# The LHC
# Journey to the Early Universe

**10th Edition of Beamline for Schools**

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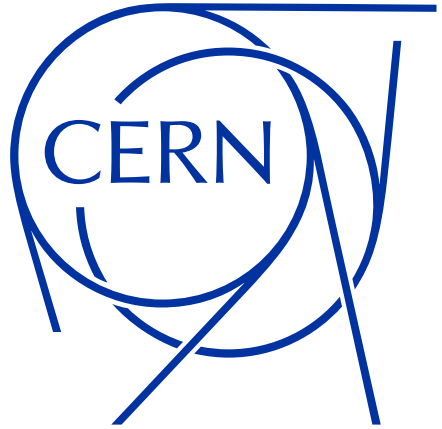
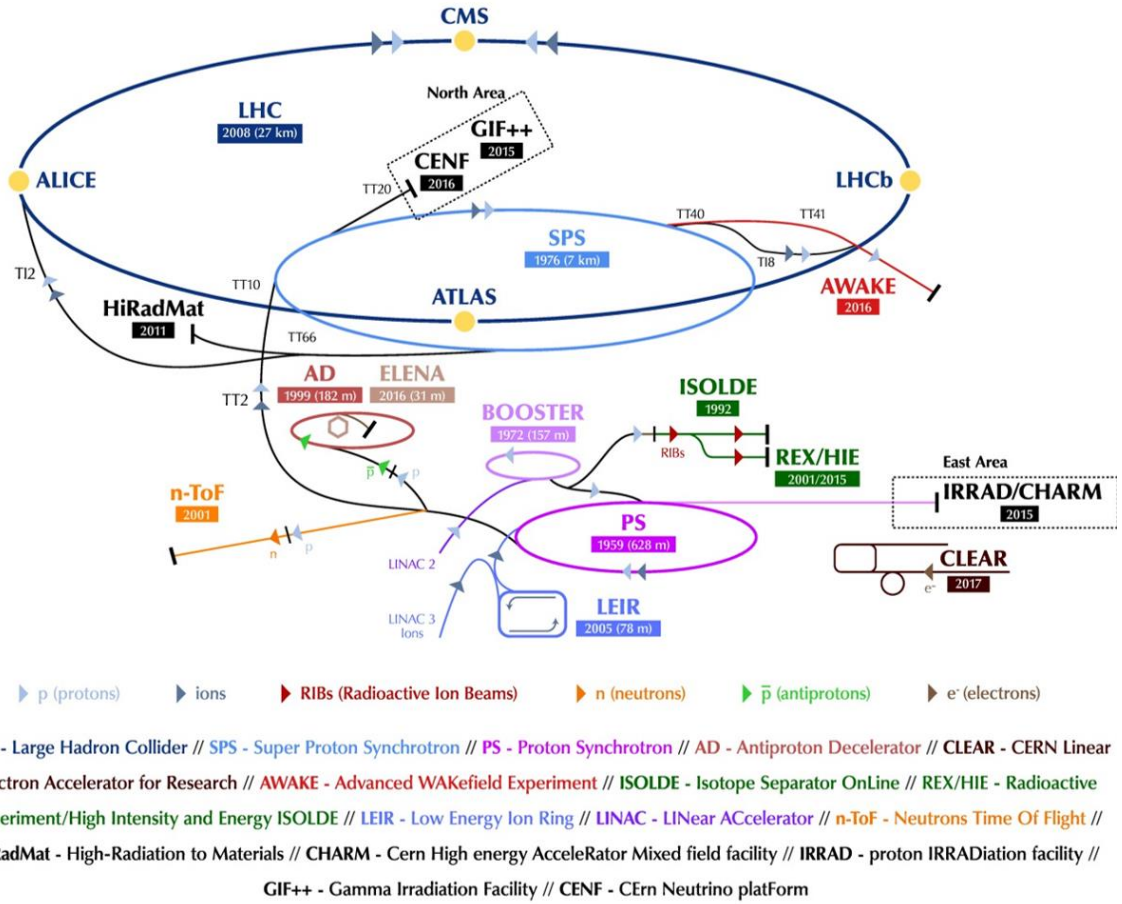
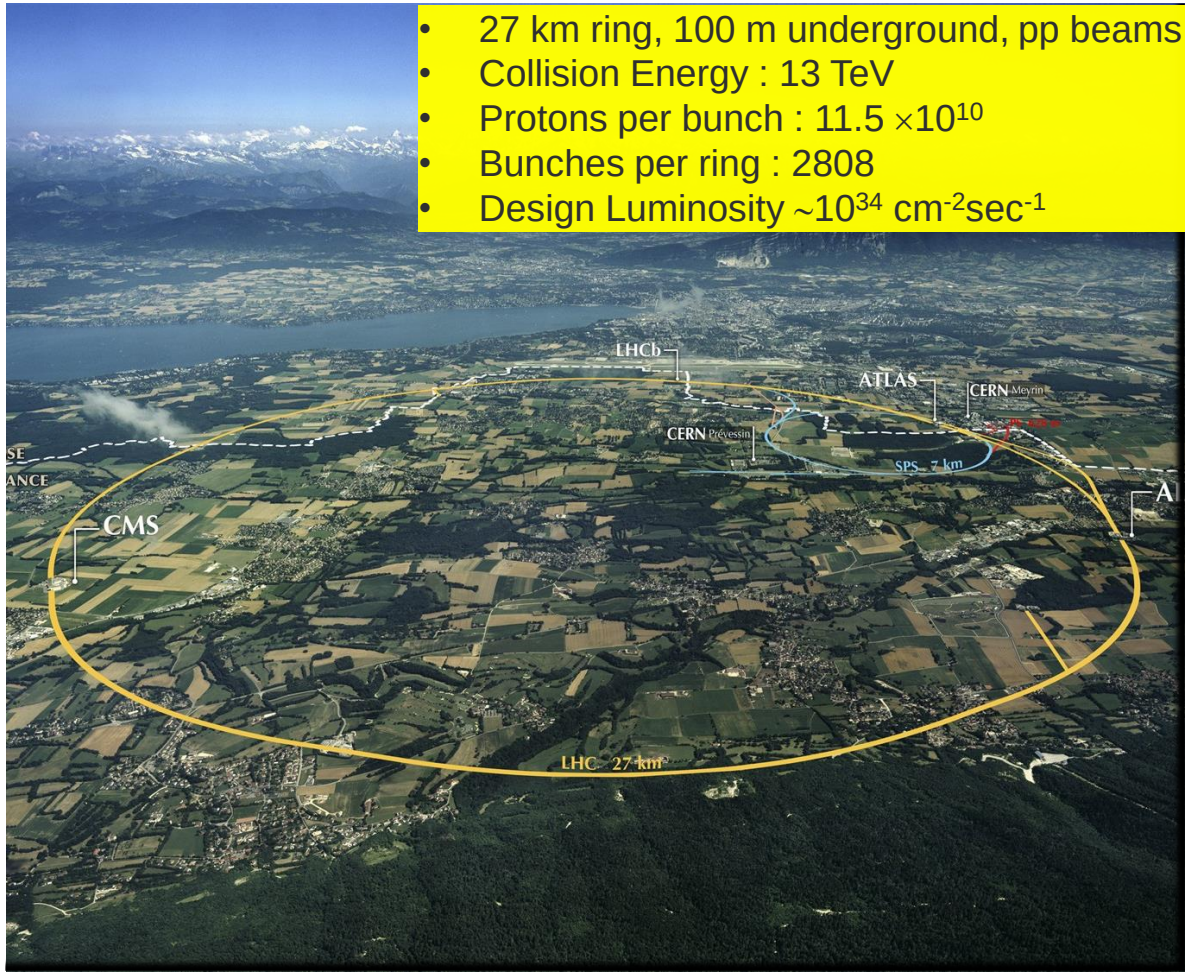



# Introduction to CERN

# Accelerator Complex

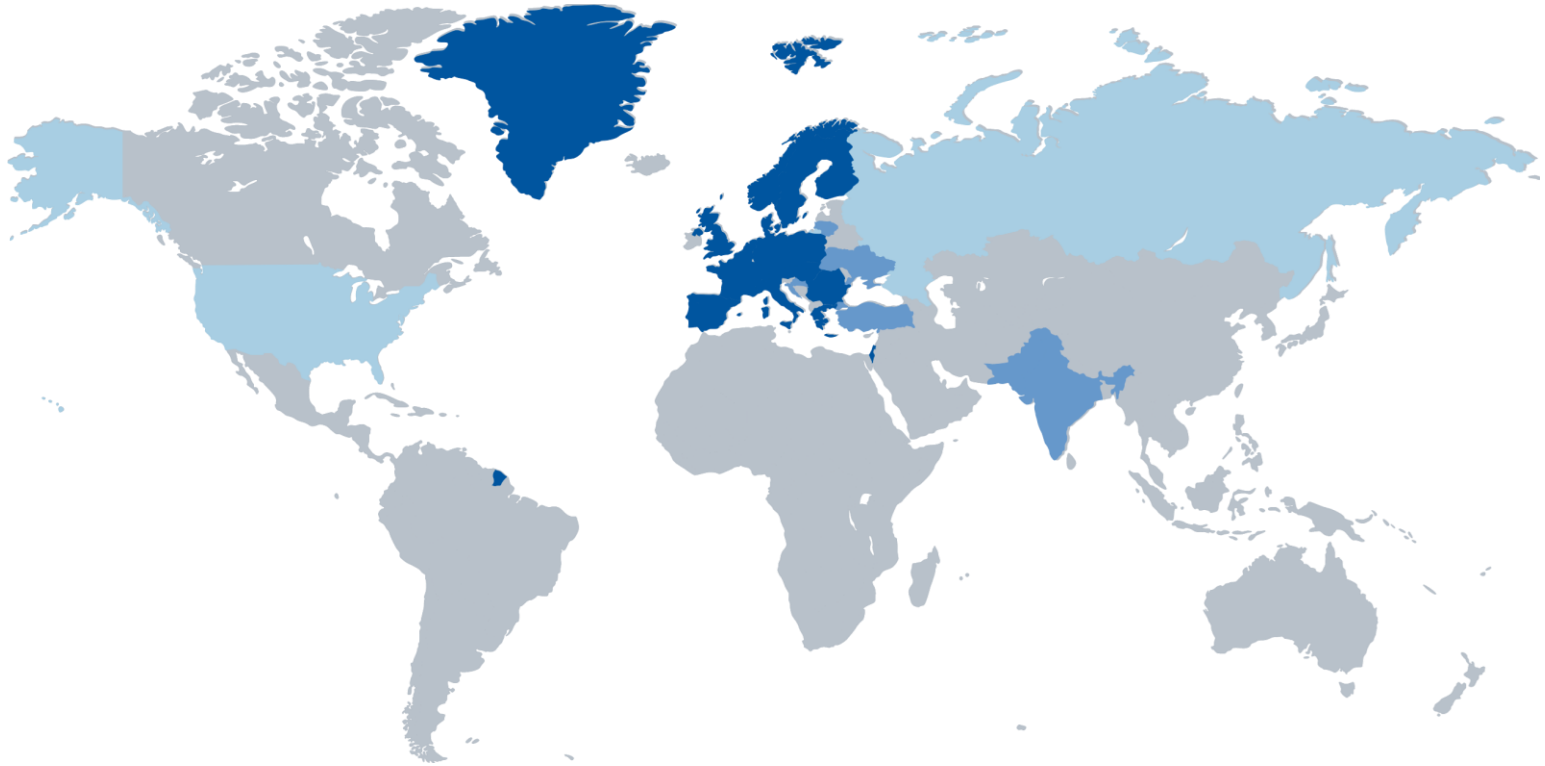



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n-ToF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // CHARM - Cern High energy AcceleRator Mixed field facility // IRRAD - proton IRRADiation facility // GIF++ - Gamma Irradiation Facility // CENF - CErn Neutrino platForm




- 27 km ring, 100 m underground, pp beams
- Collision Energy : 13 TeV
- Protons per bunch : 11.5 $\times 10^{10}$
- Bunches per ring : 2808
- Design Luminosity ~$10^{34}$ $cm^{-2}sec^{-1}$

# CERN in Numbers



- In 1954 CERN had 12 Member States
- Today CERN has 23 Member States
- 03 Associate Member States in the pre-stage to membership
- 06 Associate Member States
- 06 Observer: Japan – Russia (suspended) – USA, European Union – JINR (suspended) – UNESCO

**Yearly budget ~ 1200 MCHF**

~ **2 658** Staff members (31/12/2022), **900** Fellows

~ **2 000** Contractors' employees

~ **11 860** Physicists / Users

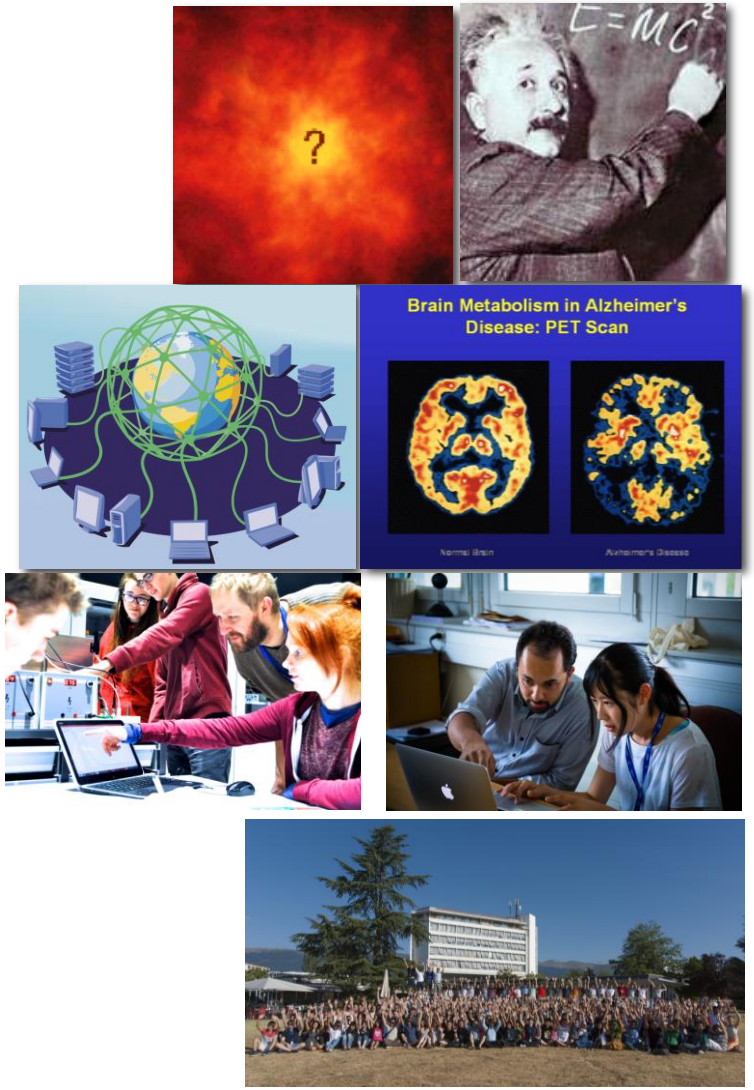
Geographical & cultural diversity: **110** nationalities

# The Mission of CERN

- **Push back the frontiers of knowledge**
- **the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?**

- **Develop new technologies for accelerators and detectors**
- **Information technology - the Web and the GRID**
- **Medicine - diagnosis and therapy**
- **Train scientists and engineers of tomorrow**

