Detector Physics
Part 1 - Tracking

Sigve Haug
AEC-LHEP University of Bern
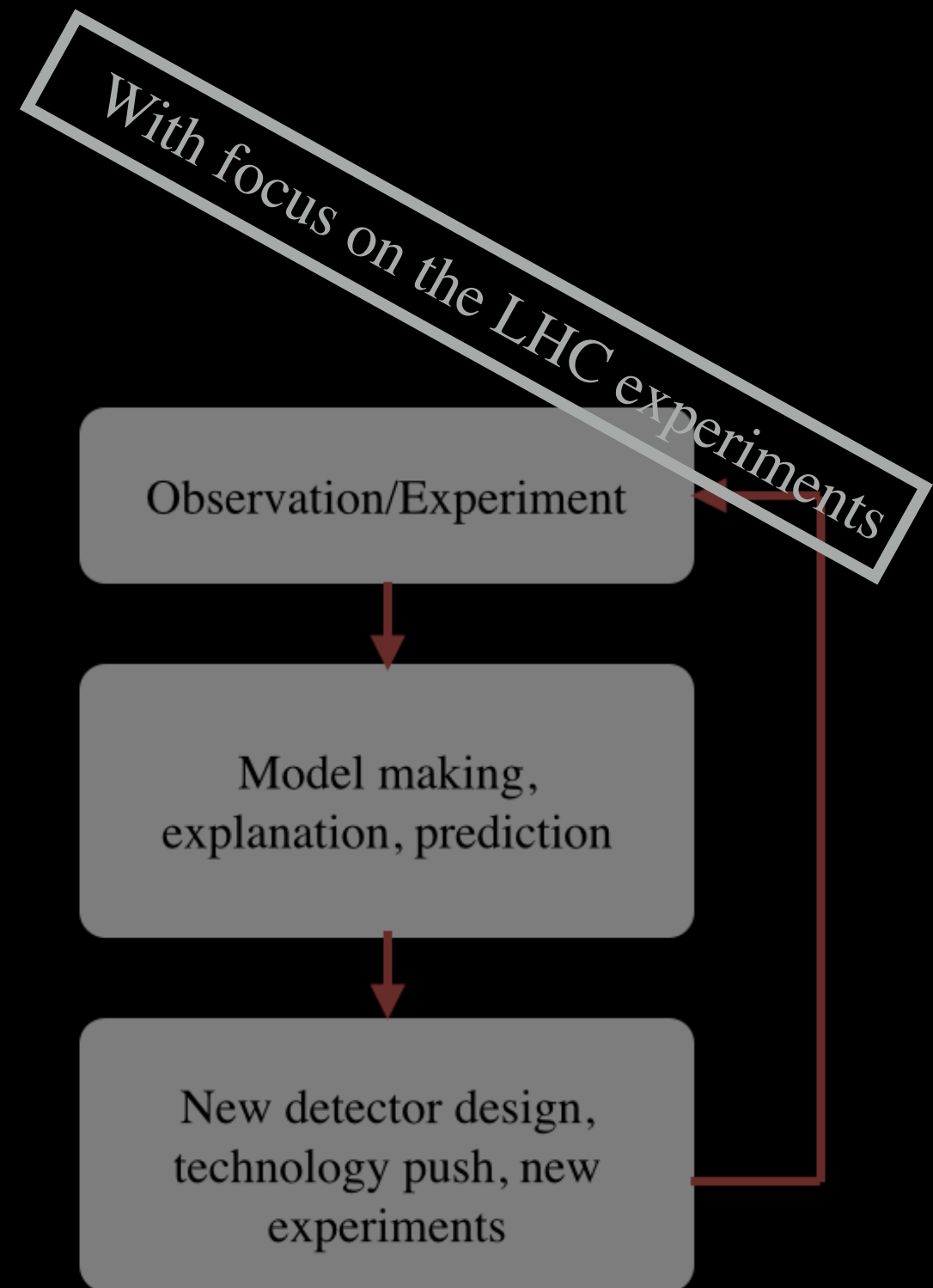
(Part 2 : Calorimetry by Claudio Santoni)

HASCO14, HS 5, University of Goettingen, 14:00 - 15:00, 2014-07-22

Physics Department II. Institute of Physics Friedrich-Hund-Platz 1 37077 Göttingen

Outline

1. Motivations / Reminders

2. Magnet systems

3. Tracking detectors

    1. Principles

    2. Silicon detectors

    3. Transition radiation

    (Calorimetry)

    4. Muon detection / gas detectors

4. Summary
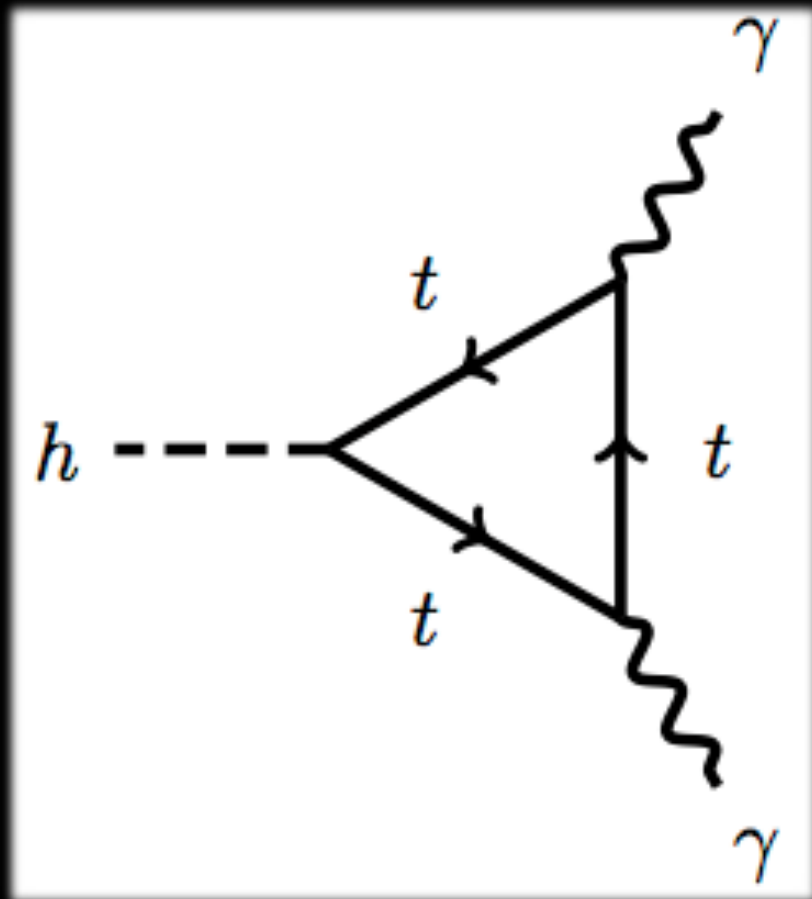
Next lecture on calorimetry by Claudio Santoni

Observation/Experiment

Model making, explanation, prediction

New detector design, technology push, new experiments

Lecture goal : Understand why the ATLAS and CMS detectors are like they are !
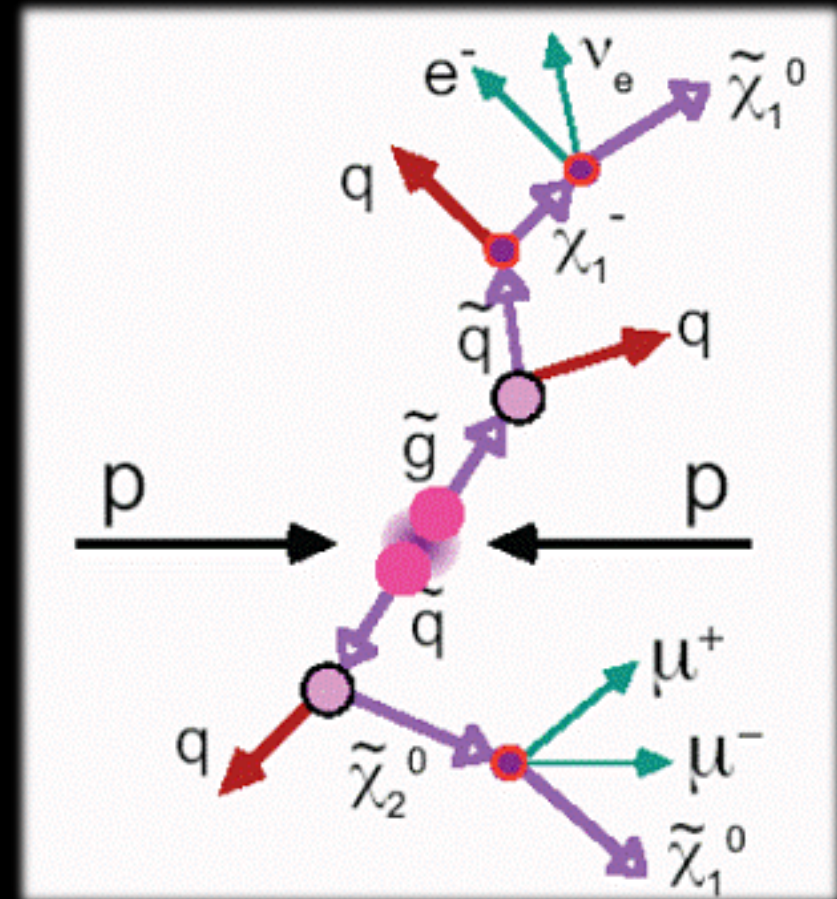
1
Motivations / Reminders

Signature examples

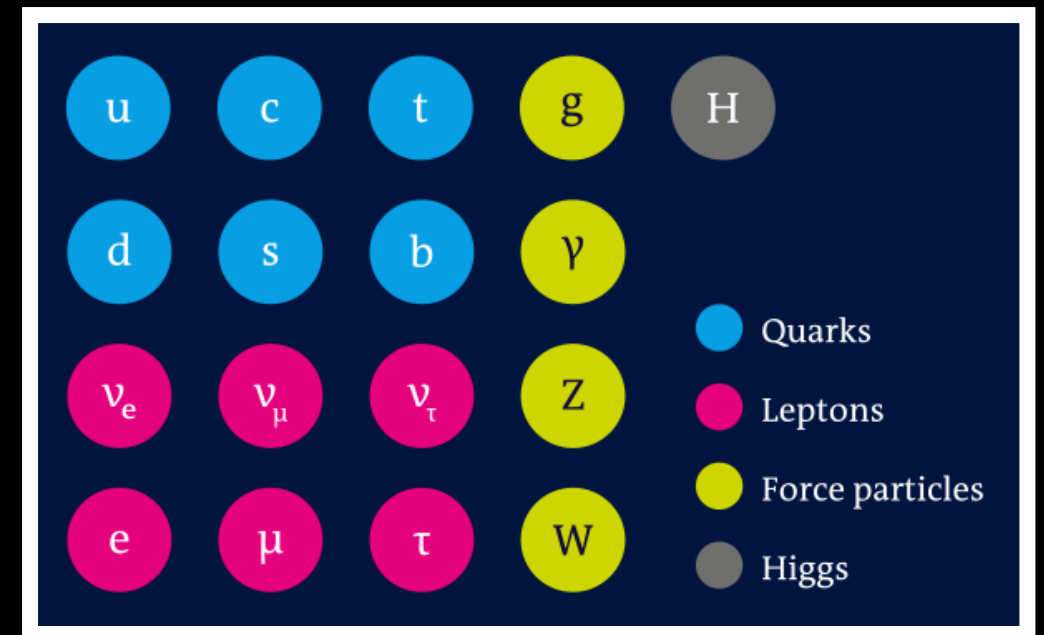Some predicted and "desired" signatures we want to verify/discover :

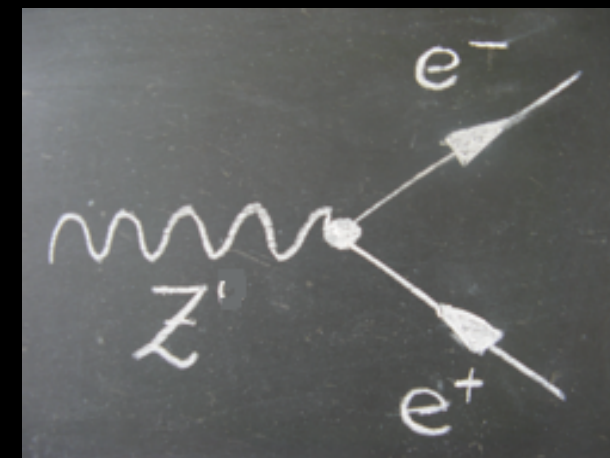The Brout-Englert-Higgs boson discovery channel (two photons)

Possible SUSY event in LHC with jets, leptons and missing transverse momentum

Which particles are detected ?

