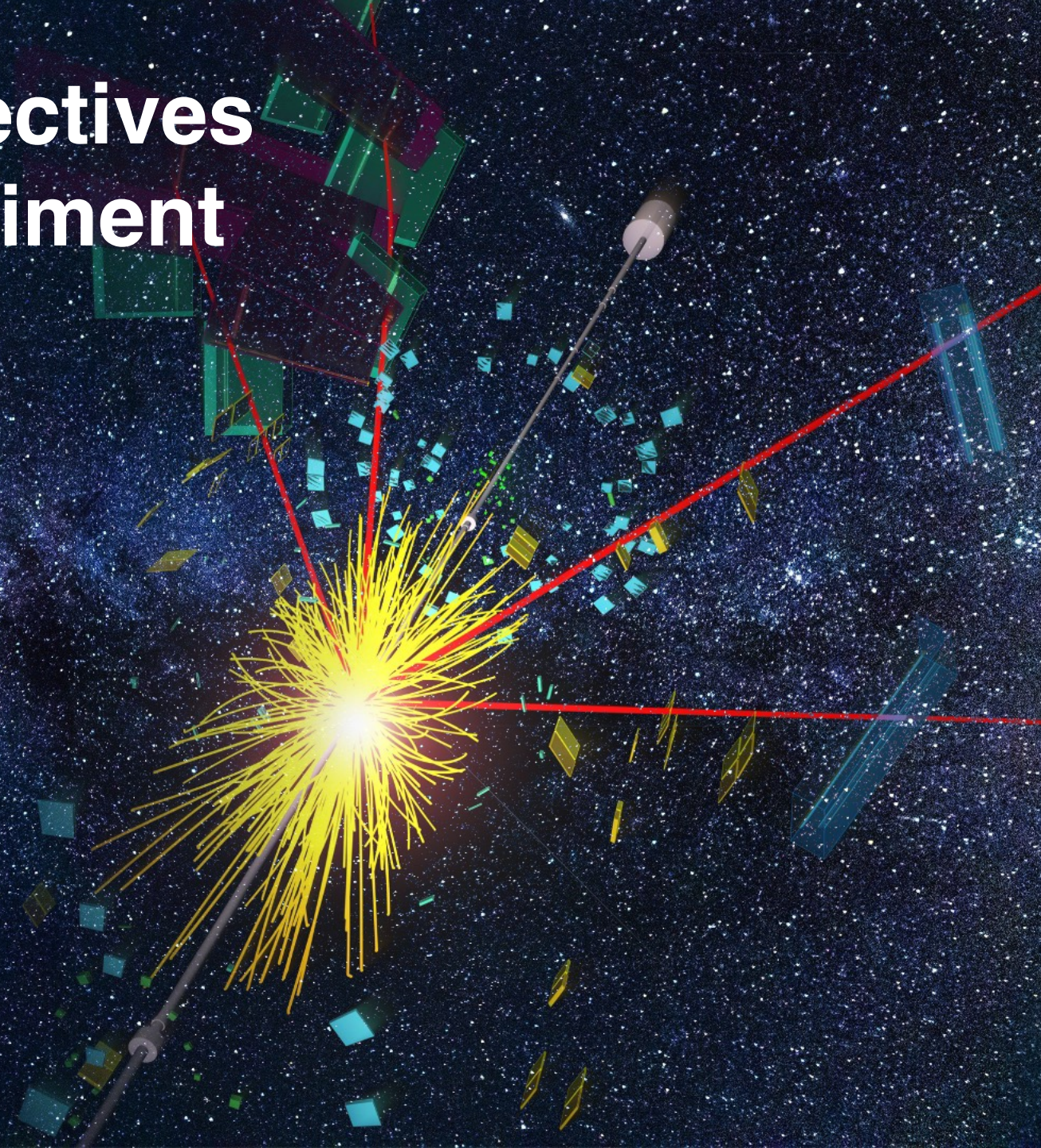


Physics and Perspectives of the ATLAS Experiment at the LHC

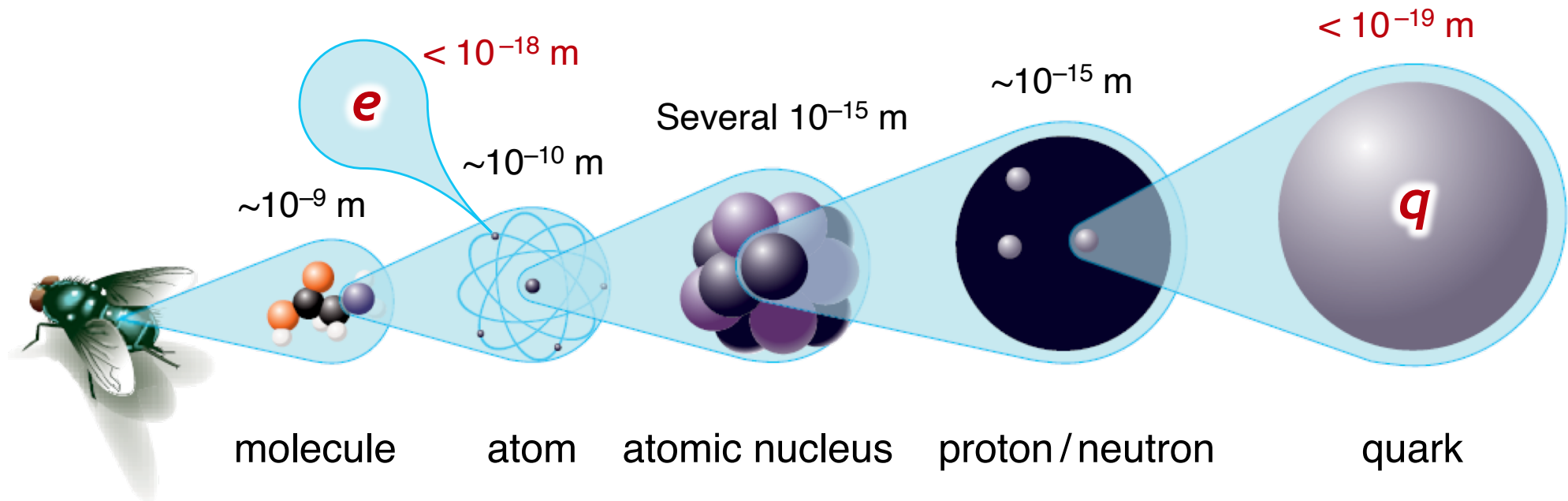
Andreas Hoecker (CERN)

