

*LHC Data Analysis – Part I*  
*PHYS 250 (Autumn 2025) – Lecture 15*

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University of Chicago

November 20, 2025

# *Outline*

## **1** *Introduction*

## **2** *Introduction to Collider Physics*

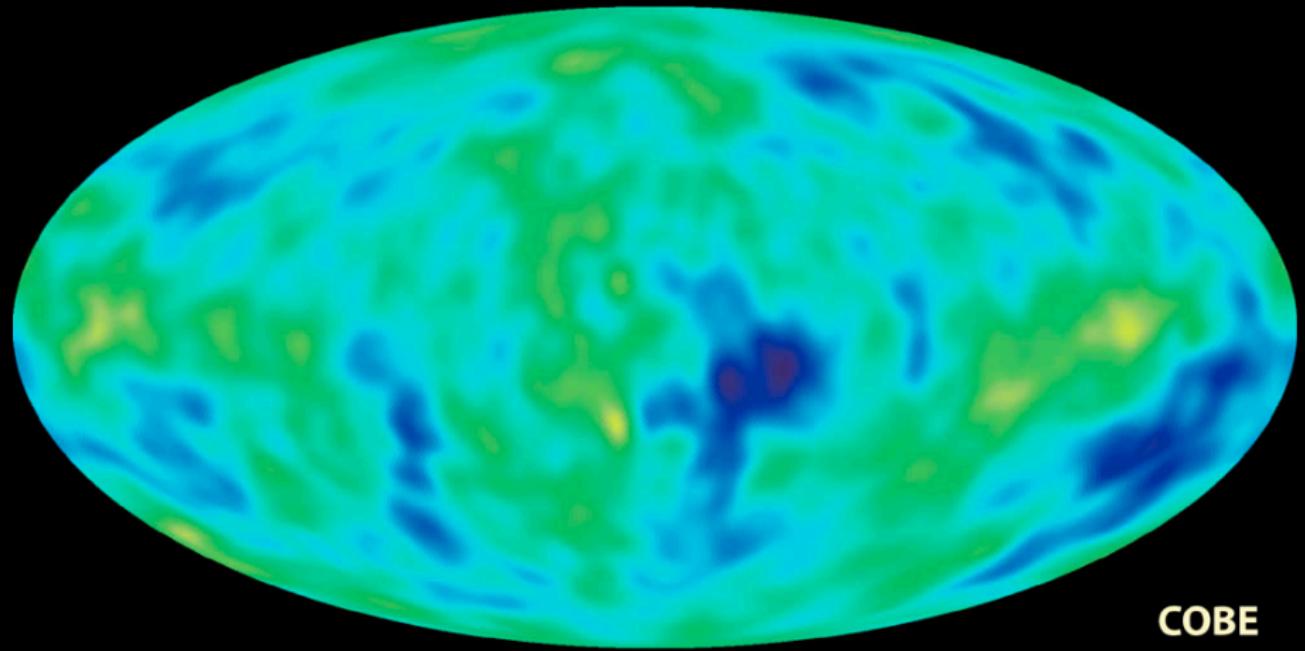
- Collider Principles
- The Large Hadron Collider

## **3** *Introduction to Collider Detectors*

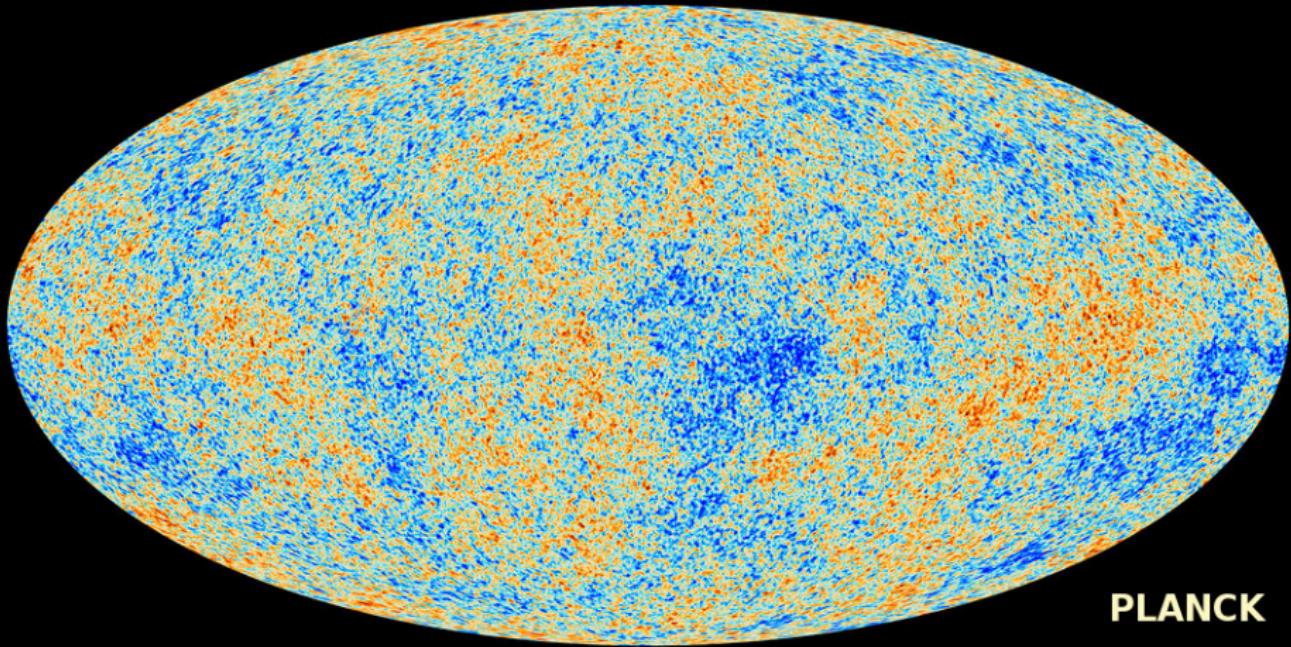
- The ATLAS Detector
- Tracking and vertexing
- Calorimetry
- Liquid argon (LAr)
- TileCal

## **4** *Introduction to Particle Physics Data Analysis*

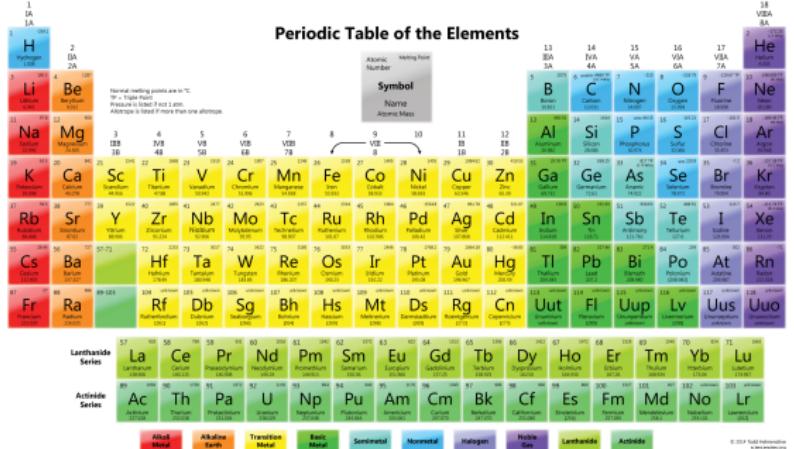
- Data and Simulation



**COBE**



# Uncovering new patterns in nature



[scienzenotes.org](http://scienzenotes.org)

# Uncovering new patterns in nature

**Periodic Table of the Elements**

Normal melting points are in °C.  
Bo = Boiling Point  
Pressure is listed if not at atm  
Atomic % listed if more than one isotope

[scienzenotes.org](http://scienzenotes.org)

## Three Generations of Matter (Fermions)

I	II	III
mass → 2.4 MeV	1.27 GeV	171.2 GeV
charge → $\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin → $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name → up	charm	top

mass → 4.8 MeV	104 MeV	4.2 GeV
charge → $-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
spin → $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name → down	strange	bottom

