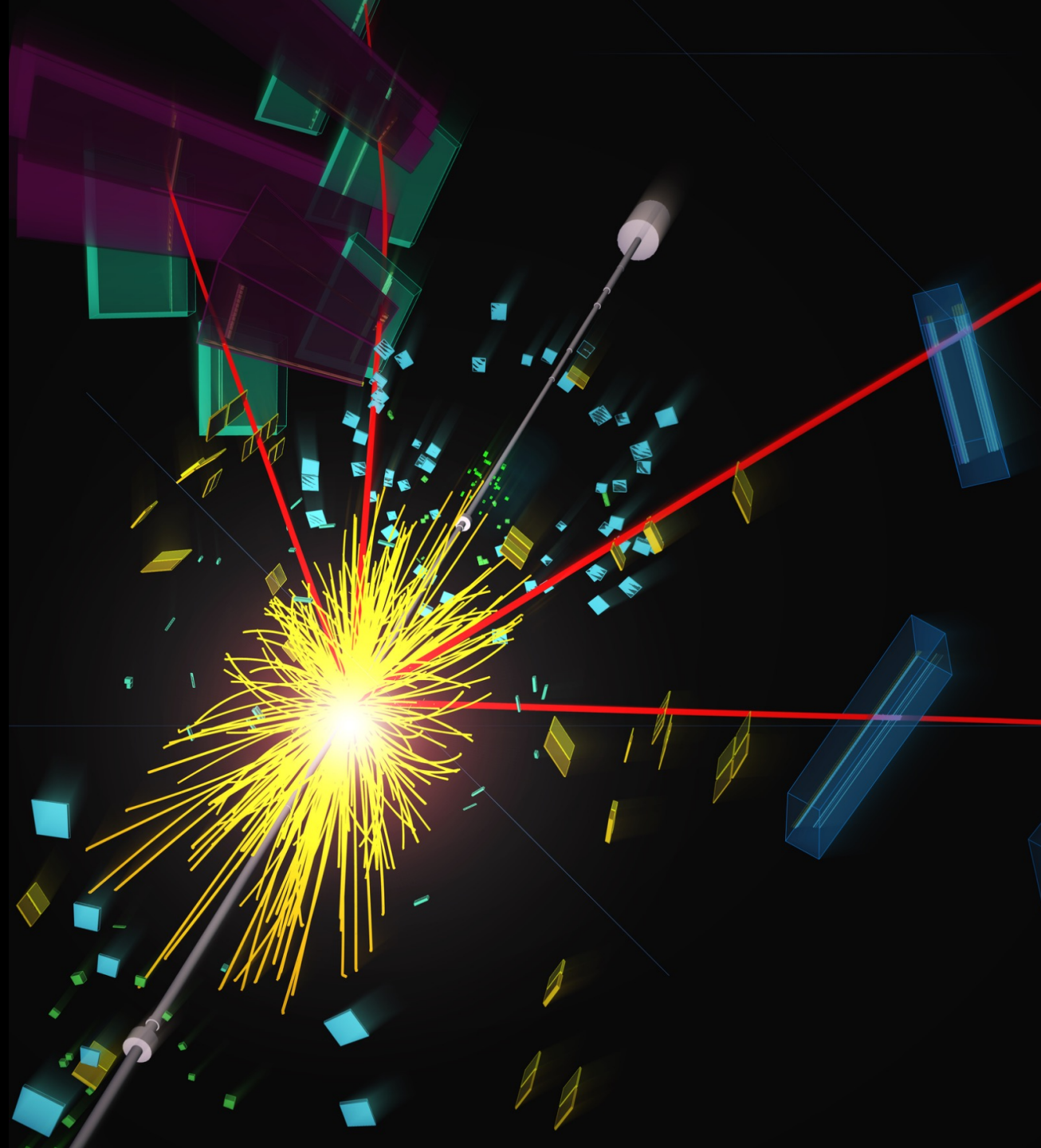


Smashing discoveries — the Large Hadron Collider at CERN

From the Higgs boson to the quest for
new physics

Andreas Hoecker (CERN)

NYU Abu Dhabi, 22 November 2021



“It’s all made of a handful of particles and forces”

“Through its relation with cosmology the study of particles and forces is also a journey back in time”

“Can we truly grasp the magnitude of everything that has unfolded in the natural universe between those first momentary particles and the present day ?”

Brian Watson in The Salem News (Aug. 16, 2012)

Humanity’s search for the **smallest unit of matter, its different forms, and the forces acting** is much, much older than ***particle physics***

Particle physics is a term naming the **search for the ultimate laws of Nature**

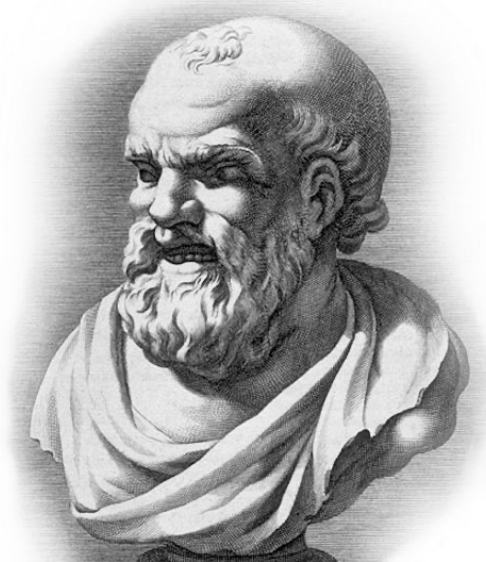
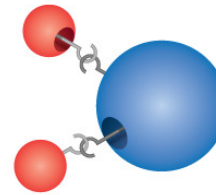
Setting the stage

About 2500 years ago, the Greek “laughing philosopher” Democritus developed a new doctrine: **atomism** (atomos = indivisible)

*Two realities would compose the natural world: **atoms** and **void***

Atoms are infinite in number and various in size and shape, and perfectly solid, with no internal gaps. Atoms may combine into clusters by means of tiny hooks and barbs on their surfaces, which become entangled.

Atoms move in an infinite void.

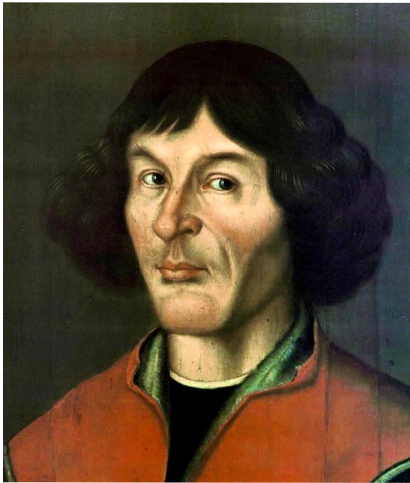


Democritus (460–370 BC)

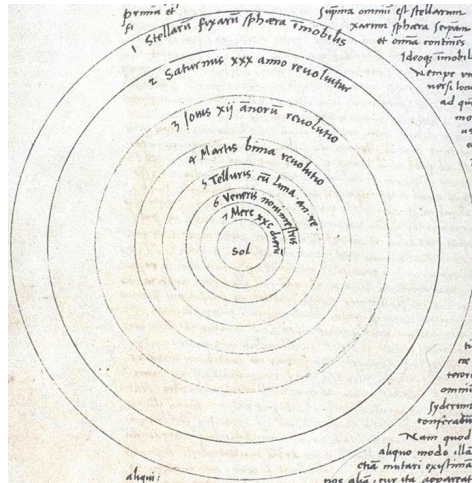
Since these times, philosophers, mathematicians, astronomers, physicists, chemists have tried to understand the laws of matter and the forces acting on them, to find answers to the fundamental question of “How”, and hoping to also get some insight into the “Why”

Setting the stage

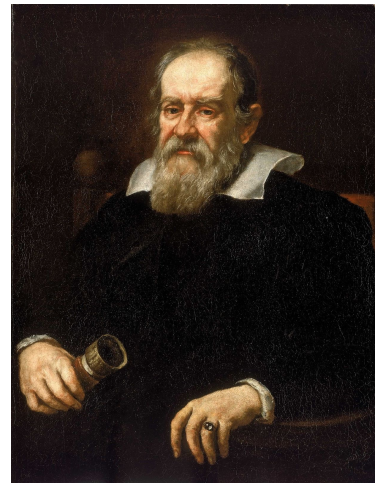
The scientific revolution began with **Nicolaus Copernicus** in the 16th century, shifting paradigms from the Ptolemaic model of the heavens to the heliocentric one, continued with **Galileo Galilei** and his *Dialogue Concerning the Two Chief World Systems* (1632), to find its culmination and accomplishment with the 1687 publication of **Isaac Newton's** *Philosophiæ Naturalis Principia Mathematica*, laying the foundations of modern mathematical physics



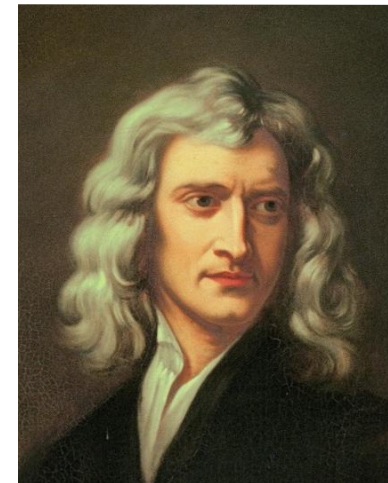
N. Copernicus (1473–1543)



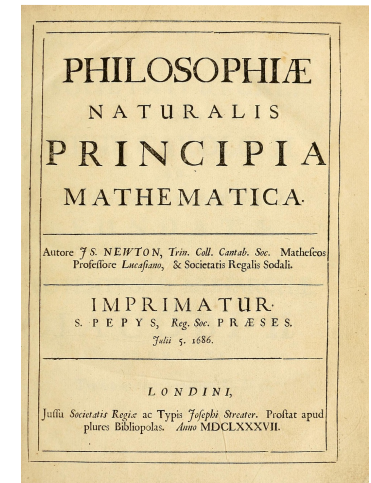
On the Revolutions of the Celestial Spheres, published in 1543



Galileo Galilei (1564–1642)



Isaac Newton (1642–1726)

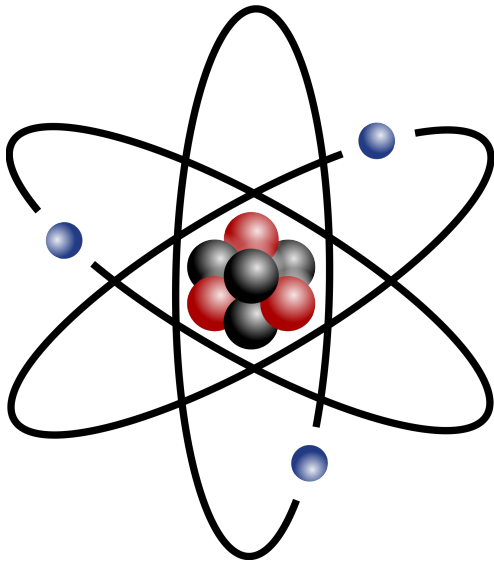


Philosophiæ Naturalis Principia Mathematica, published in 1687

Democritus relied on phenomenology, since the scientific revolution physicists rely on observation and mathematics to study and describe the physical laws

Setting the stage

Today, you all know what atoms are, and we know they exist as we can count them one by one



Light electrons surround a nucleus made of heavy protons and neutrons like planets the sun...

Really? This classical picture fails in many respects. Only quantum mechanics, developed in the 1920s was able to provide a mathematical description of the atom. Heisenberg understood that the “trajectories” are imagined, and only exist when we observe them (one among a distribution of options occurred)

We still do not know what an atom really is, but we can compute all its properties along statistical probabilities following strict physical law



Werner Heisenberg
(1901–1976)

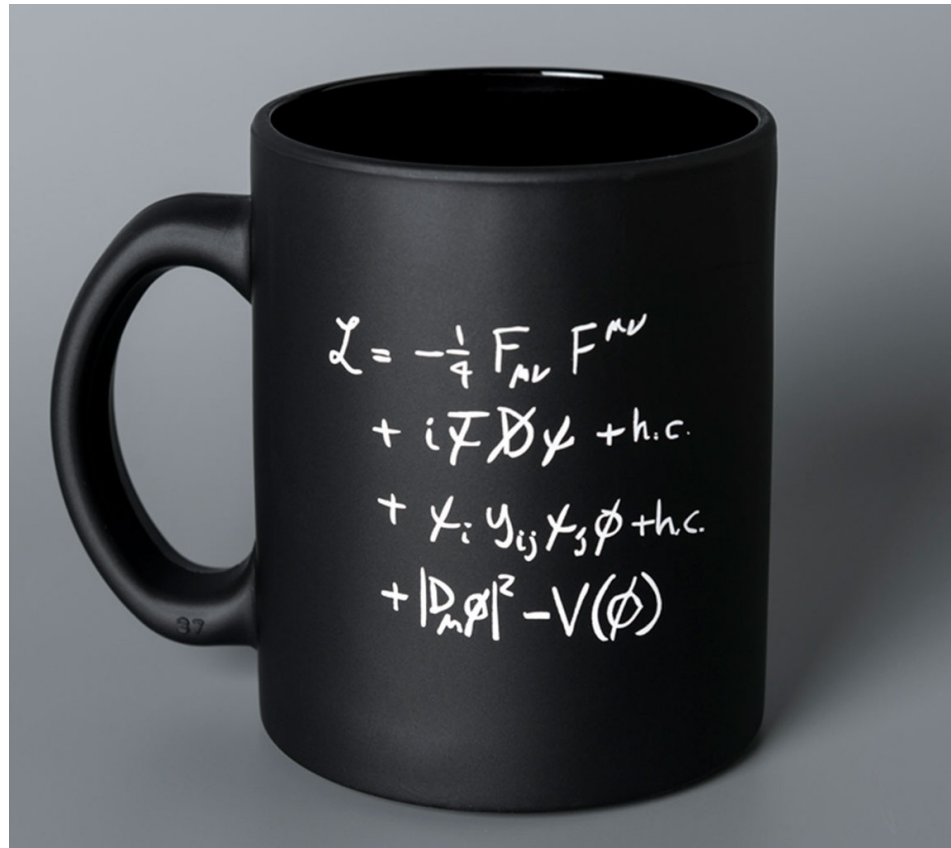
Physical laws are thus not what is *in the* Nature, but our way to *describe* Nature

Everyday life and particle physics are described by the Standard Model

Since the birth of quantum mechanics, physicists of the twentieth century have developed the **Standard Model**, a *quantum field theory* which describes all known forms of matter and forces, except gravity

The Standard Model unifies quantum mechanics, special relativity and field theory

It also unifies electromagnetic and weak interactions



It can be written in a very compact form so that it fits on a mug

The Standard Model

Since the birth of quantum mechanics, physicists of the twentieth century have developed the **Standard Model**, a *quantum field theory* which describes all known forms of matter and forces, except gravity

The **Lagrangian** allows to derive the equations of motion of a system

This term is related to the **Higgs sector**

It was postulated before the LHC but not experimentally confirmed

These terms describe **interactions among force particles (top) and among matter and force particles (bottom)**

This part was experimentally probed to good precision before the start of the LHC

The top term describes how **matter particles couple to the Higgs field ϕ and thereby obtain mass**

The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

The lower right term describes the **Higgs potential $V(\phi)$ with a non-zero ground state**

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c. + \bar{\chi}_i Y_{ij} \chi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

The Standard Model

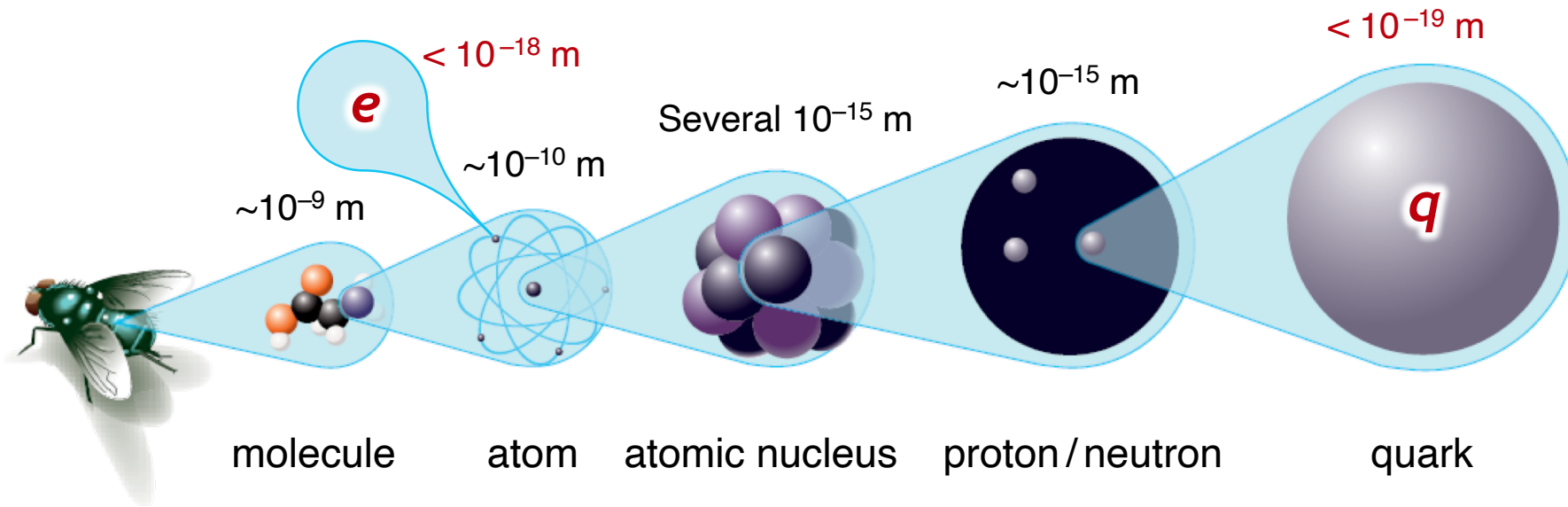
In its full (and rather frightening) form, the Standard Model looks like this

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
 & g\alpha_h M (H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-) - \\
 & \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & gMW_\mu^+ W_\mu^- H - \frac{1}{2}g\frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g\frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - ig\frac{s_w}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig\frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \dots
 \end{aligned}$$

$$\begin{aligned}
 & \dots - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$

The Standard Model

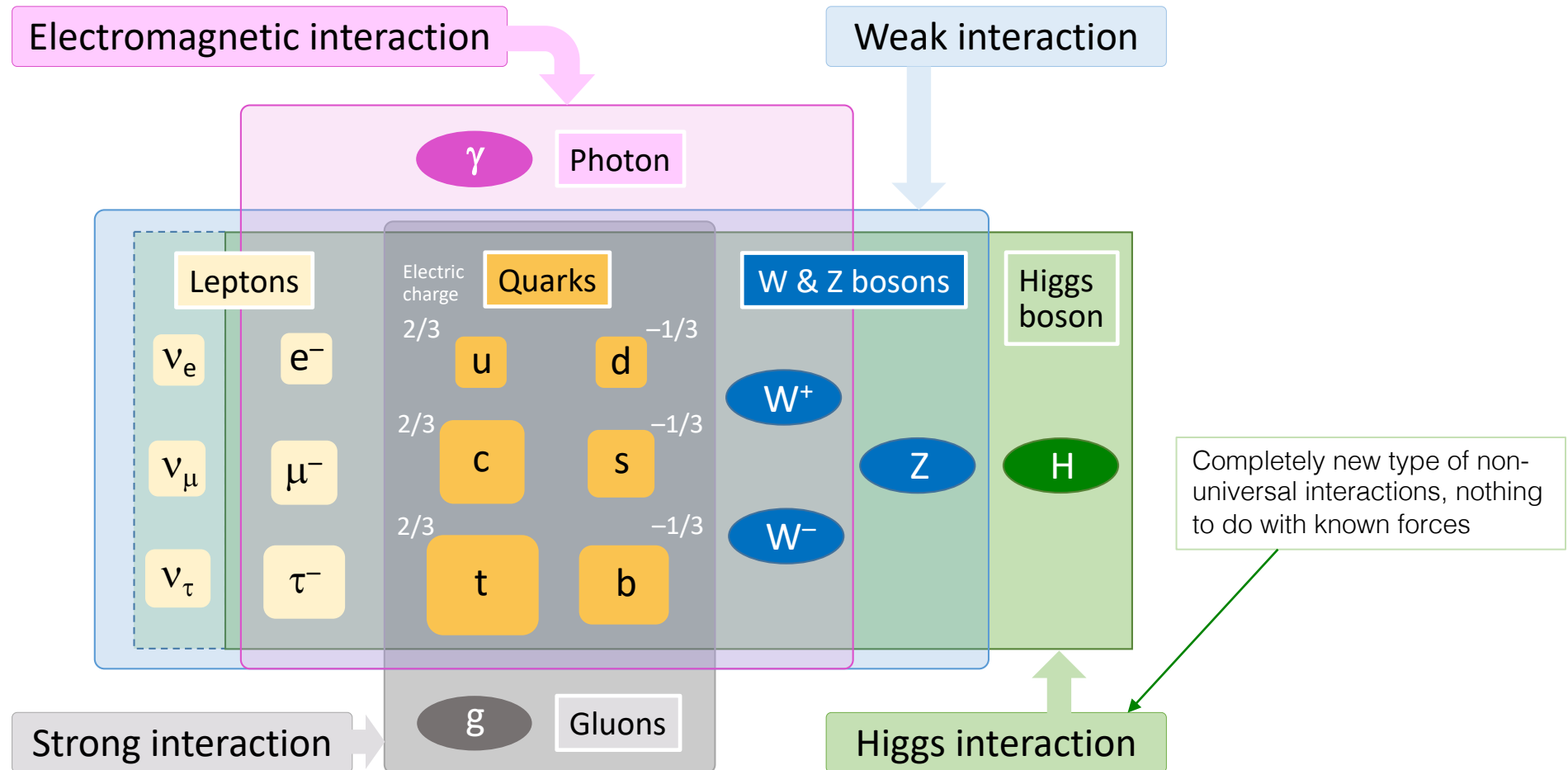
The Standard Model describes the properties of macroscopic objects, molecules, atoms, the atomic nucleus, the structure of the protons and neutrons



In the Standard Model, the elementary particles have no substructure, they are “point-like”. All experimental attempts to resolve further substructure have failed so far. Most physicists believe there must be some form of tiny structure ...

