The Standard Model

CSU-NUPAX/CERN IRES Program

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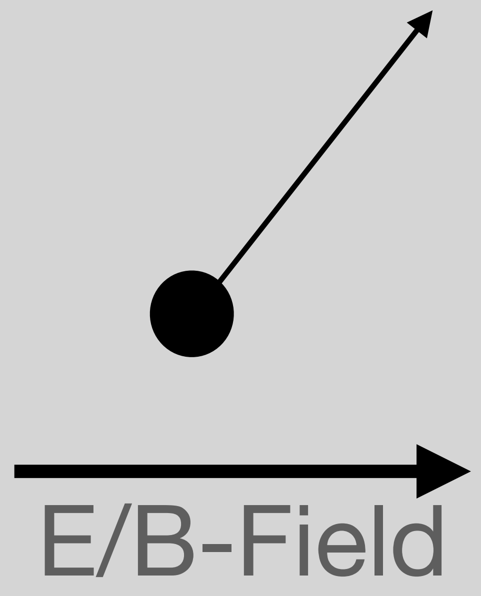
See Particle Data Group at LBNL

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

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

Gauge Transformations

Identities

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

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

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

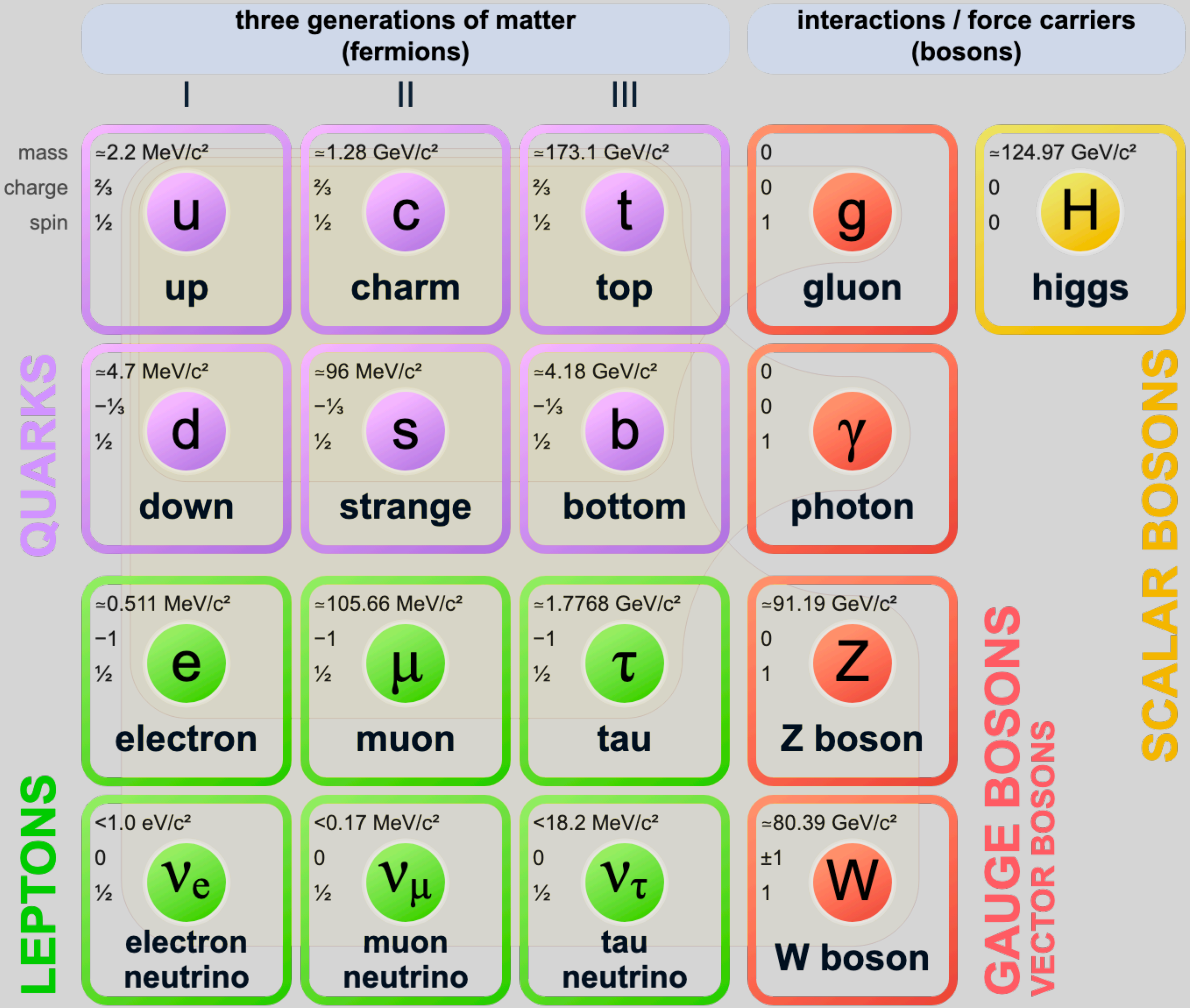
$$\mathbf{A} \to \mathbf{A} + \nabla \psi$$

$\partial_\mu A^\mu = 0$ $(\mu = 0,1,2,3)$,	Lorenz gauge
$\nabla \cdot \mathbf{A} = \partial_j A_j = 0$ $(j = 1, 2, 3)$,	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

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

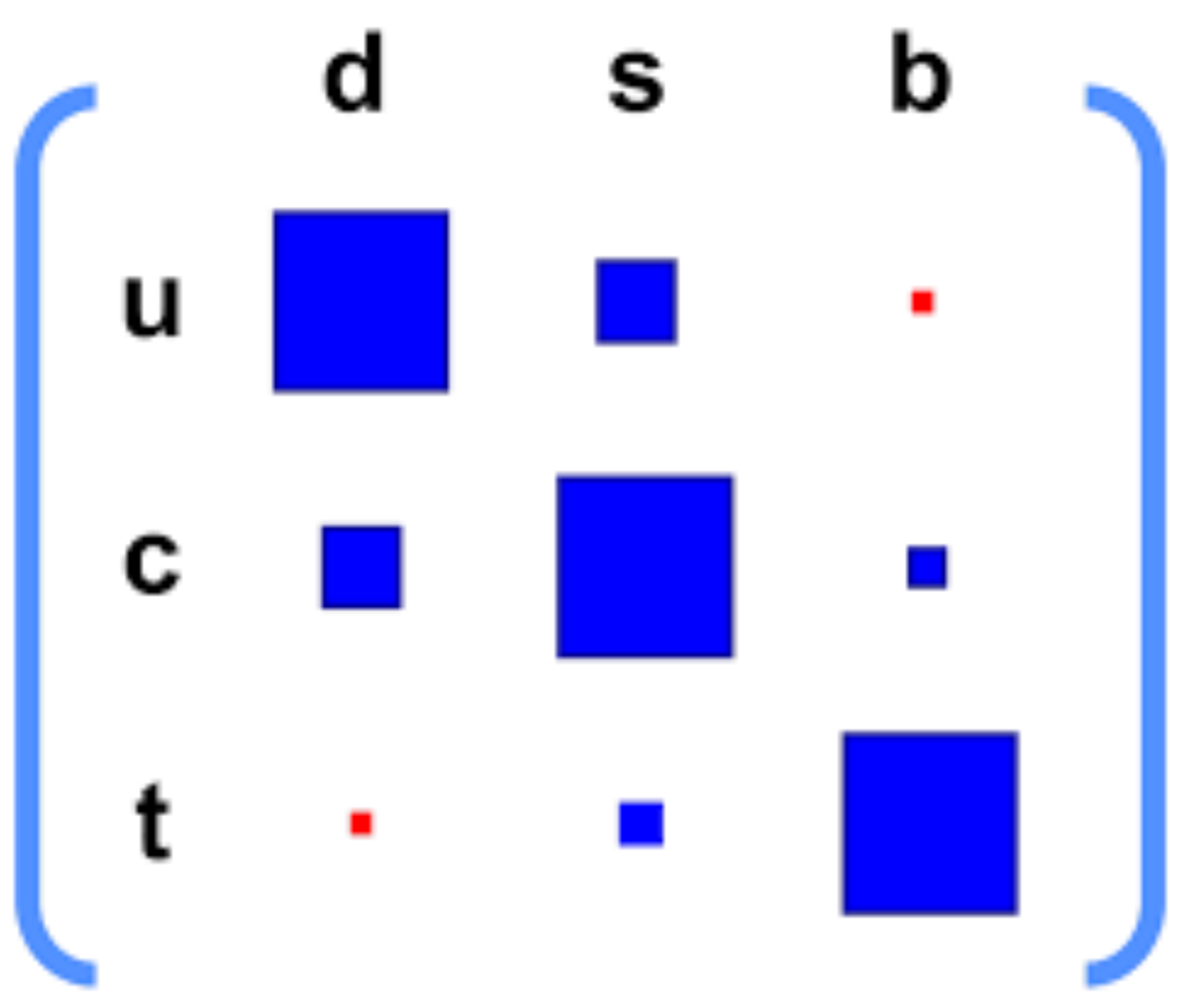
$$\mathbf{B} = \nabla \times (\mathbf{A} + \nabla\psi) = \nabla \times \mathbf{A}.$$

Standard Model of Elementary Particles



CKM Matrix

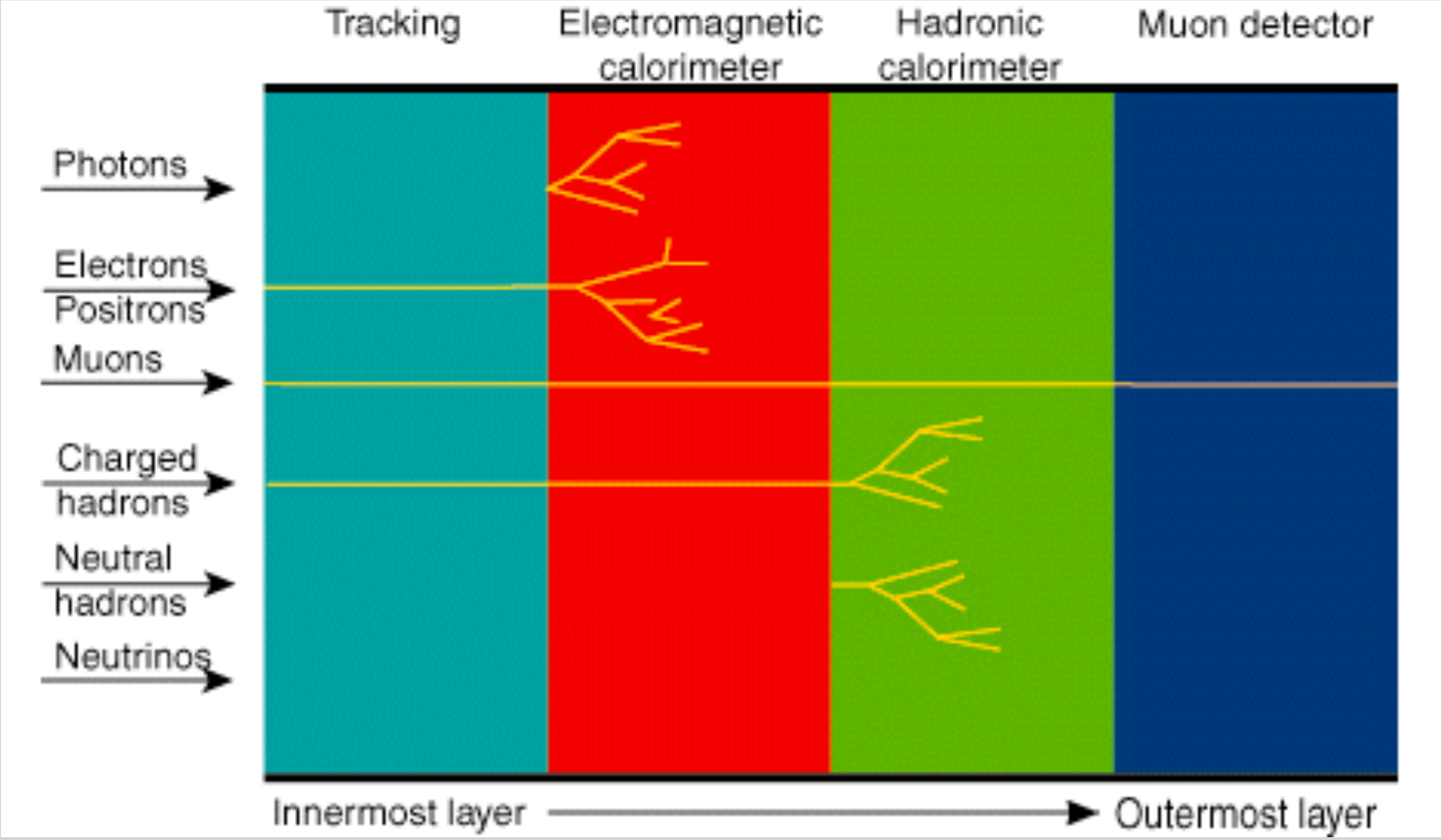
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm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