- **Unite people from different countries and cultures**



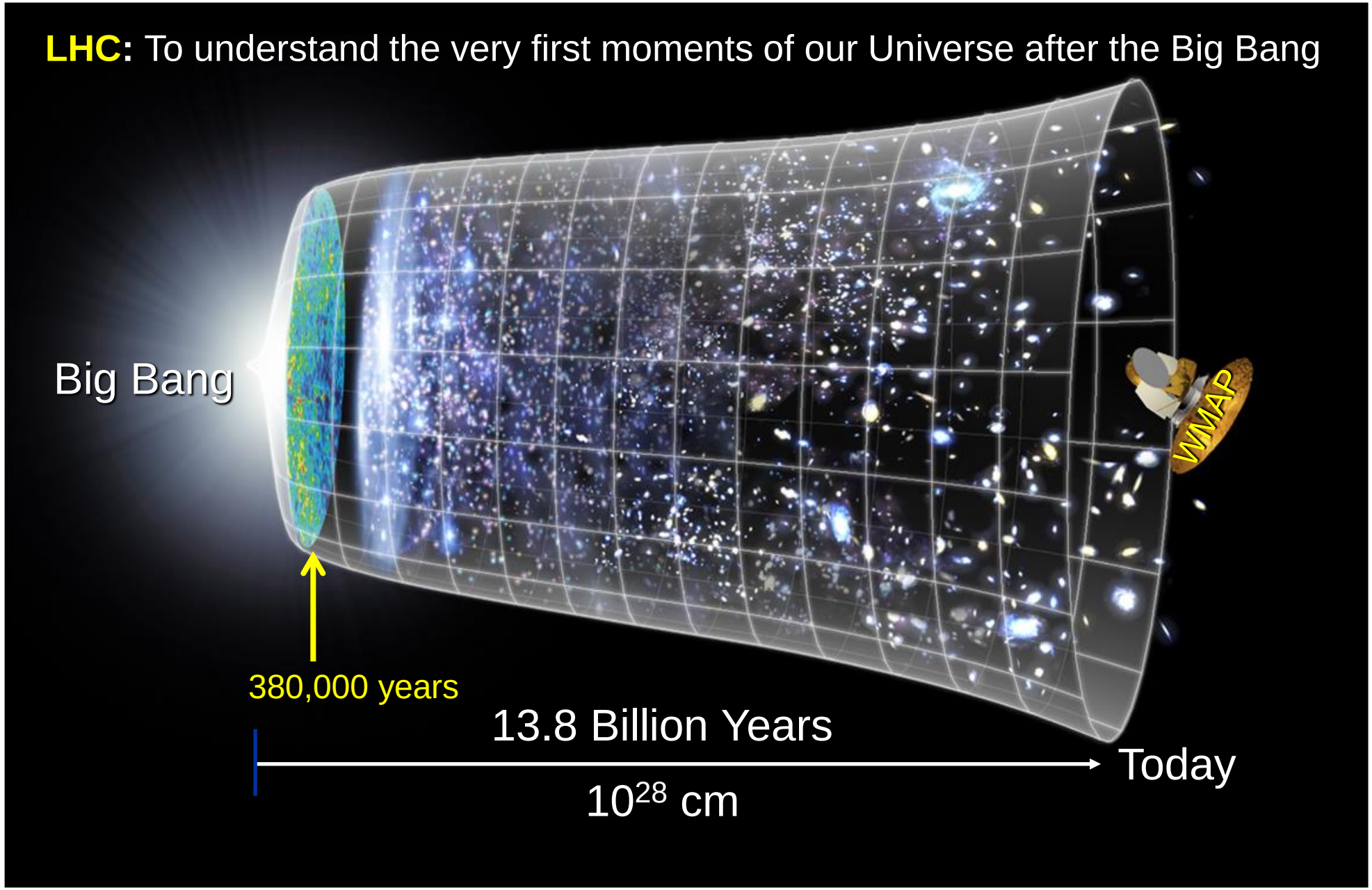
# The Large Hadron Collider

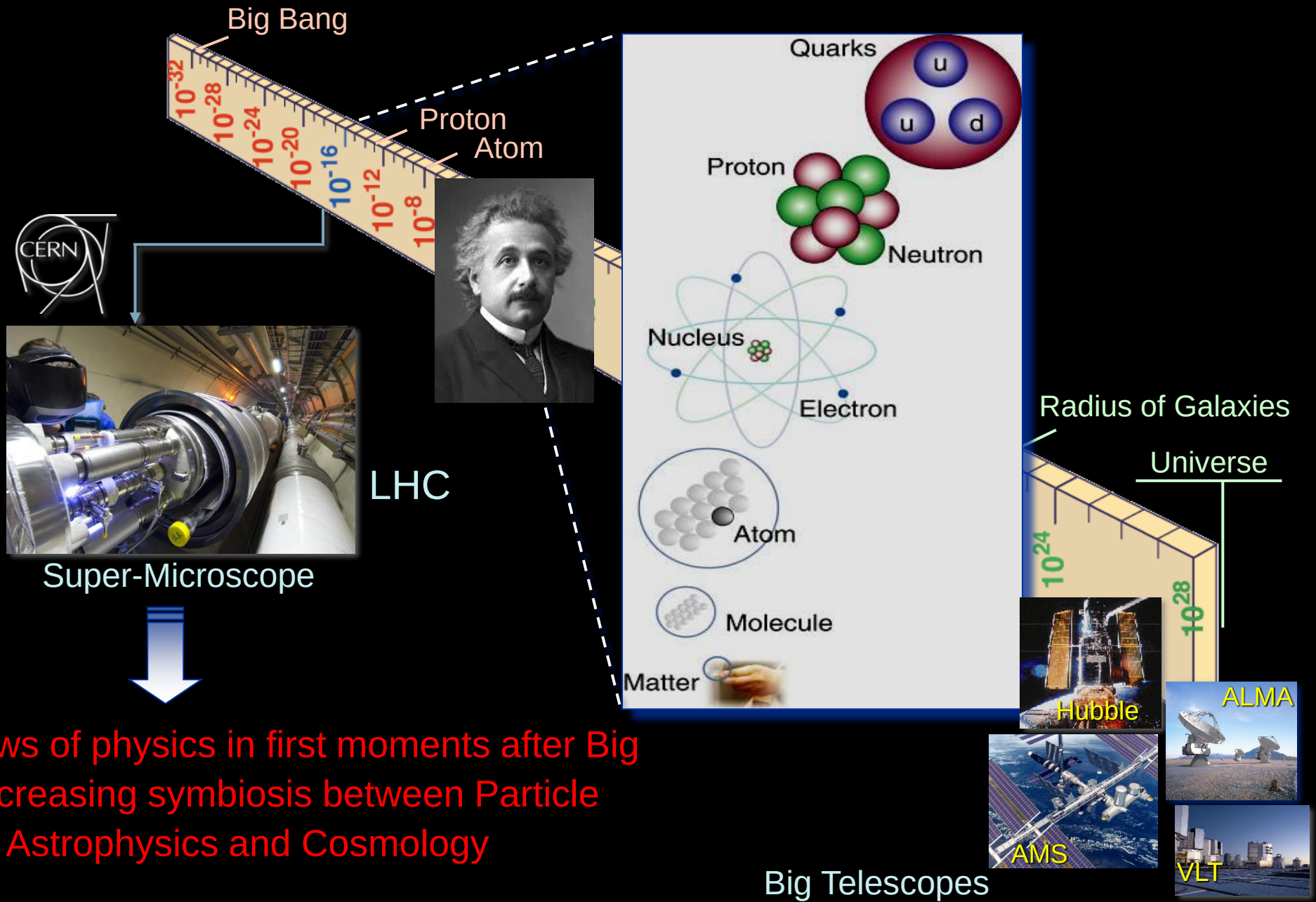
# LHC

LHC results will determine the future of High-Energy Physics;

- Origin of Mass
- Understanding space-time
- Nature of the dark matter and energy
- Matter vs Antimatter (CP violation)
- Primordial Plasma (Quark-Gluon Plasma)

**LHC:** To understand the very first moments of our Universe after the Big Bang





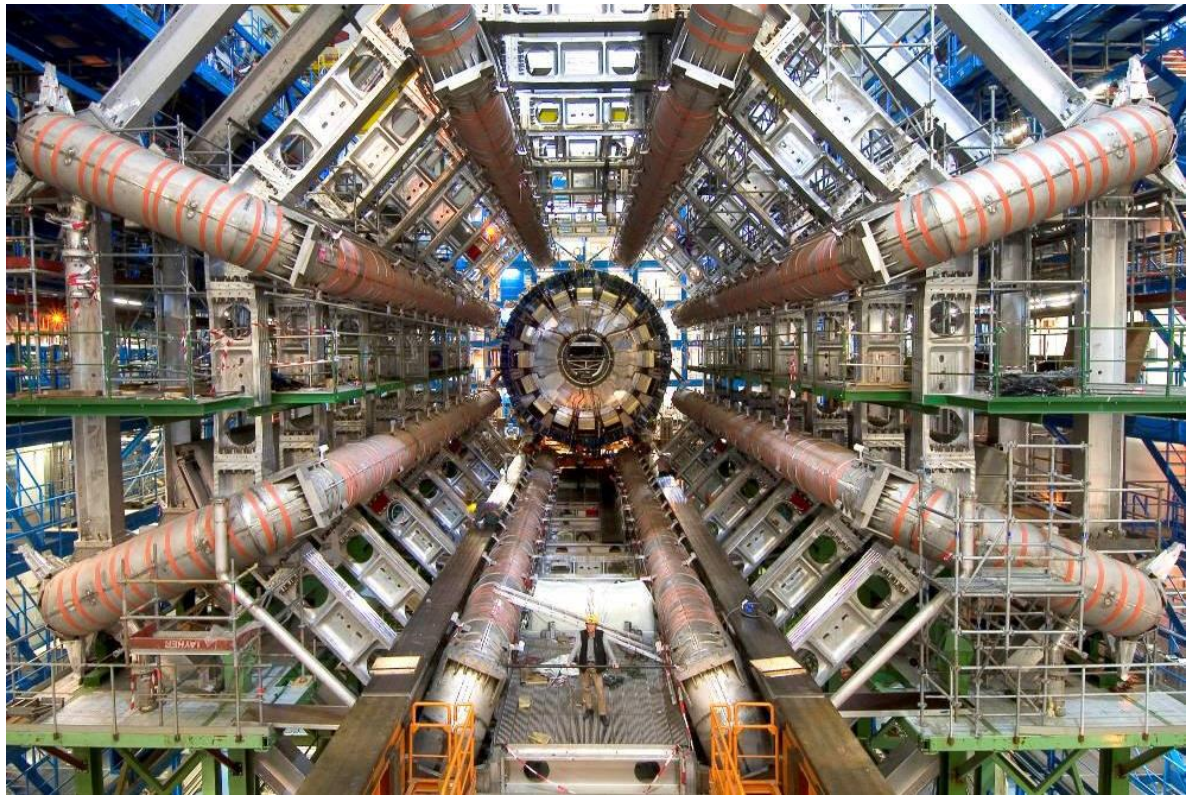

Study laws of physics in first moments after Big Bang, increasing symbiosis between Particle Physics, Astrophysics and Cosmology


CMS
LHCb
ATLAS
ALICE
CMS
LHCb
SPS 7 km
ALICE
LHC 27 km

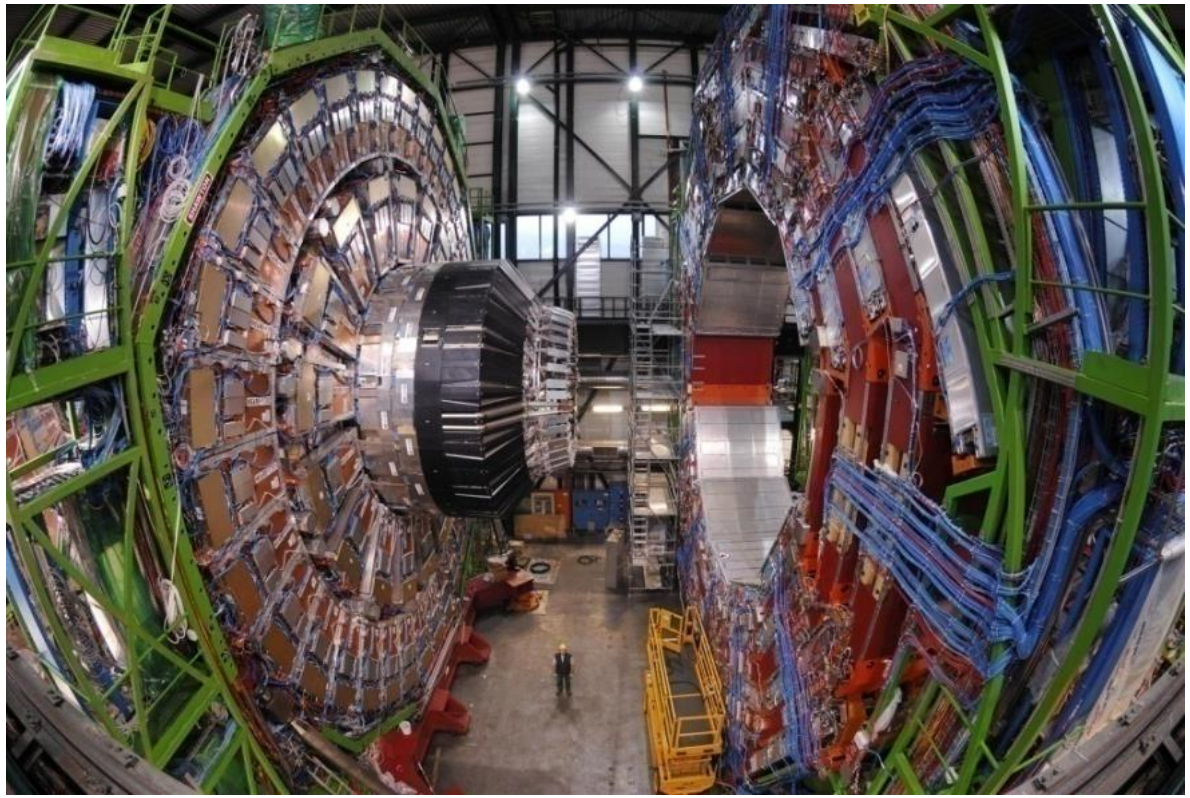
# ATLAS & CMS Detectors – Discovery Experiments

**Each detector is like a 100-megapixel camera which takes 40 million pictures per second. The largest and most complex scientific instruments ever built.**

**ATLAS**



**CMS**



# LHC Beams & Luminosity

$$N = \sigma \mathcal{L}$$

$N = \text{No. of interactions in one sec}$

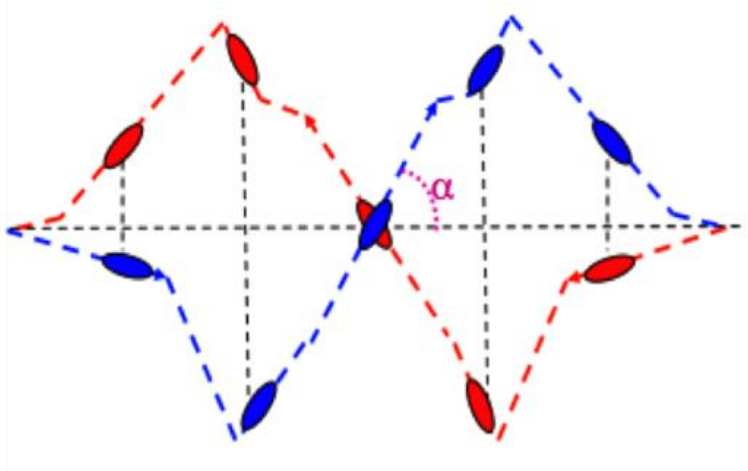
$\sigma = \text{Interaction cross} - \text{section}$