CERN TE Graduate Workshop 2025



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

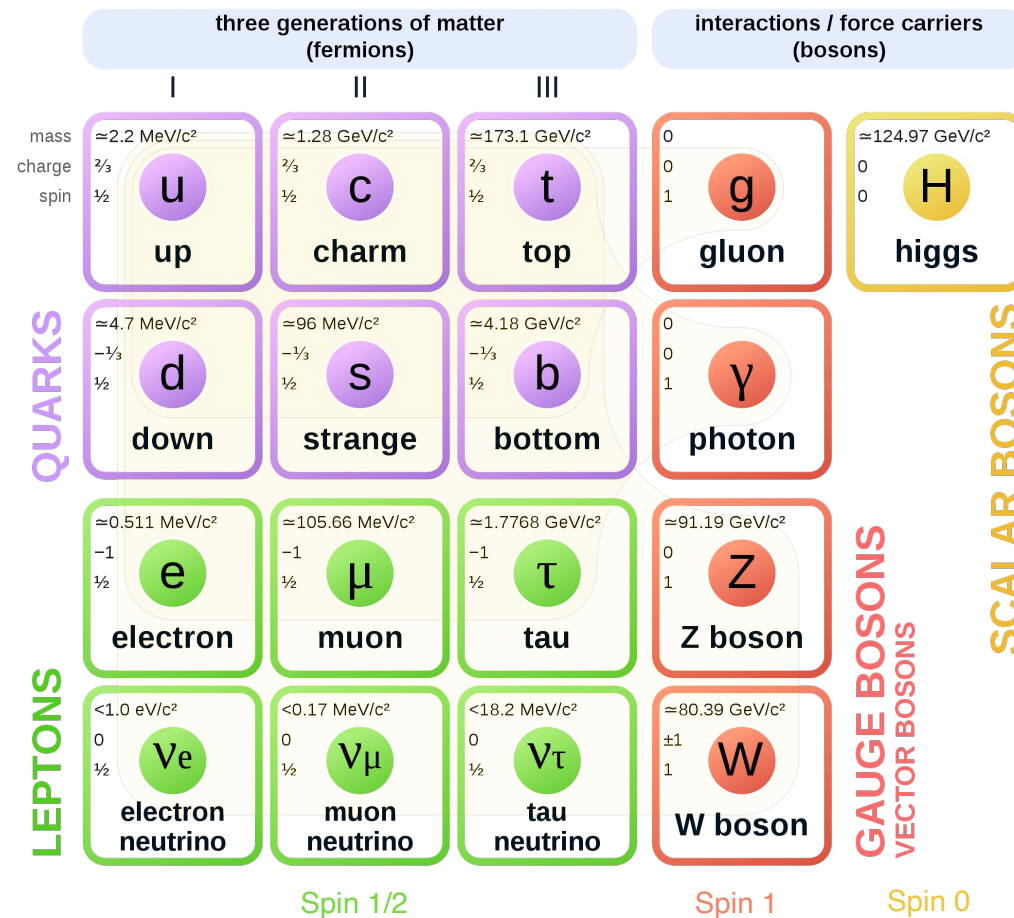
The sub-atomic structure of matter (a very simplified picture)



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



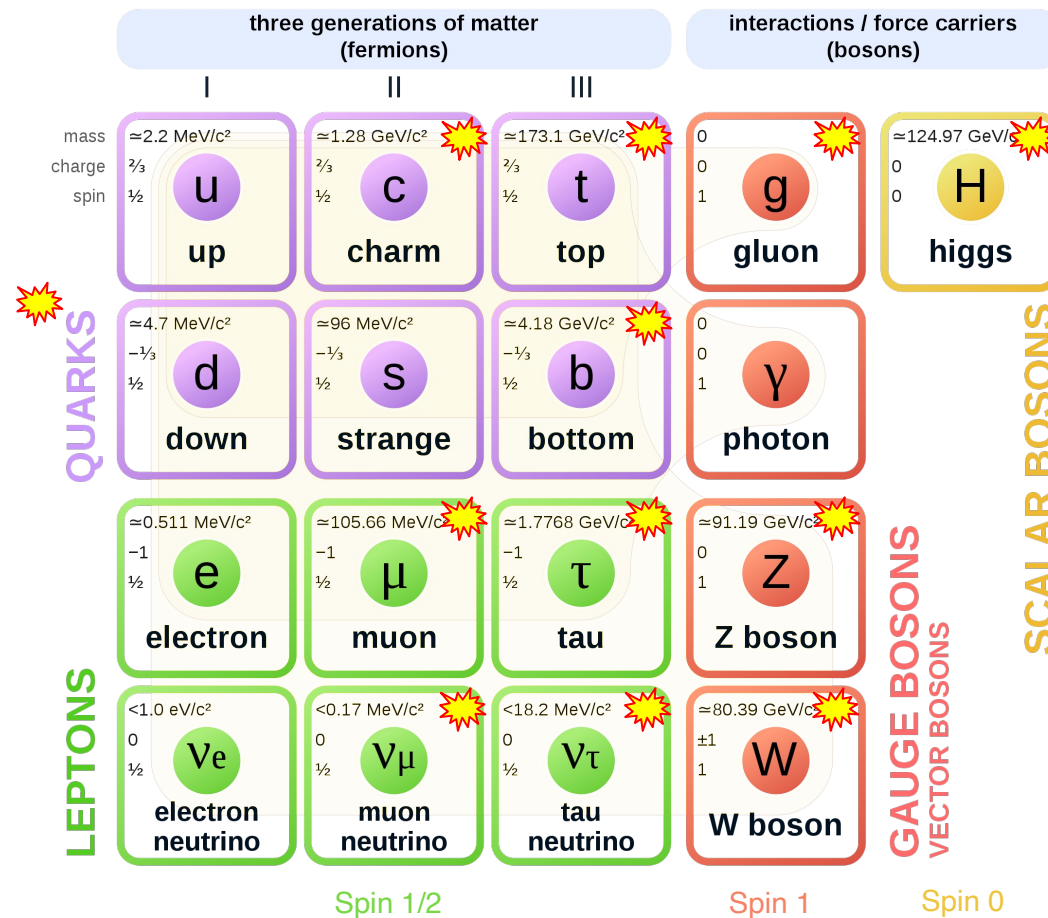
In mathematical terms, **particles are local excitations of quantum fields**. There are matter fields (fermions) and force fields (bosons)

