

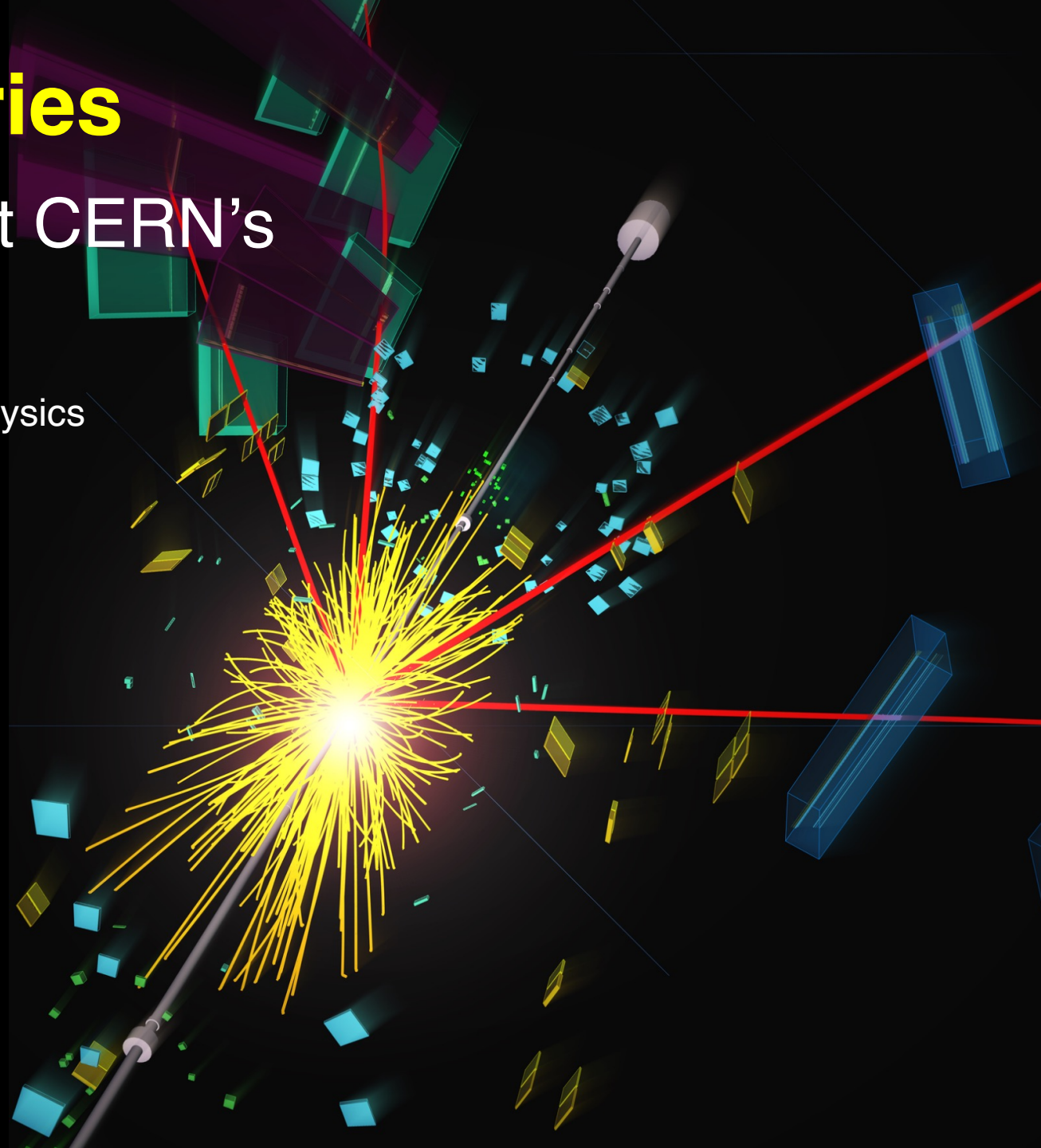
Smashing discoveries

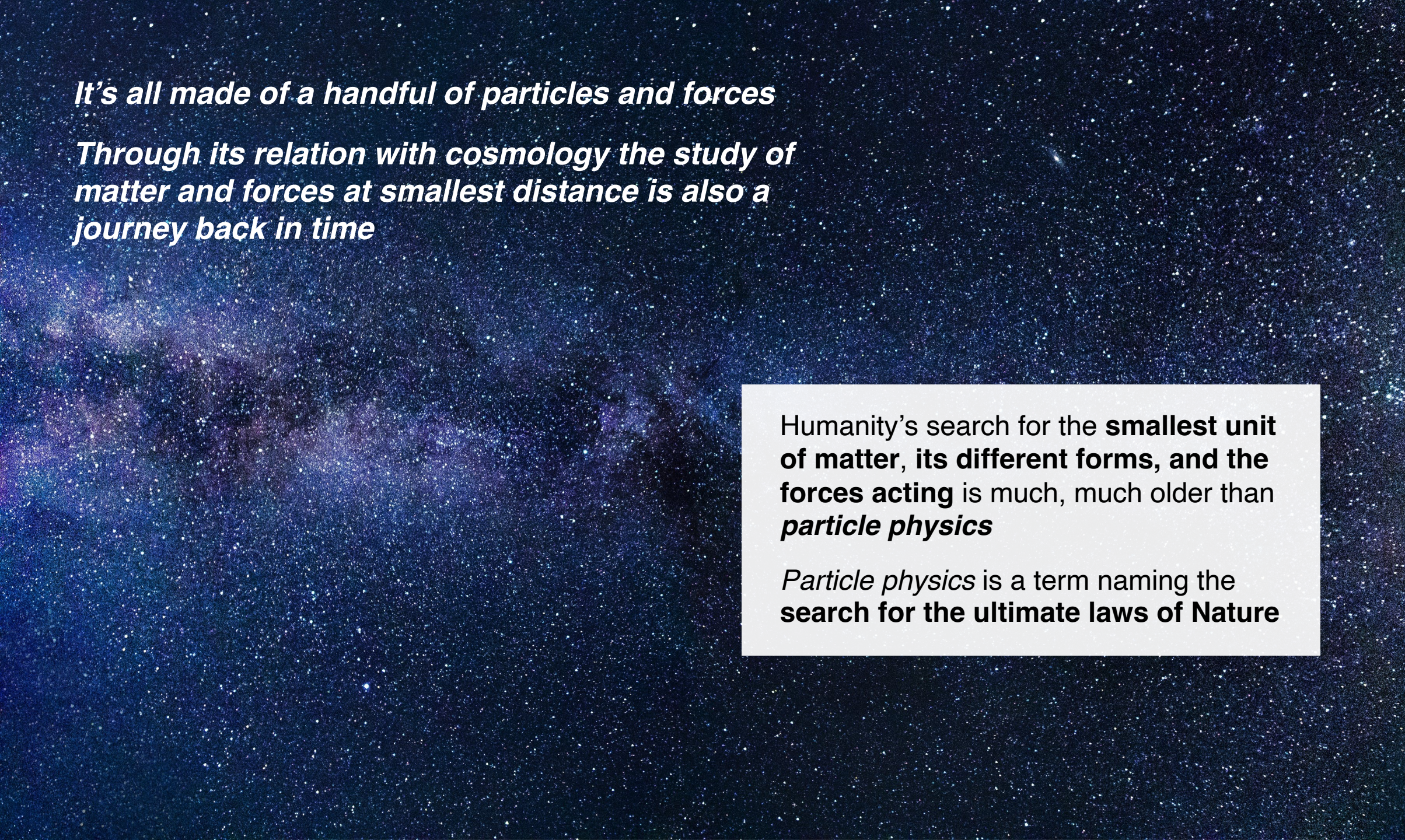
The ATLAS Experiment at CERN's Large Hadron Collider

From the Higgs boson to the quest for new physics

Andreas Hoecker (CERN)

Seminar, Rabat, 20 January 2022





It's all made of a handful of particles and forces

Through its relation with cosmology the study of matter and forces at smallest distance is also a journey back in time

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**

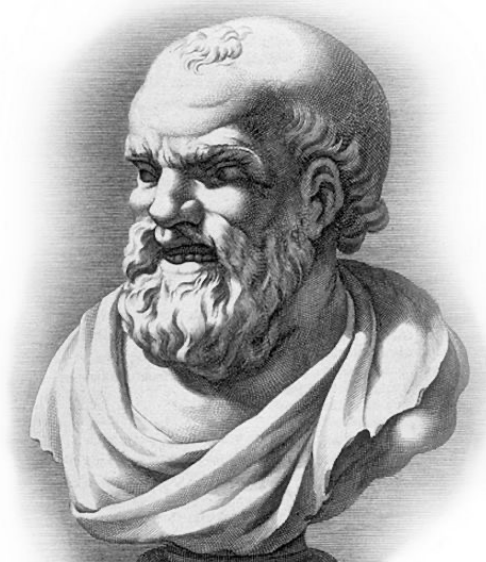
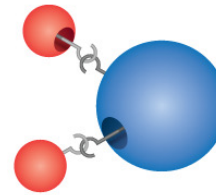
Setting the stage

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.



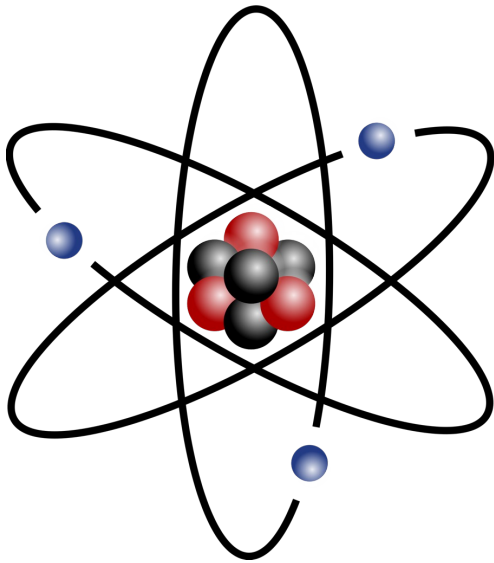
Democritus (460–370 BC)

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”

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)

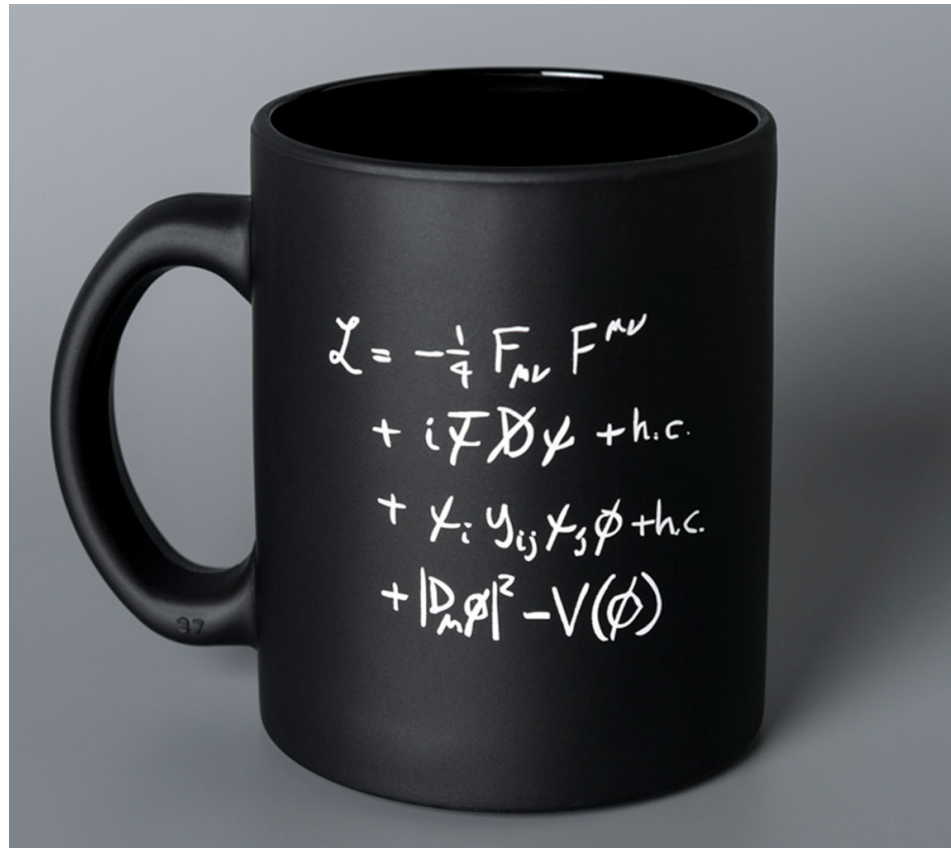
Physical laws are thus not what is *in the* Nature, but our way to *describe* Nature

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

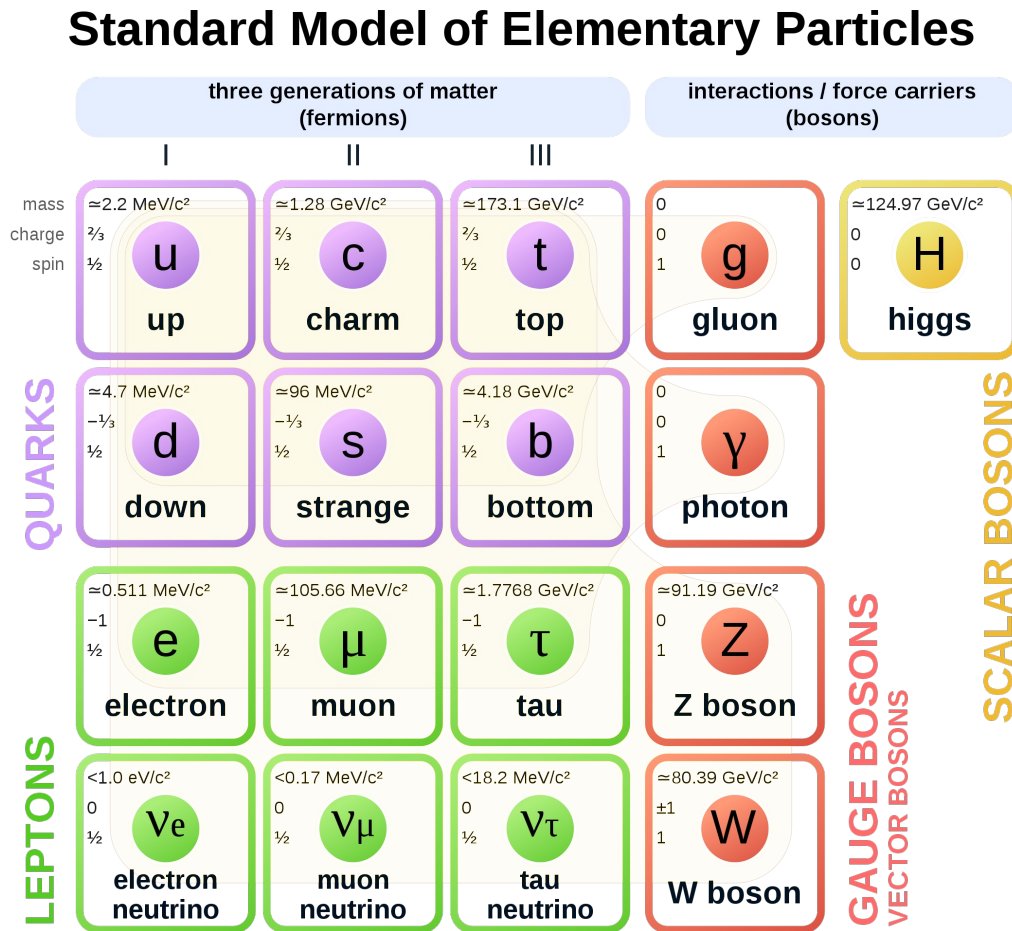
In its full (and rather frightening) form, the Standard Model looks like this

$$\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

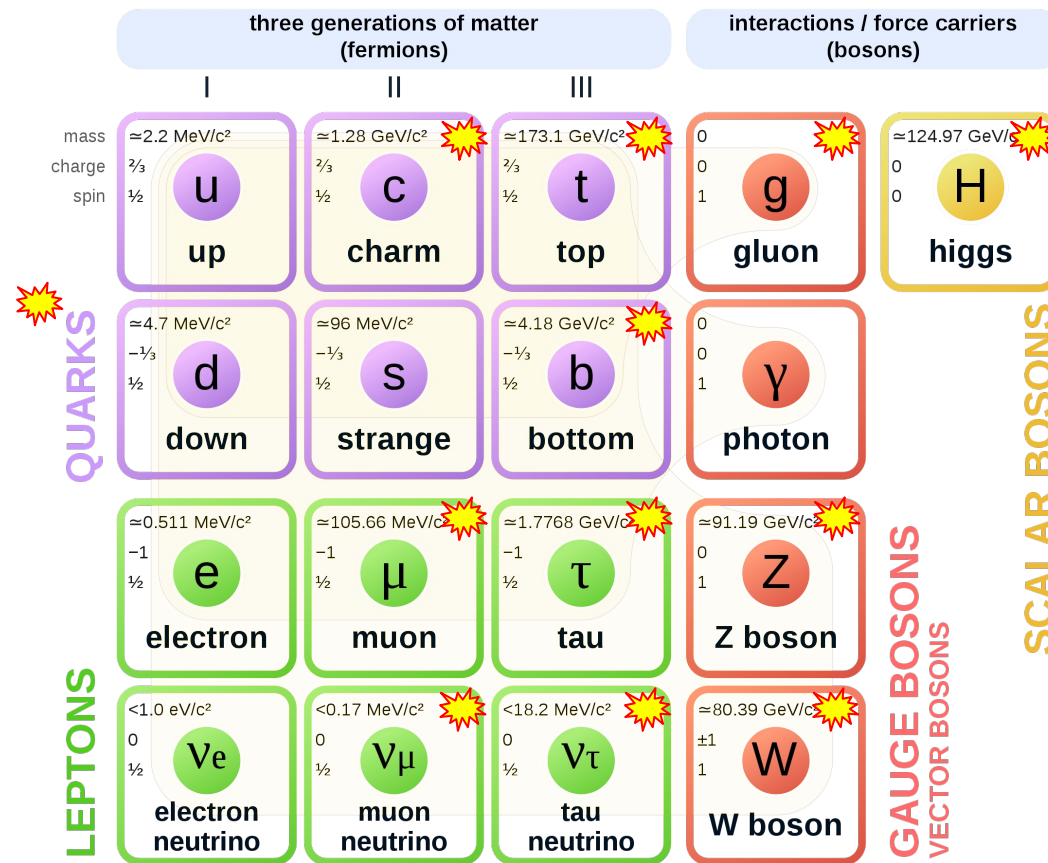
These equations describe all known particles and their interactions



The Standard Model

These equations describe all known particles and their interactions

Standard Model of Elementary Particles

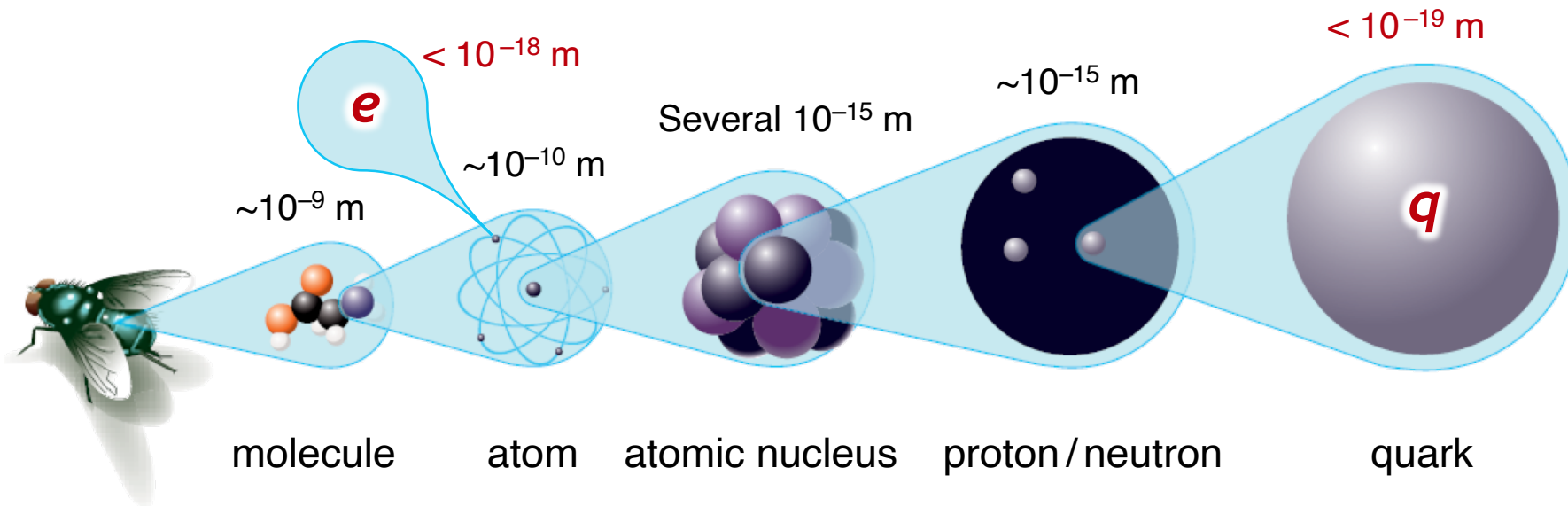


Decades of international high-technology **accelerator-based** research brought us thus far

Completely new type of non-universal interactions, nothing to do with known forces

The Standard Model

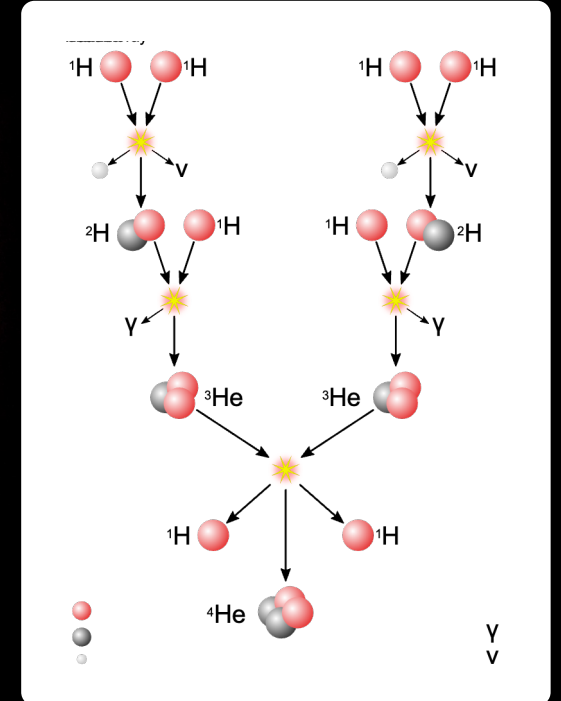
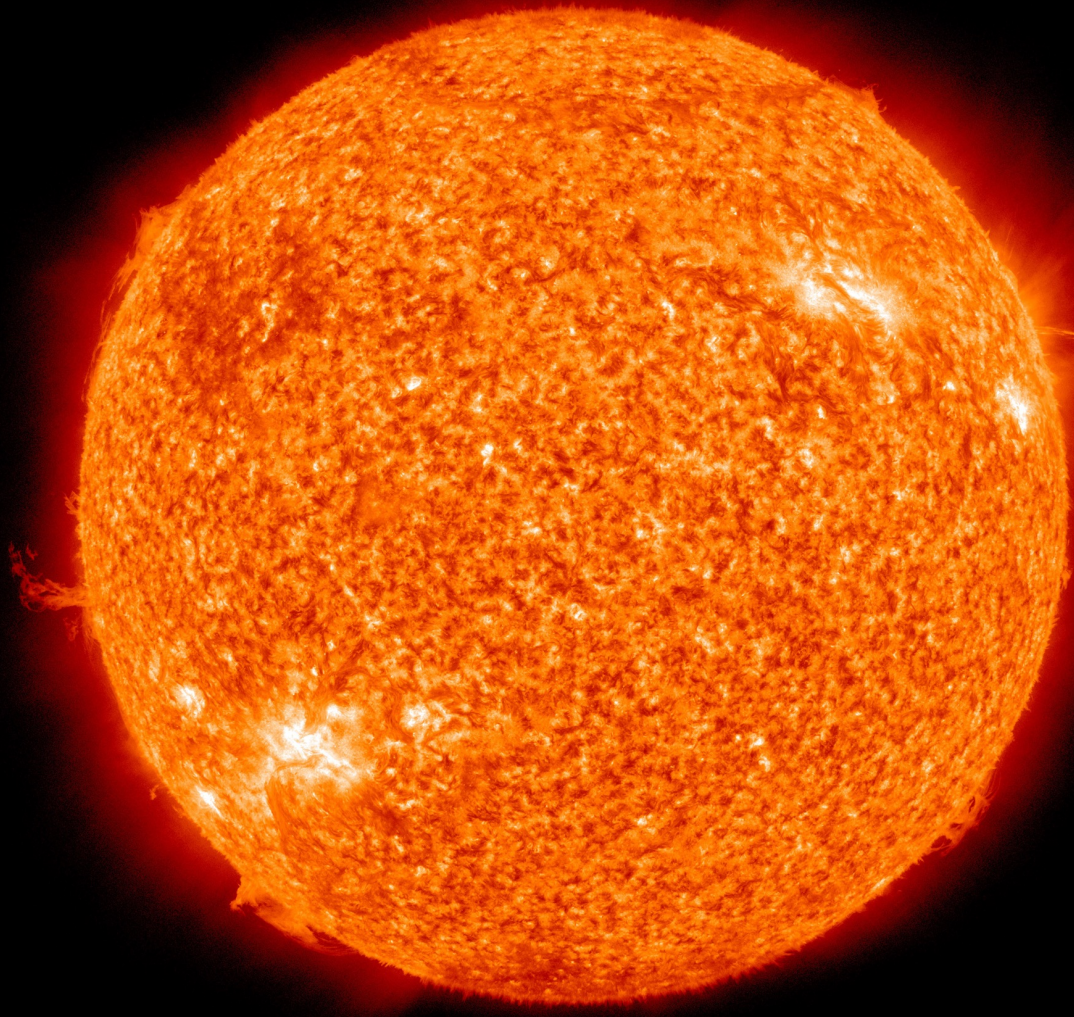
The Standard Model describes the properties of macroscopic objects, molecules, atoms, the atomic nucleus, the structure of the protons and neutrons