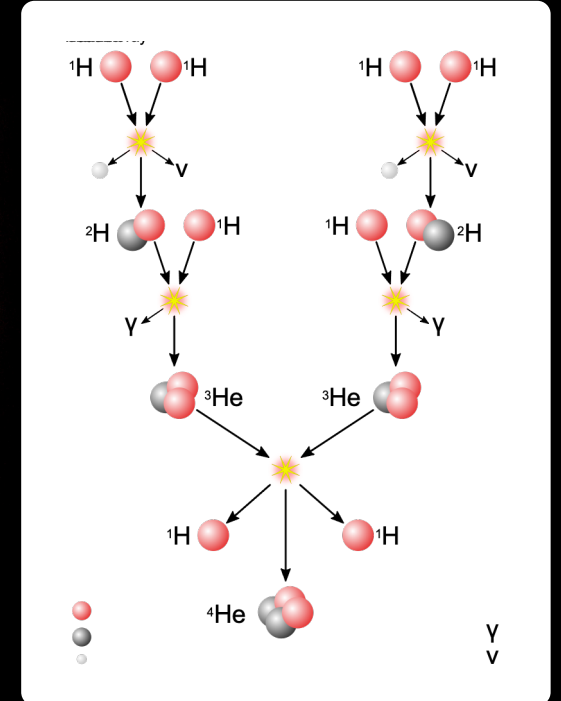
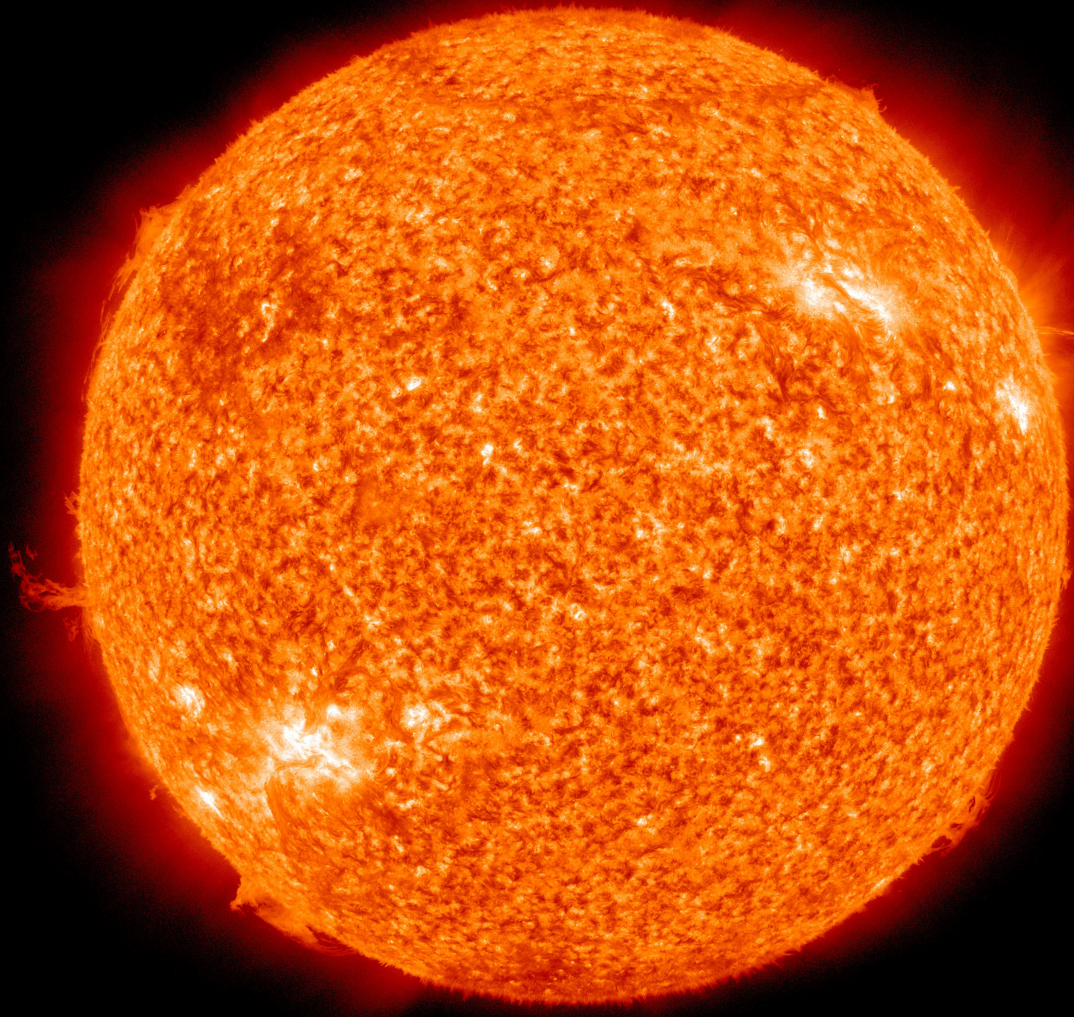
The Standard Model

These equations describe all known particles and their interactions



The Standard Model

The Standard Model does not only describe the tiniest objects in space, it also explains how, e.g. the Sun burns



The Standard Model

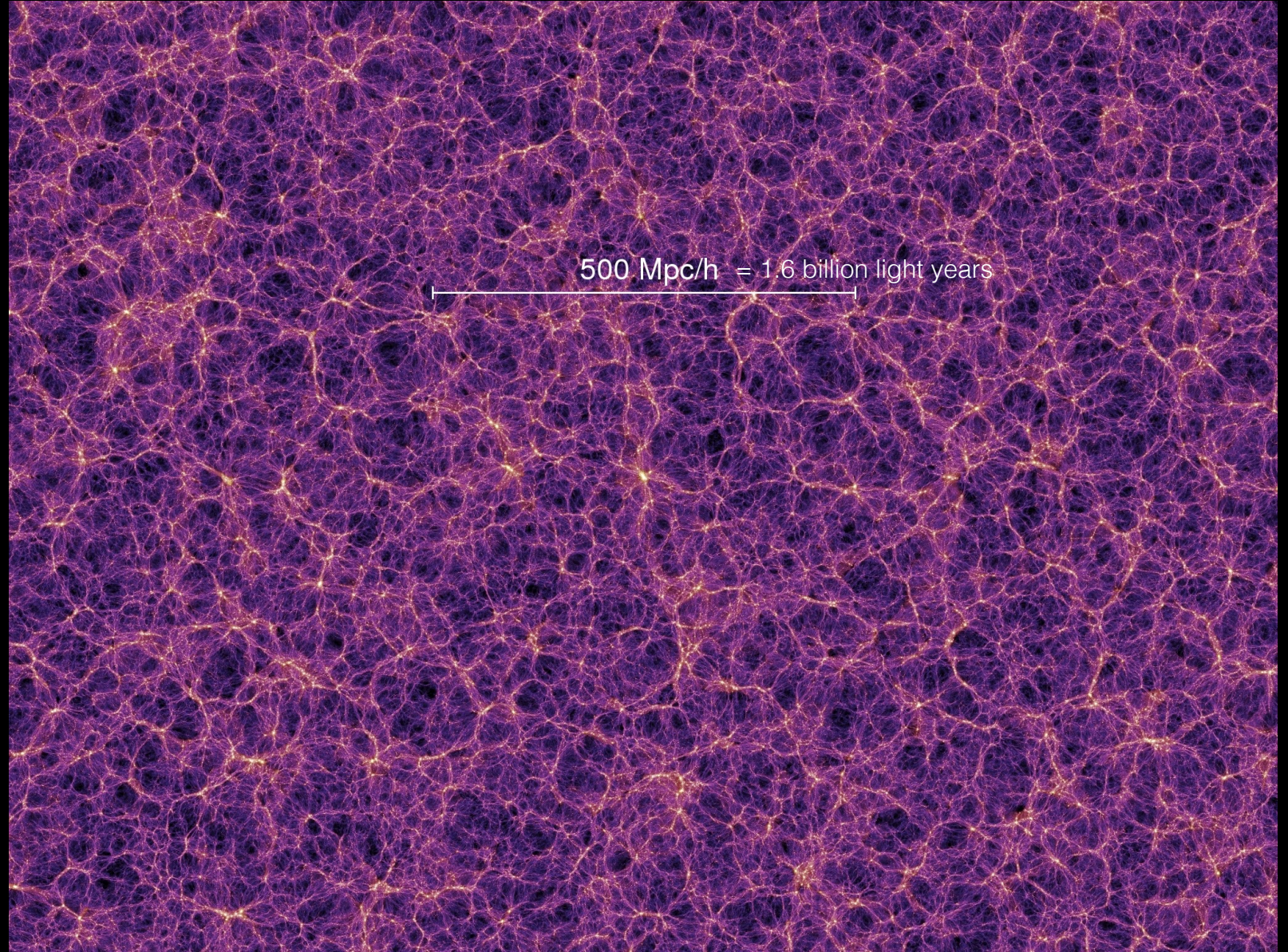
As well as larger
scales of the universe



Andromeda Galaxy
(2.5 million light years from Earth)

The Standard Model

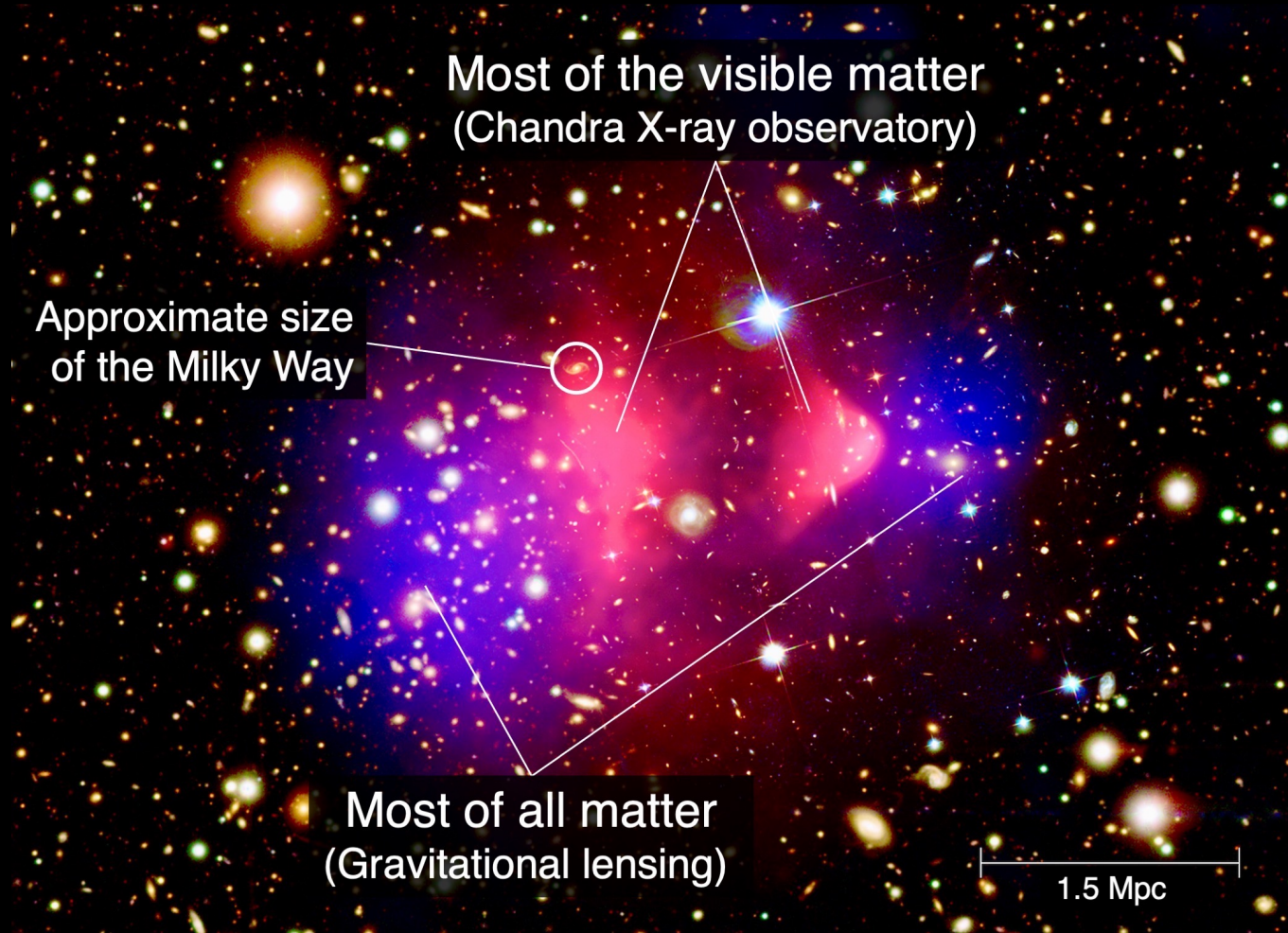
... up to the largest
scales ...



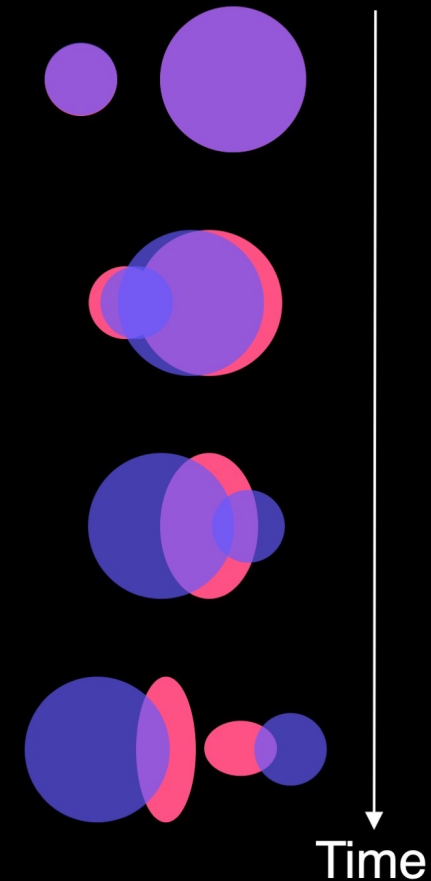
Simulation of structure formation
(dark matter, astro-ph/0504097)

The Standard Model

... but something is wrong



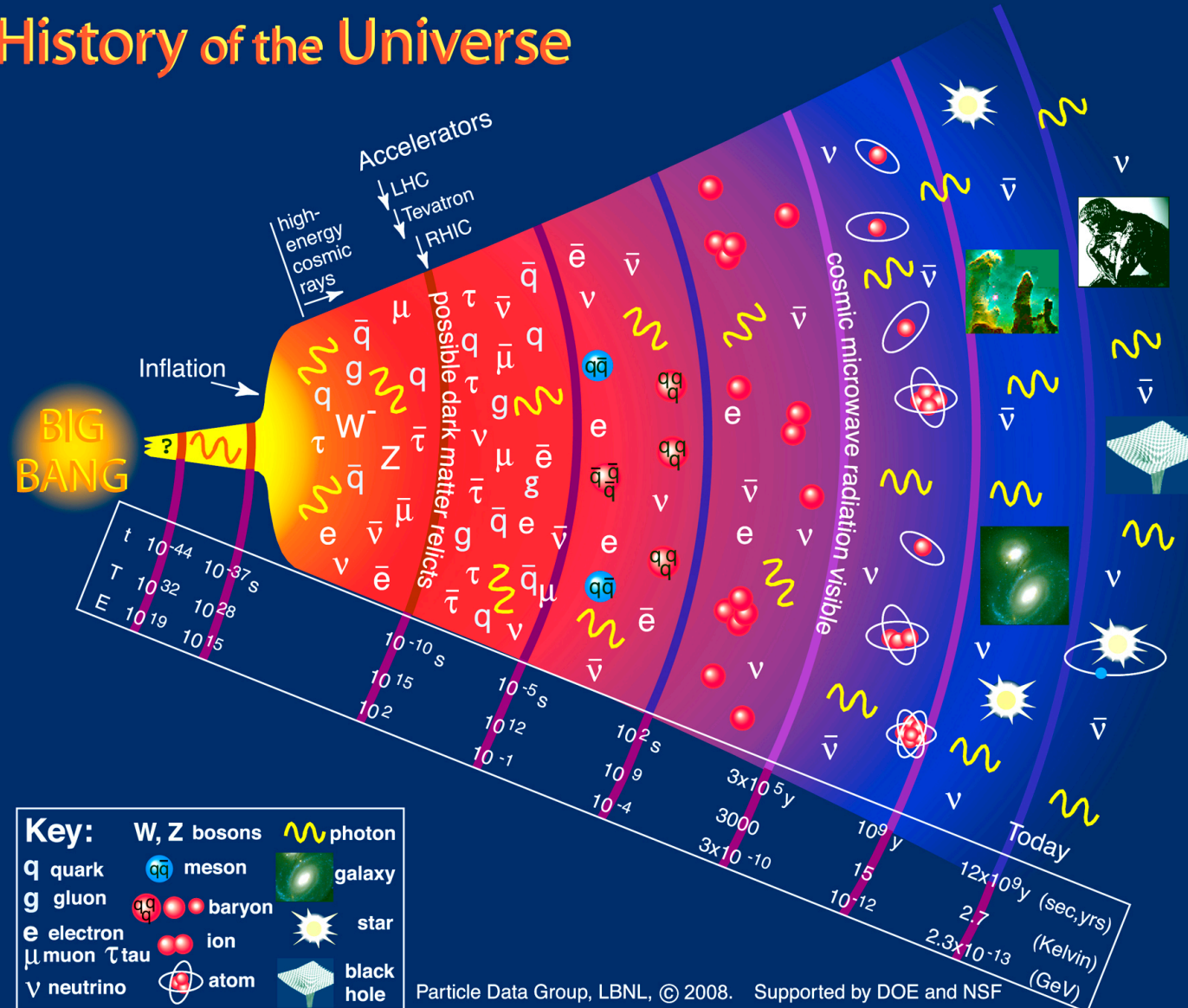
Bullet Cluster: one among many evidences of gravitational dark matter



The Standard Model

... and throughout its full history since the Big Bang, 13.8 billion years ago

History of the Universe



The Higgs mechanism

Fundamental “gauge” symmetry requires all force and matter particles to be massless

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase – early universe

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

The Higgs mechanism

Masses can be dynamically generated by **spontaneously breaking electroweak symmetry**

The universe expands and cools down, after about 10^{-11} seconds after the big bang electroweak symmetry breaks

A Higgs field displaces ground state breaking gauge symmetry

It fills all space time (but without orientation as it has no spin)

Particles interact with Higgs field and effectively reduce their velocity. Acquired mass proportional to interaction strength

→ Action of the Higgs field creates “vacuum viscosity”

Higgs quantum liquid in broken phase

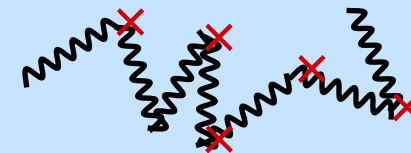
Gravity



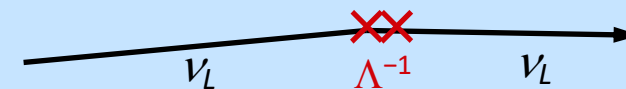
Photon



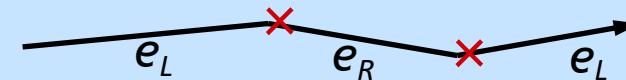
Weak boson



Neutrinos



Electrons



Top quark

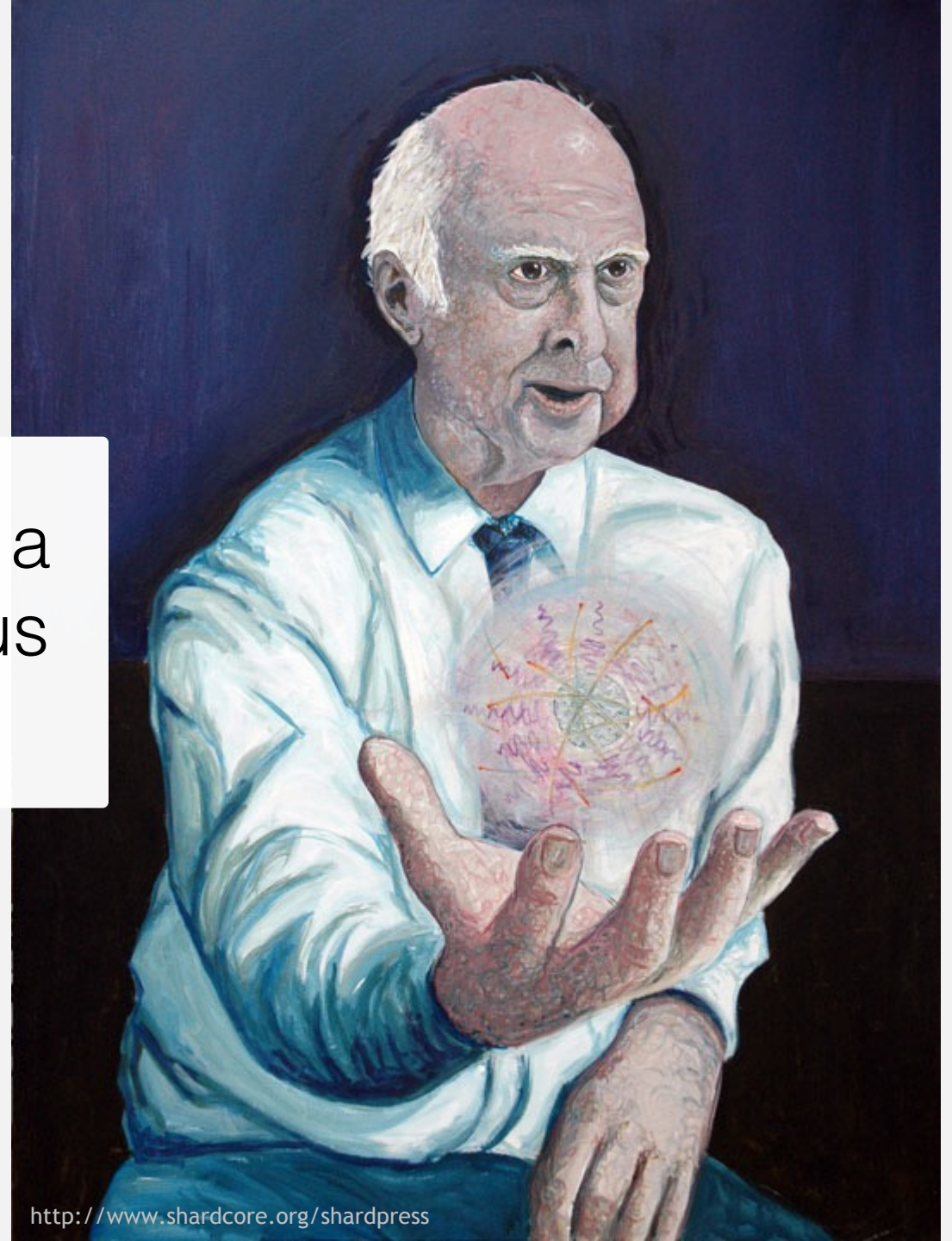


Interaction with Higgs field alters chirality of massive Dirac fermion

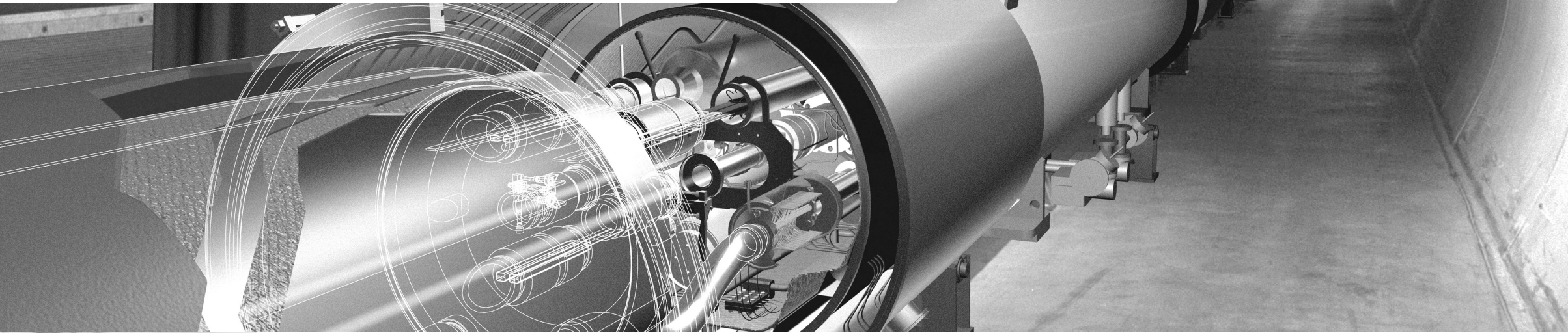
The Higgs mechanism was only a hypothesis before the LHC

To prove it one had to find a new particle: the mysterious
Higgs boson

If the Higgs boson existed, it had to be rather massive and its production would be rare



Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine



Lawrence
(First cyclotron
provided 80 keV
proton acceleration)

Particle accelerators

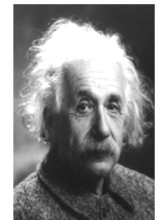
- Look deeper into matter (size $\sim 1/E$) (powerful microscope)
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie



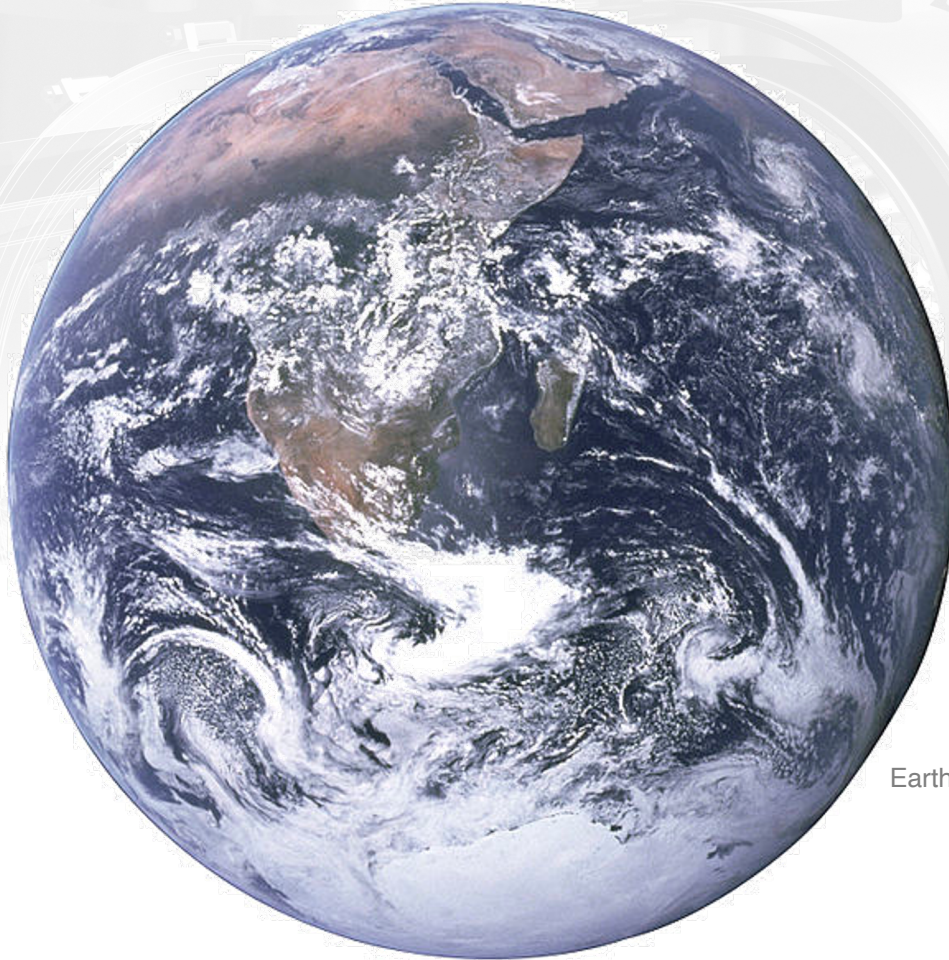
Boltzmann



Einstein

A 1 TeV-frequency microscope looks at really, really tiny objects...