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

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



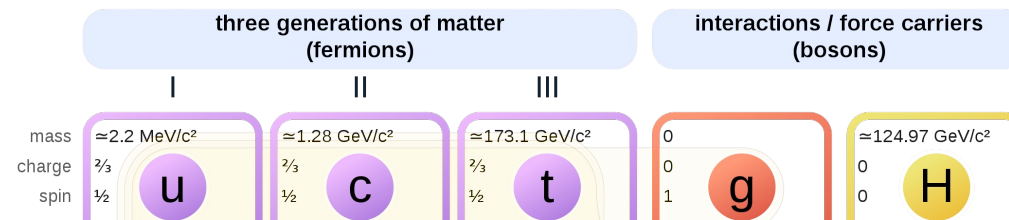
Decades of international high-technology **accelerator-based research** gave us these insights

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

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

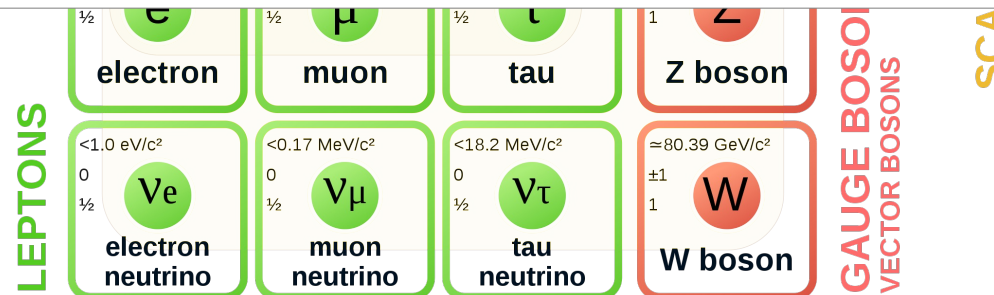


The Standard Model is a highly predictive theory

For example, prediction of the magnetic dipole moment of the electron:

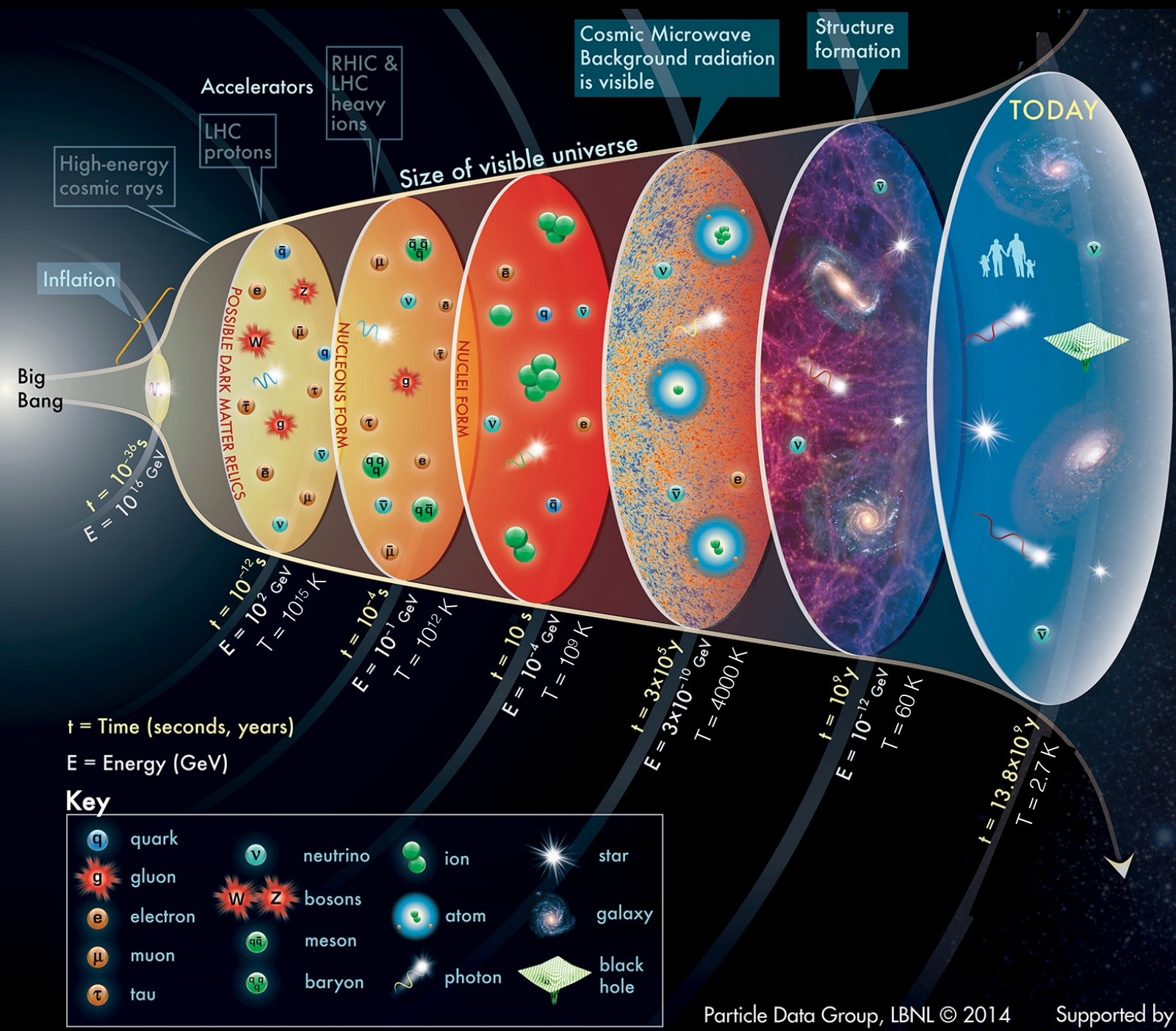
$$g/2 = 1.001\,159\,652\,180\,59 \pm 0.000\,000\,000\,000\,13$$

In agreement with experiment within a precision of 10^{-10} !



