

# The Standard Model

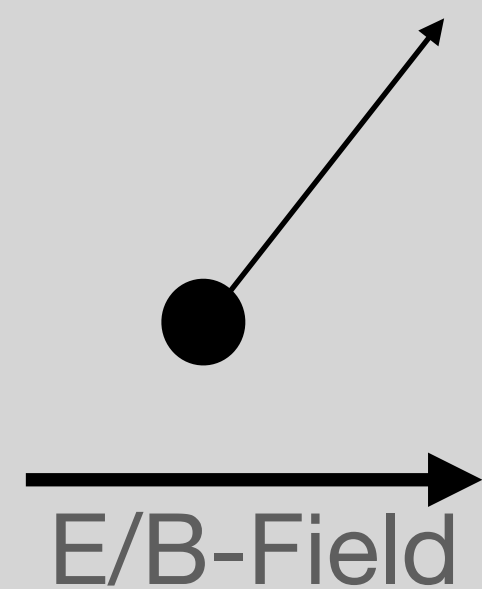
CSU-NUPAX/CERN IRES Program

Johan S Bonilla

March 1st and 3rd, 2022

# 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

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

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

# Maxwell's E&M Equations

Differential equations
$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{B} = \mu_0 \left( \mathbf{J} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$

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

# Gauge Transformations

Identities

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

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

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

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

$$\partial_\mu A^\mu = 0 \ (\mu = 0, 1, 2, 3), \quad \text{Lorenz gauge}$$

$$\nabla \cdot \mathbf{A} = \partial_j A_j = 0 \ (j = 1, 2, 3), \quad \text{Coulomb gauge or radiation gauge}$$

$$n_\mu A^\mu = 0 \ (n^2 = 0), \quad \text{light cone gauge}$$

$$A_0 = 0, \quad \text{Hamiltonian or temporal gauge}$$

$$A_3 = 0, \quad \text{axial gauge}$$

$$x_\mu A^\mu = 0, \quad \text{Fock-Schwinger gauge}$$

$$x_j A_j = 0, \quad \text{Poincaré gauge}$$

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

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

# Standard Model of Elementary Particles

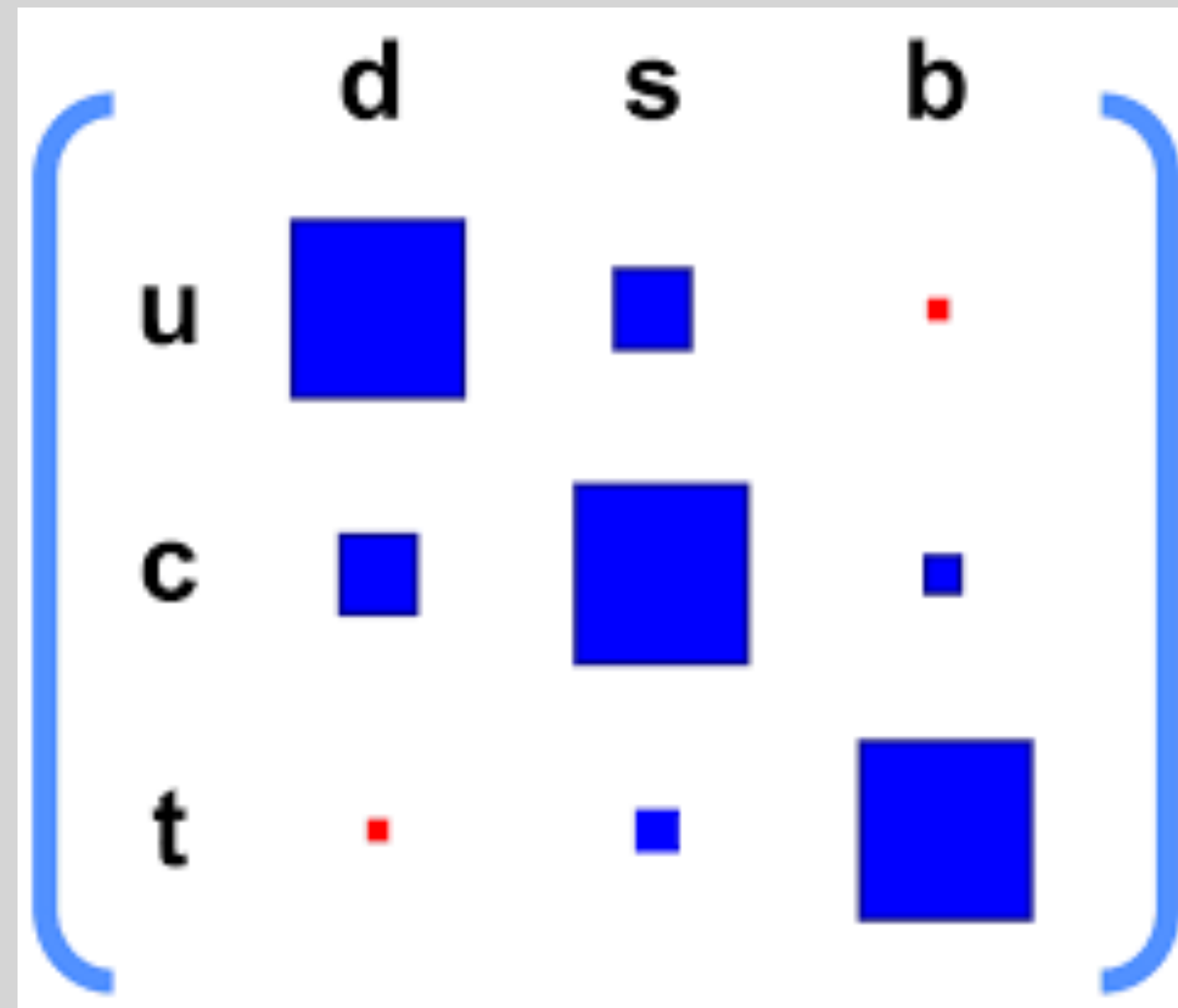
		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> higgs
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
LEPTONS		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
		-1	-1	-1	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$		
	0	0	0	$\pm 1$		
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1		
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson		

**GAUGE BOSONS**  
**VECTOR BOSONS**

**SCALAR BOSONS**

# CKM Matrix

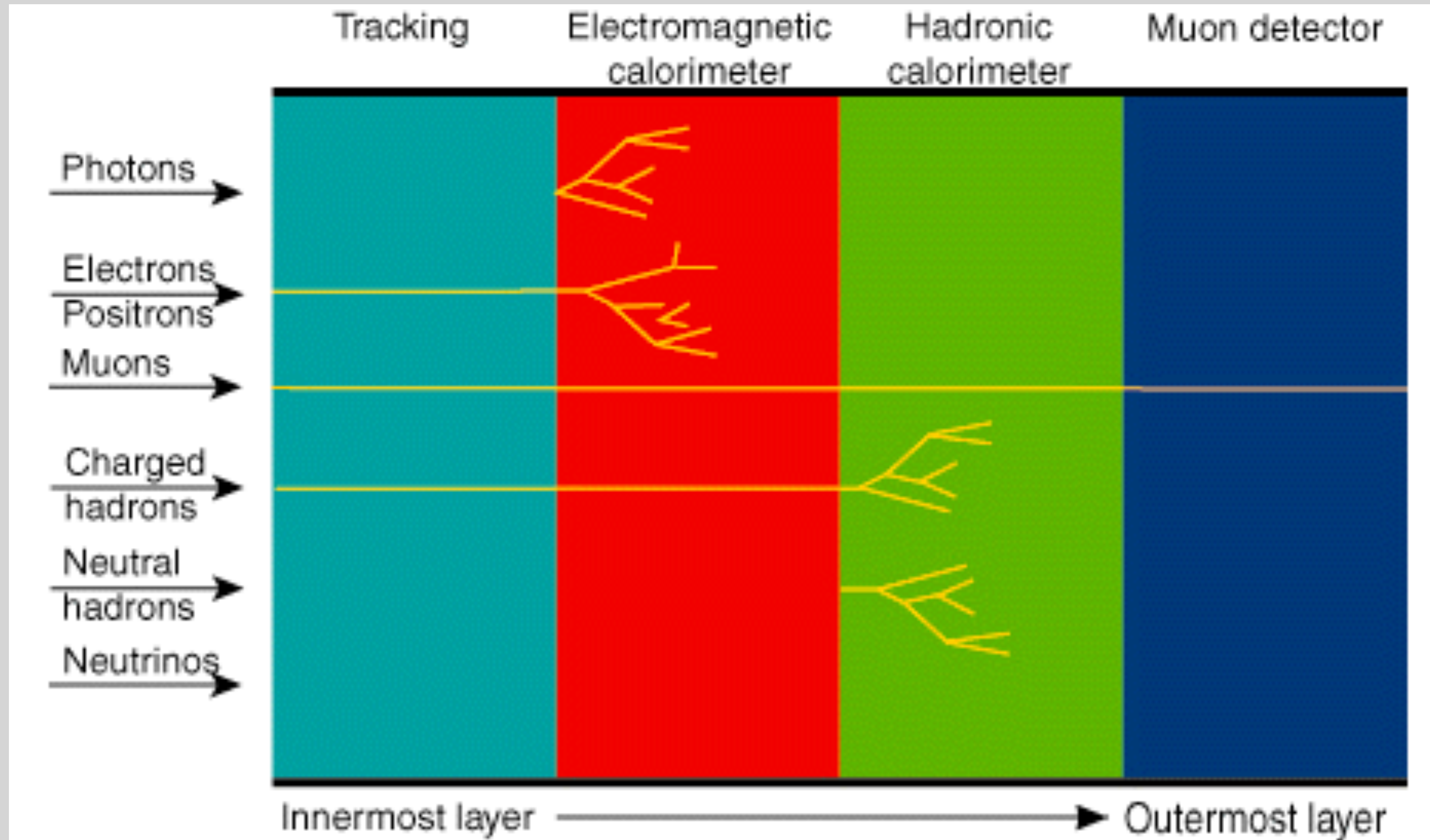
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & 0.00382 \pm 0.00024 \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & 0.0410 \pm 0.0014 \\ 0.0080 \pm 0.0003 & 0.0388 \pm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



# PMNS Matrix

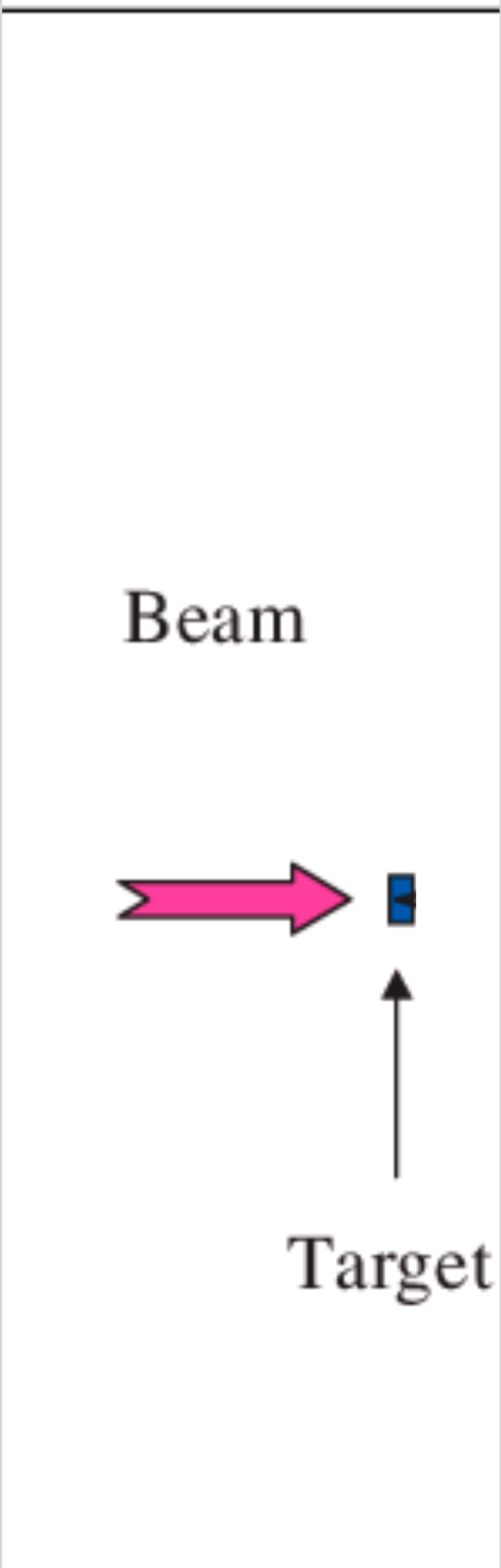
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

