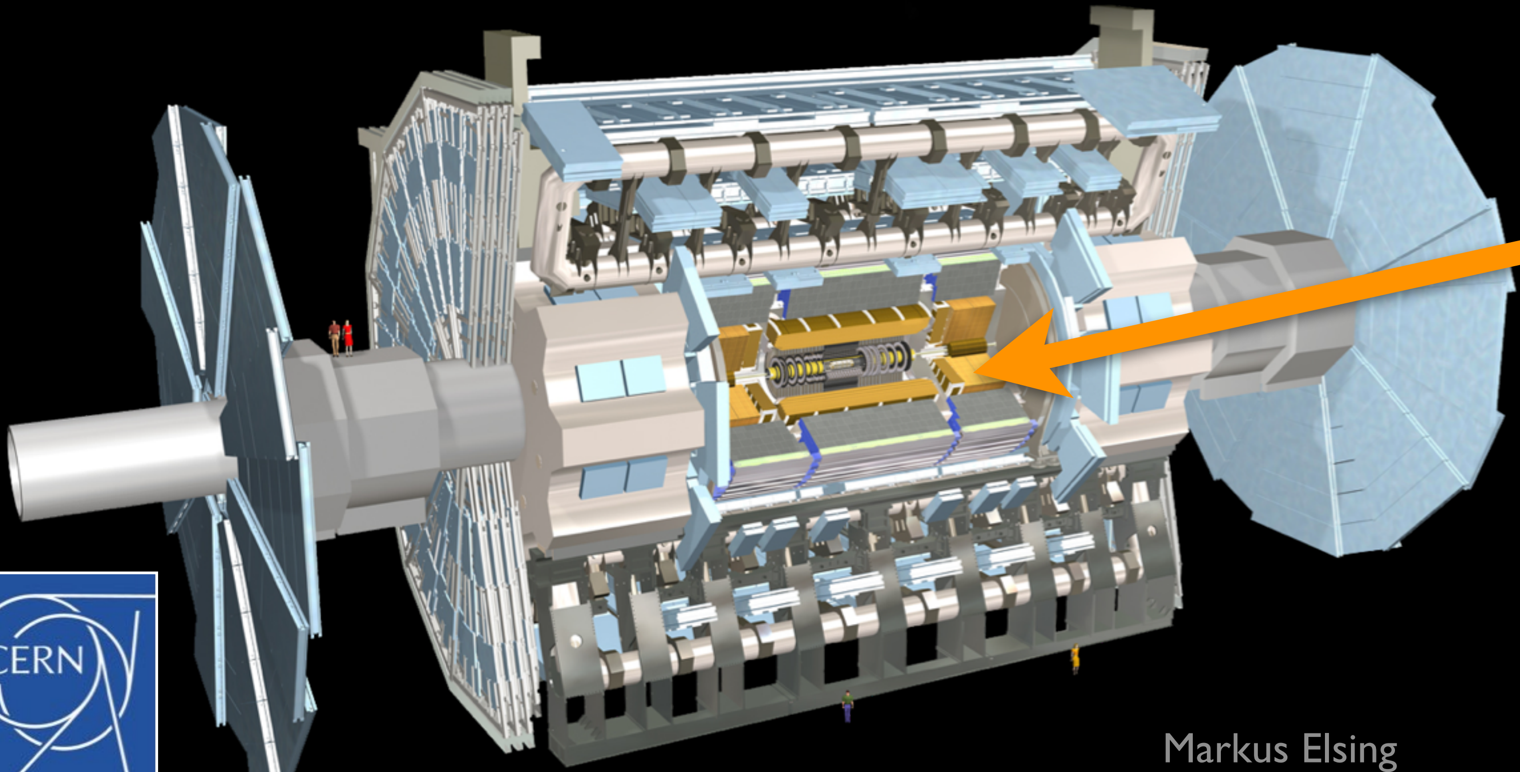

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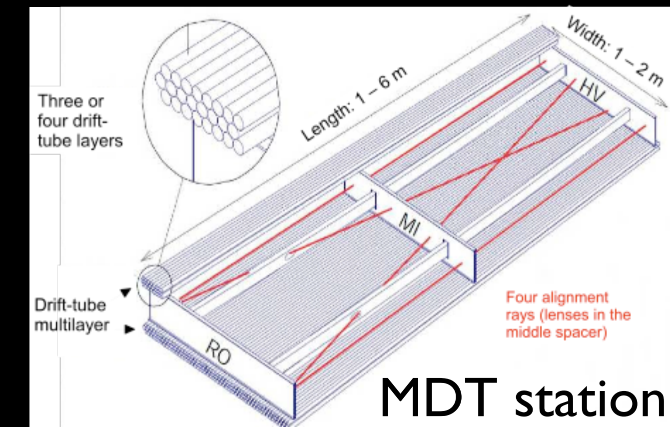
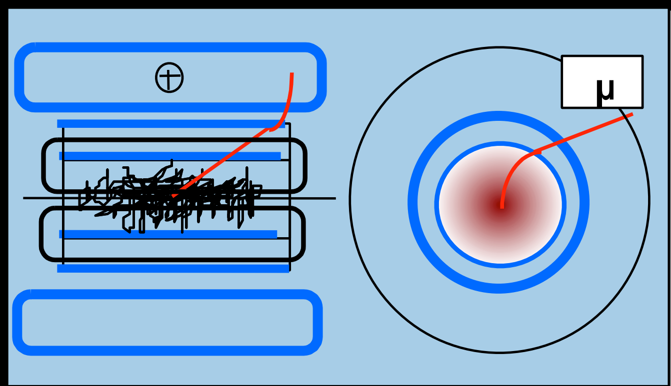
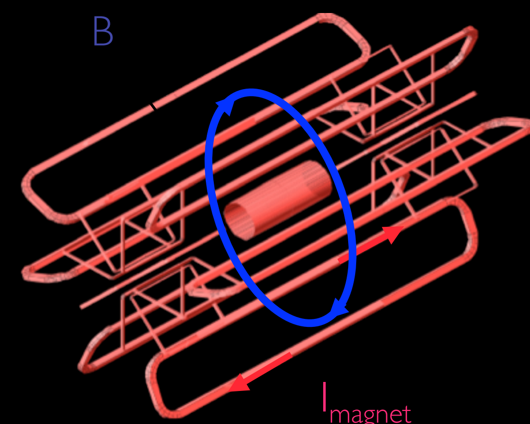
- let' have a brief look at the **muon systems**
  - ➡ ATLAS and CMS

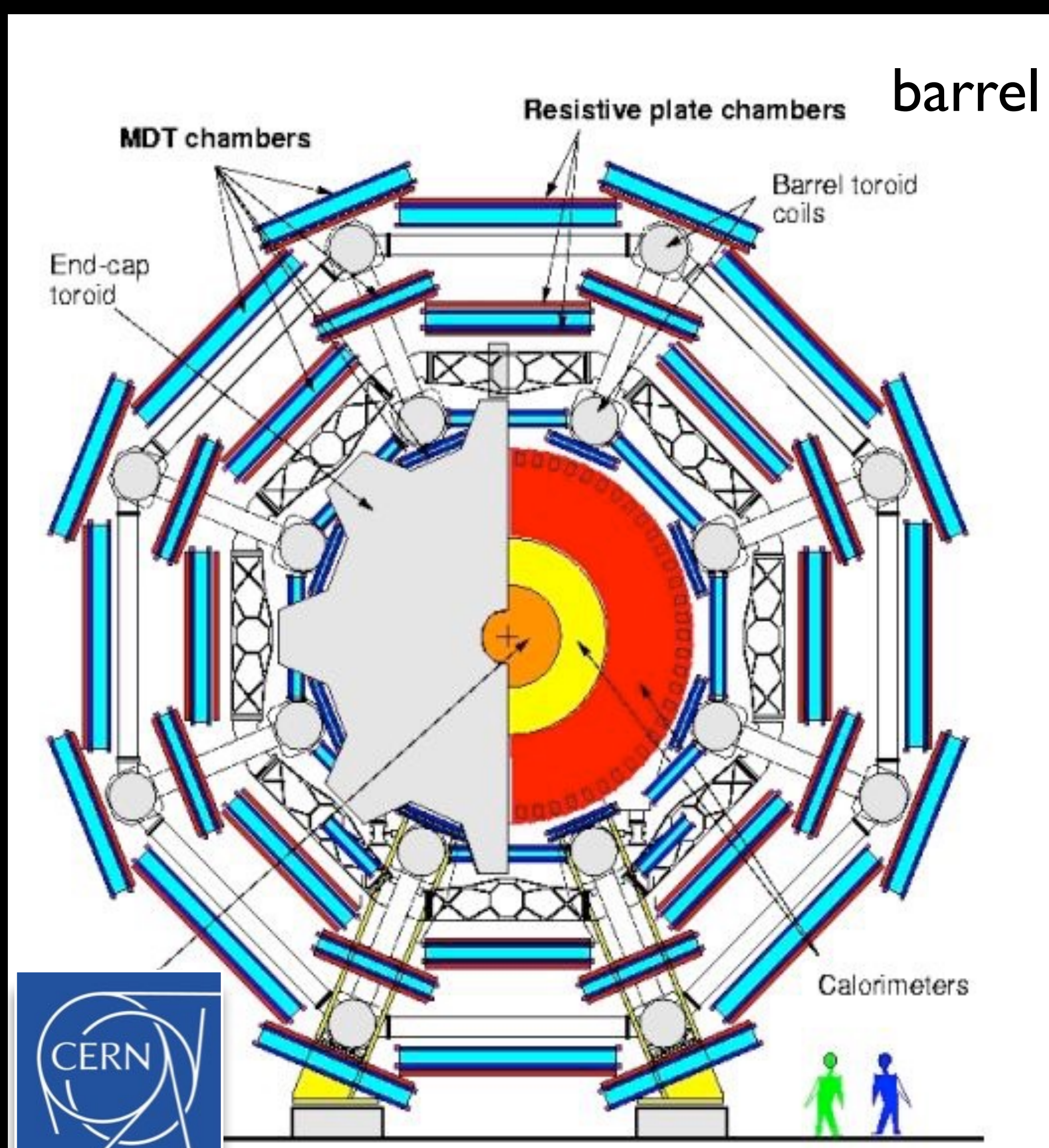
ATLAS Muon Spectrometer

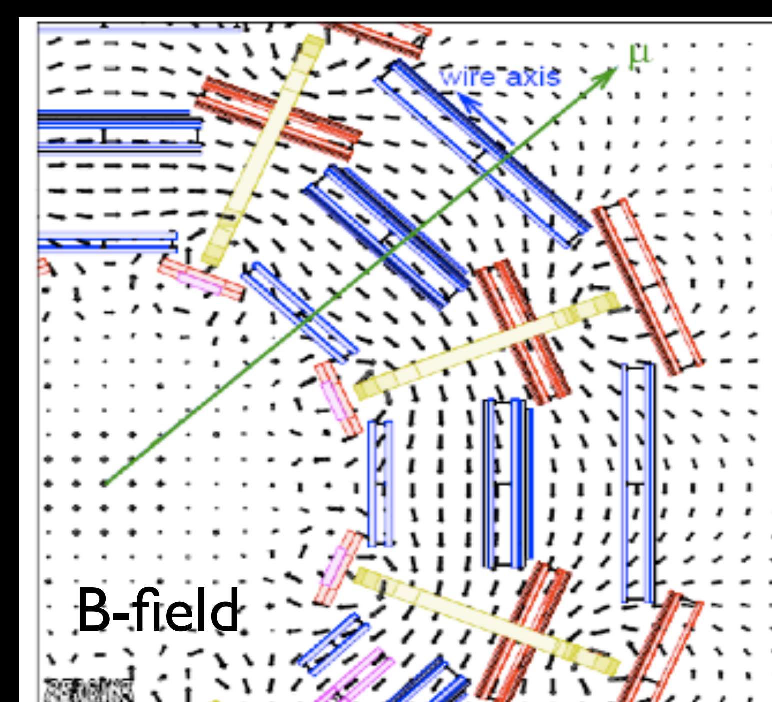


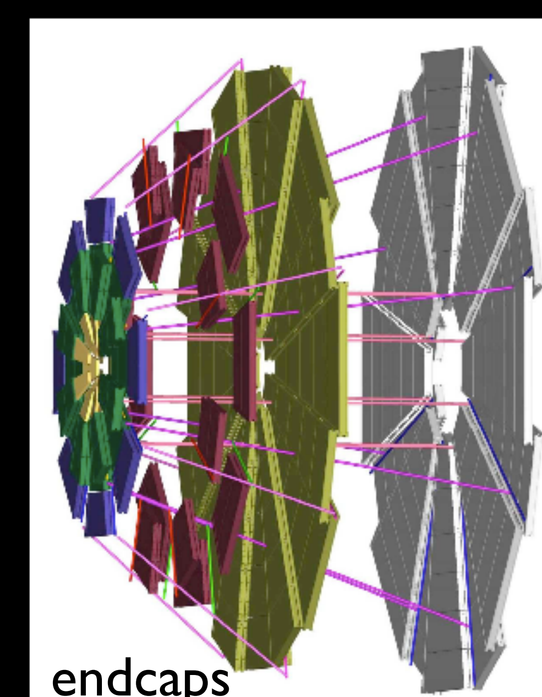




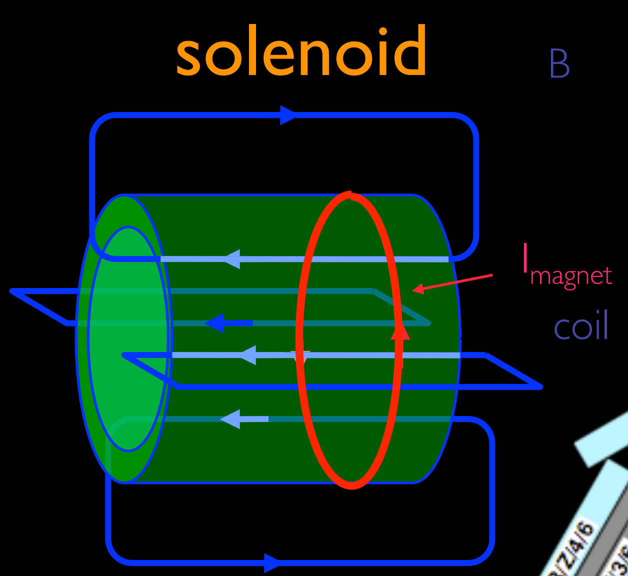
- a huge system
  - ➡ 4 different technologies (MDT,CSC,RPC,TGC)
  - ➡ large area (10.000 m²)
  - ➡ many channels (1 M)
- toroid field configuration
  - ➡ large magnetic field variations in toroid
  - ➡ field 4 Tesla near coils
- optical alignment system