1. Charged leptons, photons and hadrons: e, μ, γ, π, K, p, n … (maybe new long-lived particles, i.e. particles that enter detector)

2. B (and D) mesons and τ lepton have cτ ~ 0.09…0.5x10^{-3} m large enough for additional vertex reconstruction

3. Neutrinos (maybe also new particles) are reconstructed as missing transverse momentum

4. All other particles decay or hadronise in primary vertex (top quark decays before it hadronises)

Only e, μ and γ of the fundamental Standard Model particles are directly detected

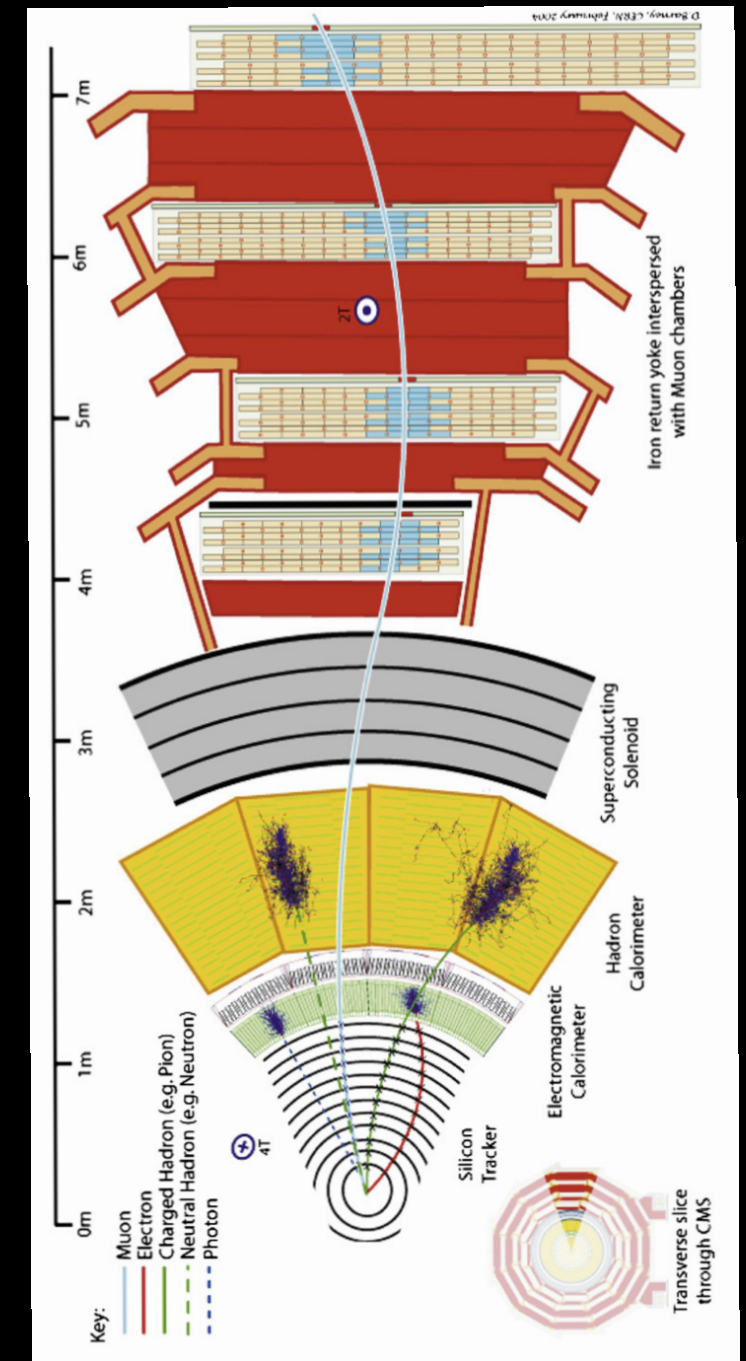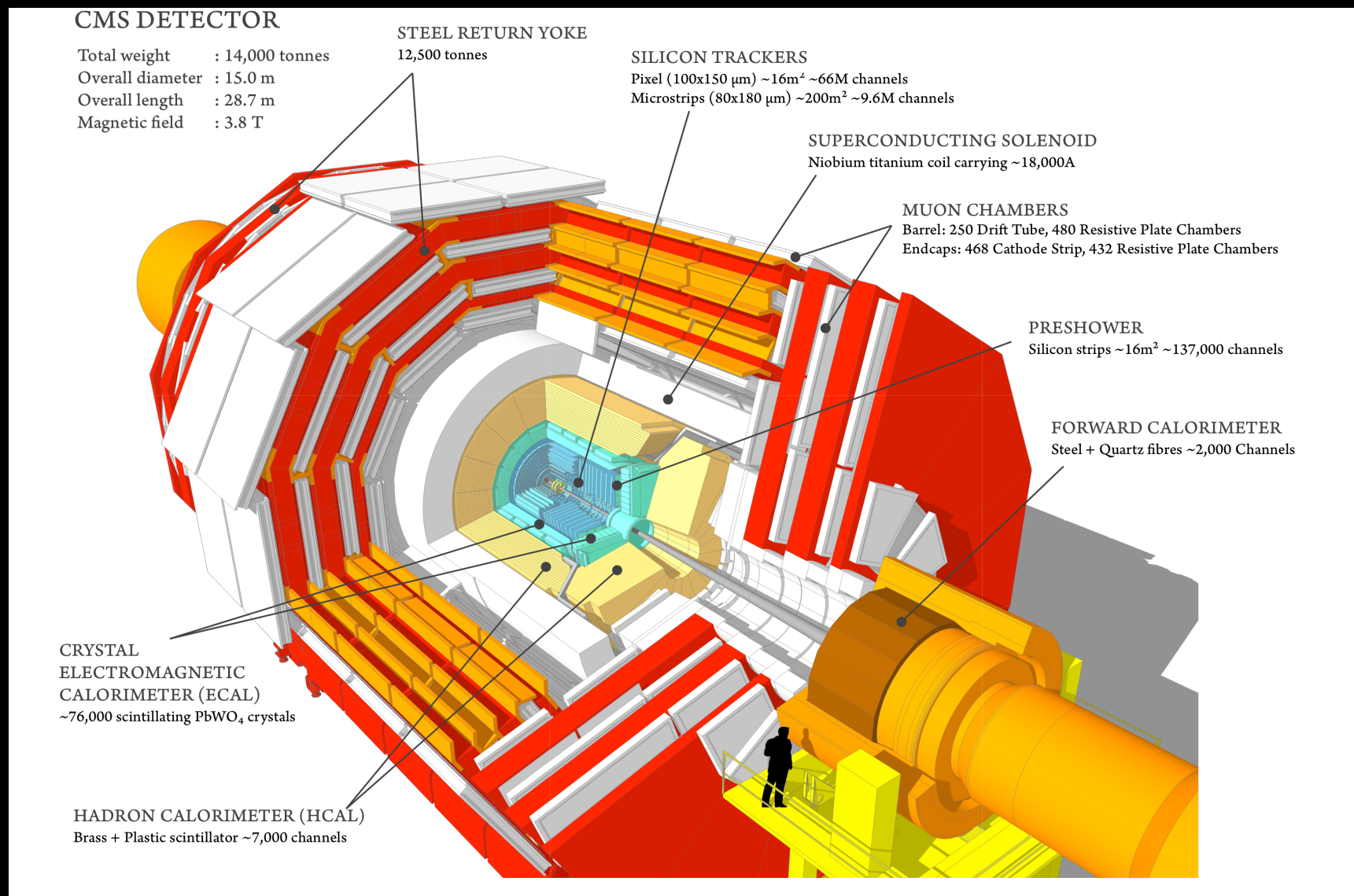Heavy particles like Z and W decay immediately

The detected particles and …

1. Photon makes photo effect, compton scattering and pair production. It has no track but an electromagnetic cascade in the calorimeter.

2. Charged particles makes scattering, ionisation, excitation and bremsstrahlung, transition and cherenkov radiation. They produce tracks.

3. Electrons make electromagnetic cascades (clusters) in the calorimeter.

4. Hadrons also interact strongly via inelastic interactions, e.g. neutron capture, induced fission, etc. They make hadronic cascades (clusters) in the hadronic calorimeter.

5. Only weakly interacting particles are reconstructed via missing transverse momentum ("missing energy")

… their observables
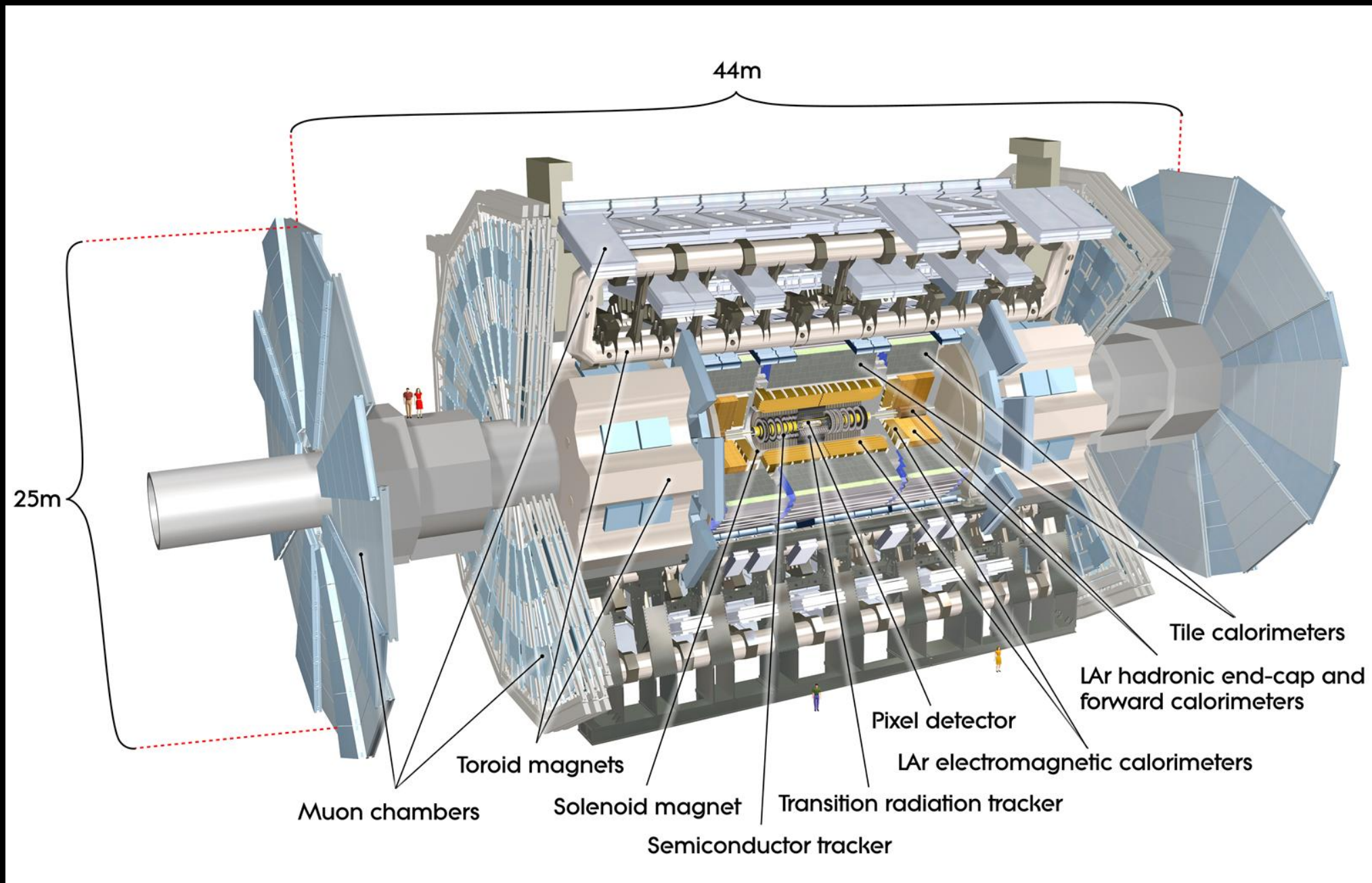
The CMS example

Typical 4π cylindrical onion design

Left : CMS Detector. Right : CMS slice showing subsystems, particles and their detector objects (hits, tracks, clusters, vertices and missing transverse momentum)

The ATLAS example

Typical 4π cylindrical onion design

Reconstructed properties

From the hits, tracks, clusters, missing transverse momentum and vertices we reconstruct the particle properties:

1. Momentum from curved tracks

2. Charge from track curvature

3. Energy from full absorption in calorimeters and curved tracks

4. Spin from angular distributions

5. Mass from invariant mass from decay products

6. Lifetime from time of flight measurement

7. Identity from dE/dx, lifetime or special behaviour (e.g. transition radiation)
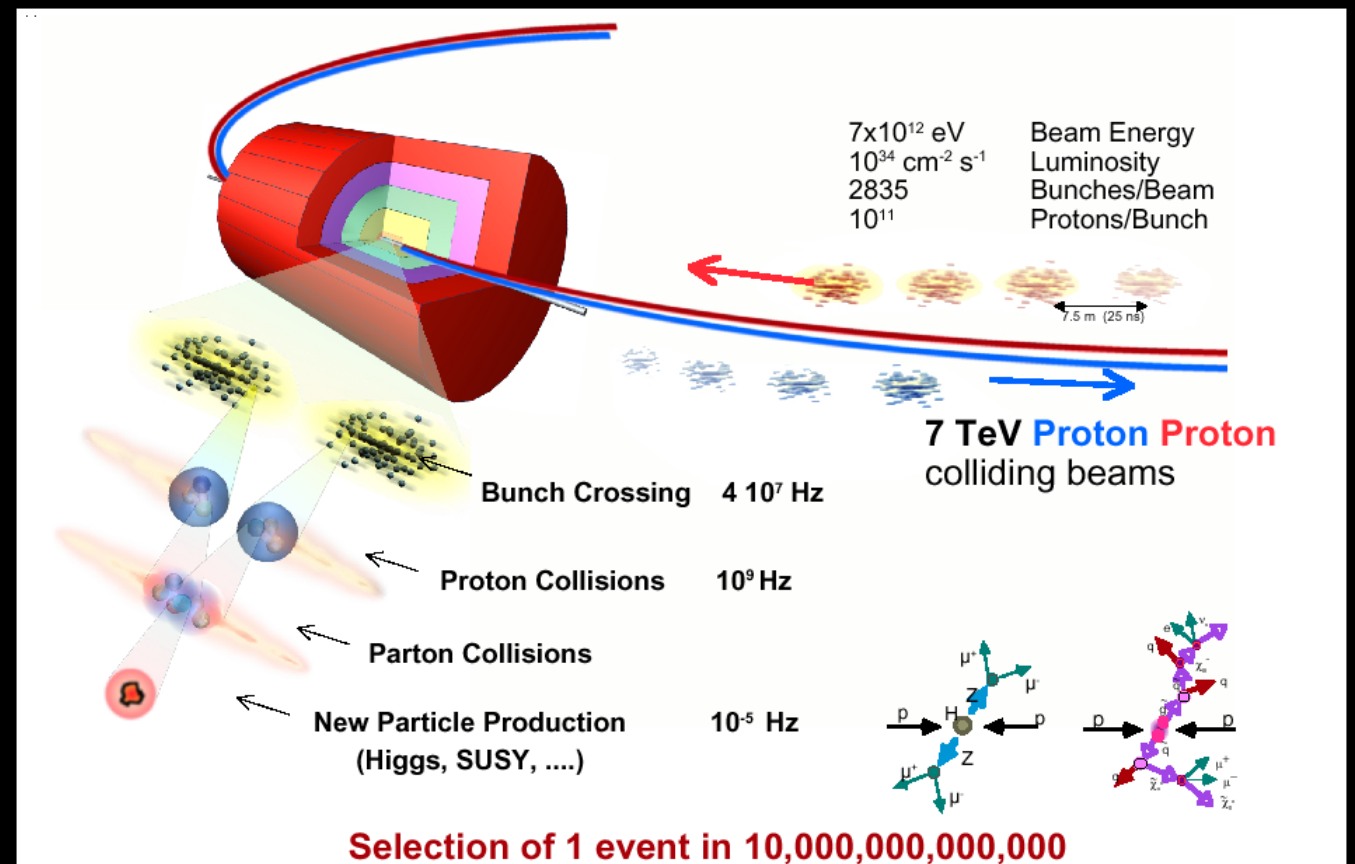
Detector design constraints I

Desired constraints from physics:

1. High detection efficiency demands minimal cracks and holes, high coverage

2. High resolution demands little material like support structures, cables, cooling pipes, electronics etc (avoid multiple scattering)

3. Irradiation hard active materials to avoid degradation and changes during operation

4. Low noise

5. Easy maintenance (materials get radioactive)

6. …

Detector design constraints II

Environmental constraints, i.e. from LHC design parameters.

1. Collision events every ~25 ns

2. Muons from previous event still in detector when current event enters tracker

3. High occupancy in inner detector

4. Pile up (more proton proton collisions in each bunch crossing)
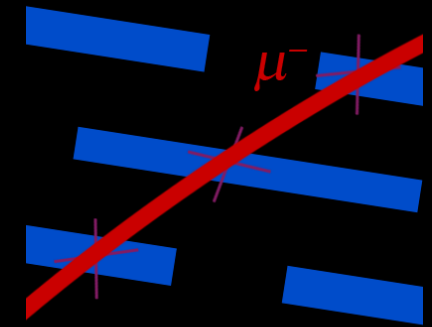
5. High irradiation

6. …

2.

Magnet systems

Magnet principle

- Use Lorentz force to curve tracks

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

Electric force   Magnetic force

- Max E is about 50 MV/m in high vacuum, thus B field used (5 T gives ~10^3 stronger force)

- Curvature or radius : $qvB = mv^2/T$ ➡ $p = qBR$

- At least three hits needed to reconstruct a unique R of a track

- Remember the solenoid resolution :

$$(\Delta p_T/p_T)_{solenoid} \sim (\Delta s /L^2 B) \; p_T$$

(in GeV with s in μm L in cm and B in T. Large B is good against high occupancy)
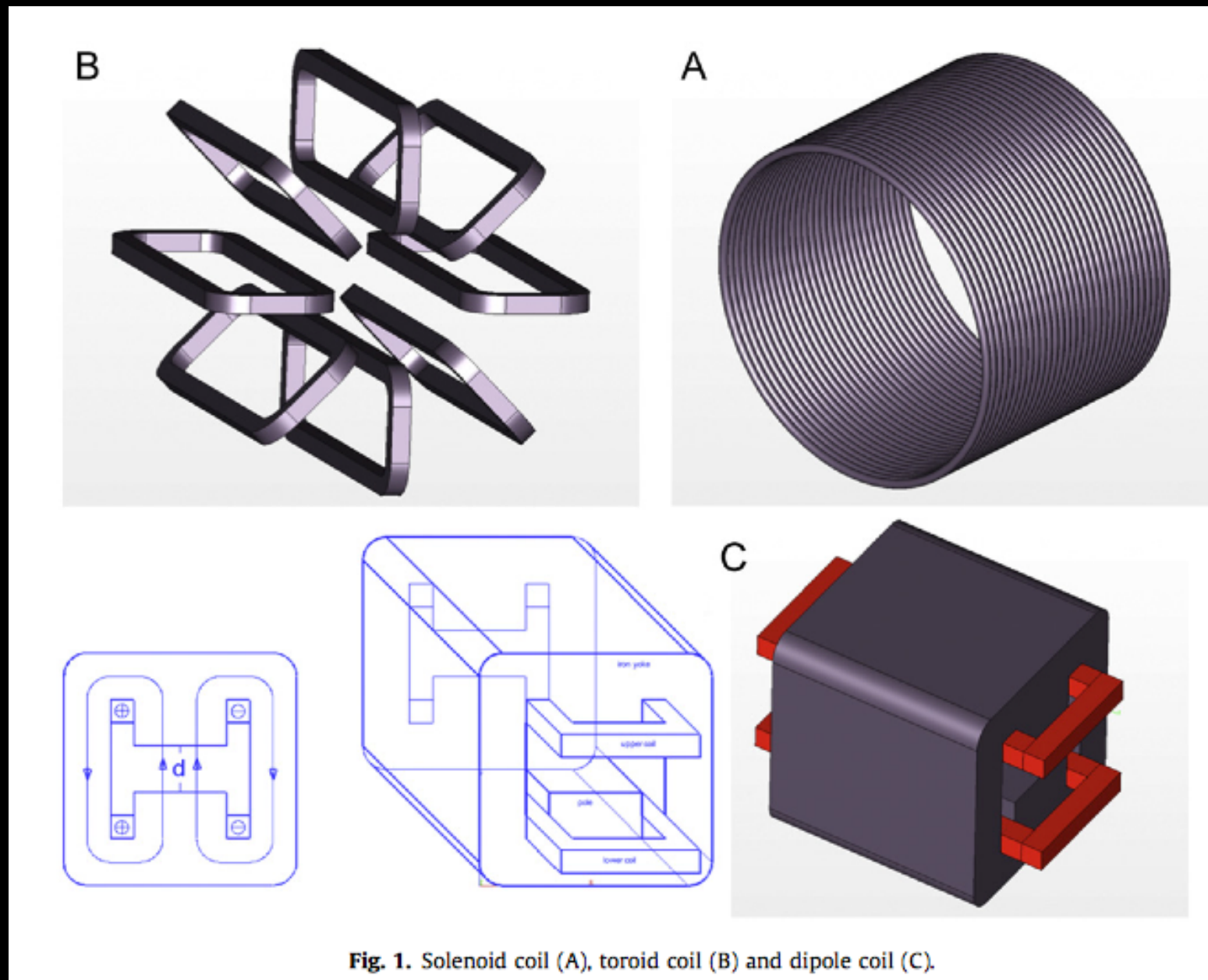
Frequent magnet designs

Fig. 1. Solenoid coil (A), toroid coil (B) and dipole coil (C).

Solenoid (A)

Deployed in ATLAS and CMS

$(dp/p)_{solenoid} \sim p \cos theta / BR^2$

$cost \sim LR^2B^2$

Toroid (B)

Deployed in ATLAS

$(dp/p)_{toroid} \sim p \cos theta /$
$$B_{in}R_{in} \ln(R_{out}/R_{in})$$

Dipole (C)

Used in fixed target / forward experiments.

Deployed in ALICE and LHCb.

$(dp/p)_{dipole} \sim p / BL$

Size and field examples

ATLAS barrel toroid

20.5 kA, 3.9 T
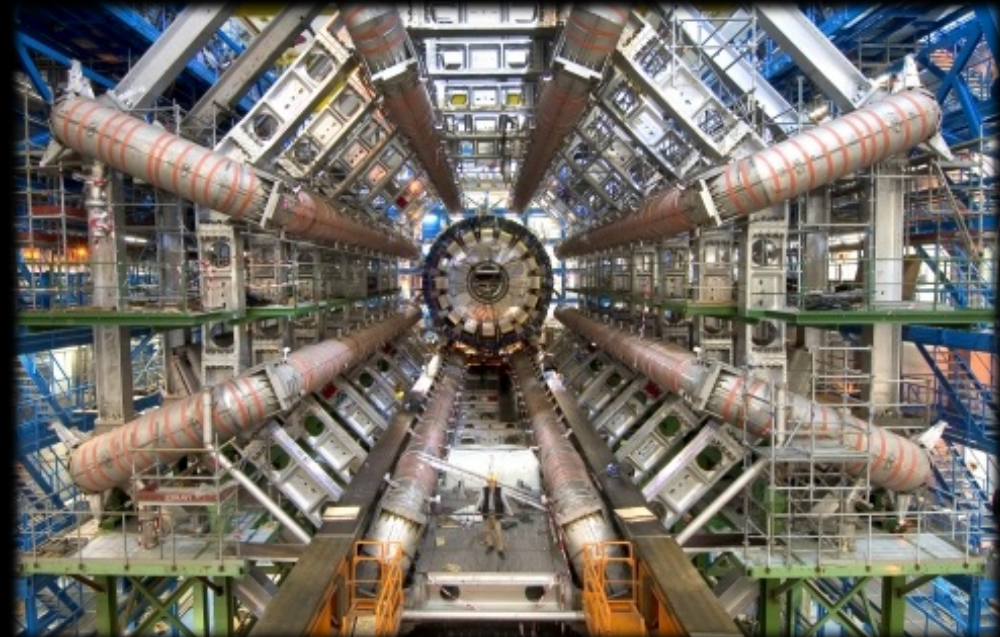
Table 1
Main parameters of some HEP detector magnets (solenoids).

	CDF	CLEO-II	ALEPH	ZEUS	H1	KLOE	BaBar	Atlas	CMS
B (T)	1.5	1.5	1.5	1.8	1.2	0.6	1.5	2.0	4.0
R (m)	1.5	1.55	2.7	1.5	2.8	2.6	1.5	1.25	3.0
L (m)	4.8	3.5	6.3	2.45	5.2	3.9	3.5	3.66	12.5

The magnet layout is a major constraint for the rest of the detector !

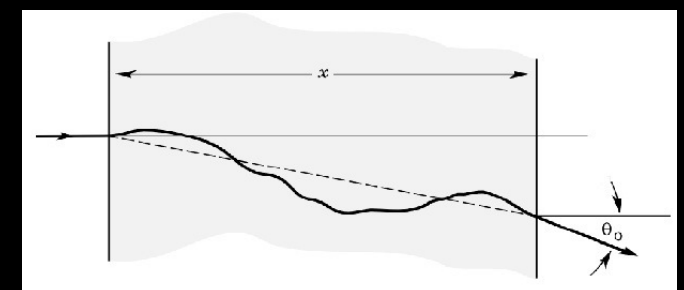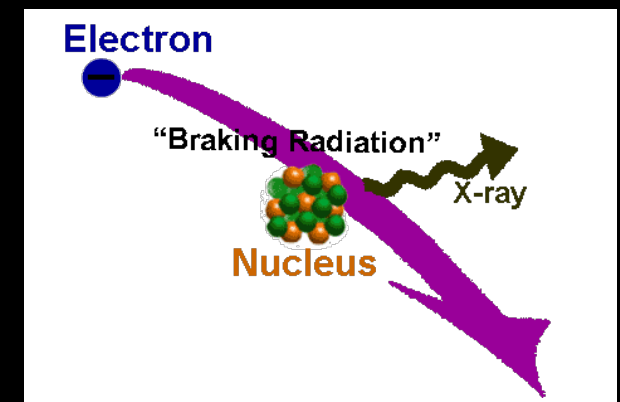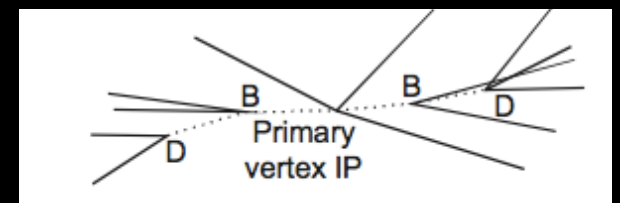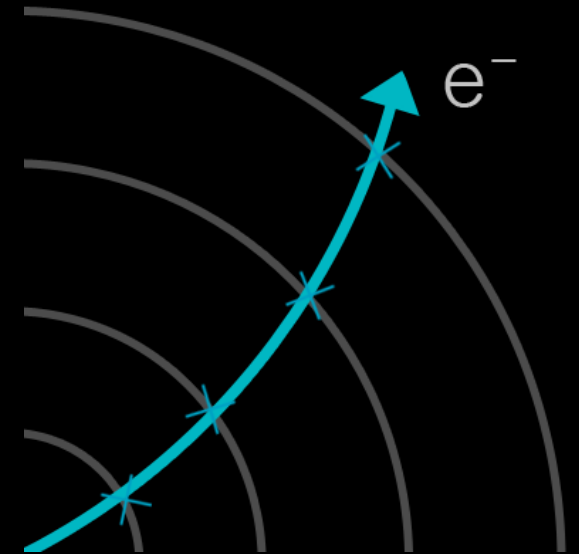See A. Gaddi, A magnet system for HEP experiments, NIMA 666 (2012) 10-24

