The Standard Model

CSU-NUPAX/CERN IRES Program

Johan S Bonilla
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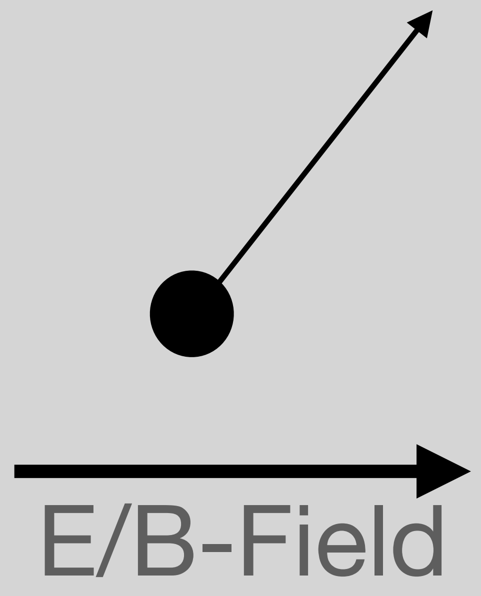
[See Particle Data Group at LBNL]

What is a Particle?

Classical



Quantum Mechanics

$$\psi_n(x) = \sqrt{\frac{1}{2^n\, n!}} \cdot \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \cdot e^{-\frac{m\omega x^2}{2\hbar}} \cdot H_n\left(\sqrt{\frac{m\omega}{\hbar}}x\right),$$

Does NOT play nice
with special relativity

Quantum Field Theory

$$\hat{\phi}(\mathbf{x}, t) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2\omega_{\mathbf{p}}}} \left(\hat{a}_{\mathbf{p}} e^{-i\omega_{\mathbf{p}}t + i\mathbf{p}\cdot\mathbf{x}} + \hat{a}^\dagger_{\mathbf{p}} e^{i\omega_{\mathbf{p}}t - i\mathbf{p}\cdot\mathbf{x}}\right).$$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^2 - \frac{\lambda}{4!}\phi^4,$$

Maxwell’s E&M Equations

Differential equations
$\nabla \cdot \mathbf{E} = \dfrac{\rho}{\varepsilon_0}$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \dfrac{\partial \mathbf{E}}{\partial t}\right)$

Formulation	Homogeneous equations
Fields 3D Euclidean space + time	$\nabla \cdot \mathbf{B} = 0$ $\nabla \times \mathbf{E} + \dfrac{\partial \mathbf{B}}{\partial t} = 0$
Potentials (any gauge) 3D Euclidean space + time	$\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{E} = -\nabla\varphi - \dfrac{\partial \mathbf{A}}{\partial t}$
Potentials (Lorenz gauge) 3D Euclidean space + time	$\mathbf{B} = \nabla \times \mathbf{A}$ $\mathbf{E} = -\nabla\varphi - \dfrac{\partial \mathbf{A}}{\partial t}$ $\nabla \cdot \mathbf{A} = -\dfrac{1}{c^2}\dfrac{\partial \varphi}{\partial t}$

Gauge Transformations

Identities

$$\nabla \cdot (\nabla \times \mathbf{A}) = 0$$

$$\nabla \times (\nabla \varphi) = \mathbf{0}$$

$$\varphi \to \varphi - \frac{\partial \psi}{\partial t}$$

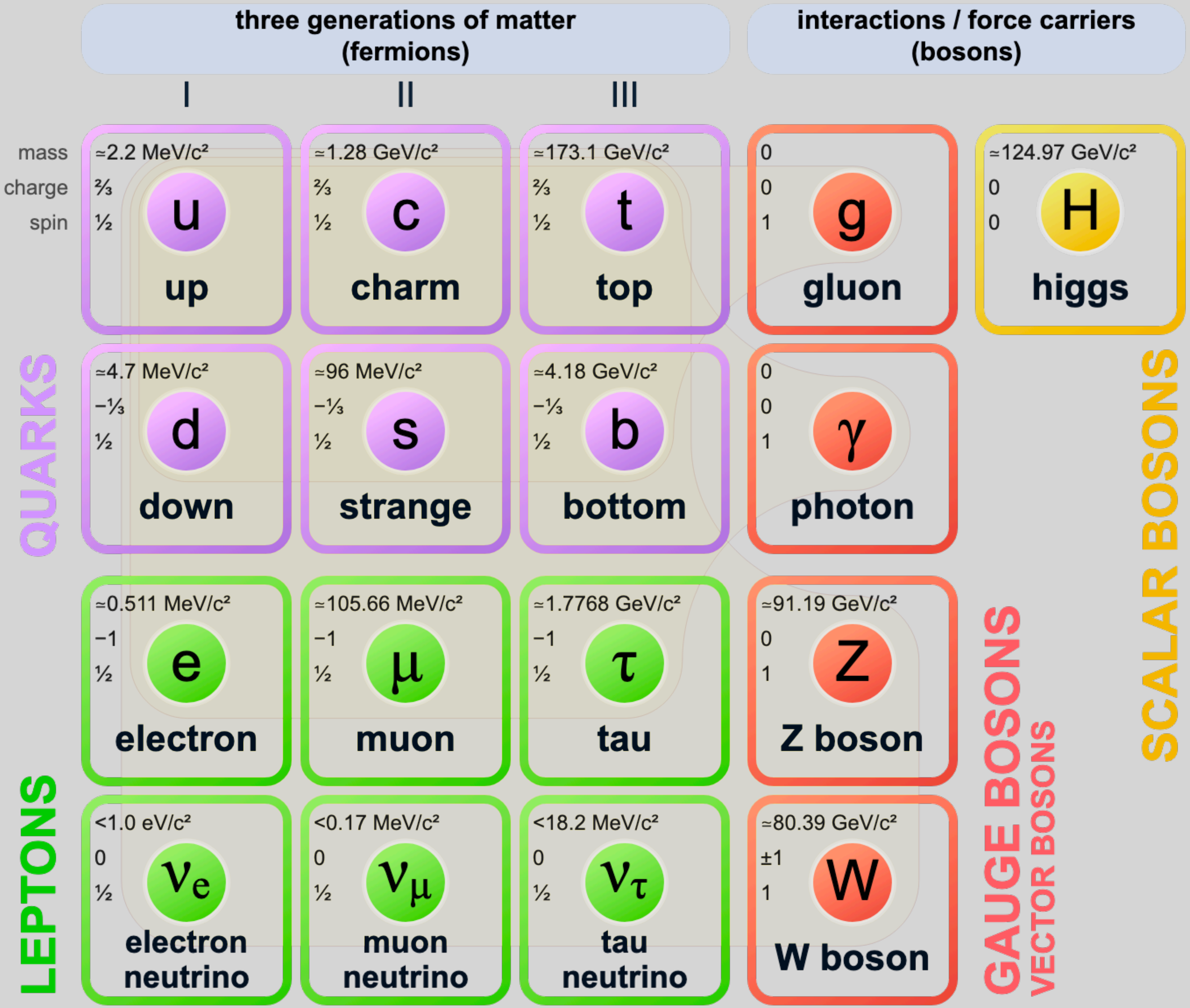
$$\mathbf{A} \to \mathbf{A} + \nabla \psi$$

$\partial_\mu A^\mu = 0$ ($\mu = 0,1, 2, 3$) ,	Lorenz gauge
$\boldsymbol{\nabla} \cdot \boldsymbol{A} = \partial_j A_j = 0$ ($j = 1, 2, 3$) ,	Coulomb gauge or radiation gauge
$n_\mu A^\mu = 0$ ($n^2 = 0$) ,	light cone gauge
$A_o = 0$,	Hamiltonian or temporal gauge
$A_3 = 0$,	axial gauge
$x_\mu A^\mu = 0$,	Fock-Schwinger gauge
$x_j A_j = 0$,	Poincaré gauge

$$\mathbf{E} = -\nabla \varphi - \frac{\partial \mathbf{A}}{\partial t} - \nabla \frac{\partial \psi}{\partial t} = -\nabla \left(\varphi + \frac{\partial \psi}{\partial t} \right) - \frac{\partial \mathbf{A}}{\partial t}$$

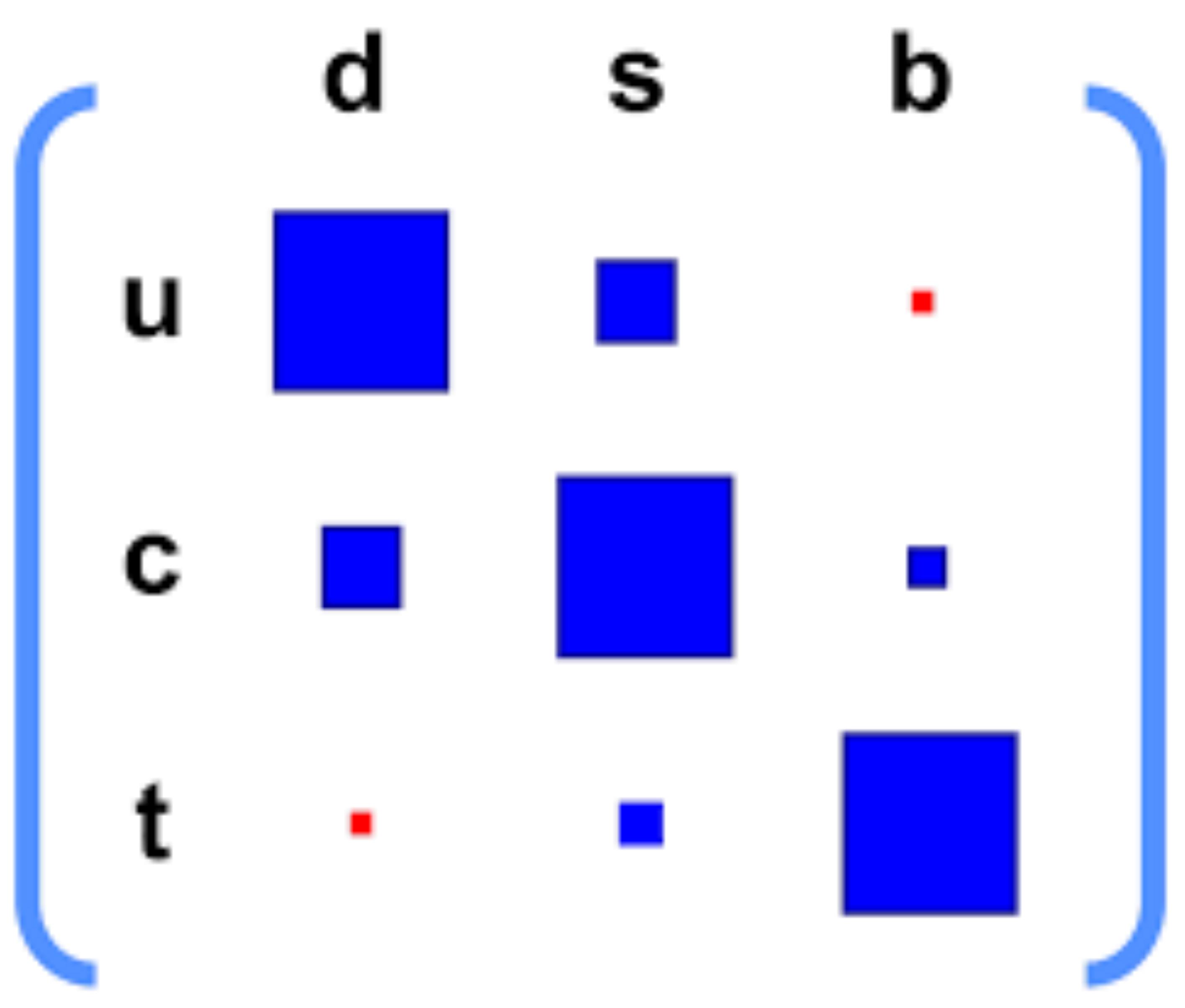
$$\mathbf{B} = \nabla \times (\mathbf{A} + \nabla \psi) = \nabla \times \mathbf{A}.$$

