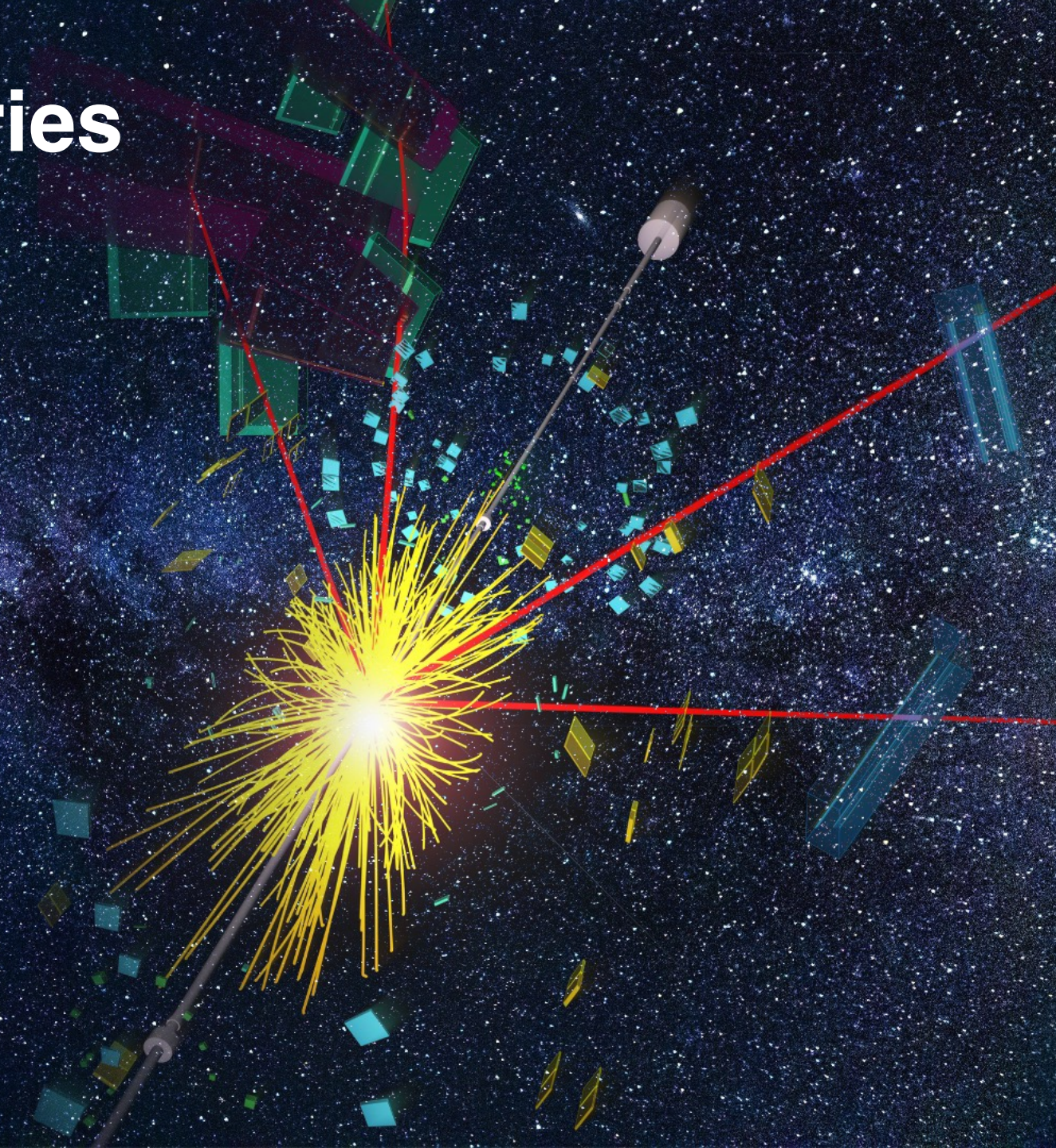


Smashing discoveries

Particle physics at the
high-energy frontier

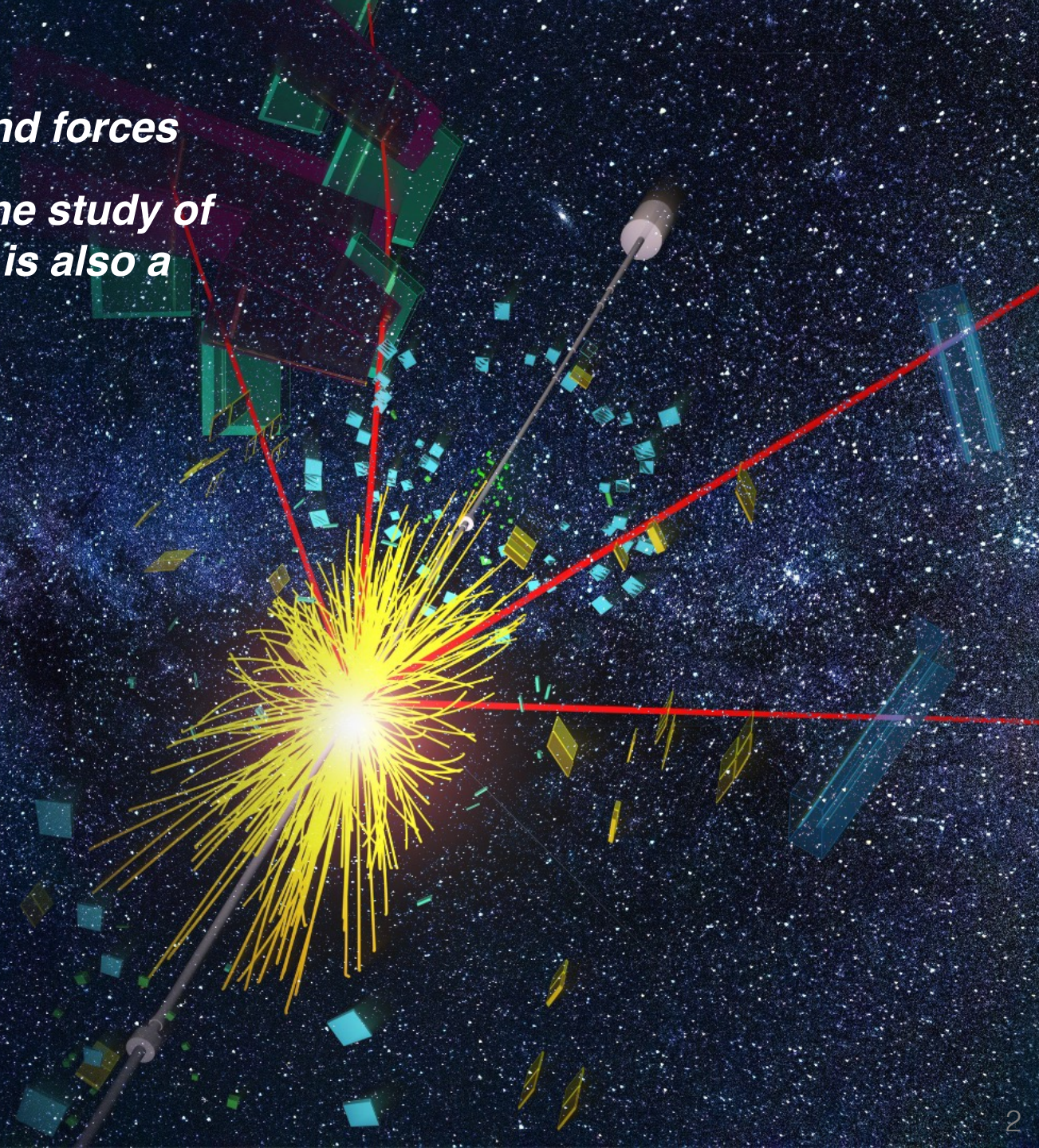
Andreas Hoecker (CERN)

Colloquium, USTC, 16 May 2024



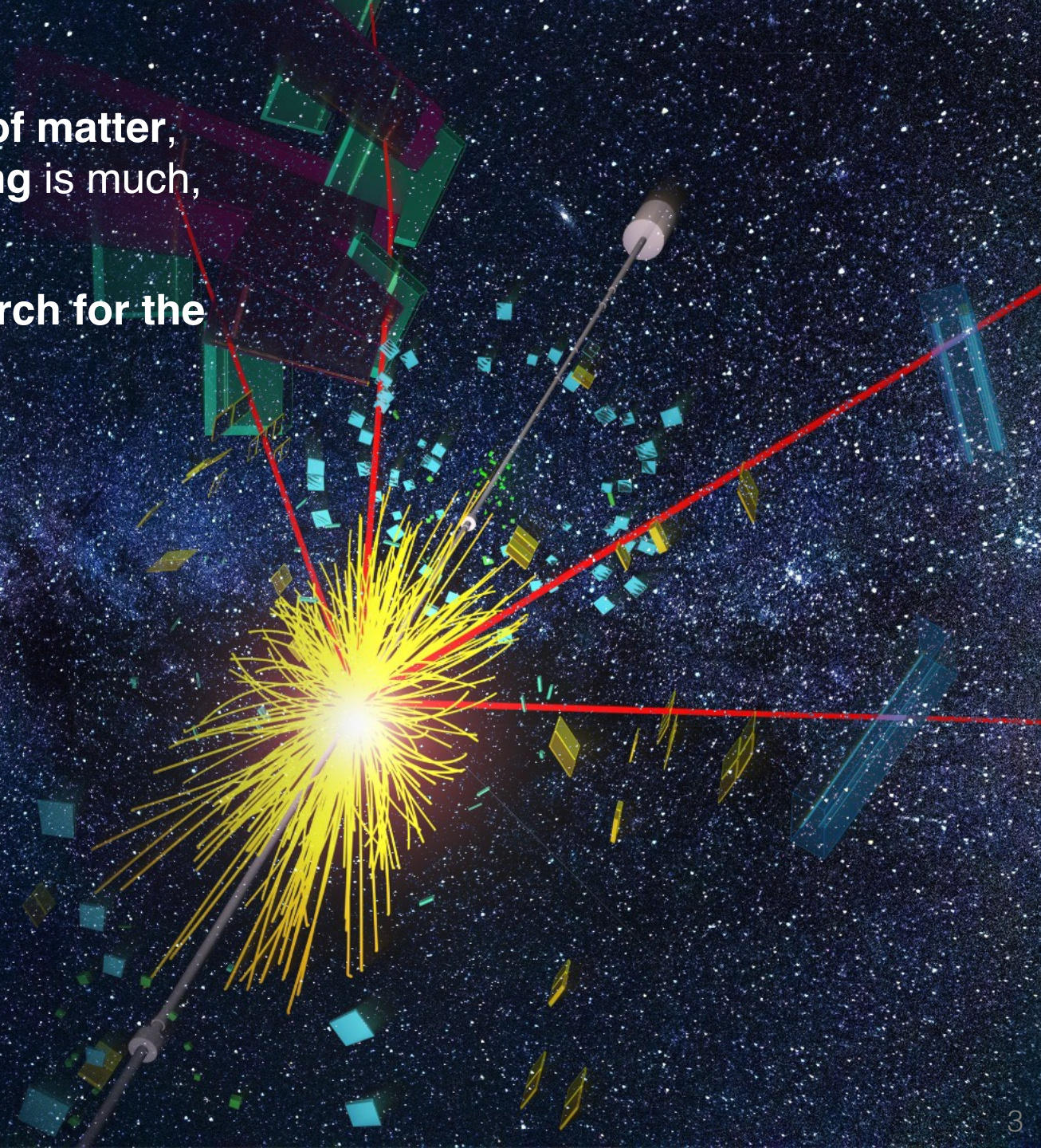
It's all made of a handful of particles and forces

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



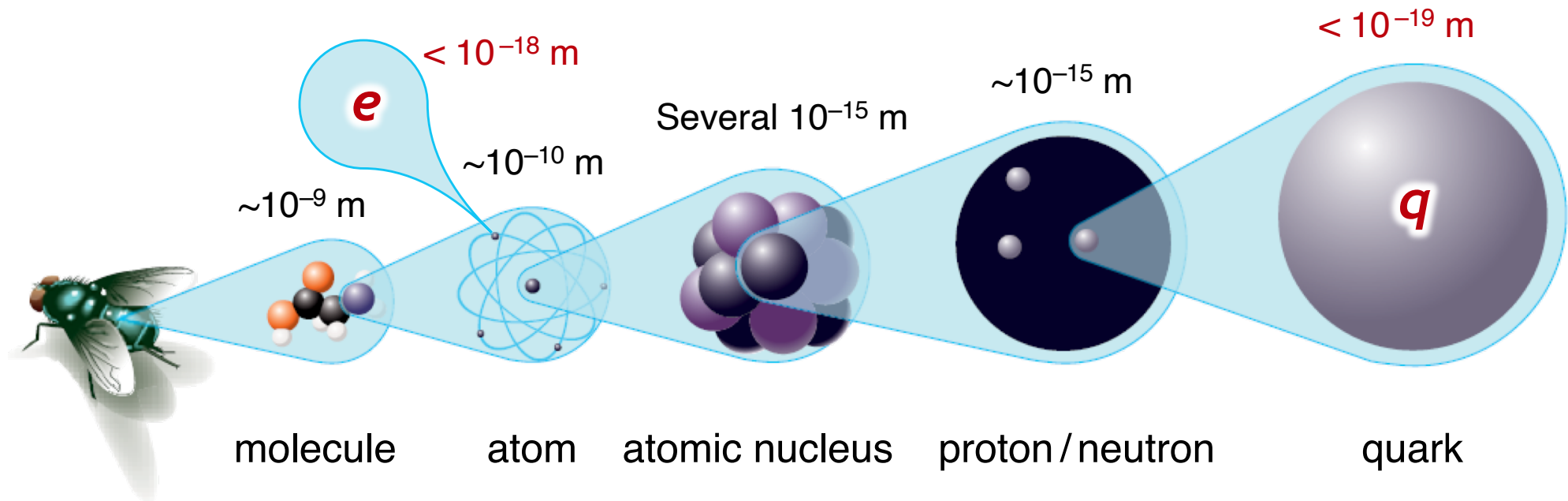
Humanity's search for the **smallest unit of matter, its different forms, and the forces acting** is much, much older than *particle physics*

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



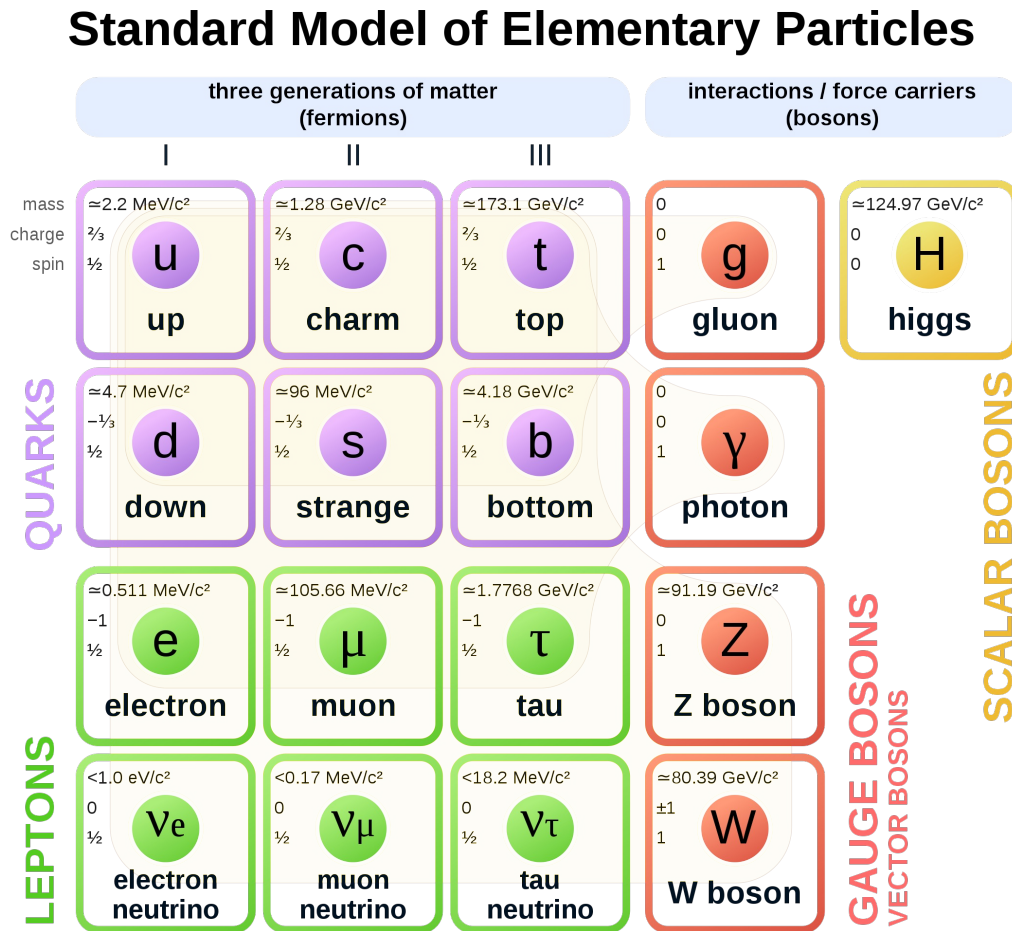
It's all made of a handful of particles and forces

The sub-atomic structure of matter



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

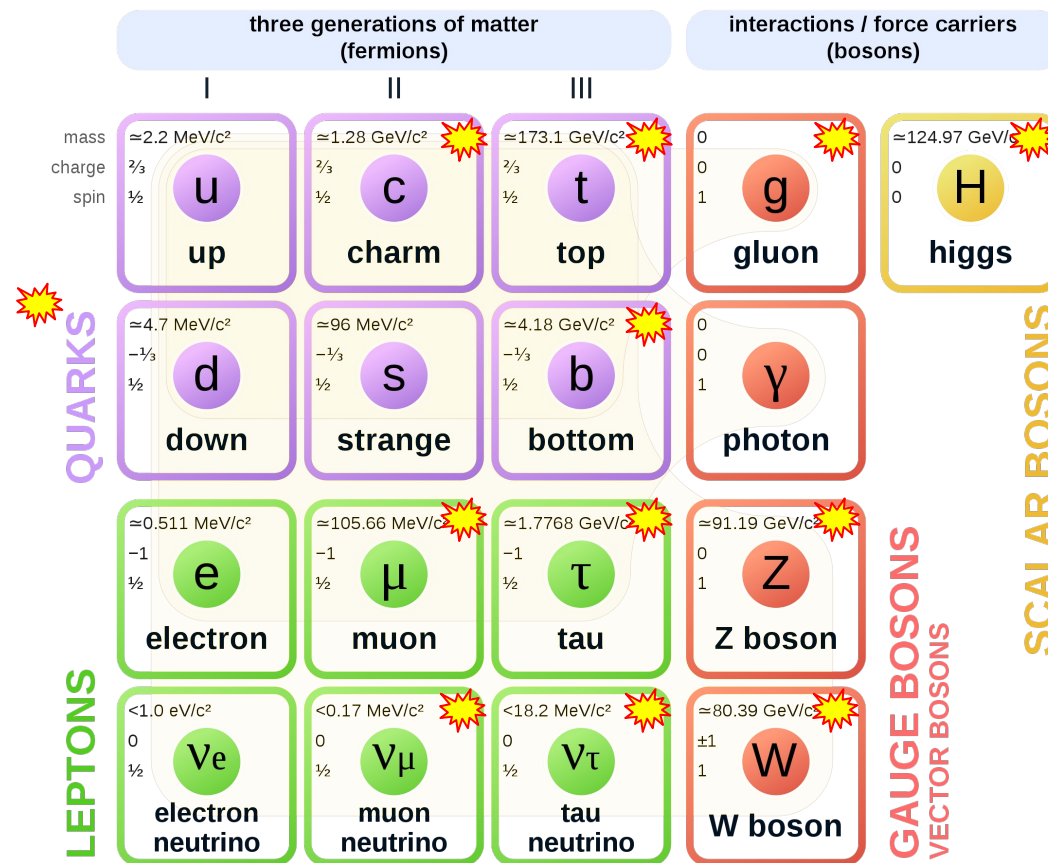
The sub-atomic structure of matter and its interactions **is described by the Standard Model**



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

The sub-atomic structure of matter and its interactions **is described by the Standard Model**

Standard Model of Elementary Particles



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

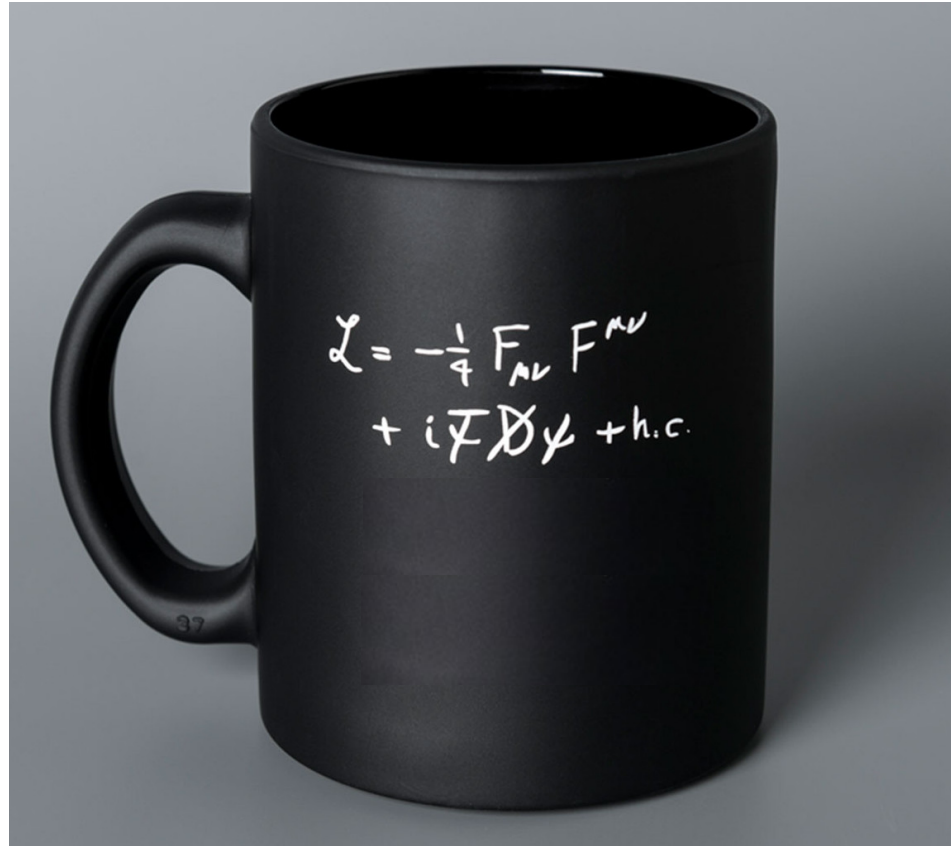
Completely new type of non-universal interactions, nothing to do with known forces

The Standard Model

The **Standard Model** is 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

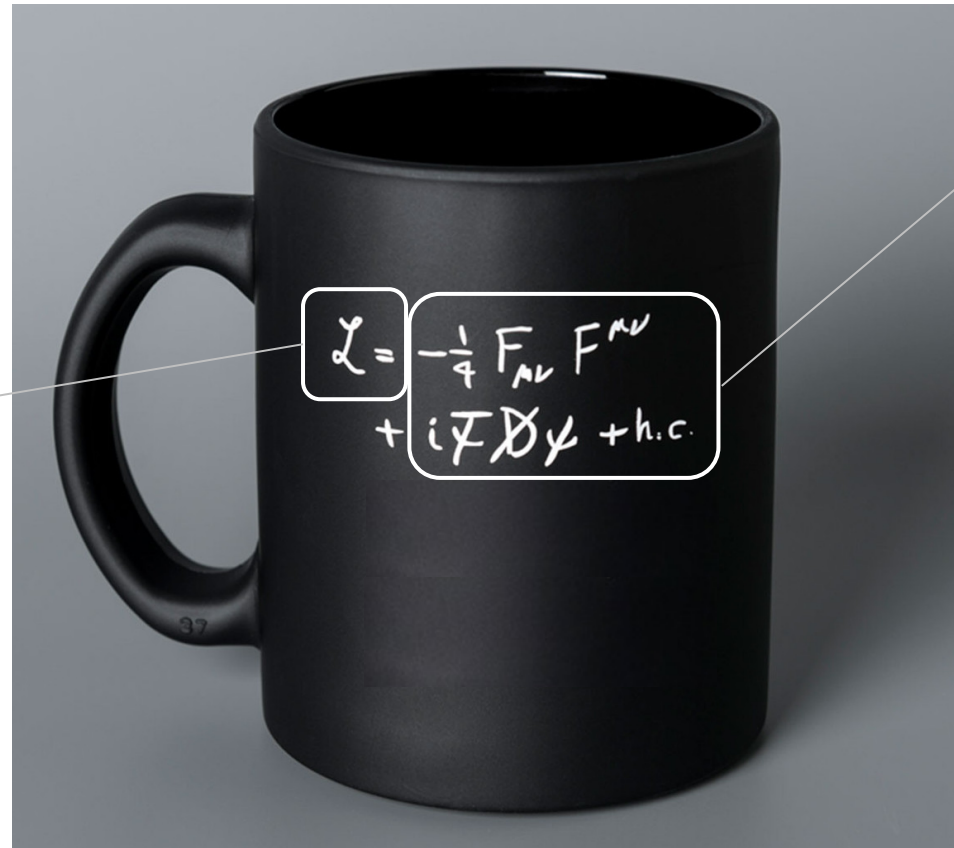
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The **Lagrangian** allows to derive the equations of motion of a system



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

Beauty: interactions governed by gauge symmetries with only 3 (EW) and 2 (QCD, θ_{strong} tiny $\rightarrow$ strong CP problem) parameters