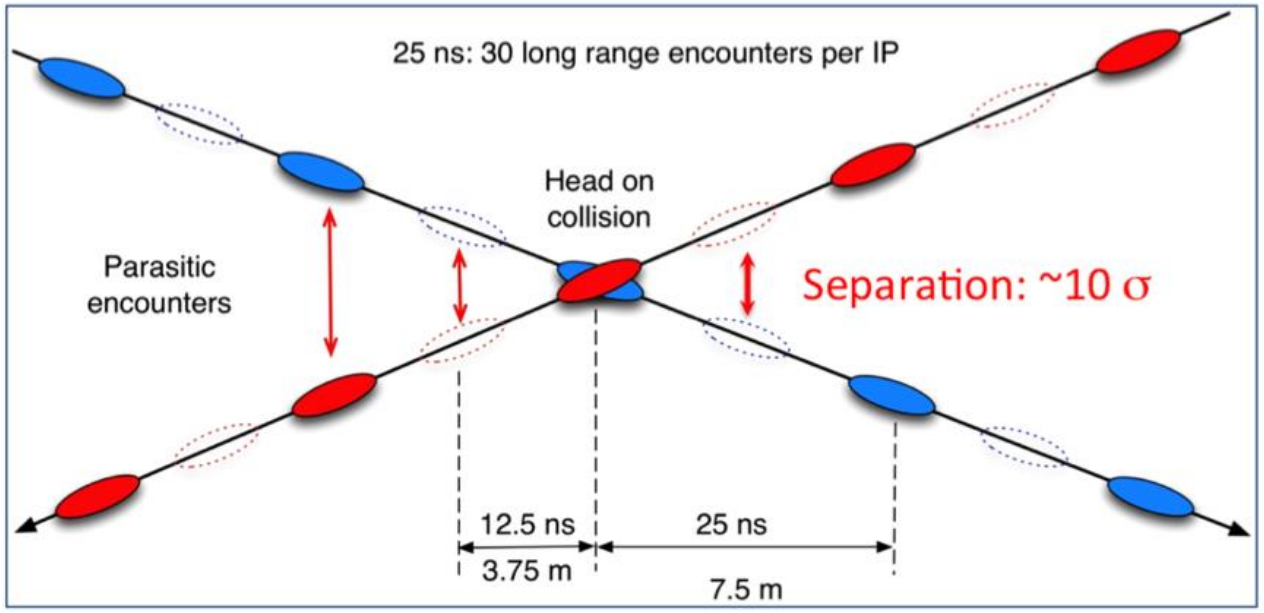
$\mathcal{L} = \text{Instantaneous Luminosity}$

Designed LHC $\mathcal{L} = 10^{34} cm^{-2} sec^{-1}$

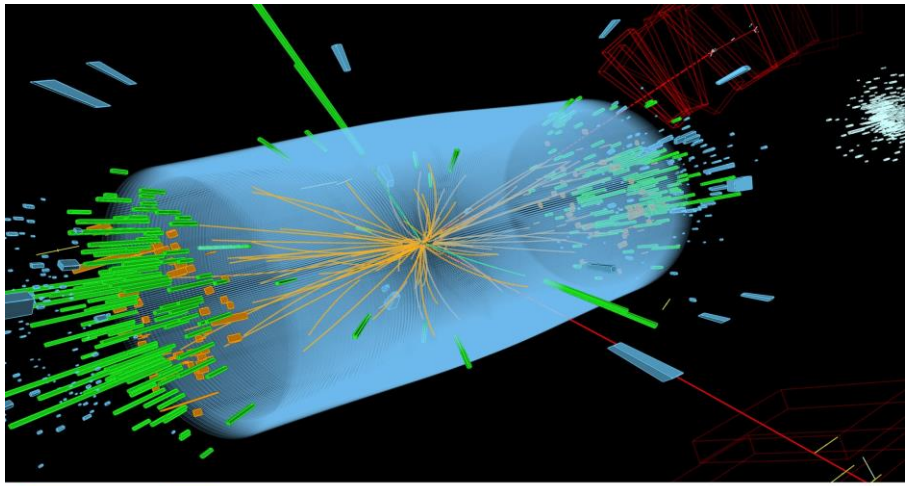
$$\sqrt{s} = 13\ TeV$$

- More energy means increasing potential for massive particles
- More data means increasing chances to see rare processes (with small cross-section $\sigma$)

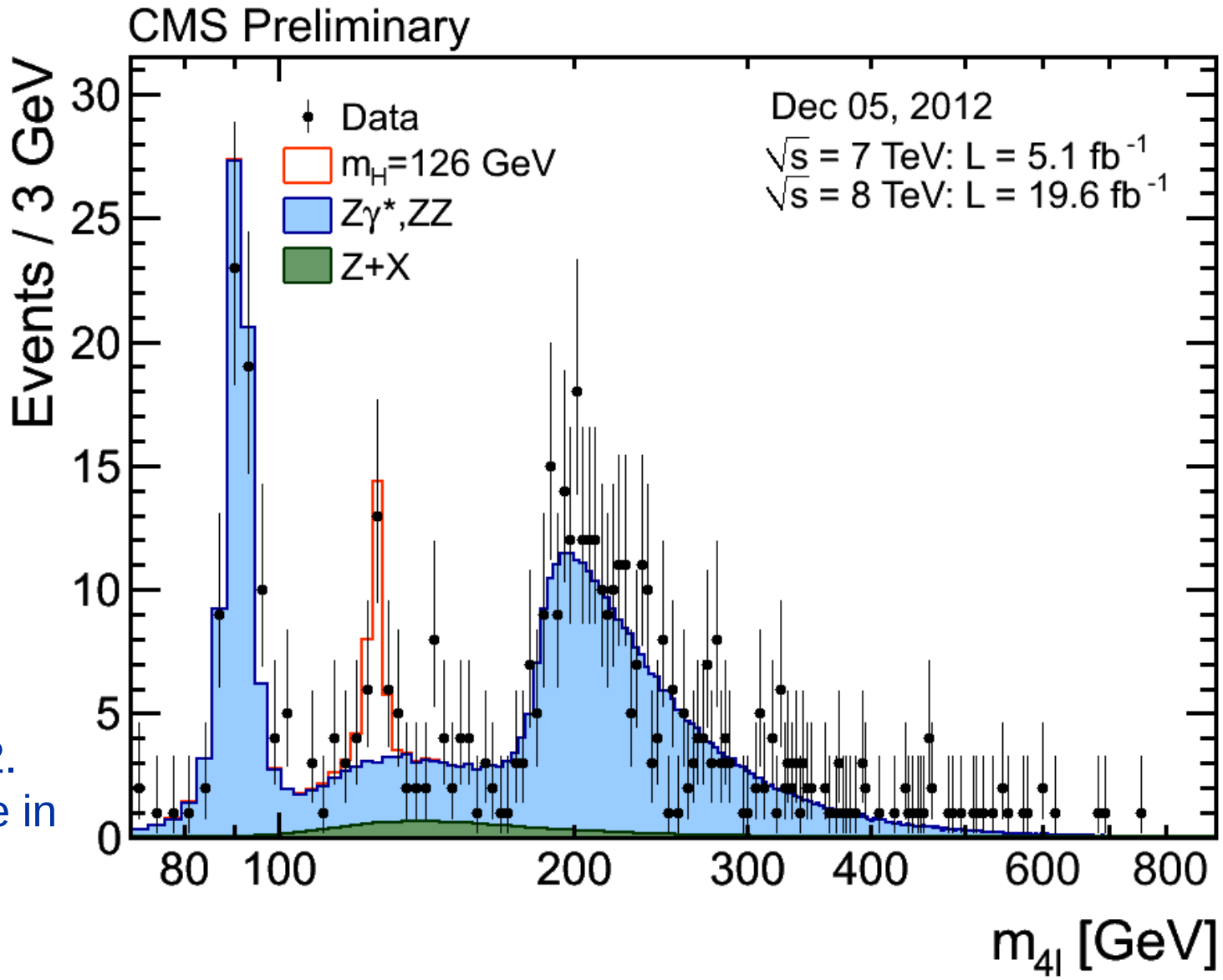


## Higgs Boson decay in CMS Detector into 4 leptons ($e^+e^-\mu^+\mu^-$)

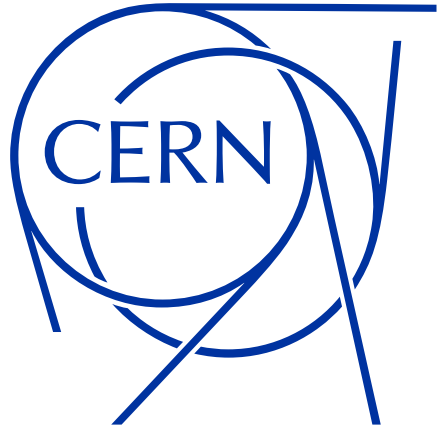


Higgs candidate detected with RPCs built with contributions from Pakistan.
Presented to Dr Ansar Parvez, The Pakistan Atomic Energy Commission.
CMS Experiment at the LHC, CERN, 25.09.2012




- The discovery of Higgs Boson was announced at CERN on July 4, 2012.
- This was followed by the Nobel Prize in 2013


The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*


# Standard Model of Particle Physics

# The Standard Model of Particle Physics


## The Fundamental Interactions

Gravitation ($10^{-43}$) Electromagnetism ($10^{-2}$) Weak Nuclear Force ($10^{-6}$) Strong Nuclear Force (1)

# The Standard Model (SM) is a beautiful theory and unarguably one that is most precisely tested experimentally

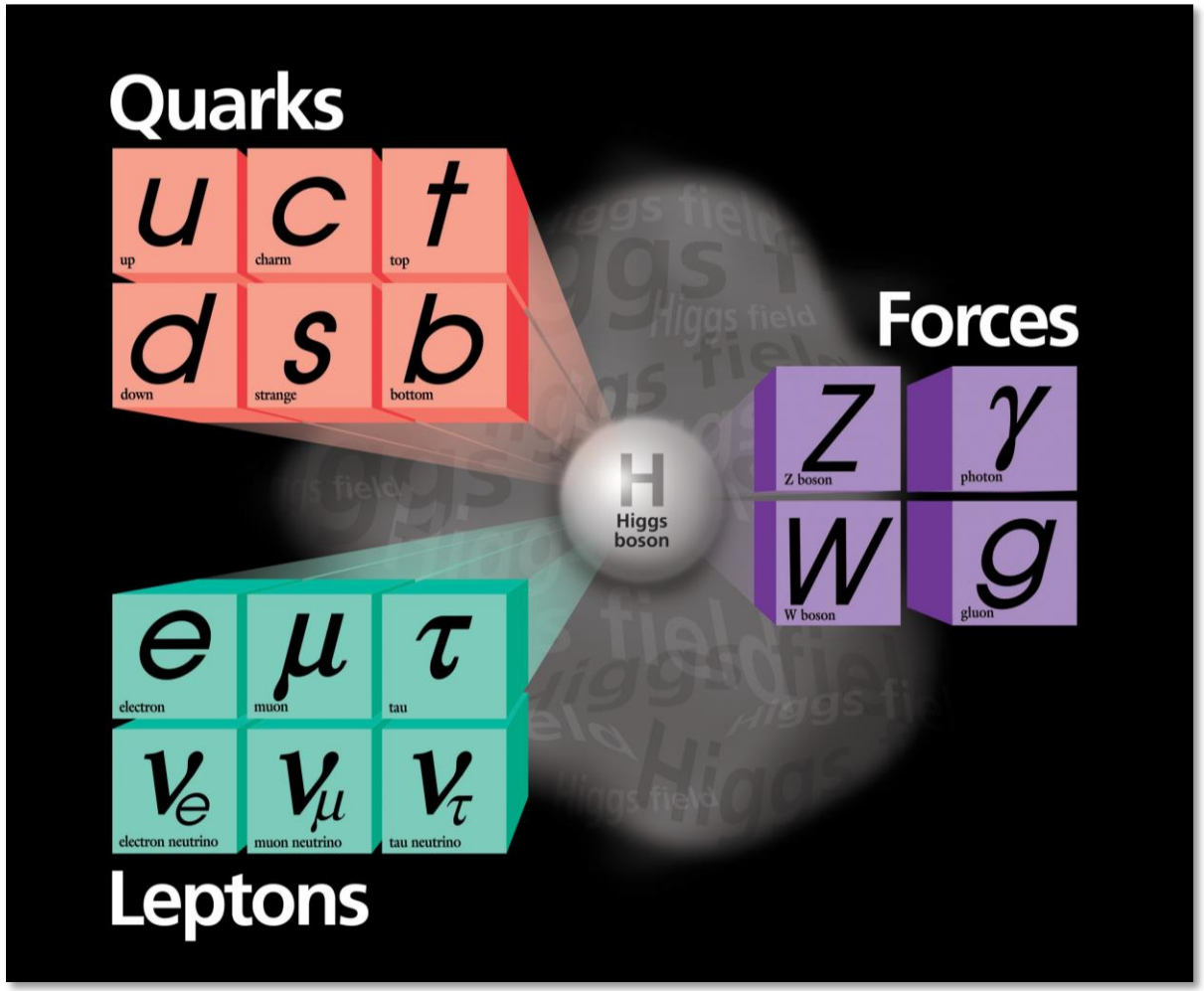
| Quantity | Value | Standard Model | Pull |
|---|---|---|---|
| $m_t$ [GeV] | | 172.76 ± 0.30 | 0.0 |
| $M_W$ [GeV] | | 80.377 ± 0.017 | 1.3 |
| | | | 0.4 |
| $M_Z$ [GeV] | 91.1876 ± 0.0021 | 91.1874 ± 0.0021 | 0.1 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4968 ± 0.0011 | −0.7 |
| $\Gamma$(had) [GeV] | 1.7444 ± 0.0020 | 1.7434 ± 0.0010 | — |
| $\Gamma$(inv) [MeV] | 499.0 ± 1.5 | 501.65 ± 0.11 | — |
| $\Gamma(\ell^+\ell^-)$ [MeV] | 83.984 ± 0.086 | 83.996 ± 0.021 | — |
| $\sigma_{had}$ [nb] | 41.541 ± 0.037 | 41.467 ± 0.009 | 2.0 |
| $R_e$ | 20.804 ± 0.050 | 20.756 ± 0.011 | 1.0 |
| $R_\mu$ | 20.785 ± 0.033 | 20.756 ± 0.011 | 0.9 |
| $R_\tau$ | 20.764 ± 0.045 | 20.801 ± 0.011 | −0.8 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21578 ± 0.00010 | 0.8 |
| $R_c$ | 0.1721 ± 0.0030 | 0.17230 ± 0.00004 | −0.1 |
| $A_{FB}^{(0,e)}$ | 0.0145 ± 0.0025 | 0.01622 ± 0.00025 | −0.7 |
| $A_{FB}^{(0,\mu)}$ | 0.0169 ± 0.0013 | | 0.5 |
| $A_{FB}^{(0,\tau)}$ | 0.0188 ± 0.0017 | | 1.5 |
| $A_{FB}^{(0,b)}$ | 0.0992 ± 0.0016 | 0.1031 ± 0.0008 | −2.4 |
| $A_{FB}^{(0,c)}$ | 0.0707 ± 0.0035 | 0.0737 ± 0.0006 | −0.8 |
| $A_{FB}^{(0,s)}$ | 0.0976 ± 0.0114 | 0.1032 ± 0.0008 | −0.5 |
| $\bar{s}^2_\ell(A_{FB}^{(0,q)})$ | 0.2324 ± 0.0012 | 0.23152 ± 0.00014 | 0.7 |
| | 0.2238 ± 0.0050 | | −1.5 |

$M_Z$ = 91.1876 ± 0.0021 (exp)

*$M_Z$ = 91.1874 ± 0.0021 (SM)*

$M_W$ = 80.392 ± 0.039 (exp)

*$M_W$ = 80.376 ± 0.017 (SM)*



# Symmetry Breaking in SM

- **Massless gauge bosons, e.g., the photon has 2 polarization states: +1, -1**
- **Massive gauge bosons, e.g., W, Z, need additional polarization state with zero spin projection**
- **Provided by scalar field as postulated by Higgs, Brout and Englert**
- **Minimal Standard Model has extra particle as pointed out by Higgs: the Higgs boson**
- **Higgs pointed out a massive scalar boson**