Standard Model of Elementary Particles



CKM Matrix

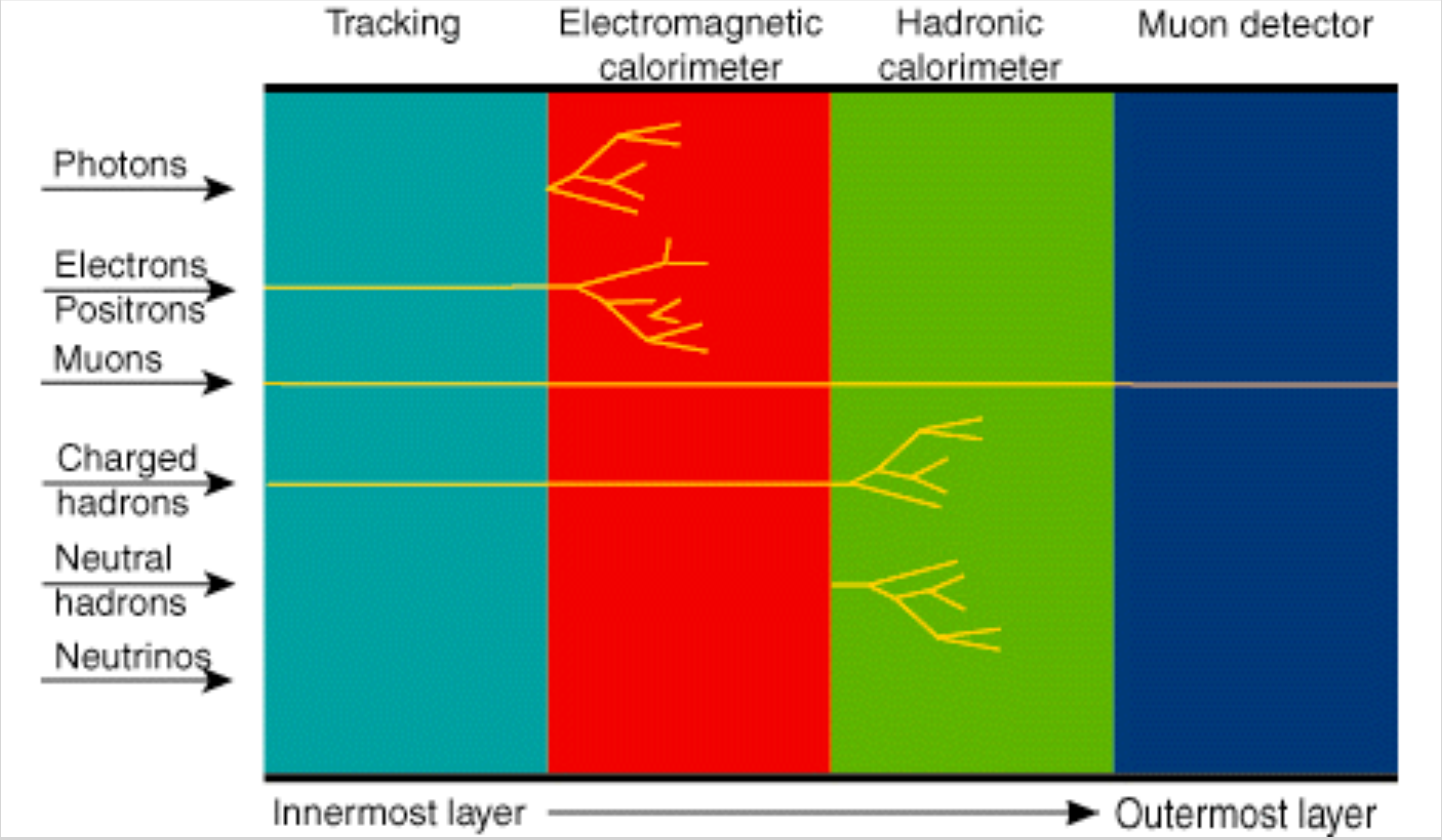
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm 0.0011 & 1.013 \pm 0.030 \end{bmatrix}$$



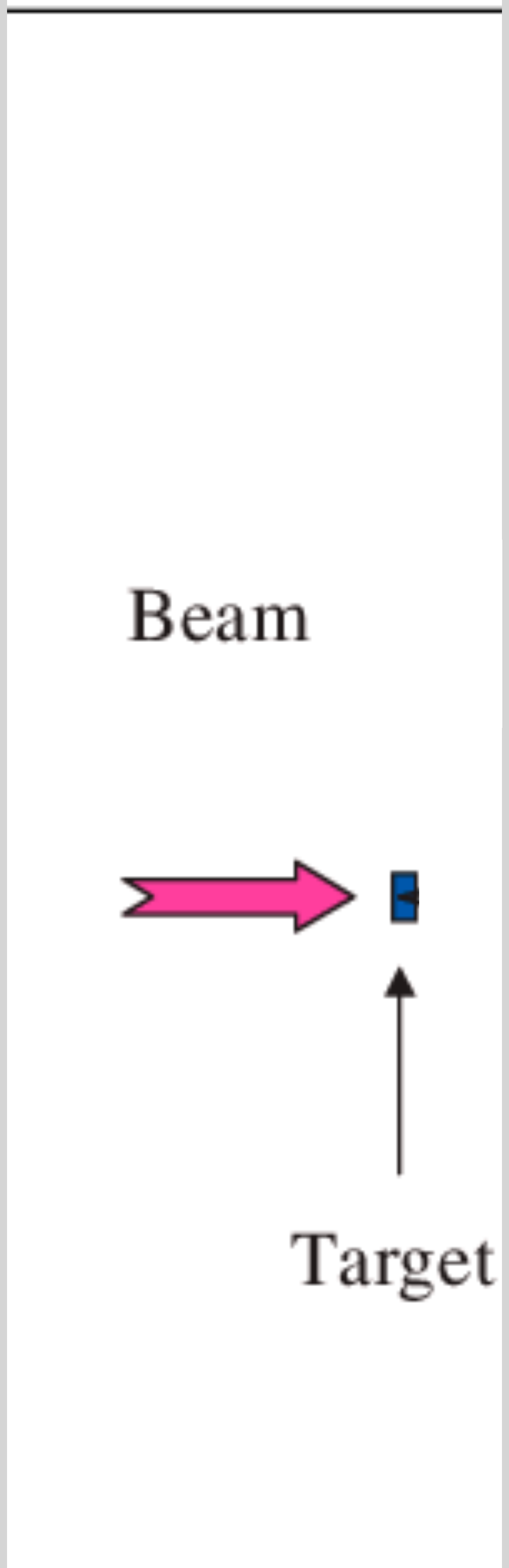
PMNS Matrix

$$\begin{bmatrix} \nu_{\mathrm{e}} \\ \nu_{\mu} \\ \nu_{\tau} \end{bmatrix} = \begin{bmatrix} U_{\mathrm{e}1} & U_{\mathrm{e}2} & U_{\mathrm{e}3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