Nanoscience



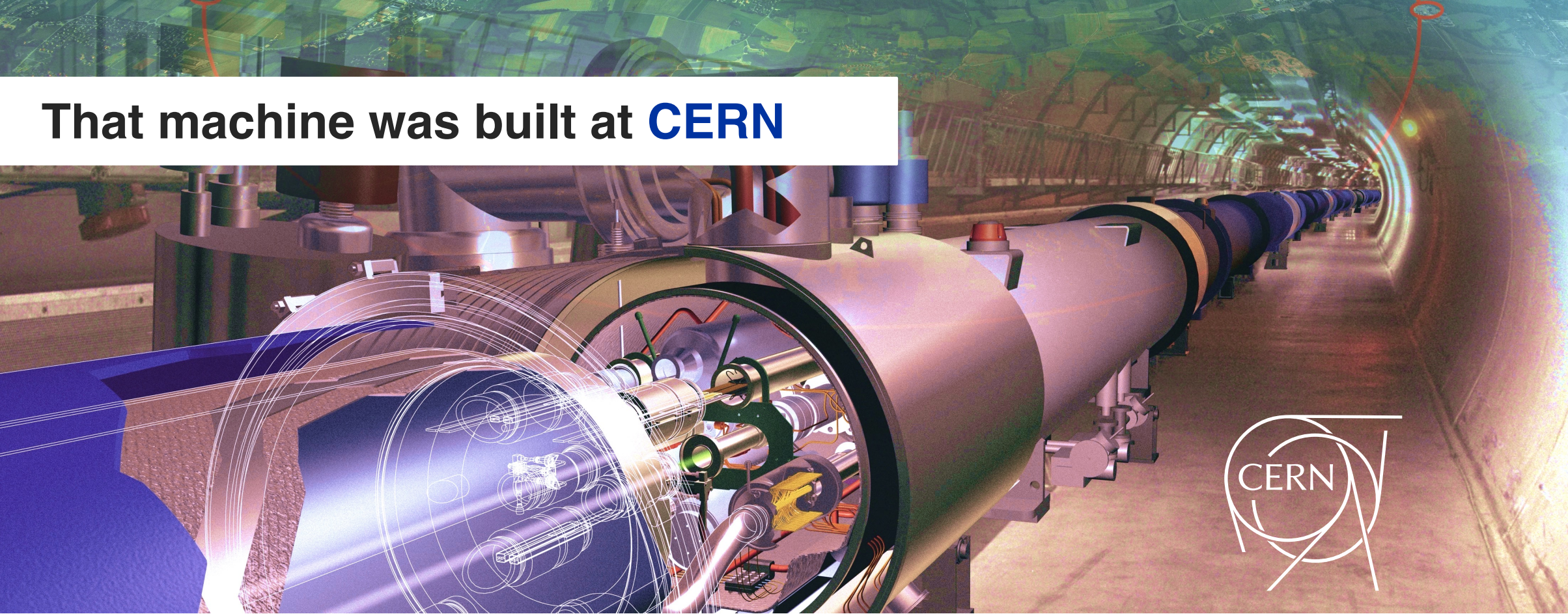
Earth

Particle physics today
(TeV scale)



Siphonaptera (flea)

That machine was built at **CERN**



CERN

Founded in 1954 has become a
paradigm for Scientific Cooperation





On 17 May 1954, the first shovel of earth was dug on the Meyrin site in Switzerland under the eyes of Geneva officials and members of CERN staff



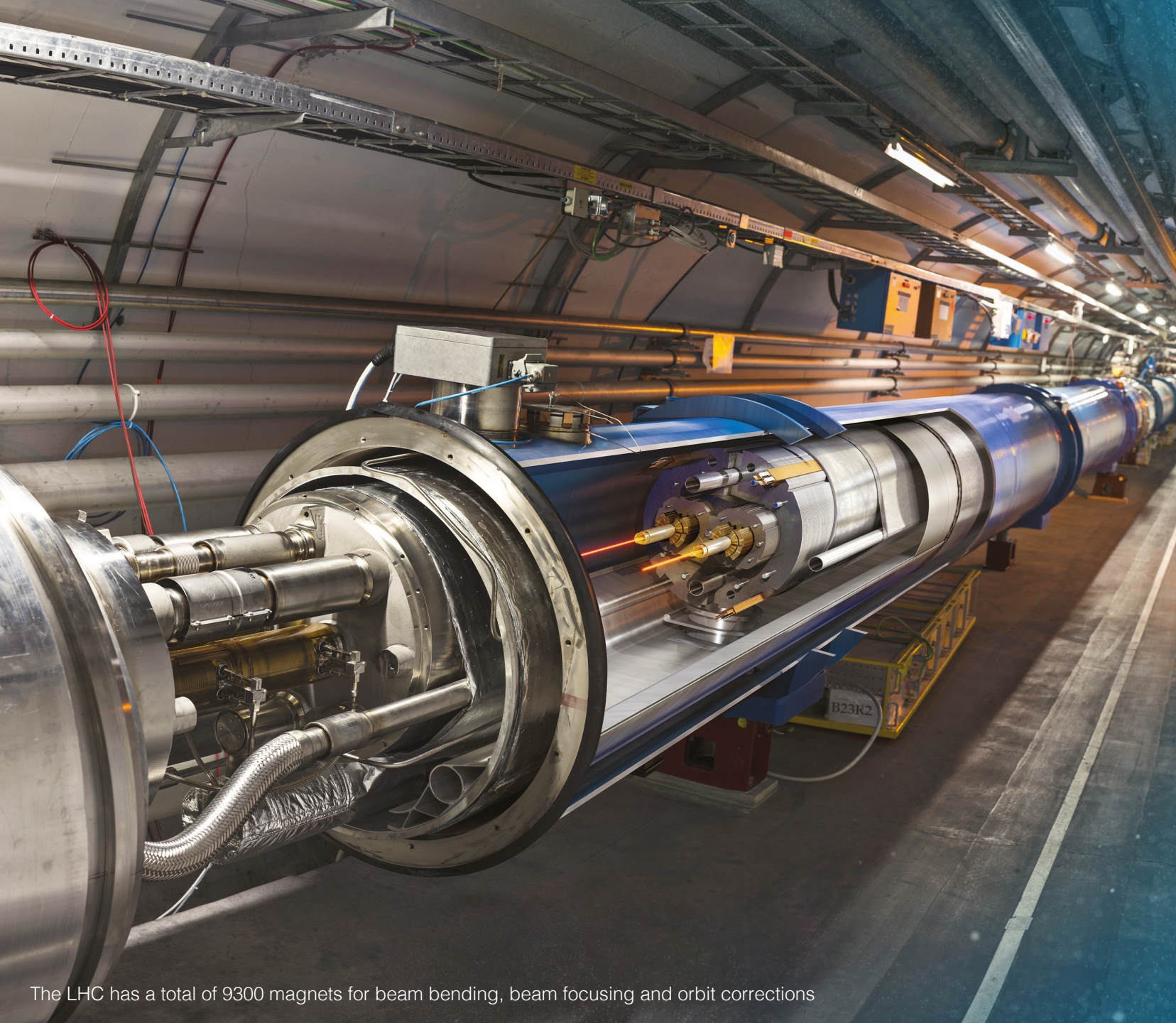
Aerial view of the 25 GeV Proton Synchrotron at CERN in 1965

CERN today

CERN is the world's biggest laboratory for particle physics

Its mission is to understand the most fundamental particles and laws of the universe





Large Hadron Collider (LHC)

- 27 km in circumference
- About 100 m underground
- Superconducting magnets steer the particles around the ring
- Proton and ions are accelerated to close to the speed of light

The LHC has a total of 9300 magnets for beam bending, beam focusing and orbit corrections



CMS

LHC

ALICE »

CERN
Preessin

ATLAS

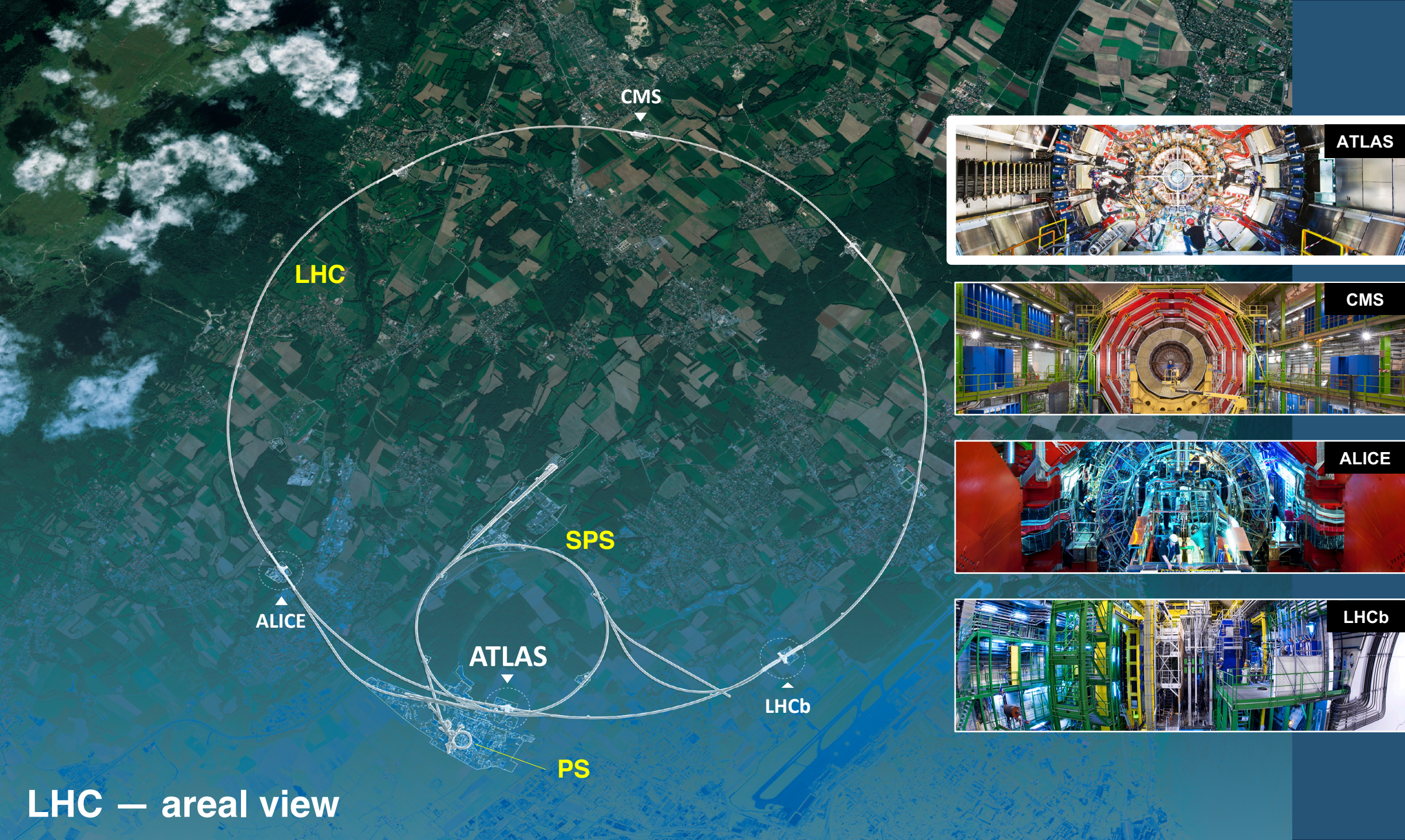
CERN
Meyrin

« LHCb

LHC

LHC — areal view

1 km



CMS

LHC

SPS

ALICE

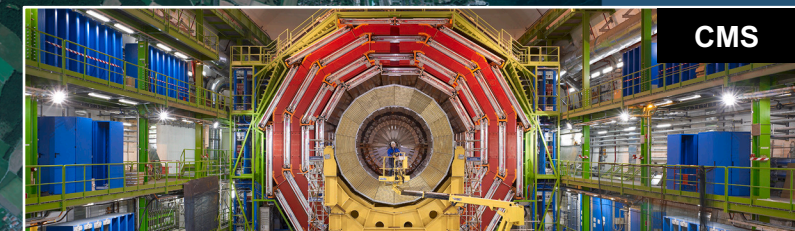
ATLAS

LHCb

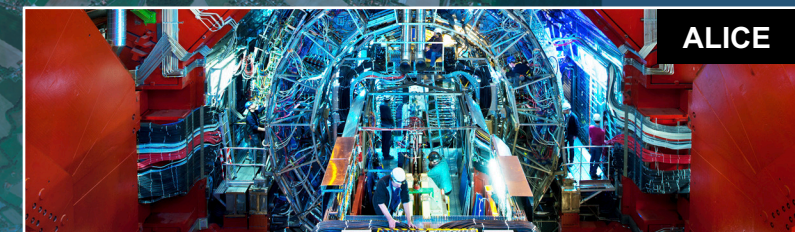
PS



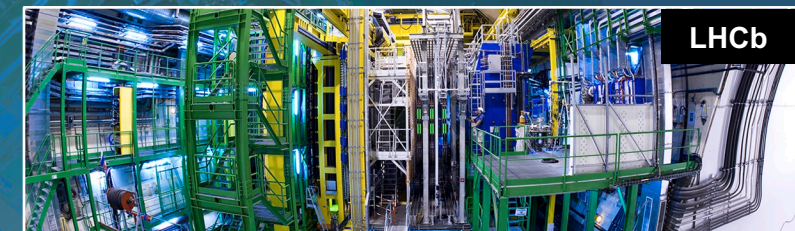
ATLAS



CMS

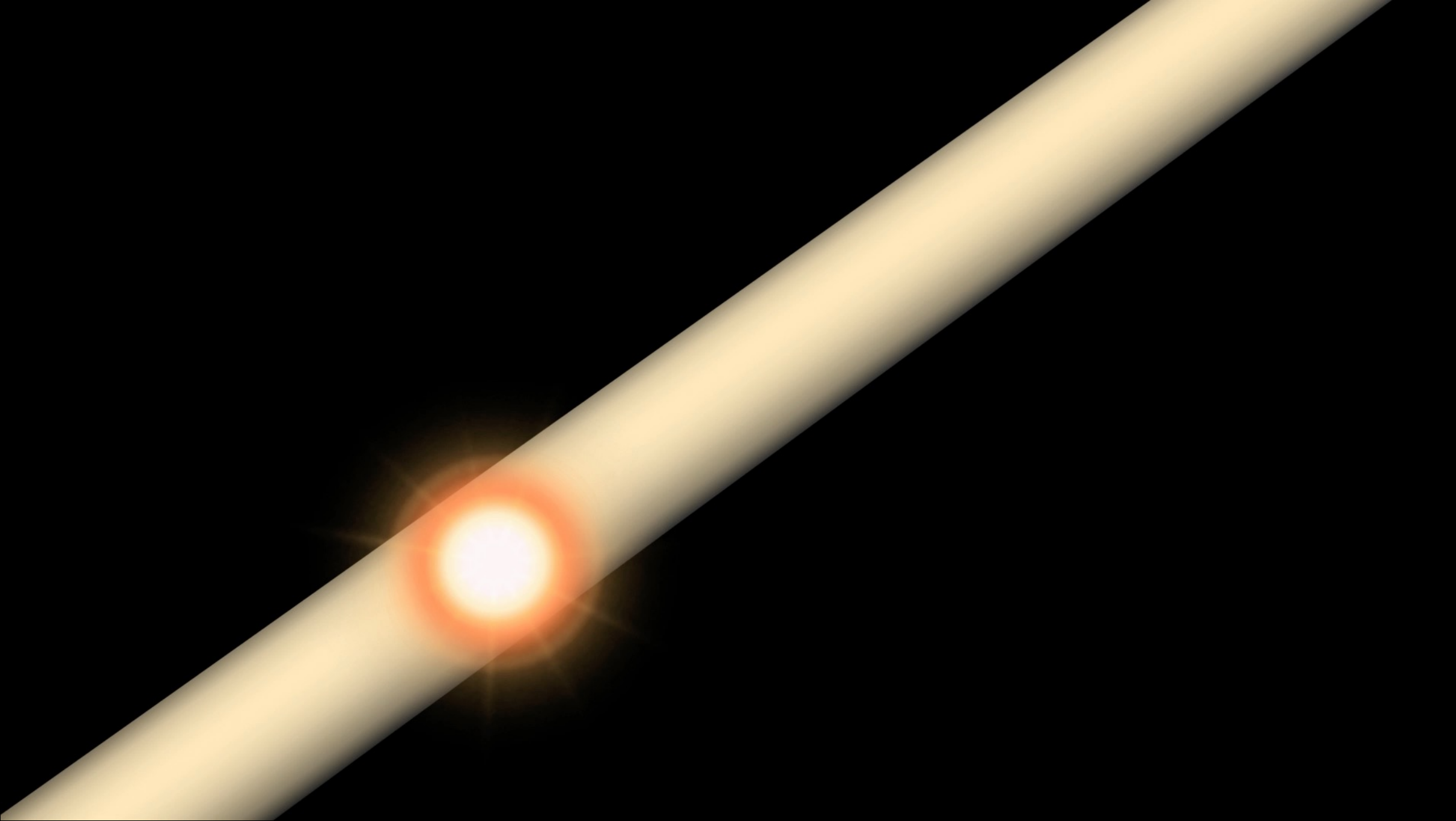


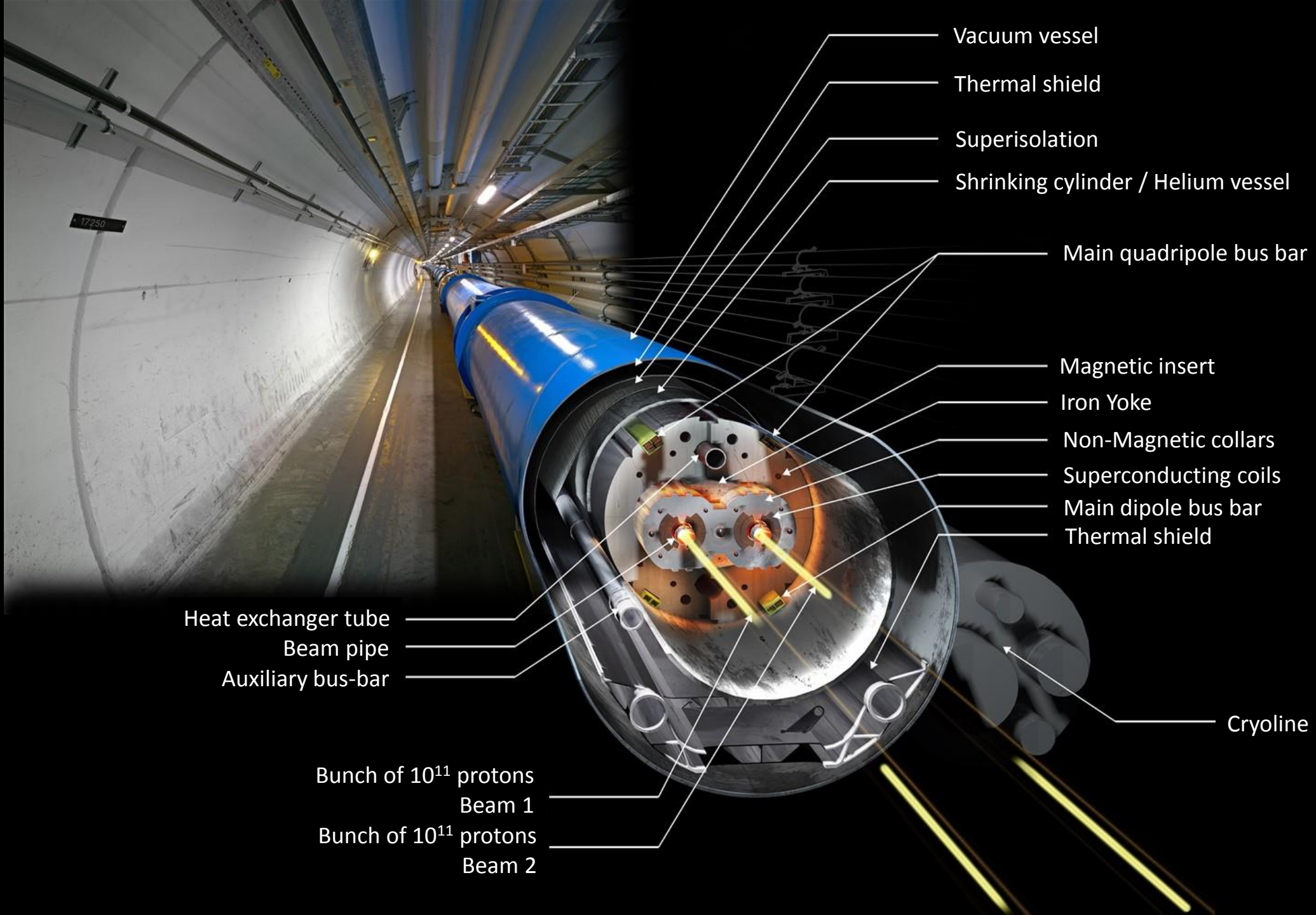
ALICE



LHCb

LHC — areal view





Vacuum vessel

Thermal shield

Superisolation

Shrinking cylinder / Helium vessel

Main quadripole bus bar

Magnetic insert

Iron Yoke

Non-Magnetic collars

Superconducting coils

Main dipole bus bar

Thermal shield

Cryoline

Heat exchanger tube

Beam pipe

Auxiliary bus-bar

Bunch of 10^{11} protons

Beam 1

Bunch of 10^{11} protons

Beam 2



Vacuum vessel

Thermal shield

Superisolation

Shrinking cylinder / Helium vessel



LHC dipoles waiting for their installation in the tunnel



Lowering of the first dipole magnet into the tunnel on March 7th 2005

Cryoline

Bunch of 10^{11} protons

Beam 1

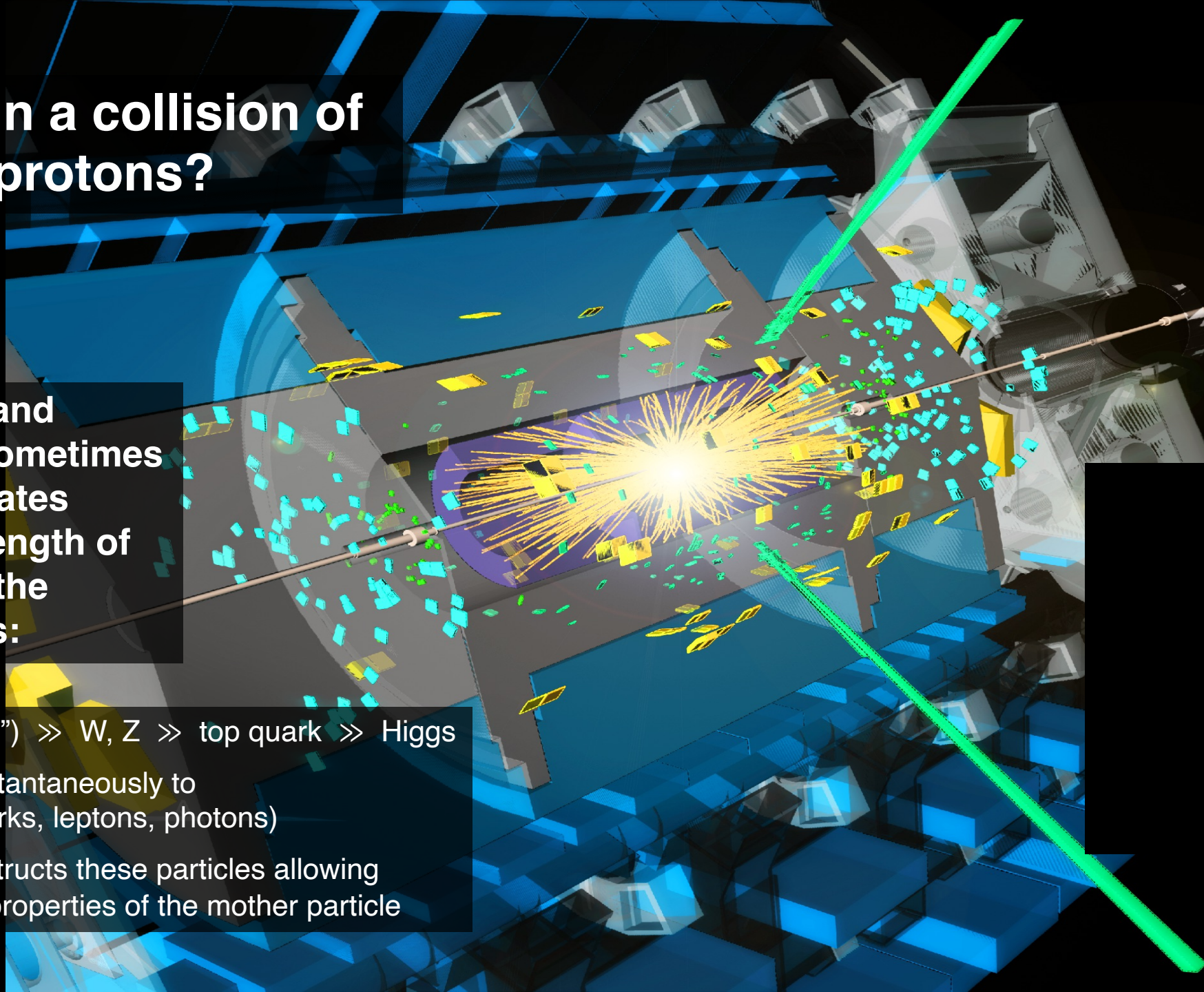
Bunch of 10^{11} protons

Beam 2

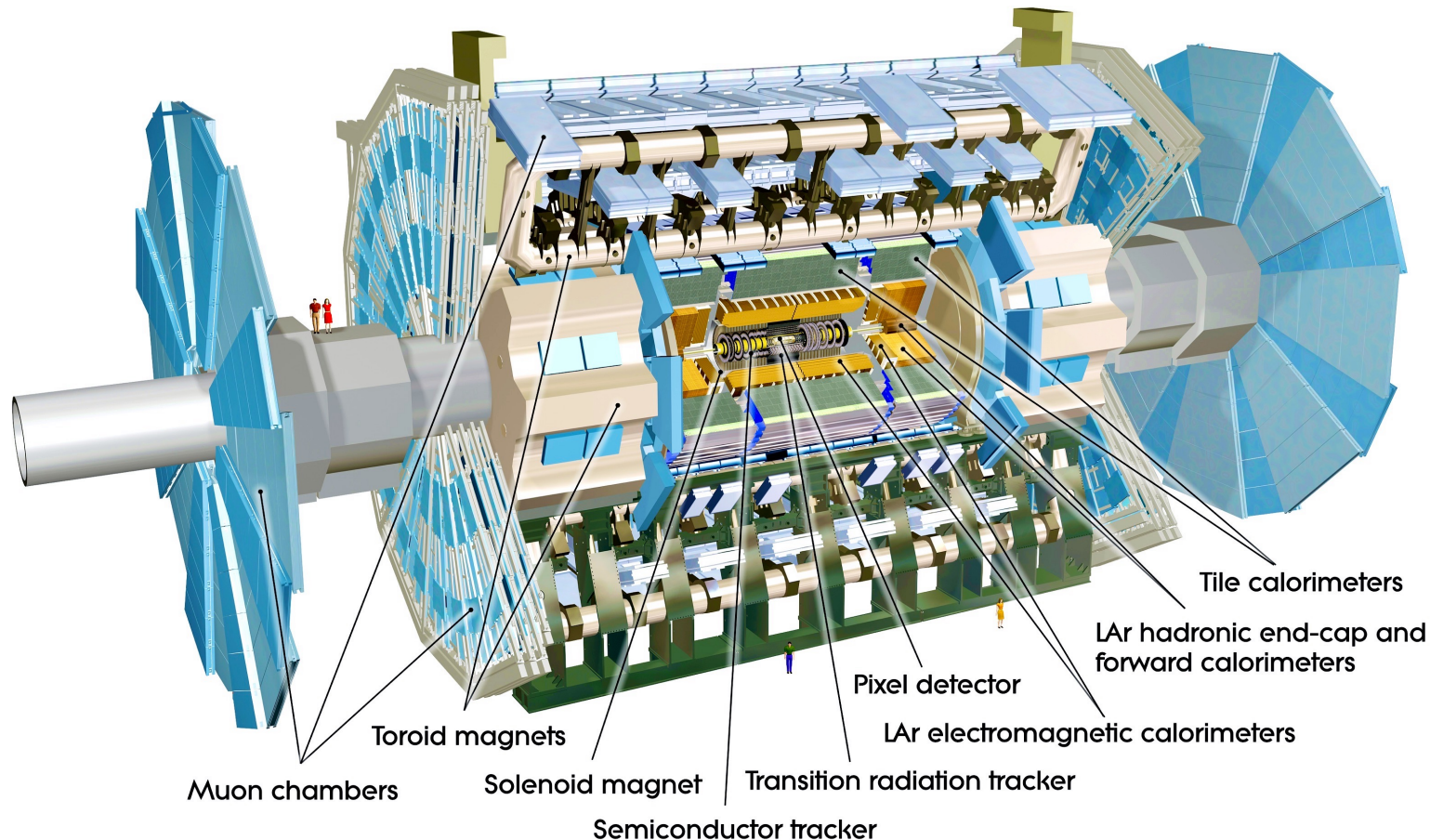
What happens in a collision of high-energetic protons?