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

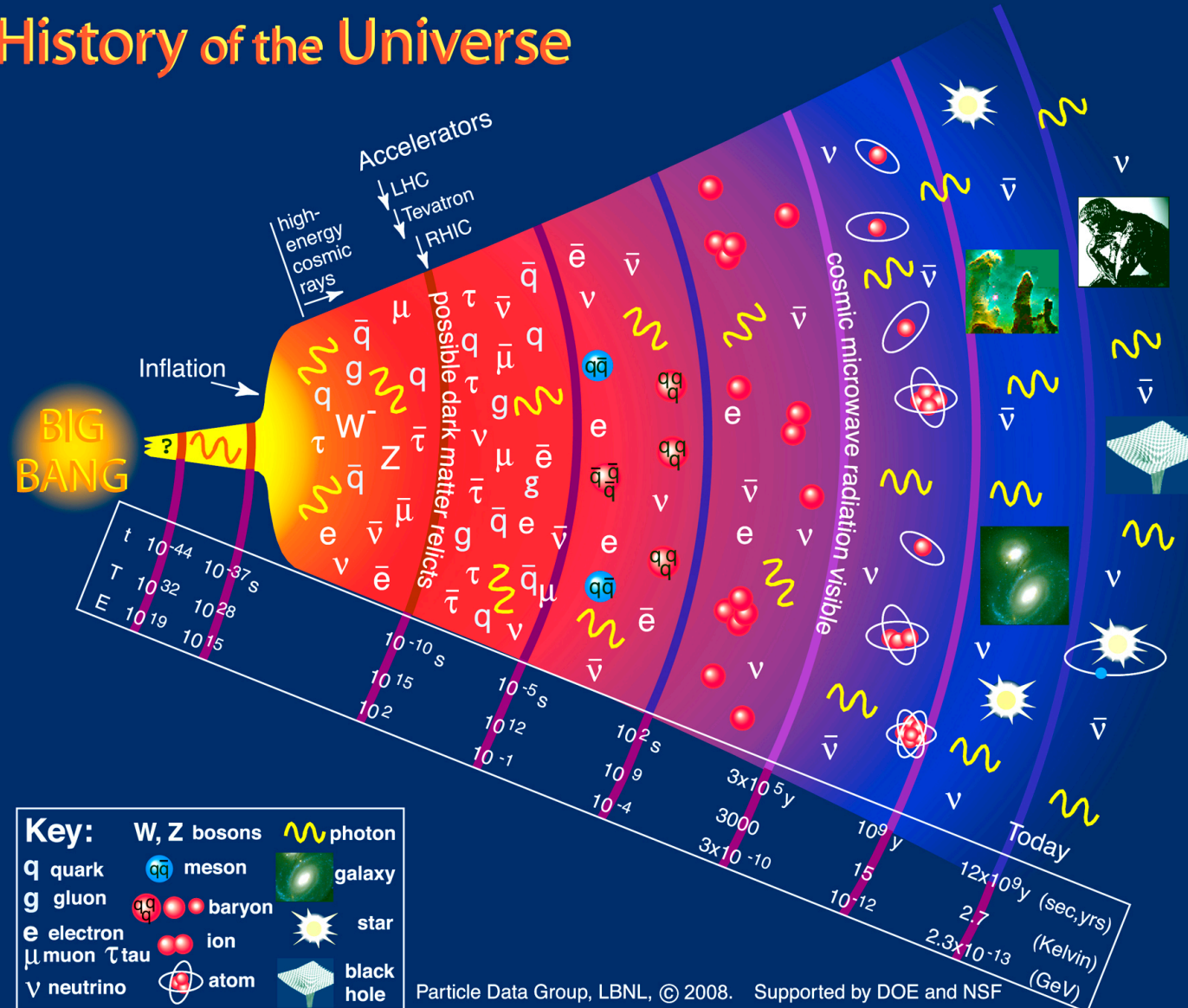
The Standard Model does not only describe the tiniest objects in space, it also explains how, e.g. the Sun burns



The Standard Model

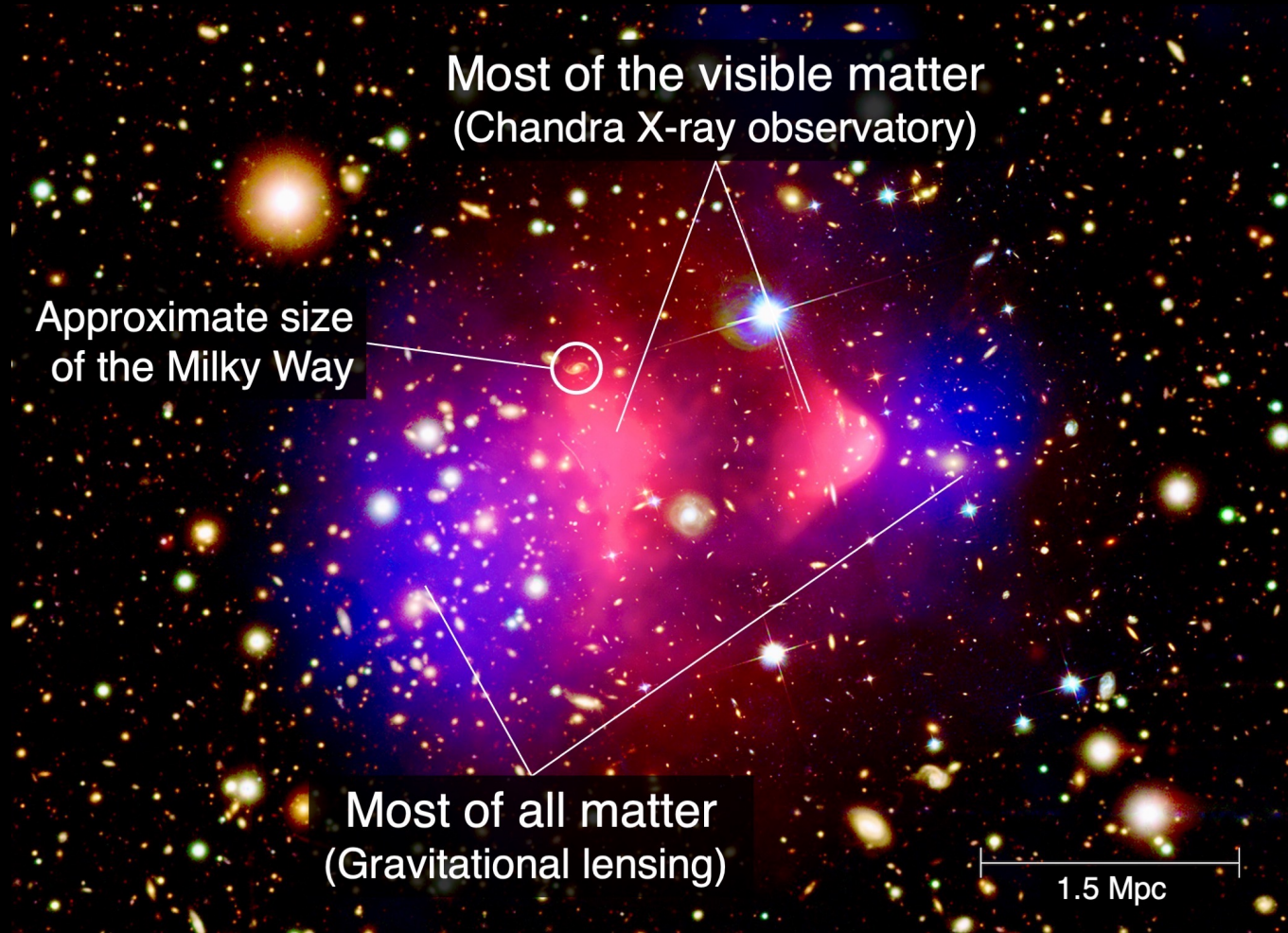
... and should describe the full history since the Big Bang, 13.8 billion years ago

History of the Universe

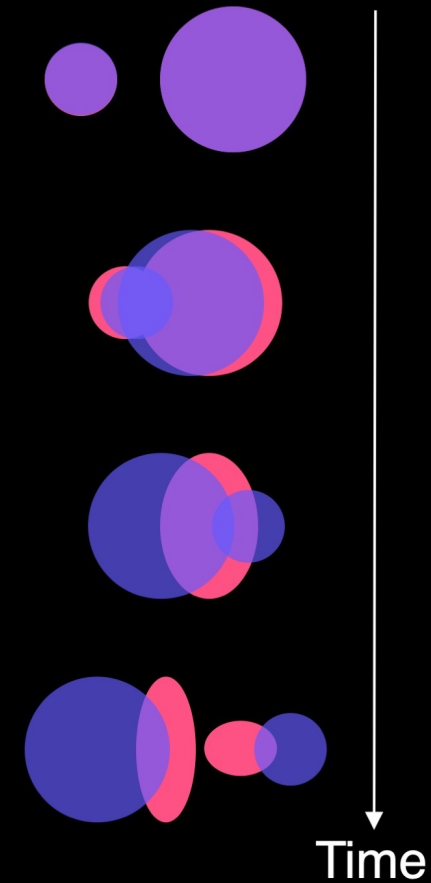


The Standard Model

... but something is wrong



Bullet Cluster: one among
many evidences of
gravitational dark matter



The Higgs mechanism

A very simplifying picture!

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

A very simplifying picture!

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)

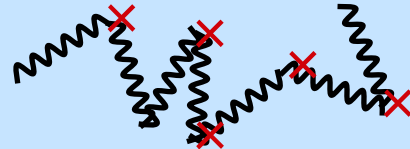
Particles interact with Higgs field and effectively reduce their velocity. Acquired mass proportional to interaction strength

→ Action of the Higgs field creates “vacuum viscosity” (caution — not quite!)

Higgs quantum liquid in broken phase

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

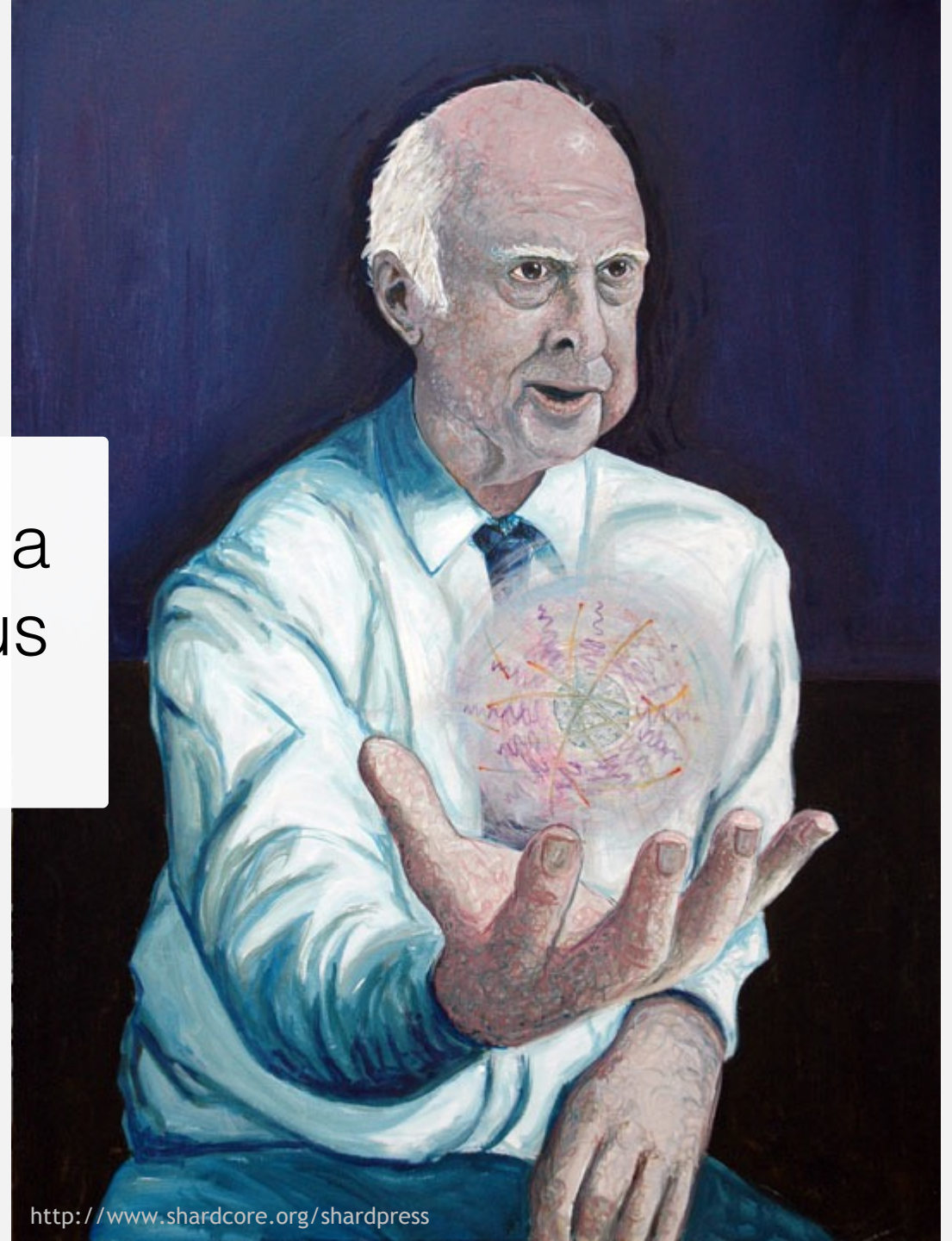
Top quark 

Interaction with Higgs field alters chirality of massive Dirac fermion

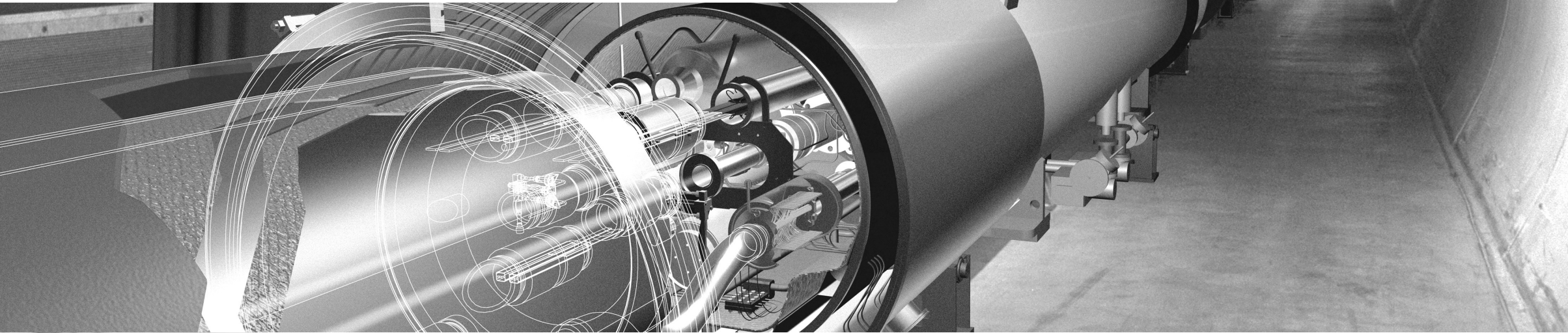
The Higgs mechanism was only a hypothesis before the LHC

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

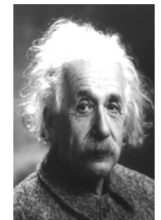
- Look deeper into matter (size $\sim 1/E$) (powerful microscope)
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie

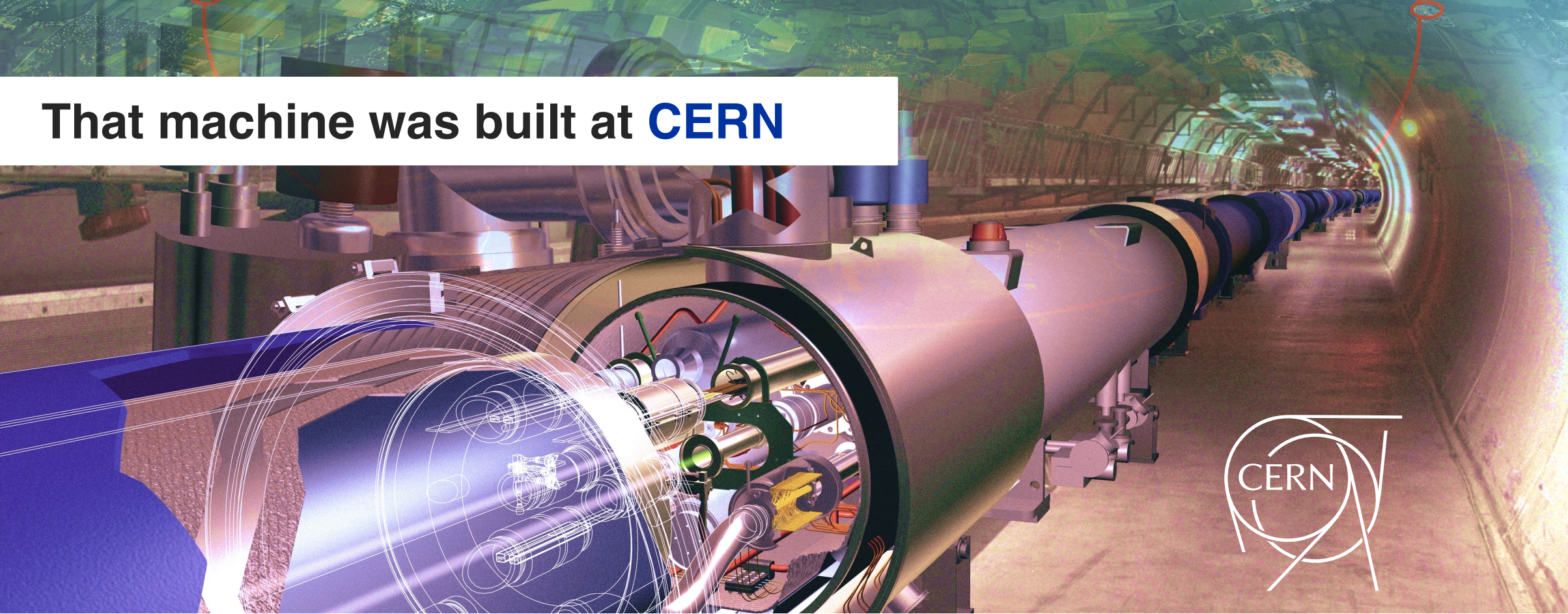


Boltzmann



Einstein

That machine was built at **CERN**



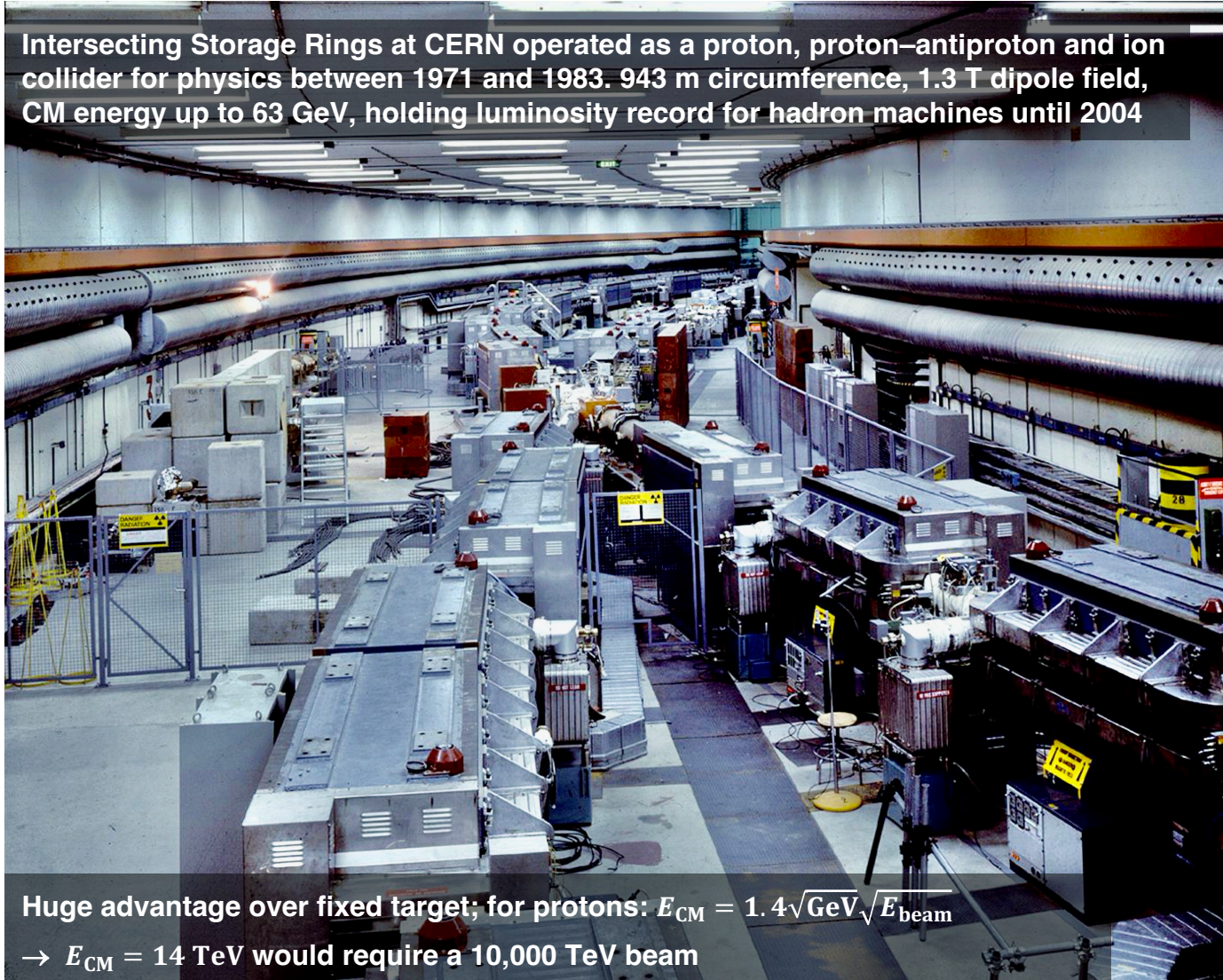
CERN

Founded in 1954 has become a
paradigm for Scientific Cooperation



1971 — the *(almost forgotten — Steve Myers)* first ever hadron collider

Intersecting Storage Rings at CERN operated as a proton, proton-antiproton and ion collider for physics between 1971 and 1983. 943 m circumference, 1.3 T dipole field, CM energy up to 63 GeV, holding luminosity record for hadron machines until 2004

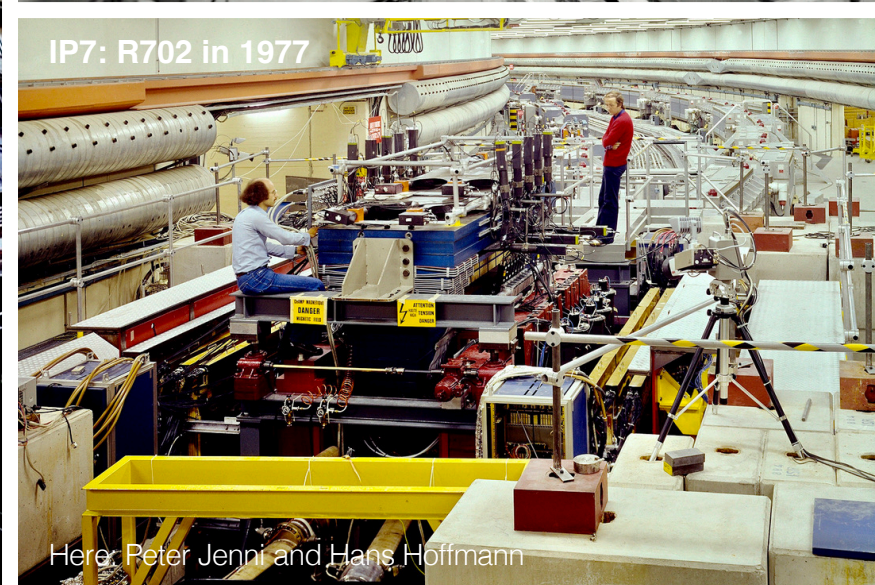


Huge advantage over fixed target; for protons: $E_{\text{CM}} = 1.4\sqrt{\text{GeV}}\sqrt{E_{\text{beam}}}$
→ $E_{\text{CM}} = 14 \text{ TeV}$ would require a 10,000 TeV beam

IP5



IP7: R702 in 1977



Here: Peter Jenni and Hans Hoffmann

ISR Control Room (early 70s)

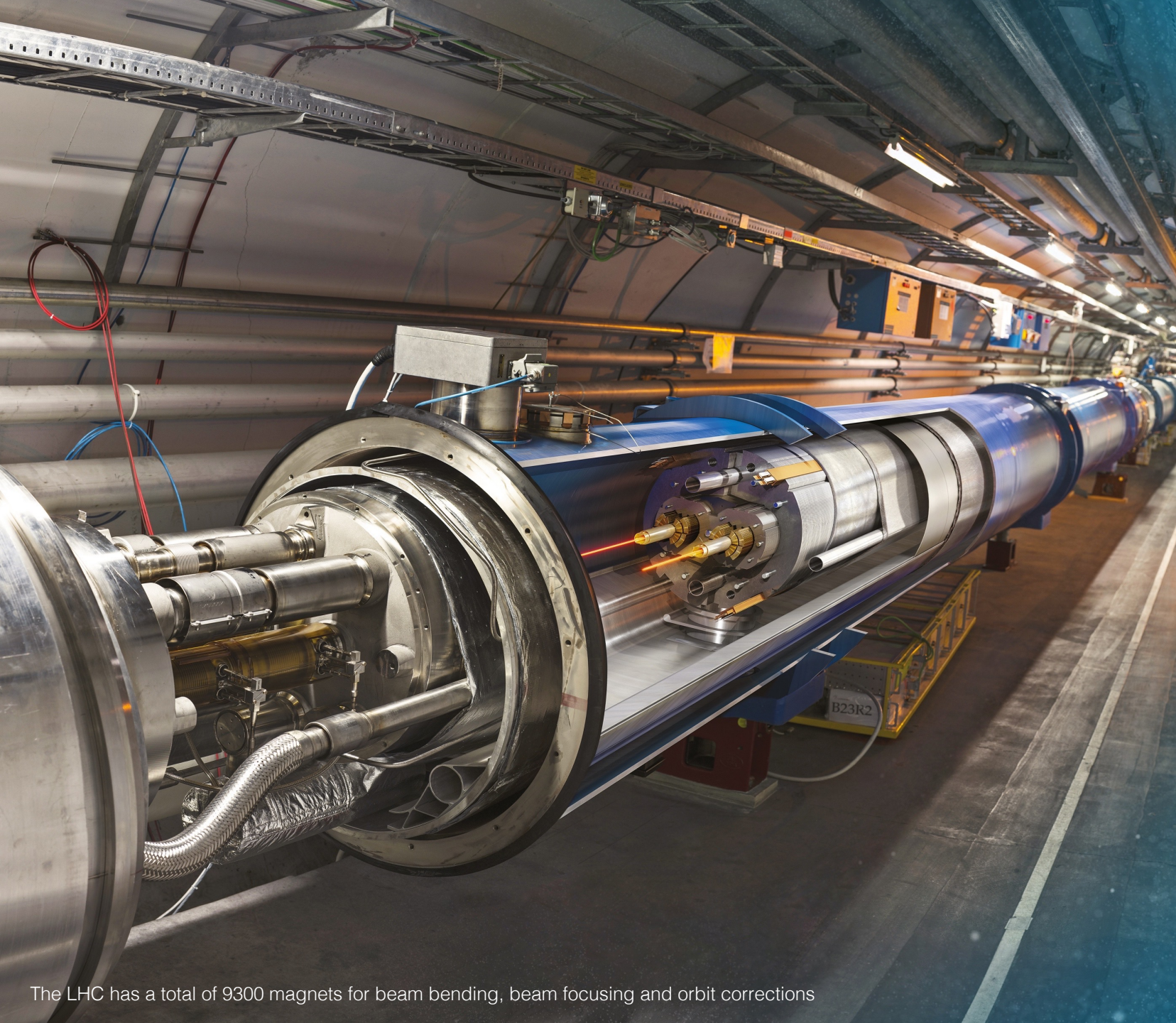


CERN today

CERN is the world's biggest laboratory for particle physics located near Geneva, Switzerland