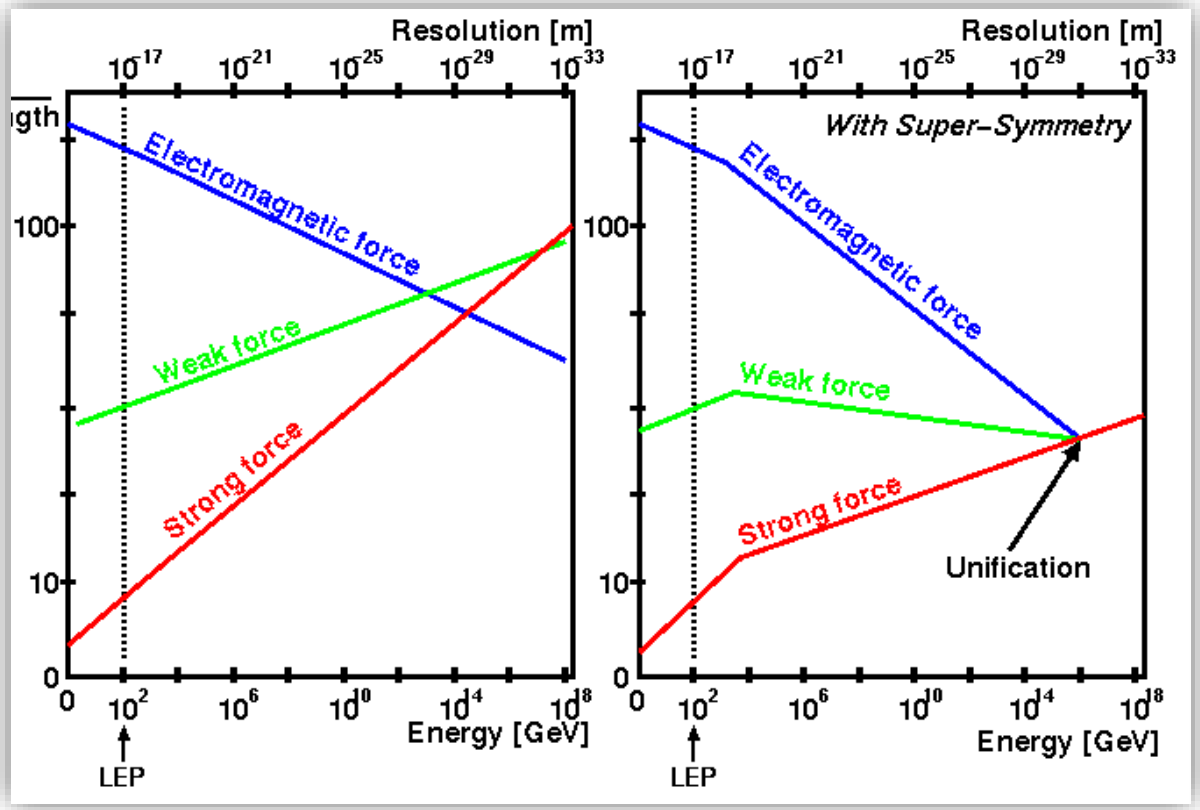
*"… an essential feature of [this] type of theory … is the prediction of incomplete multiplets of vector and scalar bosons"*

$$\{\partial^2 - 4\varphi_0{}^2 V''(\varphi_0{}^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

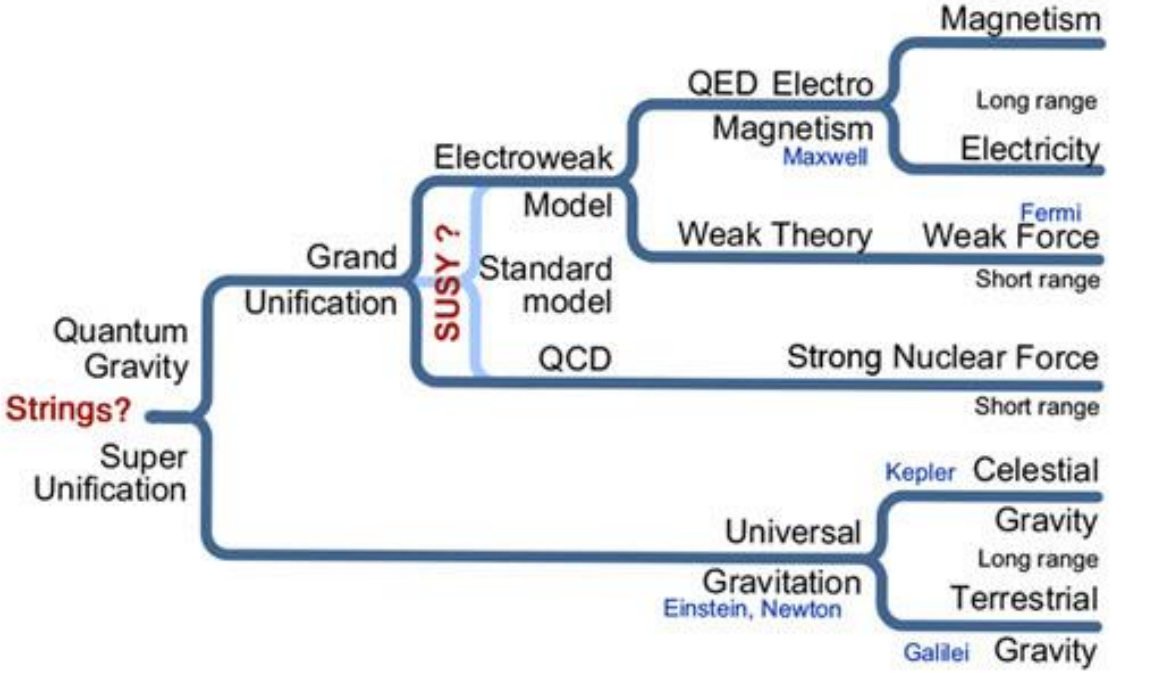
Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0{}^2)\}^{1/2}$

# Unification of Forces

## Supersymmetry vs No Supersymmetry




## Right to Left Energy Increases



# Standard Model of Cosmology

# What GOD was doing before creating this Universe?

**HE was creating Hell for those who asked this question.**

# Big Bang Cosmology

- **The Big Bang Model is a theory for the origin and evolution of our universe.**
- **Based on two theoretical pillars:**
  - Einstein's General Theory of Relativity (GR)
  - The Cosmological Principle (CP) - Matter distribution is homogenous and isotropic
- **Uniformity of Cosmic Microwave Background (CMB) supports CP**
- **A Fireball existed at time t = 0.**
- **Infinite temperature & density - a real singularity**
- **Big Explosion ⟶ BIG BANG**
- **This big impulse created an expanding Universe**

# Big Bang Cosmology

**GR predicts expansion naturally - Einstein introduced Cosmological Constant $\Lambda$ to make it static. E Hubble in 1929 observationally confirmed the expansion:**

$$v = H_0 d$$

$$H_0 = 70.8 \pm 1.6 \text{ (km/s)/Mpc}$$

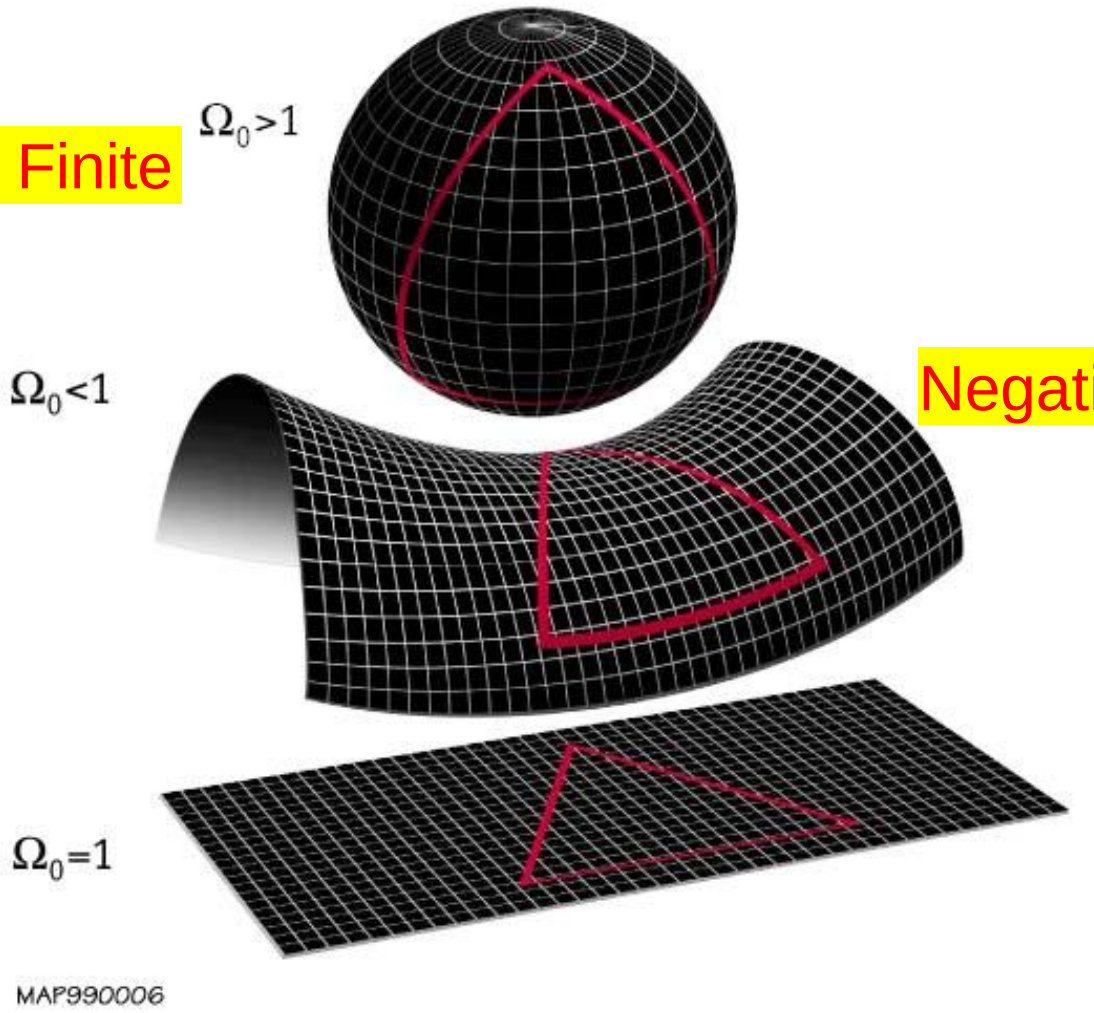
$$1 \text{ Mpc} = 3.26 \text{ million light years} = 3.08 \times 10^{18} \text{ km}$$

- $H_0$ is determined by combining WMAP & Cosmological data

- **Critical Density $\Omega$ (density parameter) :**
  - $\Omega > 1$ Universe is finite in size and closed
  - $\Omega < 1$ Universe is infinite in size and open
  - $\Omega = 1$ Universe is flat, open and infinite