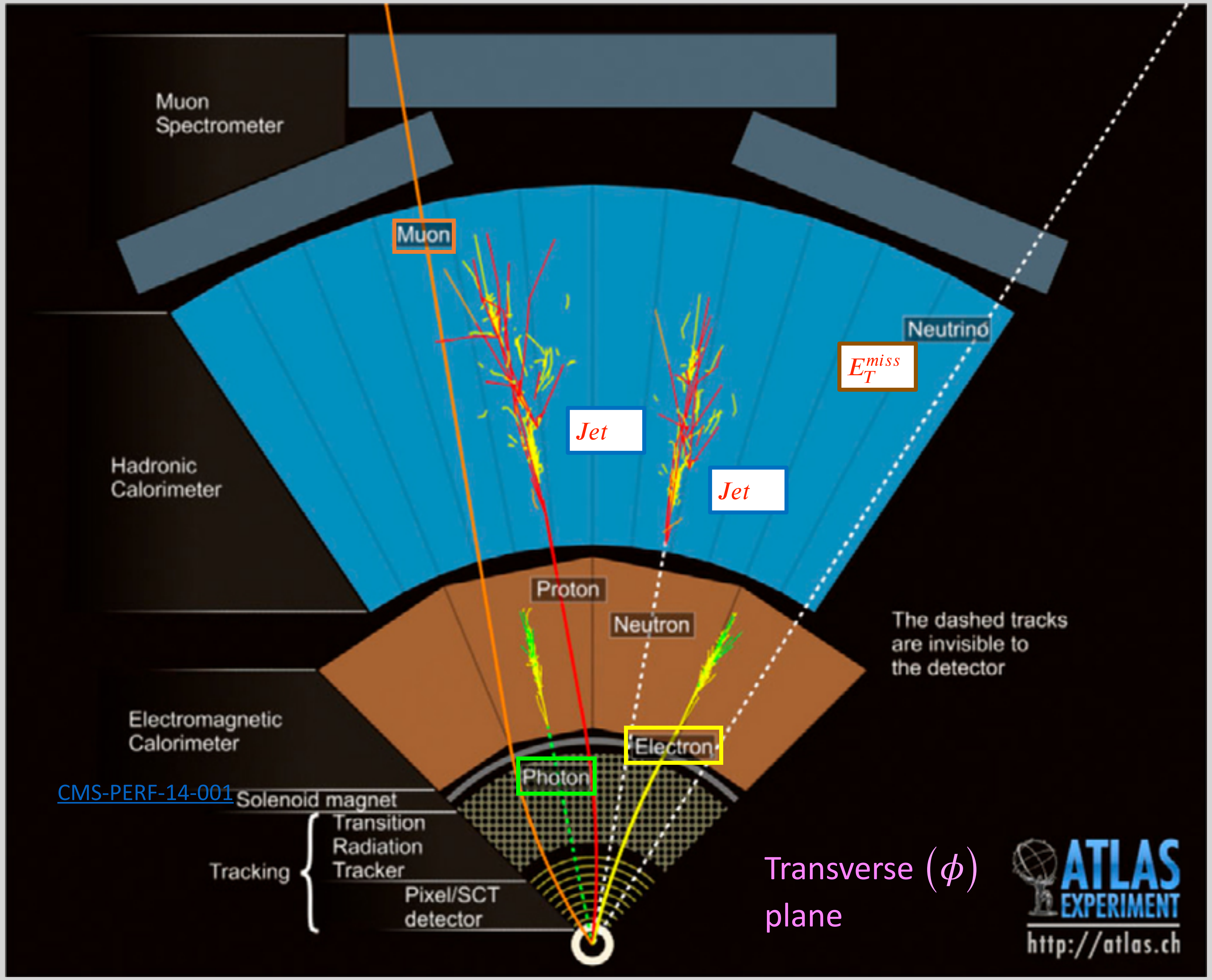
Particle Detection

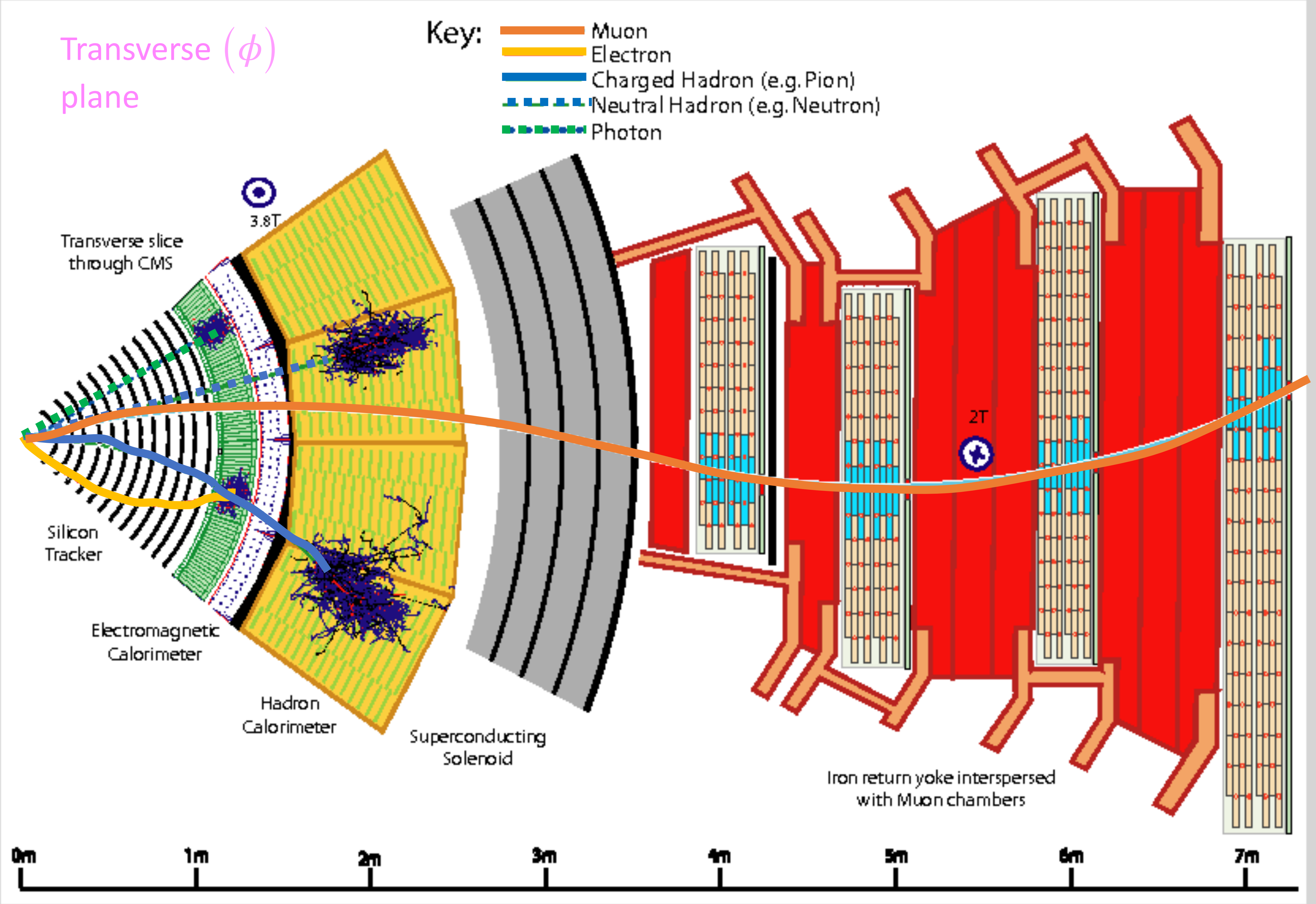


General Collider Detector



Detecting Particles with ATLAS/CMS





Electron: Charged, EM

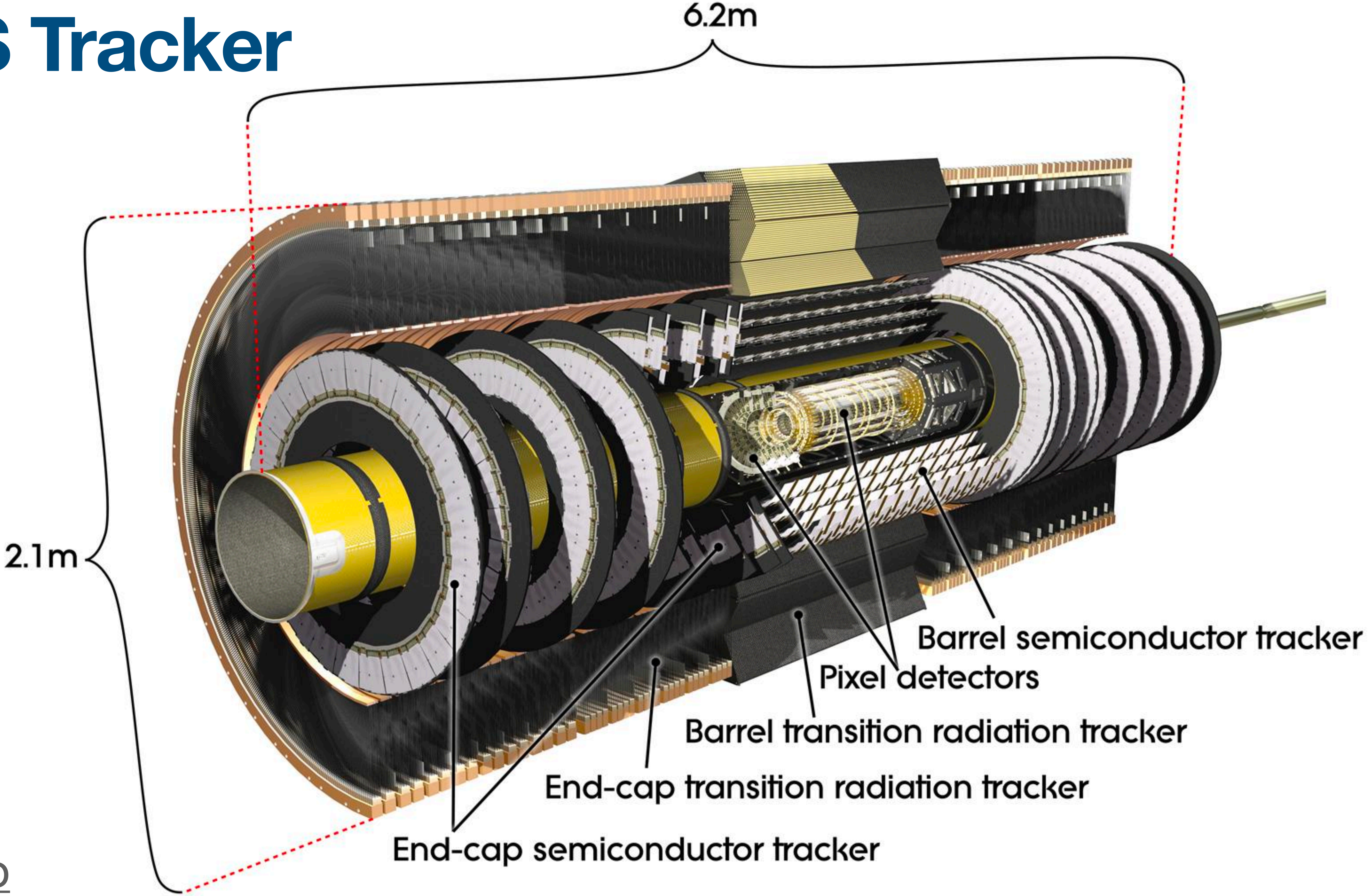
Photon: Neutral, EM

Muon: Charged, MIP

Jet: Calorimeter Object

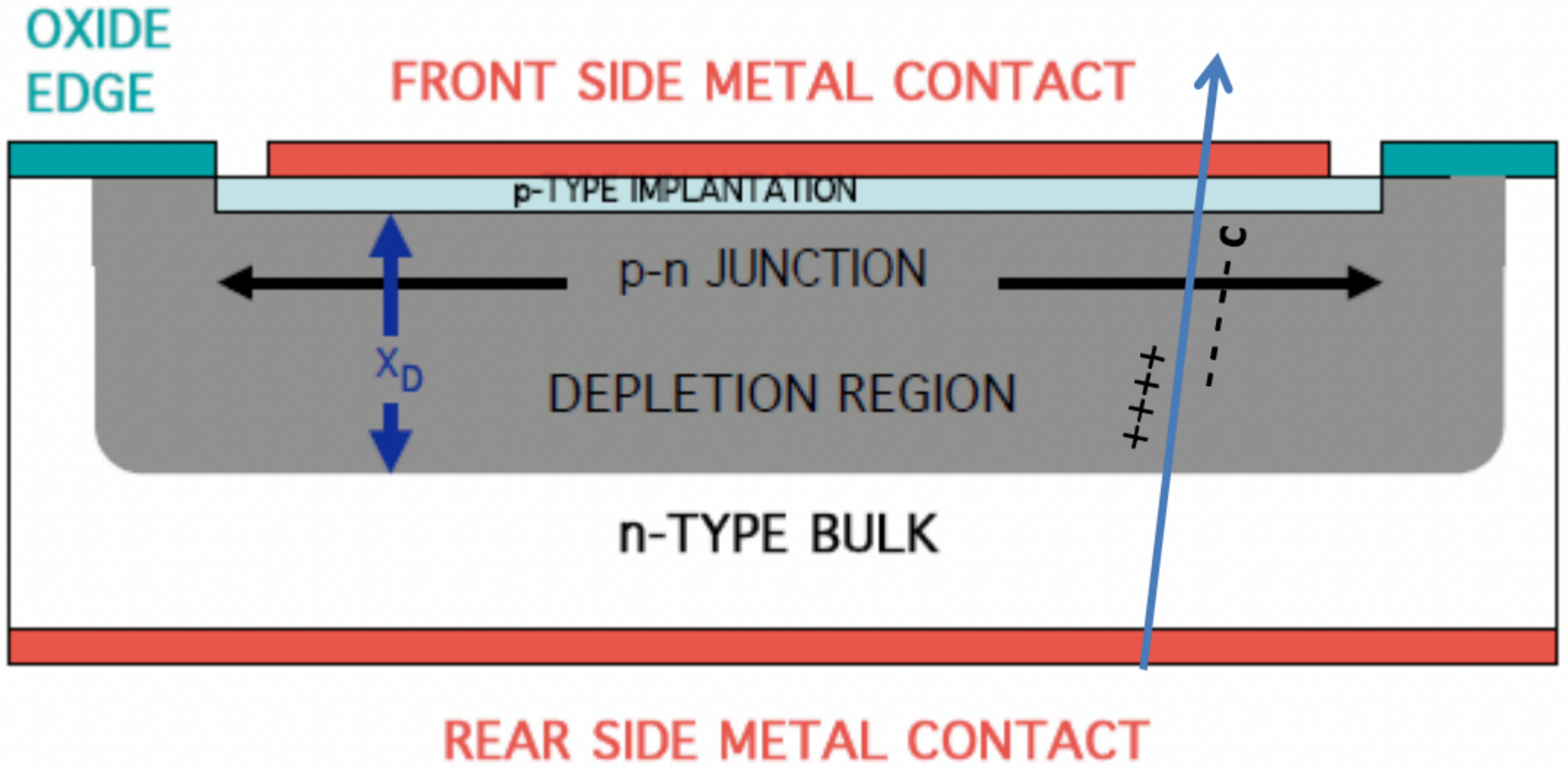
E_T^{miss}: Missing Energy (Transverse)