# Particle Detection

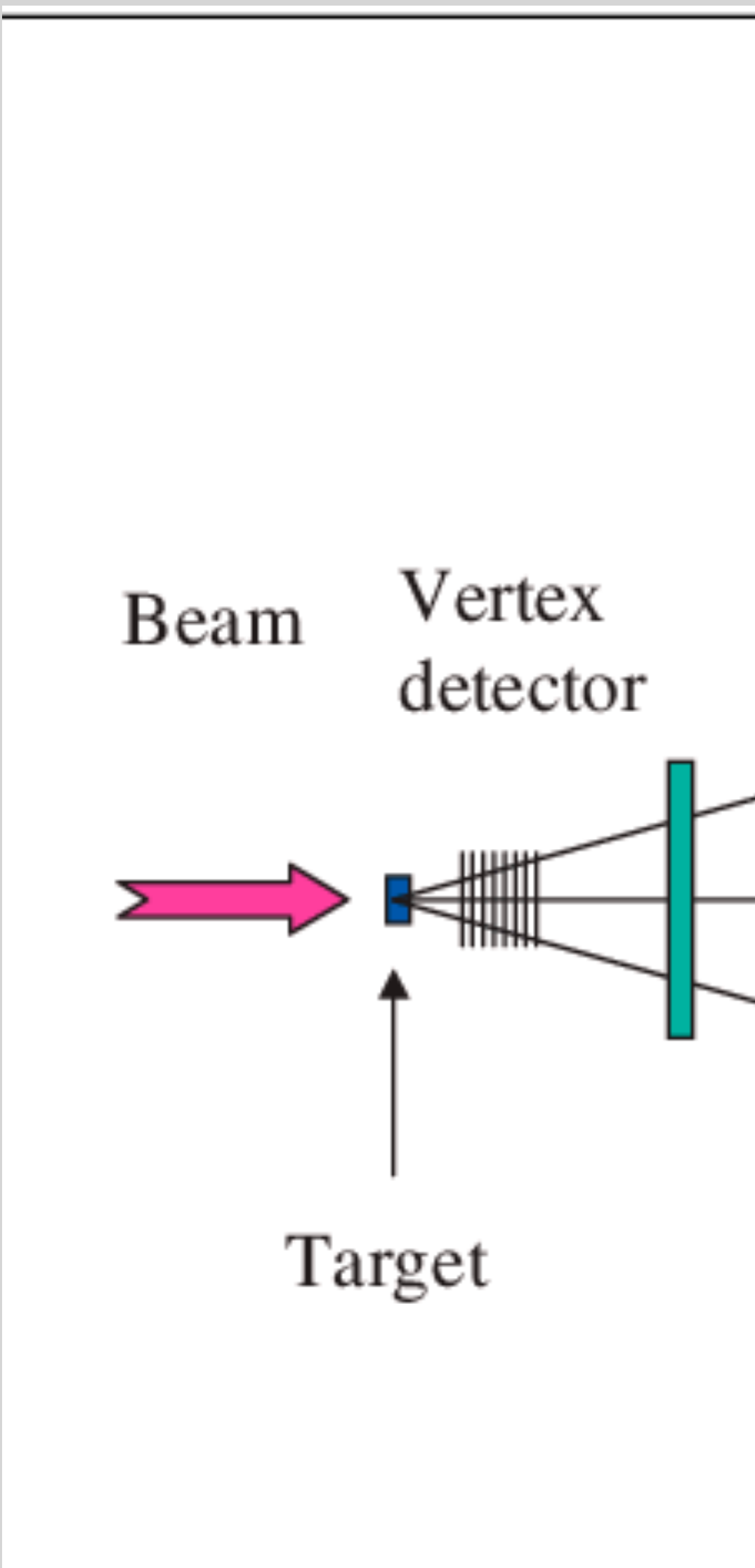




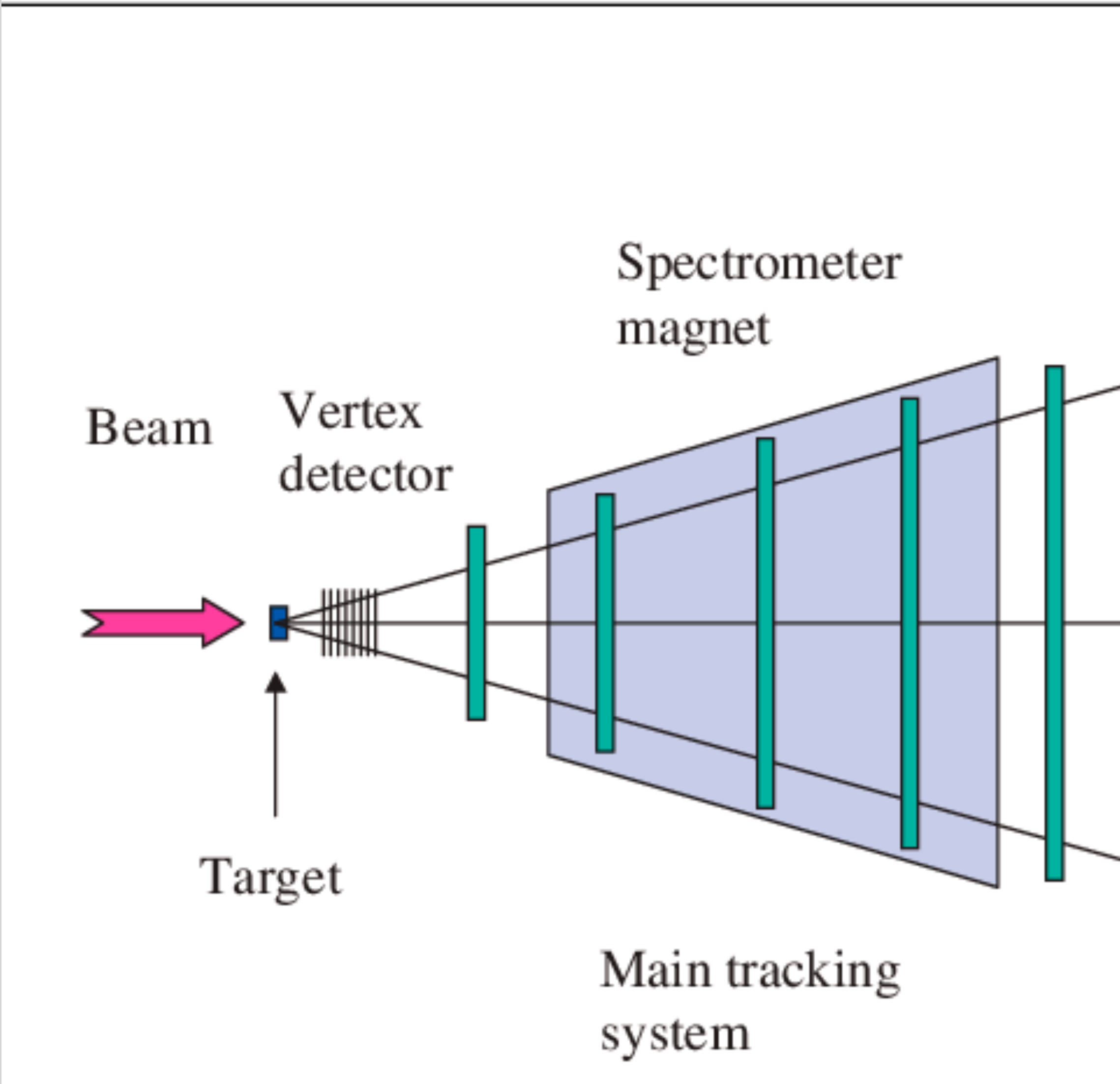
# General Collider Detector



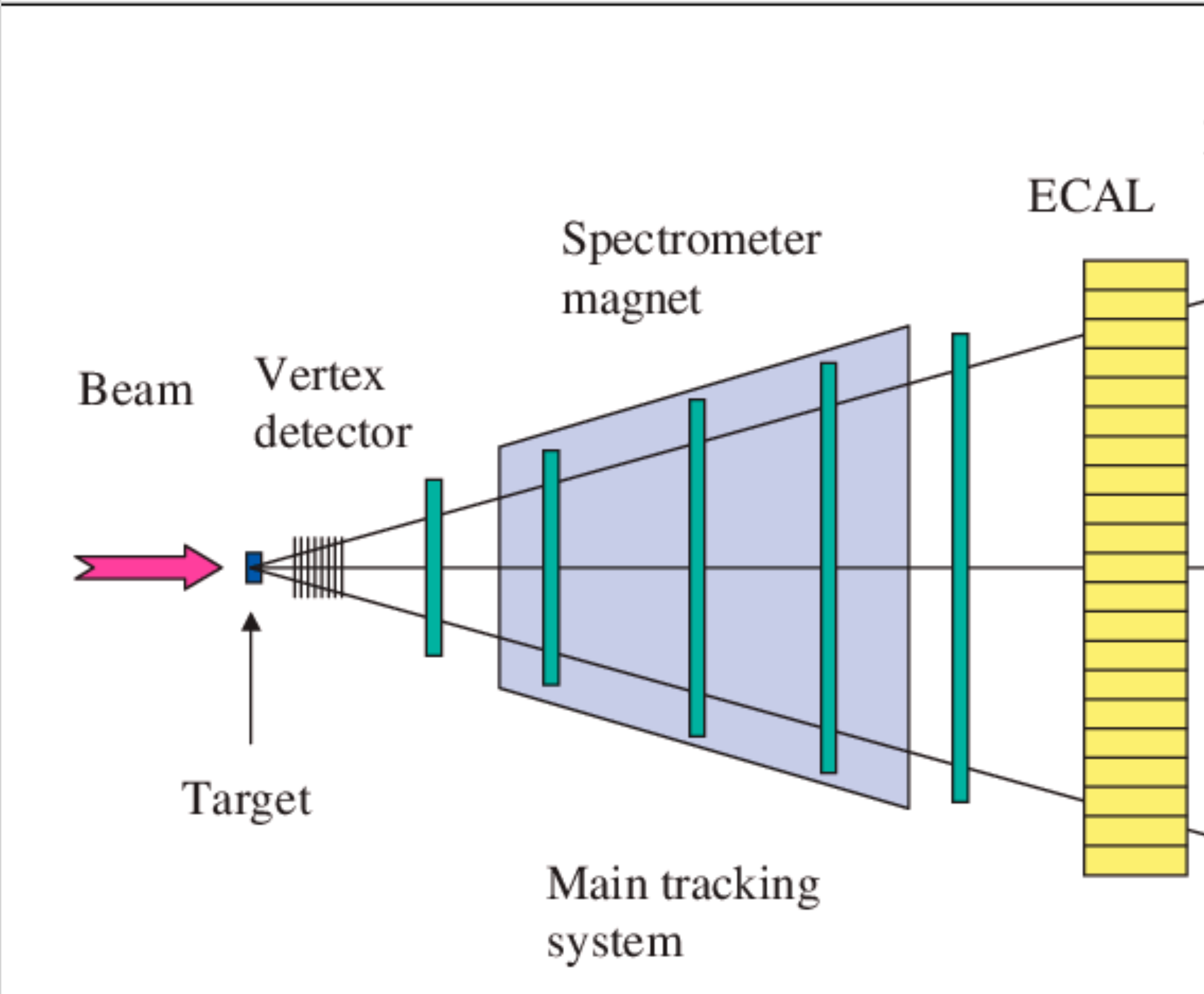
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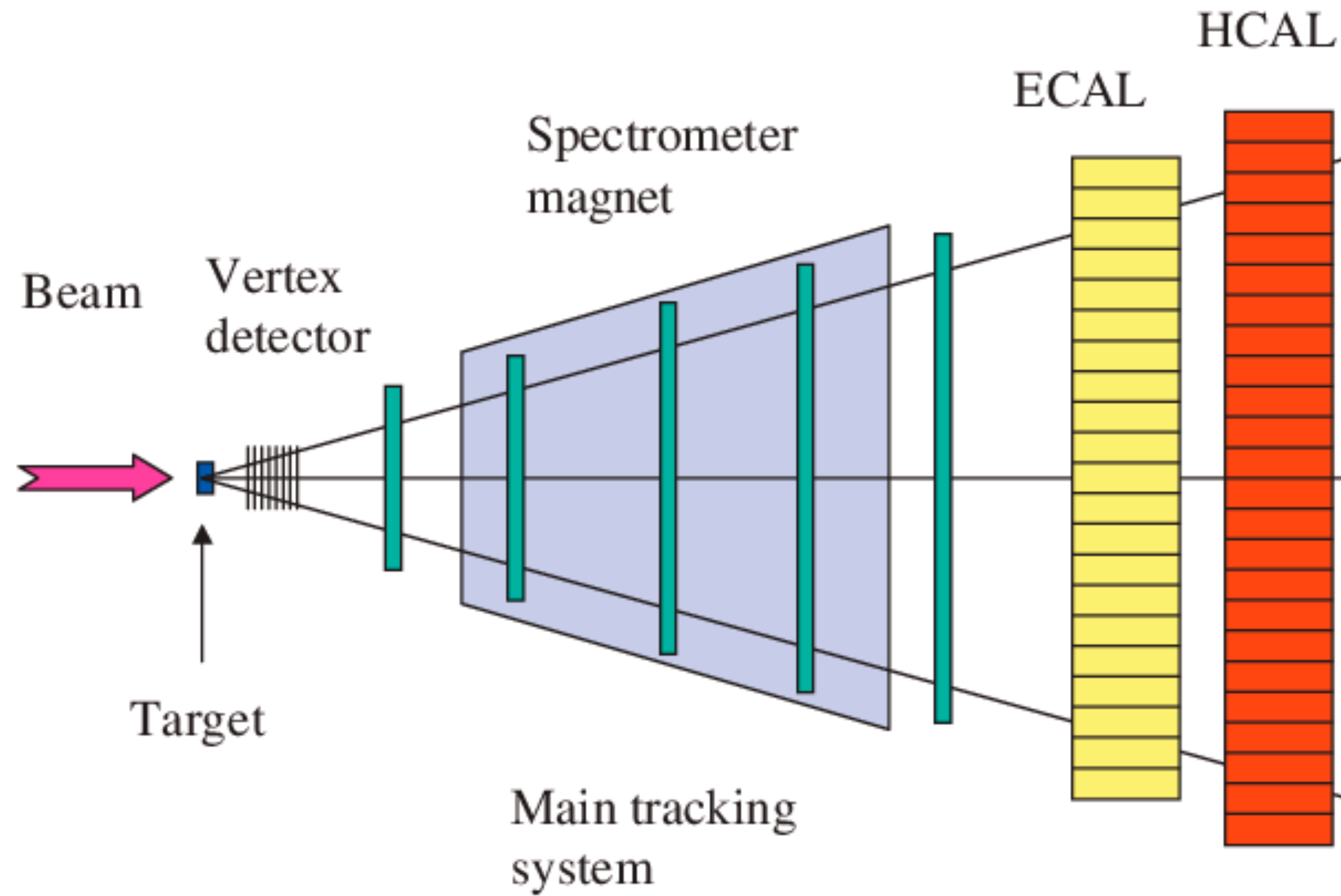
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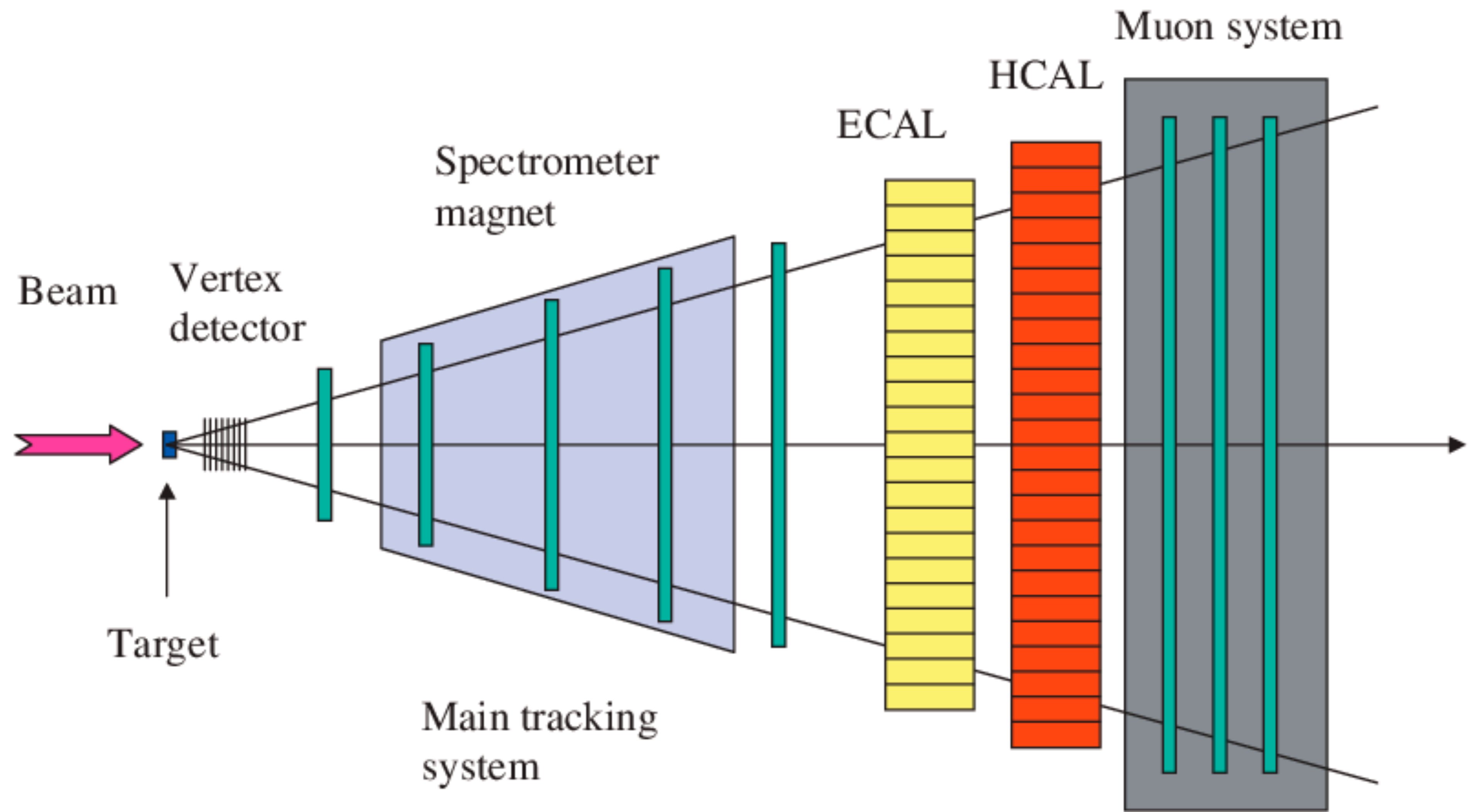
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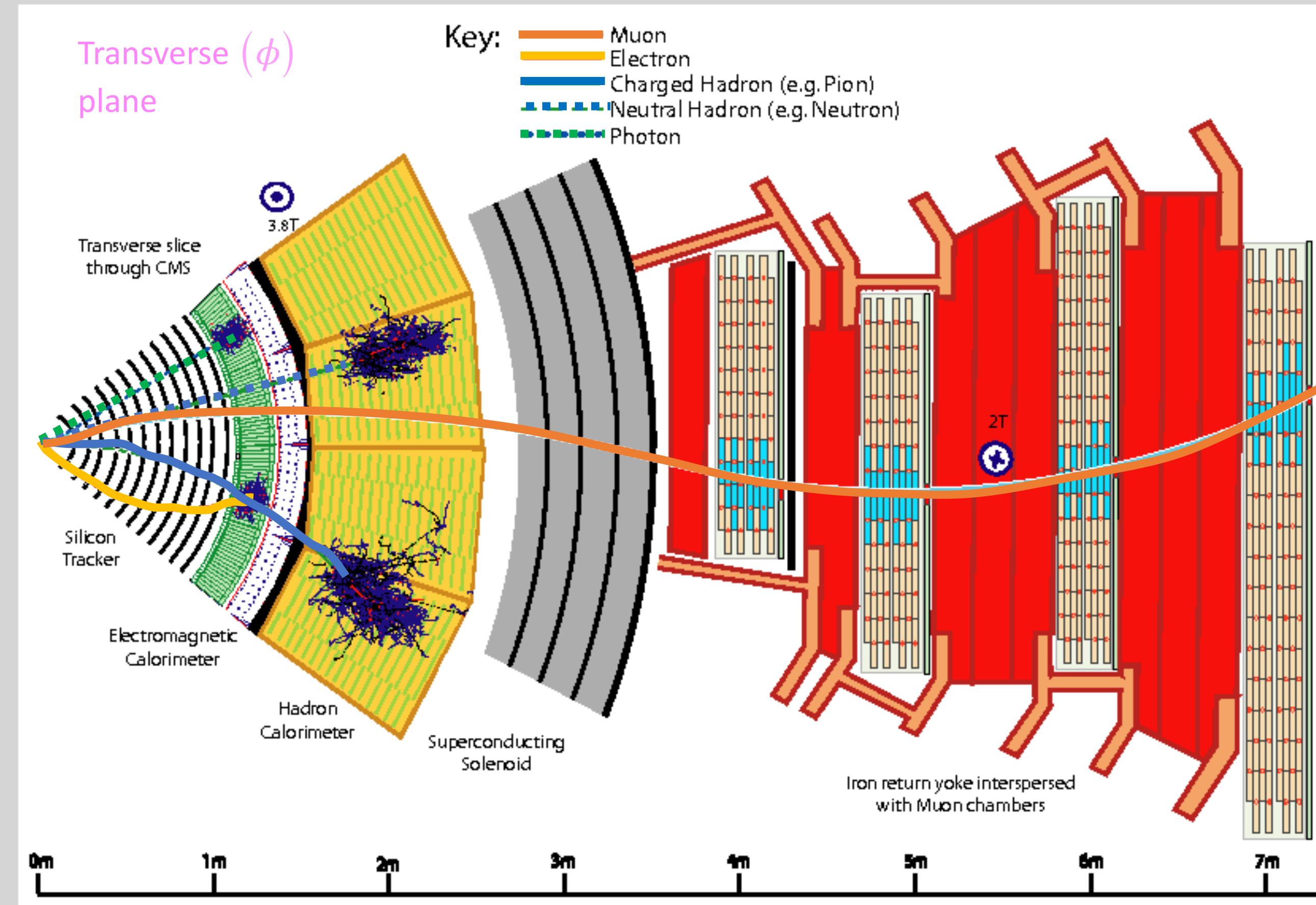
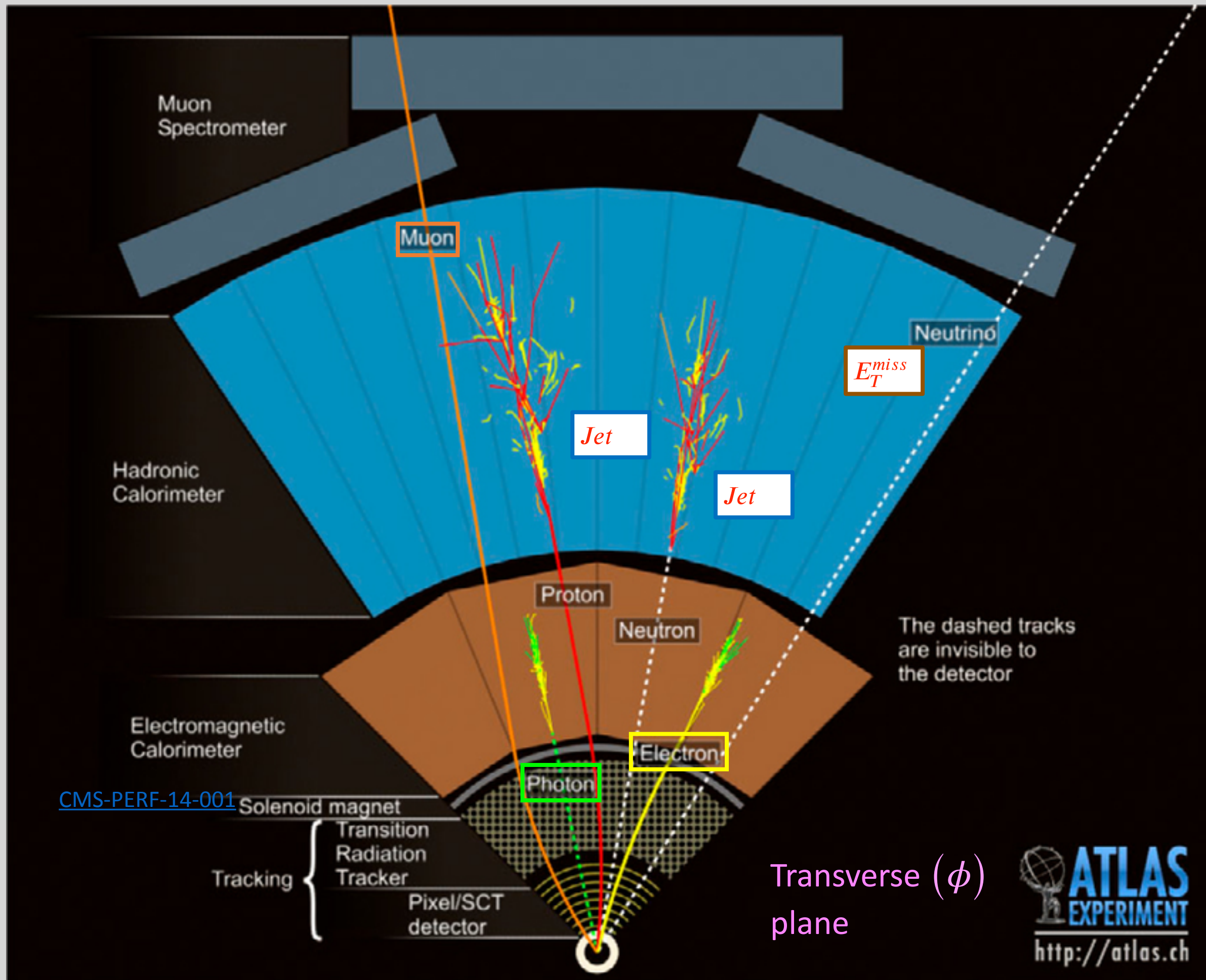
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# Detecting Particles with ATLAS/CMS

