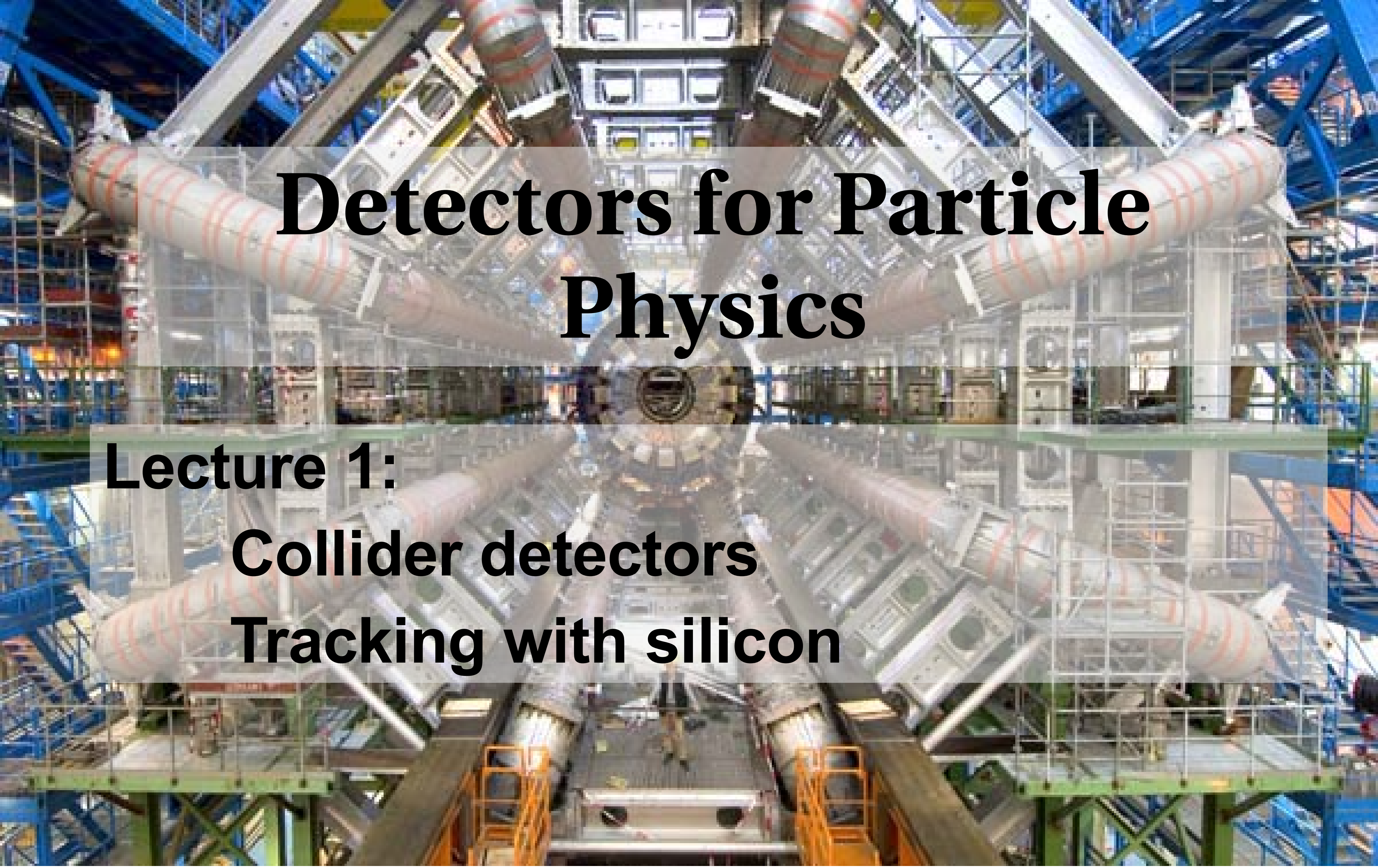


Detectors for Particle Physics

Lecture 1:

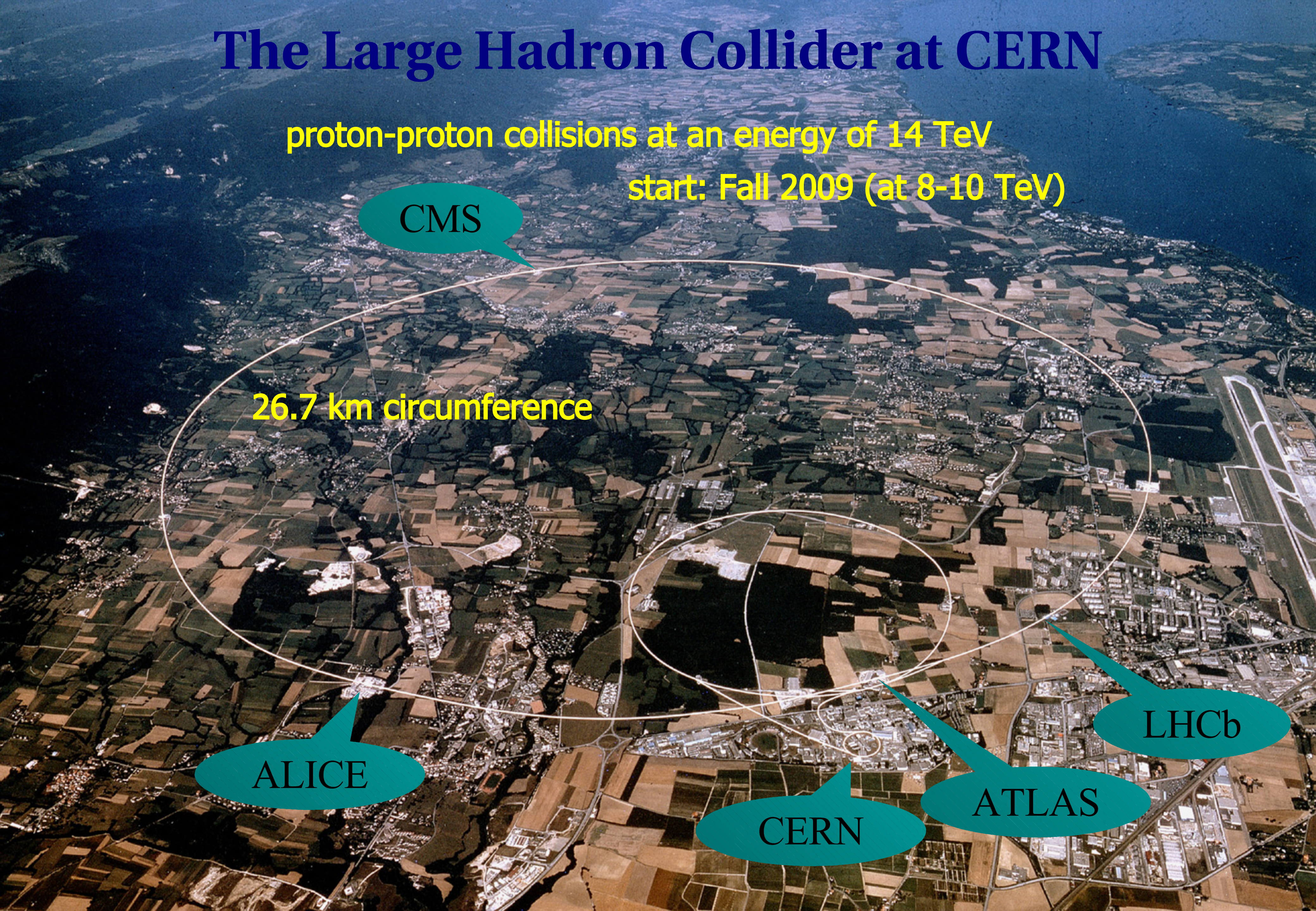
Collider detectors

Tracking with silicon

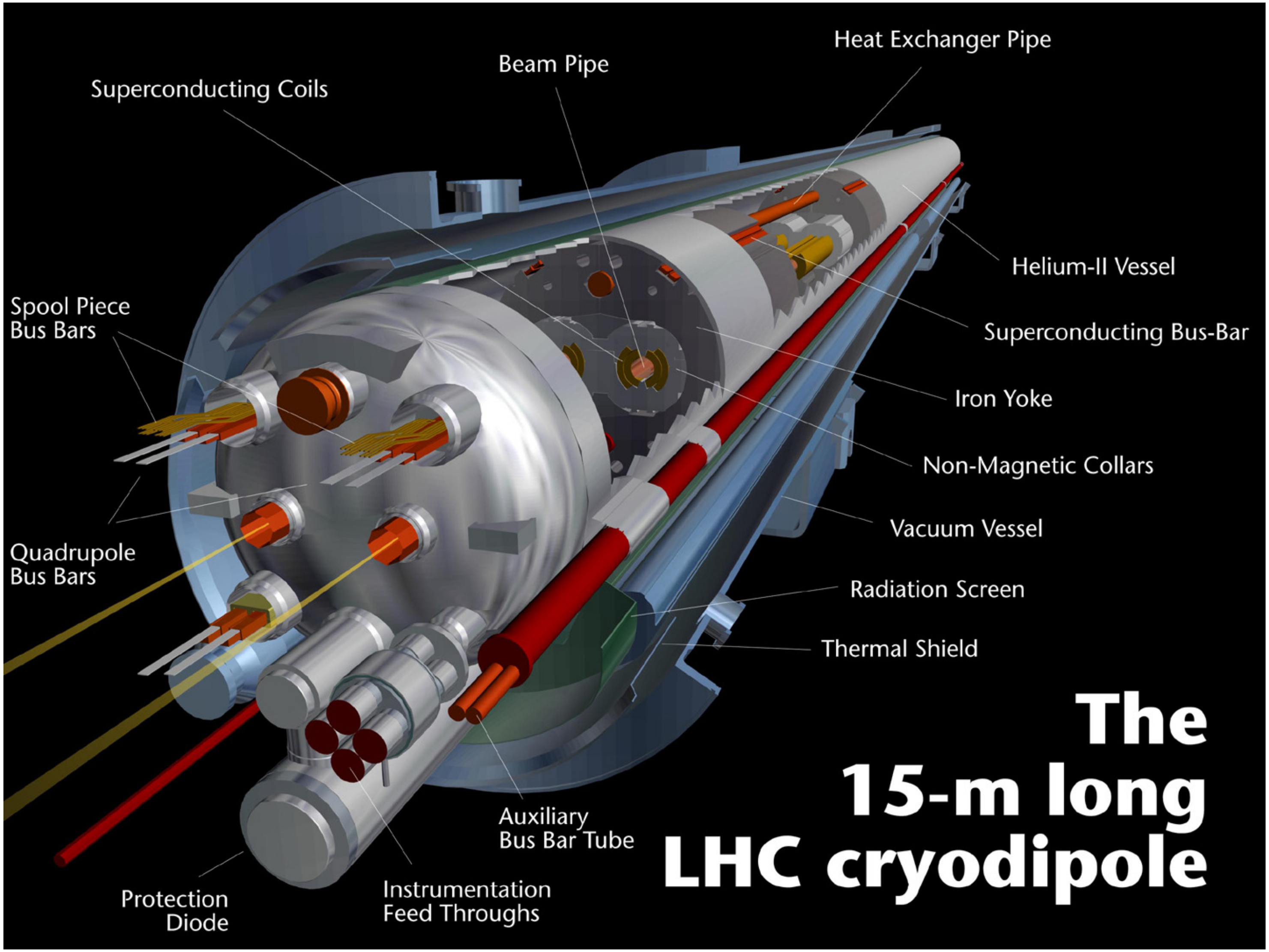
Outline

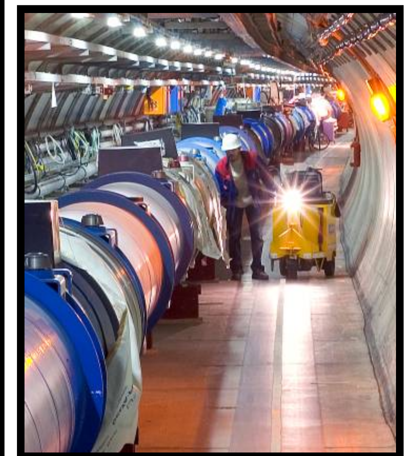
- Lecture 1:
  - Collider detectors
  - Charged particles in a magnetic field
  - Silicon detectors
- Lecture 2:
  - Drift detectors
  - Muon systems
  - TRTs, TPCs, Cherenkovs
- Lecture 3:
  - Electromagnetic showers and calorimeters
  - Photon detectors
  - Hadronic showers and calorimeters
  - Particle flow technique
- Discussion sessions:
  - Your questions, please

The Large Hadron Collider at CERN



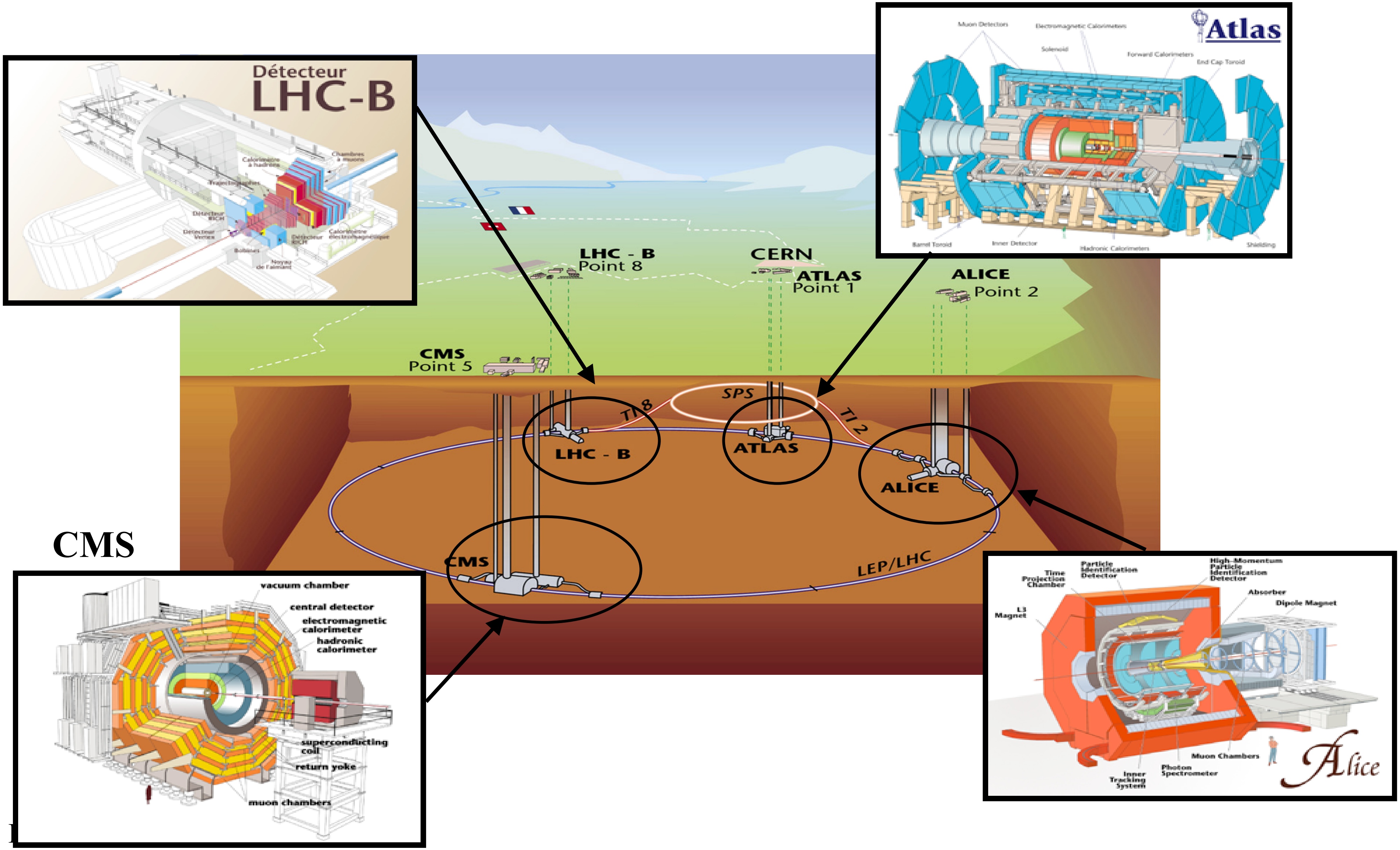
Superconducting LHC bending magnets



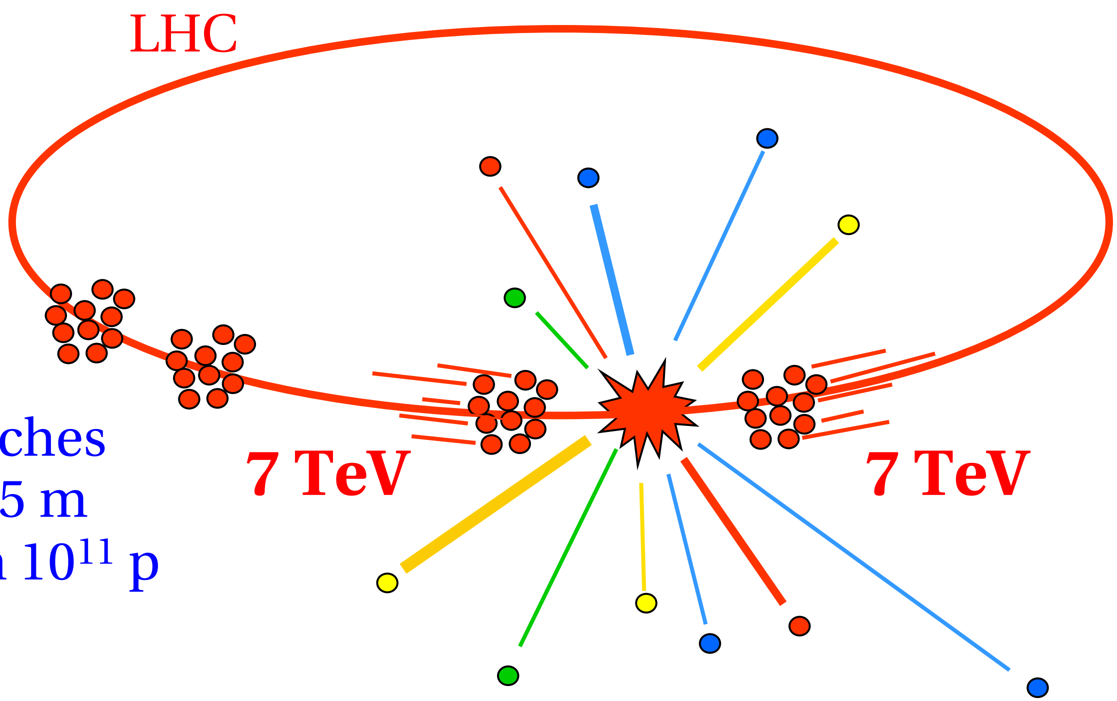


1200 dipoles installed.
Final tests underway...