ATLAS Tracker

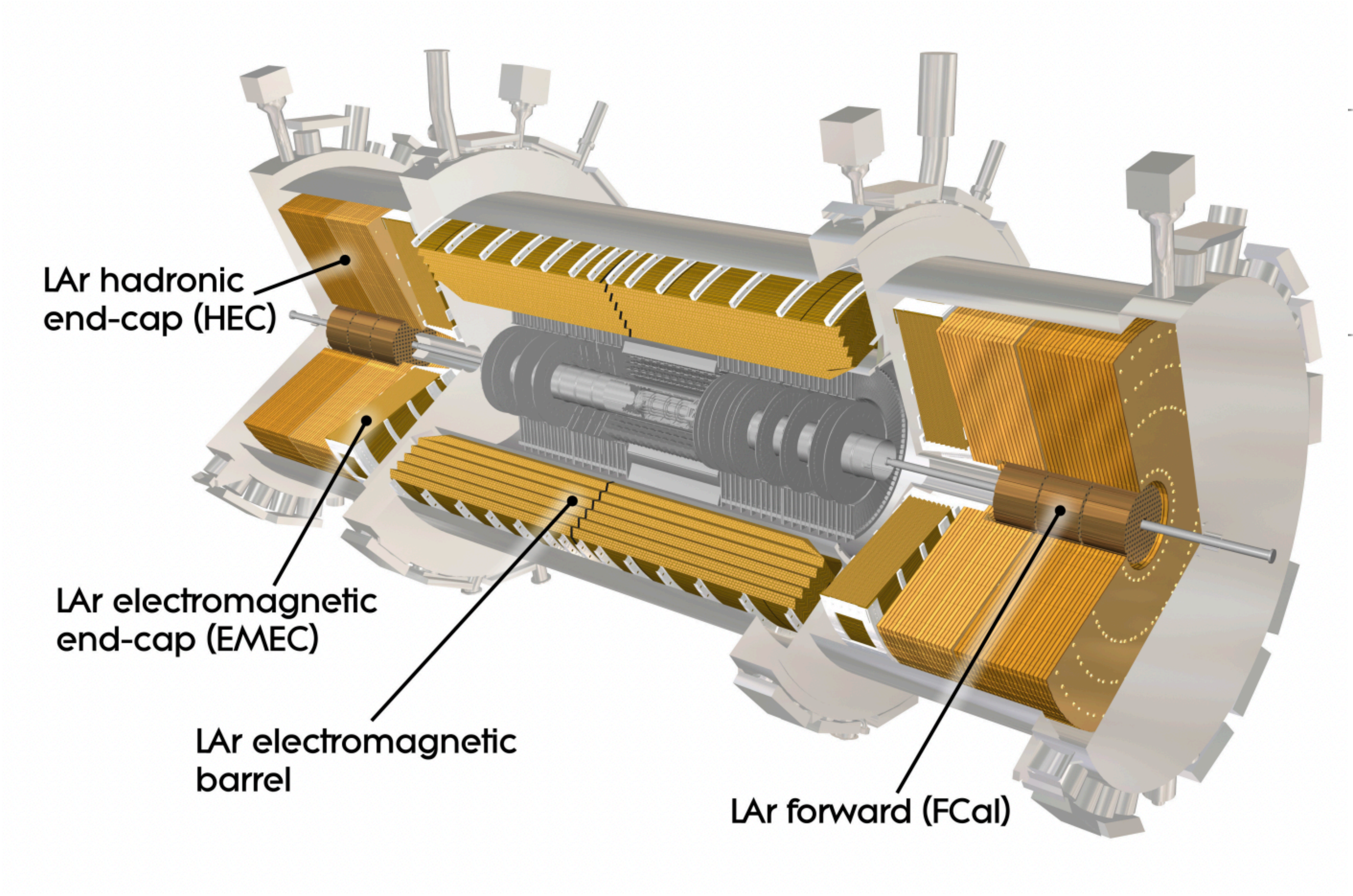


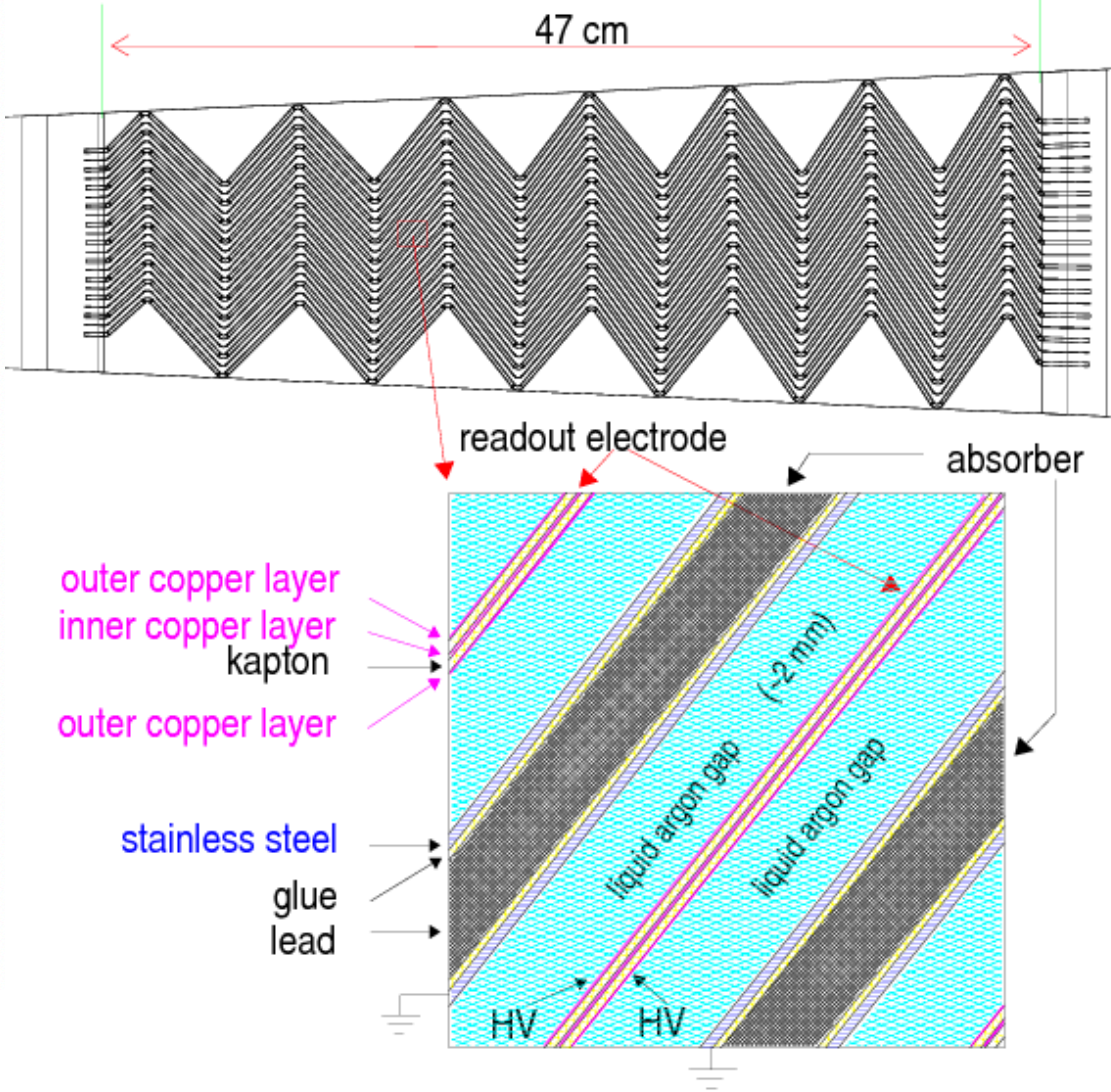
See Video

Silicon (Semiconductor) Strip Detectors

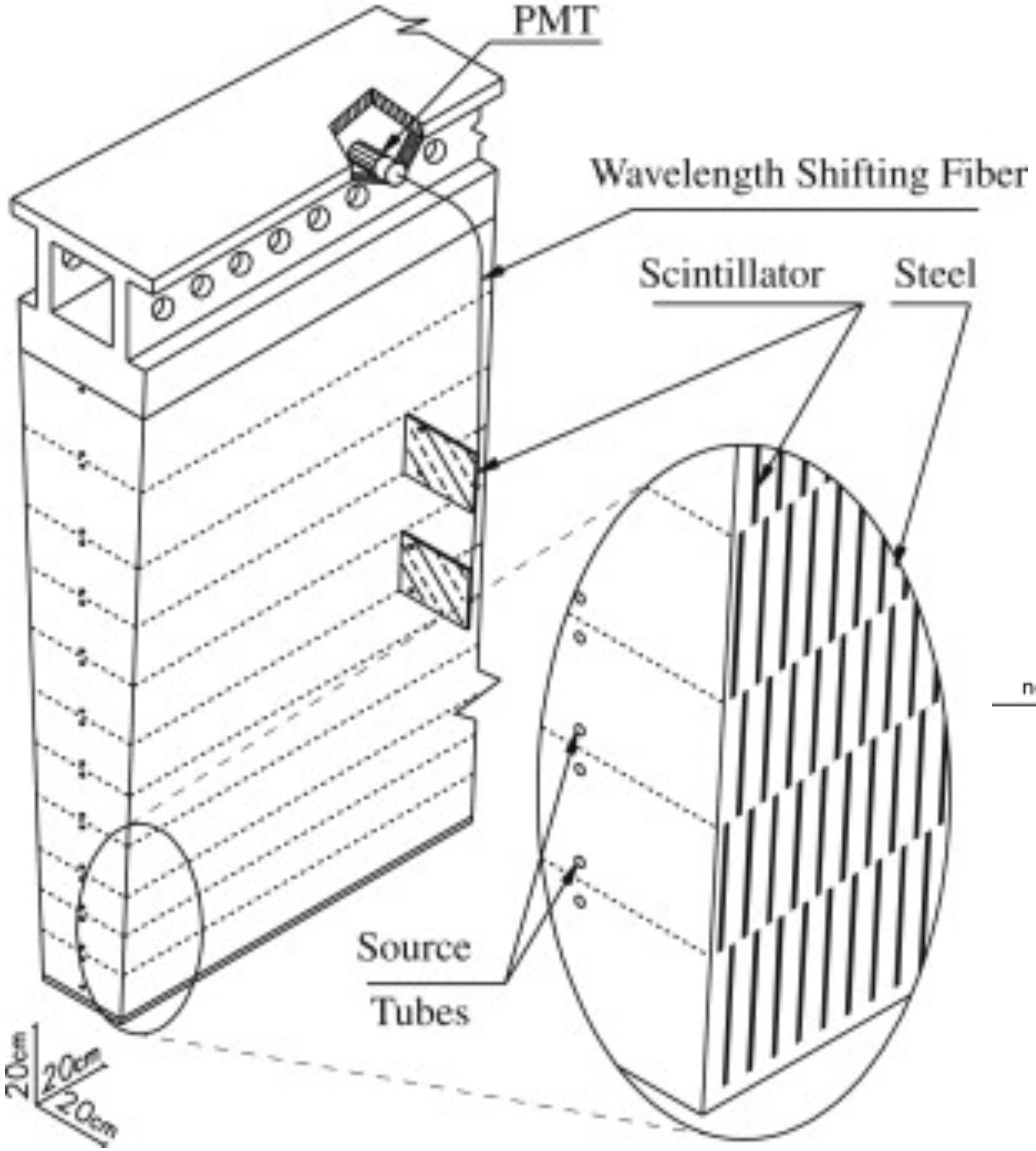


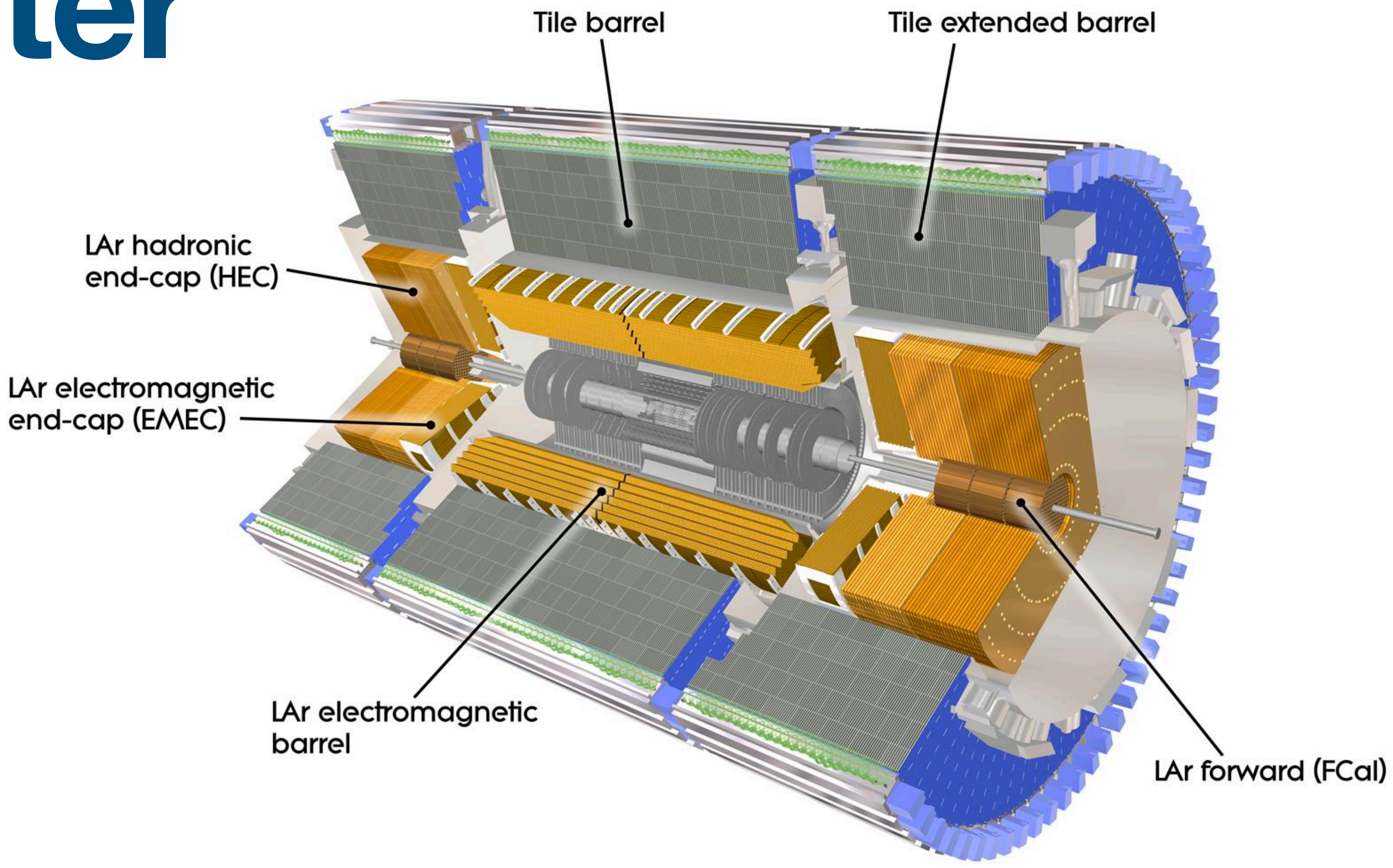
Liquid Argon Calorimeter

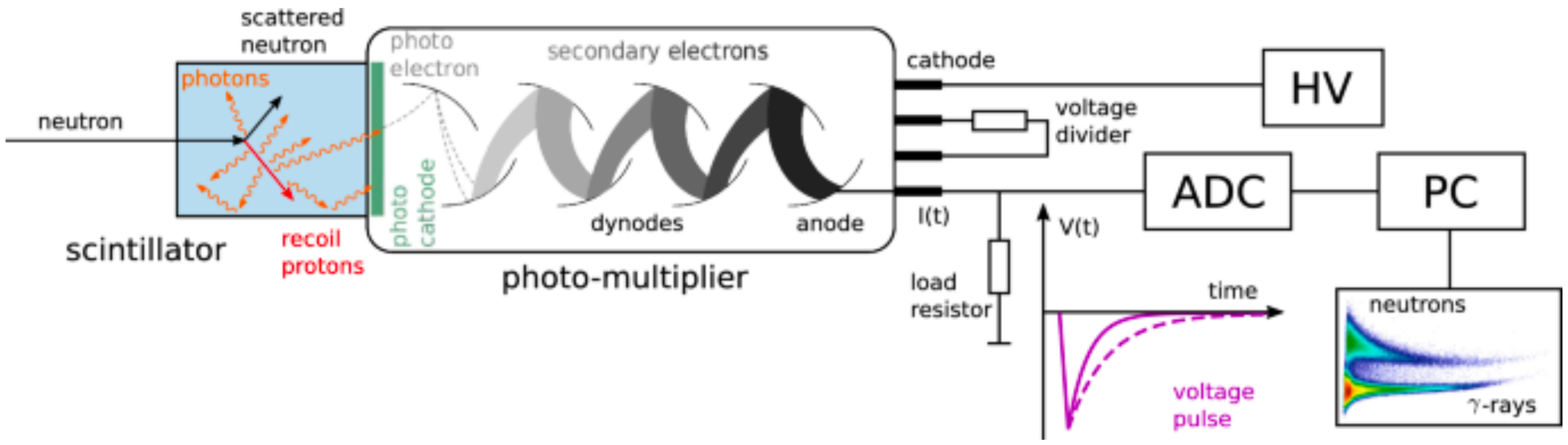




Hadronic Calorimeter



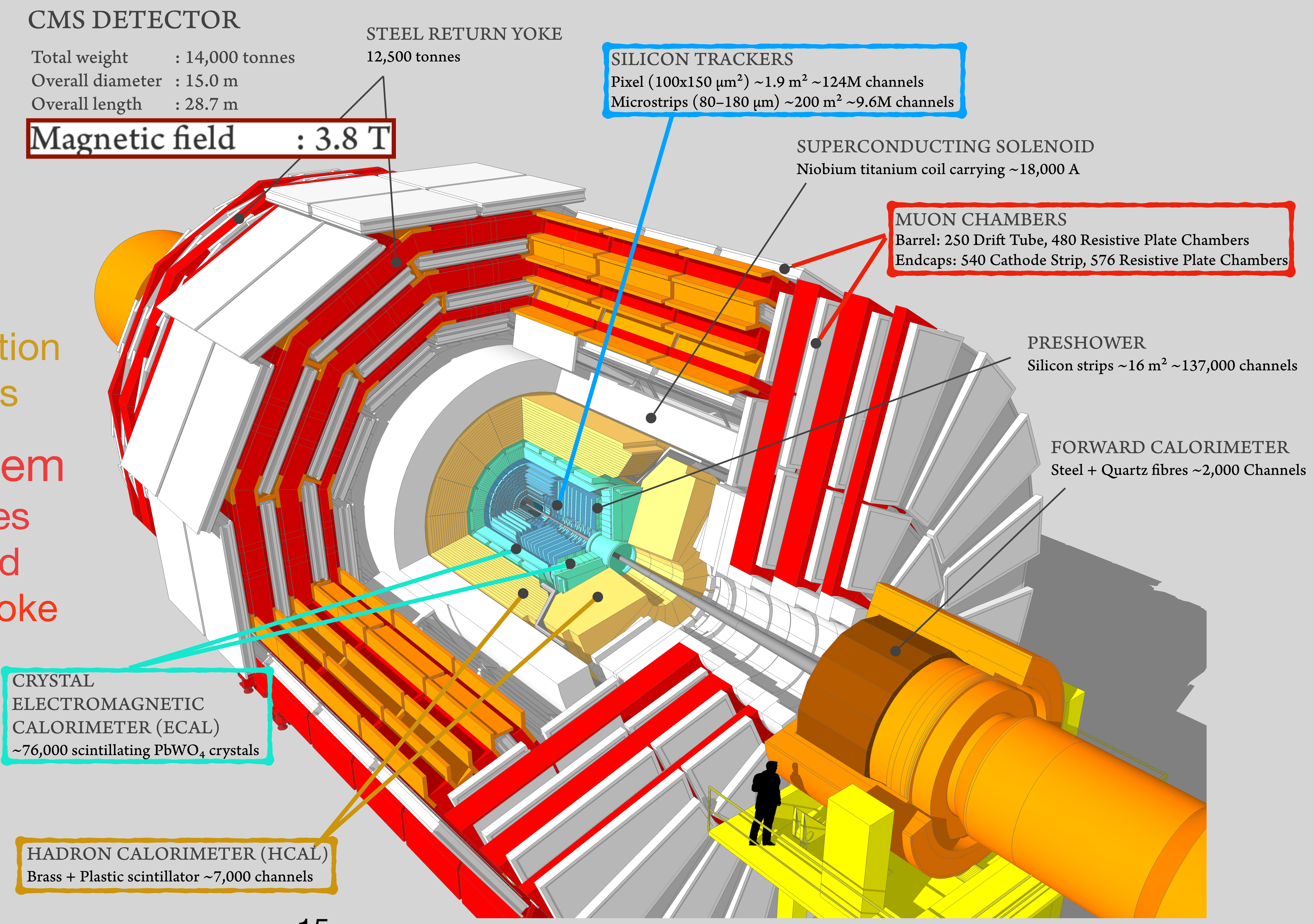




See Video

The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$
- $PbWO_4$ EM Calorimetry
- Brass Hadron Calorimeter
  — Provides excellent energy resolution for strongly-coupled parton showers
- Excellent, Robust Muon System
  — Superconducting solenoid creates 3.8*T* magnetic field in tracker and calorimeters, 2*T* is steel return yoke
- **Cost: ~500 MCHF**
  + ~200 MCHF (Upgrades)



