LHC Data Analysis – Part I

PHYS 250 (Autumn 2025) – Lecture 15

David Miller

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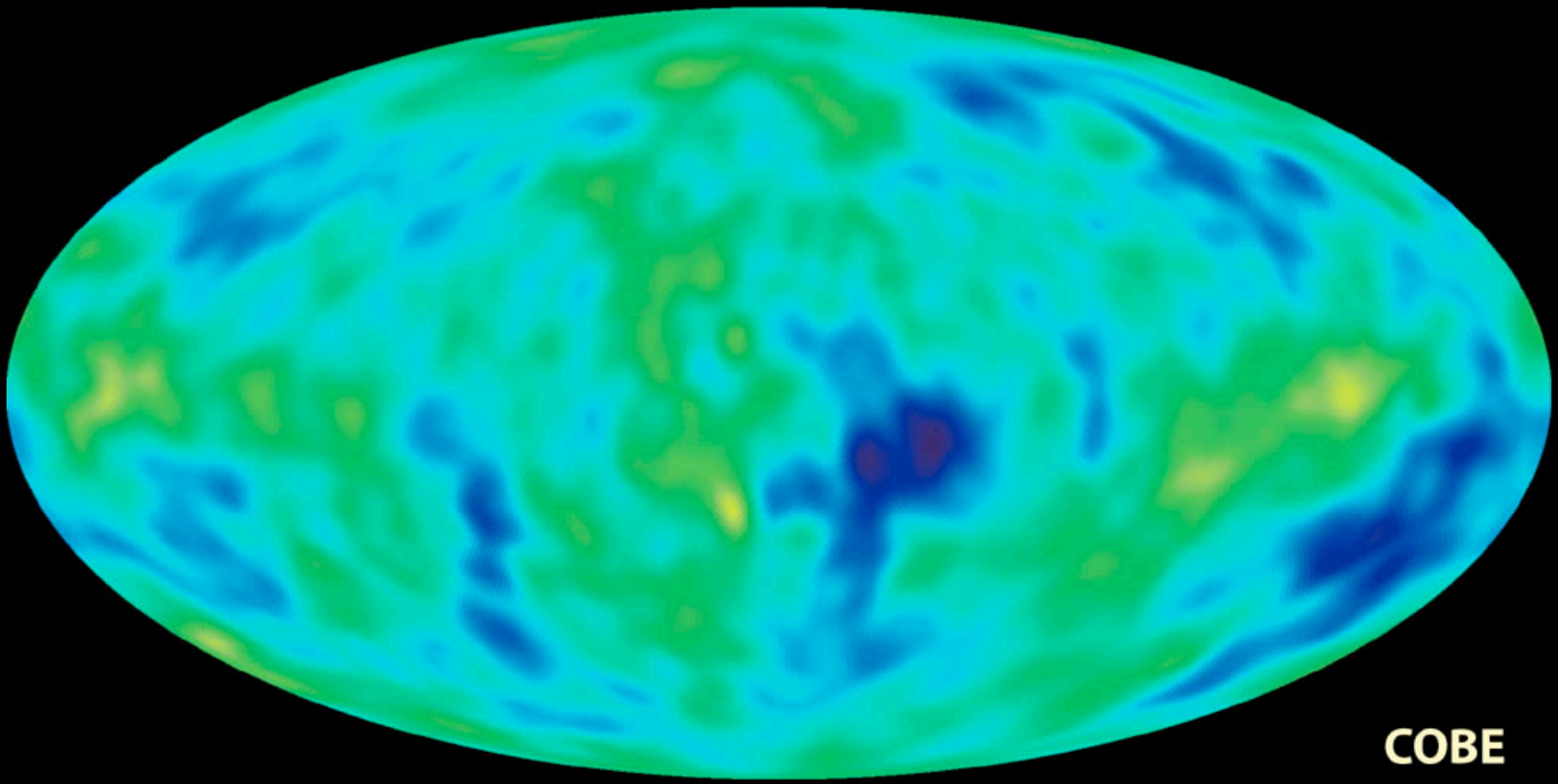
University of Chicago

November 20, 2025

Outline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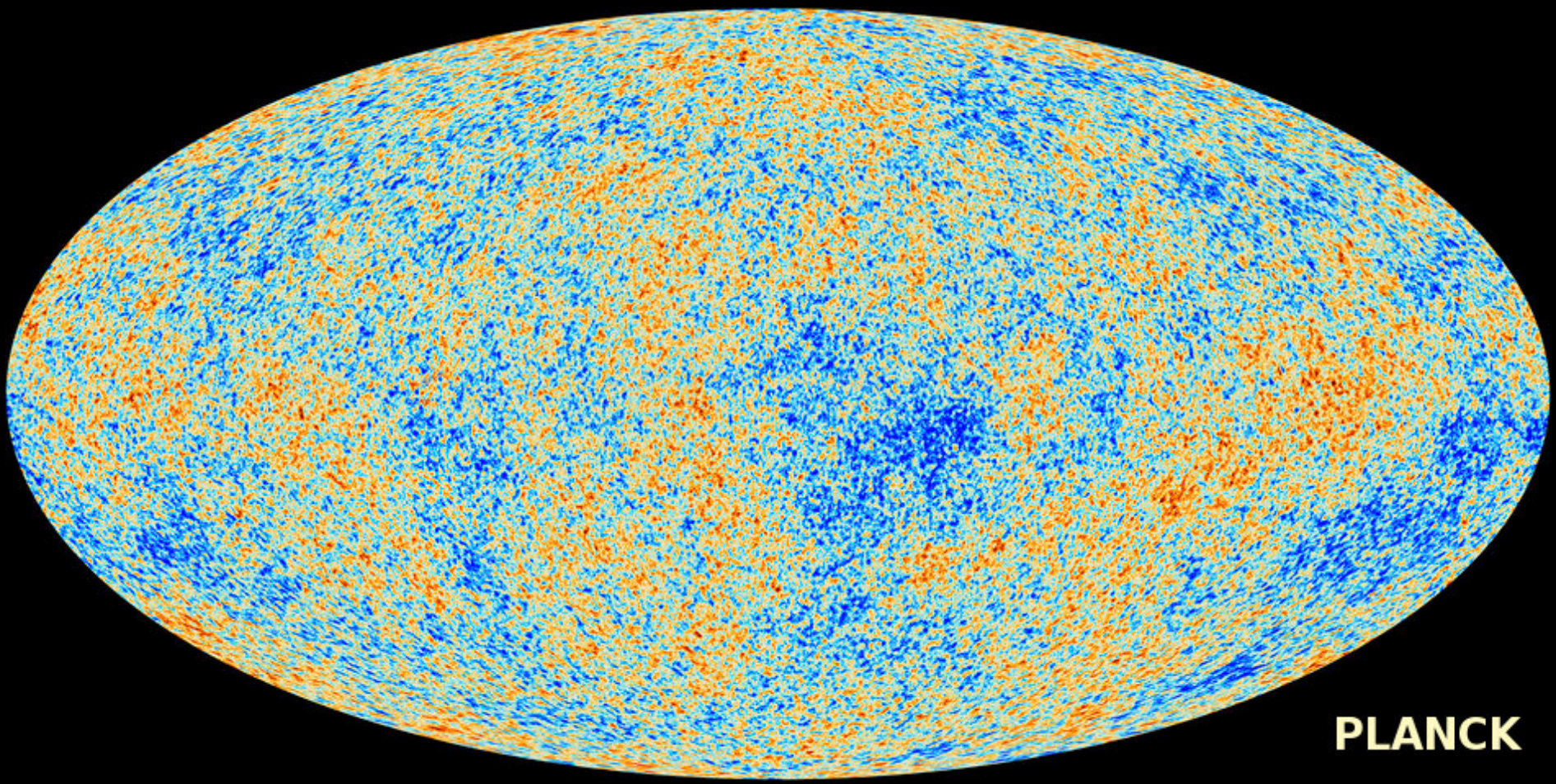
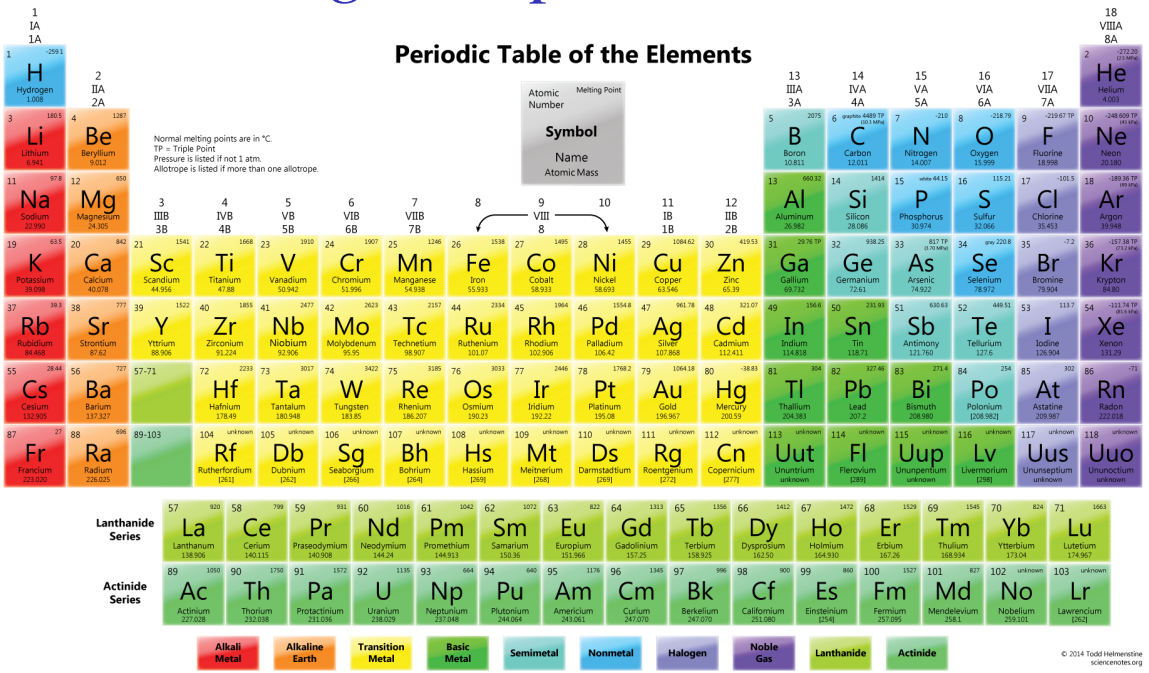

PLANCK

Uncovering new patterns in nature



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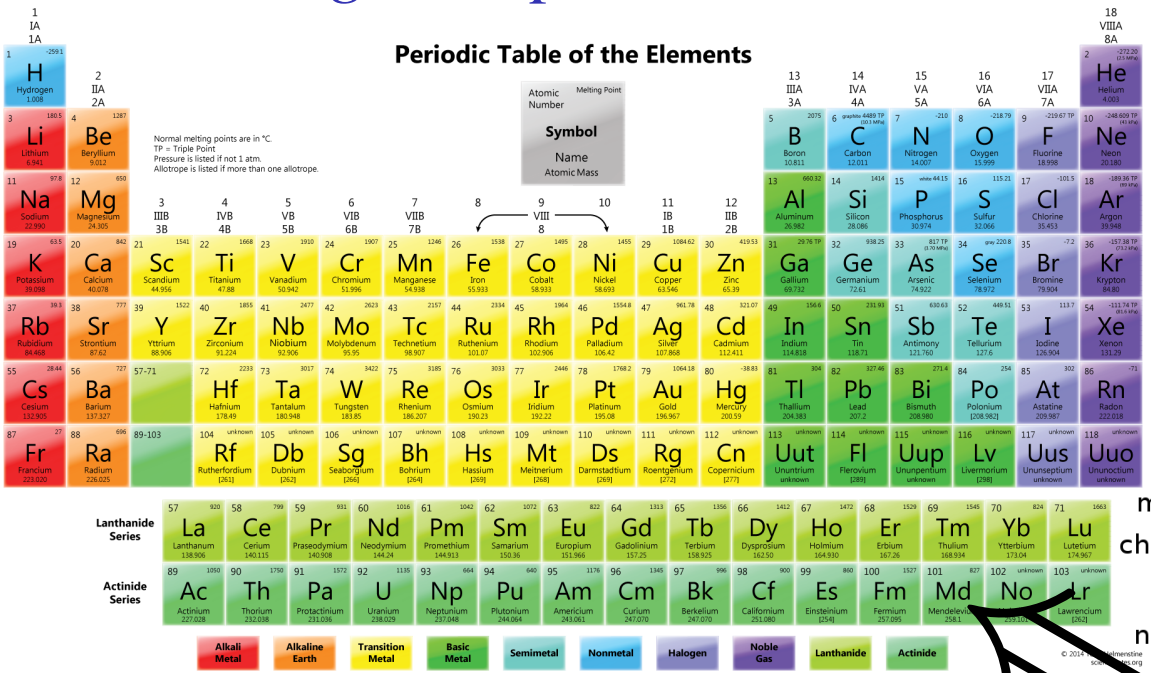
Uncovering new patterns in nature