LHC Experiments underground



Head-on collisions

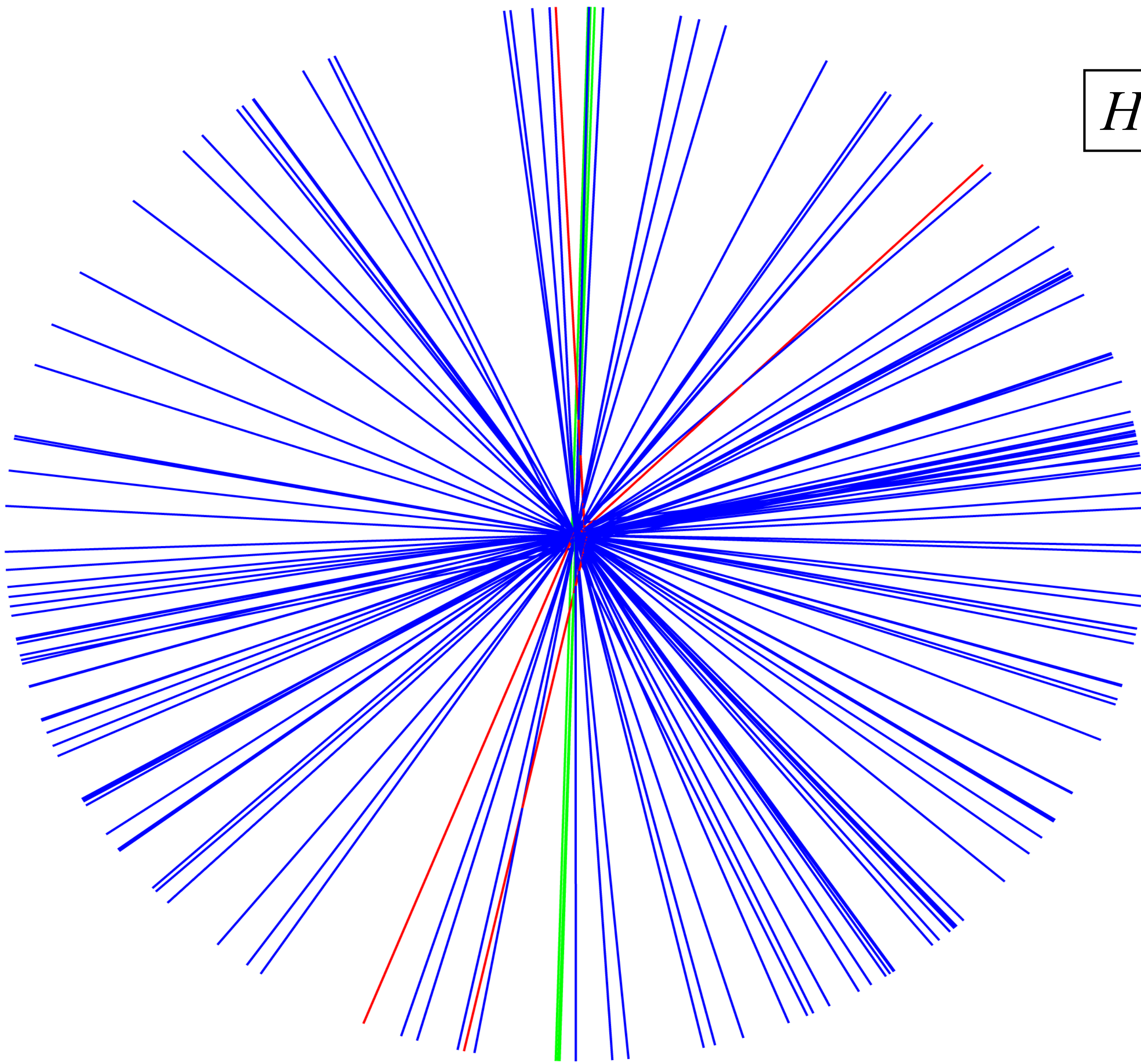


3300 bunches
spaced 7.5 m
each with 10^{11} p

Some energy
is converted
into secondary
particles at
large angles.

Collision occur every 25 ns.
20 pp interactions at the same time.
(mostly producing low energy secondaries)

An interesting collision at the LHC (simulation)



Higgs → 4 muons

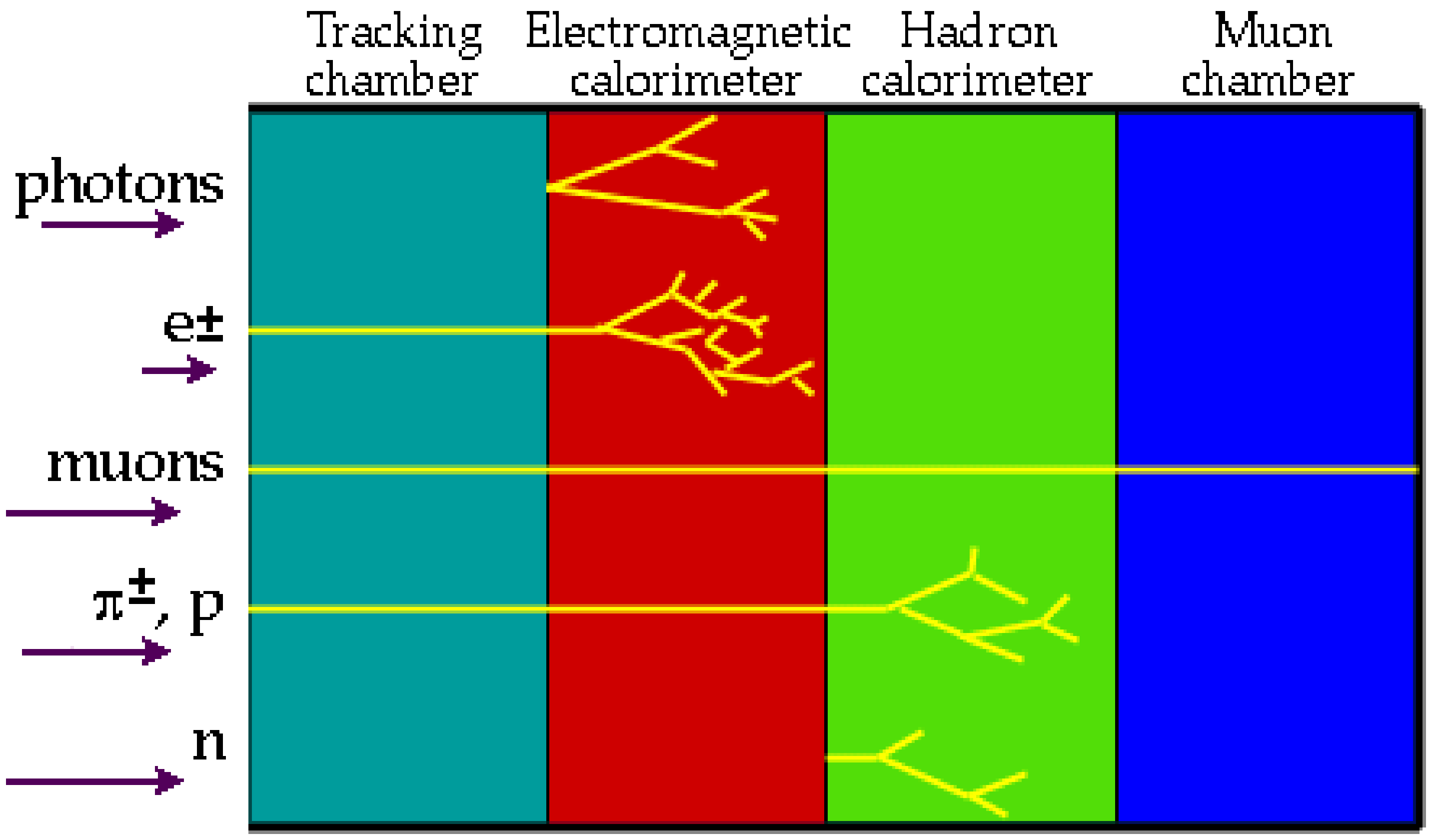
Where are the muons?

Red lines show the muons (simulation!)

Particles, interactions, and signatures

neutrinos	none	Missing energy
electrons	Ionisation, electromagnetic	Track and EM shower
muons	Ionisation	Penetrating track
p, K, π	Ionisation, hadronic	Track and hadron shower
photons	electromagnetic	EM shower
neutrons, K^0_L	hadronic	hadron shower
B, D	Weak decay	Secondary vertex
J/ψ, Υ, W, Z, H, t	prompt decay	Invariant mass

Particles Signatures and detectors

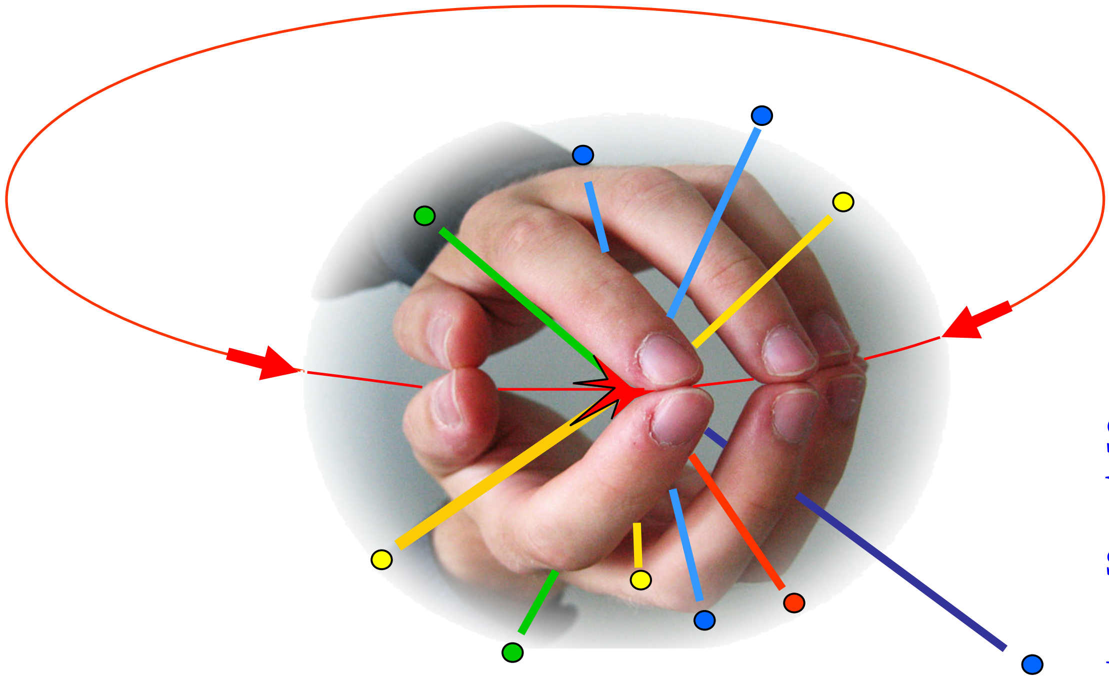


non-destructive measurement

destructive measurements

Tail catcher

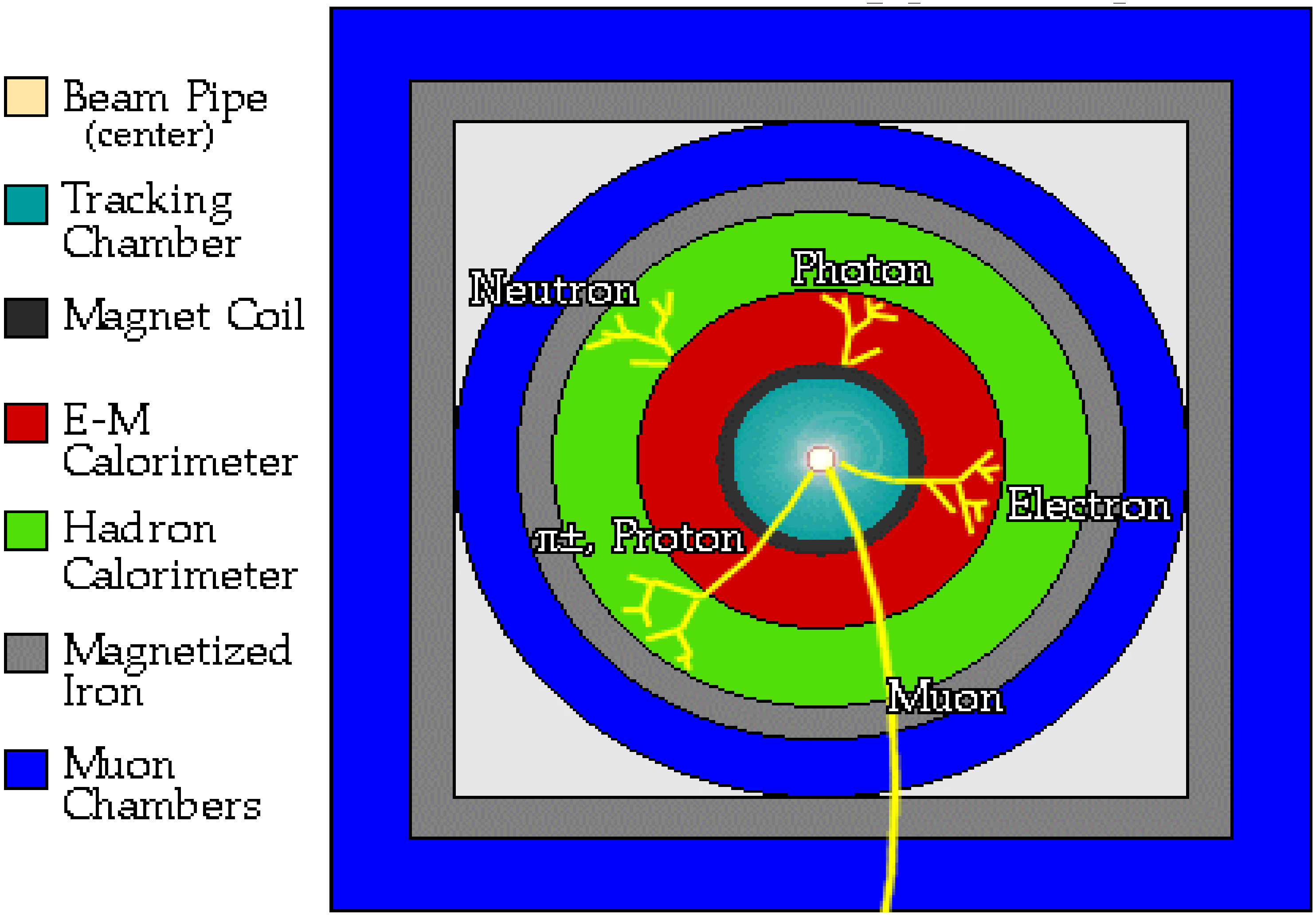
Watching the collisions



Surround the collision point by a detector to capture the secondary particles.

Leptons are rare in pp collisions: emphasize muons and electrons!

Surrounding the beam pipe



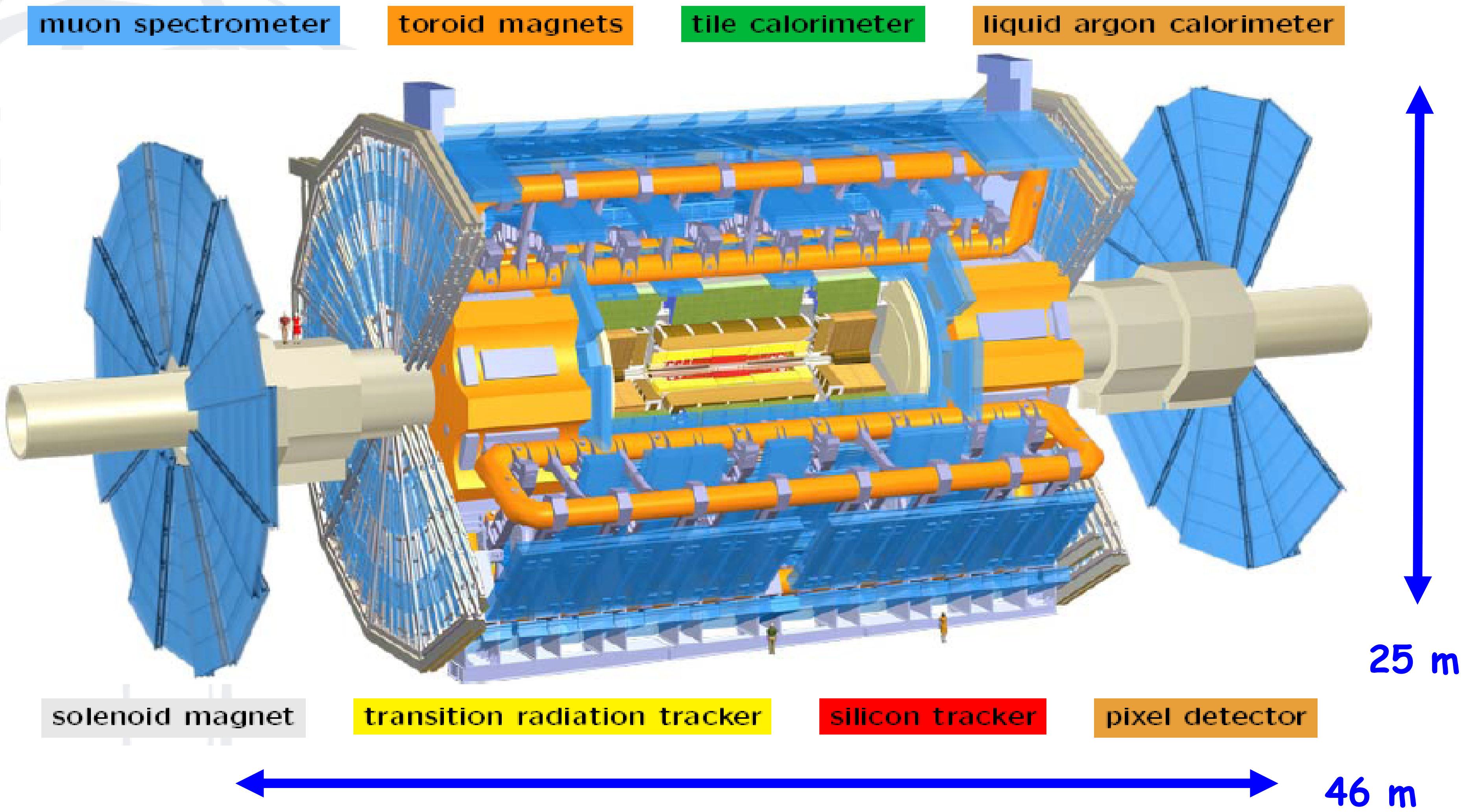
Detector design criteria

- Coverage and hermeticity:
  - Capture all particles.
  - No holes, no cracks, no dead regions.
- Resolution:
  - Resolve all particles (high granularity, many channels).
  - Measure energies and directions with high precision.
- Constraints:
  - Cost and available technology.
  - Beam pipe and first machine magnets.
  - Mechanics, power and signal cables, cooling.
  - Radiation.