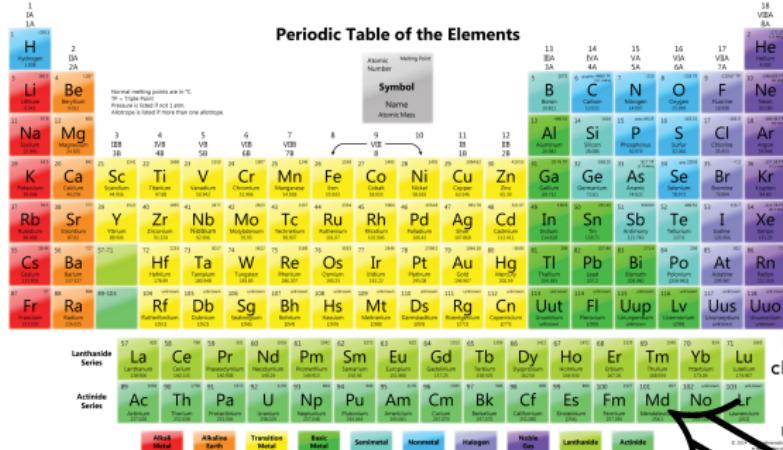
mass → <2.2 eV	0.17 MeV	<15.5 MeV	91.2 GeV
charge → 0	$\frac{1}{2}$	$\frac{1}{2}$	0
spin → $\frac{1}{2}$	electron neutrino	muon neutrino	tau neutrino

mass → 0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
charge → -1	$-\frac{1}{2}$	$-\frac{1}{2}$	$\pm\frac{1}{2}$
spin → $\frac{1}{2}$	electron	muon	tau

Bosons (Forces)

[meta-synthesis.com](http://meta-synthesis.com)

# Uncovering new patterns in nature



[sciencenotes.org](http://sciencenotes.org)

## 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.*

### Three Generations of Matter (Fermions)

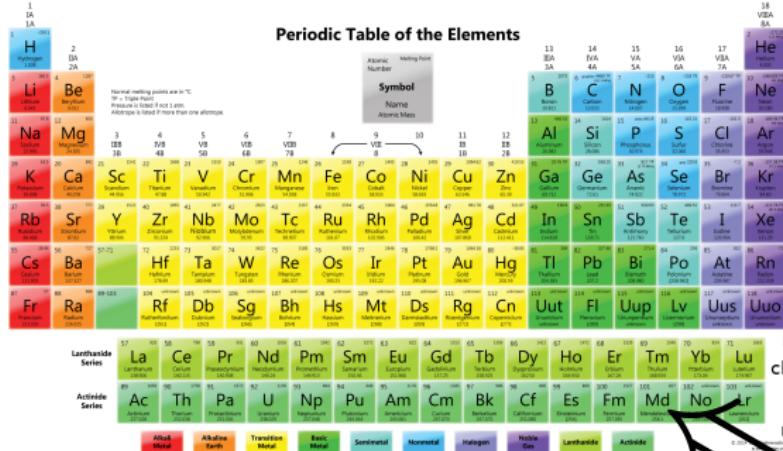
I	II	III
mass → 2.4 MeV	1.27 GeV	171.2 GeV
charge → $\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin → $\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name → up	charm	top
Quarks		
4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ bottom

$<2.2 \text{ eV}$ 0 $\frac{1}{2}$ electron neutrino	$<0.17 \text{ MeV}$ 0 $\frac{1}{2}$ muon neutrino	$<15.5 \text{ MeV}$ 0 $\frac{1}{2}$ tau neutrino	$<91.2 \text{ GeV}$ 0 0 weak force
0.511 MeV -1 $\frac{1}{2}$ electron	105.7 MeV -1 $\frac{1}{2}$ muon	1.777 GeV -1 $\frac{1}{2}$ tau	80.4 GeV $\pm 1$ 1 weak force

Leptons

[meta-synthesis.com](http://meta-synthesis.com)

# Uncovering new patterns in nature



## 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.*

Quarks → hadrons → JETS

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

Three Generations of Matter (Fermions)			
Quarks	I	II	III
mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
name →	up	charm	top
	d down	s strange	b bottom
	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	down	bottom	gluon

Leptons	$<2.2 \text{ eV}$	$<0.17 \text{ MeV}$	$<15.5 \text{ MeV}$	$91.2 \text{ GeV}$
	0 $\nu_e$	0 $\nu_\mu$	0 $\nu_\tau$	0 $Z^0$
	$\frac{1}{2}$ electron neutrino	$\frac{1}{2}$ muon neutrino	$\frac{1}{2}$ tau neutrino	weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1 $e^-$	-1 $\mu^-$	-1 $\tau^-$	$\pm 1 W^\pm$
	electron	muon	tau	weak force

meta-synthesis.com

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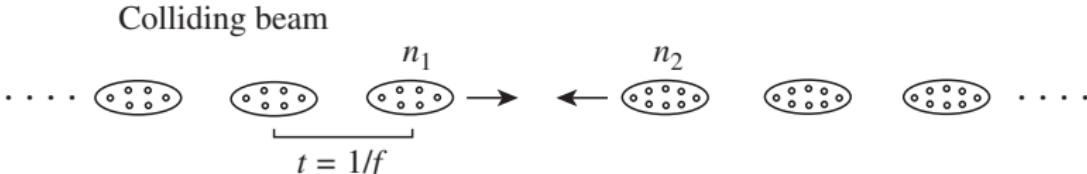
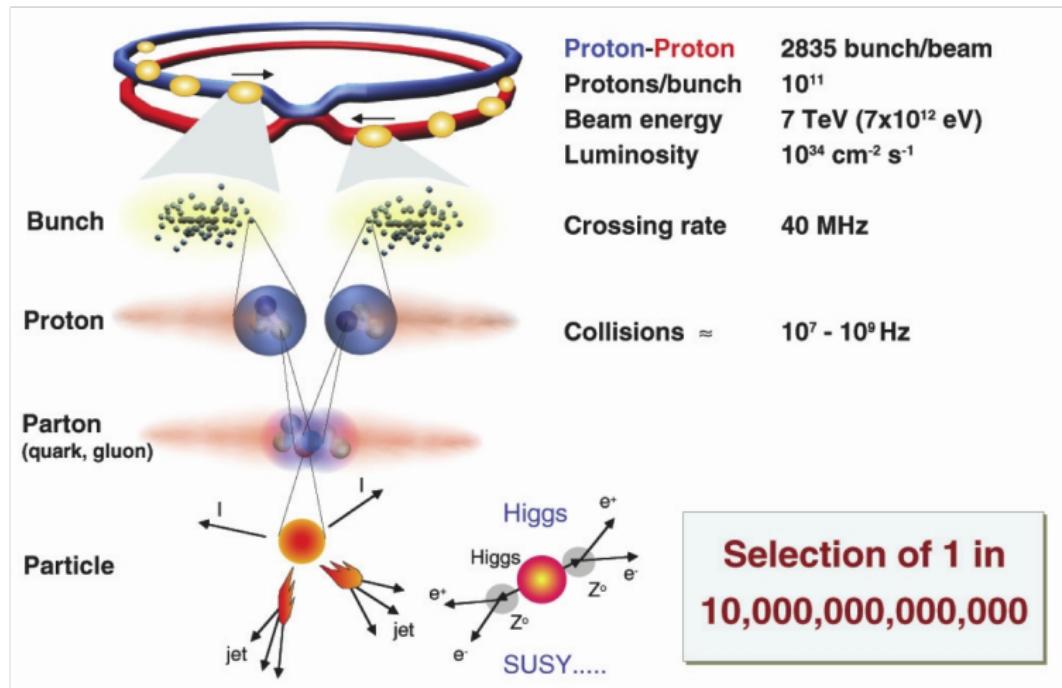
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- Tracking and vertexing
- Calorimetry
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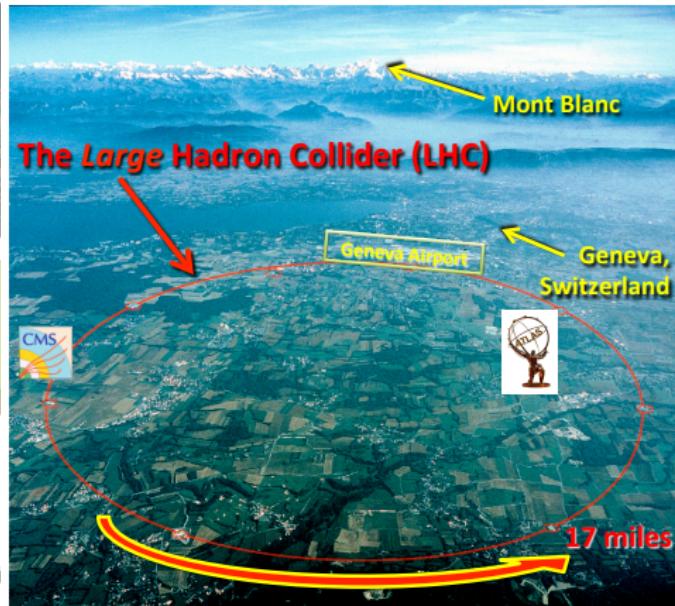
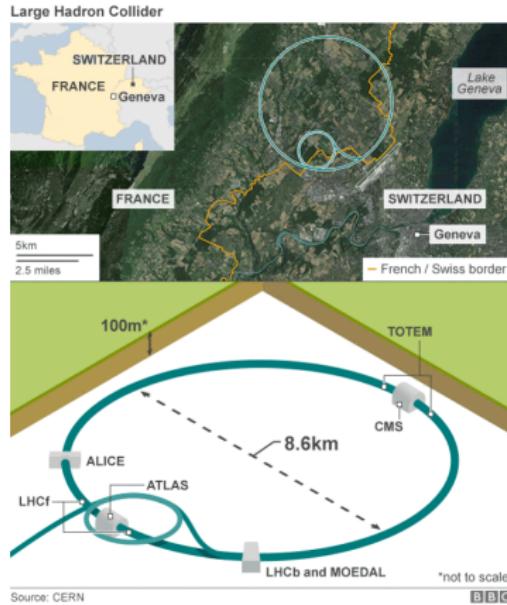
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- Data and Simulation