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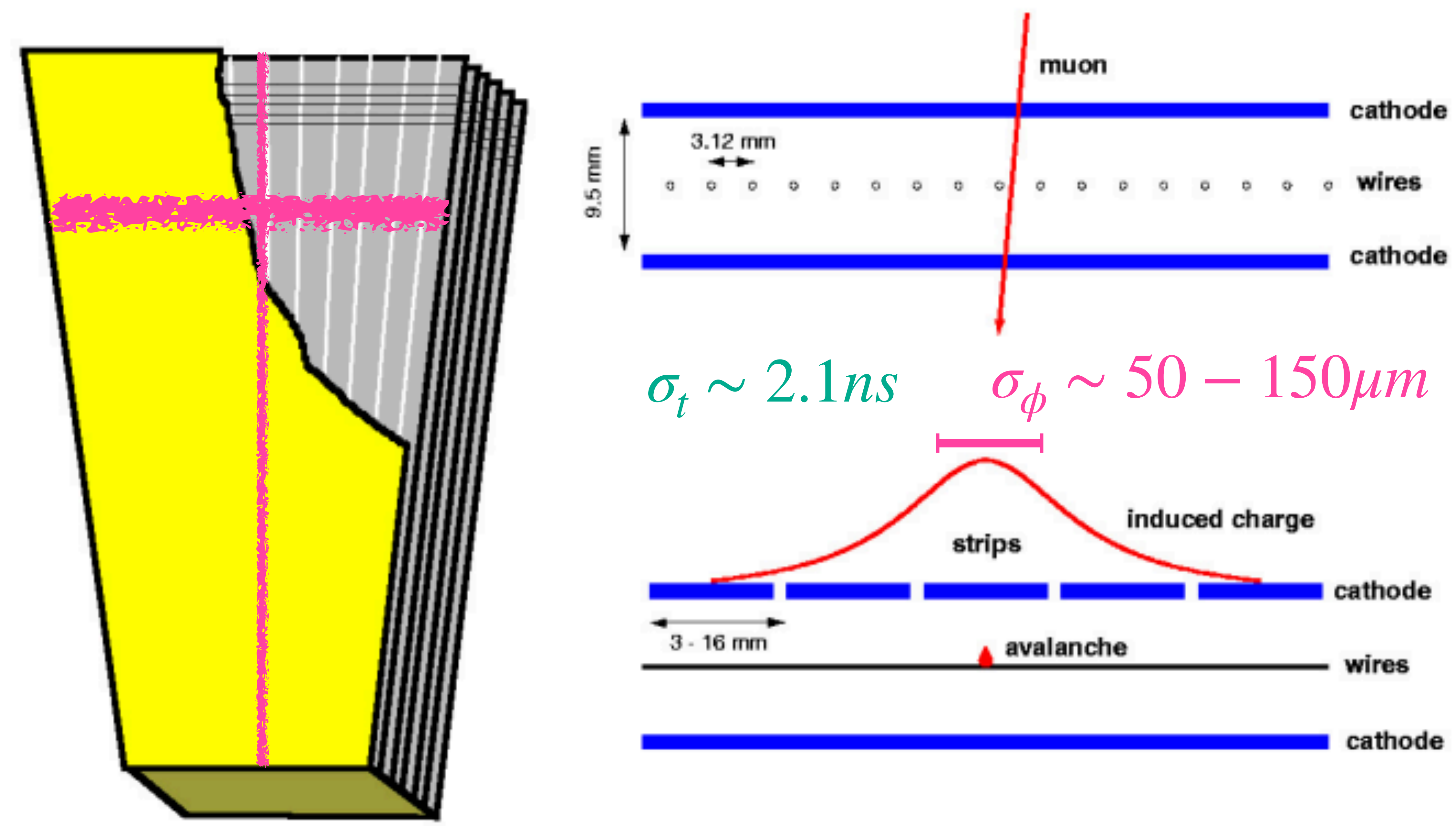
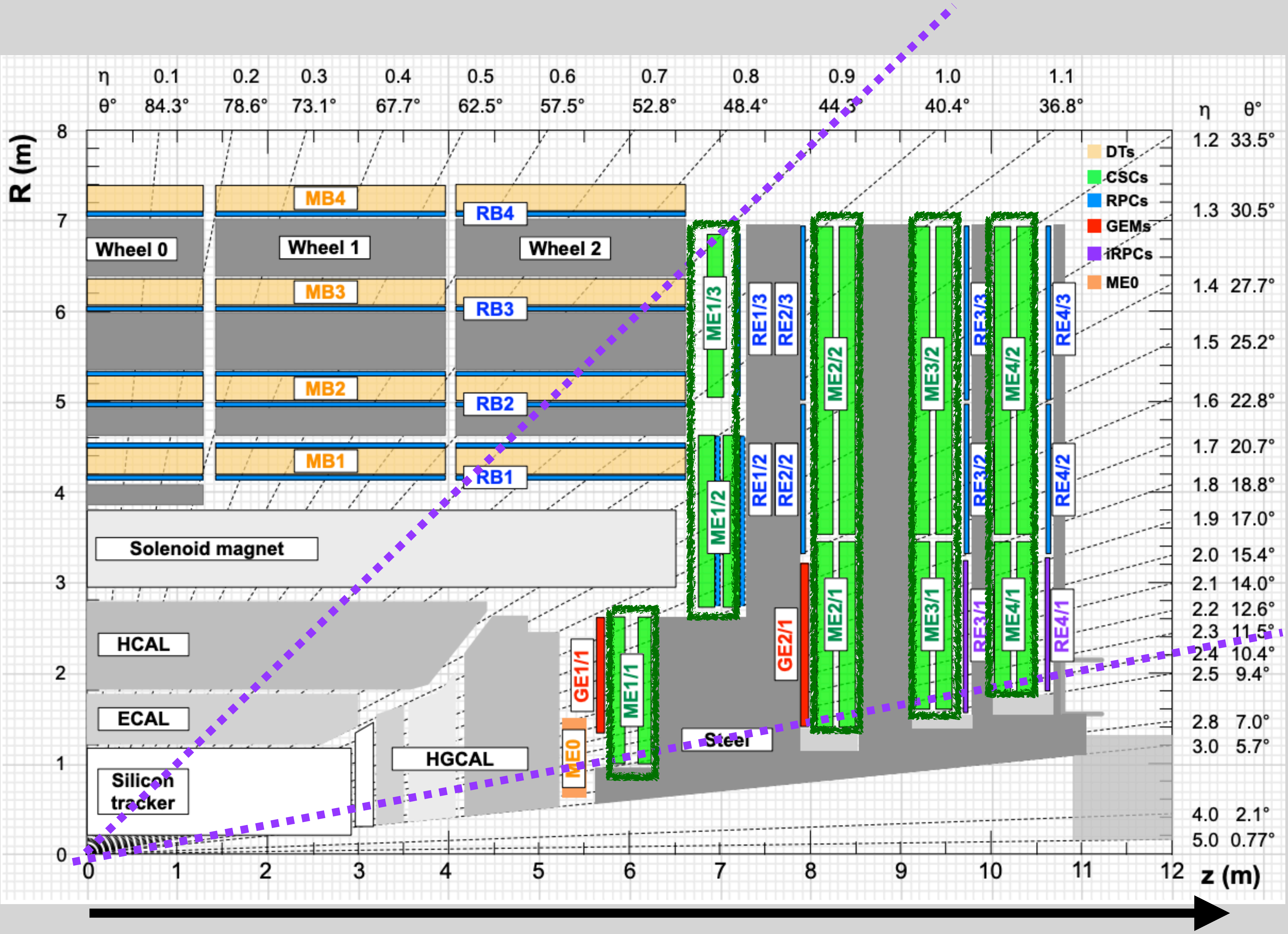
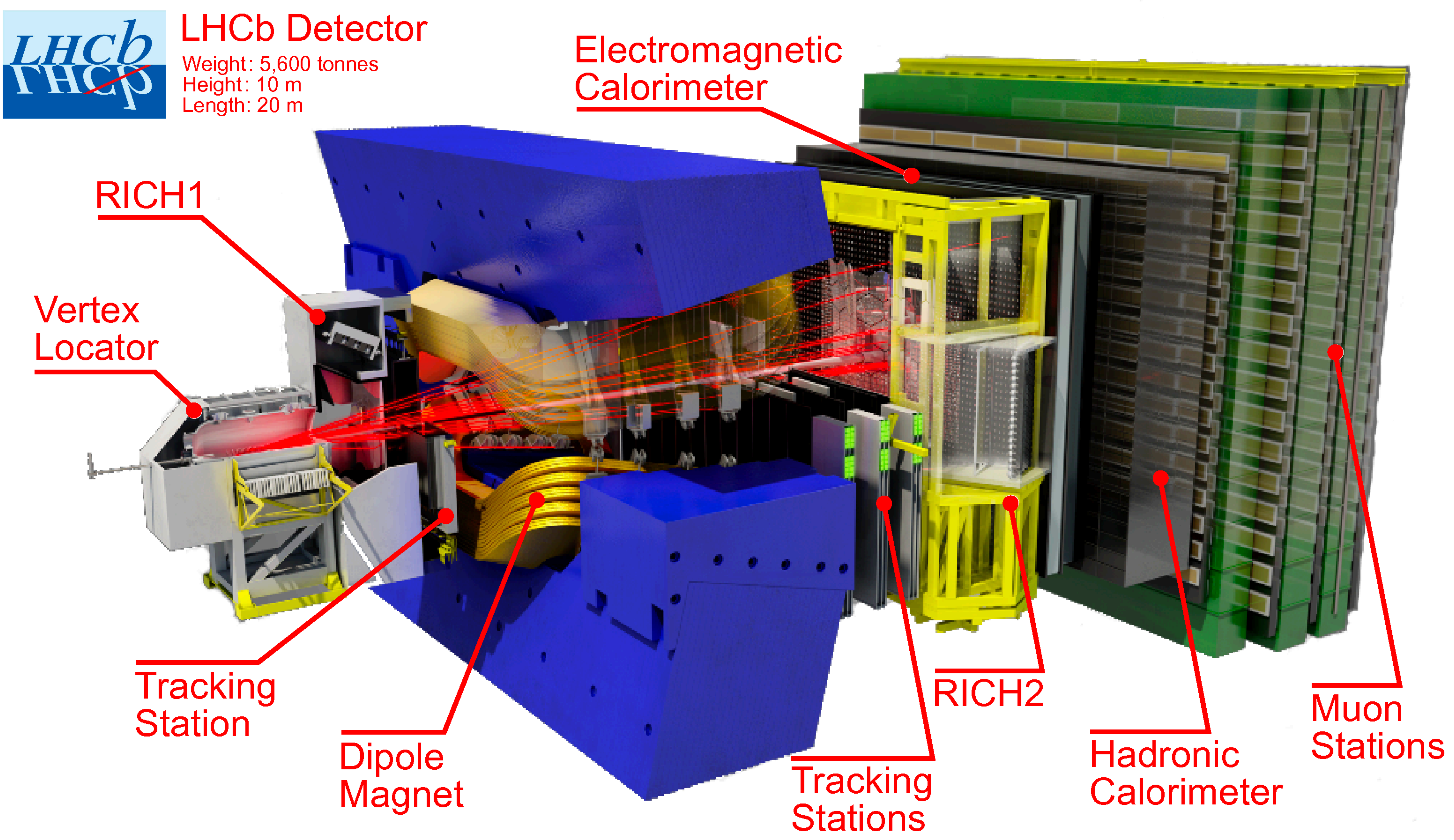
What Are Cathode Strip Chambers (CSCs)?

- Muon system employs different technologies
  - Barrel: Drift Tube + Resistive Plate Chamber (RPC)
  - End-Caps: CSC + RPC + Gas Electron Multipliers (GEM)
- CSCs are 6-layers of wires (anodes) and strips (cathodes) in $Ar/CO_2/CF_4$ gas mixture
  - Traversing muons ionize gas at HV
  - Avalanche signal read by anode and cathode electronics
- CSCs measure <u>4D</u> position, $|\eta| \in [0.9, 2.4]$
  - Work great in intense, non-uniform magnetic fields