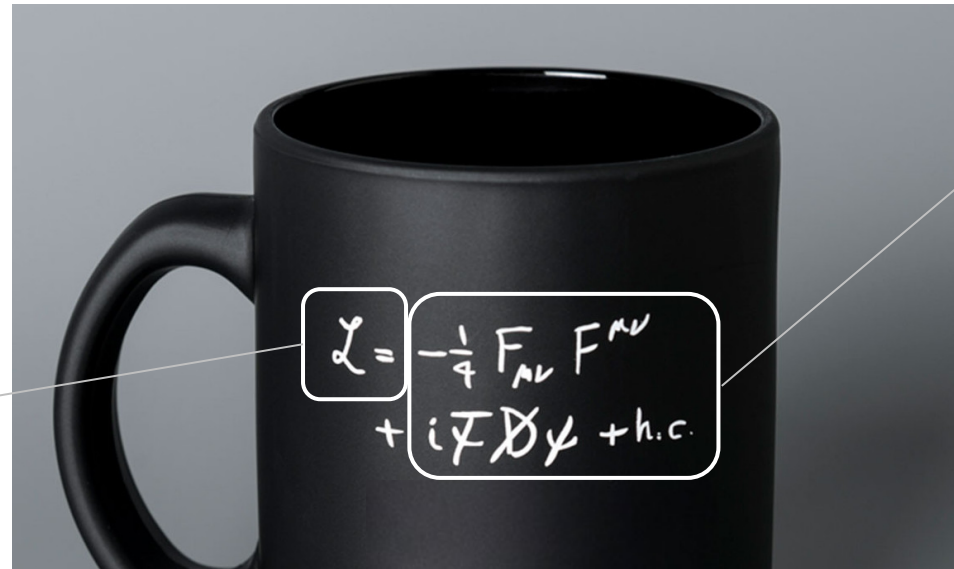
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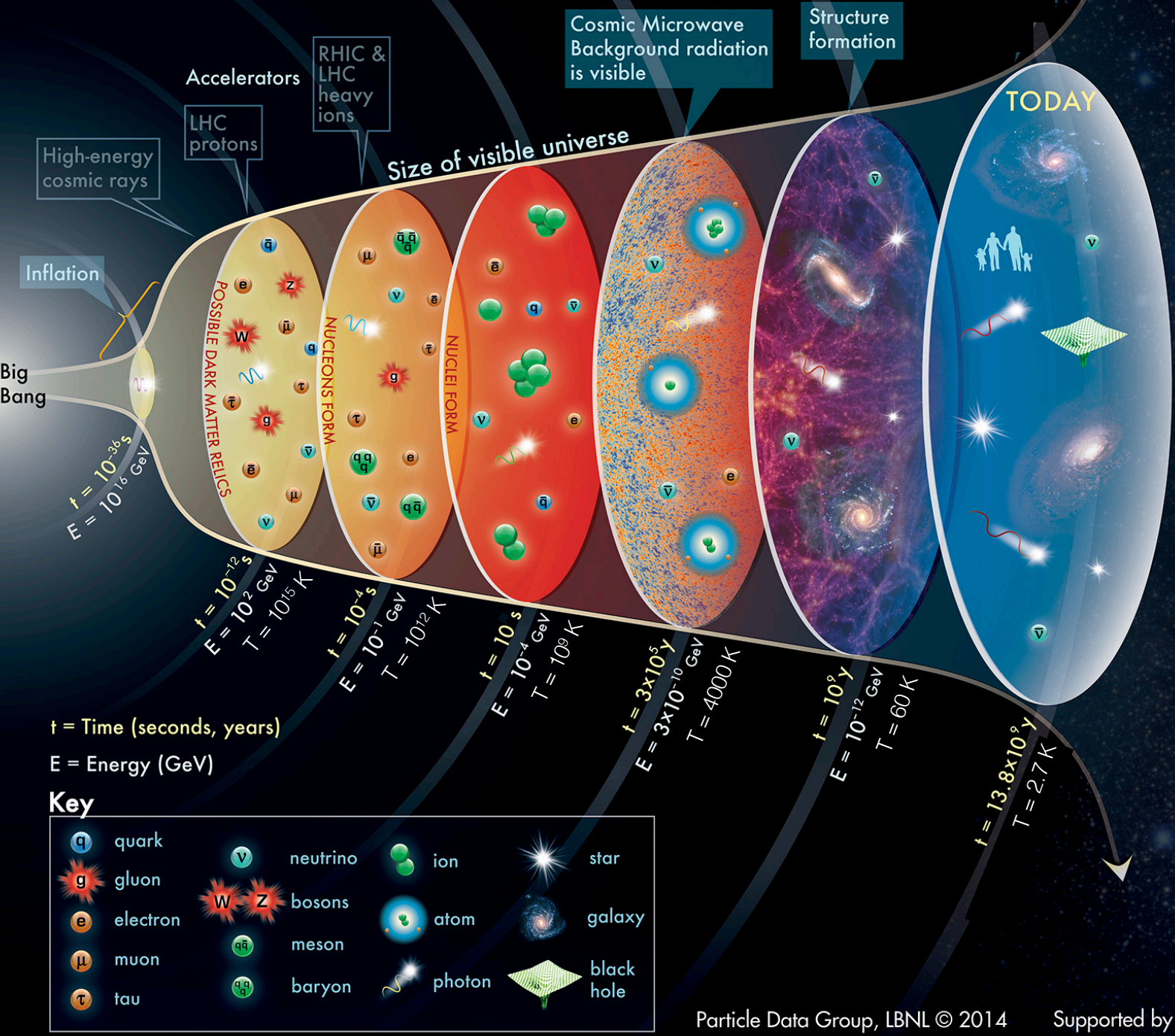
The Standard Model is a highly predictive theory

For example, the currently best experimental measurement of the magnetic dipole moment of the electron finds: $g/2 = 1.001\,159\,652\,180\,59 \pm 0.000\,000\,000\,000\,13$

Standard Model and experiment agree within a relative precision of 10^{-10} !

The Standard Model

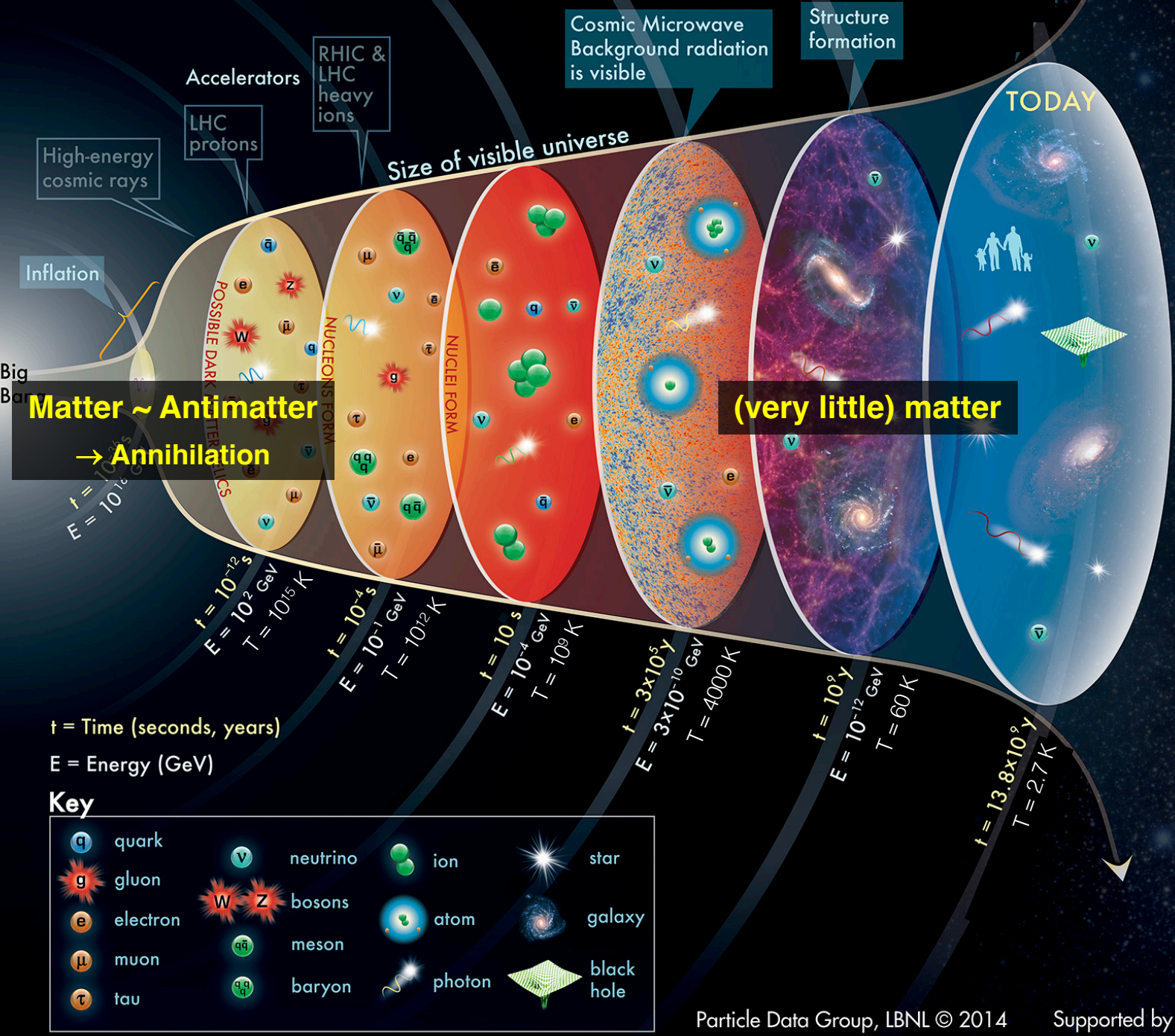
... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago



The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

But something is odd: why is there only matter left in the universe?

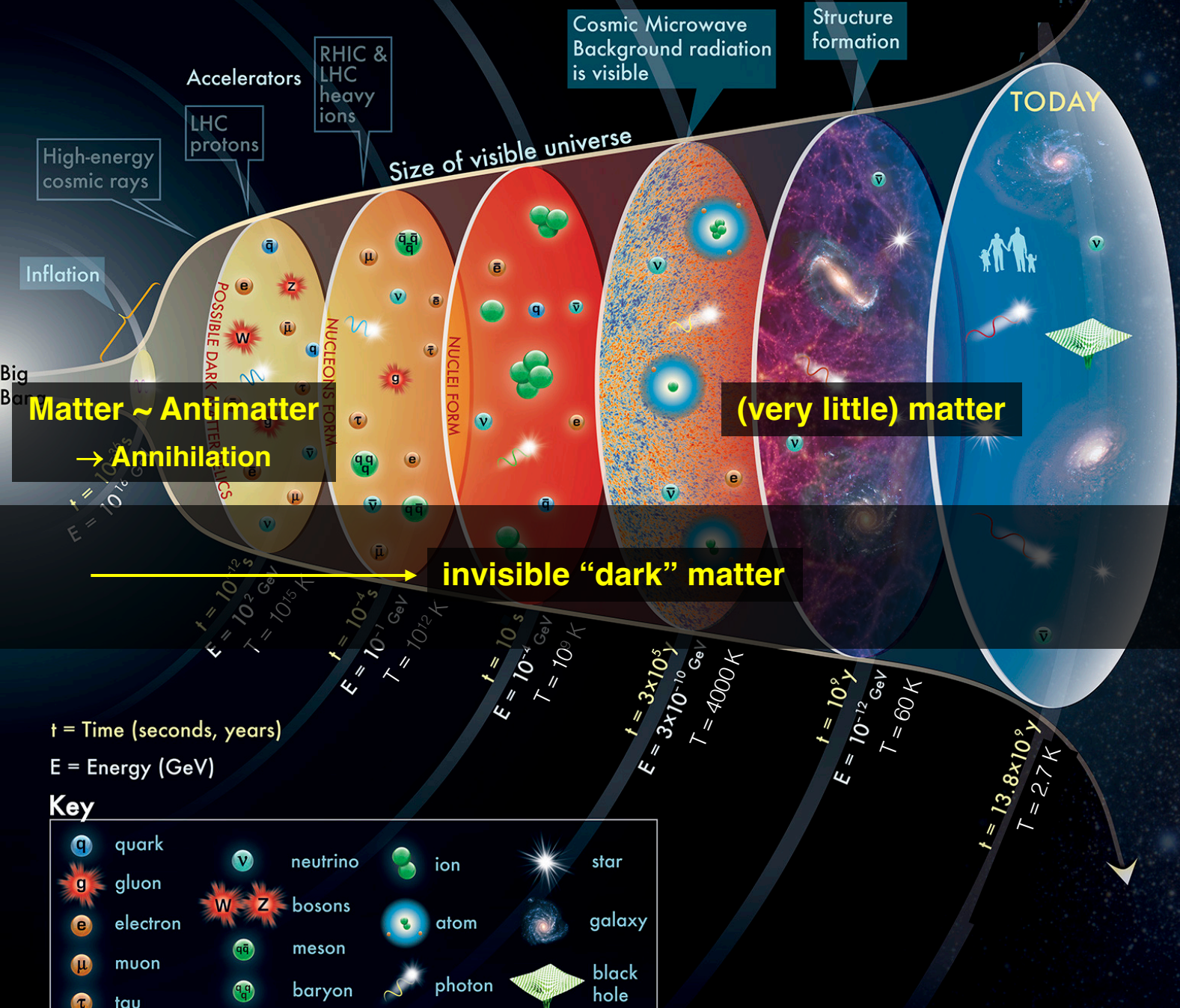


The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

But something is odd: why is there only matter left in the universe?

And what is the origin of the huge quantity of *dark matter*?



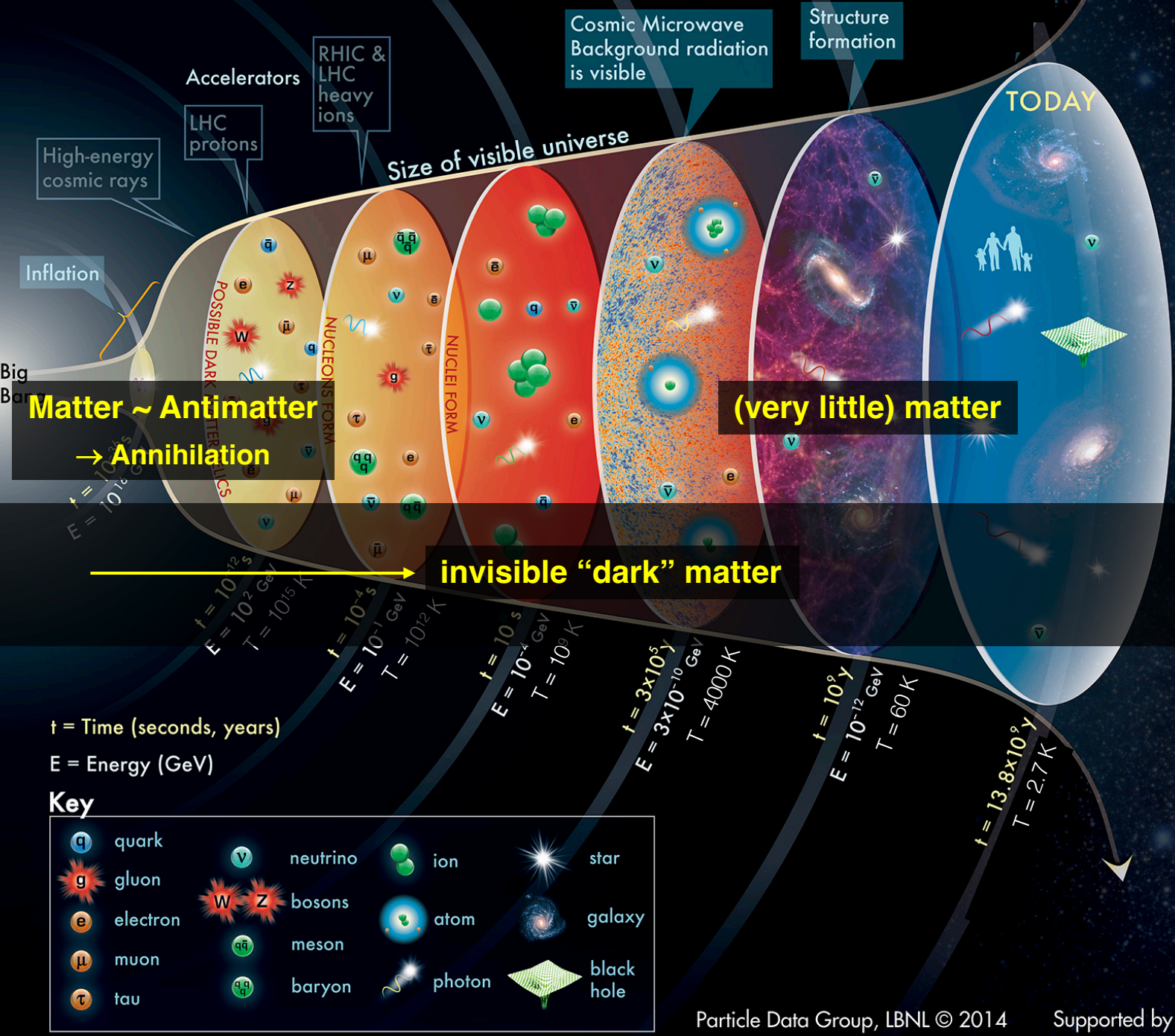
The Standard Model

... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

But something is odd: why is there only matter left in the universe?

And what is the origin of the huge quantity of *dark matter*?

And why do elementary particles have mass at all?
How and when did this occur?



Gauge symmetry and the Higgs mechanism

Interactions in the **Standard Model** are described by “**local gauge theories**”

A problem: gauge symmetry requires massless spin-1 “gauge” (=force) bosons and spin-1/2 matter particles

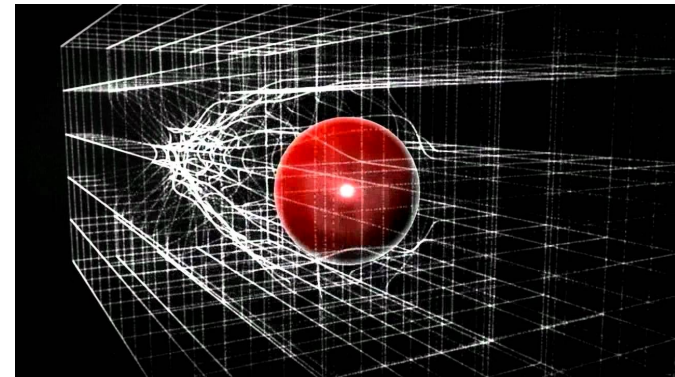
Applying an arbitrary local gauge transformation $A_\mu \rightarrow A_\mu + \partial_\mu \alpha$ on a mass term $m^2 A^\mu A_\mu$, invariance requires $m = 0$

However, the W, Z bosons are massive (= finite range of weak interaction $\sim 10^{-15}$ cm)

A solution is to introduce a new complex scalar field ϕ , which couples to the weak bosons, and whose energy potential is such that the field condensates below a critical temperature T_{EW} with a non-zero vacuum expectation value $\langle 0|\phi|0\rangle = v \neq 0$, thus spontaneously breaking the symmetry of the vacuum

The field pervades all space. The coupling of the Higgs field with a particle gives the particle potential energy (ie, the particle “sucks” energy out of the Higgs field) and thus mass. The stronger the coupling, the greater the mass. This mechanism gives mass to the W, Z bosons, and also to the fermions

A local excitation of the Higgs field ϕ around its ground state is the **Higgs boson**



Gauge symmetry and the Higgs mechanism

*Note that in the SM, this phase transition is a smooth crossover, ie, of 2nd order with no Higgs bubble creation

The Higgs potential energy:

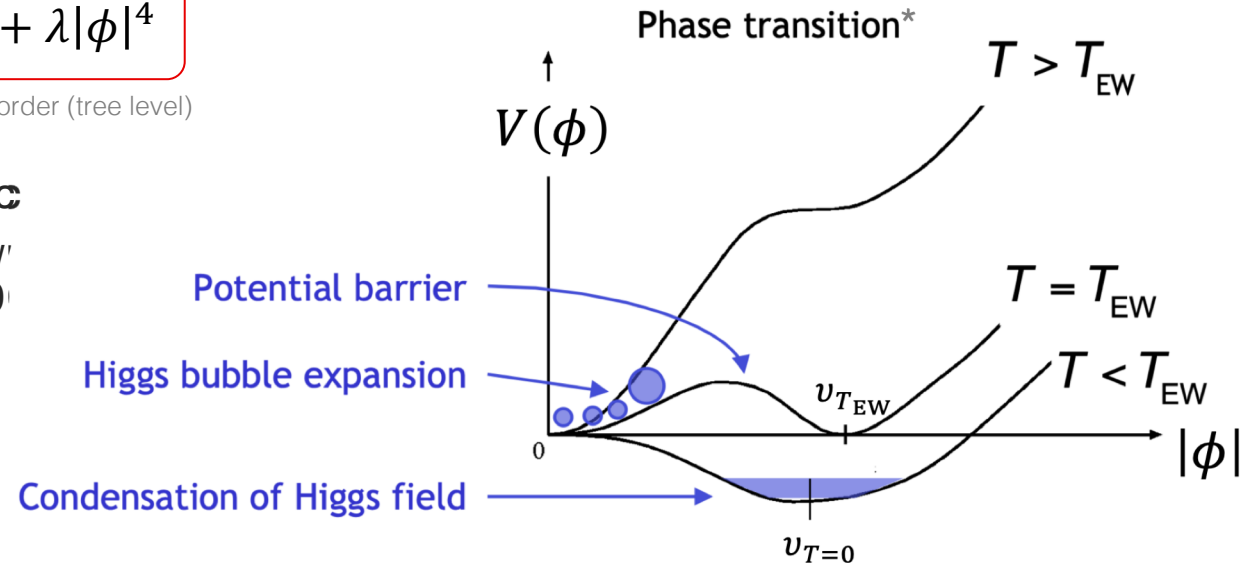
$$V(\phi) = -\mu^2 |\phi|^2 + \lambda |\phi|^4$$

At lowest order (tree level)

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{\min}| = v_T = 0$), a phase transition at $\sim T_{EW}$ ($\sim 10^{15}$ K, 10^{-12} s after the big bang) led to $|\phi_{\min}| = v_{T_{EW}} > 0$

At $T = 0$, $V(\phi)$ has a minimum at:

$$v = v_{T=0} = \sqrt{\frac{\mu^2}{2\lambda}} \quad (v \approx 246 \text{ GeV})$$

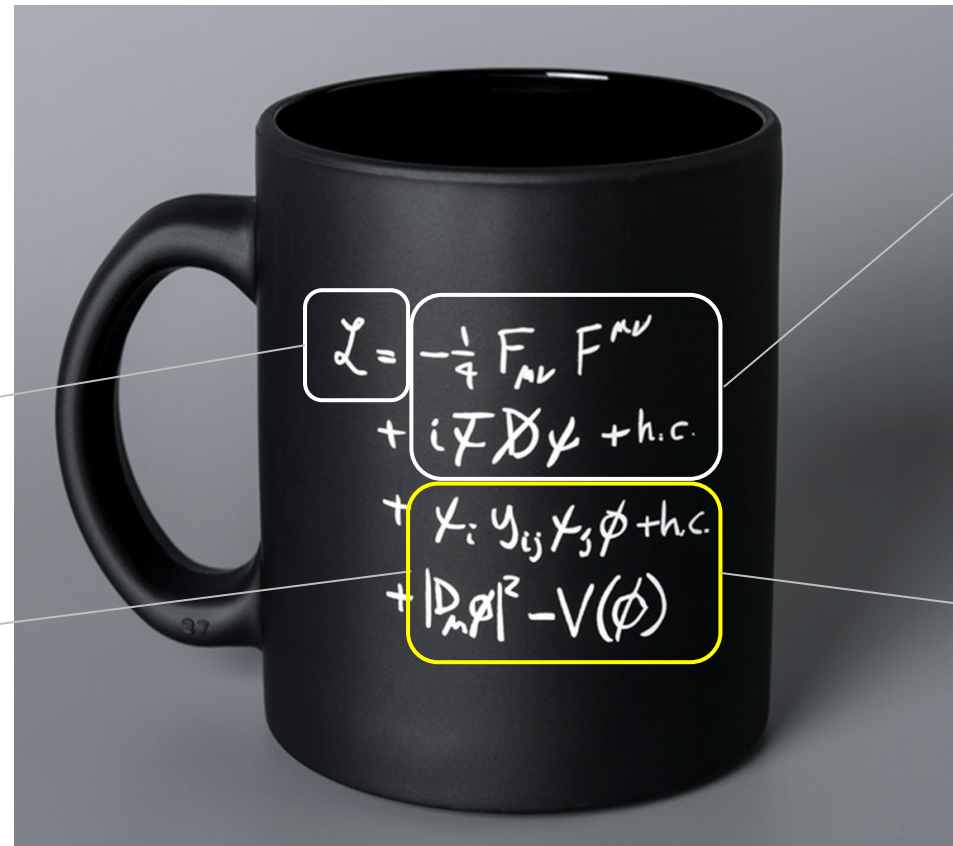


Developing $\phi(x) \propto (0, v + H(x))$ around the minimum and inserting it into the SM Lagrangian expanded by particle interactions with $\phi(x)$, determines the particle spectrum

- $m_\gamma = 0$, $m_W = \frac{1}{2} g v$, $m_Z = \frac{1}{2} \sqrt{g^2 + g'^2} \cdot v$, $m_W/m_Z = \cos \theta_W$
- $m_f = \frac{1}{\sqrt{2}} g_f v$, (g_f (Yukawa couplings) not predicted by Higgs mechanism, note that $g_{\text{top}} \approx 1$, but $g_e \approx 0.3 \cdot 10^{-5}$)
- $m_H = \mu = v\sqrt{2\lambda} + \Delta\lambda$ (energy-dependent quantum corrections)

Completing the Standard Model

The Higgs mechanism is a necessary ingredient of the Standard Model to accommodate the reality of boson and fermion masses



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

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

Unpleasant: not governed by symmetries, 26 free parameters, large hierarchy among masses

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

Beauty: interactions governed by gauge symmetries with only 3 (EW) and 2 (QCD, θ_{strong} tiny $\rightarrow$ strong CP problem) parameters