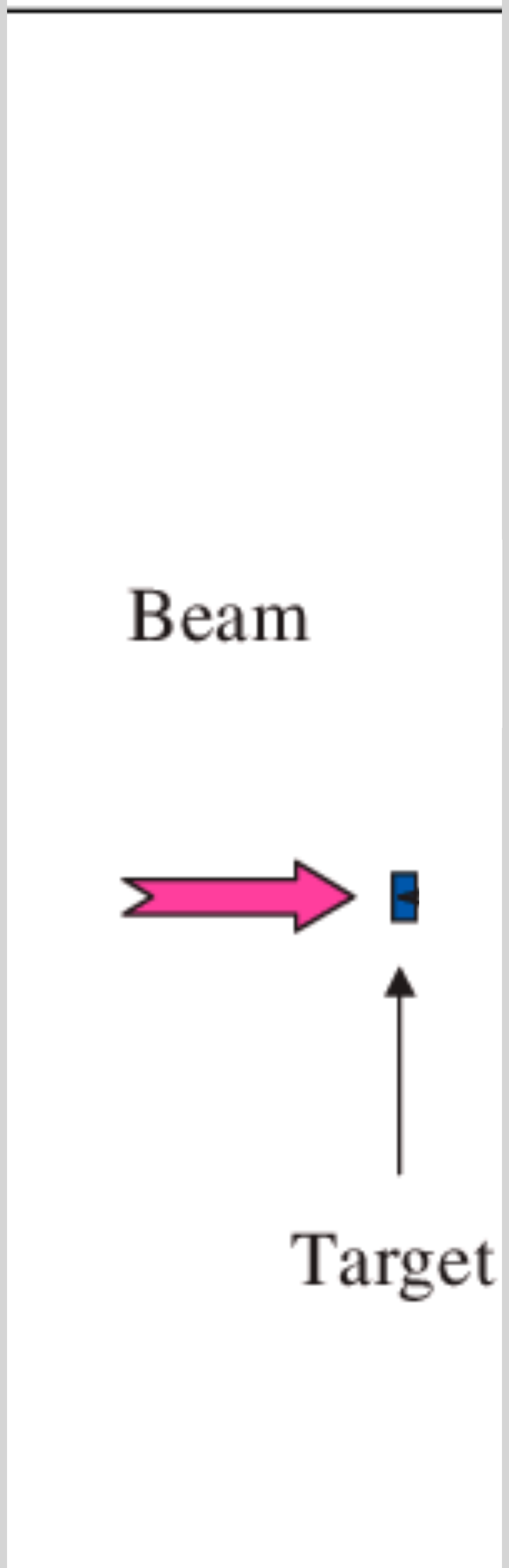
PMNS Matrix

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

Particle Detection



General Collider Detector



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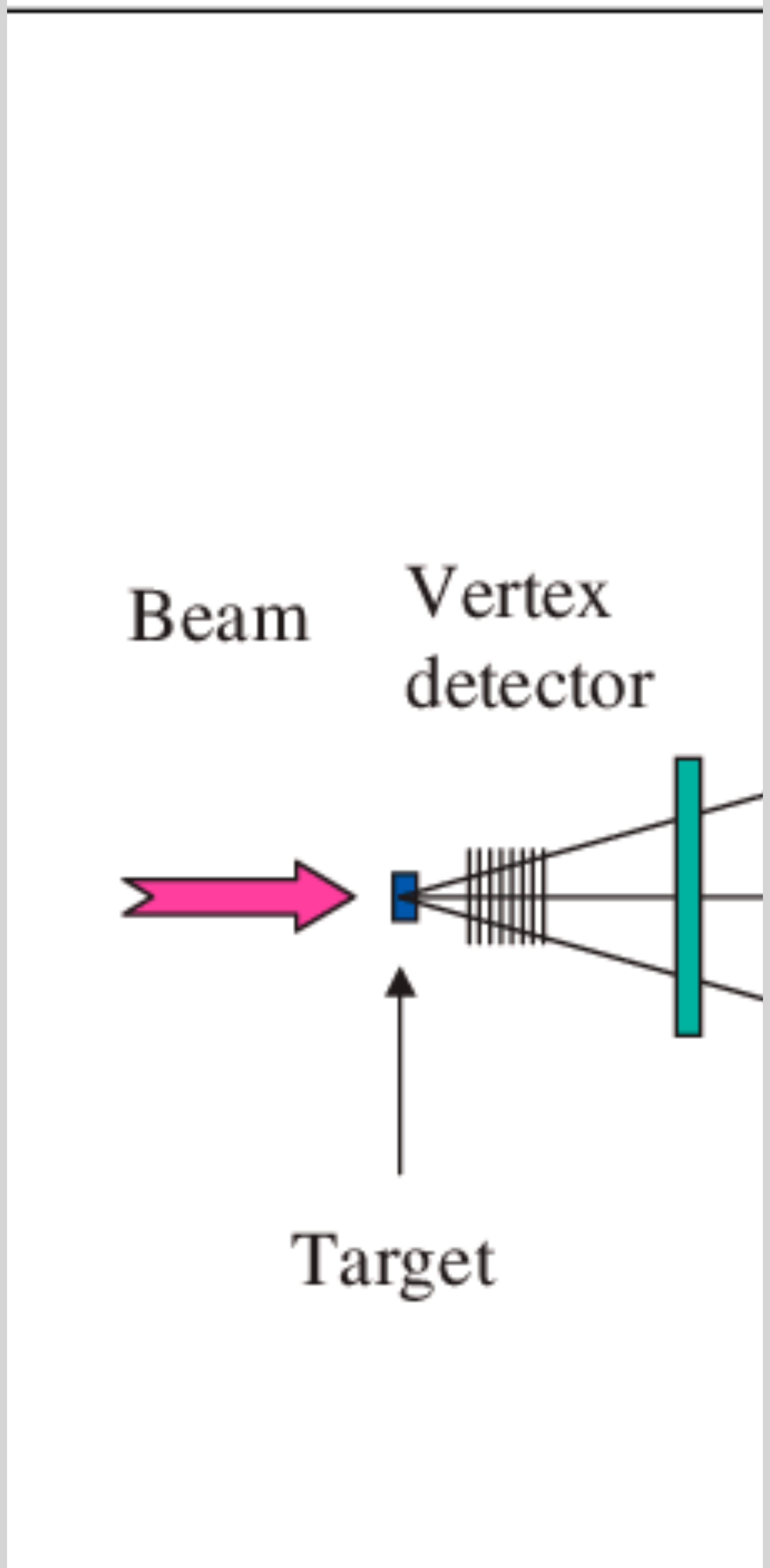
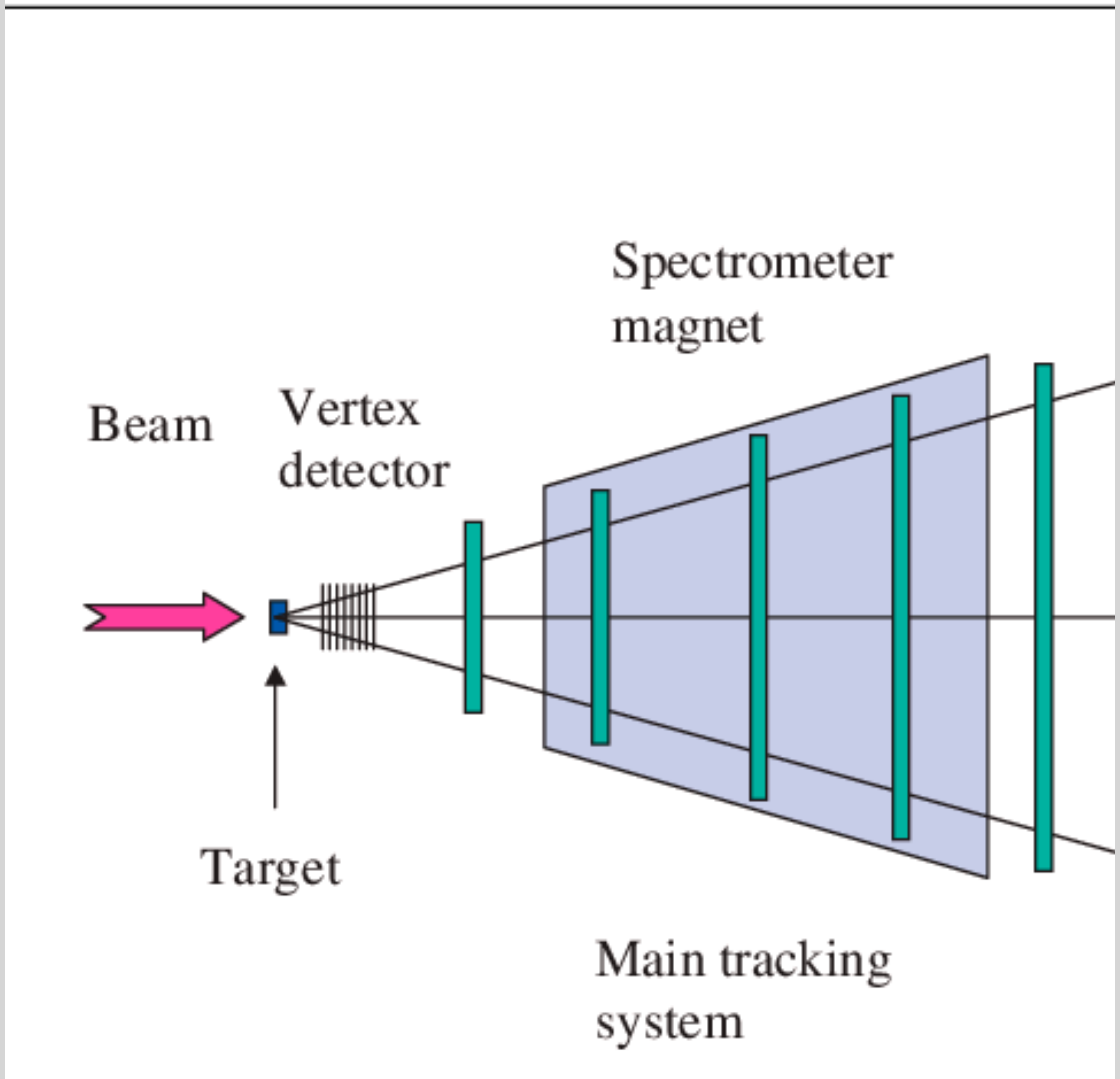
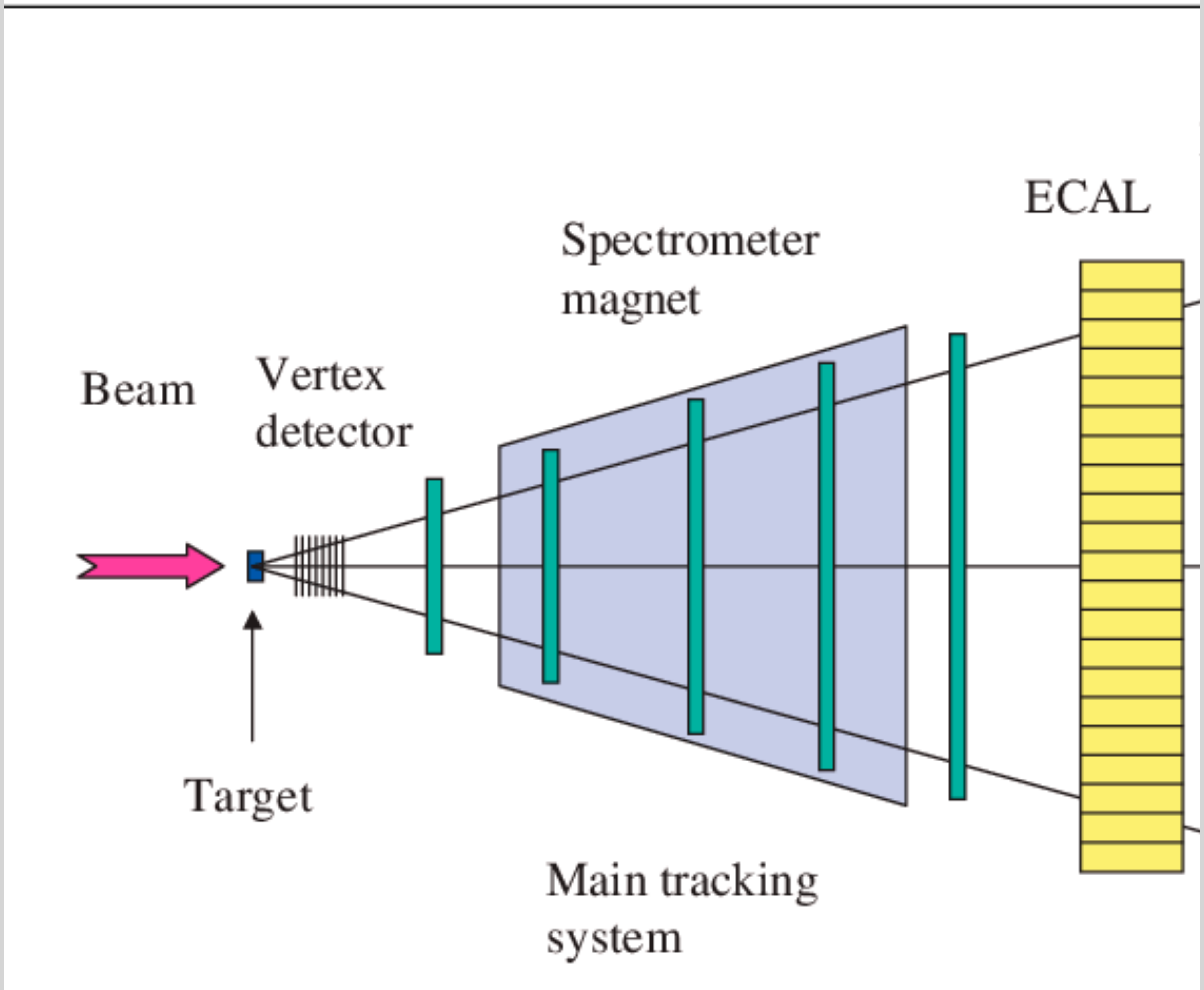


General Collider Detector



General Collider Detector



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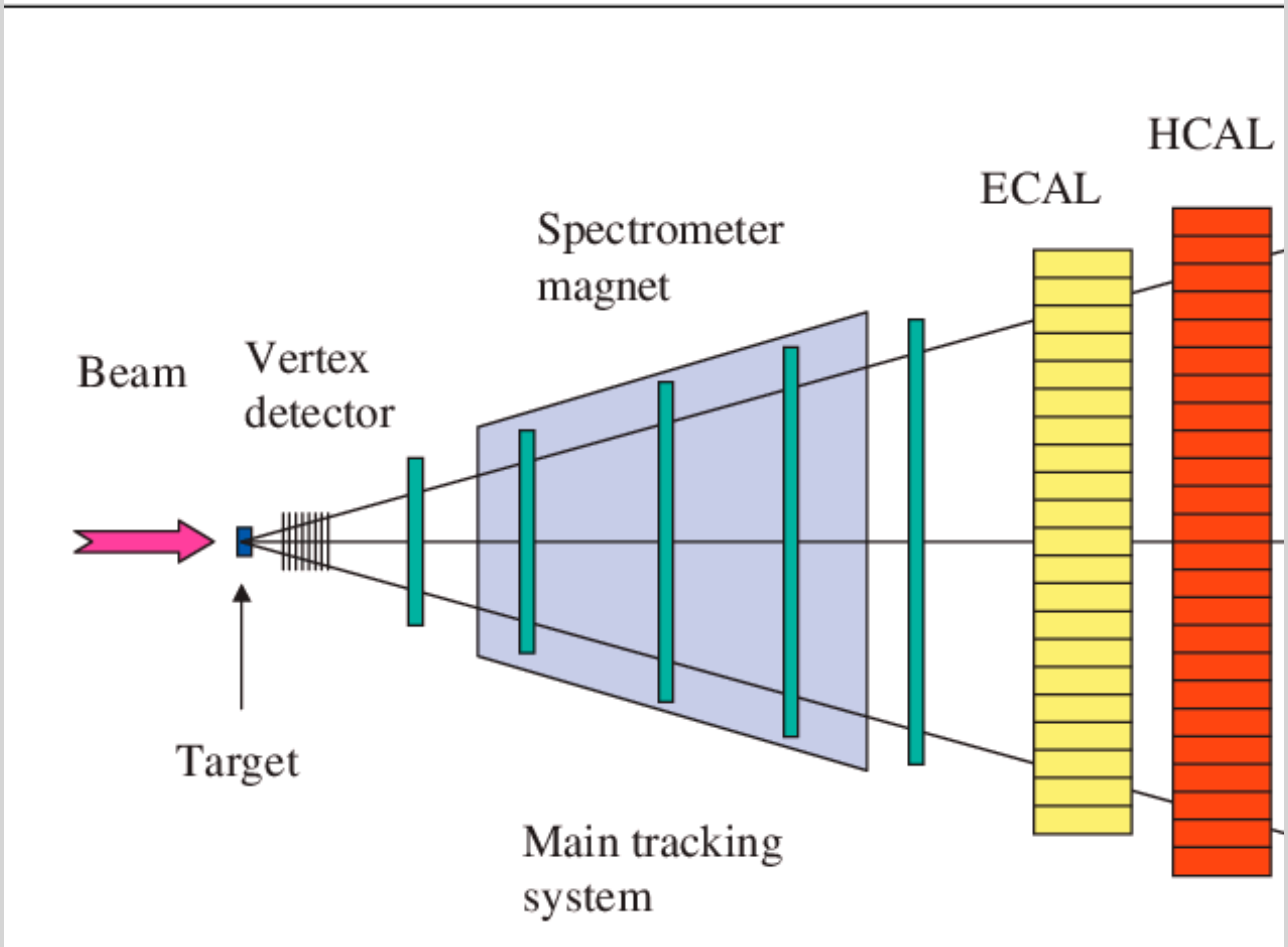

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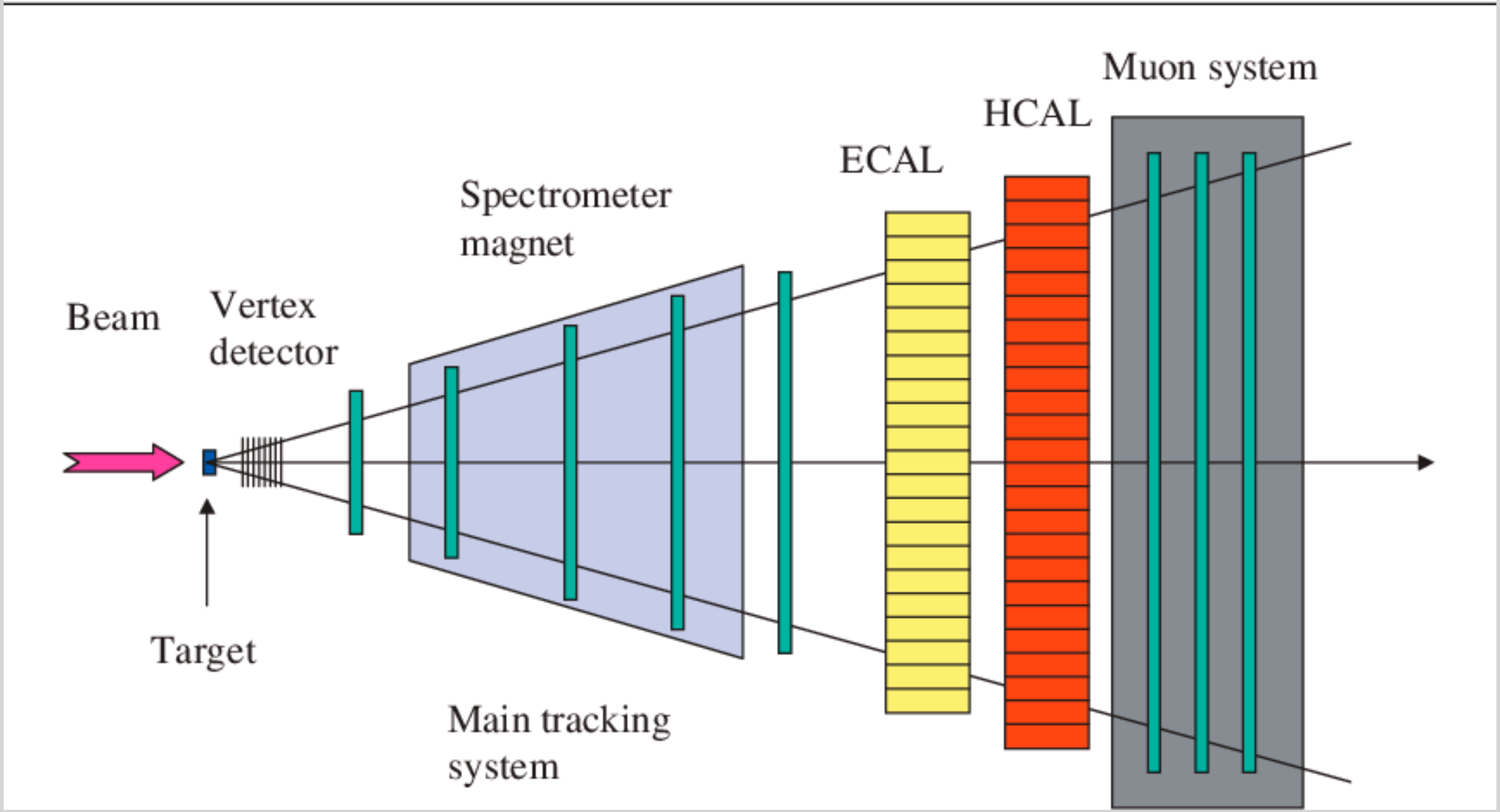
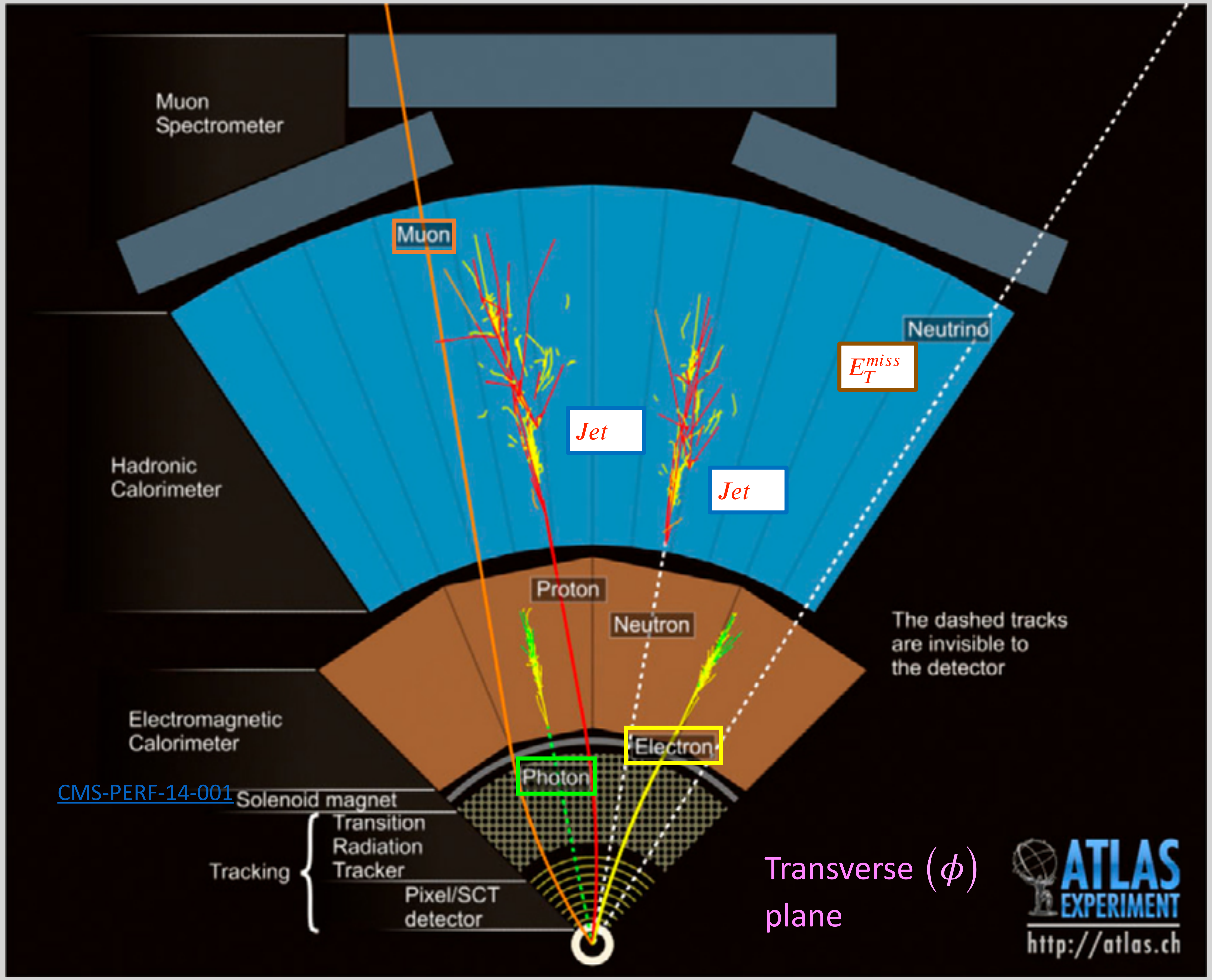
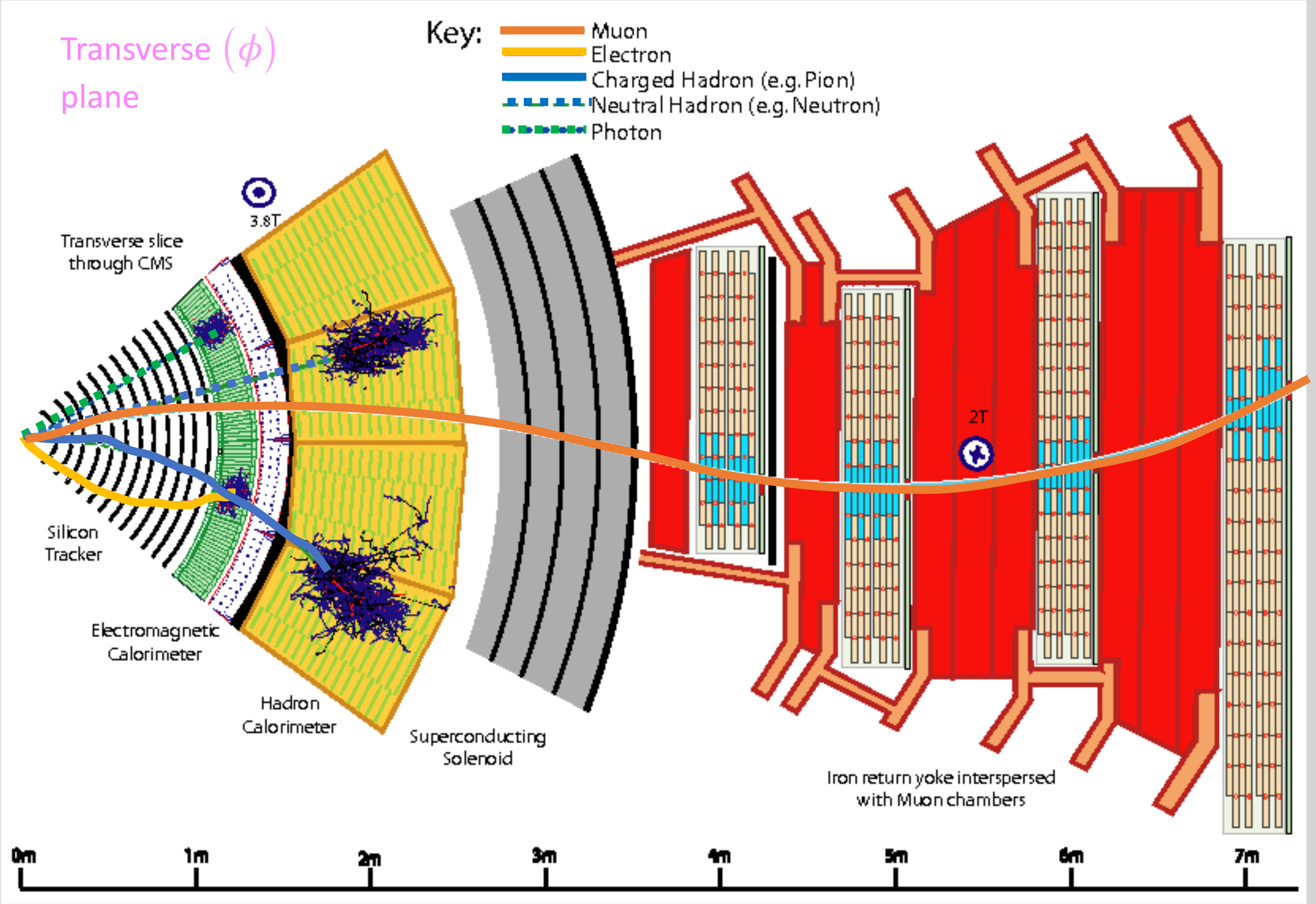