3.
Tracking Detectors

Tracking principles

Exploit physical processes of moving charged particles in a magnetic field :

1. Ionisation (Bethe-Bloch) is the main detection process for heavy particles (m > m_e)

   - Collect the charges with an electric field -> hits

   - Reconstruct hits to tracks in B field -> p_T, vertices, isolation

2. Bremsstrahlung is the main process for $e^{-/+}$ above some 100 MeV

3. Multiple scattering (unwanted, degrades the resolution)

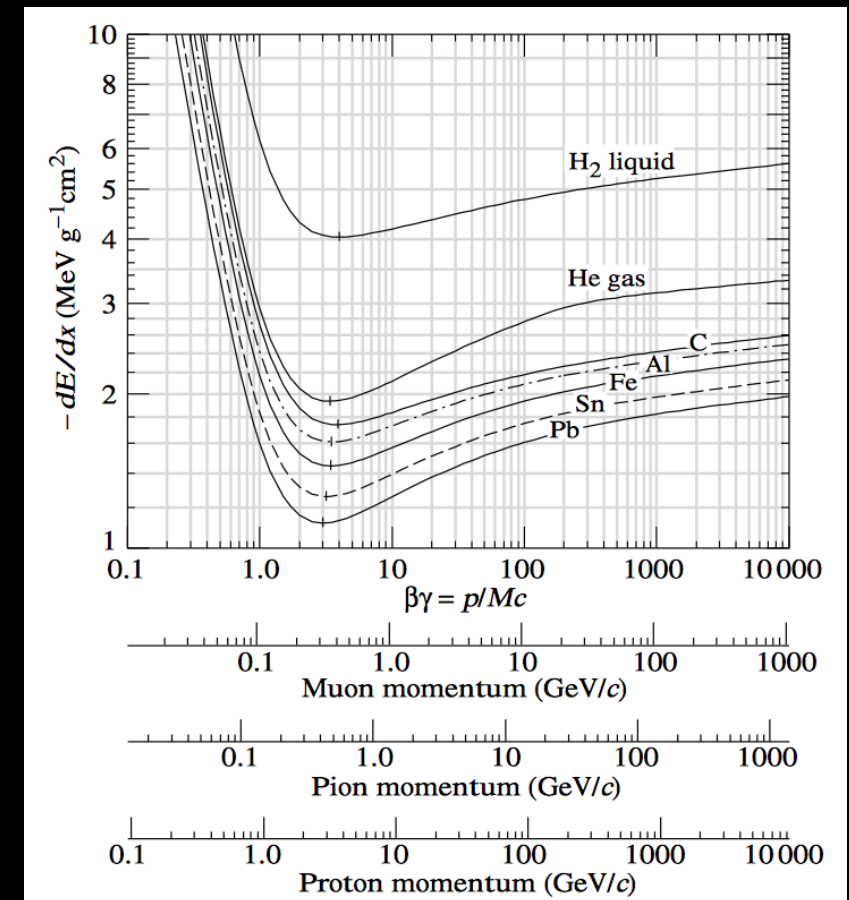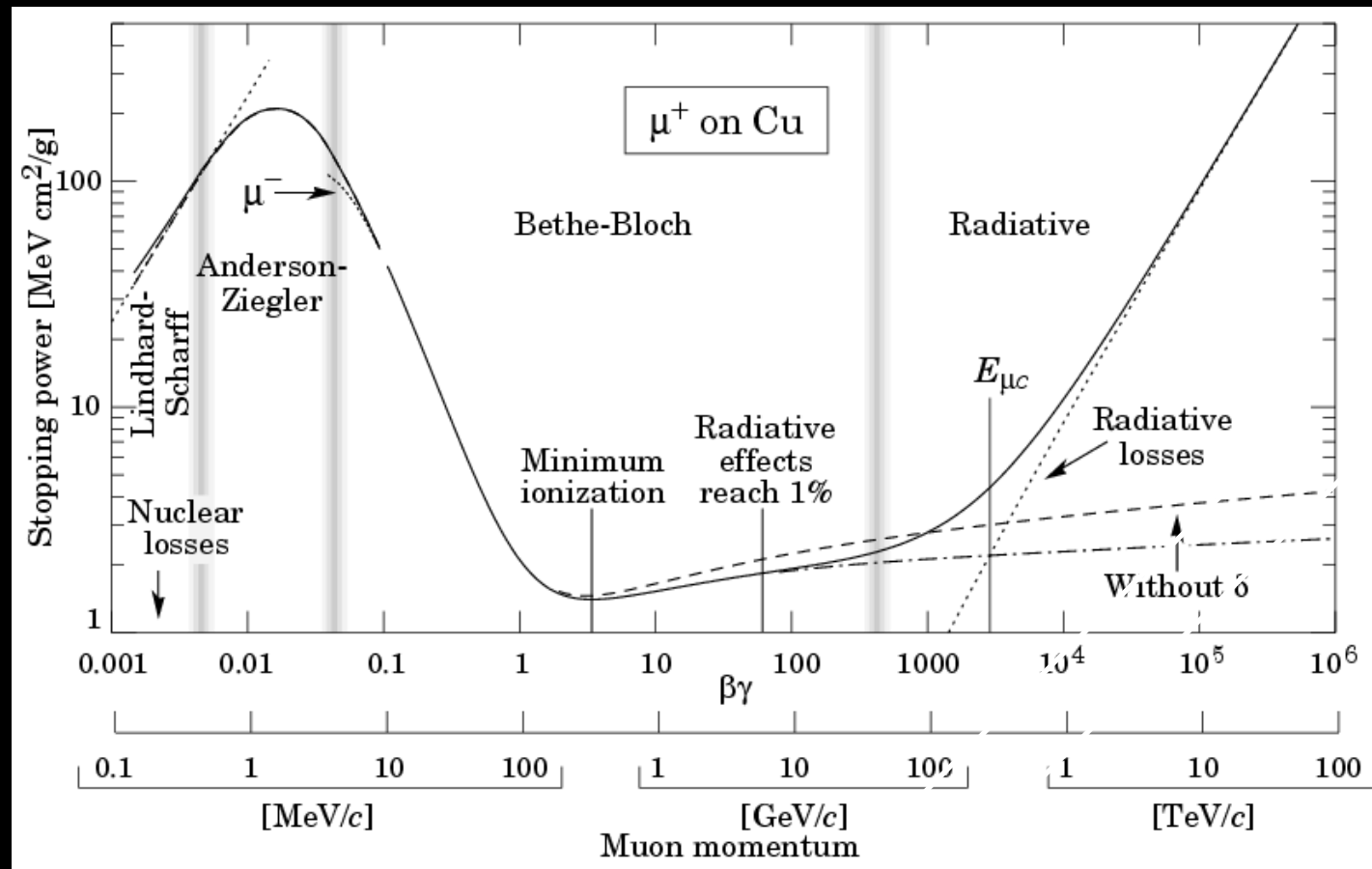4. Irradiation damage (unwanted; degrades efficiency)

Bethe-Bloch formula

Describes stopping power of heavy charged (heavier than electron) particle in matter [MeV g^{-1} cm^2]

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2} \left[\frac{1}{2}\ln\left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2}\right) - \beta^2 - \frac{\delta(\gamma)}{2} \right]$$

- The energy loss depends only on charge z and velocity β of the particle

- Rest is material dependent: I = mean ionization/excitation energy [MeV], δ density effect correction, T_{max} is maximum energy transfer in one collision.
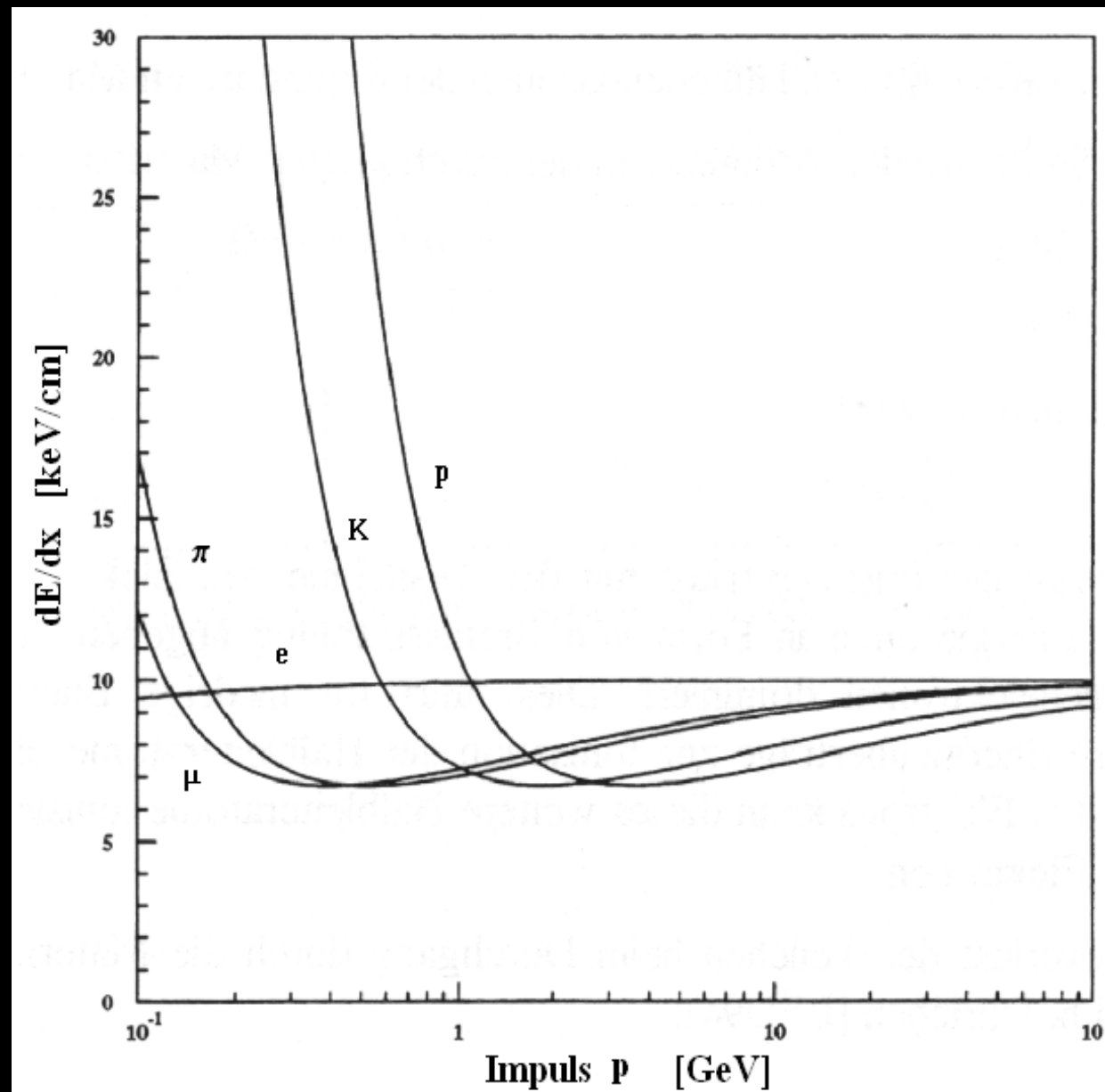
Bethe-Bloch formula

Right figure :

- At low β : dE/dx ~ 1/β²

- Minimum at βγ ~ 3..4 (minimal ionising particle)

- At high β : dE/dx slowly increasing due to relativistic enhancement of transversal E field. At very high β : saturation due to shielding/polarization

Bethe-Bloch formula

Energy loss used for particle identification

Silicon detectors

Semiconductor with following advantages:

- High resolution for track reconstruction, i.e. p_T and vertices

- Low excitation energy = 3.6 eV for one electron-hole pair (~30 eV in gas)