# Particle Collider: General Principles

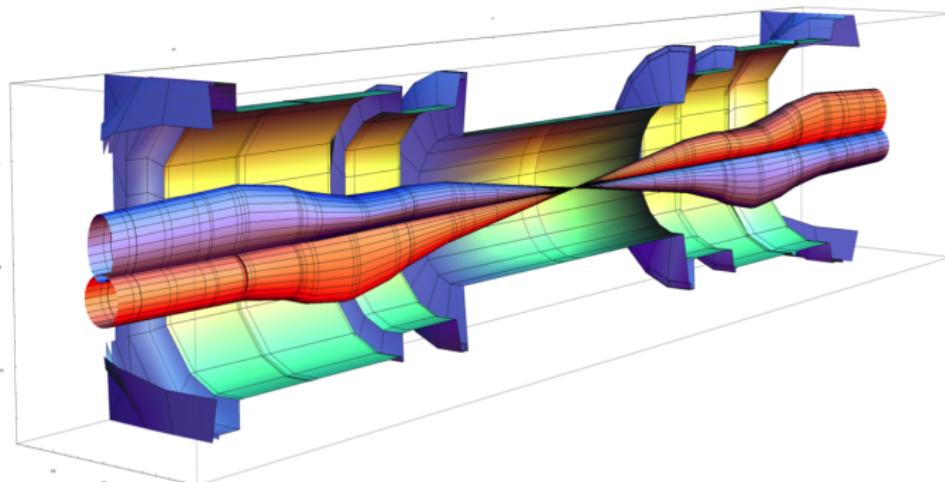
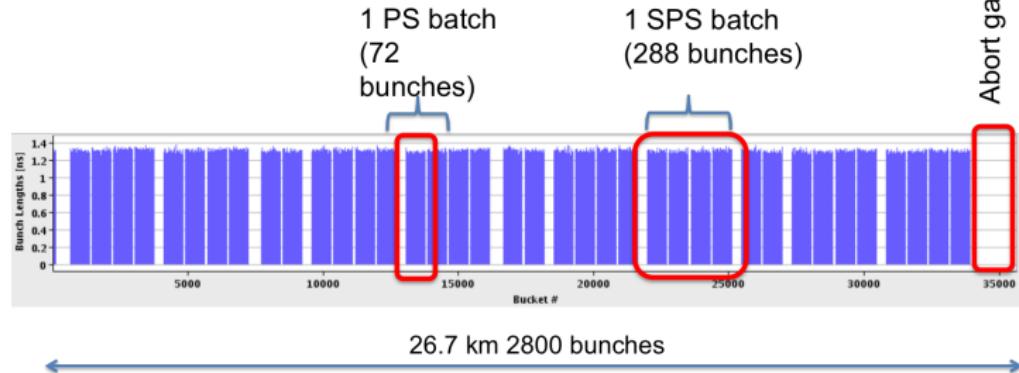


# Particle Collider: The Large Hadron Collider



- 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



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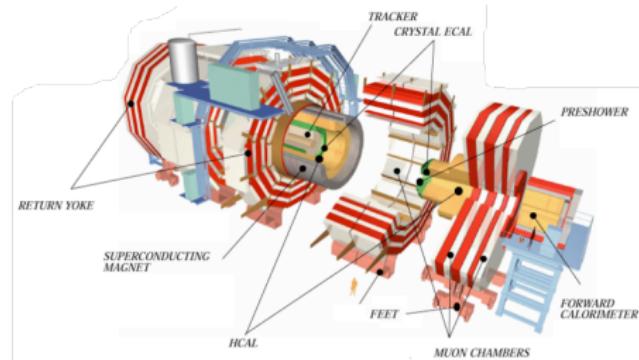
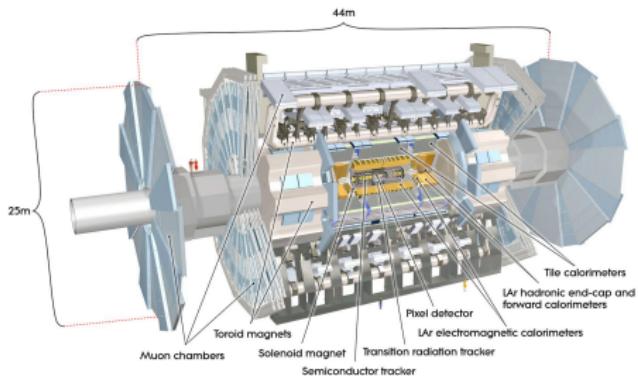
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# The experimental tools at the LHC

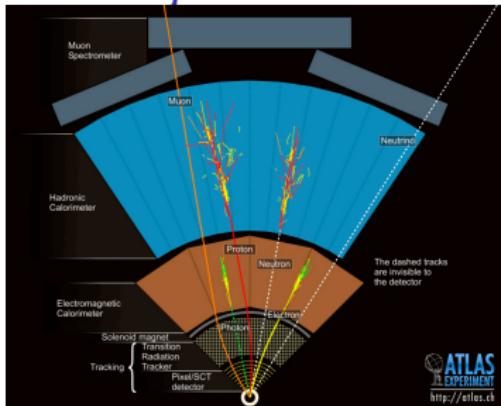


- **Weight:** 7000 tons
- **Length × height:**  $46\text{m} \times 25\text{m}$
- **B-field:** 4 T (2 T solenoid)
- 100,000,000 electronic channels
- 3000 km of cables

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

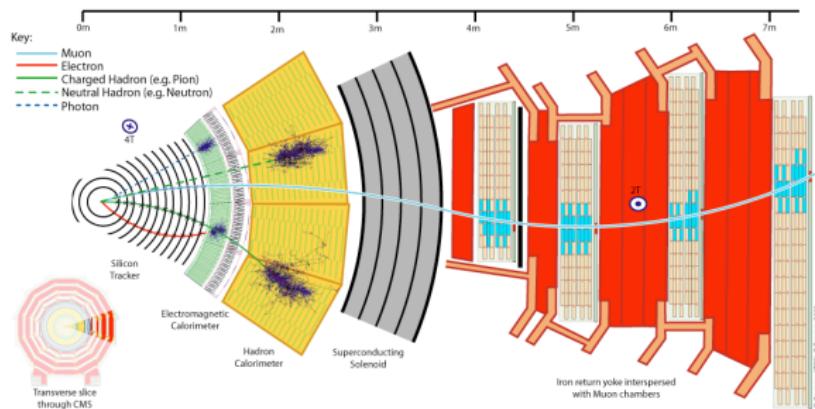
Each is a hugely complex **single** detector built out of many