The Standard Model

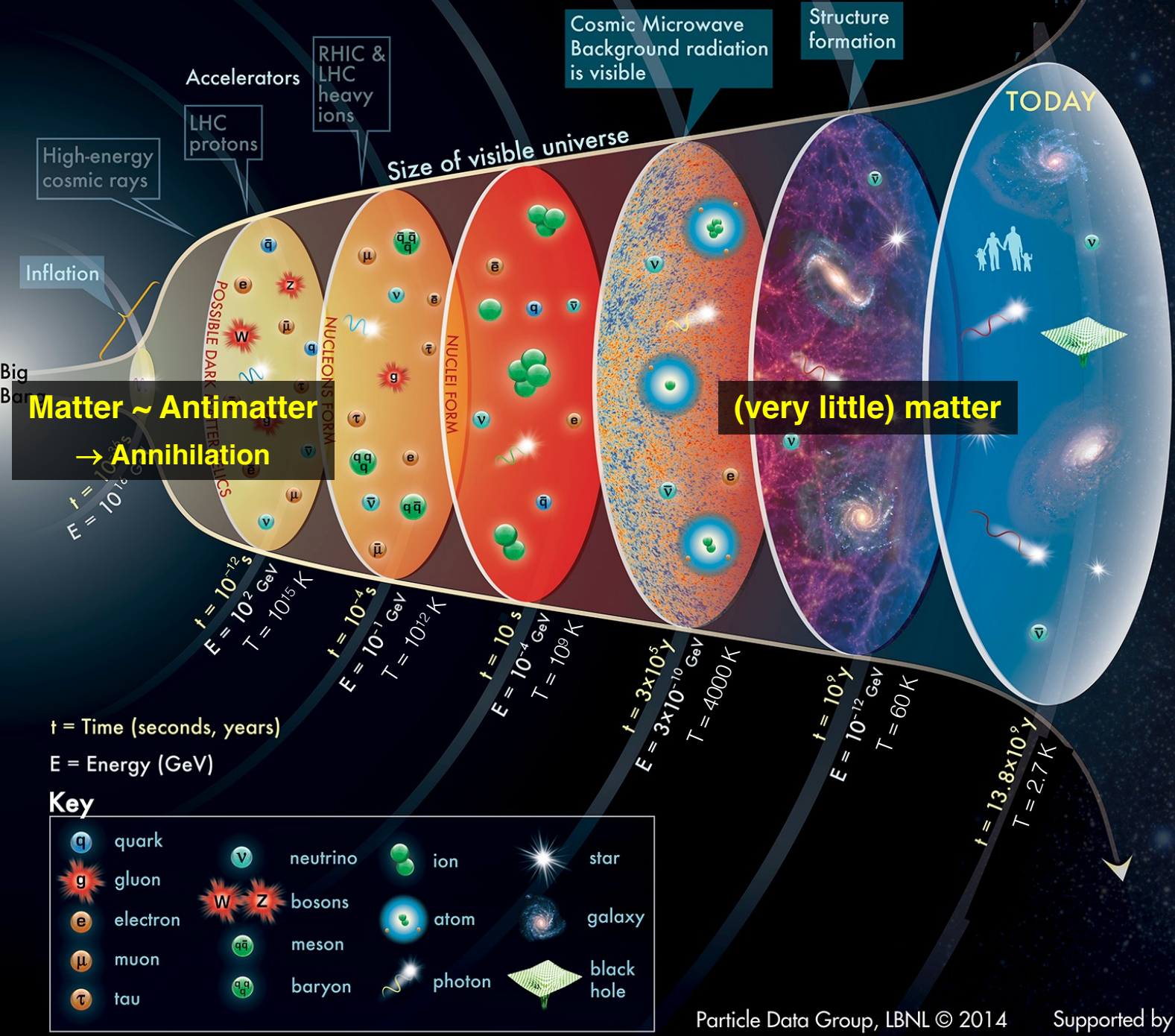
... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago



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?