# Geometry of our universe

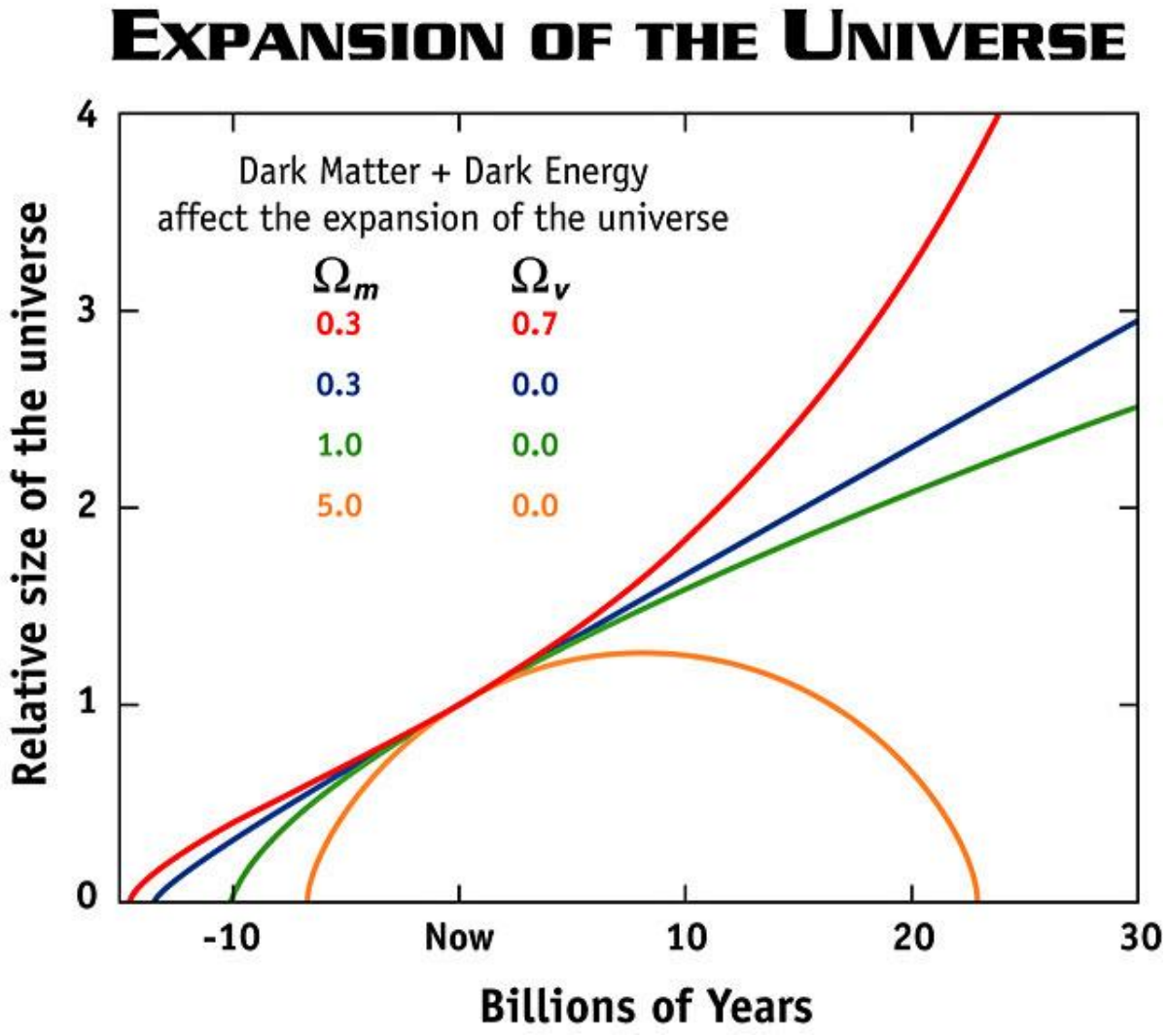
Positive Curvature and Finite




Negative Curvature and Infinite

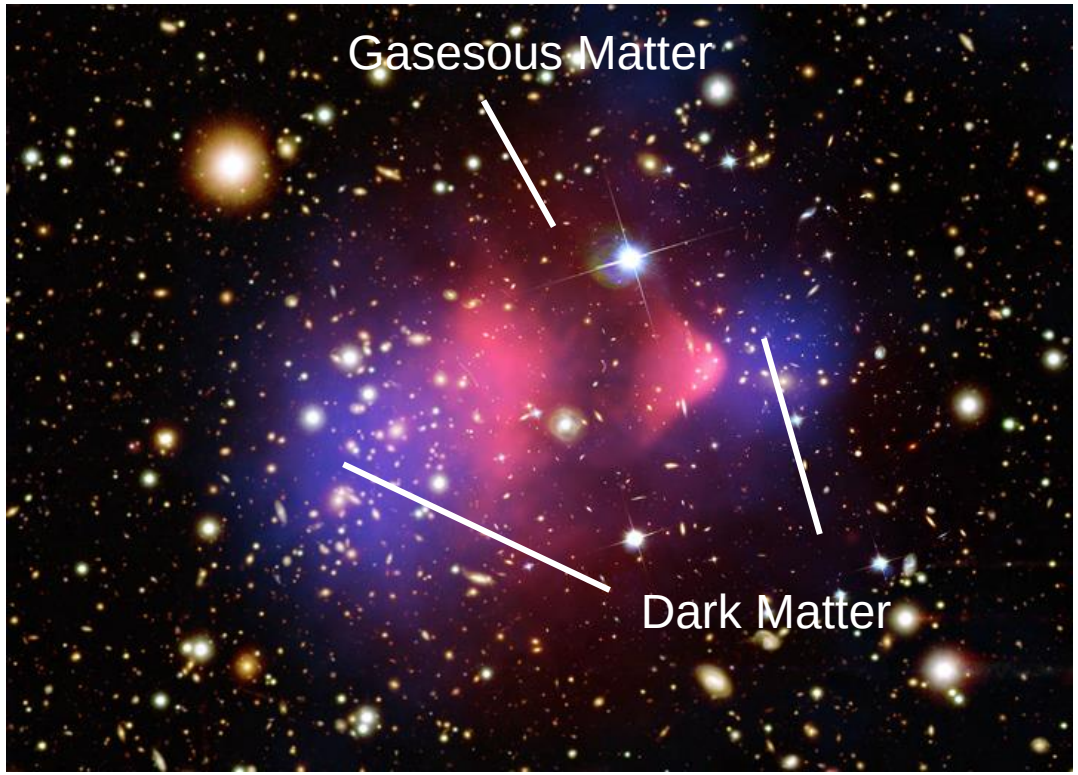
Flat and Infinite

# Hubble's Expanding Universe

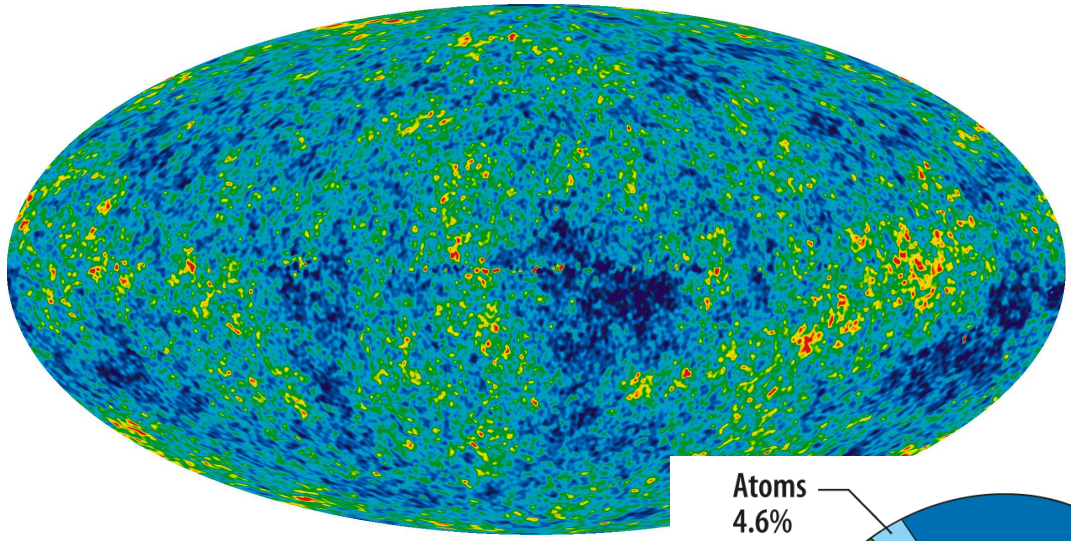


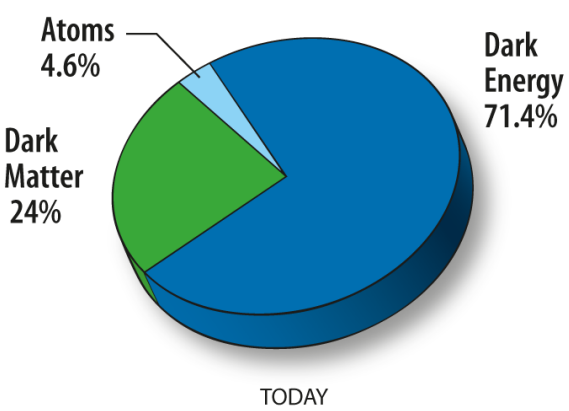
# The Dark Side of the Universe

**Dark Matter?**
Lightest SUSY particle would be a prime candidate




**Dark Energy?**
Remnant of some elementary scalar field analogous to the Higgs field?

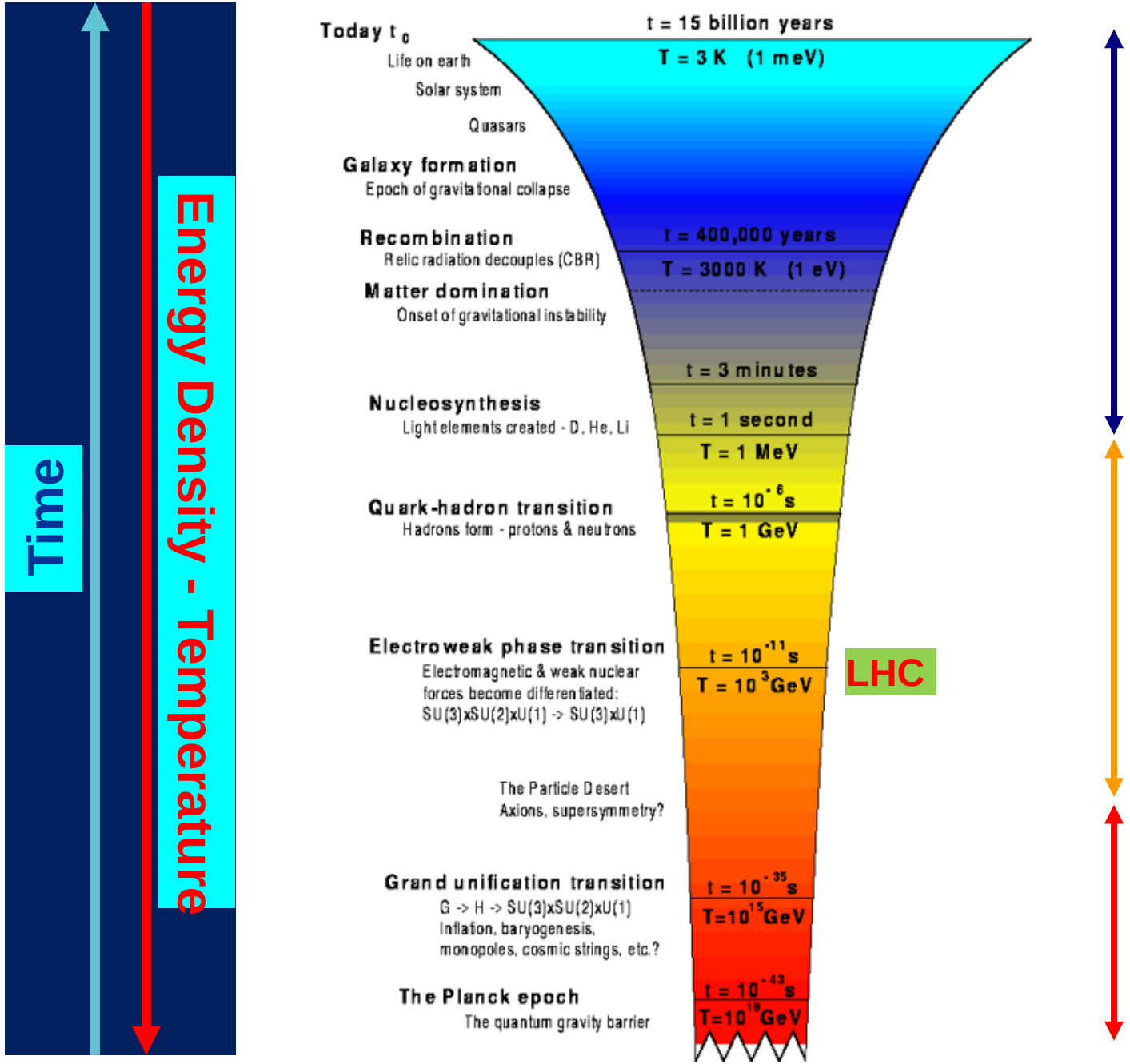




# Cosmic Connection

# The Cosmic Connection

- **Through the "Hot Big Bang model", the laws of Elementary Particle Physics determines the early stages of cosmic evolution**
- **The next crucial step in discovering these laws will be the exploration of phenomena around and above 1 TeV – electroweak symmetry breaking and more (super-symmetry?)**
- **At high energies, we effectively emulate, at an elementary level, the conditions that prevailed in the early universe**
- **Cosmologists have a perfect model for times > 0.01 sec after the big bang. For earlier times (higher temperature and density), particle physics is relevant, but not all of it is known – we try to push back boundaries! By increasing the energy**
- **For the earliest times, energies become so high that gravity has to start playing a role in elementary particle interactions – string theory?**




## Standard Cosmology

Supported by considerable observational evidence

## Elementary Particle Physics

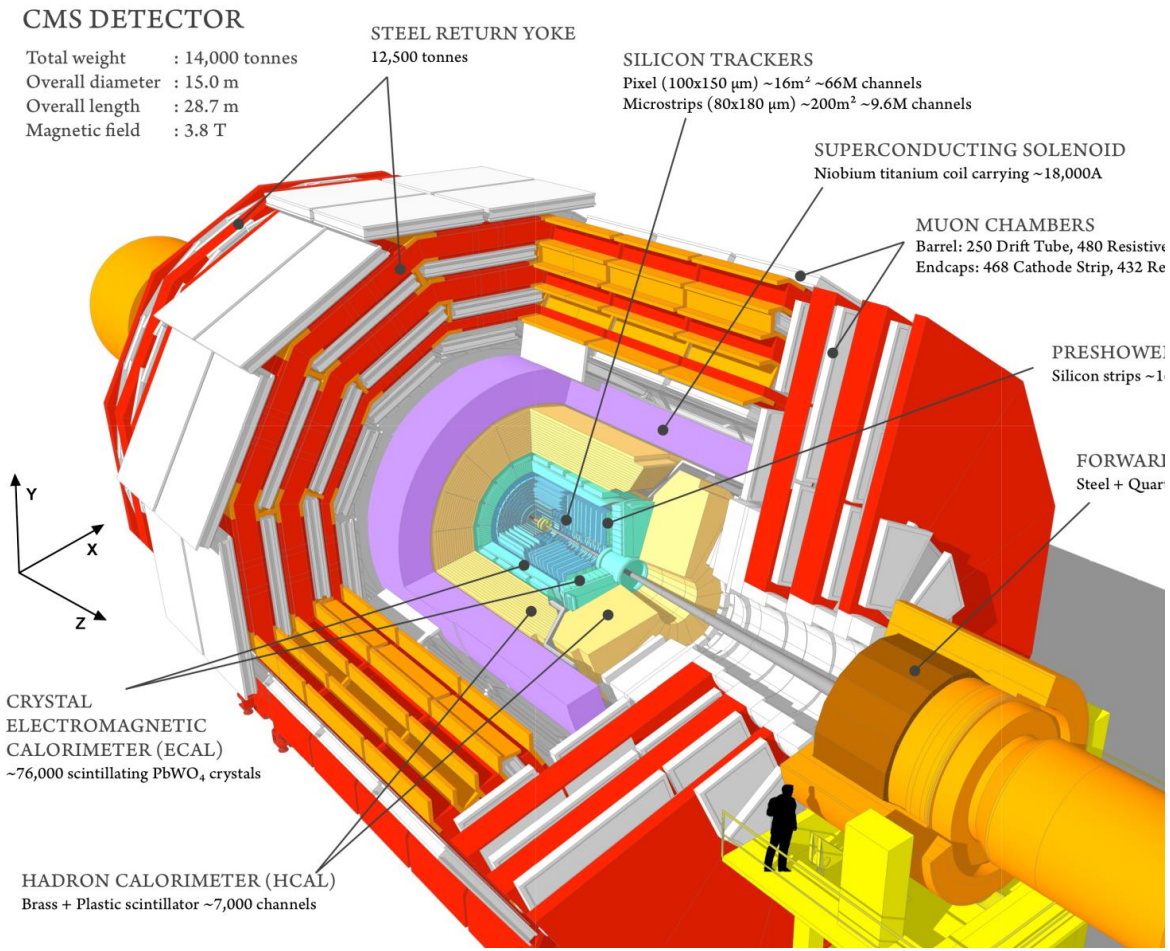
From the Standard Model into the unknown: towards energies of 1 TeV and beyond: the **Terascale**

## Towards Quantum Gravity

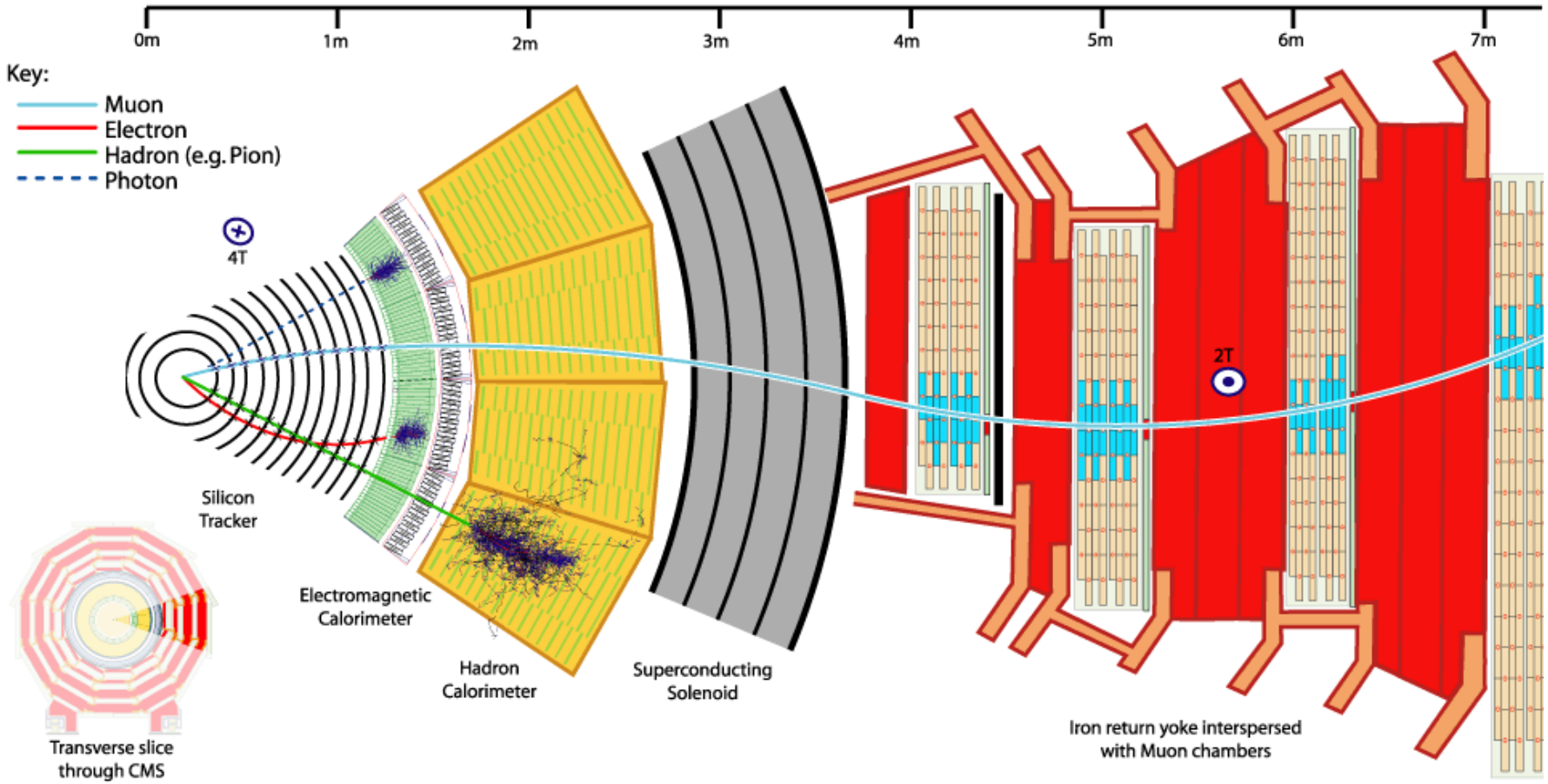
From the unknown into the unknown...