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

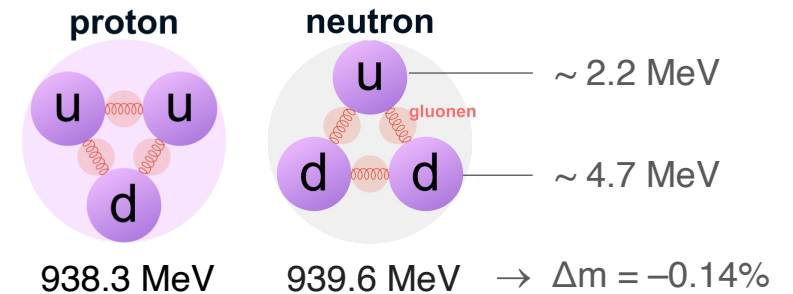
The lower left term describes the **interaction of the Higgs field with the weak-interaction bosons, which thereby obtain mass**

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

Gauge symmetry and the Higgs mechanism

A few comments:

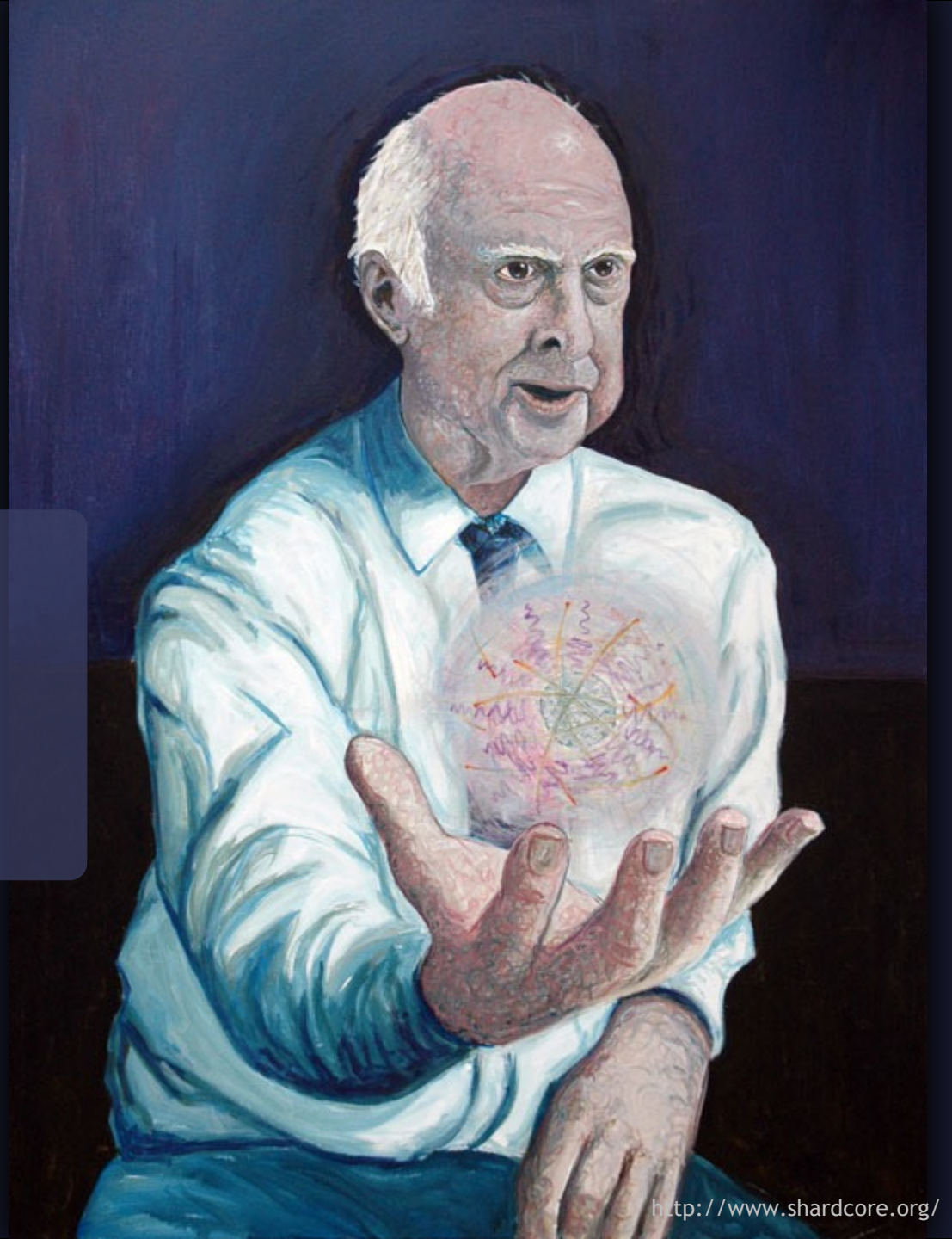
- The Higgs mechanism is required because we assume the bosons and fermions to be elementary. It would be different had they substructure: binding energy could give mass
- The resulting mass values govern the history of the universe (incl. complex chemistry and life) → what would happen had we (or nature) a dial to change the particle masses? [see [R. Cahn](#)]
- $V(\phi)$ is the simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems → carries the seeds for new physics
- The Higgs mechanism doesn't tell us everything: there is this field which generates mass, but we do not know why some particles suck a lot of energy out of this field and others much less → this is the “flavour” problem
- The vacuum energy density of the Higgs field (among others) generates a "cosmological constant" that is 10^{56} times larger than the dark energy observed*. It would curve the universe into an object roughly the size of a football, contrary to reality → this is the “cosmological constant” (finetuning) problem



*Accelerating universe (dark energy) corresponds to $\rho_{\text{vacuum}} = \mu^4$, $\mu \sim 0.002 \text{ eV}$

The Higgs mechanism was only a hypothesis
before the start of the LHC

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



Producing and studying the Higgs boson requires a huge machine



Particle accelerators

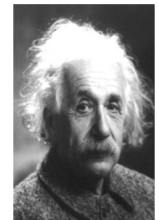
- Look deeper into matter (size $\sim 1/E$) (powerful microscope)
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)



de Broglie



Boltzmann



Einstein

This machine was realized at CERN



CERN

Founded in 1954 became a role model
of international scientific cooperation

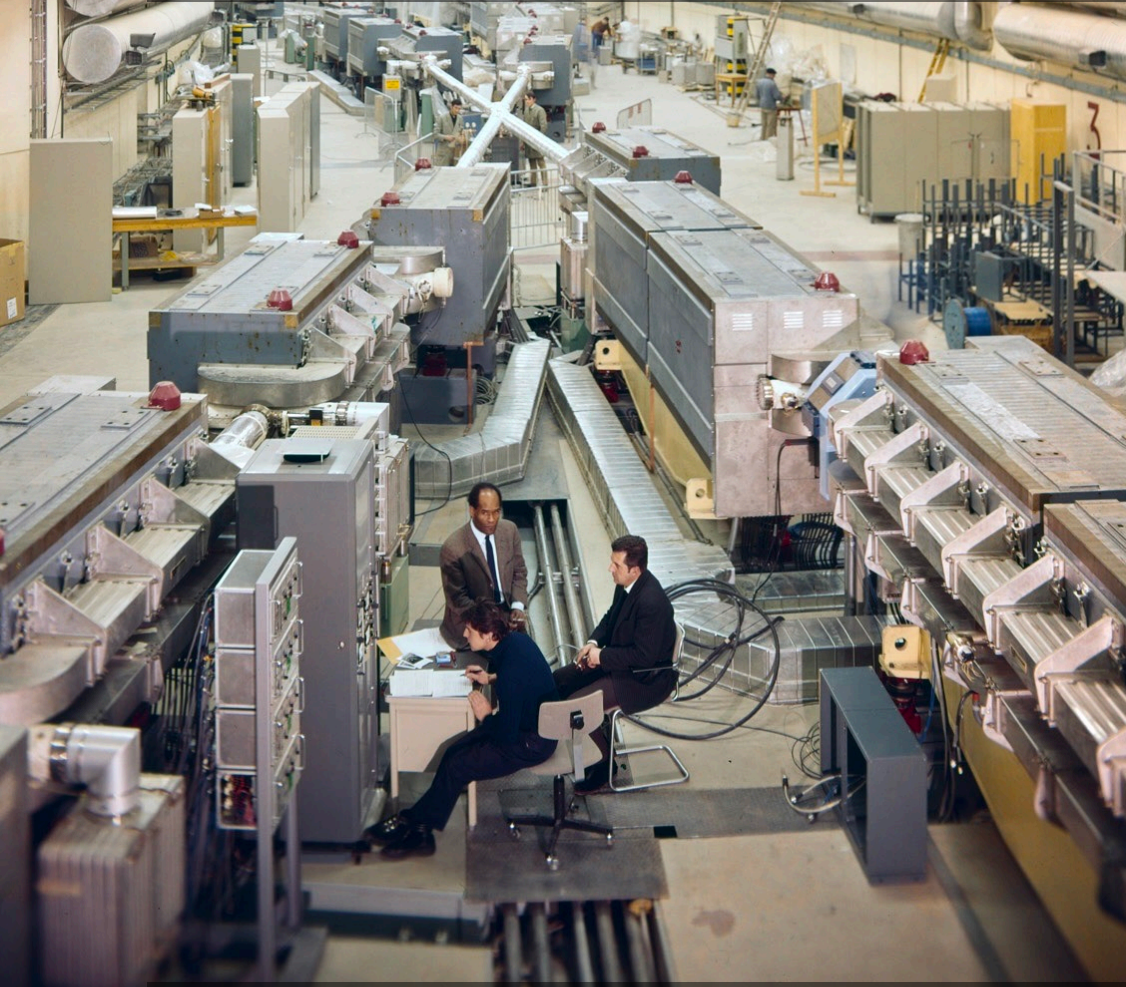


CERN — the world's largest center for fundamental research

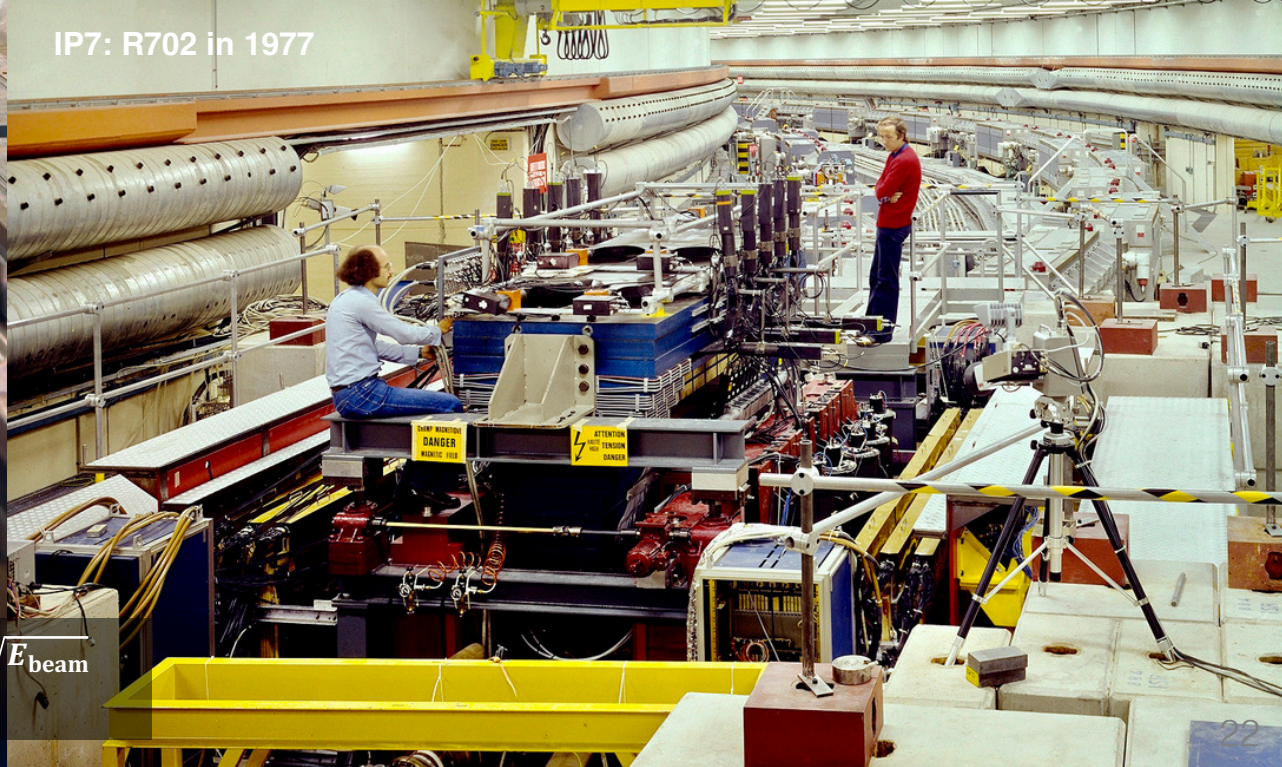


1971 — the first Hadron-Collider

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



IP7: R702 in 1977



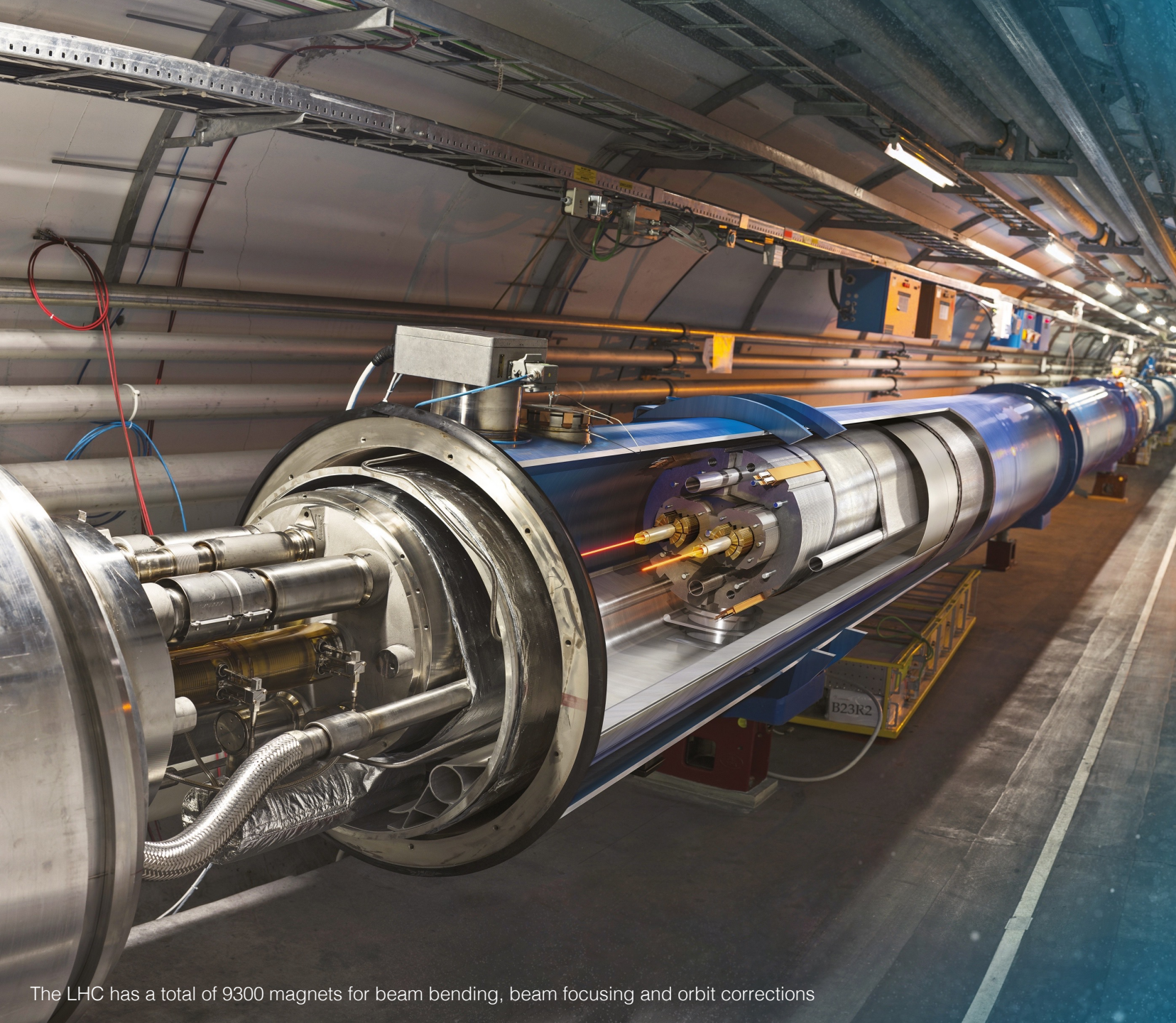
Huge advantage over fixed target; for protons: $E_{CM} = 1.4\sqrt{\text{GeV}}\sqrt{E_{beam}}$
 $\rightarrow E_{CM} = 14 \text{ TeV}$ would require a 10,000 TeV beam

ISR Control Room (early 70s)



LHC Control Room (July 2022)





Large Hadron Collider (LHC)

- 27 km circumference underground accelerator and collider
- Superconducting magnets ($1.9\text{ K} = -271.3\text{ }^{\circ}\text{C}$) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies and brought to collision

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

Large Hadron Collider

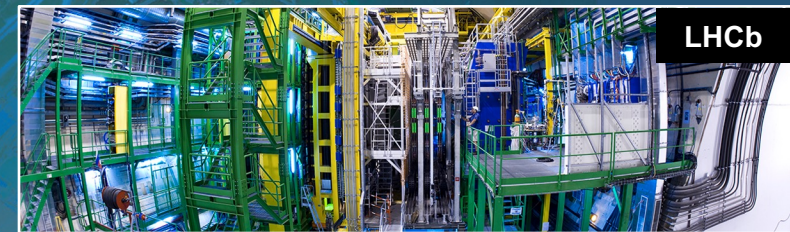
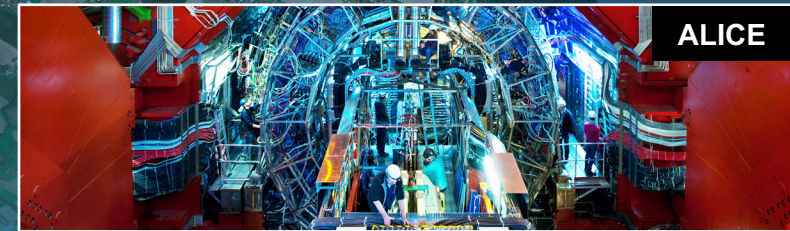
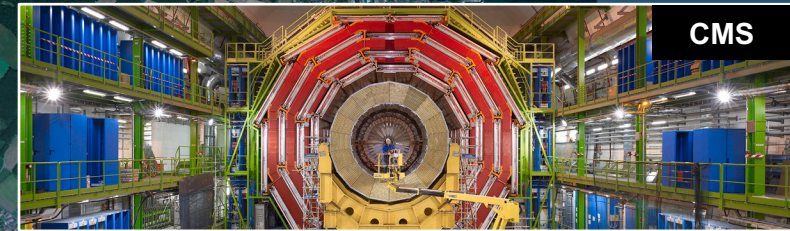
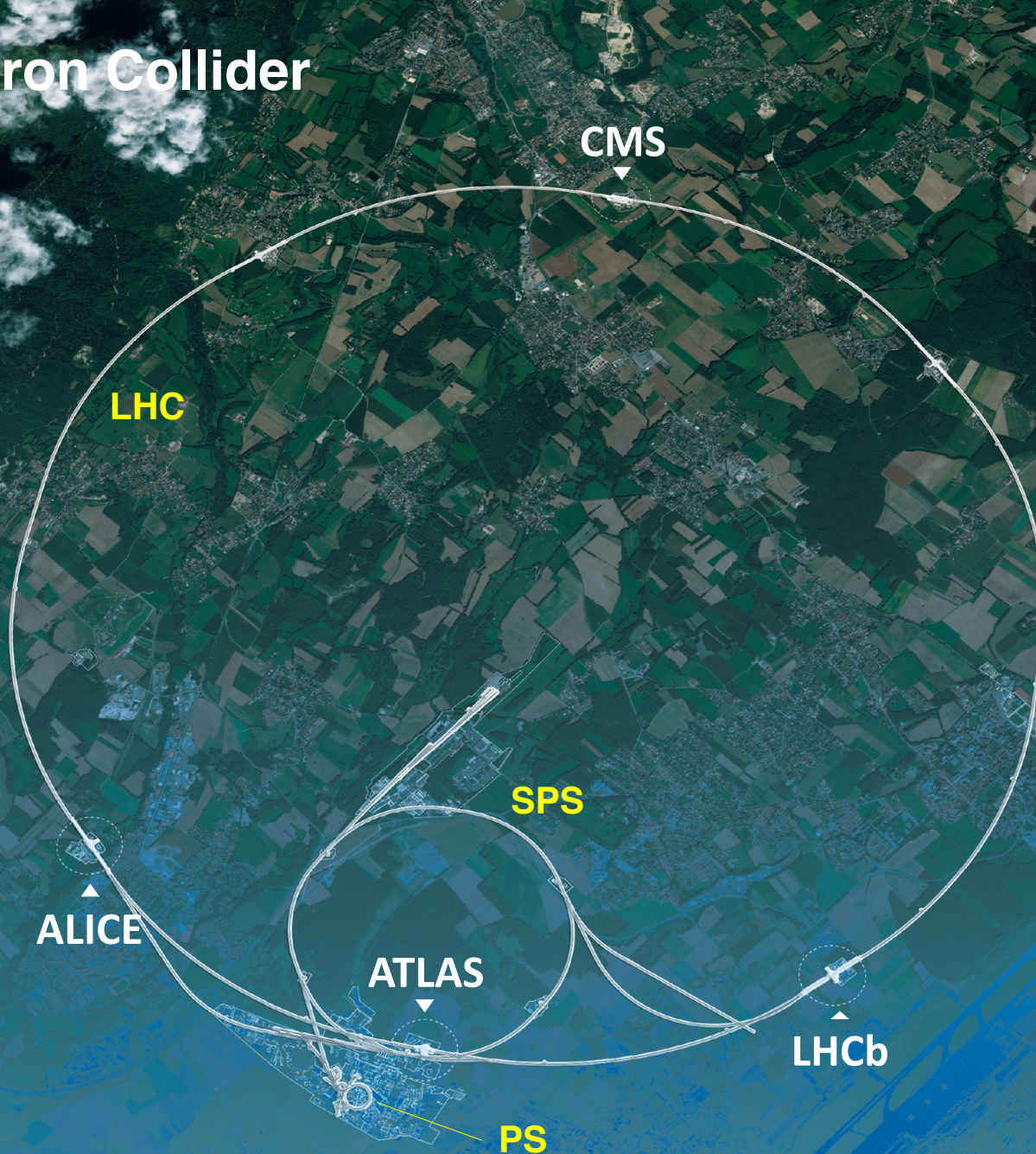


Aerial view

1 km

Large Hadron Collider

Aerial view



Large Hadron Collider

The LHC and its experiments are projects of superlatives in terms of size, beam energy and intensity, magnetic field strengths, detector design, technology and radiation hardness, software and computing, size and time scale of experimental collaborations, ...