Detecting Particles with ATLAS/CMS





Electron: Charged, EM

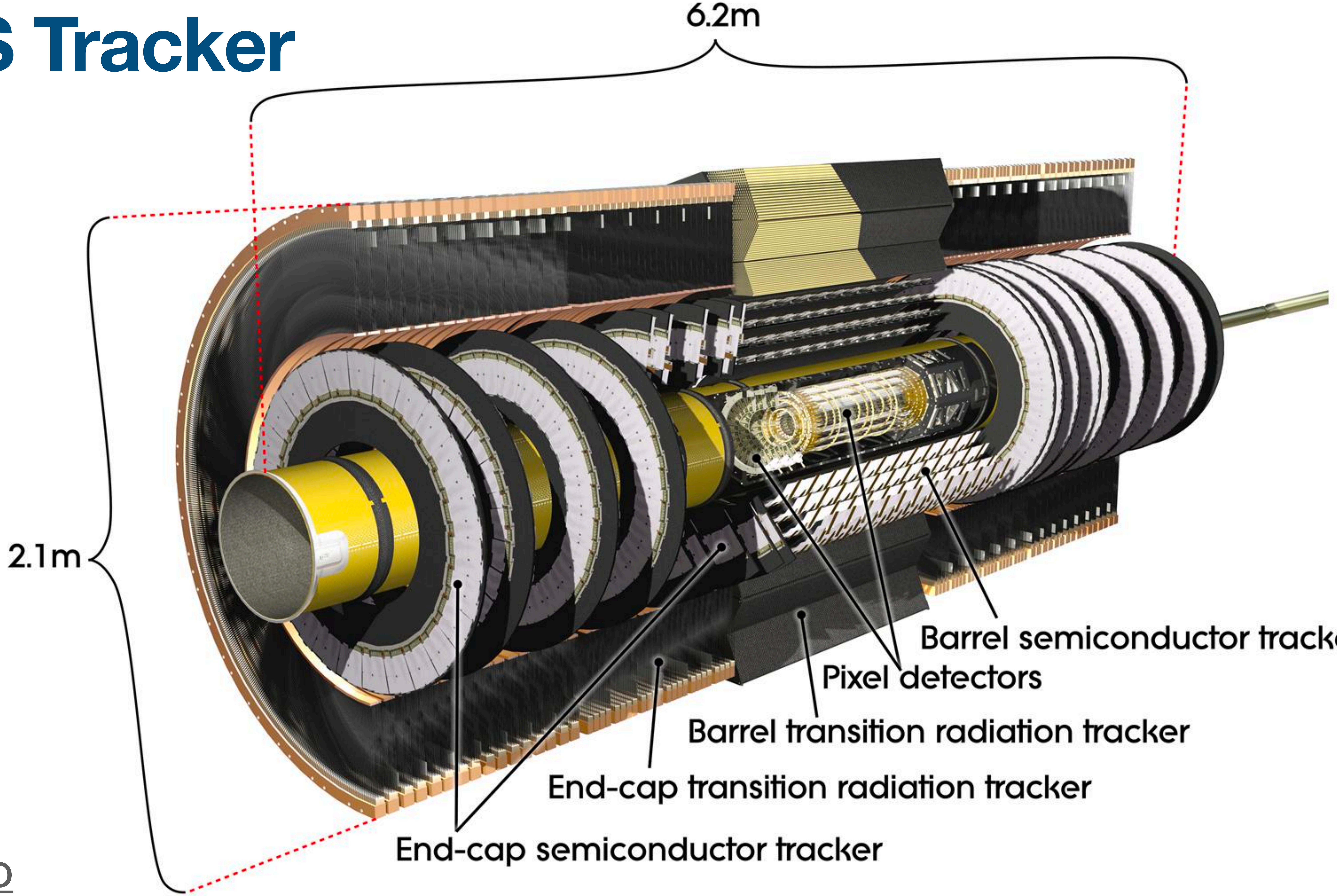
Photon: Neutral, EM

Muon: Charged, MIP

Jet: Calorimeter Object

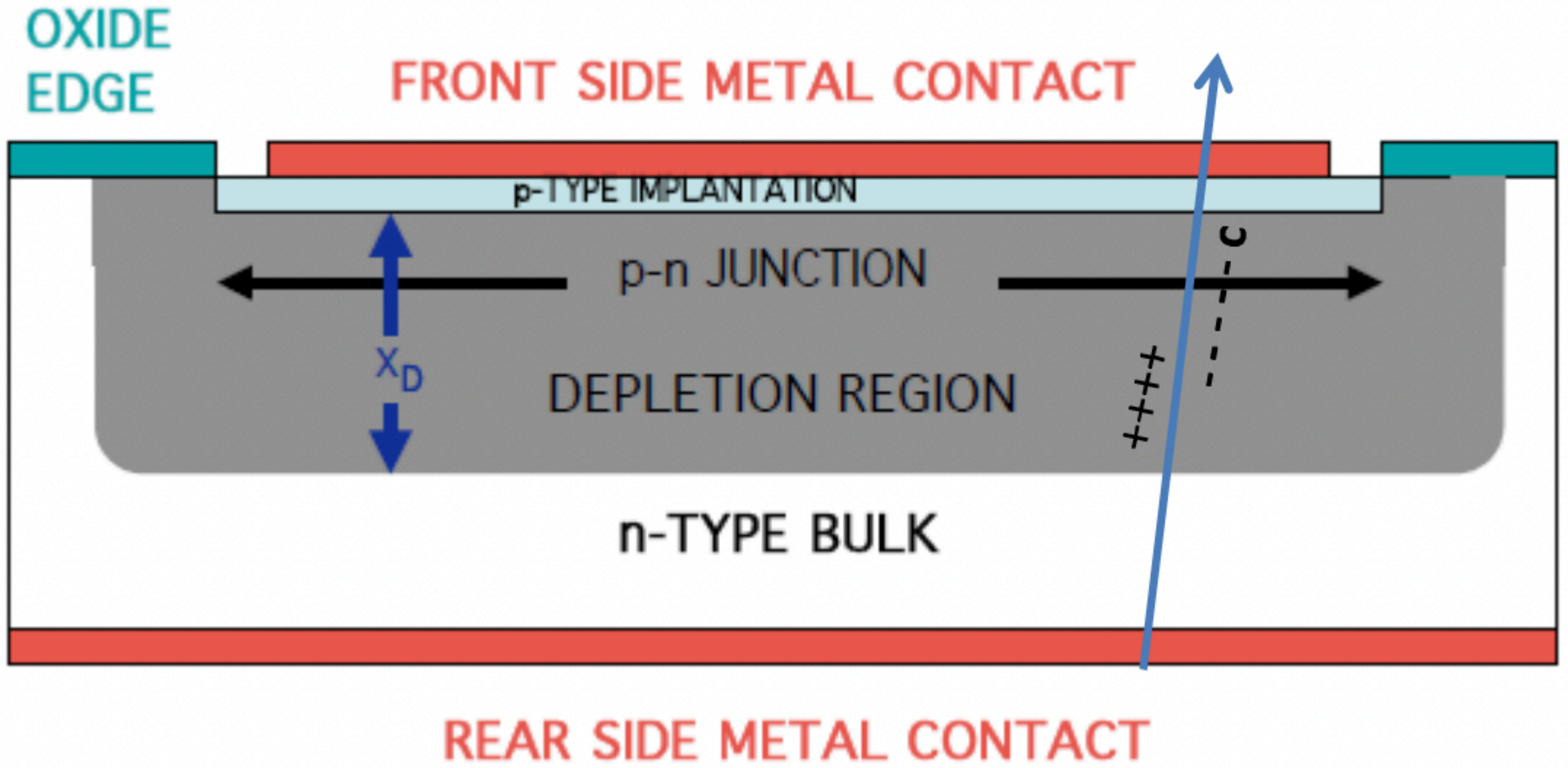
E_T^{miss}: Missing Energy (Transverse)