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
- Protons and ions are accelerated to multi-TeV scale energies

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



CMS

LHC

LHC

CERN
Preessin

ALICE »

ATLAS

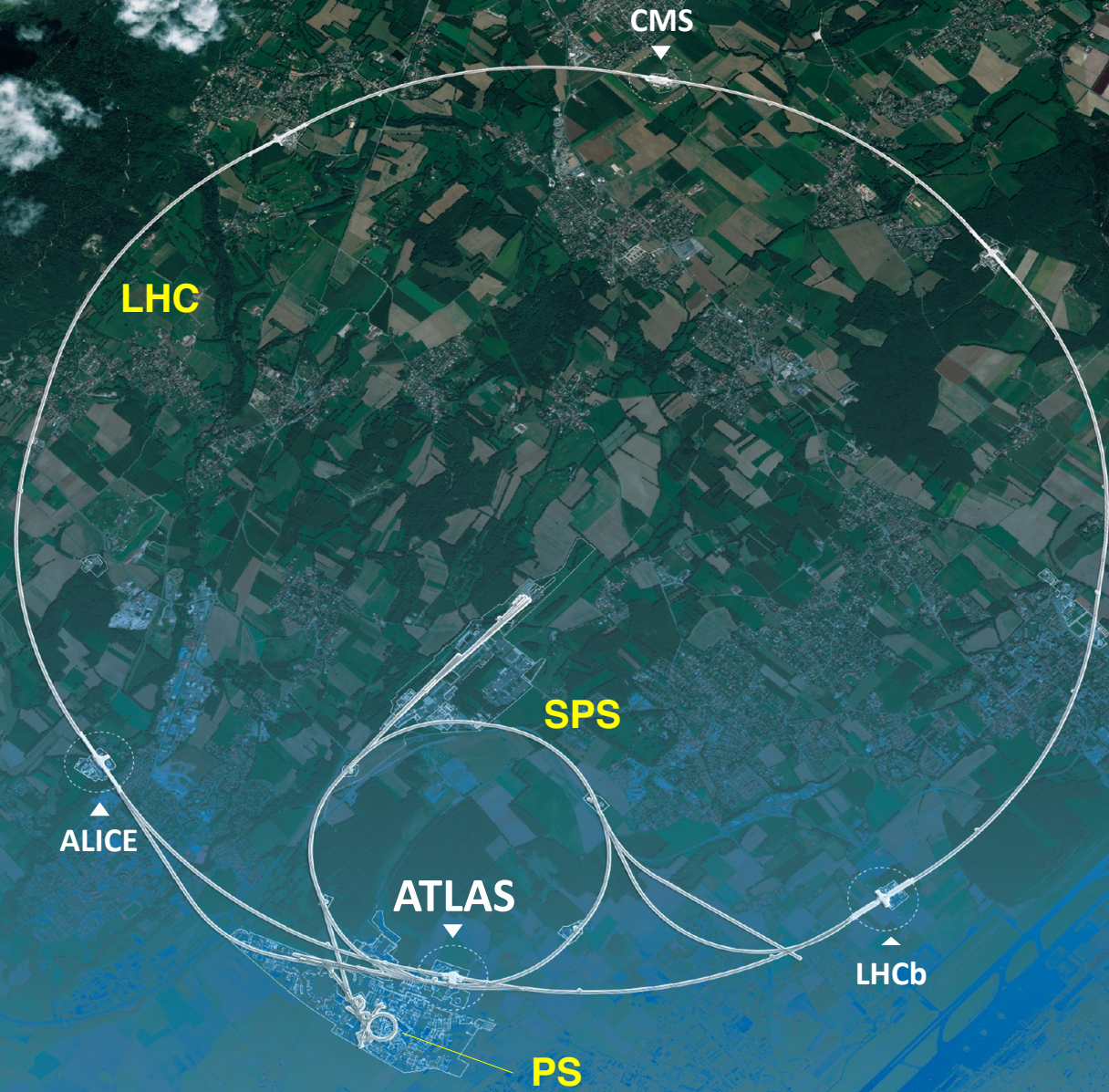
« LHCb

CERN
Meyrin

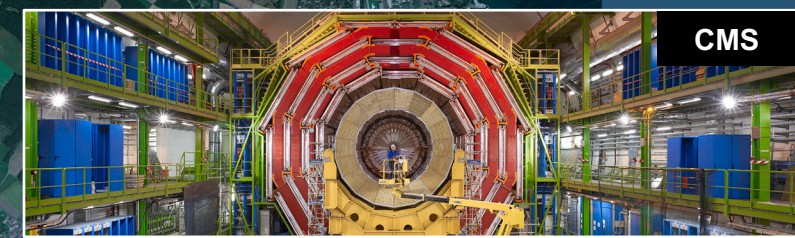
LHC — areal view

1 km

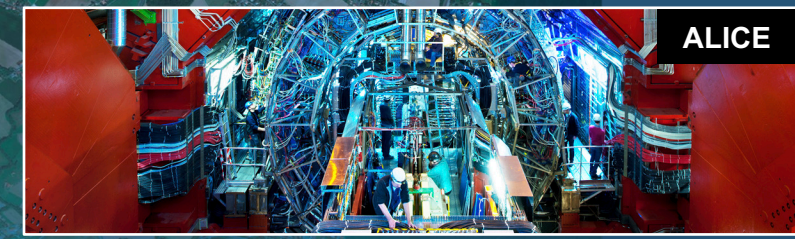
LHC — areal view



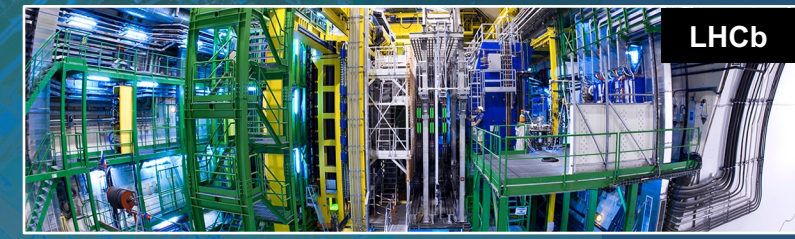
ATLAS



CMS

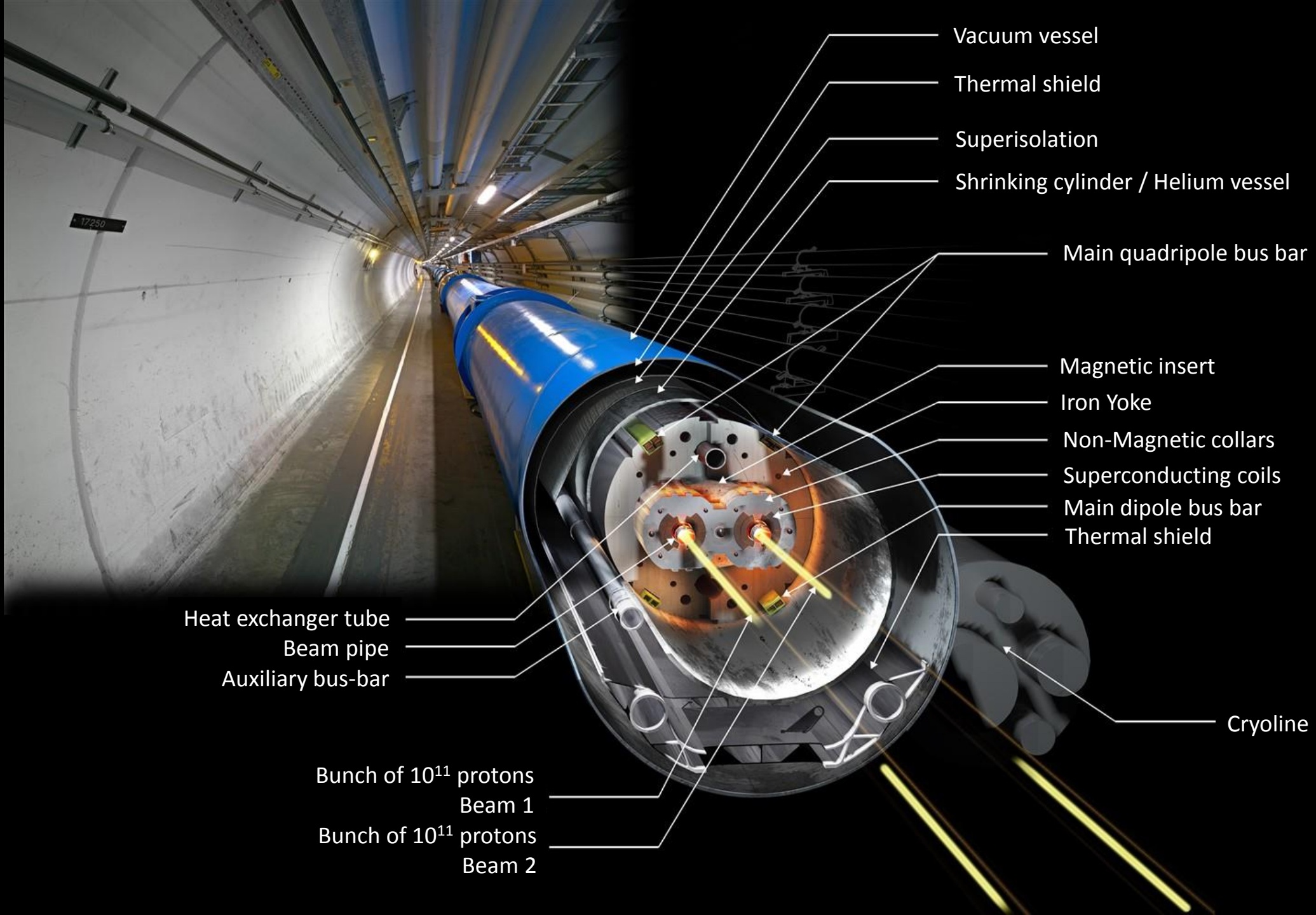


ALICE



LHCb







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

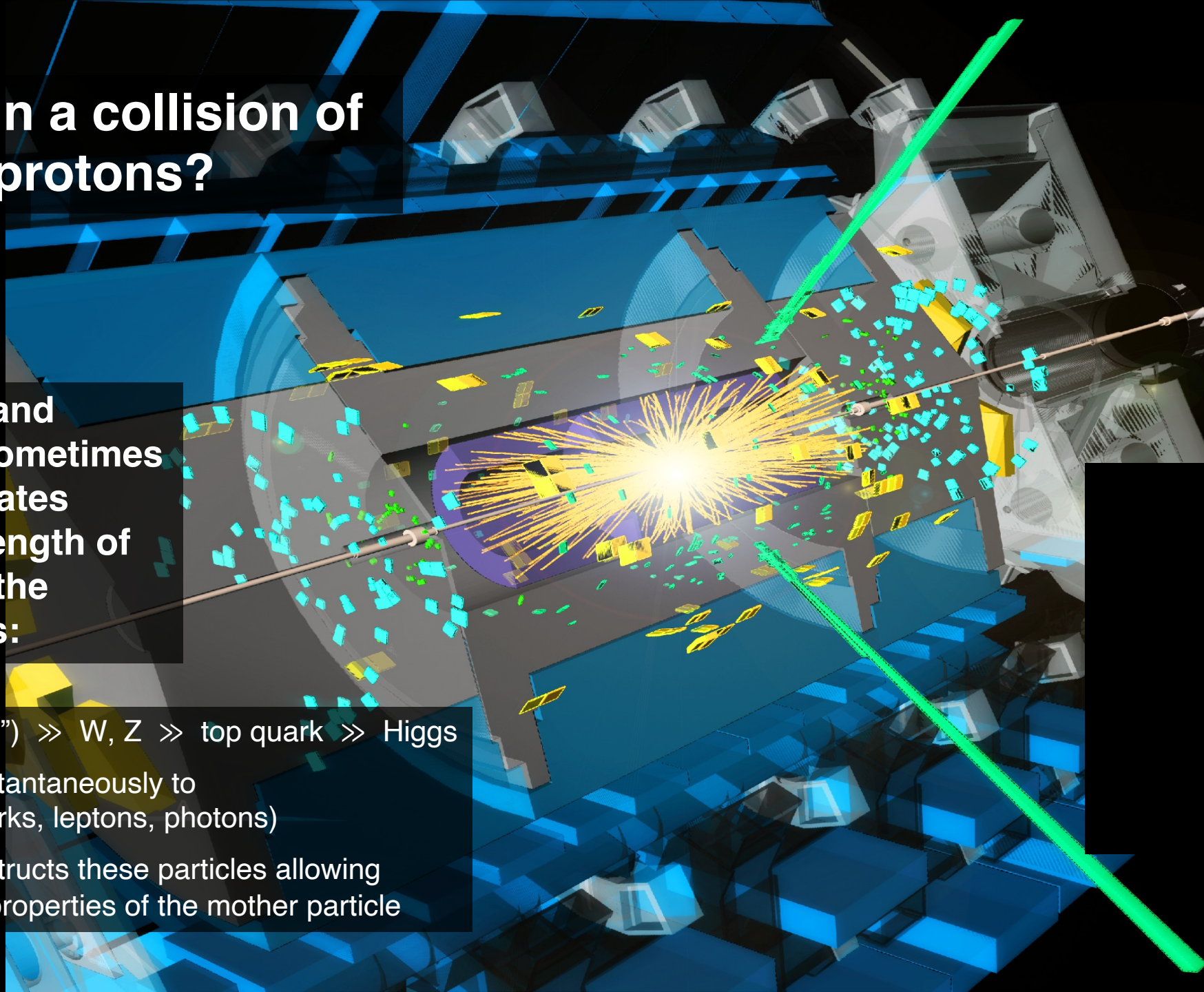
Bunch of 10^{11} protons

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



History of the ATLAS

March 1992: Evian Meeting with presentations of the Expressions of Interest (EoI)

For proton–proton:

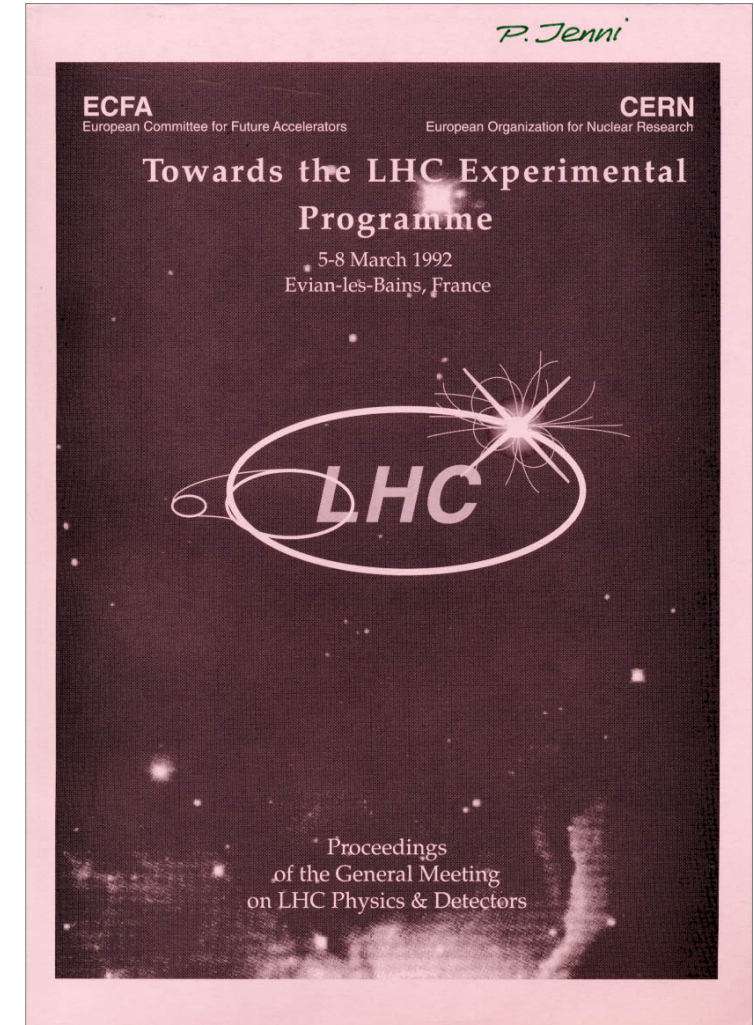
- **ASCOT** P. Norton
- **CMS** M. Della Negra / H. Desportes
- **EAGLE** P. Jenni
- **L3P** S. Ting, F. Pauss

In addition:

- LHC Beauty Collider P. Schlein
- B extracted beam G. Carboni
- B gas jet T. Nakada
- Neutrino at LHC F. Vannucci
- LHC HI J. Schukraft
- DELPHI LHC HI G. Jarlskog



Peter Jenni (CERN)



The birth of ATLAS

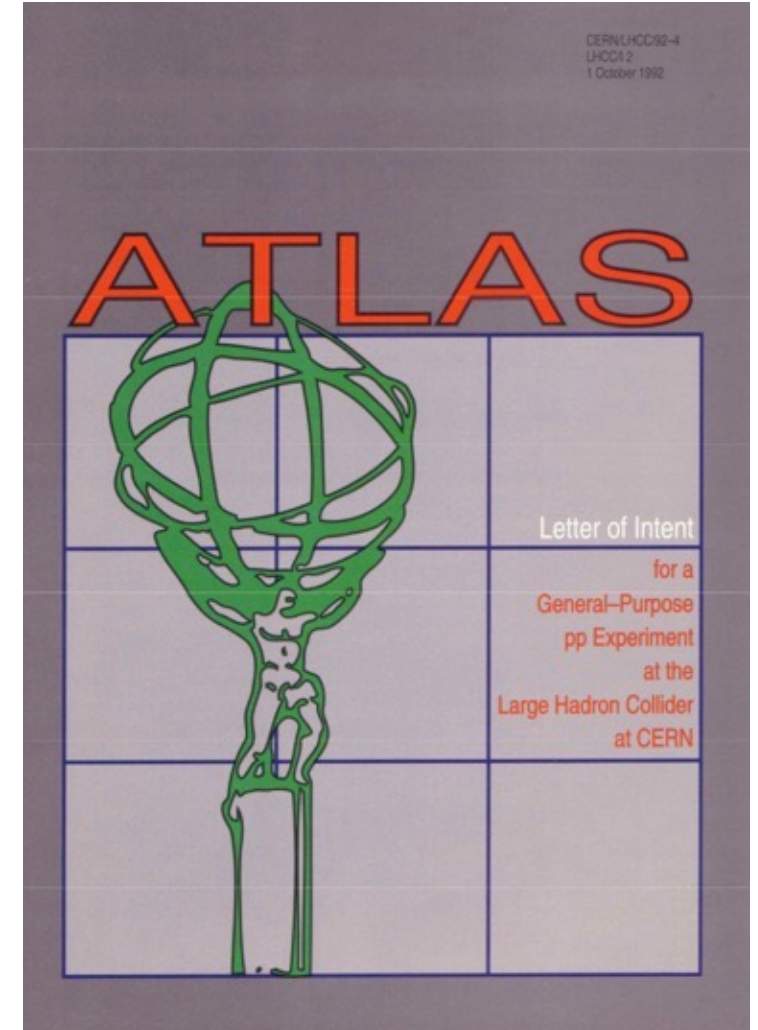
March 1992 – Summer 1992: merging of EAGLE and ASCOT

September 1992: the new baby needs a name, decision:

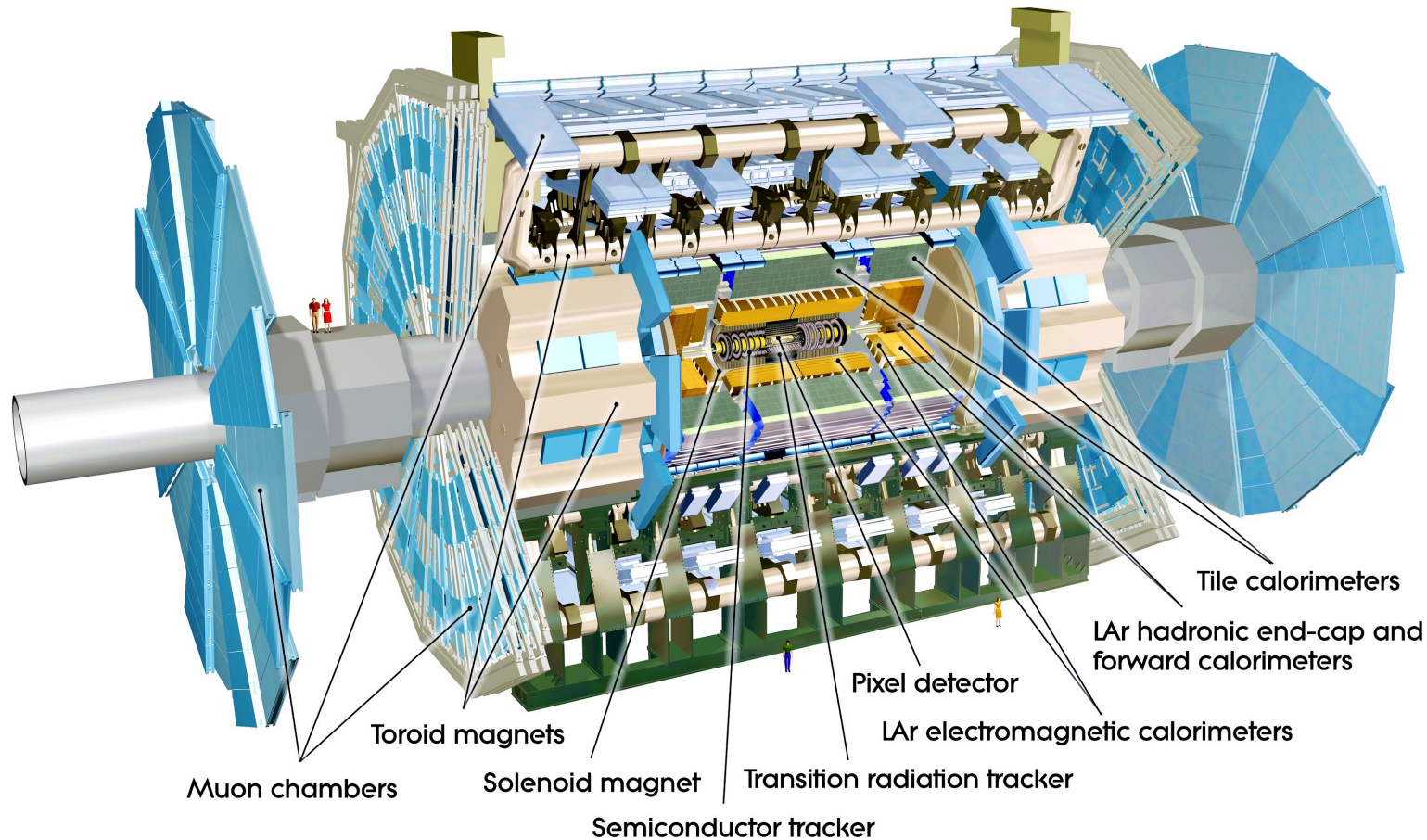
<u>1st round:</u>		<u>2nd round:</u>	
ATLAS	31	ATLAS	40
ALICE	12	ALICE	13
ACE	5		
ALEX	5		
LHD	0		

1st October 1992: ATLAS Letter of Intend (LoI)
submitted to the LHCC

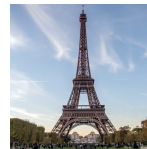
Official birth of the **ATLAS* Collaboration**



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 offer scientific research at the energy frontier, technological breakthroughs, highest level and broad education, international cooperation

The ATLAS Collaboration

- 5900 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- 1200 PhD students
- 247 institutes from 42 countries
- 1122 scientific papers to date



CERN offers various renowned educational programmes



The ATLAS Collaboration

- 5900 physicists, engineers, technicians from 103 nationalities
- 2900 scientific authors
- **1200 PhD students**
- 247 institutes from 42 countries
- 1122 scientific papers to date



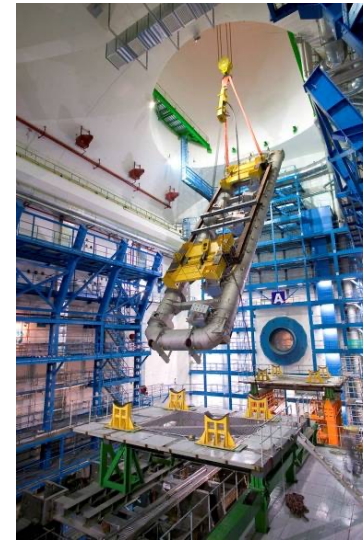
ATLAS Detector construction and installation