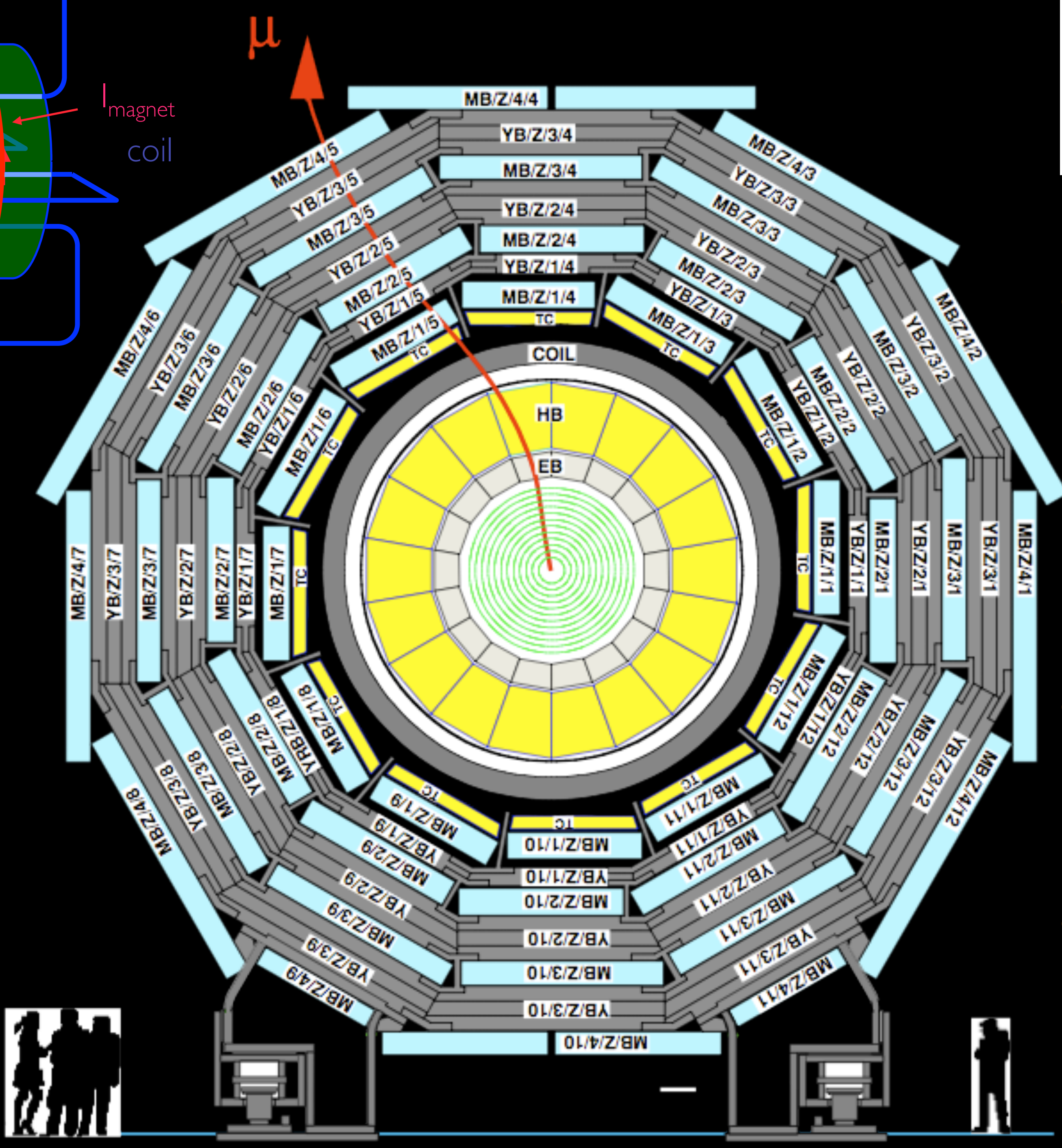


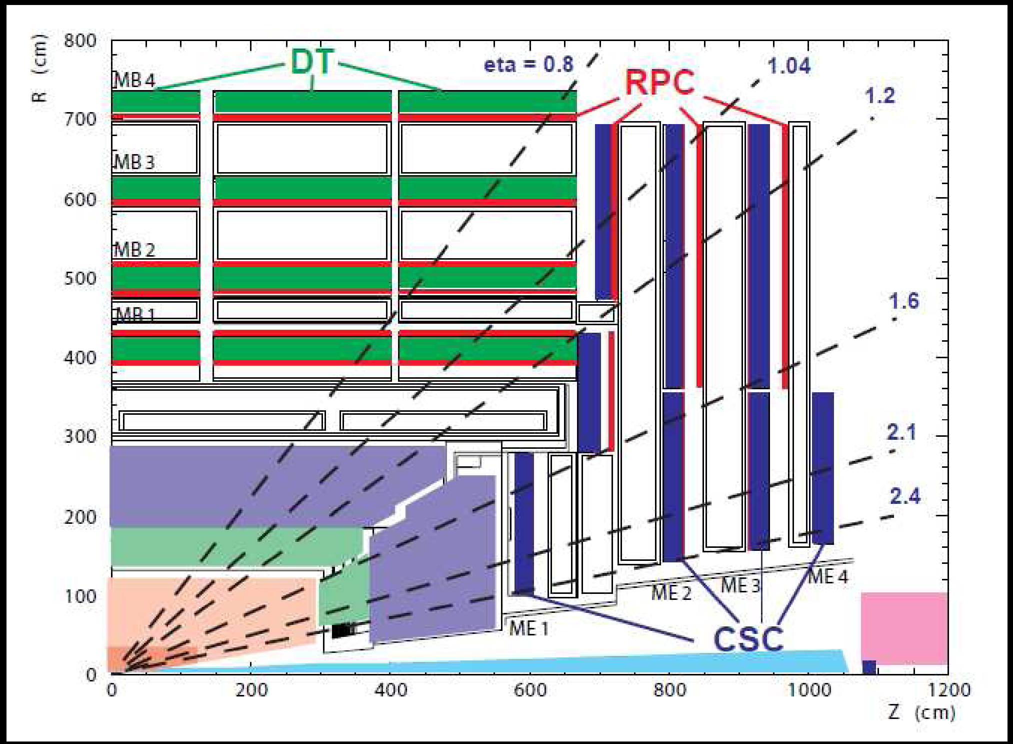




CMS Muon System

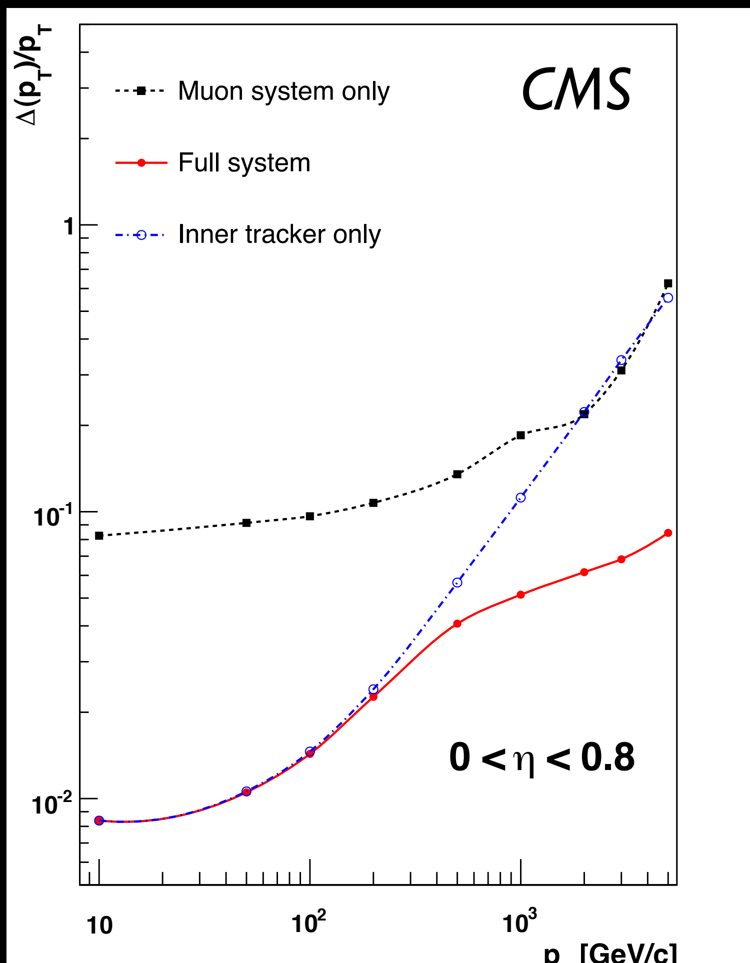


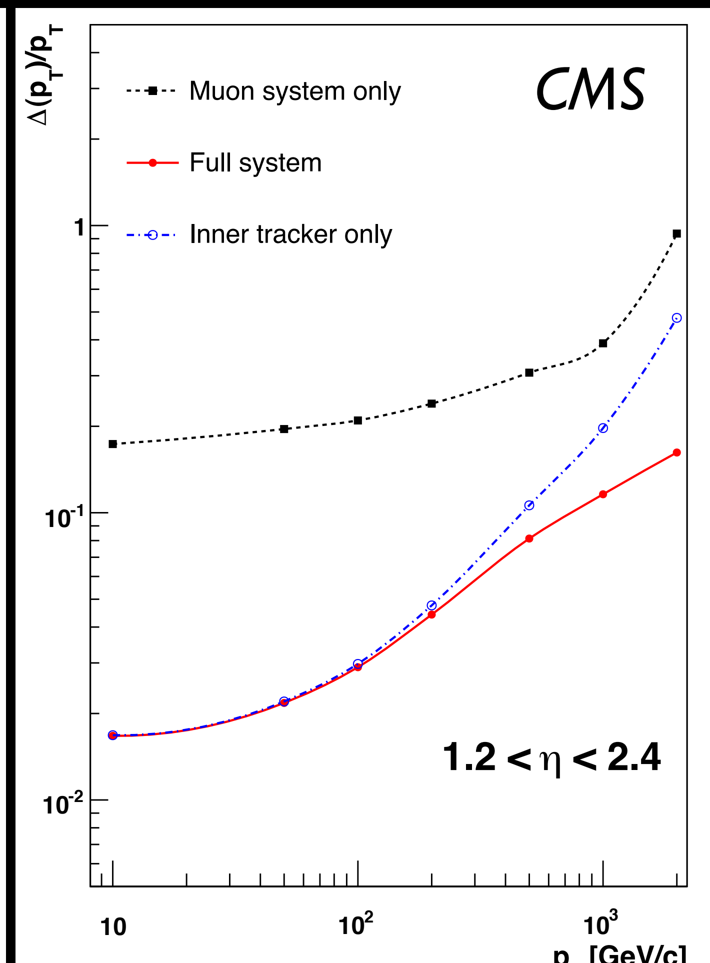


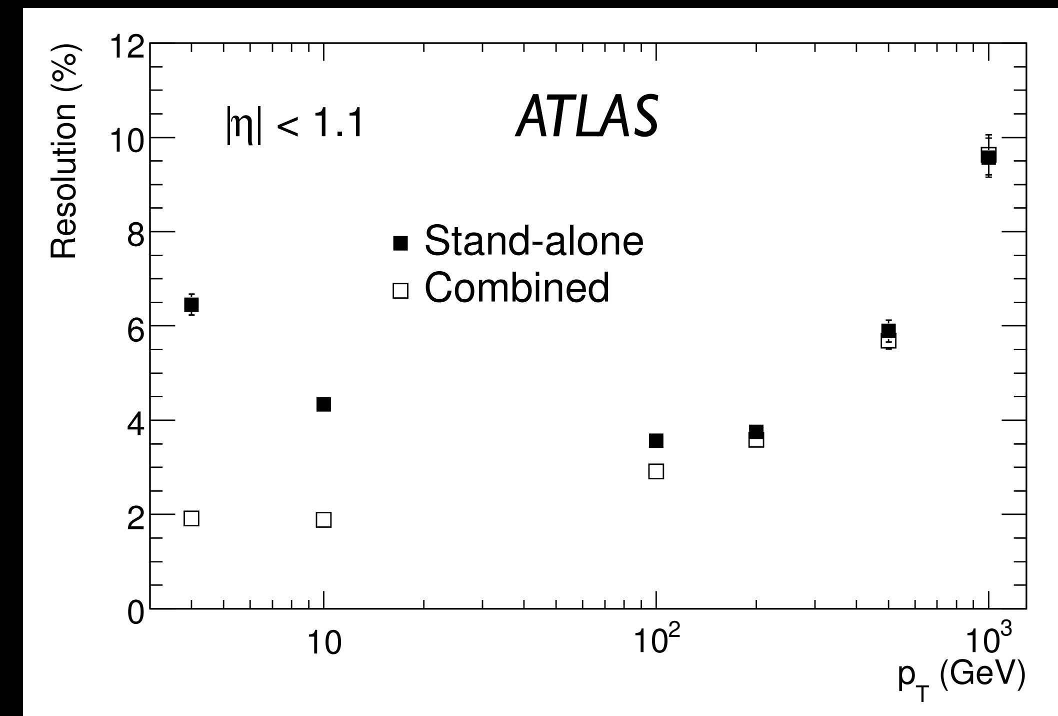


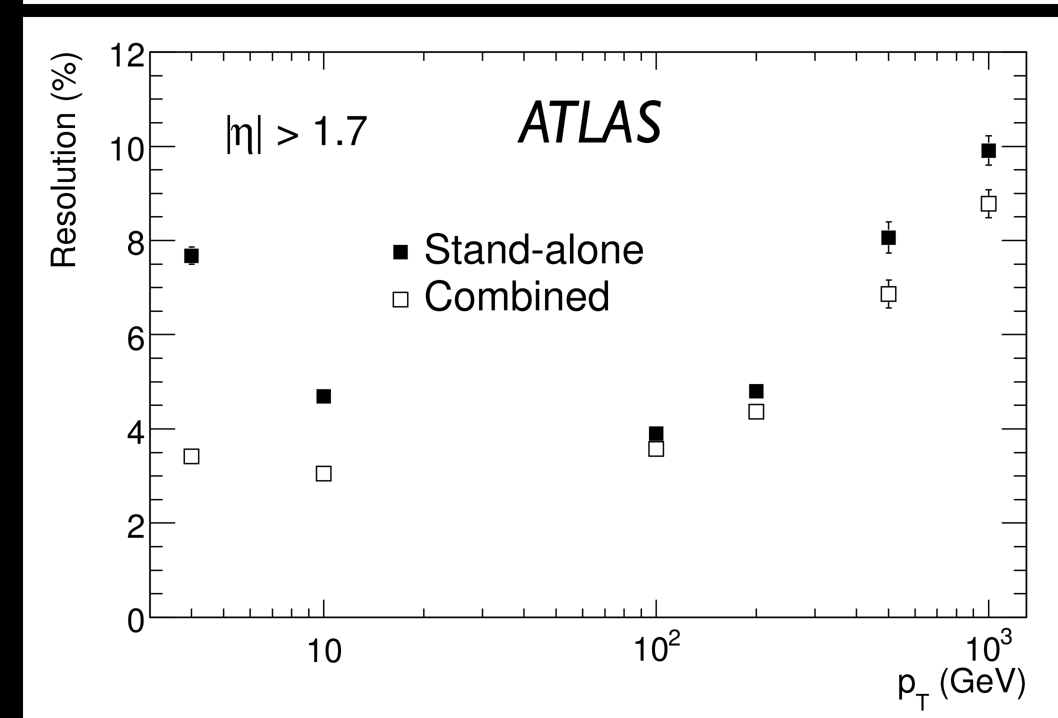
- **Muon Drift Tubes**
  - ➡ magnetic field return in iron yoke of solenoid
  - ➡ combine with precise p_T measurement in Tracker
- **Cathode Strip Chambers**
  - ➡ in the endcaps
- **Resistive Plate Chambers**

Expected Momentum Resolution





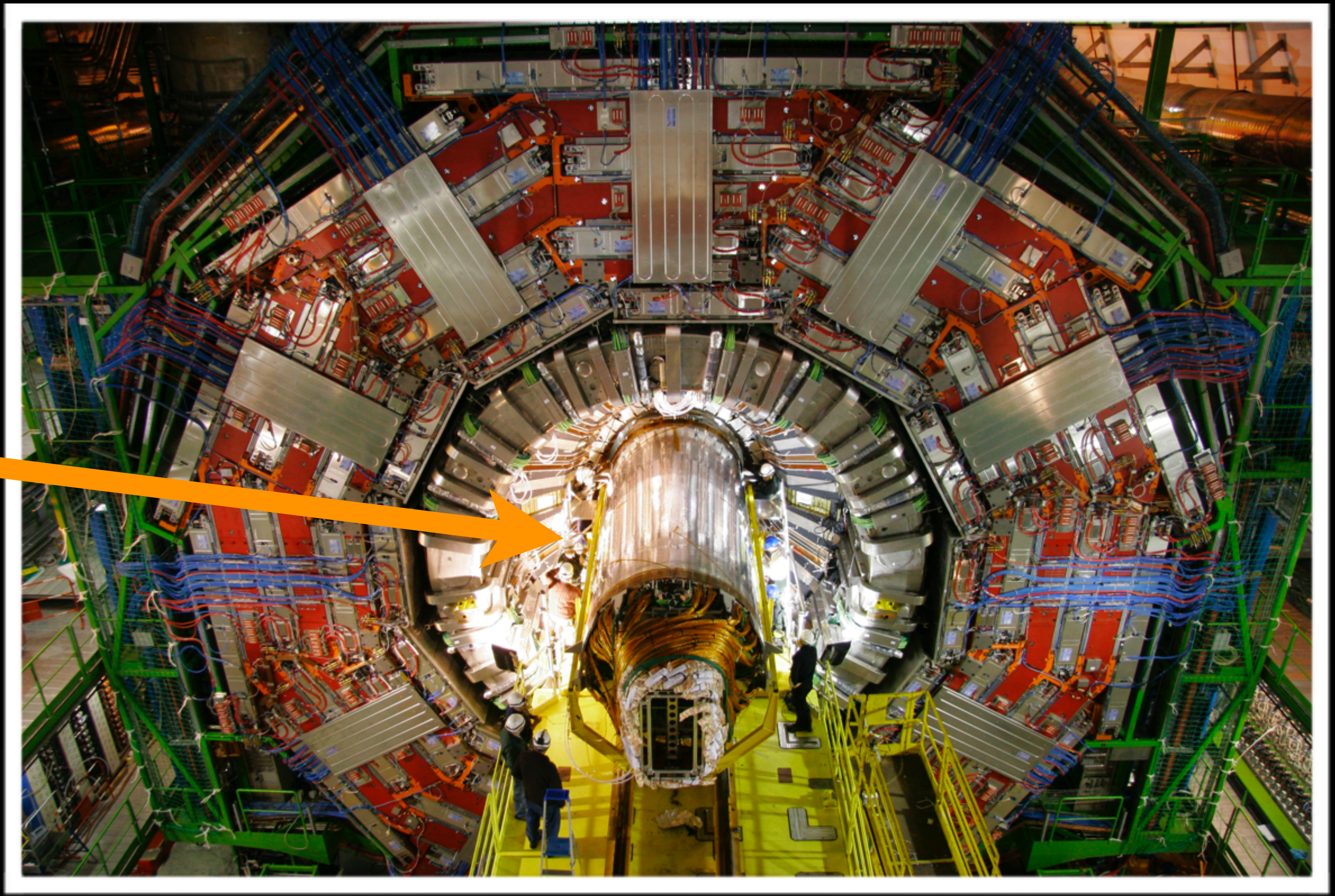


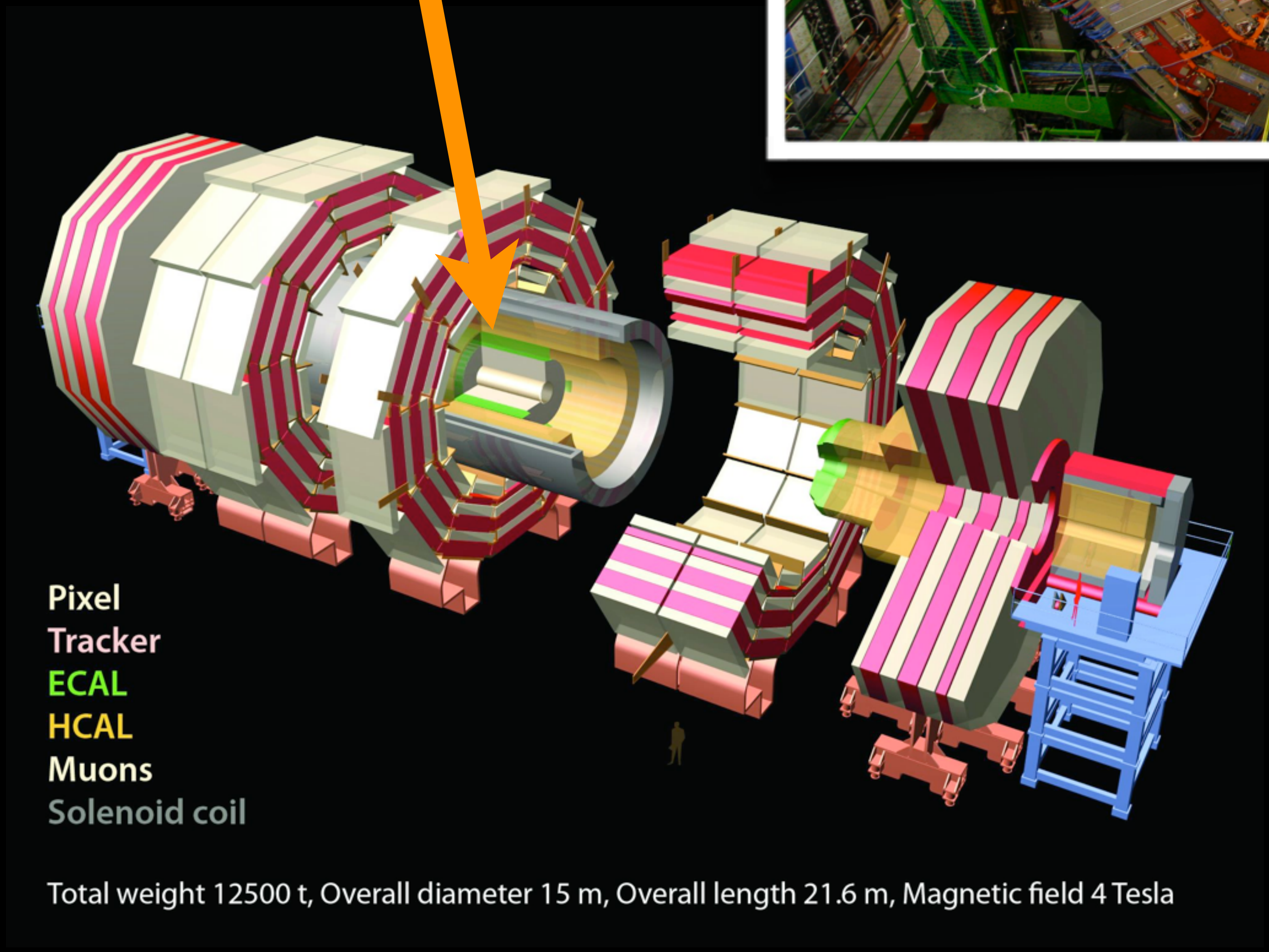


- comparable performance
  - ➡ CMS benefits from good Inner Tracker resolution
  - ➡ in ATLAS Muon Spectrometer dominates at high p_T
  - ➡ ATLAS has slightly larger η coverage

CMS

- in the following will concentrate on the central trackers





Constraints on Tracking Detectors

- high occupancy, high radiation dose, high data rate
  - ➡ during Run-1/2 we operated with more than **35 interactions** per p-p bunch crossing
    - more than a **2000 charged particles** in tracker, every 25 ns
  - ➡ 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...
  - ➡ **minimise material** to optimise tracking performance and to minimise 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

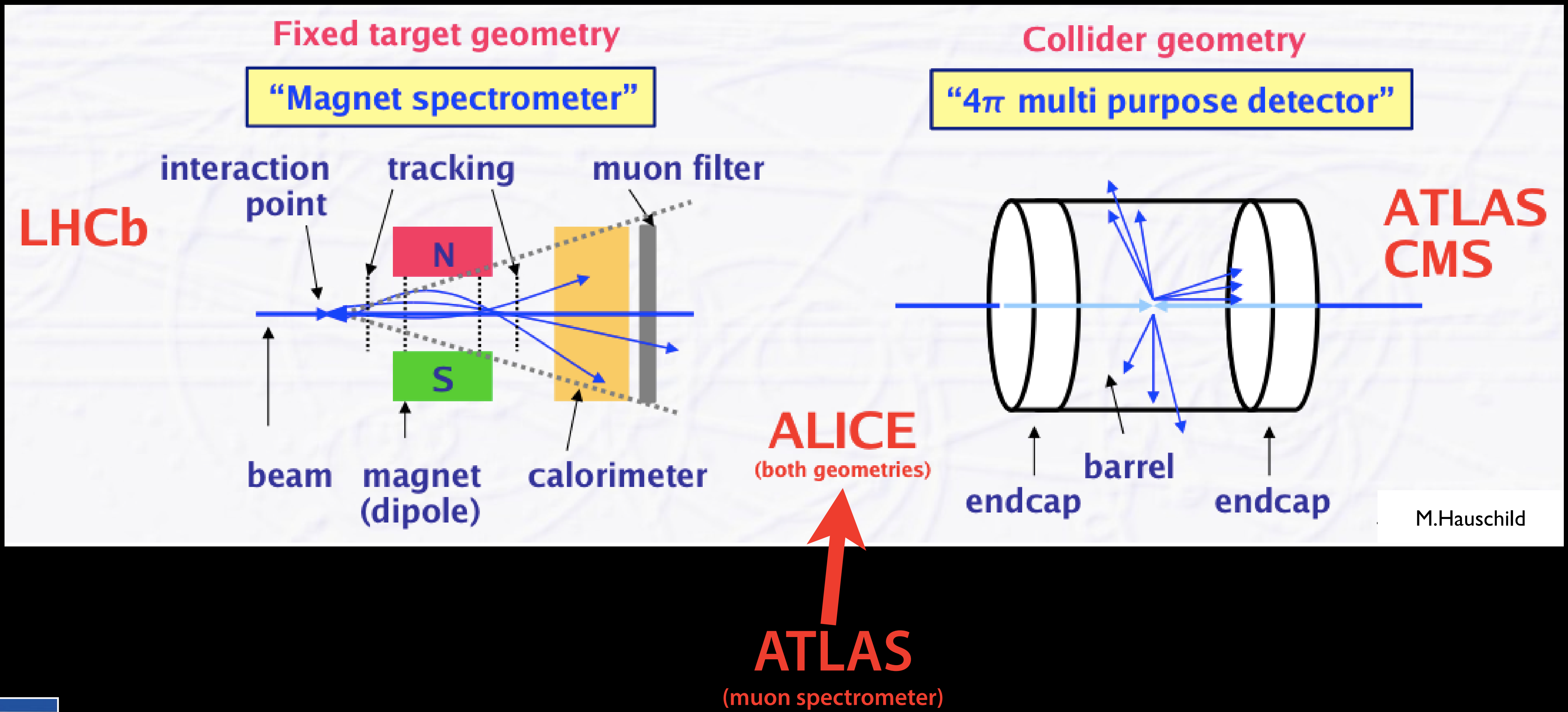
- tracker also contribute to particle identification (PID)
  - ➡ use dedicated detectors to distinguish different particle types
    - Transition Radiation detectors also contribute to tracking
    - Ring Imaging Cherenkov detectors
    - time of flight
- match central tracks with muon chamber segments
  - ➡ muon chamber information improves muon momentum measurement
- match tracks with showers in the calorimeter
  - ➡ e.g. identify electron tracks matching electromagnetic showers
- pileup mitigation and particle flow for jets and missing energy
  - ➡ with the increase in LHC luminosity the use of tracking to reduce pileup effects and to improve jet and missing energy resolution

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 muon detectors
- 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