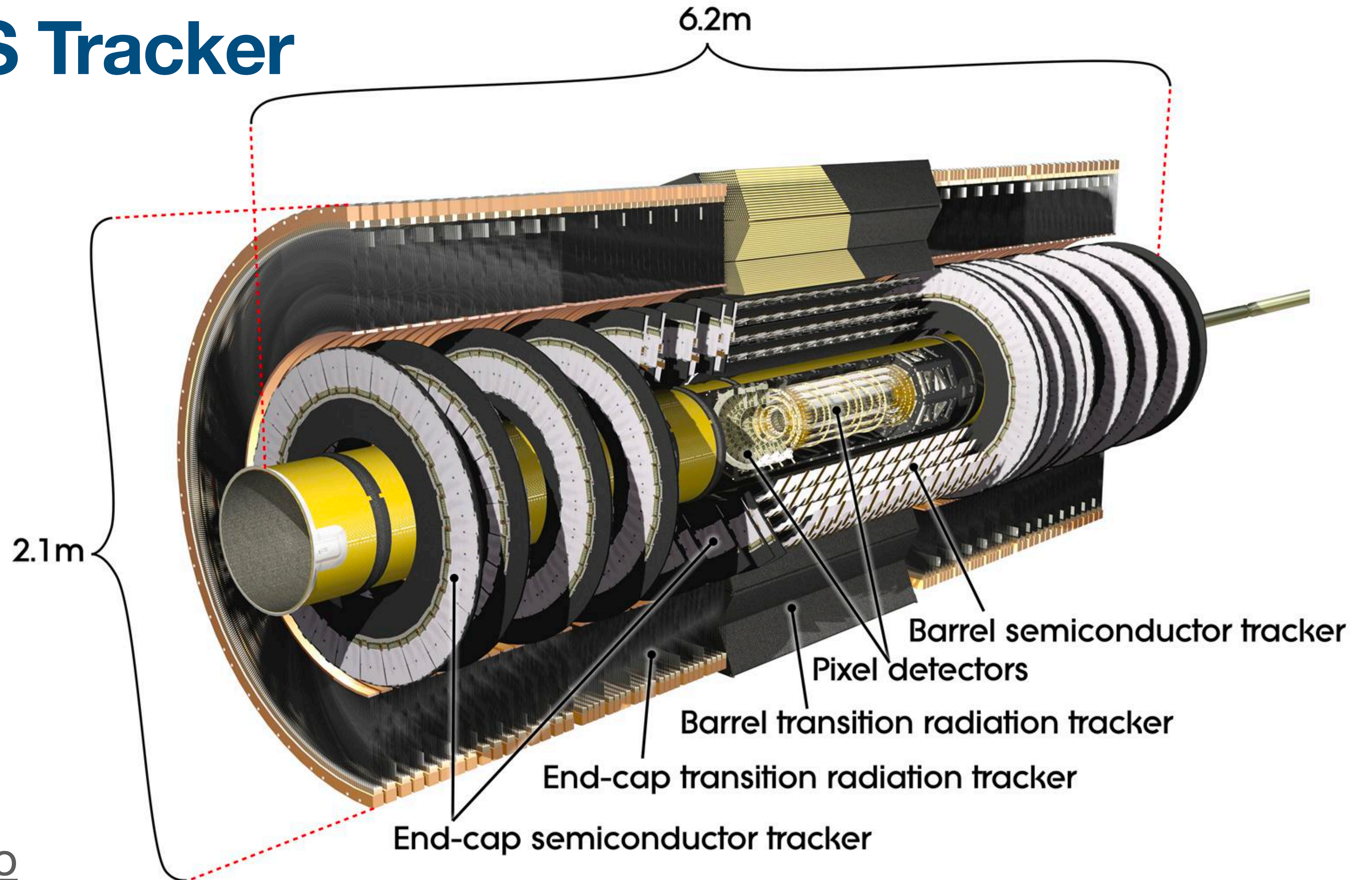


Electron: Charged, EM  
Photon: Neutral, EM

Muon: Charged, MIP  
Jet: Calorimeter Object

$E_T^{miss}$ : Missing Energy  
(Transverse)

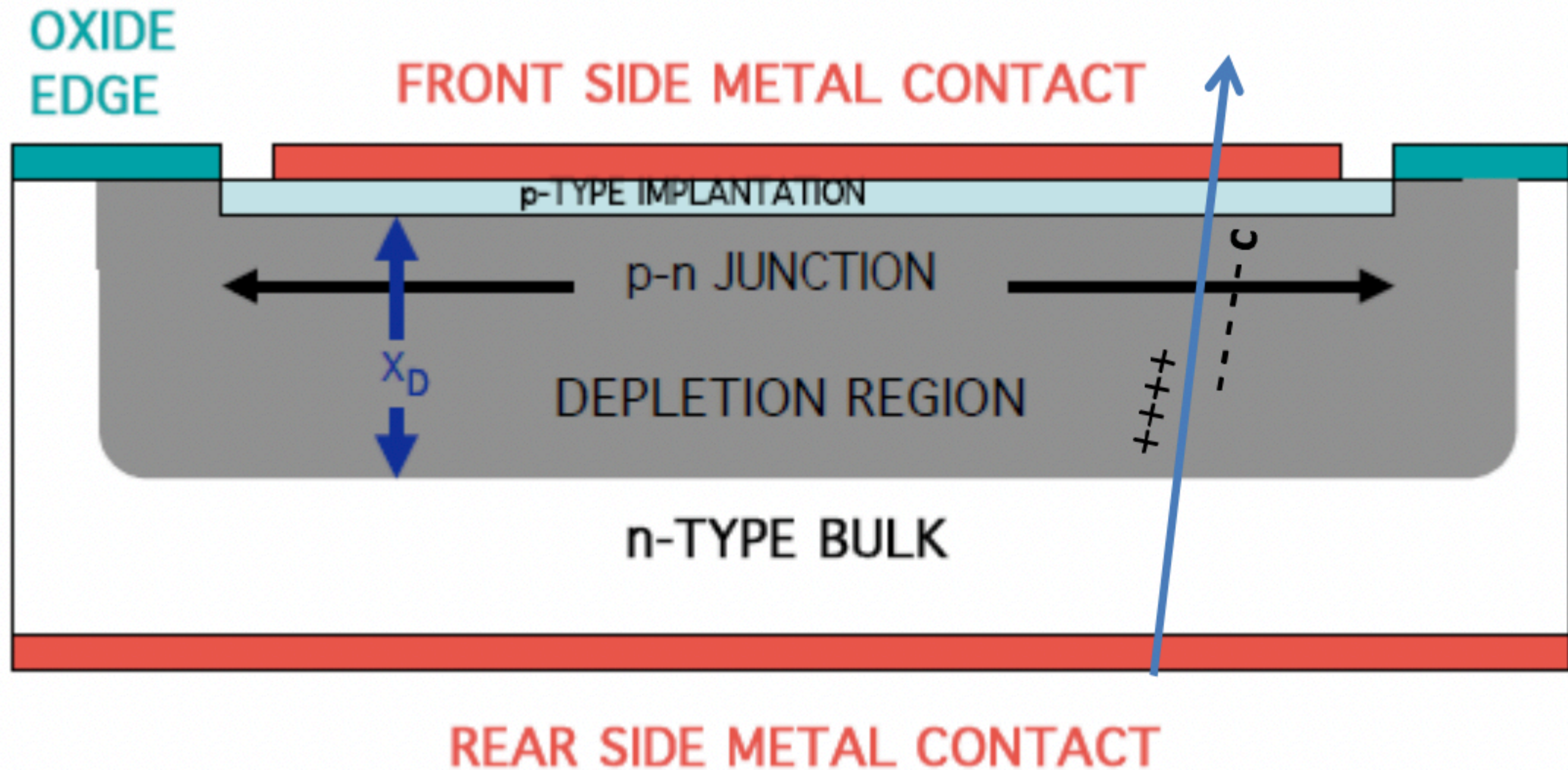
# ATLAS Tracker



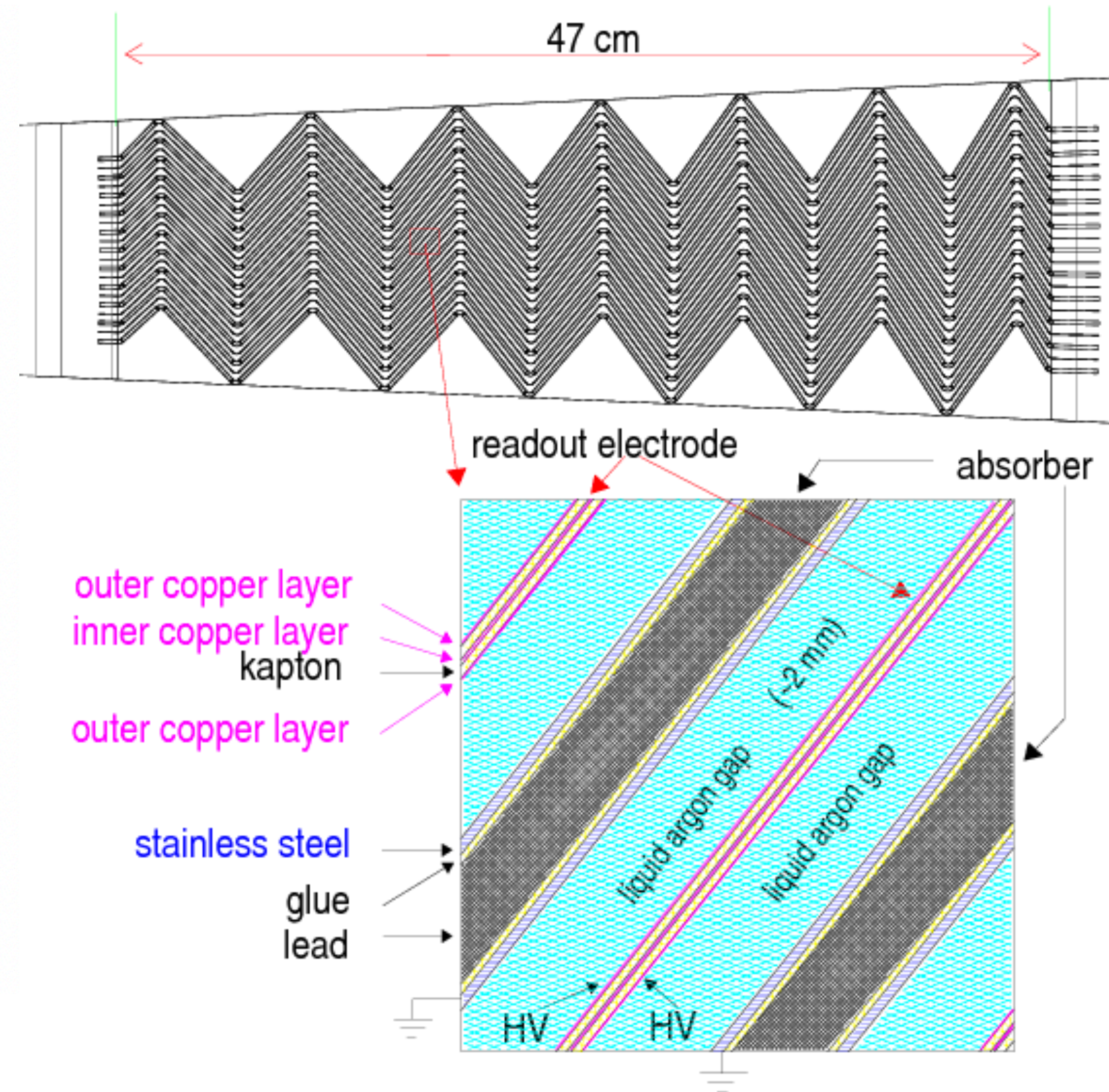
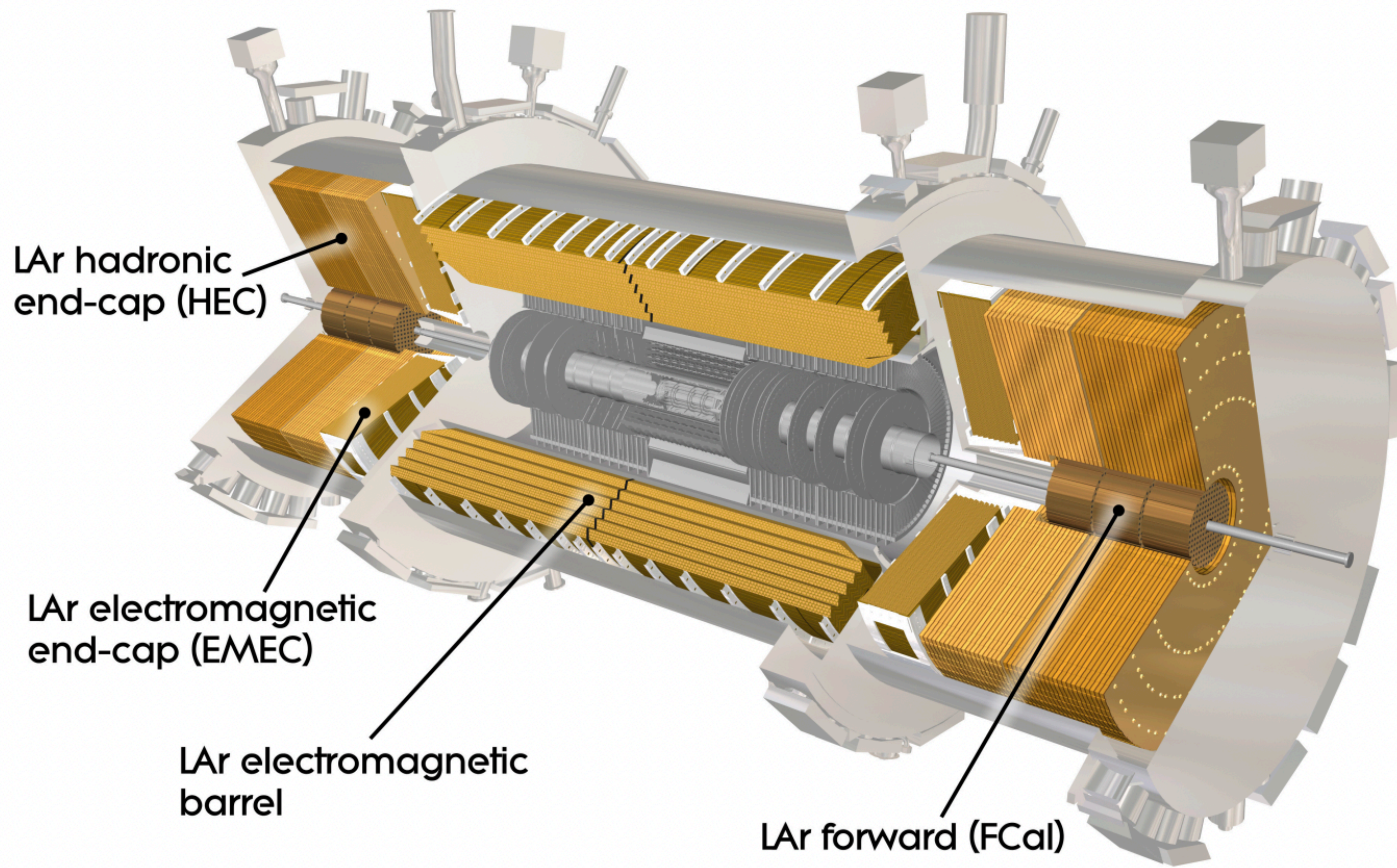
[See Video](#)