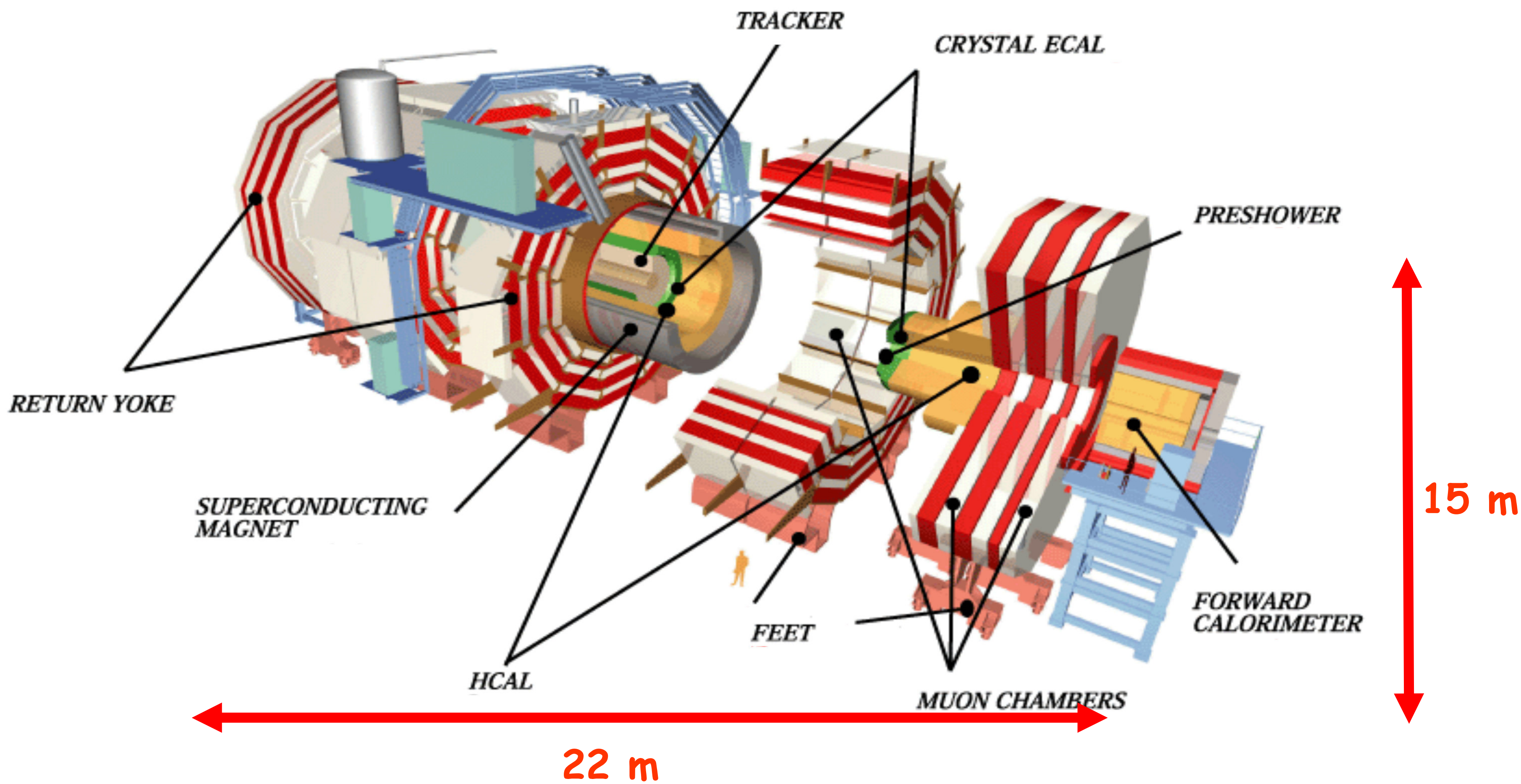
ATLAS: A Toroidal LHC Aparatus

- **ATLAS detector:**

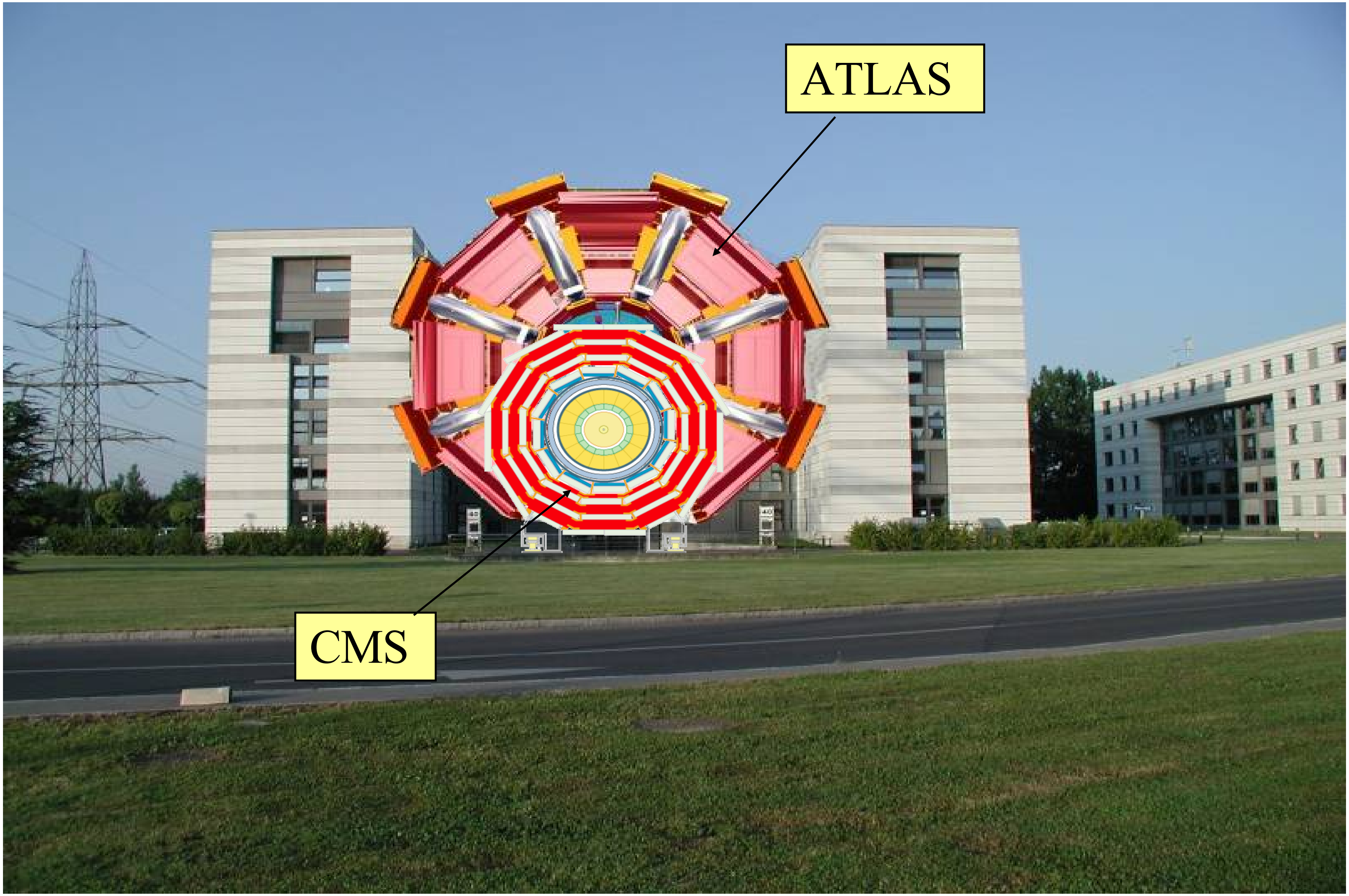
  diameter 25 m, length 46 m, mass 7,000 tons, 10^8 channels, 3,000 km cables



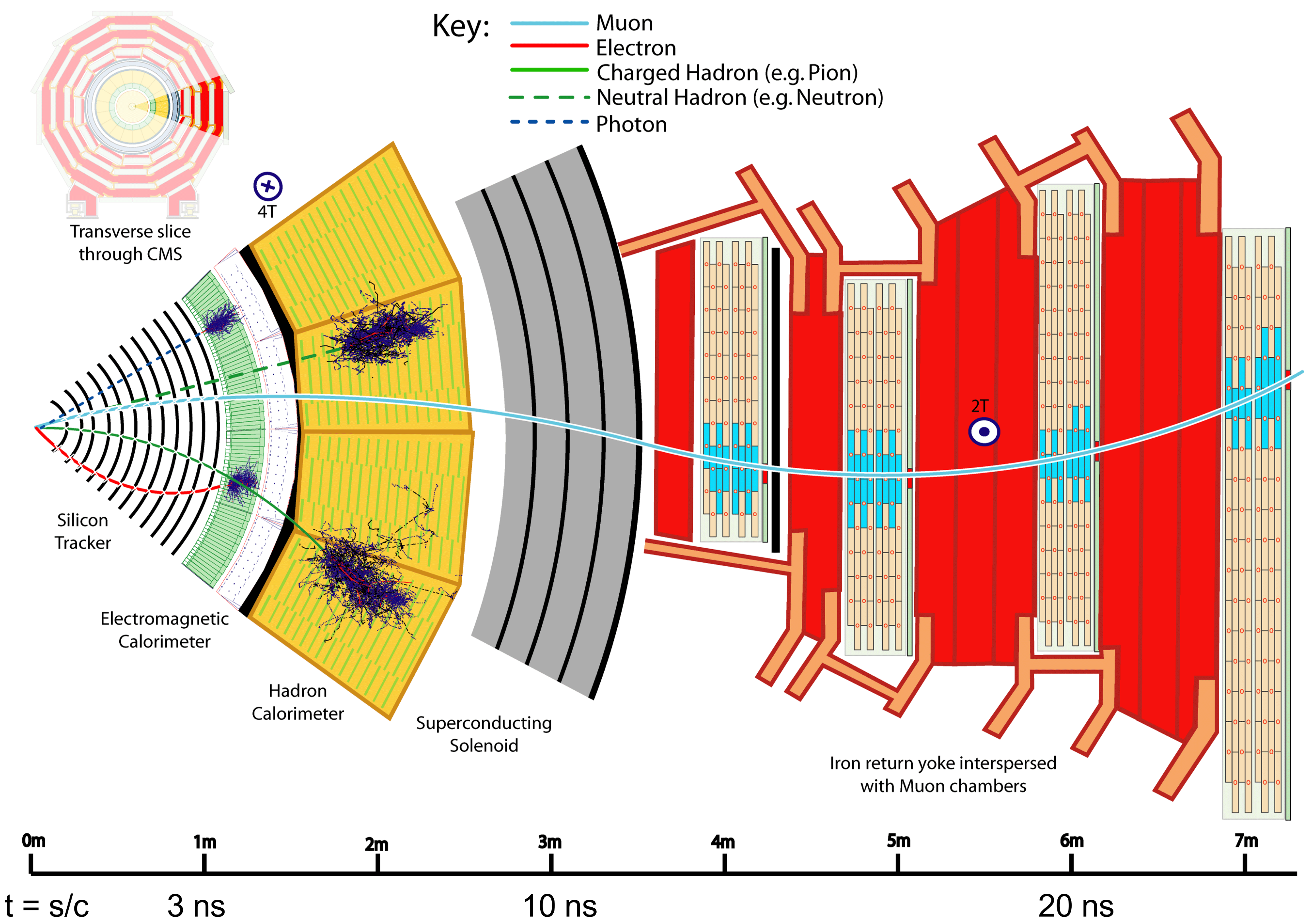
CMS: Compact Muon Spectrometer

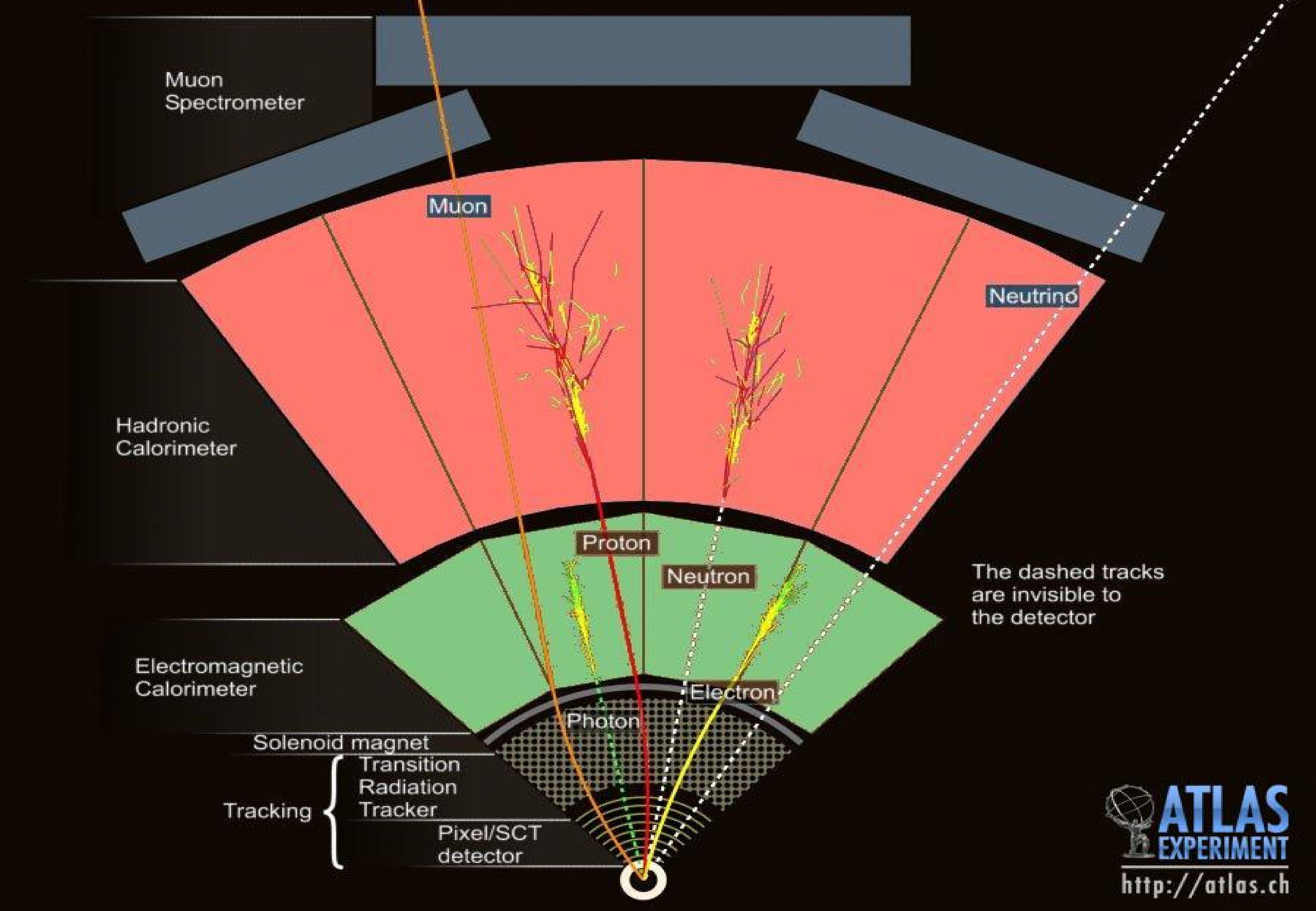


CMS is 'compact' compared to ATLAS



A slice of CMS



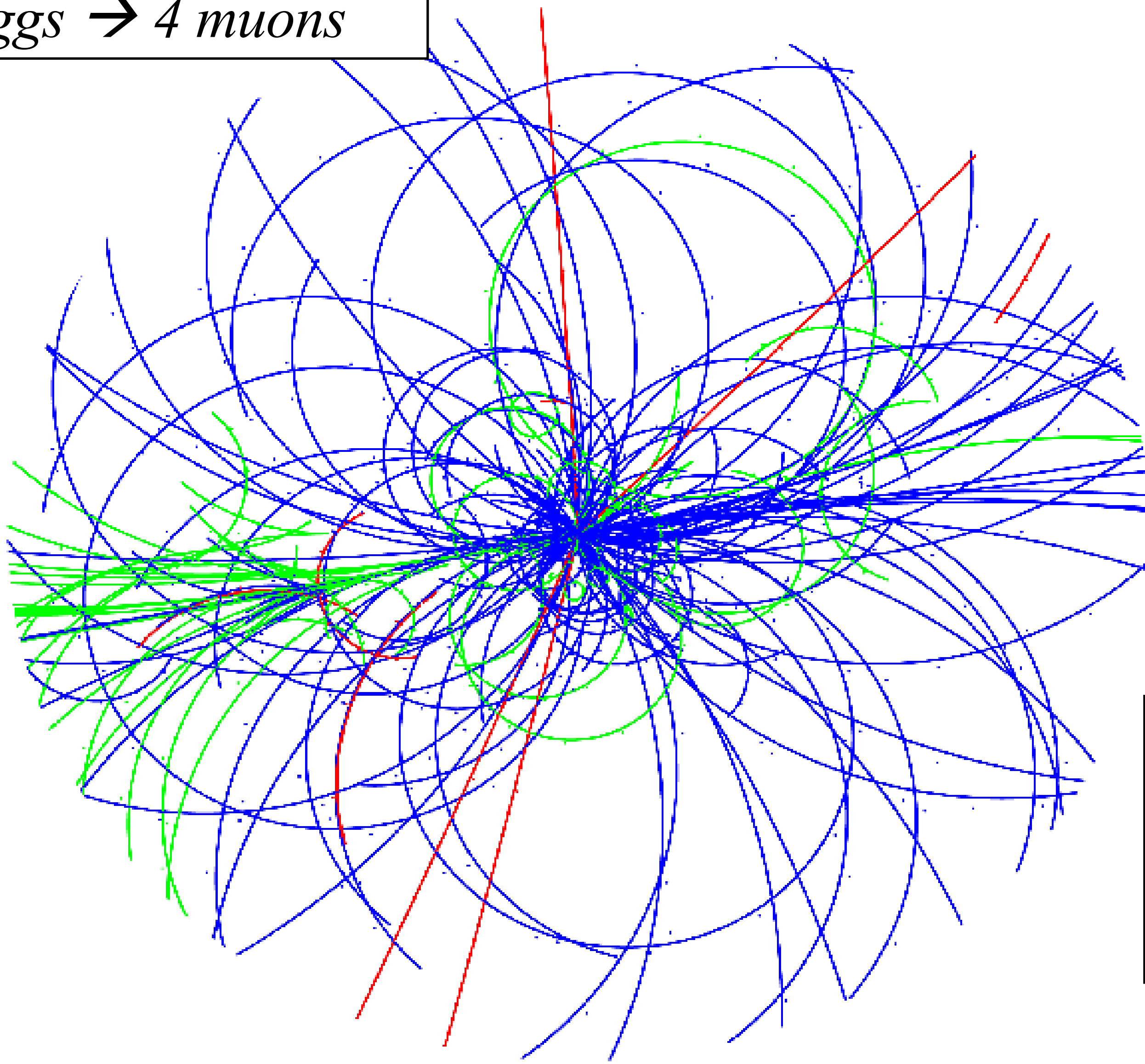

Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Transition
Radiation
Tracker
Tracking
Pixel/SCT
detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks
are invisible to
the detector
ATLAS
EXPERIMENT
http://atlas.ch

ATLAS vs CMS

	ATLAS	CMS
Tracker or Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker. 2T magnetic field	Silicon pixels, Silicon strips. 4T magnetic field
Electromagnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ($PbWO_4$) crystals absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer part of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke

Let's add a magnetic field!

Higgs → 4 muons



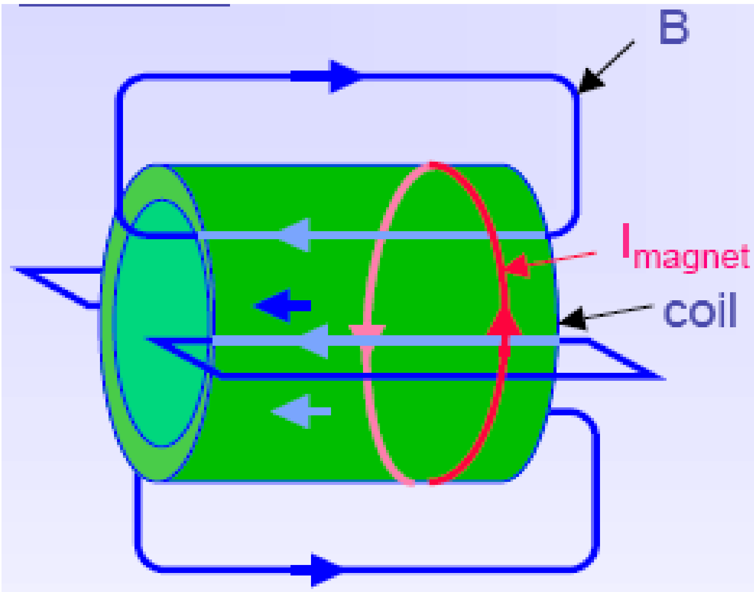
Charged particles bend in the magnetic field

The lower the particle momentum the more they bend.