CMS

ATLAS

CMS

ALICE

LHCb

ALICE

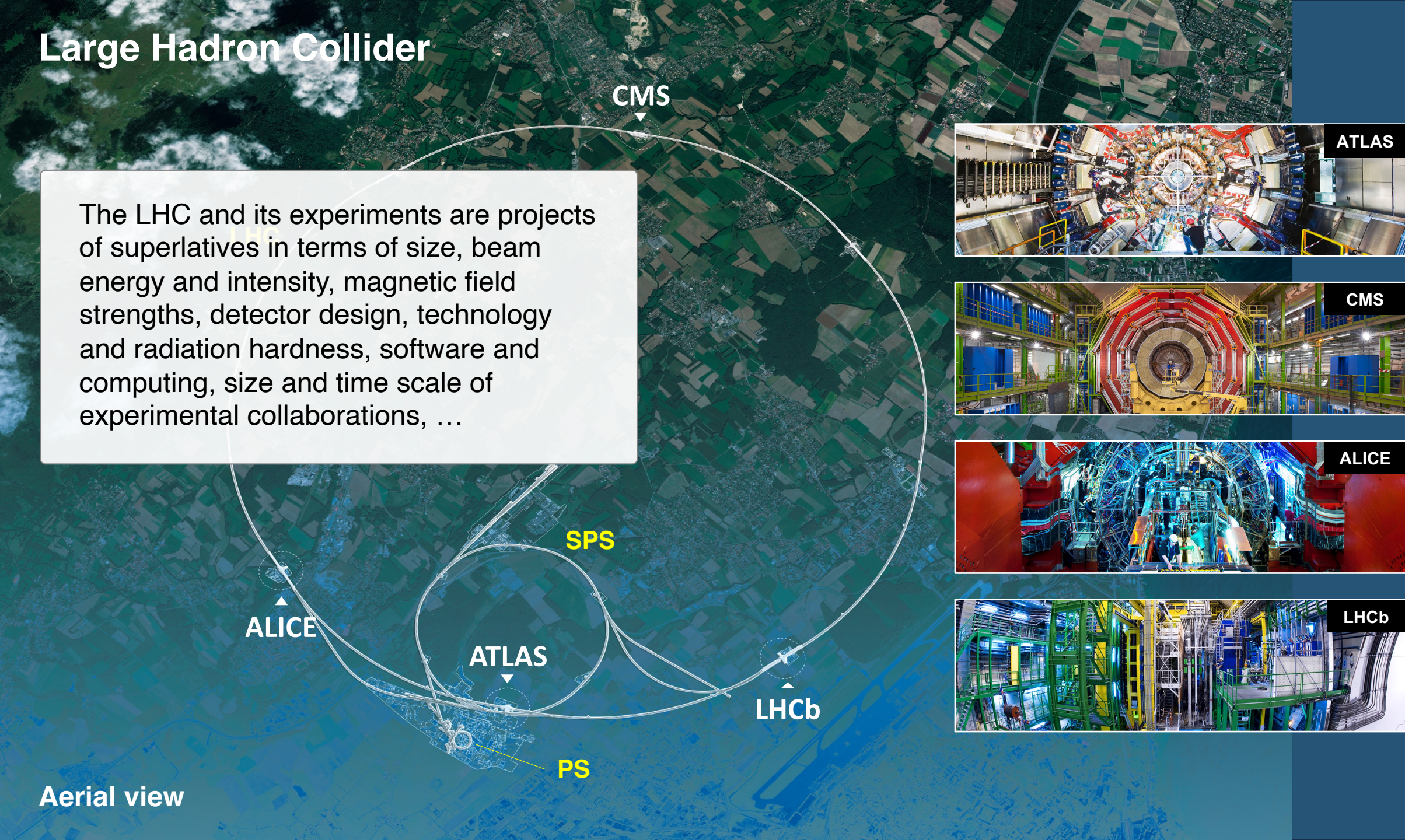
ATLAS

LHCb

SPS

PS

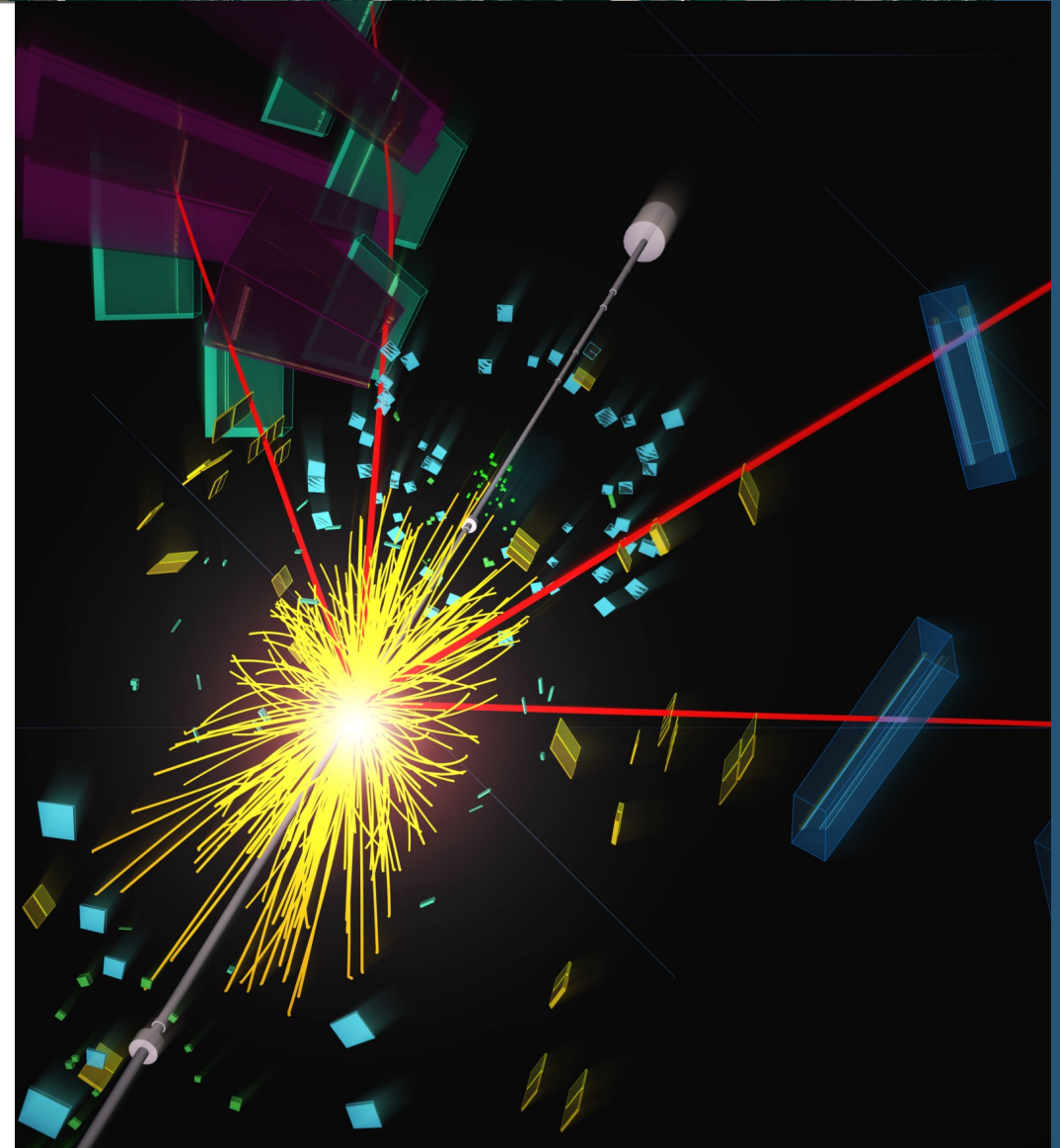
Aerial view



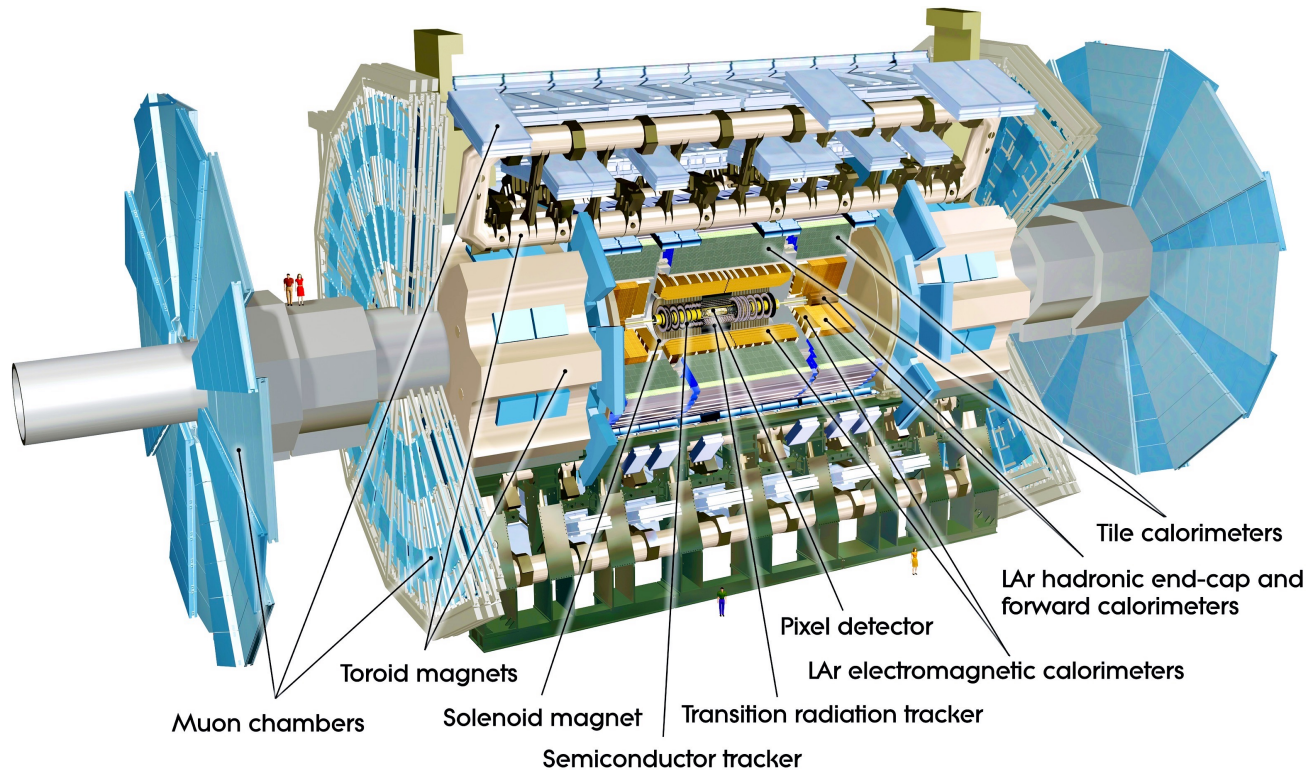
What happens in a high-energy proton–proton collision?

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

- Light quarks, gluons (“jets”) $\gg$ W, Z $\gg$ top quark $\gg$ Higgs boson (1 out of 2 billion proton collisions)
- Heavy particles decay instantaneously to light, stable particles (quarks/hadrons, leptons, photons)
- A particle detector precisely measures these decay particles, which allows to deduce the properties of the mother particle
- An online filter (“trigger”) reduces the huge rate of particle interactions by a factor of 20,000 focusing on the most interesting processes
- Data reconstruction and analysis is done in computing centers worldwide



The ATLAS Detector



25 m diameter, 44 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 ($80\ \mu\text{m} \times 12\ \text{cm}$)

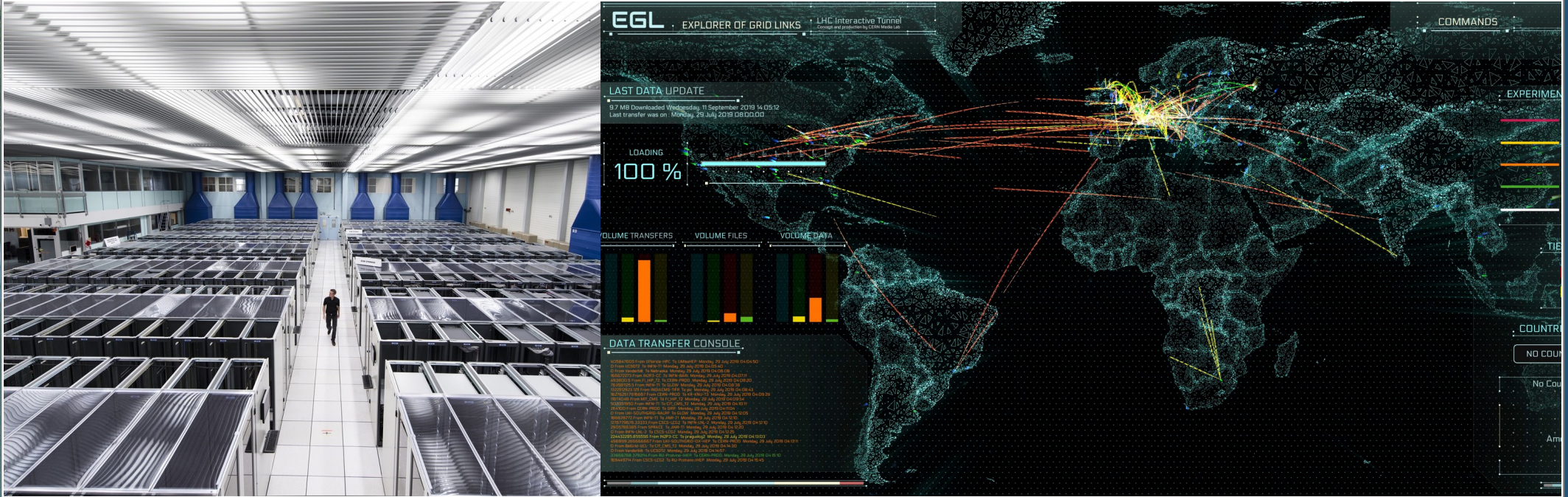
spatial resolution $\sim 15\ \mu\text{m}$ (in azimuthal direction)

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

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

Ultra-fast custom electronics and high-performance computers filter the collisions: only 1 out of 30,000 collisions is kept

The Worldwide LHC Computing Grid

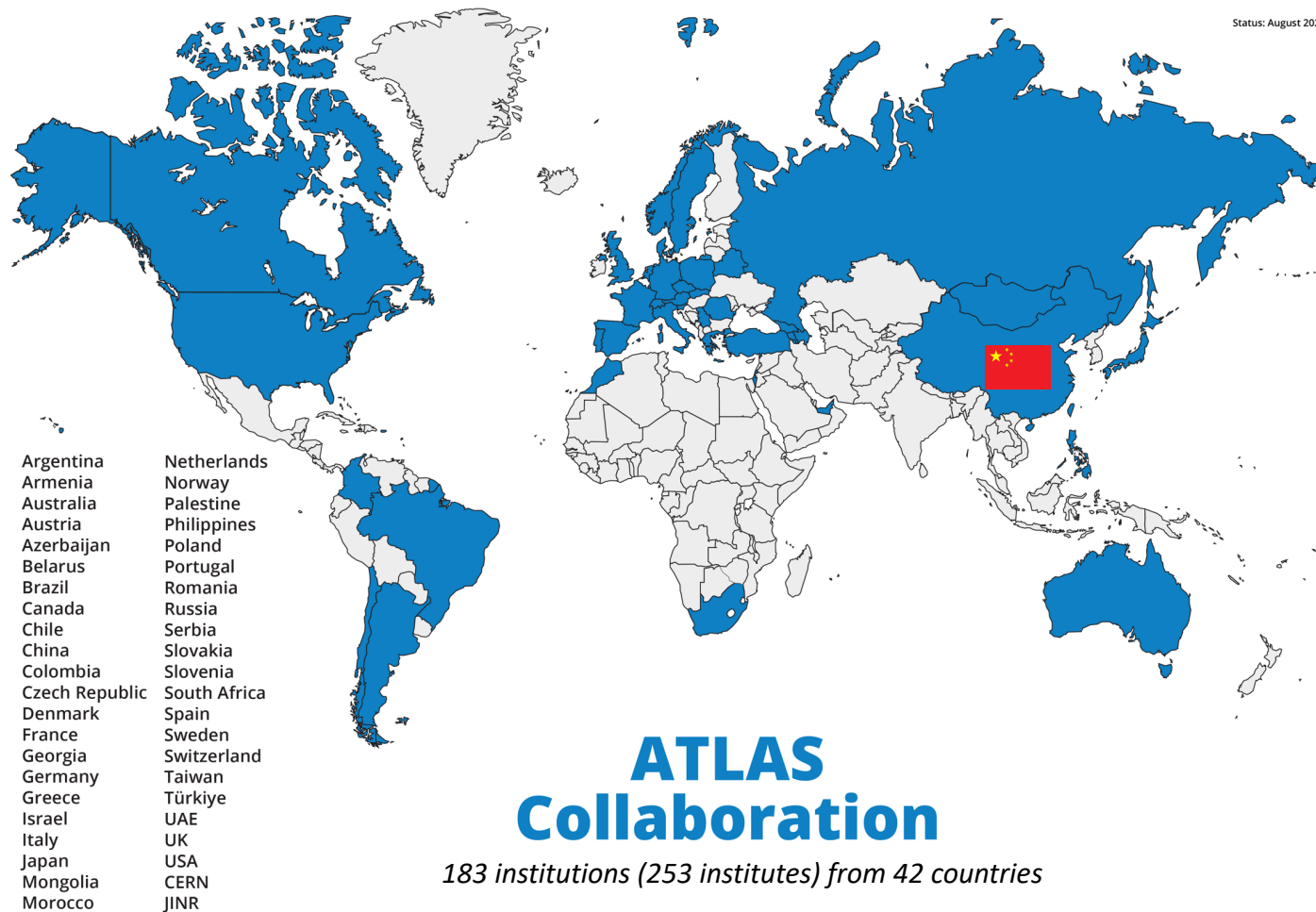


Distribution, processing and analysis
of the experimental data

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

> 1000 petabytes CERN
data are stored worldwide

The ATLAS Collaboration



ATLAS Collaboration

253 institutes from 42 countries

2900 Scientific authors

1200 Physics PhD students

1300 Engineers or technicians

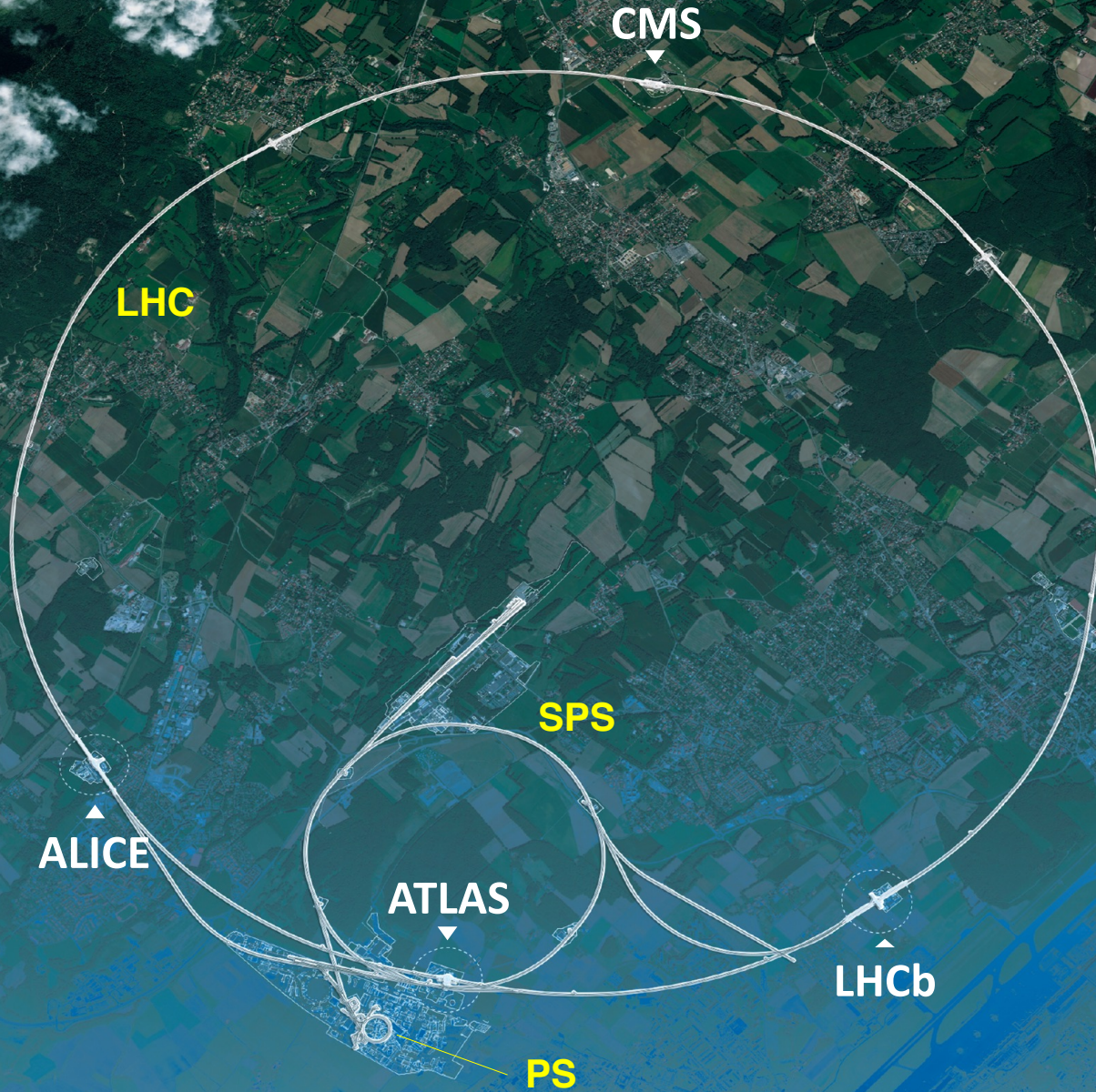
China in ATLAS

China joined ATLAS in the 1990s with four institutes: IHEP, Nanjing U, Shandong U, **USTC Hefei**, contributing to the construction of calorimeter and muon systems

It evolved to today 12 institutes with broad contributions:

- IHEP, Nanjing, Tsinghua, **USTC**, Shandong, Shanghai, SYSU, TDLI, Zhengzhou (130 authors, 78 PhD students)
- Hong Kong cluster (3 institutes, 14 authors, 10 PhD)

Large Hadron Collider



Aerial view



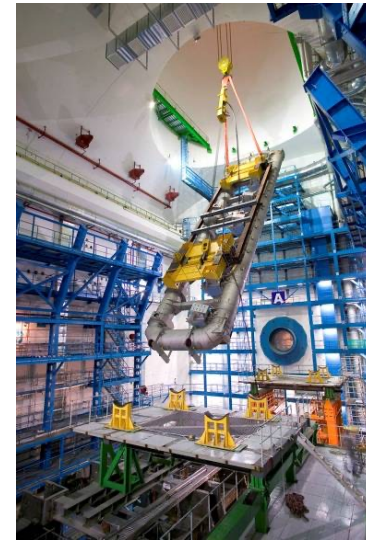
ATLAS Detector: construction und installation

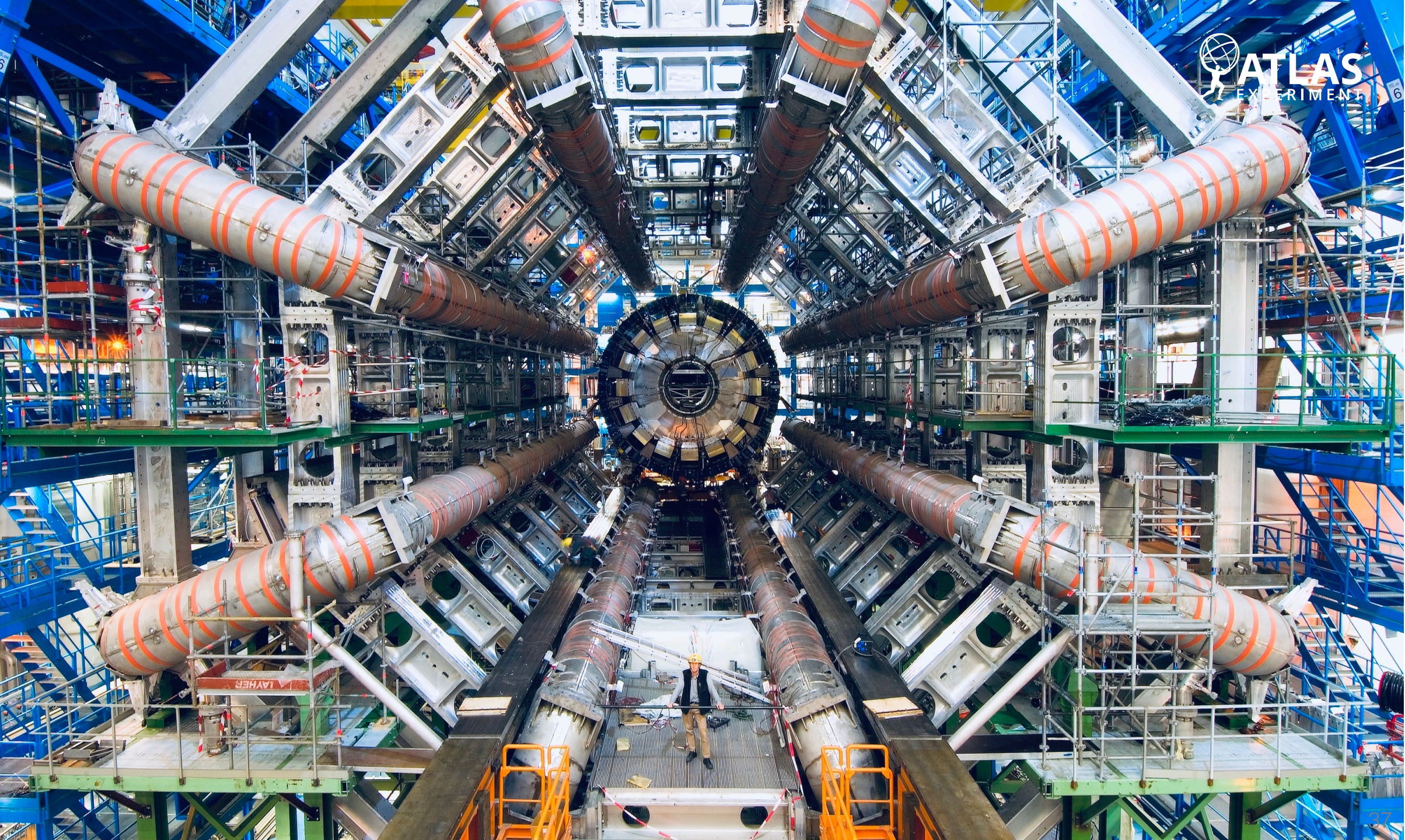


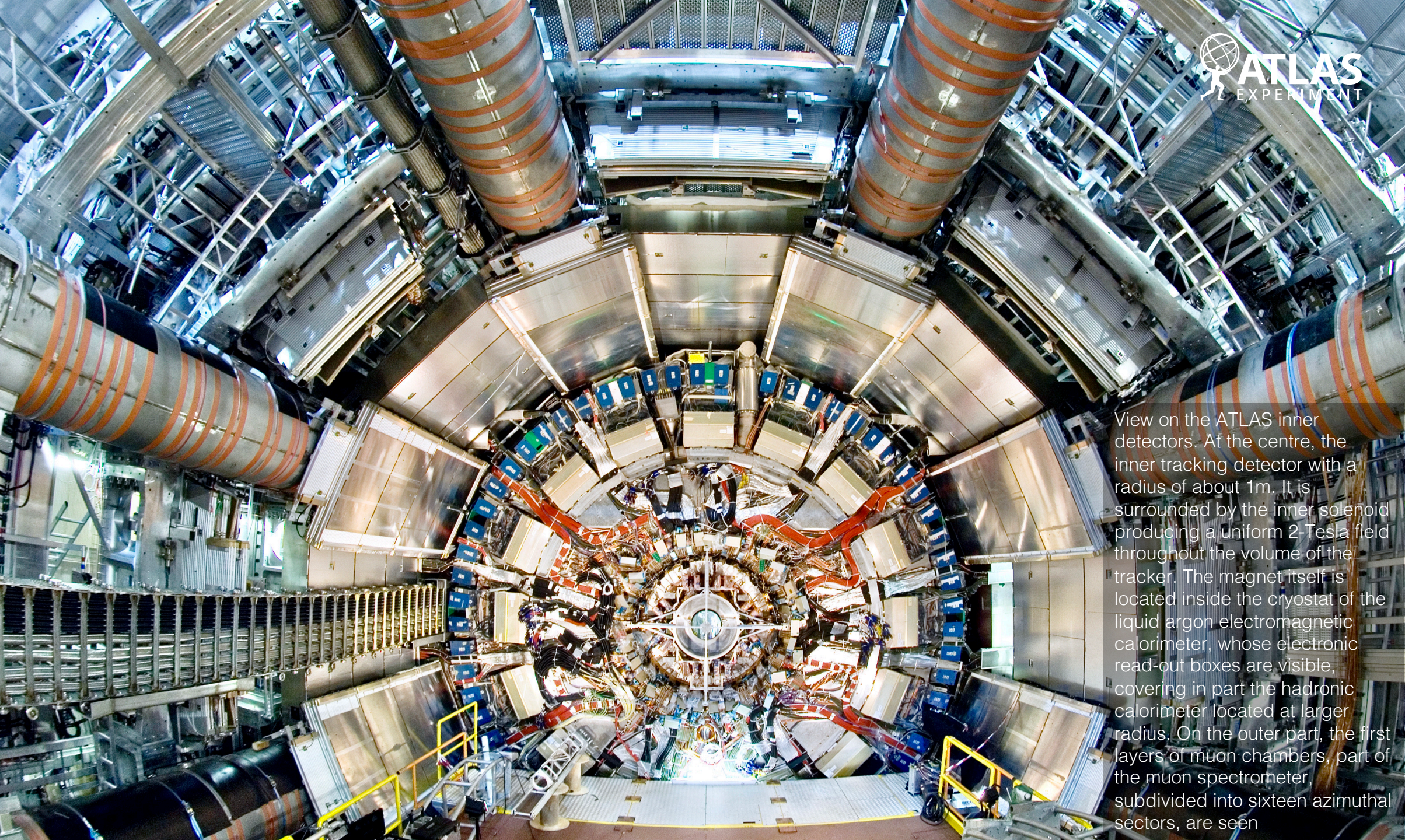
ATLAS cavern after excavation in July 2002