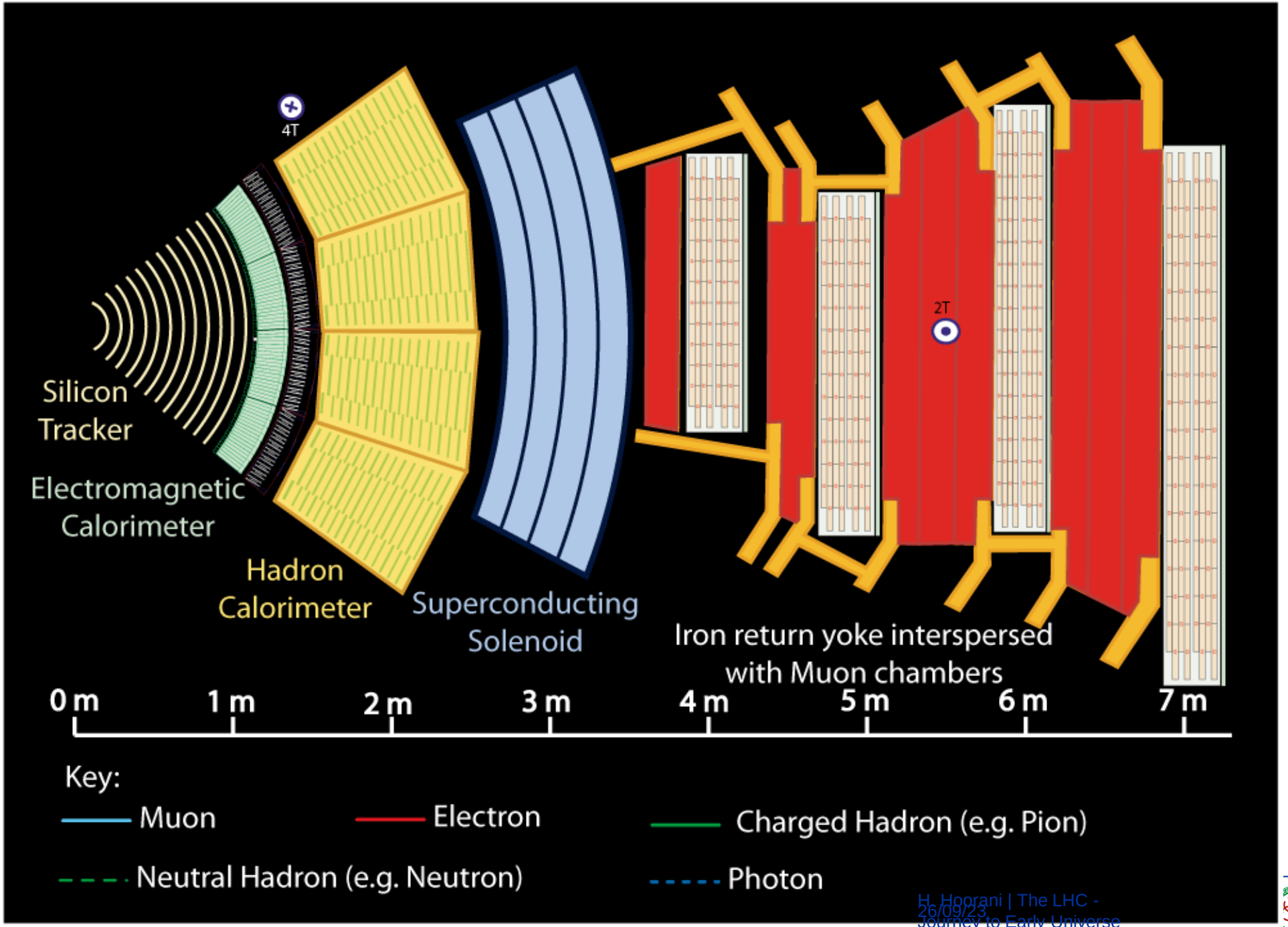
# Particle Detector
# The Compact Muon Solenoid (CMS)

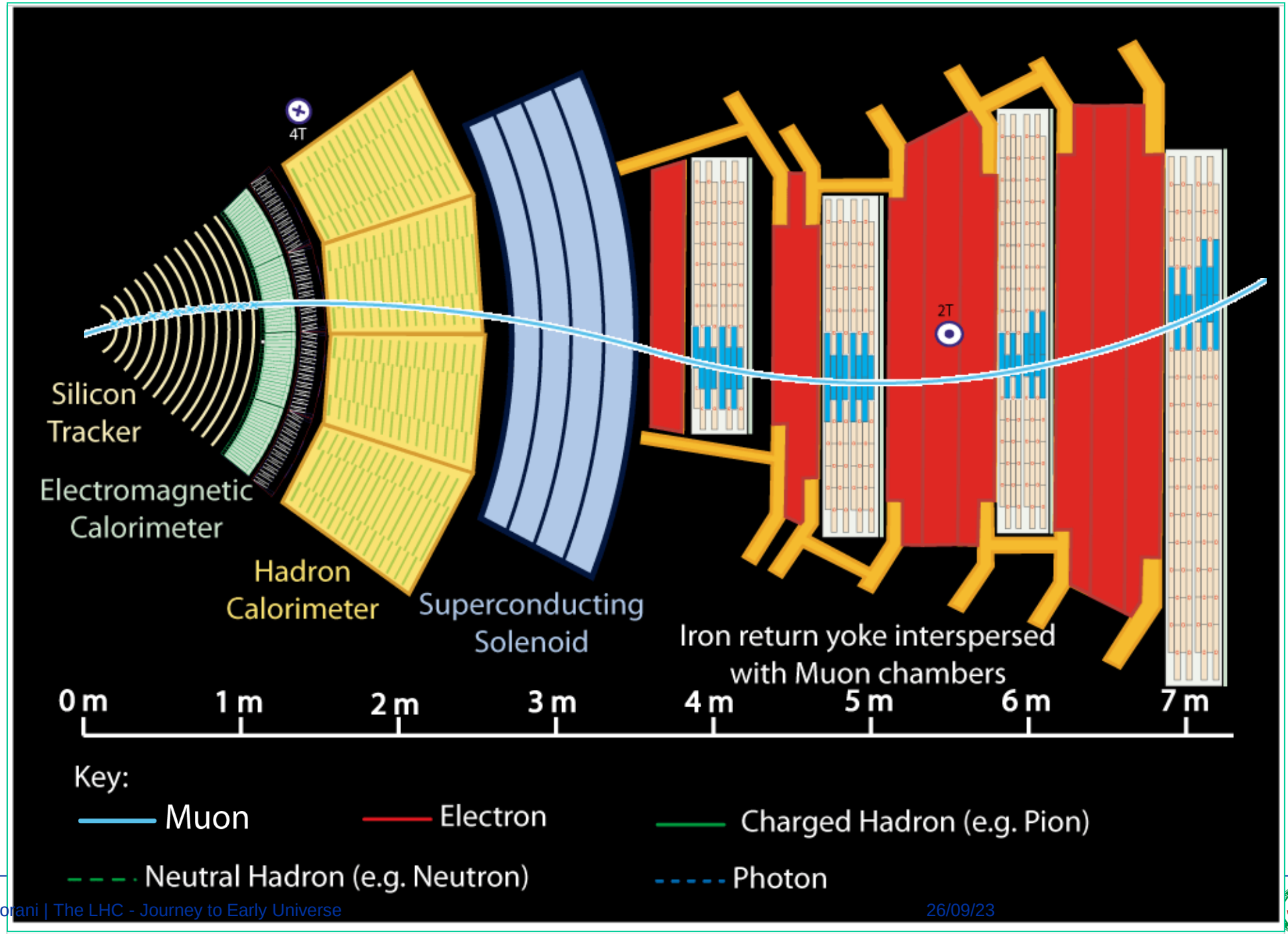
# The Compact Muon Solenoid Experiment



# Cross-sectional View of CMS




4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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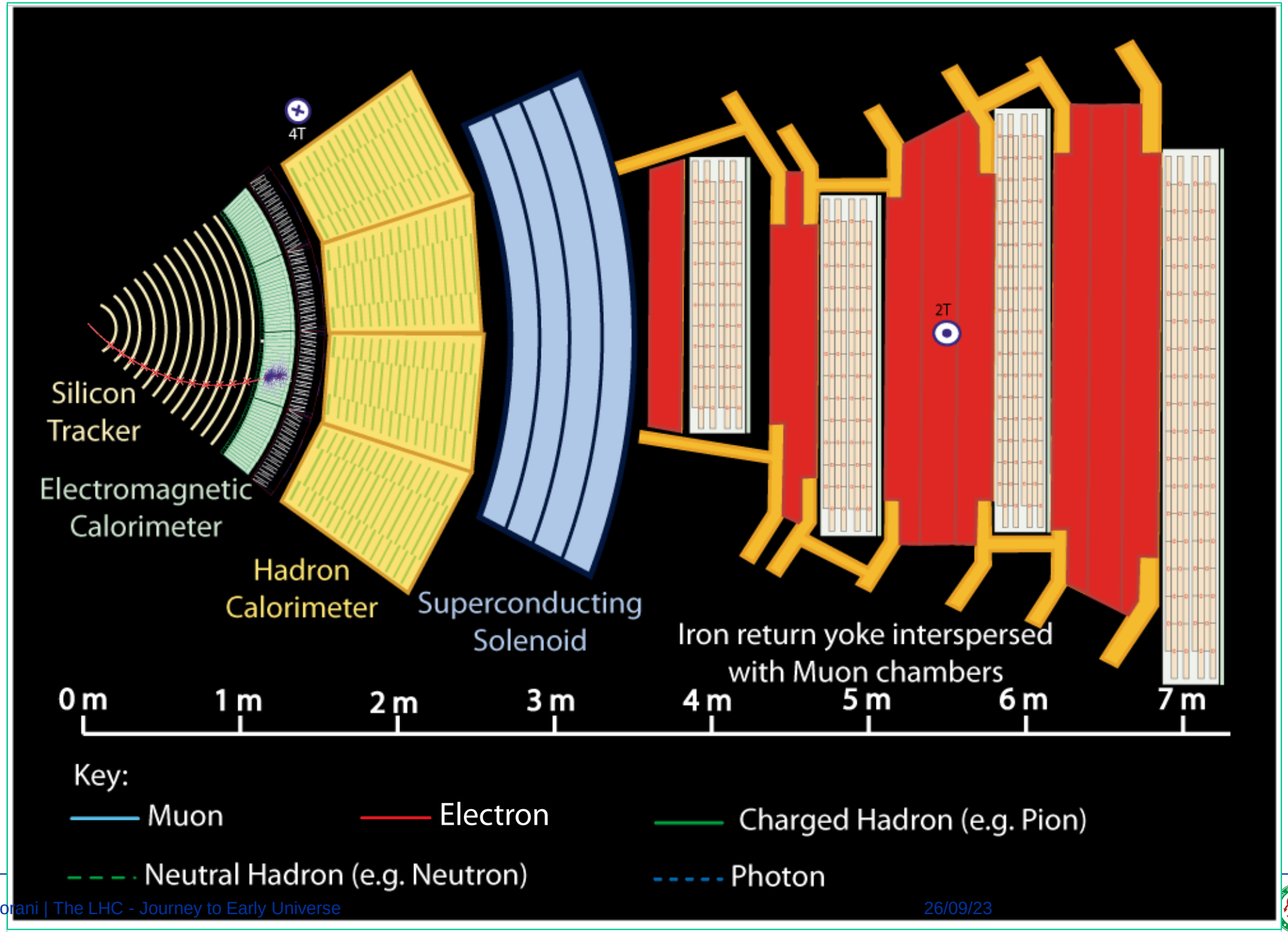
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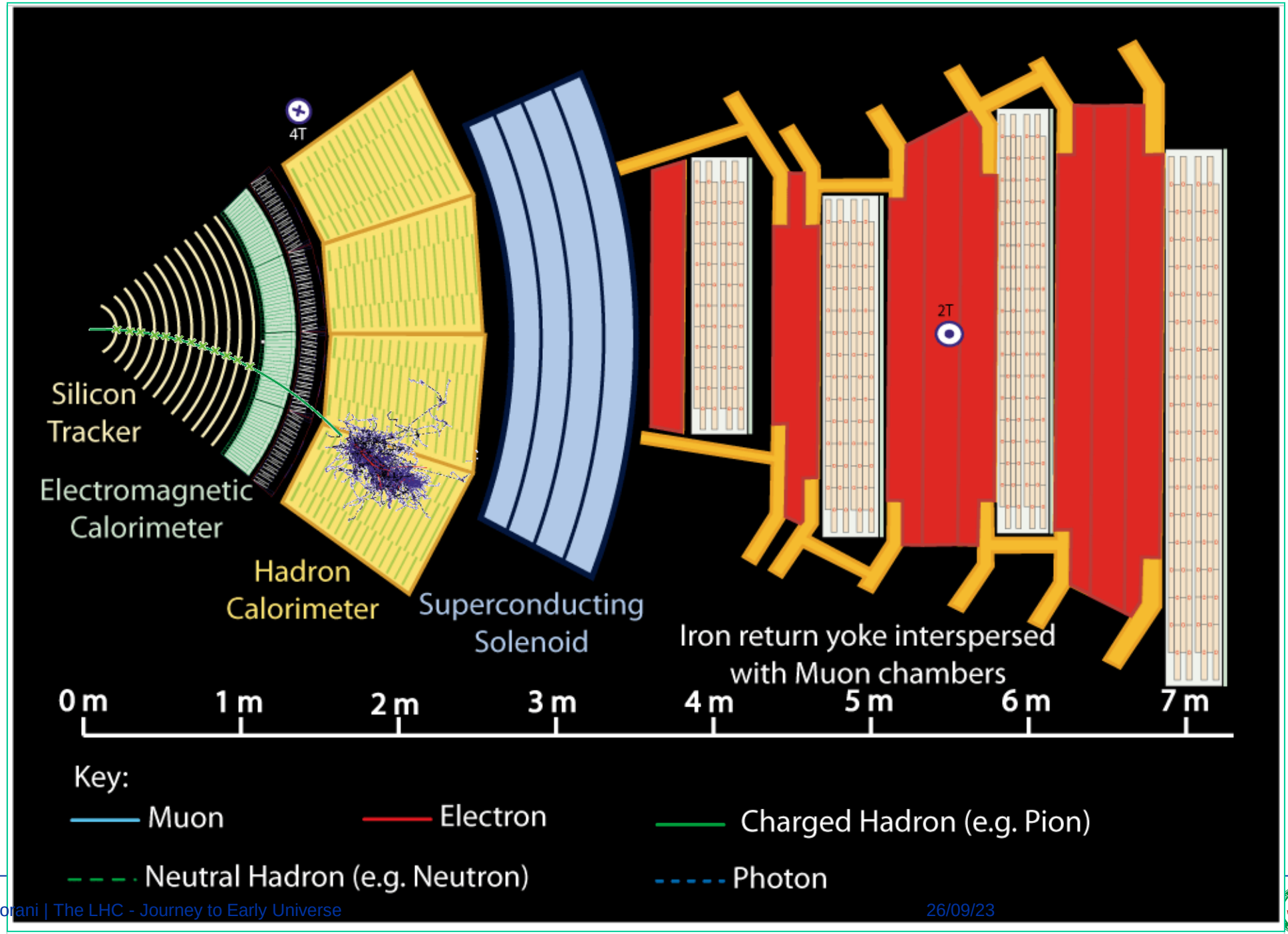
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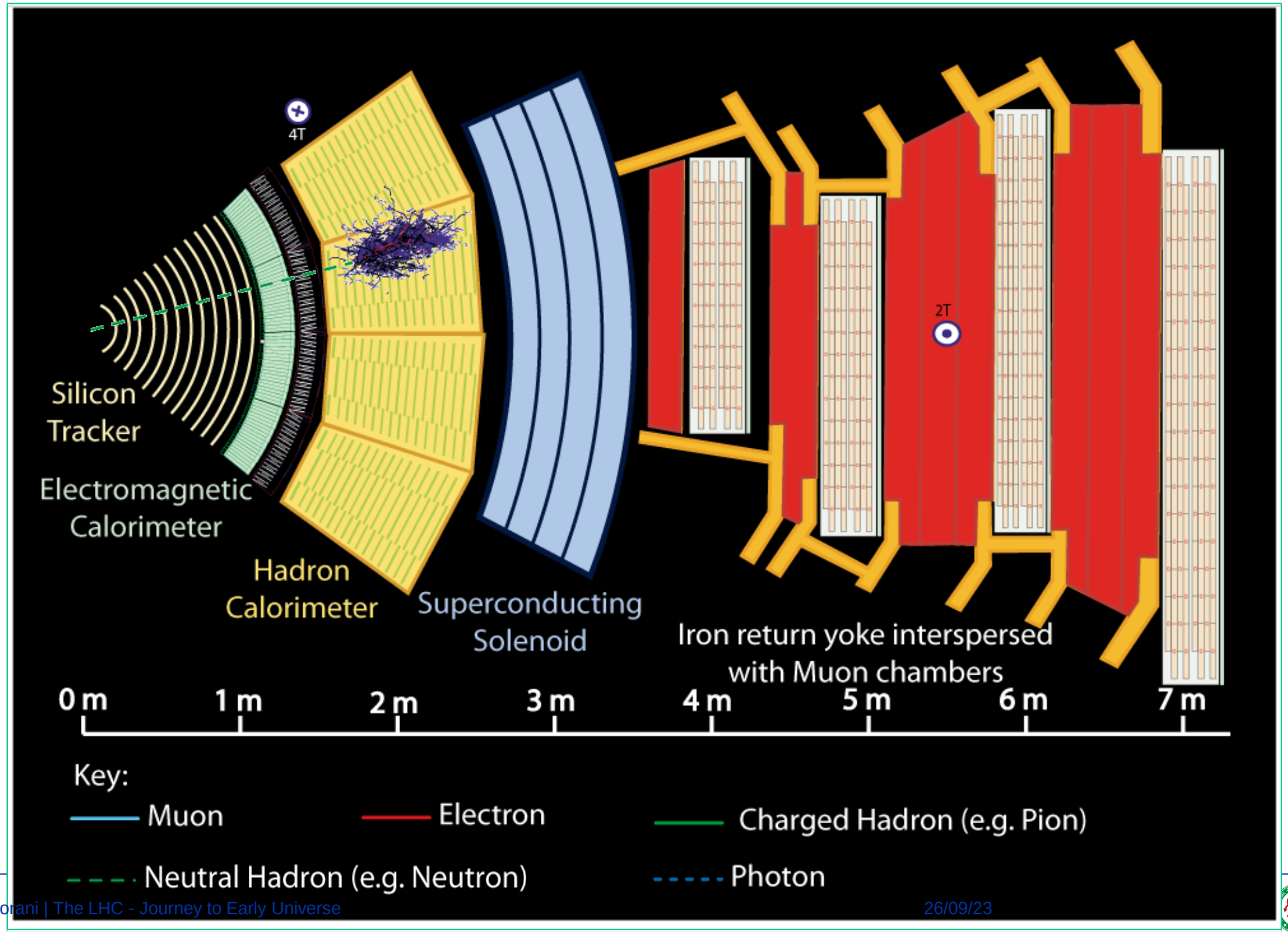
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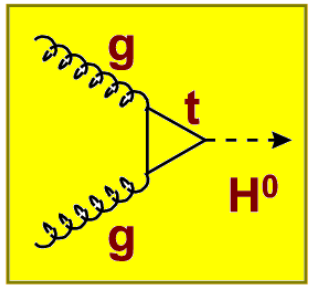
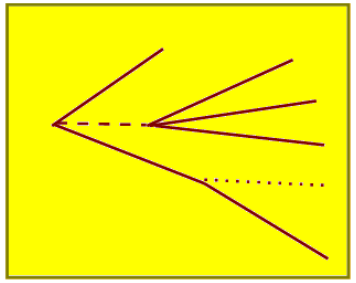
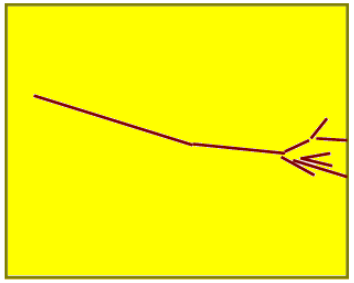
# SIMULATIONS – Physics to Raw Data