- Possible to change band gap by doping

- In industrial production (CMS has more than 15k modules)
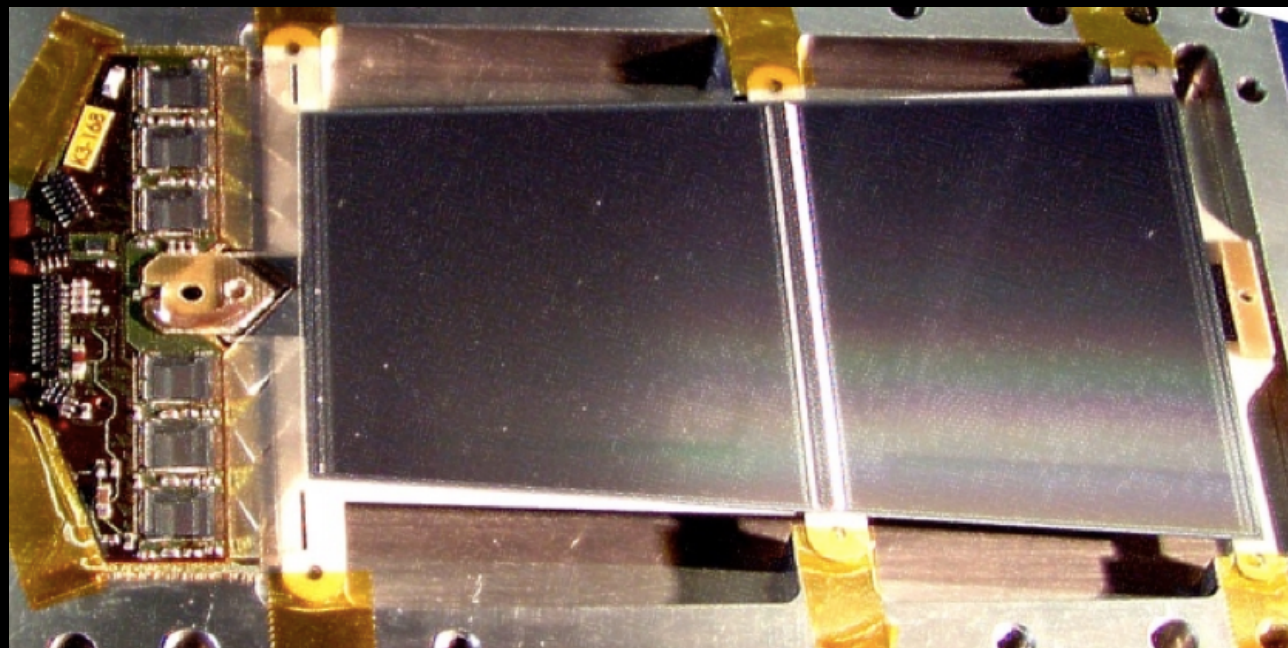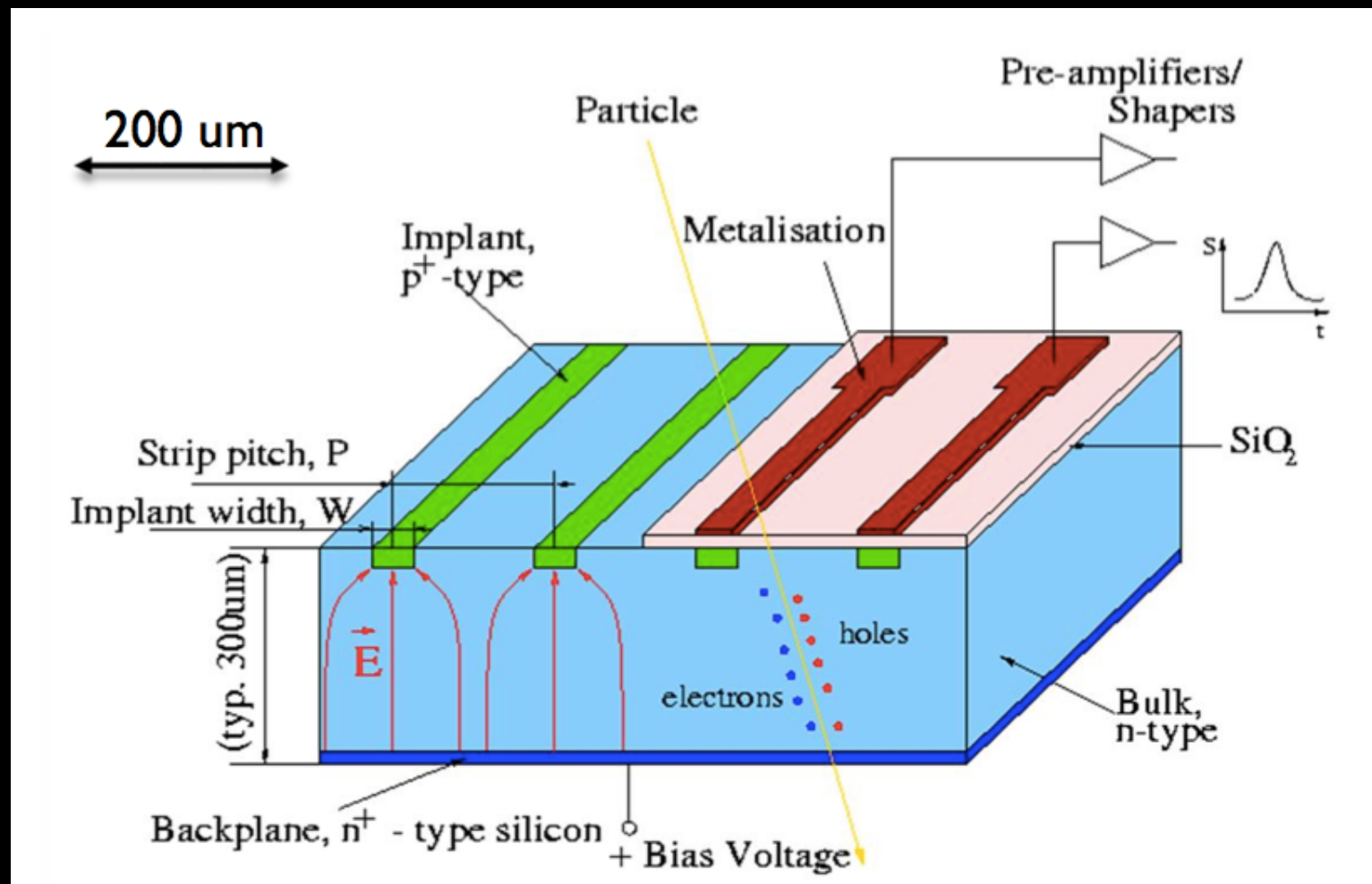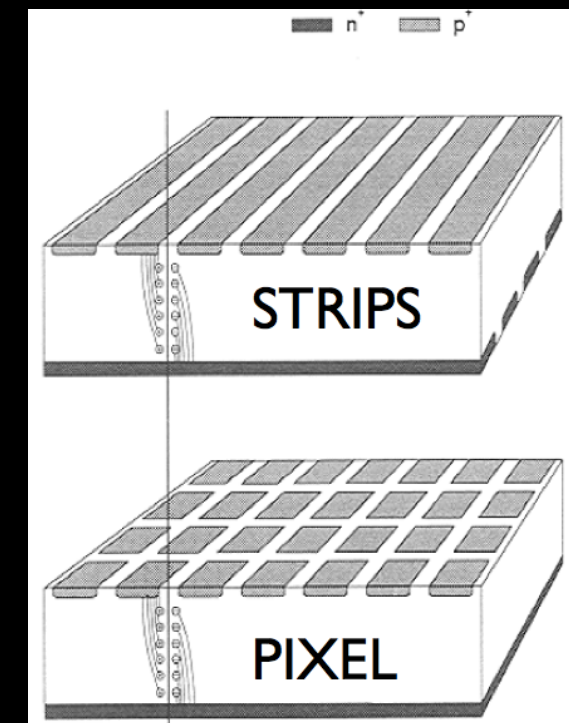
- A natural oxide with high abundance

Figure : ATLAS silicon strip module in transport frame (about 10 cm).

Typically some hundred μm thick to have enough hole-electron pairs.

Silicon detectors - principle
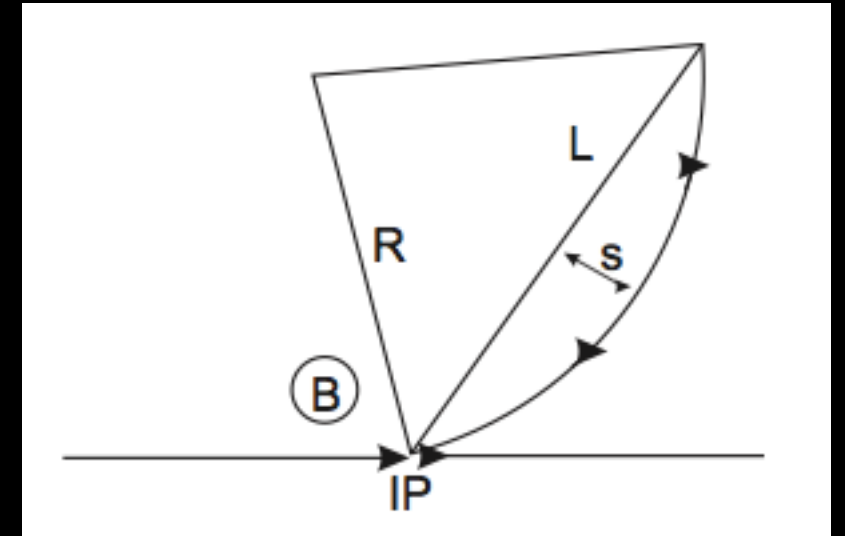

pn-junction: Either strip or pixel-like:

With $dE/dx_{min} = 1.664$ MeVg^{-1}cm^2, density = 2.33 g/cm^3 and excitation energy = 3.6 eV -> 10^6 electron-hole pair/cm. Must be higher than noise -> typical thickness around 300 μm.

p_T and d_0 resolution

- Transverse momentum resolution:

$$(\Delta p_T/p_T)_{solenoid} \sim (\Delta s / L^2 B) \ p_T$$

$s = R - (R^2 - (L/2)^2)^{1/2}$

- Impact parameter d_0 resolution (smallest distance from vertex to interaction point) example from a two layer setup:

$$\sigma_{d_0}^2 = \sigma_{MS}^2 + \sigma_{geom}^2$$

with

$$\sigma_{geom}^2 = \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2 \quad \text{and} \quad \sigma_{MS}^2 = \sum_{j=1}^{n_{scatt}} (R_j \Delta\Theta_j)^2$$
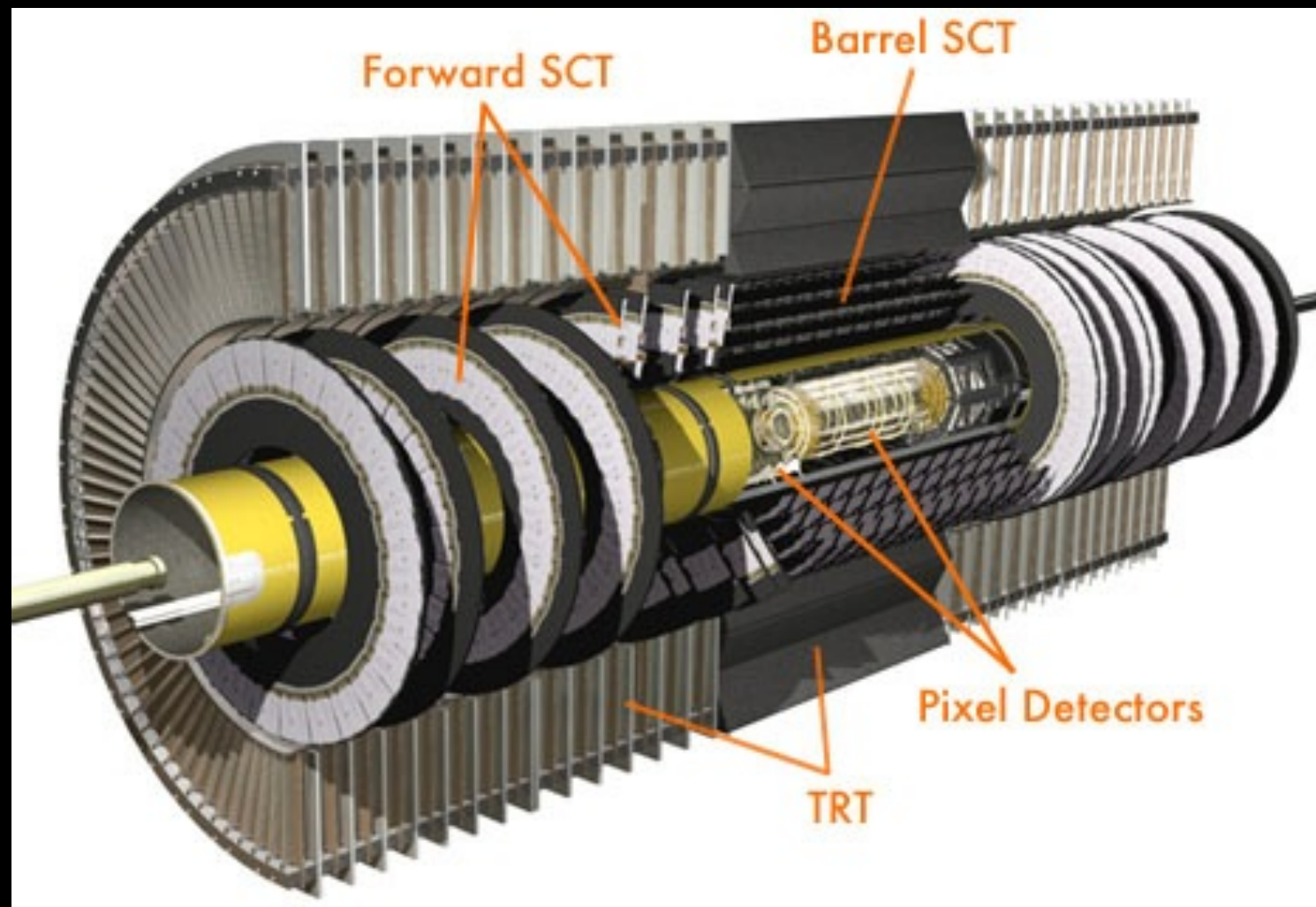
There is a multiple scattering part and a geometrical part. Intrinsic resolution from the silicon detector σ_x = strip pitch / (signal/noise) ~ 5 μm with ~25 μm between strips.