# The experimental tools at the LHC



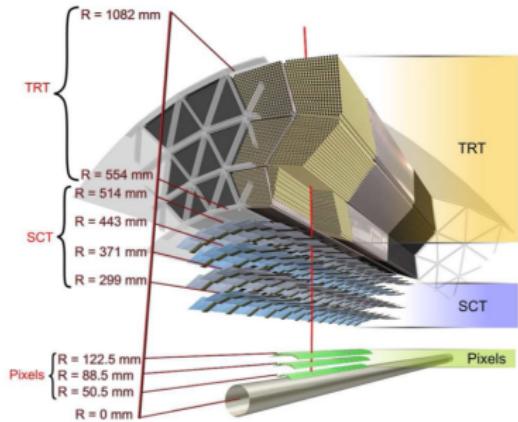
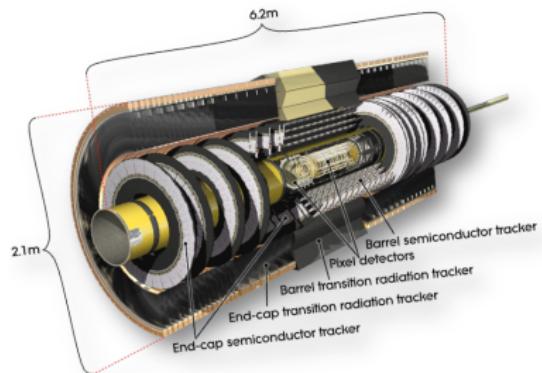
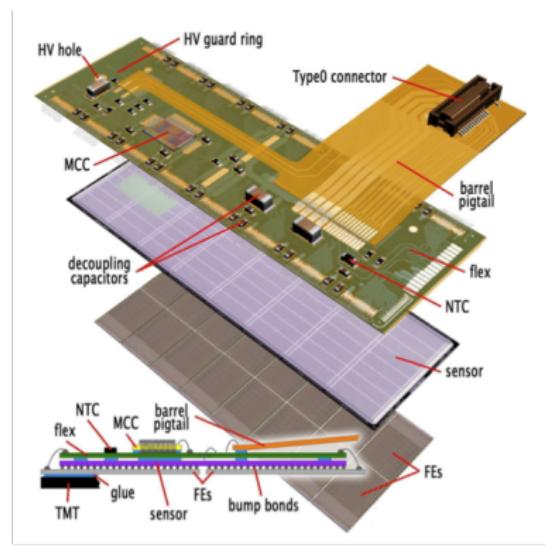
Each “detector” is comprised of several “sub-detectors” with each devoted to a specific task

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



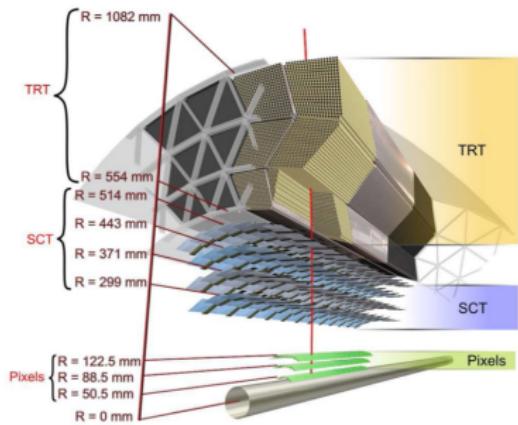
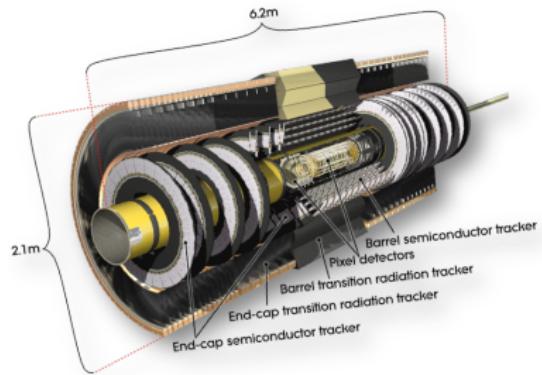
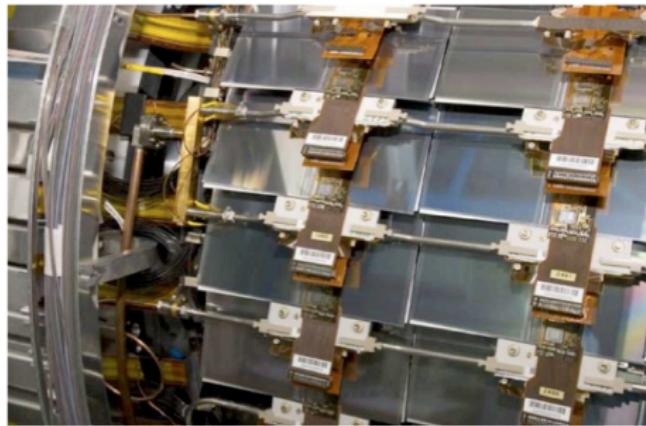
# The ATLAS Tracking and Vertexing System

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



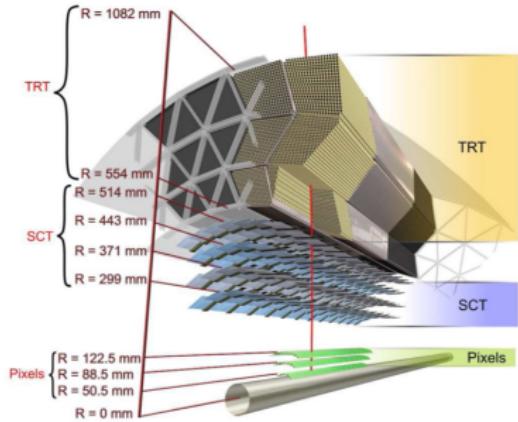
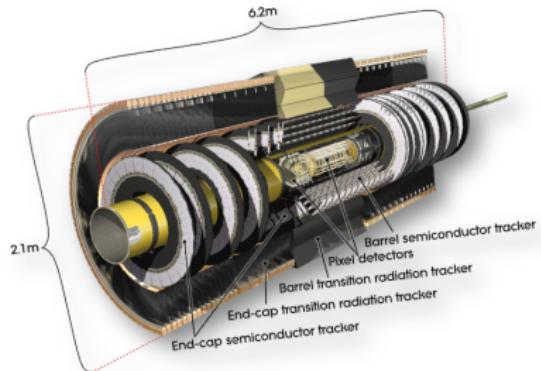
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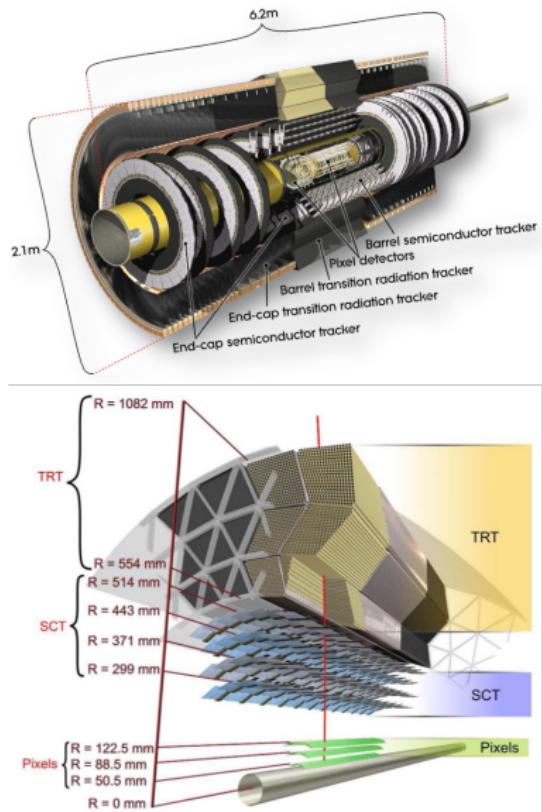
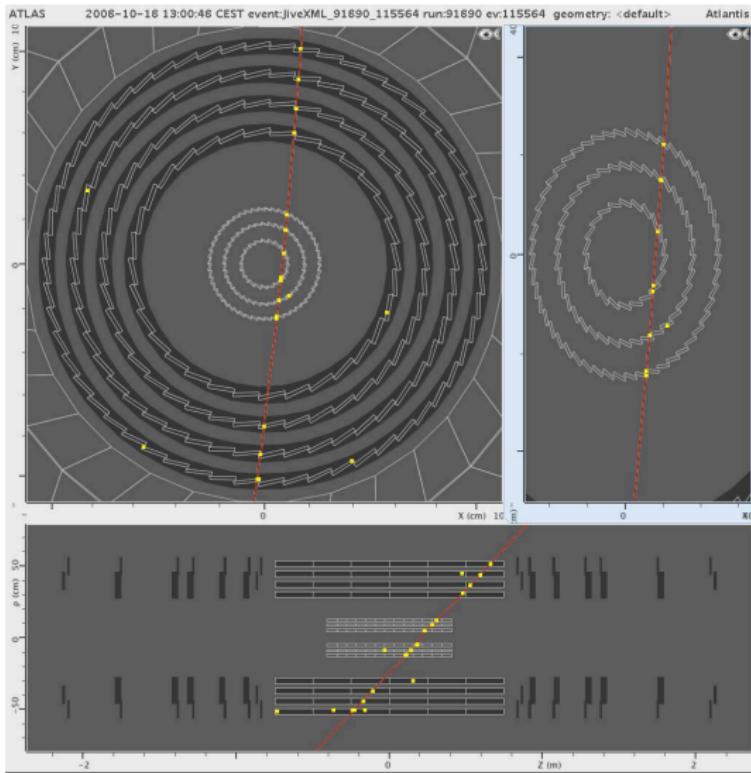