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

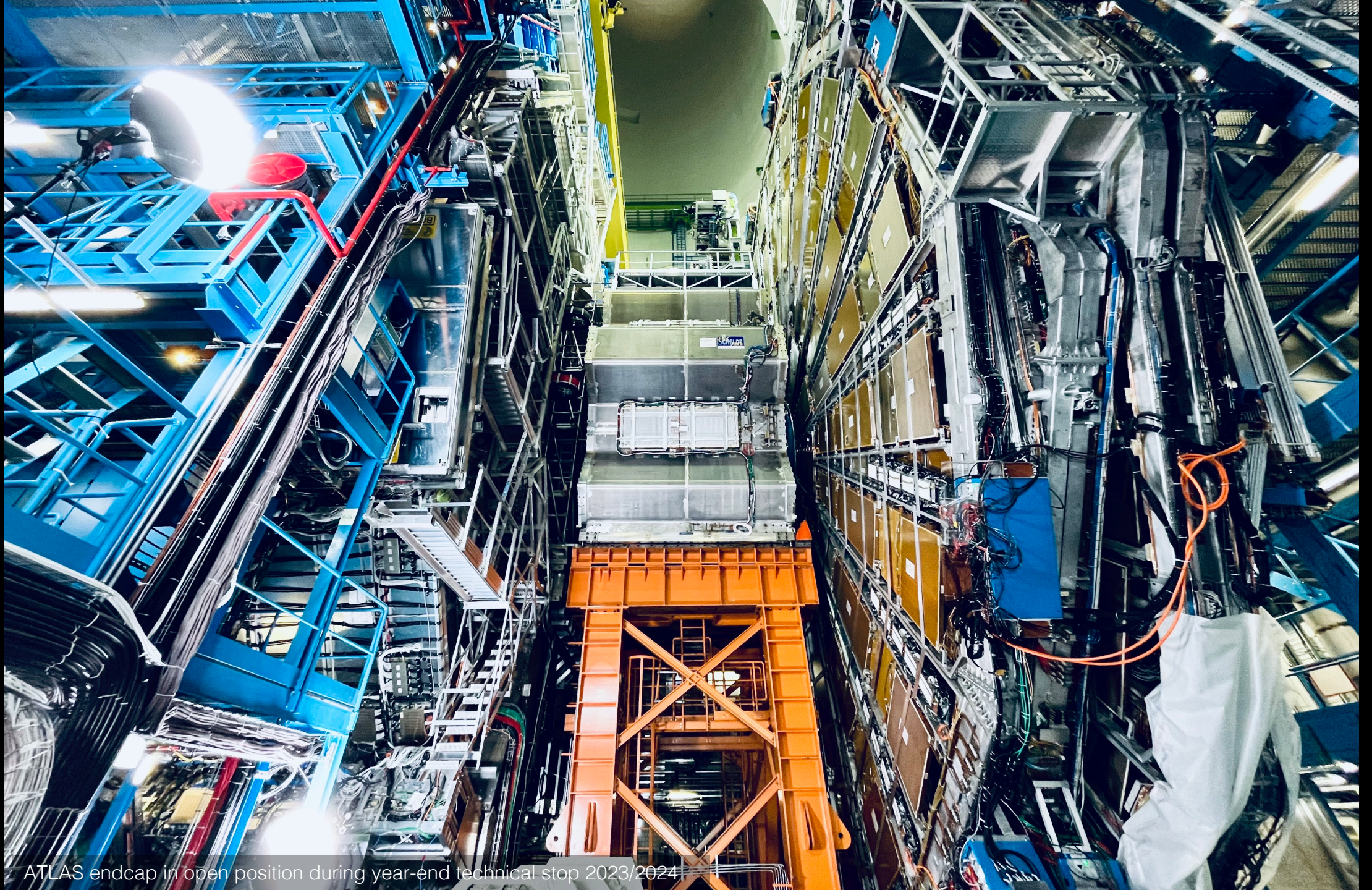
ATLAS Detector: construction und installation



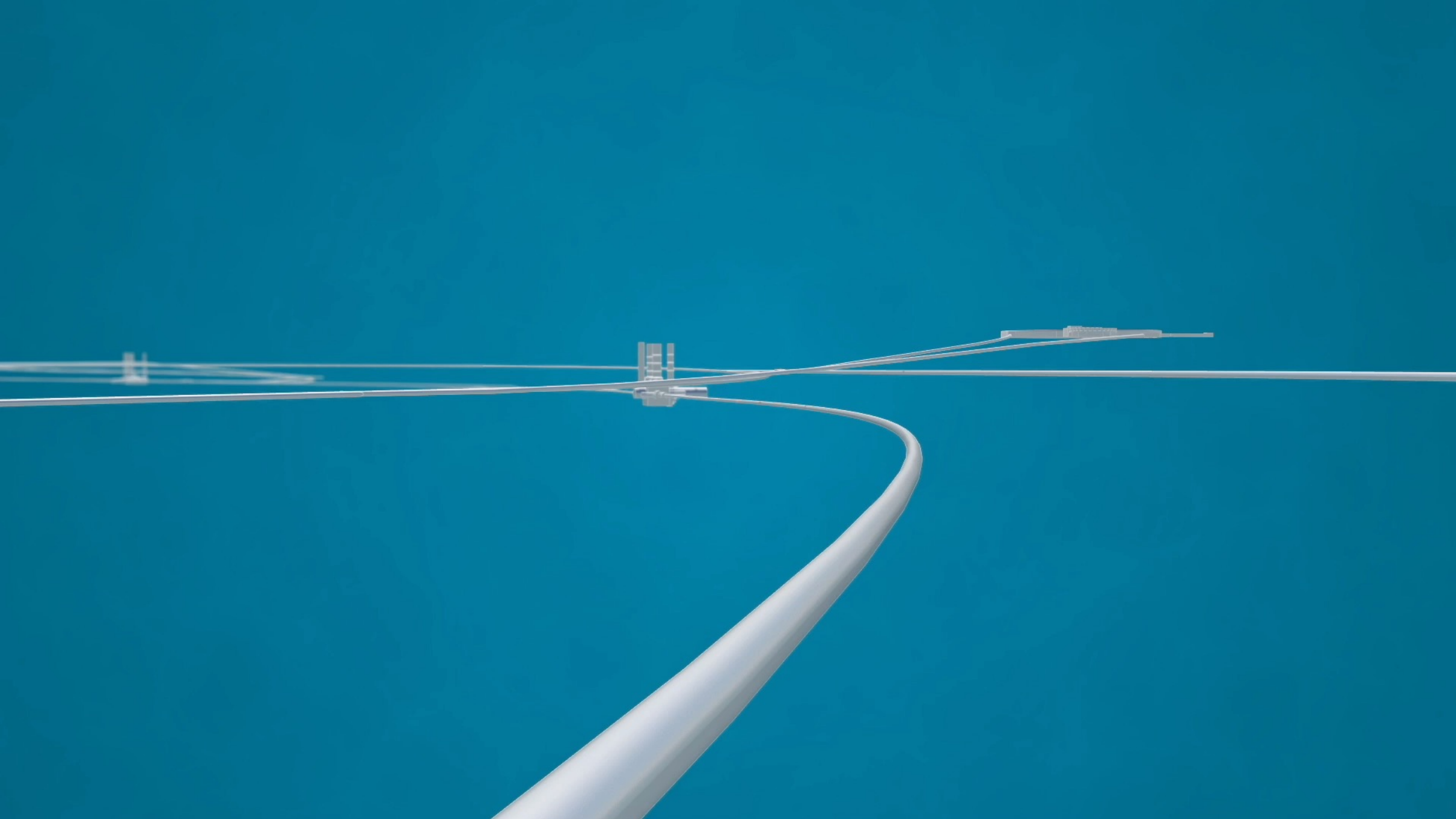




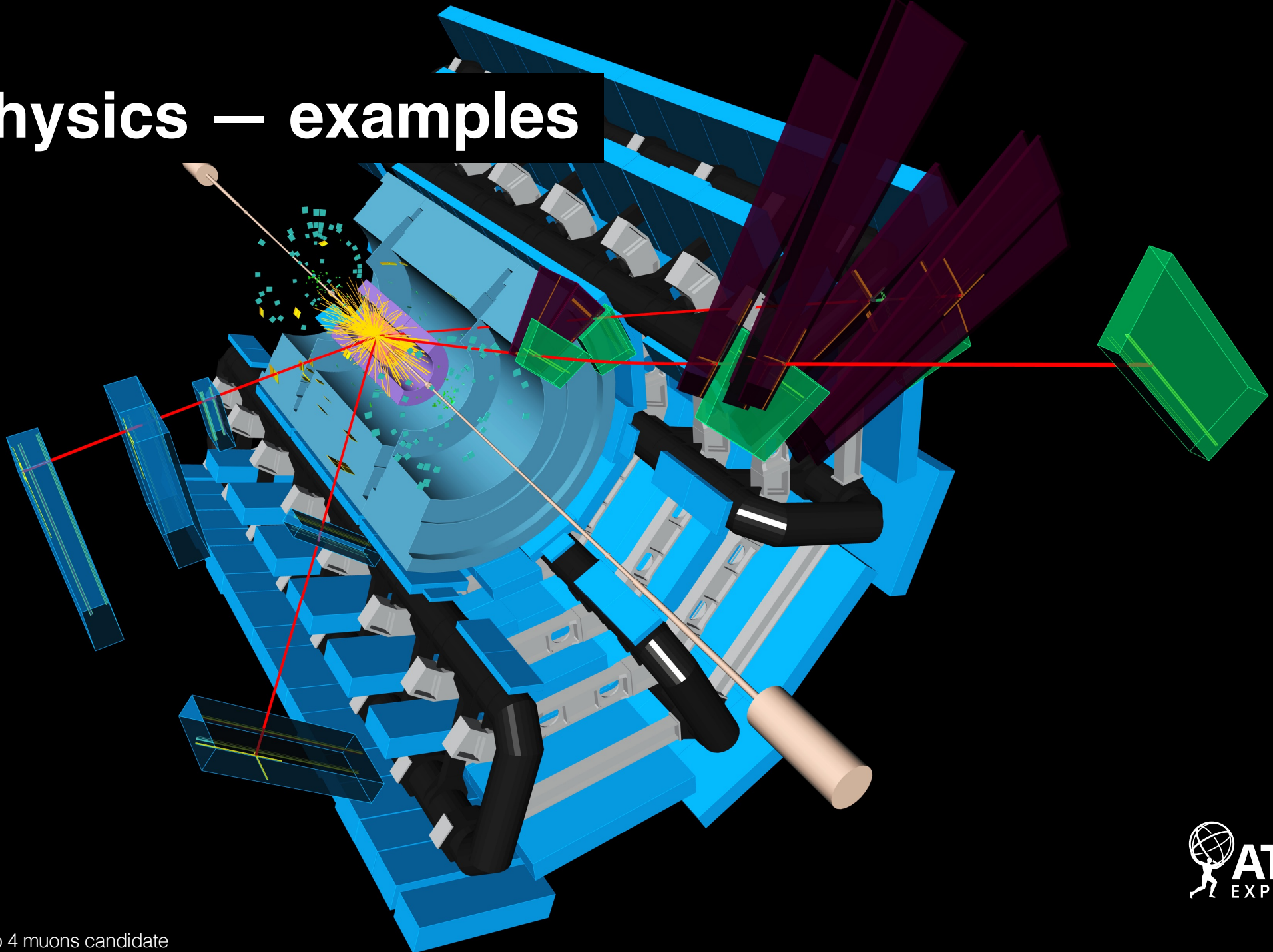
View on the ATLAS inner detectors. At the centre, the inner tracking detector with a radius of about 1m. It is surrounded by the inner solenoid producing a uniform 2-Tesla field throughout the volume of the tracker. The magnet itself is located inside the cryostat of the liquid argon electromagnetic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



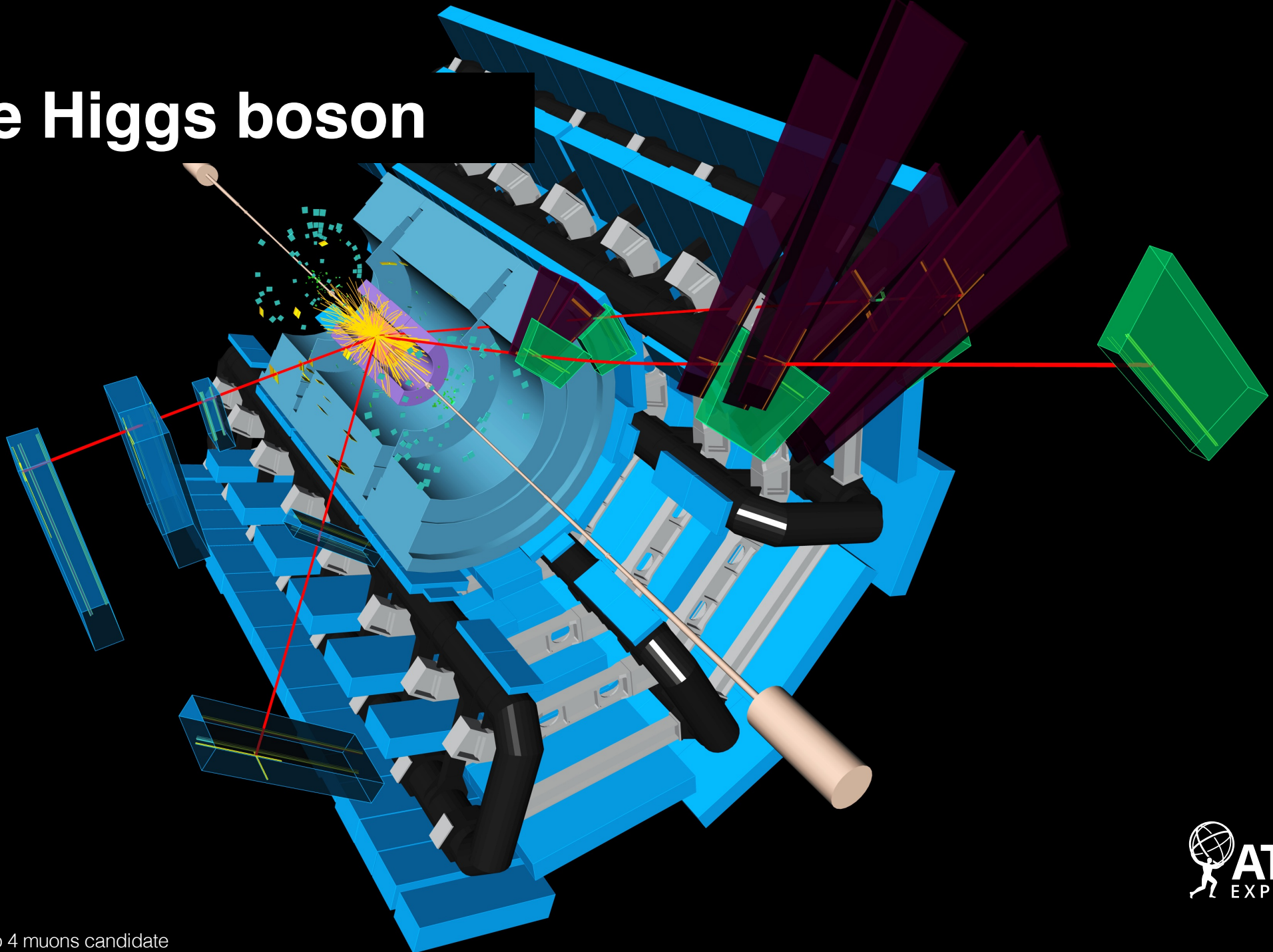
ATLAS endcap in open position during year-end technical stop 2023/2024



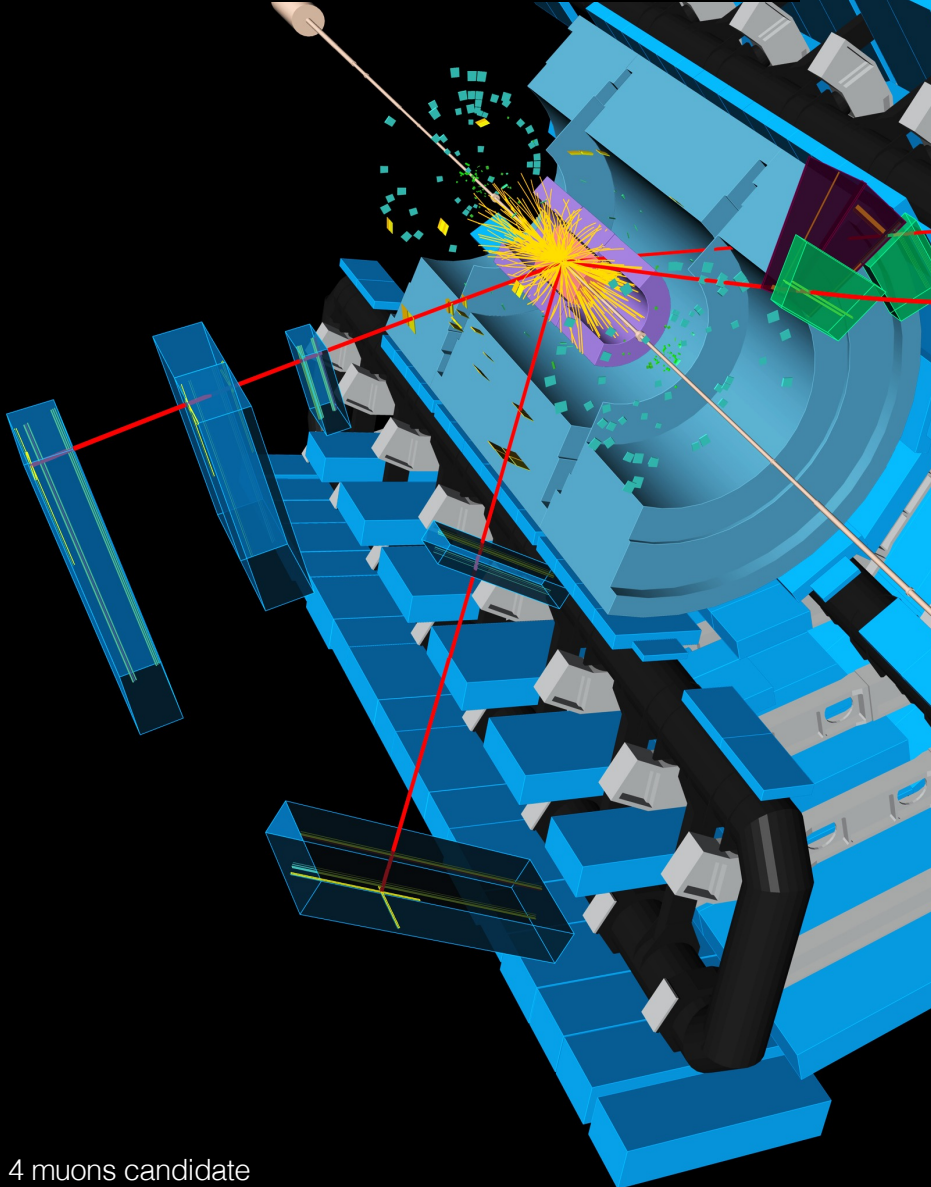
Physics — examples



The Higgs boson

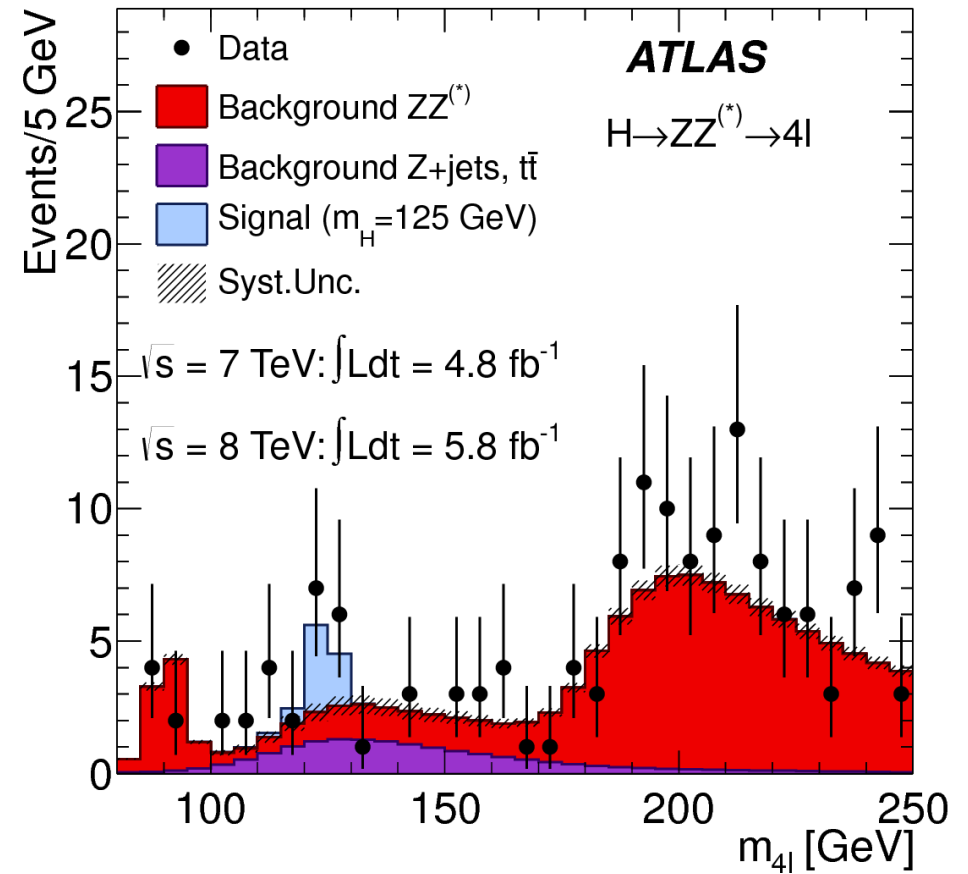


The Higgs boson



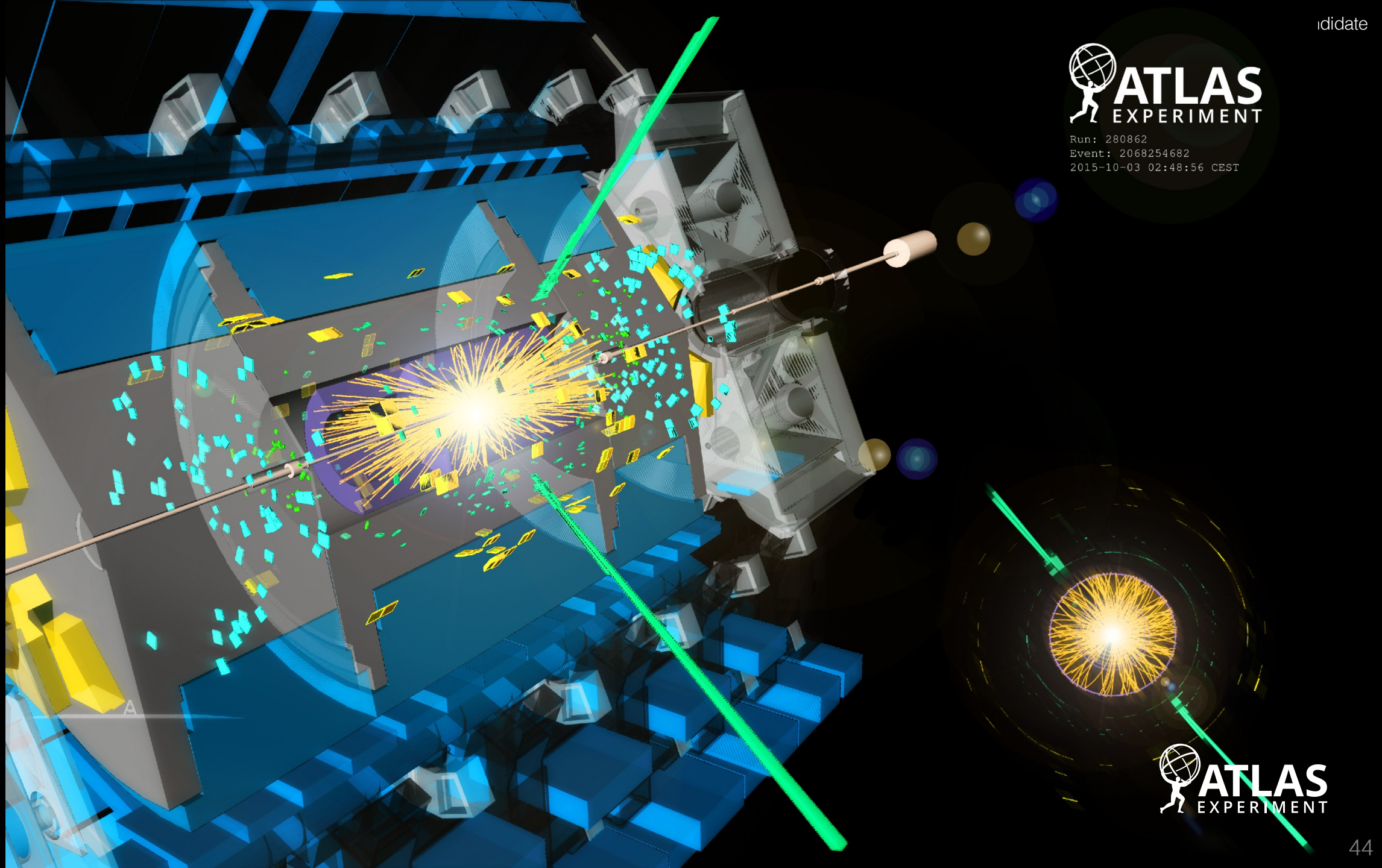
2012

[Phys. Lett. B 716 \(2012\) 1-29](#)