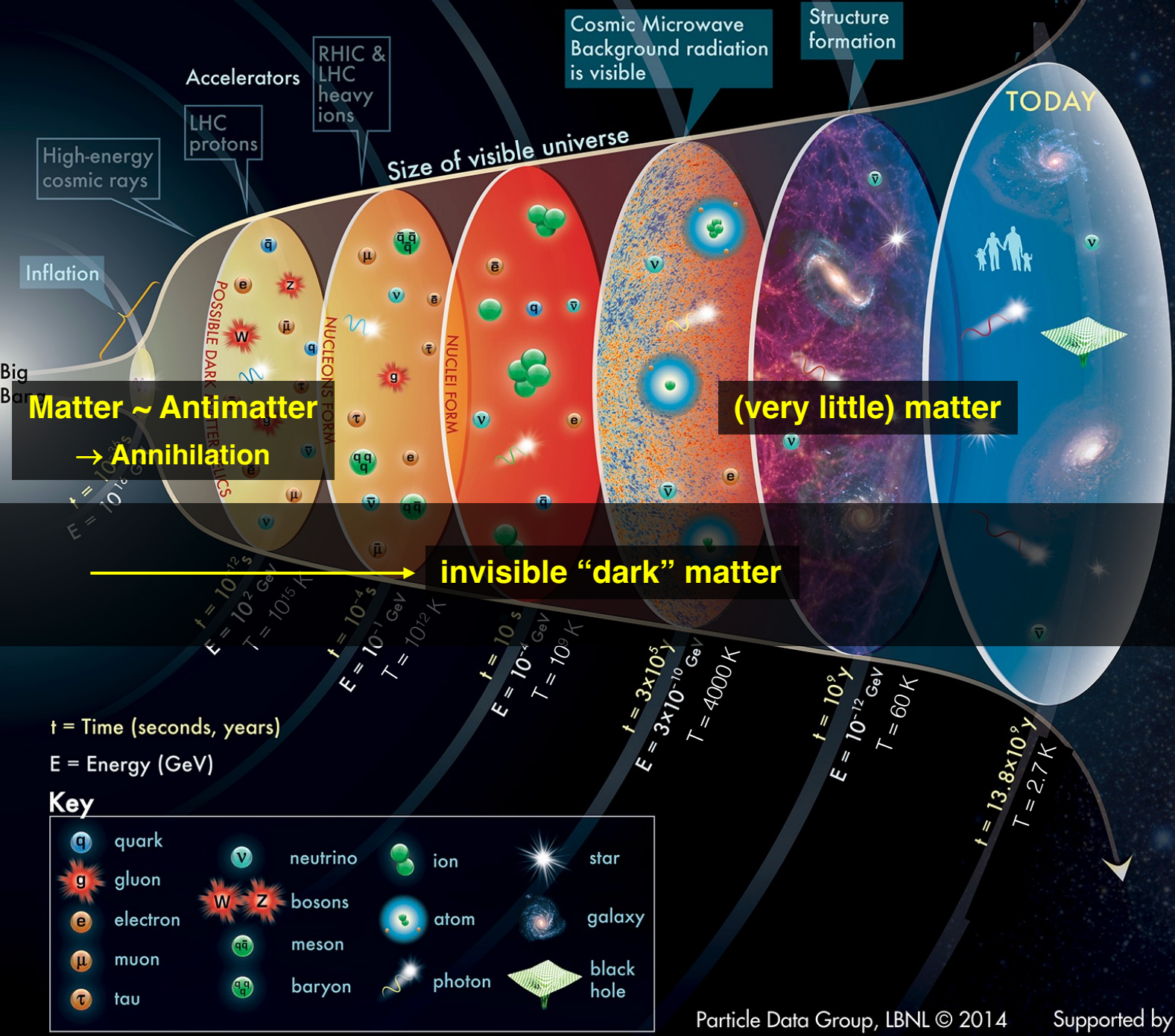


The Standard Model

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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

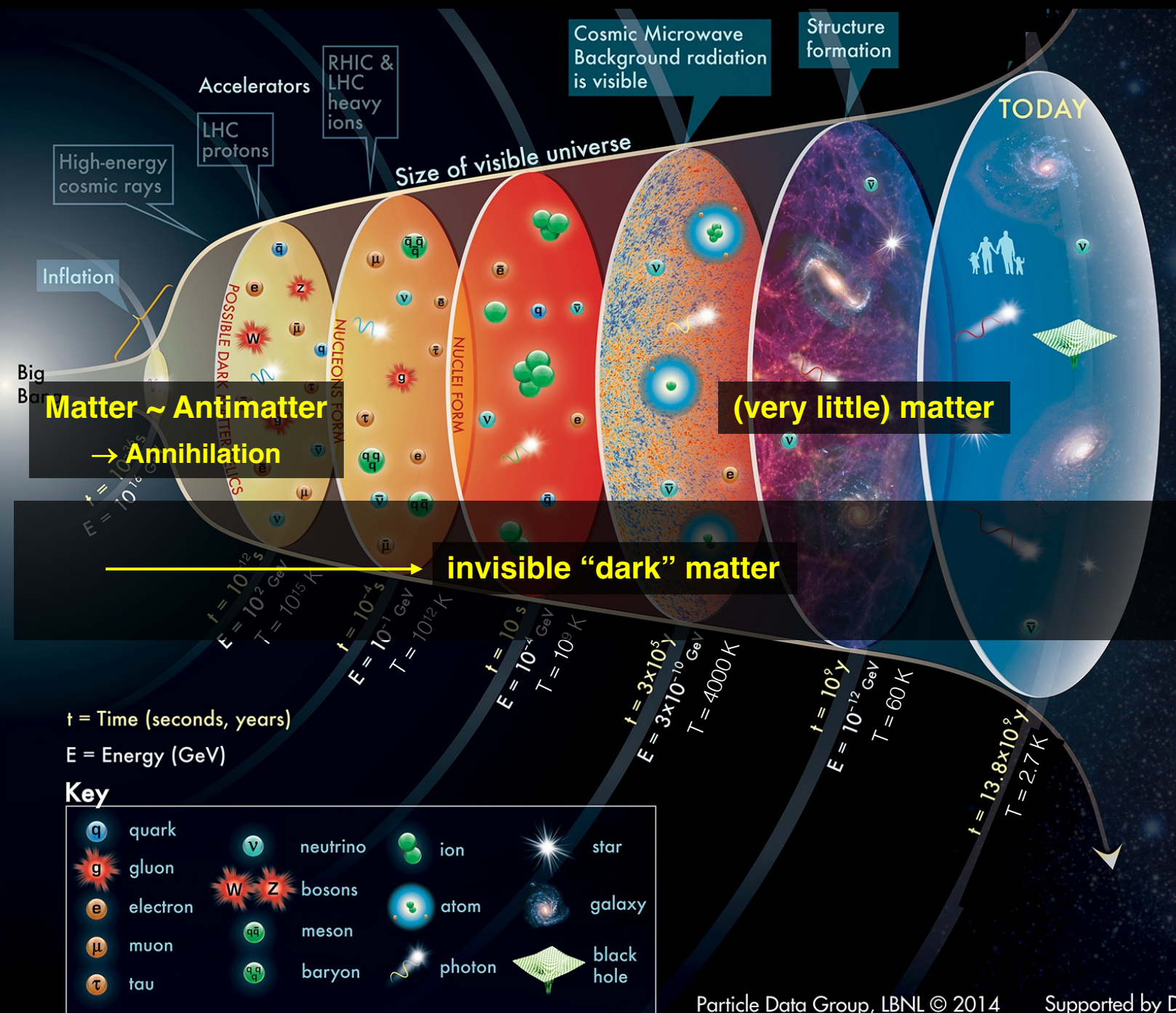
... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago

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?
(Simply sticking masses onto particles has disastrous effects, causing certain predictions to diverge to infinity and creating mathematical inconsistencies)

A simple, though very profound question: *how and when* did mass occur?