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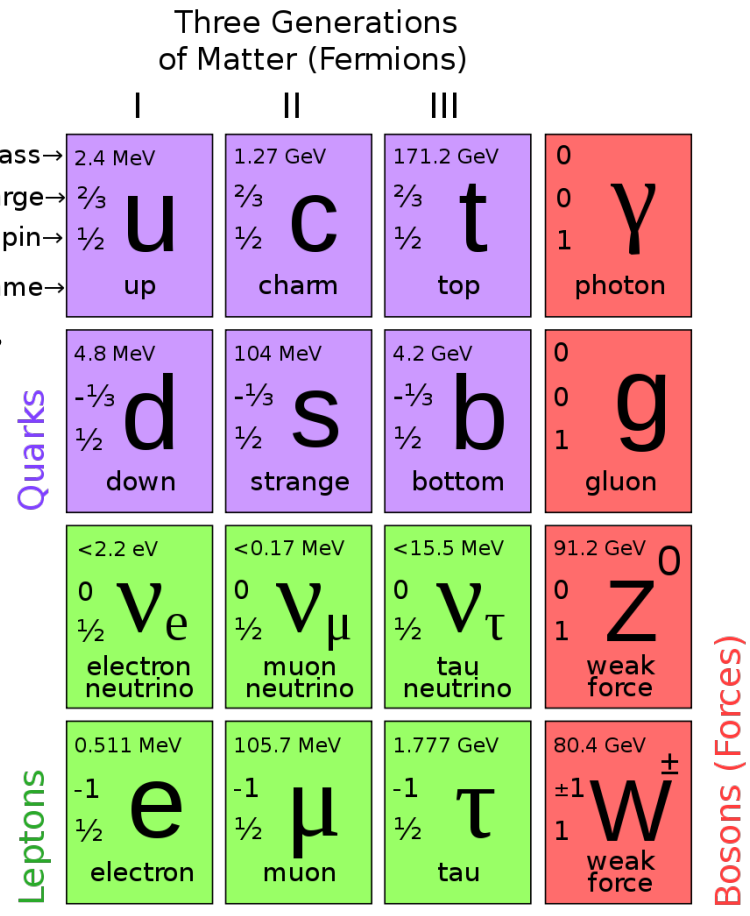

meta-synthesis.com

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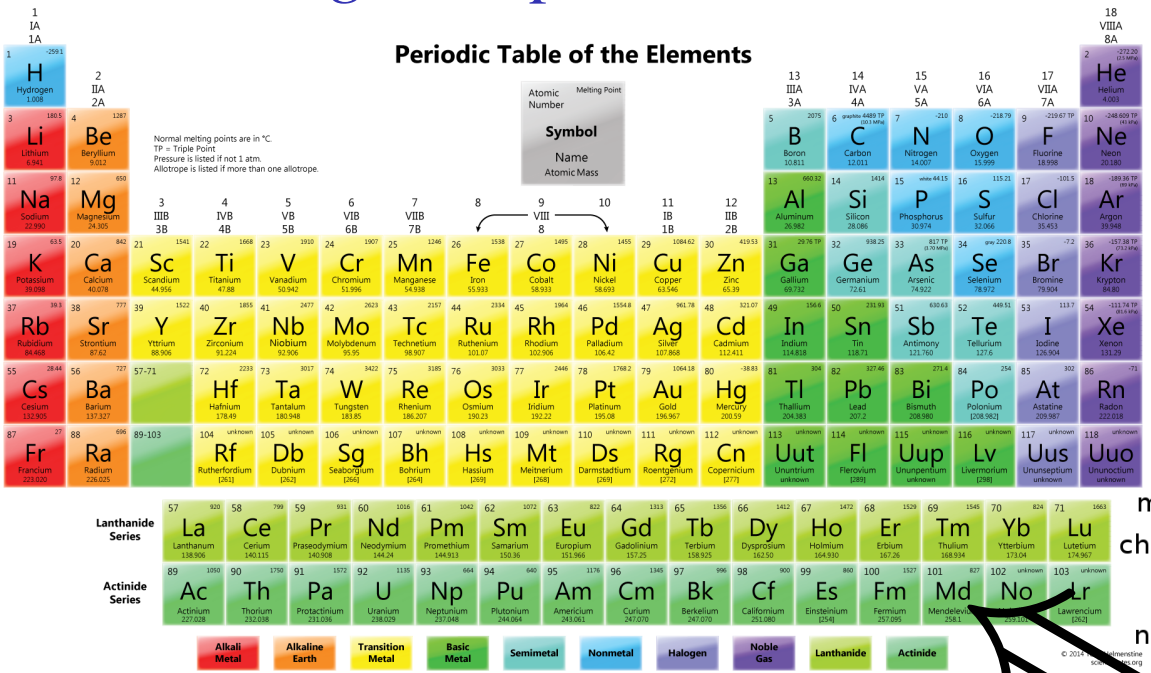
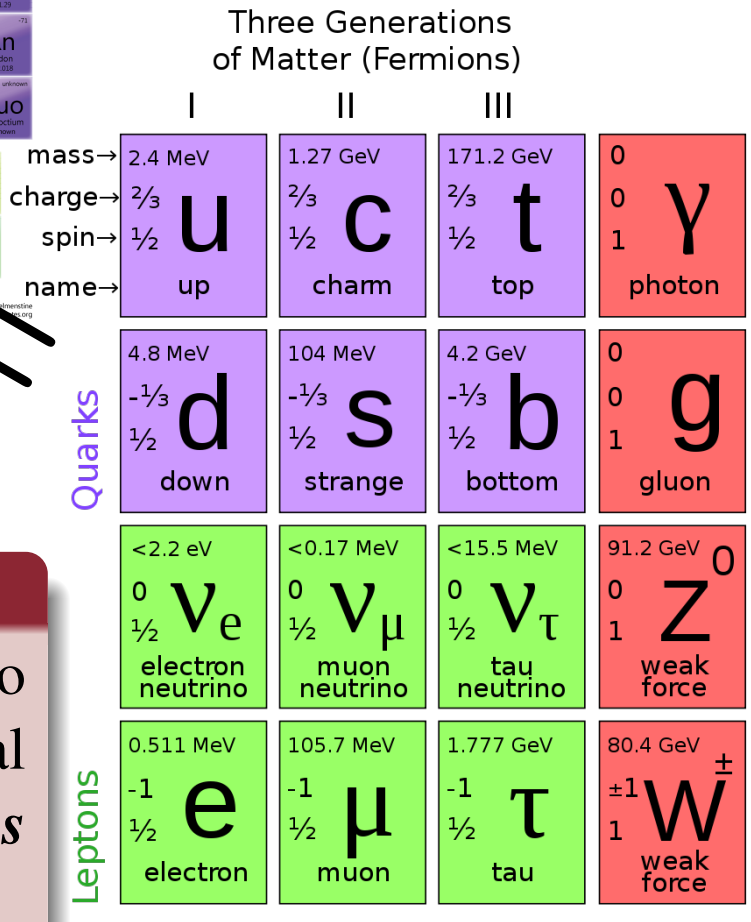
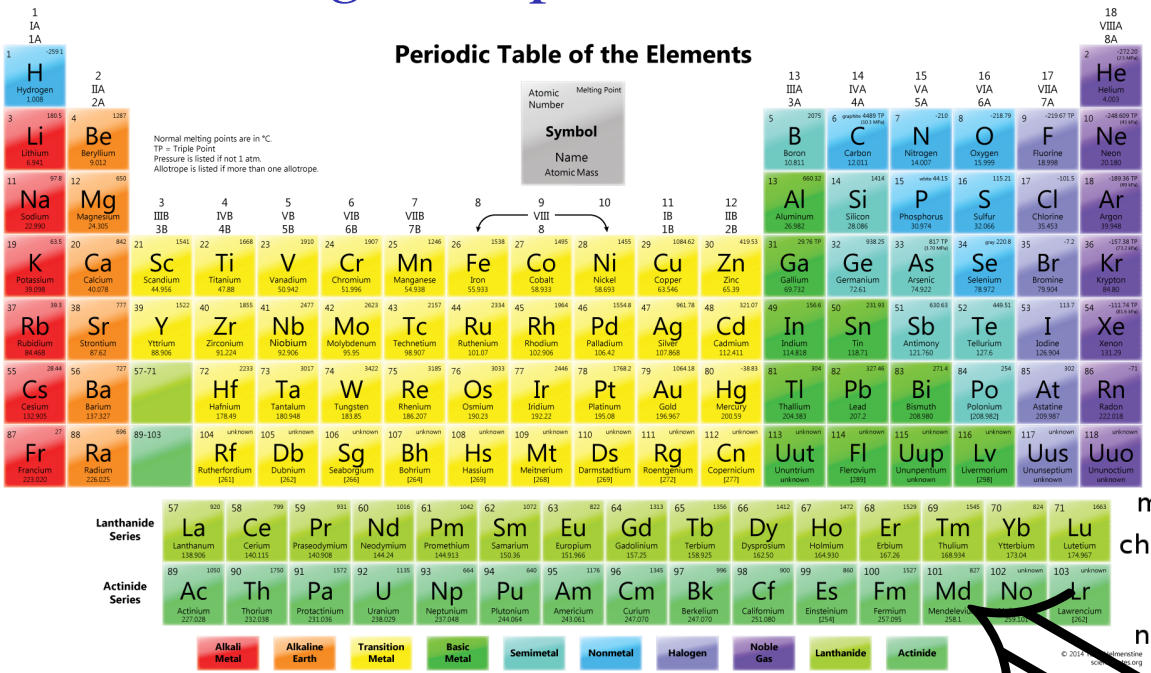




Periodic Table of the Fundamental Particles

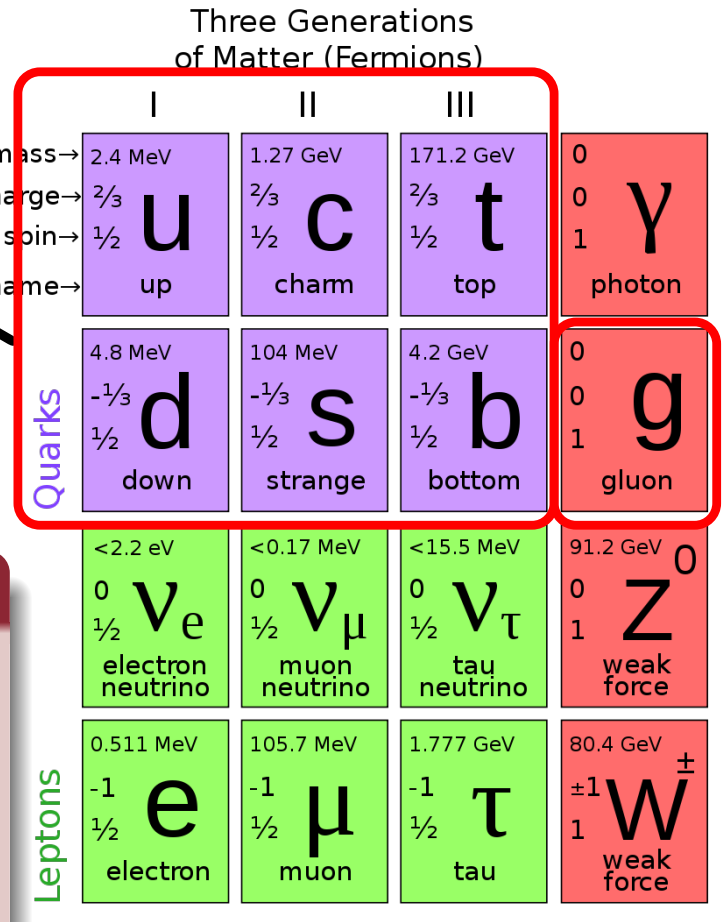
Seeking to understand patterns has led us to our current understanding of the fundamental structure of matter....***but we know that pieces are still missing.***

Uncovering new patterns in nature



Quarks → hadrons → **JETS**

Much of what I do focuses on these particles and their visible signatures: **JETS**



Periodic Table of the Fundamental Particles

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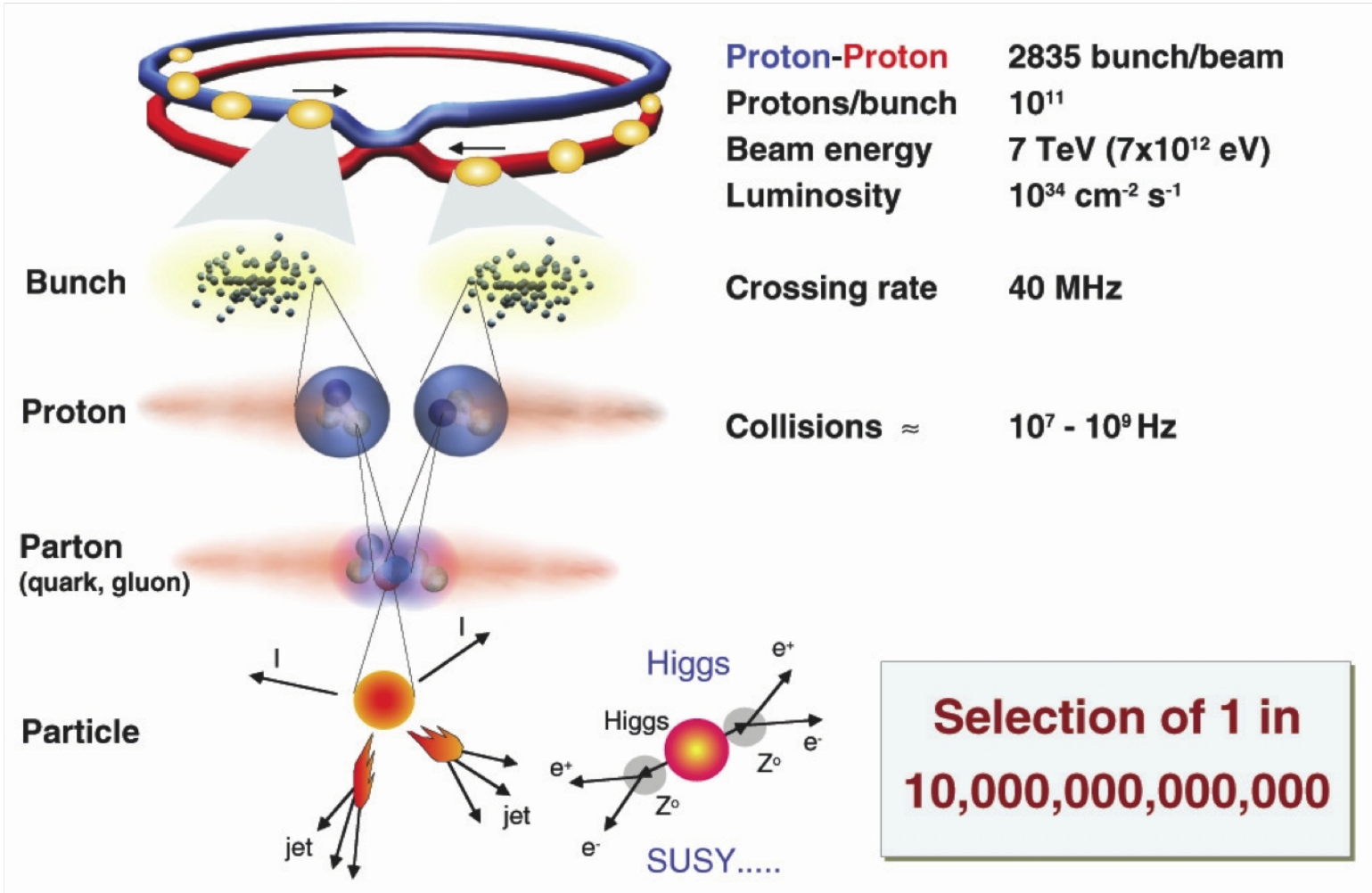
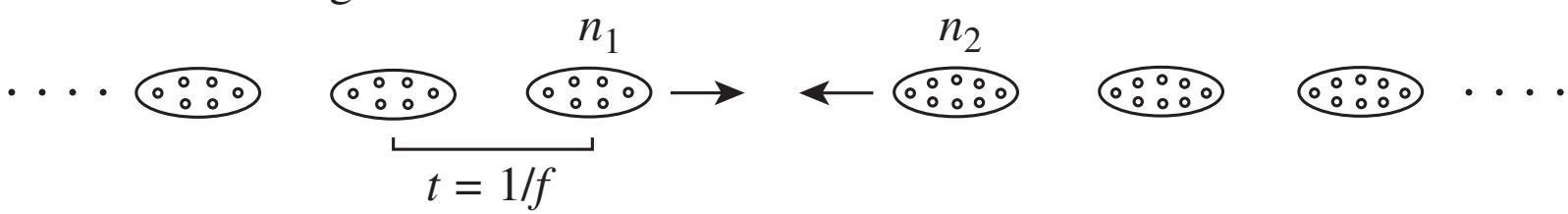
Outline