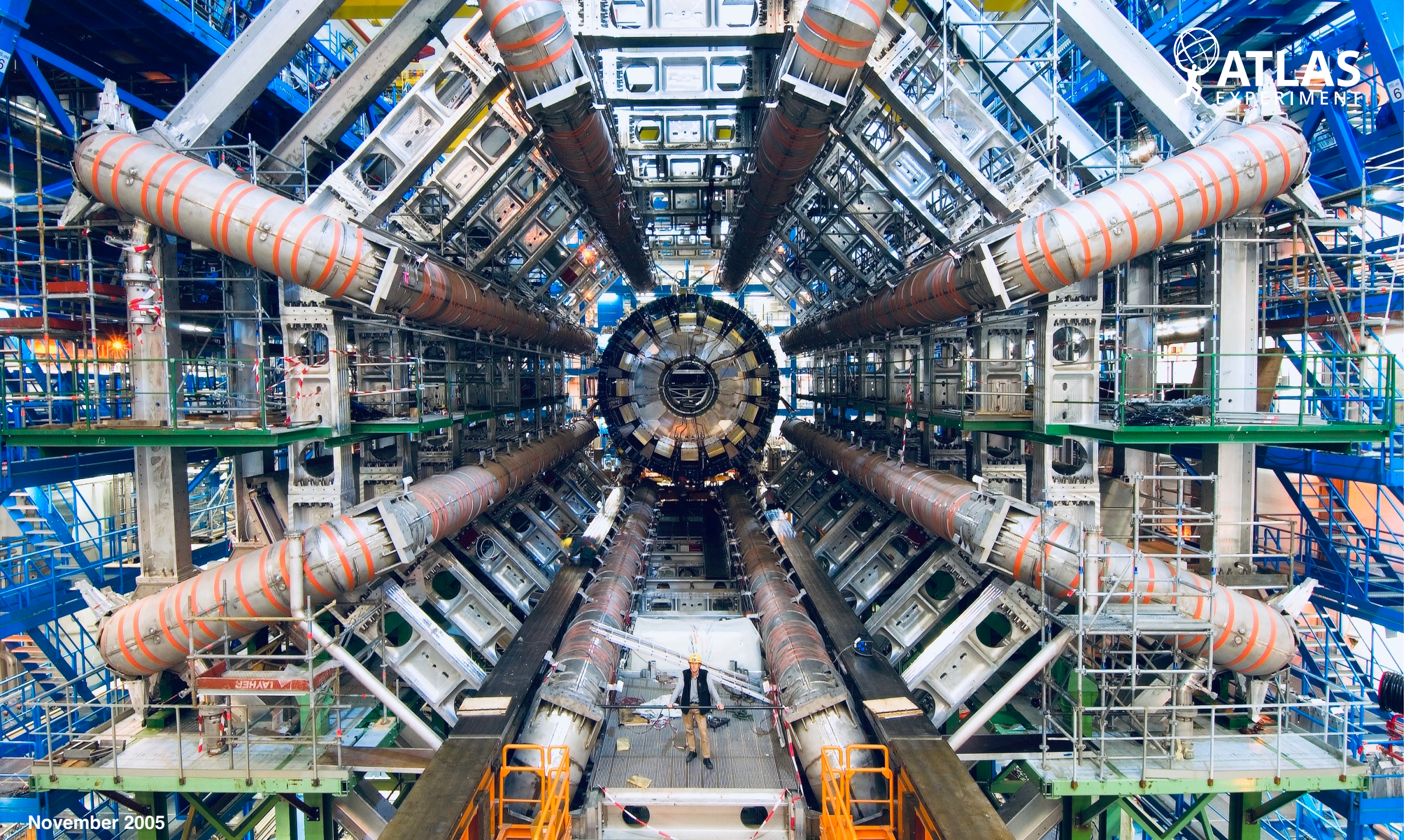


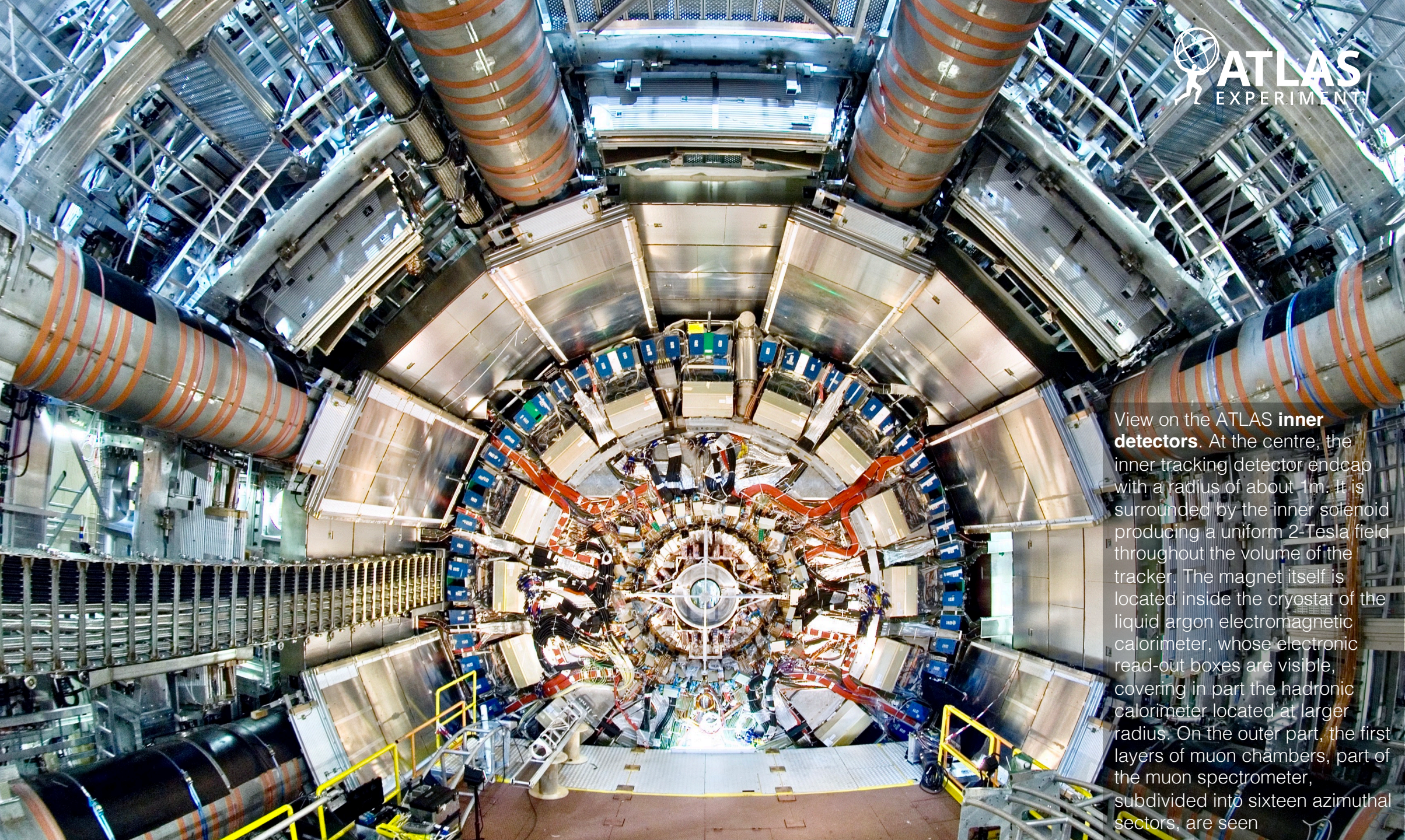
ATLAS cavern after excavation in July 2002

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

ATLAS Detector construction and installation

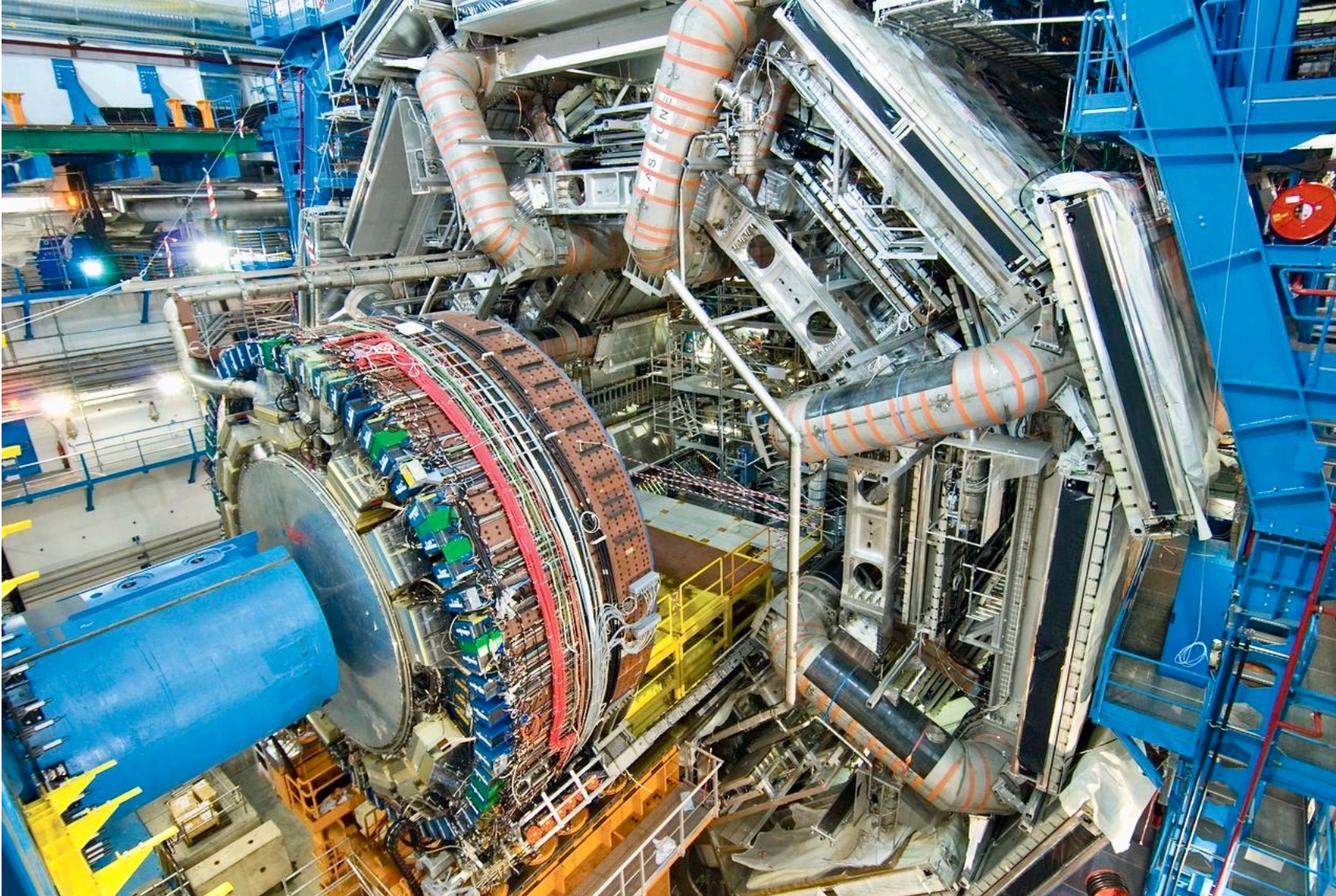






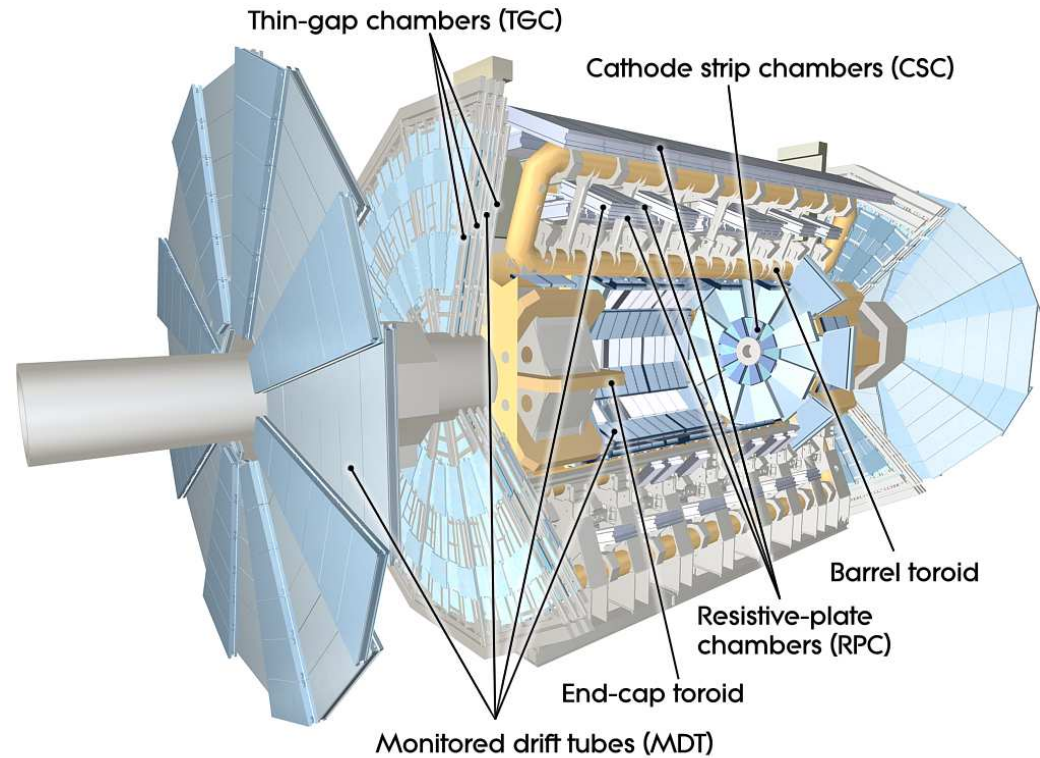
View on the ATLAS **inner detectors**. At the centre, the inner tracking detector endcap with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic 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

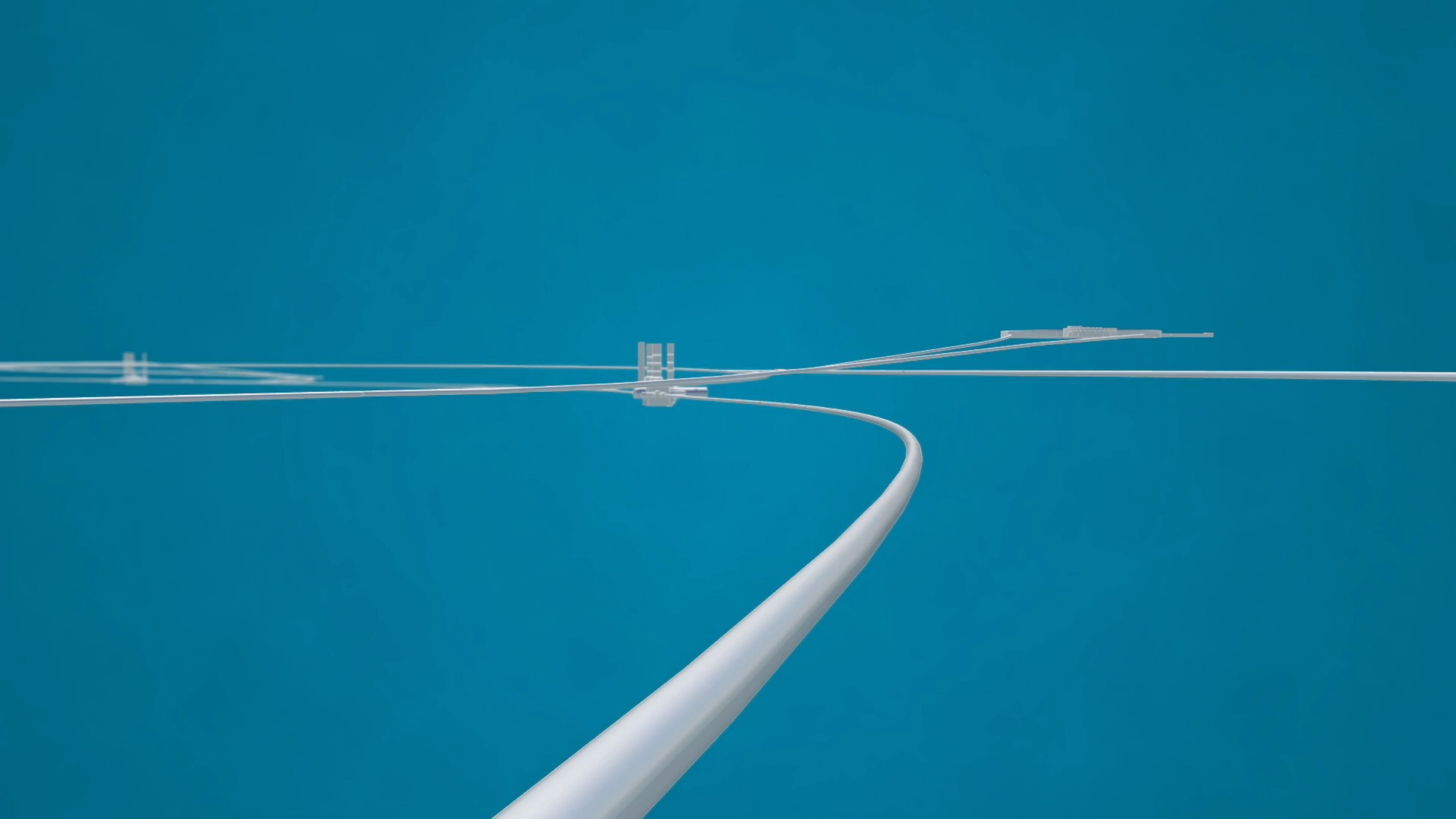


View of the central part of ATLAS during final assembly stages. The wire chambers mounted inside and around the toroid magnet cryostats are well visible, as is part of the end-cap hadronic calorimeter before its insertion inside the magnet

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

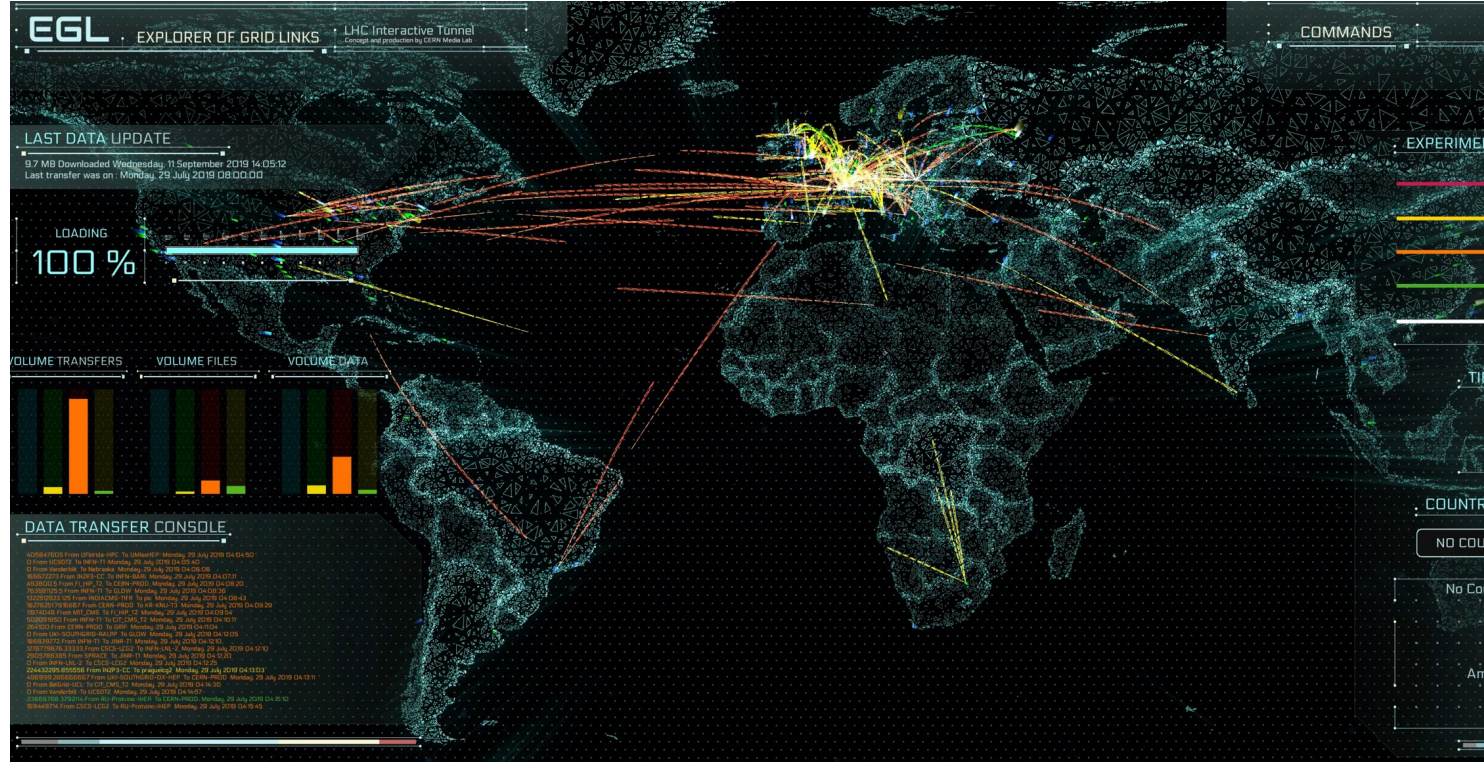
High-speed internet and data replication to computer centres across the world allows ATLAS physicists all over the world to analyse the data and contribute to the scientific publications



Data processing relies on the worldwide LHC Computing Grid



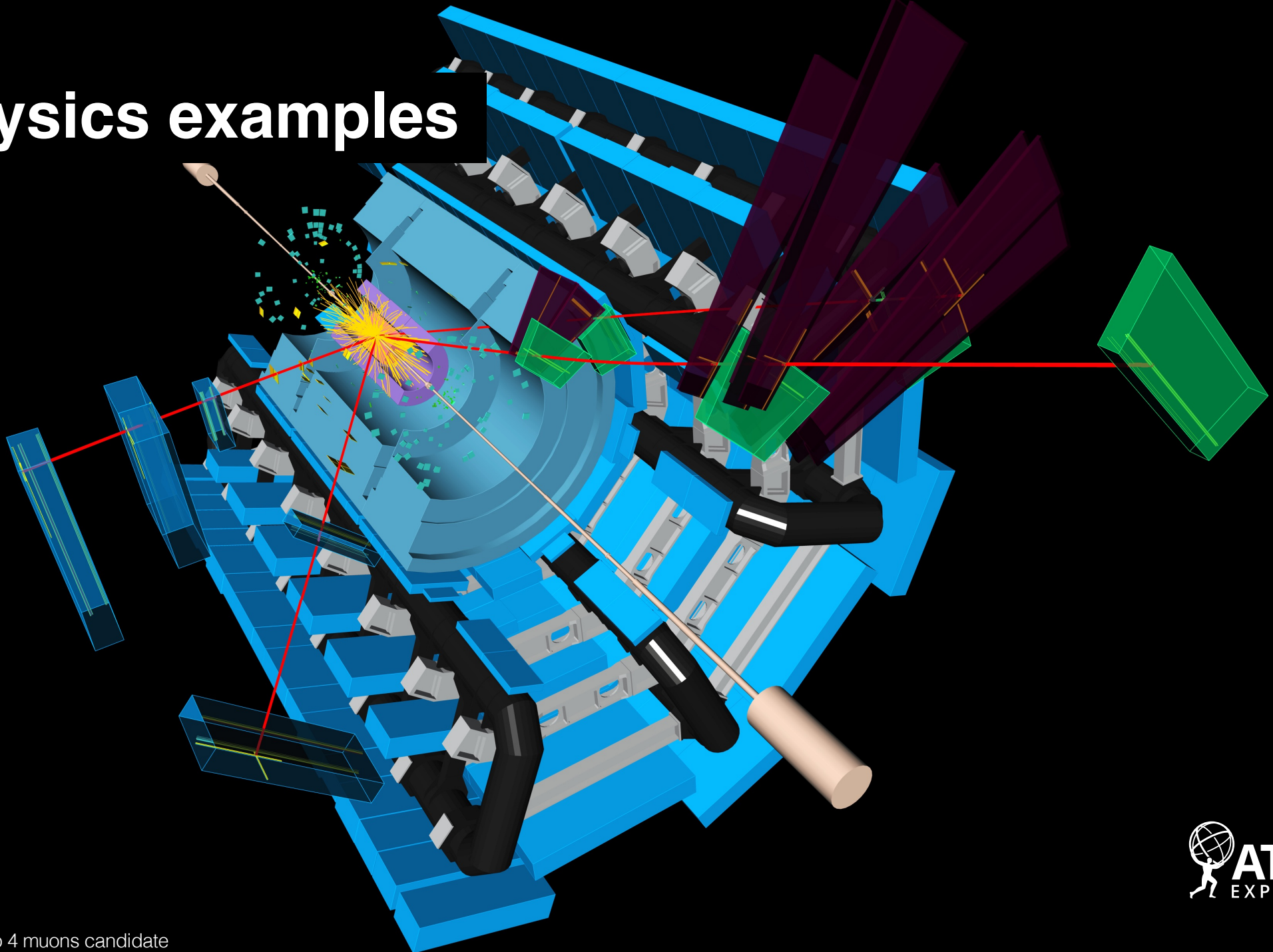
Used to store, distribute, process and analyse data