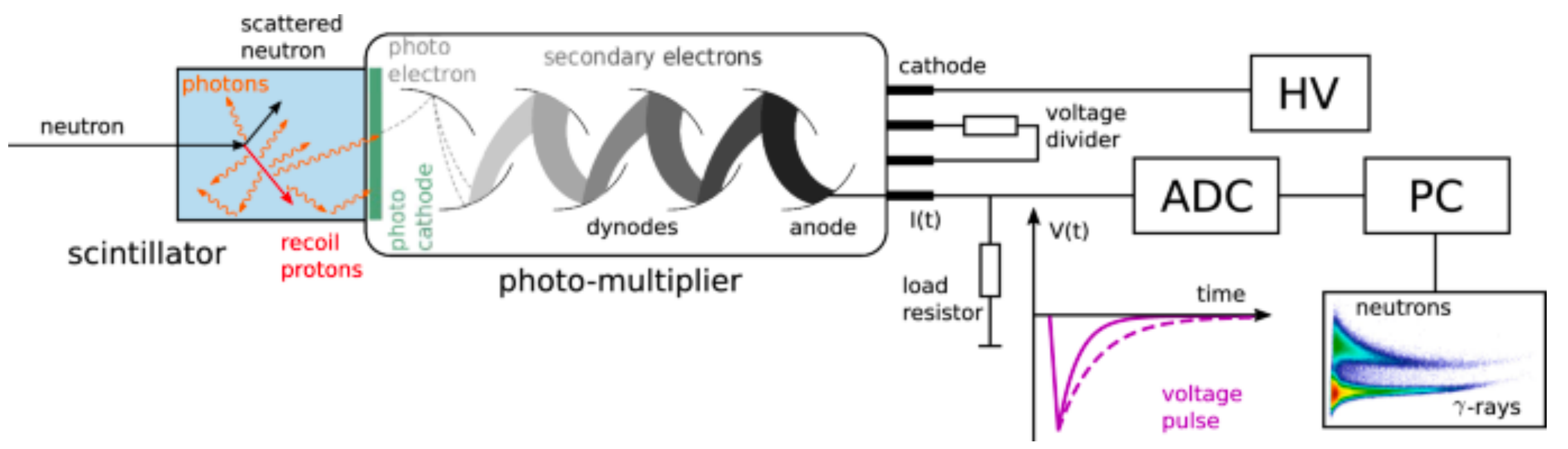
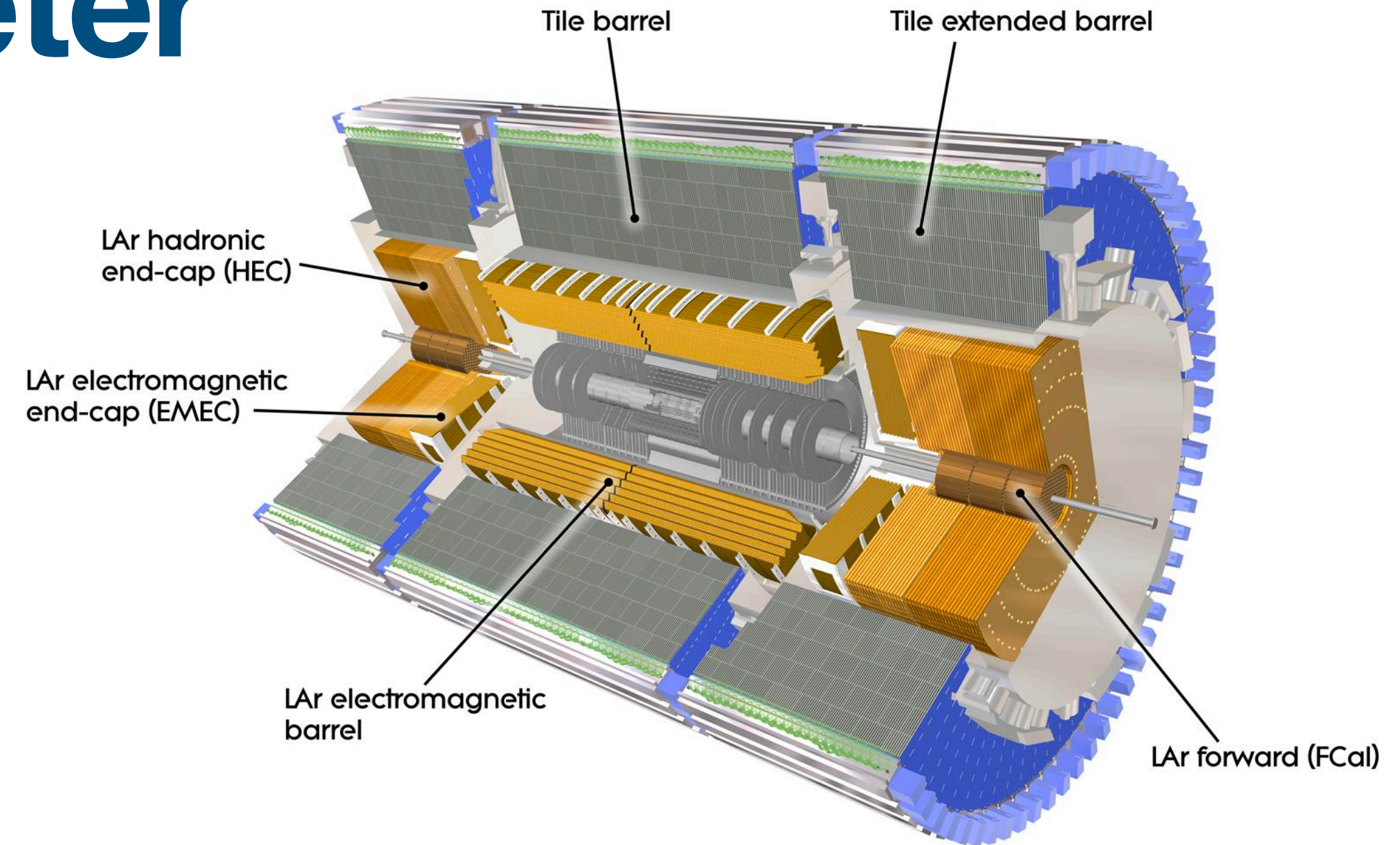
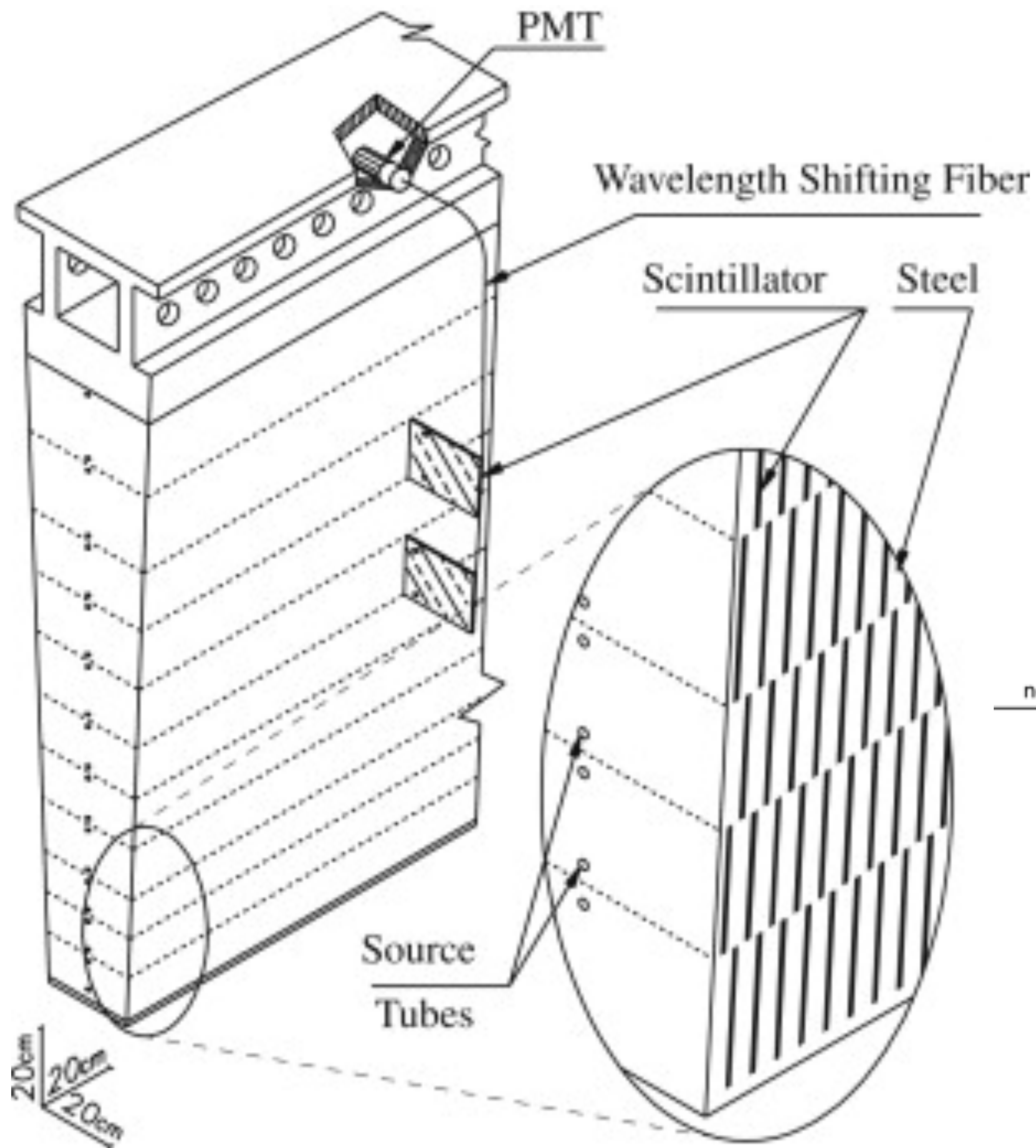
# Silicon (Semiconductor) Strip Detectors



# Liquid Argon Calorimeter



# Hadronic Calorimeter



[See Video](#)

# The Compact Muon Solenoid

## CMS DETECTOR

Total weight : 14,000 tonnes  
Overall diameter : 15.0 m  
Overall length : 28.7 m

**Magnetic field : 3.8 T**

STEEL RETURN YOKE  
12,500 tonnes

### SILICON TRACKERS

Pixel ( $100 \times 150 \mu\text{m}^2$ )  $\sim 1.9 \text{ m}^2 \sim 124\text{M}$  channels  
Microstrips ( $80\text{--}180 \mu\text{m}$ )  $\sim 200 \text{ m}^2 \sim 9.6\text{M}$  channels

### SUPERCONDUCTING SOLENOID

Niobium titanium coil carrying  $\sim 18,000 \text{ A}$

### MUON CHAMBERS

Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

### PRESHOWER

Silicon strips  $\sim 16 \text{ m}^2 \sim 137,000$  channels

### FORWARD CALORIMETER

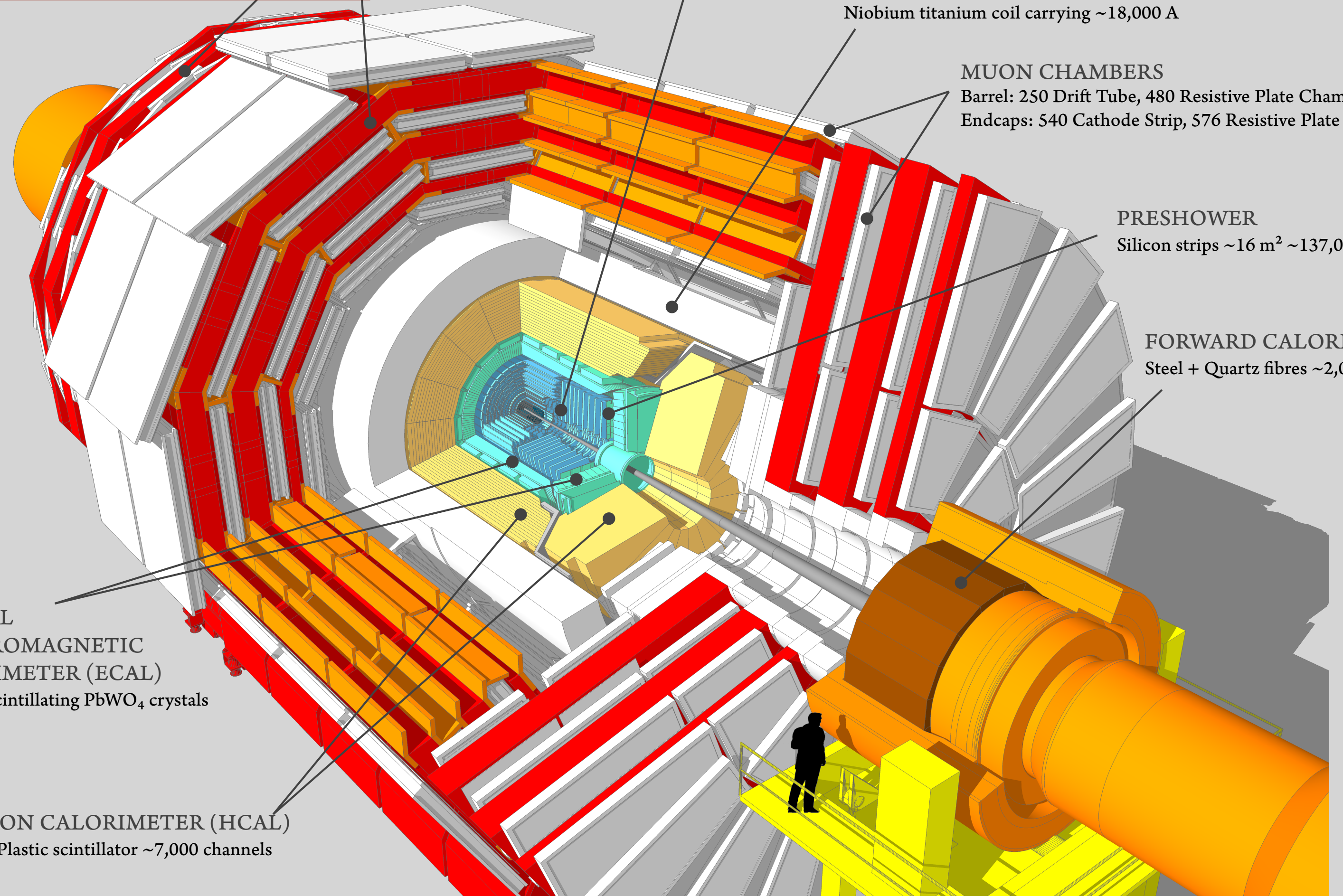
Steel + Quartz fibres  $\sim 2,000$  Channels

### CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)

$\sim 76,000$  scintillating  $\text{PbWO}_4$  crystals

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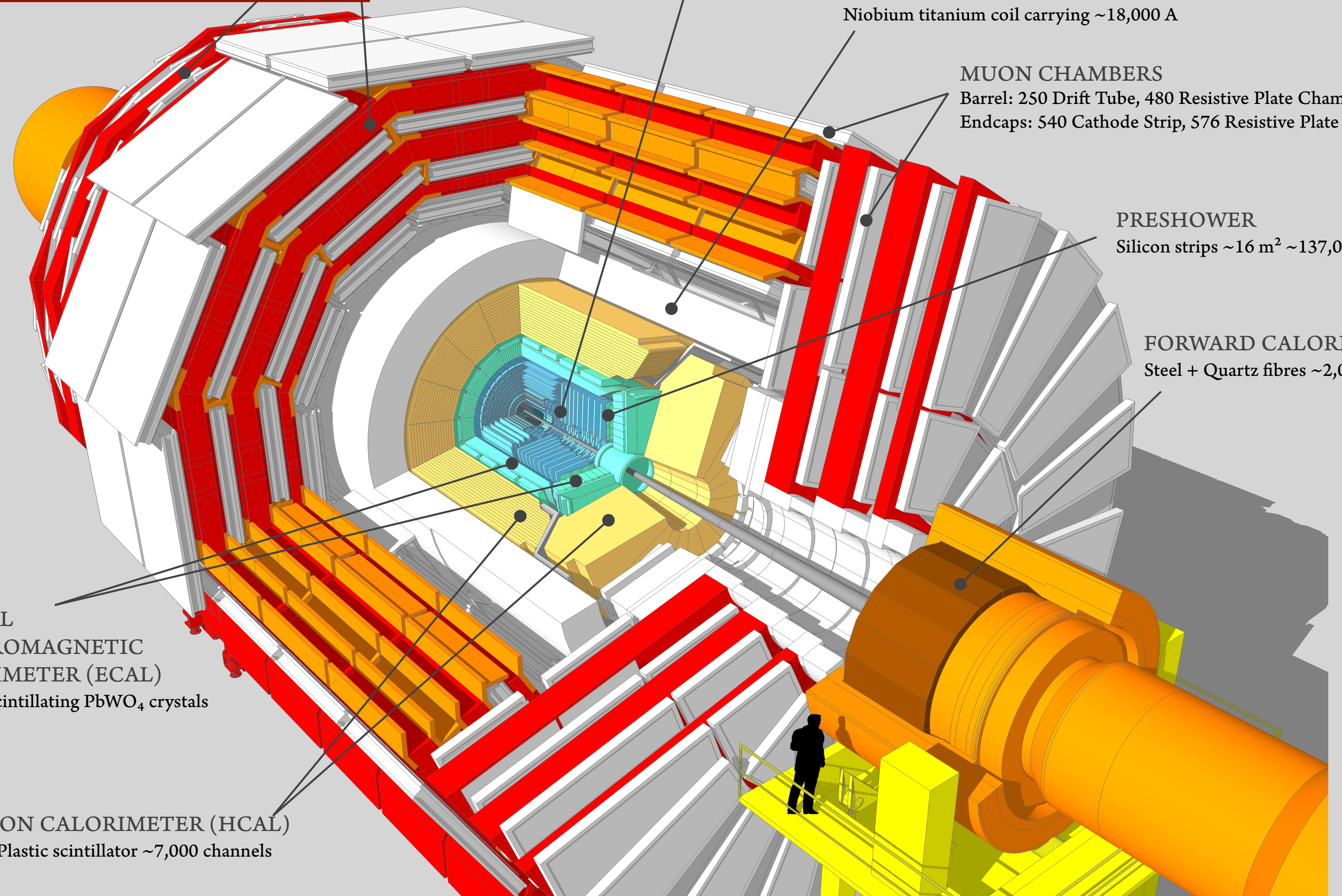
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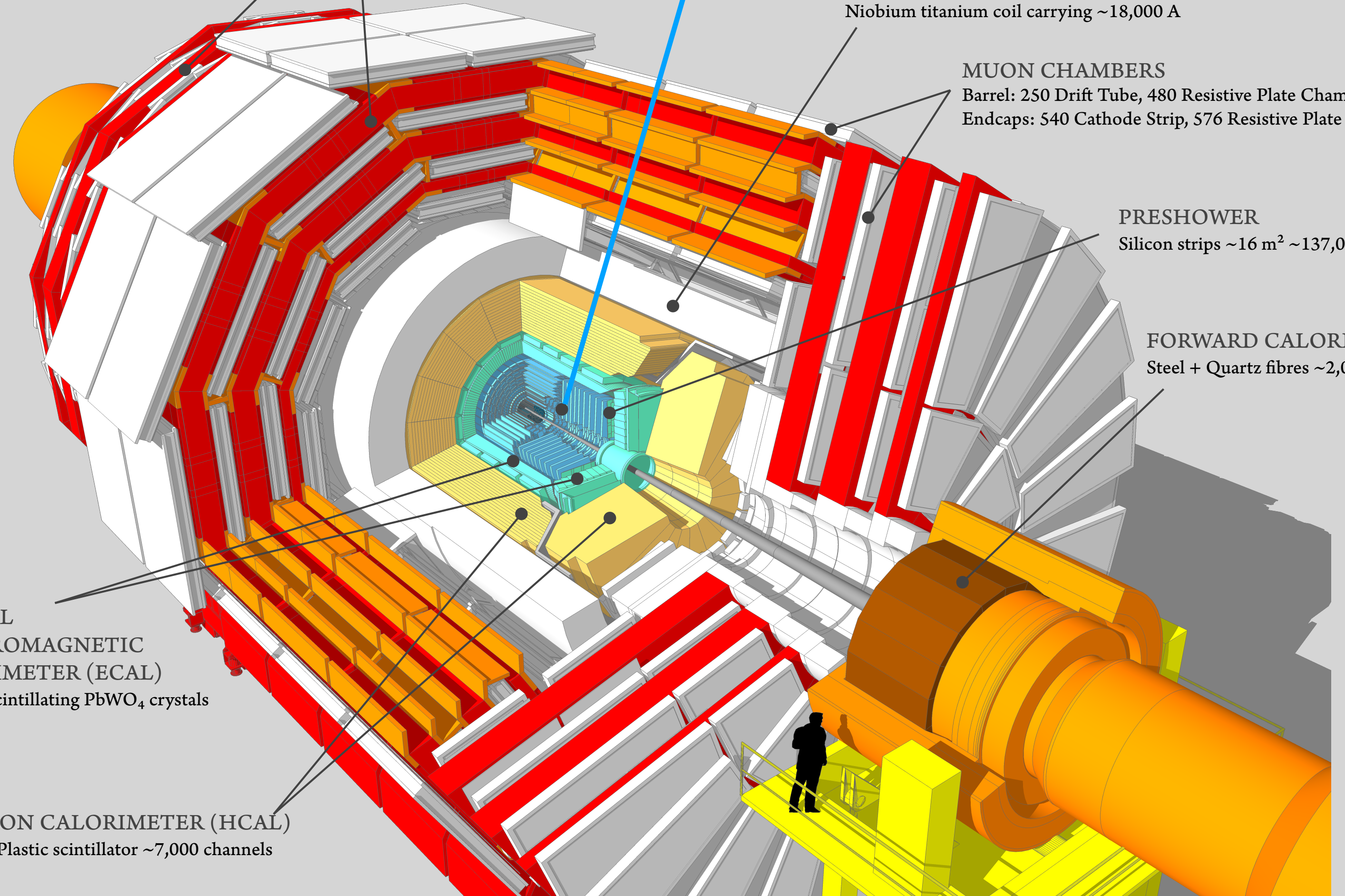
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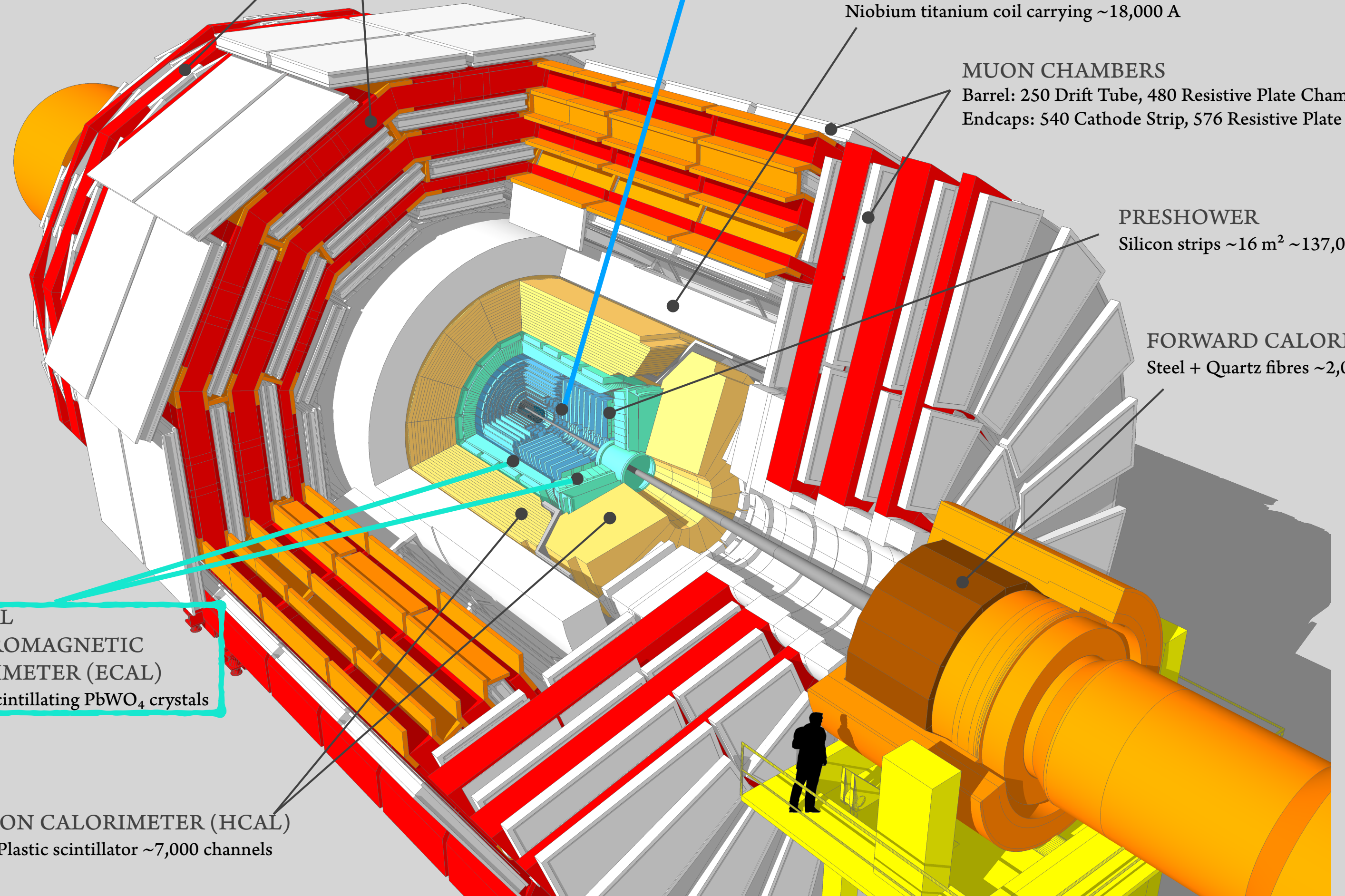
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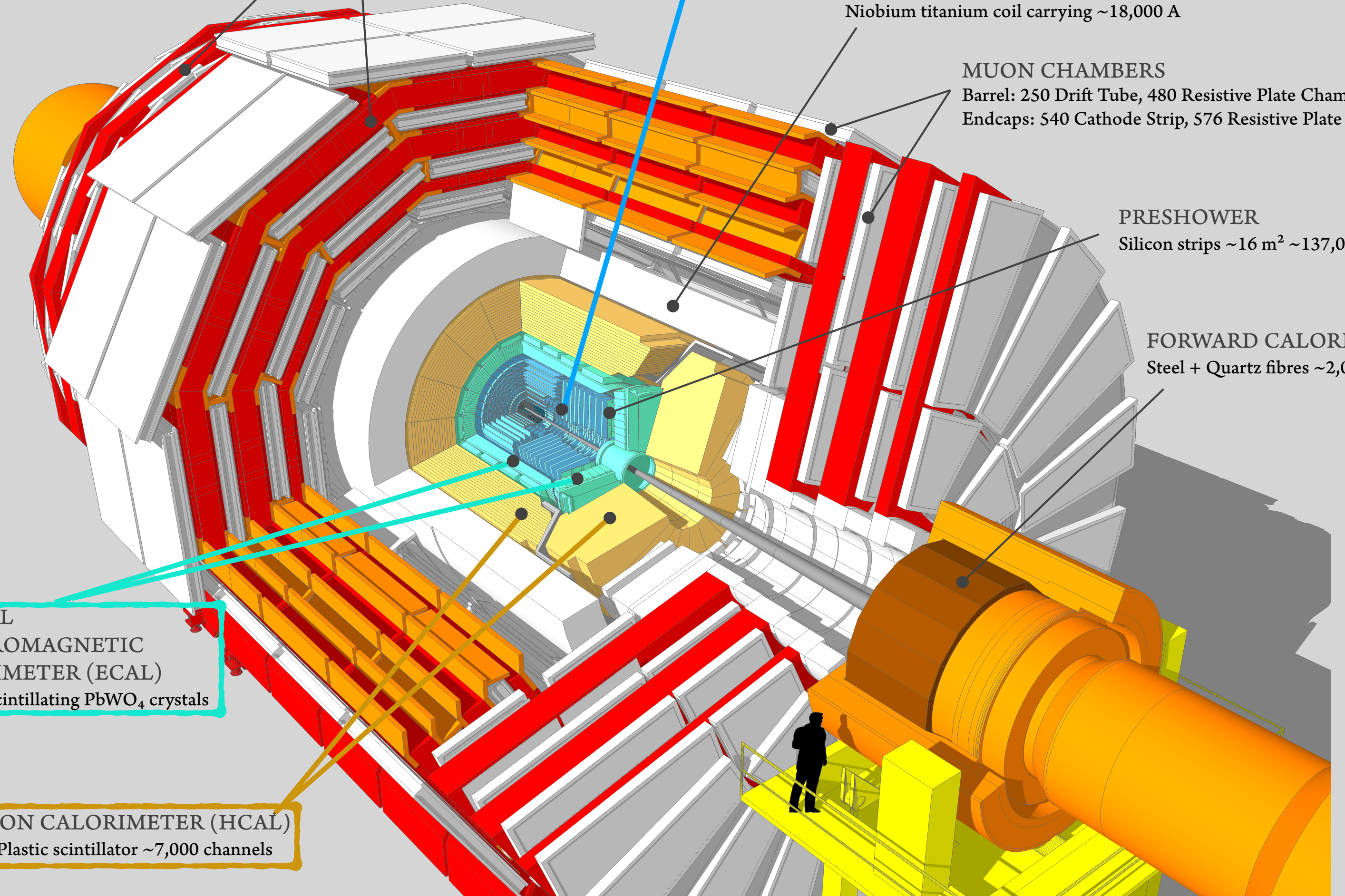
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- Brass Hadron Calorimeter
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- Excellent, Robust Muon System
  - Superconducting solenoid creates 3.8T magnetic field in tracker and calorimeters, 2T is steel return yoke

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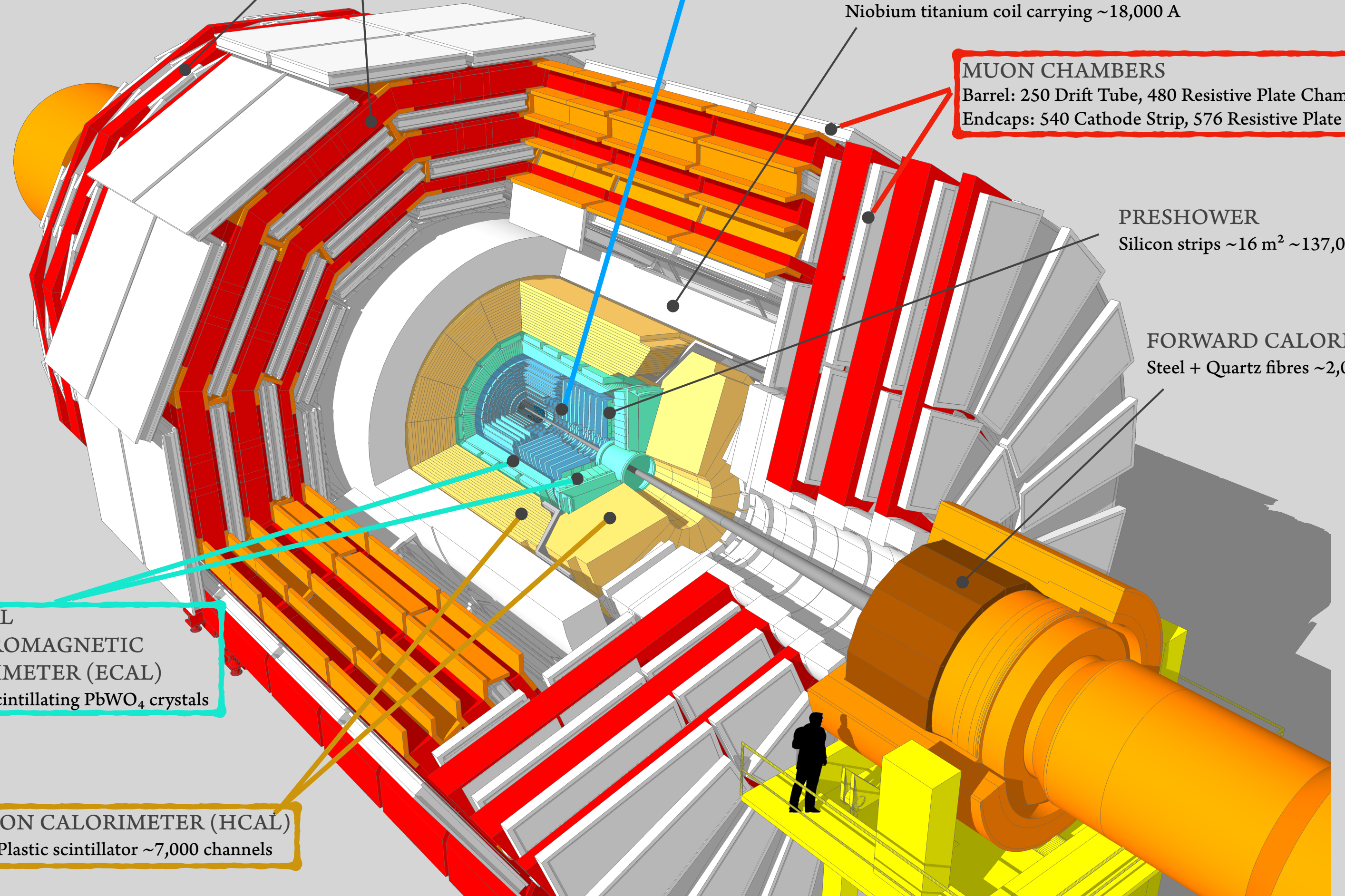
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- Cost: ~500 MCHF  
+ ~200 MCHF (Upgrades)