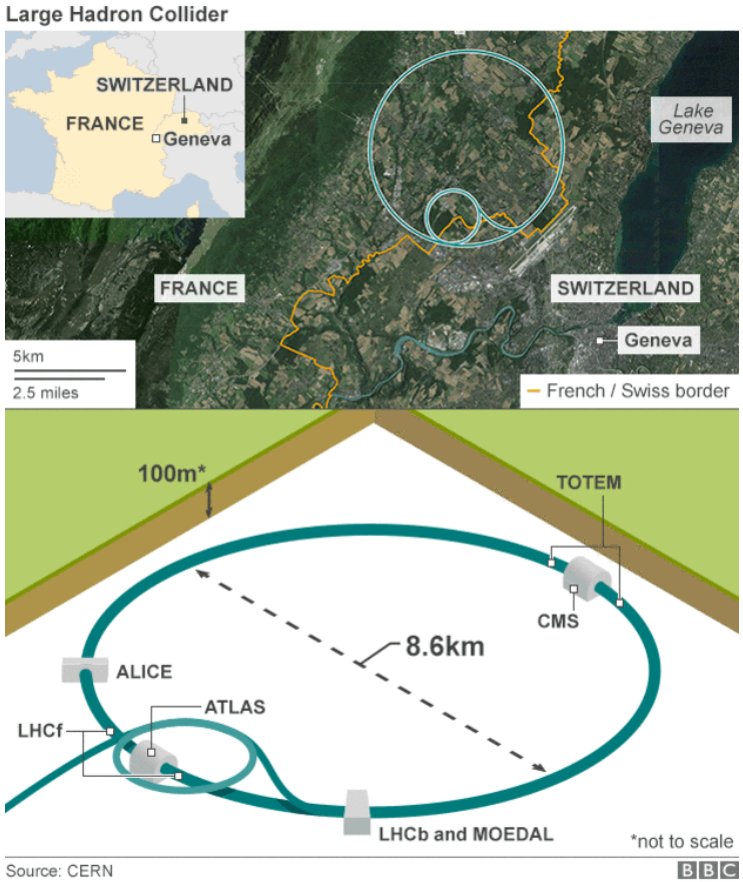
Particle Collider: General Principles

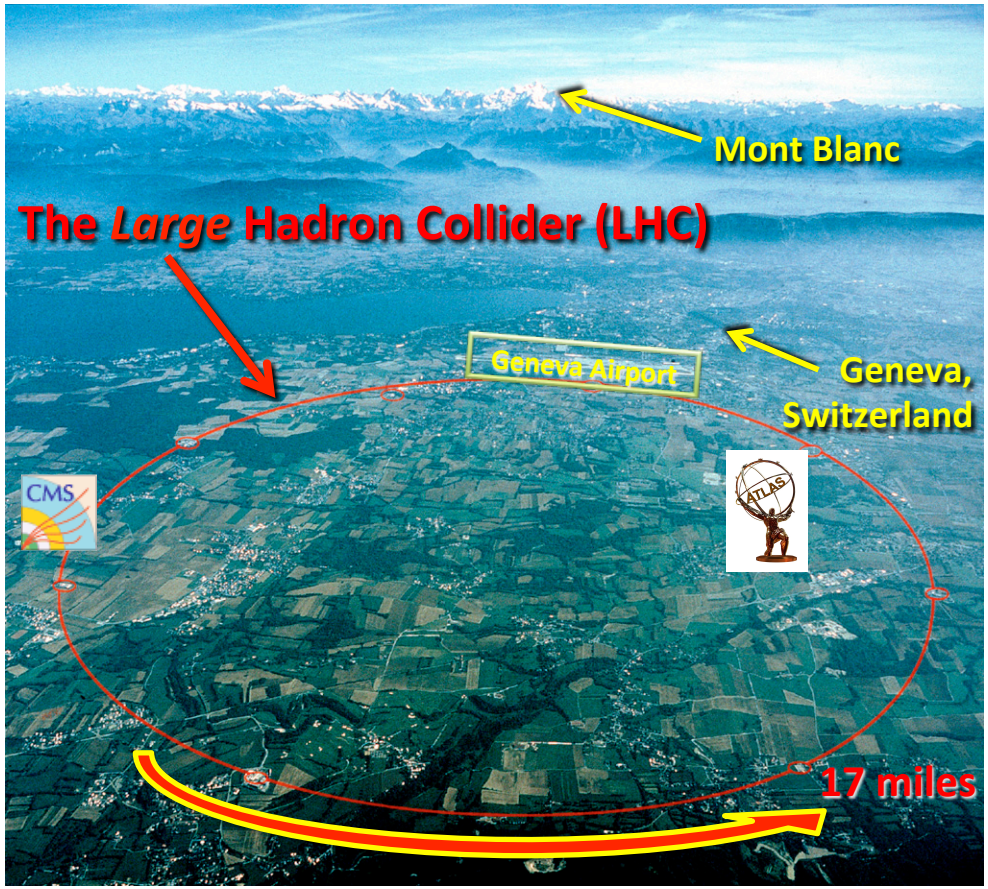


Colliding beam



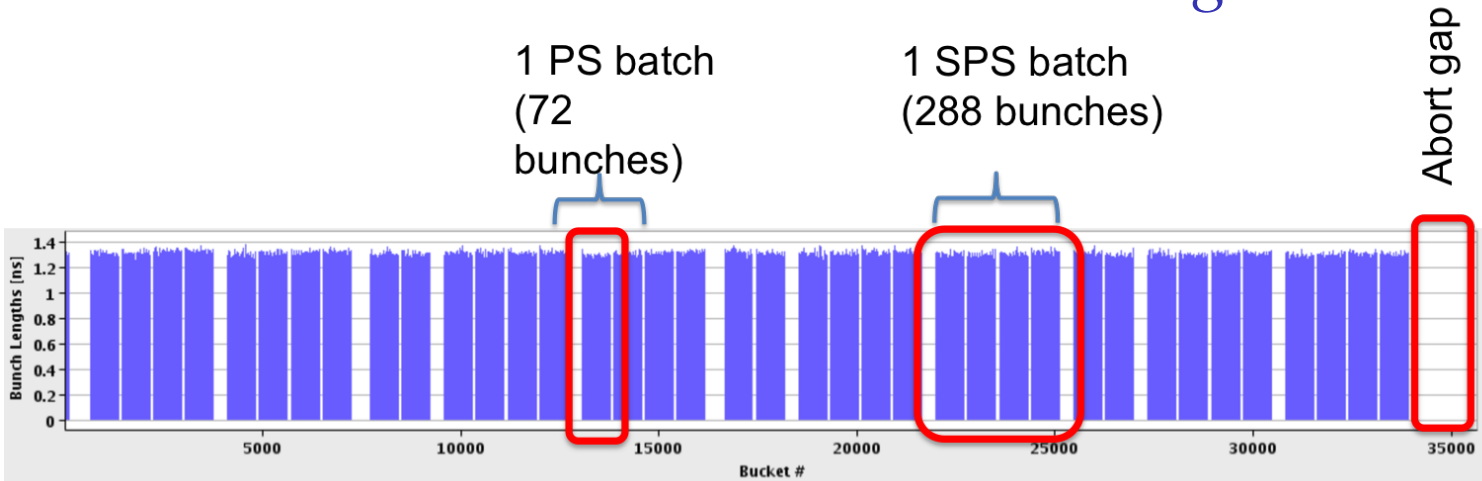
Particle Collider: The Large Hadron Collider



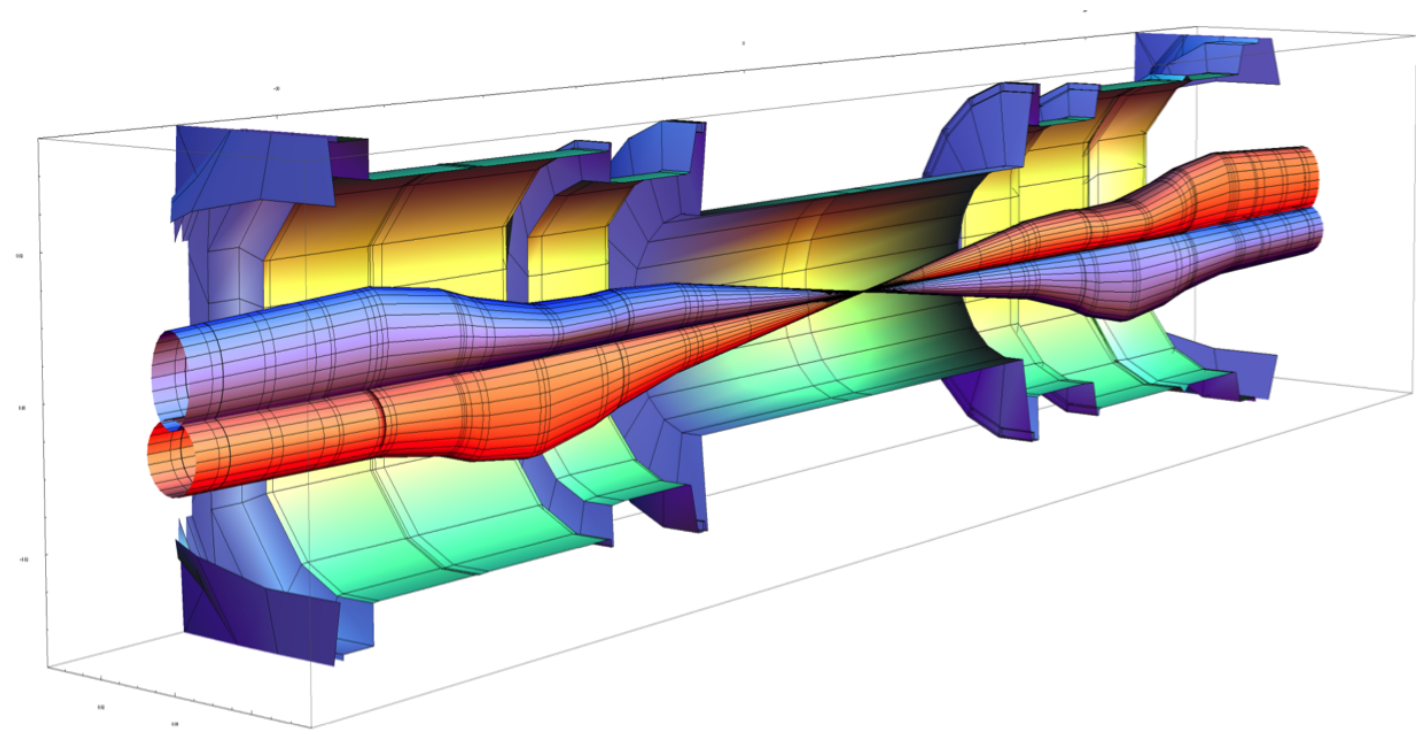


- Some key characteristics:
  - 100 m underground, 17 miles (27 km) in circumference, 25ns bunch spacing, 10^{11} protons per bunch, 2808 bunches per ring

The LHC bunch structure and interaction region

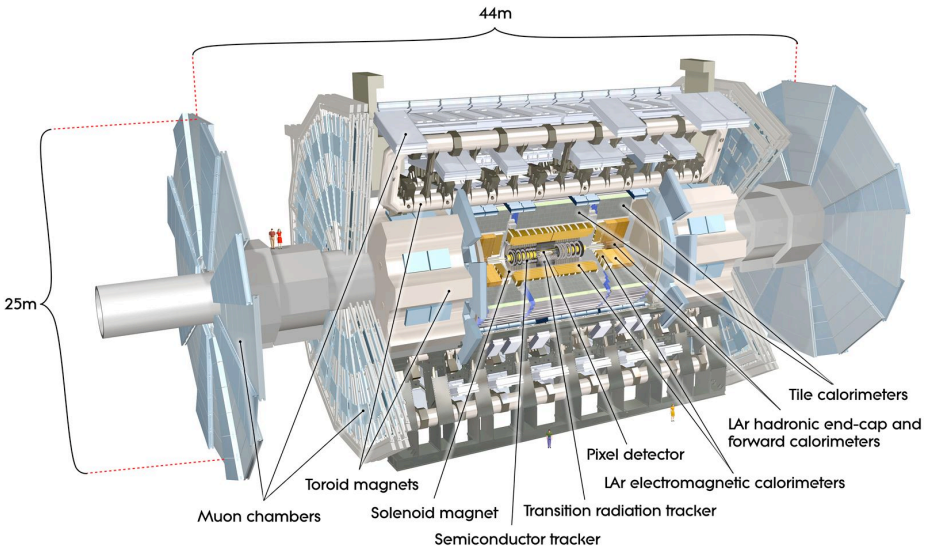


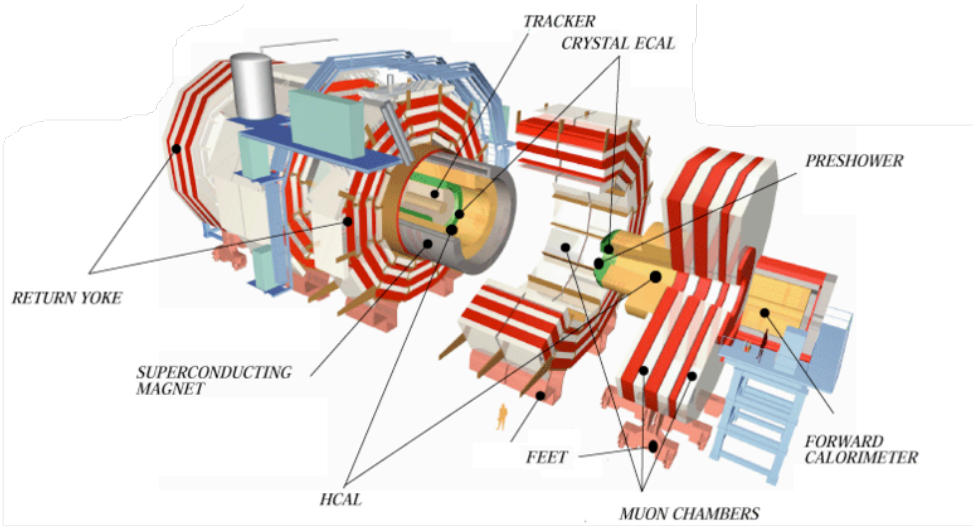
26.7 km 2800 bunches



Outline

The experimental tools at the LHC



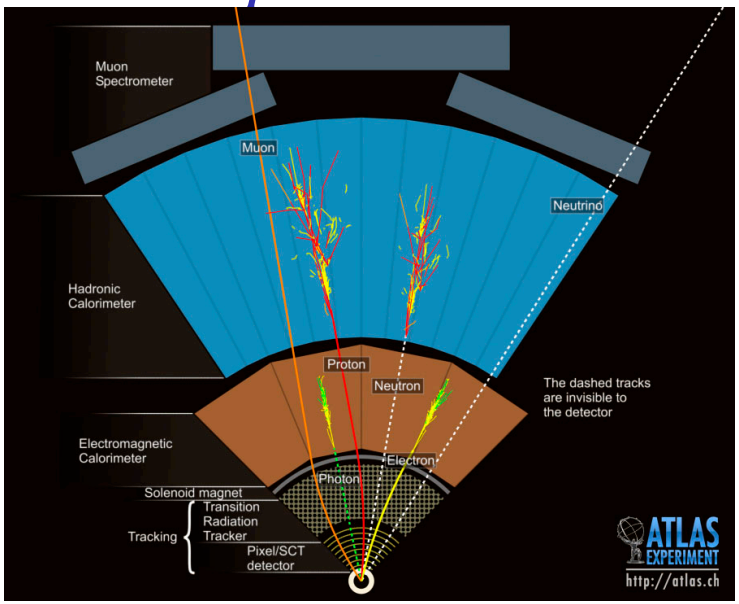


- **Weight**: 7000 tons
- **Length** $\times$ **height**: 46m $\times$ 25m
- ***B*-field**: 4 T (2 T solenoid)
- 100,000,000 electronic channels
- 3000 km of cables