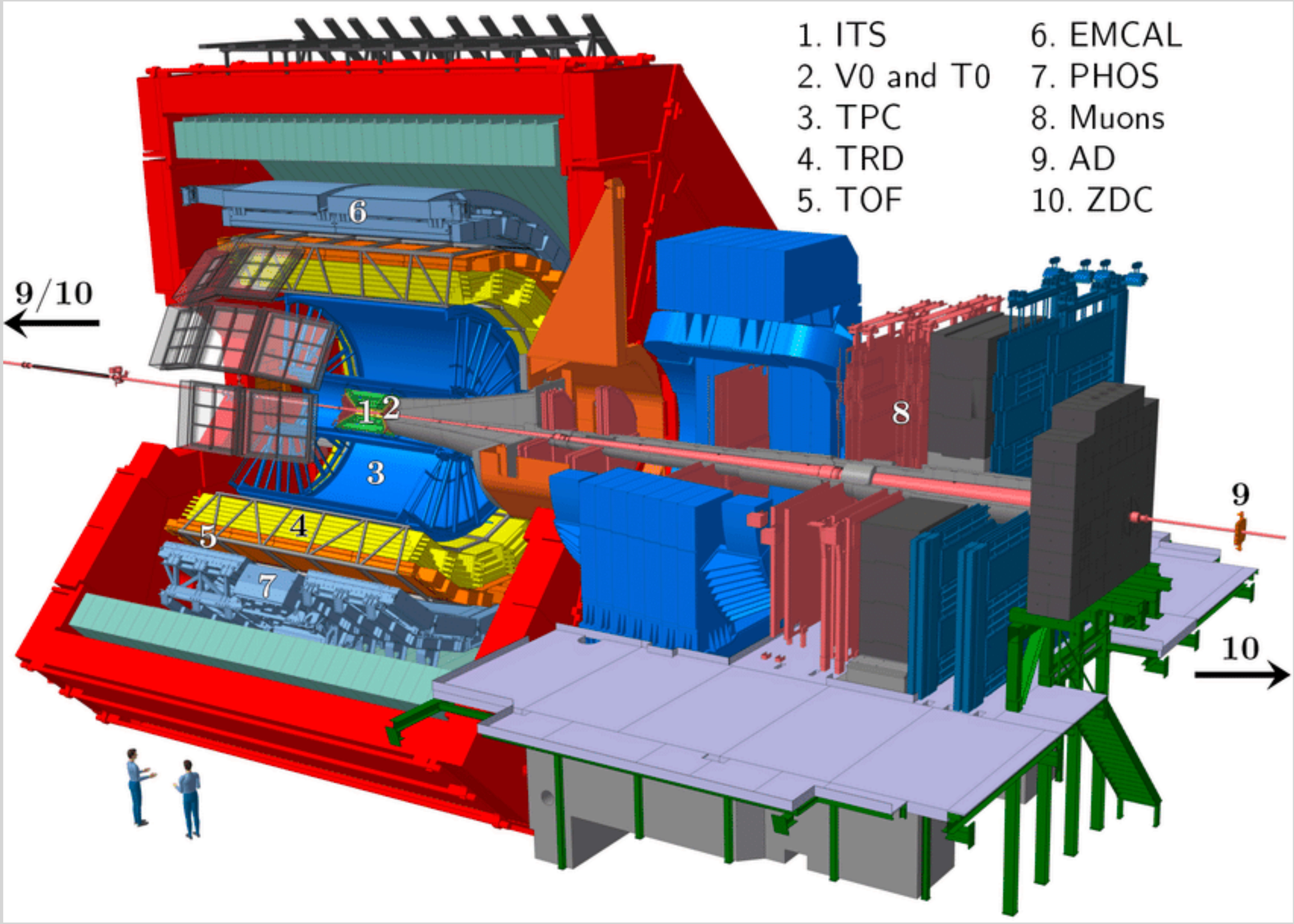




[CMS-TDR-016](CMS-TDR-016)


LHCb Detector
Weight: 5,600 tonnes
Height: 10 m
Length: 20 m
Electromagnetic Calorimeter
RICH1
Vertex Locator
Tracking Station
Dipole Magnet
Tracking Stations
RICH2
Hadronic Calorimeter
Muon Stations

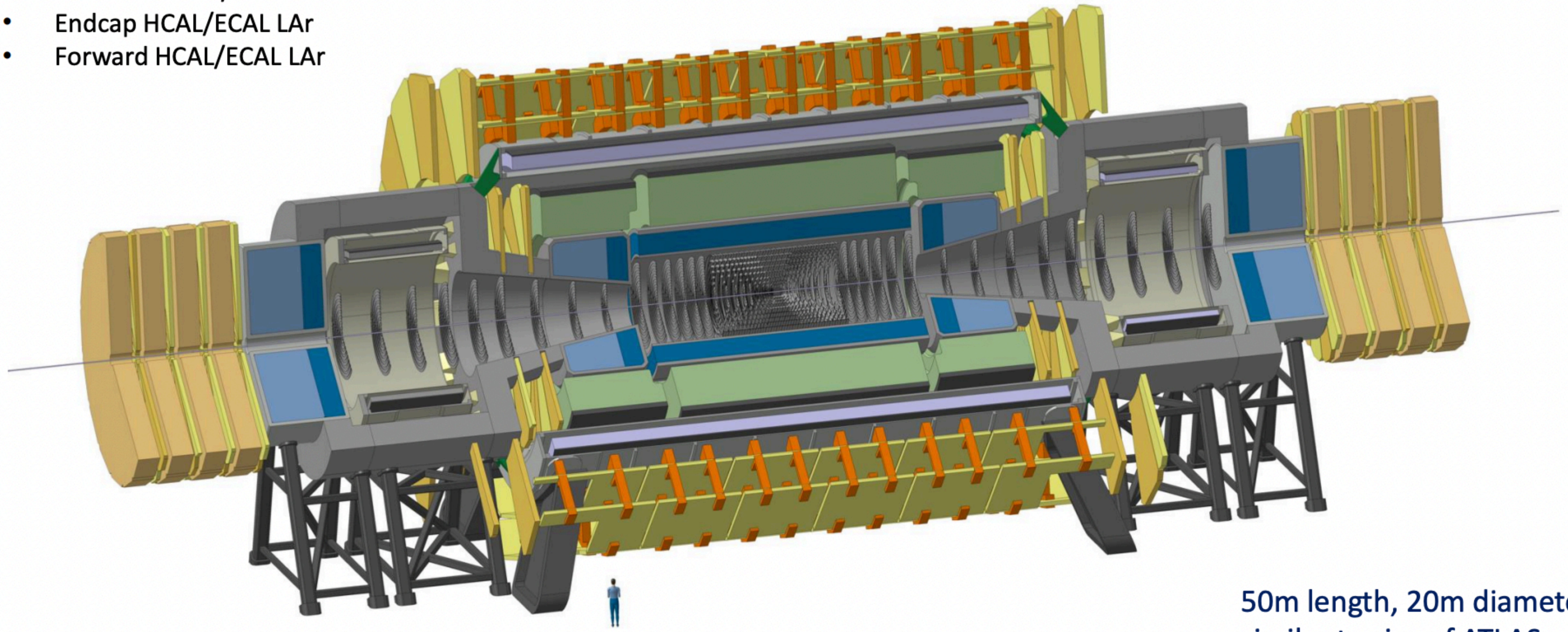
ALICE


1. ITS
2. V0 and T0
3. TPC
4. TRD
5. TOF
6. EMCAL
7. PHOS
8. Muons
9. AD
10. ZDC
9/10
1
2
3
4
5
6
7
8
9
10

FCC-hh Reference Detector

W. Riegler

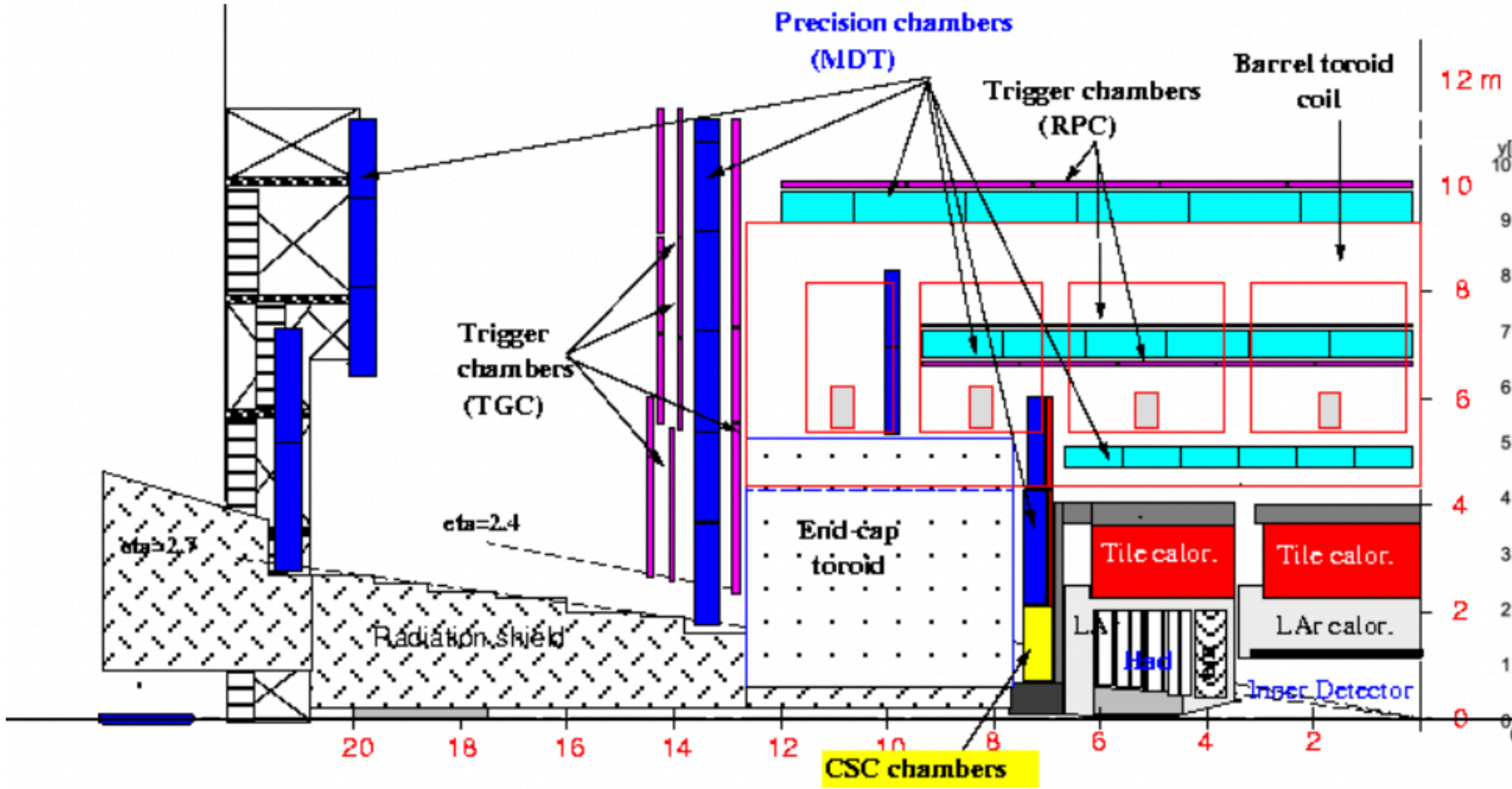
- 4T, 10m solenoid, unshielded
- Forward solenoids, unshielded
- Silicon tracker
- Barrel ECAL LAr
- Barrel HCAL Fe/Sci
- Endcap HCAL/ECAL LAr
- Forward HCAL/ECAL LAr