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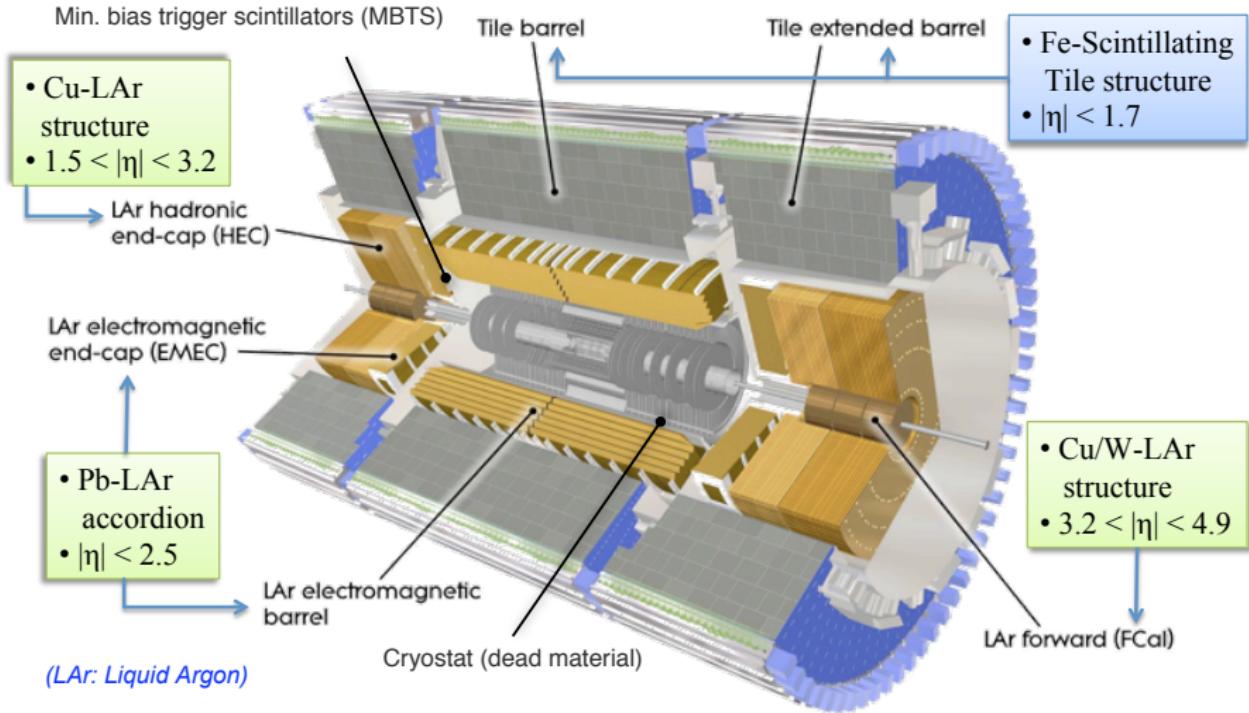
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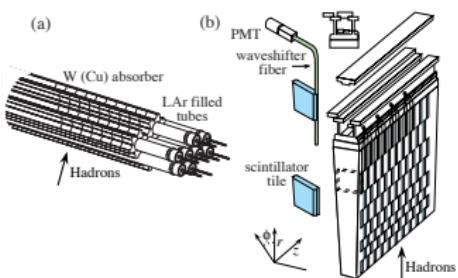
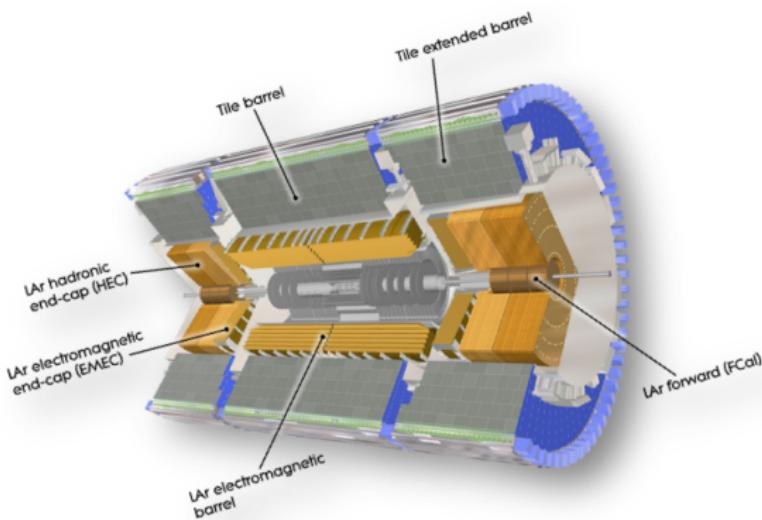


# The ATLAS Calorimeter System



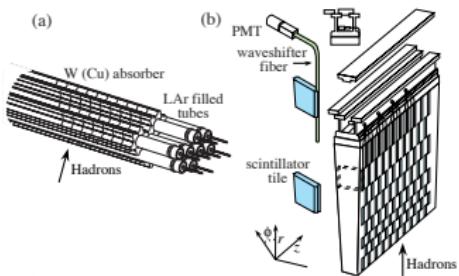
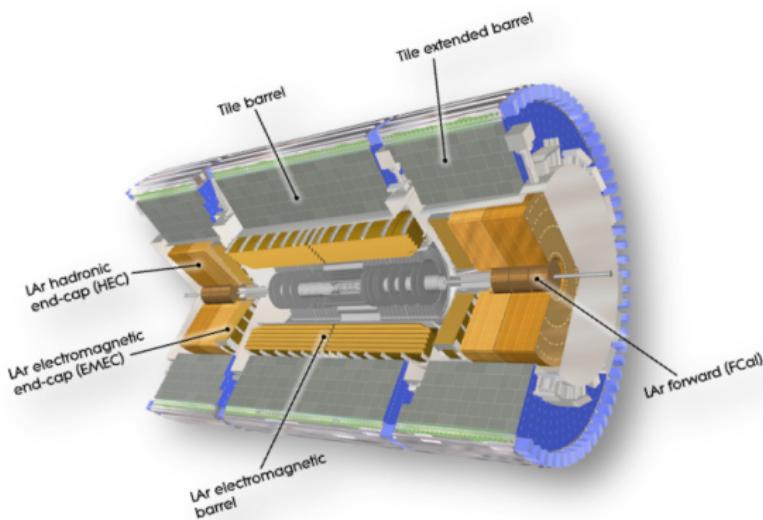
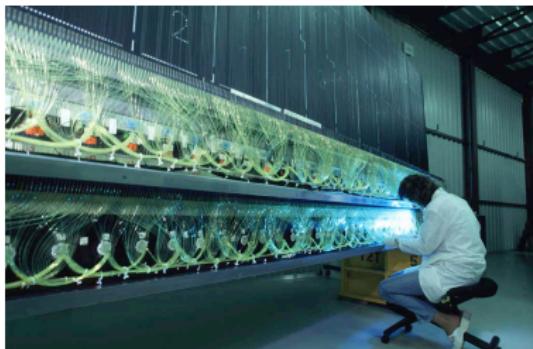
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- Liquid Argon electromagnetic (**LAr EM**) barrel and end-caps
- Hadronic Tile barrel and extended barrel (**TileCal**)
- LAr hadronic end-cap (**HEC**)
- LAr forward calorimeter (**FCAL**)