Its constituents fuse and transform into new, sometimes heavy particles with rates depending on the strength of their interaction with the proton and their mass:

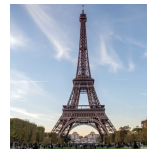
- Light quarks, gluons (“jets”) $\gg$ W, Z $\gg$ top quark $\gg$ Higgs
- Heavy particles decay instantaneously to light, stable particles (quarks, leptons, photons)
- A particle detector reconstructs these particles allowing physicists to deduce the properties of the mother particle



The ATLAS Detector



25 m diameter, 46 m long, 7000 tons weight ~



Axial field provided by **solenoid** (2 T) in central region (momentum measurement)

High resolution silicon **detectors**:

- 100 Mio. channels ($50\ \mu\text{m} \times 250\ \mu\text{m}$)
- 6 Mio. channels ($80\ \mu\text{m} \times 12\ \text{cm}$)

spatial resolution $\sim 15\ \mu\text{m}$ (in azimuthal direction)

Energy measurement down to 1° to the beam line with a **calorimeter system**

Independent **muon spectrometer** (superconducting toroid system)

Ultra-fast custom electronics filters the collisions: only 1 out of 30,000 collisions is kept!

ATLAS Collaboration

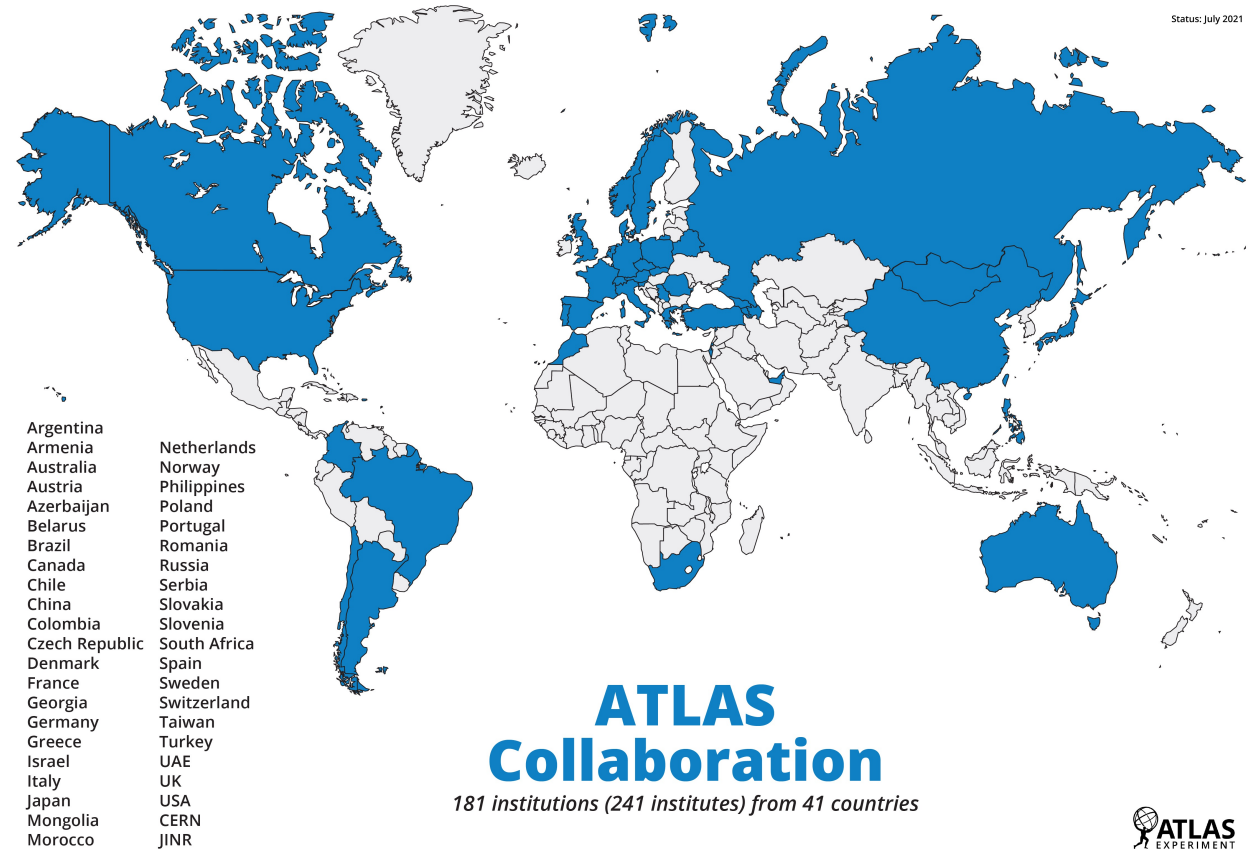
The LHC and its experiments are technological prowess **designed, built, operated and upgraded by large international consortia (→ collaborations)**

They study the most fundamental properties of matter and force at the energy frontier, and learn about the origin of our universe

They offer scientific and technological breakthroughs, highest level education, international cooperation

The ATLAS Collaboration

- 5900 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- 1200 PhD students
- 243 institutes from 41 countries
- 1024 scientific papers



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The **United Arab Emirates (UAE)** joined the ATLAS Collaboration in 2021

- **University of Sharjah (UoS)** — Dr. R. Soualah, Prof. A. Ahriche
- **New York University Abu Dhabi (NYUAD)** — Prof. M. Losada
- **United Arab Emirates University (UAEU)** — Prof. S. Nasri



CERN offers many renowned educational programmes



The ATLAS Collaboration

- 5900 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- **1200 PhD students**
- 243 institutes from 41 countries
- 1024 scientific papers



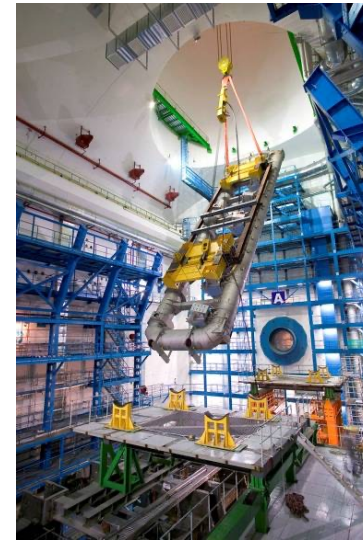
ATLAS Detector construction and installation

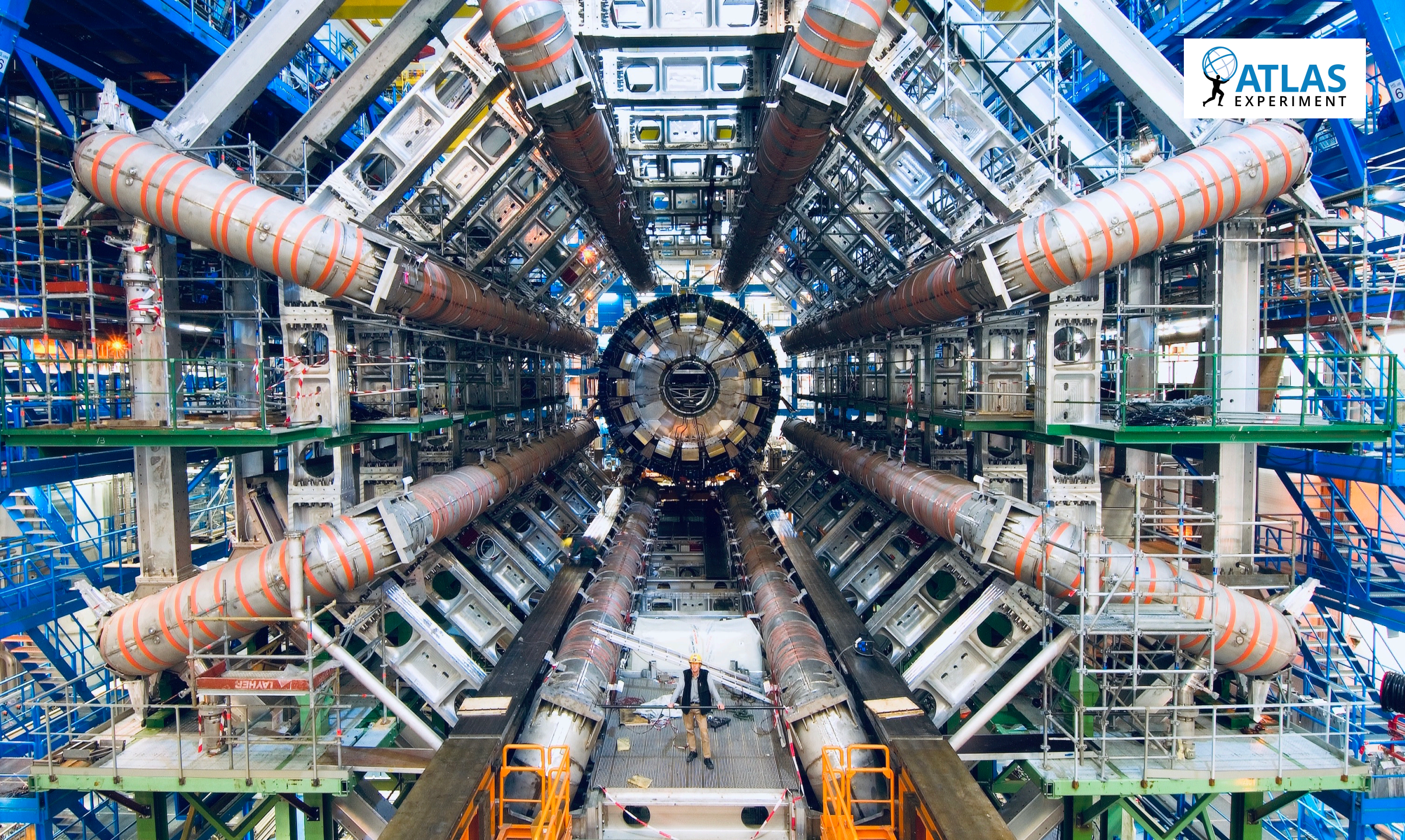


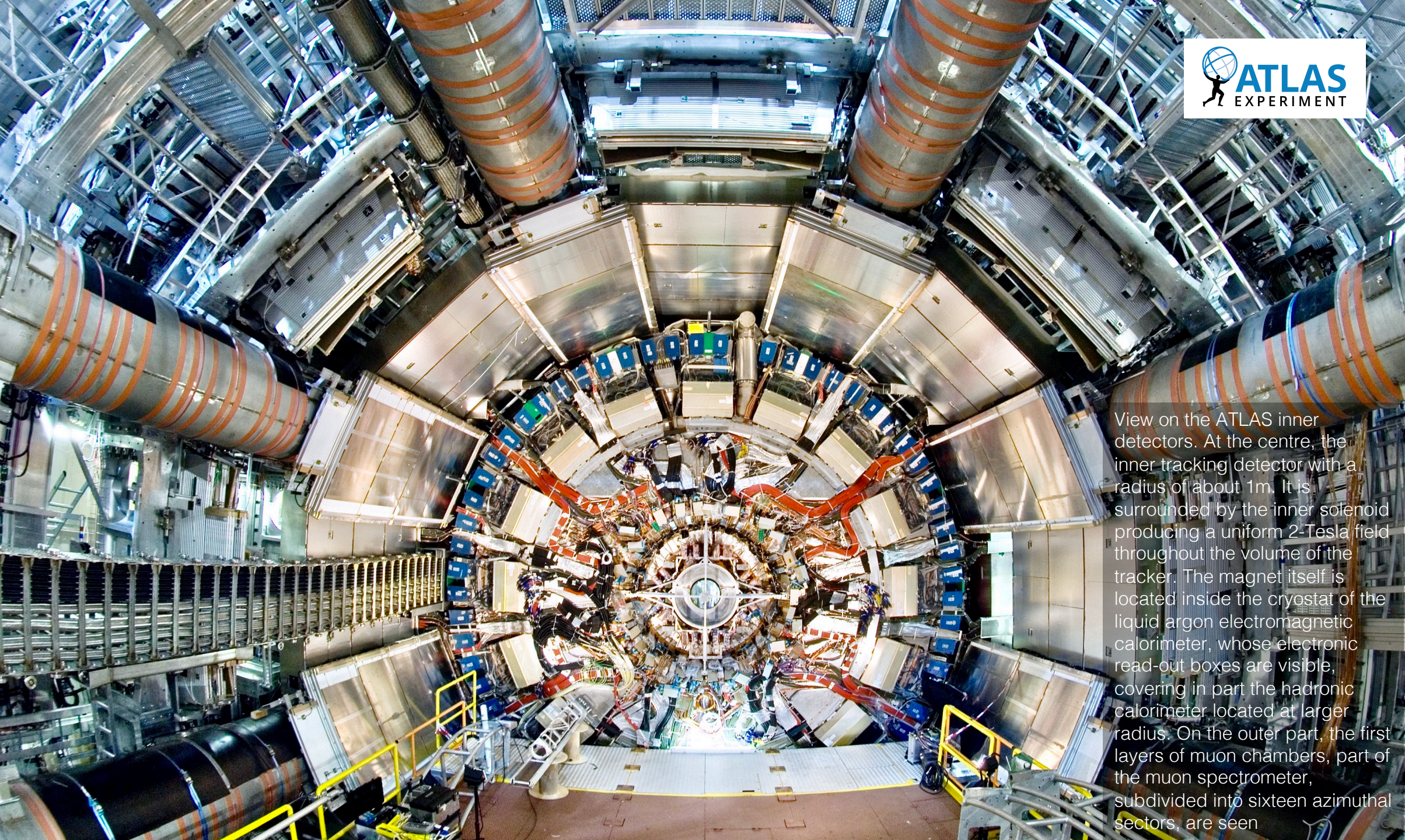
ATLAS cavern after excavation in July 2002

- 53 m long
- 35 m high (10-storey building)
- 30 m wide

ATLAS Detector construction and installation

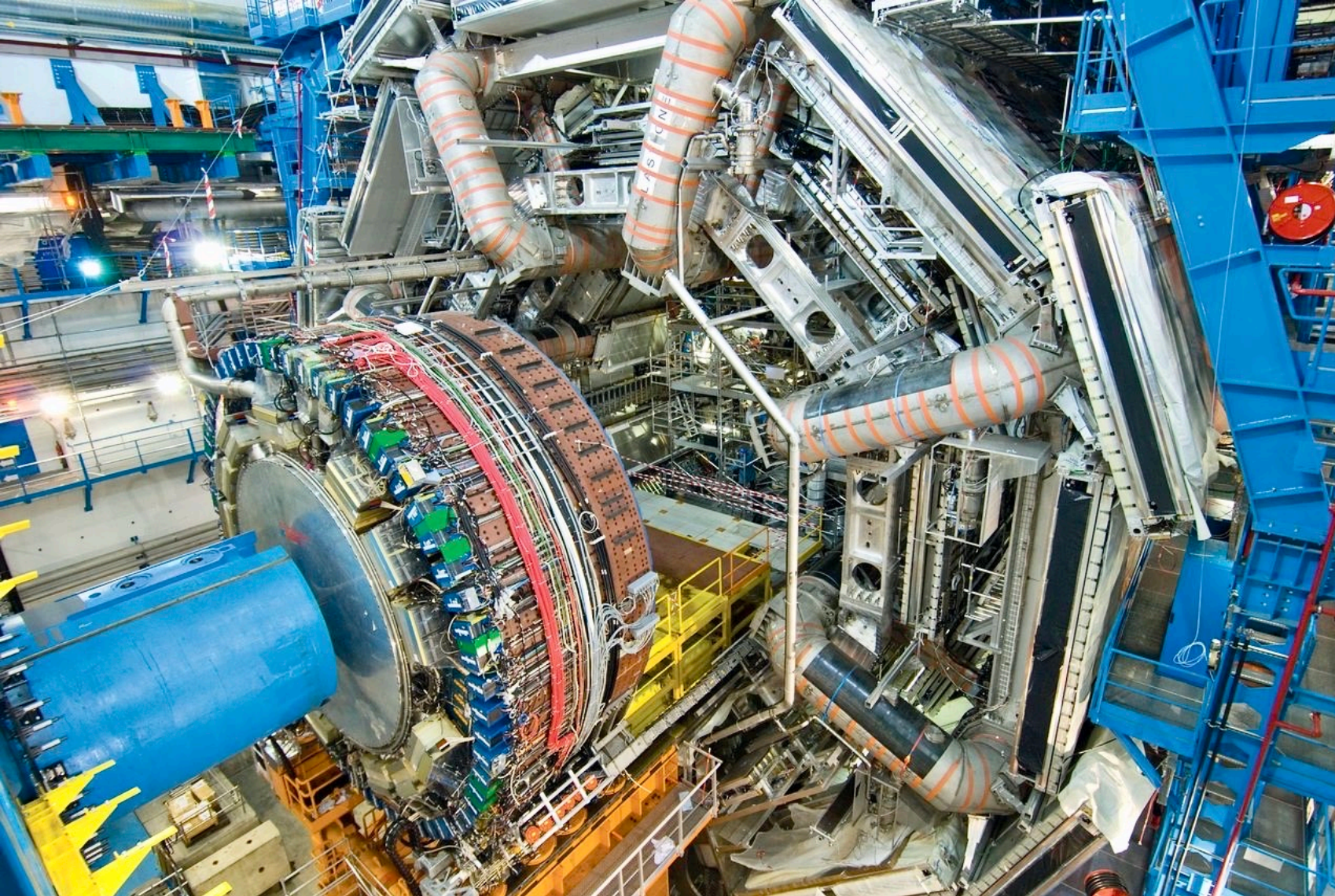






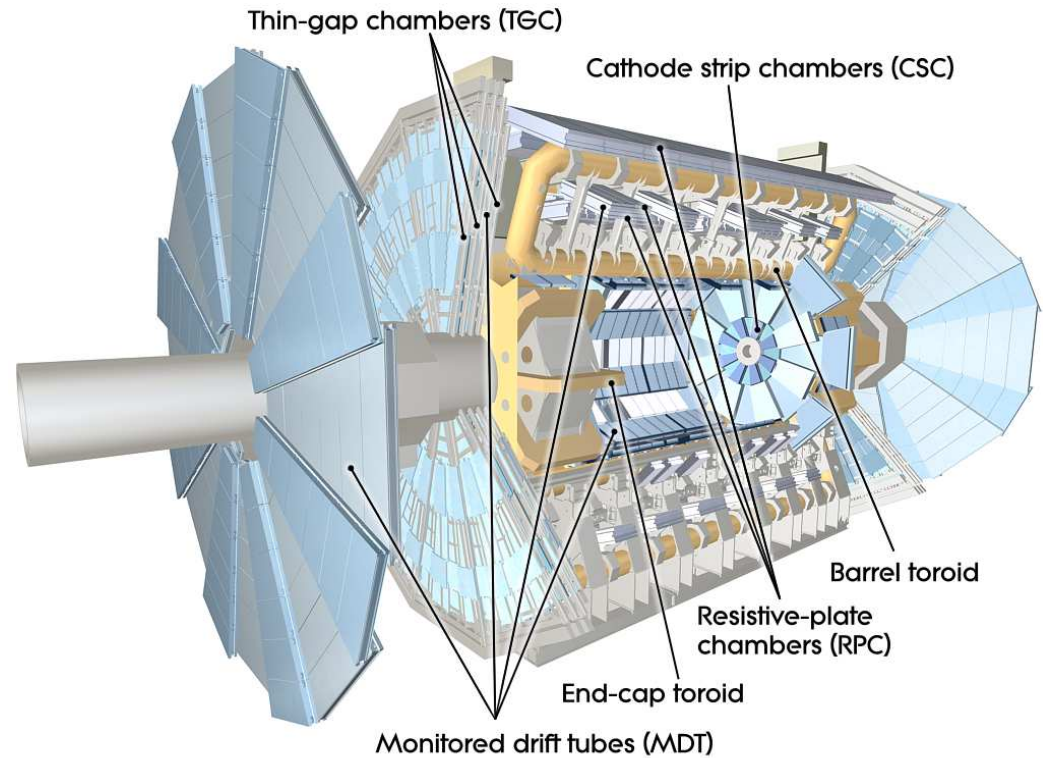
View on the ATLAS inner detectors. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic calorimeter, whose electronic read-out boxes are visible, covering in part the hadronic calorimeter located at larger radius. On the outer part, the first layers of muon chambers, part of the muon spectrometer, subdivided into sixteen azimuthal sectors, are seen

ATLAS Detector construction and installation – Calorimeters

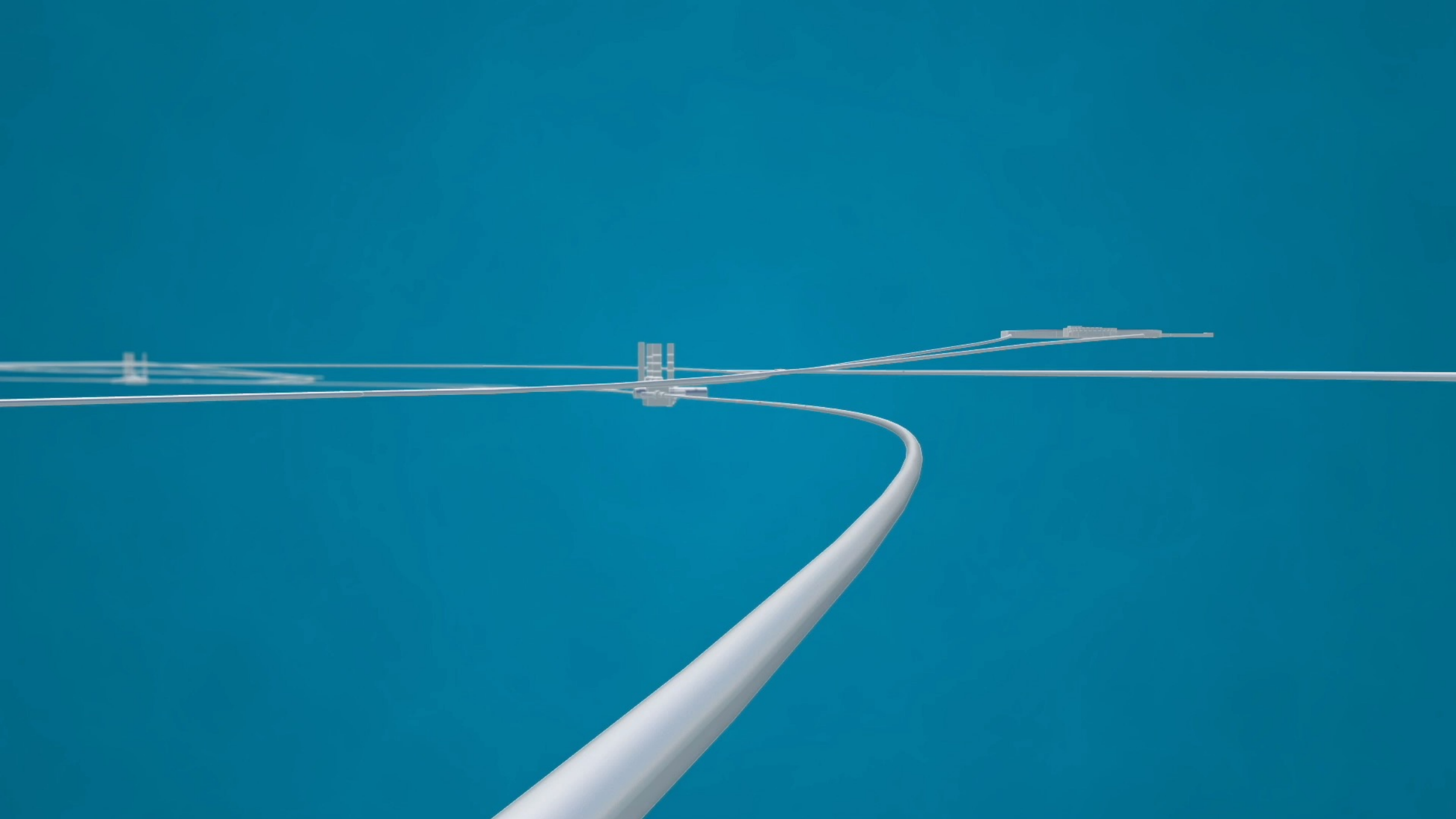


View of the central part of ATLAS during final assembly stages. The wire chambers mounted inside and around the toroid magnet cryostats are well visible, as is part of the end-cap hadronic calorimeter before its insertion inside the magnet