Straight tracks from high momentum particles are the most interesting!

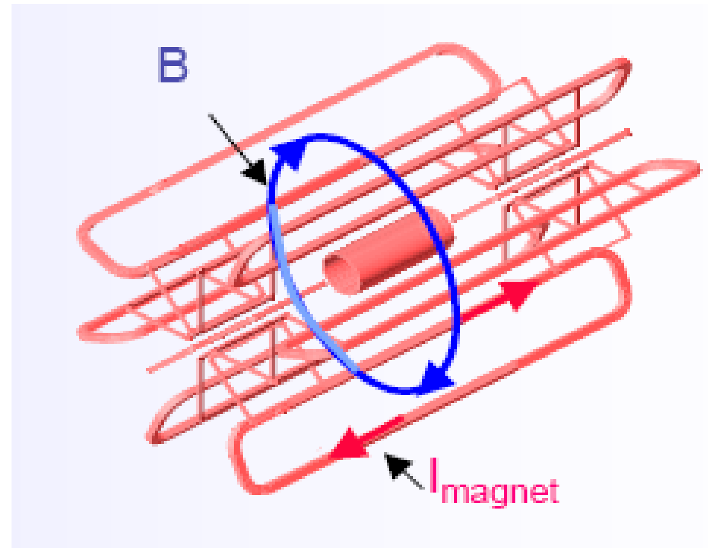
Magnets

Solenoid



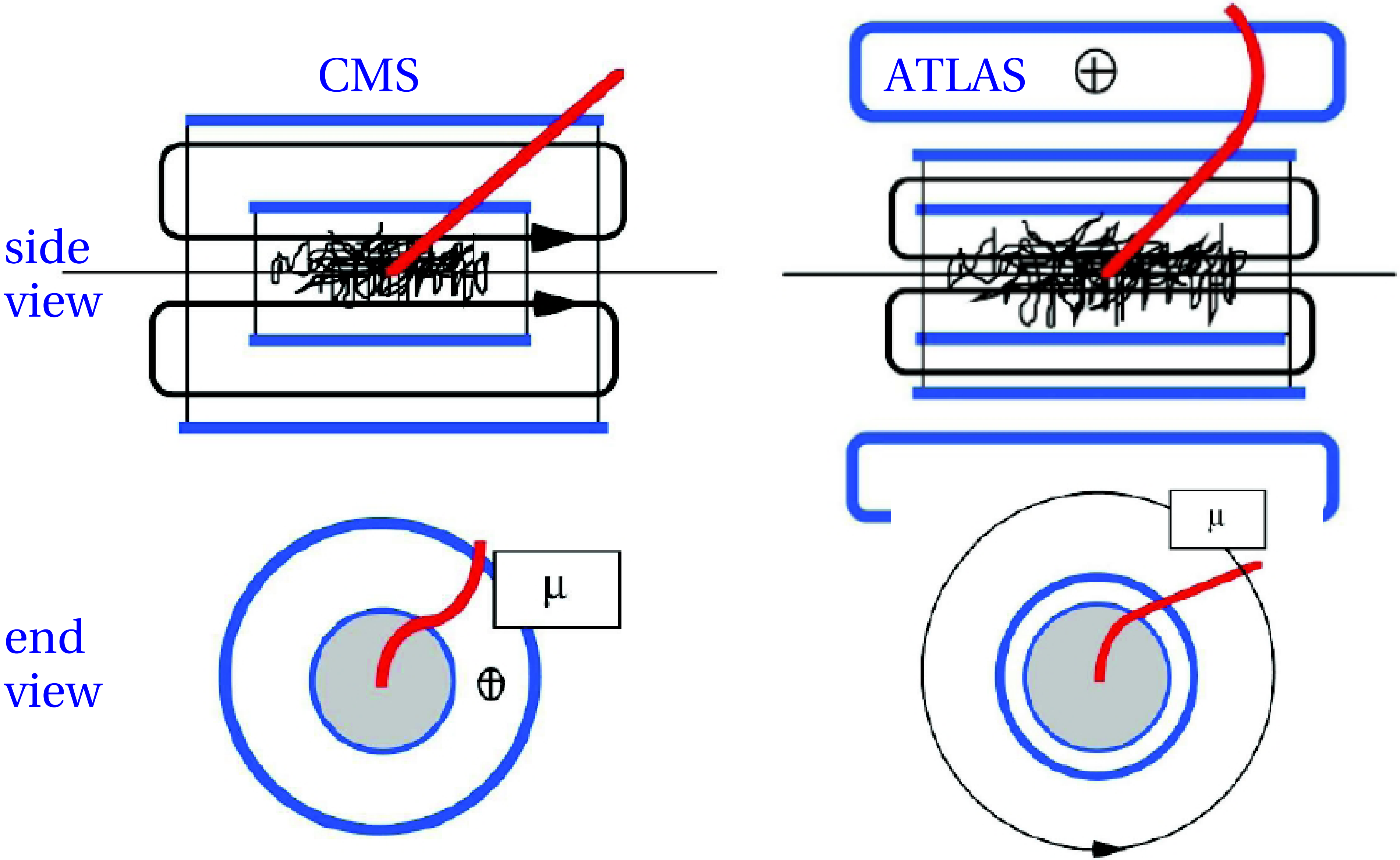
Field direction along beam axis.
Homogenous field inside the coil.
Need surrounding iron structure to capture the 'return field'.
CMS: I = 20 kA, B = 4T.
Superconducting (4K).

Toroid

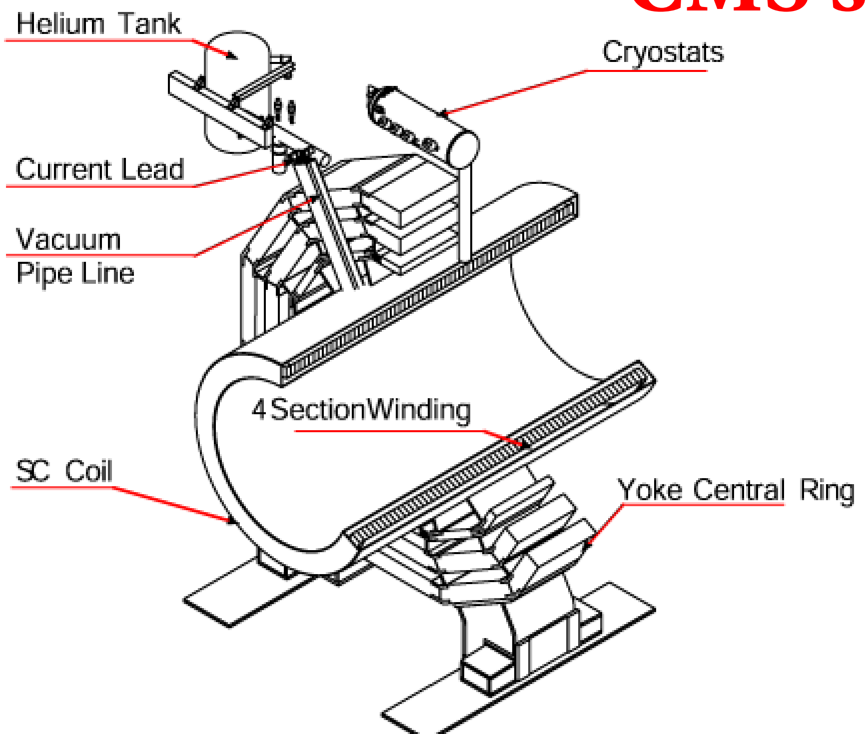


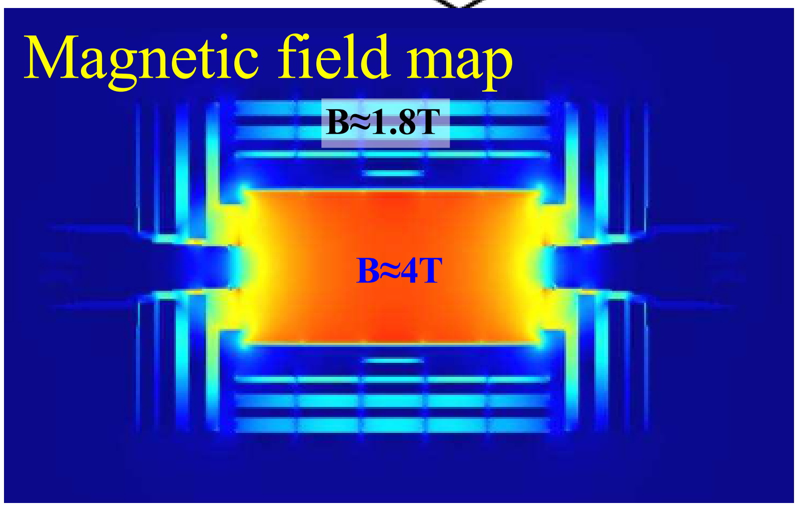
Field circles around the detector.
Detailed field map needed.
No iron structure needed.
ATLAS: I = 20 kA, B up to 4 T.
Superconducting (4K).

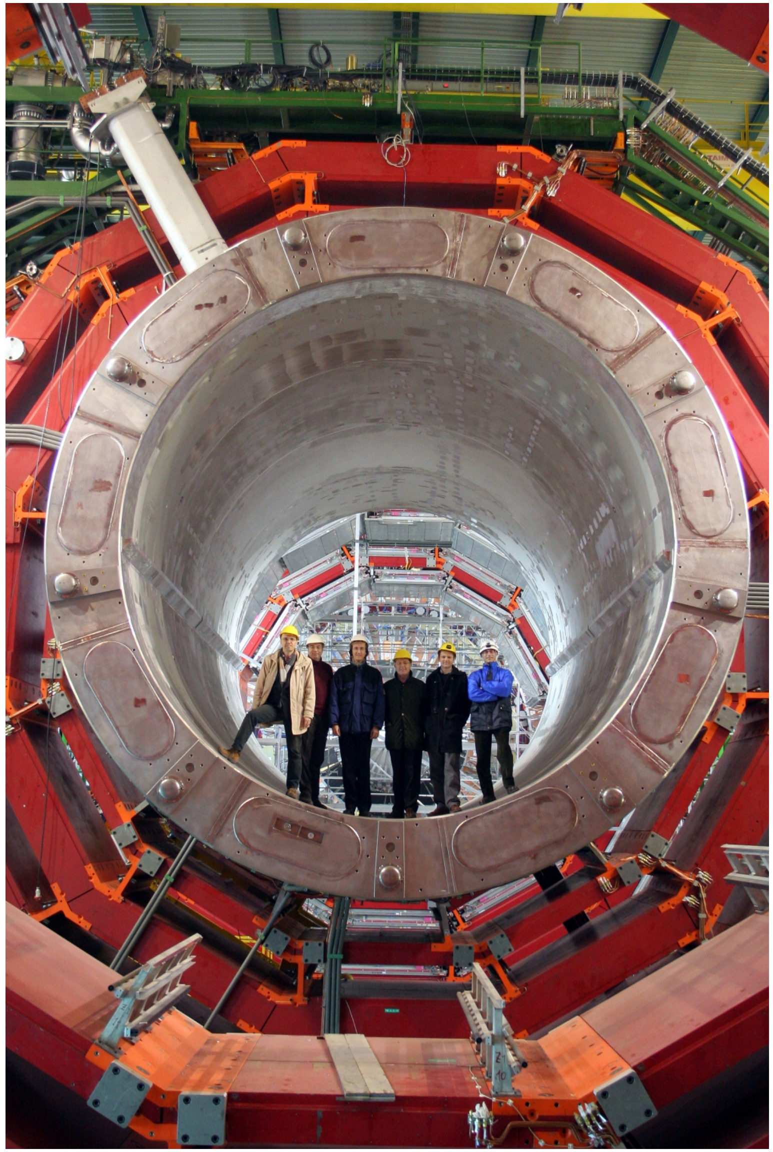
Bending muons in CMS and ATLAS



CMS solenoid



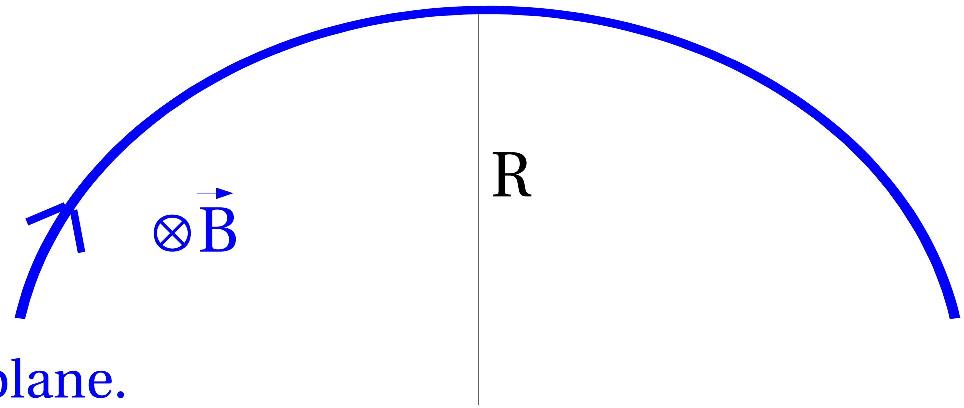




Charged particles in a magnetic field

Lorentz Force:

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



For B = constant:
circular motion in the transverse plane.
Equation of motion:
Lorentz force balanced by centrifugal force: $q\,v_t\,B = m\,v_t^2 / R$

$p_t = m\,v_t \quad \Rightarrow \boxed{p_t = qRB}$ also holds relativistically.

$$\boxed{cp_t\,[GeV] = 0.3\,R\,[m]\,B\,[T]}$$

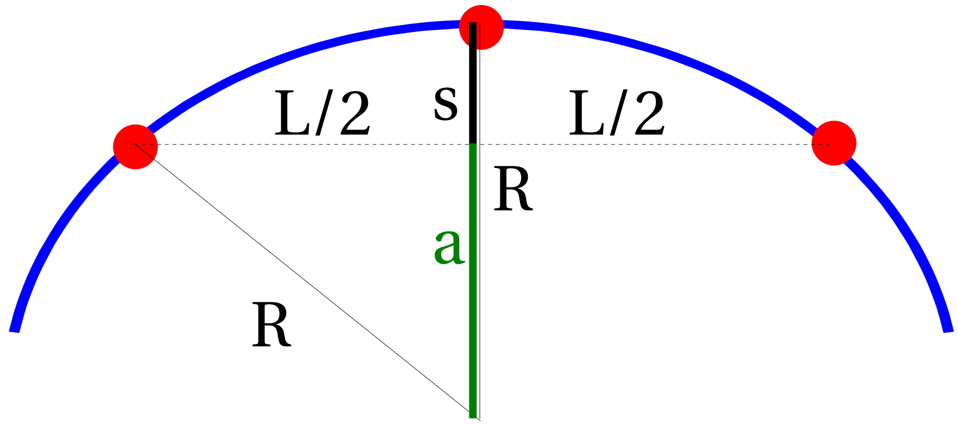
for q = e

CMS: B = 4 T

p_t [GeV/c]	R [m]
100	83.33
10	8.33
1	0.83

Low p_t tracks curl up inside the tracker: 2R<L

Sagitta measurement



1. Pythagoras: $a^2 + L^2/4 = R^2$

$$\Rightarrow a = R\sqrt{1 - L^2/4R^2}$$

Taylor: $\sqrt{1-x} \approx 1 - x/2$

$$\Rightarrow a \approx R\,(1 - L^2/8R^2)$$

2. Sagitta: $s = R - a$, insert a

$$\Rightarrow \boxed{s = L^2/8R}$$

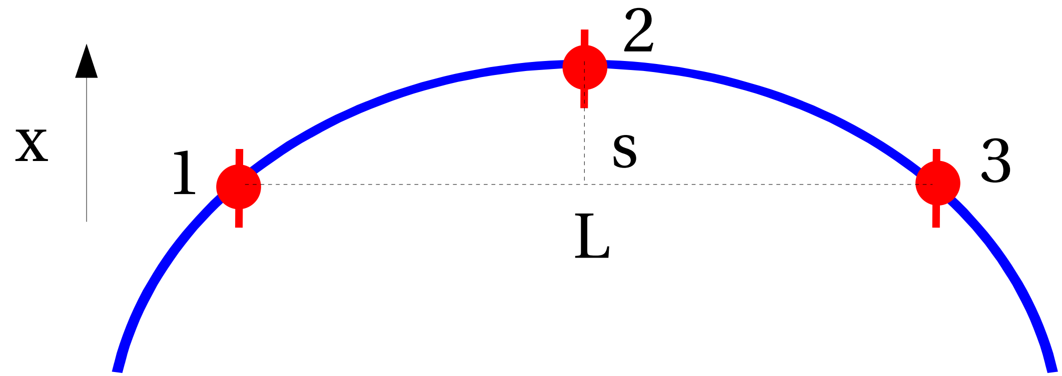
$$\Rightarrow p_t = qBL^2/8s$$

CMS: B = 4 T, L = 1 m

P_t [GeV/c]	s [**cm**]
100	0.15
10	1.50
1	15.00

Momentum resolution

Sagitta: $s = x_2 - \dfrac{x_1 + x_3}{2}$



Error propagation: $\sigma_s^2 = \sigma_2^2 + \sigma_1^2/4 + \sigma_3^2/4$ (usually Gaussian)

All σ equal: $\sigma_s = \sqrt{3/2}\,\sigma_x$ $\qquad p_t = qBL^2/8s$

$\Rightarrow \sigma_{p_t}/p_t = \sigma_s/s = \sqrt{96}\,\sigma_x\, p_t/qBL^2$ (always non-Gaussian)

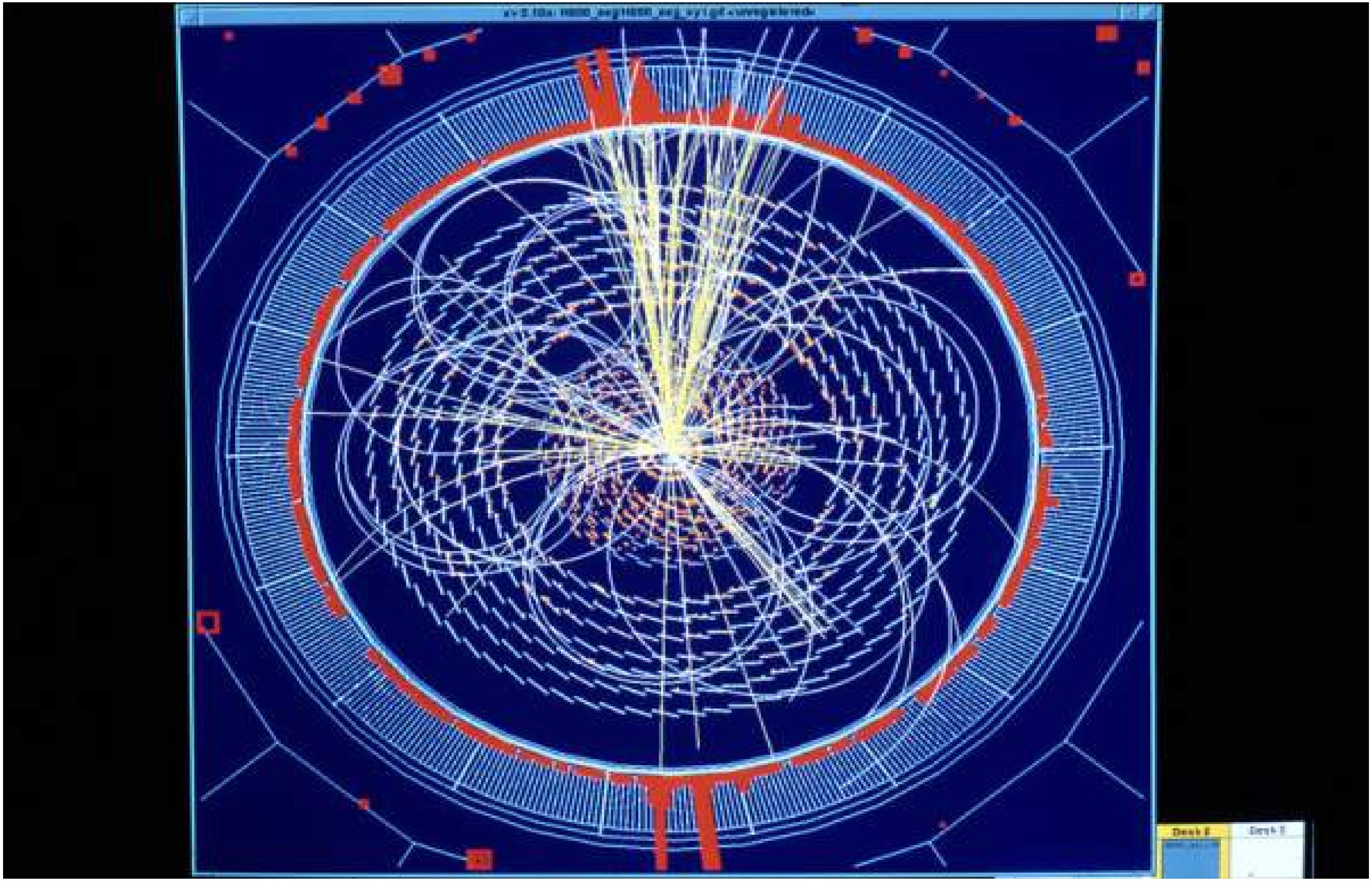
N equidistant measurements: $\boxed{\sigma_{p_t}/p_t = \sqrt{720/(N+4)}\,\sigma_x\, p_t/qBL^2}$

(Glückstern 1964)

Note: $\sigma_{p_t}/p_t \sim p_t$ worse resolution at high p_t.