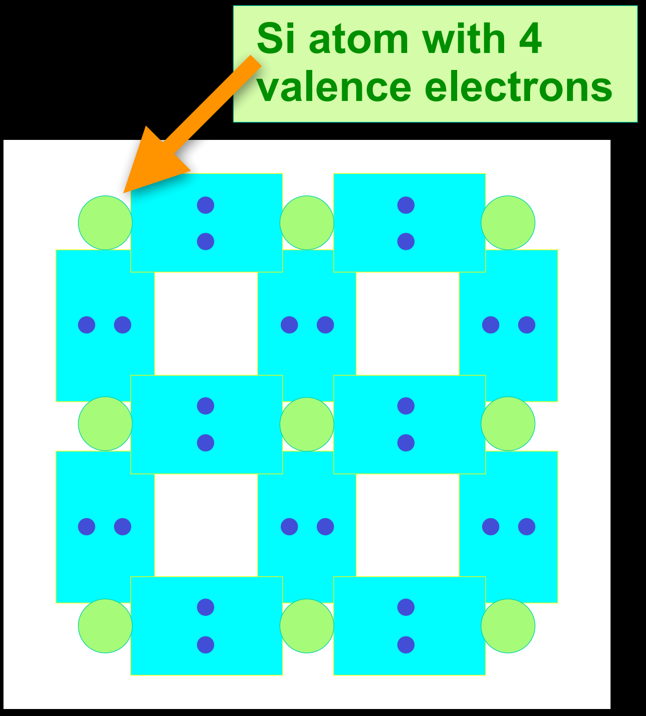
- layout of the tracking detectors
  - ➡ follow the typical geometry of fix target and collider experiments

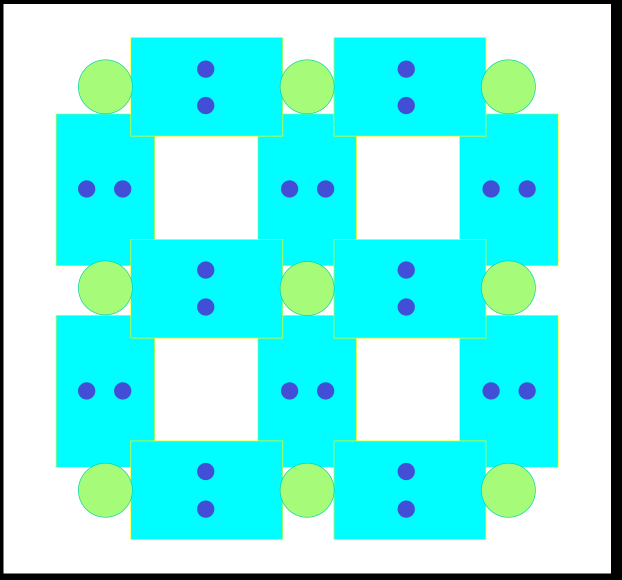


Semiconductor Trackers

Semiconductors as Particle Detectors

- schema of a silicon diode (p-n junction)
  - ➡ doping silicon cristal semiconductor to implant excess electrons or "holes"





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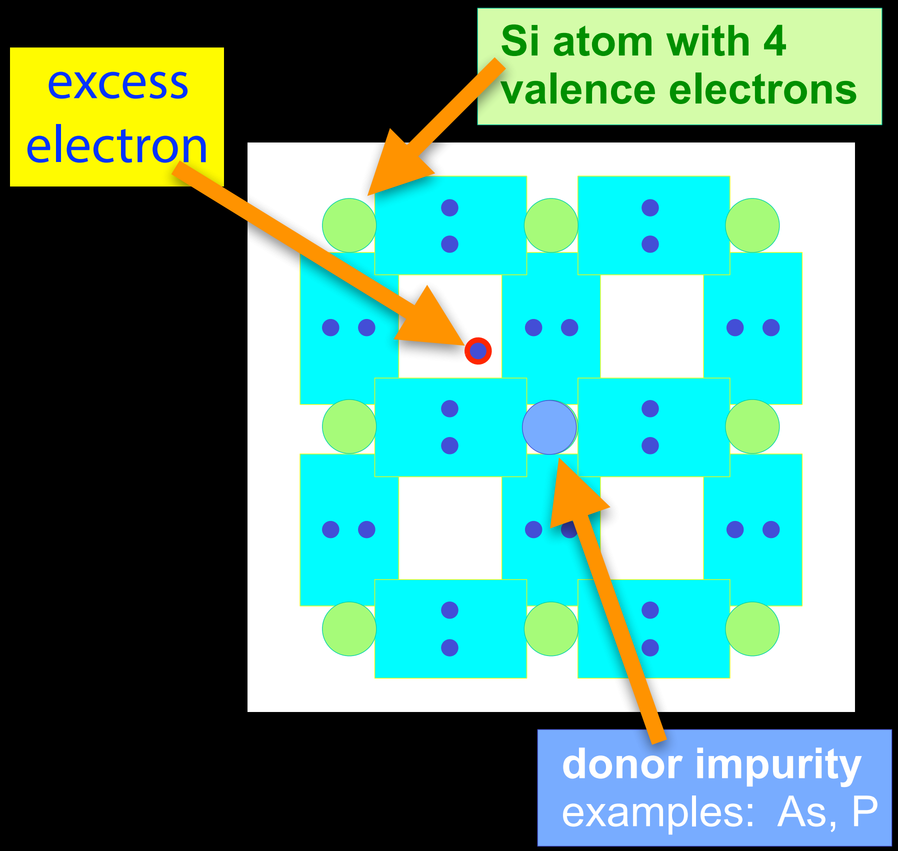

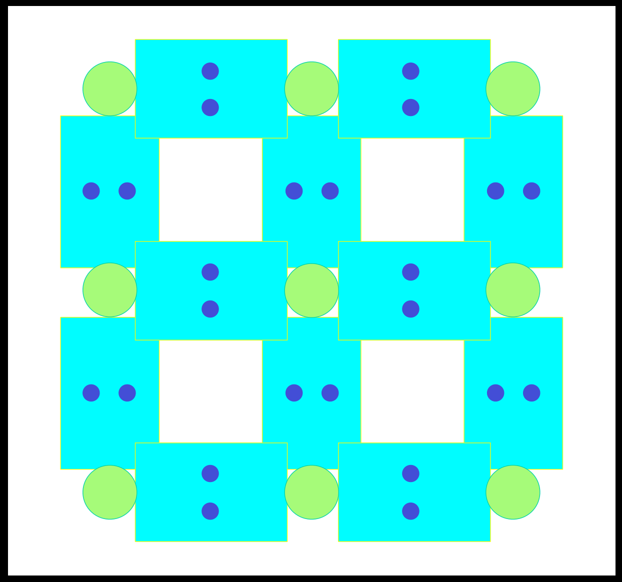

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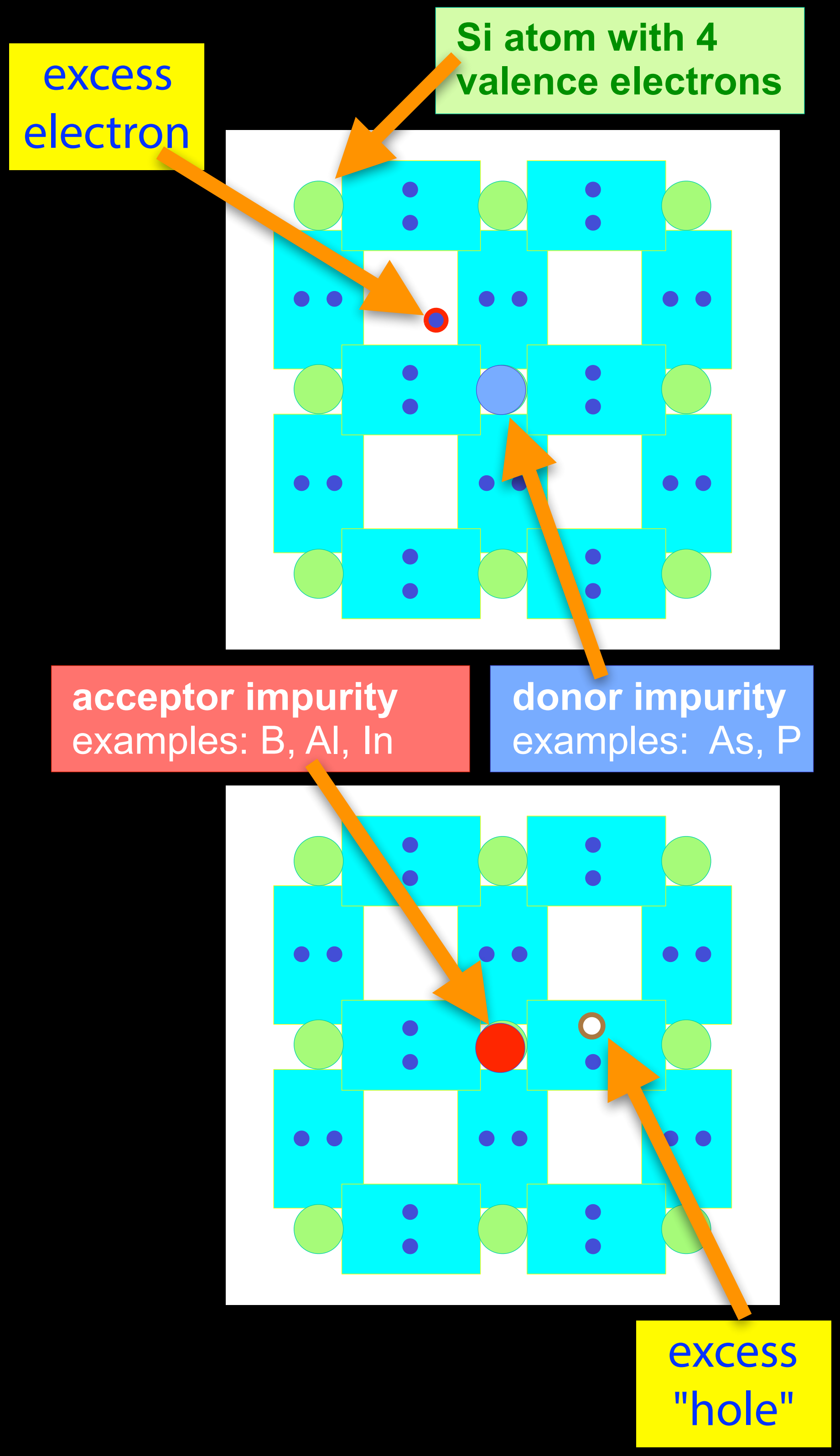

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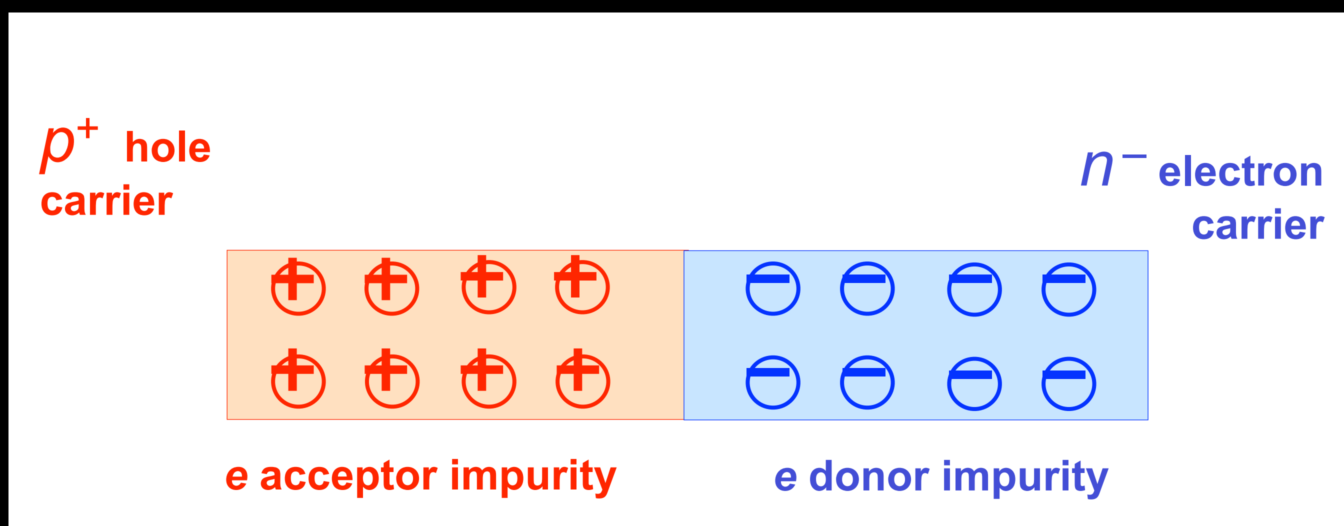

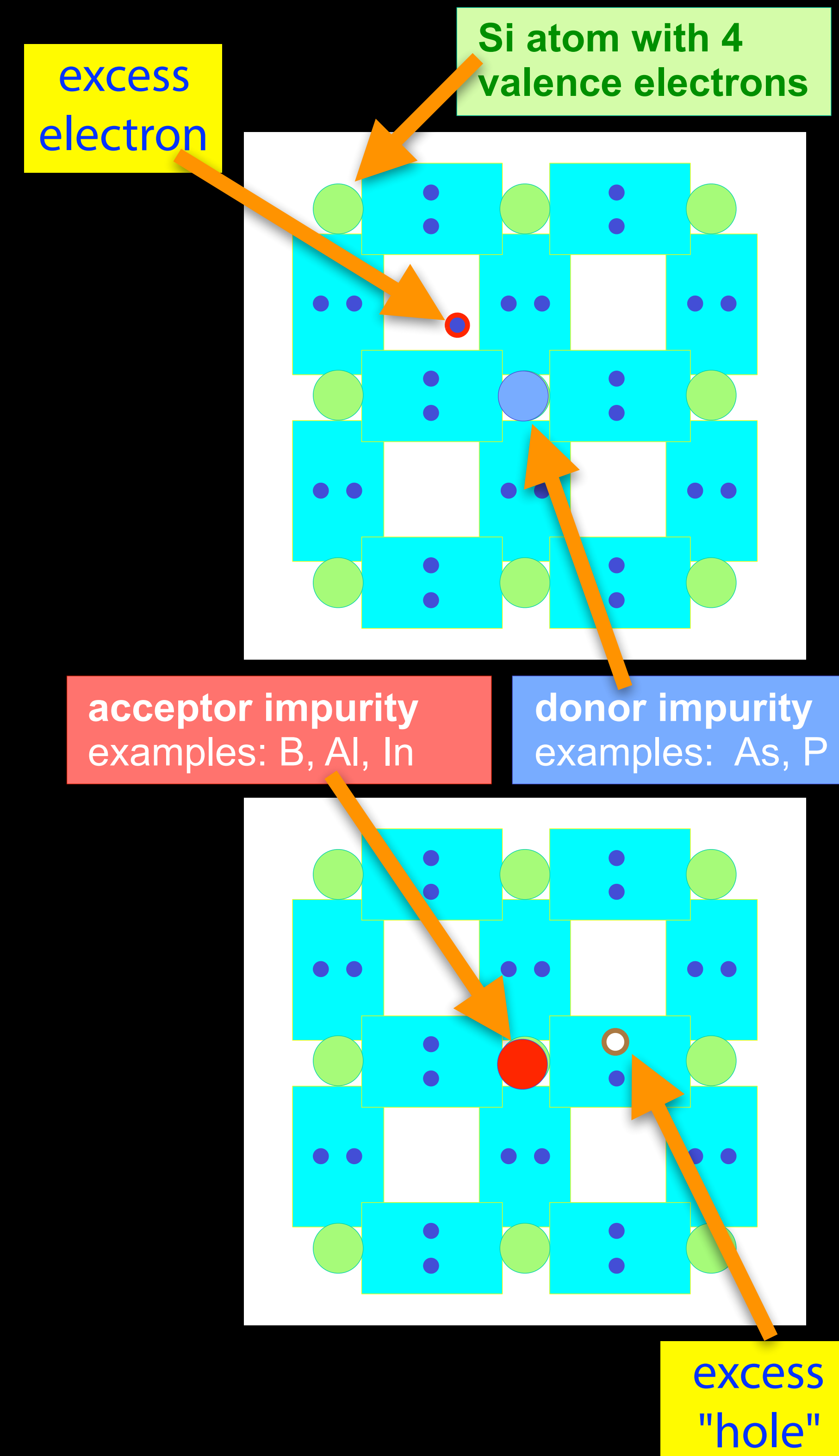

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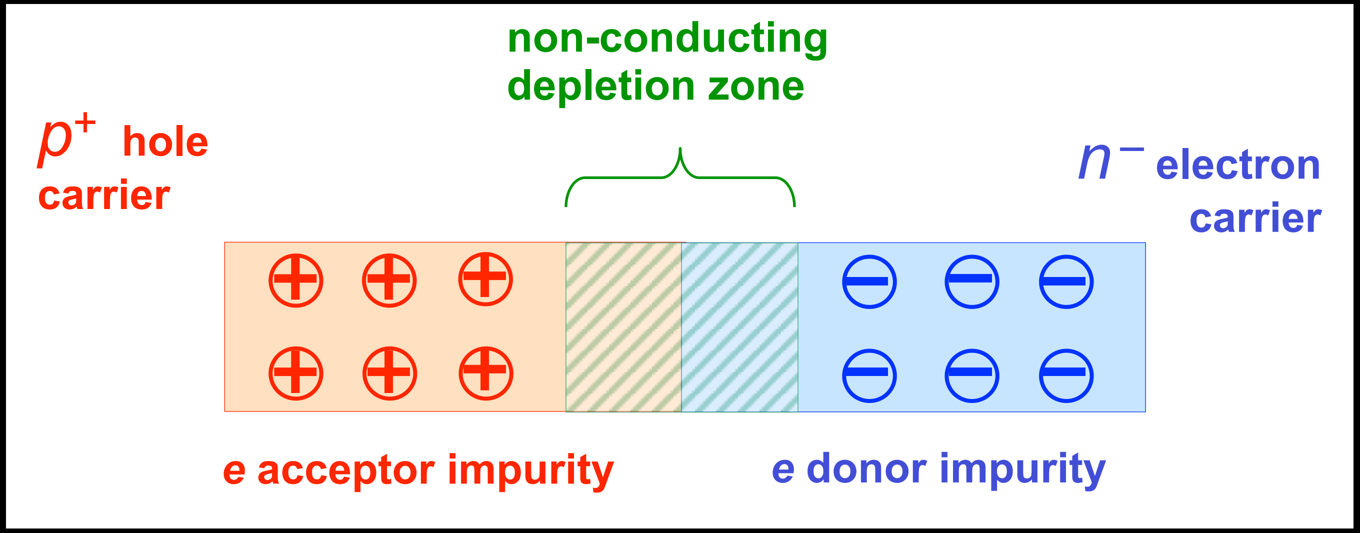

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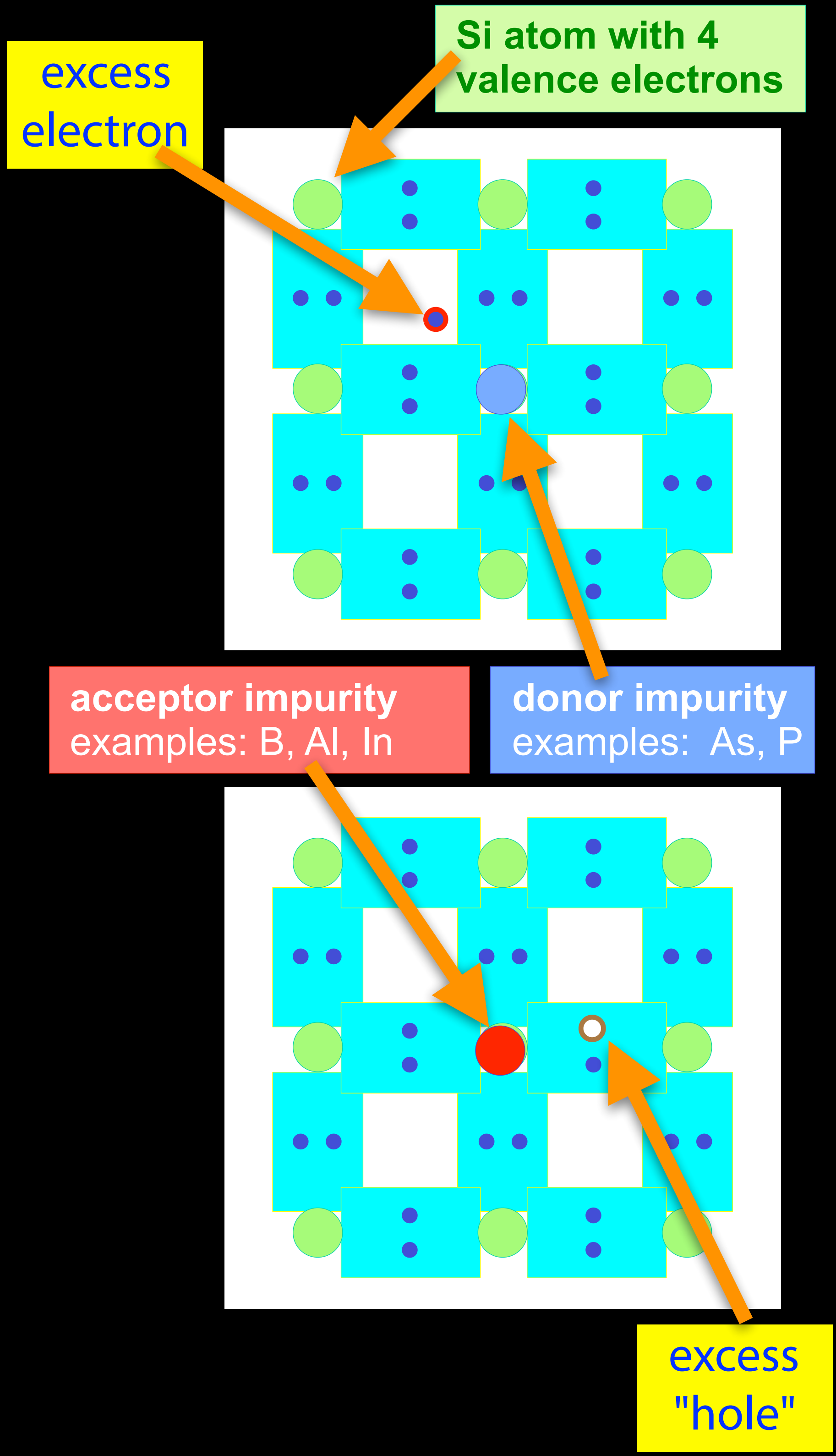