ATLAS Detector construction and installation – Muons



View on the Big Wheels, intermediate muon stations with four 25 m diameter wheels on each forward side



Data analysis

The analysis of the electronic detector data requires extremely sophisticated computer and mathematical algorithms as well as a deep understanding of statistics

Particle physicists have developed and used machine learning algorithms long before it became ubiquitous in science and industry

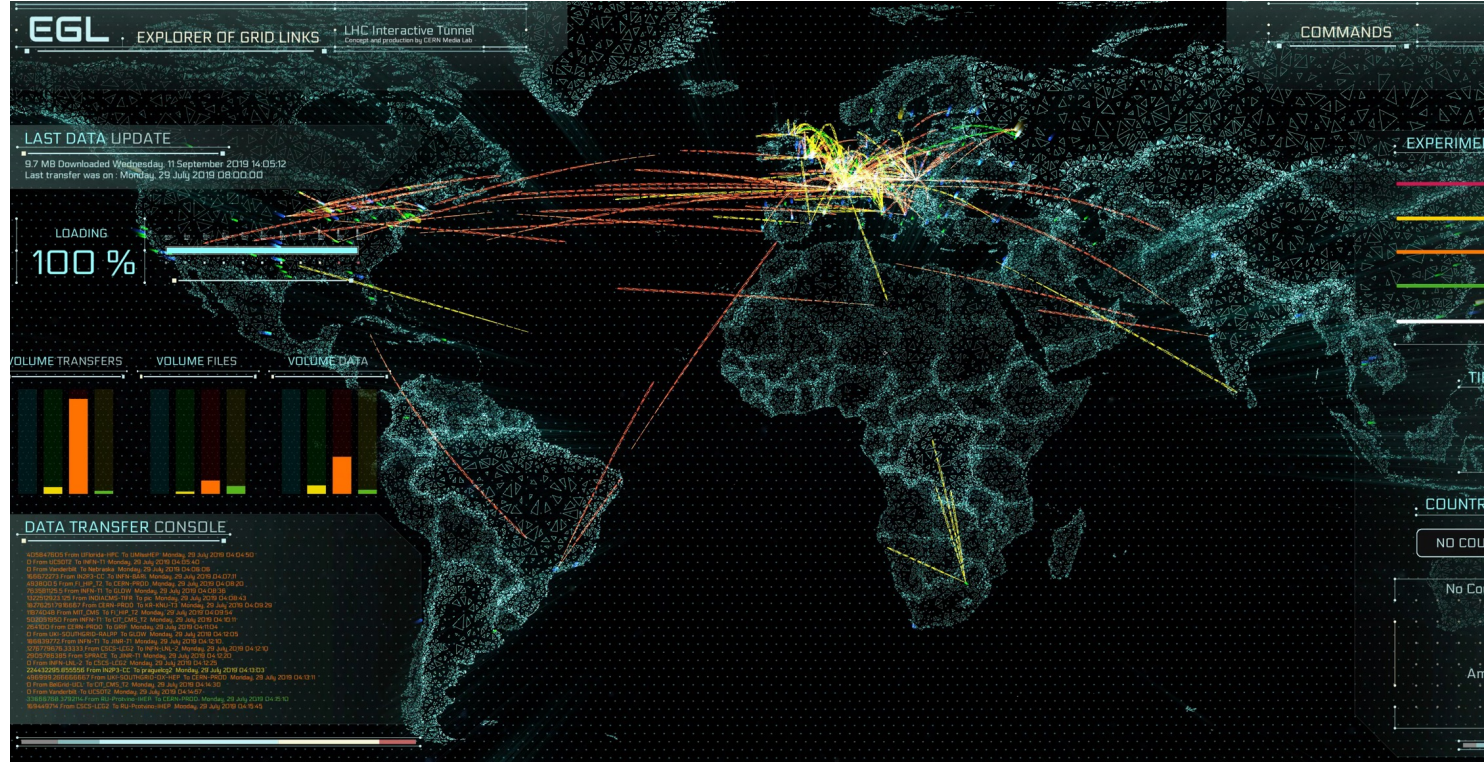
High-speed internet and data replication allows ATLAS physicists all over the world to analyse the data and contribute to the scientific publications



The data processing relies on worldwide LHC Computing Grid



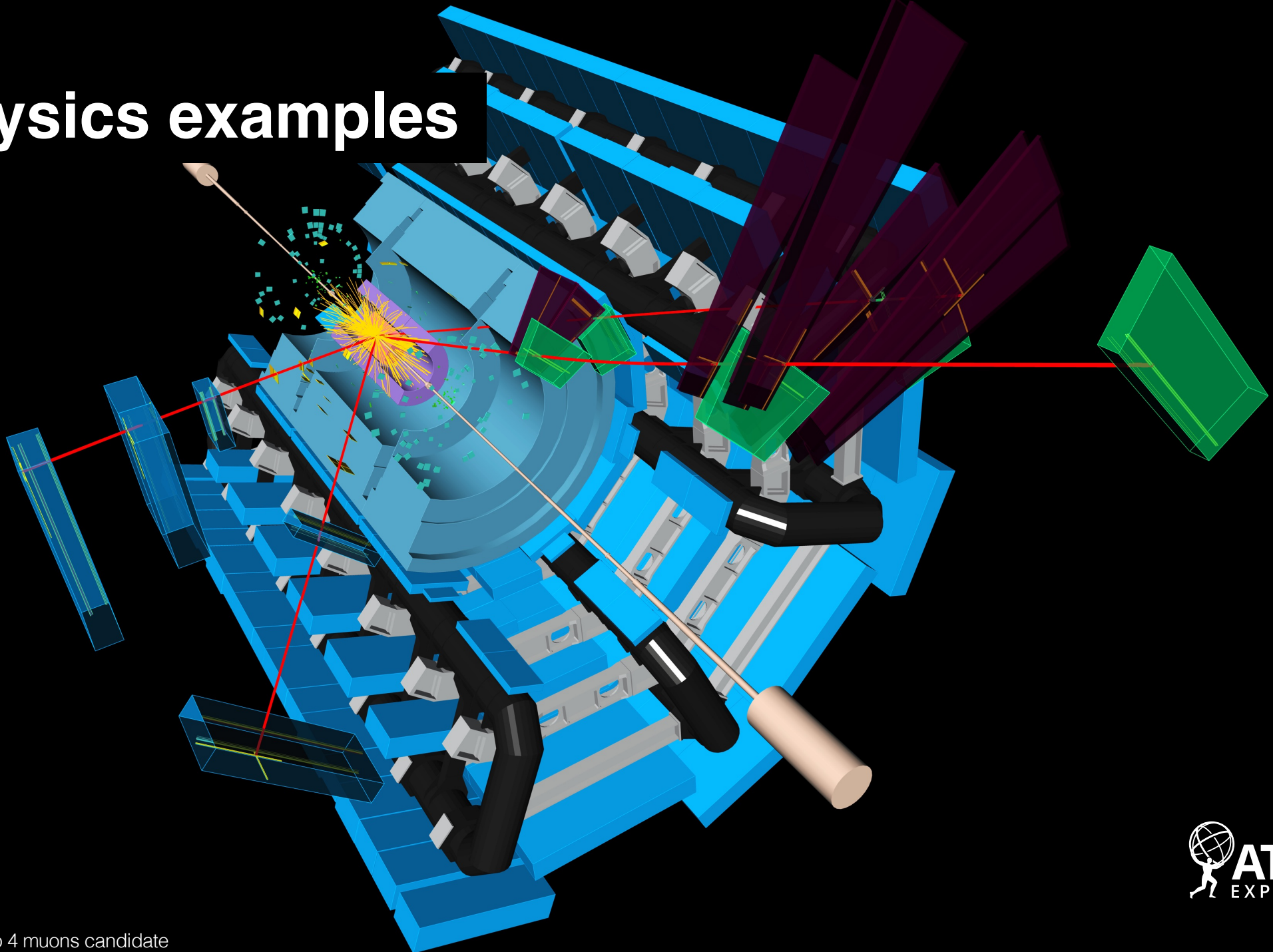
Used to store, distribute, process and analyse data



> 1 million processing cores in about 160 data centres in 42 countries

More than 1000 Petabytes of CERN data stored world-wide

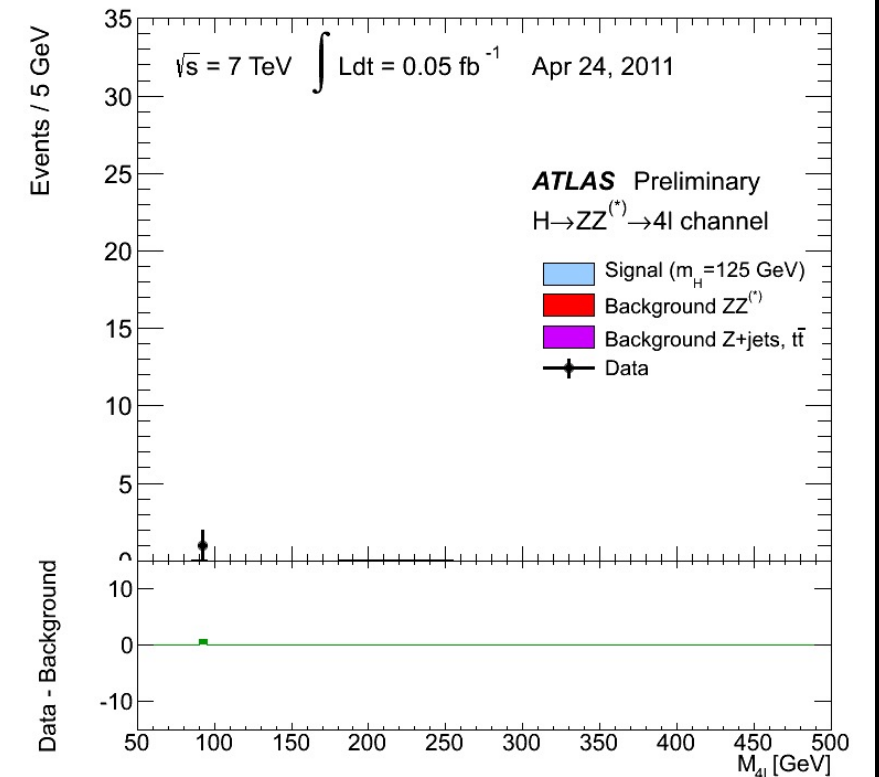
Physics examples



2012 Higgs boson discovery



Fabiola Gianotti and Peter Higgs, 4 July 2012



2012 Higgs boson discovery

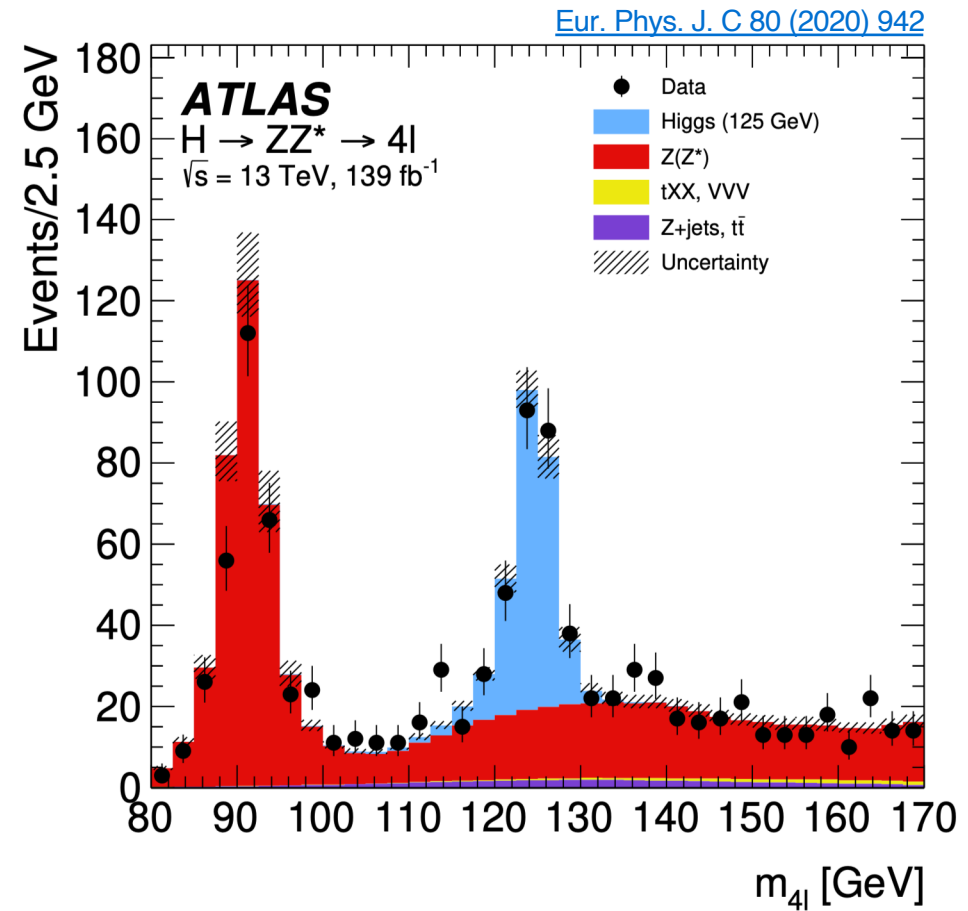
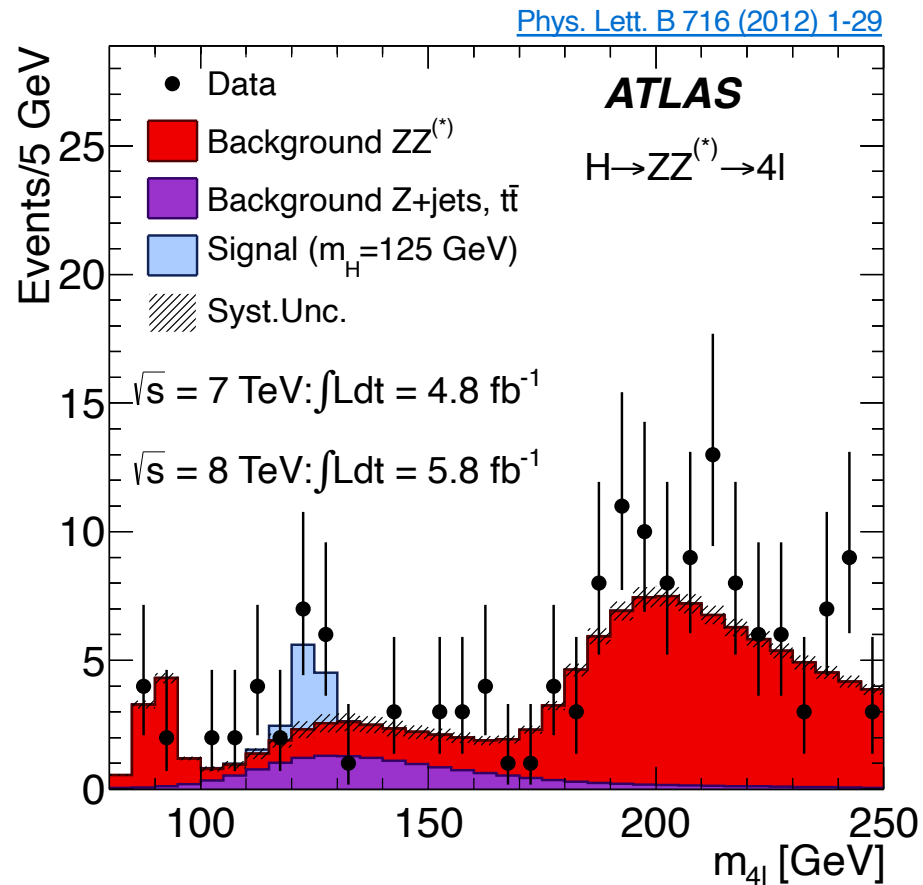


Nobel Prize in physics 2013 after Higgs boson discovery to the inventors of Higgs mechanism:
Peter Higgs and Francois Englert

ATLAS and CMS physicists building at CERN after the announcement of Nobel Prize in October 2013