ATLAS Tracker

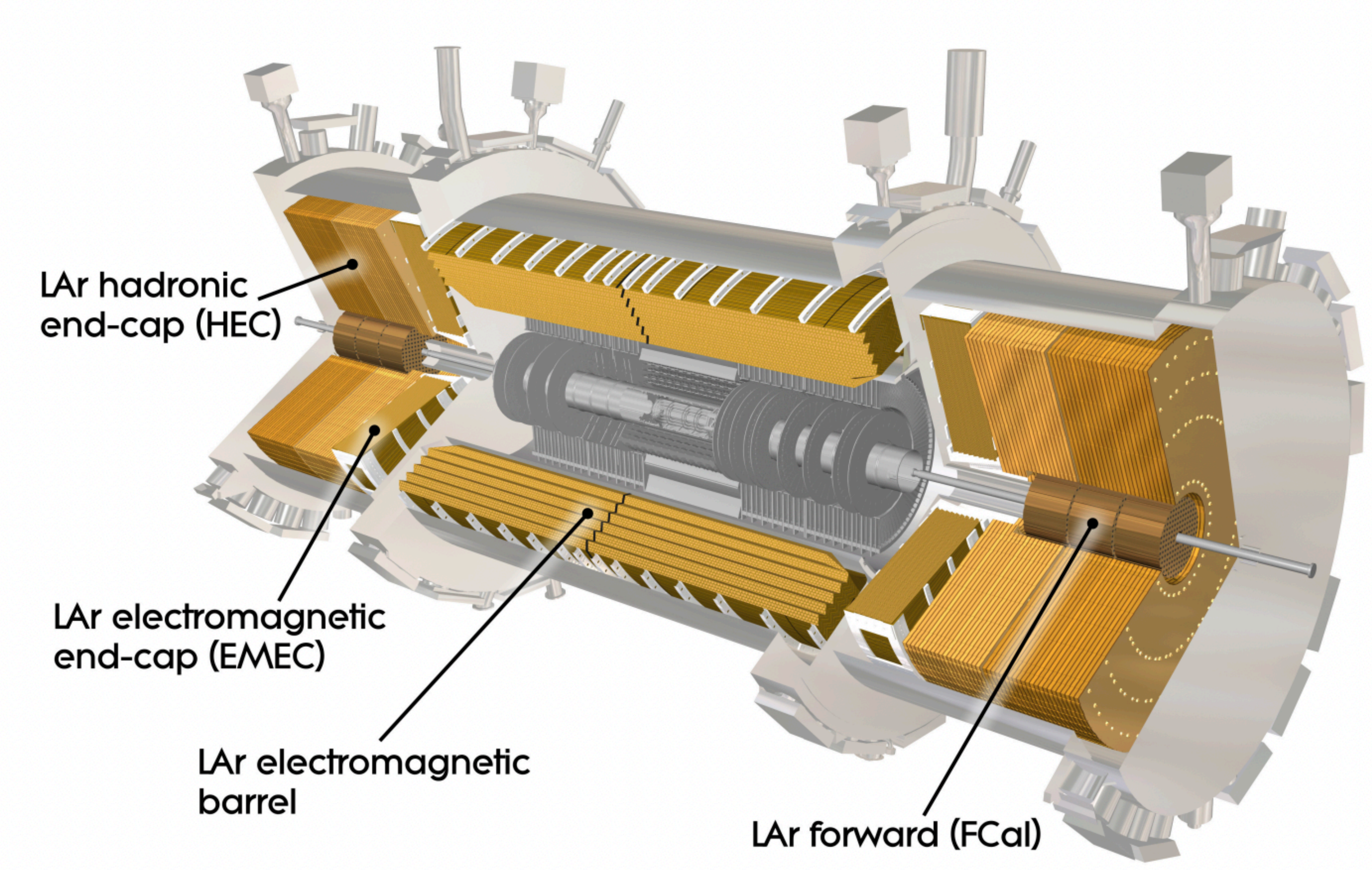


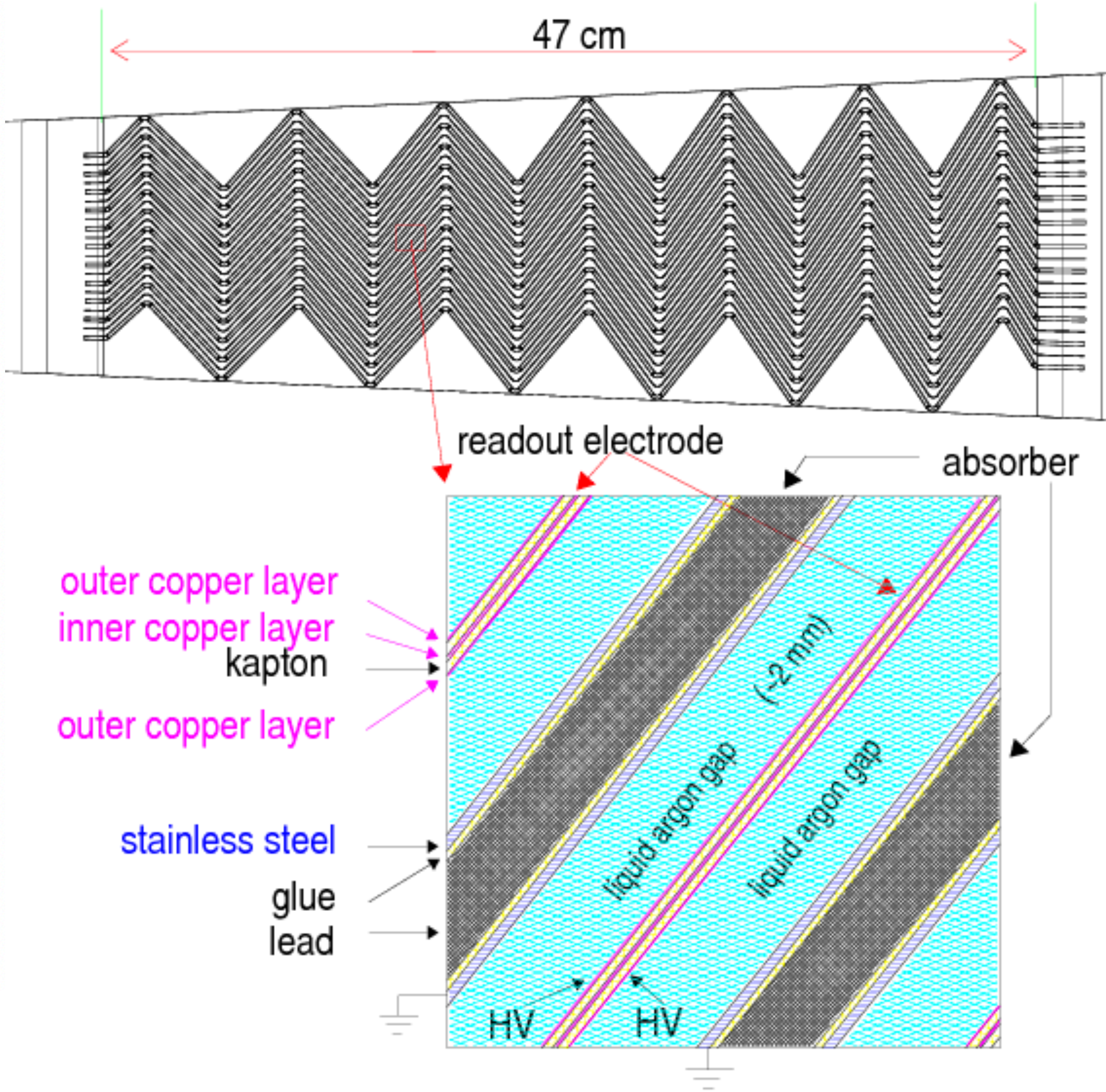
See Video

Silicon (Semiconductor) Strip Detectors

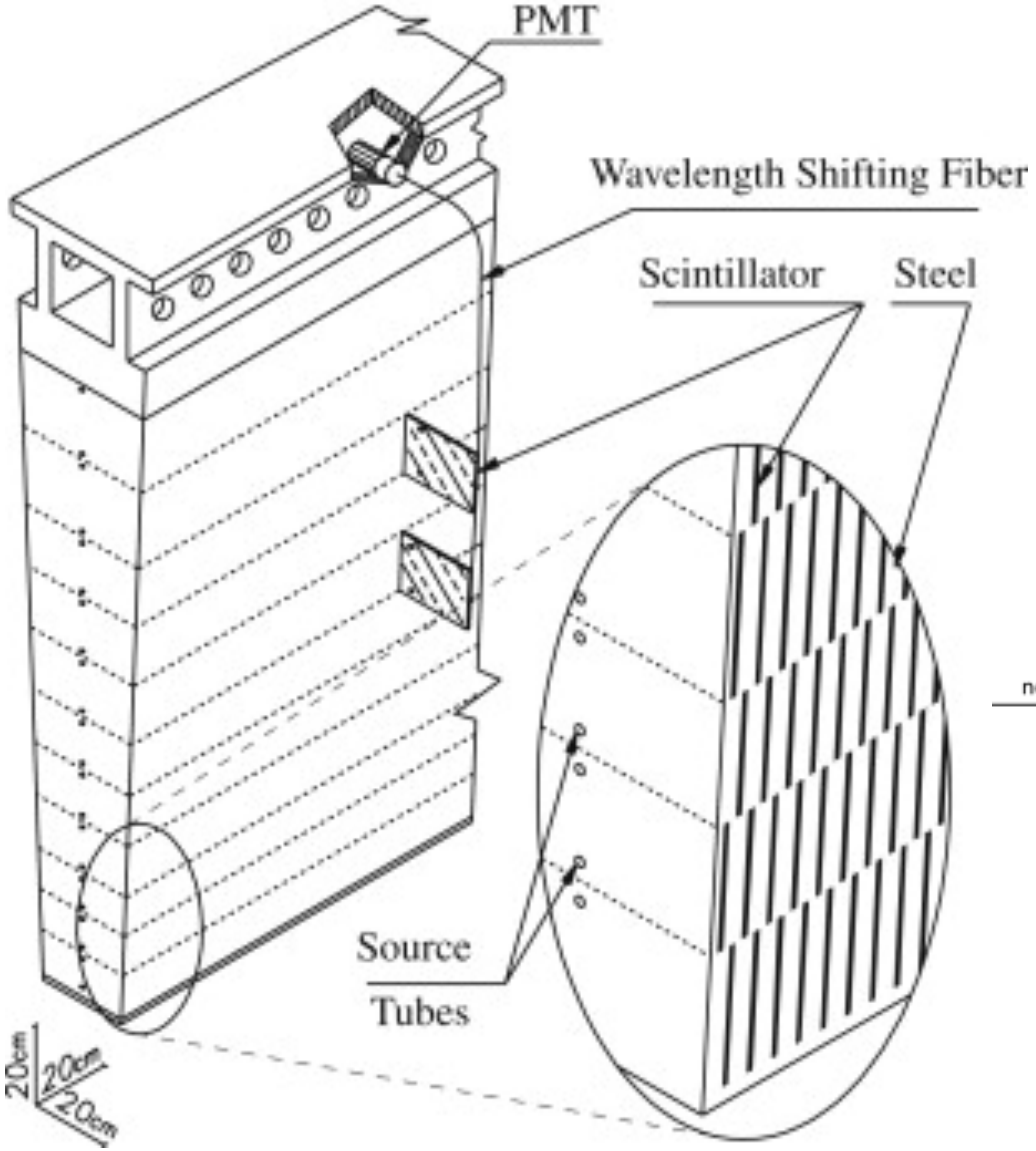


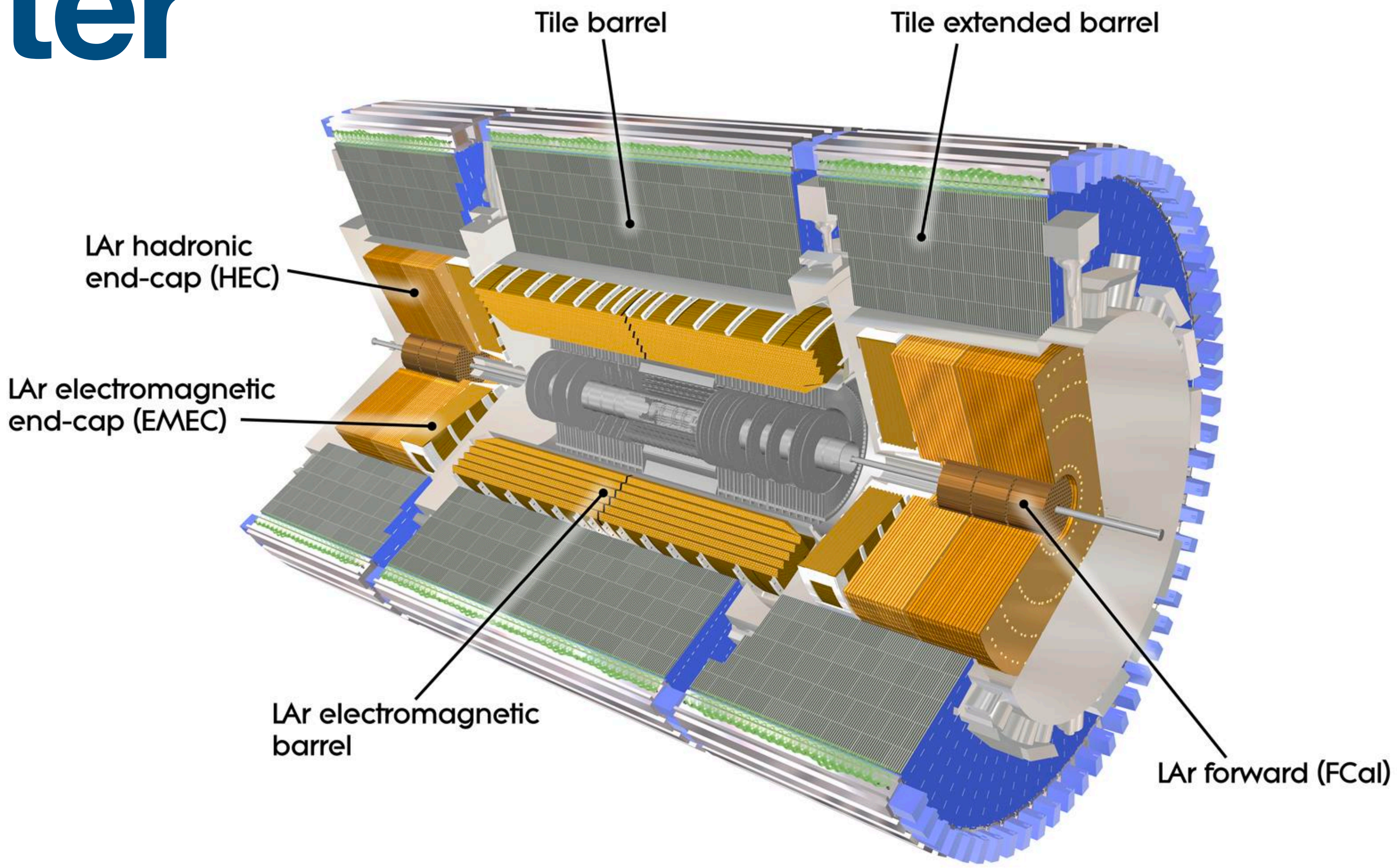
Liquid Argon Calorimeter

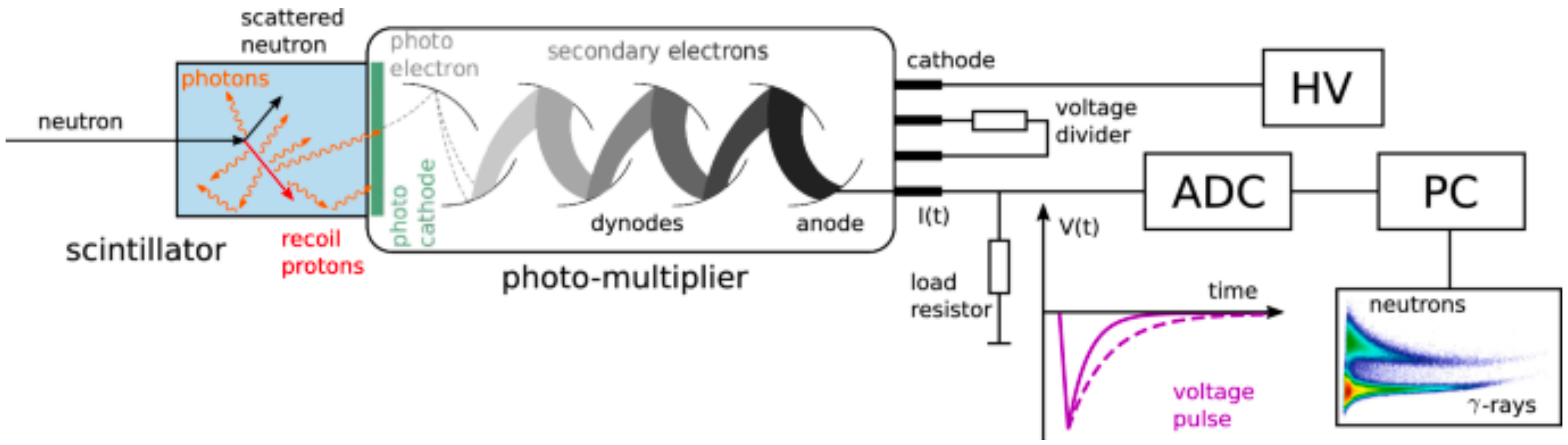




Hadronic Calorimeter

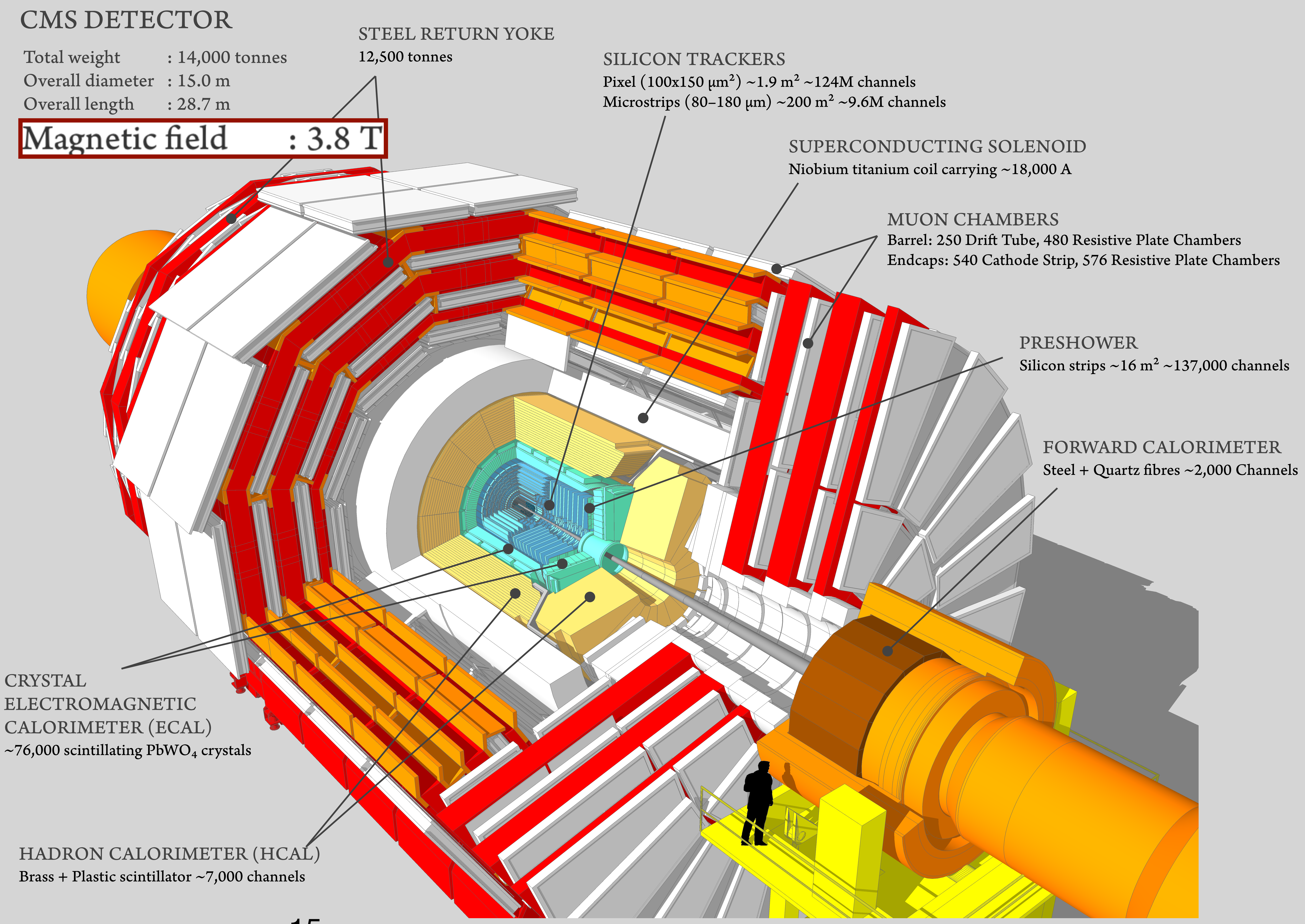






See Video

The Compact Muon Solenoid



J. Phys.: Conf. Ser. 513 022032

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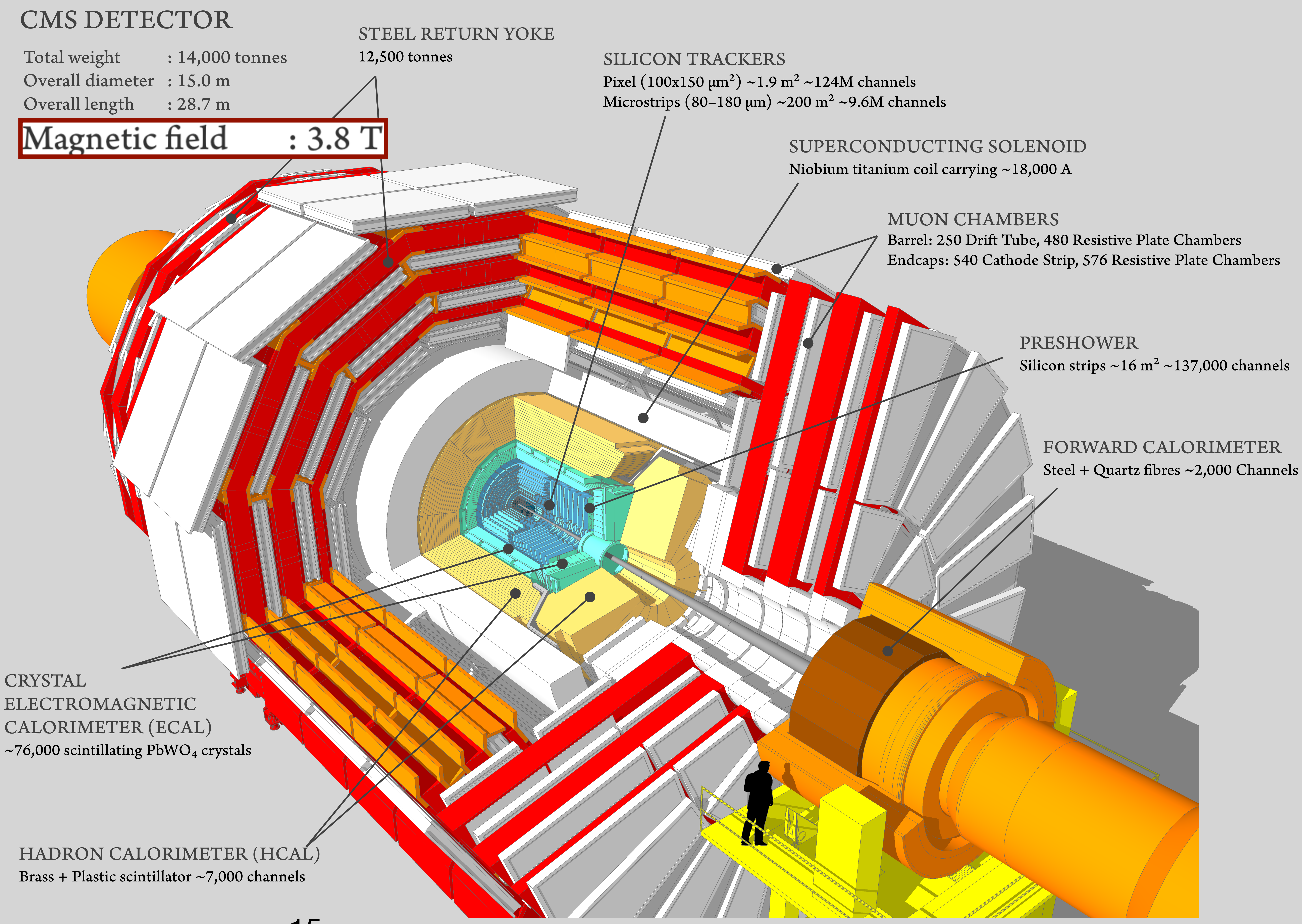