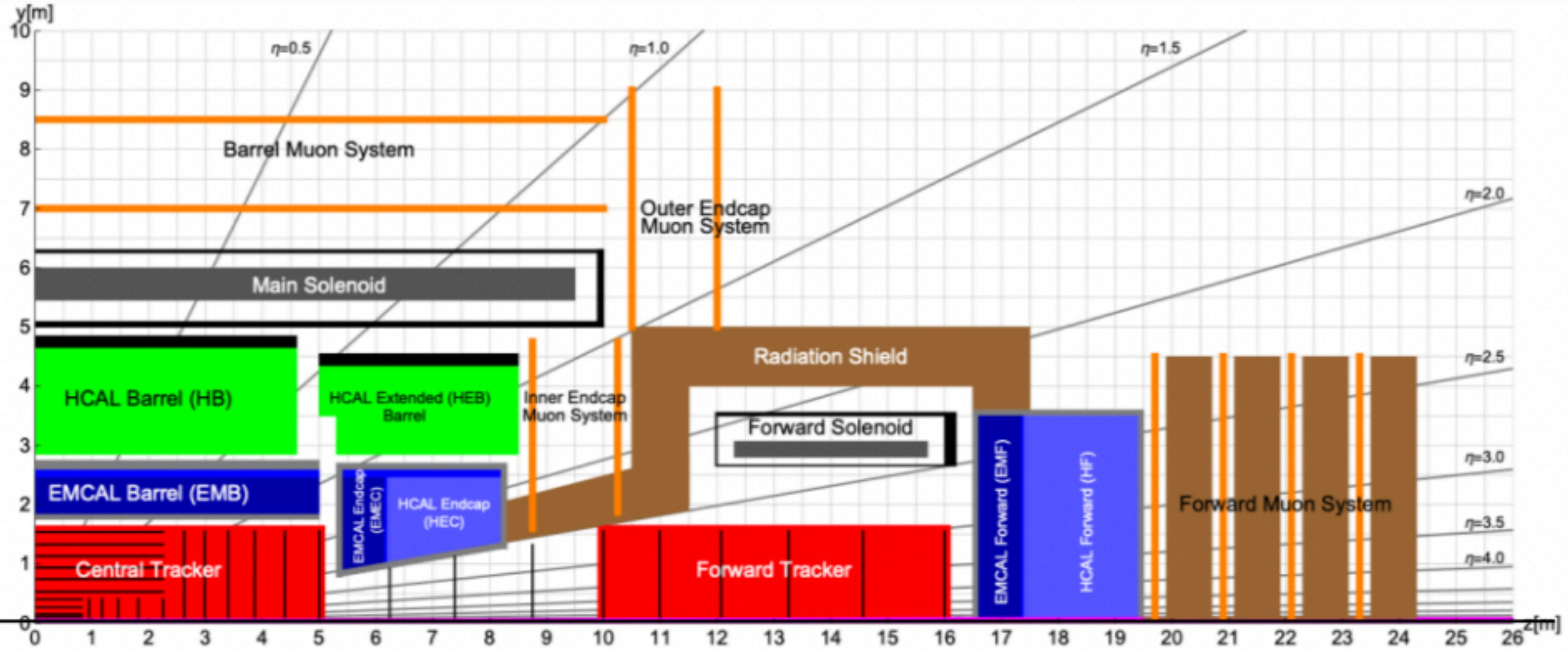


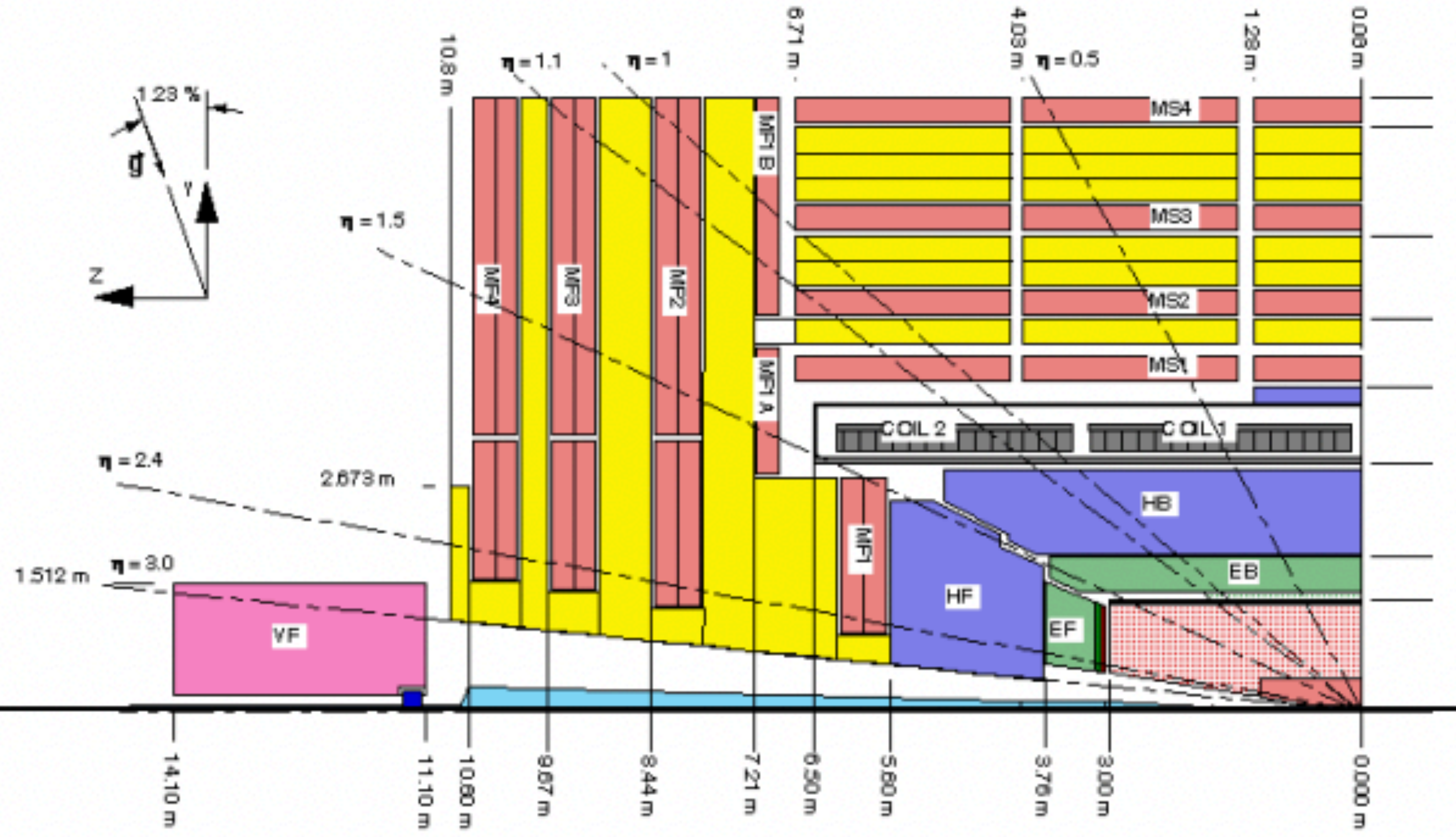
50m length, 20m diameter
similar to size of ATLAS

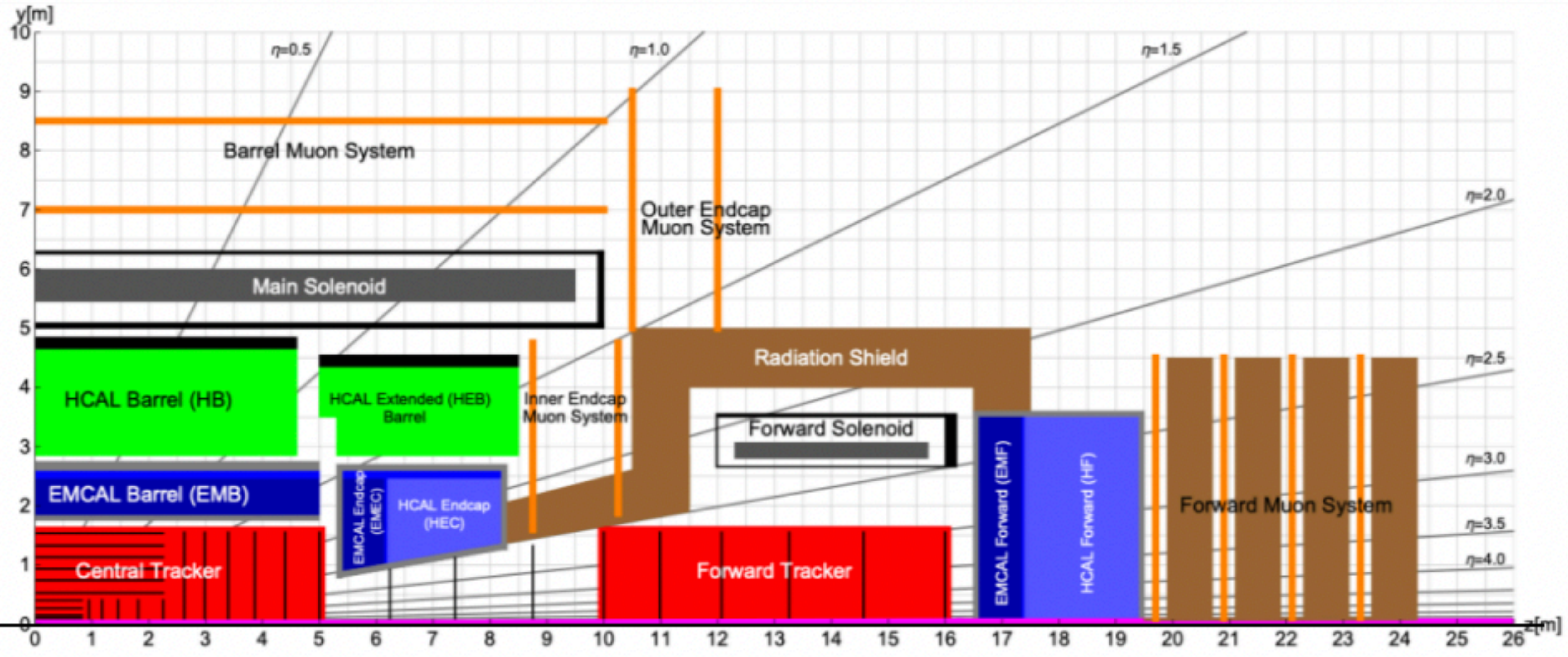
Comparison to ATLAS & CMS

W. Riegler









Intro to Group Theory

- What is a group?
  - What is an example of a group?
- What is a field?
  - How are fields related to groups?
  - What is a vector field? Is that a group?
  - How is a field related to groups?

A *group* is a ***set*** defined by axioms:
1) an associative operation X,
2) G must have an identity g_I,
3) For any element g_1 of G there exists a g_2, such that g_1 X g_2 = g_I, the identity of the group

A field is a set in which two binary operations (addition/sum and multiplication/product) and axioms: Associativity, distributivity, commutativity (only abelian), and have unique inverses and identities for both operations

Groups <-> Symmetries

- Groups can by ANYTHING that satisfies the axioms
  - Solutions to equations can be closed groups (think E&M)
    e.g: if T(f_1) = 0 and T(f_2) = 0, then T(f_1+f_2)= T(f_1)+T(f_2)=0
  - Eigenvectors can be a group
  - Rotations are definitely a group…so are rotations that leave a system invariant
  - Turns out groups can be represented by matrices

- U(N) vs SO(N) vs SU(N)
  - Unitary: $U^\dagger U = UU^\dagger = UU^{-1} = I$
  - Orthogonal: $Q^T Q = QQ^T = I \rightarrow Q^T = Q^{-1}$
  - Special Unitary/Orthogonal: Unitary/Orthogonal with norm 1

Symmetries in Physics

- For a set of transformations G (group), a theory (Lagrangian) is symmetric/invariant under G if all elements of G transform the states/operators in such a way that leaves the FORM of the Lagrangian

- Unitary Group of degree 1, U(1)
  — Set of single (n=1 -> nXn=1x1 matrices) complex numbers with norm 1
  — $e^{i\theta}$ for $\theta \in [0,2\pi]$
  — Just a circle!

- Global Symmetry -> for any θ -> Conserved quantity (Noether's theorem)

- Local/gauge symmetry -> for $\theta(x)$ dependent on x -> gauge

- Redundancies in a theory -> same physics

Standard Model Symmetries

$U(1) \times SU(2)_L \times SU(3)$ **->** $U(1)_{QED} \times SU(3)_C$

- $U(1) \times SU(2)_L$ represents Electroweak symmetry
  — 4 degrees of freedom -> electroweak symmetry breaking -> 3 leftover
  — Goldstone bosons -> physical bosons
  — Higgs ‘eats’ a degree of freedom

- $SU(3)$ represent Quantum Chromo Dynamics (QCD, aka strong force)
  — No symmetry breaking
  — Decoupled from Electroweak sector