$\sigma_{p_t}/p_t \sim \sigma_x/BL^2$ want large, precise tracker, strong field.

CMS Event Display

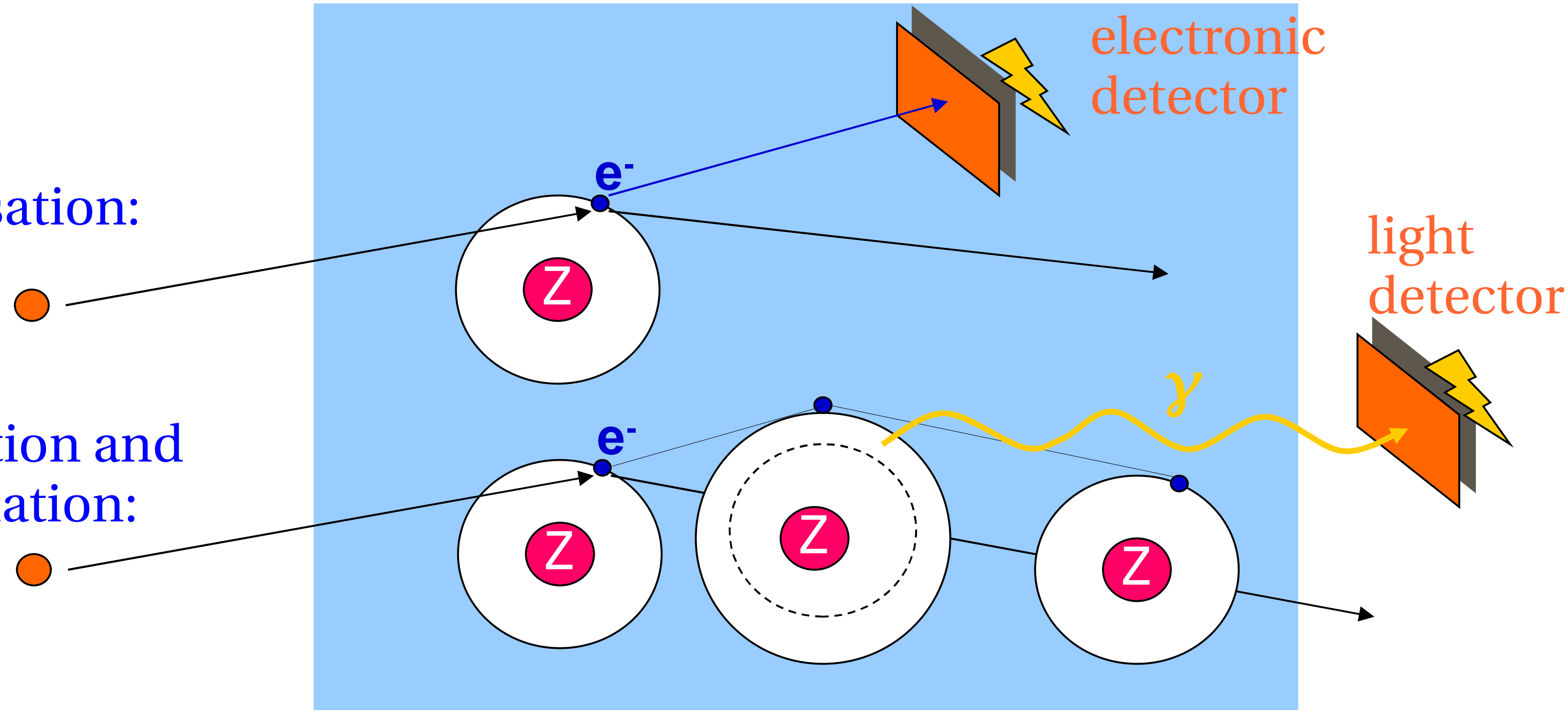


Tracker and ECAL $H \to ZZ$, $Z \to ee$ and $Z \to$ jet jet

Principles of a measurement

1. The particle must interact with the detector material.
2. An effect of the interaction must be measured.

- Ionisation:
- Excitation and scintillation:



- The ions may change the material physically or chemically:
  - Cloud chamber, bubble chamber, photographic emulsion.
- The particle may also be affected:
  - energy loss, scattering, absorption

Silicon strip detectors

- Planar sensor from a high-purity silicon wafer (here *n*-type).
- Segmented into strips by implants forming *pn* junctions.
- Strip pitch 20 to 200 µm, high precision photolithography (expensive).
- Bulk is fully depleted by a reverse bias voltage (25-500V).
- Ionizing particle creates electron-hole pairs (25k in 300 µm).

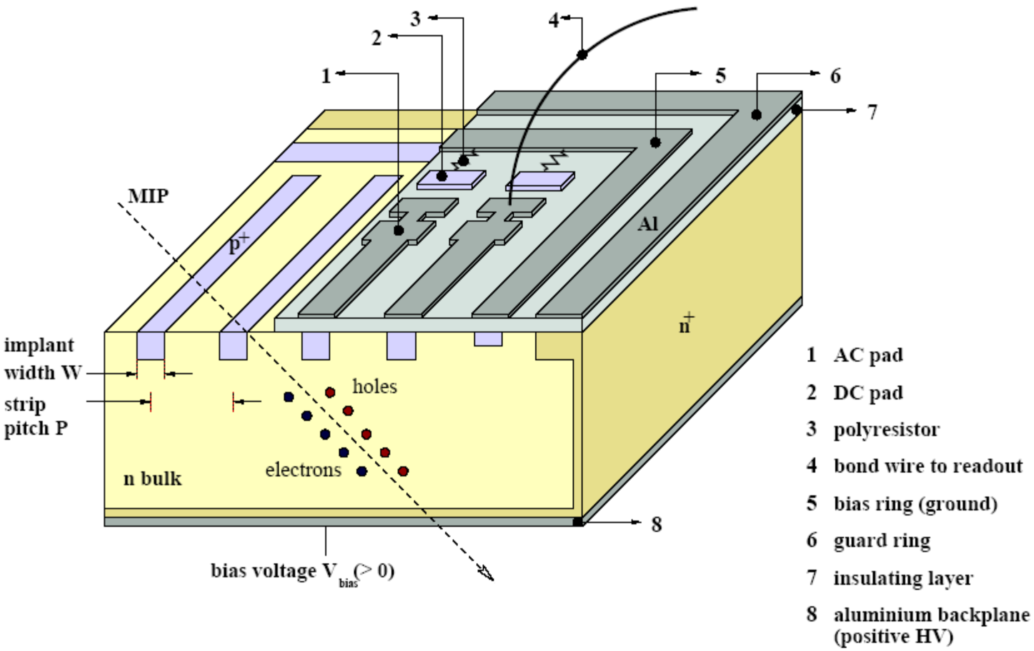
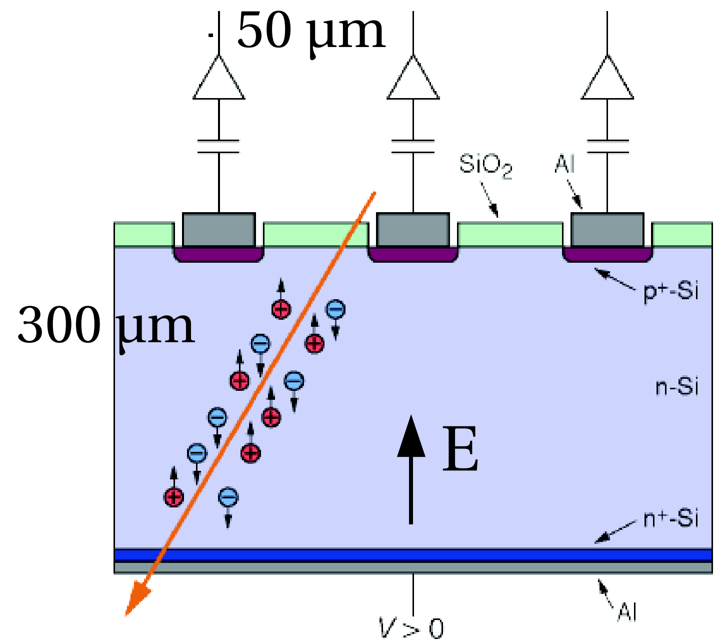
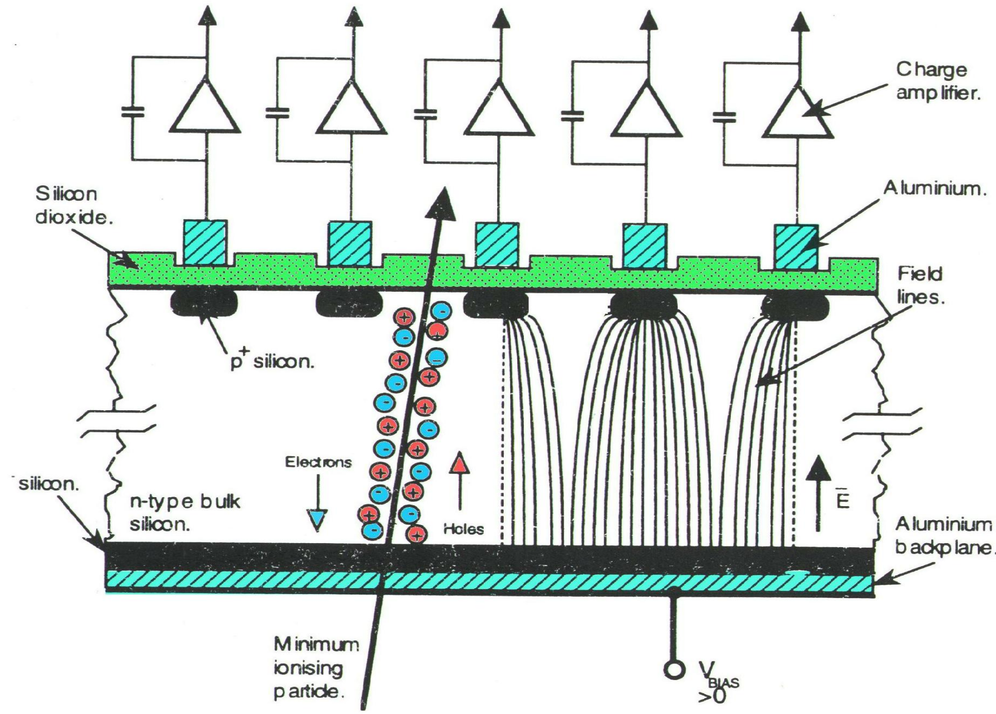


Figure 2.8: Schematic structure of a CMS silicon microstrip sensor.



Charge collection

- Electrons and holes are separated in the electric field and collected on the implanted strips:
  - Electrons drift 10 ns
  - Holes drift 25 ns
  - Need high-purity silicon to avoid trapping.
- Position resolution: 15-30 μm for strip pitch of 50-100 μm (better with pulse-height interpolation).
- Silicon detectors are fast and have high resolution.
- Further readout electronics required to amplify the charge.
  - Need many channels to cover large areas.



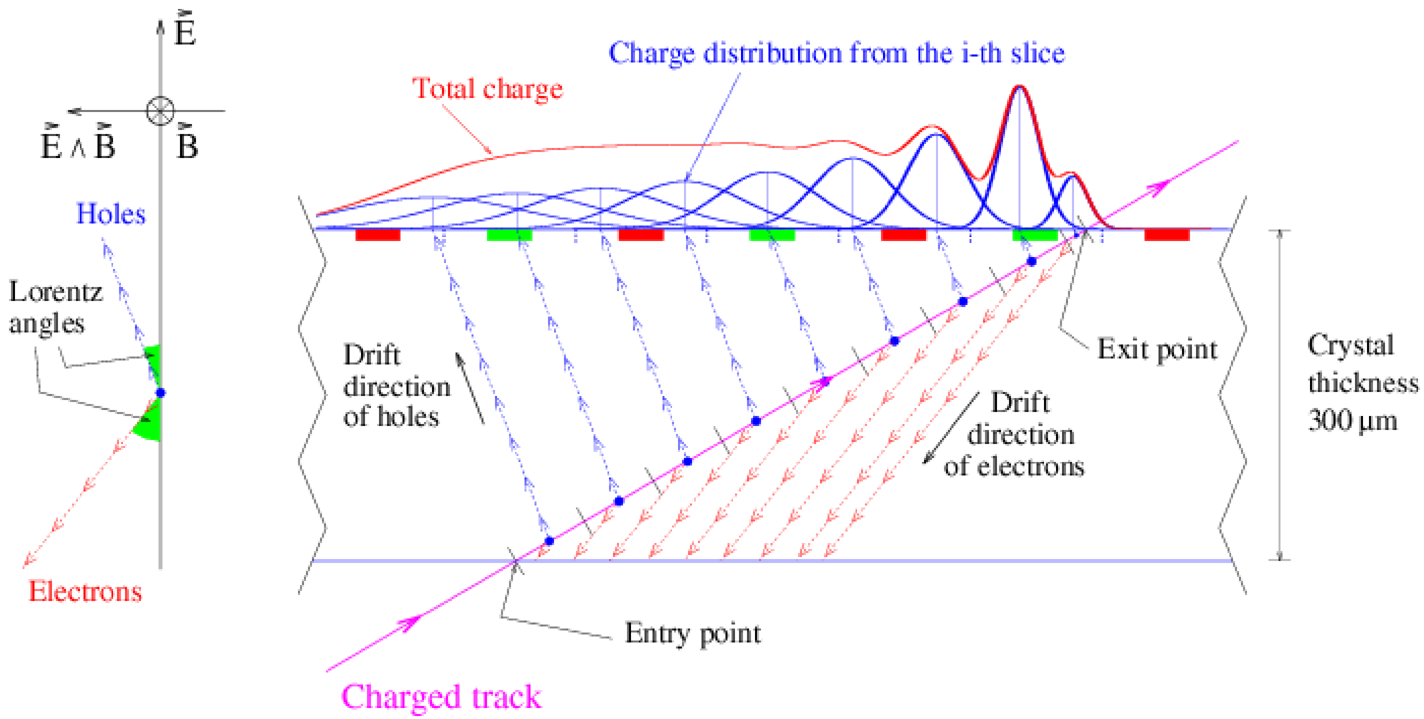
Drift and charge collection

Drift in a magnetic field occurs at the Lorentz angle:

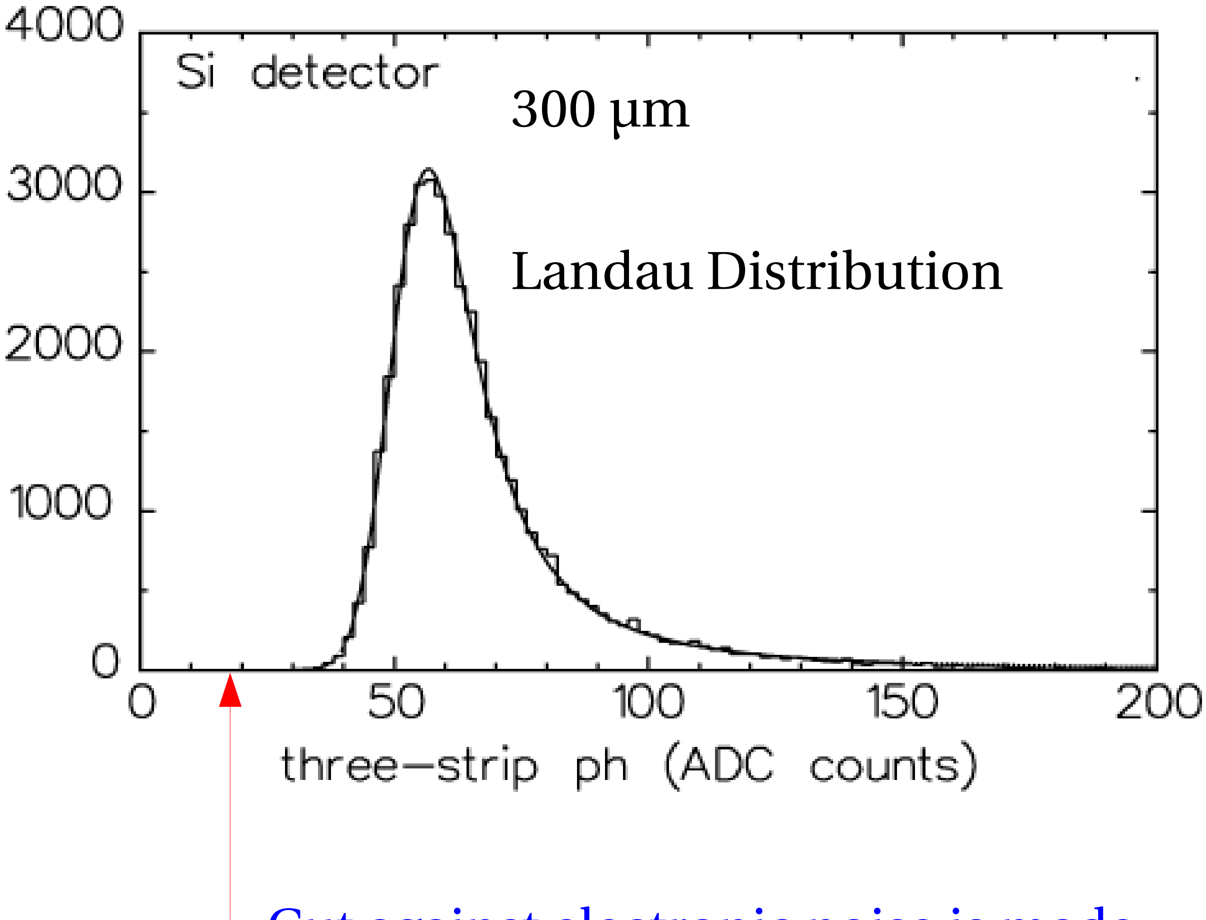
Systematic shift of charges must be taken into account.