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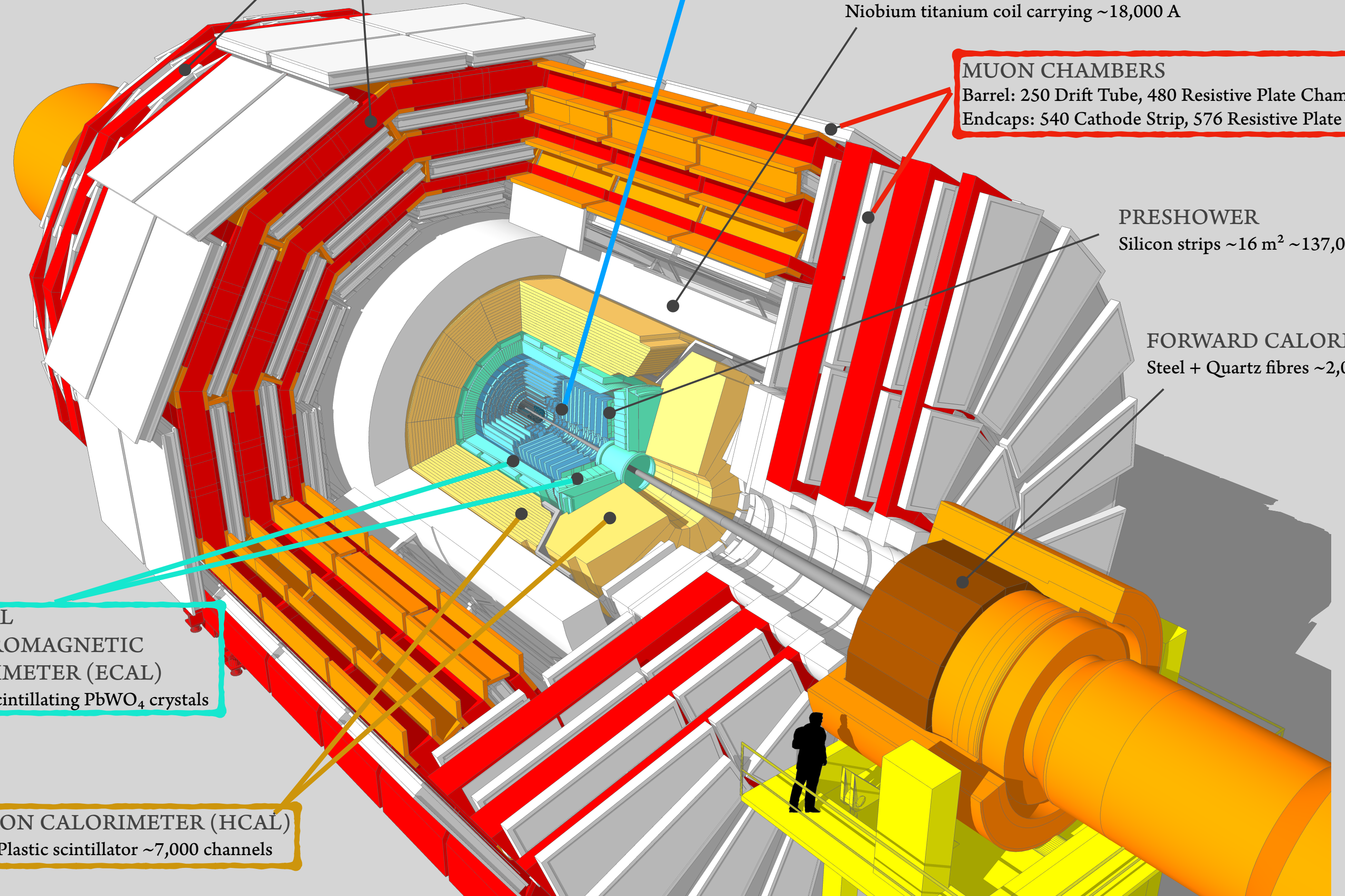
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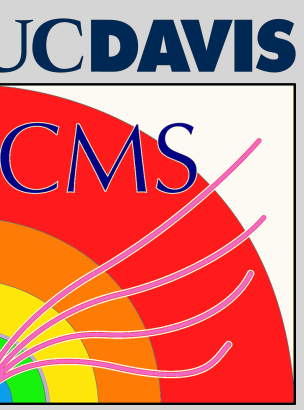
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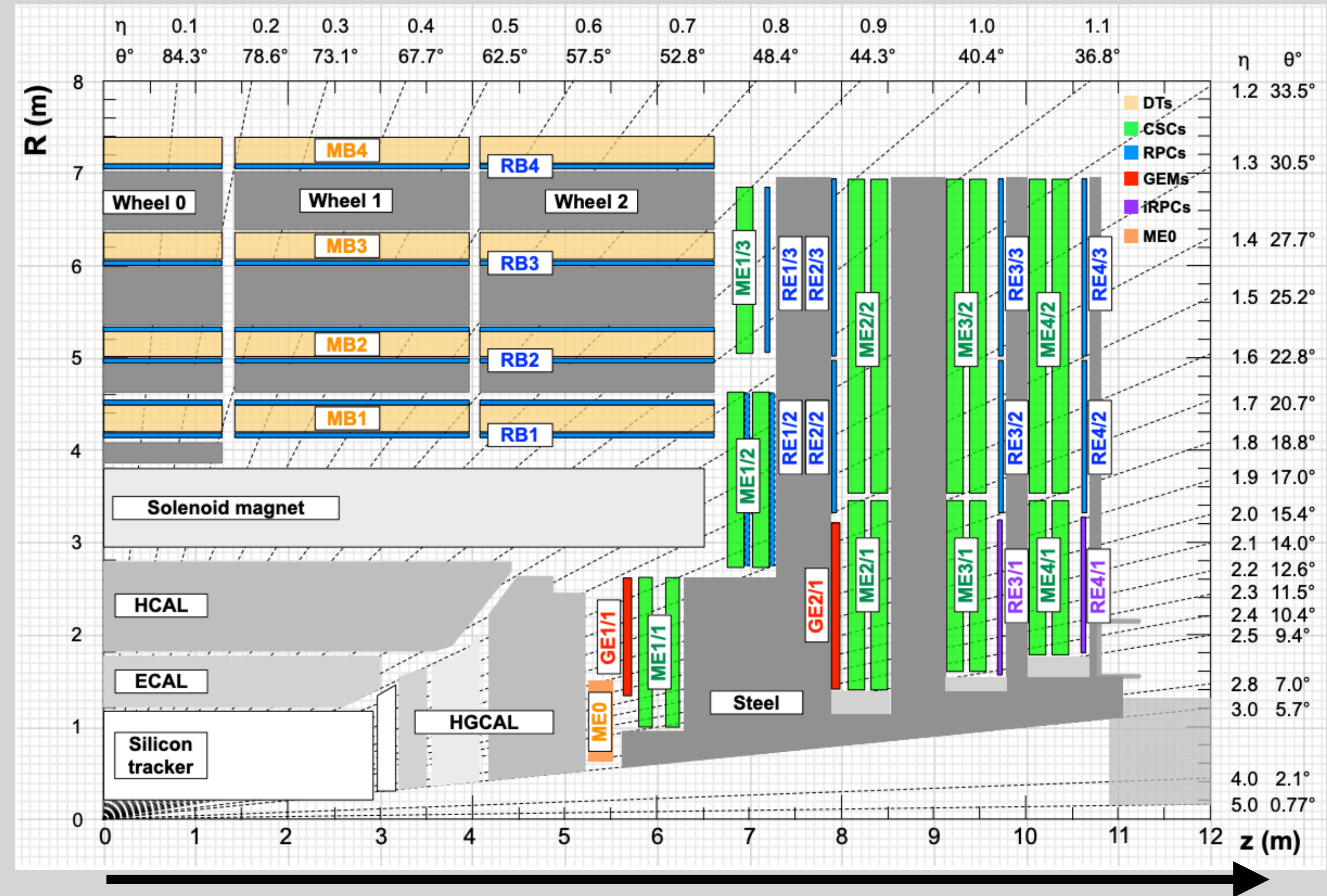


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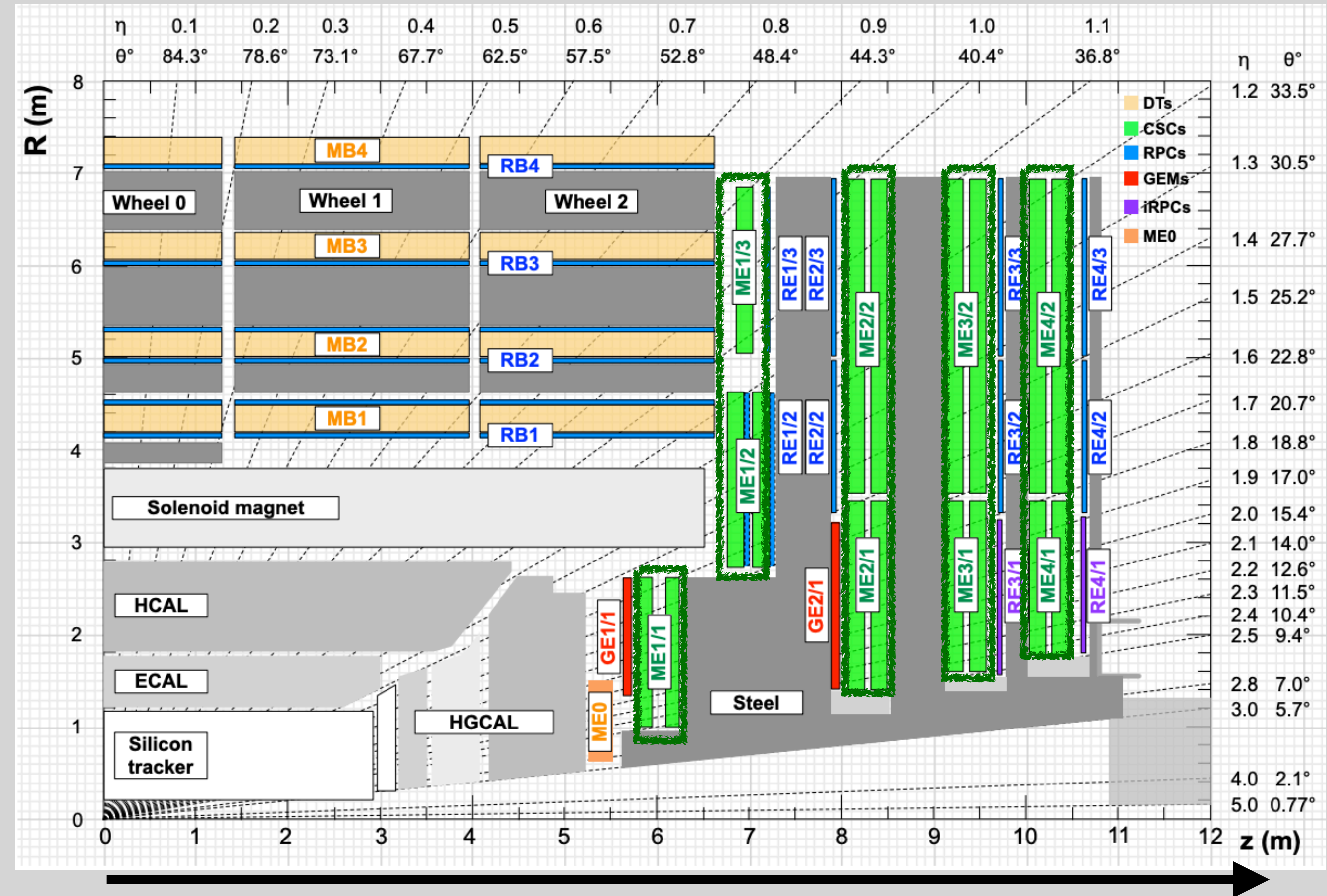
- Muon system employs different technologies
  - Barrel: Drift Tube + Resistive Plate Chamber (RPC)
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[CMS-TDR-016](#)

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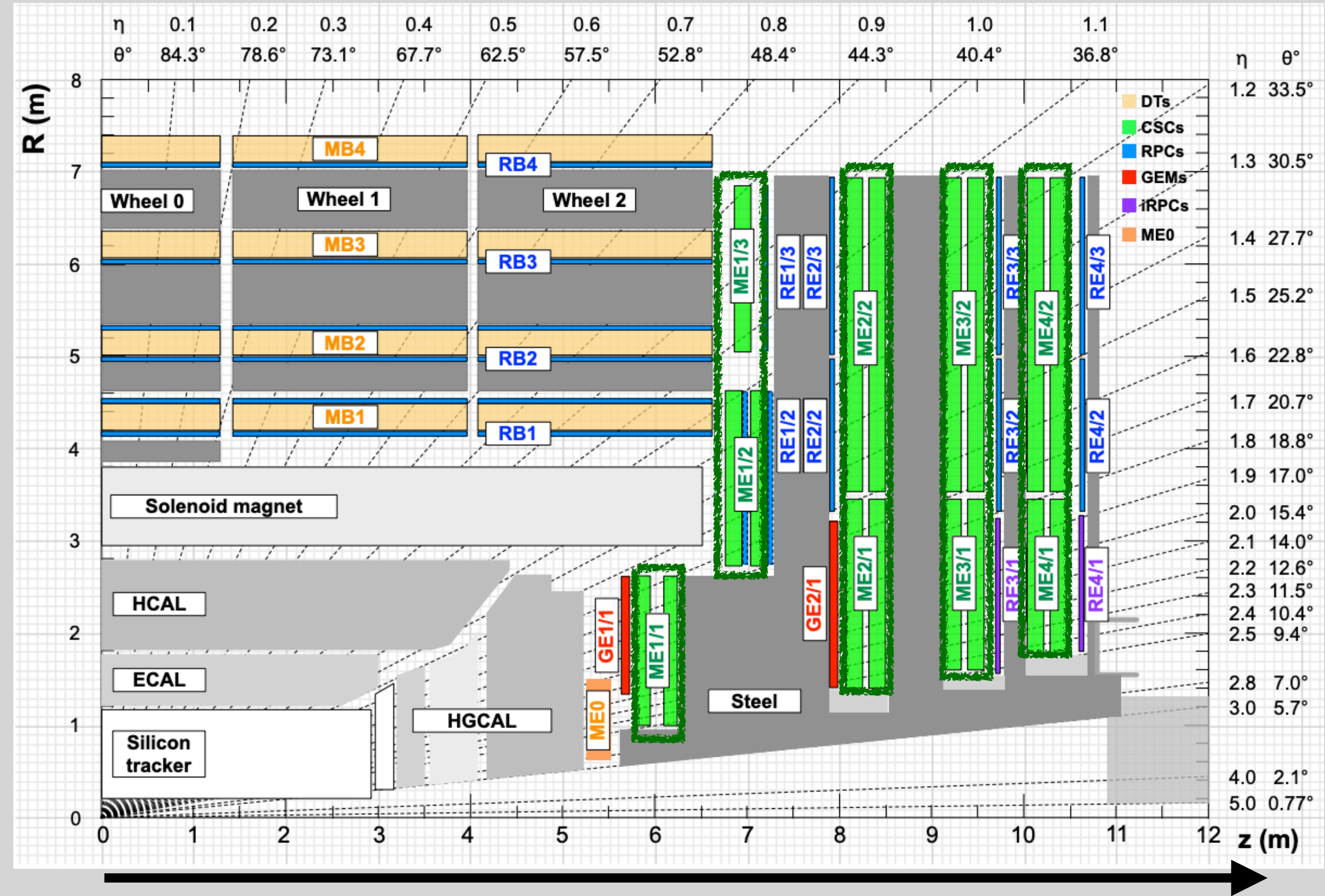
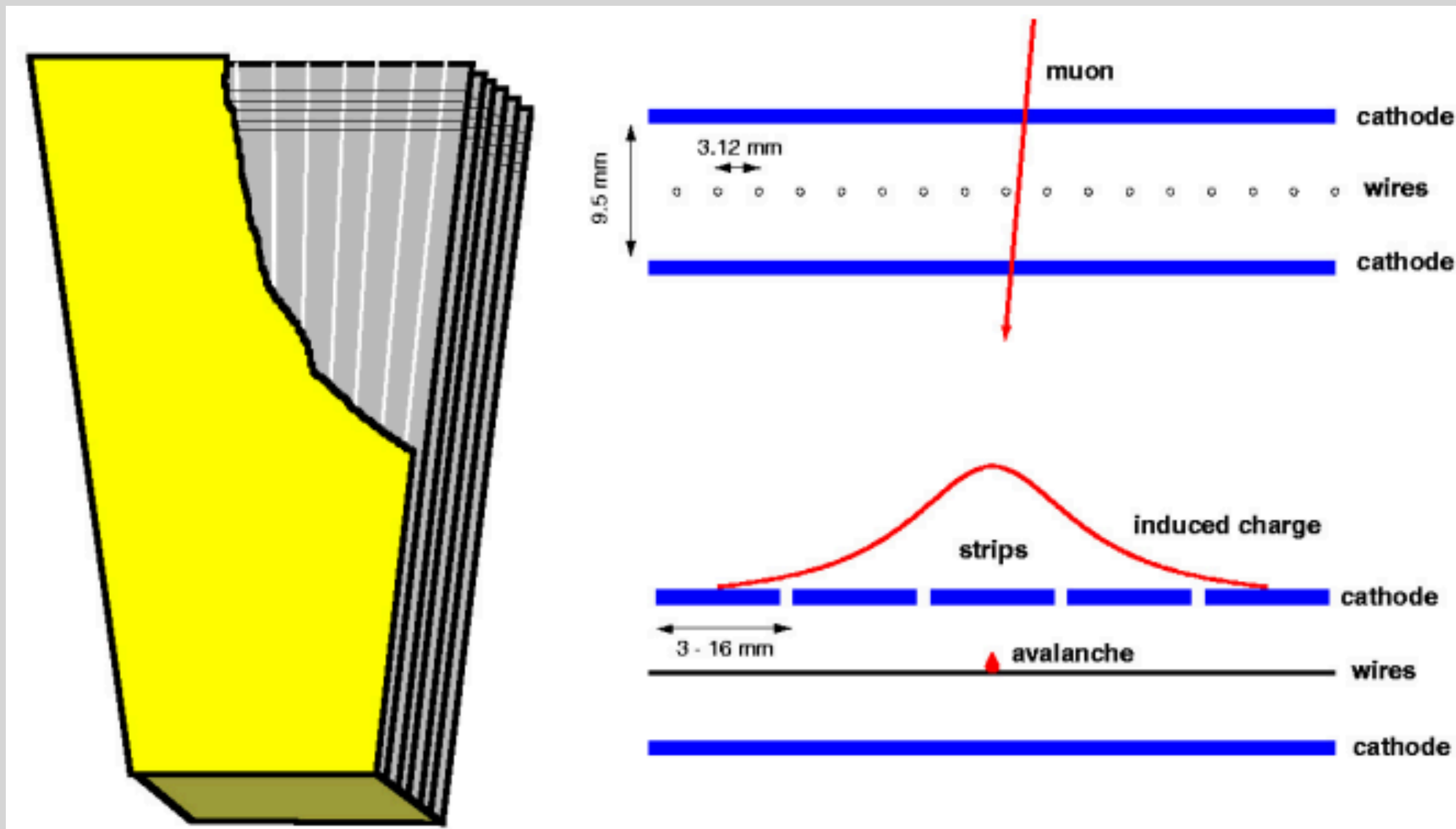
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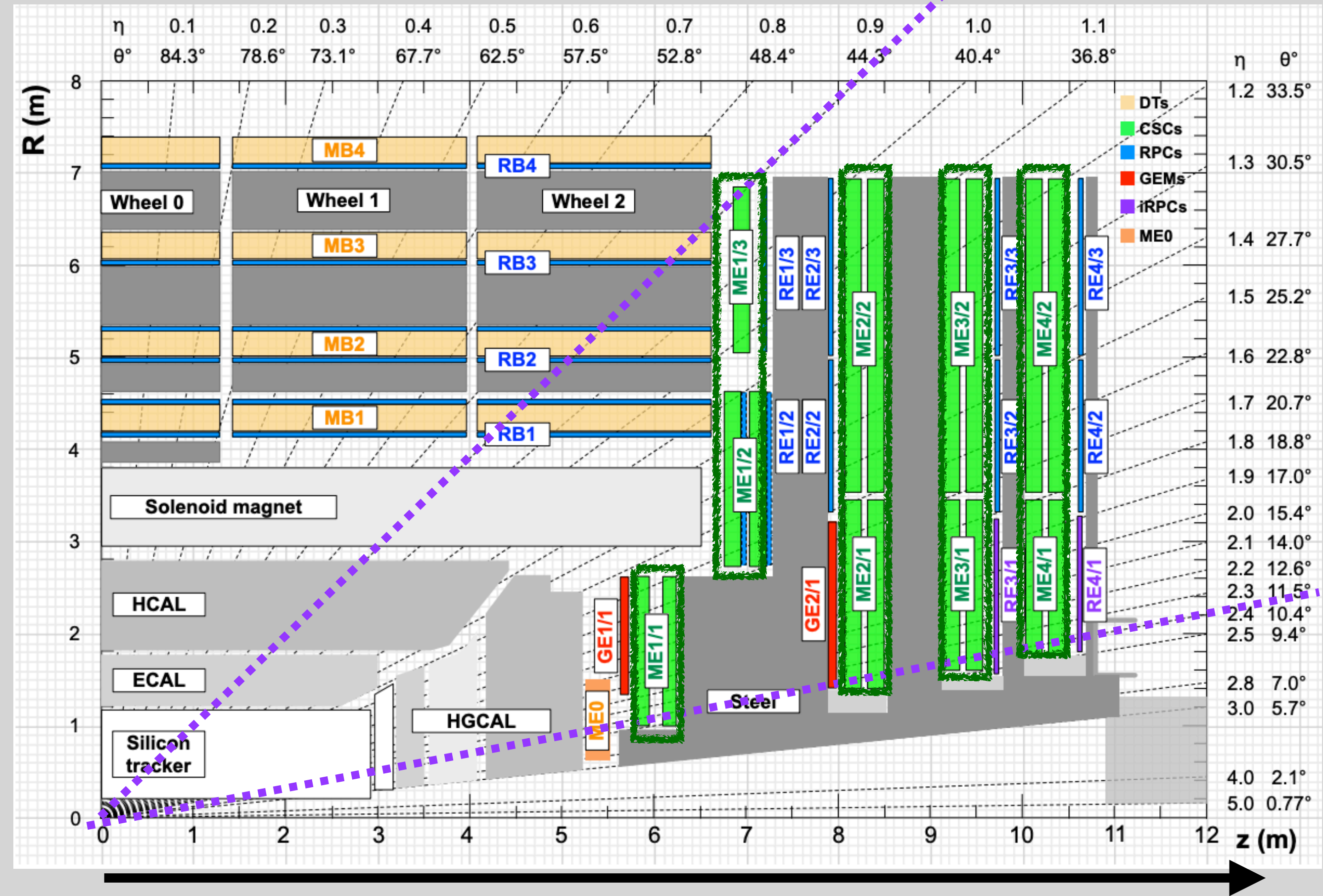
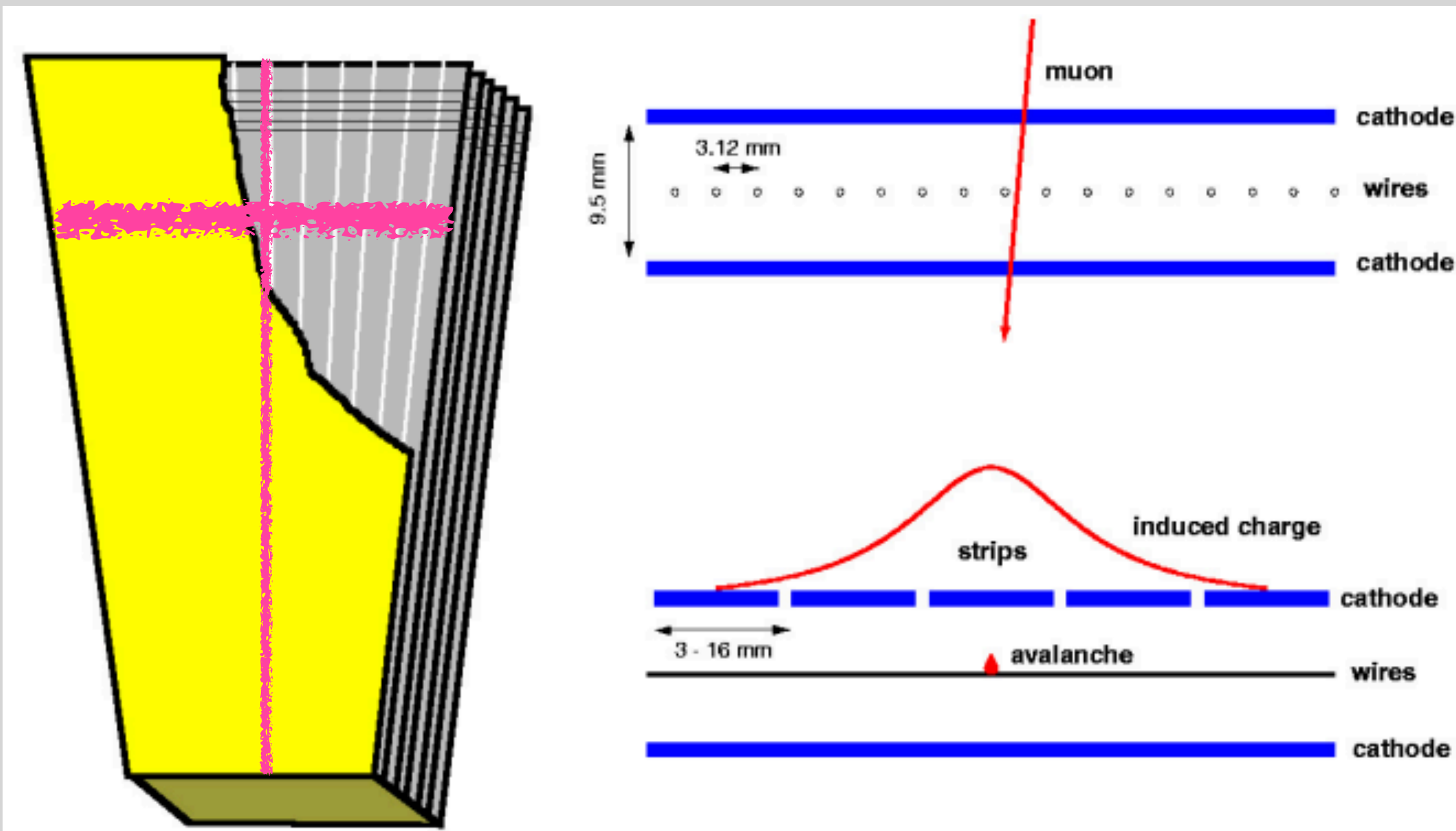
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CMS-TDR-016