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 2015-10-03 02:48:56 CEST

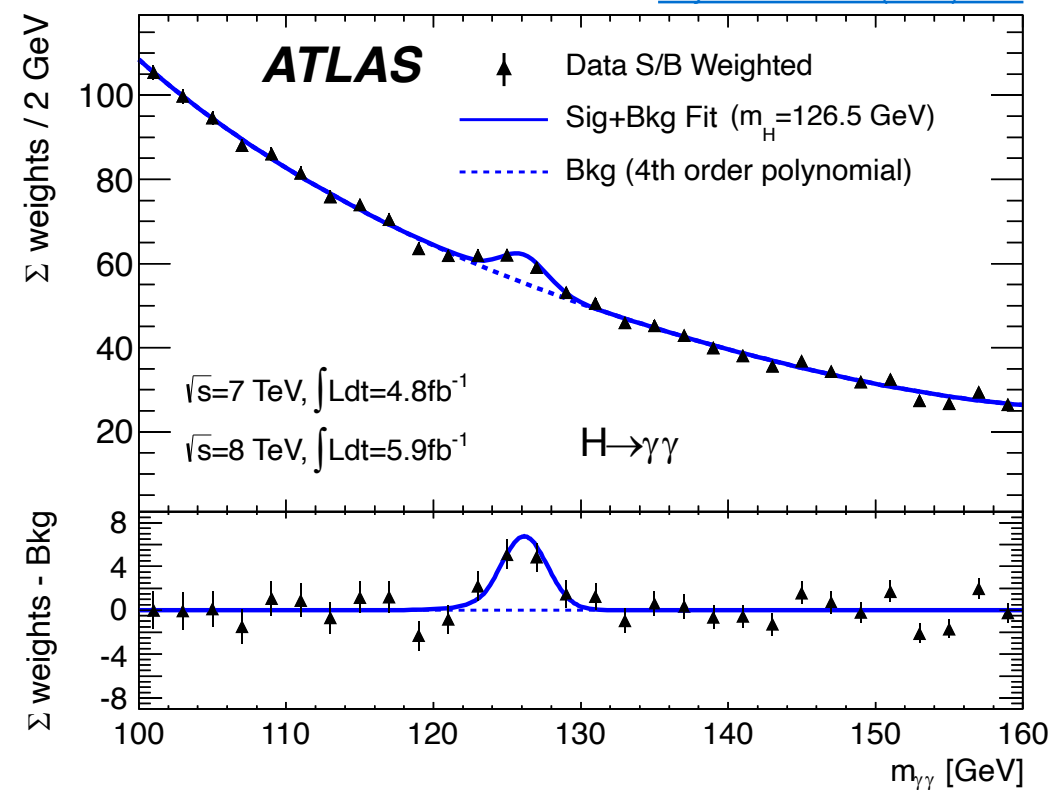




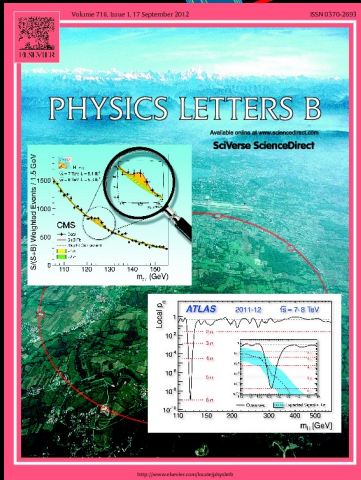
Run: 280862
Event: 2068254682
2015-10-03 02:48:56 CEST

2012

[Phys. Lett. B 716 \(2012\) 1-29](#)



The Higgs boson



Phys. Lett.B 716 (2012)
Cited almost 15,000 times
(today)



Fabiola Gianotti and Peter Higgs, 4 July 2012



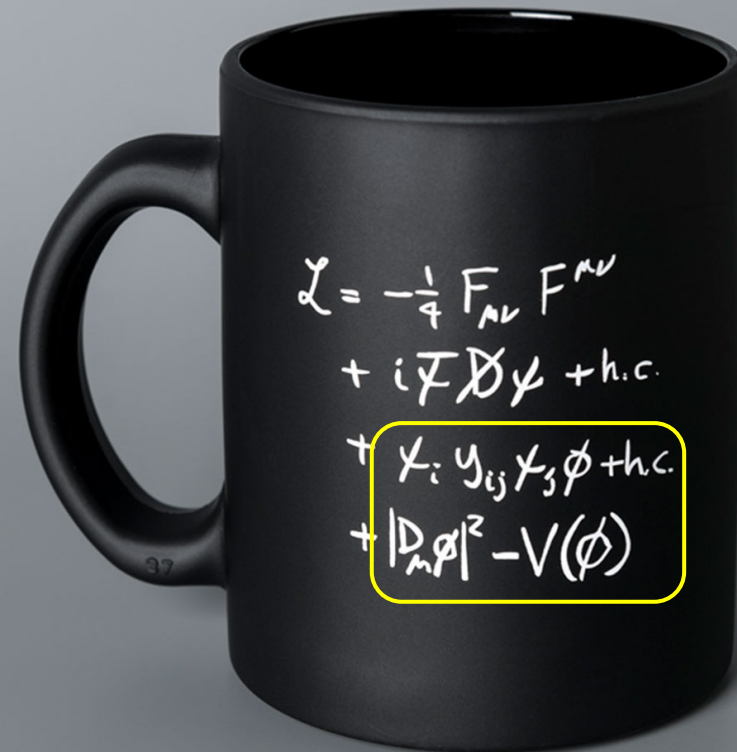
4 July 2012: ATLAS (Fabiola Gianotti) und CMS (Joseph Incandela)
announce the Higgs boson discovery before a packed auditorium

The Higgs boson

The LHC's magnum opus

A very special particle... whose discovery allows us to access a **totally new sector** of the SM Lagrangian:

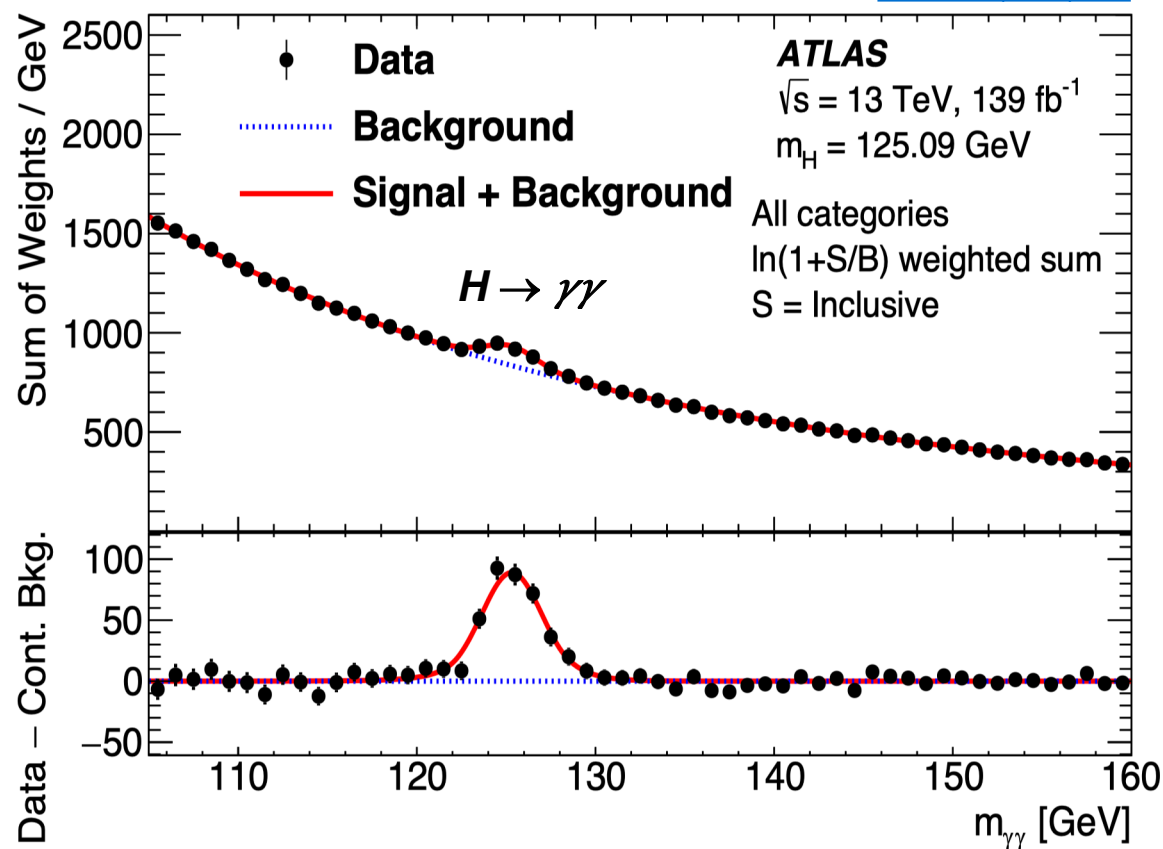
- Higgs–matter interactions
- Higgs–force particle interactions
- Higgs potential and Higgs self-interaction



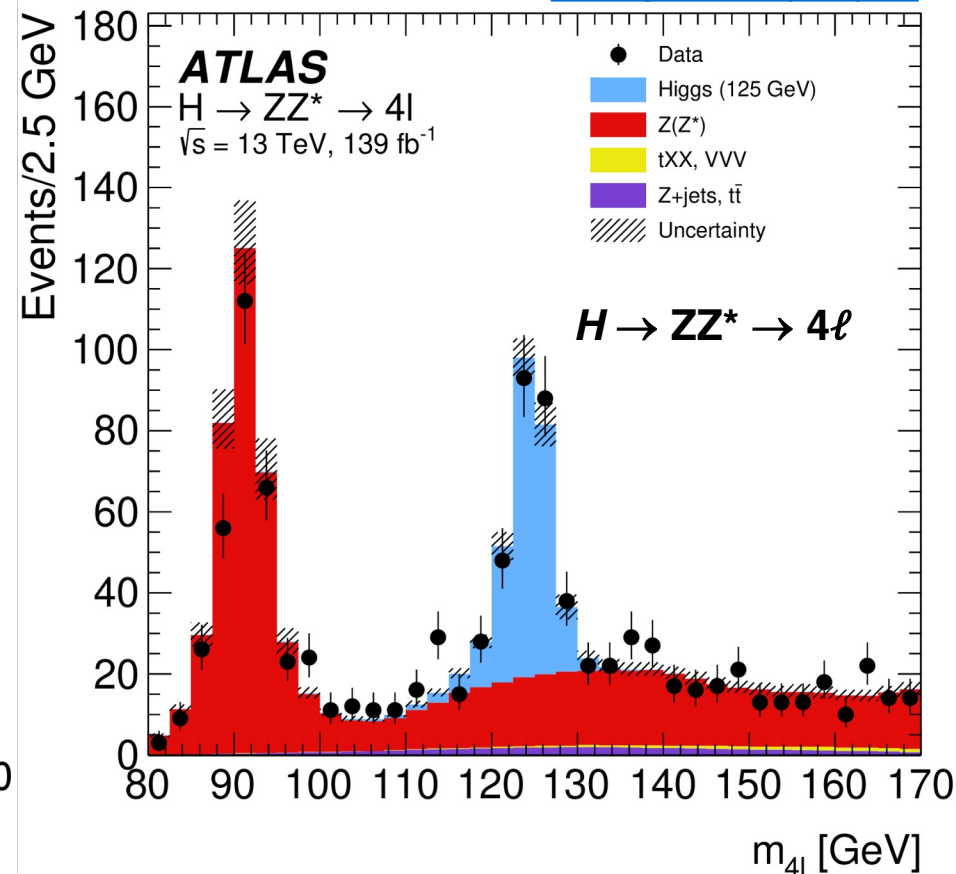
The Higgs boson — At 10

2020

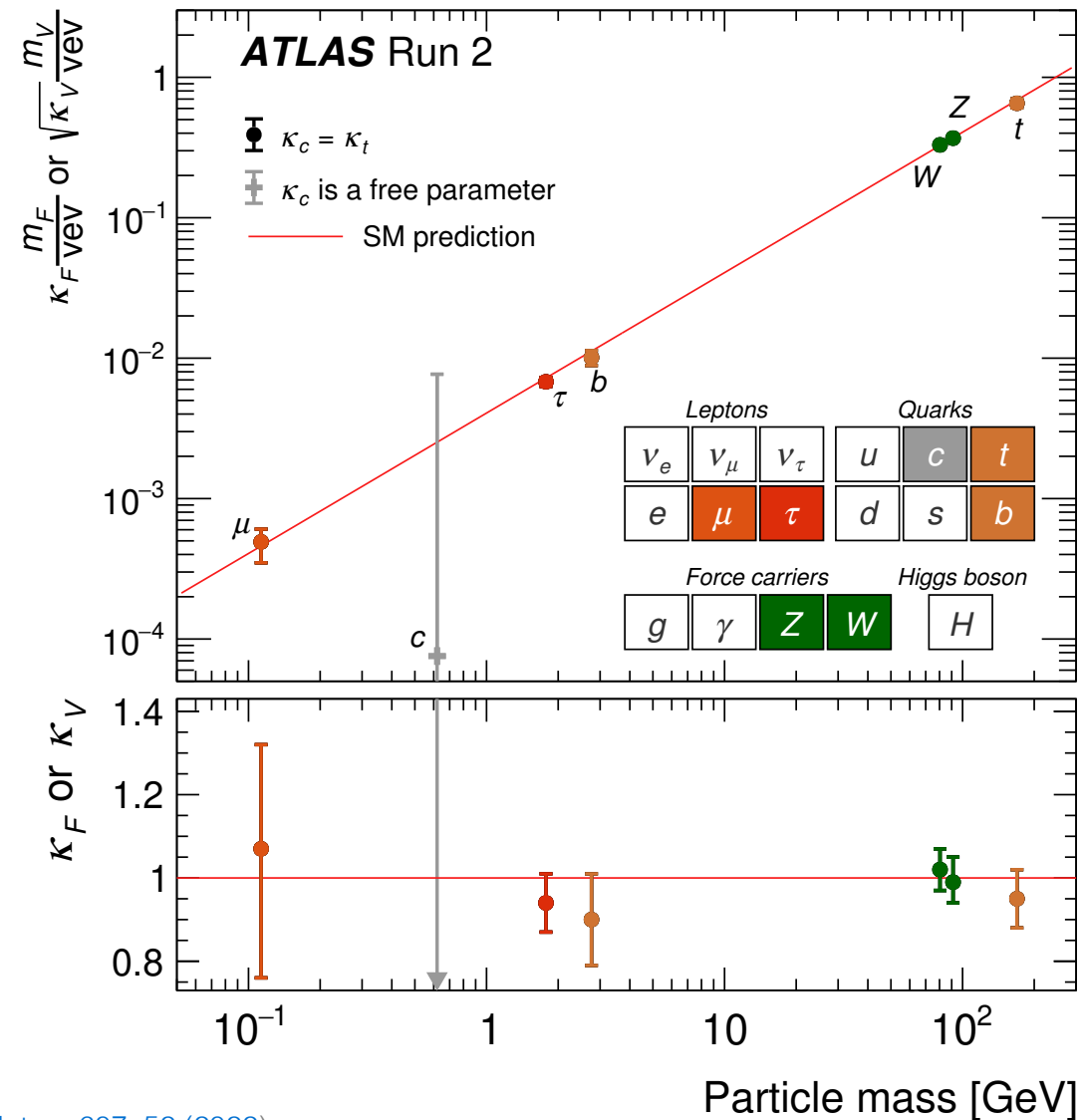
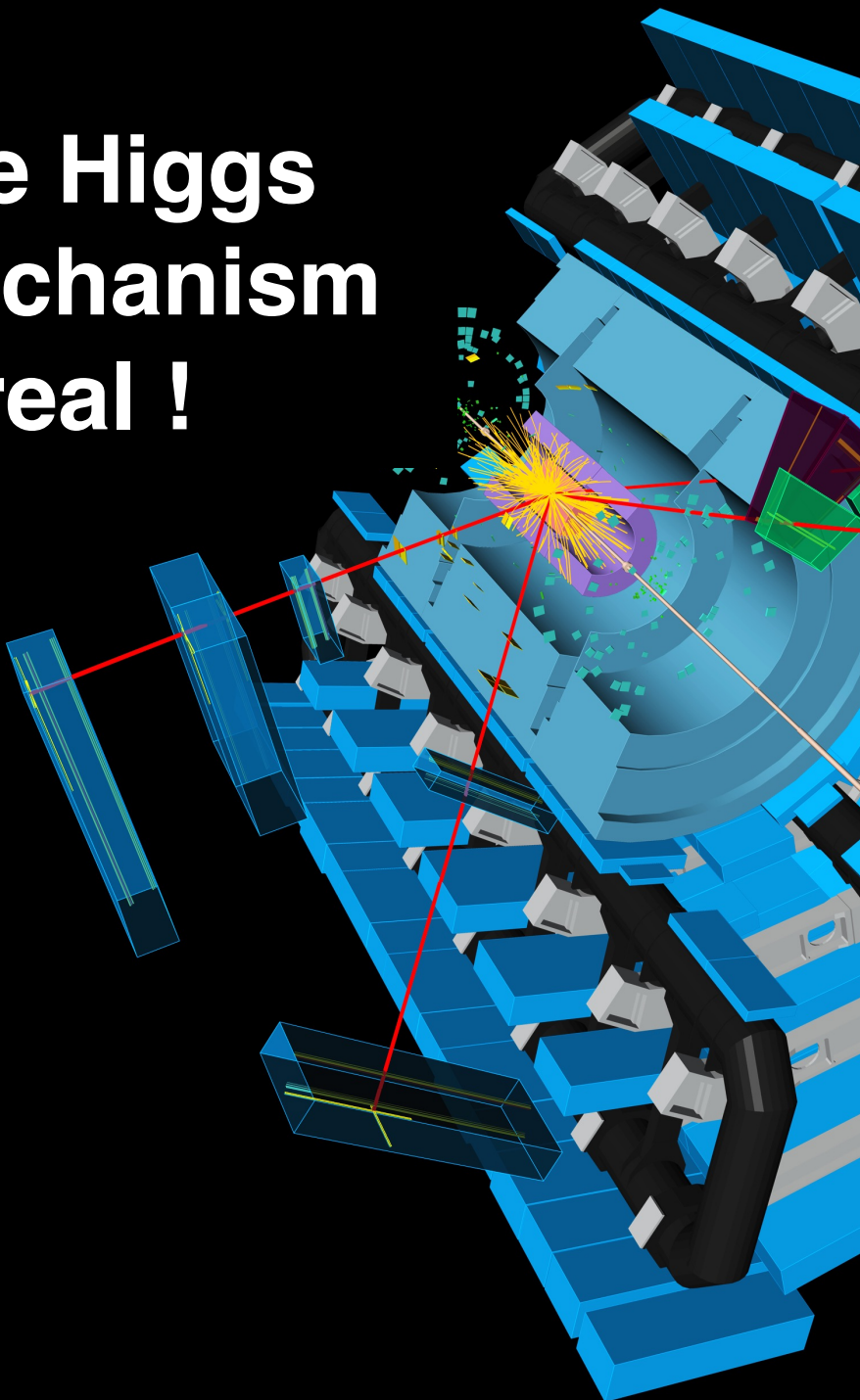
[JHEP 07 \(2023\) 088](#)



[Eur. Phys. J. C 80 \(2020\) 942](#)

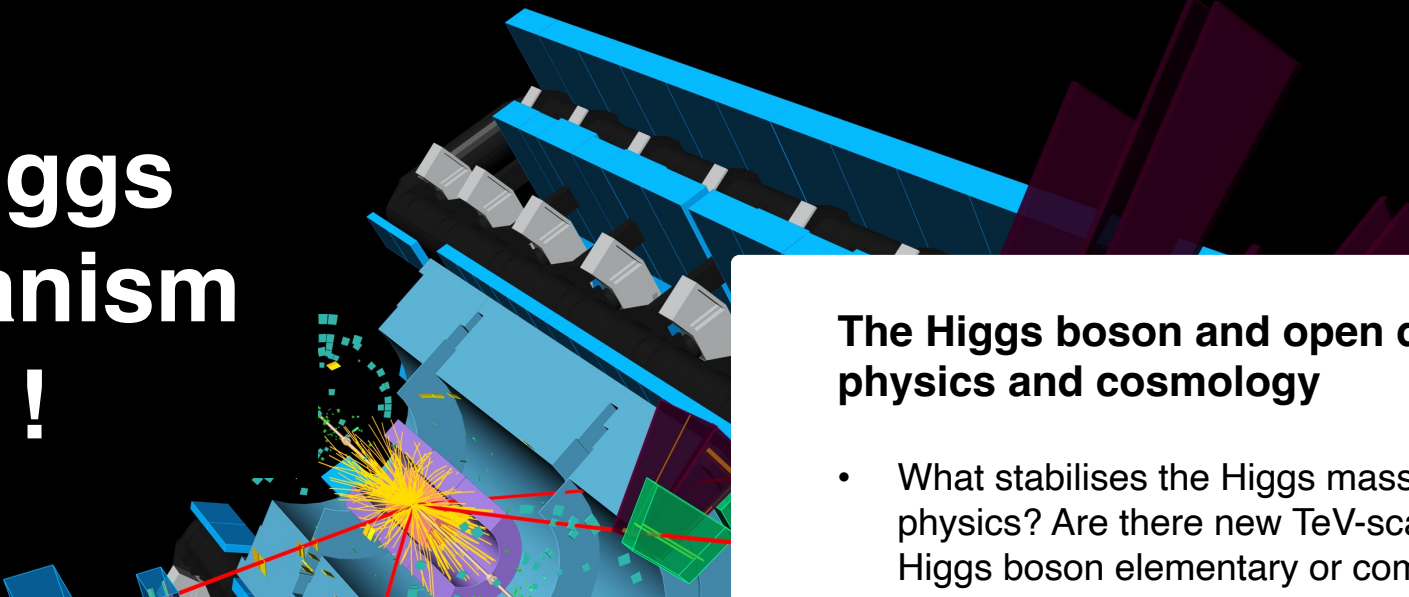


The Higgs mechanism is real !

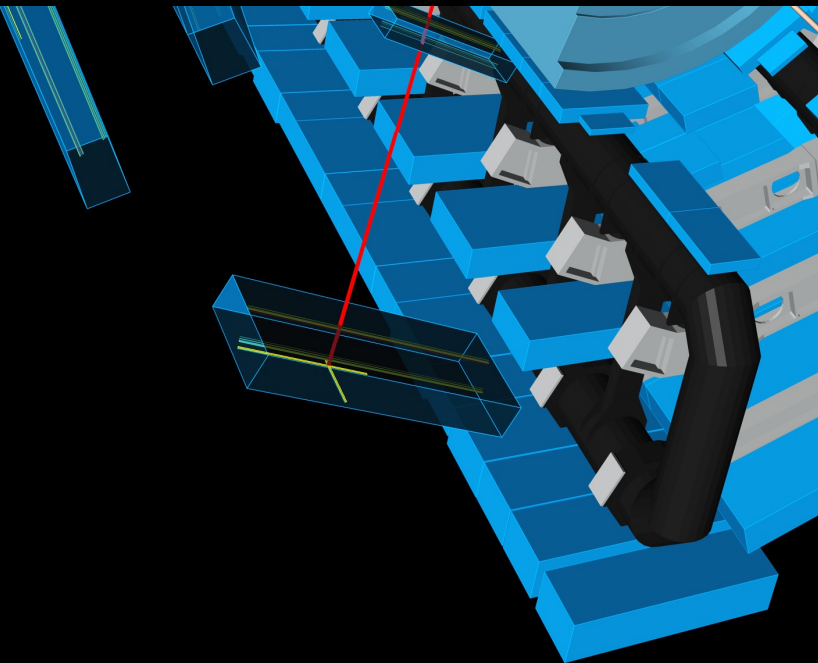


[Nature 607, 52 \(2022\)](#)

The Higgs mechanism is real !