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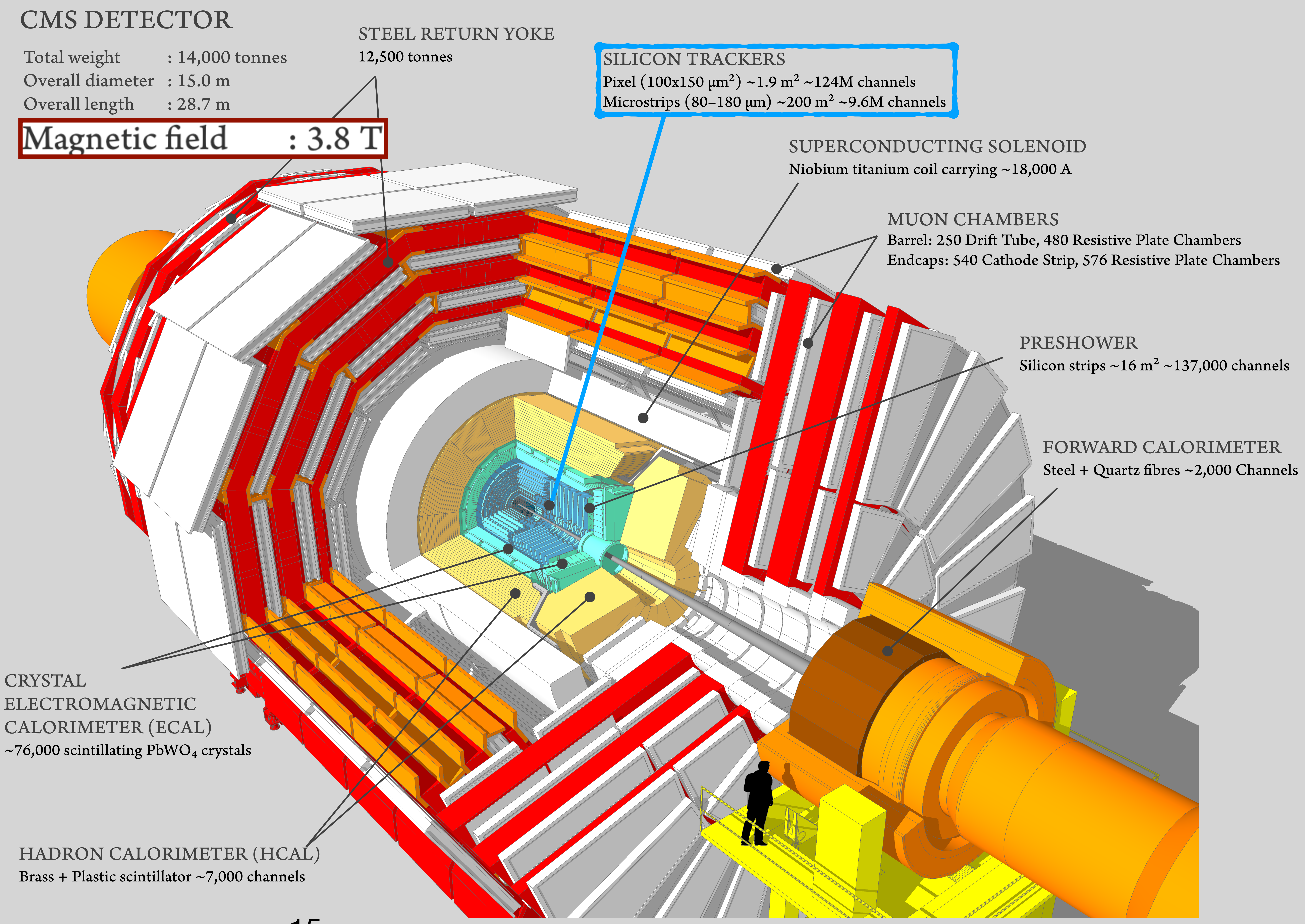
The Compact Muon Solenoid

- High resolution silicon tracking in $|\eta| < 2.4$



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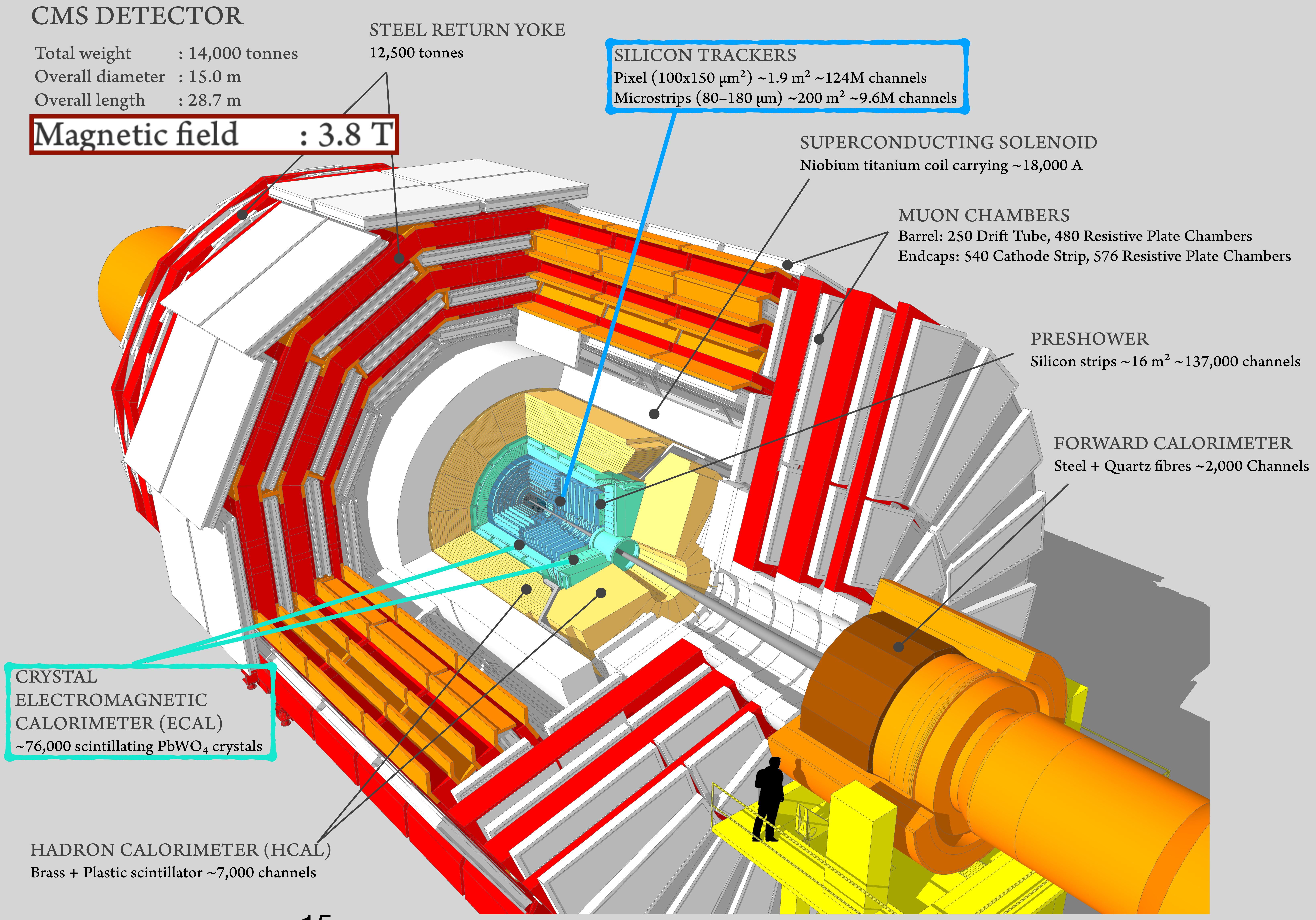
- $PbWO_4$ EM Calorimetry



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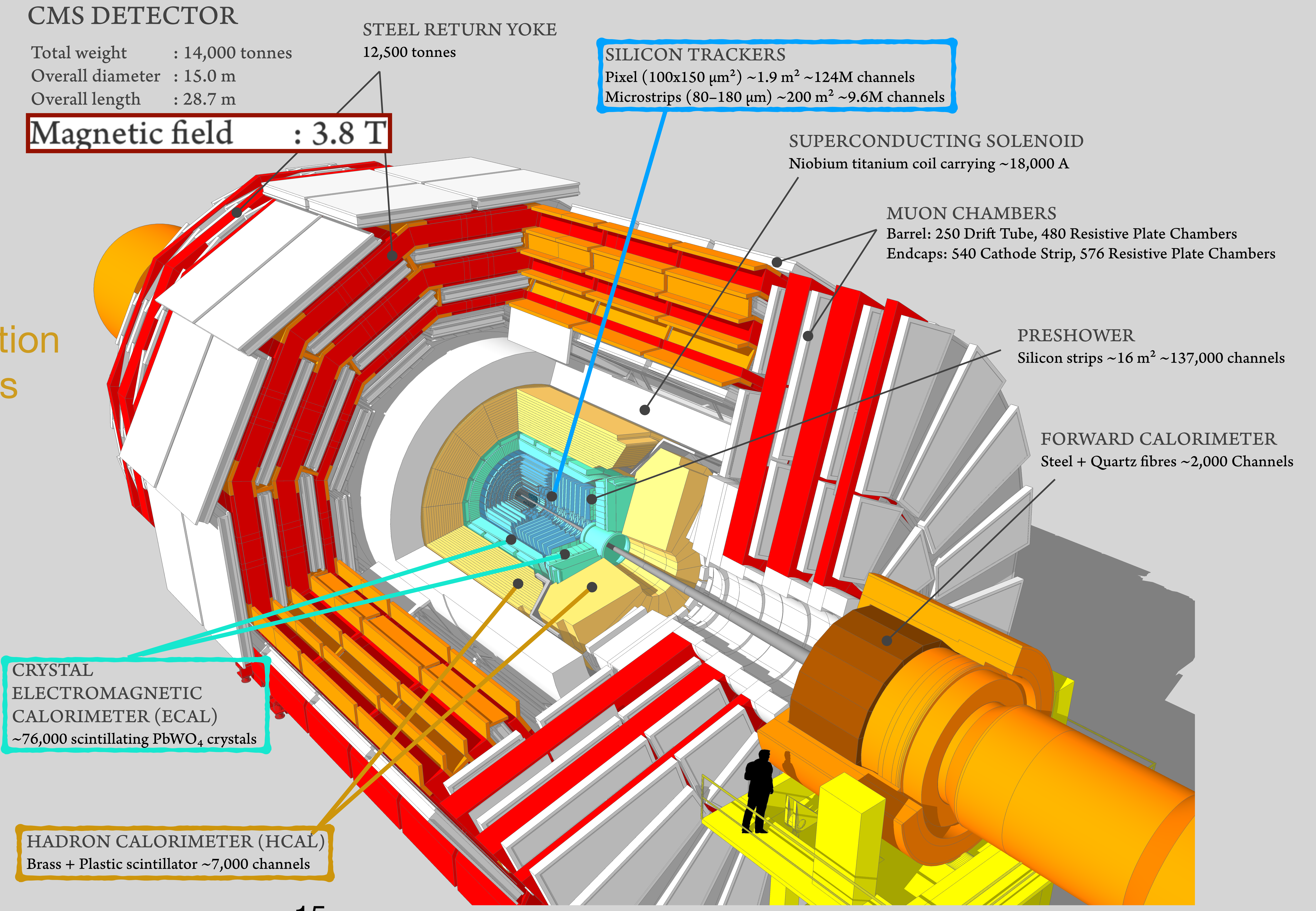
- High resolution silicon tracking in $|\eta| < 2.4$
- $PbWO_4$ EM Calorimetry
- Brass Hadron Calorimeter
  — Provides excellent energy resolution for strongly-coupled parton showers



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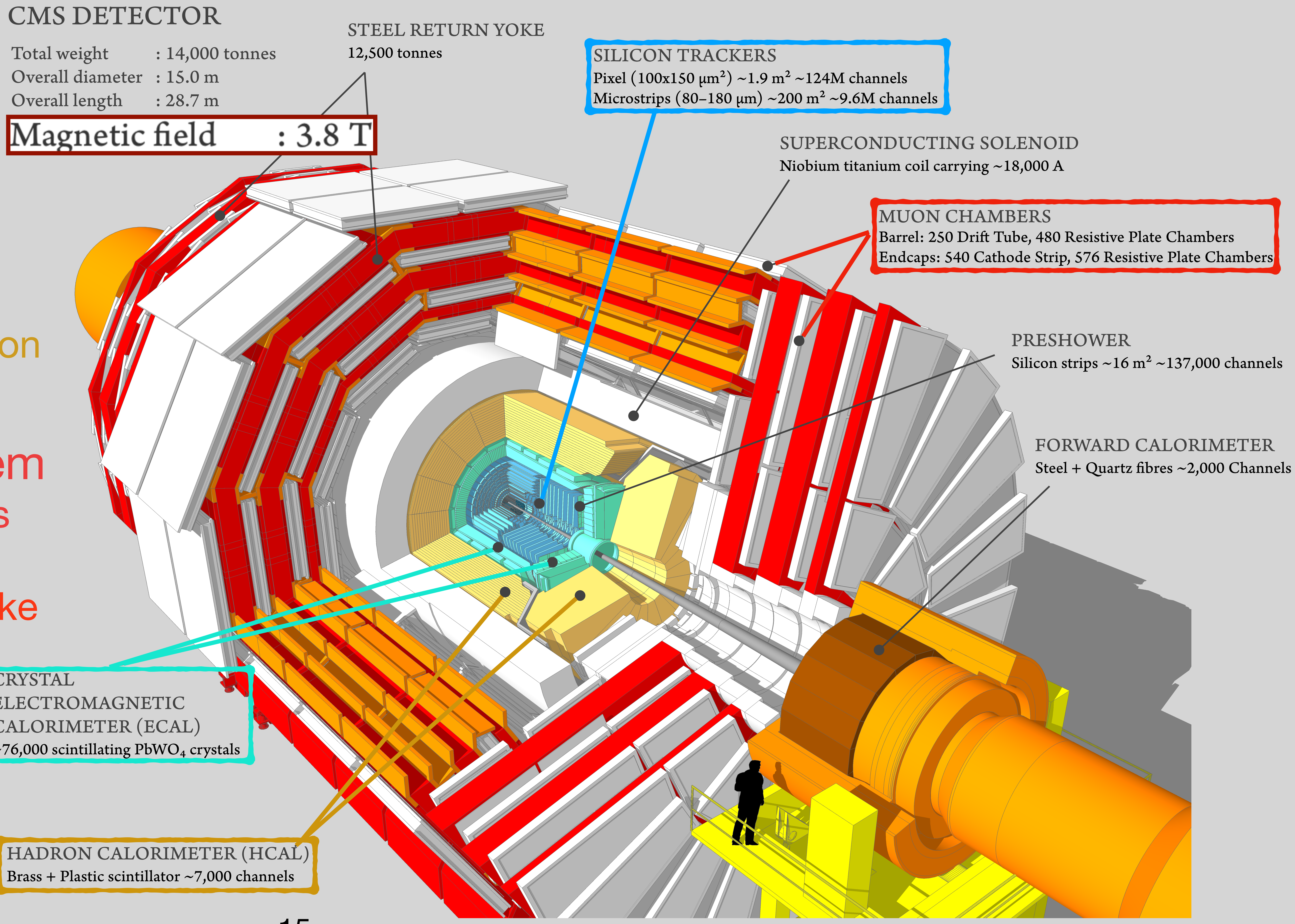
- Excellent, Robust Muon System
  — Superconducting solenoid creates 3.8*T* magnetic field in tracker and calorimeters, 2*T* is steel return yoke



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- Excellent, Robust Muon System
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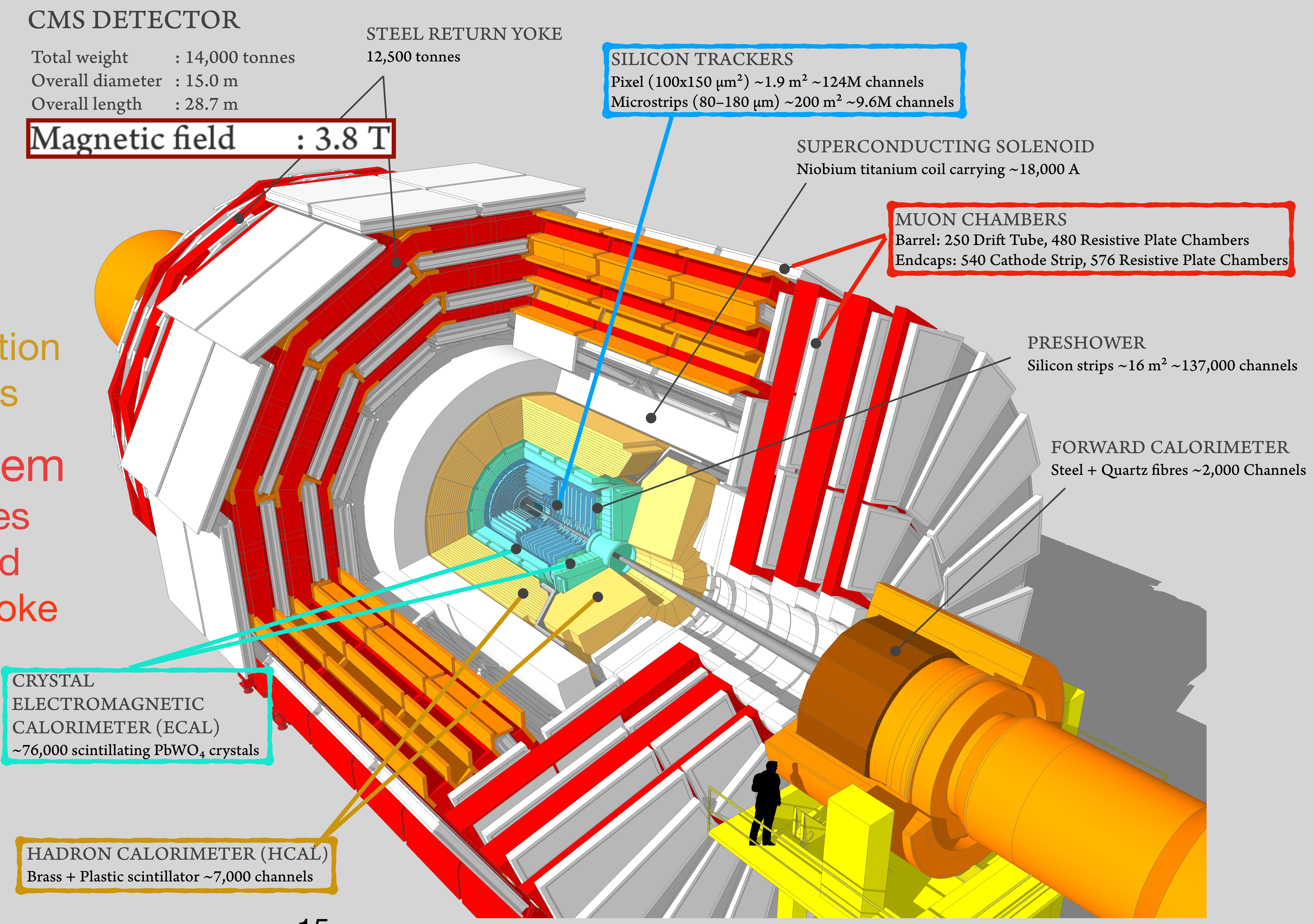
- **Cost: ~500 MCHF**
  + ~200 MCHF (Upgrades)



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What Are Cathode Strip Chambers (CSCs)?