Position resolution is worse for inclined tracks:

avoid by proper detector design: barrel cylinders and endcap disks.



Pulse height distribution



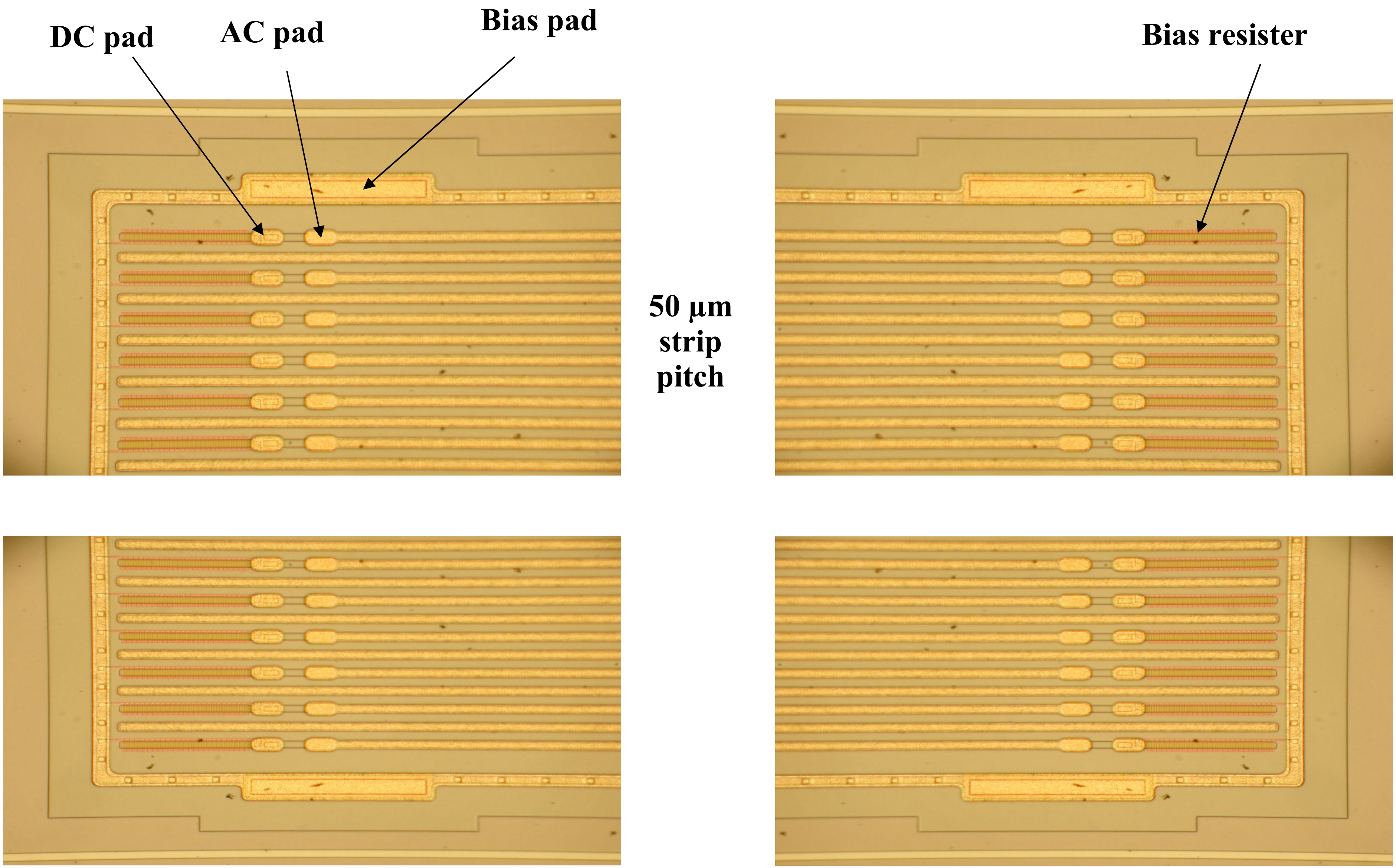
Cut against electronic noise is made

Particles looses
<ΔE> ≈ 0.1 MeV
in 300 μm silicon
⇒ negligible.

Energy loss fluctuates:
Gaussian core and
'Landau tail'.

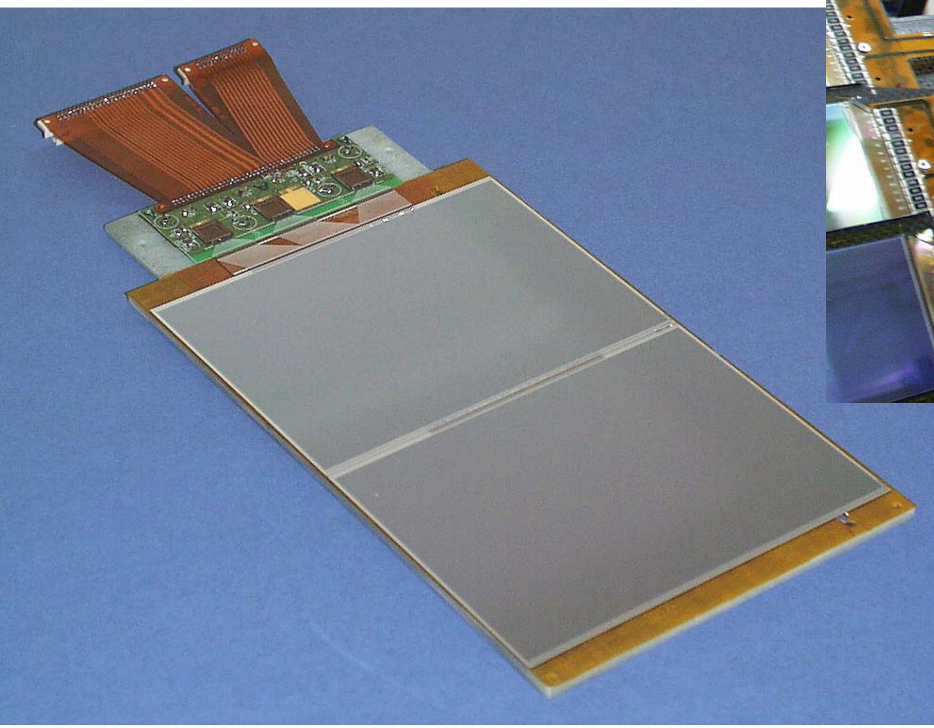
Clean identification of signal
with low-noise electronics.

SILICON MICROSTRIP DETECTOR



CMS Silicon tracking

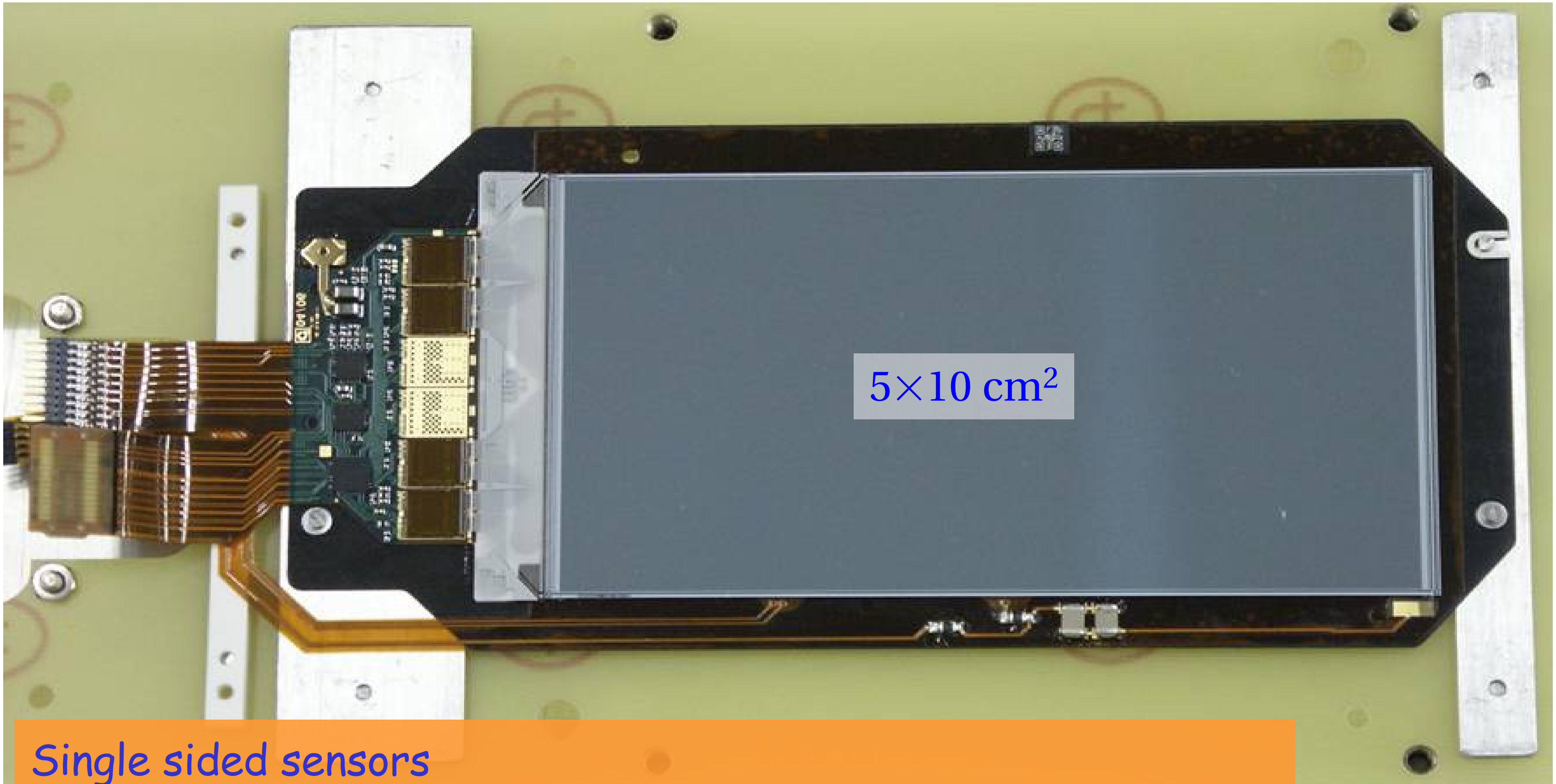
One outer barrel module:



Carbon-fibre support structure.
Sensor alignment needed, despite tight mechanical tolerances and accurate placement.

CMS Silicon Strip Modules

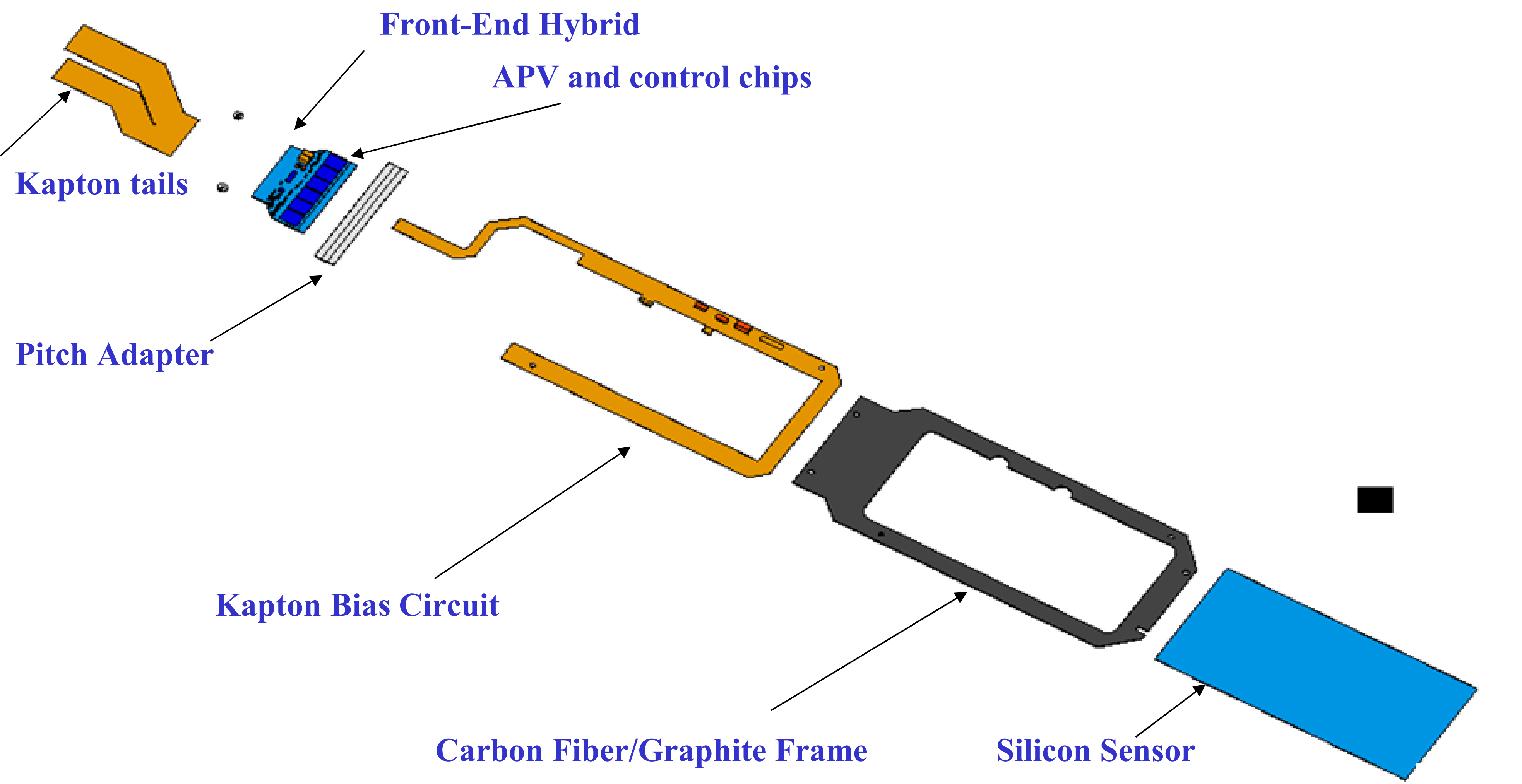
Inner barrel module:



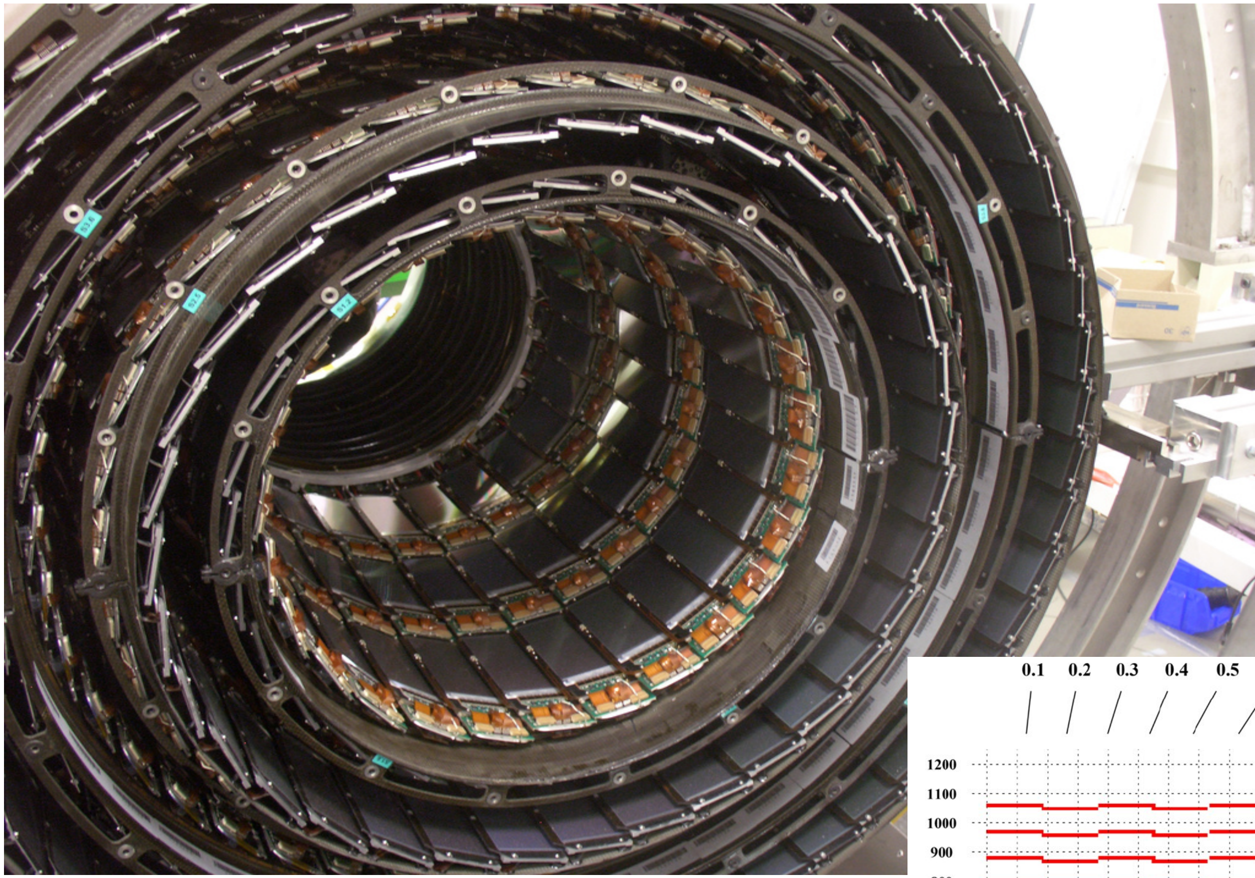
Single sided sensors

stereo layers are realized gluing back to back two modules

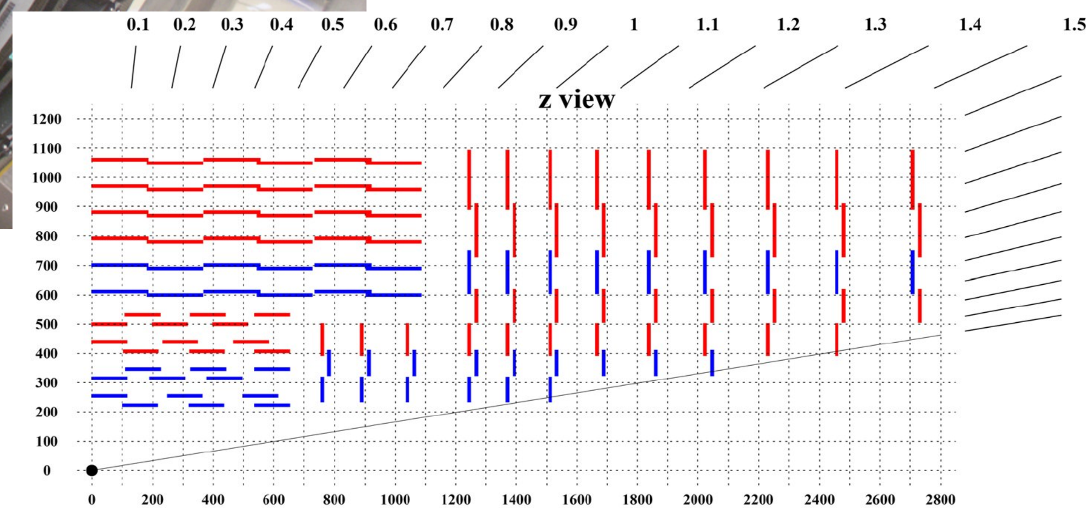
Module components



CMS Silicon Tracker

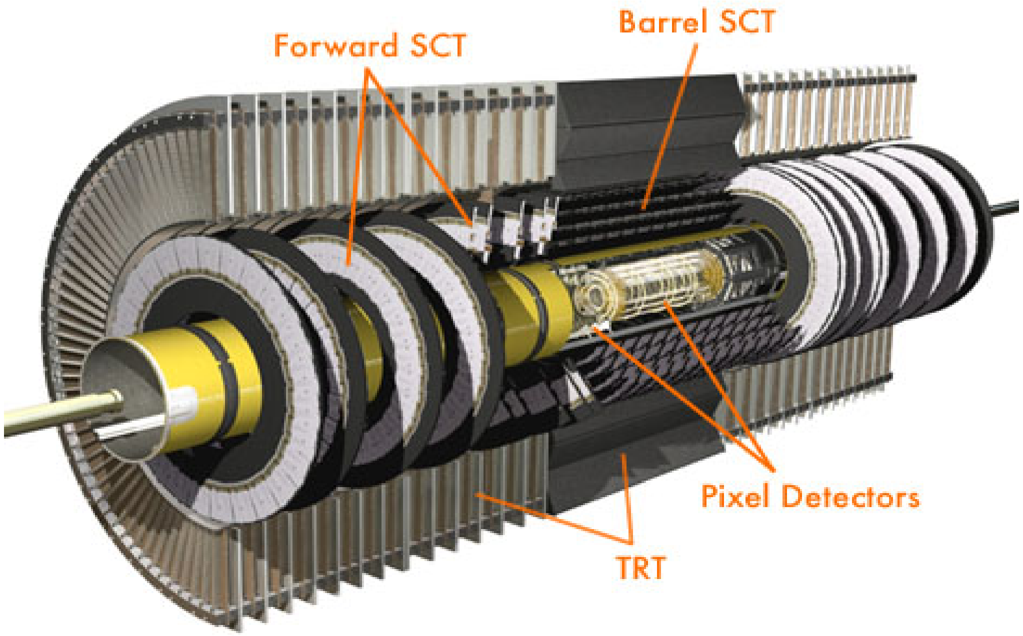


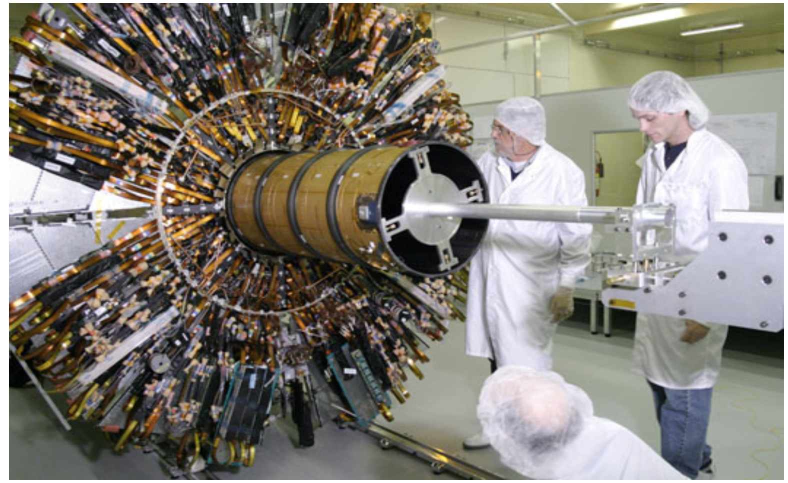
Inner barrel

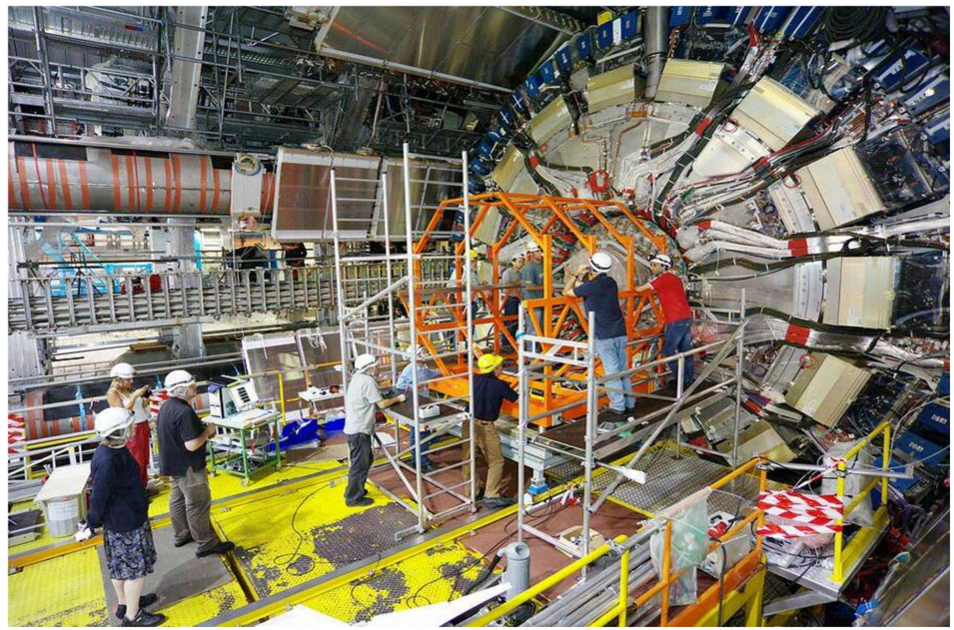


10^7 channels
200 m^2

ATLAS Inner Tracker







Silicon pixel detector in the centre

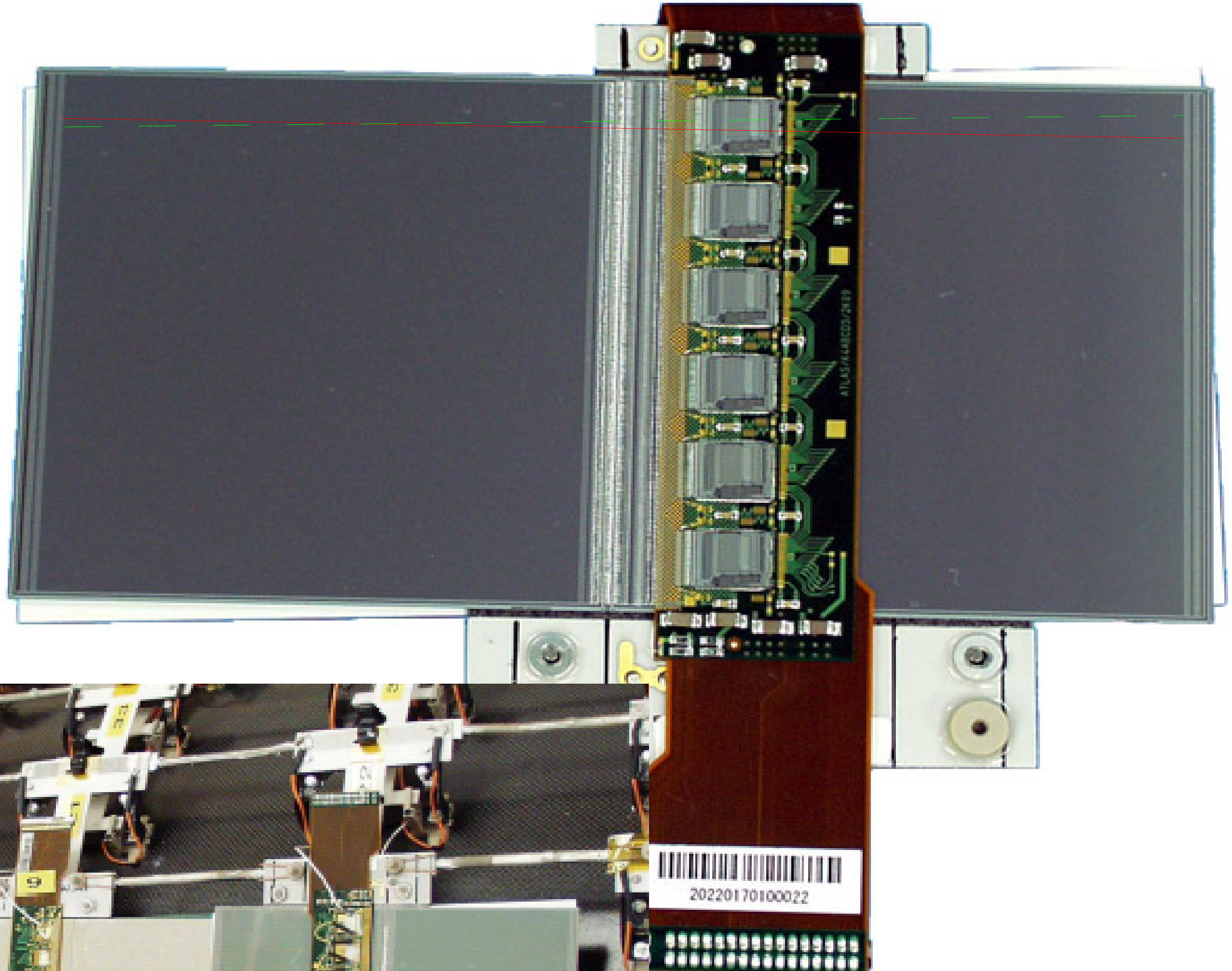
Semiconductor tracker (SCT)

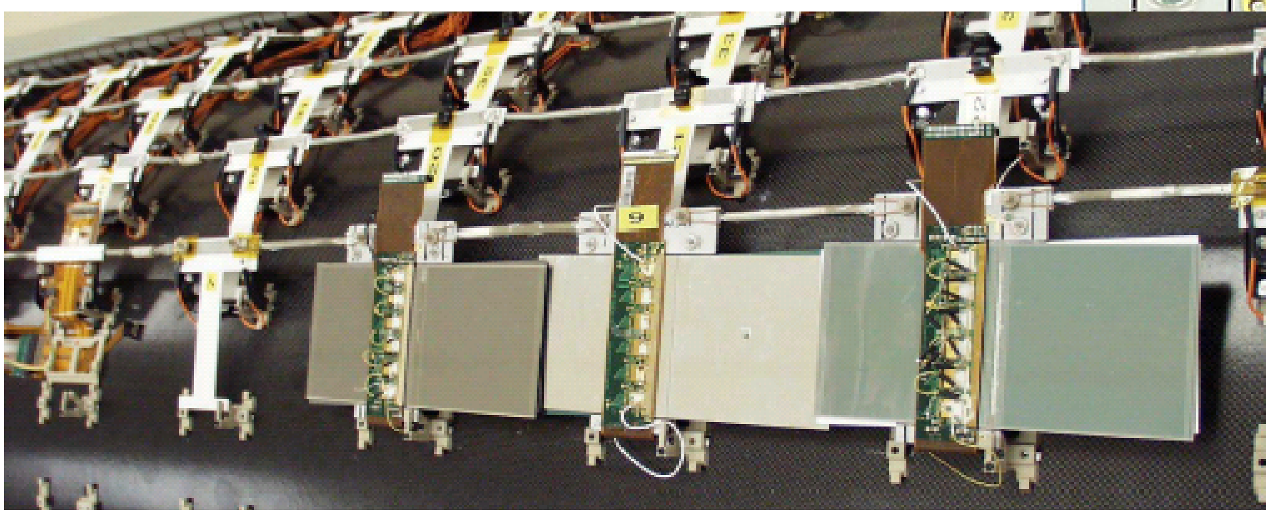
Transition radiation tracker (TRT).

ATLAS silicon tracker module

Single sided sensors
6.4 x 6.4 cm^2
738 strips
80 μm pitch
2 sensors connected

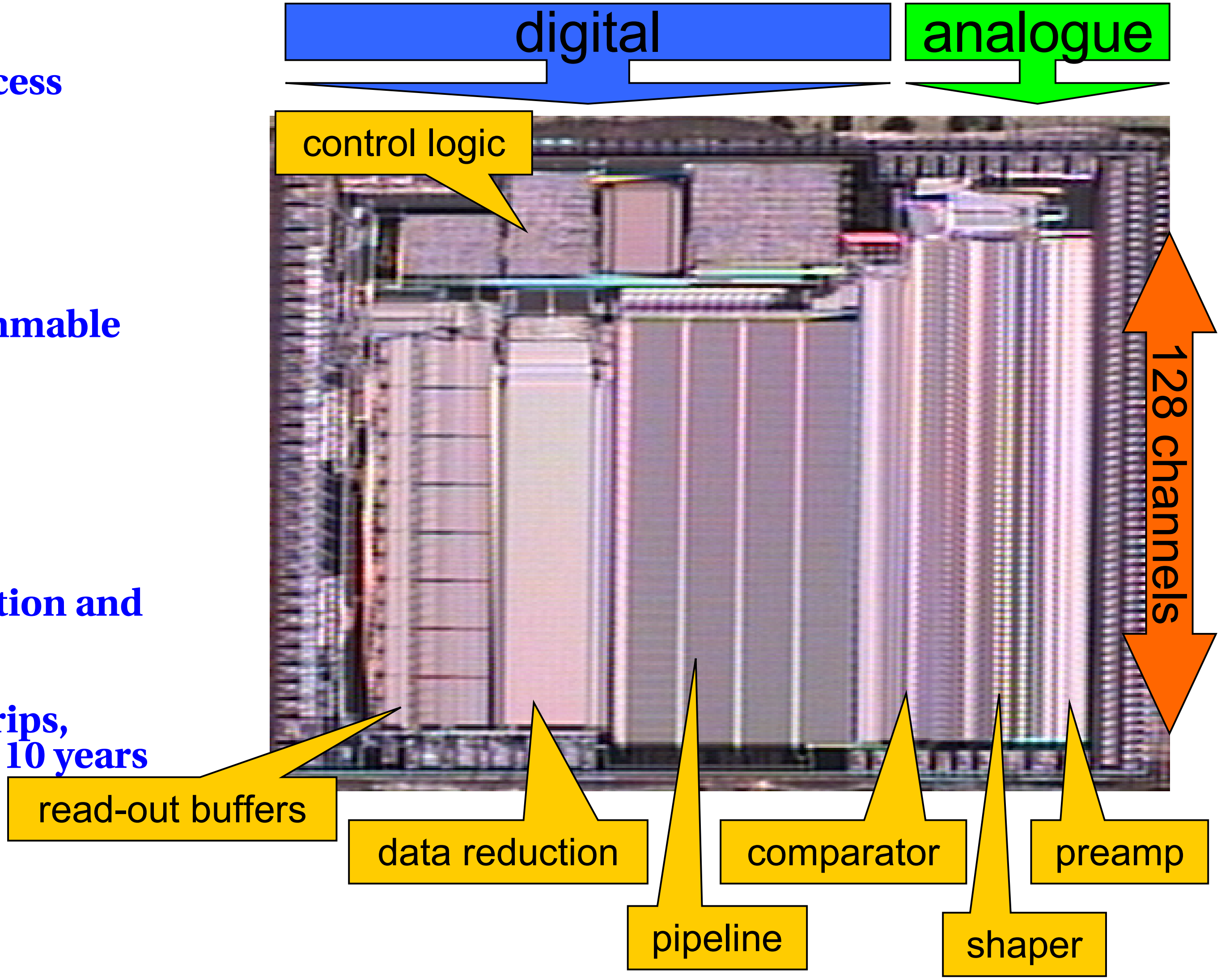
2 sensors back-to-back
40 mrad stereo angle



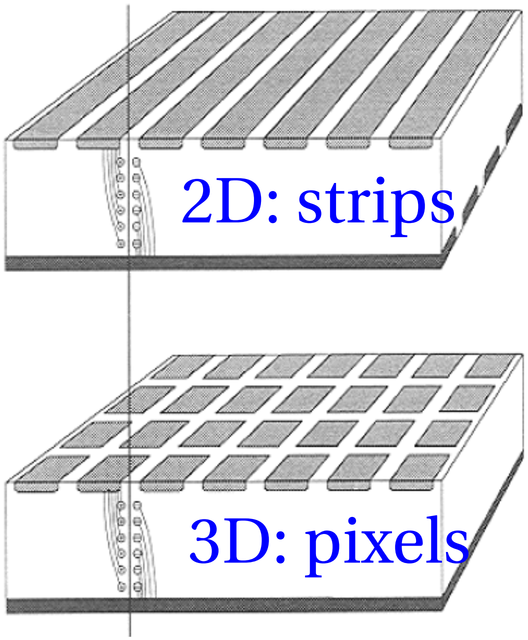


ATLAS silicon front-end ASIC ABCD3T

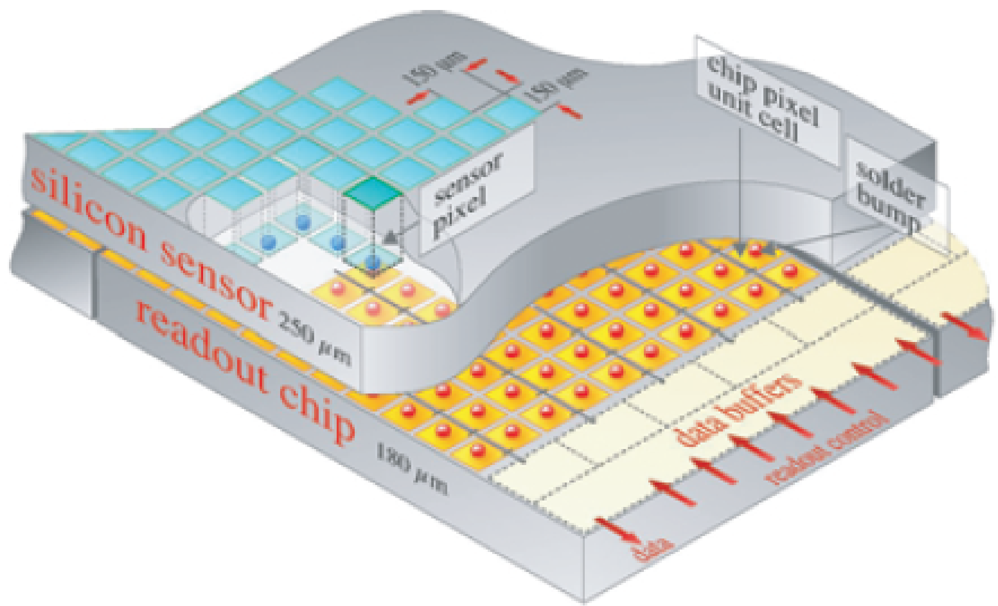
- 128 channels
- DMILL radiation hard process
- bipolar input transistor
- shaping time ~20ns
- comparator threshold trimmable for each channel
- binary read-out
- 132 cell pipeline
- edge detection, data reduction and multiplexing
- noise ~ 1500 e for 12 cm strips, increasing to ~1800 e after 10 years of irradiation
- power: ~4 mW/channel