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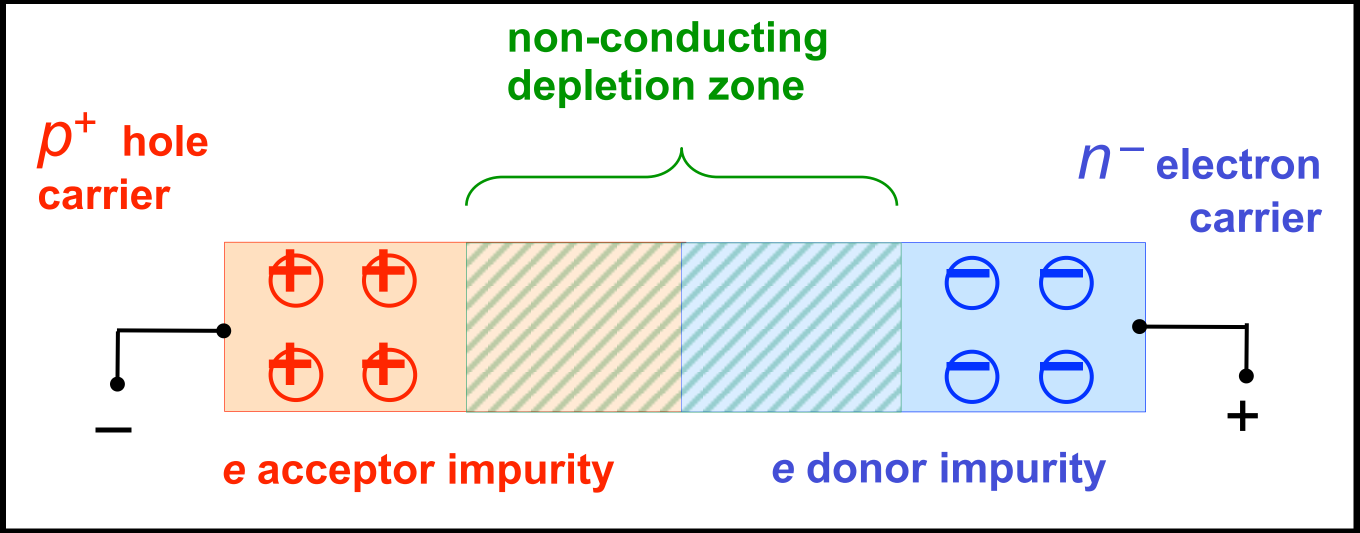

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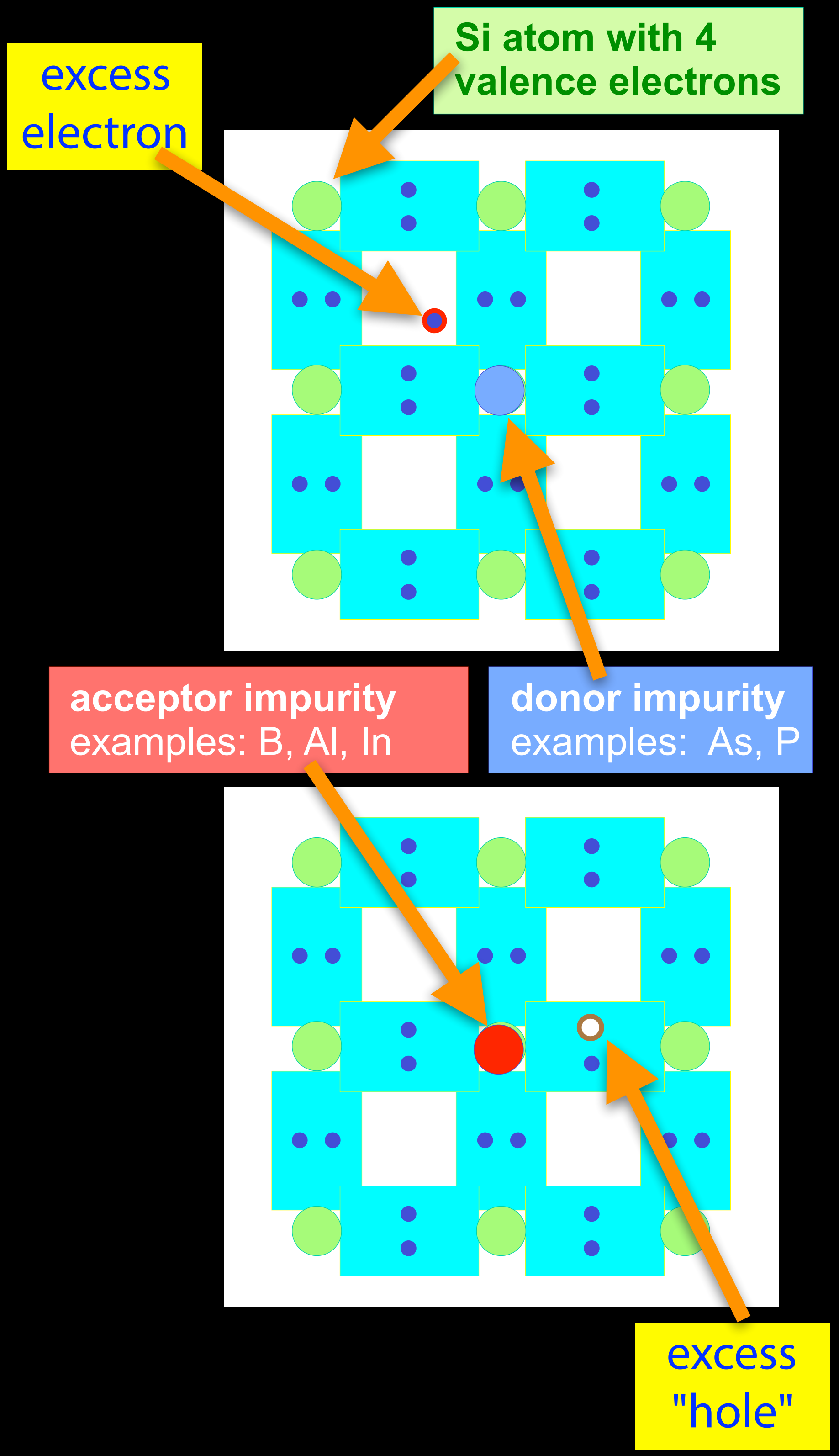
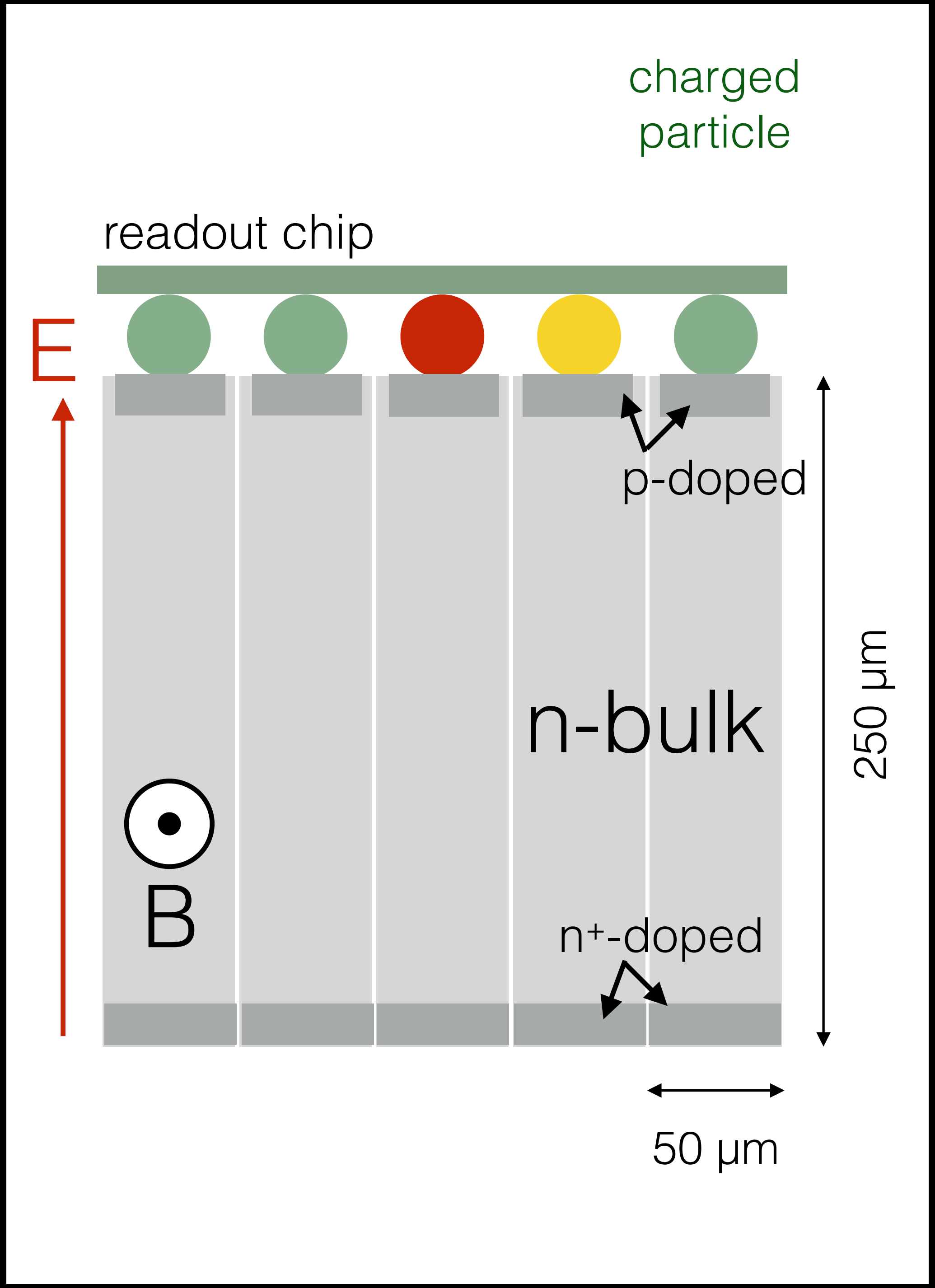
- apply reverse bias voltage to enlarge potential barrier in depletion zone, increases its resistance further



Semiconductors as Particle Detectors

- basic schema of a silicon detector
  - ➡ many reverse biased large diodes on a silicon wafer
    - allows for small structures, typical pitch is 50 μm



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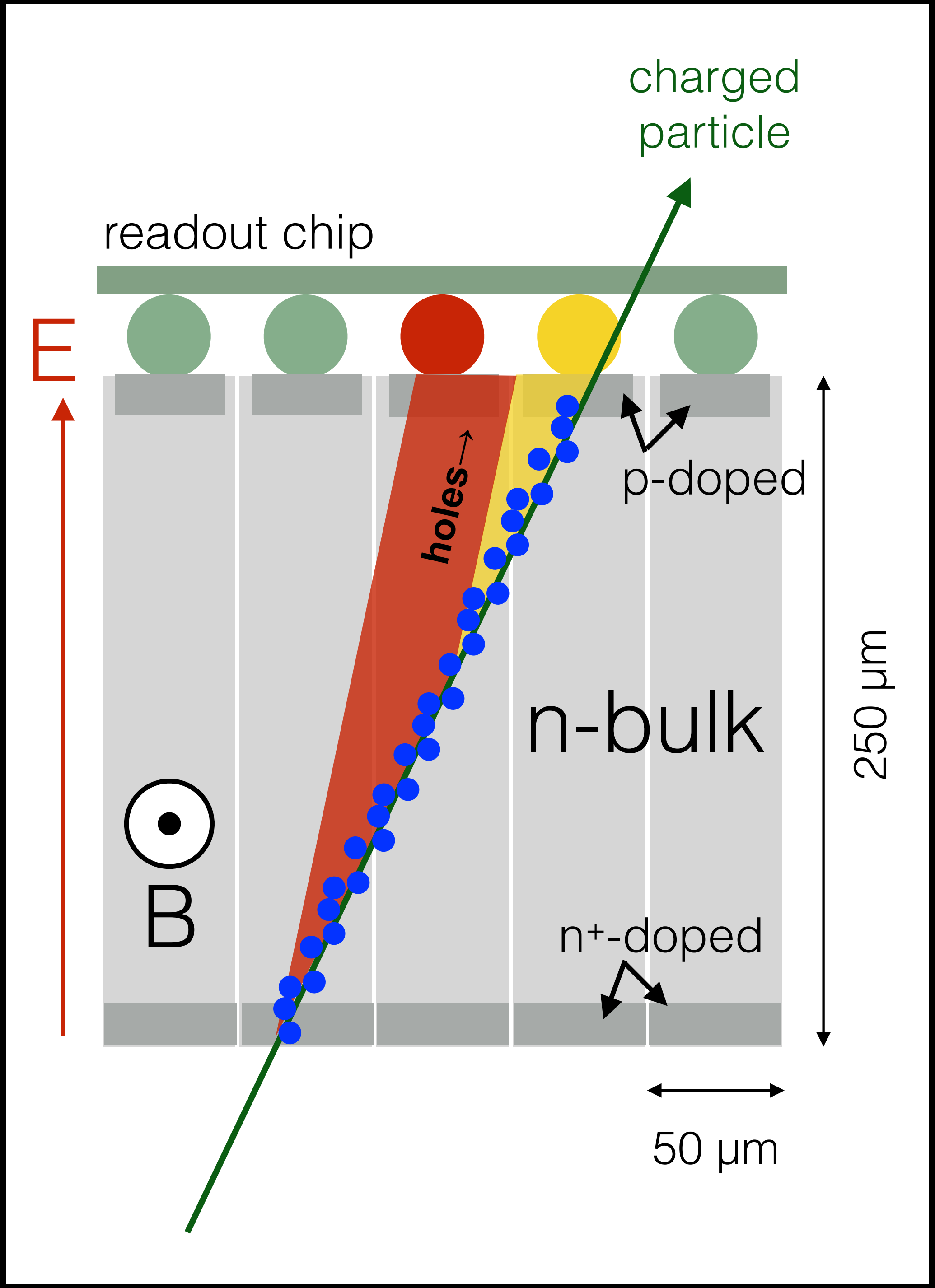

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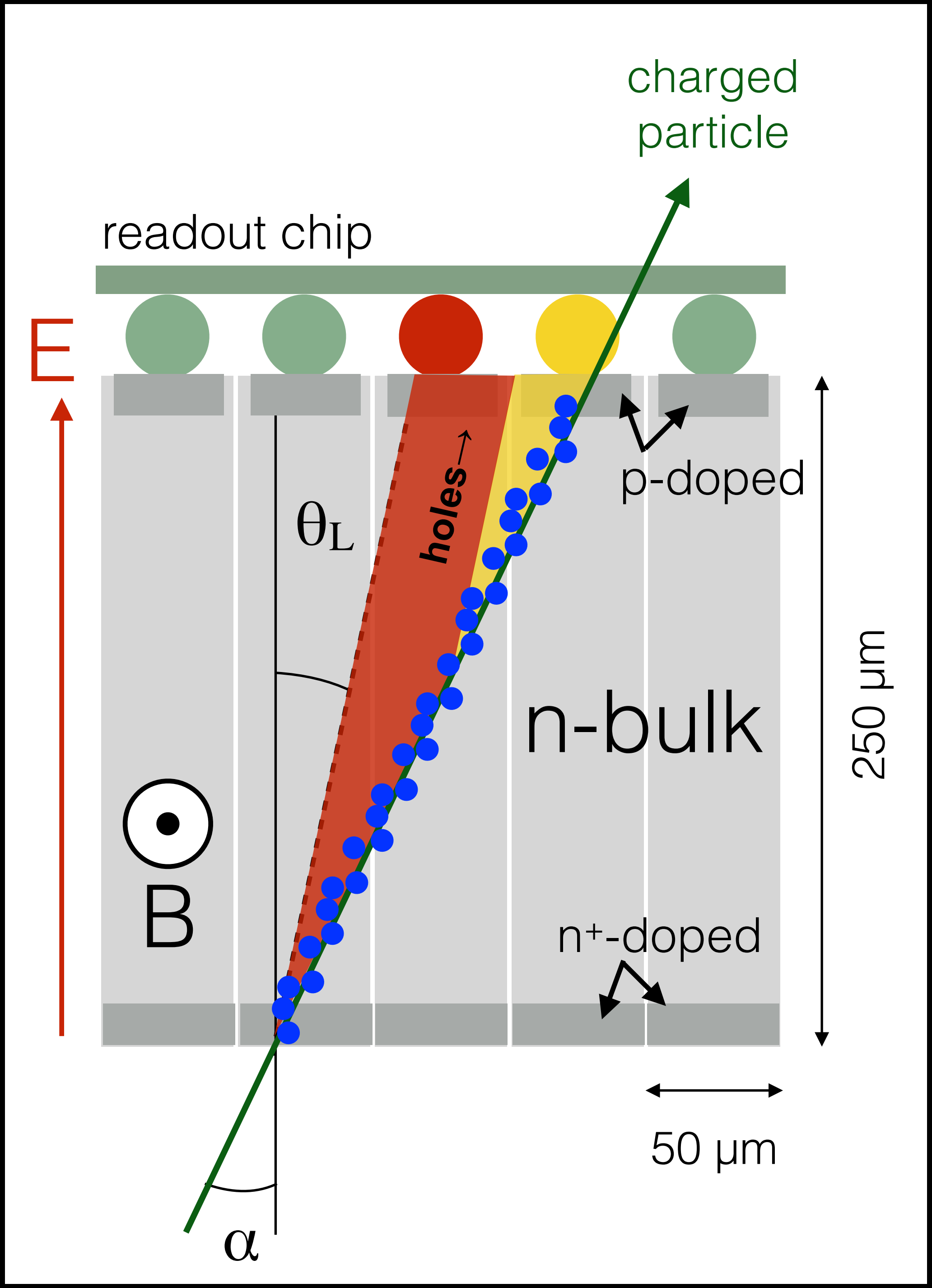