- **Weight**: 12500 tons
- **Length** $\times$ **height**: 21.6m $\times$ 15m
- ***B*-field**: 4 T
- 100,000,000 electronic channels
- 76,000,000 Si channels, 205 m^2

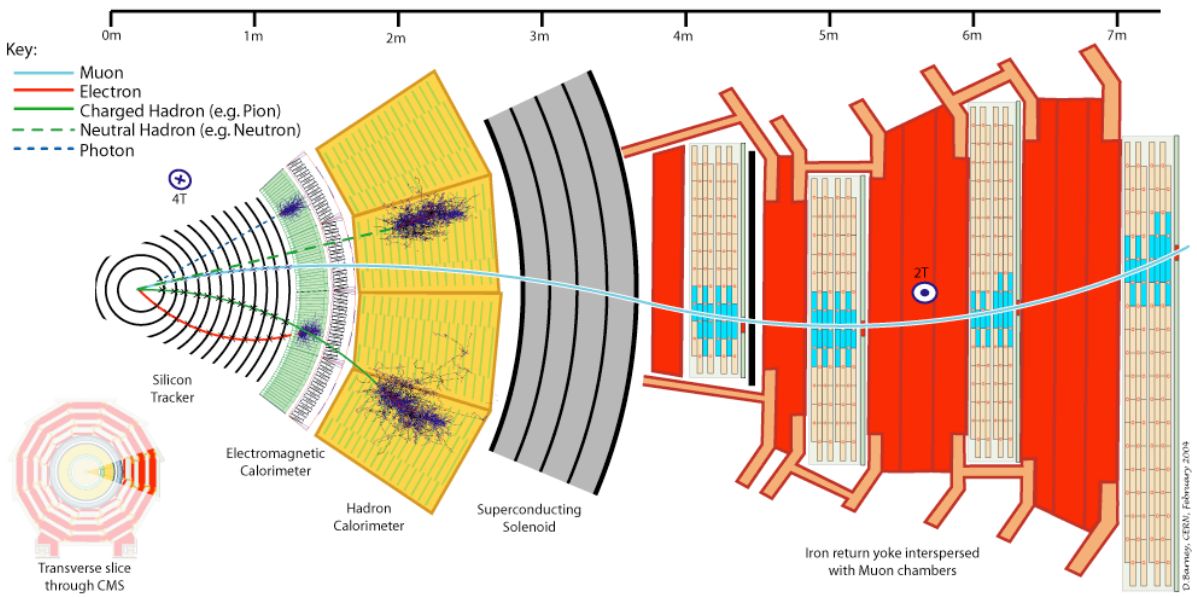
Each is a hugely complex single detector built out of many

The experimental tools at the LHC



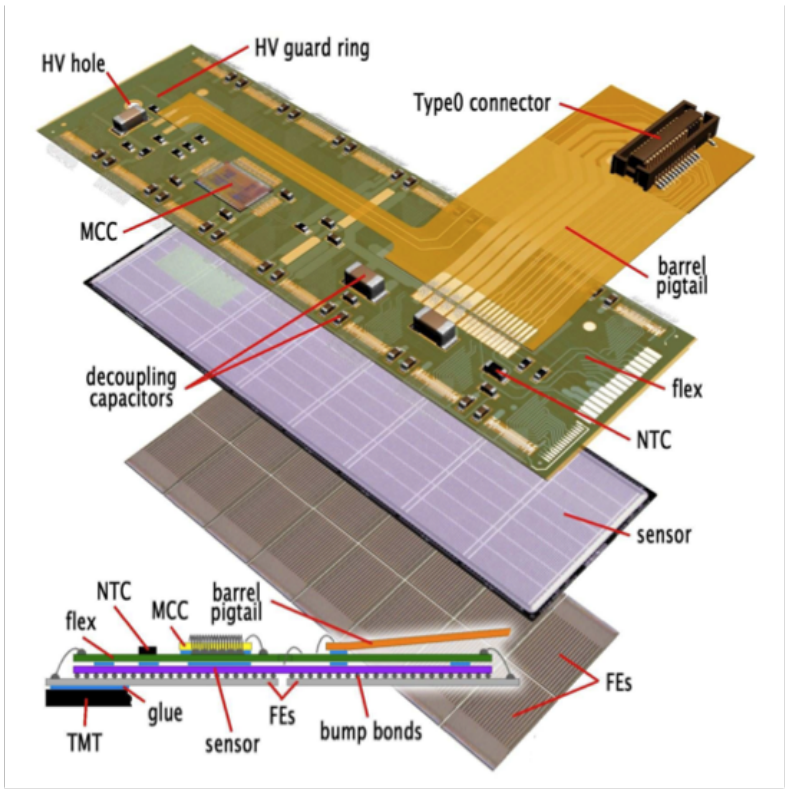
Each "detector" is comprised of several "sub-detectors" with each devoted to a specific task

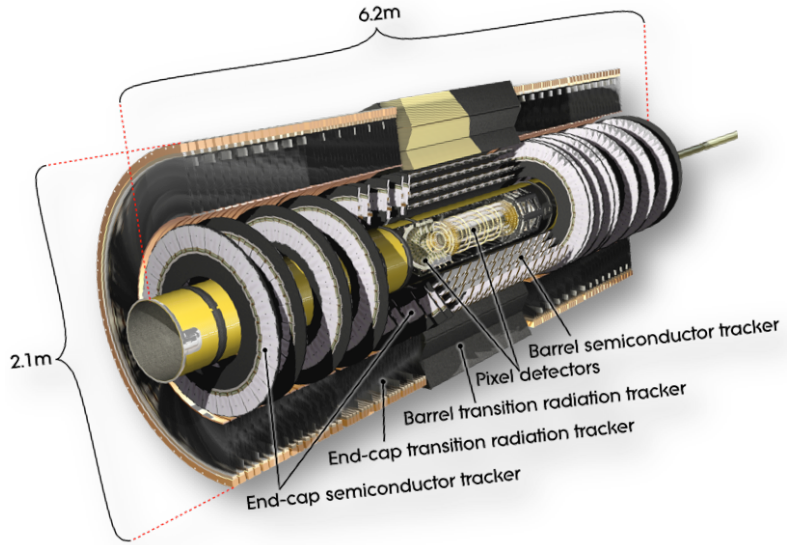
- **Tracker:** use ionization to track charged particles
- μ **Tracker:** use ionization to track μ's
- B**-field:** bend charged particles to measure p
- **Calorimeters:** use scintillation and ionization to measure energy

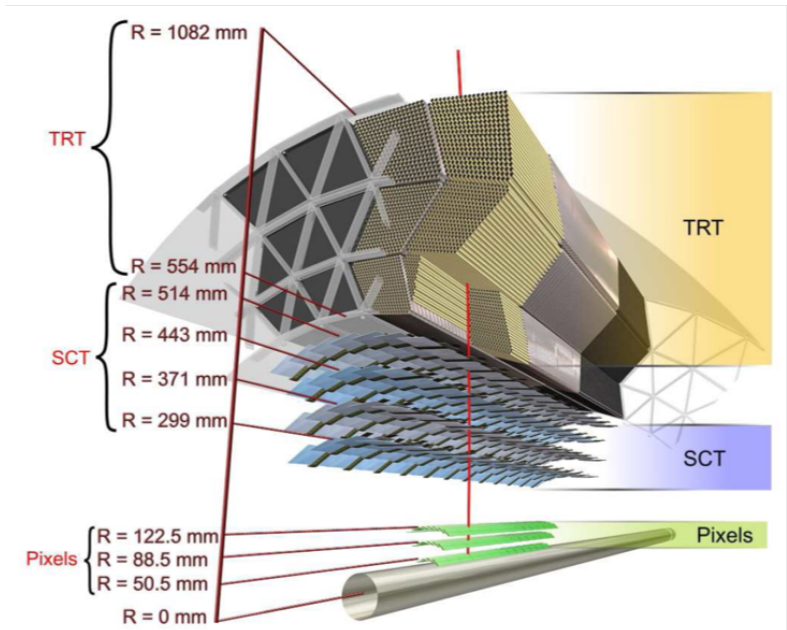


The ATLAS Tracking and Vertexing System

- Silicon Pixel Detector
- Silicon Strip Detector
- Transition Radiation Detector







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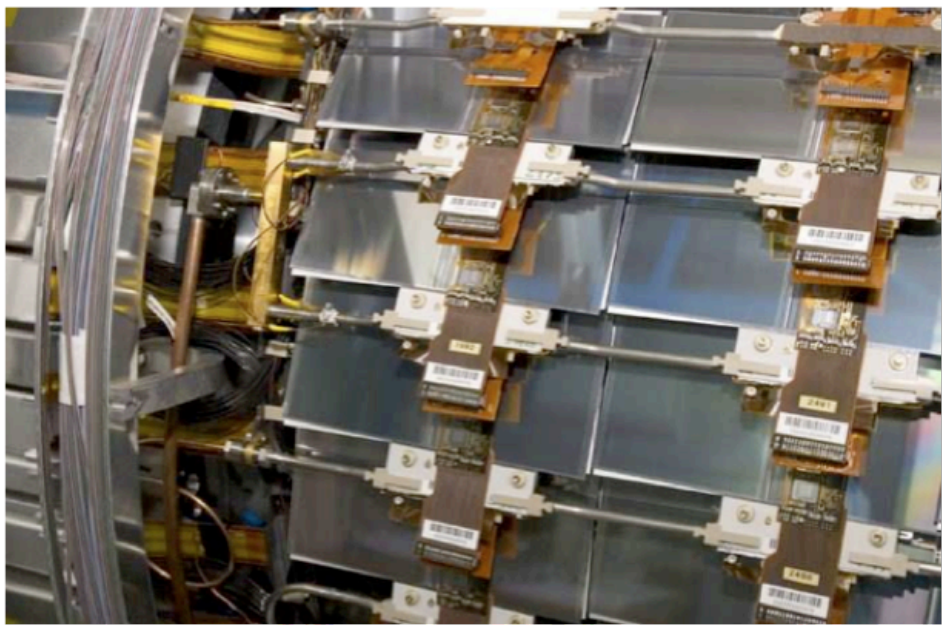

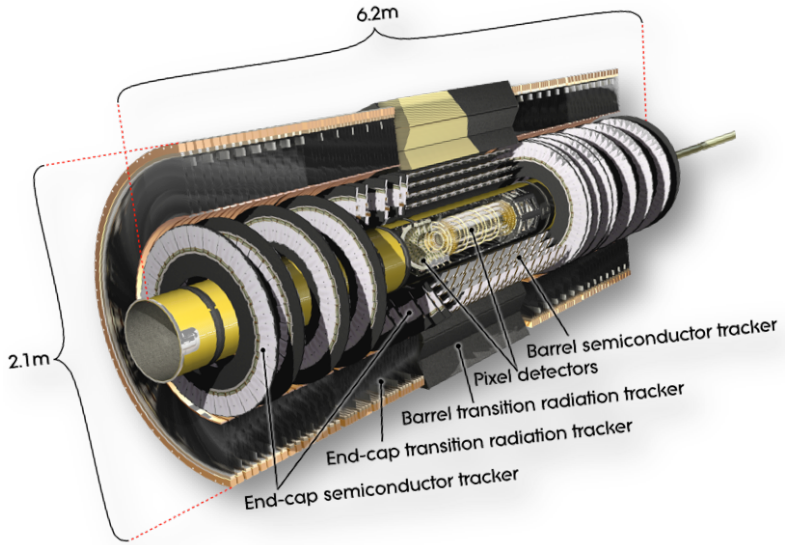

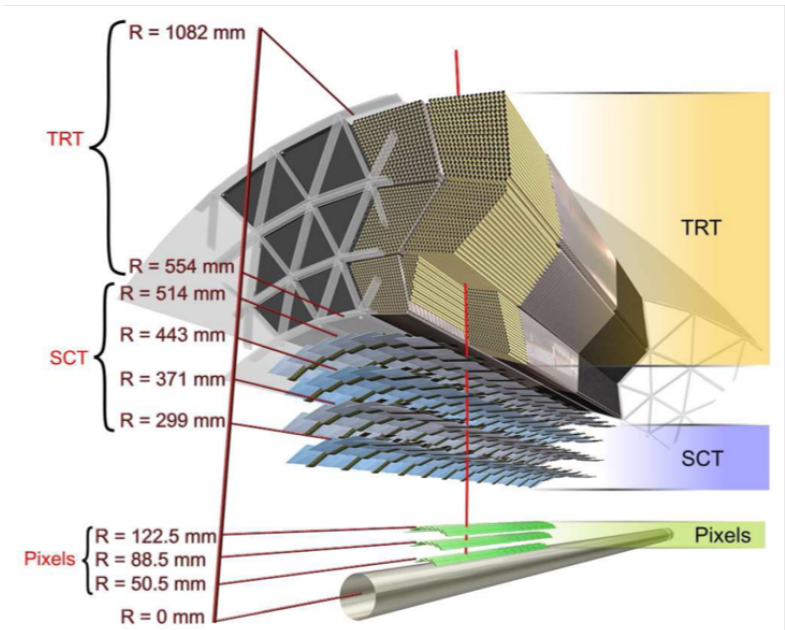

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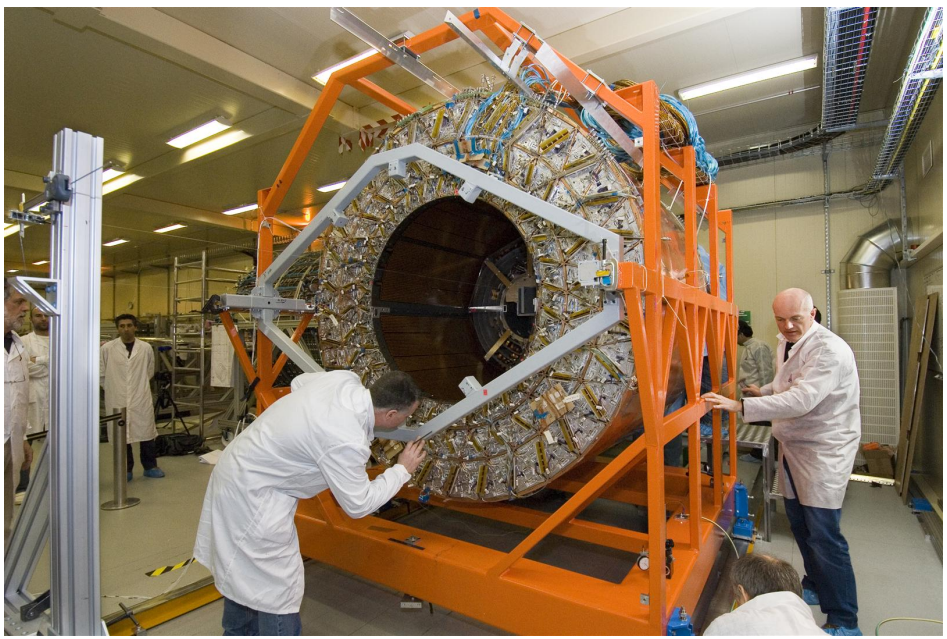