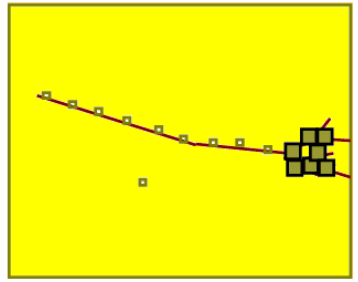

**Basic physics**



**Fragmentation, Decay**



**Interaction with detector material**
**Multiple scattering, interactions**

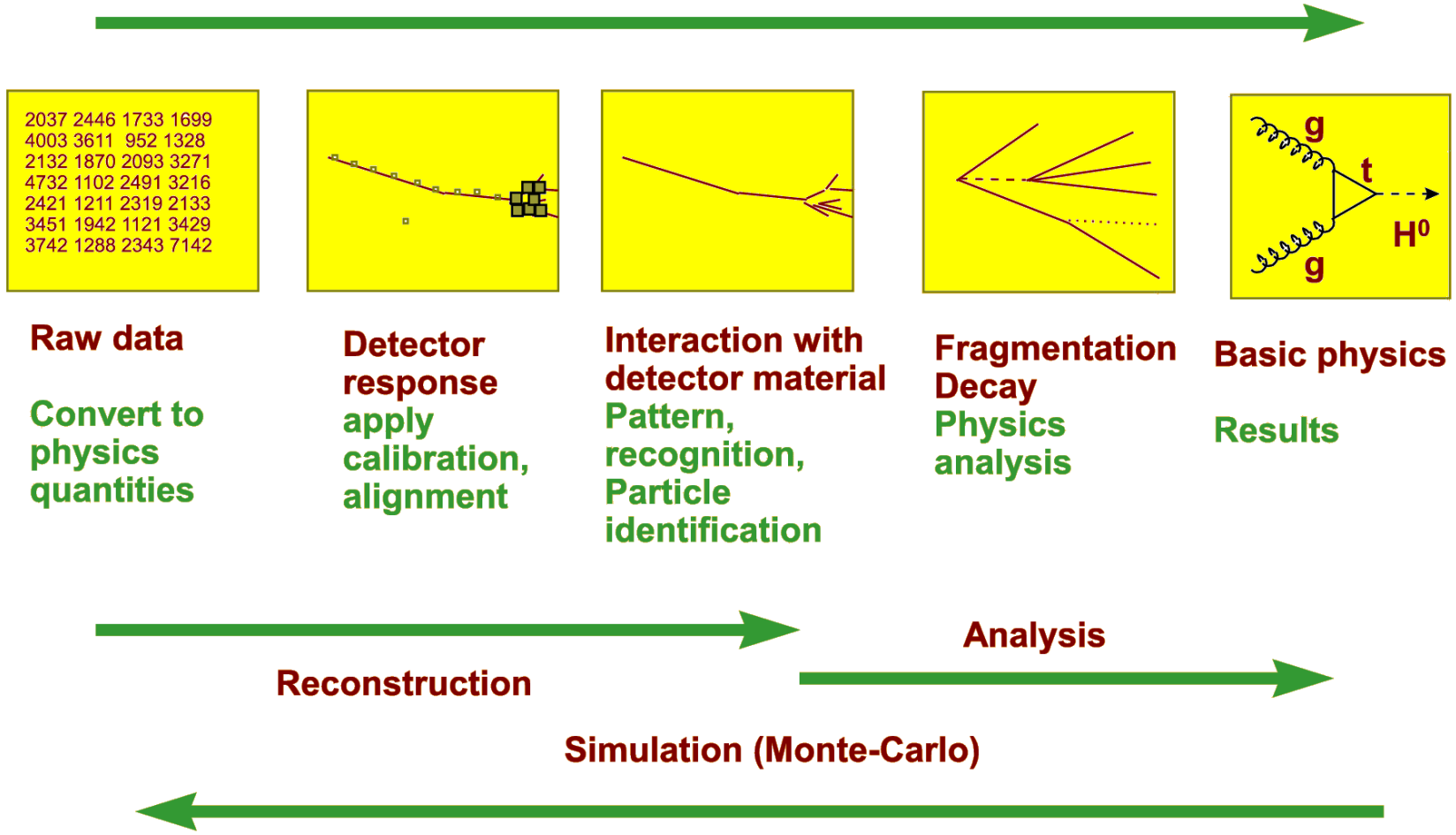


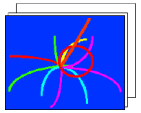
**Detector response**
**Noise, pile-up, cross-talk, inefficiency, ambiguity, resolution, response function, alignment**


**Raw data**

**Read-out addresses, ADC, TDC values, Bit patterns**

# Reconstruction & Analysis – Raw Data to Physics





**40 MHz**
**COLLISION RATE**

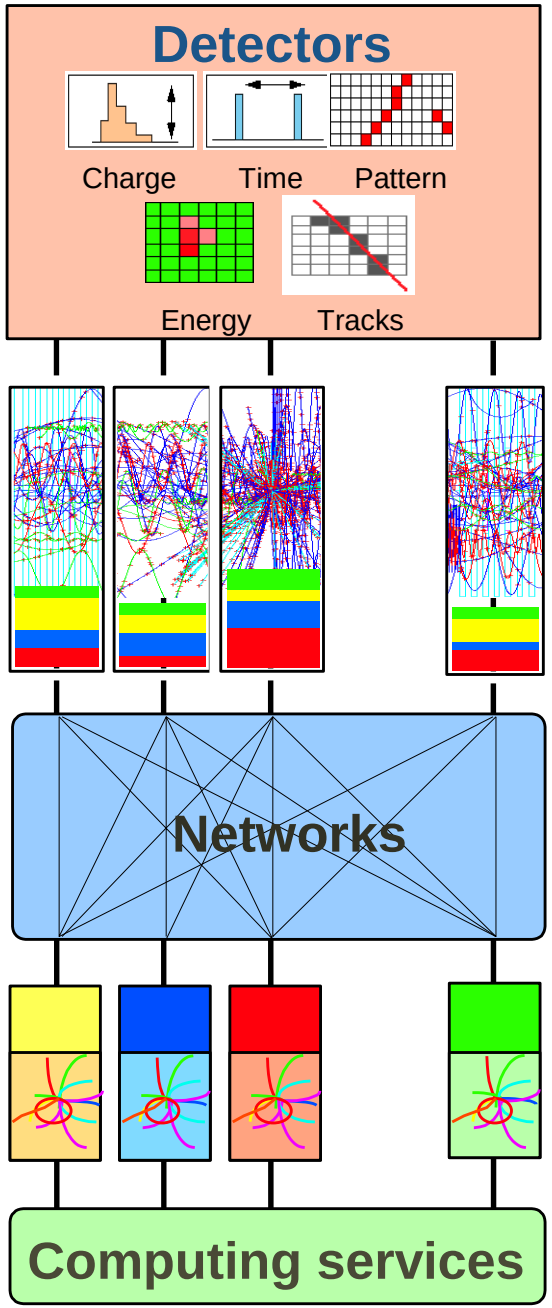
**100 kHz**
**LEVEL-1 TRIGGER**

**1 Terabit/s**
**(50000 DATA CHANNELS)**

# CMS Trigger Data Acquisition

**500 Gigabit/s**

**Gigabit/s SERVICE LAN**




**16 Million channels**
**3 Gigacell buffers**

**1 Megabyte EVENT DATA**

**200 Gigabyte BUFFERS**
**500 Readout memories**

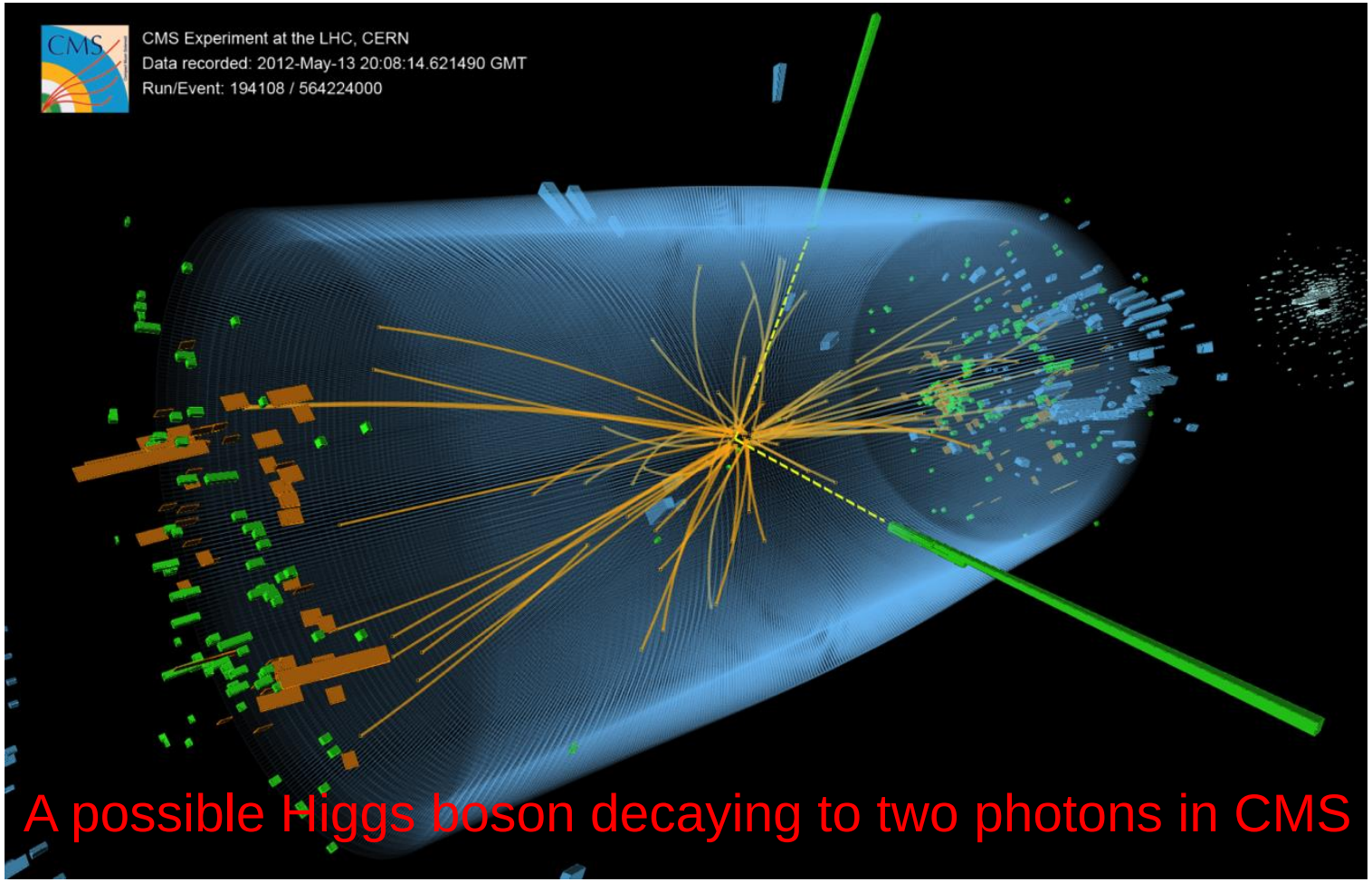
**EVENT BUILDER.** A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