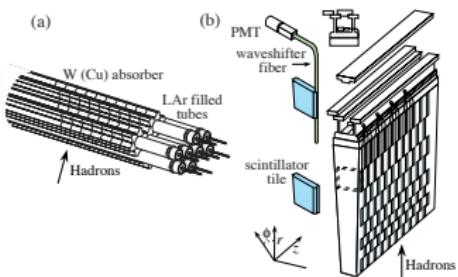
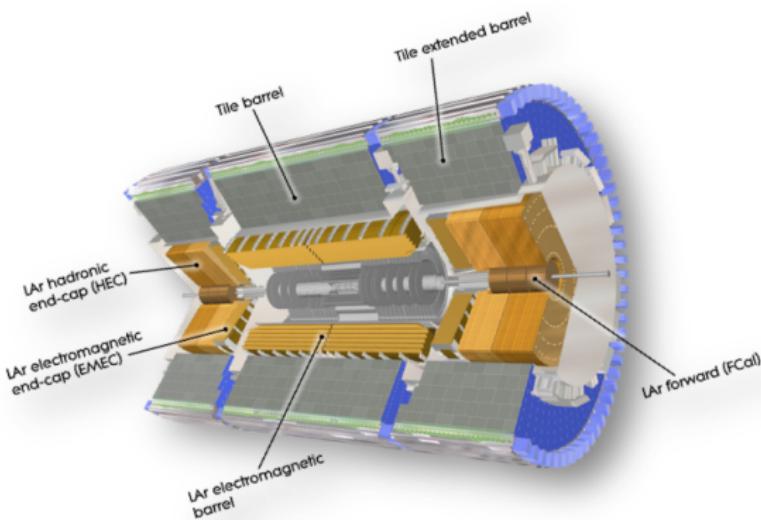
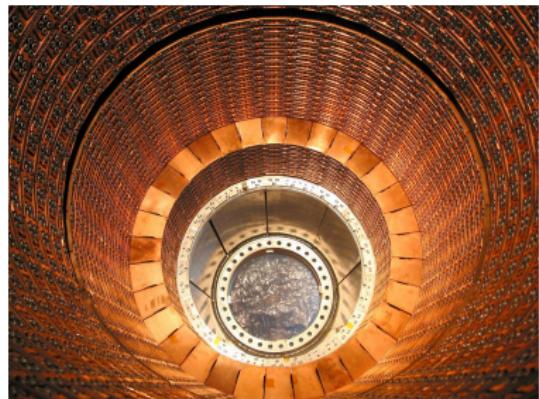
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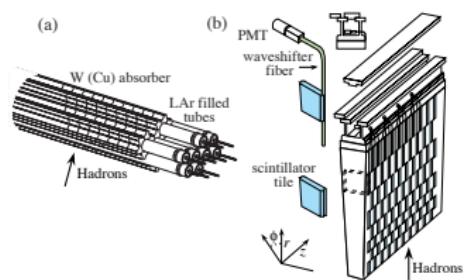
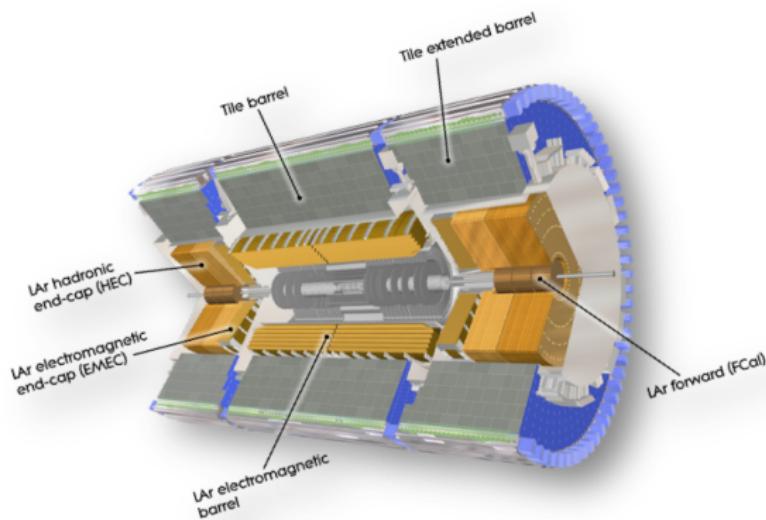
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# The ATLAS Calorimeter System

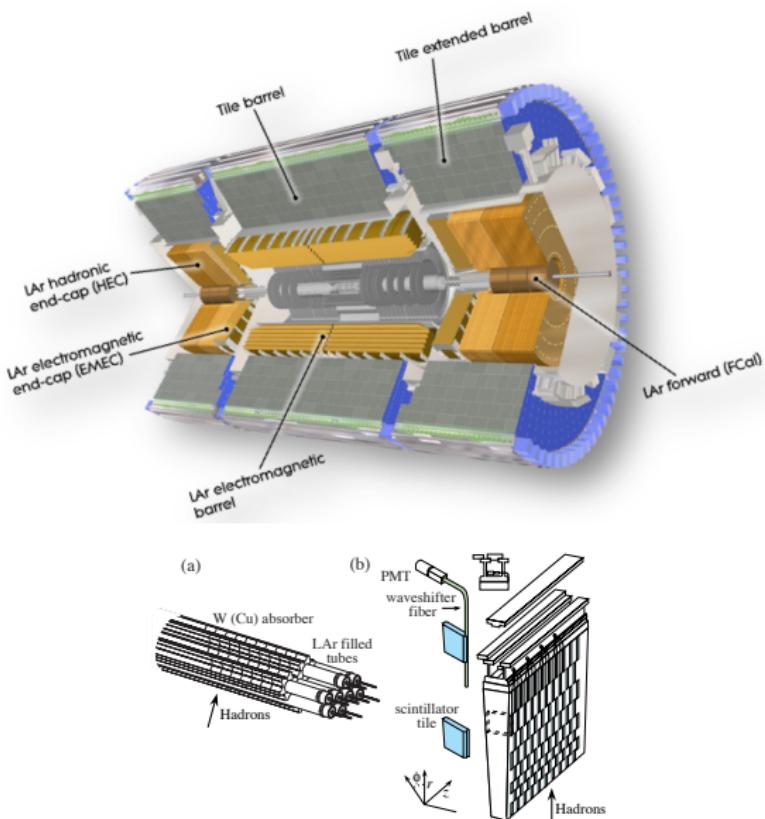
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# The ATLAS Calorimeter System

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

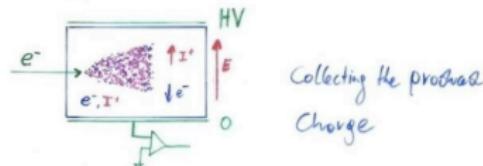
Technology (Exp.)	Depth	Energy resolution	Date
NaI(Tl) (Crystal Ball)	$20X_0$	$2.7\%/\sqrt{E}$	1983
Bi <sub>4</sub> Ge <sub>3</sub> O <sub>12</sub> (BGO) (L3)	$22X_0$	$2\%/\sqrt{E} \oplus 0.7\%$	1993
CsI (KTeV)	$27X_0$	$2\%/\sqrt{E} \oplus 0.45\%$	1996
CsI(Tl) (BaBar)	$16-18X_0$	$2.3\%/\sqrt{E} \oplus 1.4\%$	1999
CsI(Tl) (BELLE)	$16X_0$	1.7% for $E_\gamma > 3.5$ GeV	1998
PbWO <sub>4</sub> (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