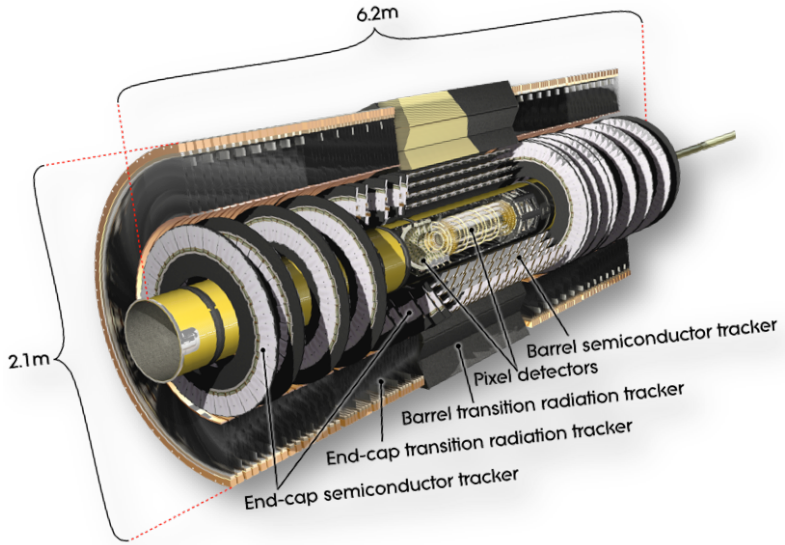

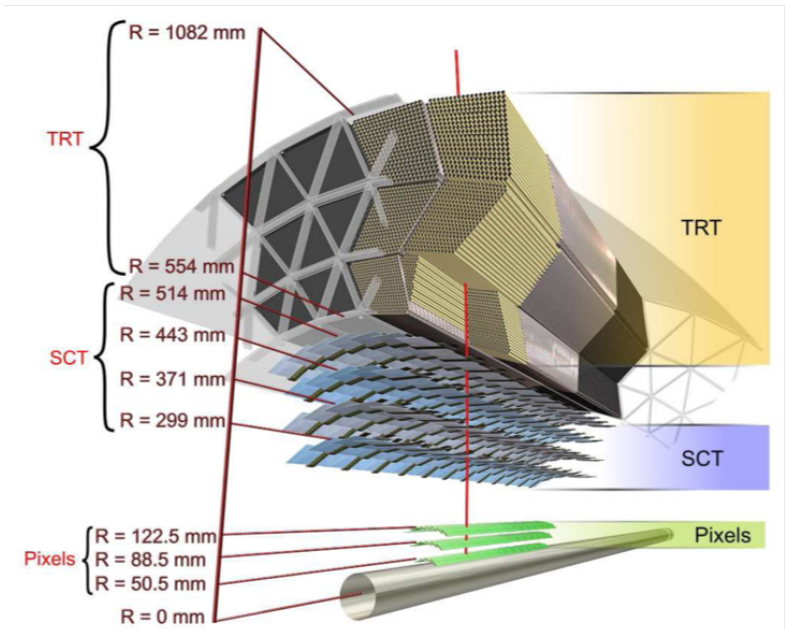

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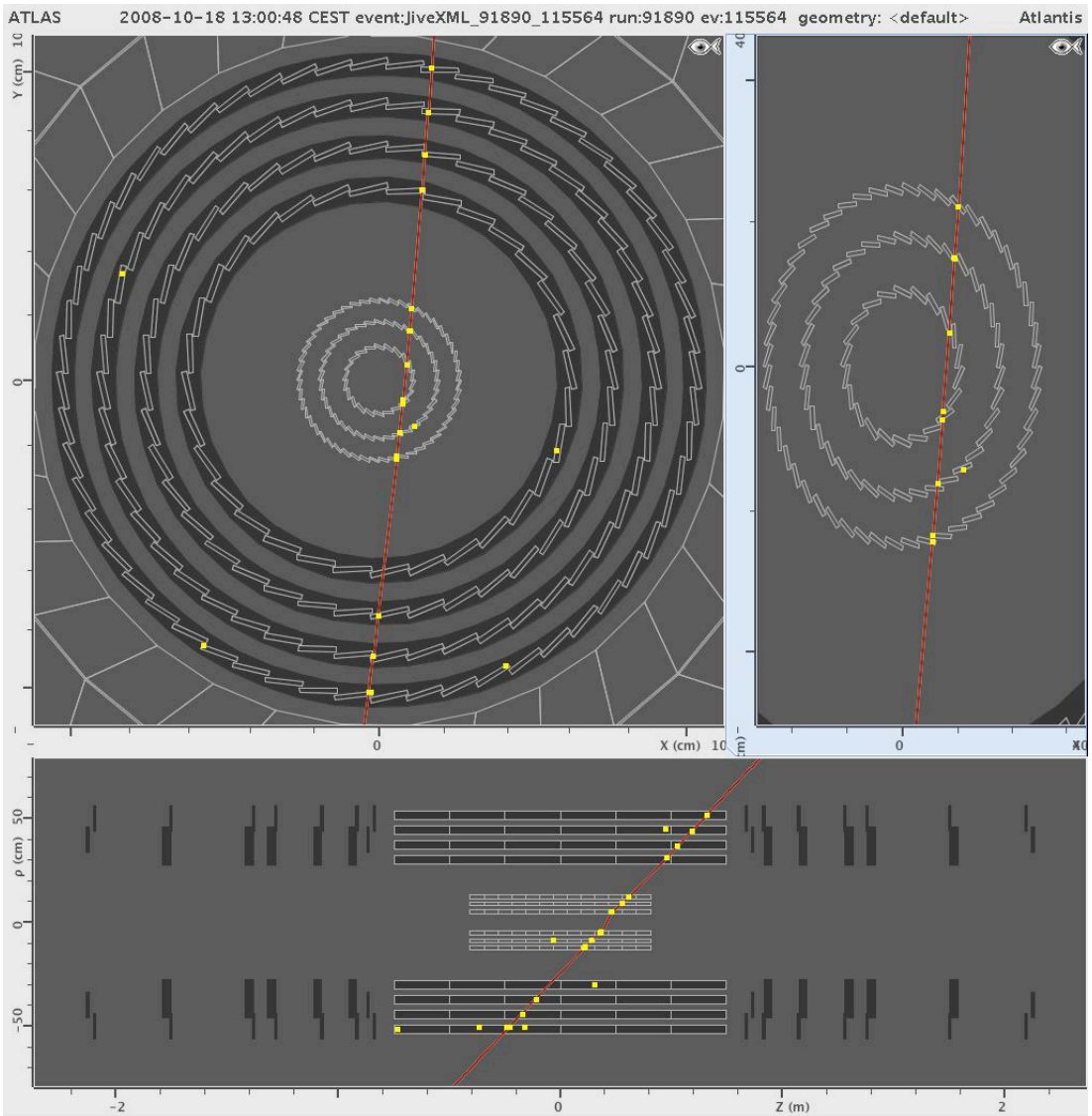
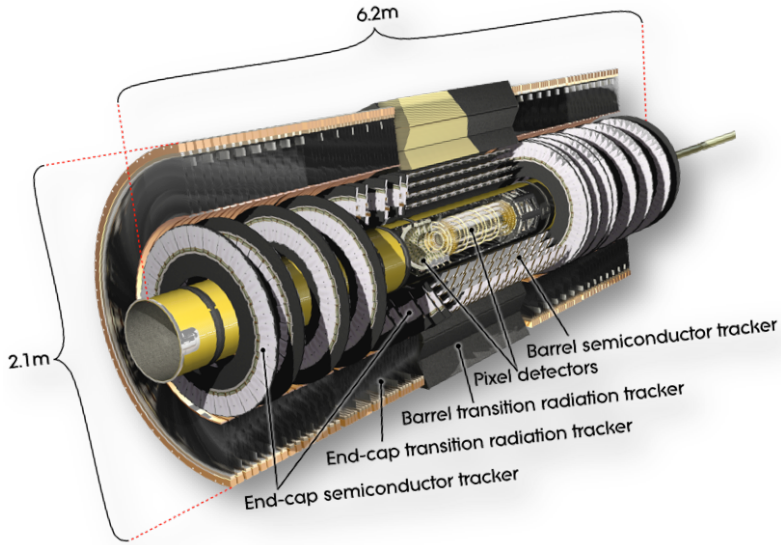
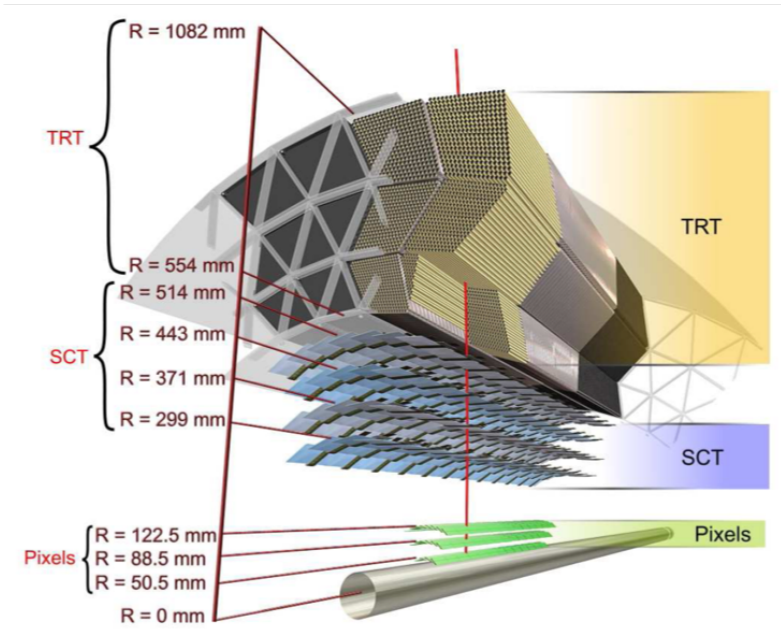
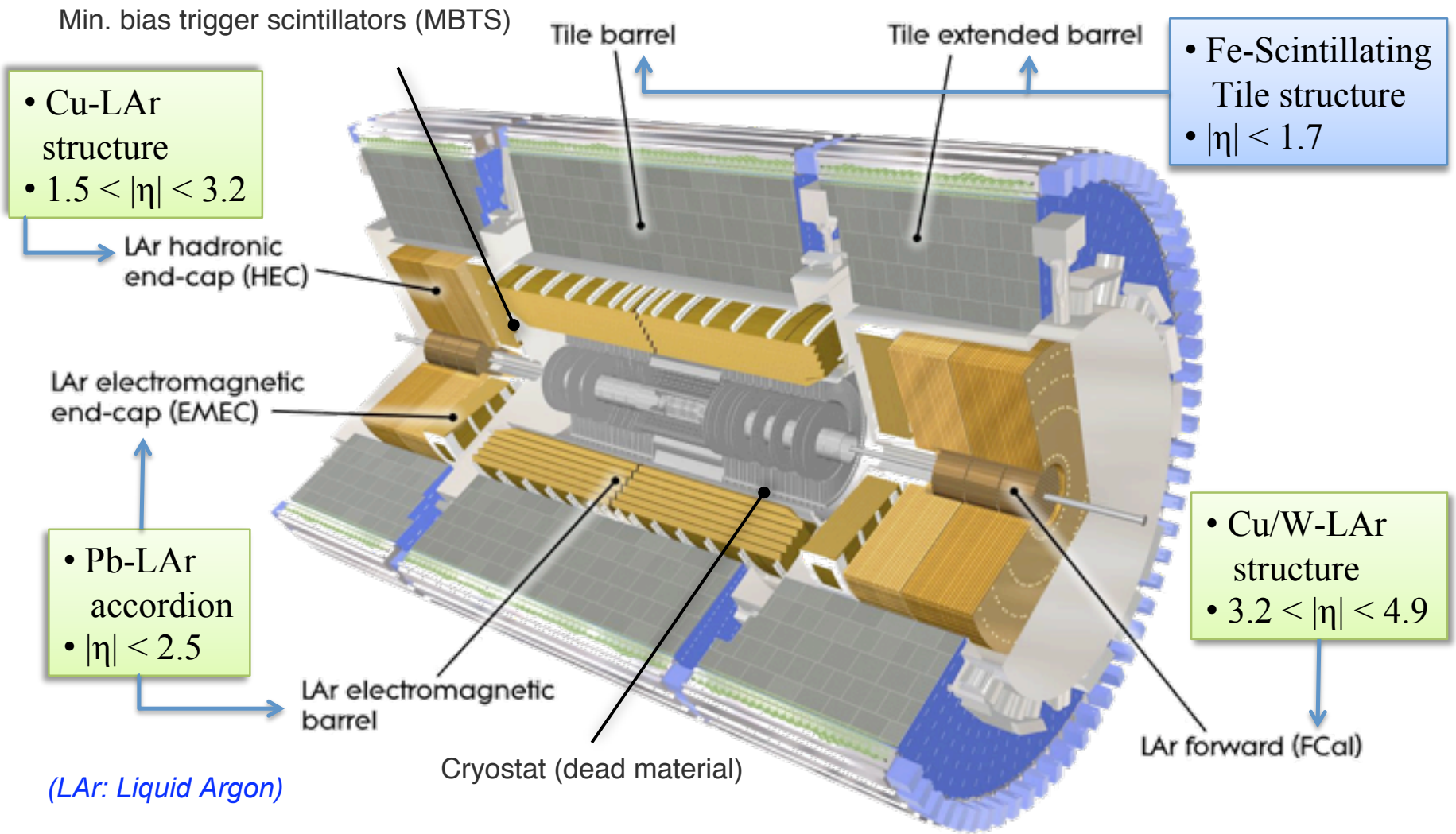




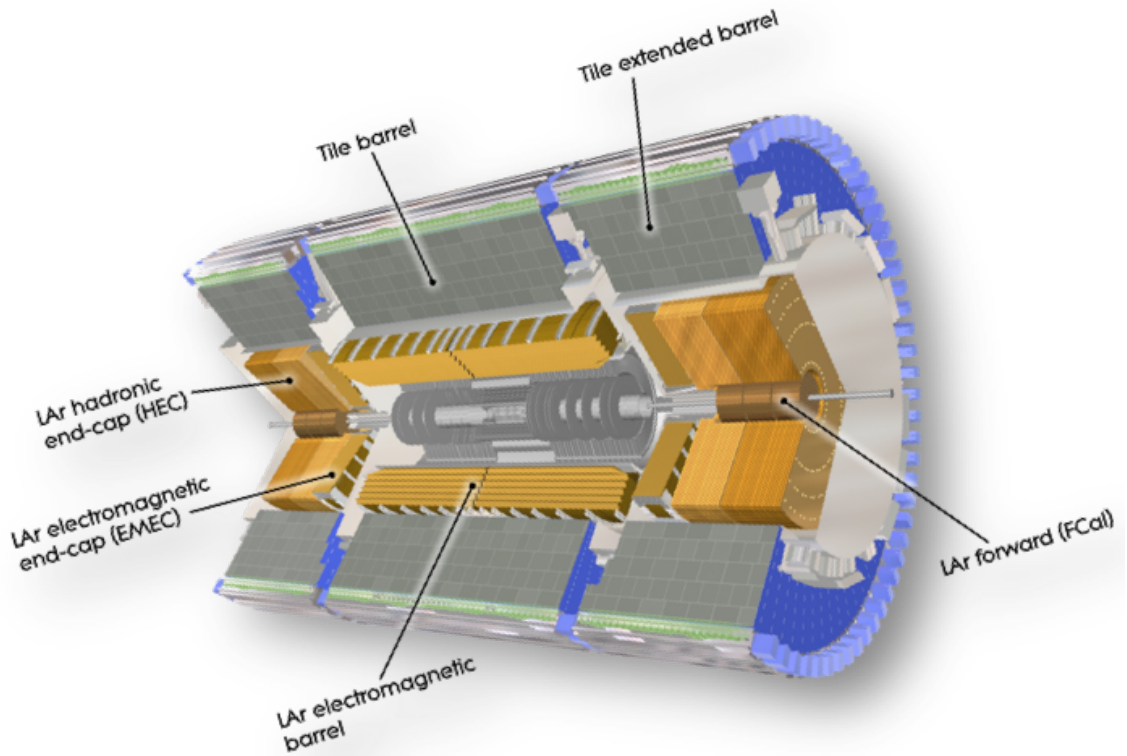


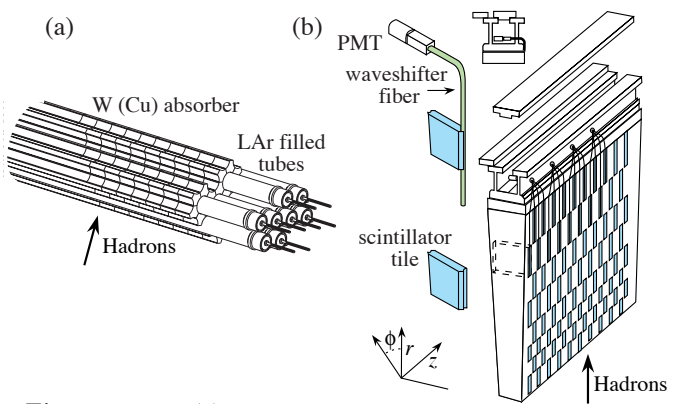
The ATLAS Calorimeter System



The ATLAS Calorimeter System

- Liquid Argon electromagnetic (LAr *EM*) barrel and end-caps
- Hadronic Tile barrel and extended barrel (TileCal)
- LAr hadronic end-cap (HEC)
- LAr forward calorimeter (FCAL)