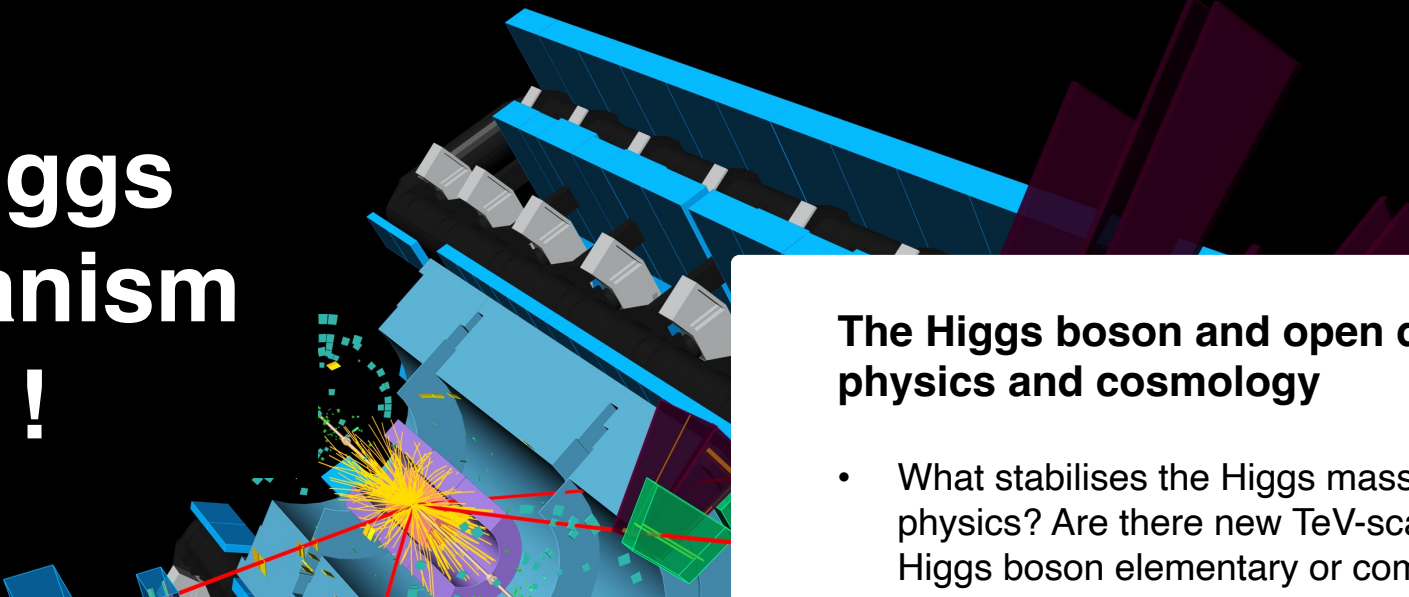
The Higgs sector is directly connected with very profound and crucial questions



The Higgs boson and open questions in particle physics and cosmology

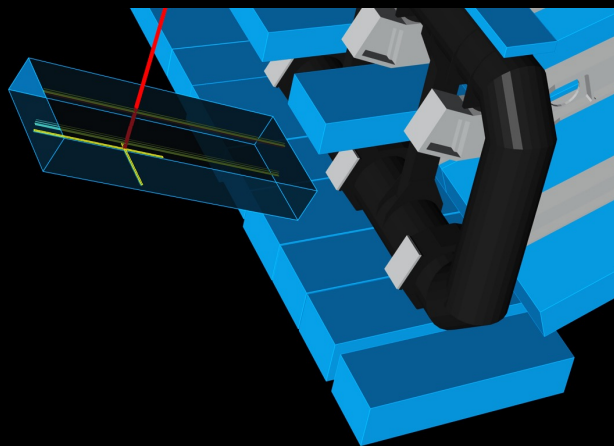
- What stabilises the Higgs mass versus high-scale new physics? Are there new TeV-scale symmetries? Is the Higgs boson elementary or composite, are there anomalies in its coupling to the W or Z?
- Do Higgs interactions violate CP? How fast is the phase transition governed by the Higgs potential?
- Is the Higgs boson unique?
- Does the Higgs boson couple to dark matter?
- What is the origin of the large mass hierarchy in the Standard Model?
- Is the vacuum metastable? Is the Higgs field connected with cosmic inflation?
- Why is the dark energy in the universe so much smaller than the Higgs vacuum energy?

The Higgs mechanism is real !



The Higgs sector is directly connected with very profound and crucial questions

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



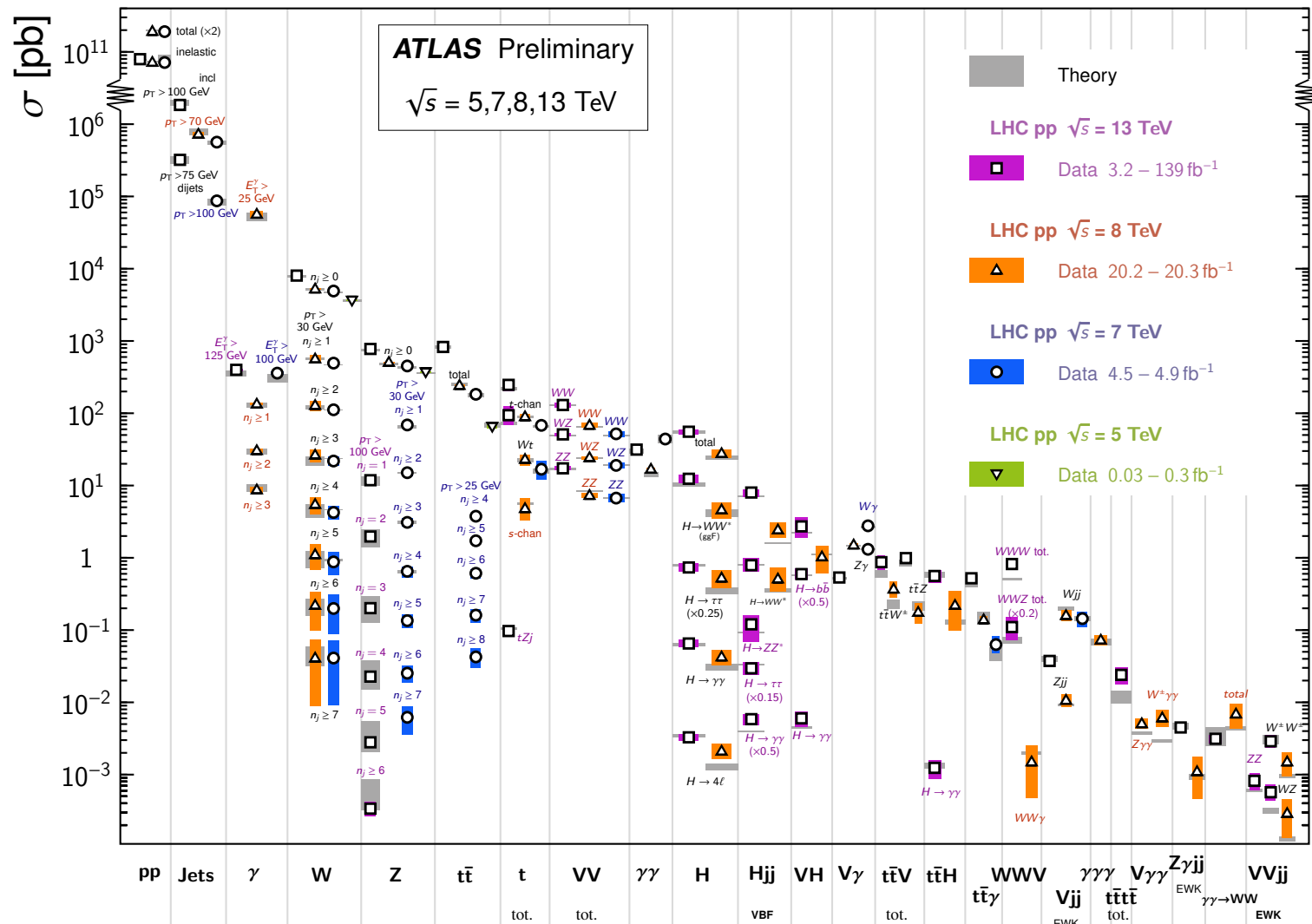
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The LHC also provides a new understanding of hadron collider processes: the observation of numerous rare channels testing the Standard Model, and huge theoretical progress

Standard Model Production Cross Section Measurements

Status: February 2022

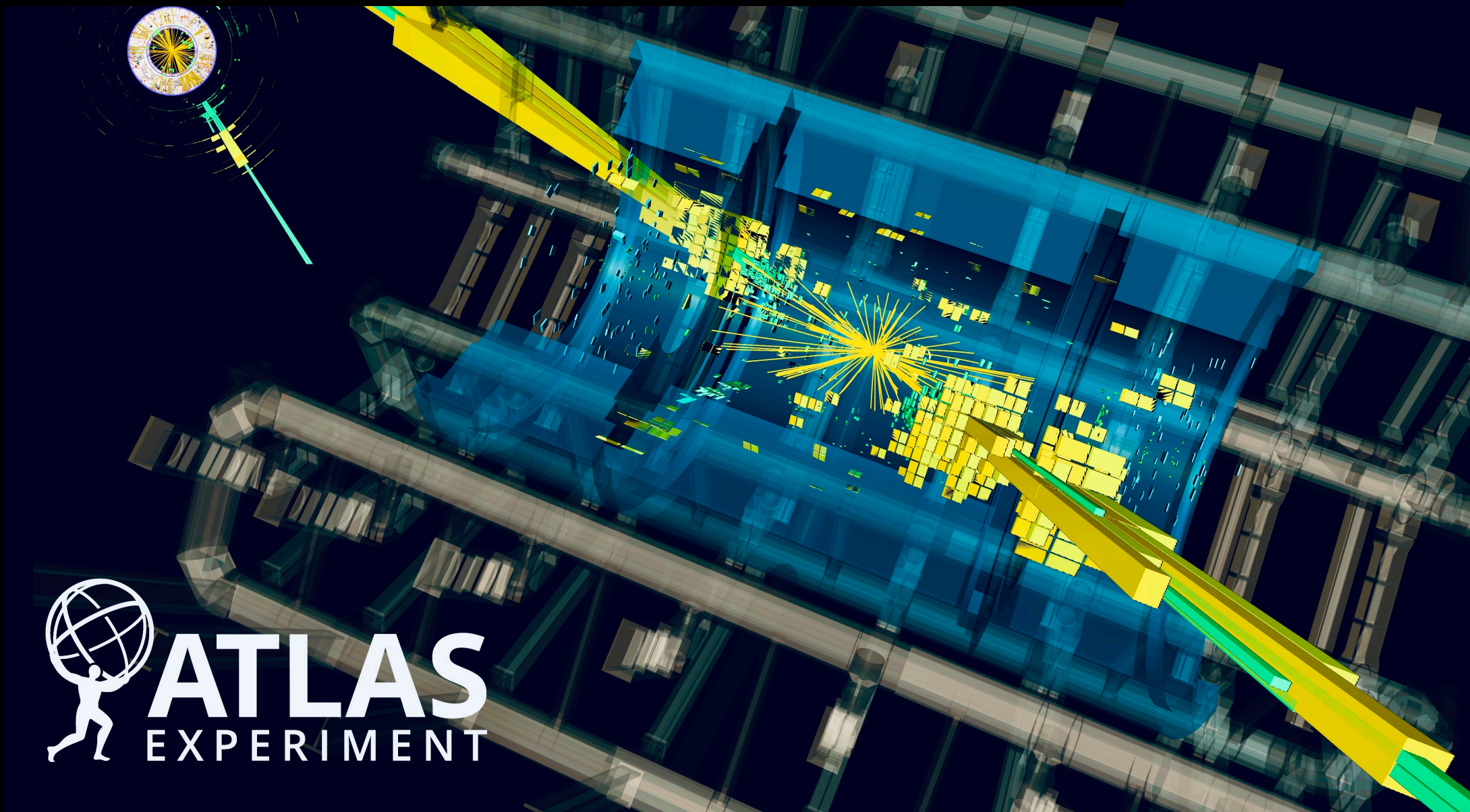


Run: 329716

Event: 857582452

2017-07-14 10:48:51 CEST

Deep searches for new phenomena



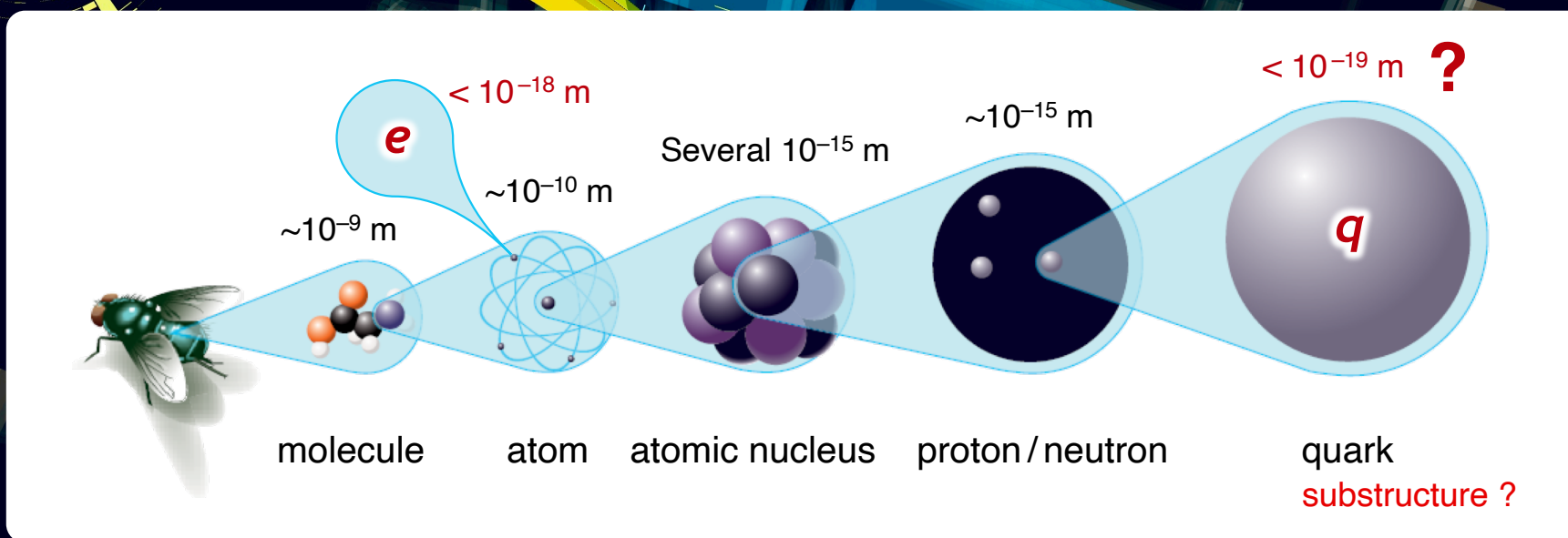
ATLAS
EXPERIMENT

Run: 329716

Event: 857582452

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Are quarks elementary particles?

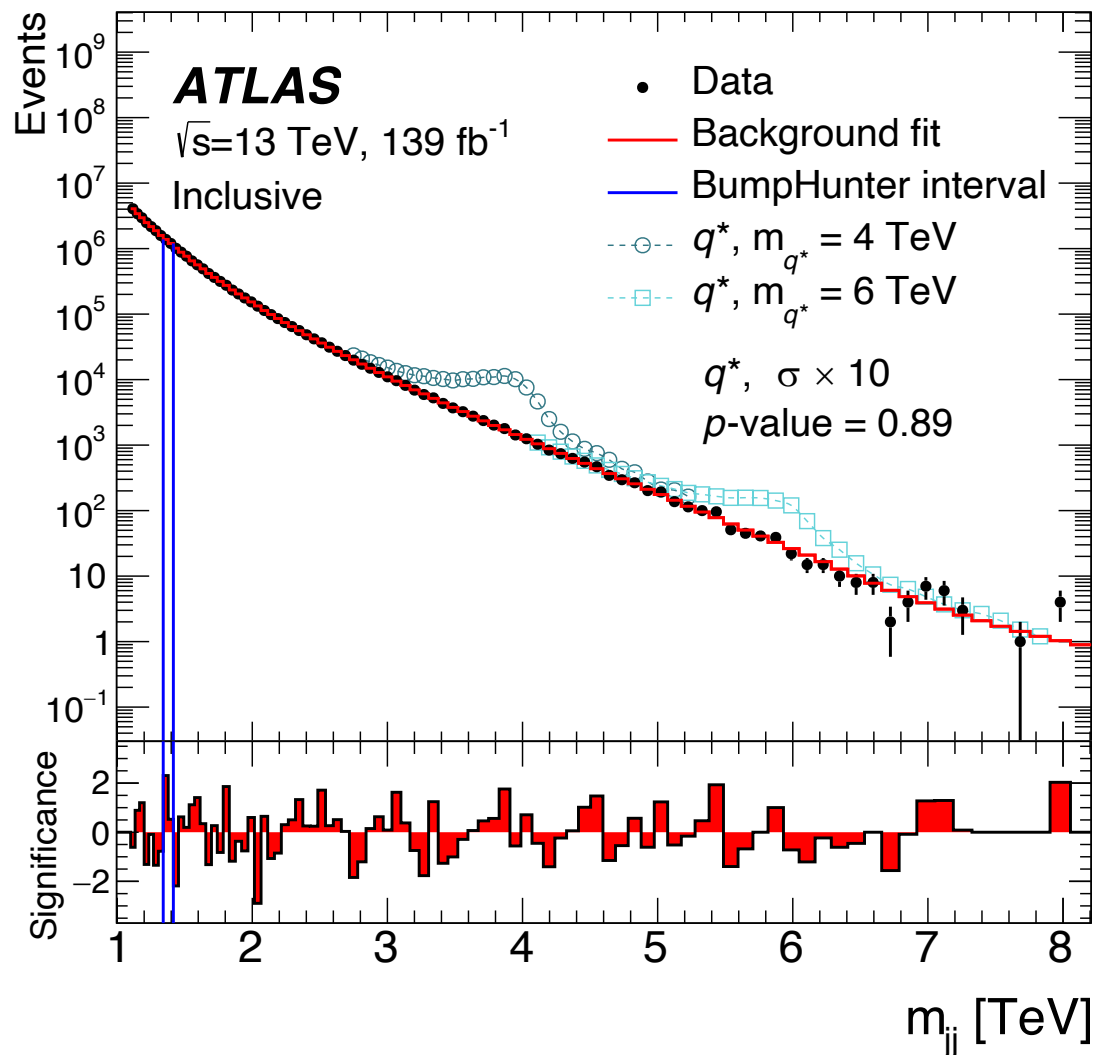


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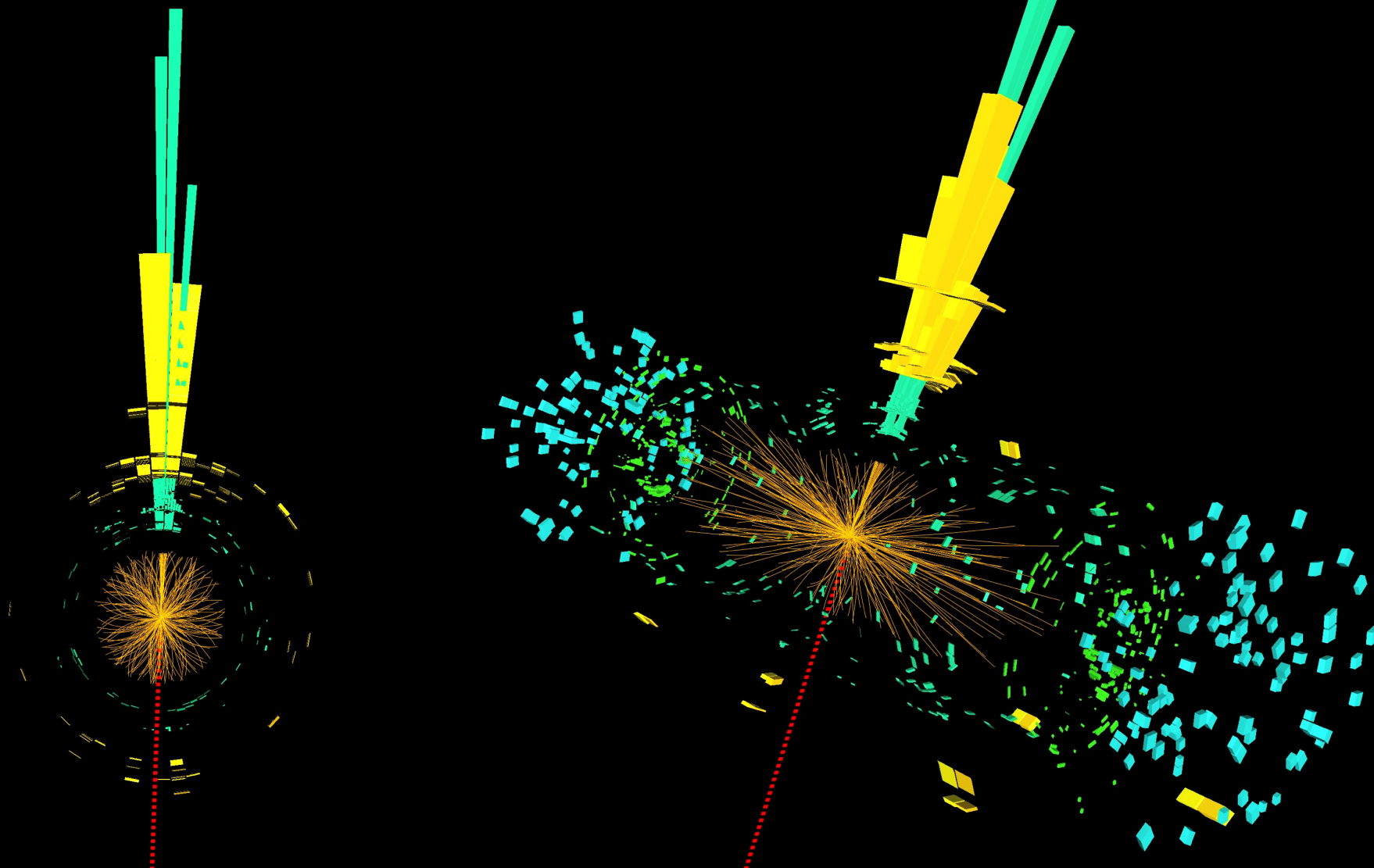
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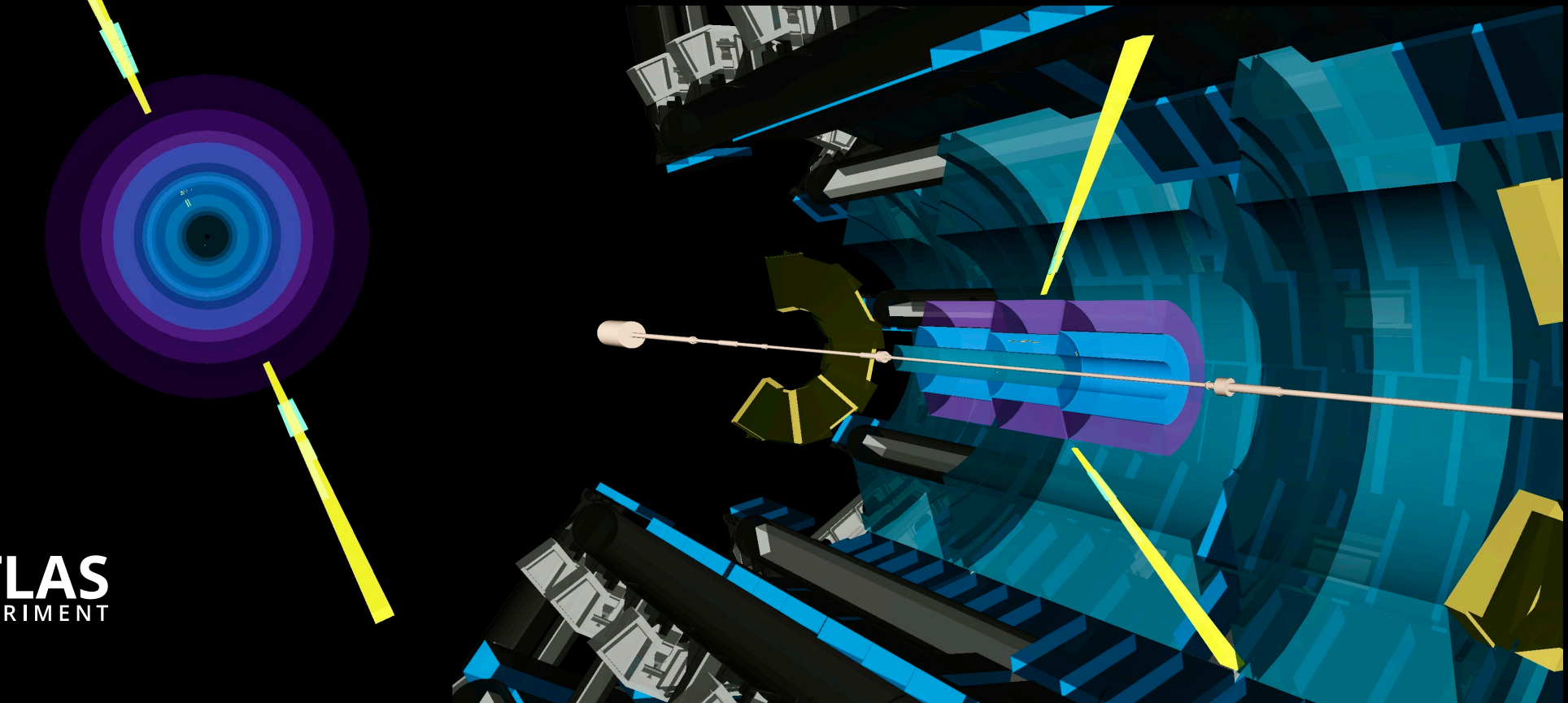
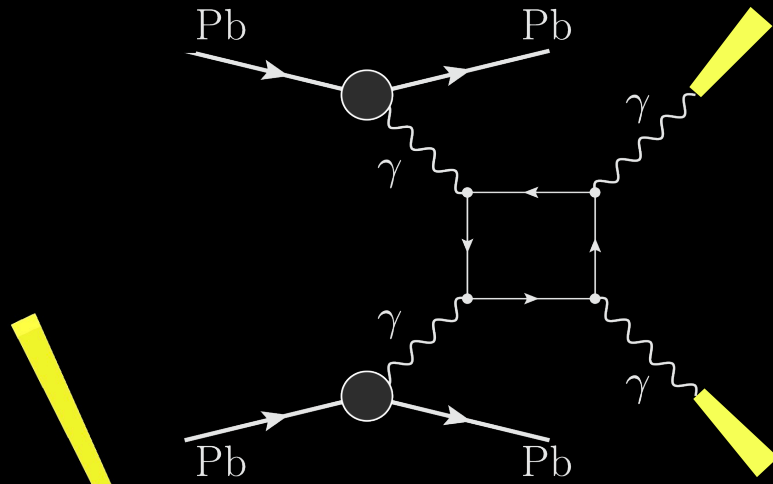


Searches for Dark Matter

Are dark matter particles produced in proton collisions or in Higgs-boson decays?