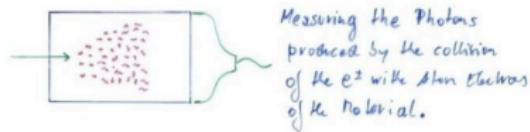
# The ATLAS Calorimeter System

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

Energy Measurement by



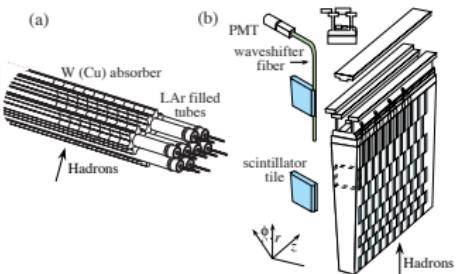
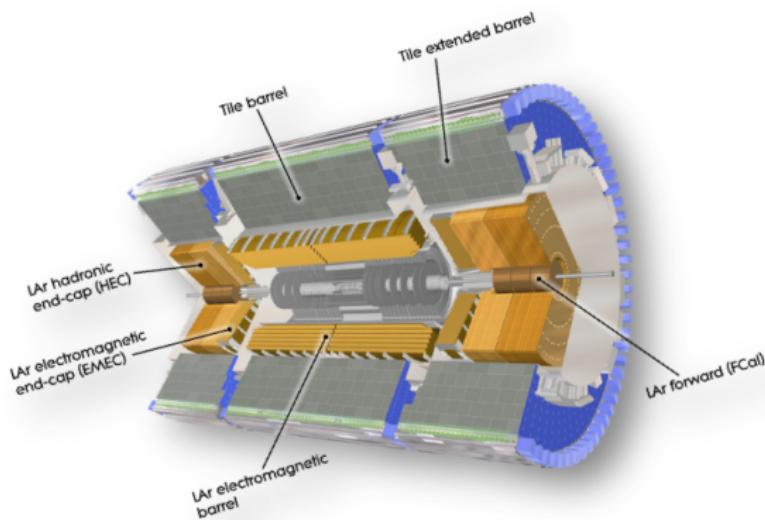
Collecting the produced Charge



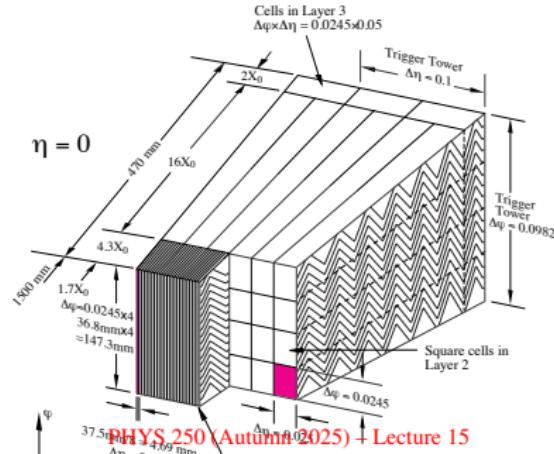
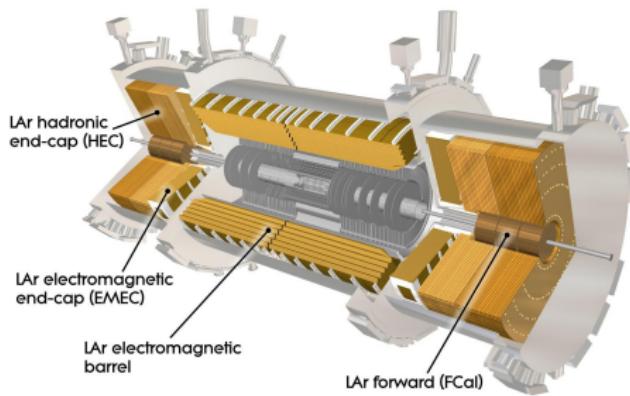
Measuring the Photons produced by the collision of the  $e^\pm$  with Atom Electrons of the material.

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

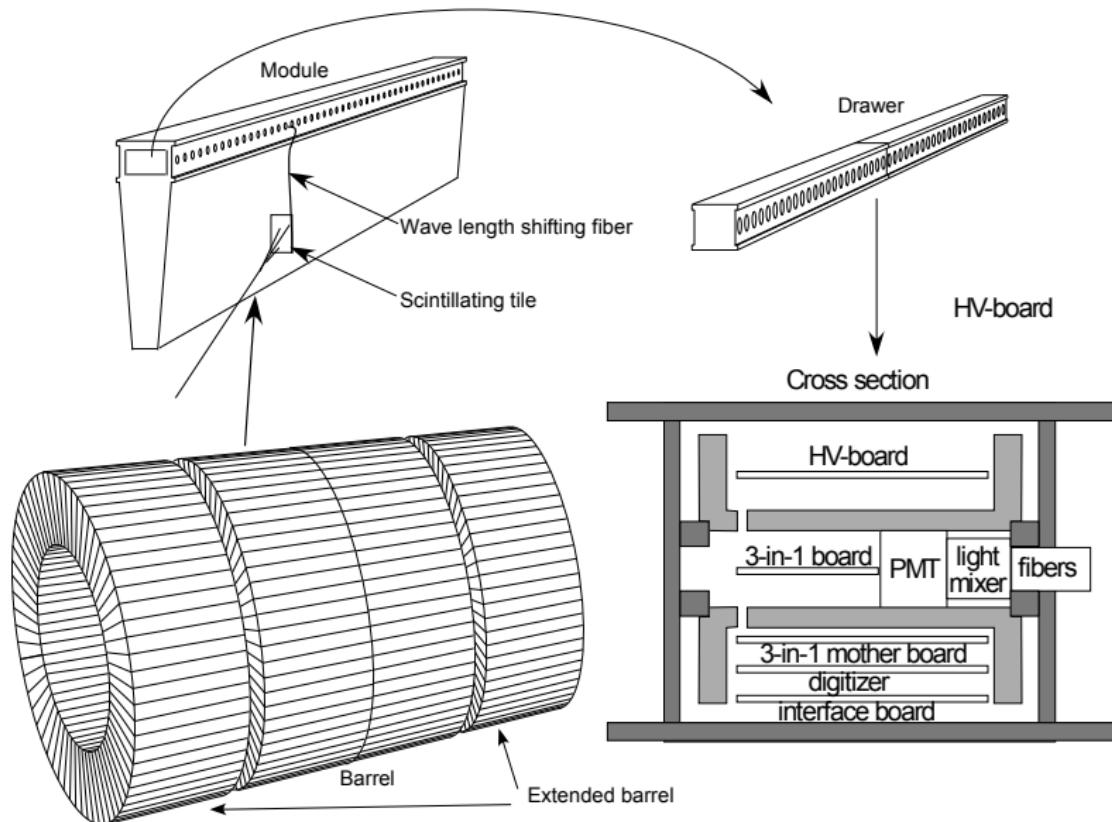
(From W. Riegler)