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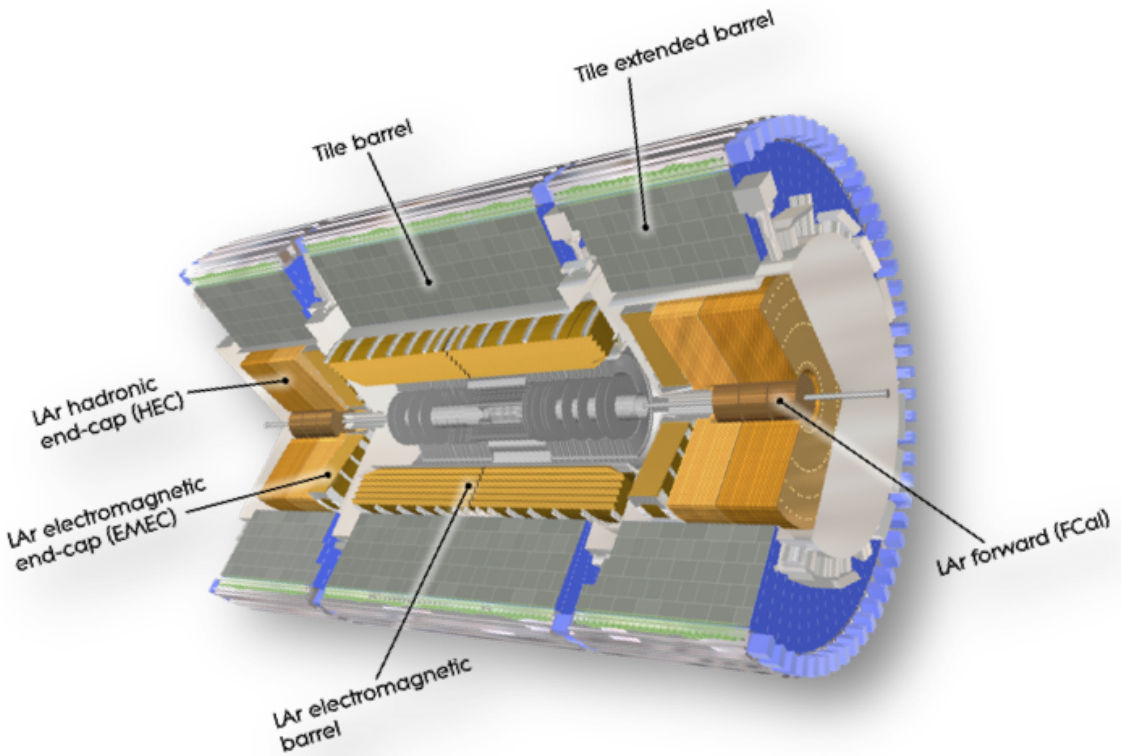

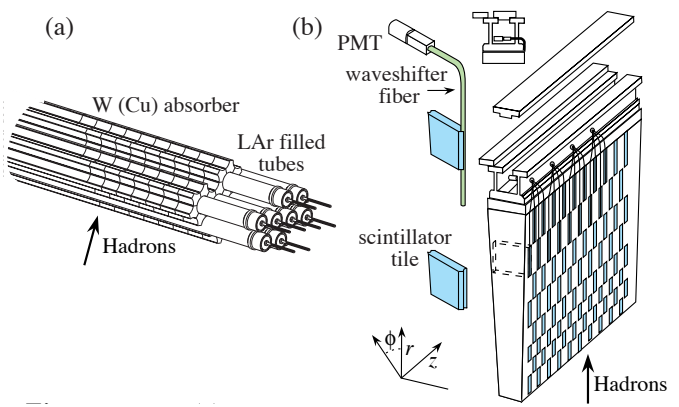

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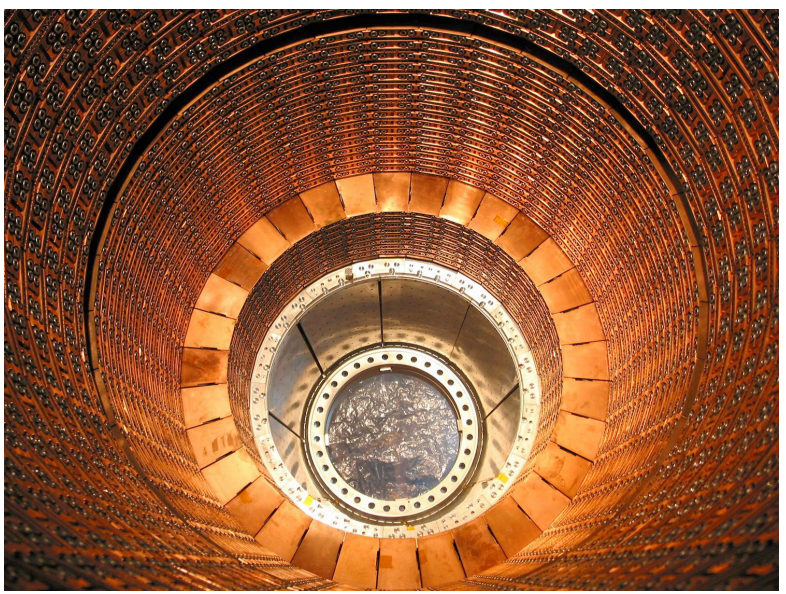

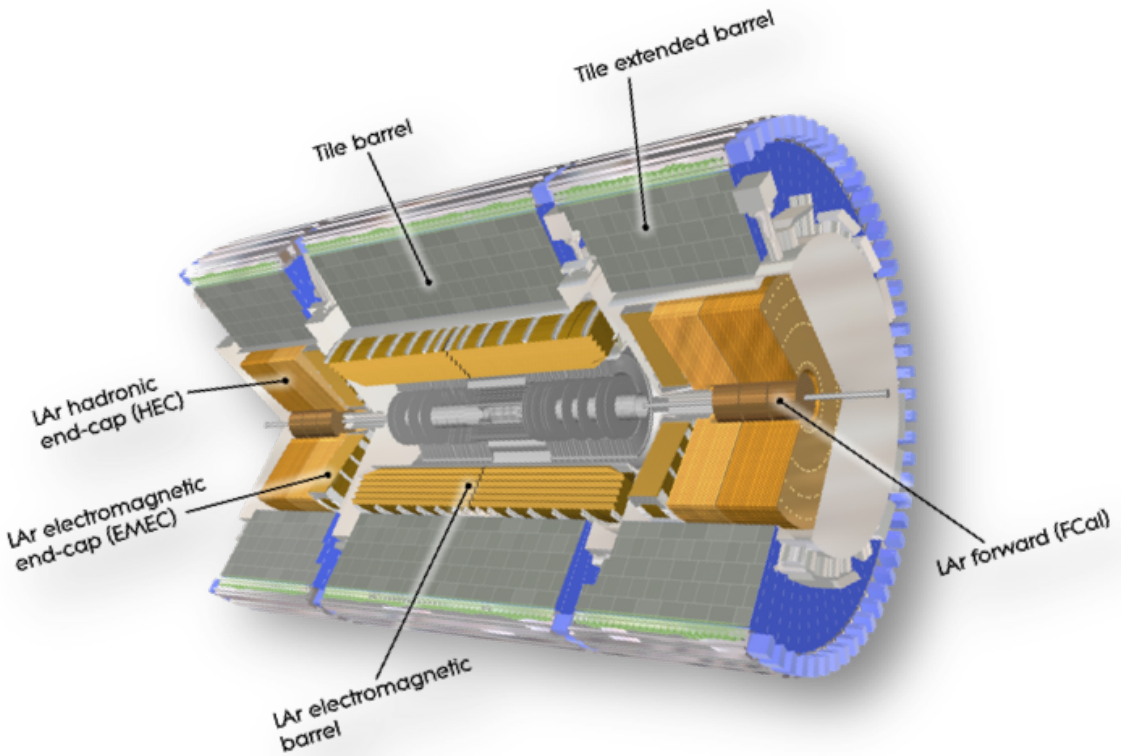

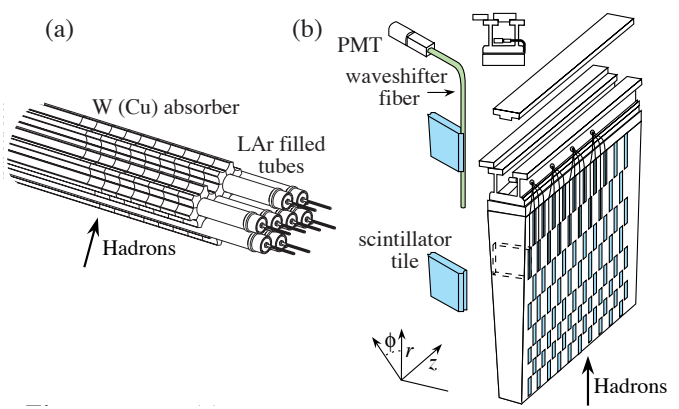

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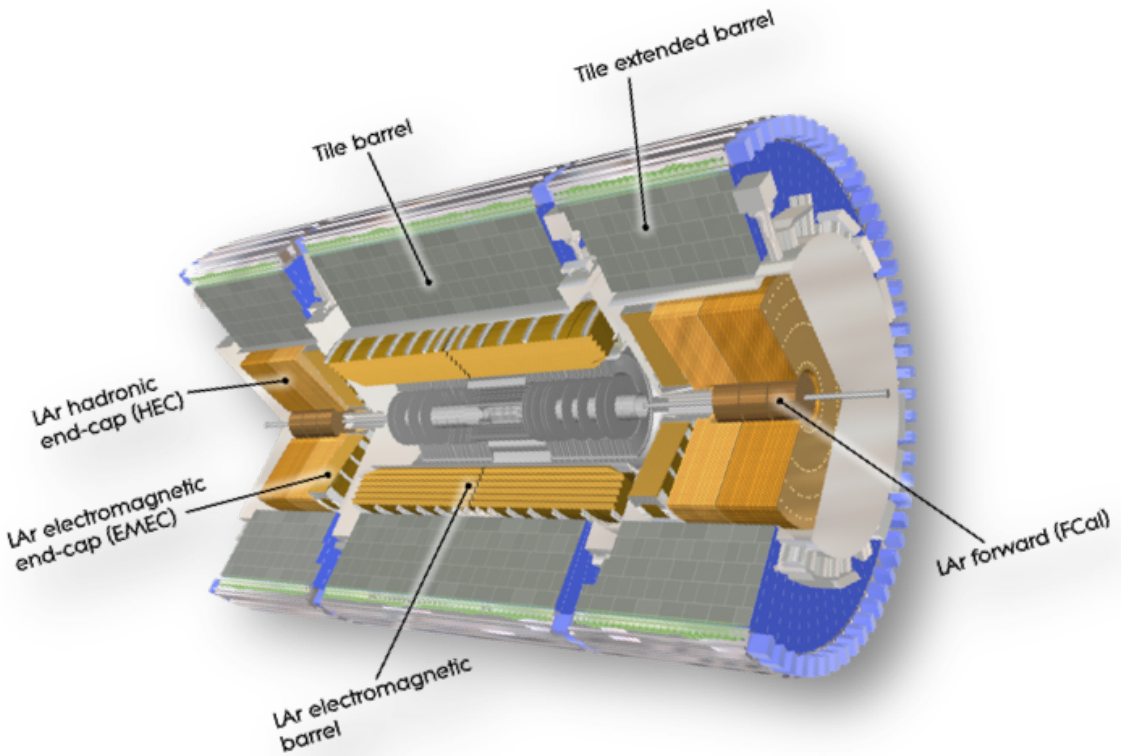
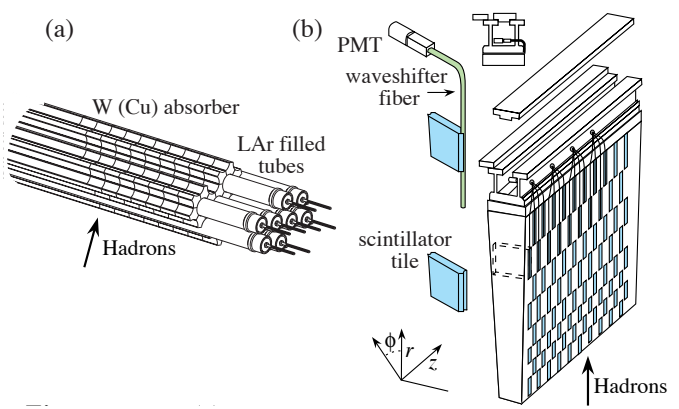
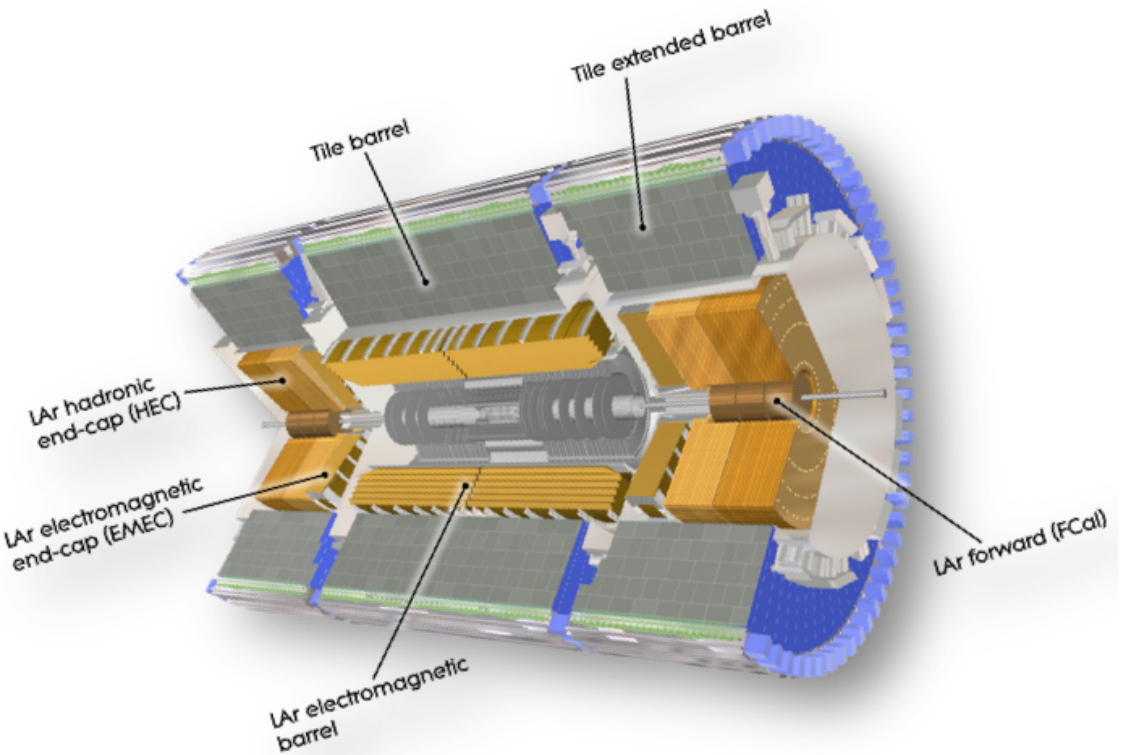




The ATLAS Calorimeter System

Table 28.9: Resolution of typical electromagnetic calorimeters. E is in GeV.