Silicon detector design

- Make it low mass (avoid multiple scattering)

- Make first layer close to interaction point (IP) (low extrapolation error)

- Make it large (dp/p ~ p/BR^2)

- Make it high B to reduce low p tracks

- Make it redundant and irradiation resistent (may consider 3D design, see student seminar presentation)

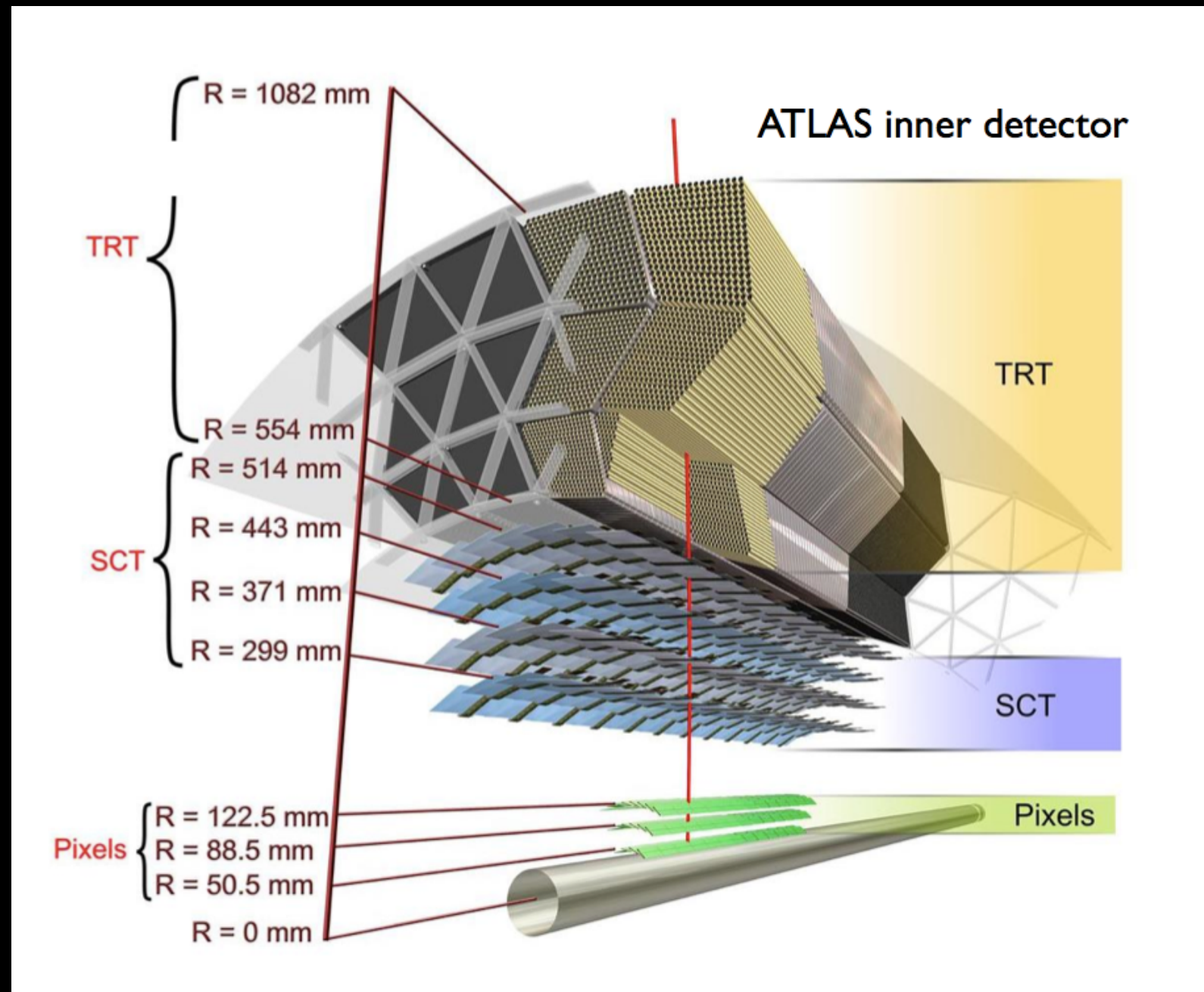| Parameter (tracking systems)	ATLAS	CMS
Dimensions (cm)		
-Radius of outermost measurement	101–107	107–110
-Radius of innermost measurement	5	4.4
-Total active length	560	540
Magnetic field B (T)	2 T m	4 T m
BR^2 (T m^2)	2.0–2.3	4.6–4.8
Total power on detector (kW)	70	60
Total weight in tracker volume (kg)	≈ 4500	≈ 3700
Total material (X/X 0)		
-At $\eta = 0$ (minimum material)	0.3	0.4
-At $\eta = 1.7$ (maximum material)	1.2	1.5
-At $\eta = 2.5$ (edge of acceptance)	0.5	0.8
Total material (λ/λ_0 at max)	0.35	0.42
Silicon microstrip detectors		
-Number of hits per track	8	14
-Radius of innermost meas(cm)	30	20
-Total active area of silicon(m^2)	60	200
-Wafer thickness (microns)	280	320/500
-Total number of channels	6.2×10^6	9.6×10^6
-Cell size (μm in $R\phi \times$ cm in z/R)	80×12	$80/120 \times 10$
-Cell size (μm in $R\phi \times$ cm in z/R)		and $120/180 \times 25$
Straw drift tubes (ATLAS only)		
-Number of hits per track ($|\eta| < 1.8$)	35	
-Total number of channels	350,000	
-Cell size (mm in $R\phi \times$ cm in z)	4×70 (barrel)	
	4×40 (end caps)	

Detector example - ATLAS ID

- 3 layers of pixel modules in barrel
- 2x5 disks of forward pixel disks
- 4 layers of strip (SCT) modules in barrel
- 2x9 disks of forward strip modules

Figure : ATLAS Inner detector (ID) in LHC run 1 with pixel and strip (SCT) silicon and transition radiation (TRT) detectors. The length is about 5.5 m.
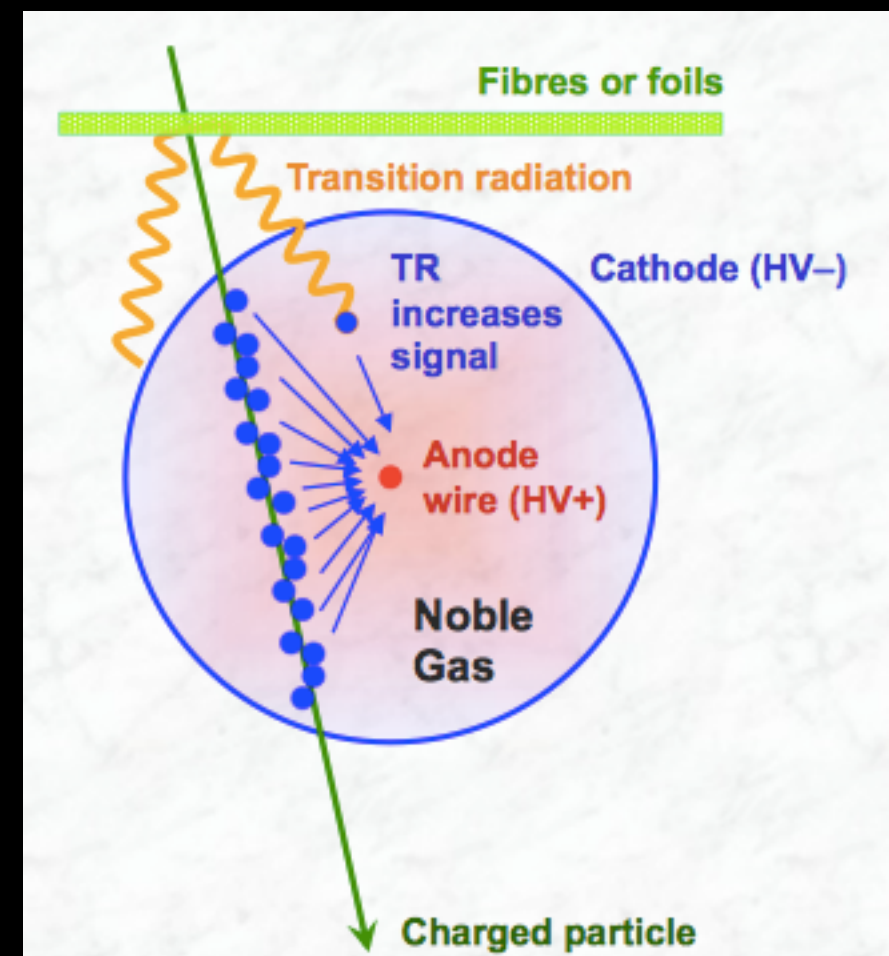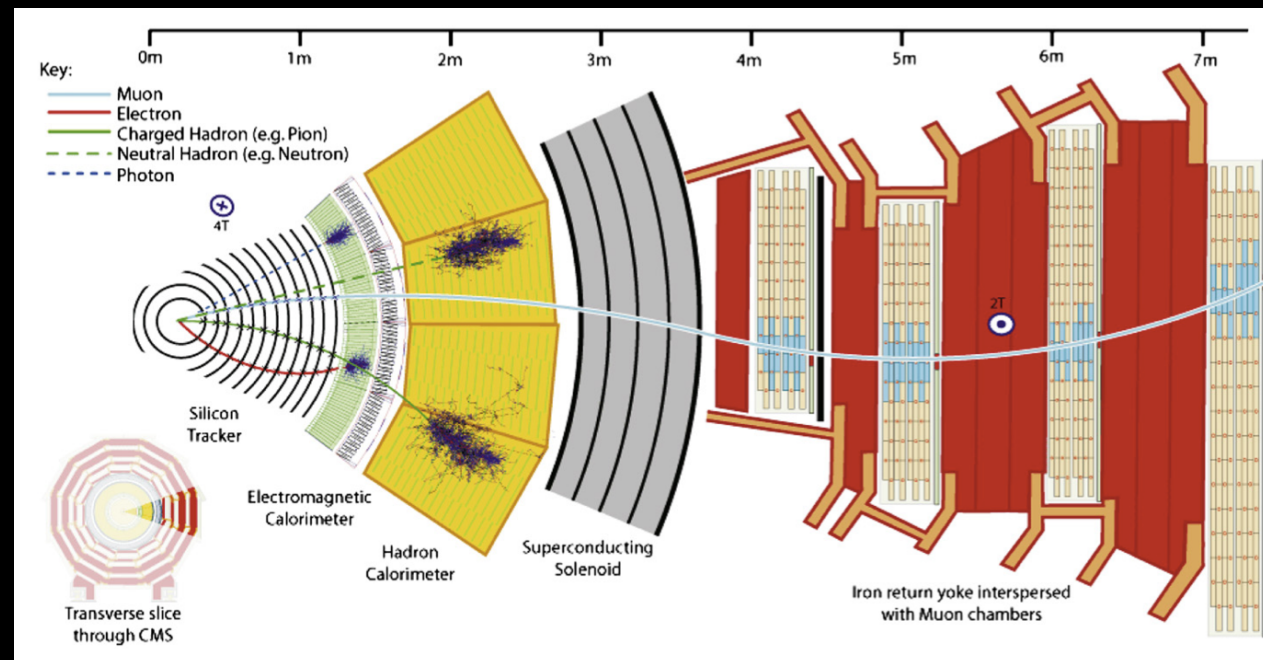
Detector example - ATLAS ID

Transition Radiation (TR) Tracker

Combine tracking with particle identification (PID)

- Charged particles radiate photons when crossing material borders

- $e^{-/+}$ radiate x-rays more than heavier particles

- Use this for particle PID, i.e. distinguish $e^{-/+}$ from hadrons

- ATLAS has a TR detector in the inner detector. It uses gas for detection.
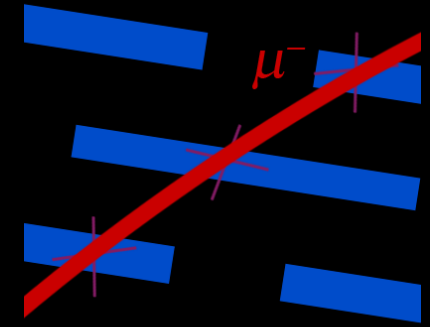
Outside the Inner Detector

we place the calorimeters
(Next Lecture)

Muon Detection

/

Gas Detectors

Basic considerations

Muon has electrical charge, $m_\mu \sim 106$ GeV $\sim 200\ m_e$, no strong charge, life time $\tau = 2.2\ \mu s$, LHC $p_\mu \sim 5\ ..\ 1000$ GeV :

- Curves in magnetic field (charge and momentum)
- Makes track in inner detector / silicon
- Penetrates the full detector, "stable" wrt detector size
- Energy loss described by Bethe-Bloch formulae

Assume (curved) tracks outside the calorimeters to be muons.
That means :