# What Are Cathode Strip Chambers (CSCs)?

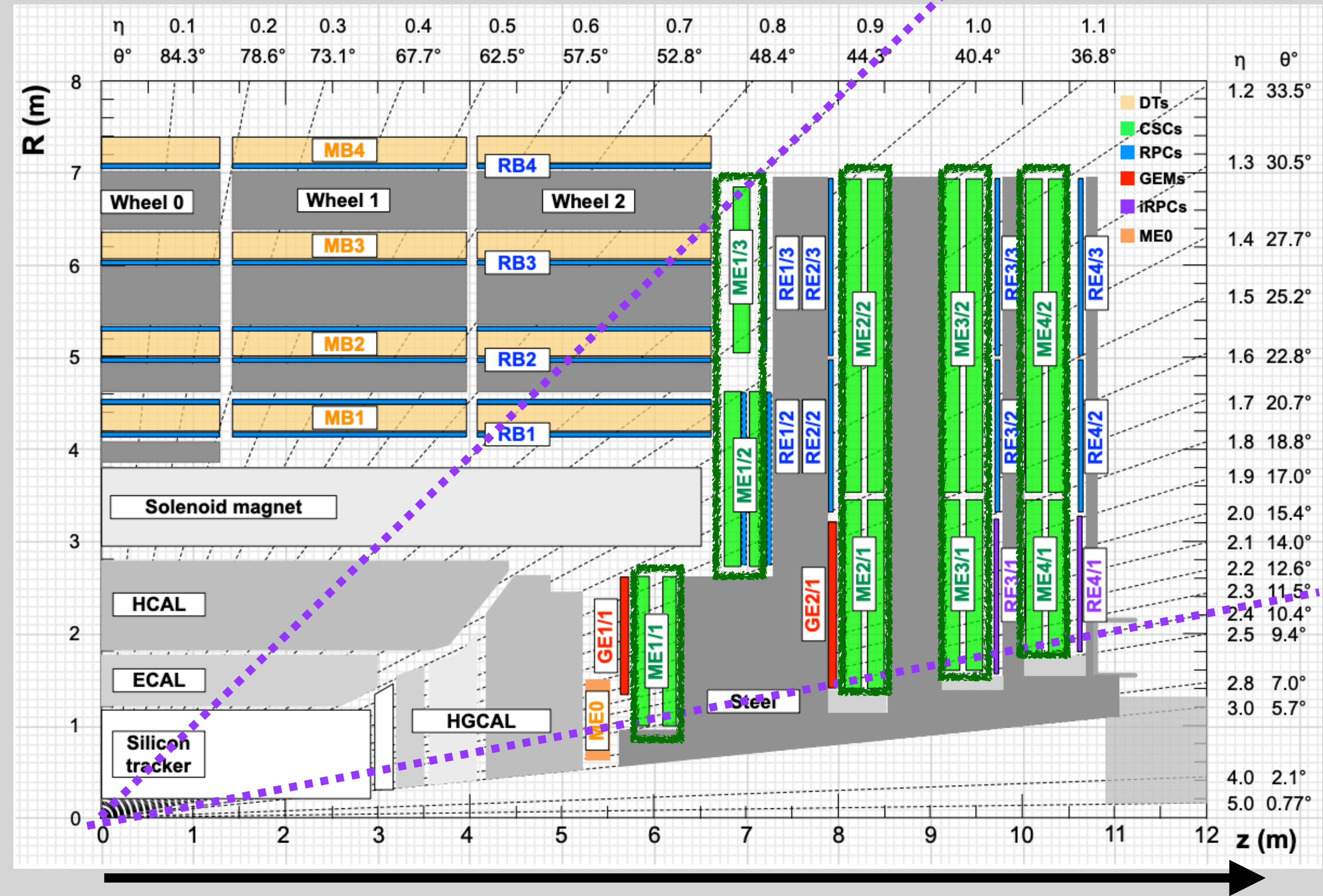
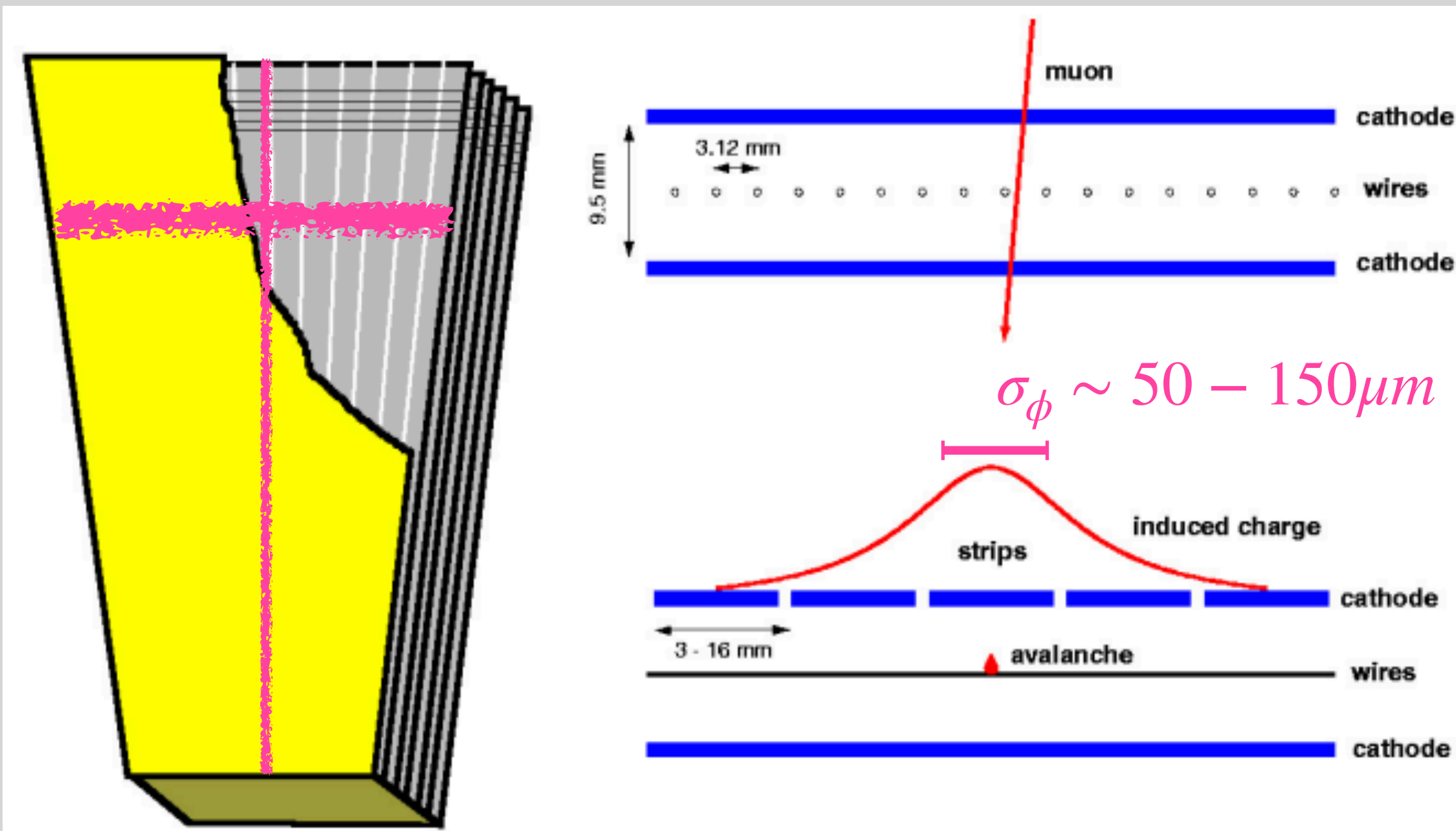
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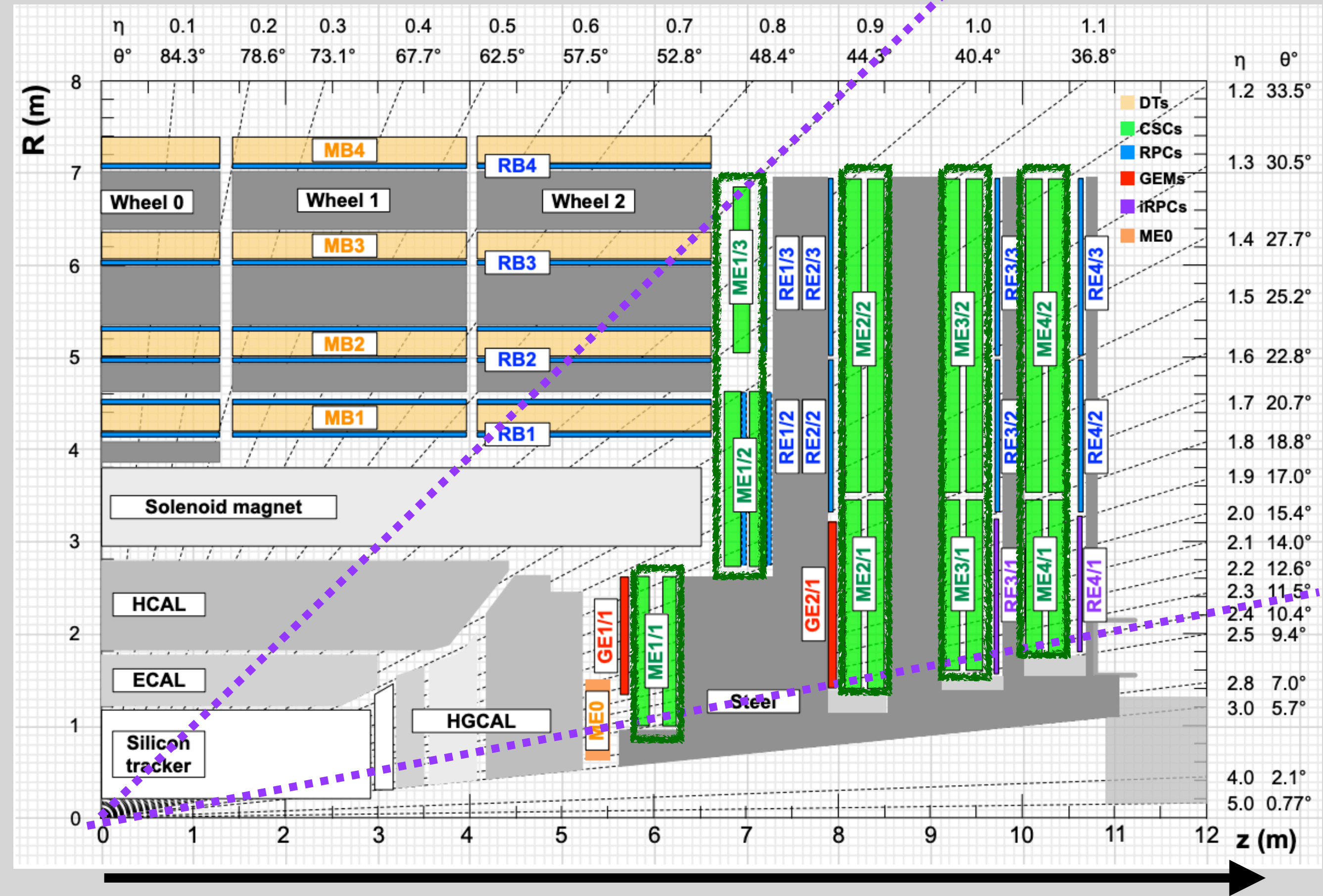
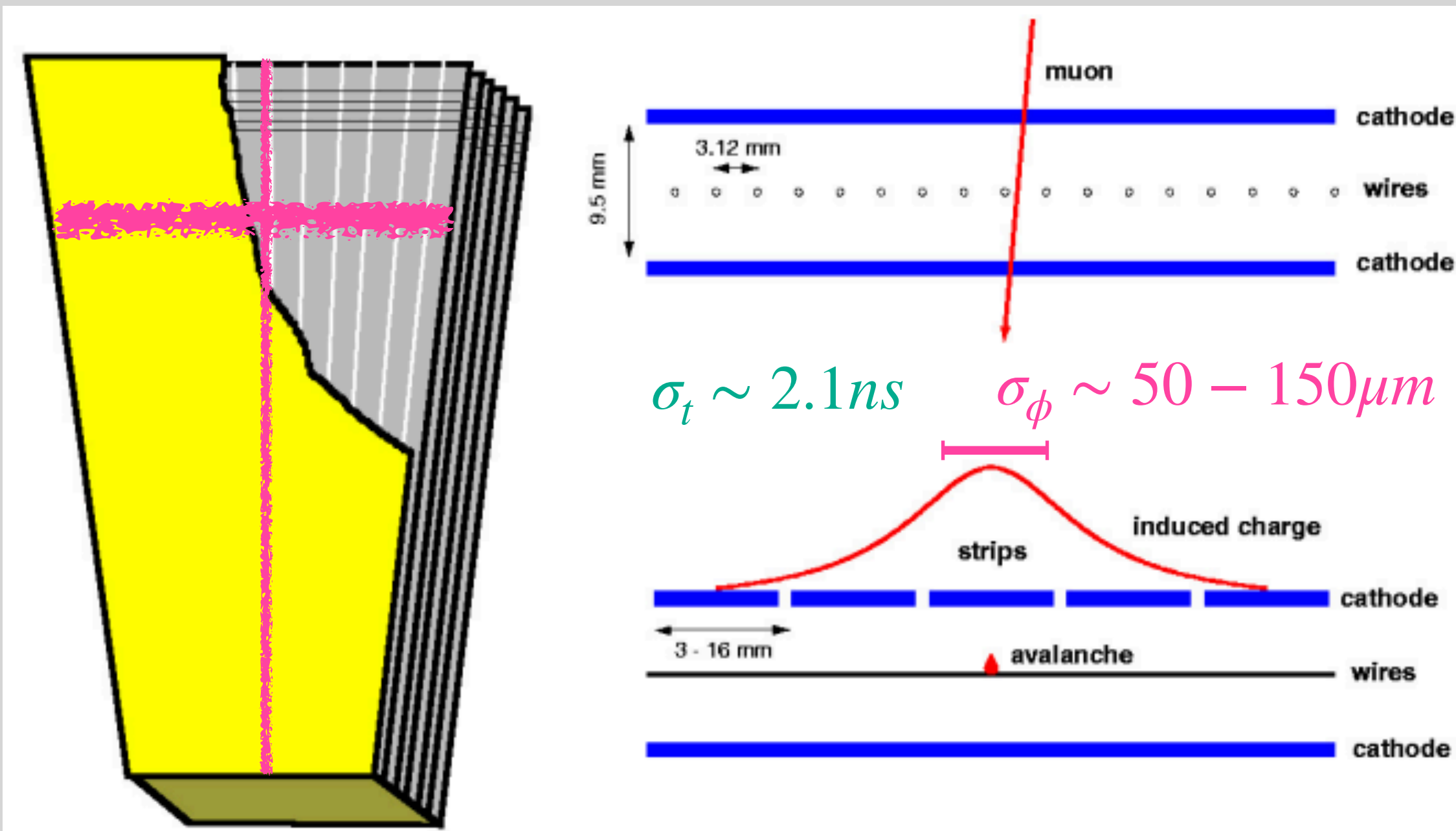