A Higgs boson to 4 muons candidate

2012 Higgs boson discovery — then and today



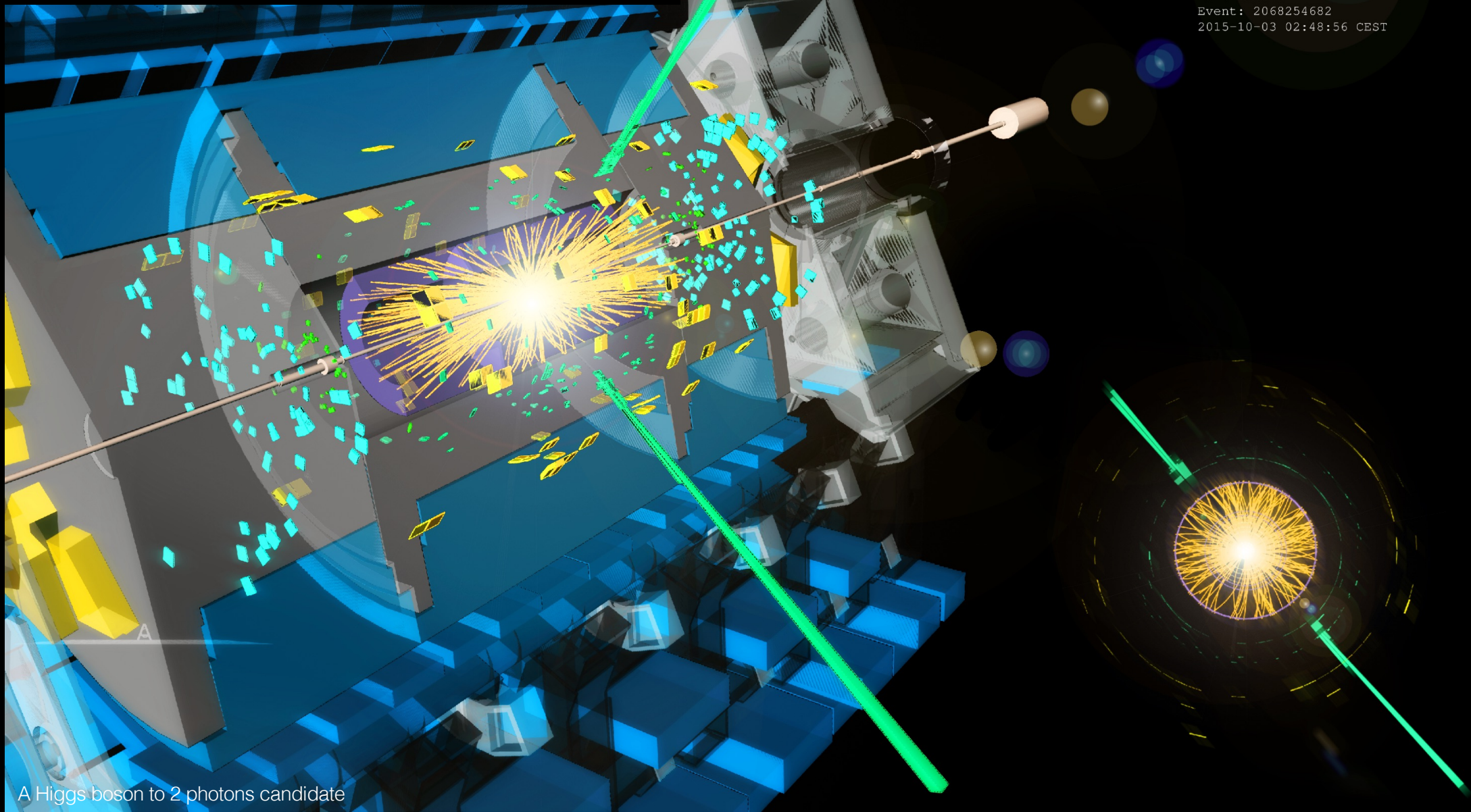
More decay channels



Run: 280862

Event: 2068254682

2015-10-03 02:48:56 CEST



A Higgs boson to 2 photons candidate

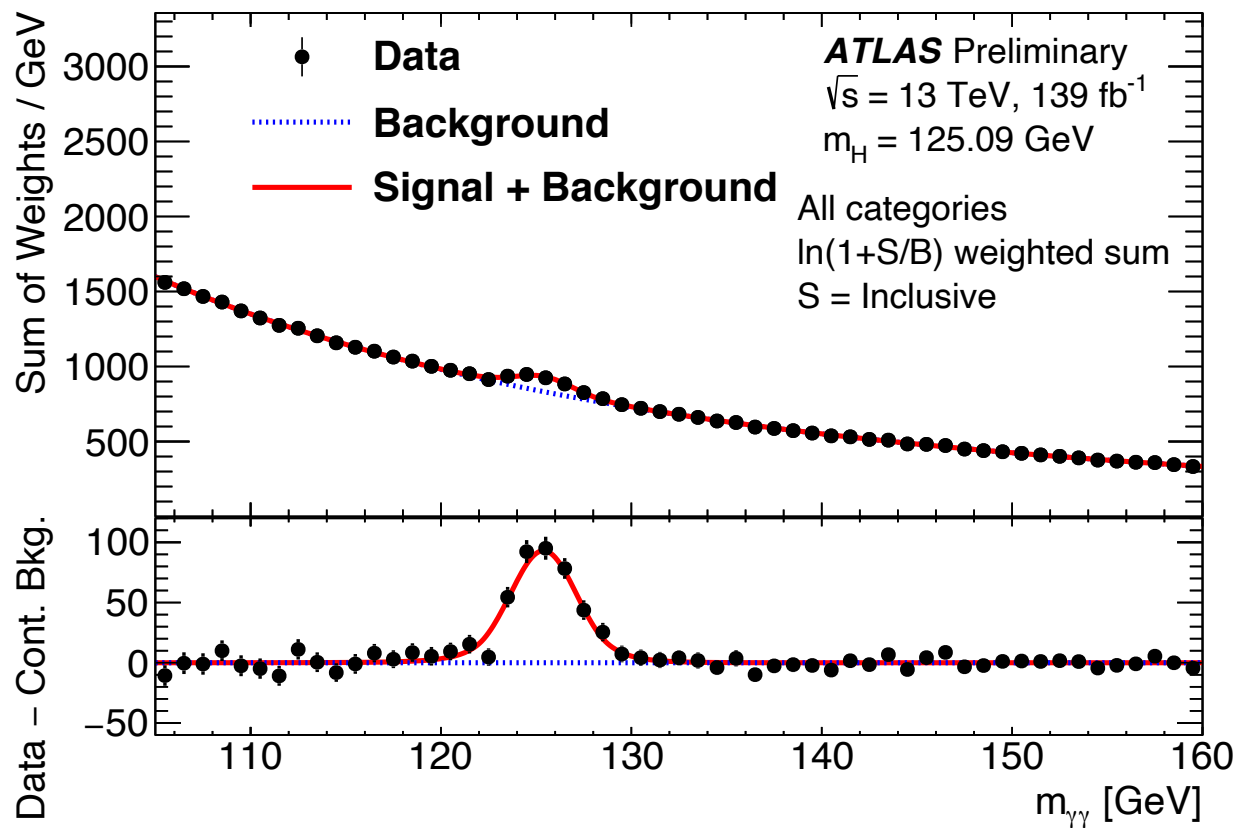
More decay channels



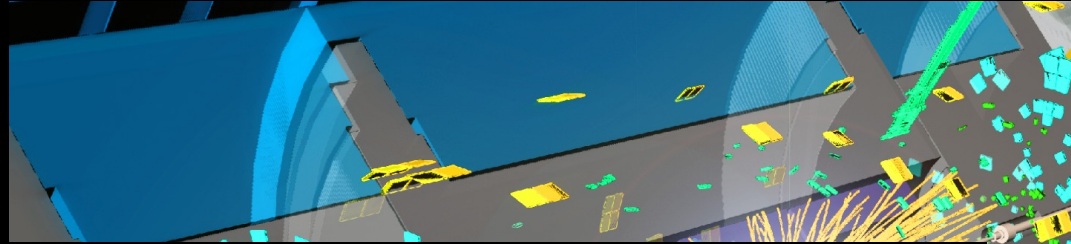
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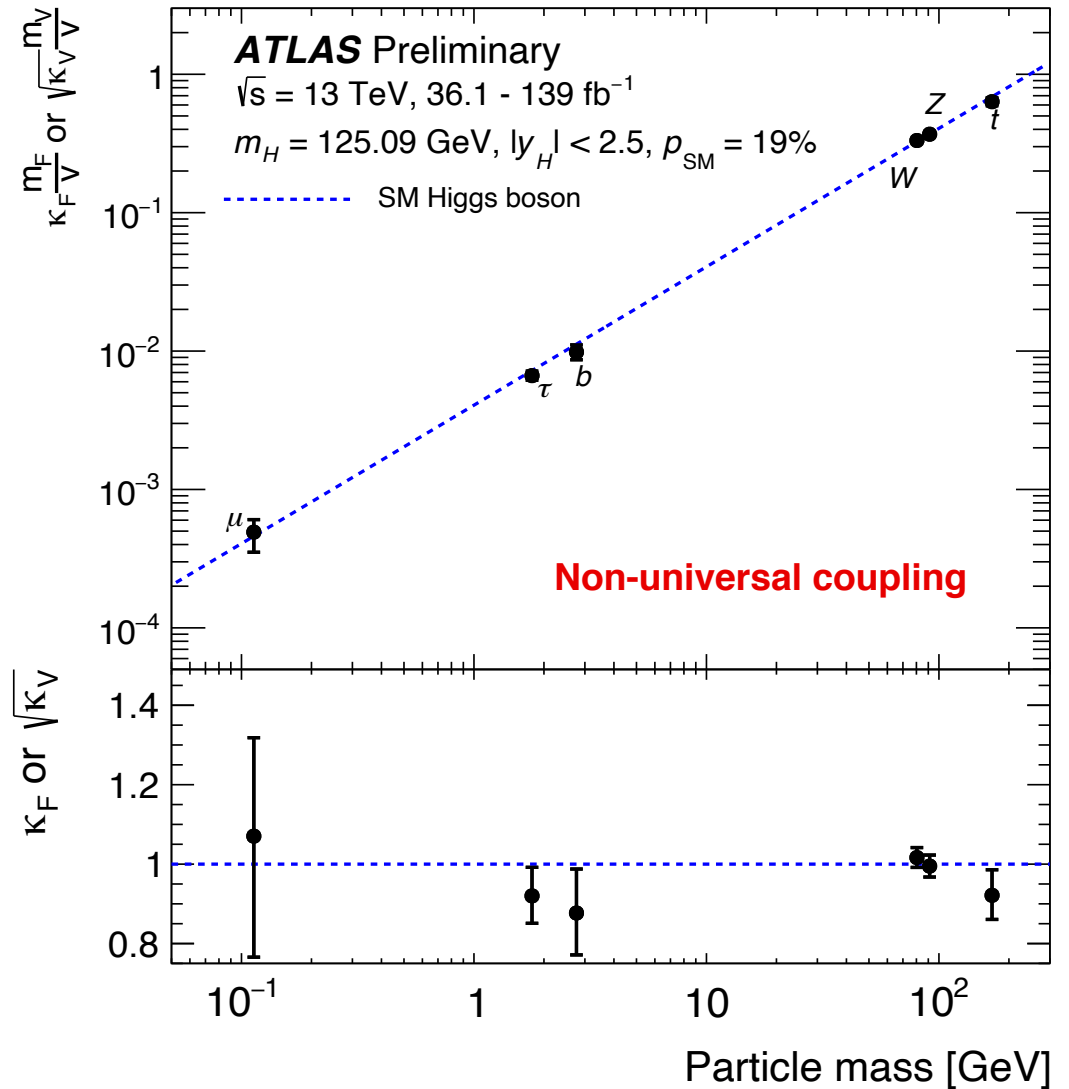
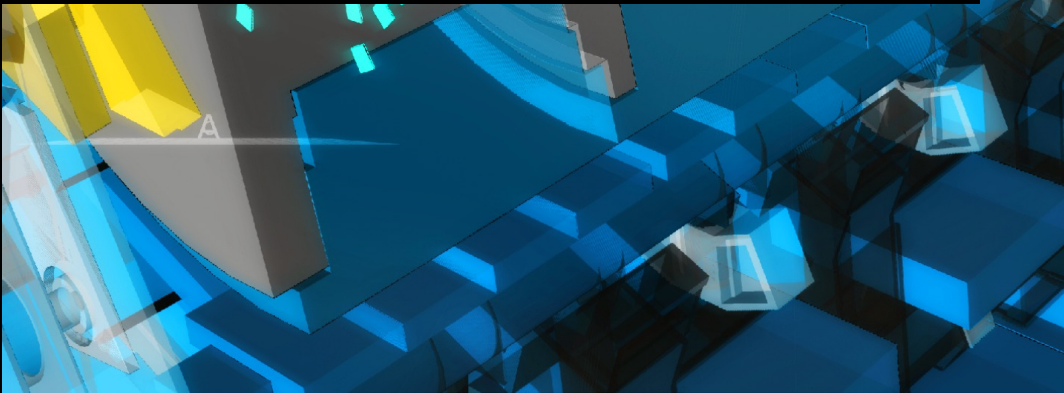


The Higgs mechanism is real !



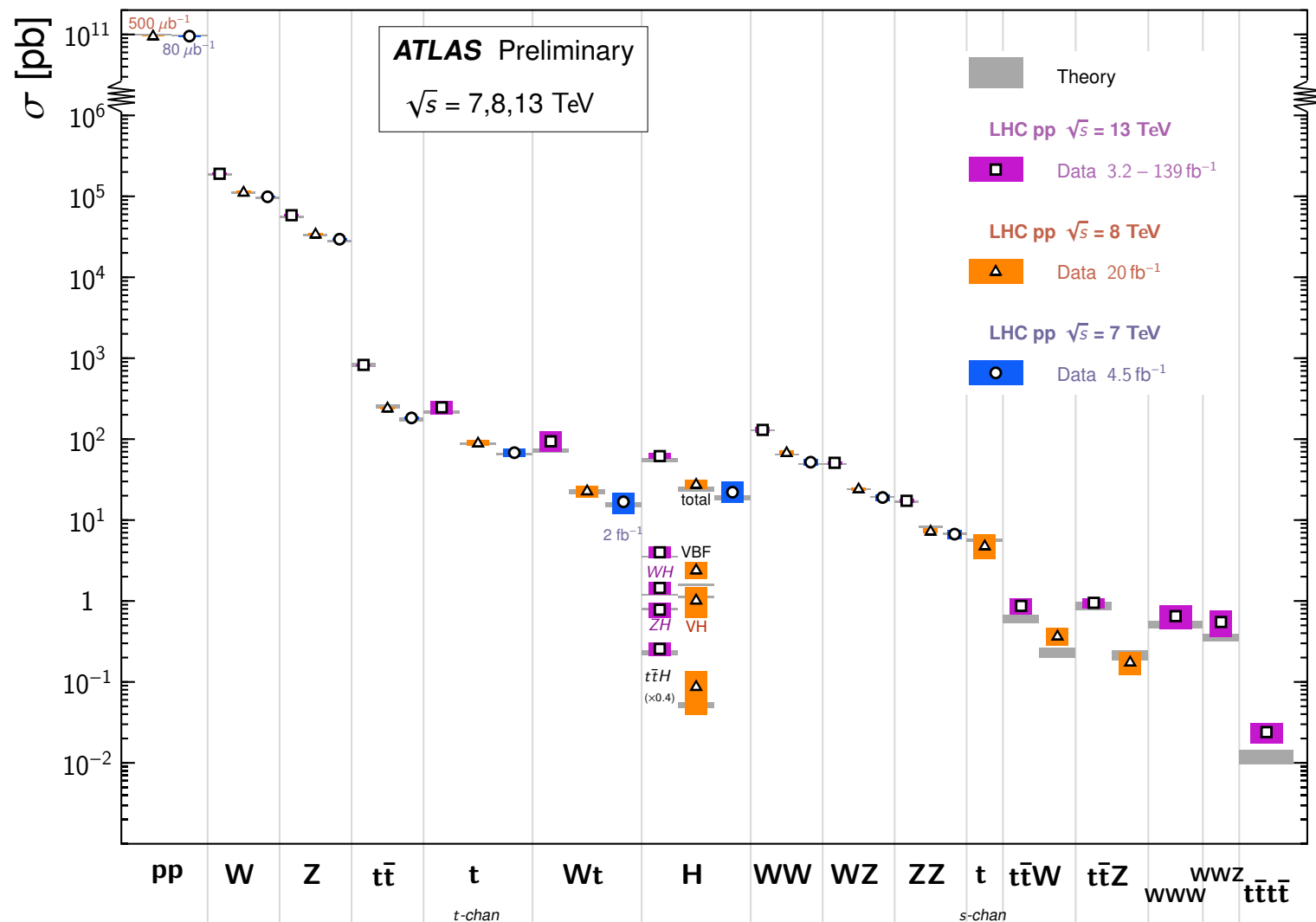
The Higgs sector is directly connected with very profound questions: naturalness, vacuum stability & energy, flavour

The Higgs boson discovery allows us to directly study this sector, requiring a broad experimental programme that will extend over decades



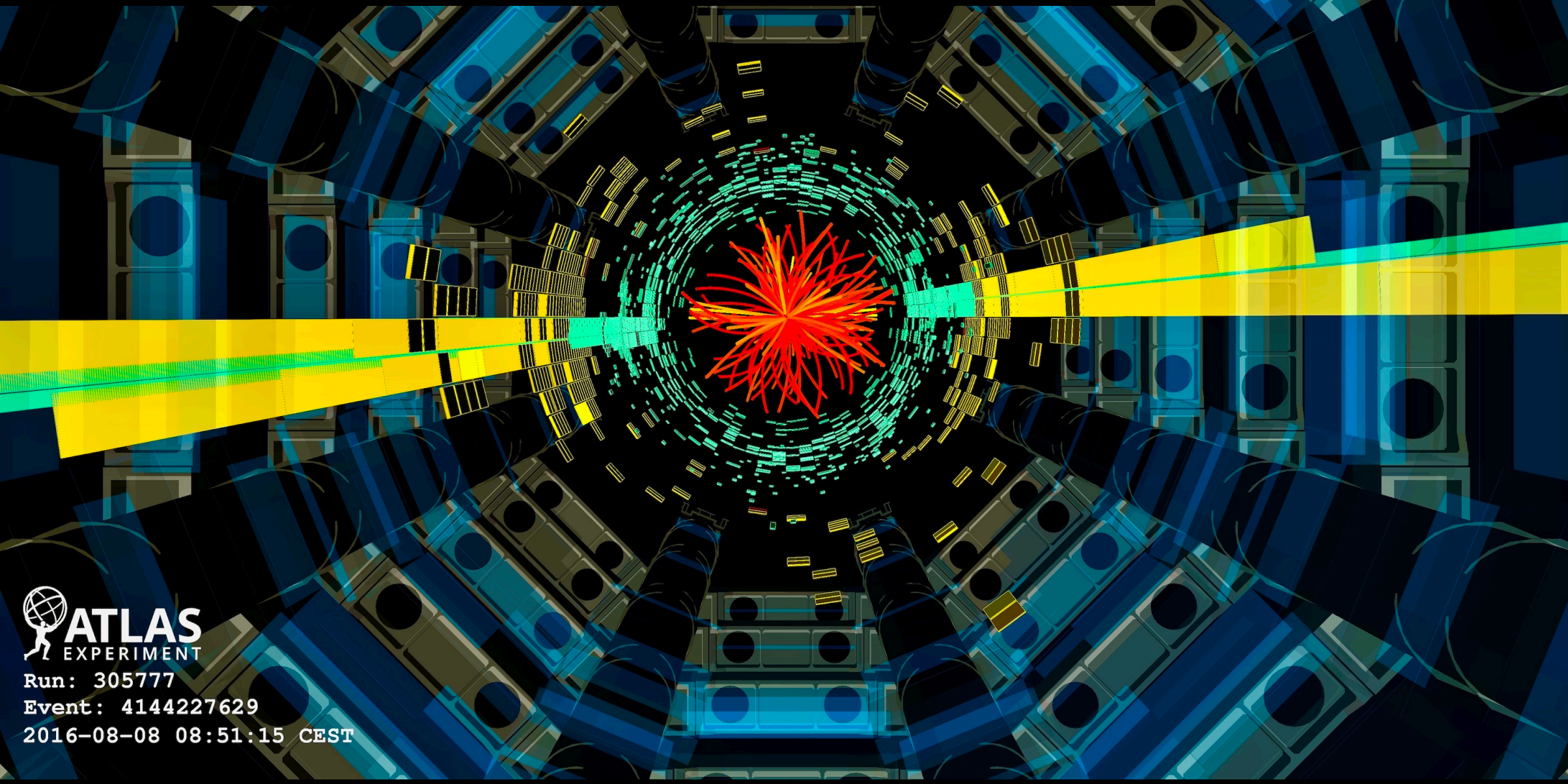
**ATLAS discovered
numerous processes
never observed before**

Standard Model Total Production Cross Section Measurements Status: March 2021



A harvest of unique measurements probing new forms of particle interactions and very rare processes

Deep searches for new phenomena

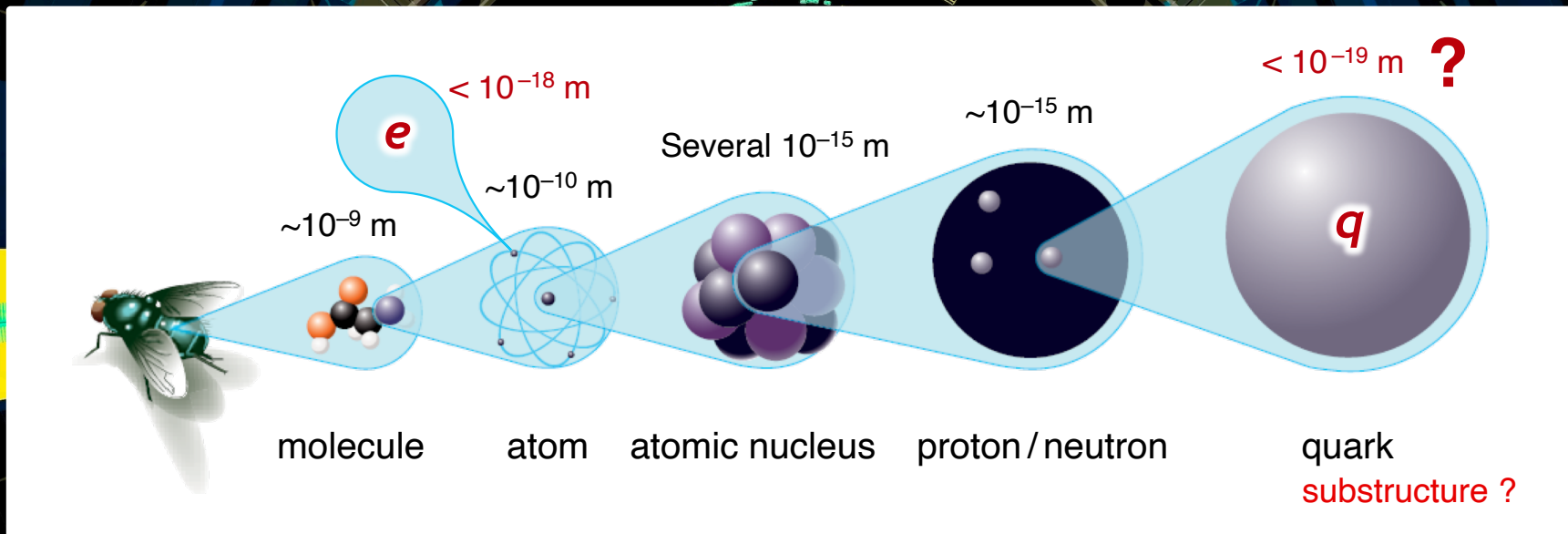


Run: 305777

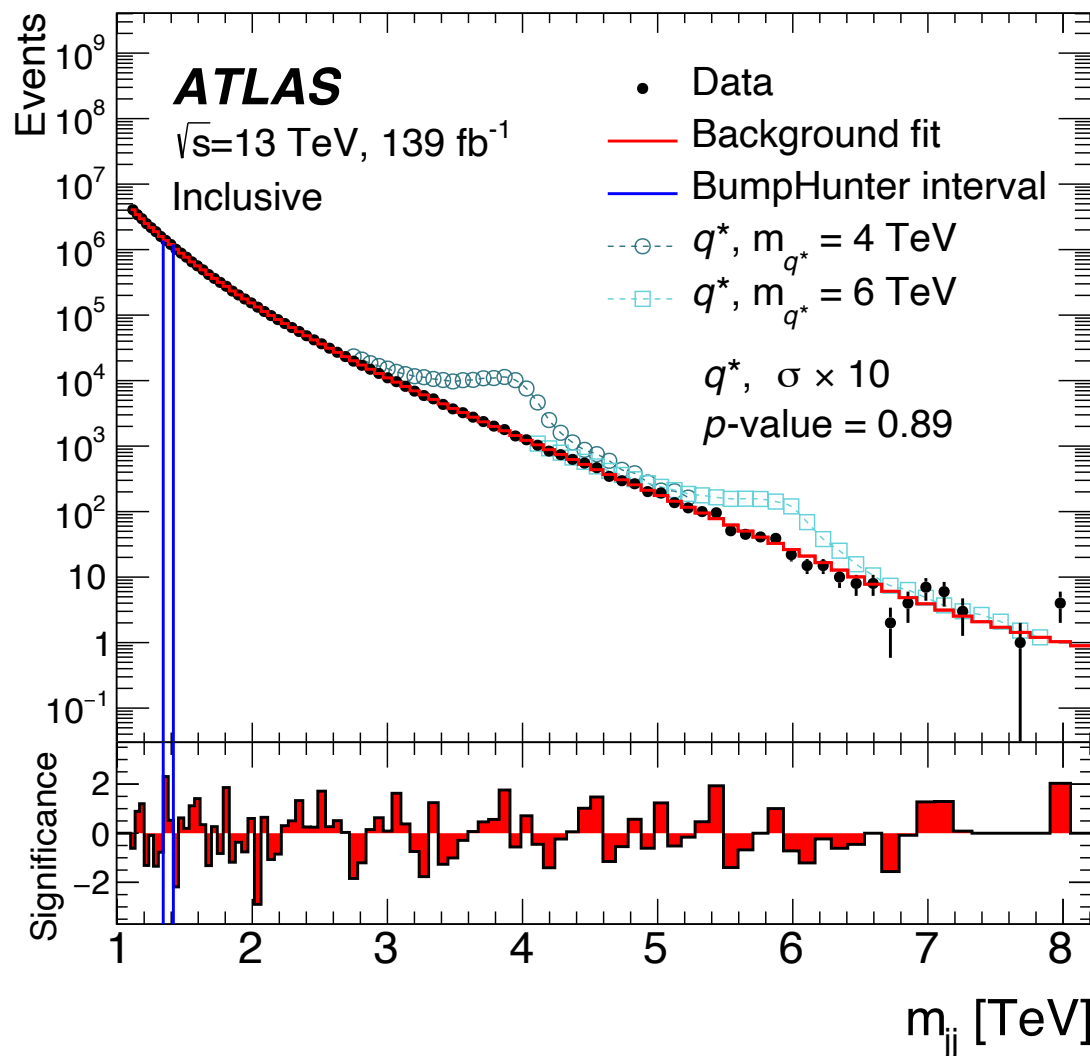
Event: 4144227629

2016-08-08 08:51:15 CEST

Are quarks elementary particles?



Are quarks elementary particles?

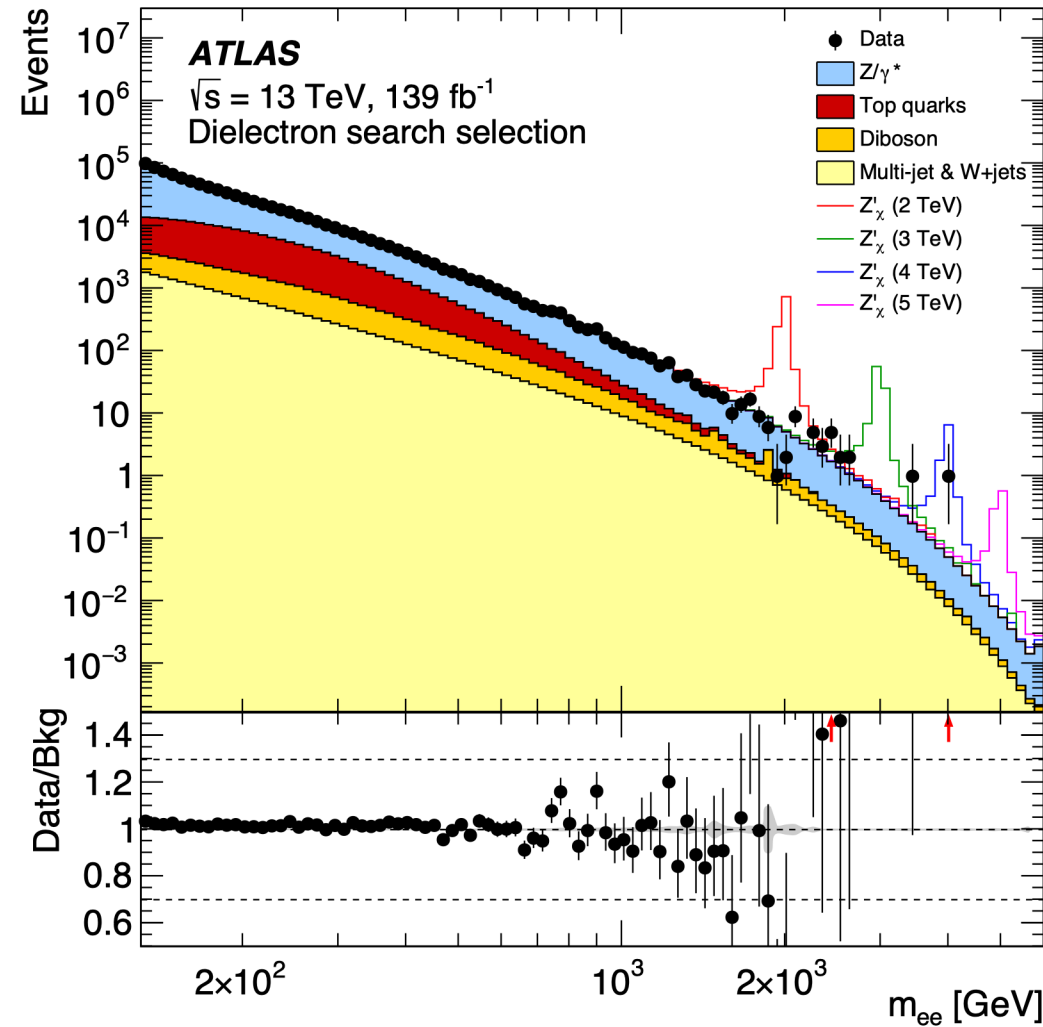


Run: 329716
Event: 857582452
2017-07-14 10:48:51 CEST



ATLAS
EXPERIMENT

Do new forces with new carriers exist?