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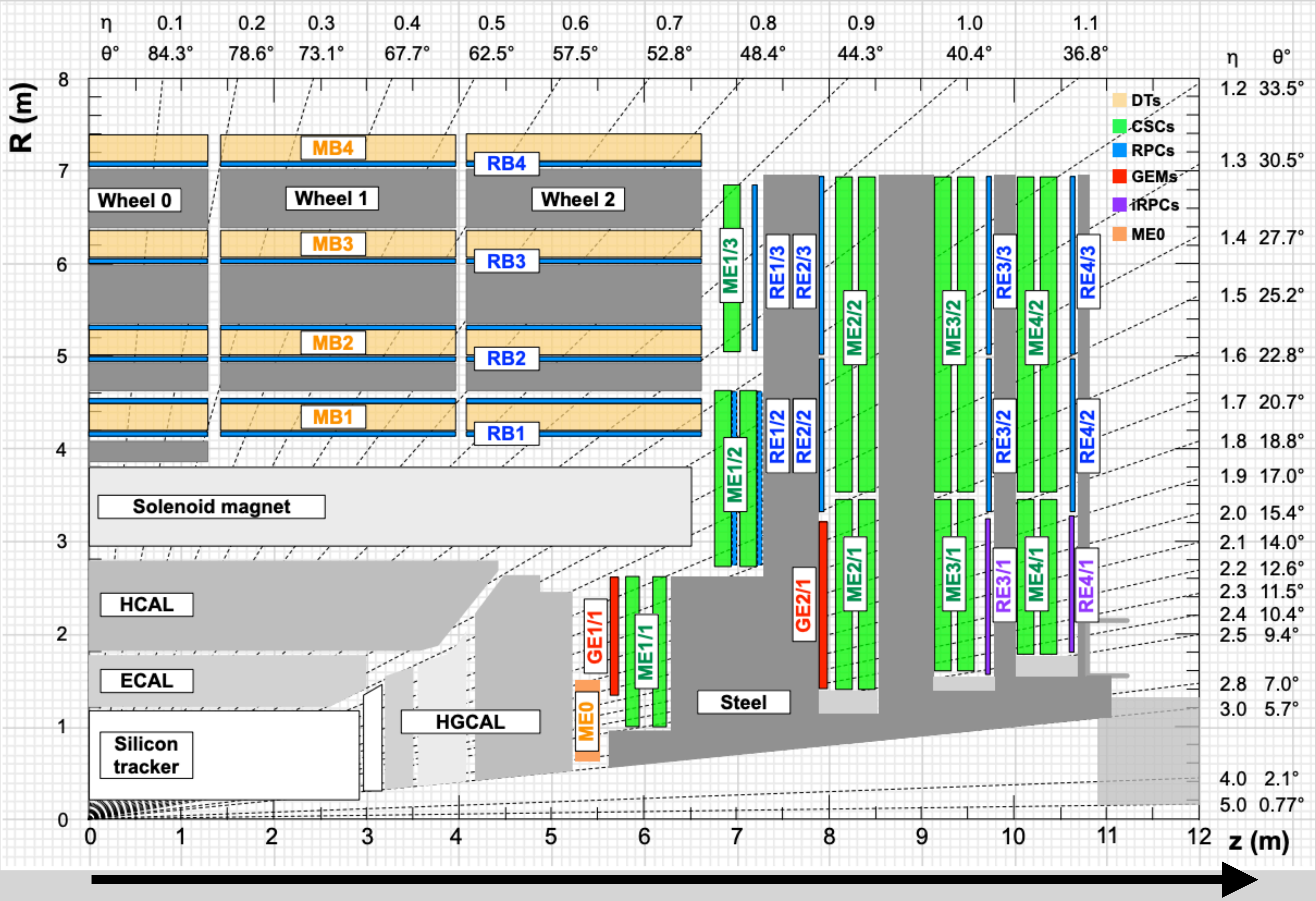
  - Barrel: Drift Tube + Resistive Plate Chamber (RPC)
  - End-Caps: CSC + RPC + Gas Electron Multipliers (GEM)



CMS-TDR-016

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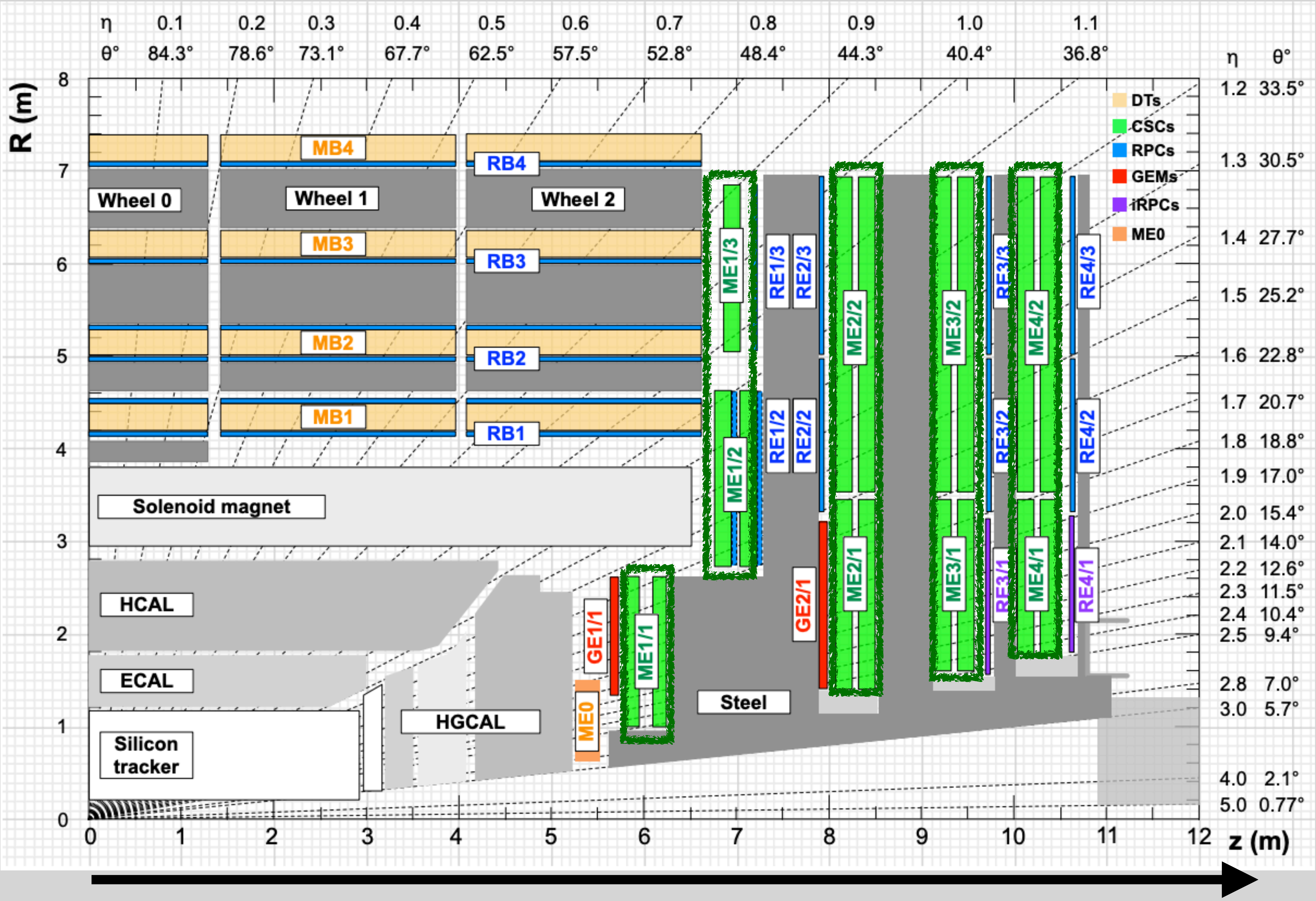

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  - Traversing muons ionize gas at HV
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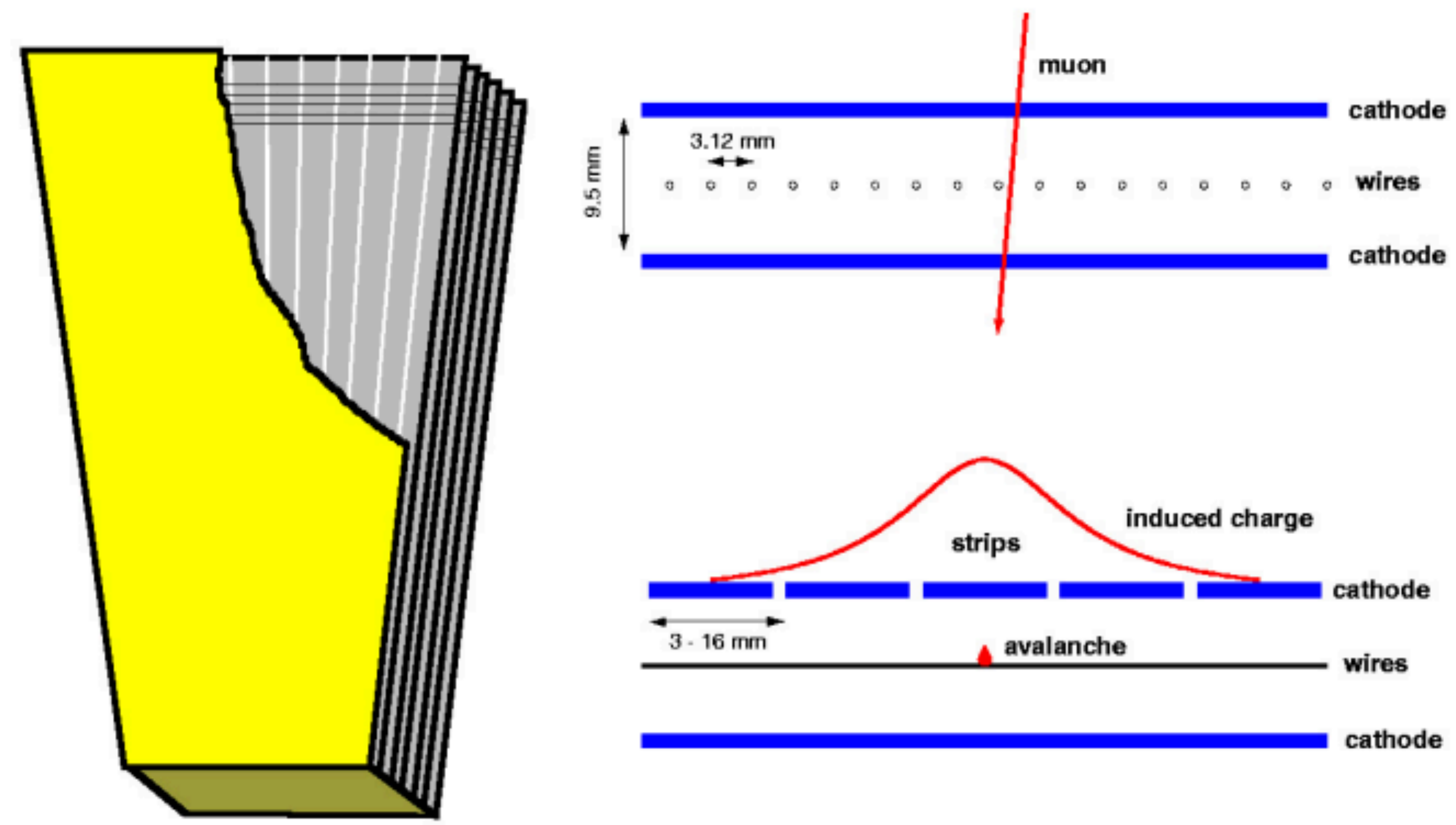