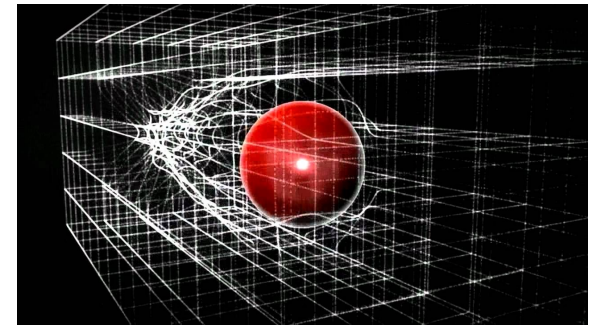


Gauge symmetry and the Higgs mechanism

A solution to the mass problem is to introduce a new complex scalar field ϕ , which couples to the weak bosons and fermions, 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

This non-zero **Higgs field** fills all space. The interaction of a particle with the field gives the particle mass. The stronger the interaction, the greater the mass.

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

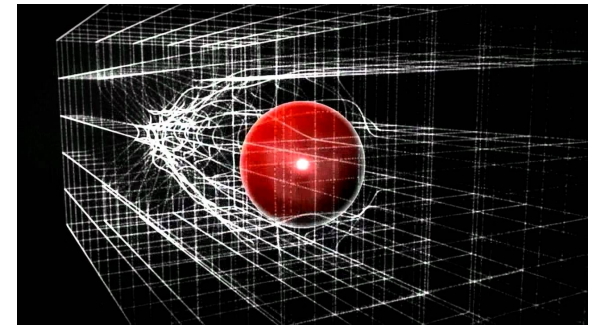


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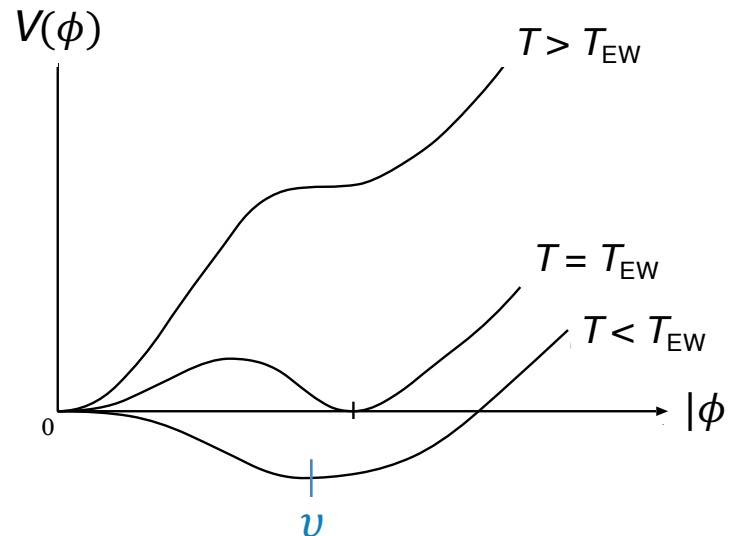
A local excitation of the Higgs field ϕ around its ground state is the **Higgs boson**



The Higgs potential energy:

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

At lowest order (tree level)

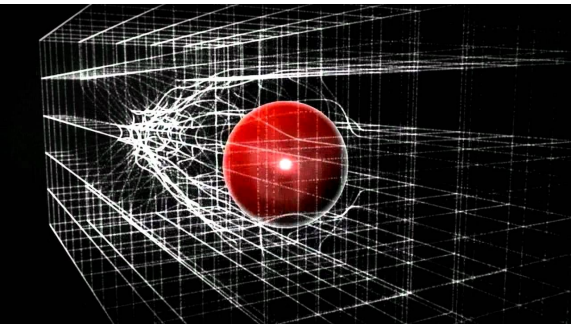


Gauge symmetry and the Higgs mechanism

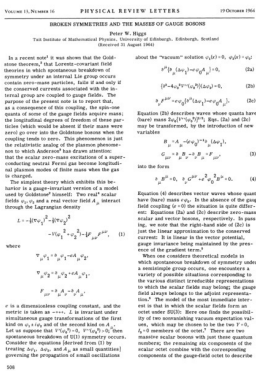
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Peter Ware Higgs (1929 – 2024)

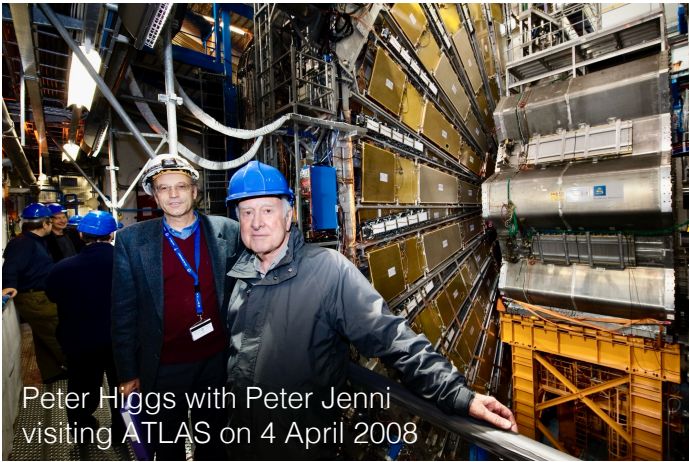


Broken Symmetries and the Masses of Gauge Bosons — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

[My life as a boson, 2010]