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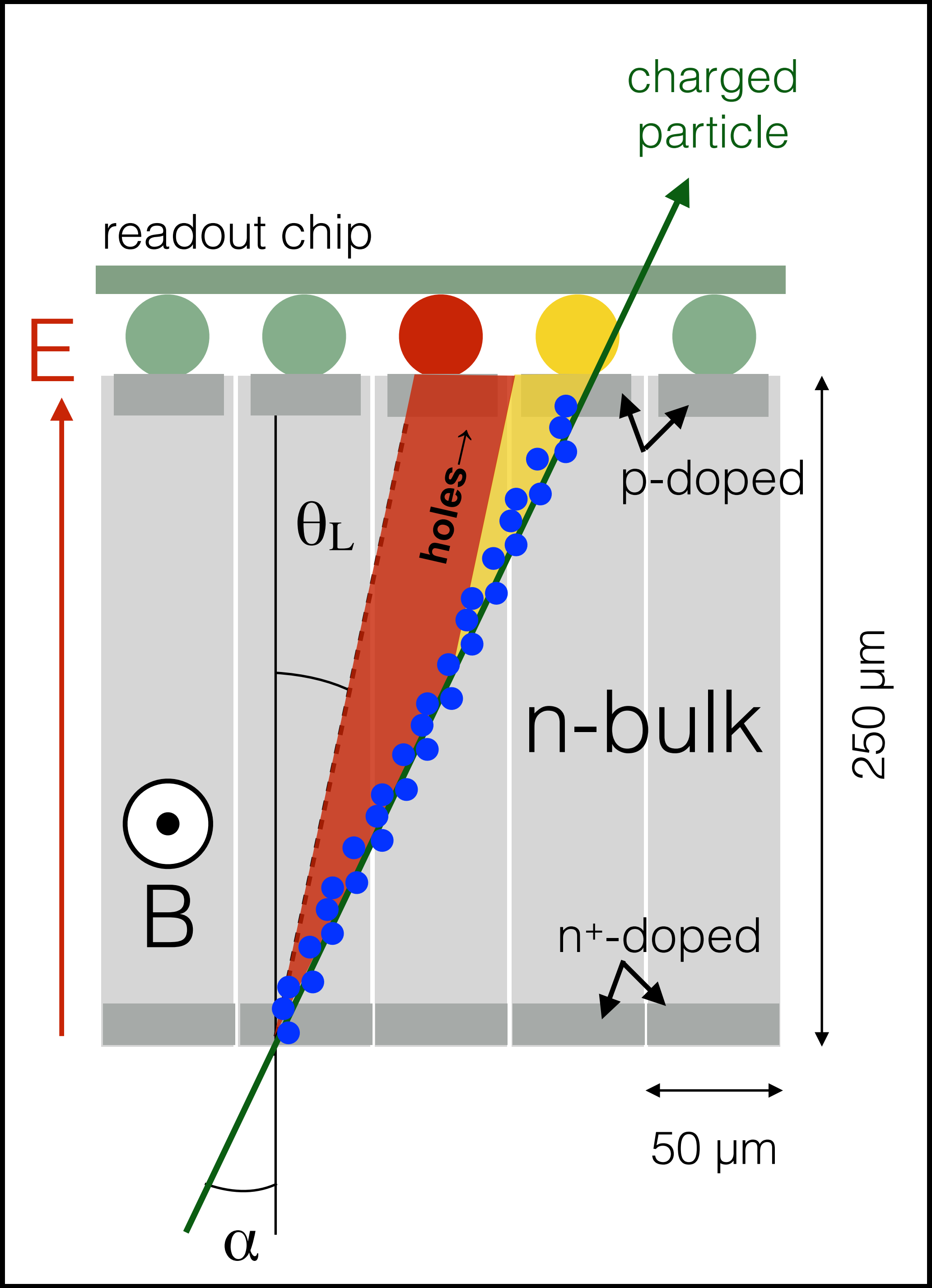
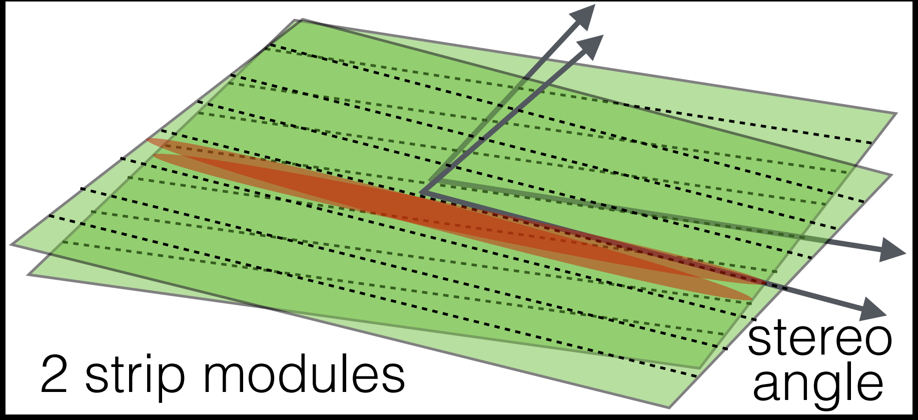
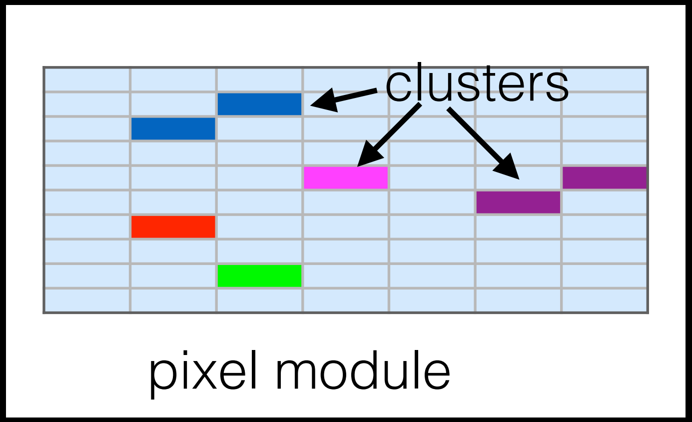
- 2 types: silicon strips and pixels
  - ➡ strip module: 50 µm pitch, wafers with ~6 cm diodes
    - needs 2 modules to measure both coordinates
  - ➡ pixel module: e.g. 50x400 µm pixel, analog readout
    - clusters measures precisely both coordinates

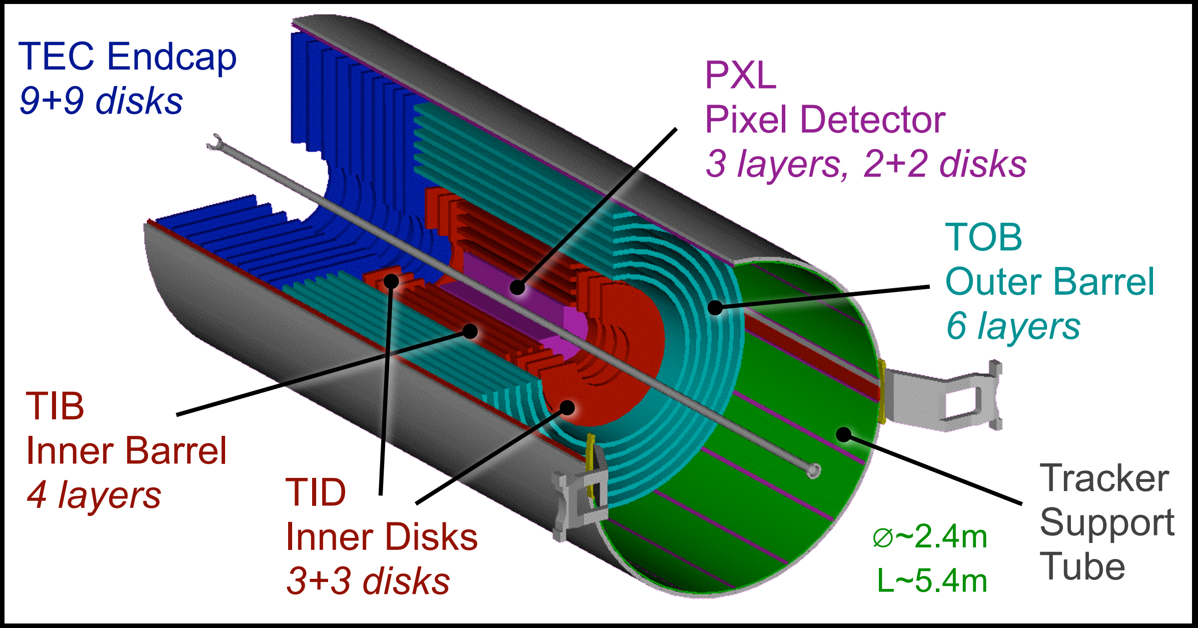




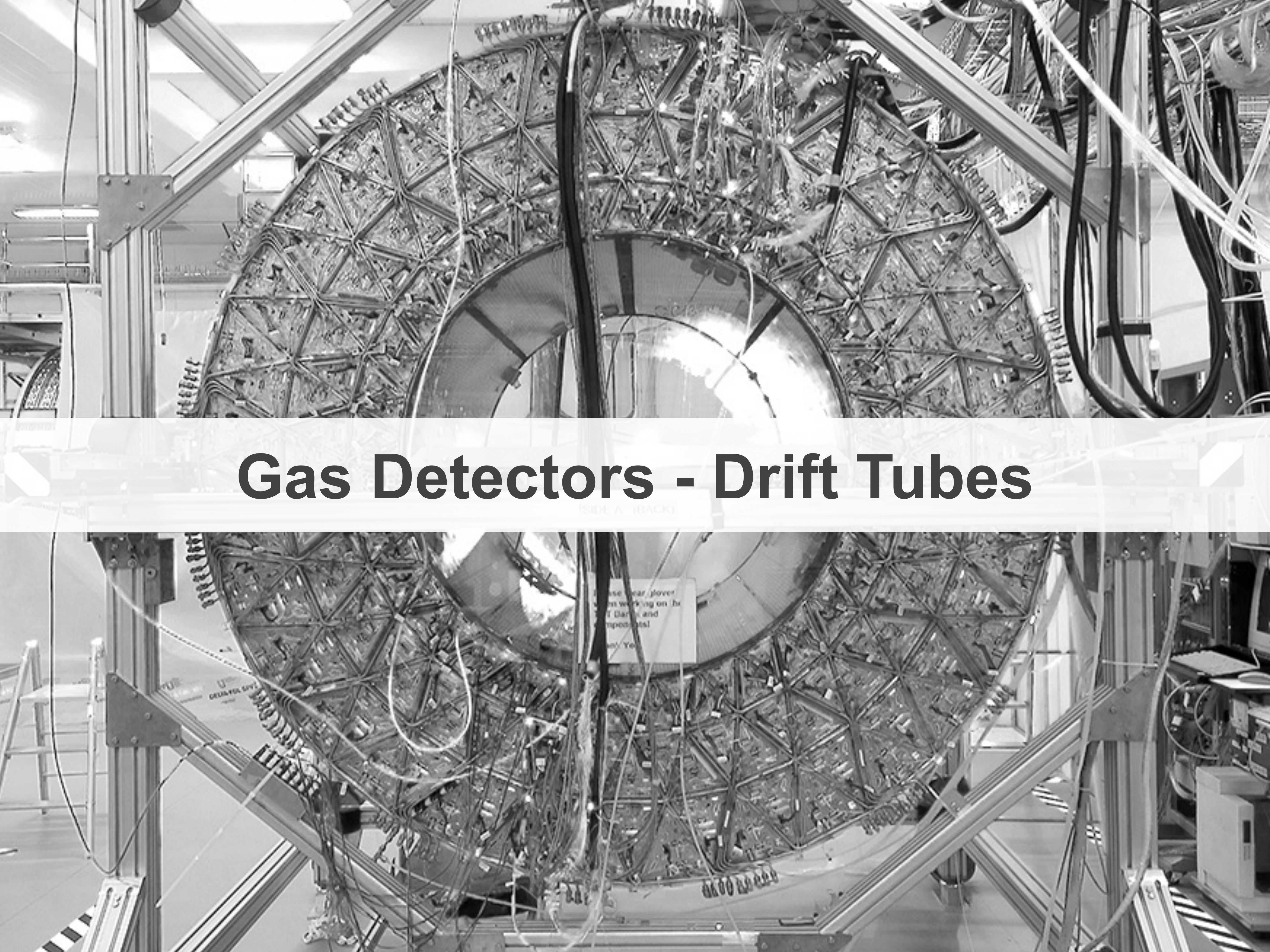


CMS Tracker

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

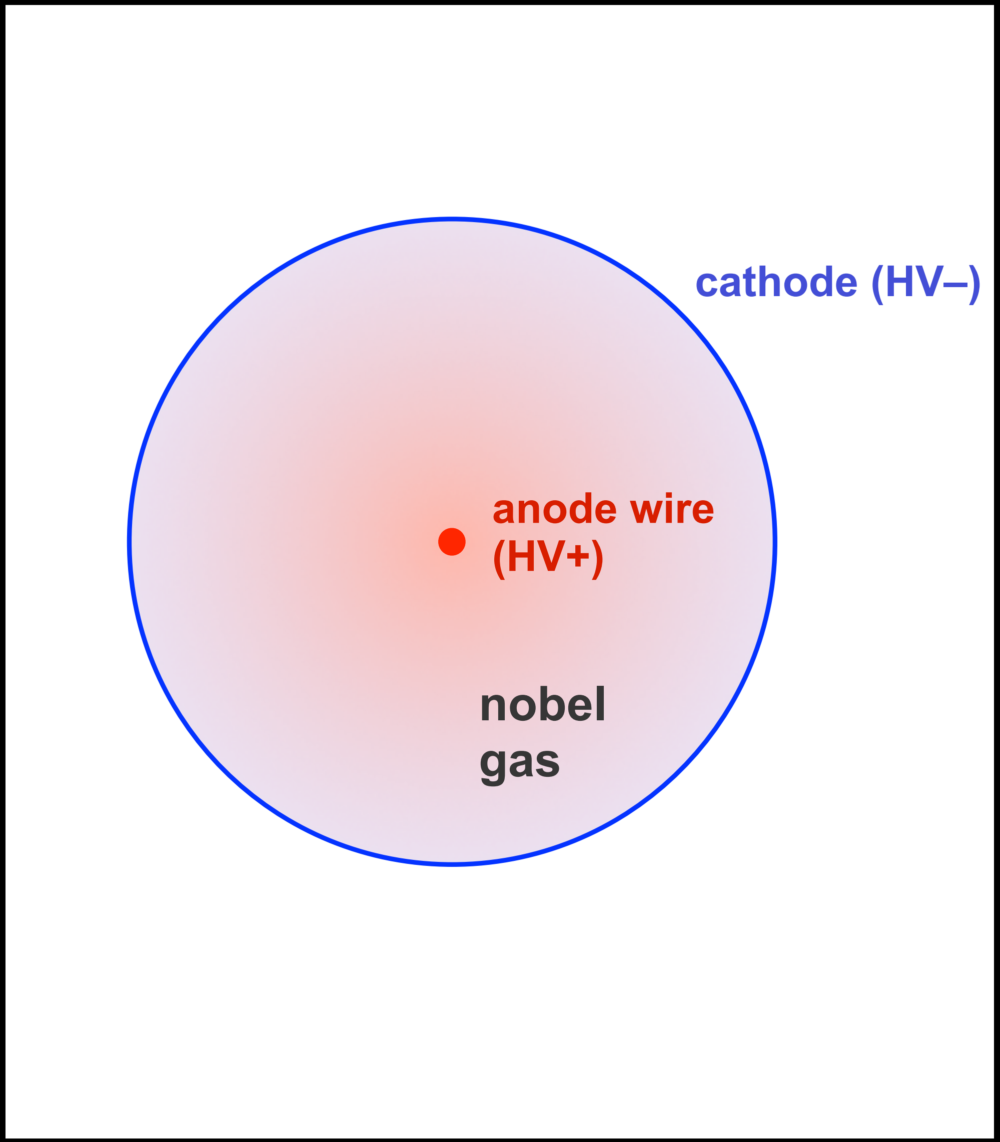


Gas Detectors - Drift Tubes



Classical Gas Detectors - Drift Tubes

- detection technique for charged particles
  - ➡ used in muon systems and ATLAS TRT



TRT: Kapton tubes, ∅ = 4 mm
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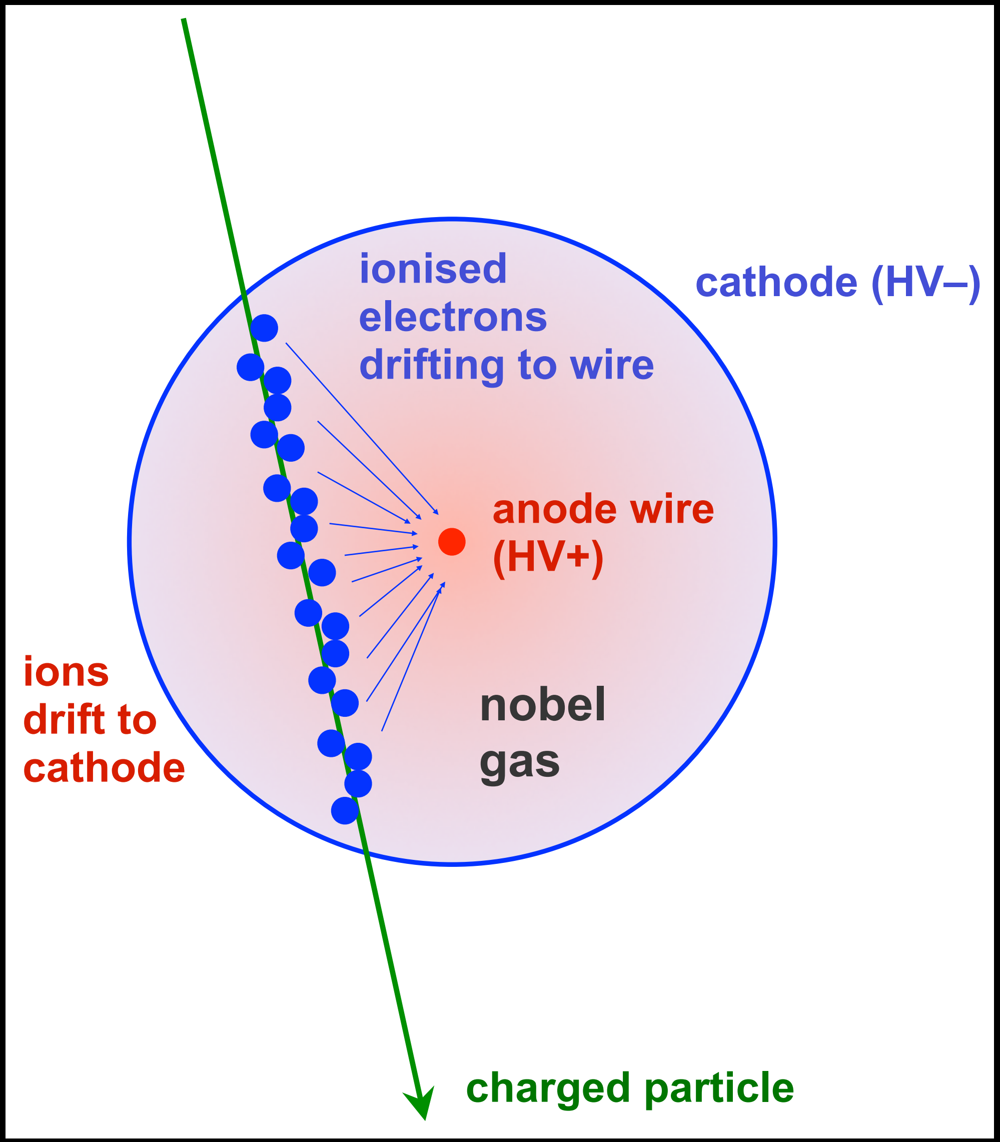
  - ➡ deposited charge drifts to anode wire in electric (E) field
    - charge amplification in high E-field in vicinity of wire leads to large signal pulse
    - Lorentz angle deflection in B-field (not shown)



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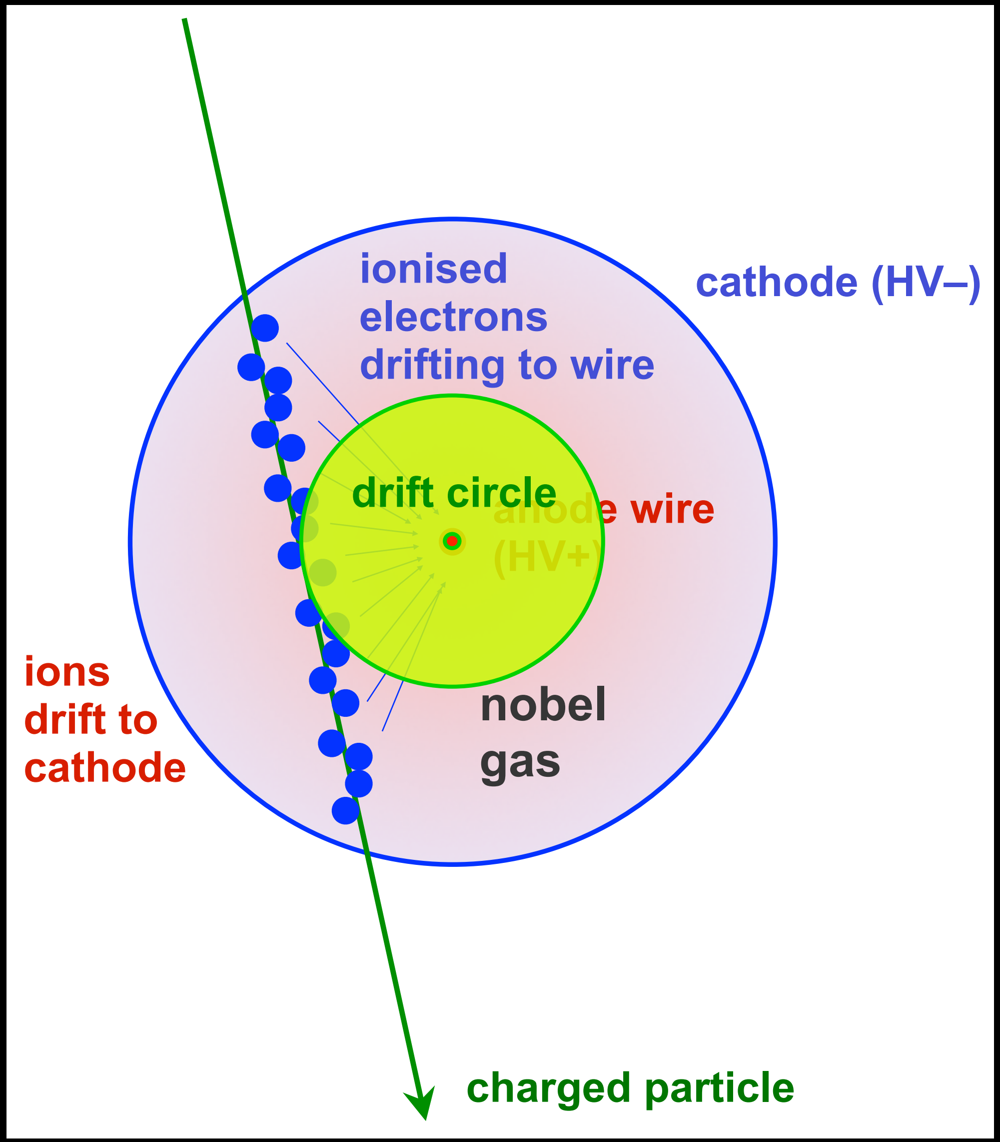
  - ➡ measure time of signal pulse to determine drift circle
    - fast signal detection (v_D~30 ns/mm)
    - resolution of O(100 μm) on measured radius