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

More than 1000 Petabytes of CERN data stored world-wide

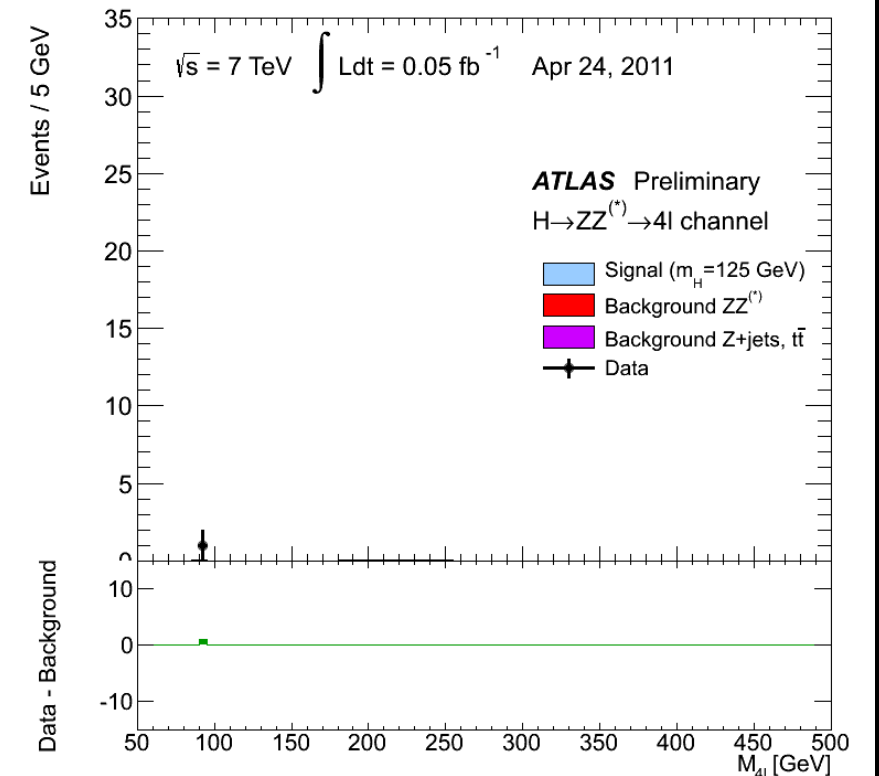
Physics examples



2012 Higgs boson discovery – 10 years ago !



Fabiola Gianotti and Peter Higgs, 4 July 2012



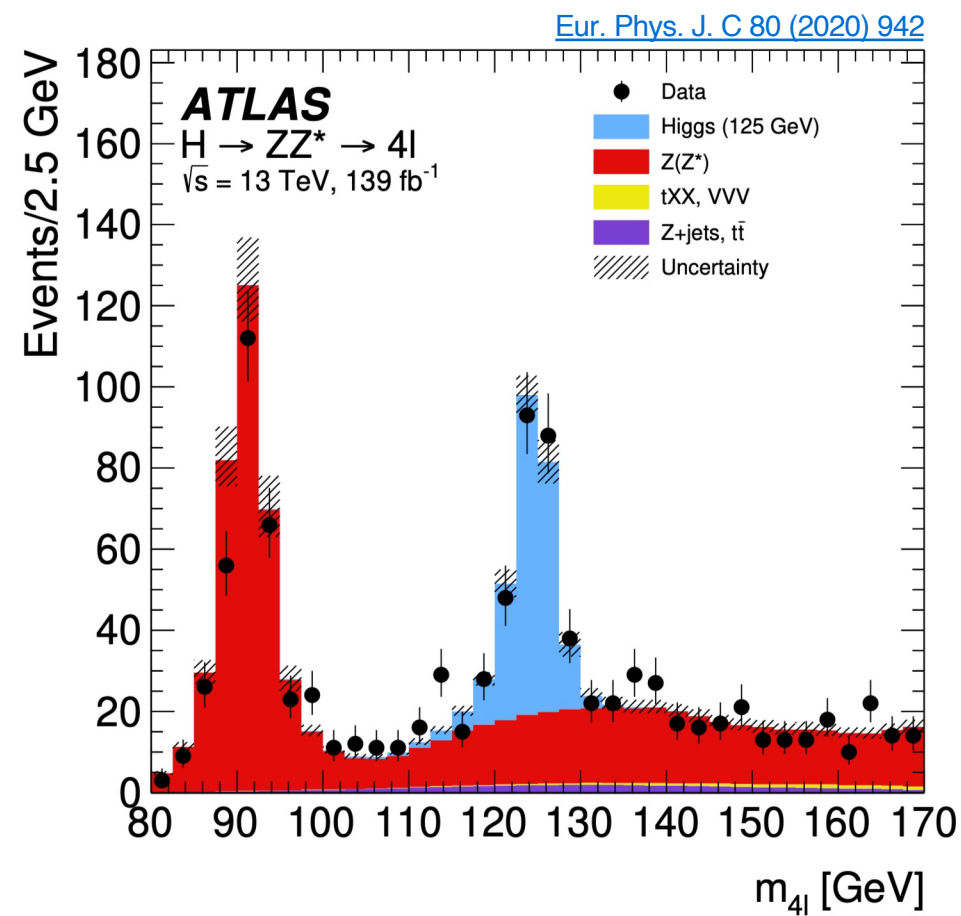
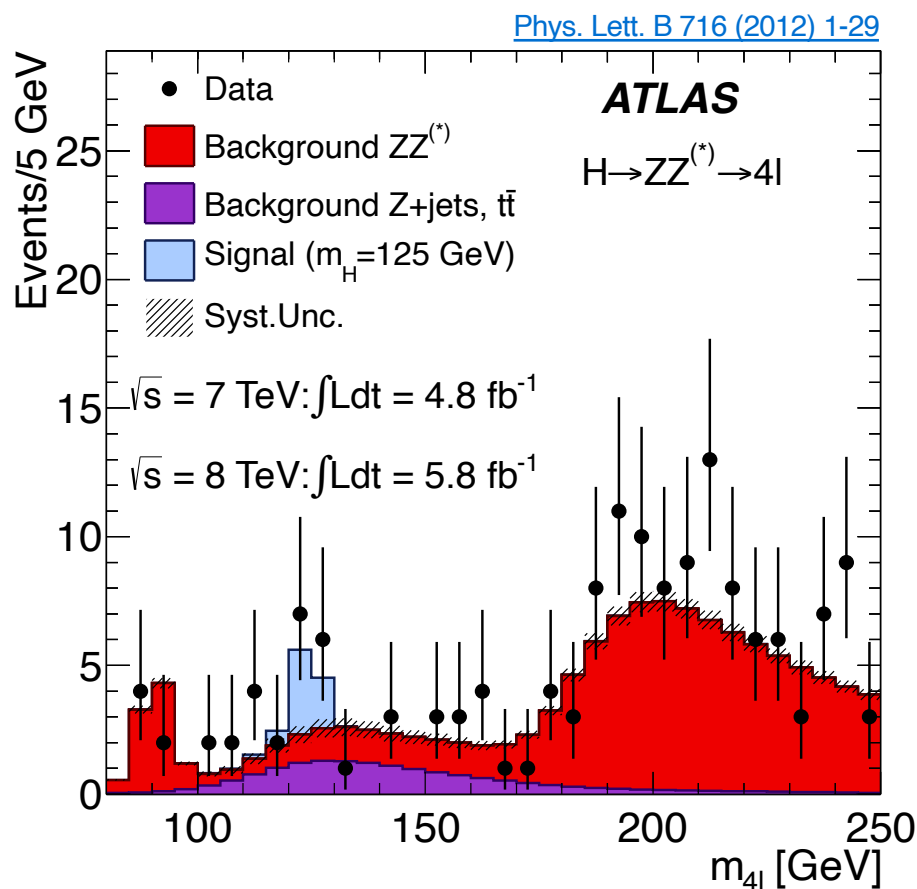
2012 Higgs boson discovery



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

2012 Higgs boson discovery — then and today



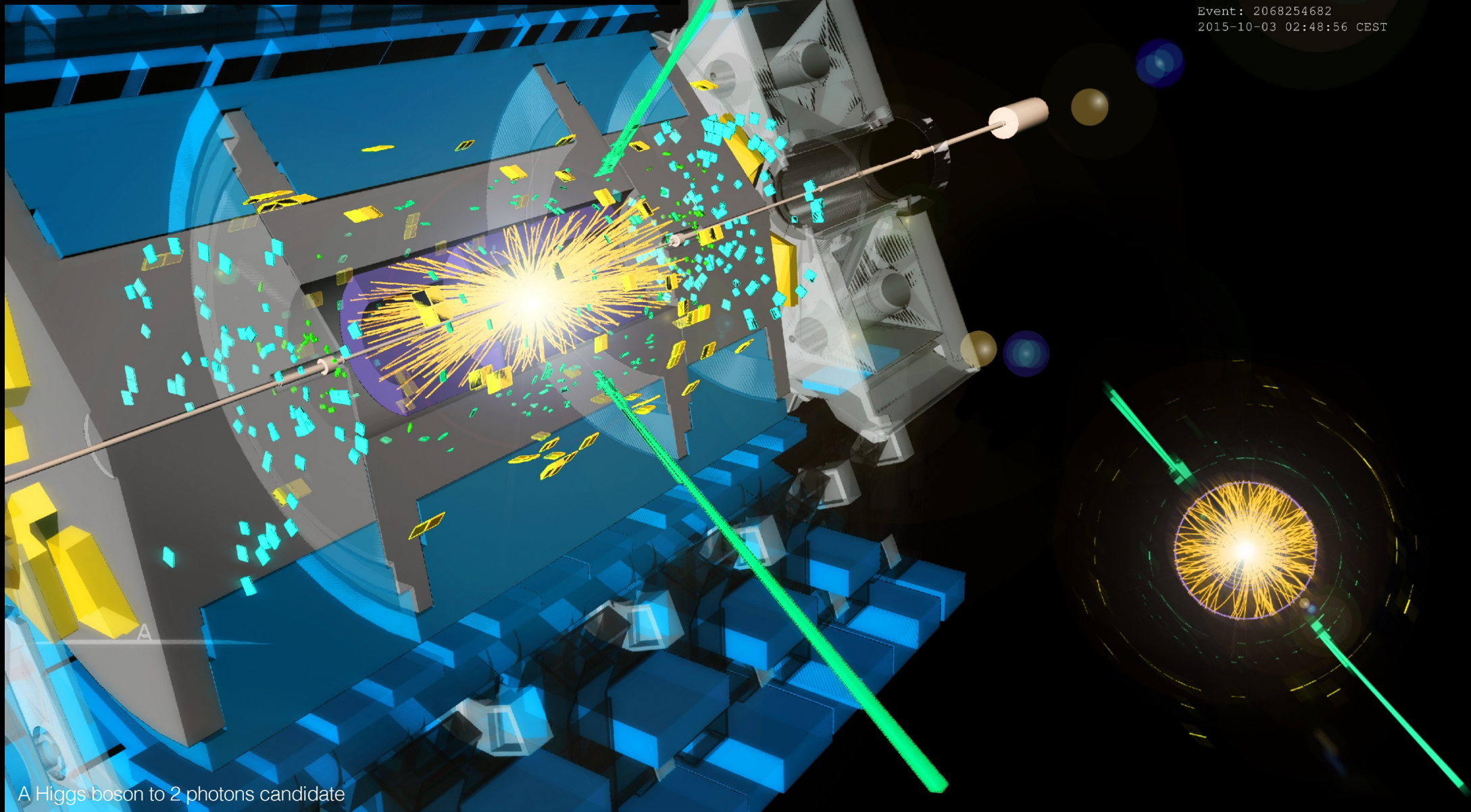
More decay channels



Run: 280862

Event: 2068254682

2015-10-03 02:48:56 CEST



A Higgs boson to 2 photons candidate

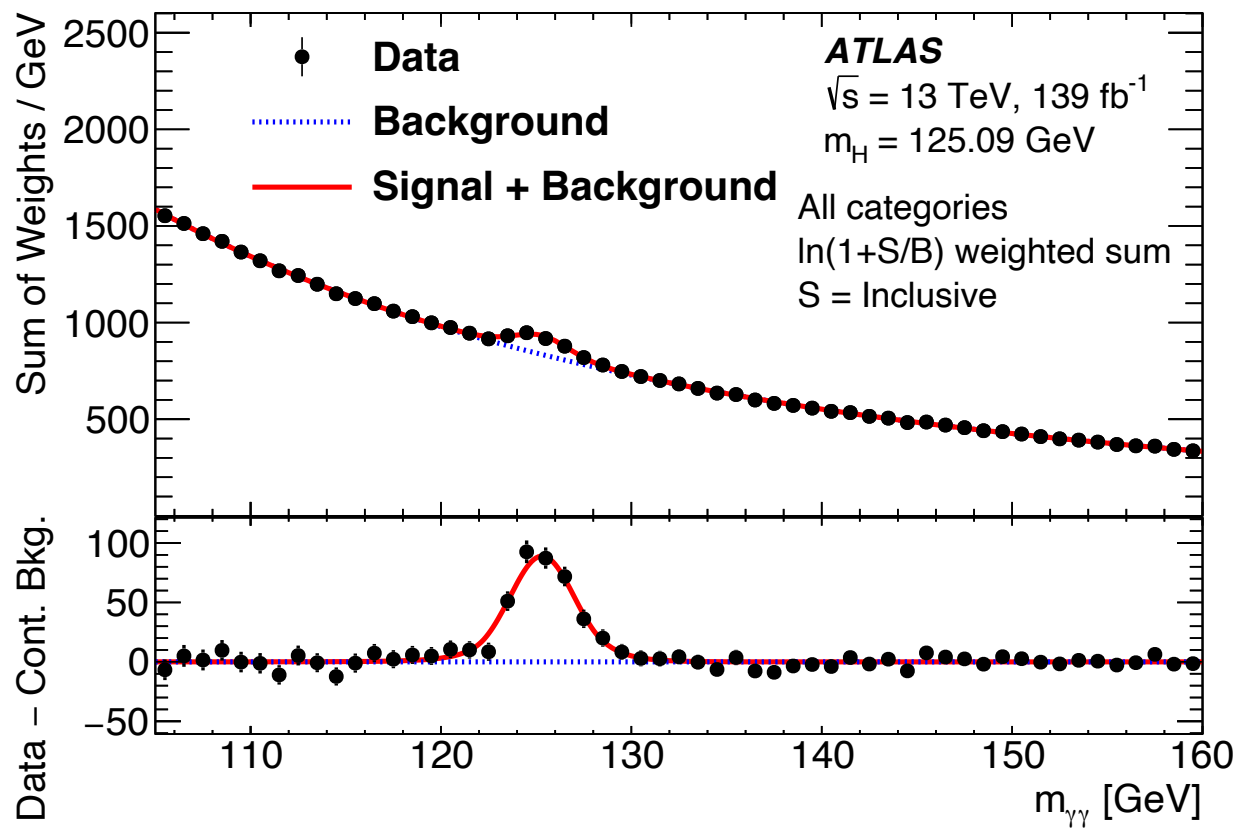
More decay channels



Run: 280862

Event: 2068254682

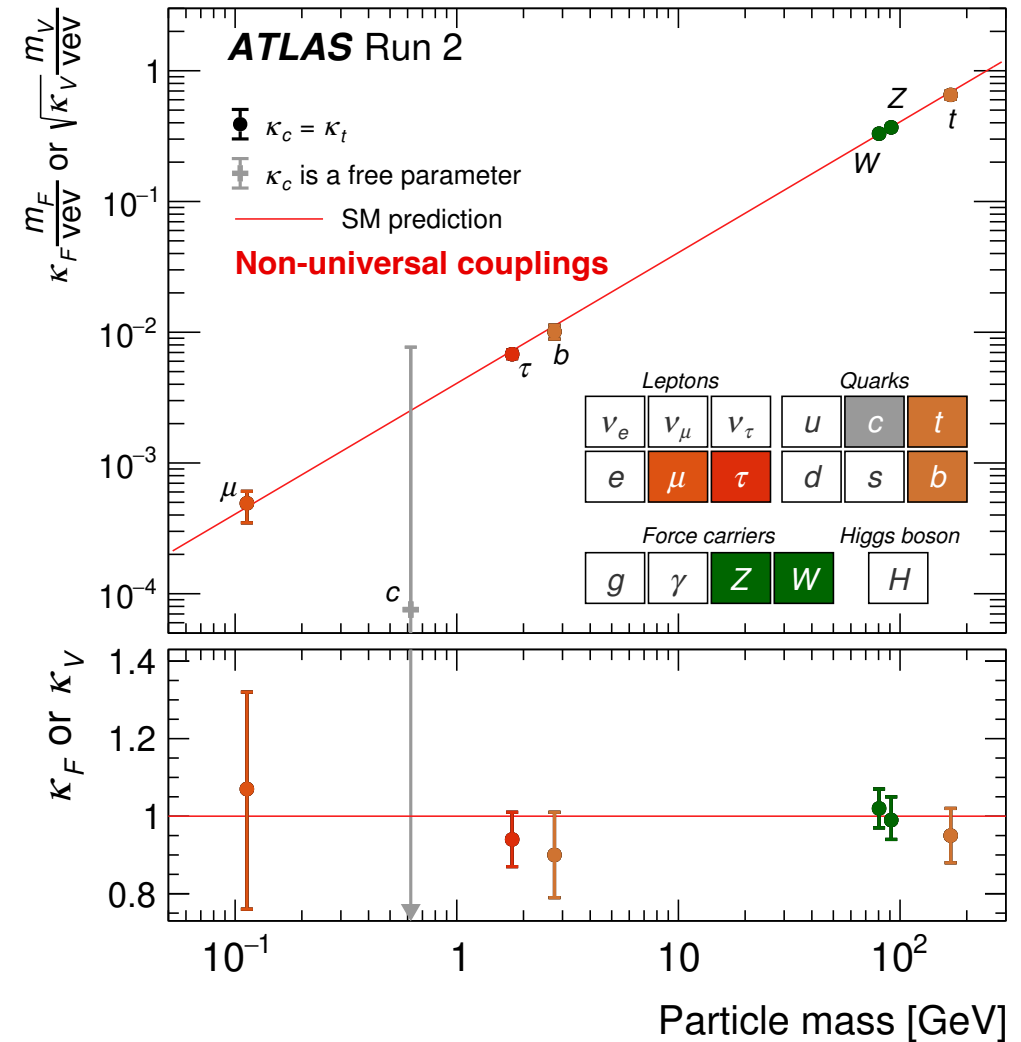
2015-10-03 02:48:56 CEST



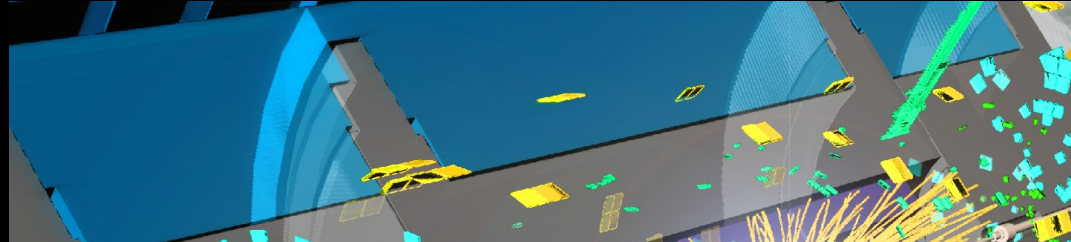
The Higgs mechanism is real !

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

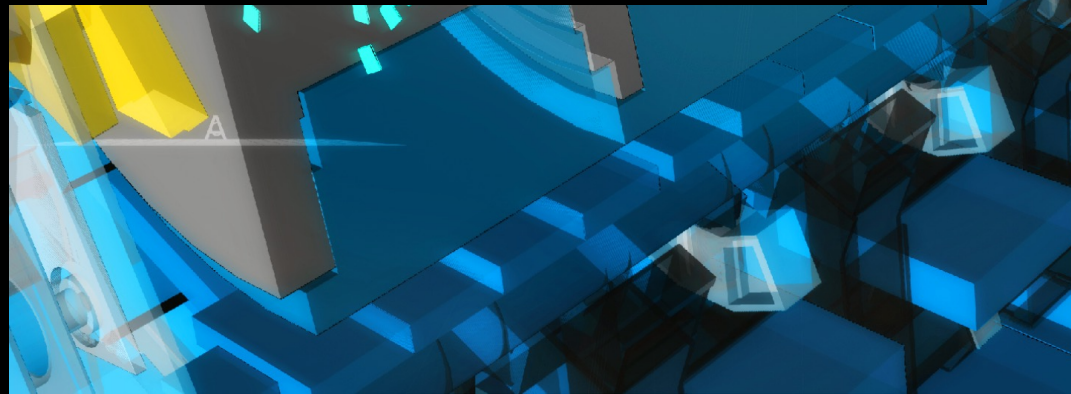


The Higgs mechanism is real !



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Possible relations between the Higgs boson and open questions in particle physics and cosmology

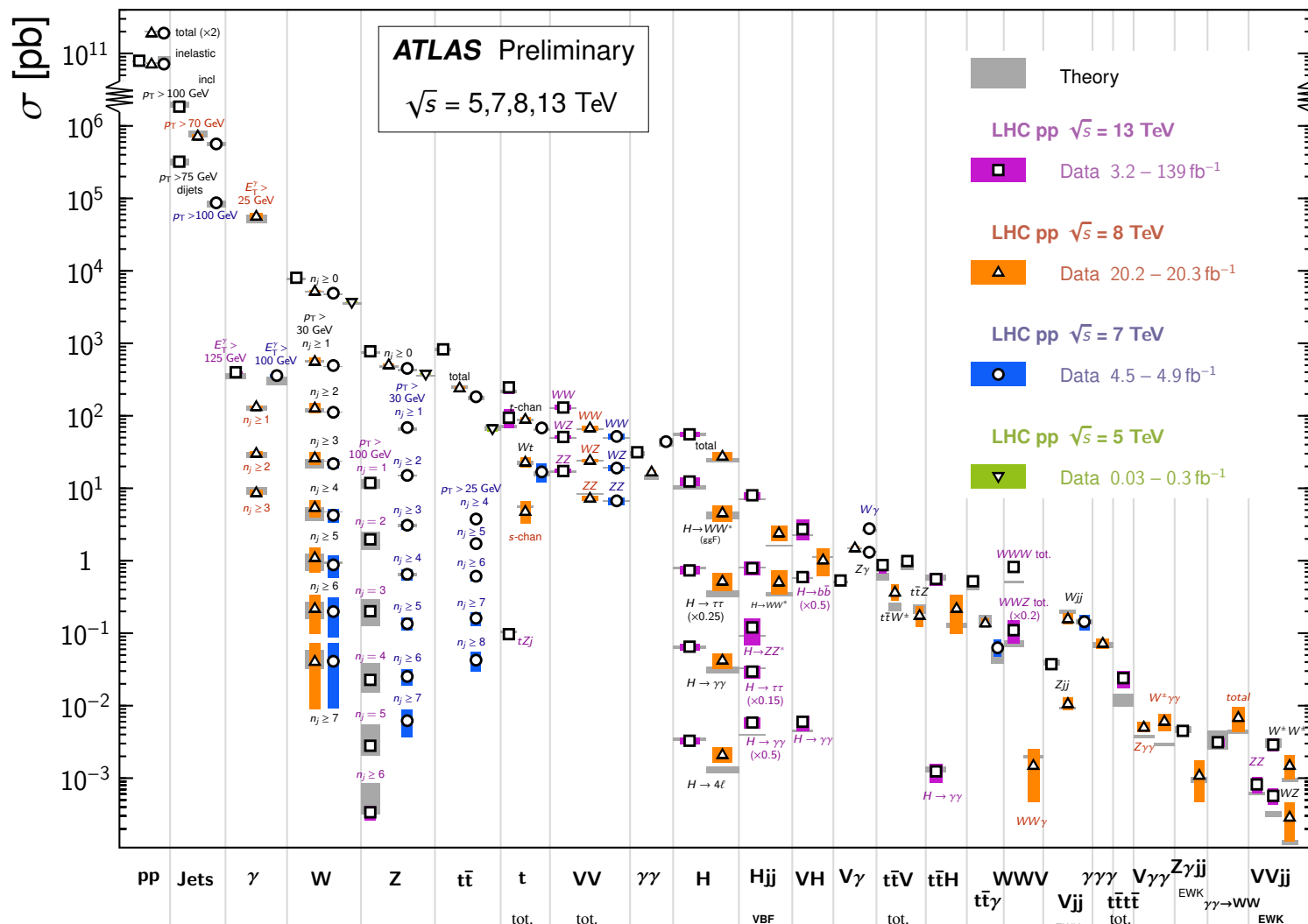
- What stabilises the Higgs mass versus high-scale new physics? Are there new TeV-scale symmetries? Is the Higgs boson elementary, are there anomalies in its coupling to the W or Z?
- Do Higgs interactions violate CP? Is there an anomalous Higgs self coupling to allow for a first order electroweak phase transition?
- Is the Higgs boson unique?
- What is the origin of dark matter, can the Higgs boson provide a portal to a dark sector? Are there new, yet unseen decay modes?
- What is the origin of the vast range of Yukawa couplings, are there modified interactions, lepton-flavour violation?
- Is the Higgs field connected with cosmic inflation? Are there possible cosmological observations related to the Higgs field?

[Salam, Wang, Zanderighi: Nature 607, 41 \(2022\)](#)

**ATLAS discovered
numerous processes
never observed before**

Standard Model Production Cross Section Measurements

Status: February 2022



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

Theory and computational developments are key to this progress

Run: 329716

Event: 857582452

2017-07-14 10:48:51 CEST

Deep searches for new phenomena



ATLAS
EXPERIMENT

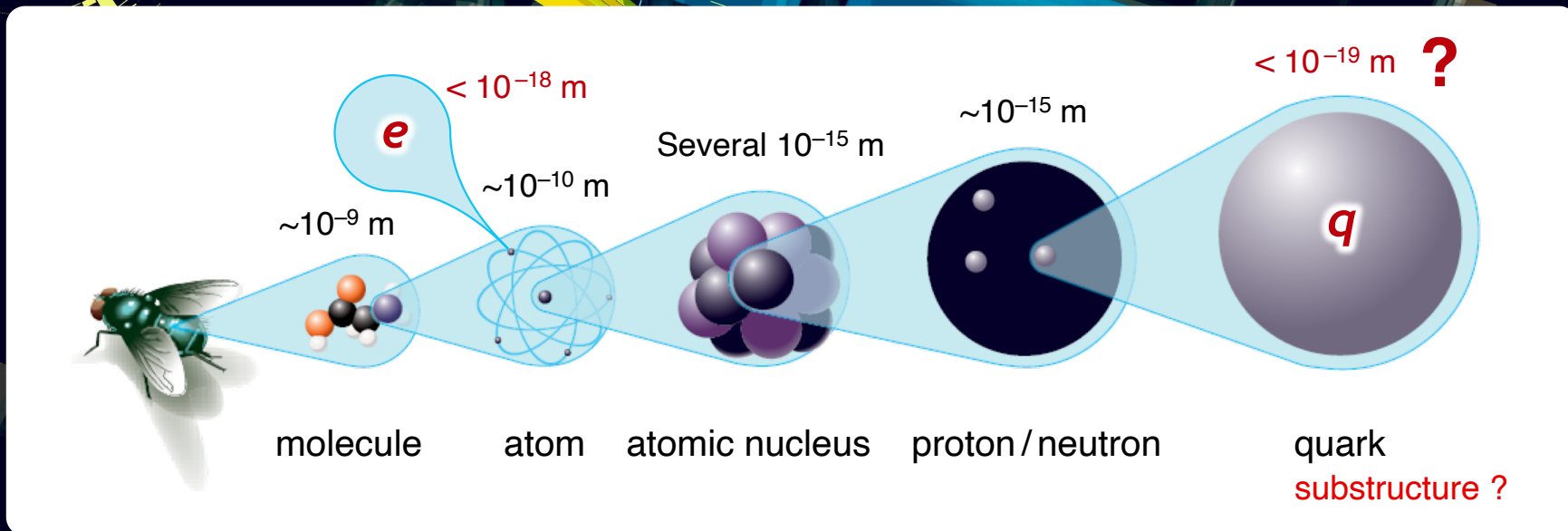


Run: 329716

Event: 857582452

2017-07-14 10:48:51 CEST

Are quarks elementary particles?