- Large detectors, i.e. usually gas
- Match with tracks from inner detector
- Watch out for non muon punch through from calorimeter
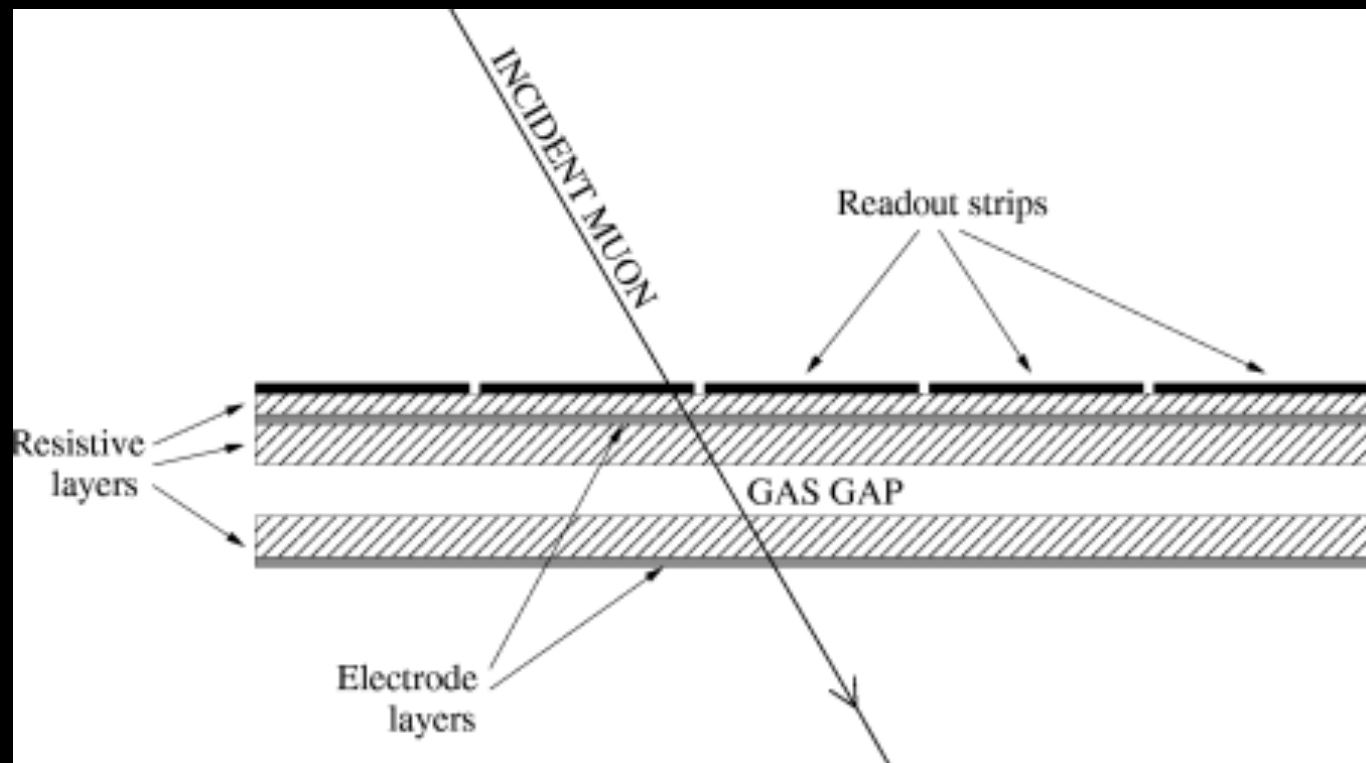
Negligible processes :

- $\sigma_{Brems} \propto E / m^2$ for low E
- Multiple scattering $m_\mu \gg m_e$

Triggering muons

Design LHC bunch spacing is 25 ns, i.e. need for fast detectors

- Resistive Plate Chambers (RPC)
- Thin Gap Chambers (TGC)

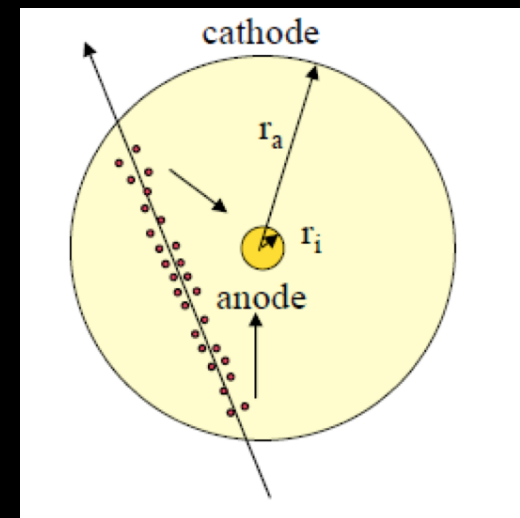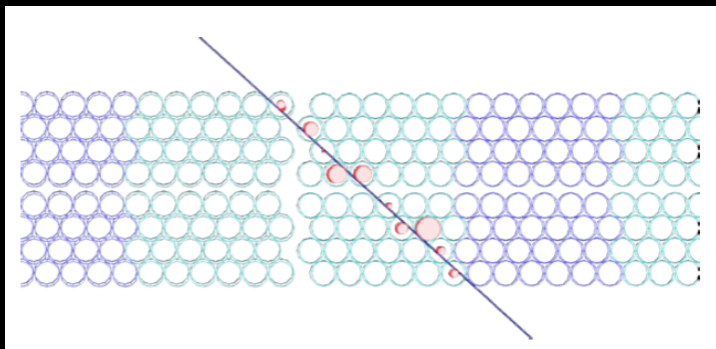Large surface chambers with thin (mm) gas layers for fast detection (ps to ns)

2 mm gap in ATLAS

Measuring muons

For high precision position measurements :

- Drift tubes with gas, position from drift time (ATLAS, CMS)

    - Array of $10^{4\text{-}5}$ tubes, 1 - 10 cm², up to 10 m long

    - 50-100 µm and some ns resolution

    - Deadtime 20-100 ns

- Cathode Strip Chambers (ATLAS, CMS, LHCb)

    - Multiwire gas chamber with strip read-out

- Micro Pattern Gas Detector (LHCb)

- Time Projection Chamber (ALICE)

Principle of a drift tube

A module with 2x4 layers of drift tubes (ATLAS)
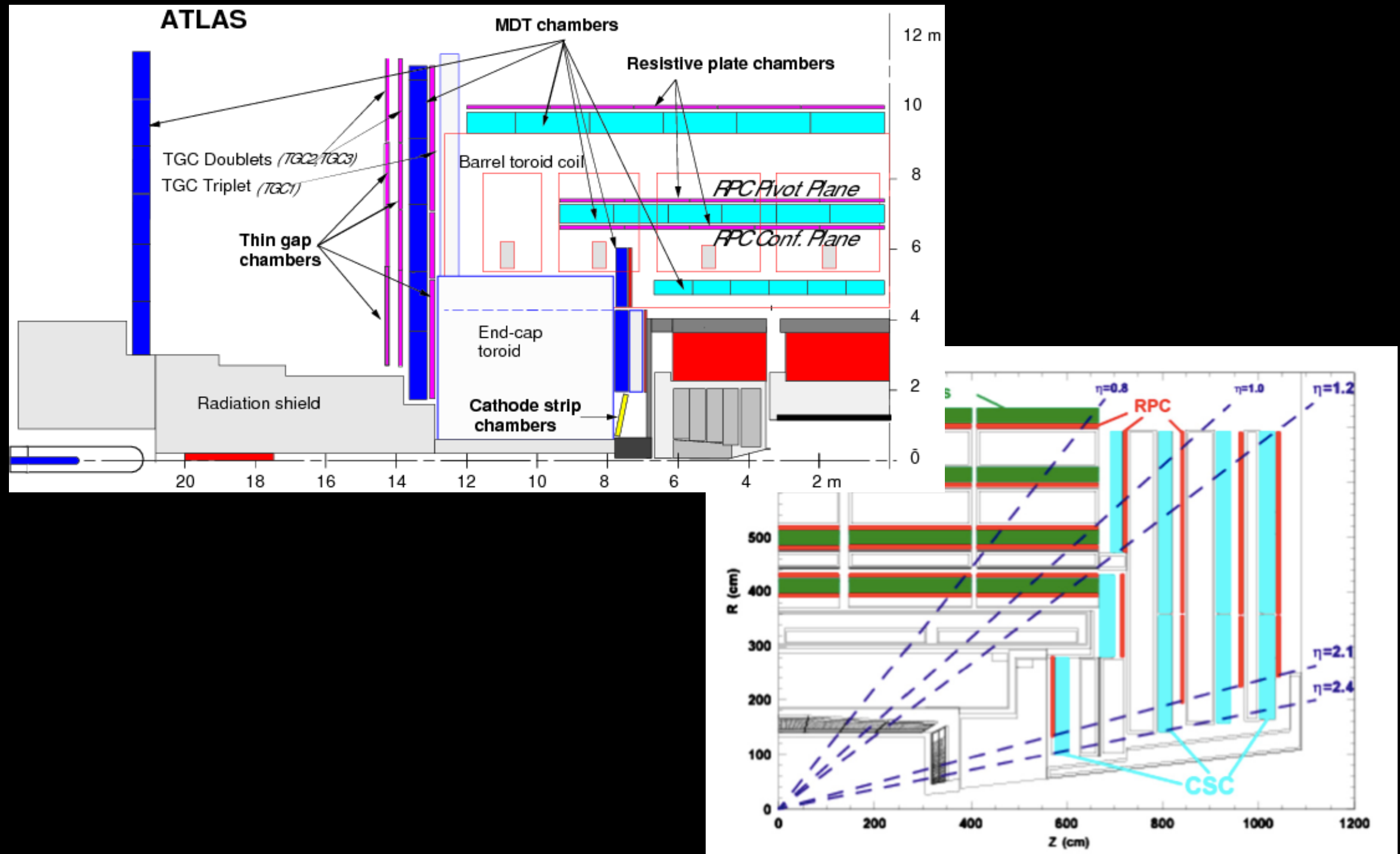

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Muon systems (1/4)- ATLAS, CMS

Table 32.1: Typical resolutions and deadtimes of common charged particle detectors. Revised November 2011.

Detector Type	Intrinsinc Spatial Resolution (rms)	Time Resolution	Dead Time
Resistive plate chamber	$\lesssim 10$ mm	1–2 ns	—
Streamer chamber	300 μm[a]	2 μs	100 ms
Liquid argon drift [7]	$\sim$175–450 μm	$\sim$ 200 ns	$\sim$ 2 μs
Scintillation tracker	$\sim$100 μm	100 ps/n[b]	10 ns
Bubble chamber	10–150 μm	1 ms	50 ms[c]
Proportional chamber	50–100 μm[d]	2 ns	20-200 ns
Drift chamber	50–100 μm	2 ns[e]	20-100 ns
Micro-pattern gas detectors	30–40 μm	< 10 ns	10-100 ns
Silicon strip	pitch/(3 to 7)[f]	few ns[g]	$\lesssim 50$ ns[g]
Silicon pixel	$\lesssim 10$ μm	few ns[g]	$\lesssim 50$ ns[g]
Emulsion	1 μm	—	—

Summary ?

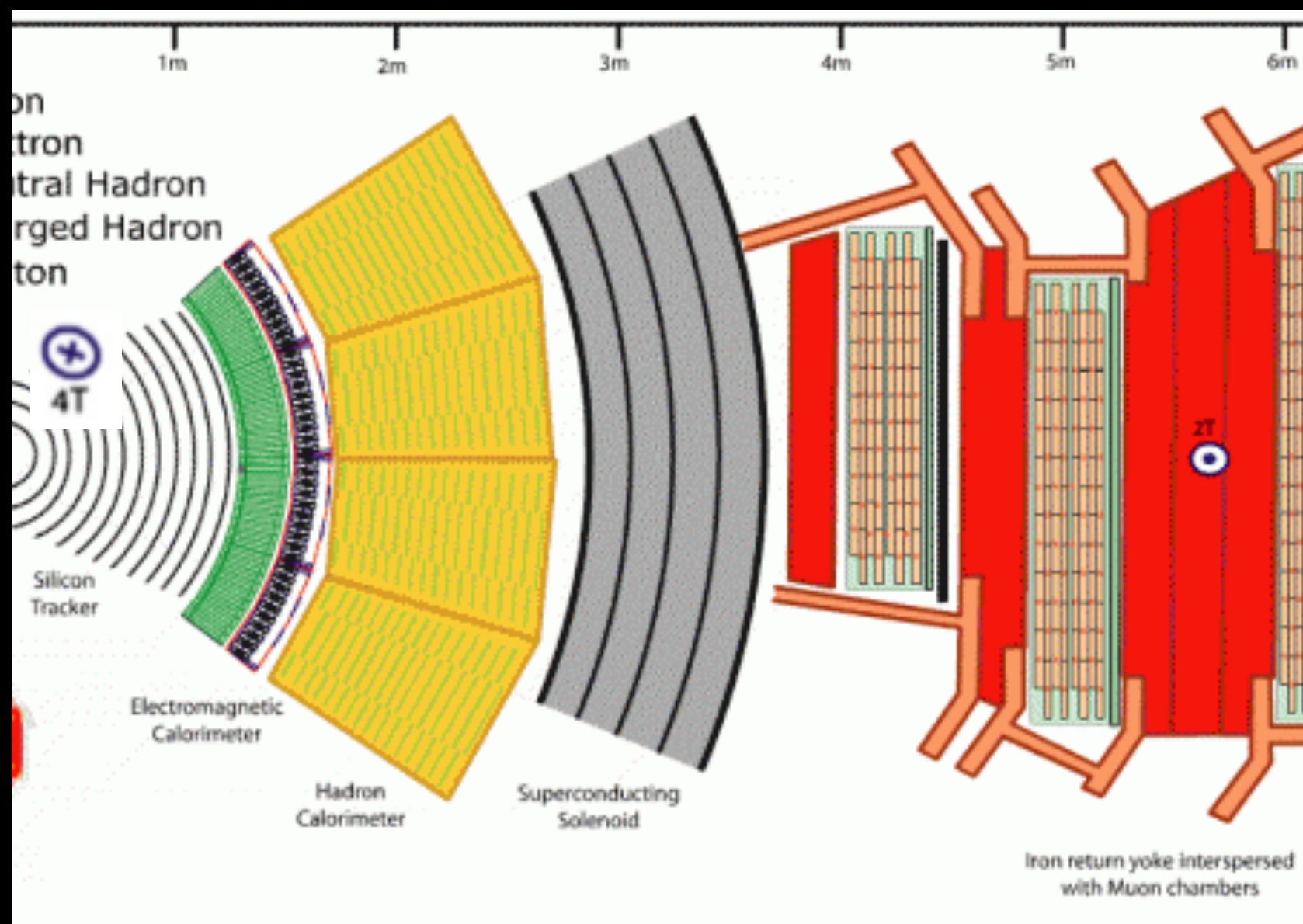We have been looking at tracking (at hadron colliders)

1. Which particles arrive in the detectors and what "objects" do we reconstruct ?
2. Magnet systems

   How does momentum resolution depend on B and L in a solenoid ?