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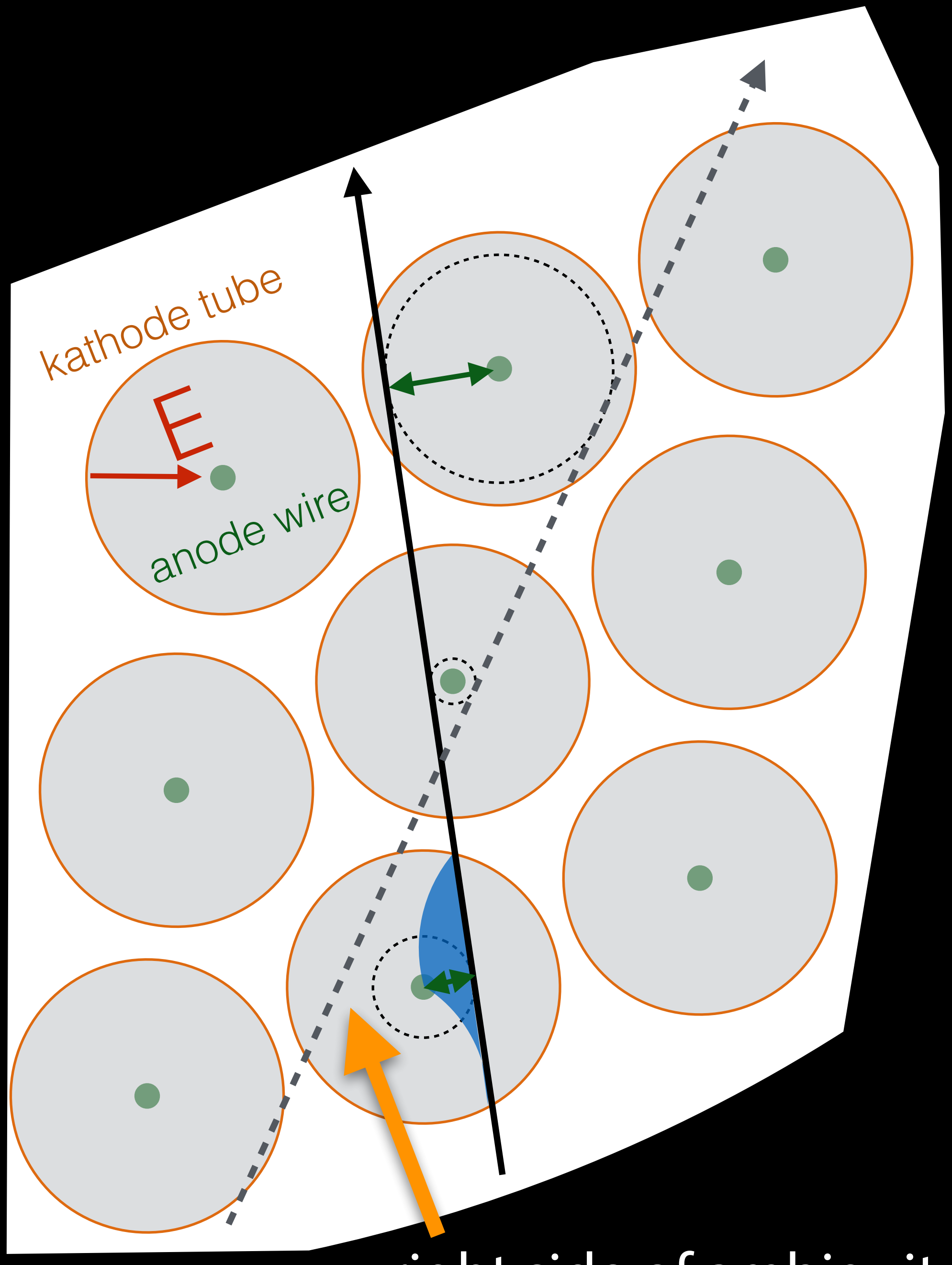
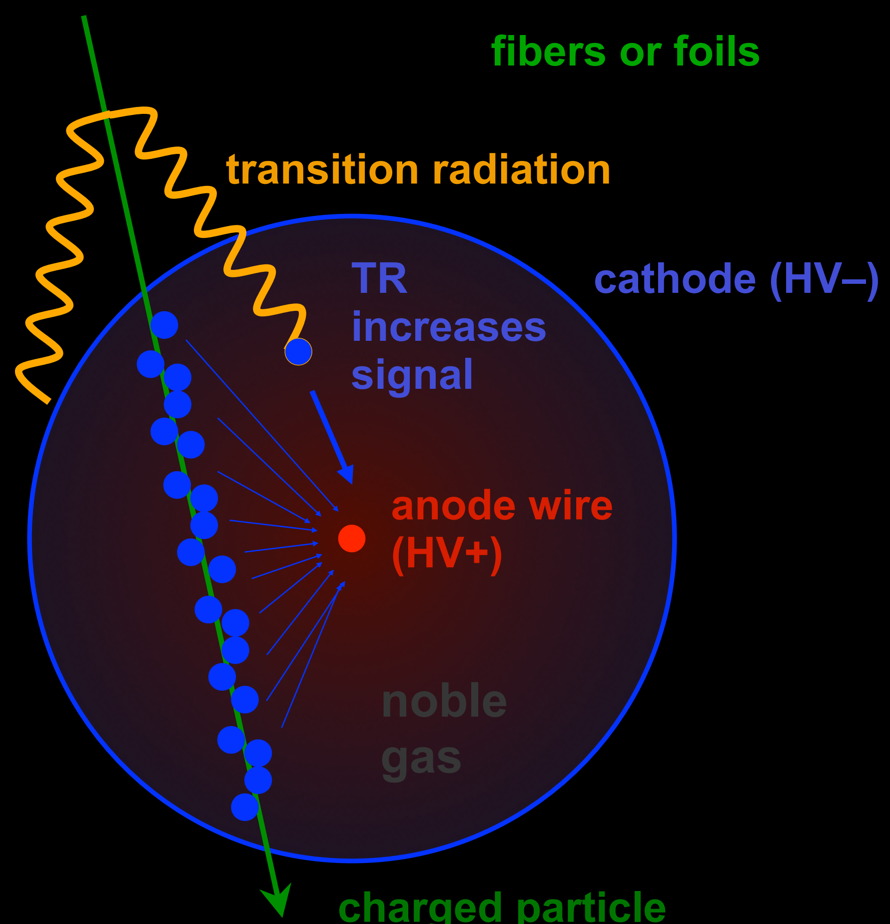
    - fast signal detection (v_D~30 ns/mm)
    - resolution of O(100 μm) on measured radius
- track reconstruction from drift circles
  - ➡ obtain drift radii from measured times
  - ➡ combined several measurements to find track
    - resolve left-right ambiguity (dotted line)
  - ➡ ATLAS TRT: as well electron identification using transition radiation

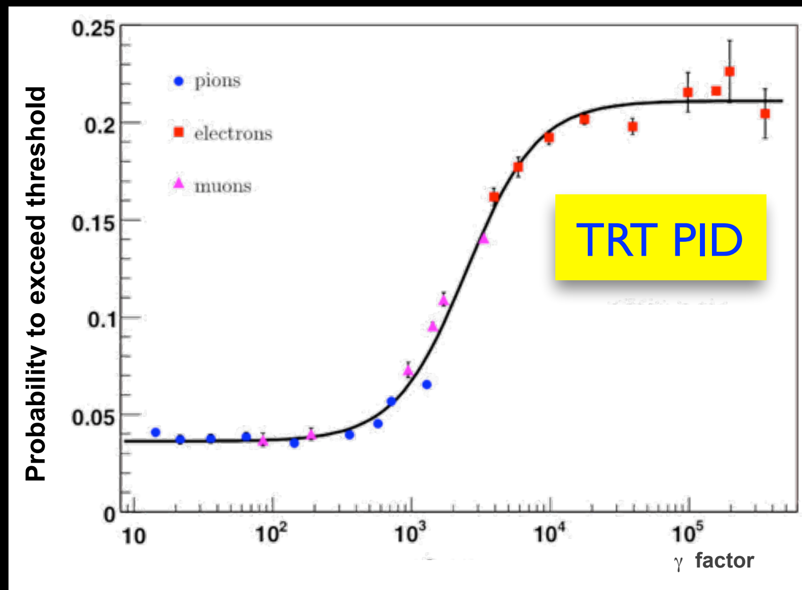


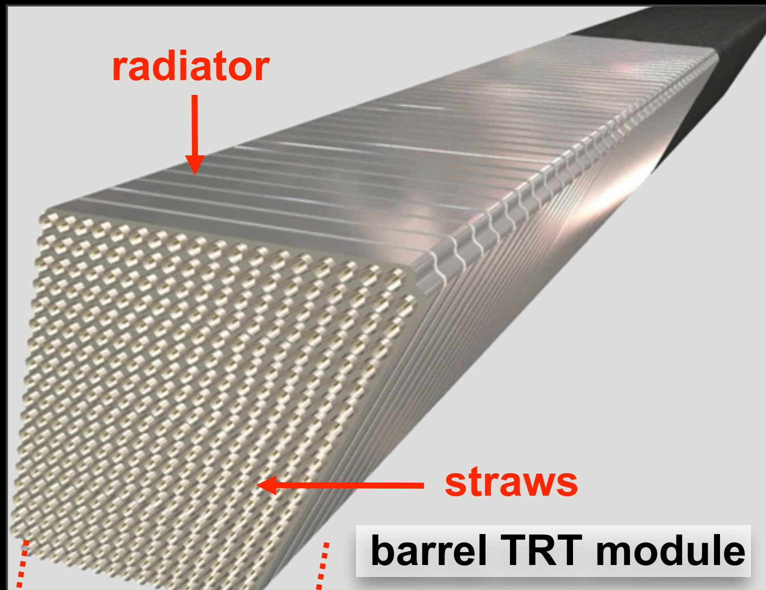
right side of ambiguity has large residual

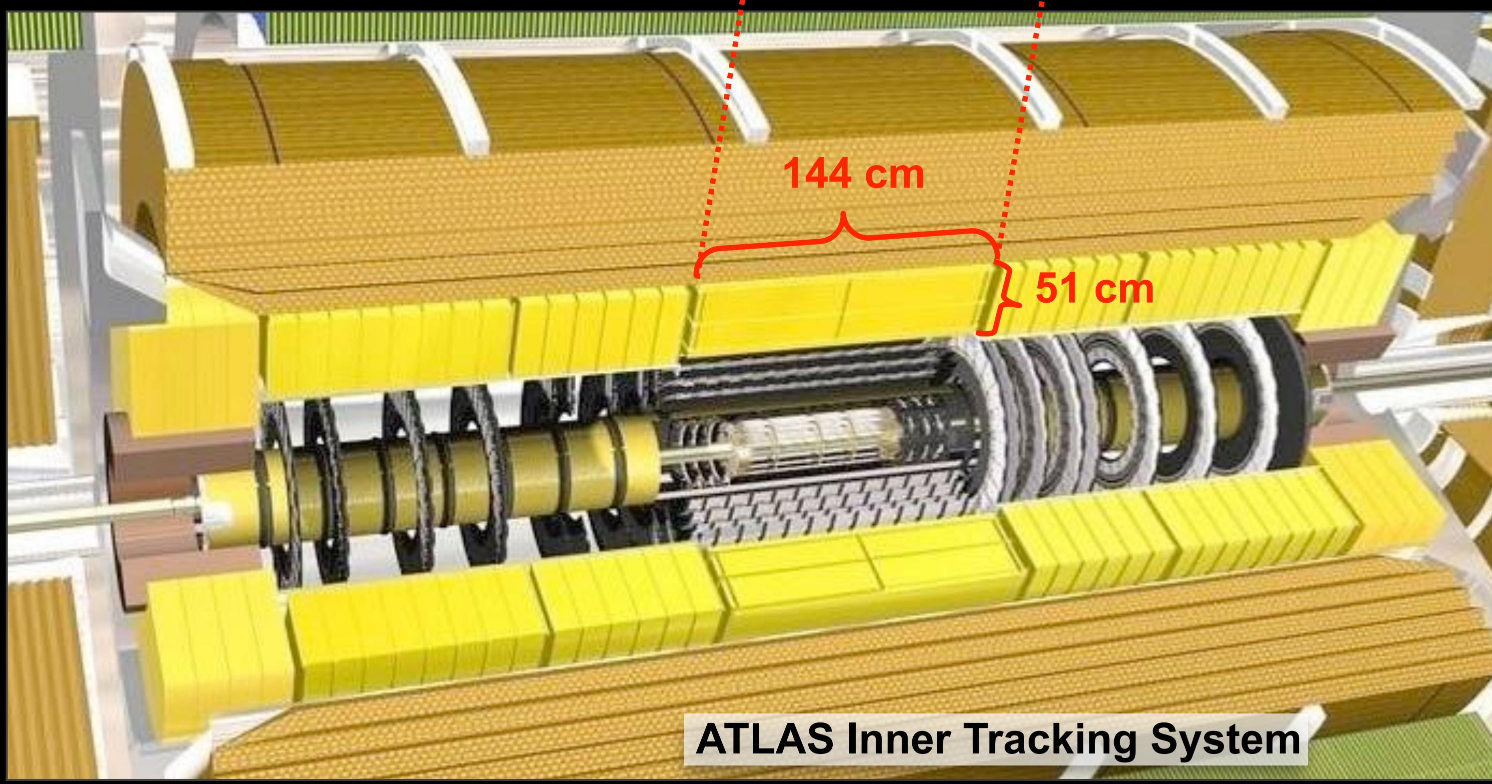
Electron Identification in the ATLAS TRT