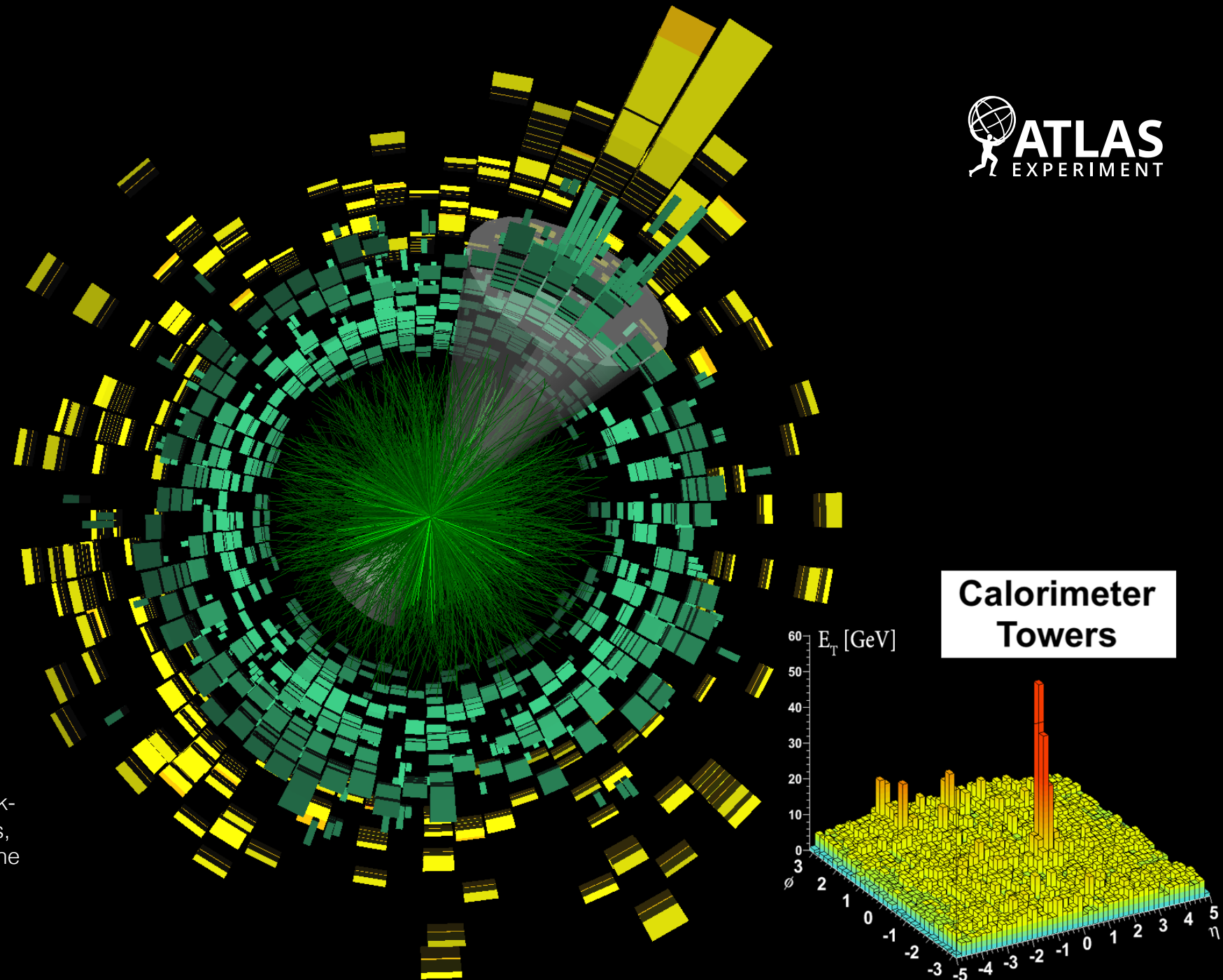


Studies of physics in extreme electromagnetic fields



And a detailed mapping of the properties of the quark-gluon plasma with soft and hard probes

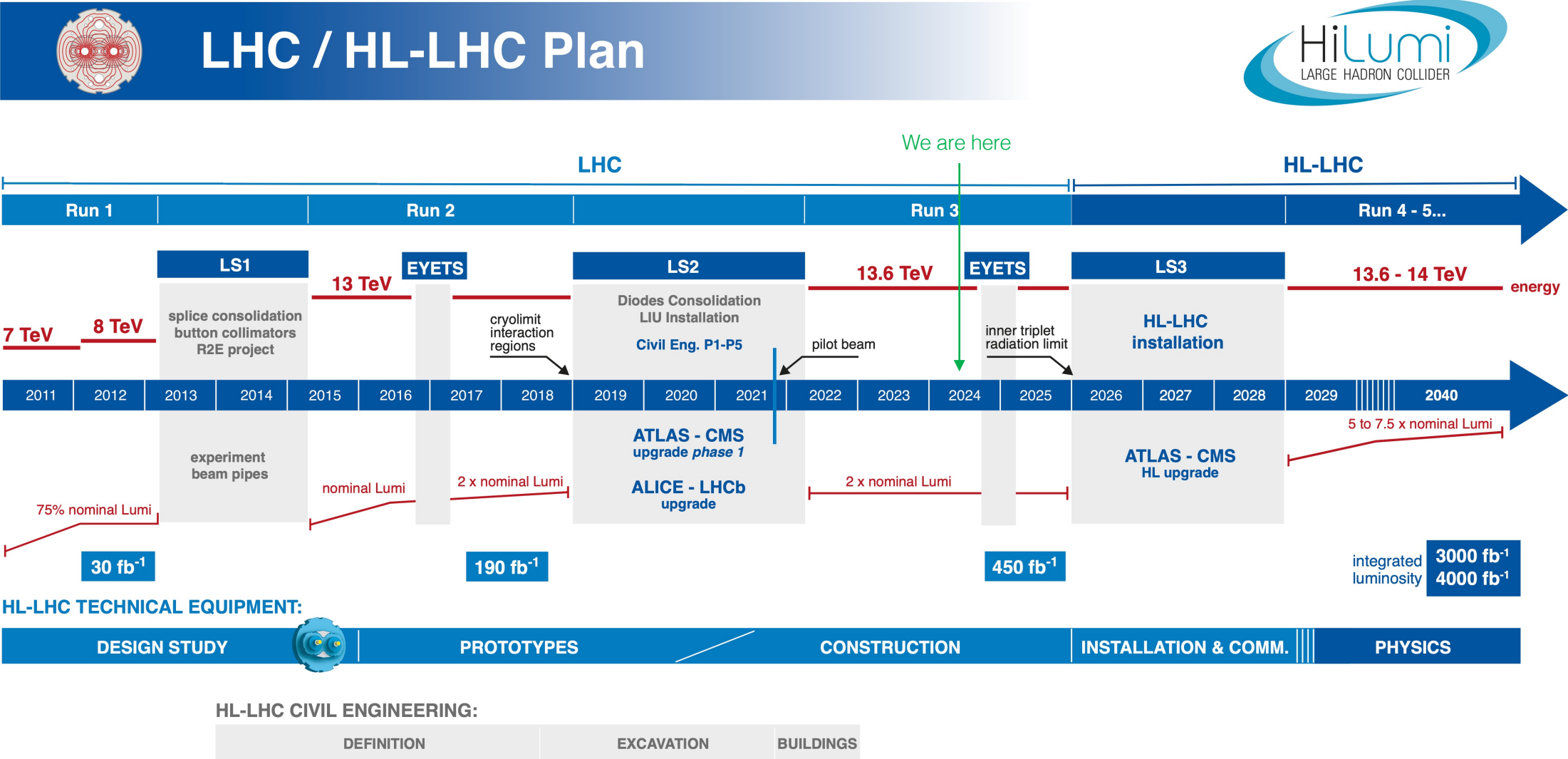
In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun



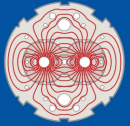
An aerial photograph of a landscape featuring a patchwork of green and brown agricultural fields, some urban areas, and a body of water in the bottom right. A white line is drawn over the map, forming a large circle with a smaller loop inside. Four small satellite icons are placed along this path: one at the top of the large circle, one at the bottom of the loop, and two others on the left and right sides of the large circle. The text "The next steps" is centered over the map.

The next steps

Preparing the future — the grand plan of the LHC



Preparing the future — the grand plan



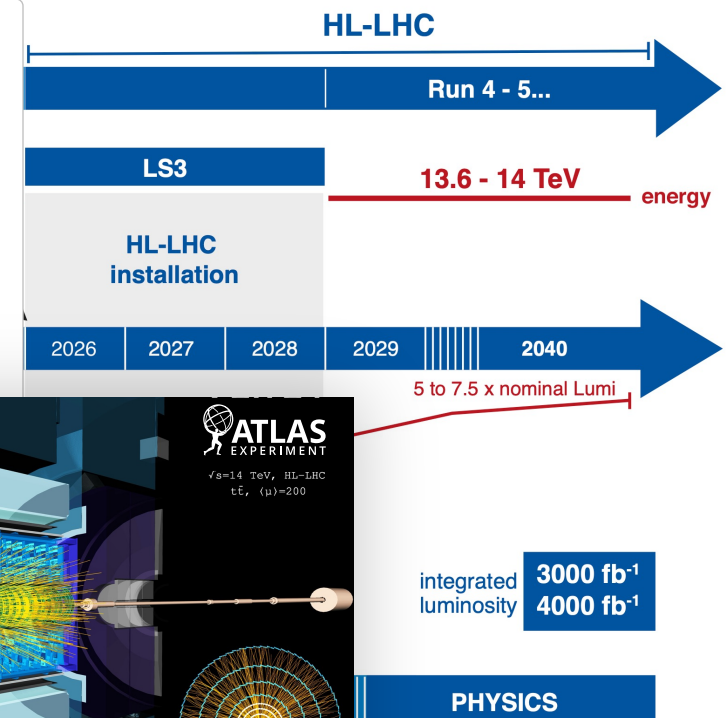
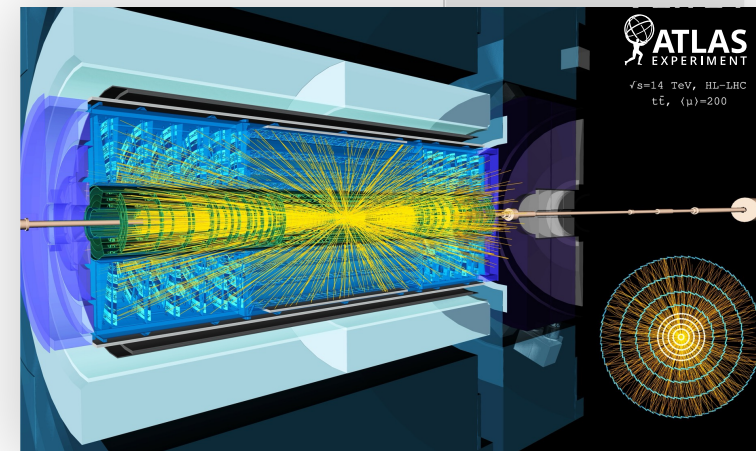
LHC / HL-LHC Plan



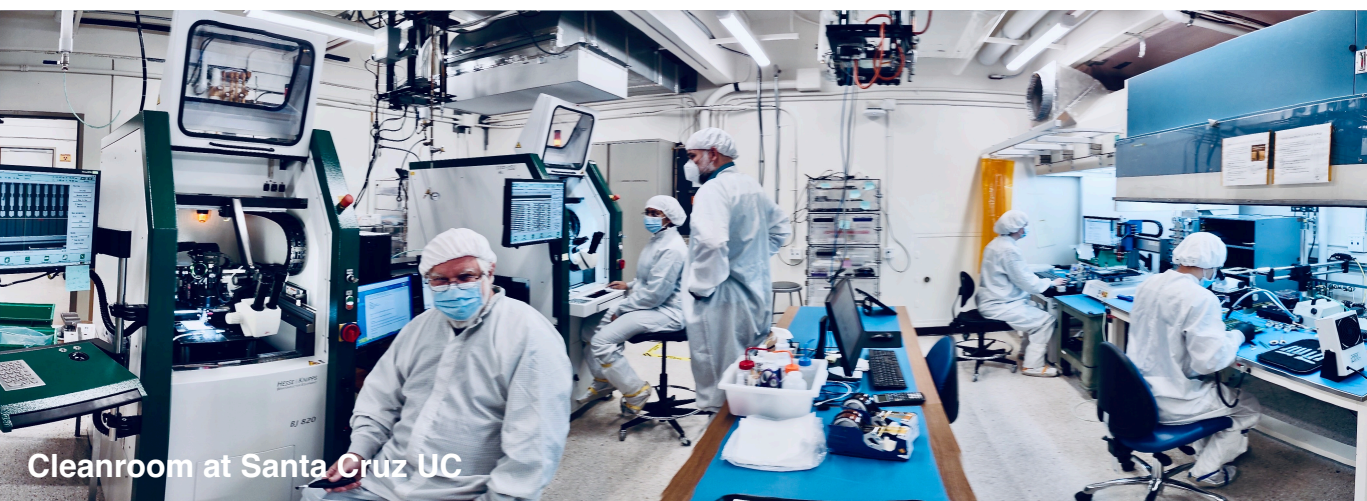
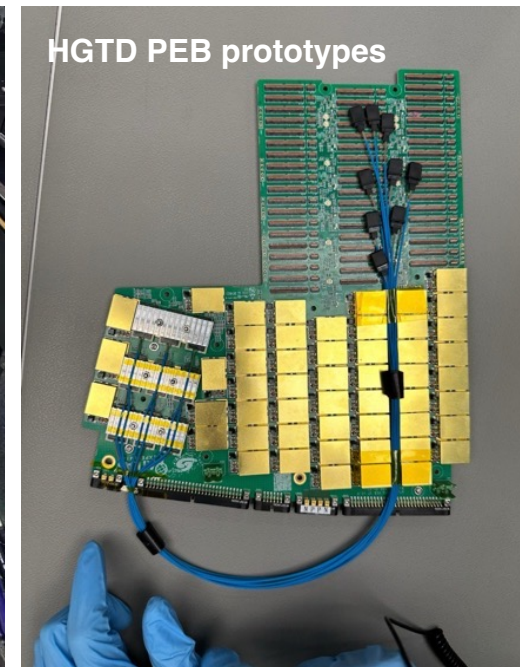
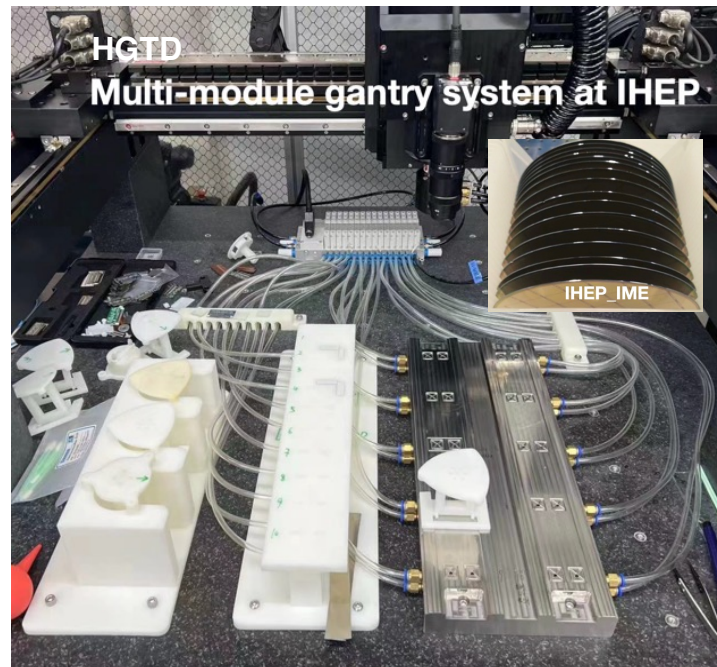
The HL-LHC promises 15 times the data sample currently collected (eg, 400 million Higgs bosons)

Its beam intensity requires unprecedented detector and computing technologies:

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



Detector upgrades for the HL-LHC

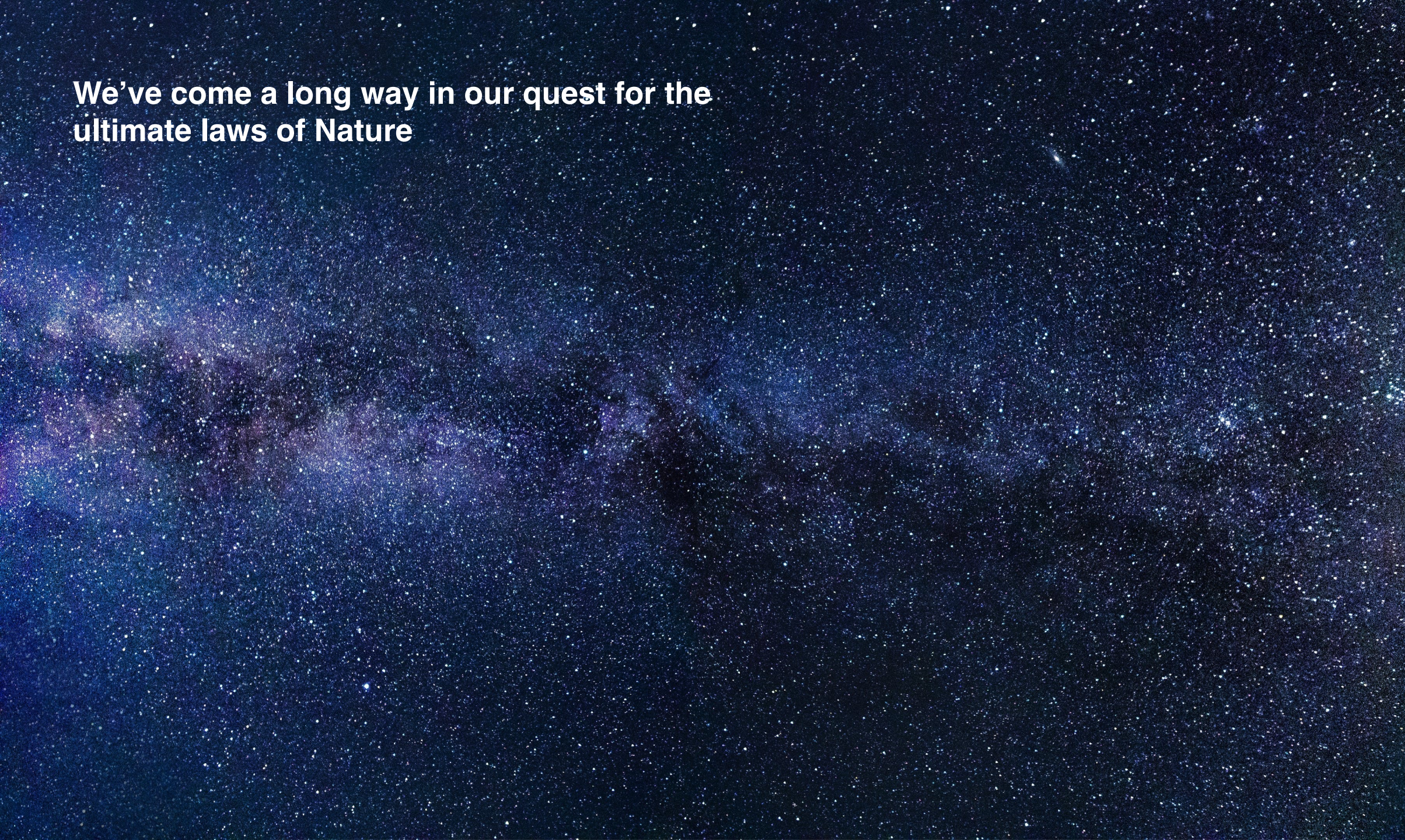


Run 3 (2022–2025) at 13.6 TeV is underway



First 13.6 TeV collisions on 5 July 2022

**We've come a long way in our quest for the
ultimate laws of Nature**



**We've come a long way in our quest for the
ultimate laws of Nature**

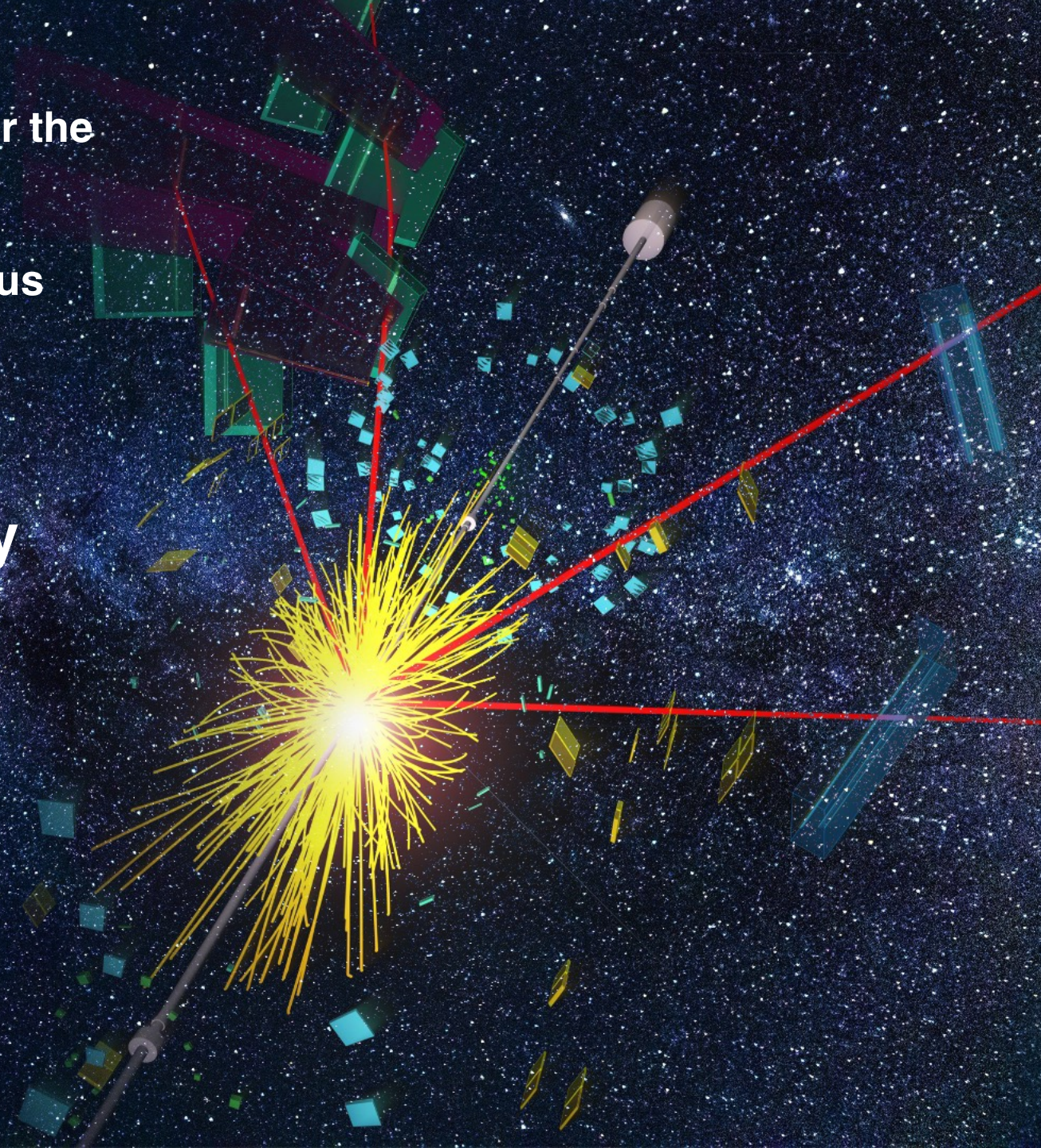
But many secrets remain hidden from us

We've come a long way in our quest for the
ultimate laws of Nature

But many secrets remain hidden from us

**ATLAS' voyage of discovery
continues at pace!**

Thank you for your attention



Additional slides



An analogy to the Higgs mechanism

Superconductivity

SC (BCS) theory

Cooper pair Bose condensation

Electrically charged ($2e$)

Mass of the photon

$T_{\text{crit}} \sim \text{mK}$ – several 10s of K

Higgs mechanism

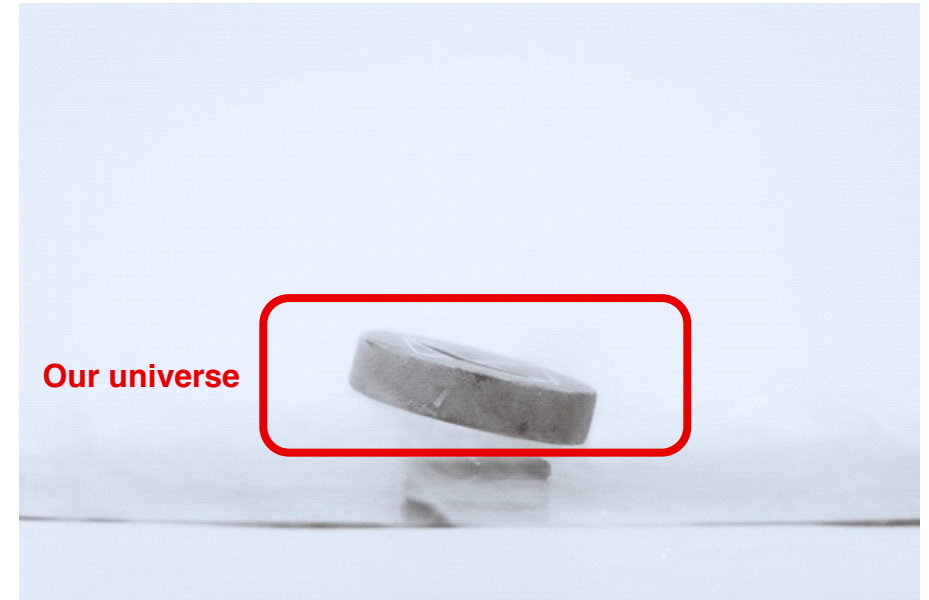
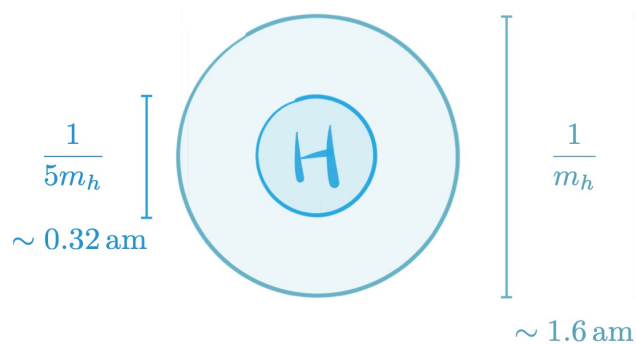
Condensed Higgs field

Weak charge

Mass of W & Z bosons

$T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K}$

→ Is the Higgs boson elementary or composite?



A superconductor is locked mid-air in different orientations above a permanent magnet — superconductive levitation due to the expulsion of the static magnetic field (Meissner effect) [\[Source\]](#)

In response to an externally applied magnetic field, perpetual eddy currents circulate in the superconductor, producing an internal magnetic field that exactly cancels the externally applied one