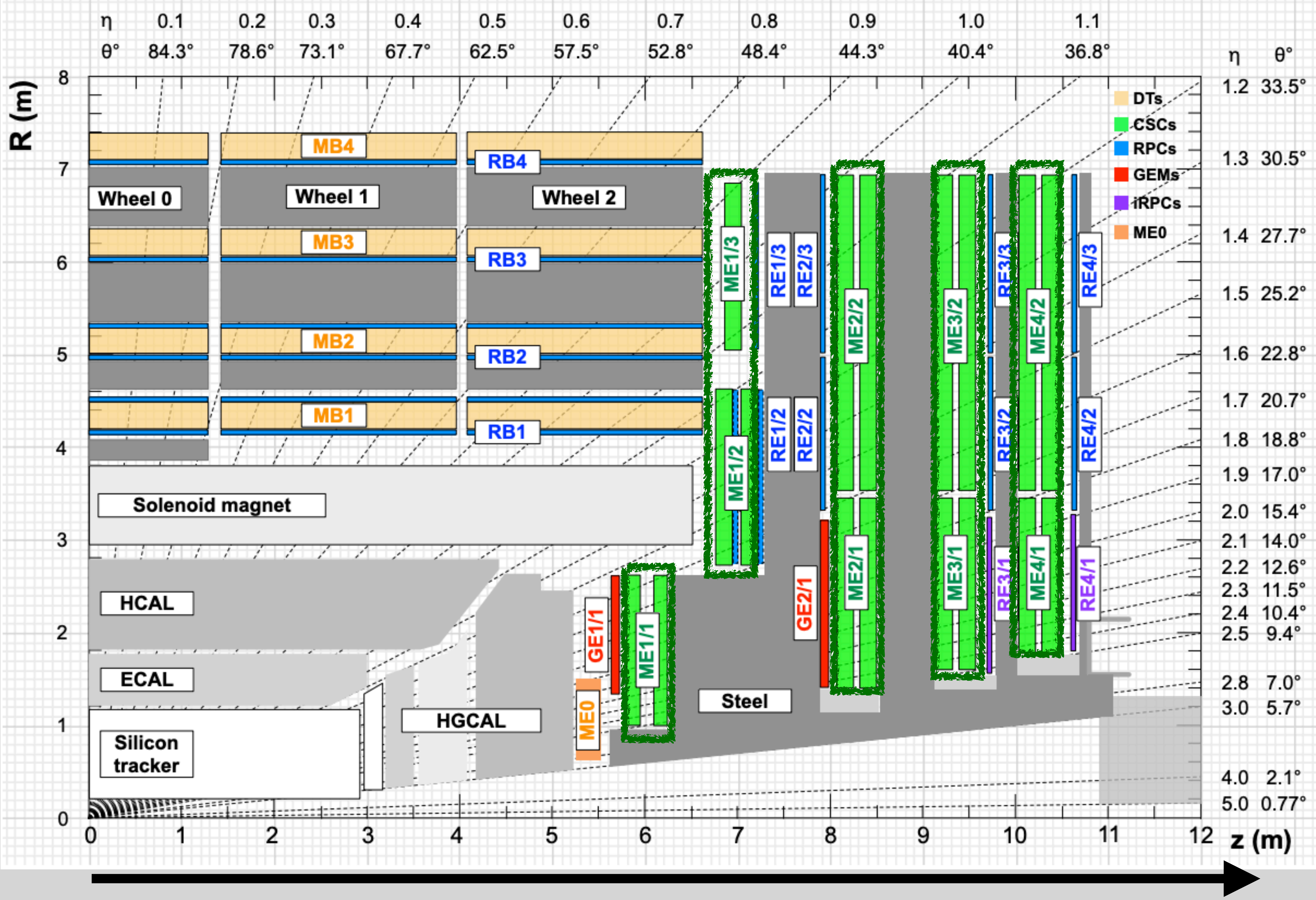

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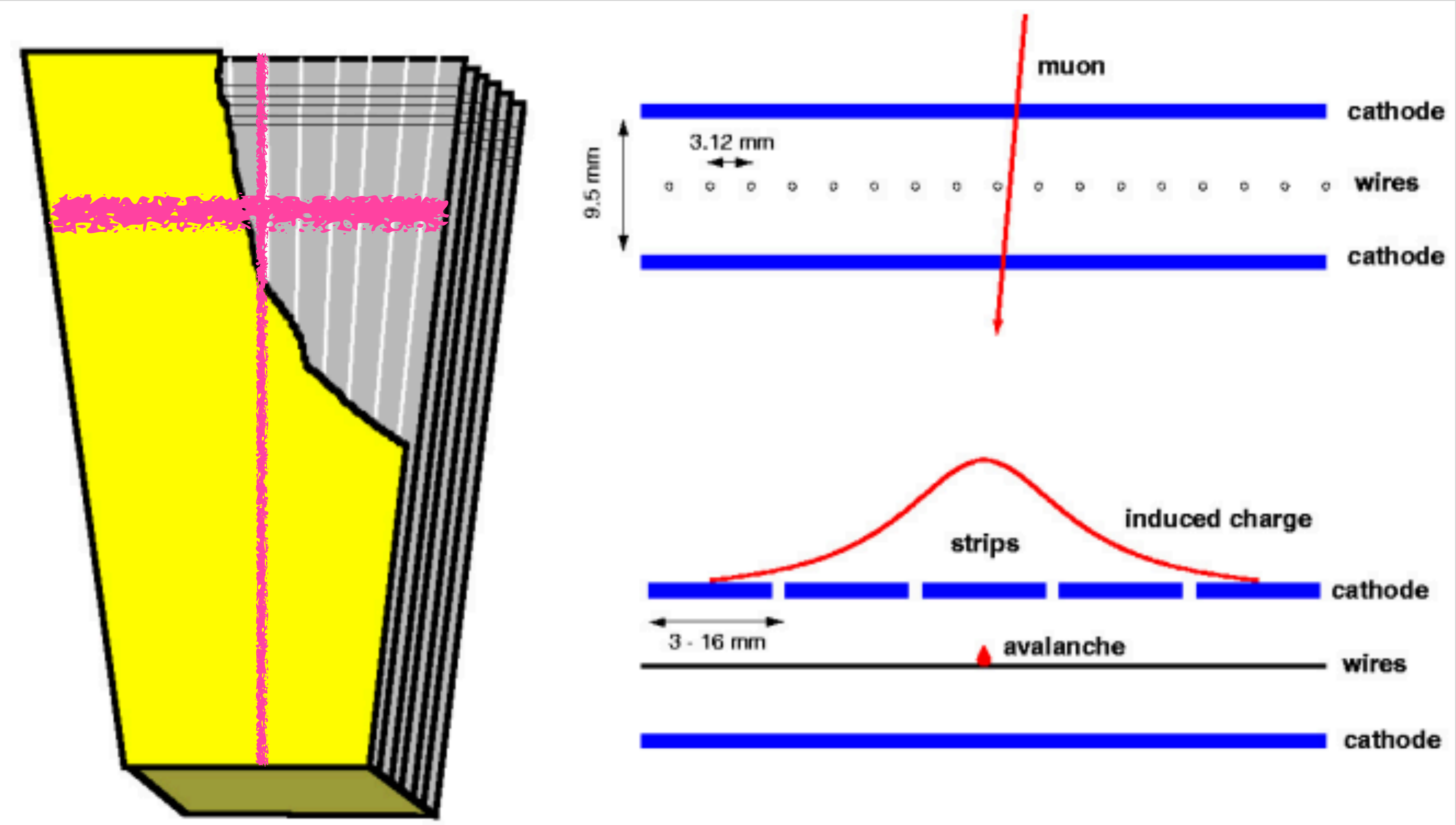
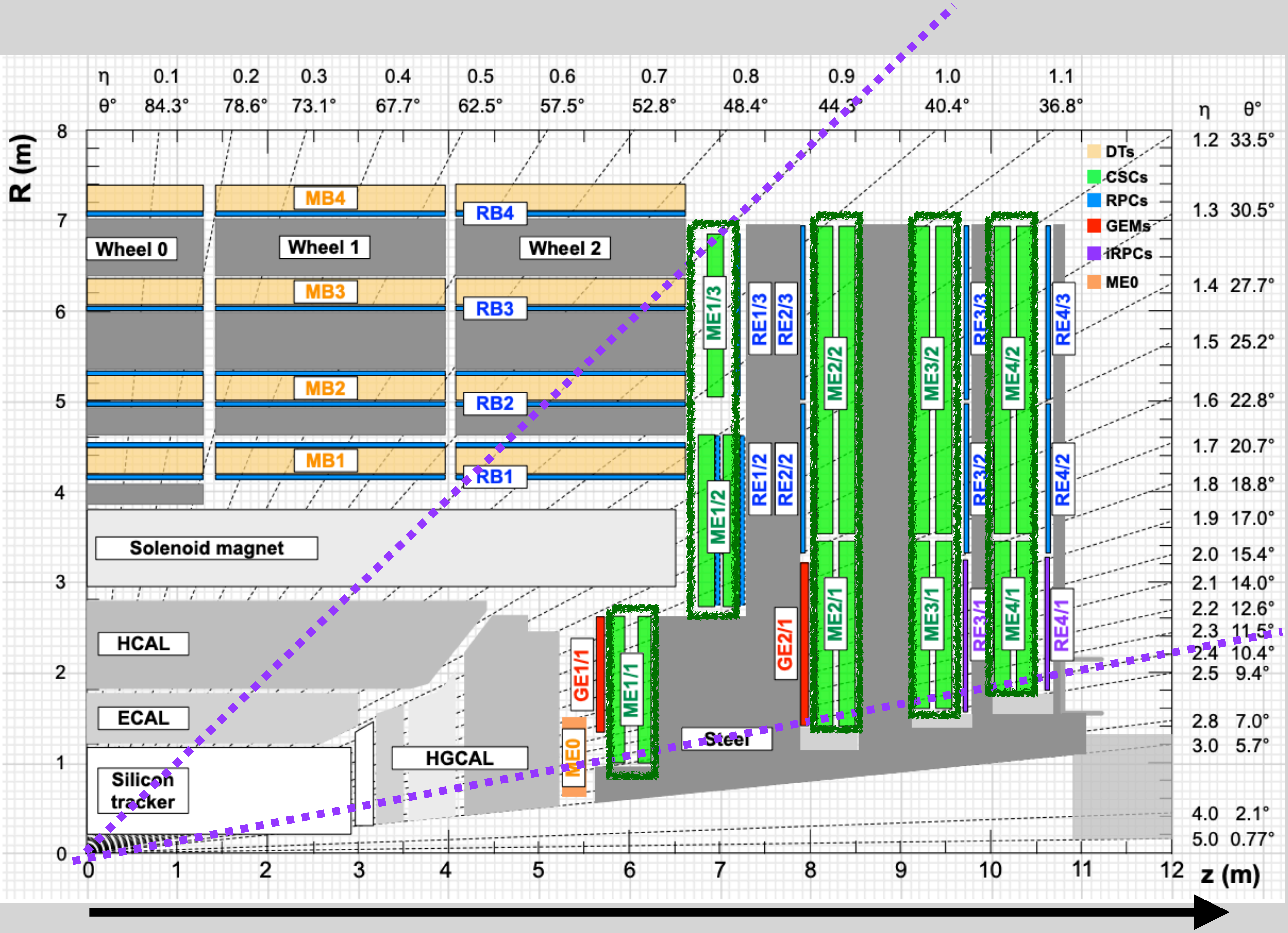
- CSCs measure 4D position, $|\eta| \in [0.9, 2.4]$
  - Work great in intense, non-uniform magnetic fields





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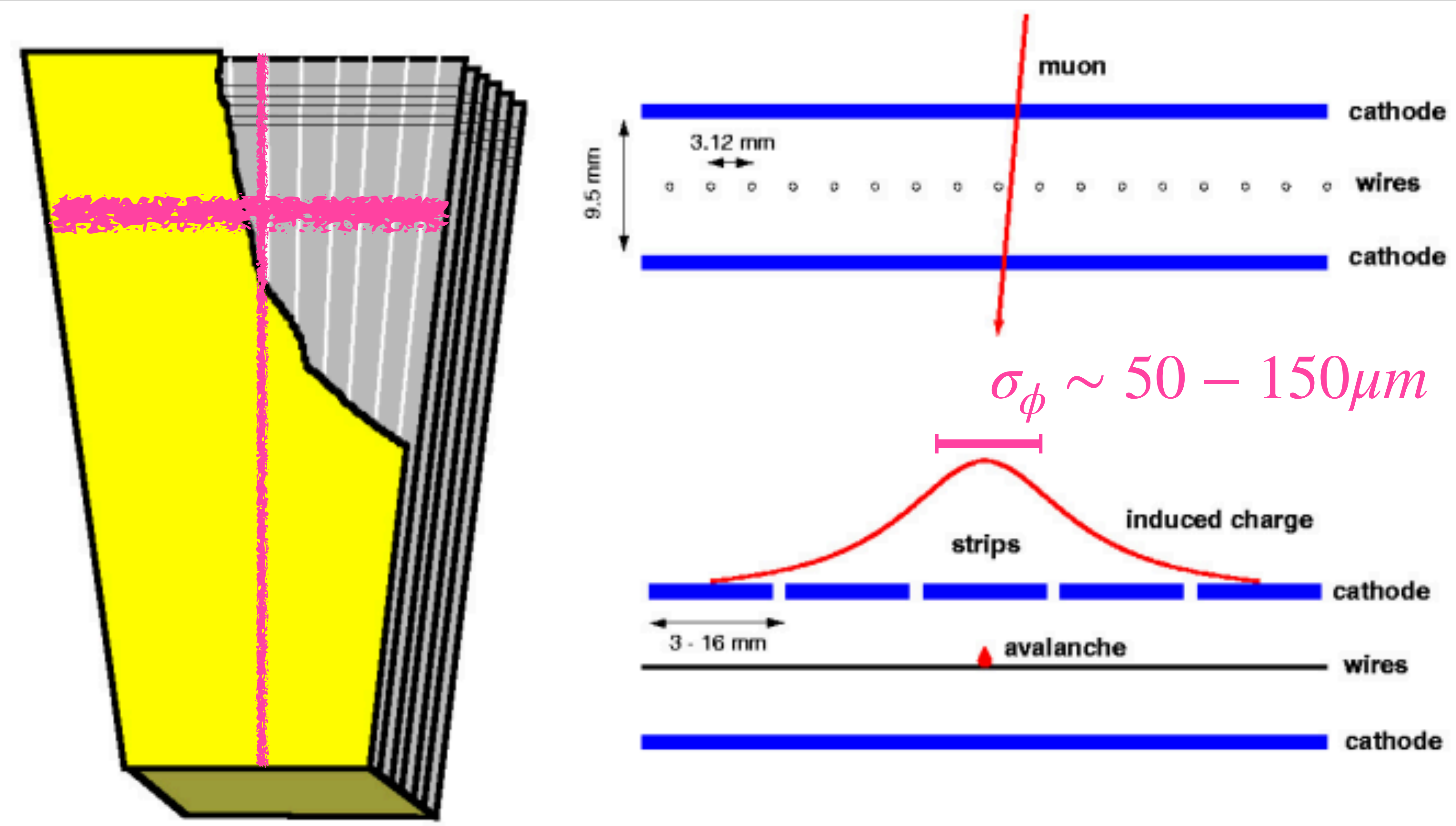

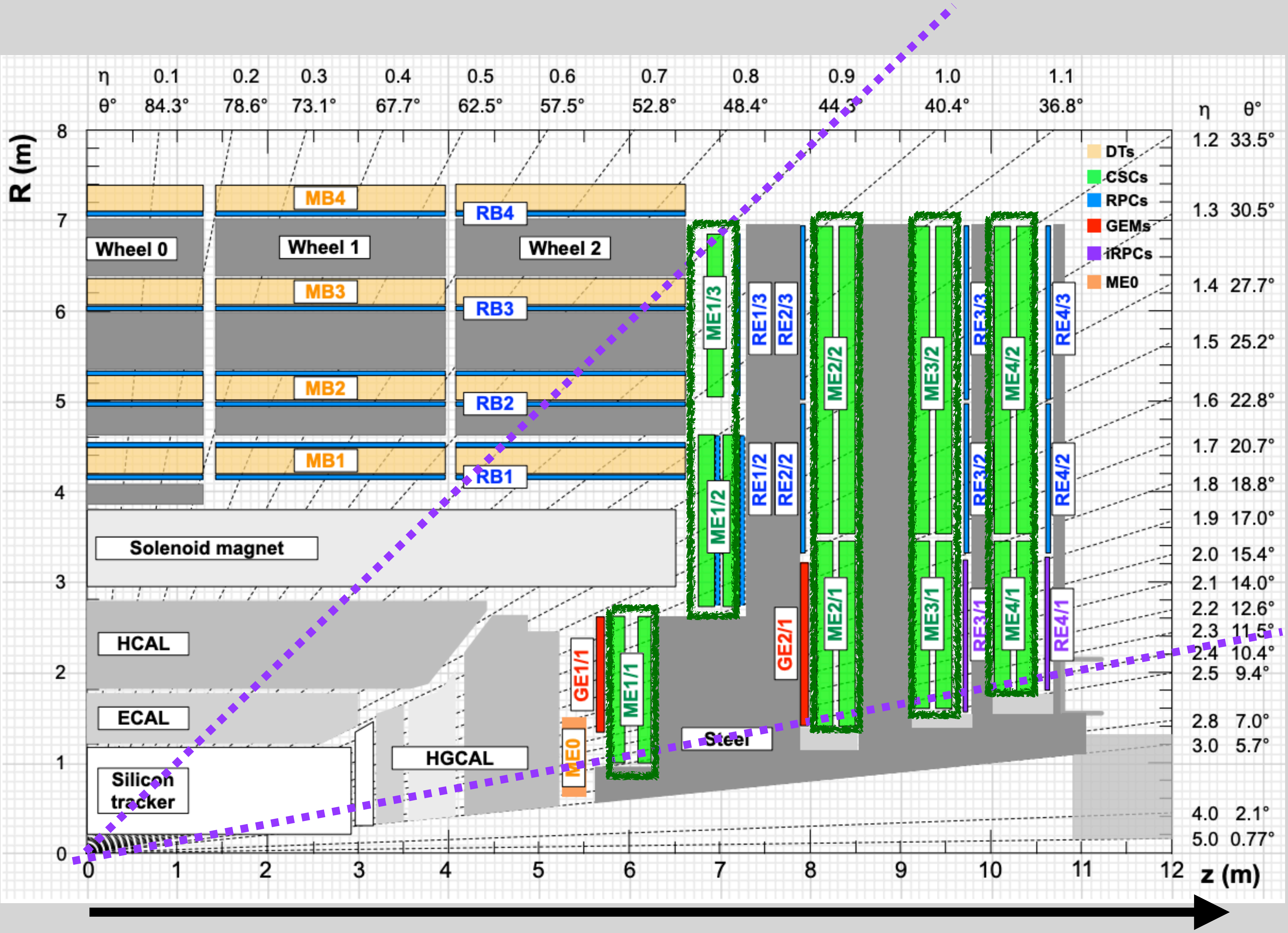

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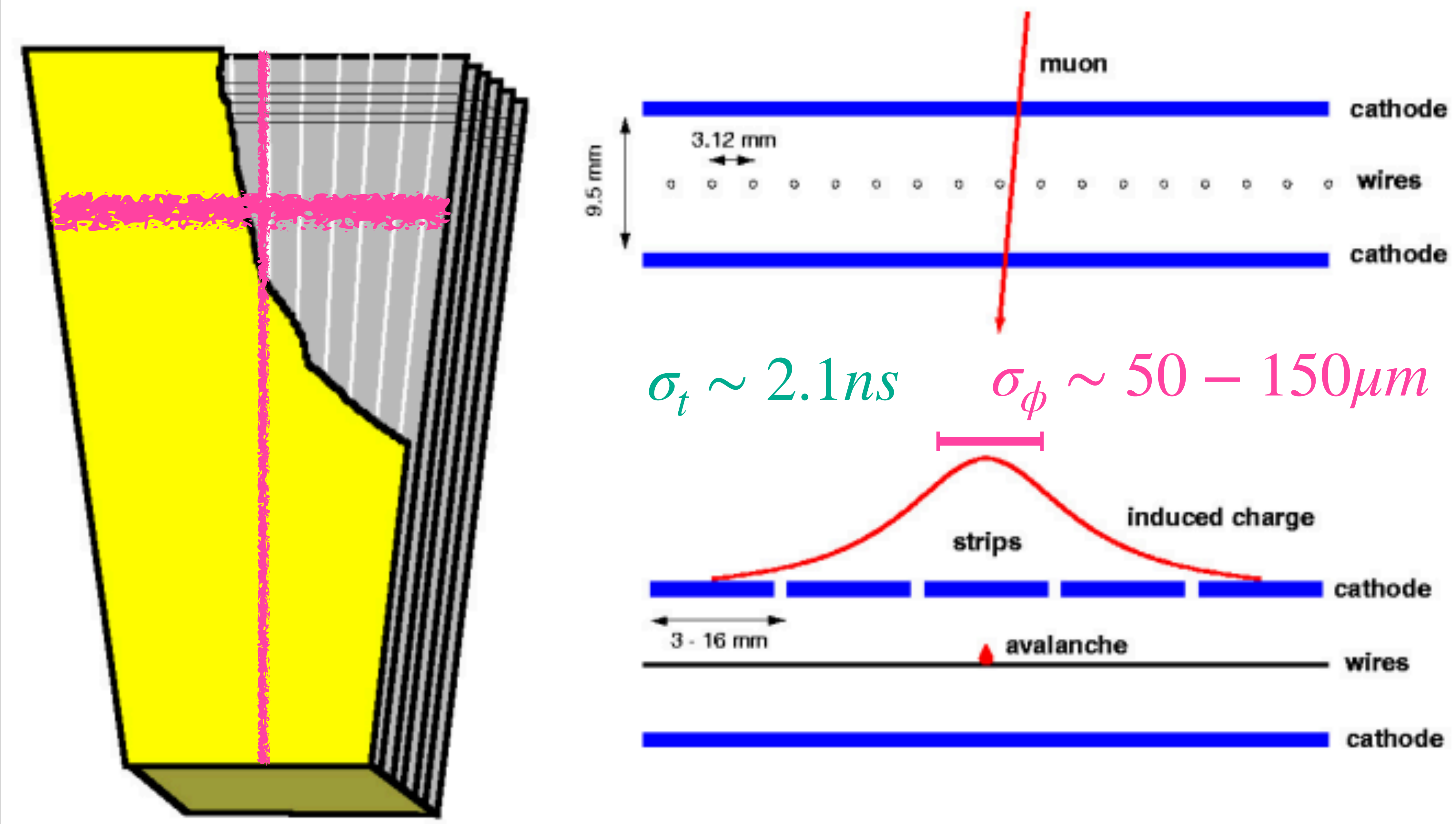