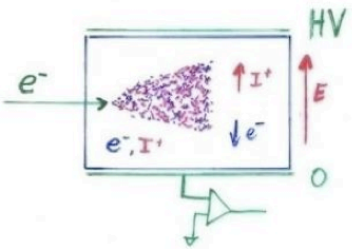
Technology (Exp.)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\mathrm{E}^{1/4}$	1983
$Bi_4Ge_3O_{12}$ (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	16–$18X_0$	$2.3\%/E^{1/4} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
$PbWO_4$ (PWO) (CMS)	$25X_0$	$3\%/\sqrt{E} \oplus 0.5\% \oplus 0.2/E$	1997
Lead glass (OPAL)	$20.5X_0$	$5\%/\sqrt{E}$	1990
Liquid Kr (NA48)	$27X_0$	$3.2/\%\sqrt{E} \oplus 0.42\% \oplus 0.09/E$	1998
Scintillator/depleted U (ZEUS)	20–$30X_0$	$18\%/\sqrt{E}$	1988
Scintillator/Pb (CDF)	$18X_0$	$13.5\%/\sqrt{E}$	1988
Scintillator fiber/Pb spaghetti (KLOE)	$15X_0$	$5.7\%/\sqrt{E} \oplus 0.6\%$	1995
Liquid Ar/Pb (NA31)	$27X_0$	$7.5\%/\sqrt{E} \oplus 0.5\% \oplus 0.1/E$	1988
Liquid Ar/Pb (SLD)	$21X_0$	$8\%/\sqrt{E}$	1993
Liquid Ar/Pb (H1)	20–$30X_0$	$12\%/\sqrt{E} \oplus 1\%$	1998
Liquid Ar/depl. U (DØ)	$20.5X_0$	$16\%/\sqrt{E} \oplus 0.3\% \oplus 0.3/E$	1993
Liquid Ar/Pb accordion (ATLAS)	$25X_0$	$10\%/\sqrt{E} \oplus 0.4\% \oplus 0.3/E$	1996



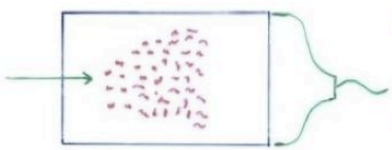
The ATLAS Calorimeter System

The Measurement is destructive. The particle can not be subject to further study.

Energy Measurement by



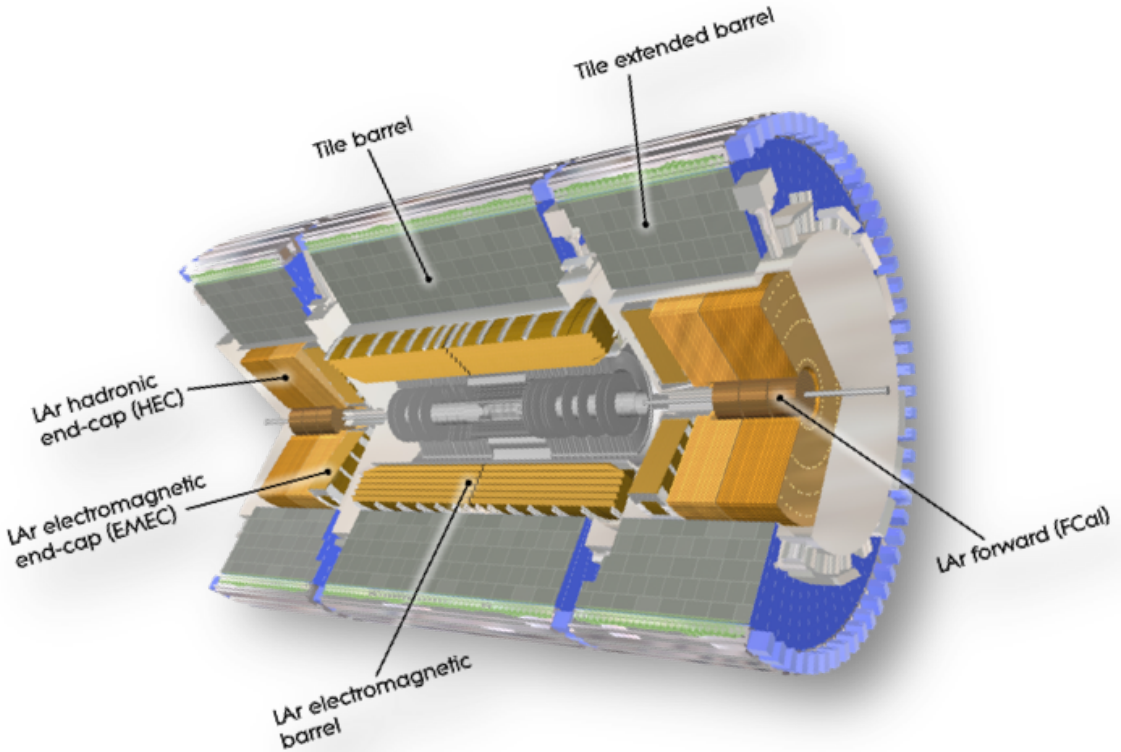
Collecting the produced Charge

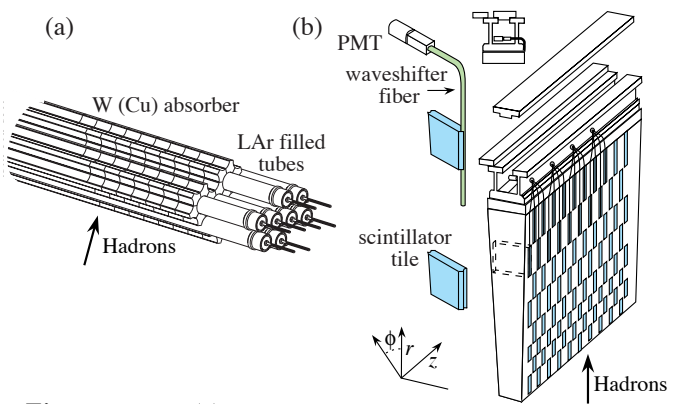


Measuring the Photons produced by the collision of the $e^{\pm}$ with Atom Electrons of the Material.

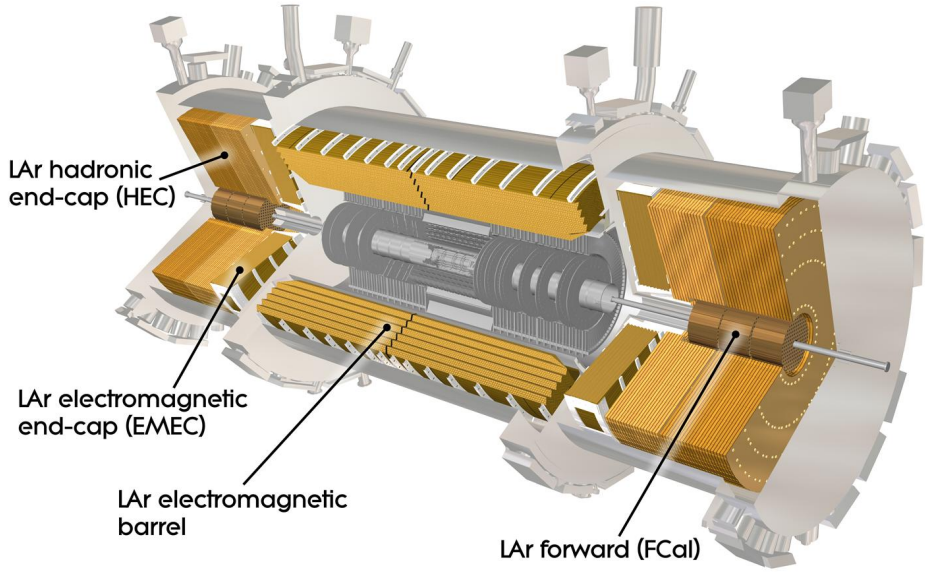
Total Amount of e^-, I^+ pairs or Photons is proportional to the total track length is proportional to the particle Energy.

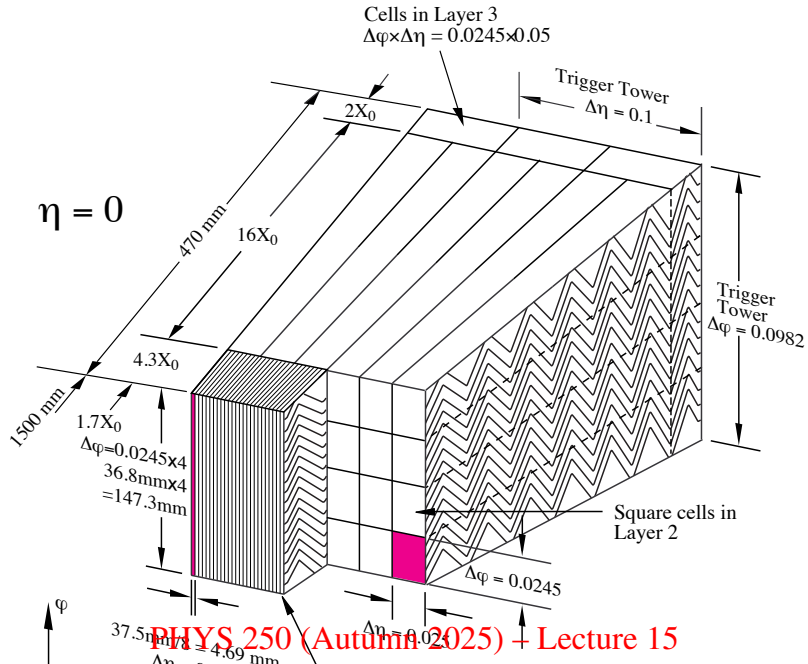
(From W. Riegler)