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







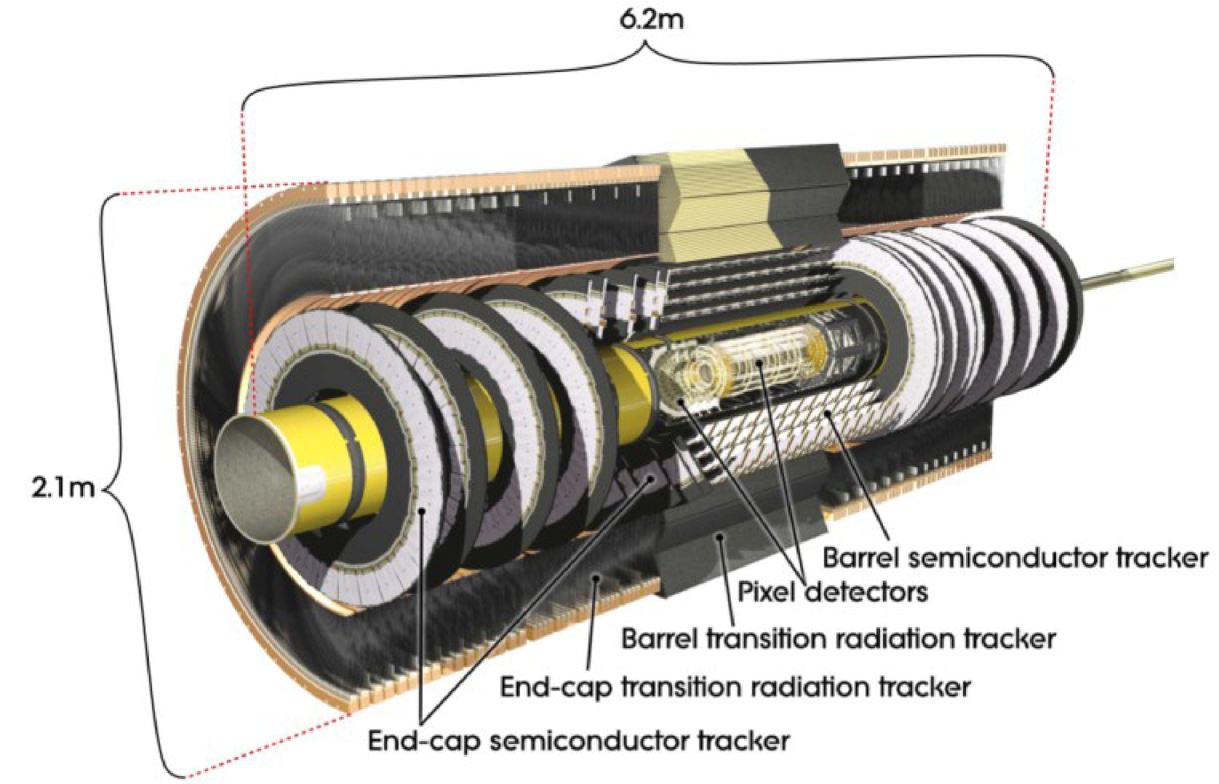


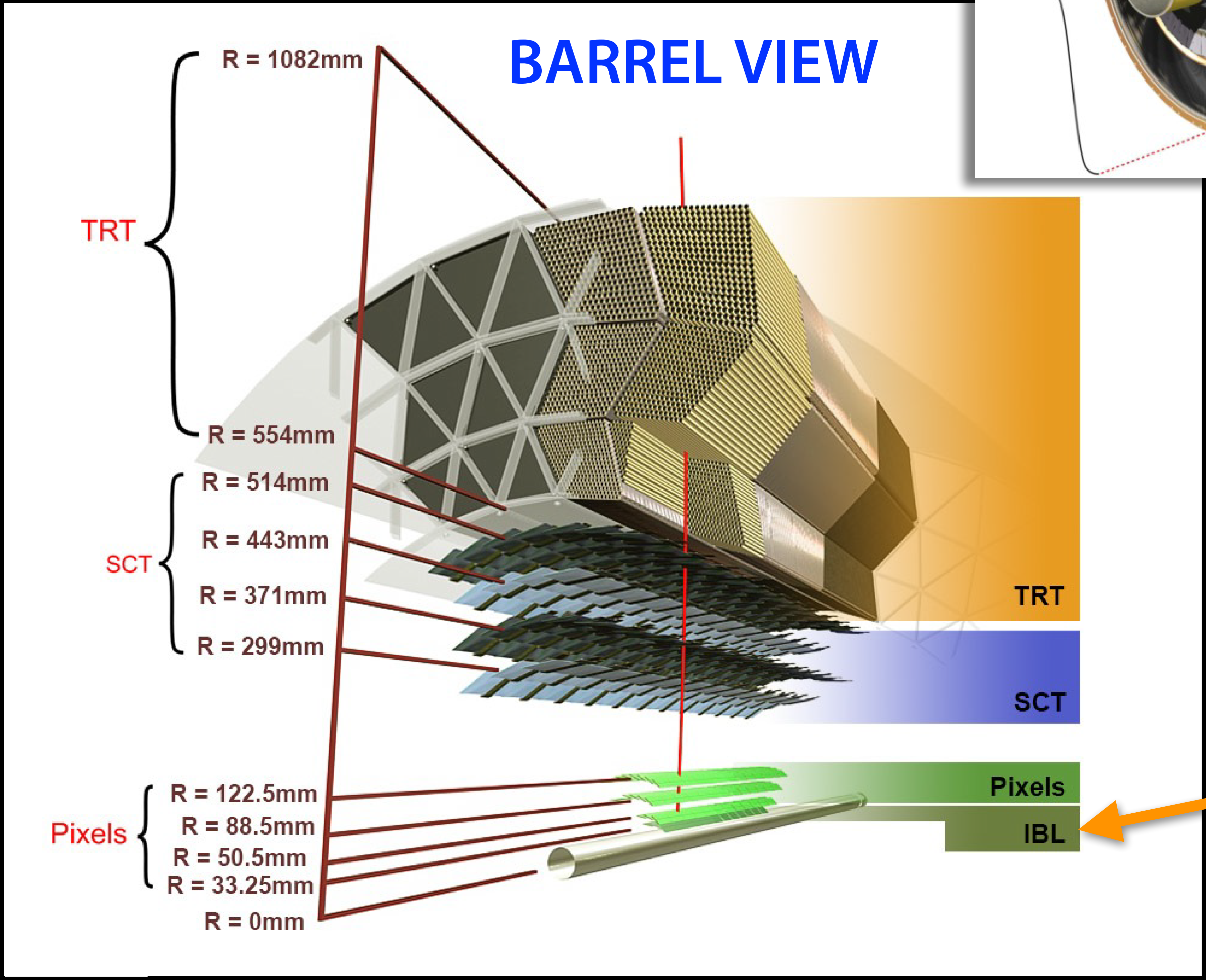
➡ electrons radiate → higher signal

- PID info by counting high-threshold hits component precisely

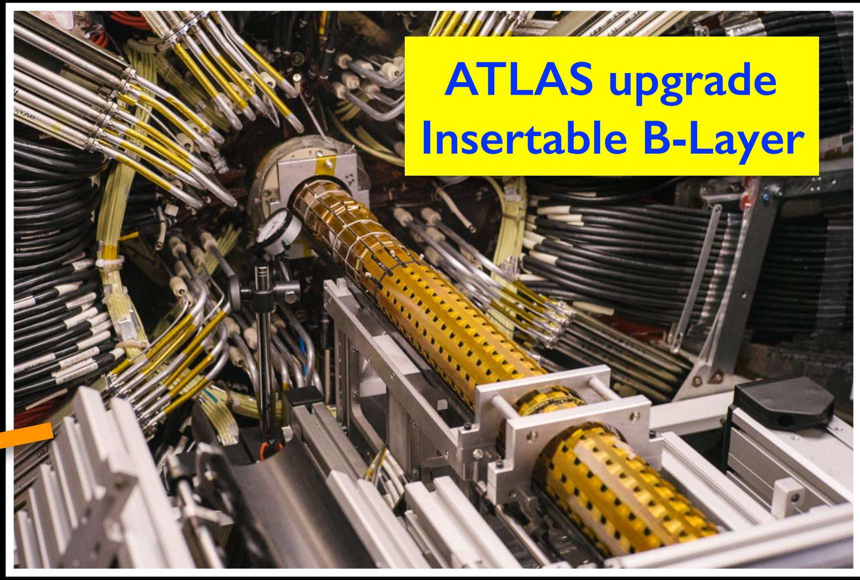
ATLAS Inner Detector

- expanded view of barrel
  - ➡ including Run-2 upgrade IBL





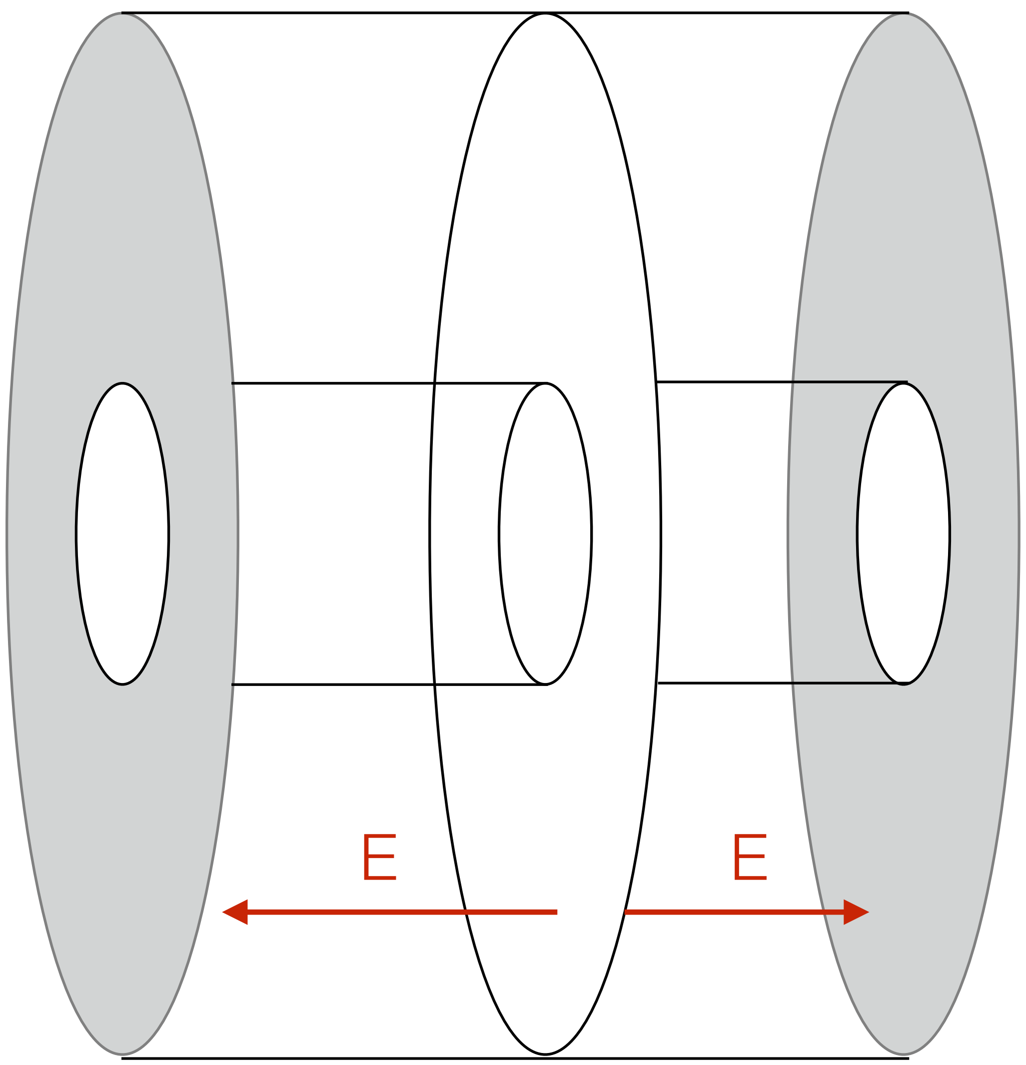
- barrel track passes:
  - ➡ 4(!) Pixel layers
  - ➡ 4x2 silicon Strips on stereo modules
  - ➡ ~36 TRT 4mm straws



Gas Detectors - Time Projection Chamber

Time Projection Chamber (TPC)

- TPC developed by D. Nygren in the 70's
  - ➡ long drift times (≈ 40 μs), thus rate limitations and very good gas quality required
  - ➡ ALICE design data taking rate 1 kHz in pp, few 100 Hz in Pb Pb



a vessel filled with ionisable gas

E-field parallel to B-field to drift charge

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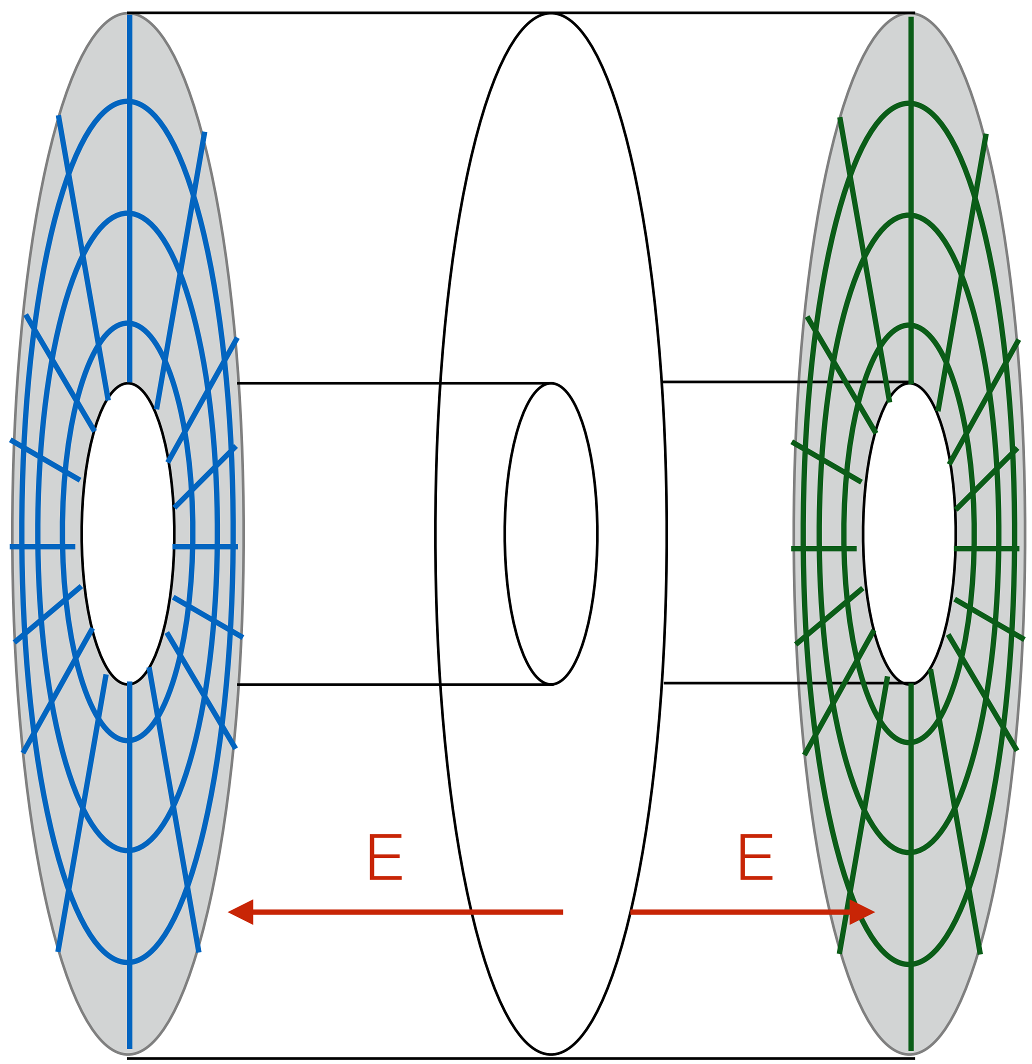

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segmented readout chambers
(e.g. MWPC with cathode pads, GEM)

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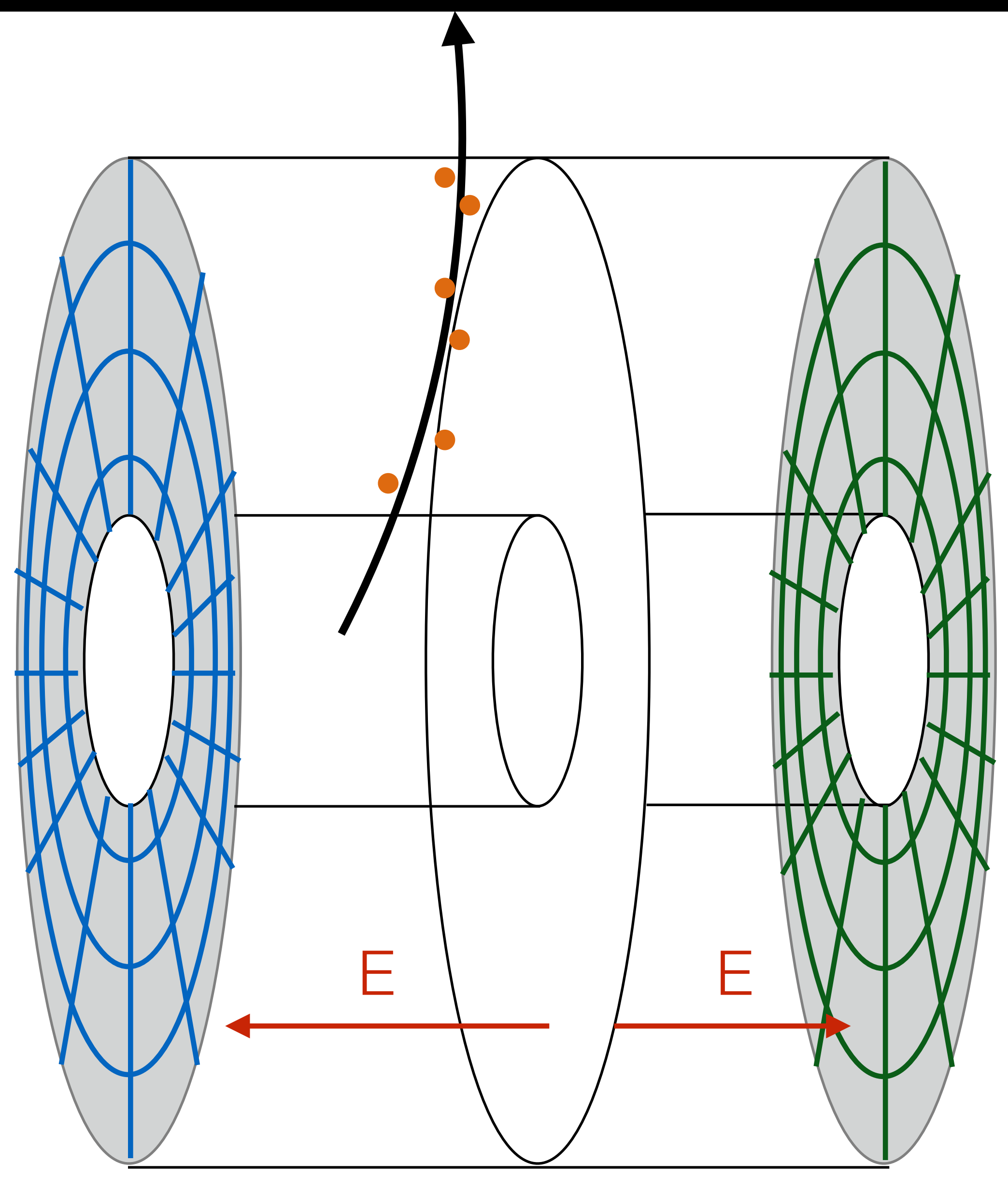

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charged particle ionises the gas

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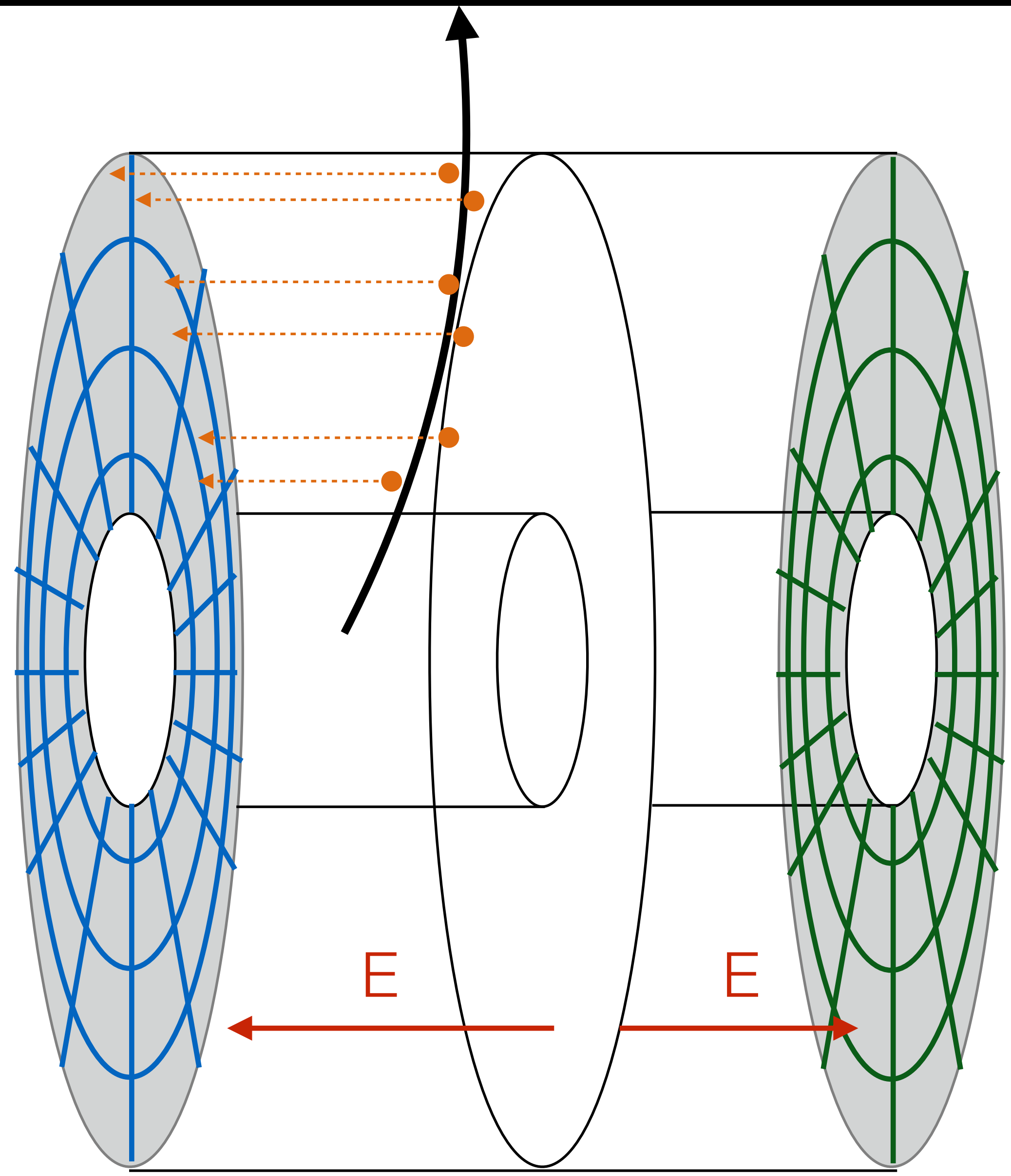

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charged particle ionises the gas

charge drifts to the readout chambers

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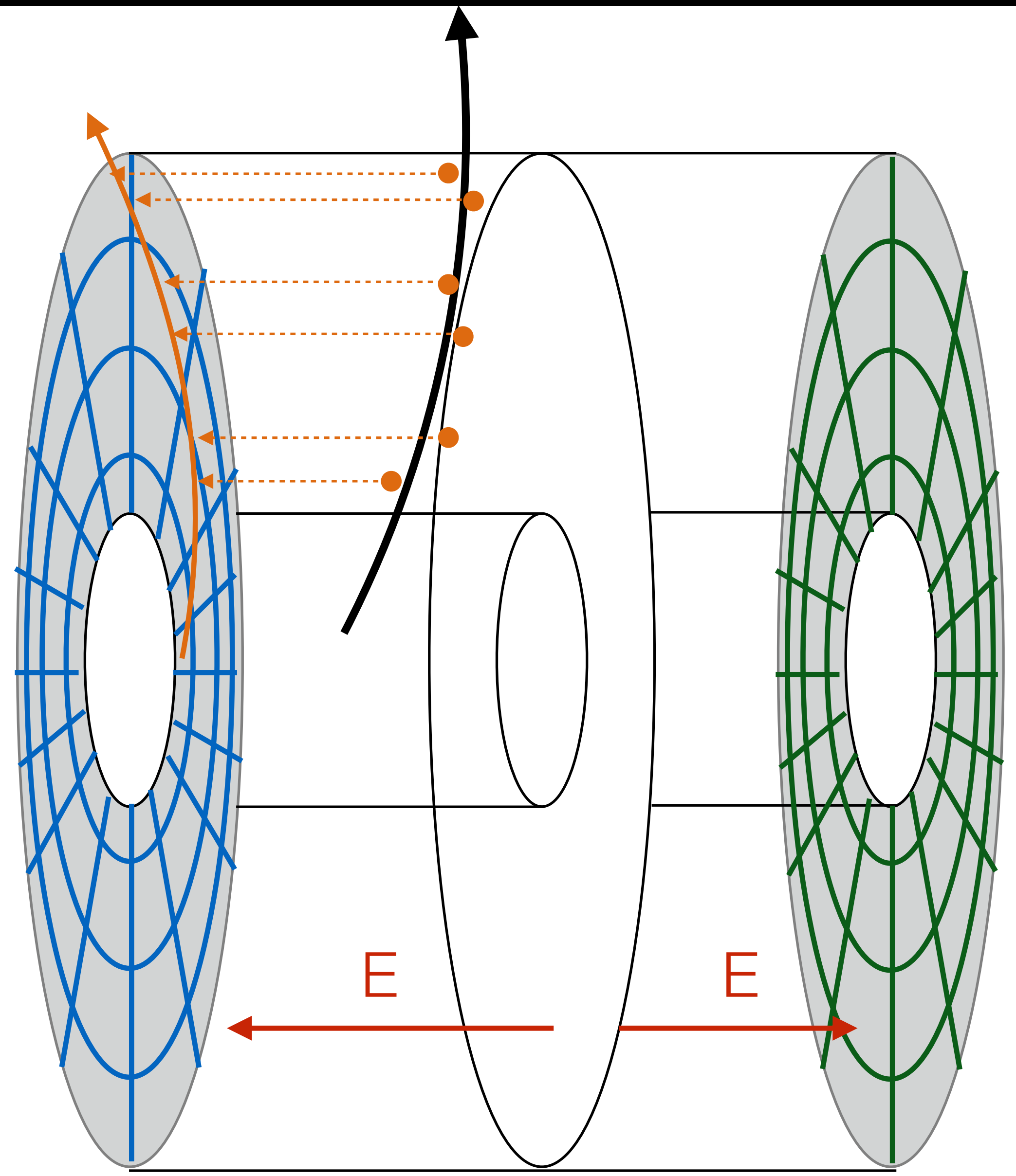


a vessel filled with ionisable gas

E-field parallel to B-field to drift charge

segmented readout chambers
(e.g. MWPC with cathode pads, GEM)