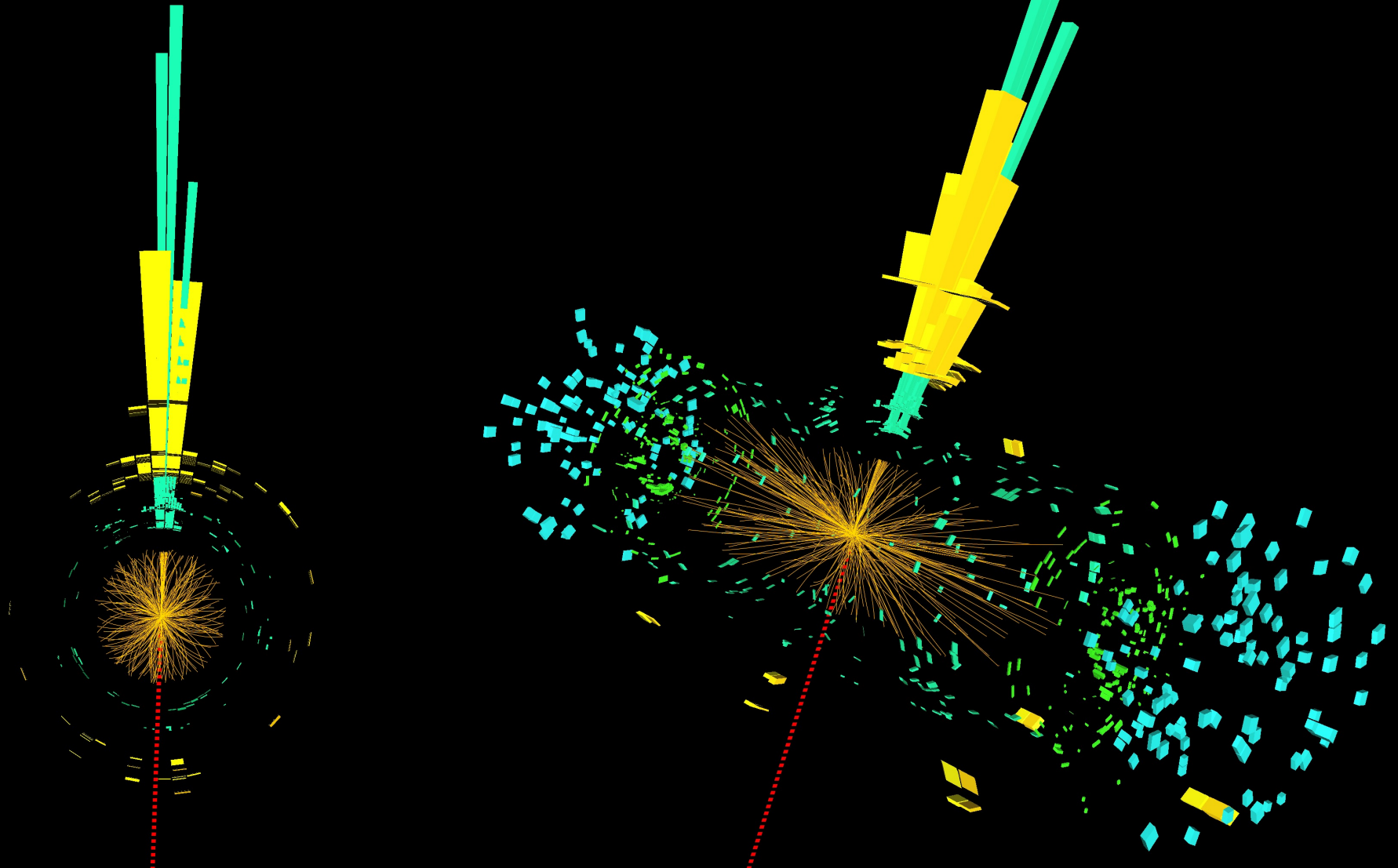


**Could gravity
be strong in
extra spatial
dimensions?**

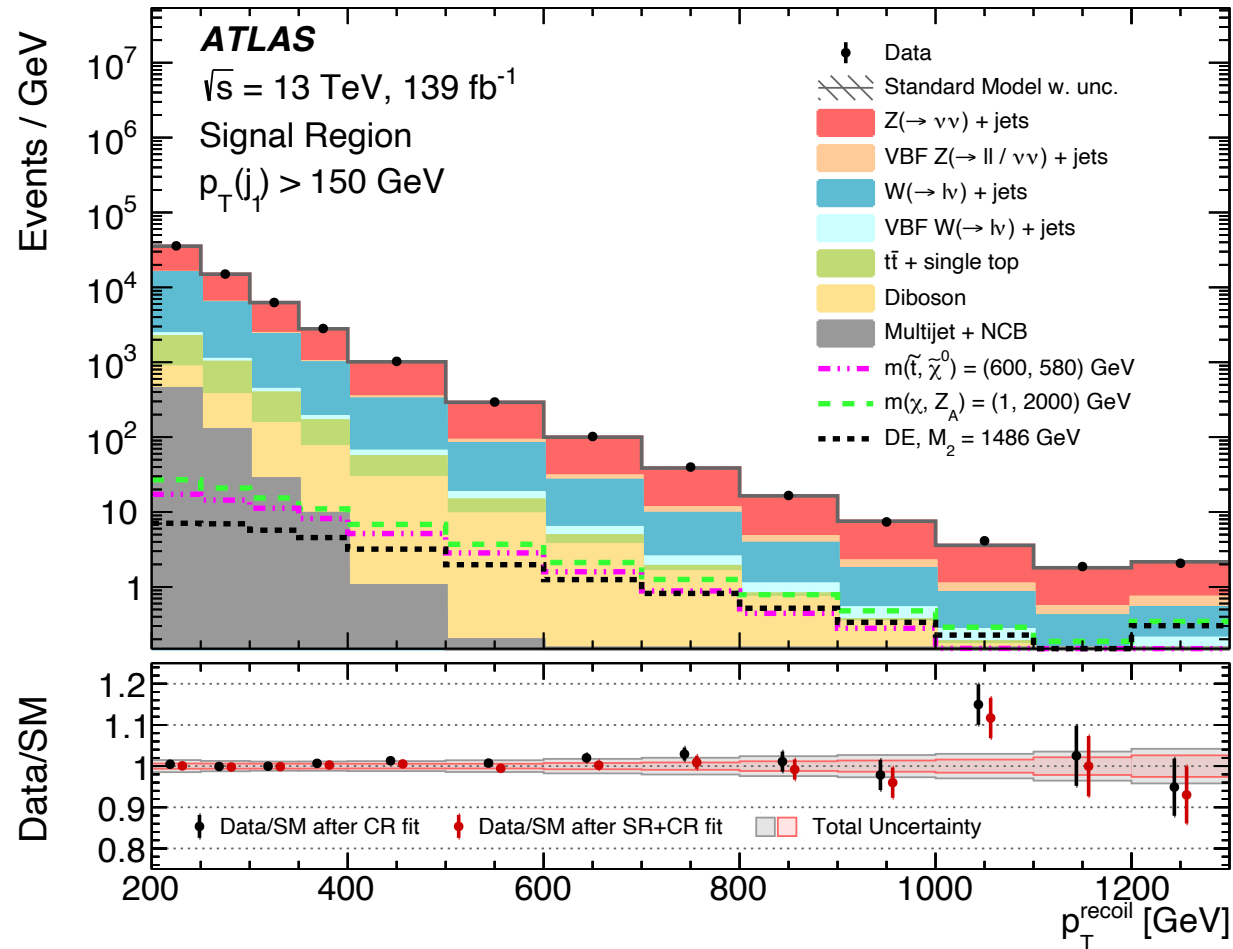


ATLAS
EXPERIMENT

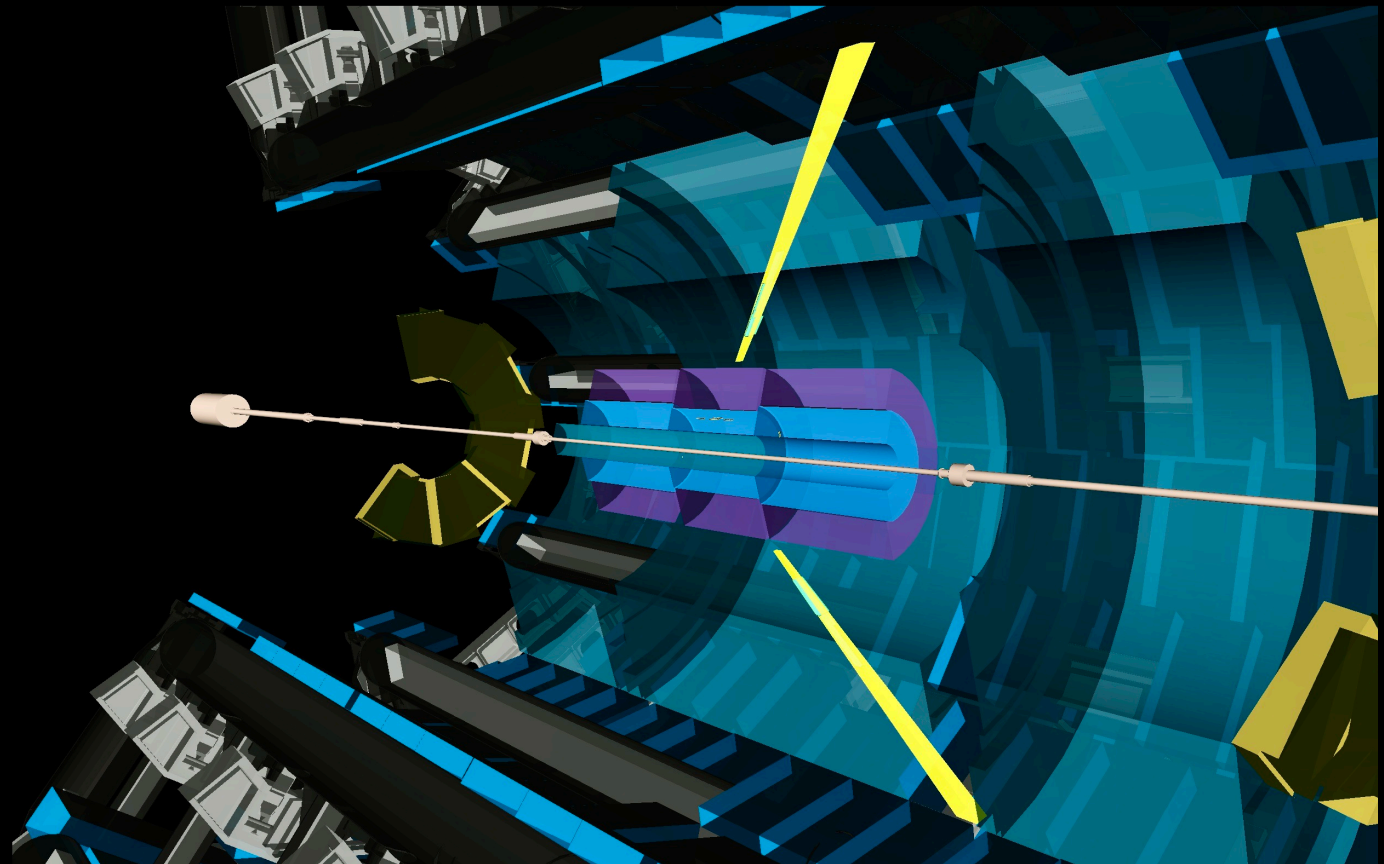
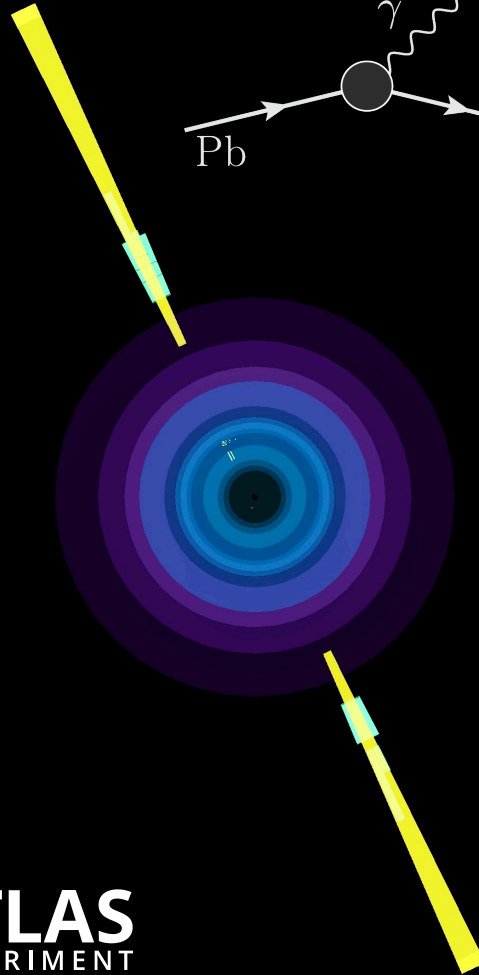
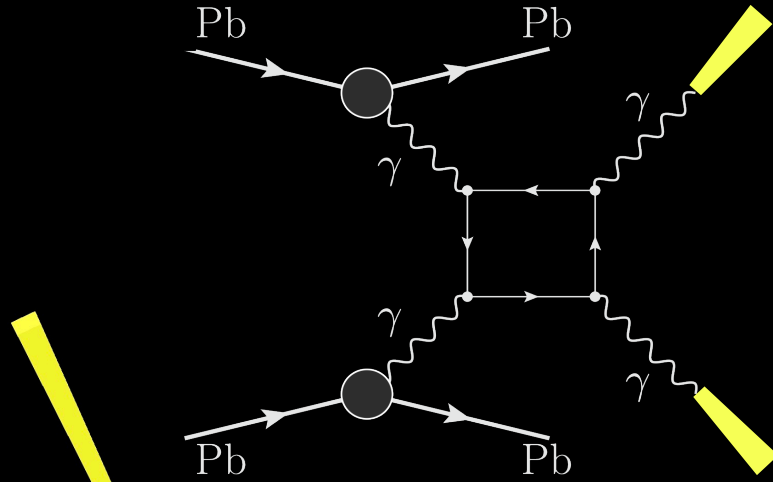
Are dark matter particles produced at the LHC ?



Are dark matter particles produced at the LHC ?

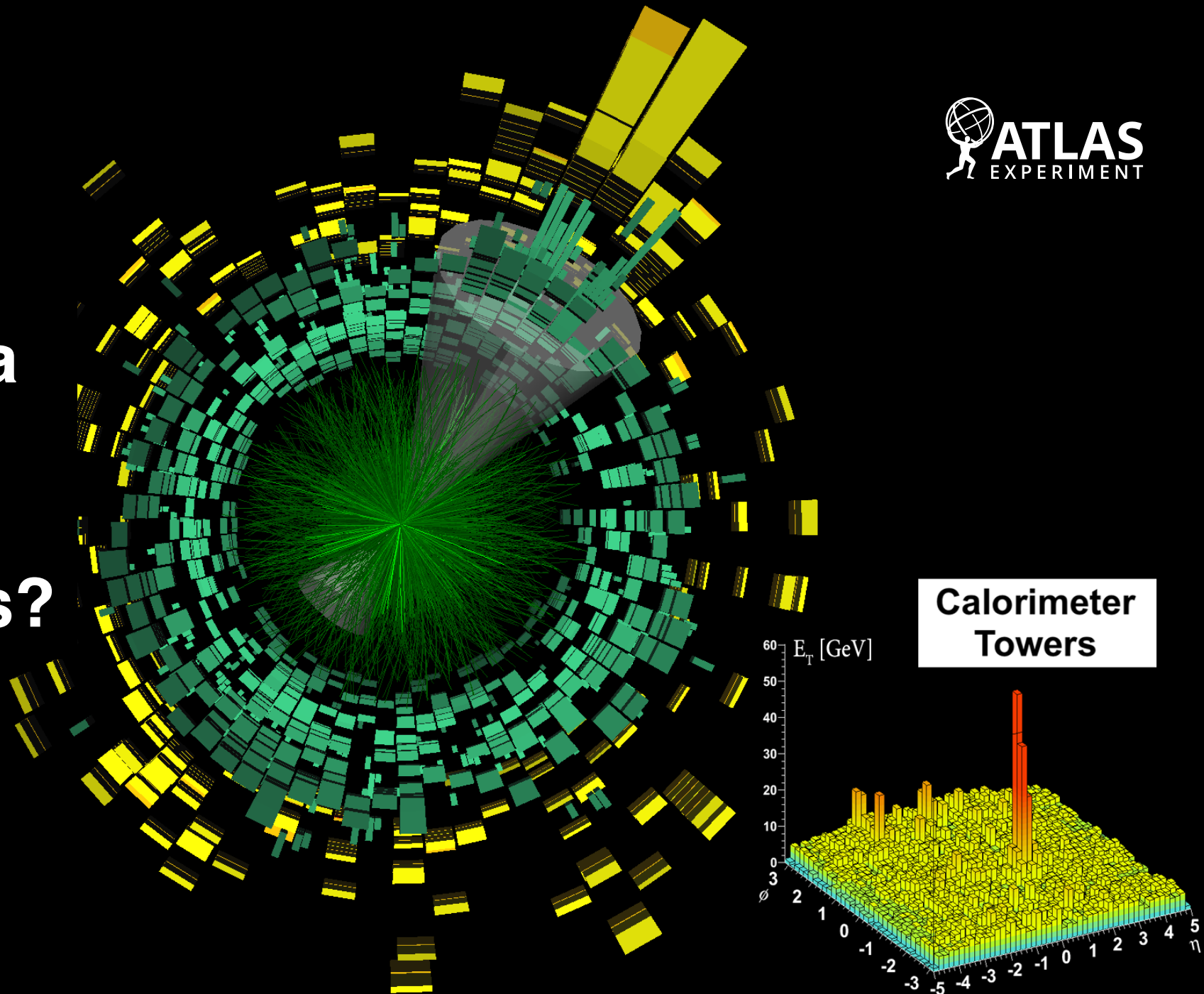


**Do we understand the
interaction of light in
extreme electromagnetic
fields ?**



What are the properties of the quark-gluon plasma created in the collision of heavy ions?

In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun



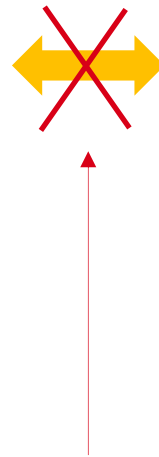
We have two beautiful, extremely precise theories

The Standard Model of electromagnetic, weak, strong and Higgs interactions

Predicting, e.g., the magnetic moment of the electron to a relative precision of better than 10^{-9} in agreement with experiment

General relativity — theory of gravitation

Tested up to an accuracy of order 10^{-5} (Cassini probe [B Bertotti et al., Nature 425, 2003])



Unfortunately, the SM and general relativity do not work in regimes where both are important (ie, at very small scales)

Many questions remain, of which many can be tackled at the LHC

Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

Expansion of Universe

- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

Strong CP problem

Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

High-scale physics

- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory

Many questions remain, of which many can be tackled at the LHC

The next steps

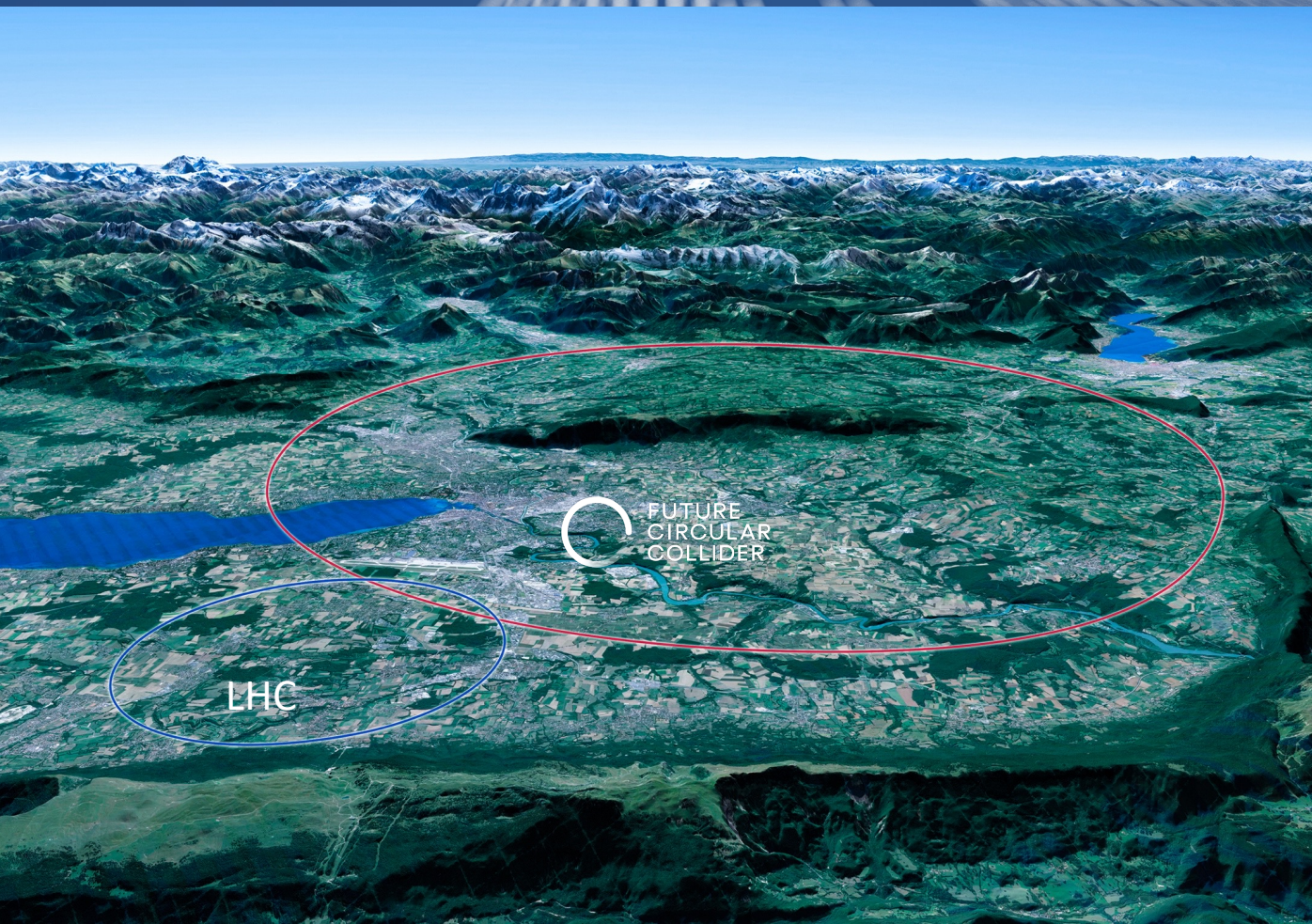
Preparing the future — the grand plan



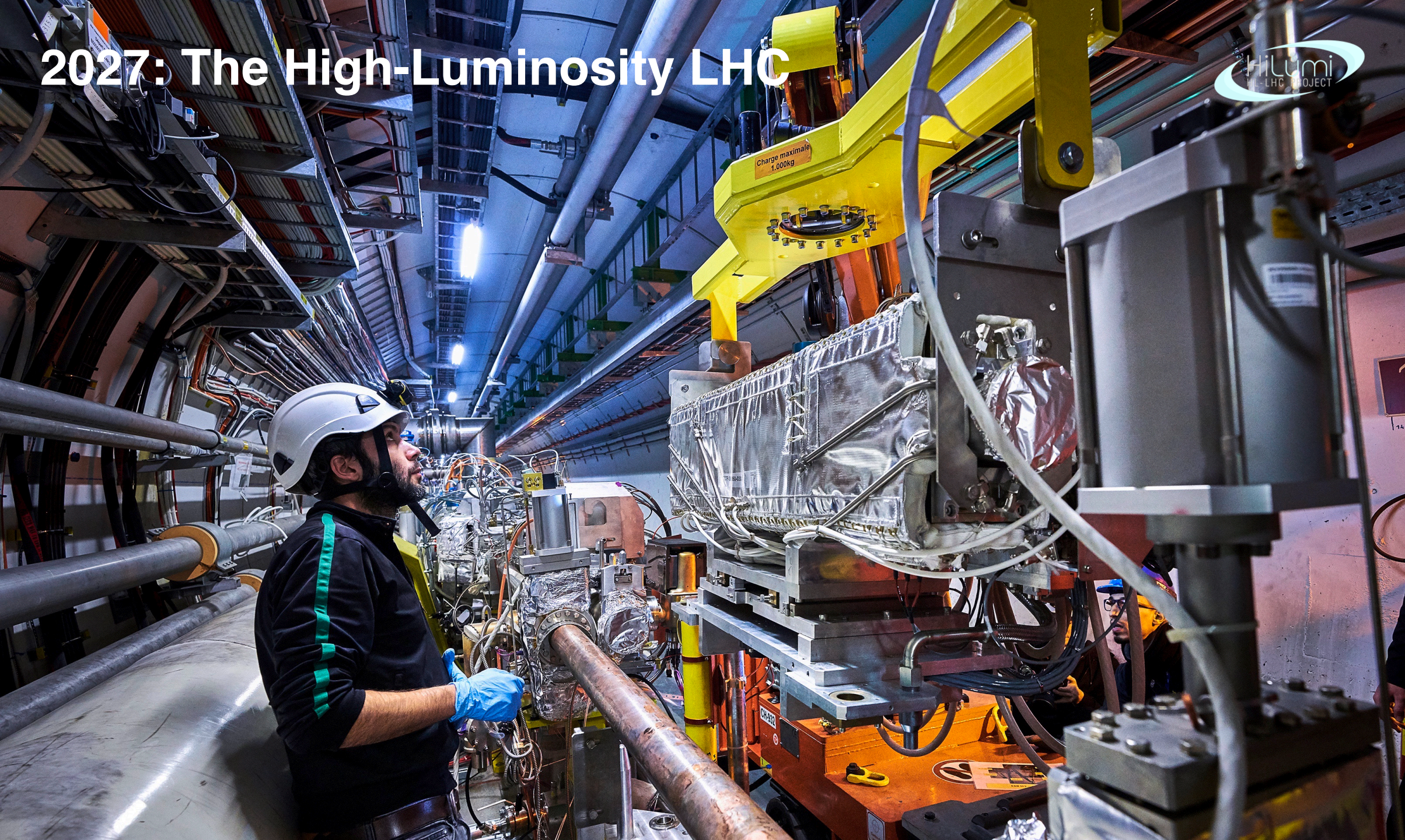
Scientific priorities for the future

Implementation of the recommendations of the 2020 Update of the European Strategy for Particle Physics:

- Fully exploit the HL-LHC
- Build a Higgs factory to further understand this unique particle
- Investigate the technical and financial feasibility of a future energy-frontier ~ 100 km collider at CERN
- Ramp up relevant R&D
- Continue supporting other projects around the world