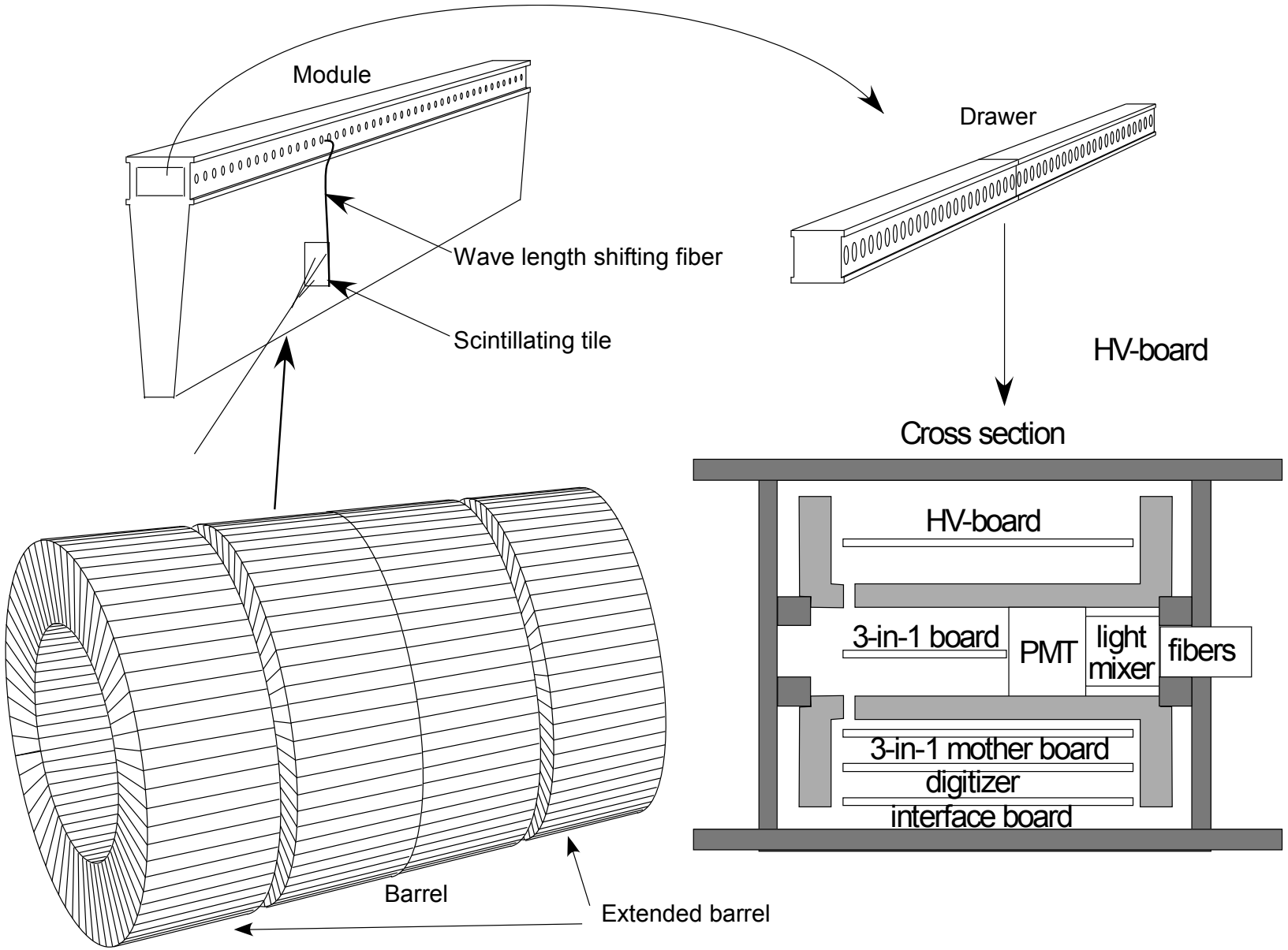


Structure of th



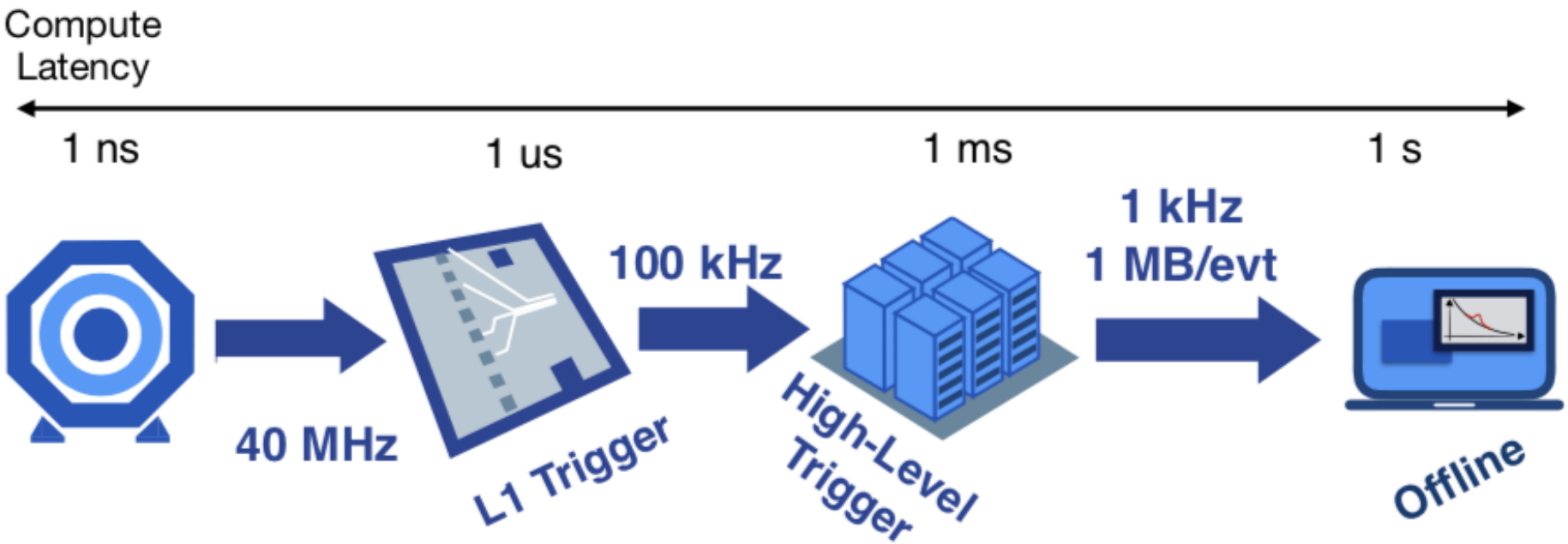


Structure of the hadronic "TileCal" calorimeter

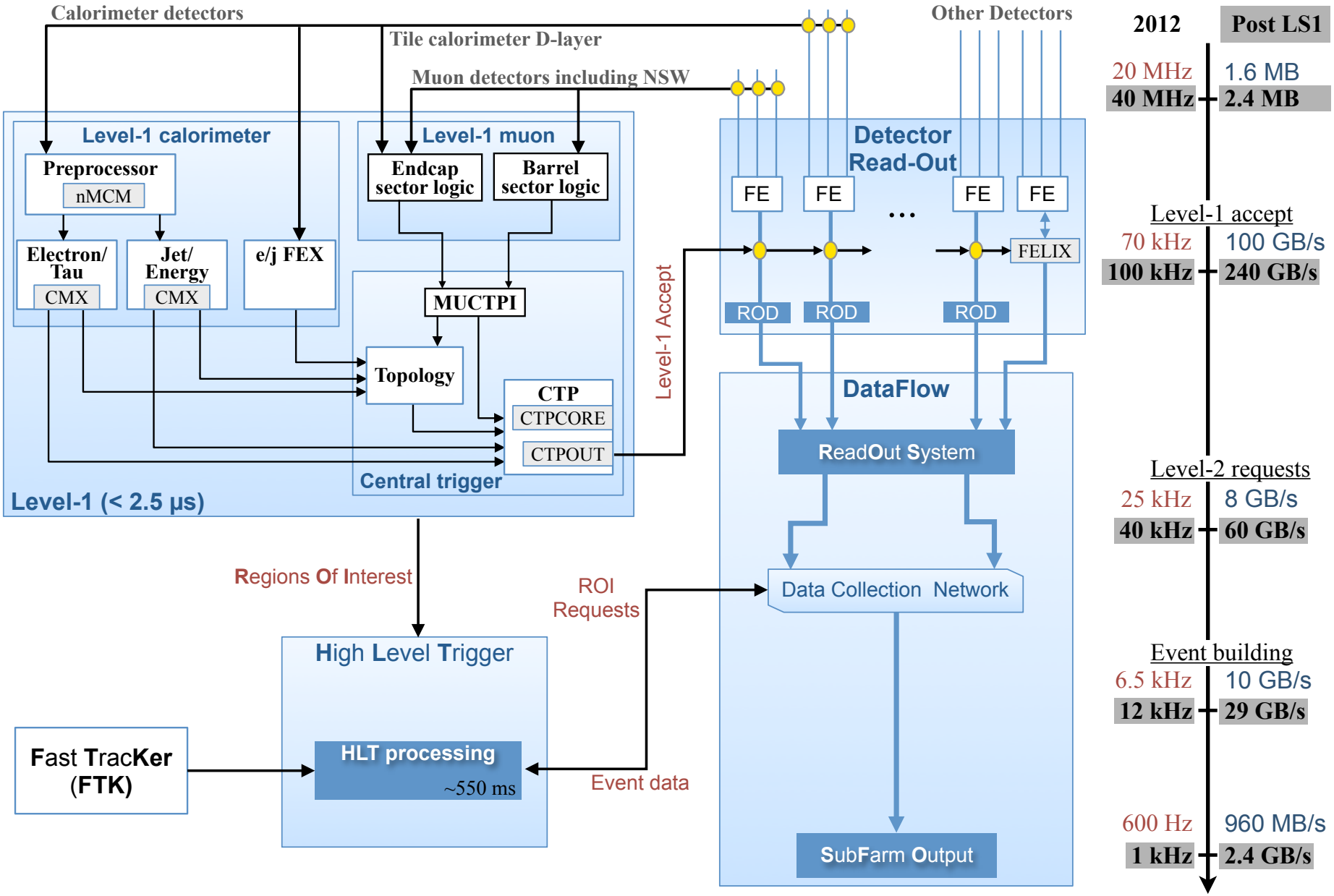


Outline

Collecting and Distributing the Data



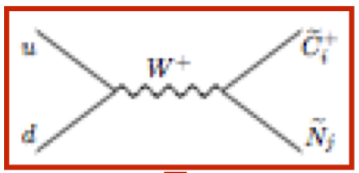
Collecting and Distributing the Data



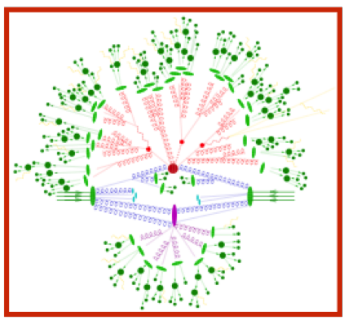
Collecting and Distributing the Data

Analyzing the Data

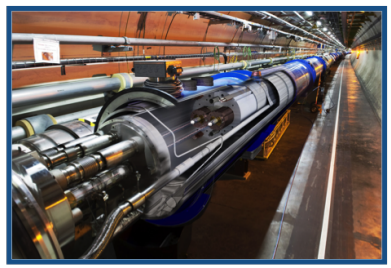
Simulation of hard-scatter for signal + SM background



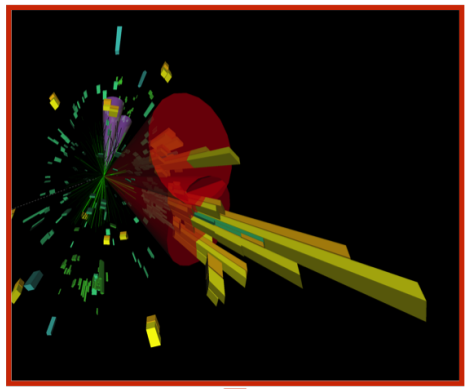
Simulation of "soft physics" (shower + hadronization)



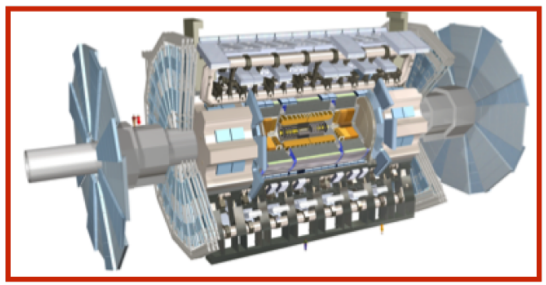
LHC real data



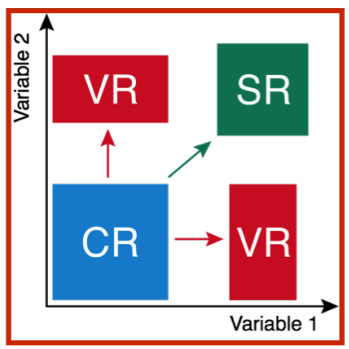
Reconstruction of physical observables



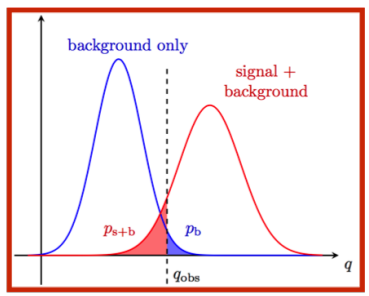
Detector simulation



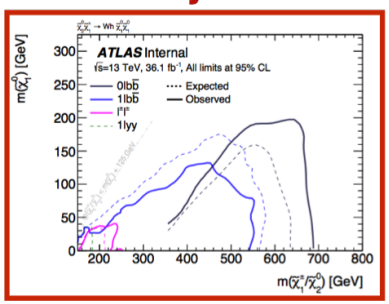
Event selection and background estimation



Hypothesis testing



Discovery or exclusion



Four-Vectors in Particle Physics

A **four-vector** is an object that transforms linearly under Lorentz transformations:

$$x'^{\mu} = \Lambda^{\mu}{}_{\nu}\, x^{\nu}.$$

A typical example is the **spacetime position four-vector**:

$$x^{\mu} = \begin{pmatrix} ct \\ x \\ y \\ z \end{pmatrix} \qquad \text{or} \qquad x_{\mu} = \begin{pmatrix} ct \\ -x \\ -y \\ -z \end{pmatrix}.$$

Its **Lorentz-invariant norm** is:

$$x^{\mu}x_{\mu} = c^2t^2 - \vec{x}^2.$$

Other common four-vectors:

$$p^{\mu} = (E/c,\ \vec{p}\,), \qquad A^{\mu} = \left(\phi,\ \vec{A}\right).$$

Four-Vectors and LHC Data Analysis

A **four-vector** transforms under Lorentz transformations:

$$p^\mu = (E, \vec{p}).$$

At the **LHC**, nearly all reconstructed physics objects (jets, muons, electrons, photons) are represented as four-vectors:

$$p^\mu = (E,\ p_x,\ p_y,\ p_z).$$

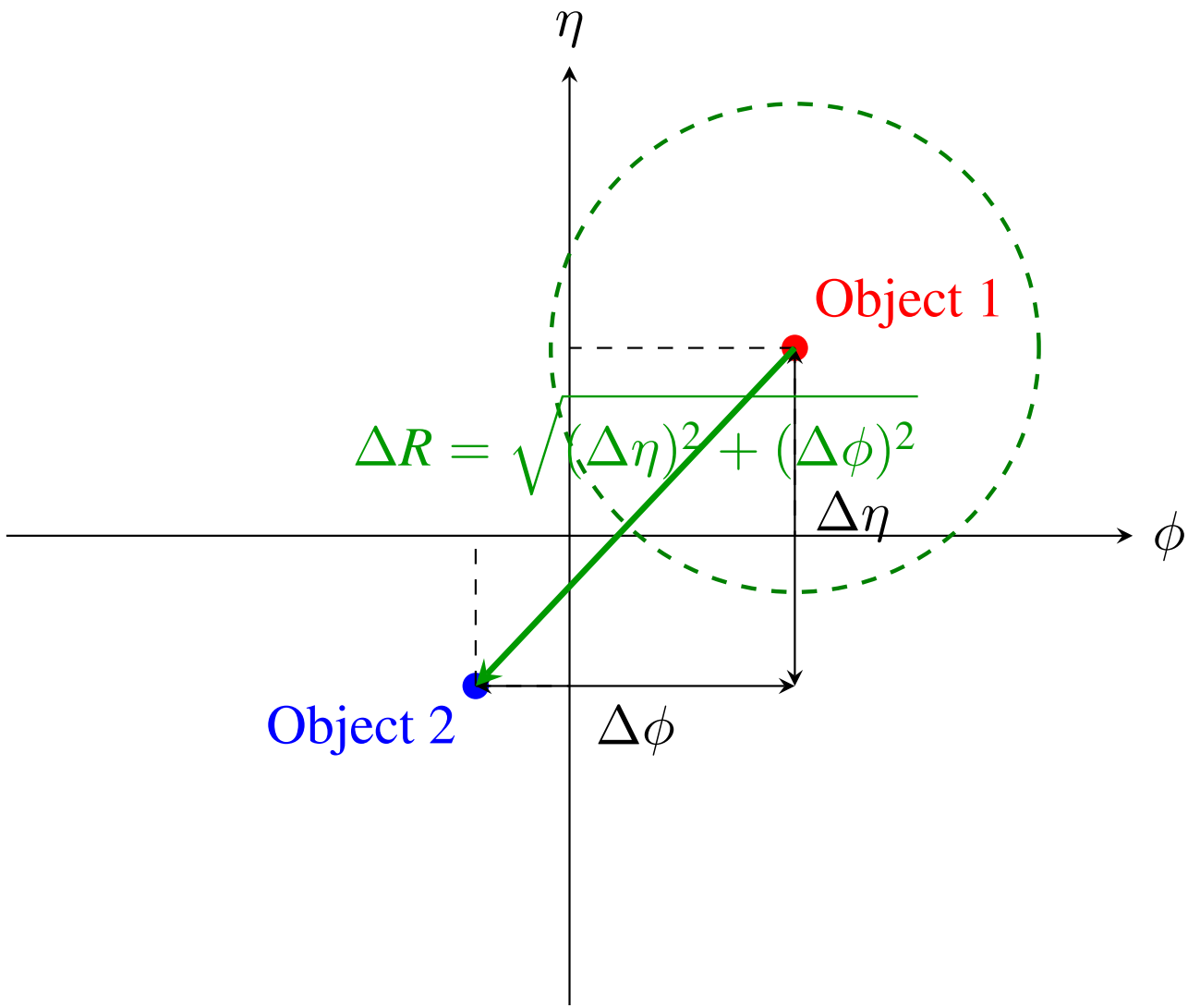
Event-level observables are Lorentz-invariant combinations of these:

$$m^2 = (p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu})$$

for example, reconstructing the:

- invariant mass of the Higgs candidate,
- missing transverse momentum for dark matter searches.

Four-Vectors and LHC Data Analysis



Four-Vectors and LHC Data Analysis