# Structure of the LAr



# *Structure of the hadronic “TileCal” calorimeter*



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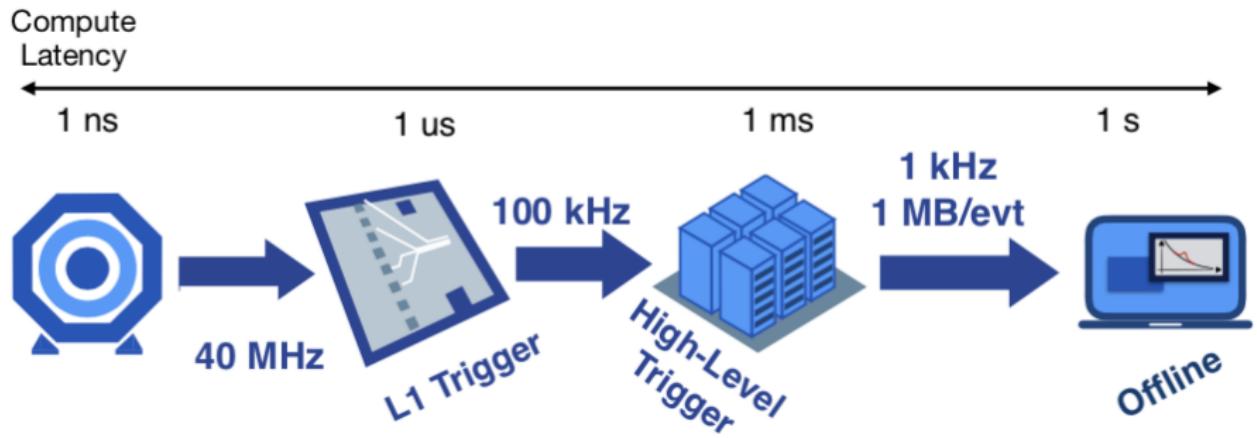
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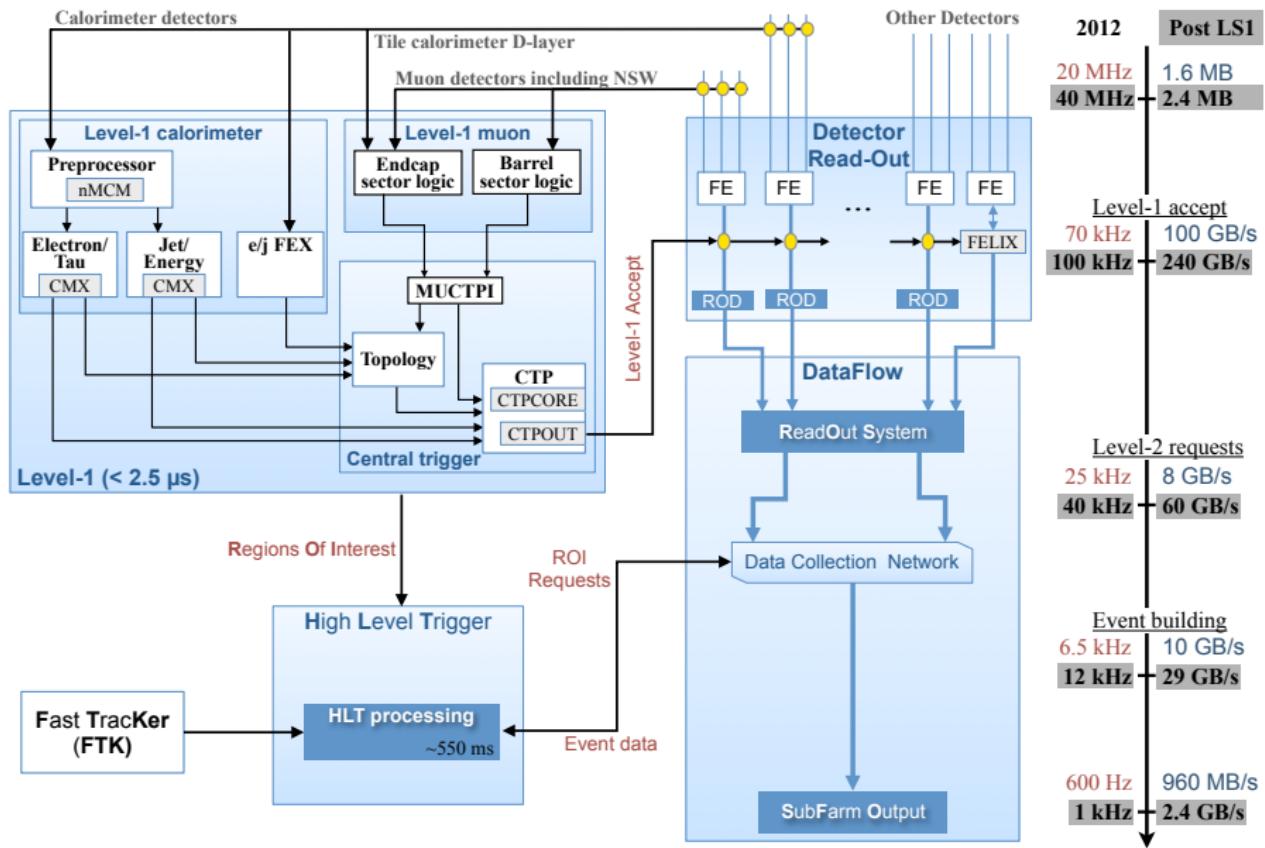
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- Data and Simulation

# Collecting and Distributing the Data



# Collecting and Distributing the Data

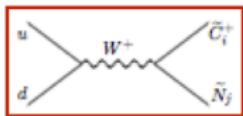


# *Collecting and Distributing the Data*

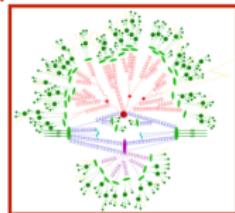


# Analyzing the Data

Simulation of hard-scatter for signal + SM background



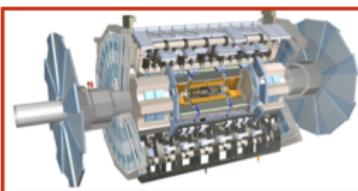
Simulation of “soft physics”  
(shower + hadronization)



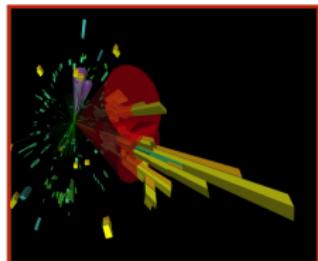
LHC real data



Detector simulation

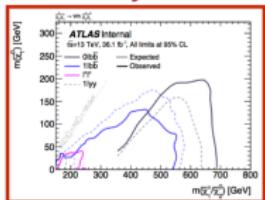


Reconstruction of physical observables

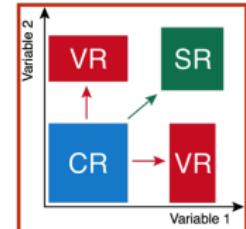
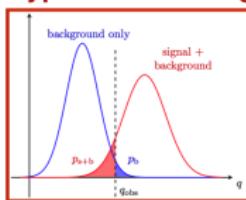


Event selection and background estimation

Discovery or exclusion



Hypothesis testing



## 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**:

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

Its **Lorentz-invariant norm** is:

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

Other common four-vectors:

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

## *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:

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

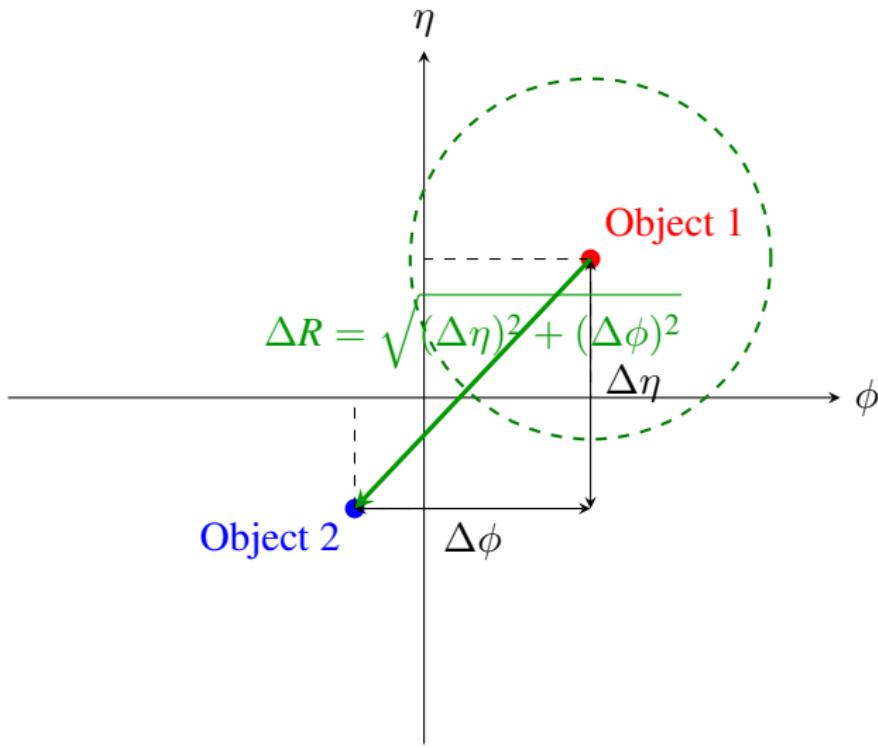
Event-level observables are Lorentz-invariant combinations of these:

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

for example, reconstructing the:

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

# Four-Vectors and LHC Data Analysis



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