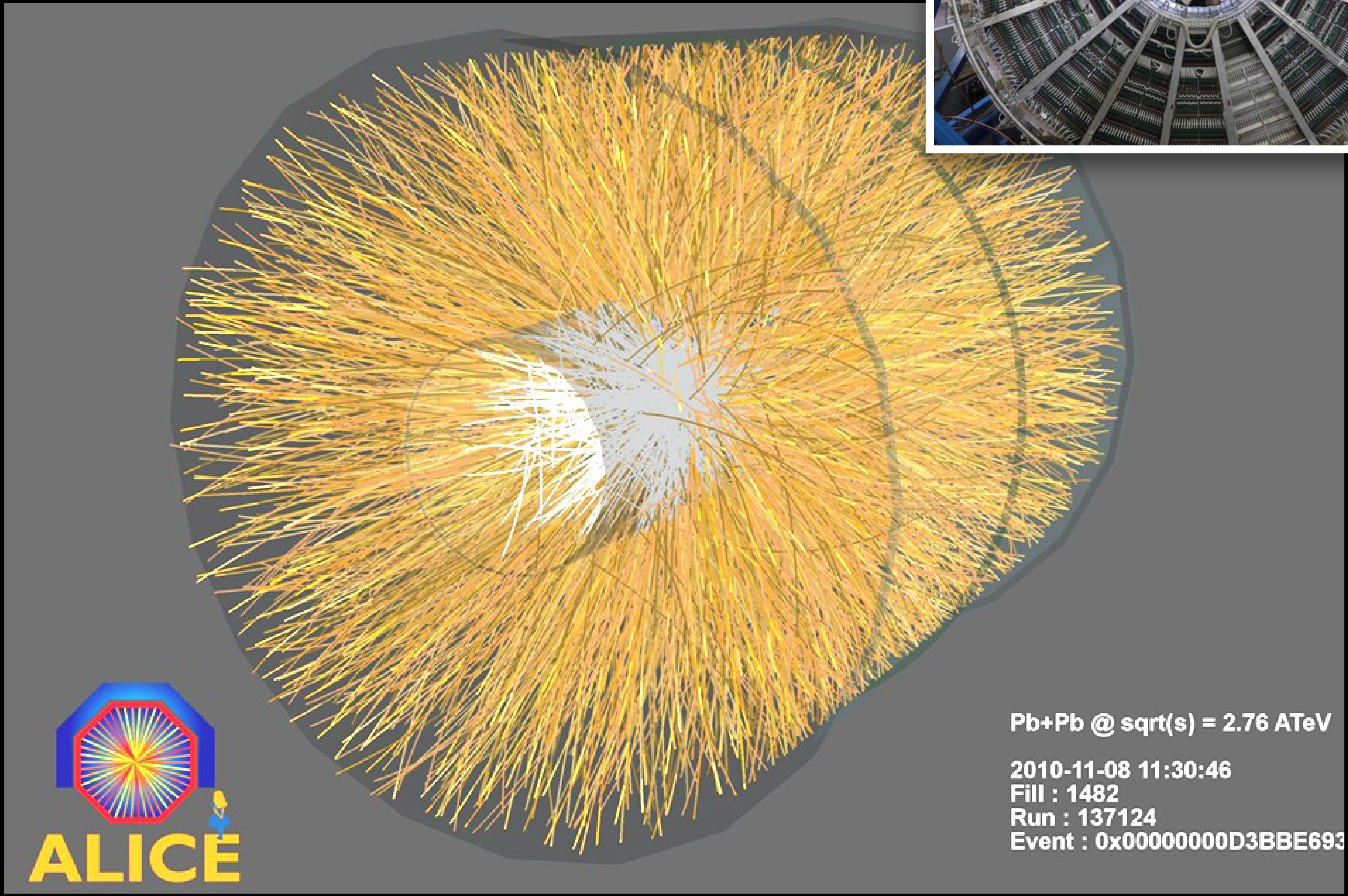
charged particle ionises the gas

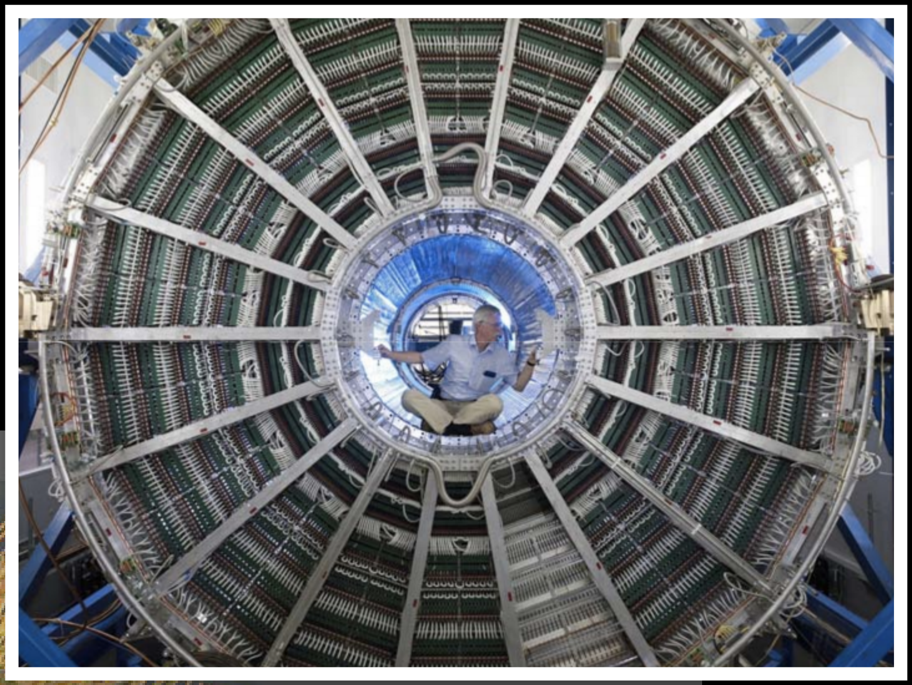
charge drifts to the readout chambers

reconstruct 3D trajectory from:
x,y ~ from readout segmentation
z ~ from drift time

ALICE TPC

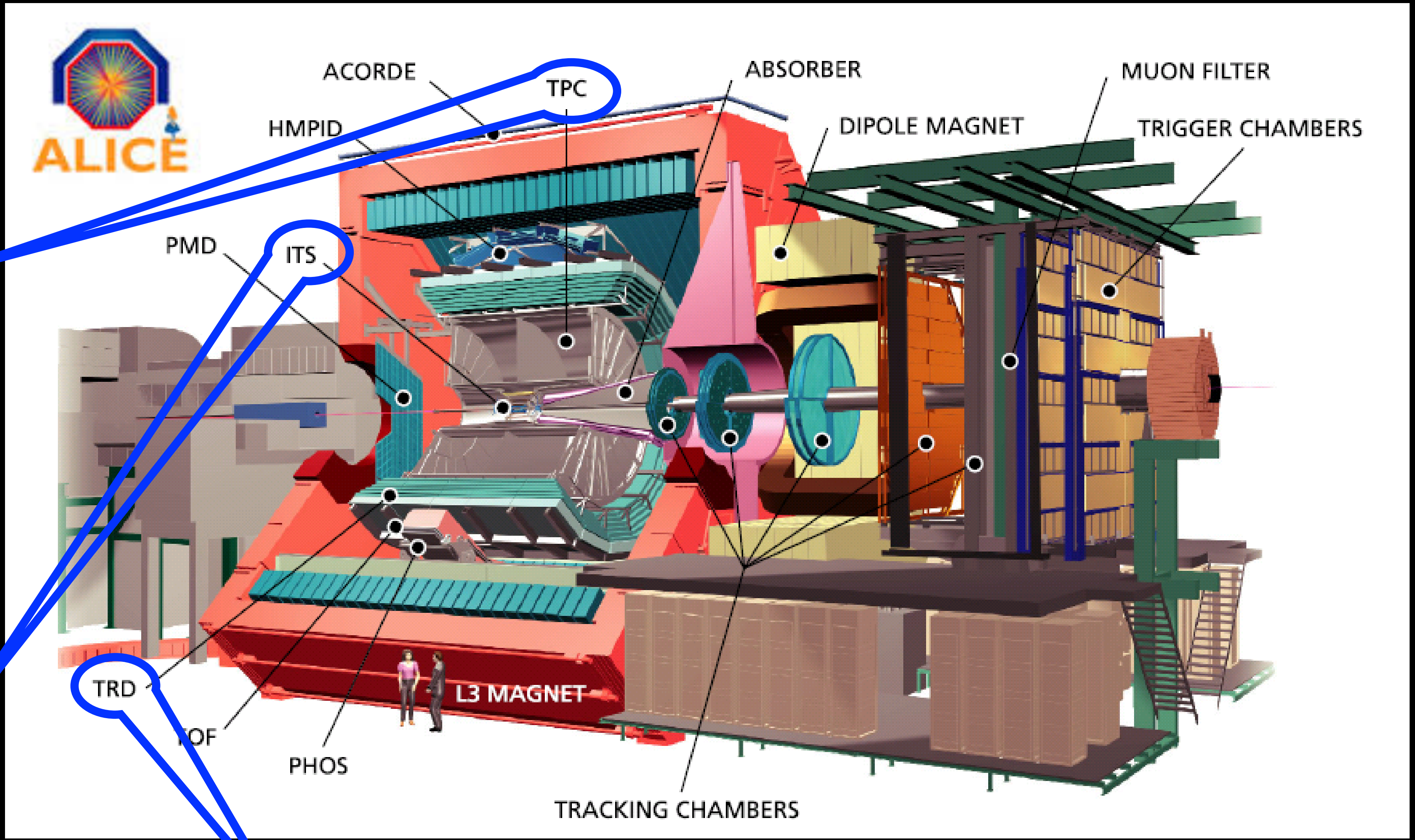
➡ most challenging TPC ever build



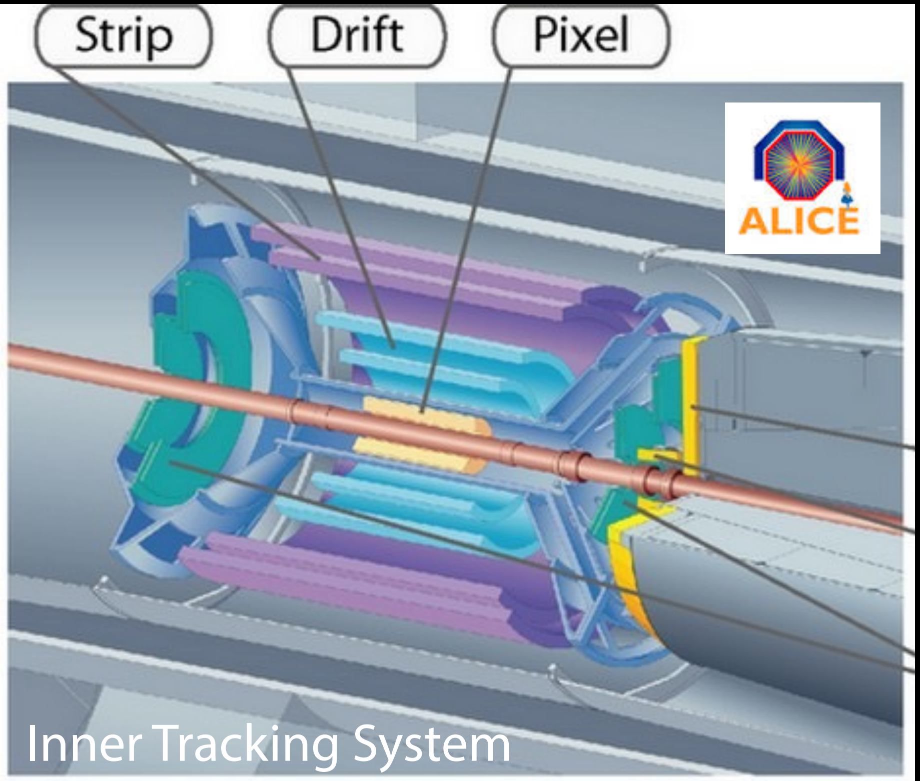


ALICE Tracking

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



➡ ITS: 6 layers, 3 technologies
- 2 Pixel layers
- 2 with silicon drift detectors
- 2 double sided strip layers



➡ Transition Radiation Detector (TRD)
- electron ID and improves momentum resolution
- outer radius 3.7m

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

➡ as well, forward muon spectrometer tracking chambers and dipole magnet

Comparison of Run-1 Barrel Tracker Layouts

*no IBL

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 $\eta=0$	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%

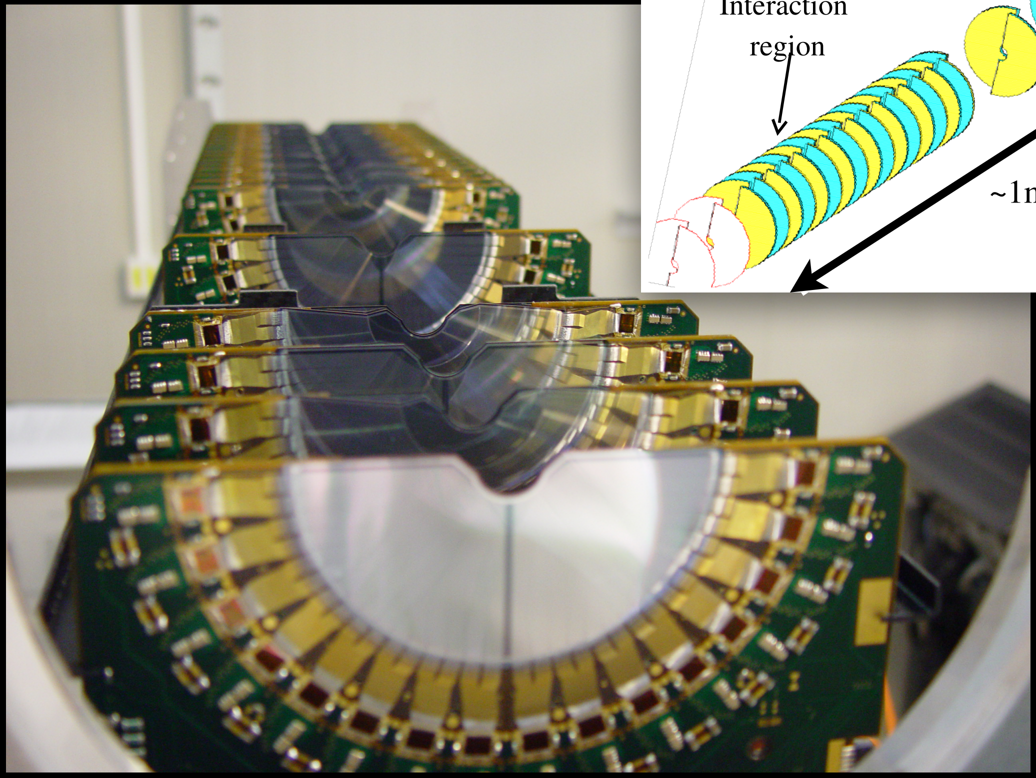
- LHCb is a spectrometer designed for B-physics
  - ➡ p_T resolution is 0.35% at 1 GeV, 0.55% at 100 GeV for good mass resolution

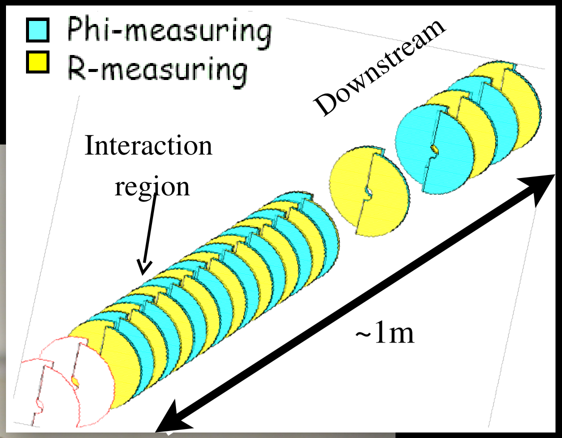
Summary of Run-1 Pixel Barrel Layouts

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	50 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

*no IBL

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





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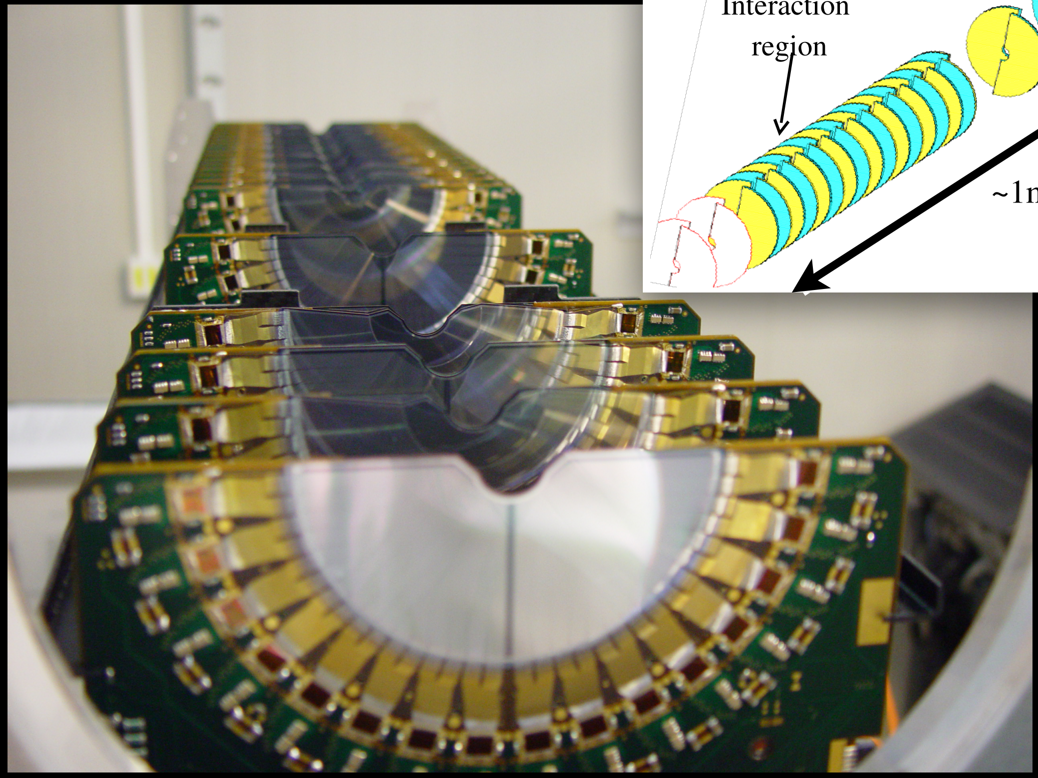
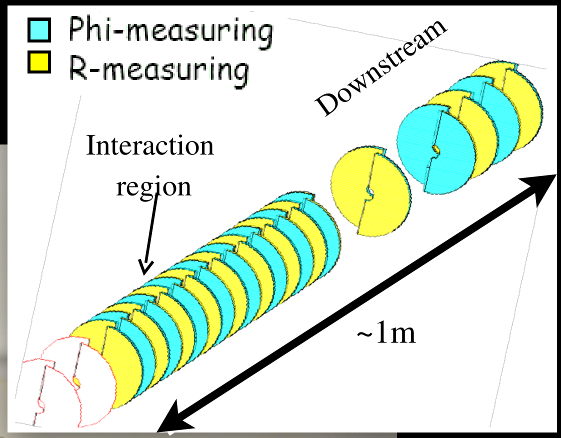
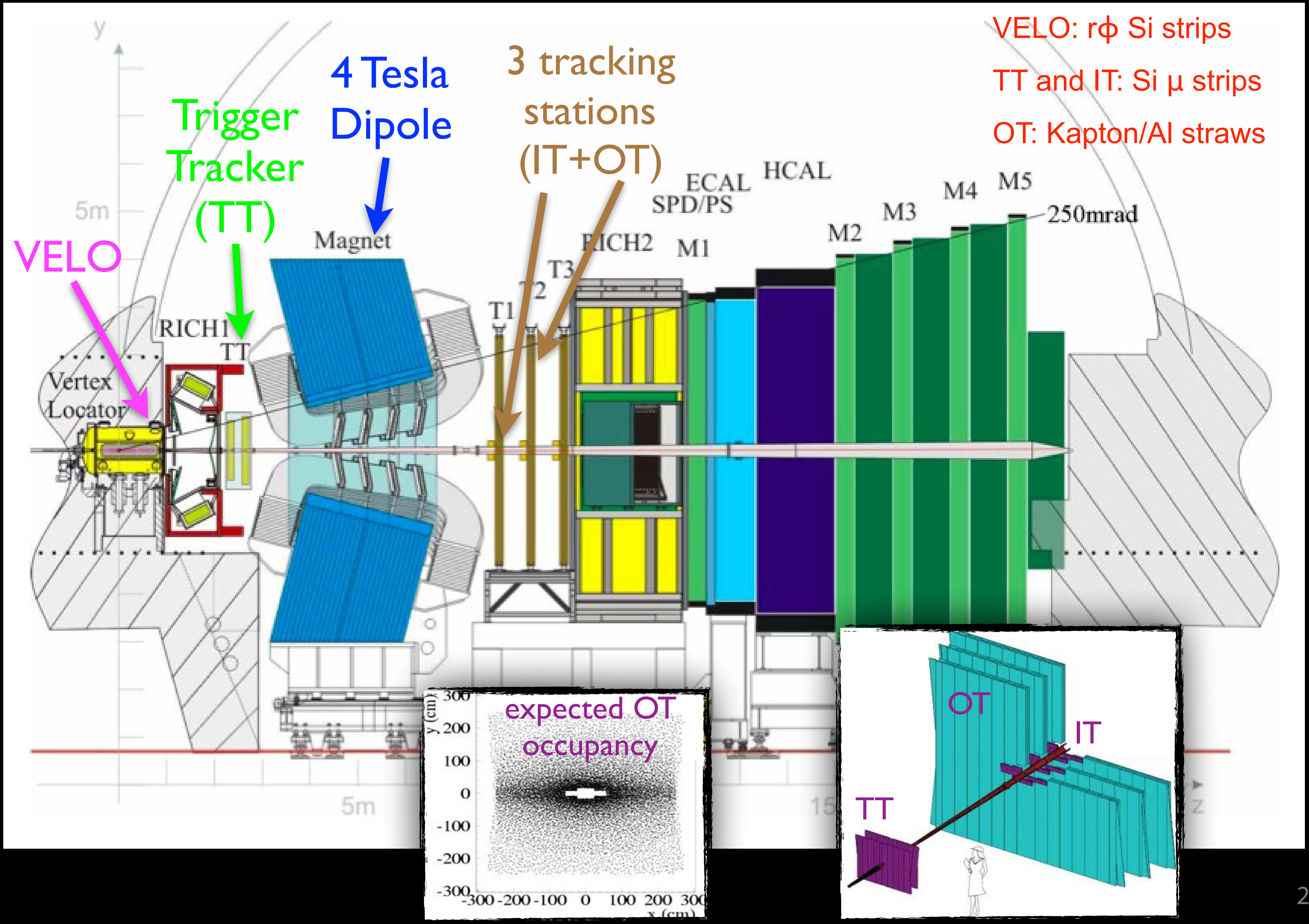




LHCb Tracking



Let's Summarise

- 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