CMS-TDR-016

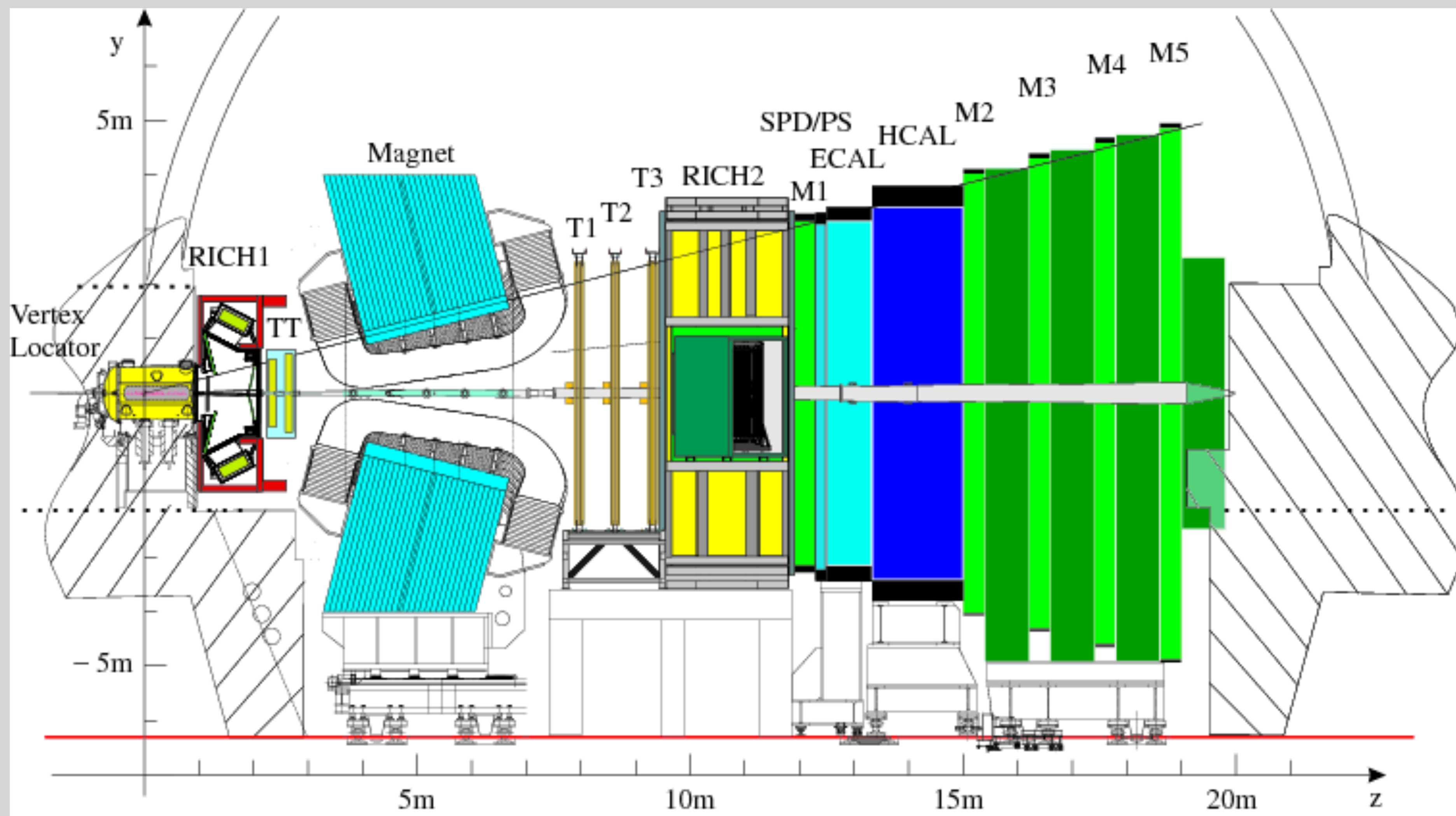


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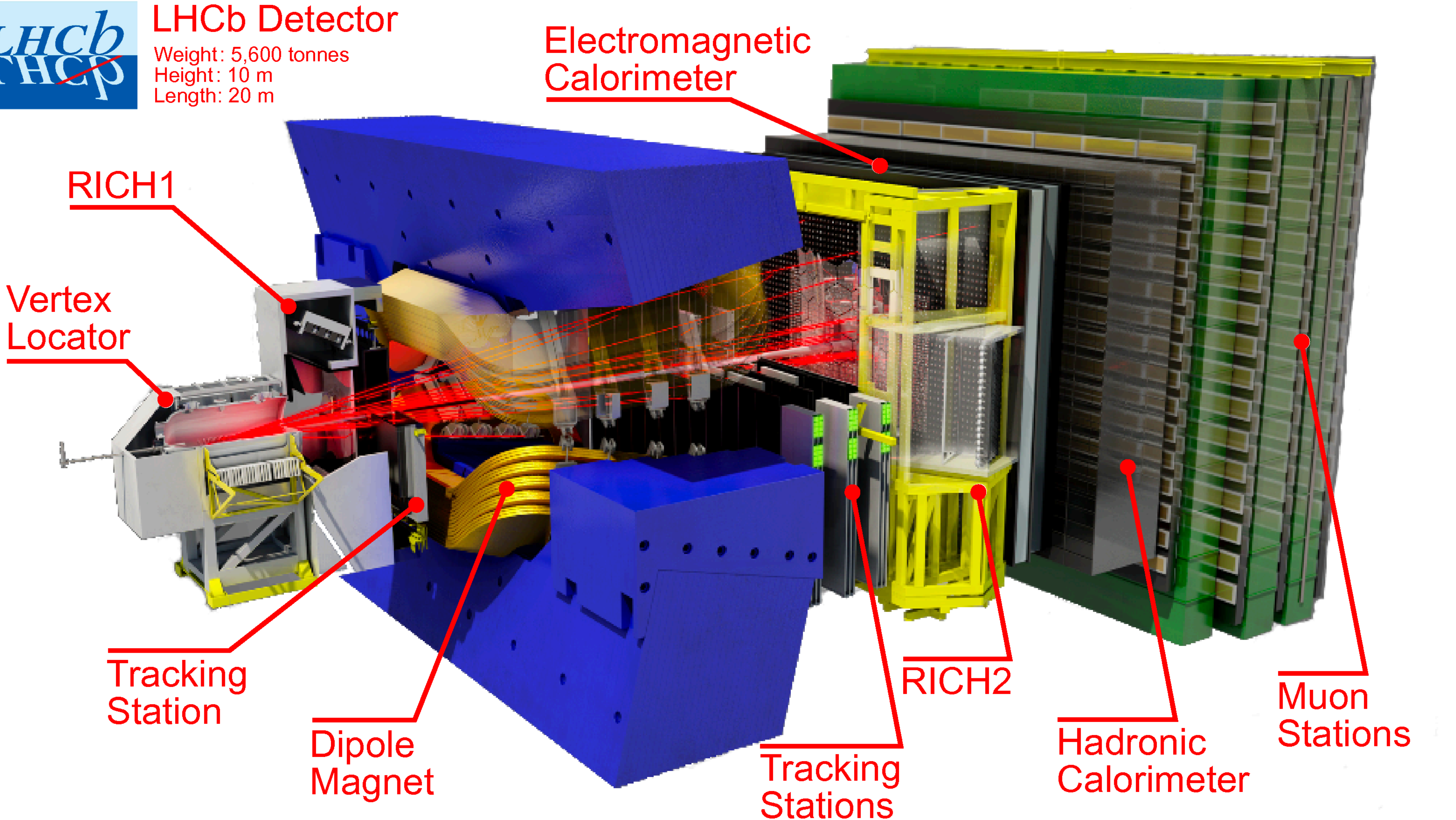
CMS-TDR-016





# LHCb Detector

Weight: 5,600 tonnes  
Height: 10 m  
Length: 20 m



RICH1

Vertex Locator

Tracking Station

Dipole Magnet

Tracking Stations

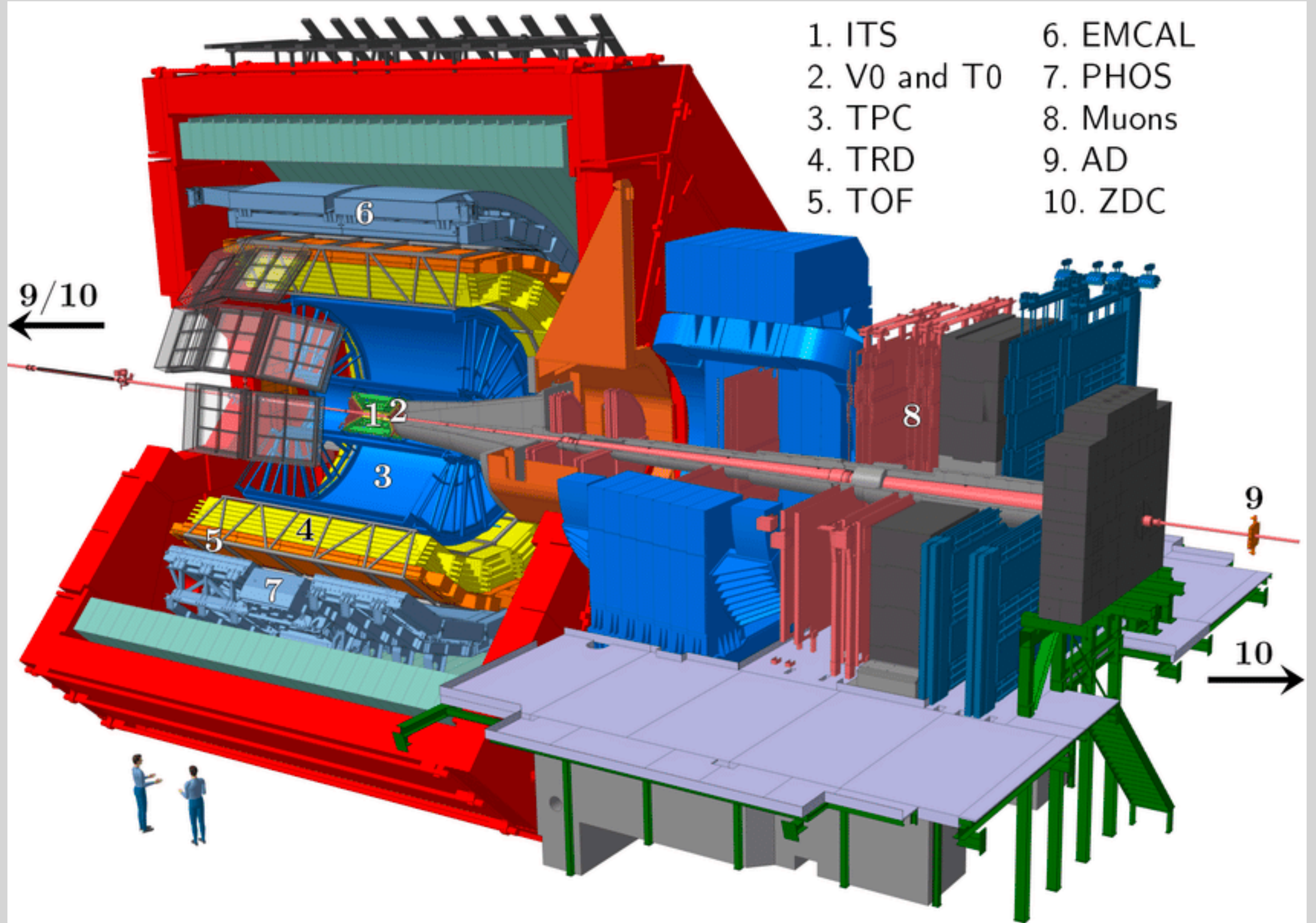
RICH2

Electromagnetic Calorimeter

Hadronic Calorimeter

Muon Stations

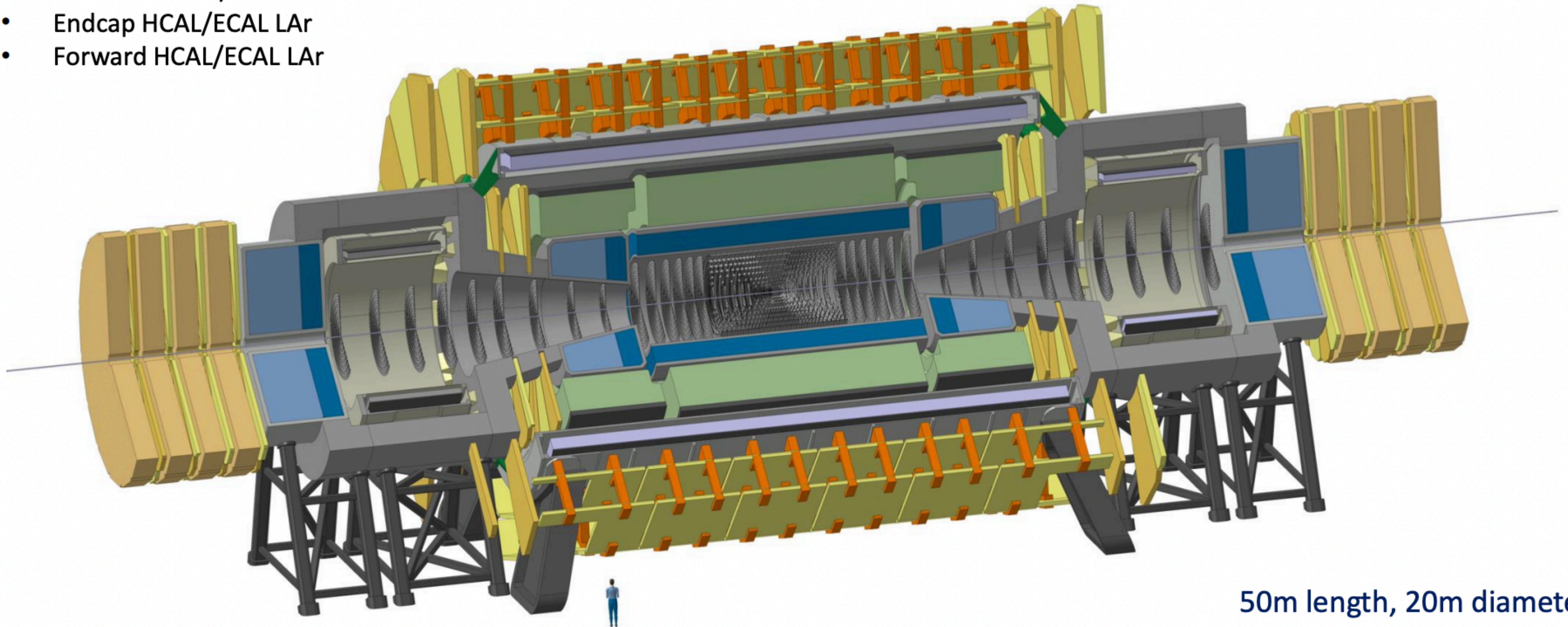
# ALICE



# 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