3. Tracking detectors
   1. Solid state (mostly silicon) detectors (inner detector systems)
   2. Gas detectors (mostly for muon systems)
4. Can you draw a photon, electron, proton, neutron and anti-muon into a slice of the CMS detector ?
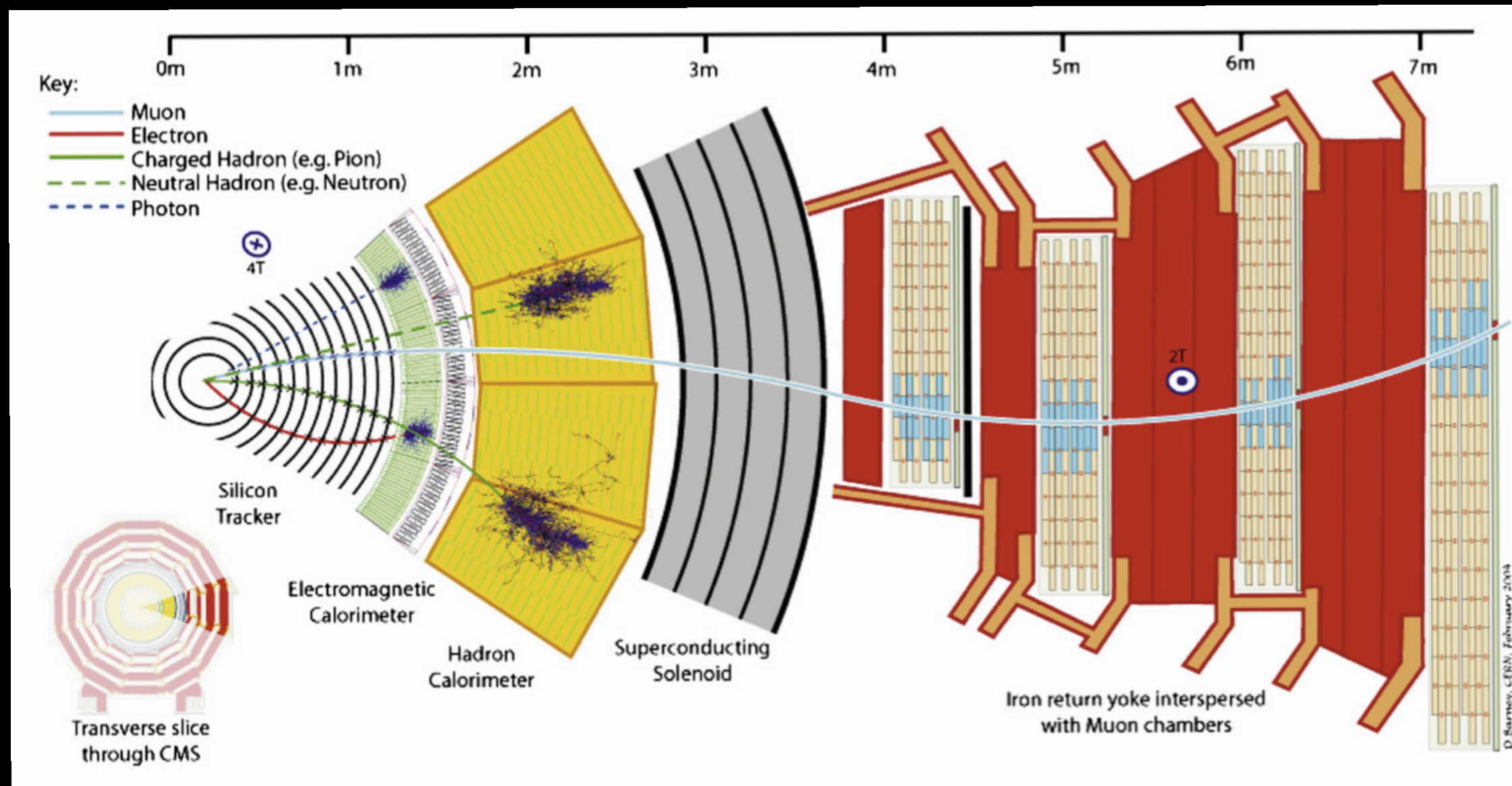
Next comes calorimetry (hadron and electromagnetic)

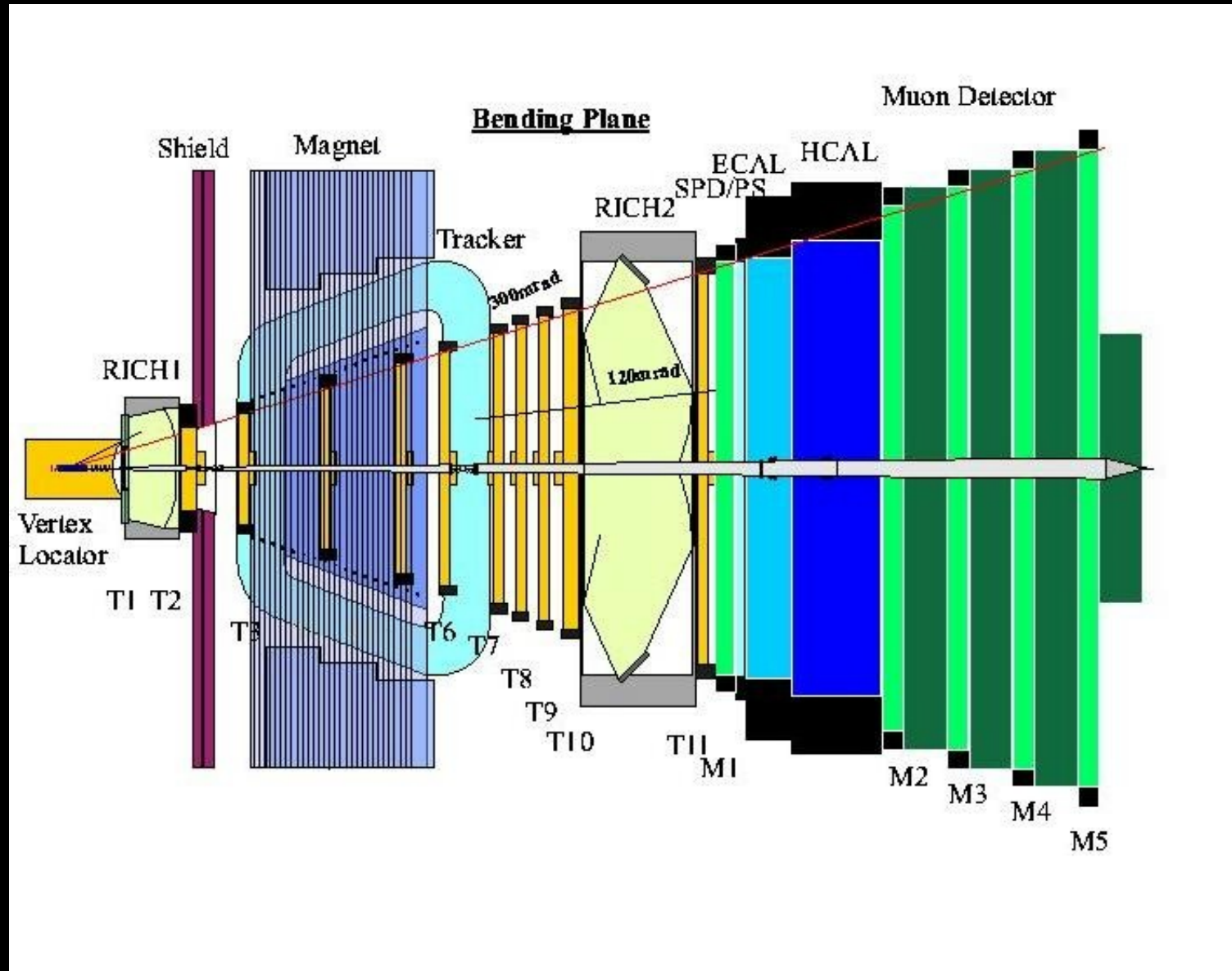# Draw the particles into this slice !

Photon, electron, neutron, proton, anti-muon.
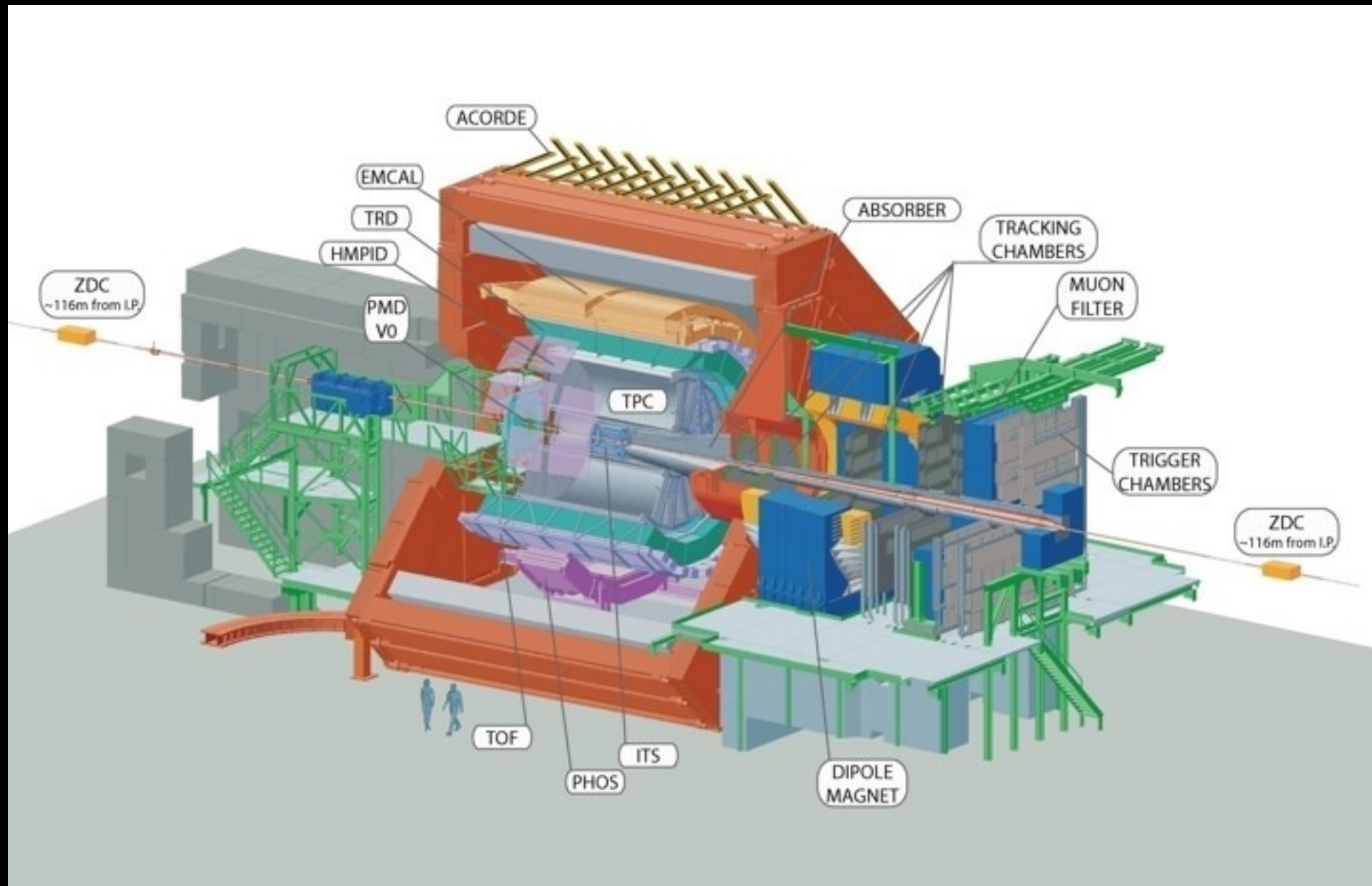
Should look like this !

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Additional Slides

LHCb Detector

Most of the B mesons go forwards/backwards. LHCb is thus located to the right of the interaction point (in this picture) close to the vertex detector. No need to have it on both sides, there is data enough on one.

ALICE Detector

ALICE has its muon system only on one side (here to the right).