**5 TeraIPS**

**EVENT FILTER.** It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

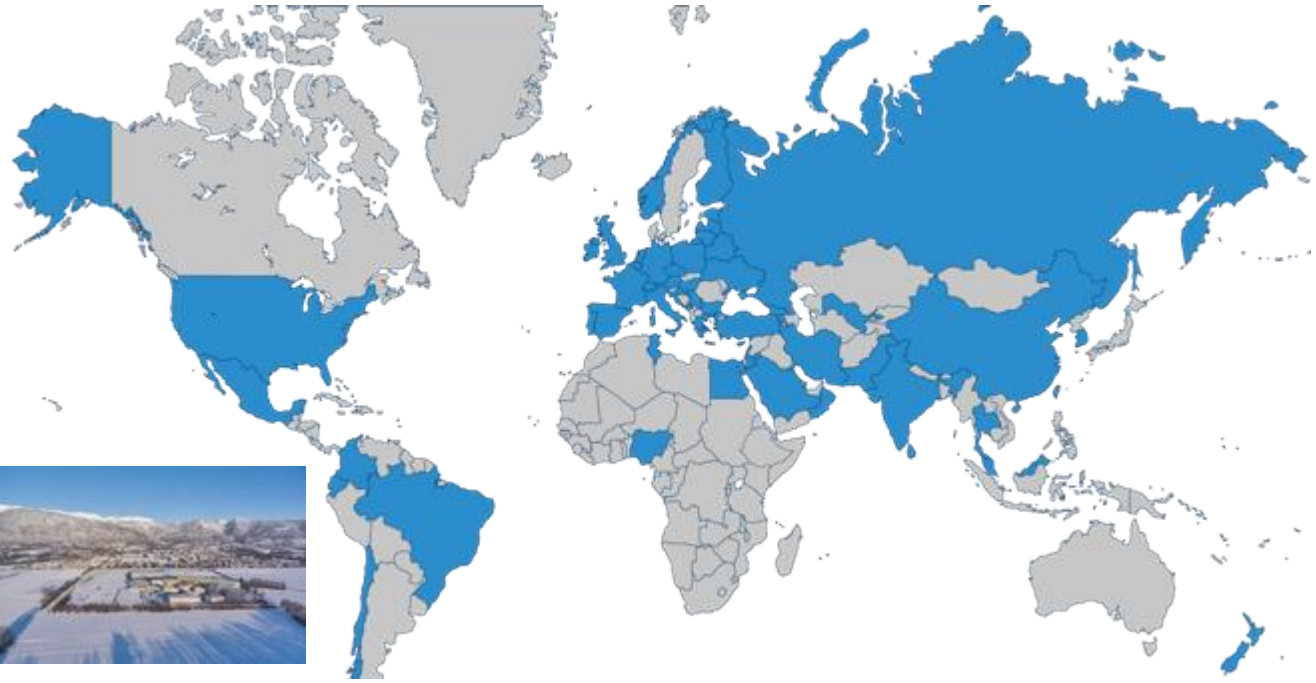
**Petabyte ARCHIVE**

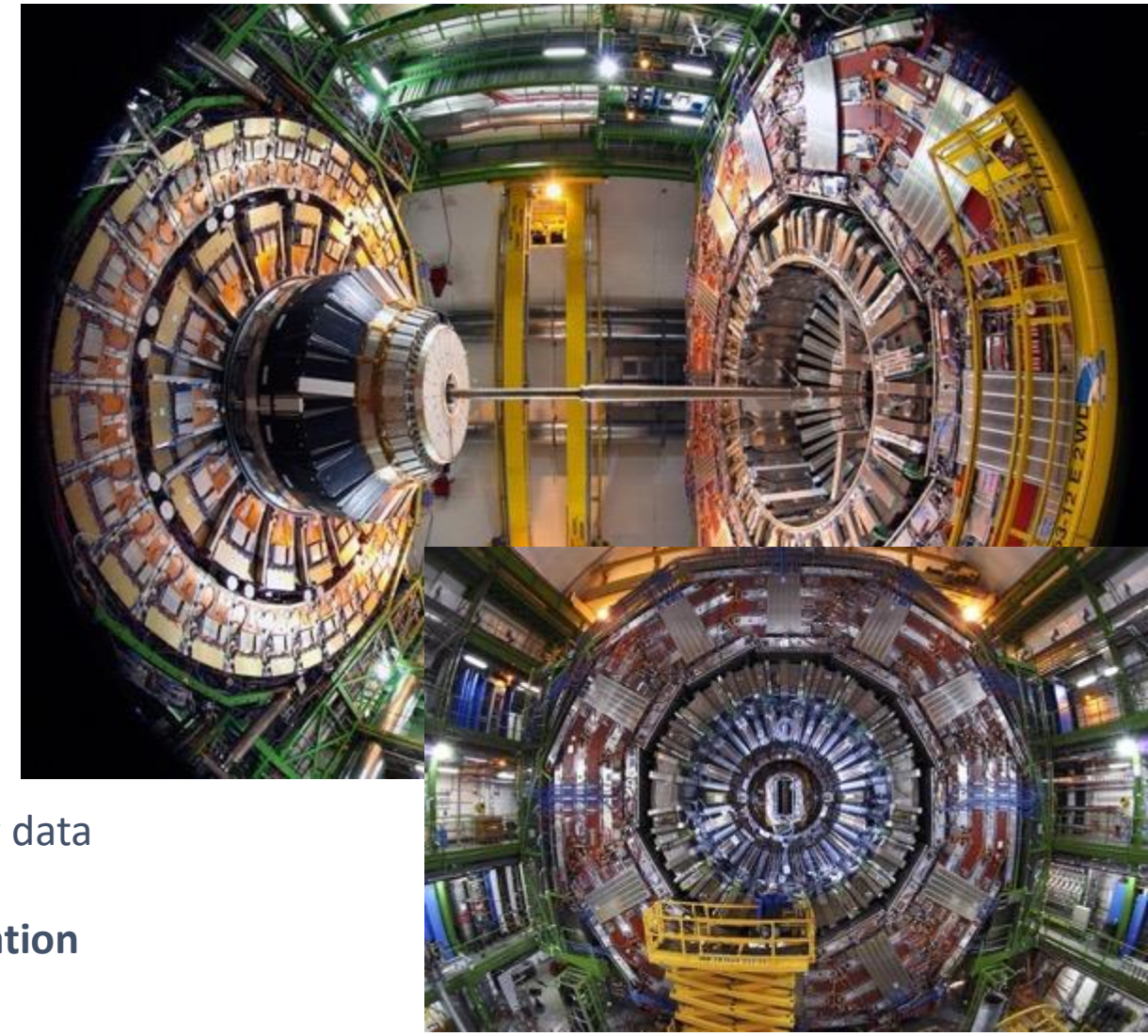
# Collisions at CMS




A possible Higgs boson decaying to two photons in CMS

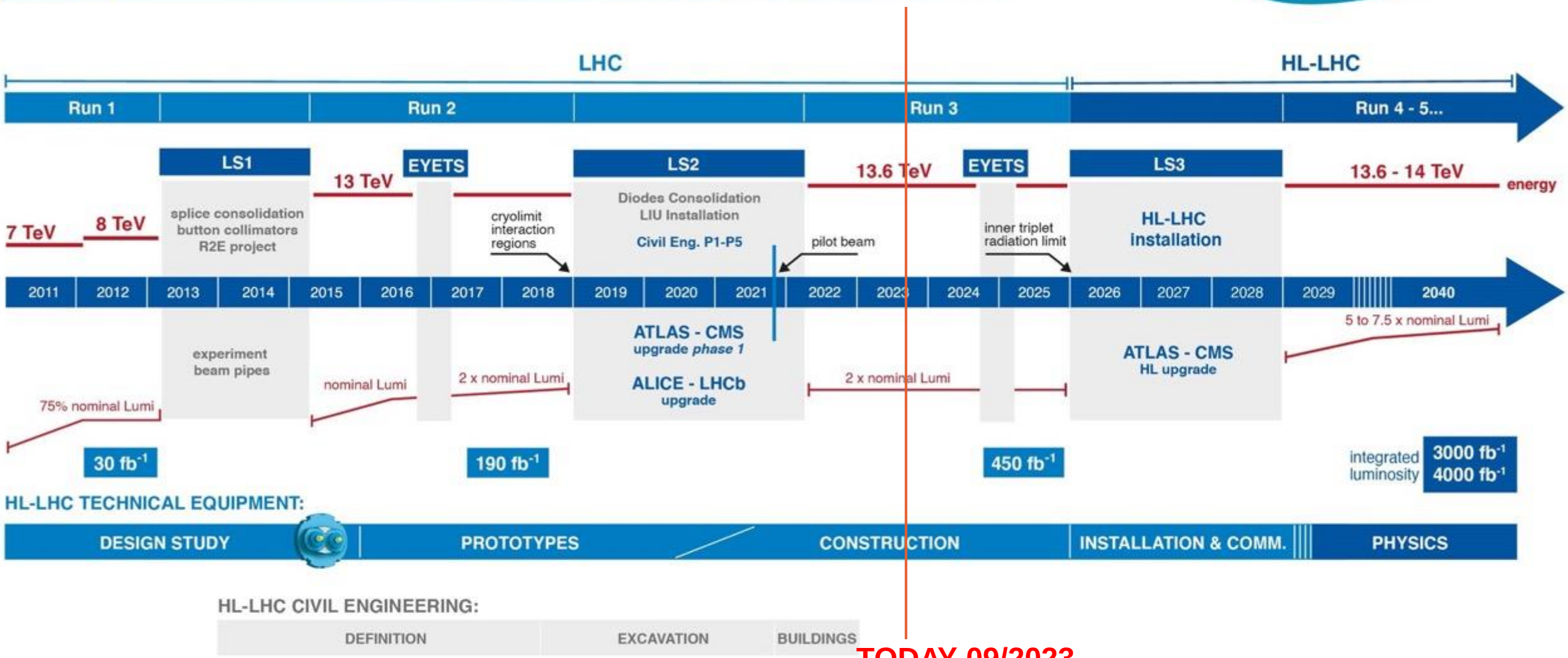
# CMS Today - collaboration & detector



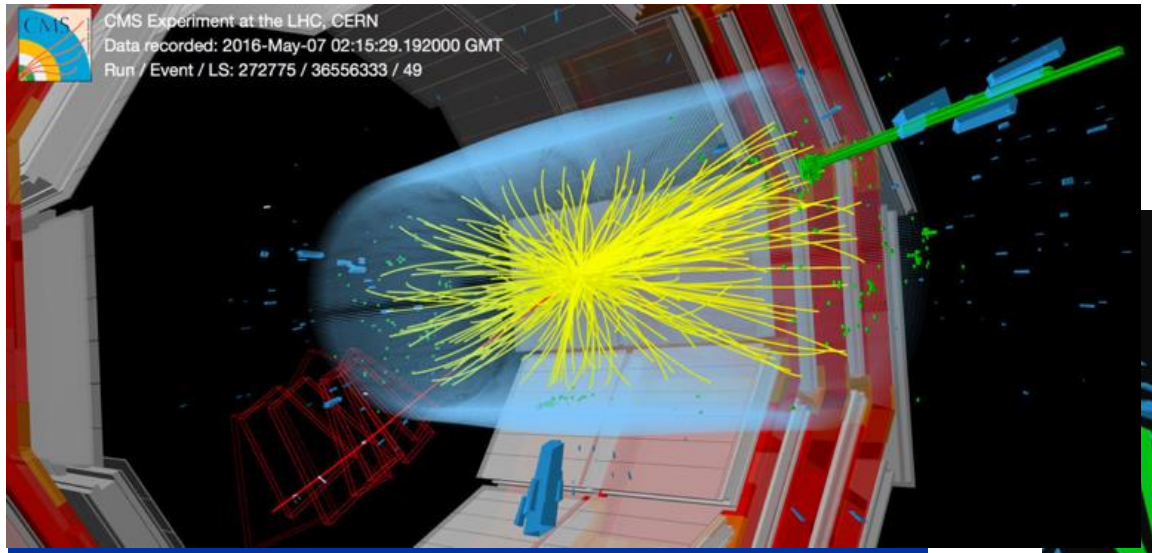
- Collected ~237 $fb^{-1}$ of p-p data and > **1210 papers** on collider data published or submitted to a journal
- Community committed to **physics exploitation**, **LHC Run 3 operation and maintenance** & **Phase II detector upgrade for HL-LHC**

# LHC / HL-LHC Plan



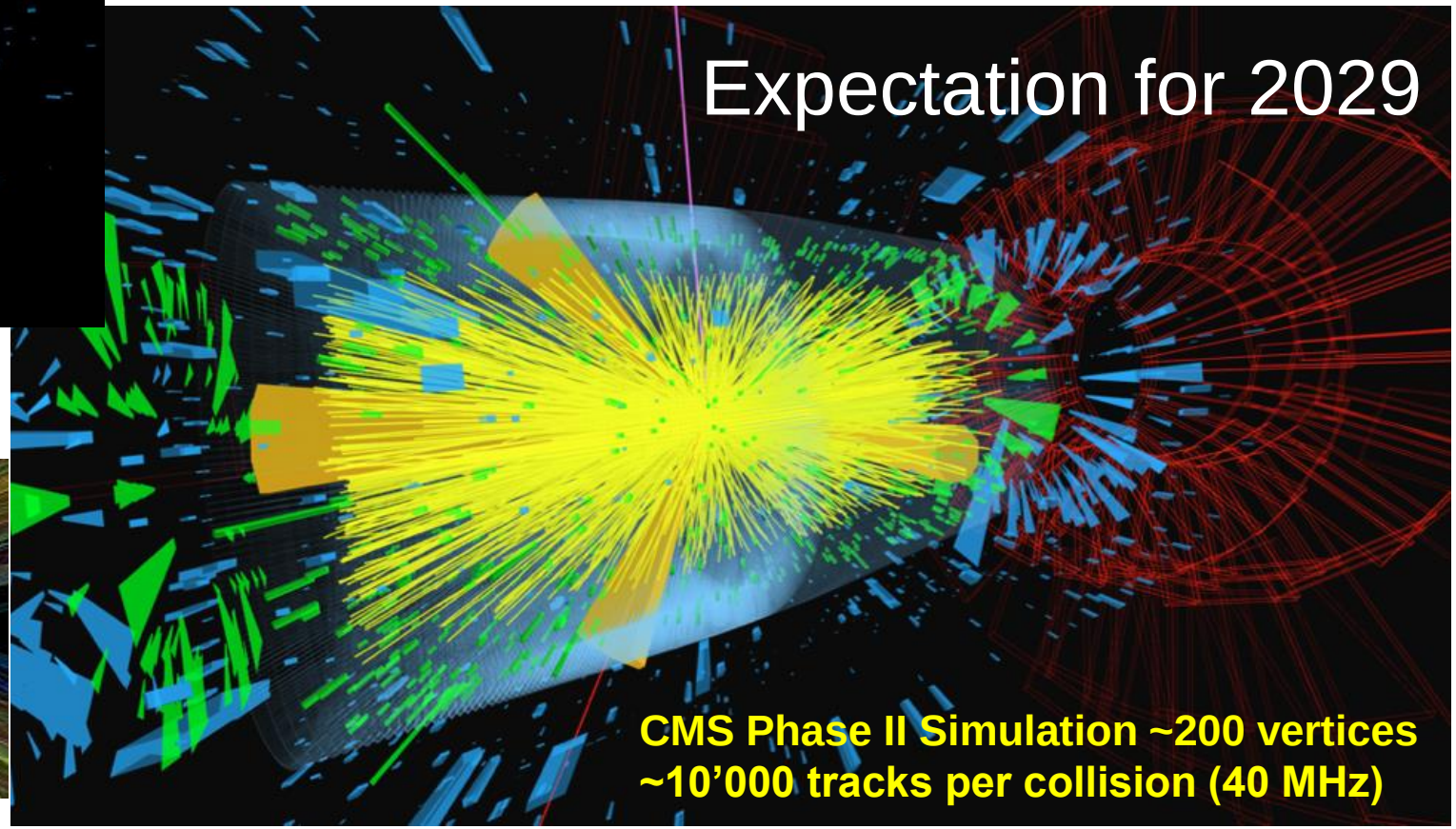

**TODAY 09/2023**

# CMS Today & @HL-LHC




**~35 vertices = 40 collisions = pile-up**
**~2'000 tracks per collision bunch (40 MHz)**

Vertex = reconstructed point of collision



# Conclusions

- LHC data is used to study a scalar field like “Higgs Boson”
- Study of the Higgs mechanism in detail helps to understand the character of this particle and understand the vacuum
- This could be very first step to understanding the “Dark Energy”
- Embarrassingly we still don’t know much about 95% of our universe, challenge for all of you
- Exciting new results are expected from the current data and the data from HL-LHC, resolving some of the mysteries of our universe
- New large-scale projects such as the Future Circular Collider (FCC) are planned spanning a time scale of several decades

**Wish you a very bright future in the Dark Universe**