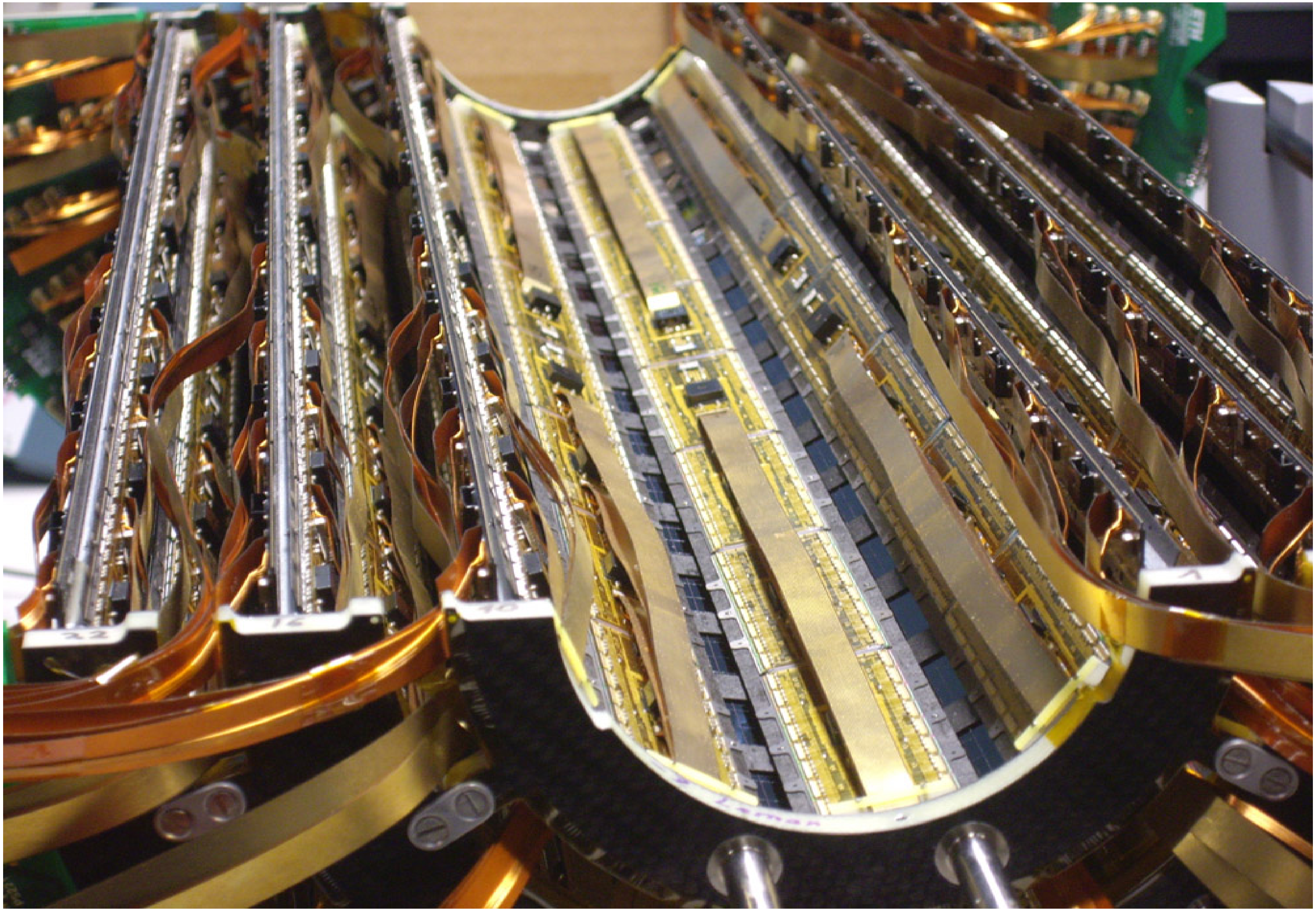
Silicon Pixels



Requires readout chip
bump-bonded
to the sensor:

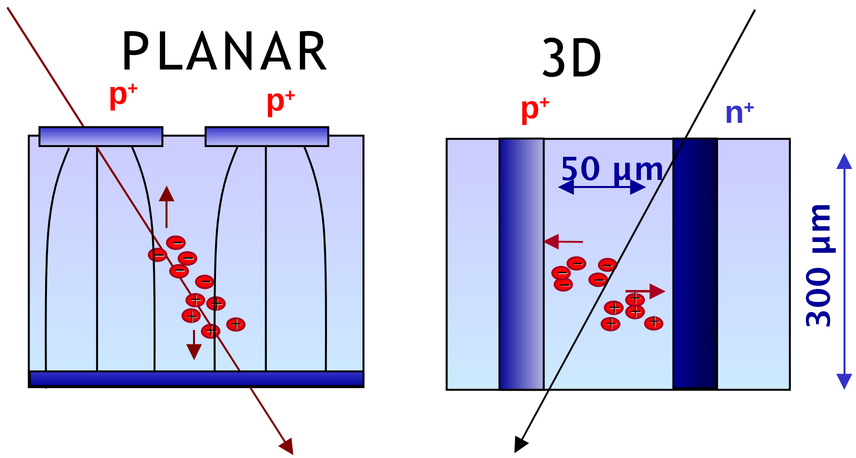


CMS silicon Pixel Detector



installed last week

New idea: 3D sensors

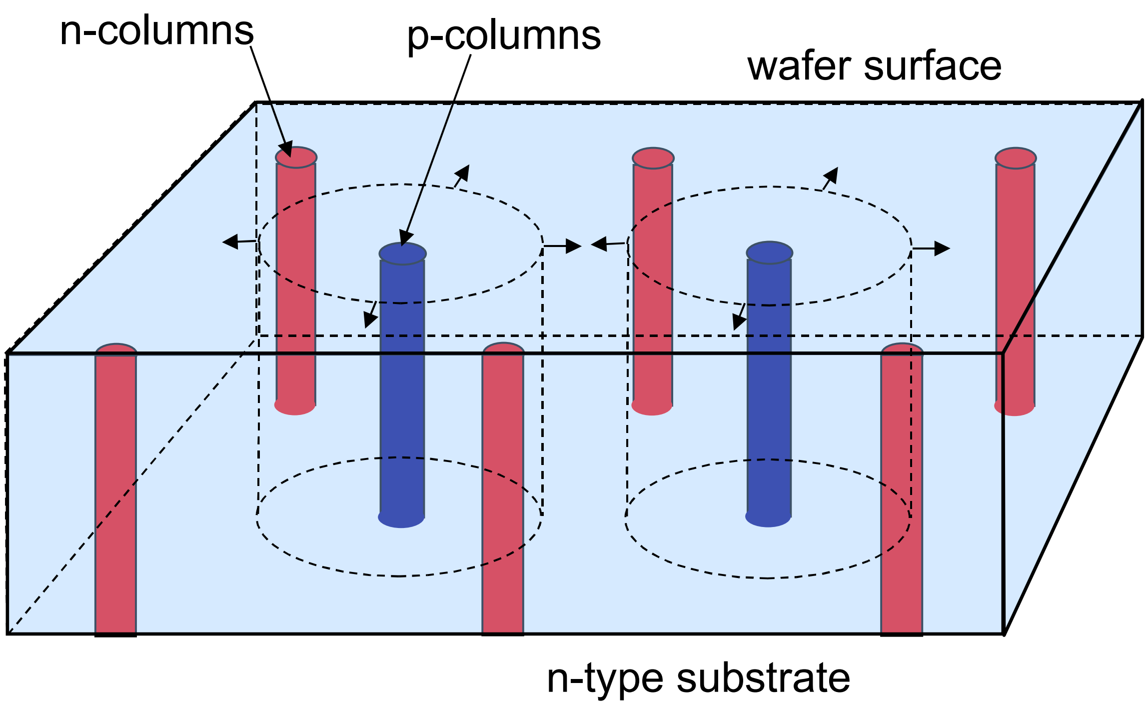


"3D" electrodes:

narrow columns along detector thickness,
diameter: 10 µm, distance: 50 - 100 µm

Lateral depletion:

lower depletion voltage needed
thicker detectors possible
fast signal
radiation hard



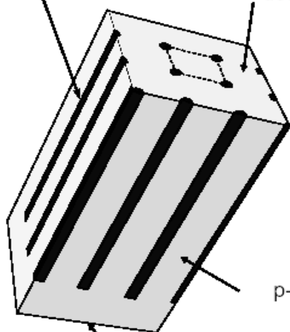
Introduced by: S.I. Parker et al., NIMA 395 (1997) 328

D. Pitzl, DESY

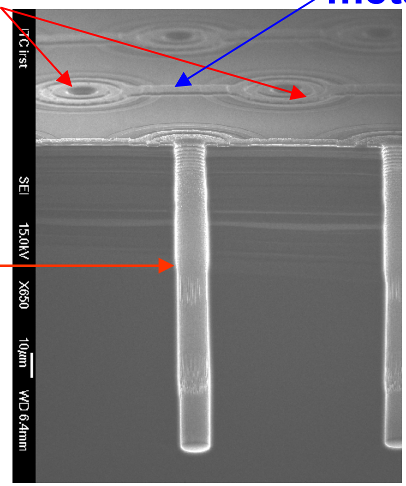
3D sensors: first prototype

- Simplified 3D architecture
  - n⁺ columns in p-type substrate, p⁺ backplane
  - operation similar to standard 3D detector

- Fabrication:
  - IRST(Italy), CNM Barcelona



[C. Piemonte et al.,
NIM A541 (2005) 441]

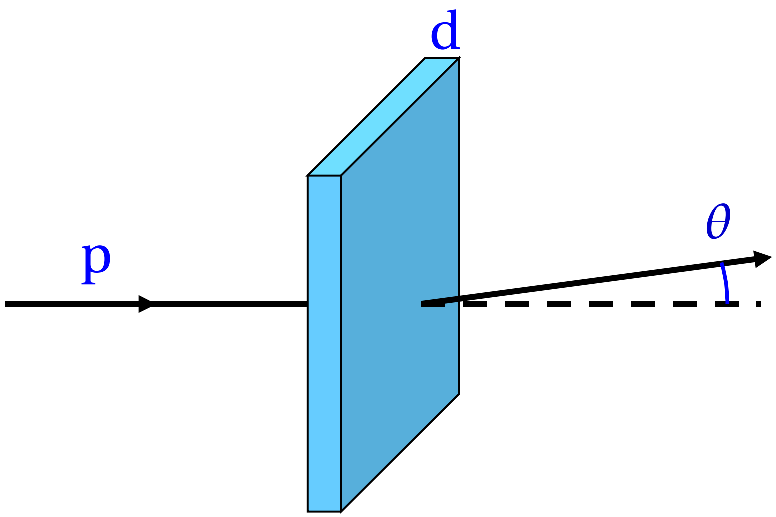


C.Piemonte et al., STD06, September 2006

- Simplified process
  - hole etching and doping only done once
  - no wafer bonding technology needed

Multiple Coulomb scattering

- Multiple elastic scattering from nuclei causes angular deviations:



$$\langle \theta \rangle [rad] \approx \frac{0.014}{p\,[GeV/c]} \sqrt{d/X_0}$$

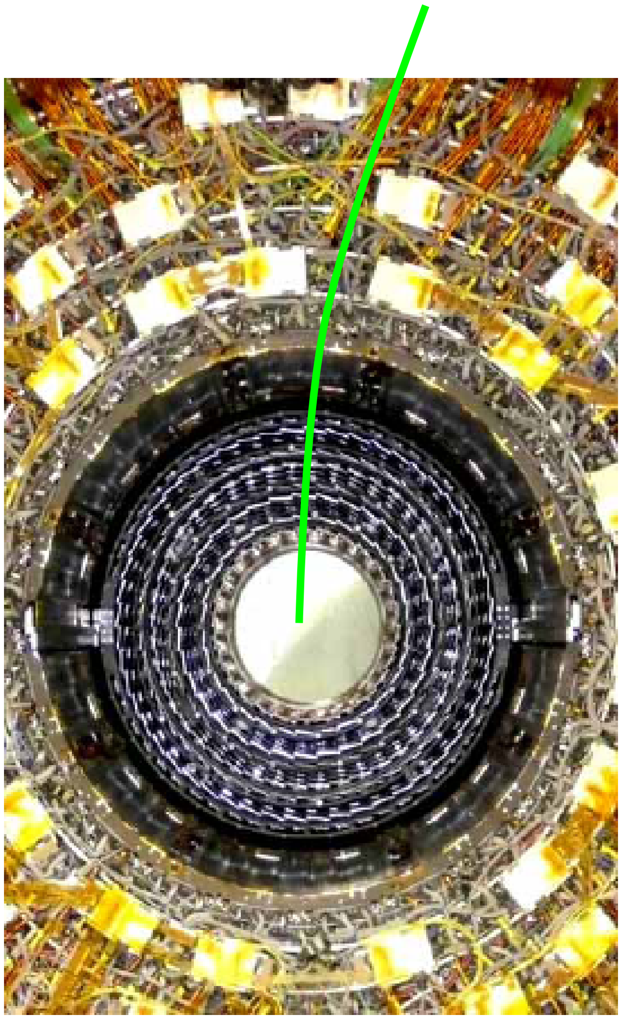
X_0 = radiation length
9.4 cm for silicon
18.8 cm for carbon

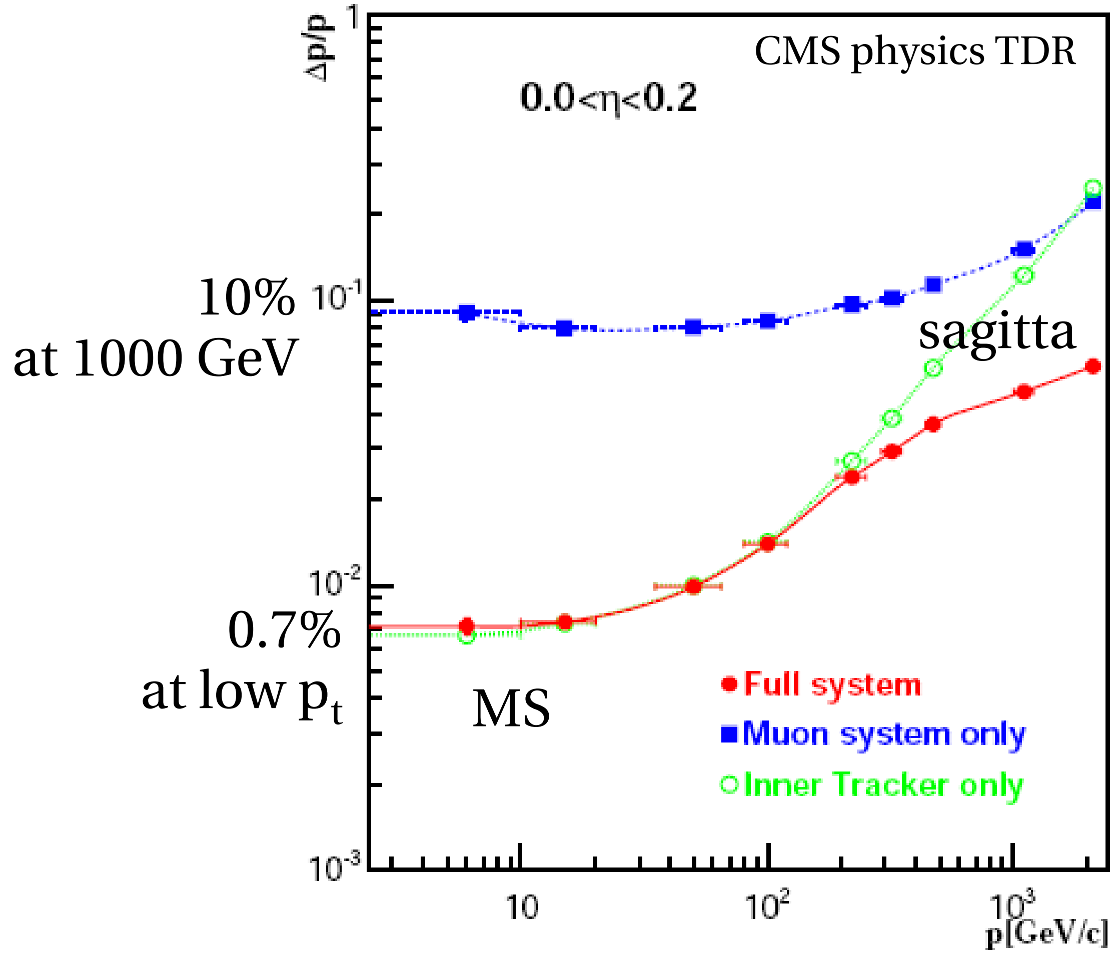
Number of scatterings is Poisson process
⇒ RMS ~ √d

Important at low momentum: ~1/p

CMS momentum resolution

Multiple scattering and momentum resolution: $\sigma_{p_t}^{MS} / p_t \approx \frac{0.016}{BL} \sqrt{\sum d / X_0}$



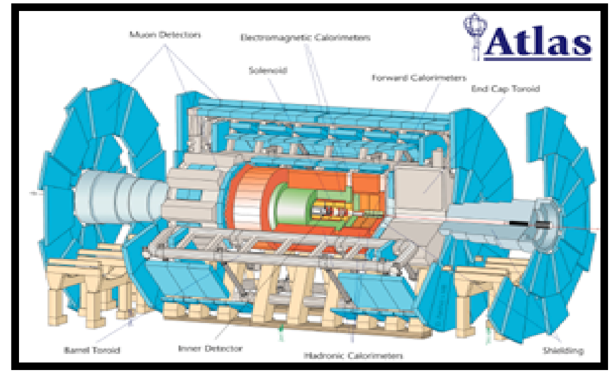


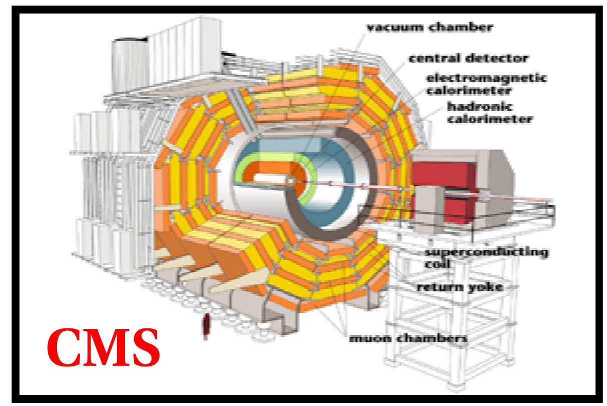
Summary

- Collider detectors:
  - Tracking – calorimeters – magnet – muons
- Charged particles in a magnetic field:
  - p_t [GeV/c] = 0.3 R [m] B [T]
- Momentum resolution:

$$\frac{\sigma_{p_t}}{p_t} \sim \frac{\sigma_x}{\sqrt{N}} \frac{p_t}{BL^2} \oplus \frac{\sqrt{d/X_0}}{BL}$$

- Silicon detectors:
  - $\sigma_x \approx 20\ \mu m$
- Pixel detectors for 3D information.





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