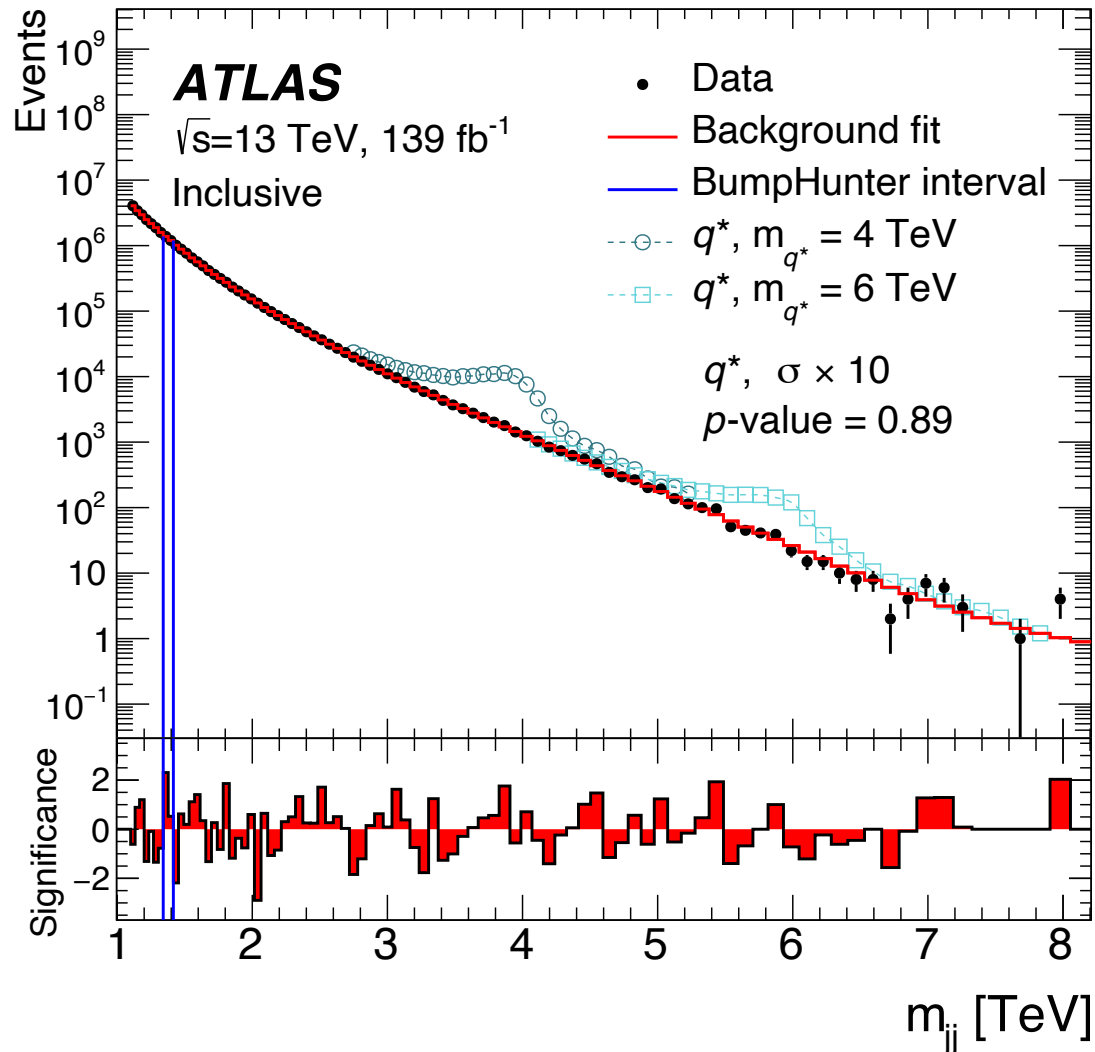
ATLAS
EXPERIMENT

Run: 329716

Event: 857582452

2017-07-14 10:48:51 CEST

Are quarks elementary particles?



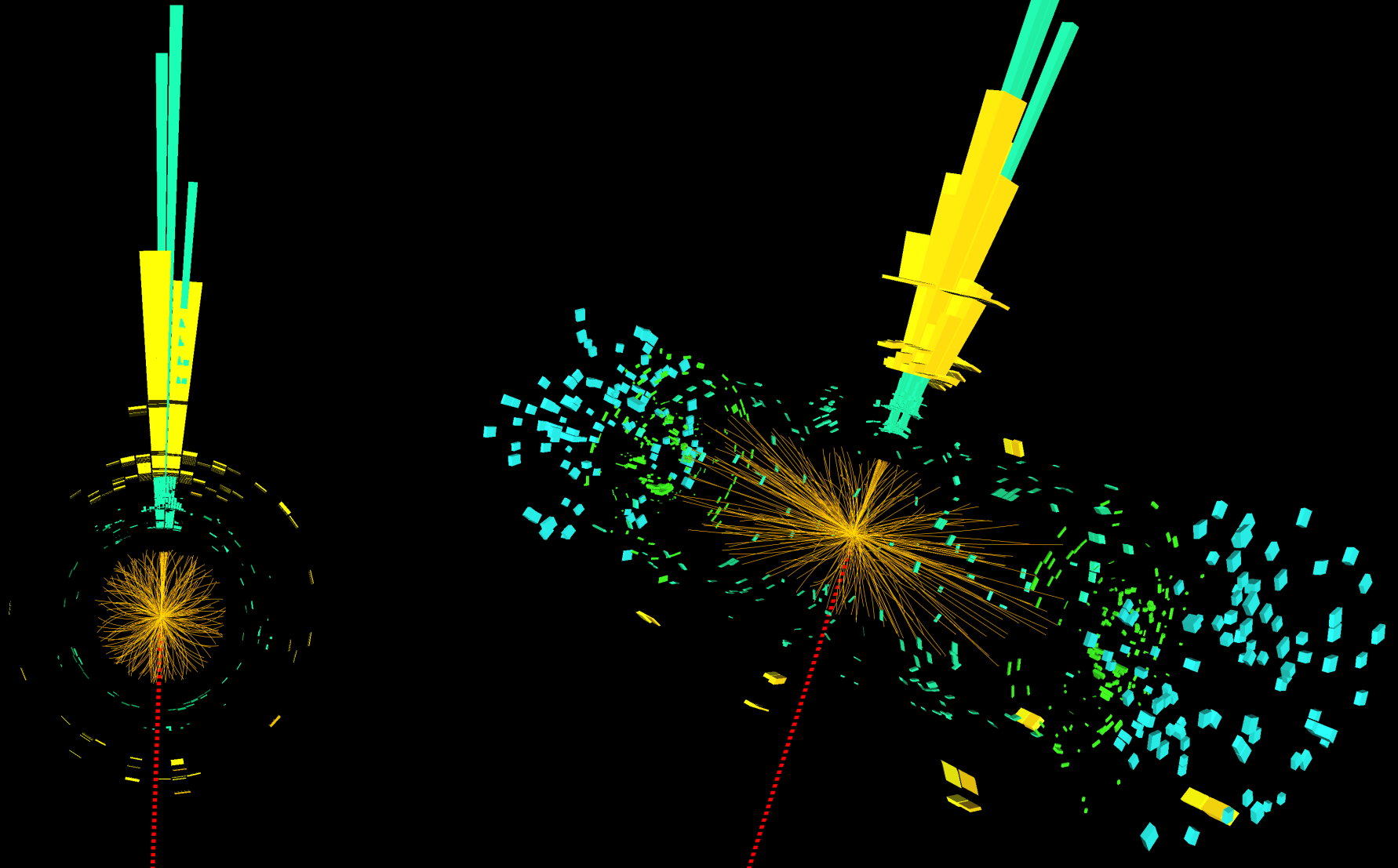
ATLAS
EXPERIMENT

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

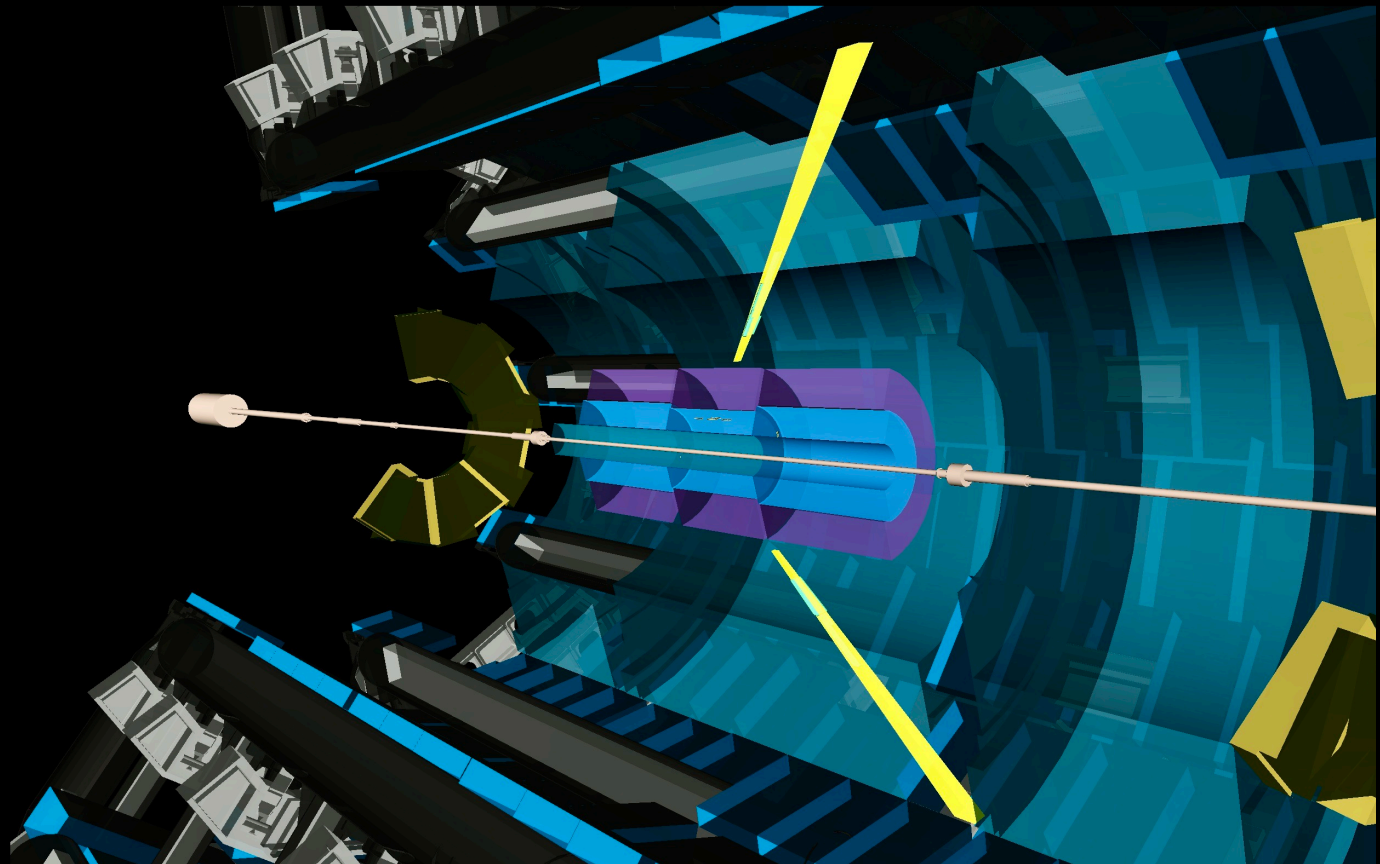
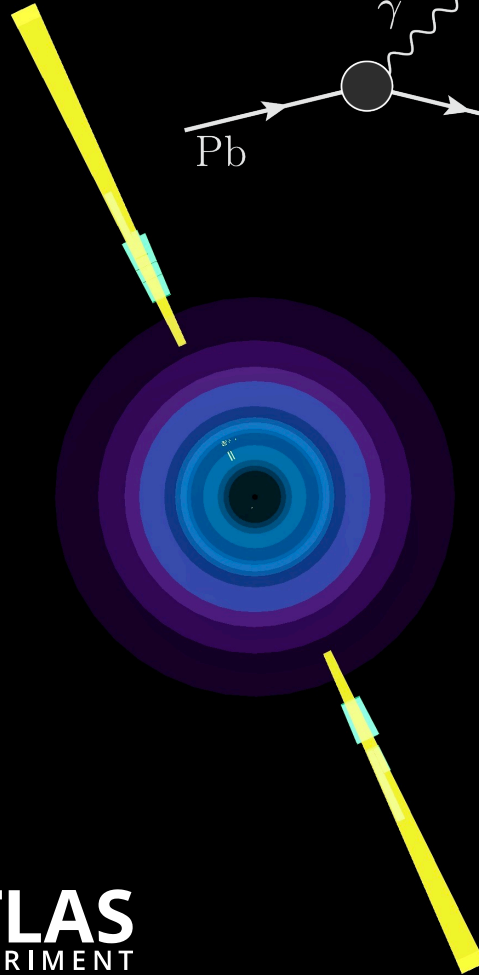
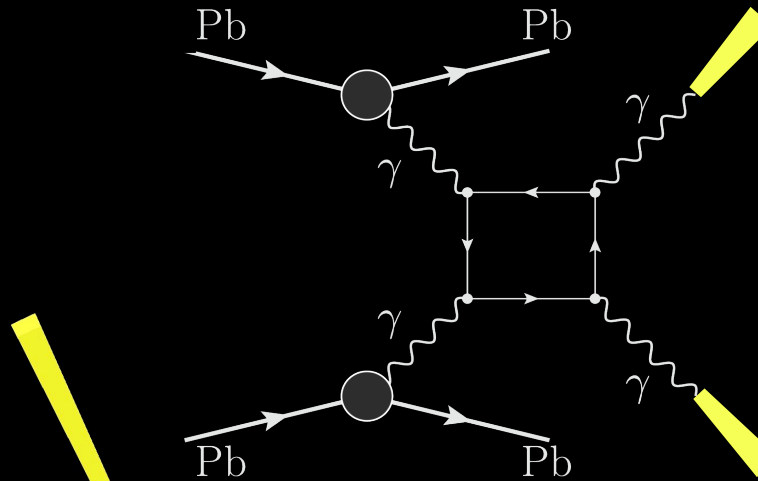


ATLAS
EXPERIMENT

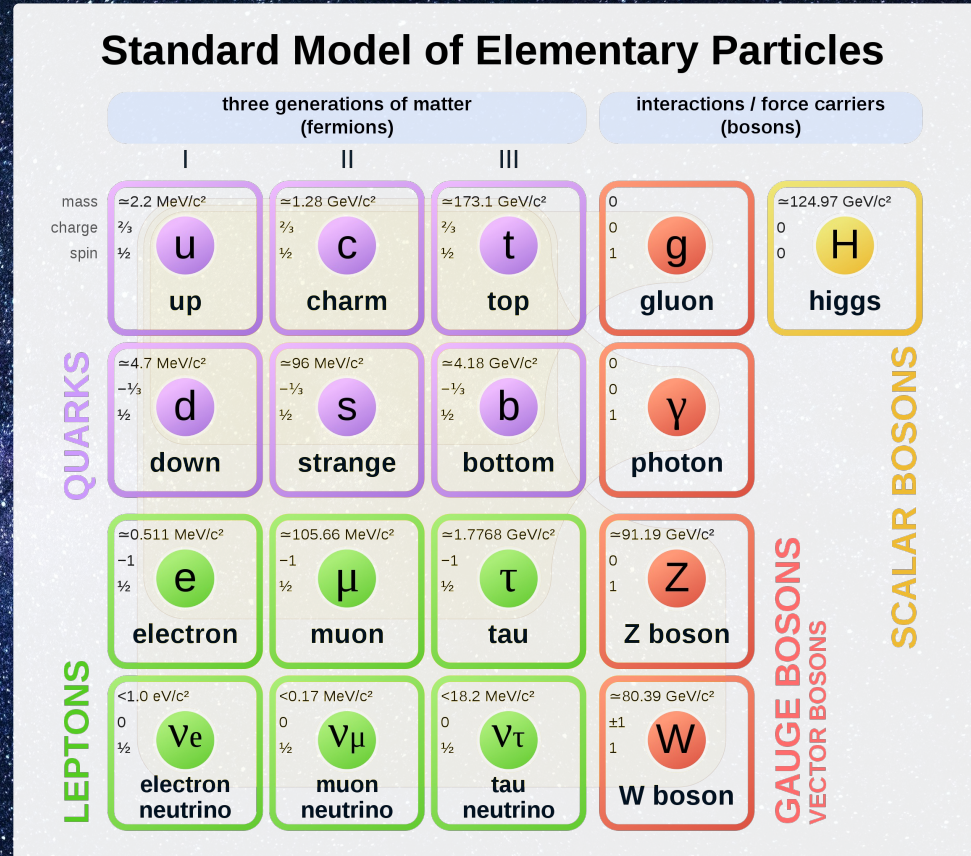
Are dark matter particles produced at the LHC ?



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



The Standard Model is complete



The eighteen arbitrary parameters of the SM in your everyday life, Bob Cahn (1996)

Many deep questions remain, many of which require energy frontier experiments

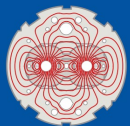
Many questions remain, of which many can be tackled at the LHC

The next steps

Preparing the future — the grand plan



Preparing the future — the grand plan

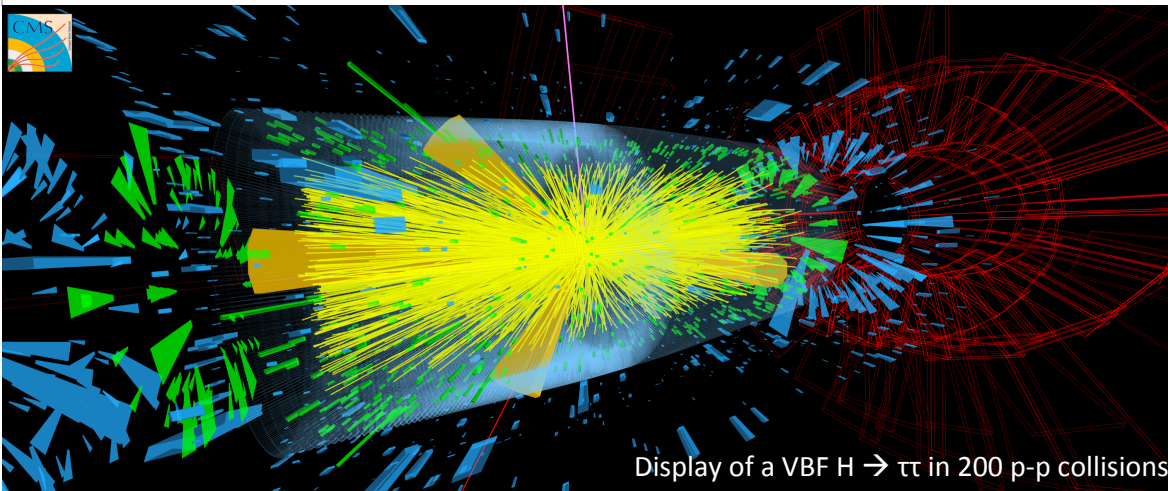
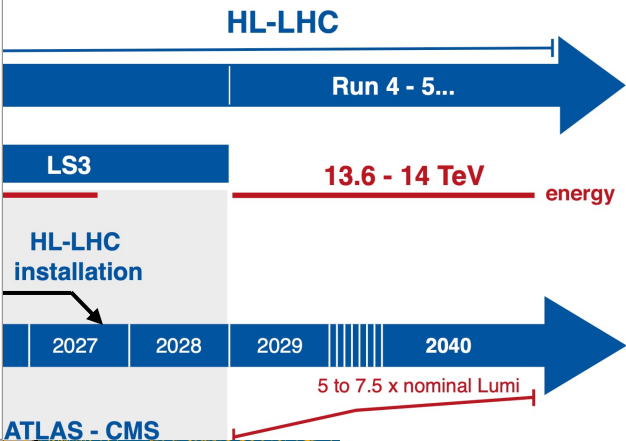


LHC / HL-LHC Plan

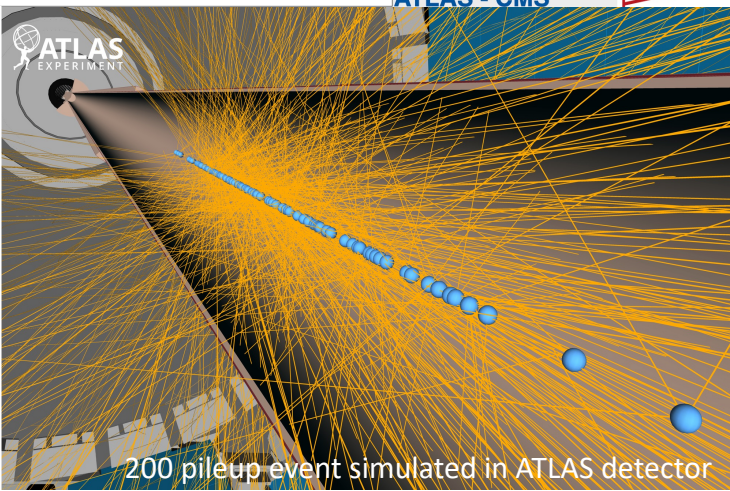


HL-LHC

- Higgs factory (400M Higgs bosons produced) for precise Higgs coupling measurements, access to Higgs self interaction and longitudinal vector boson scattering, and increased overall rare & new physics sensitivity
- With the improved LHC and injectors, large-scale detector upgrades required for improved robustness against pileup and radiation



Display of a VBF $H \rightarrow \tau\tau$ in 200 p-p collisions



200 pileup event simulated in ATLAS detector

Integrated luminosity
3000 fb⁻¹
4000 fb⁻¹

PHYSICS

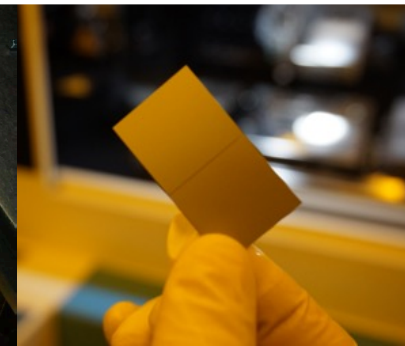
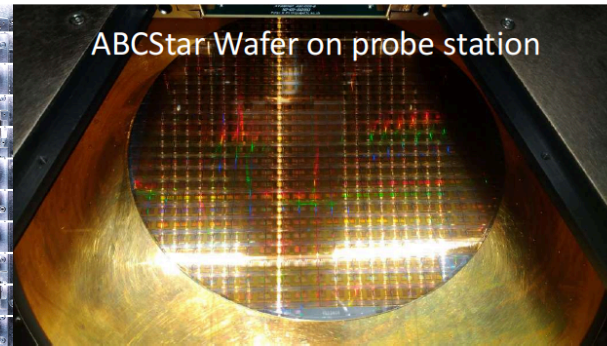
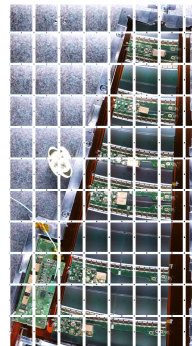
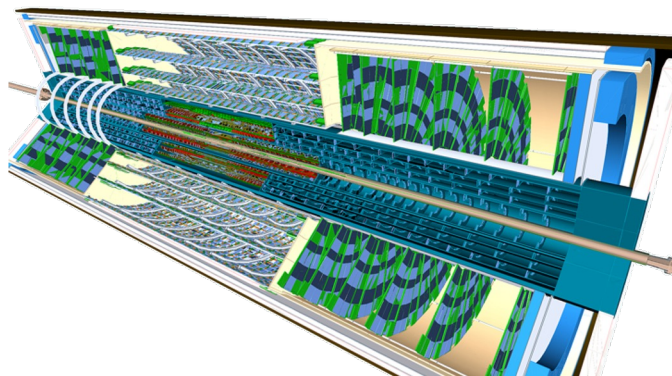
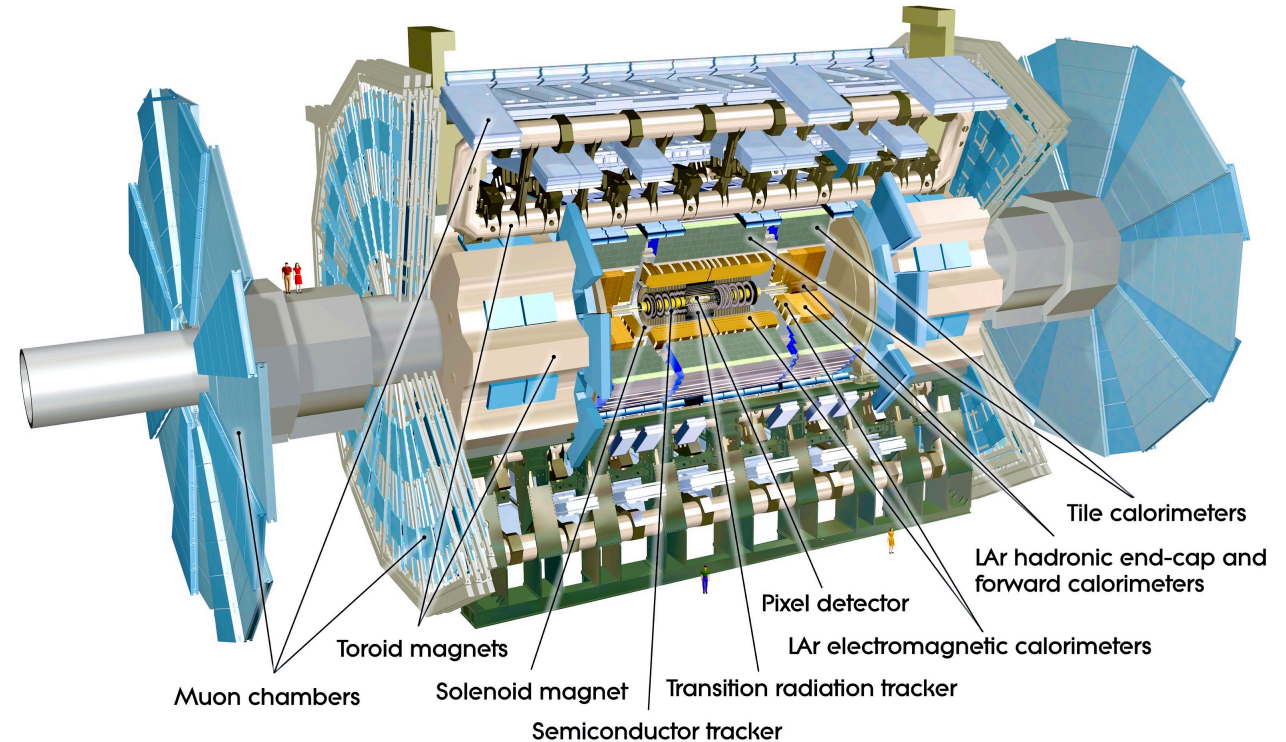
High-Luminosity LHC (HL-LHC)



The HL-LHC promises 20 times the data sample currently collected

Its beam intensity requires unprecedented detector and computing technologies:

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



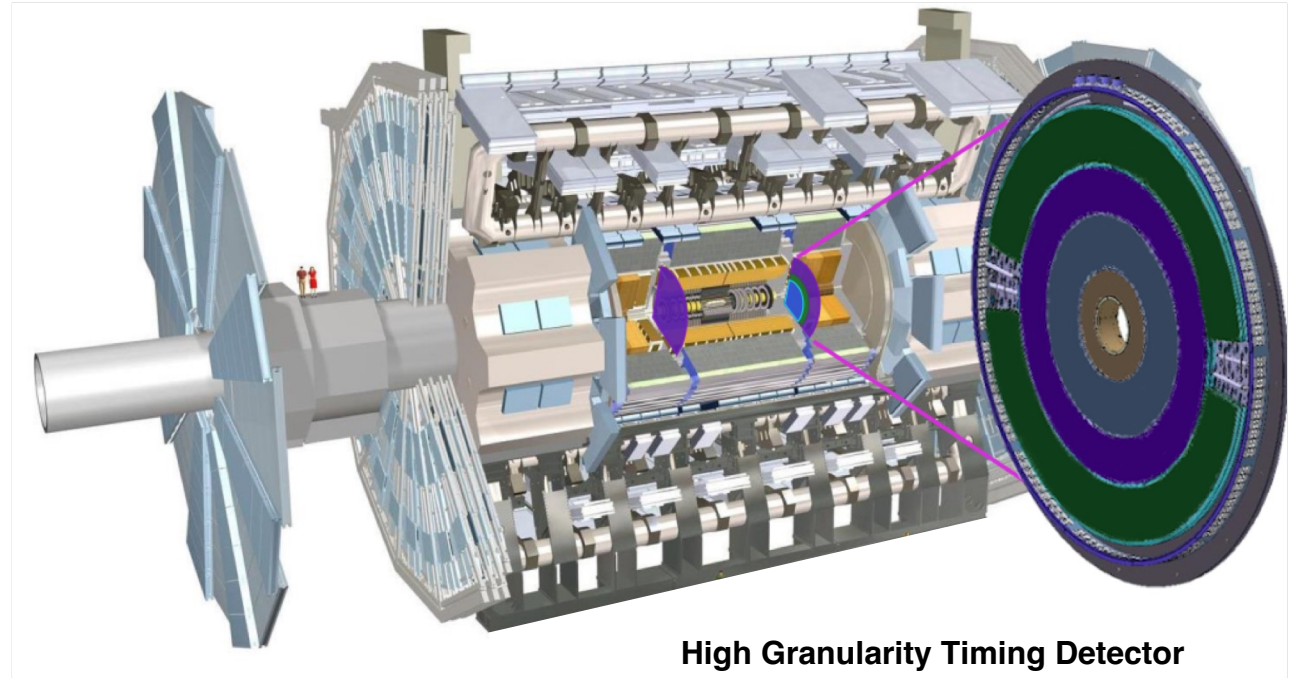
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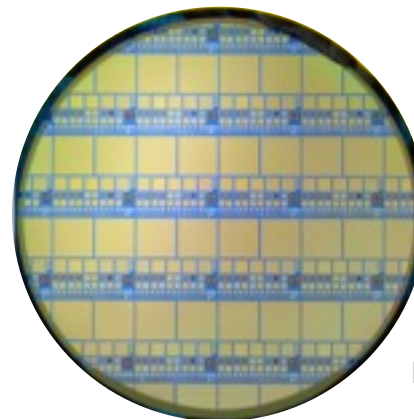
Its beam intensity requires unprecedented detector and computing technologies:

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



High Granularity Timing Detector

Novel technology with strong contributions from Moroccan ATLAS groups

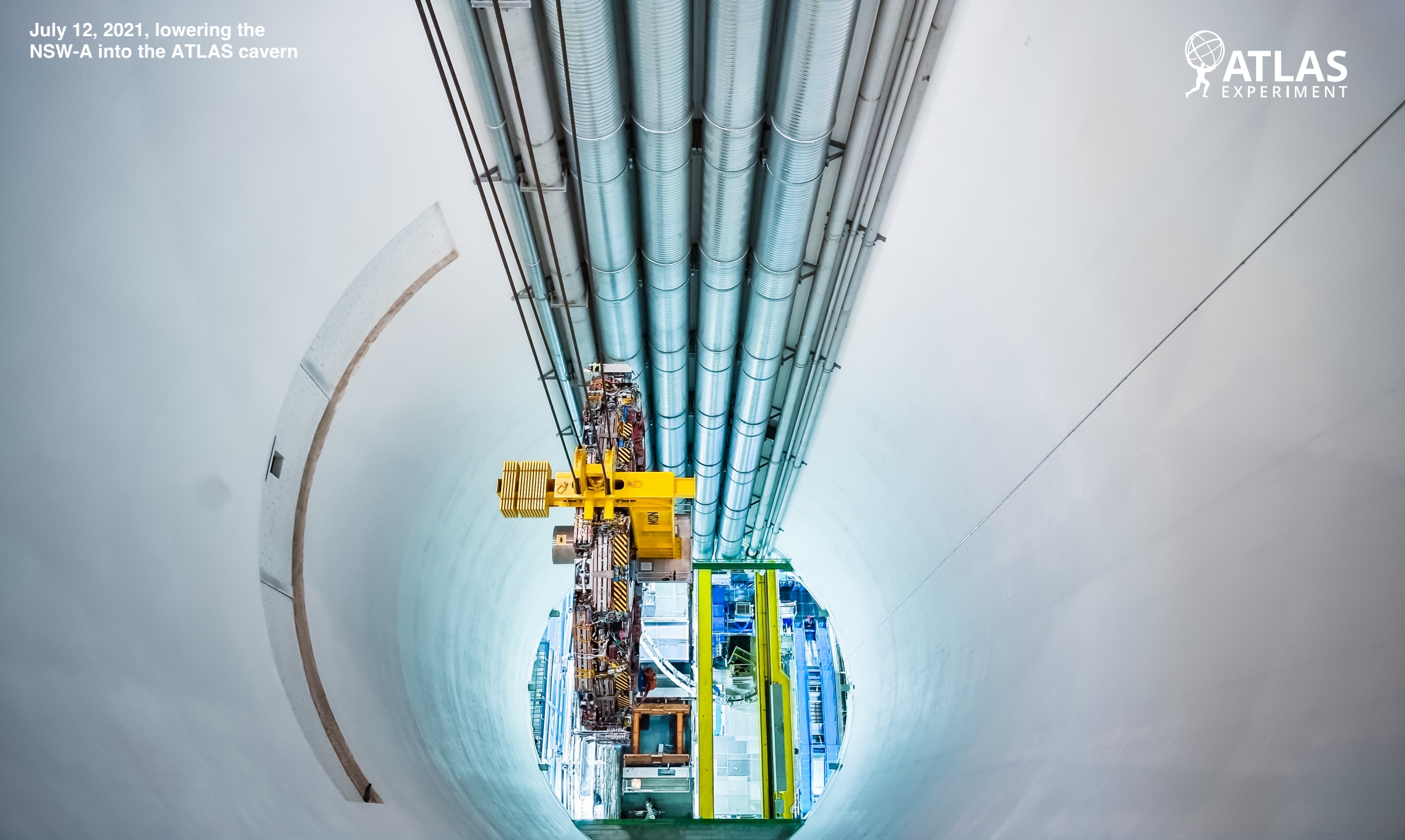


LGAD prototype wafers

Detector upgrades for the HL-LHC



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



Extremely successful LHC runs between 2010 and 2018, and continuing ...

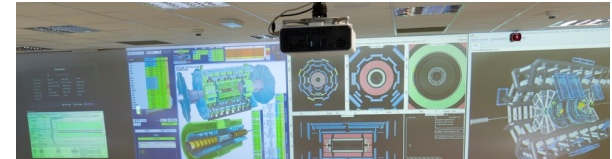
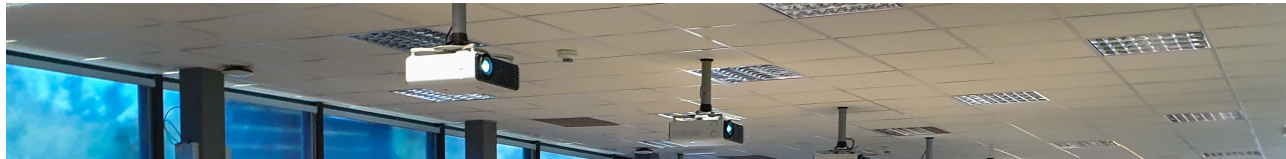
Run 3 (2022–2025) at 13.6 TeV has begun

First 13.6 TeV collisions on 5 July 2022

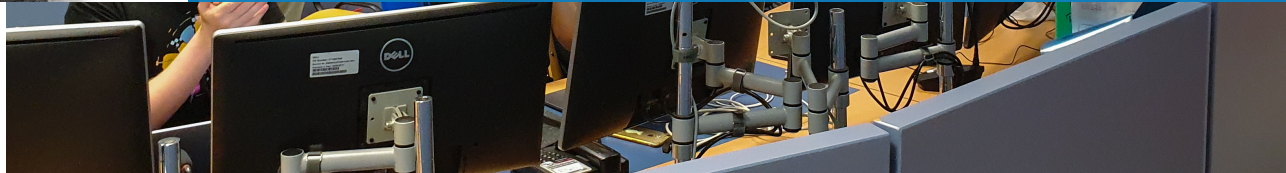
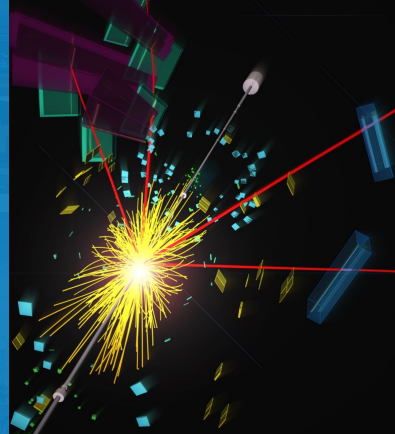
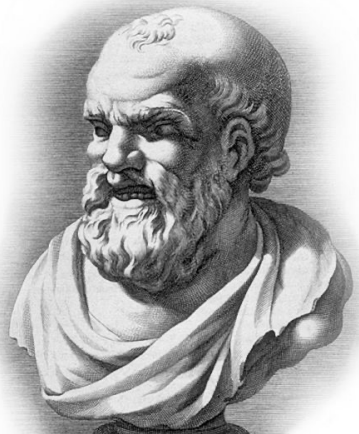


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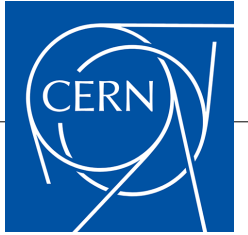
**We've come a long way —
the adventure continues**



<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

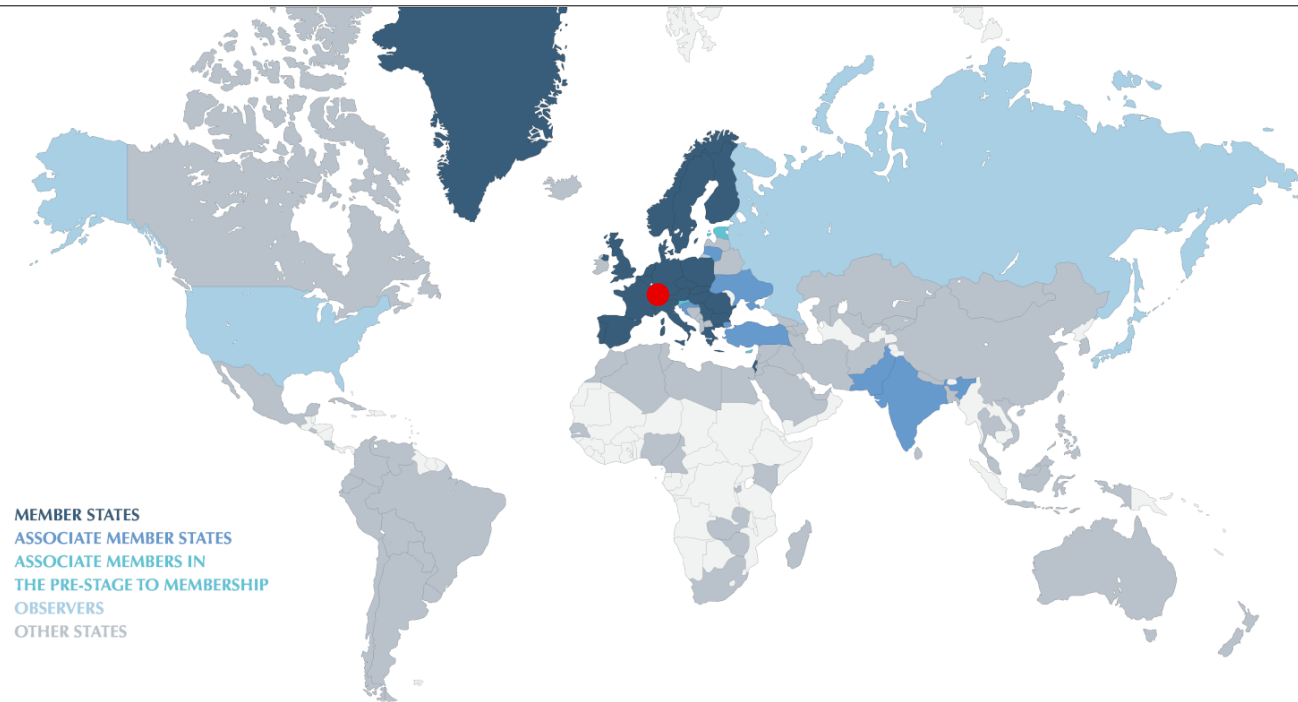
Cyprus – Estonia – Slovenia

6 Associate Member States

Croatia – India – Lithuania – Pakistan –
Turkey – Ukraine

6 Observers

Japan – Russia – USA
European Union – JINR – UNESCO

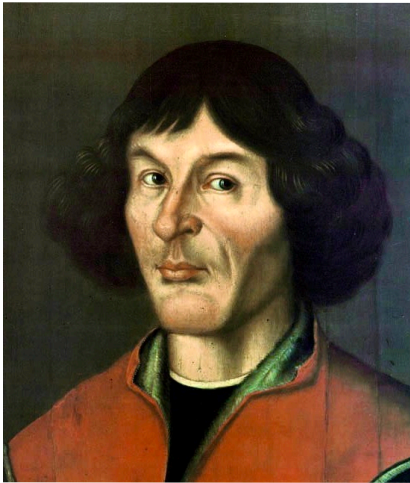


More than 50 Cooperation Agreements with non-Member States and Territories

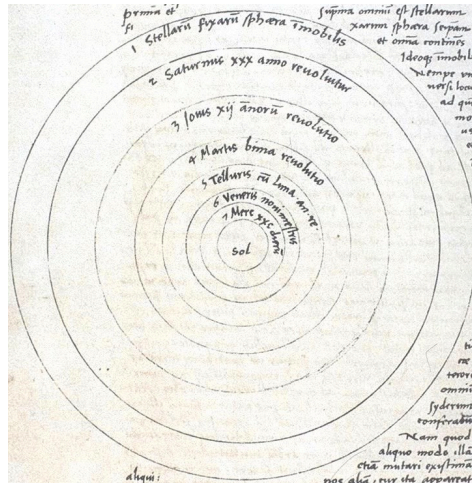
Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland
Iran – Jordan – Kazakhstan – Latvia – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco – 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

Setting the stage

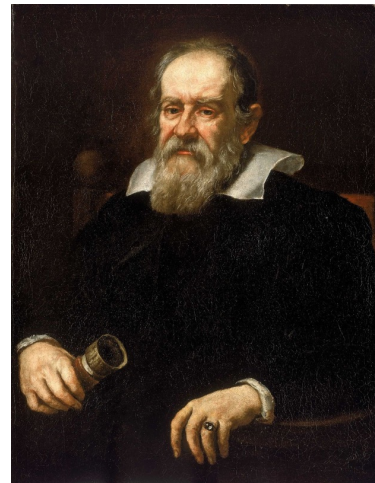
The scientific revolution began with **Nicolaus Copernicus** in the 16th century, shifting paradigms from the Ptolemaic model of the heavens to the heliocentric one, continued with **Galileo Galilei** and his *Dialogue Concerning the Two Chief World Systems* (1632), to find its culmination and accomplishment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



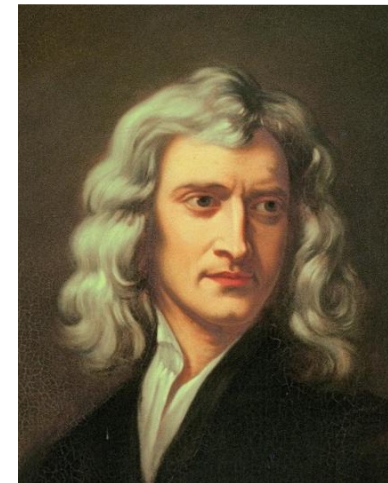
N. Copernicus (1473–1543)



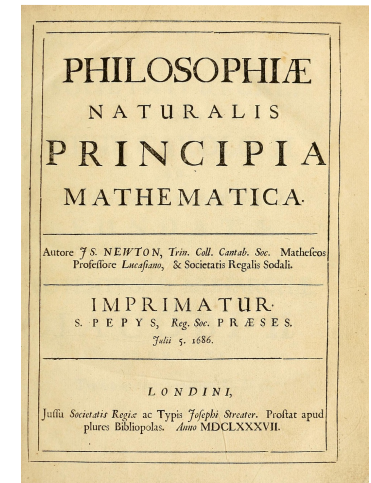
On the Revolutions of the Celestial Spheres, published in 1543



Galileo Galilei (1564–1642)



Isaac Newton (1642–1726)

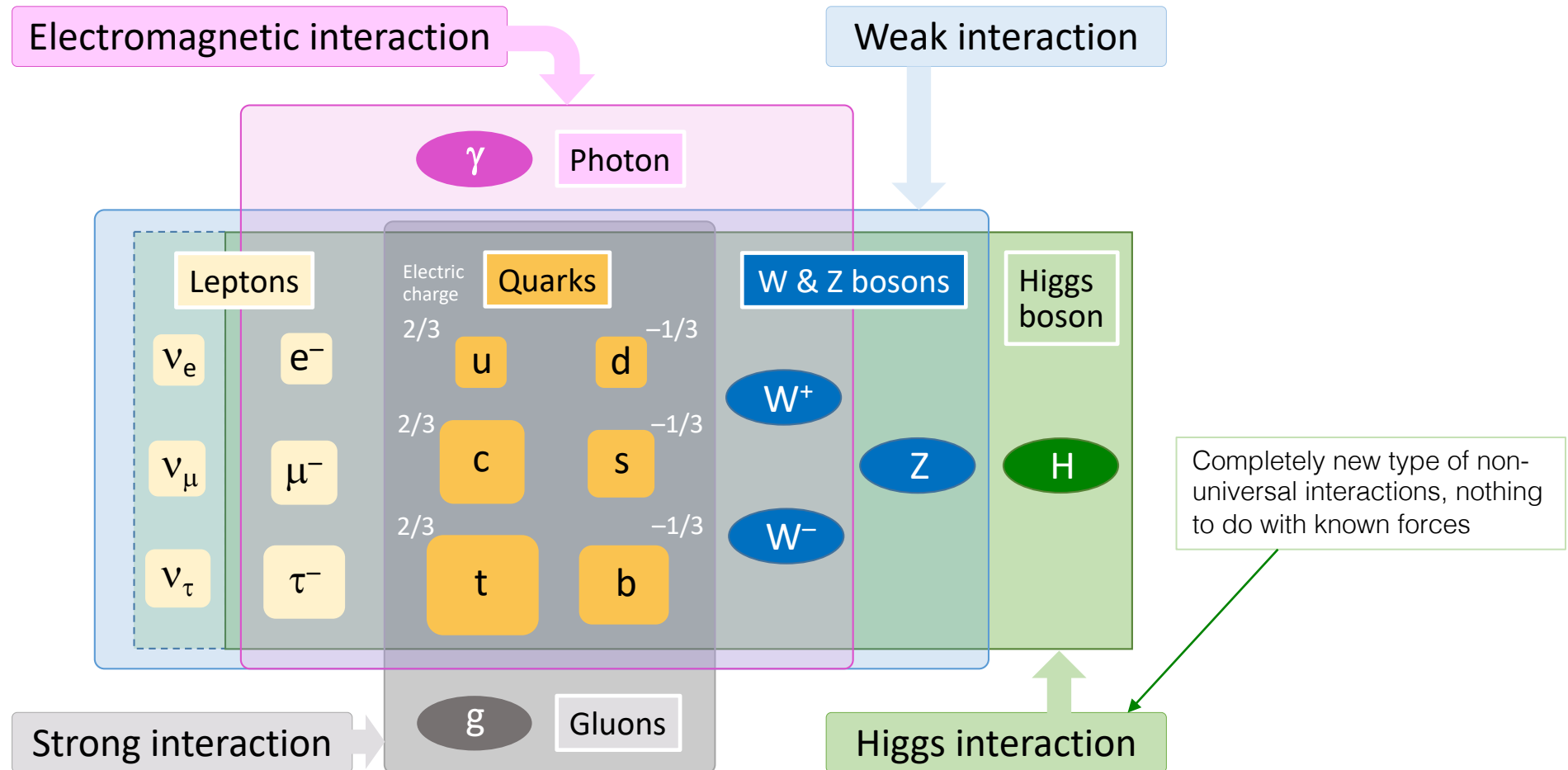


Philosophiæ Naturalis Principia Mathematica, published in 1687

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

The Standard Model

These equations describe all known particles and their interactions



The Standard Model

As well as larger
scales of the universe

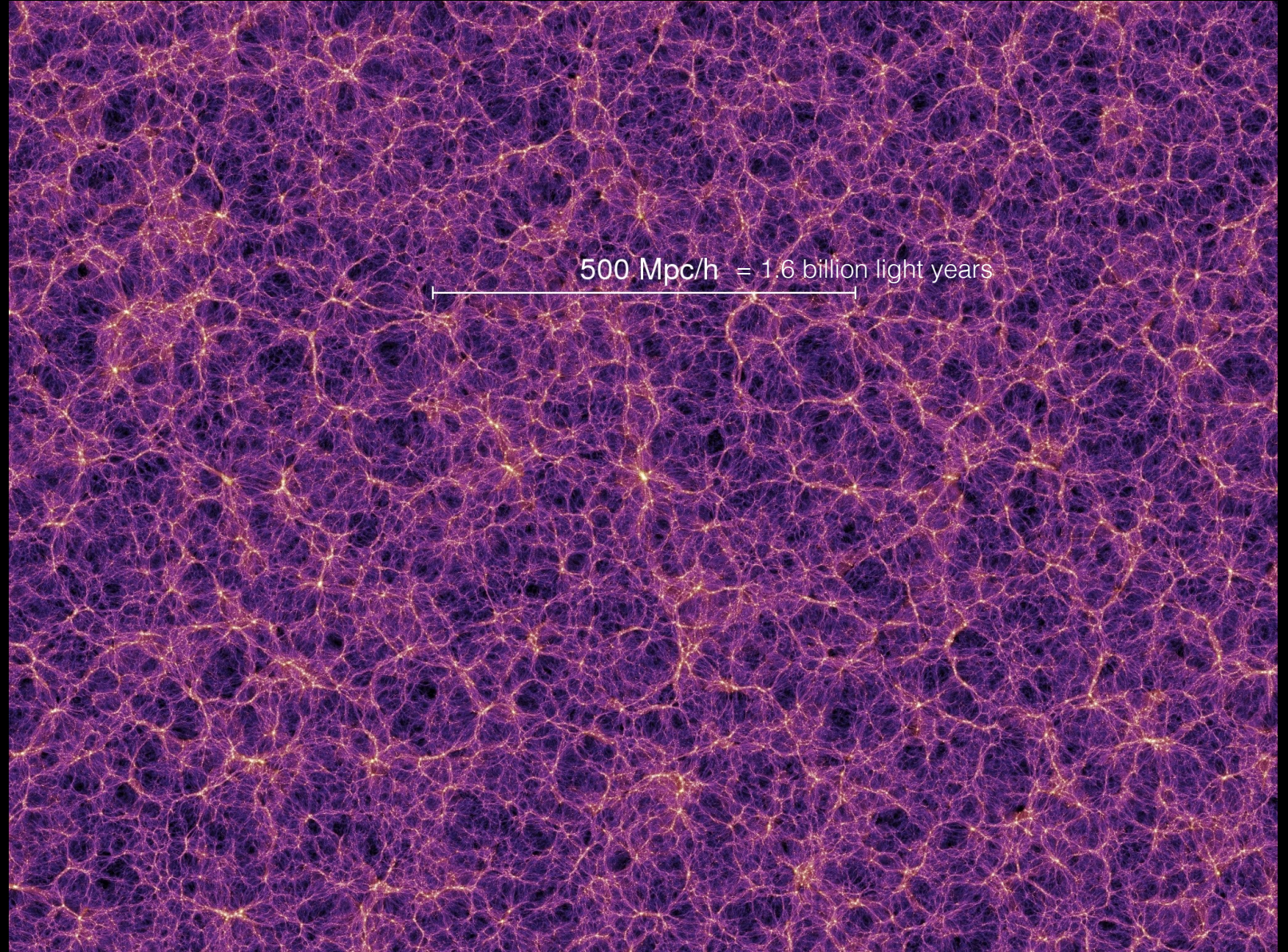


Size of about 220 thousand light years, about 1 trillion stars

Andromeda Galaxy
(2.5 million light years from Earth)

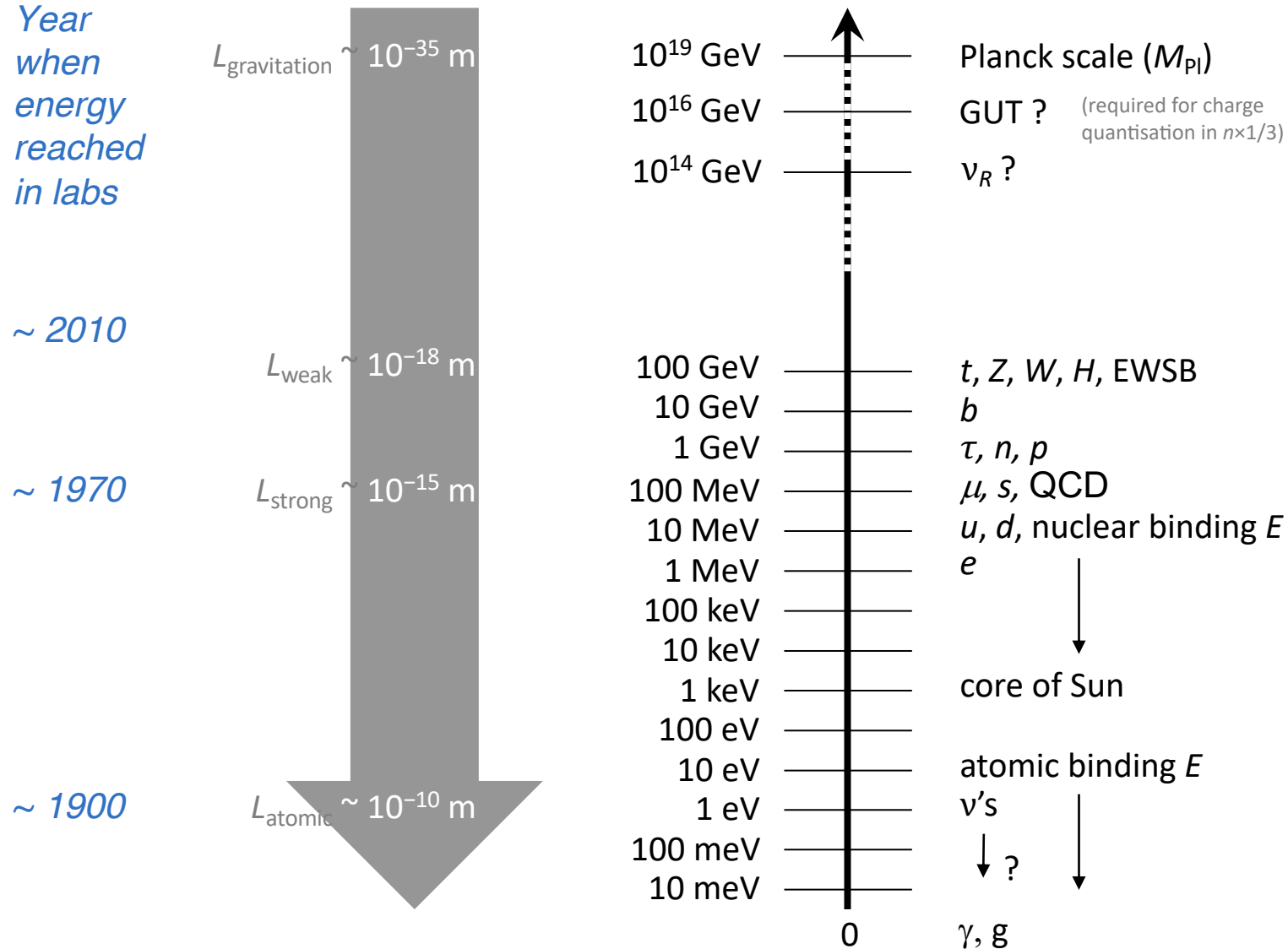
The Standard Model

... up to the largest
scales ...