2027: The High-Luminosity LHC



2027: The High-Luminosity LHC



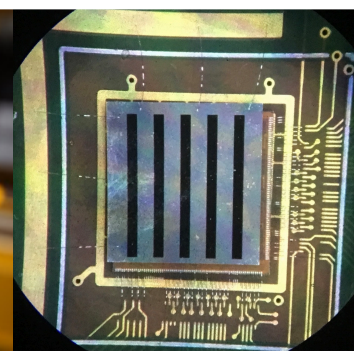
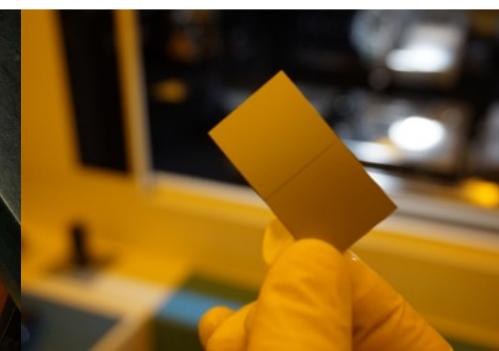
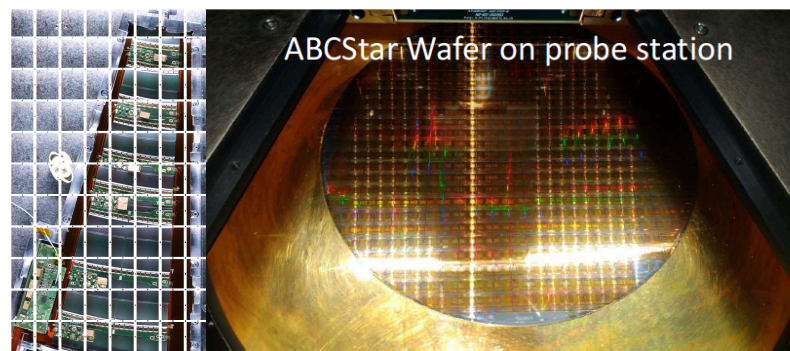
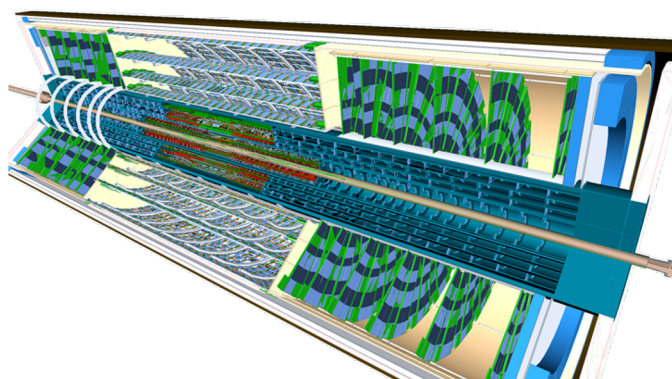
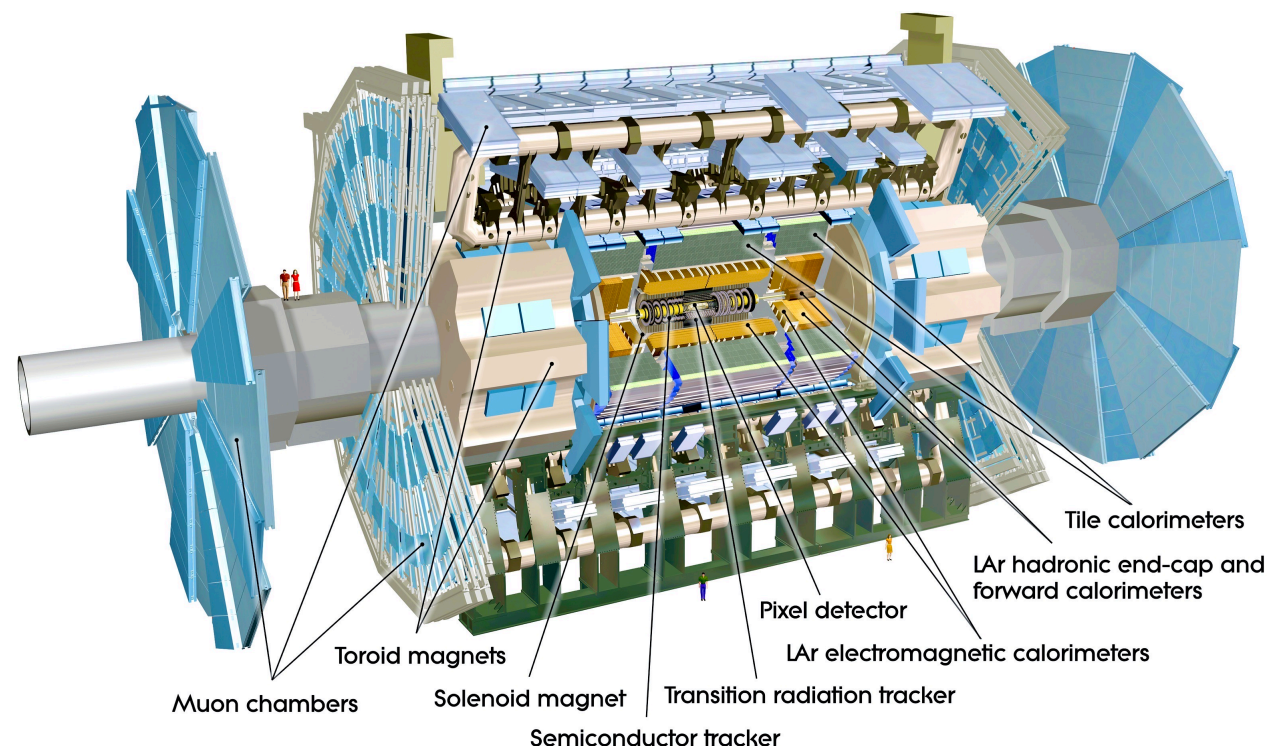
High-Luminosity LHC (HL-LHC)



The HL-LHC promises 10 times the data sample of the current LHC phase (eg: 400 million Higgs bosons produced)

Its intensity requires unprecedented detector and computing technologies:

- Radiation hardness
- High detection granularity and resolution
- Precise timing detectors
- Machine learning & data science
- High-performance computing



High-Luminosity LHC (HL-LHC)

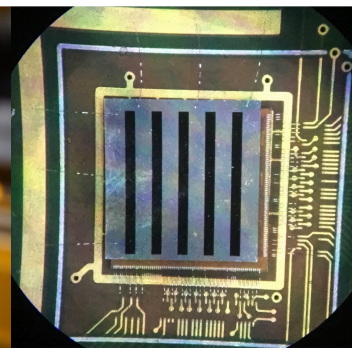
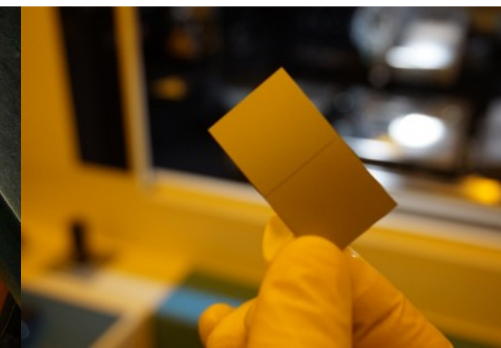
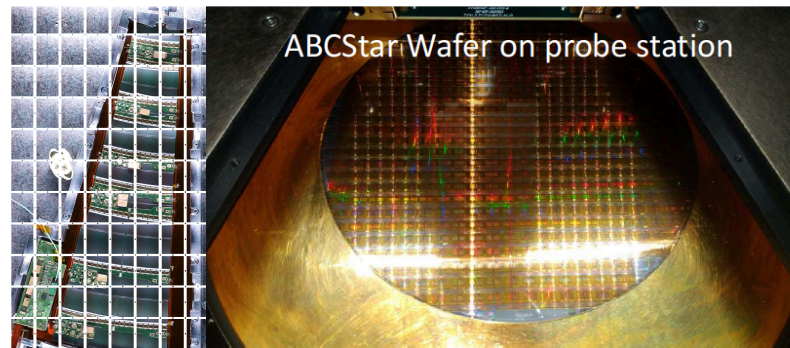
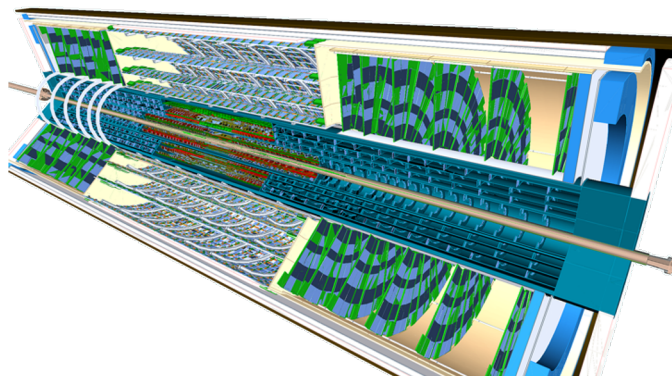


Opportunity for university groups to increase their engagement with physicists, engineers, technicians as well as local infrastructure and workshops on cutting-edge, cross-disciplinary, long-term international research projects

- **Scientific, technological and computer-science publications in high-impact journals**
- **Education for students, early career scientists, and engineers**
- **Local investment returns**

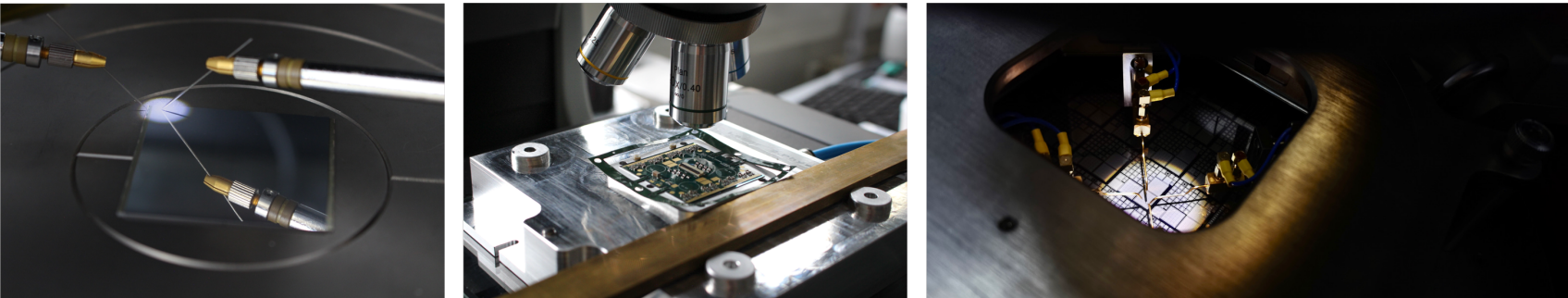
In ATLAS, particular opportunities for UAE groups to invest into high-performance computing (HPC, GPU, FPGA programming, machine learning) and trigger & data acquisition technologies

Offering local postdoc and PhD positions with support for frequent travel to CERN is key to growth



Detector upgrades for the HL-LHC

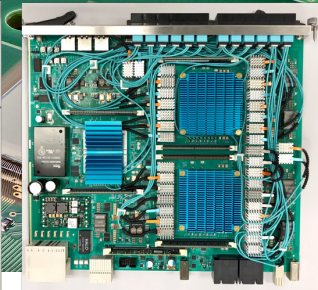
Pixel bare module probing and module metrology (Göttingen)



sMDT geometry measurement (MPI)



TDAQ
GCM
prototype
(BNL)



ITk Strip petal (SFU & TRIUMF)



HGTD testbeam at DESY

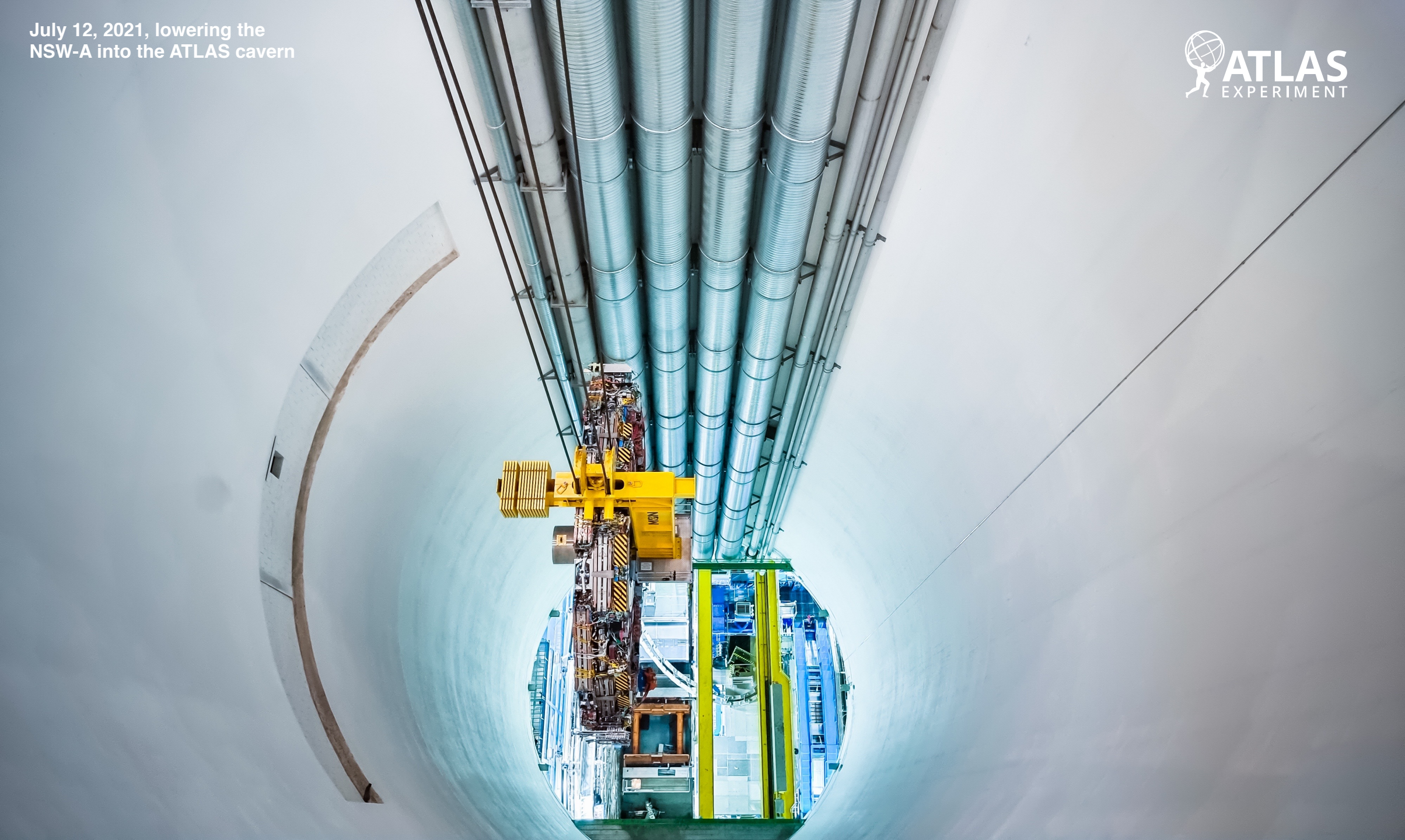


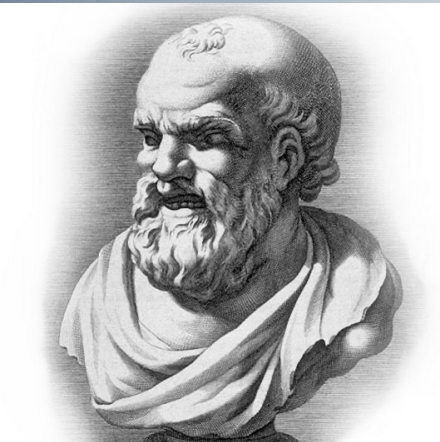
sMDT chamber measurement (MPI)

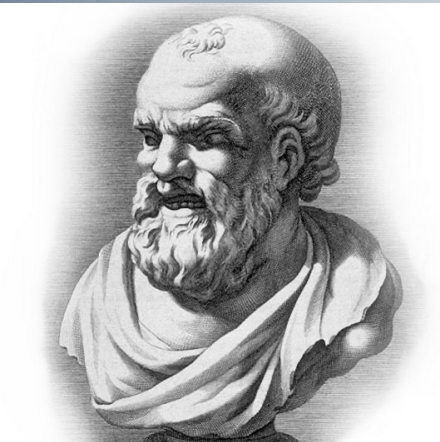
Detector upgrades for the HL-LHC



July 12, 2021, lowering the
NSW-A into the ATLAS cavern







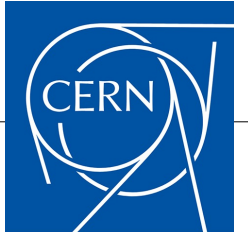
**We've come a long way —
and the adventure continues**



<http://atlas.cern/>

Extra slides





23 Member States

Austria – Belgium – Bulgaria – Czech Republic
Denmark – Finland – France – Germany – Greece
Hungary – Israel – Italy – Netherlands – Norway
Poland – Portugal – Romania – Serbia – Slovakia
Spain – Sweden – Switzerland – United Kingdom

3 Associates Member States in the pre-stage to membership

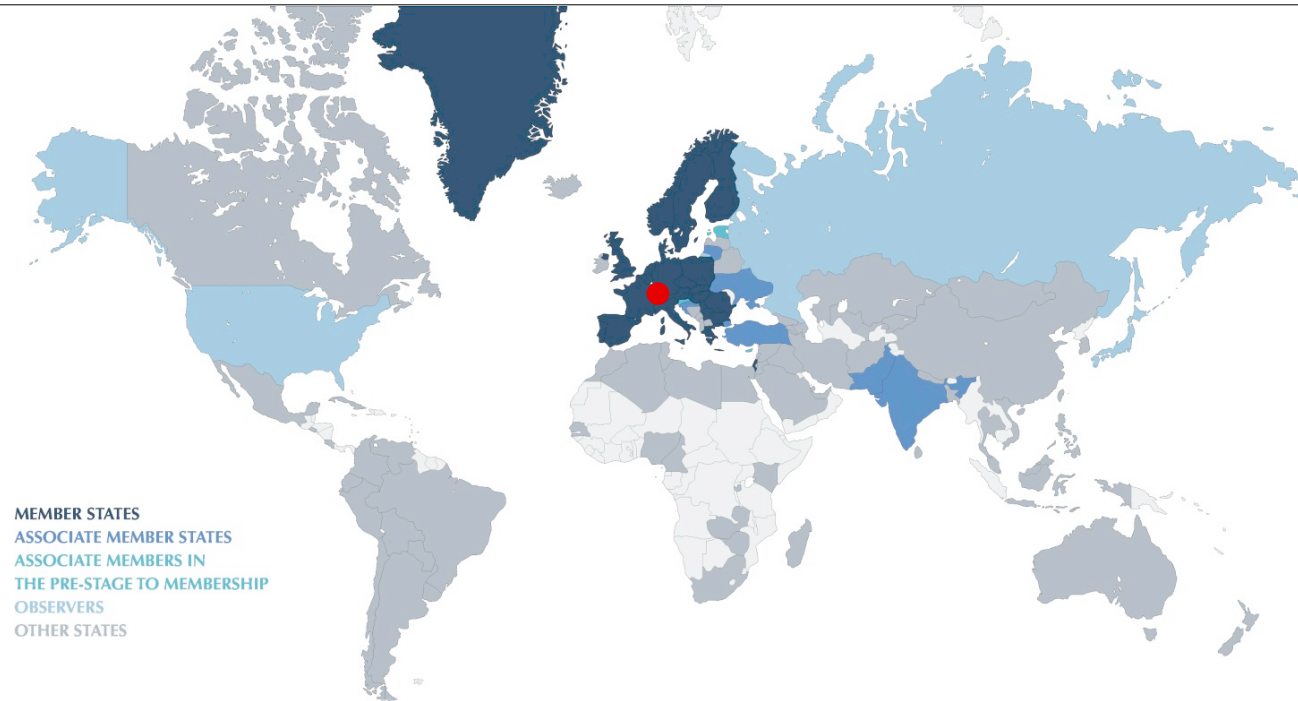
Cyprus – Estonia – Slovenia

6 Associate Member States

Croatia – India – Lithuania – Pakistan –
Turkey – Ukraine

6 Observers

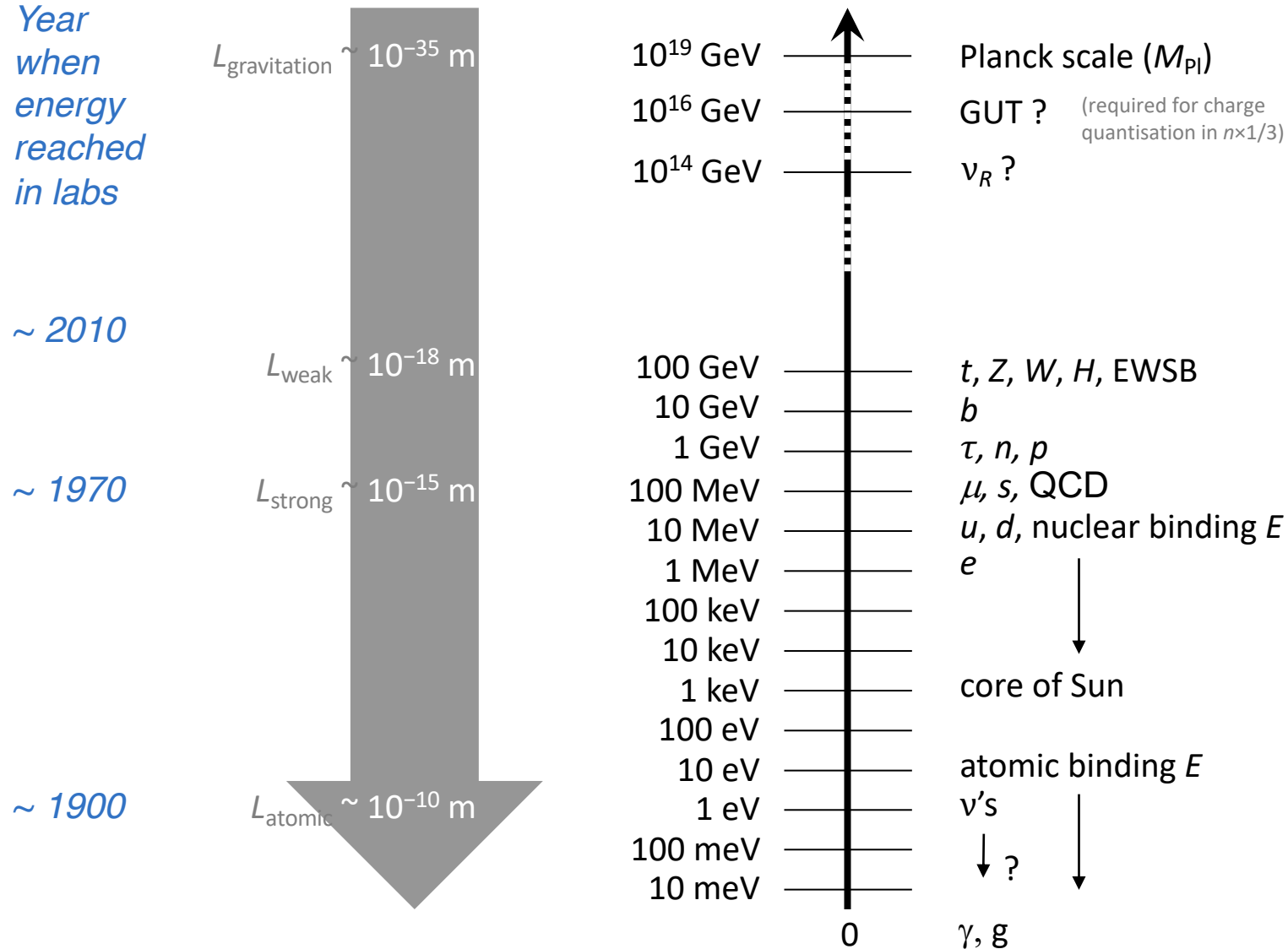
Japan – Russia – USA
European Union – JINR – UNESCO



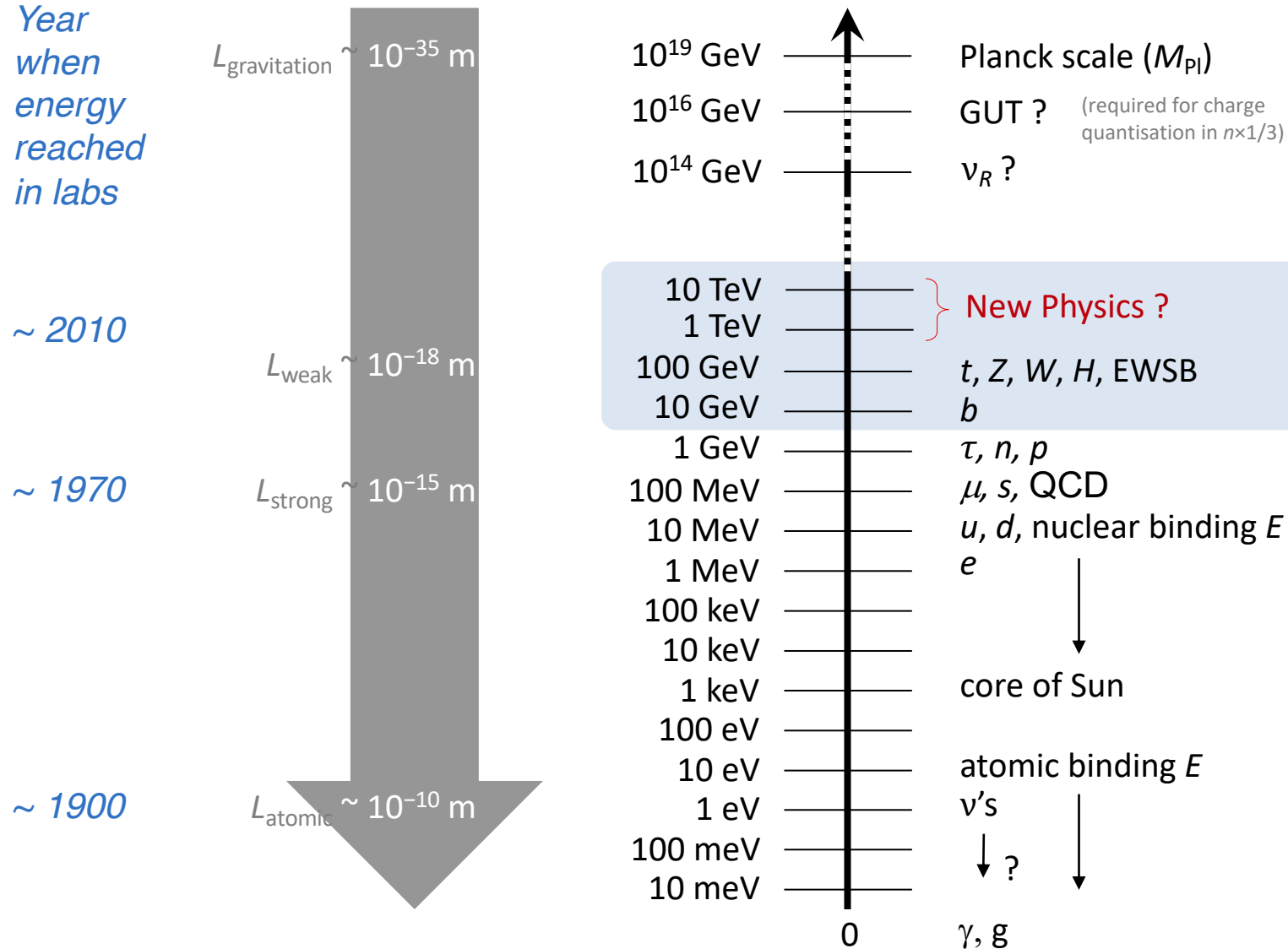
More than 50 Cooperation Agreements with non-Member States and Territories

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland
Iran – Jordan – Kazakhstan – Latvia – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – Nepal
New Zealand – North Macedonia – Palestine – Paraguay – People's Republic of China – Peru – Philippines – Qatar
Republic of Korea – Saudi Arabia – Sri Lanka – South Africa – Thailand – Tunisia – United Arab Emirates – Vietnam

Mass (= energy) and length scales



Mass (= energy) and length scales



This spring we celebrated the results of 1000 collision papers

This milestone emphasises the wealth, scientific breadth and impact of our research and publications: the LHC is itself a scientific diversity programme !

- Enjoy a timeline featuring 60 paper highlights: <https://atlas.cern/updates/news/1000-collision-papers>