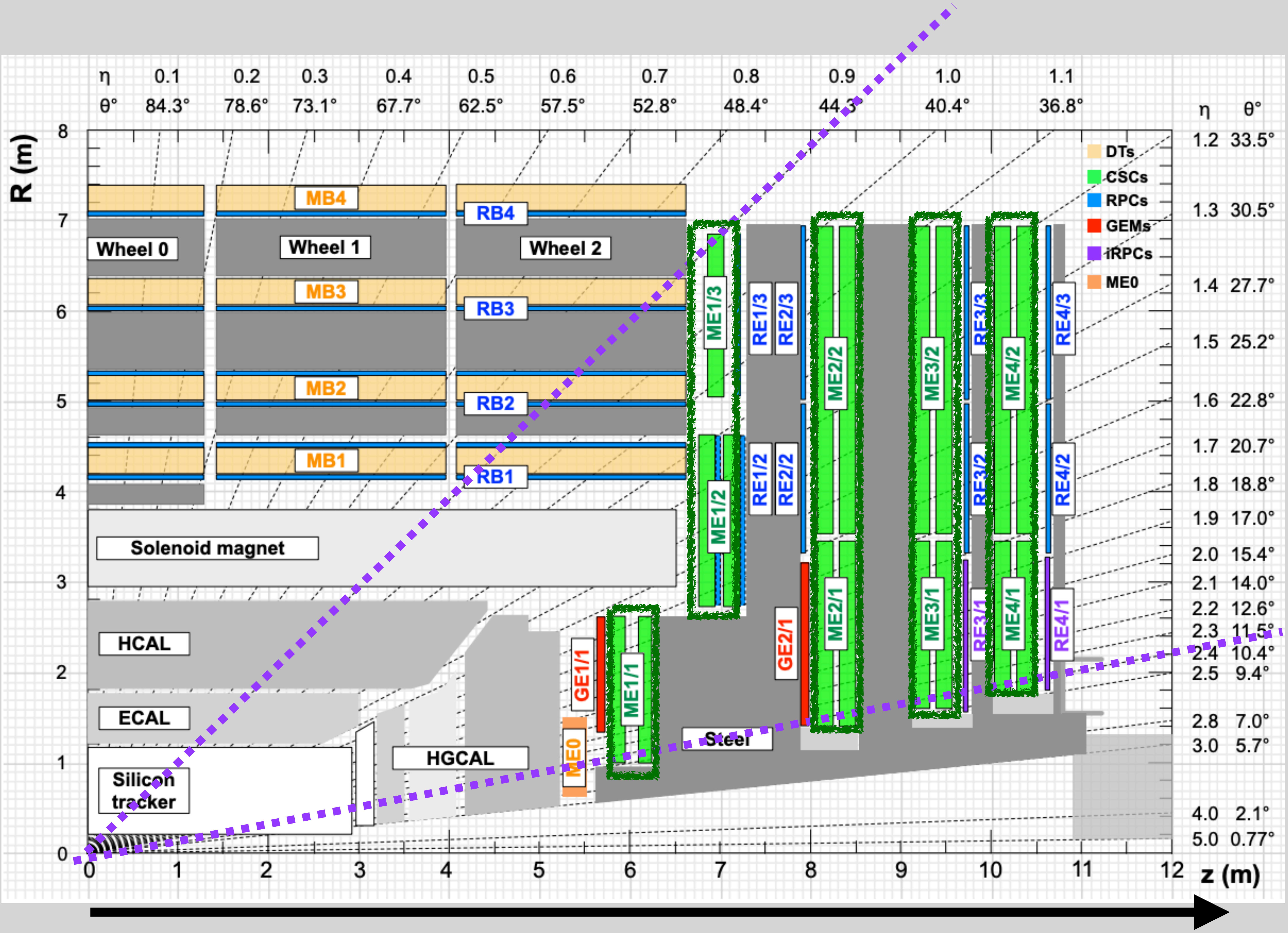

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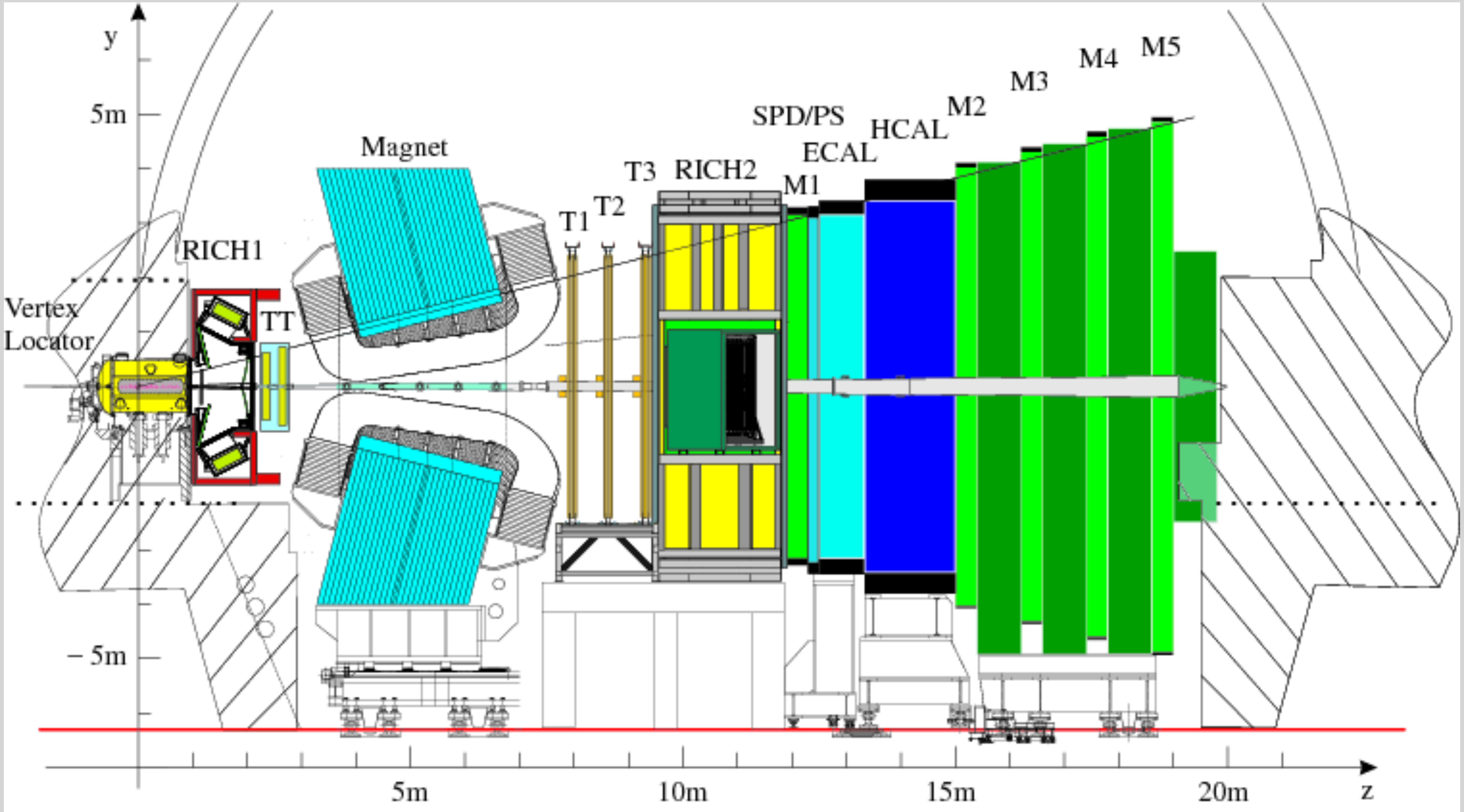
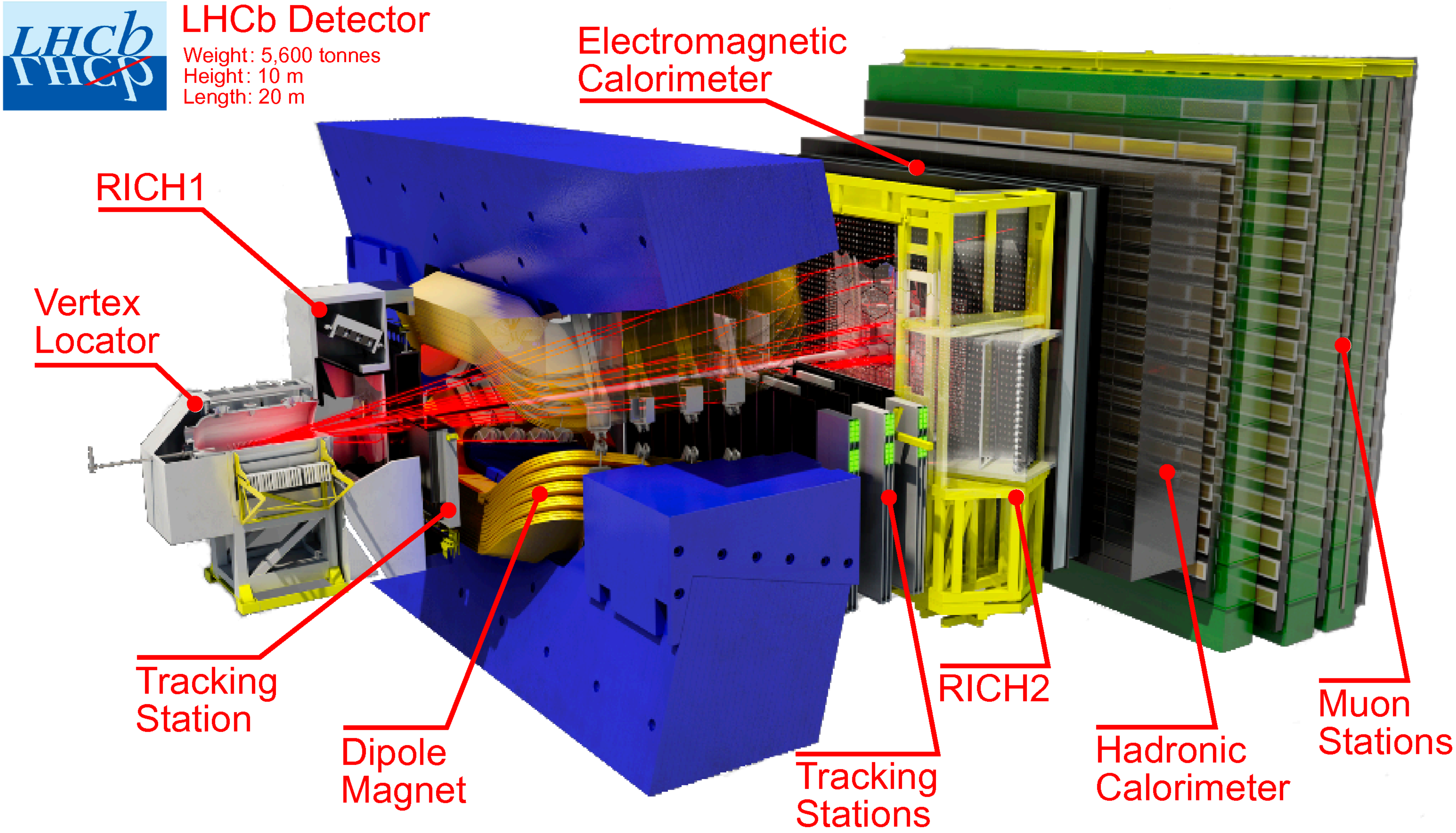
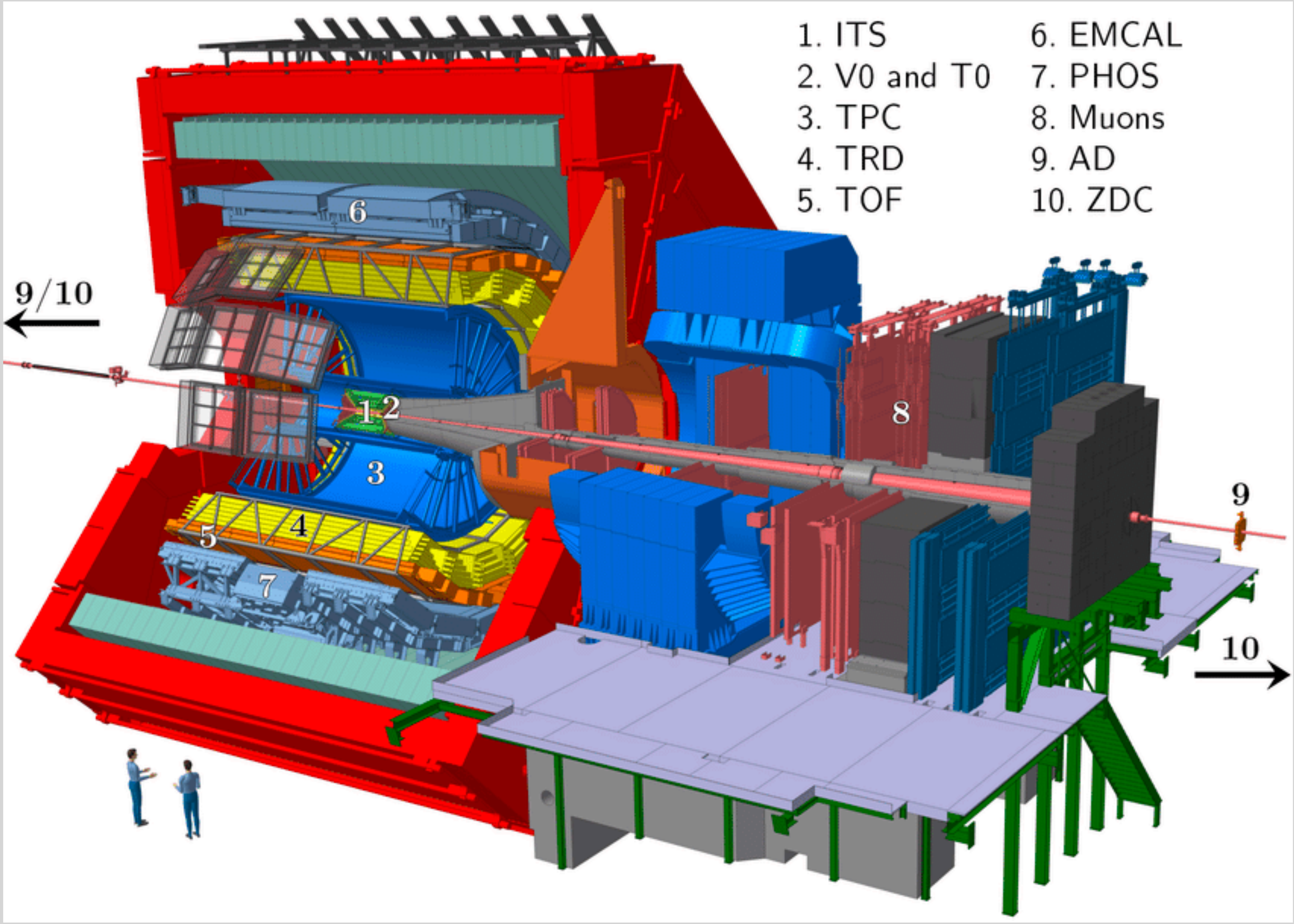

y
5m
− 5m
Magnet
T1
T2
T3
RICH2
SPD/PS
ECAL
HCAL
M1
M2
M3
M4
M5
RICH1
Vertex
Locator
TT
5m
10m
15m
20m
z


LHCb
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

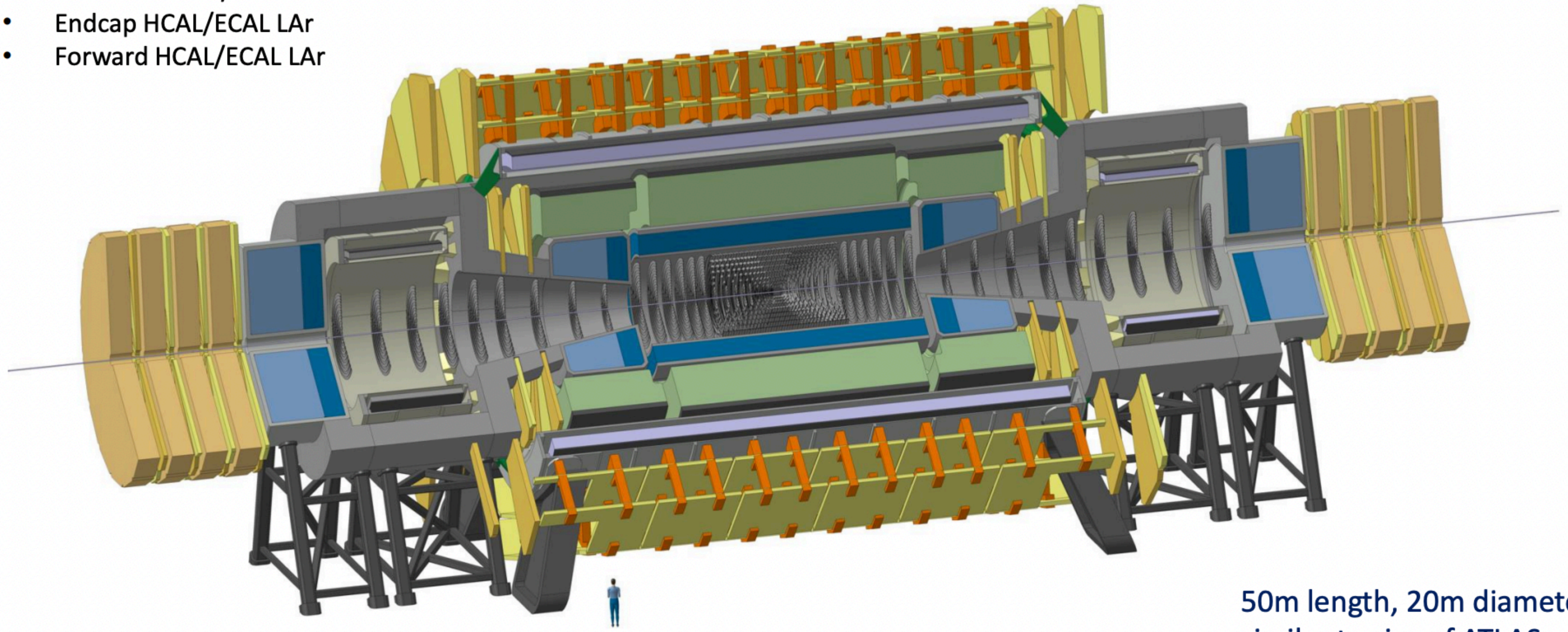
ALICE


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

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