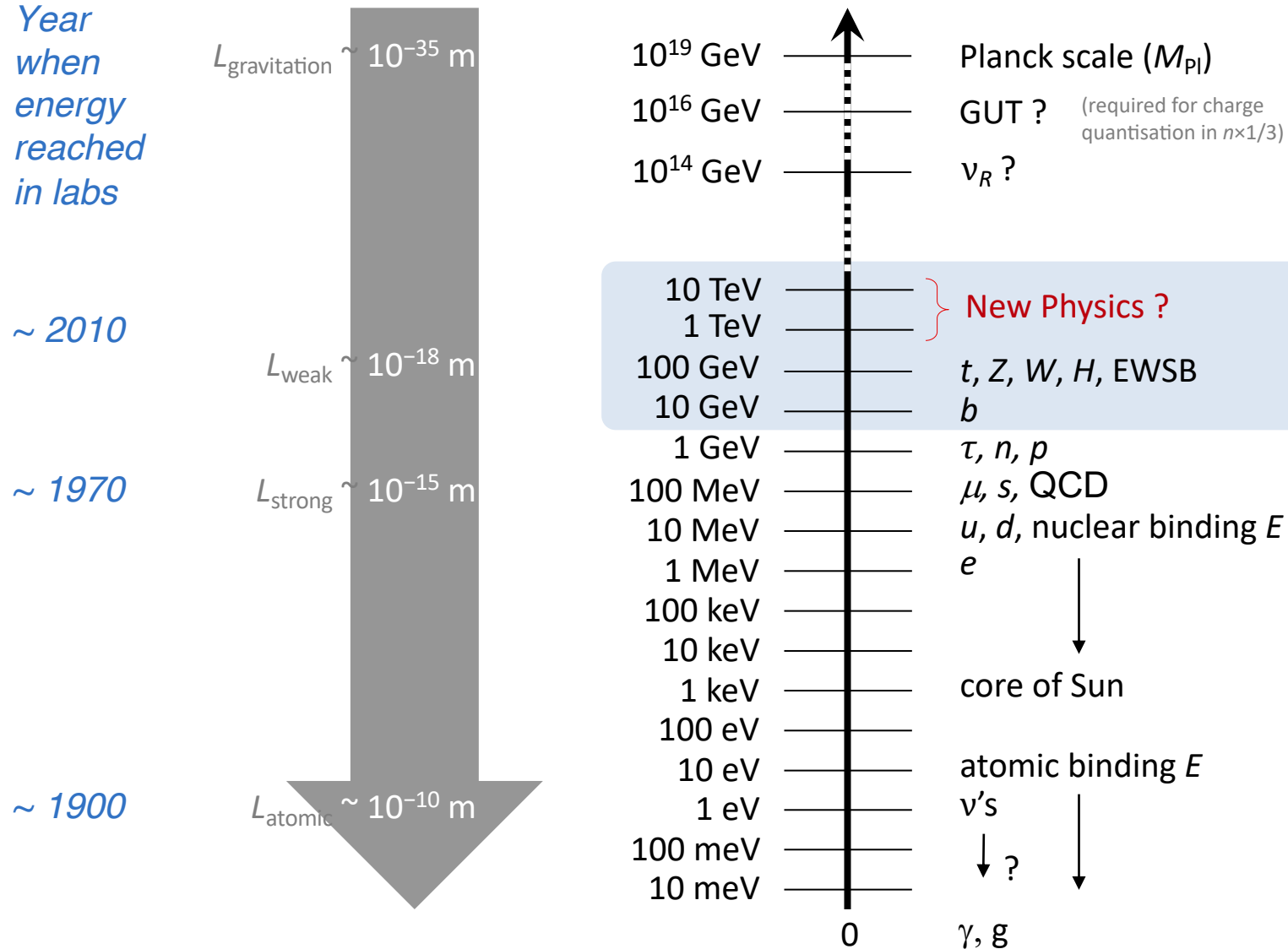


Simulation of structure formation
(dark matter, astro-ph/0504097)

Mass (= energy) and length scales

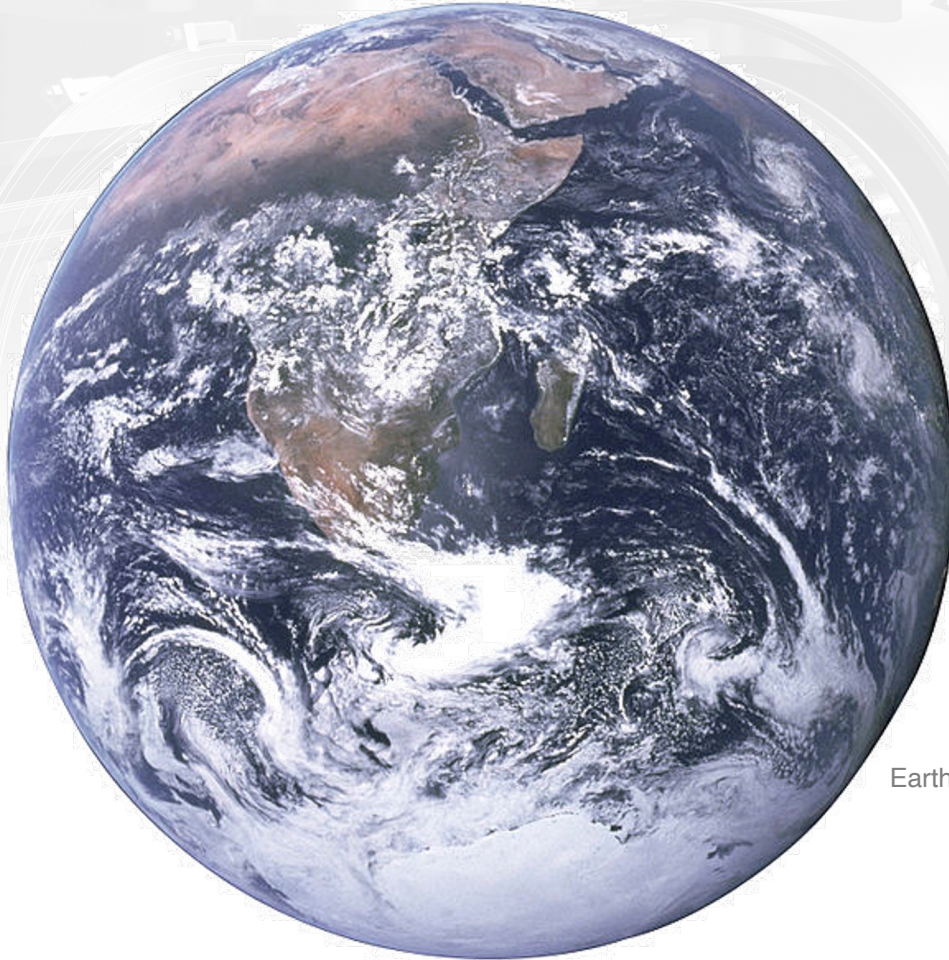


Mass (= energy) and length scales



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

Nanoscience



Earth

Particle physics today
(TeV scale)



Siphonaptera (flea)



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

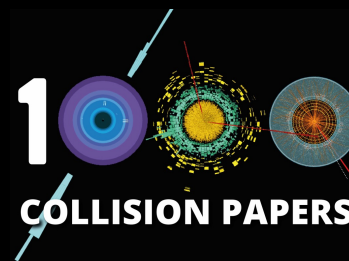
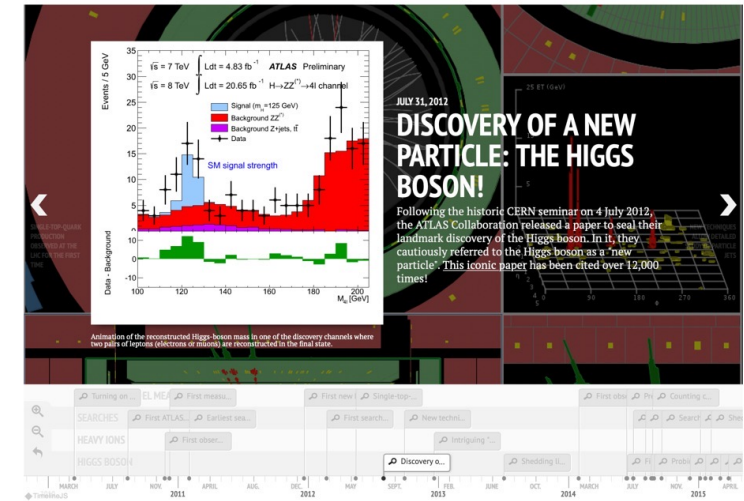
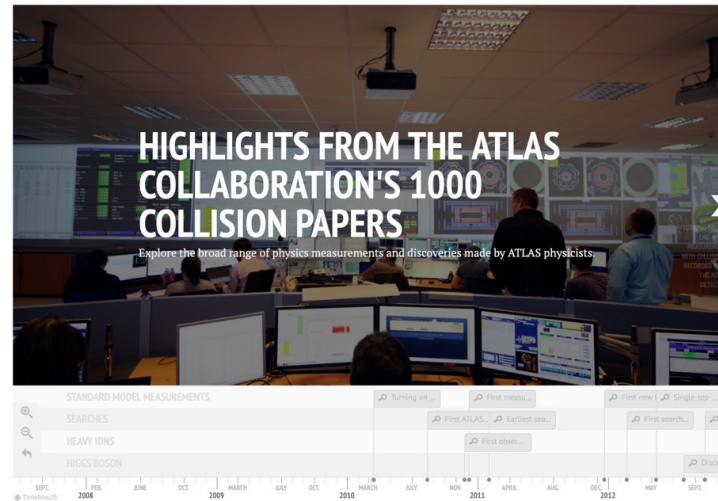
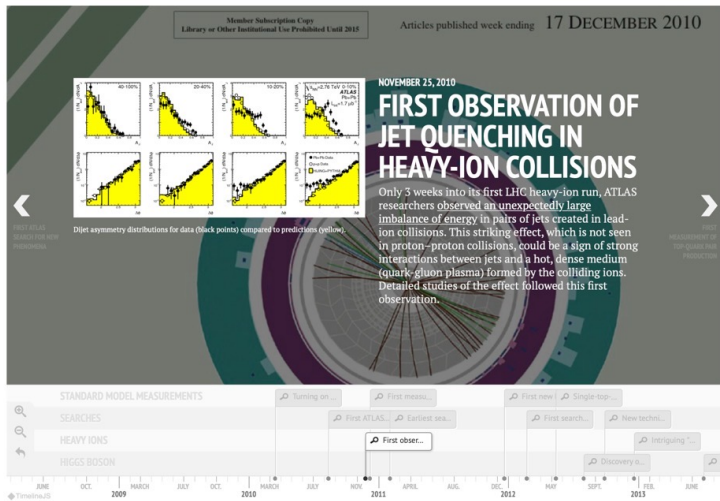


Aerial view of the 25 GeV Proton Synchrotron at CERN in 1965

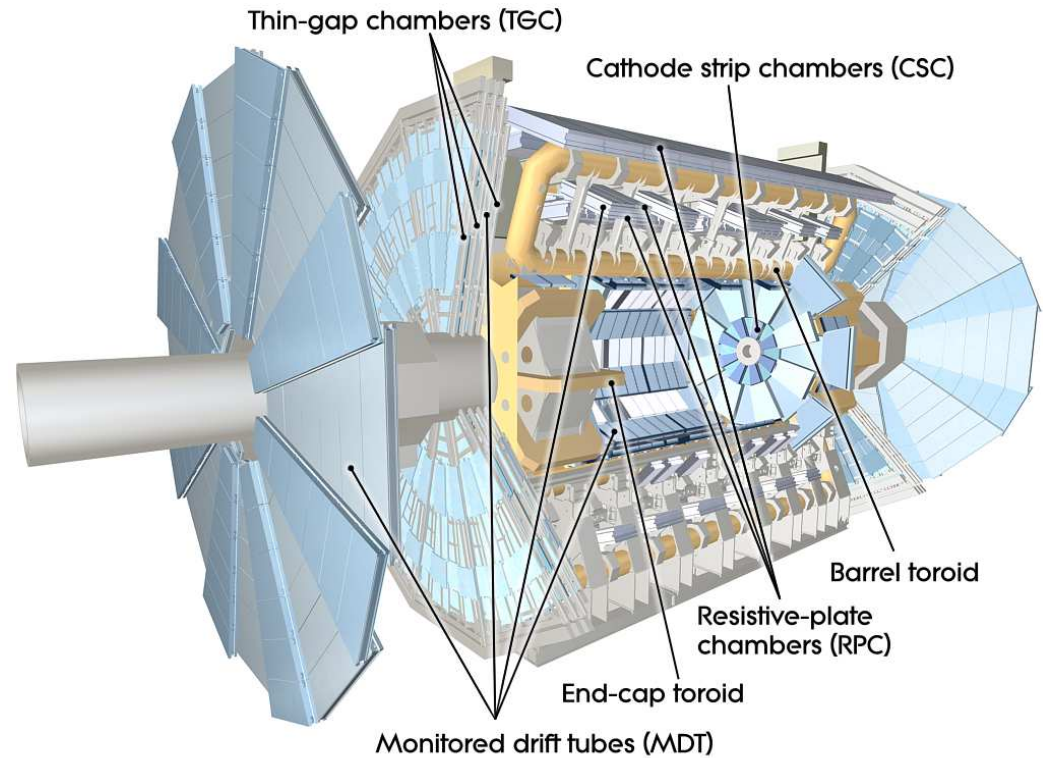
This spring we celebrated the results of 1000 collision papers

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>

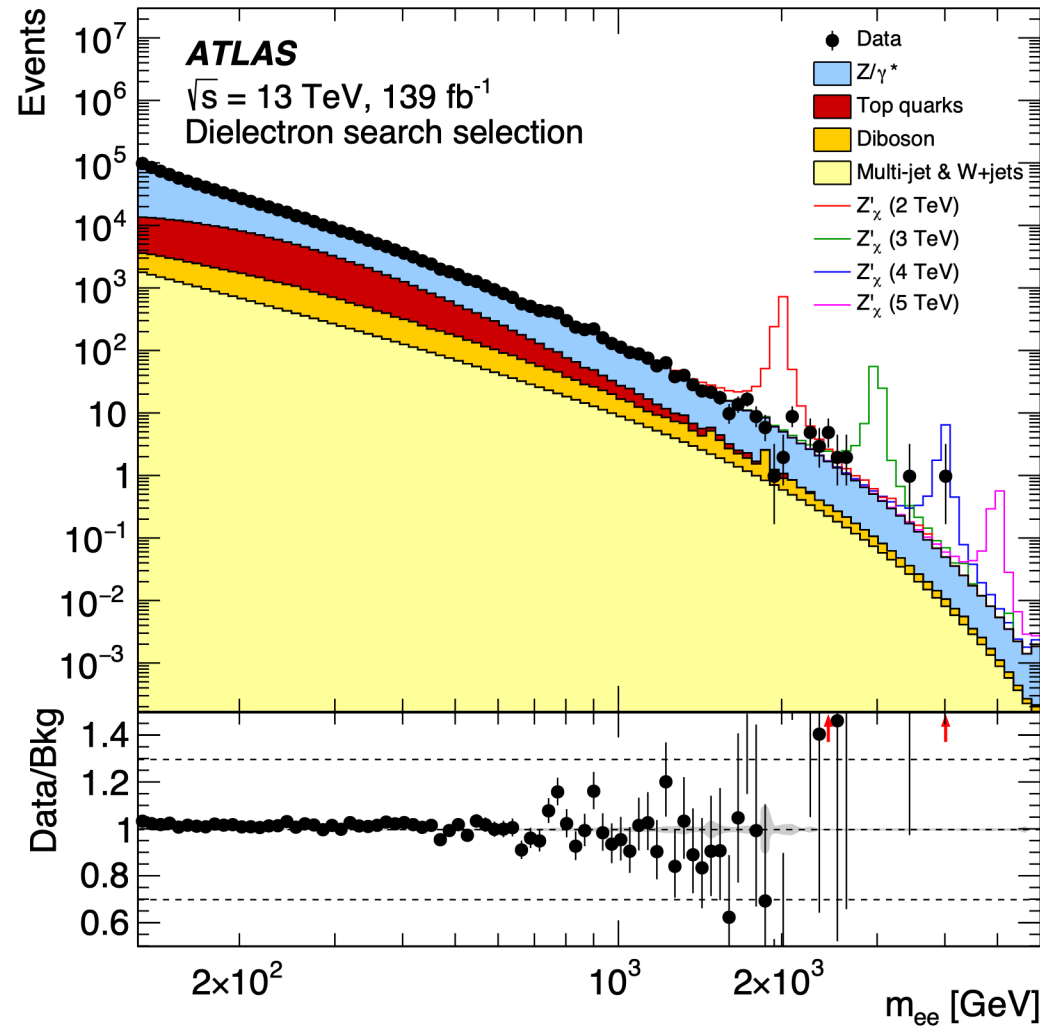


ATLAS Detector construction and installation – Muons

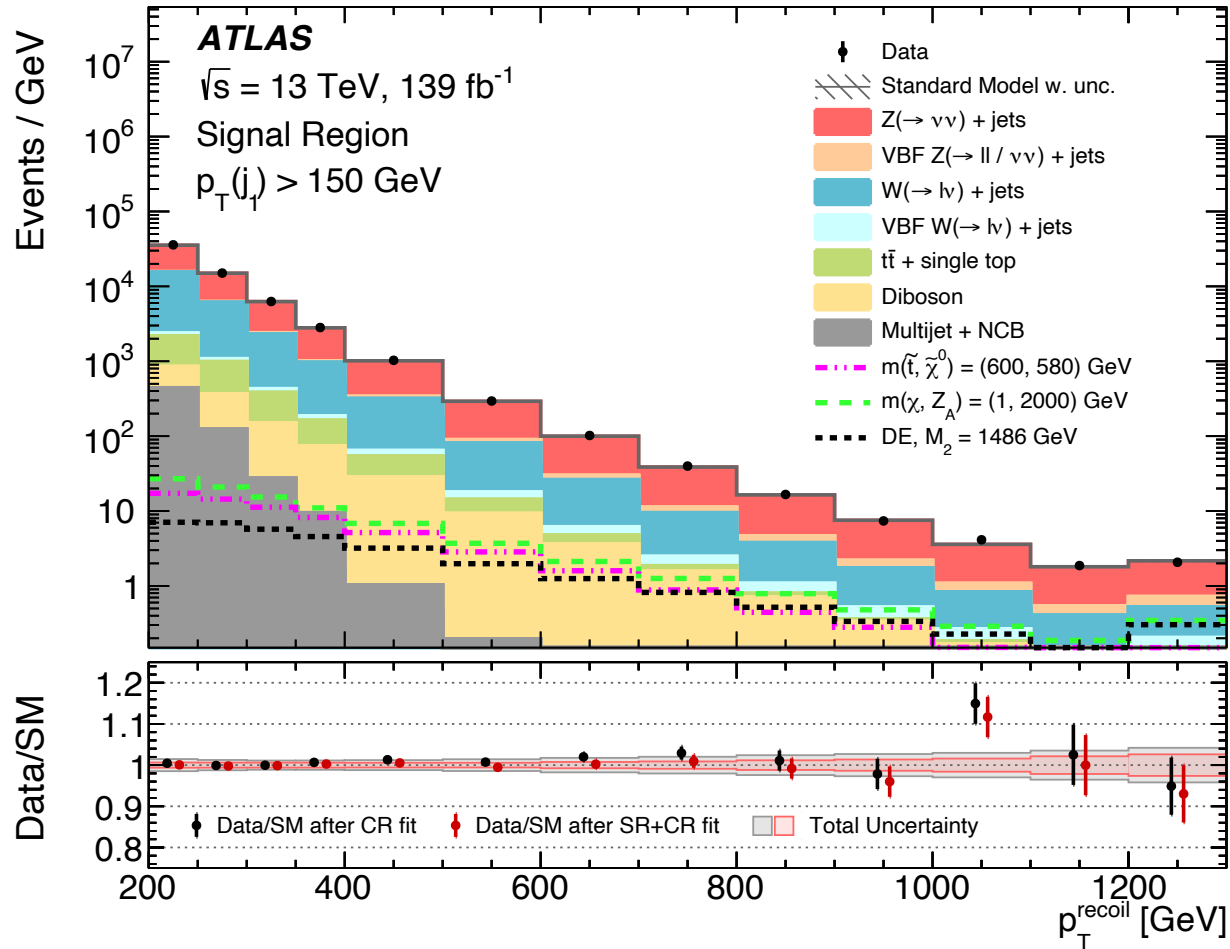


View on the Big Wheels, intermediate muon stations with four 25 m diameter wheels on each forward side

Do new forces with new carriers exist?

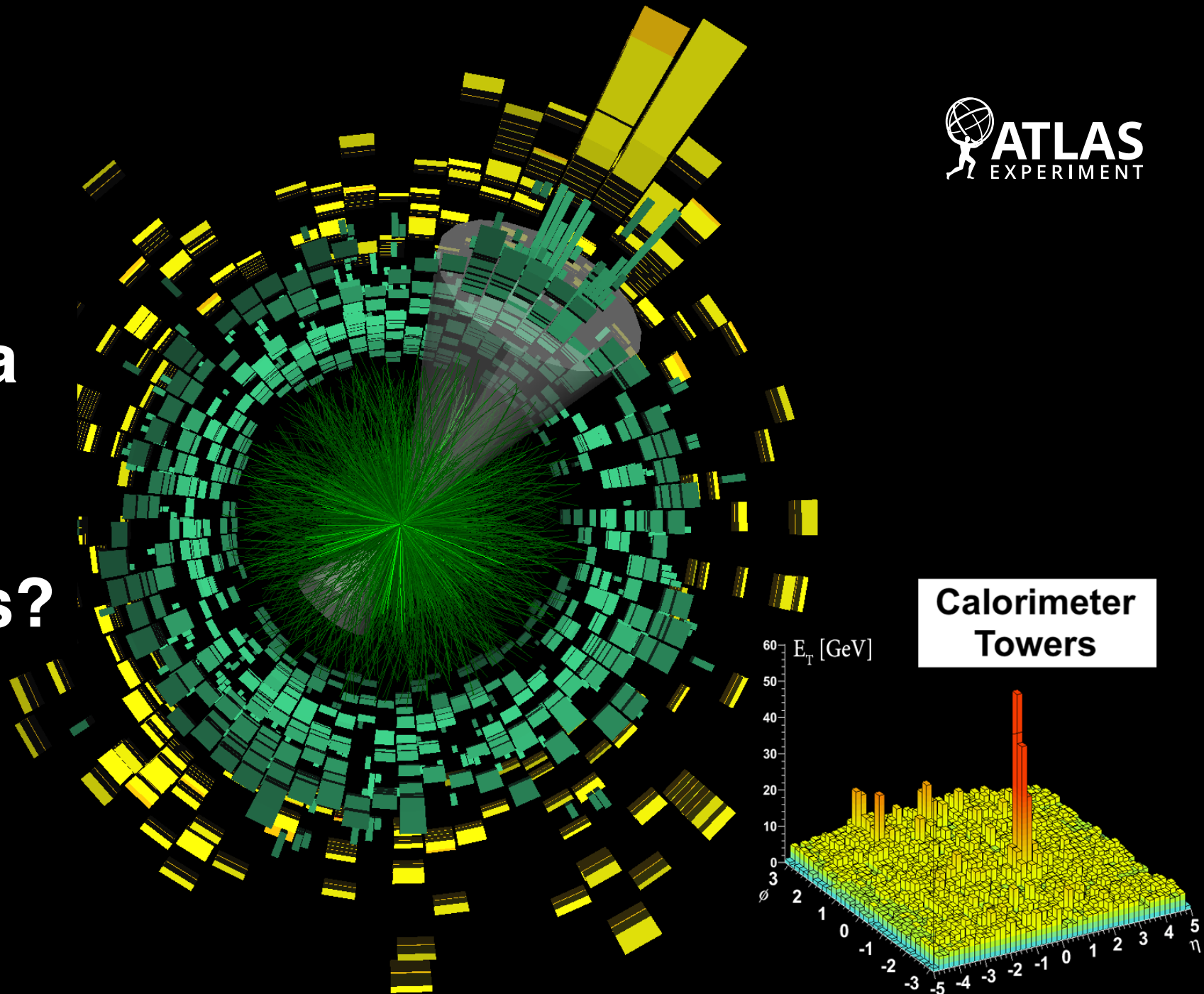


Are dark matter particles produced at the LHC ?



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



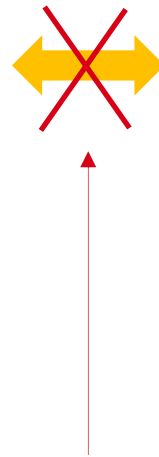
We have two beautiful, extremely precise theories

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

Preparations for the High-Luminosity LHC



Preparations for the High-Luminosity LHC



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