Peter Higgs and Fabiola on 4 July 2012



Peter Higgs with Peter Jenni visiting ATLAS on 4 April 2008

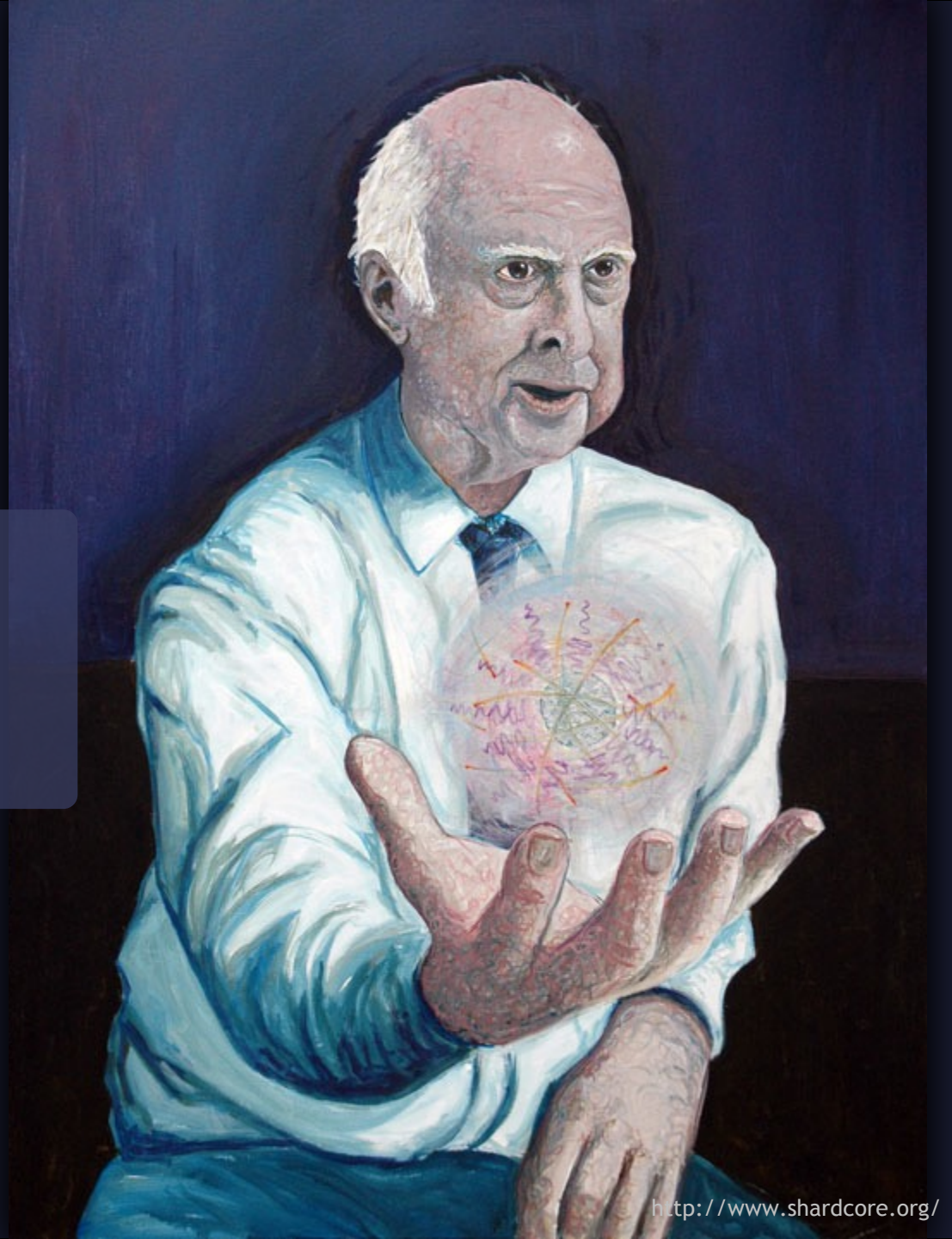
Gauge symmetry and the Higgs mechanism

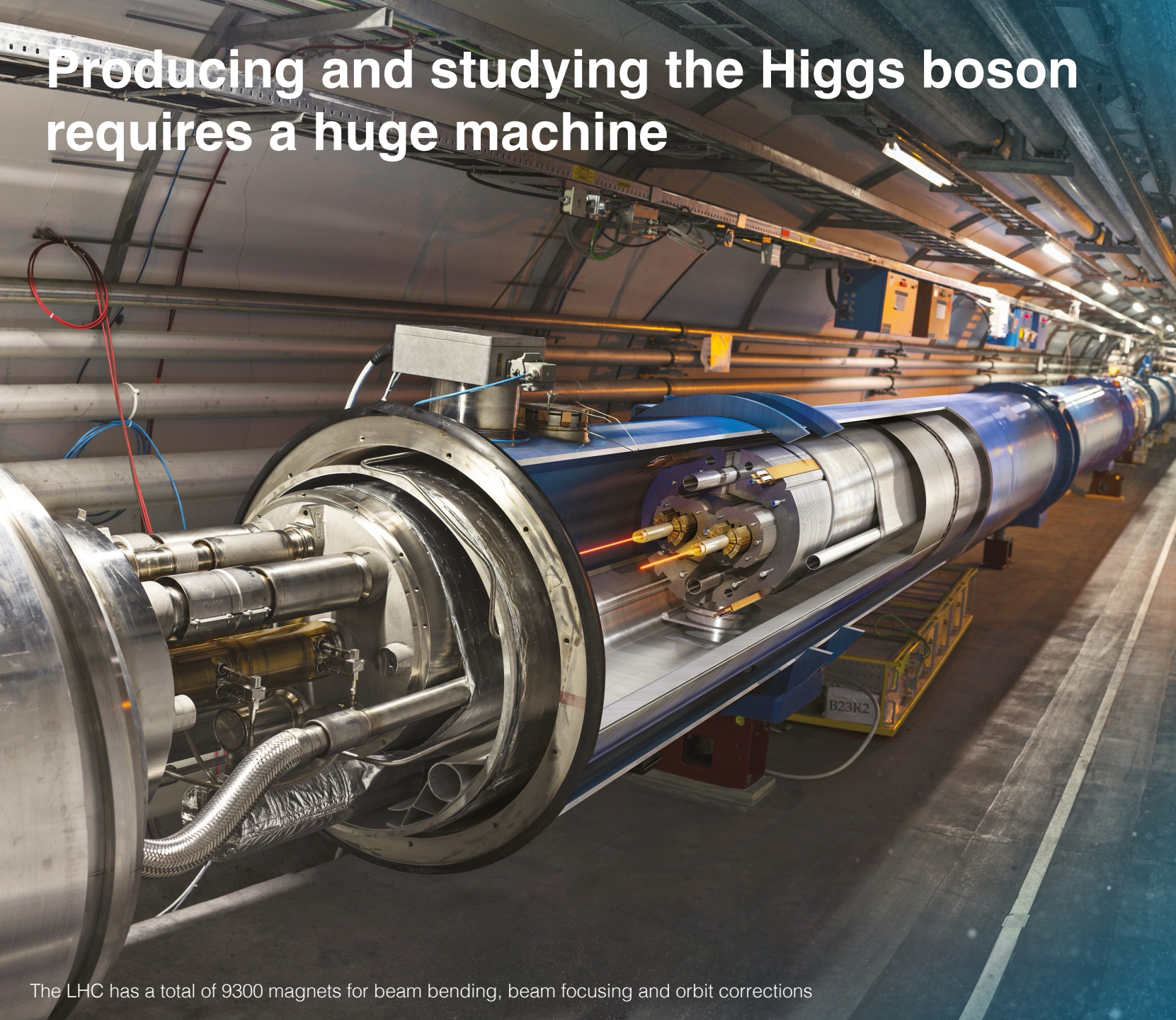
A few further comments:

- The 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](#), 1996*]
- The vacuum energy density of the Higgs field is about 10^{55} times larger than the dark energy observed
→ “It would curve the universe into an object roughly the size of a football” (Veltman, 1986)
- The remarkable similarity between the Higgs mechanism and the Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity, where the Bose condensation of a Cooper pair of two electrons plays the role of the Higgs field (note: $T_{\text{crit}} = T_{\text{EW}} \sim 10^{15} \text{ K!}$), raises the question whether the Higgs boson might not be elementary after all

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**





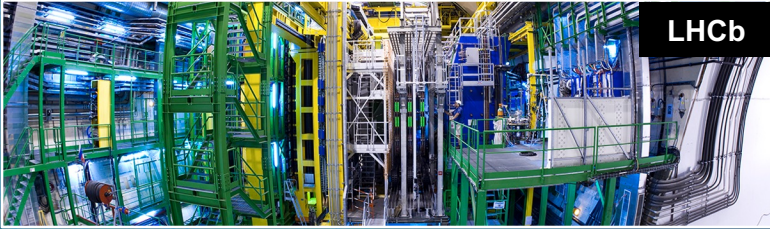
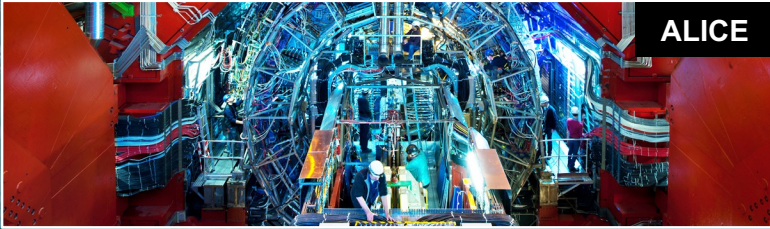
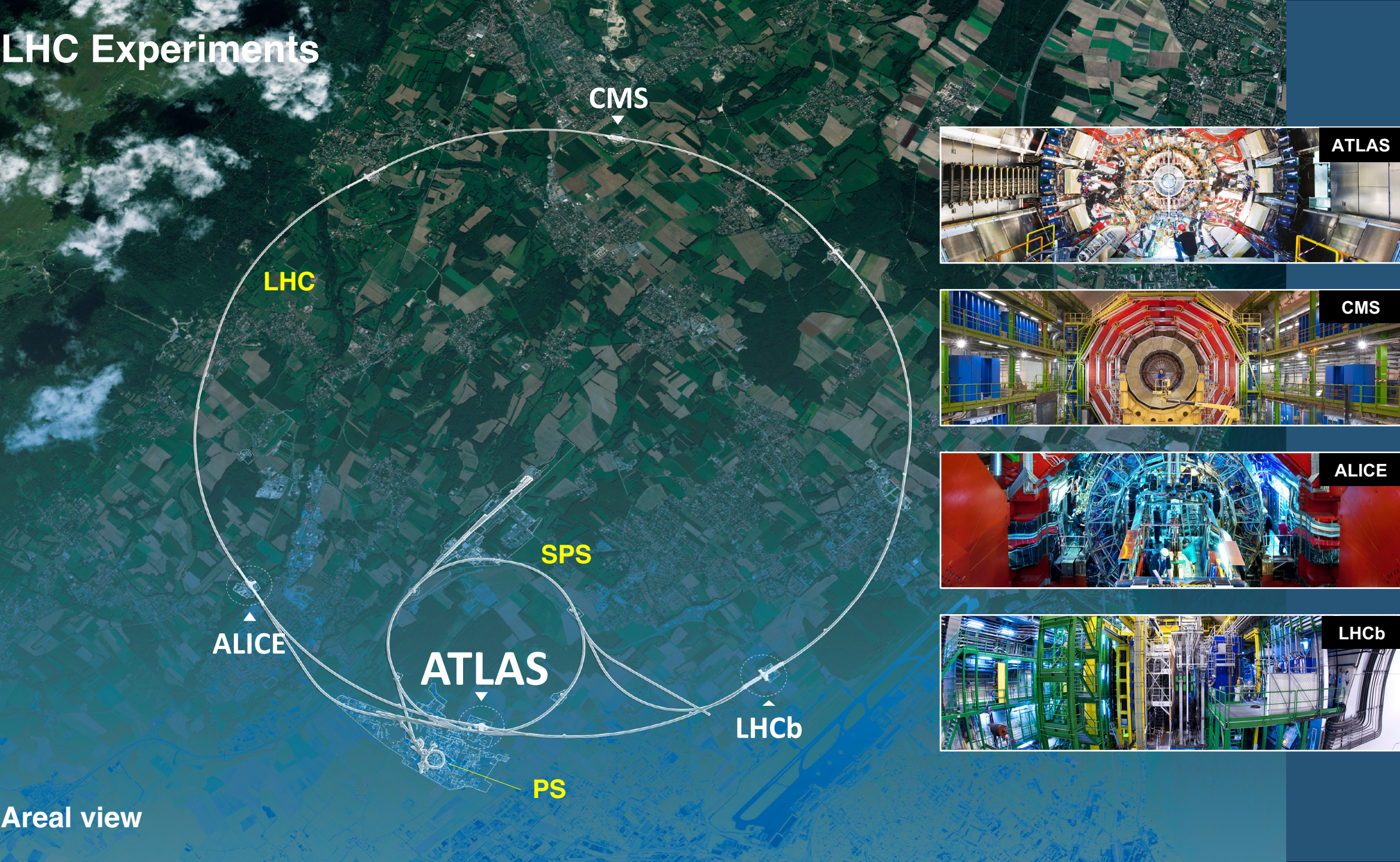
Producing and studying the Higgs boson
requires a huge machine

Large Hadron Collider (LHC)

- 27 km underground accelerator and collider
- Superconducting magnets (1.9 K = -271.3°C) steer the particles around the ring
- Proton and ions are accelerated to multi-TeV scale energies before they collide

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

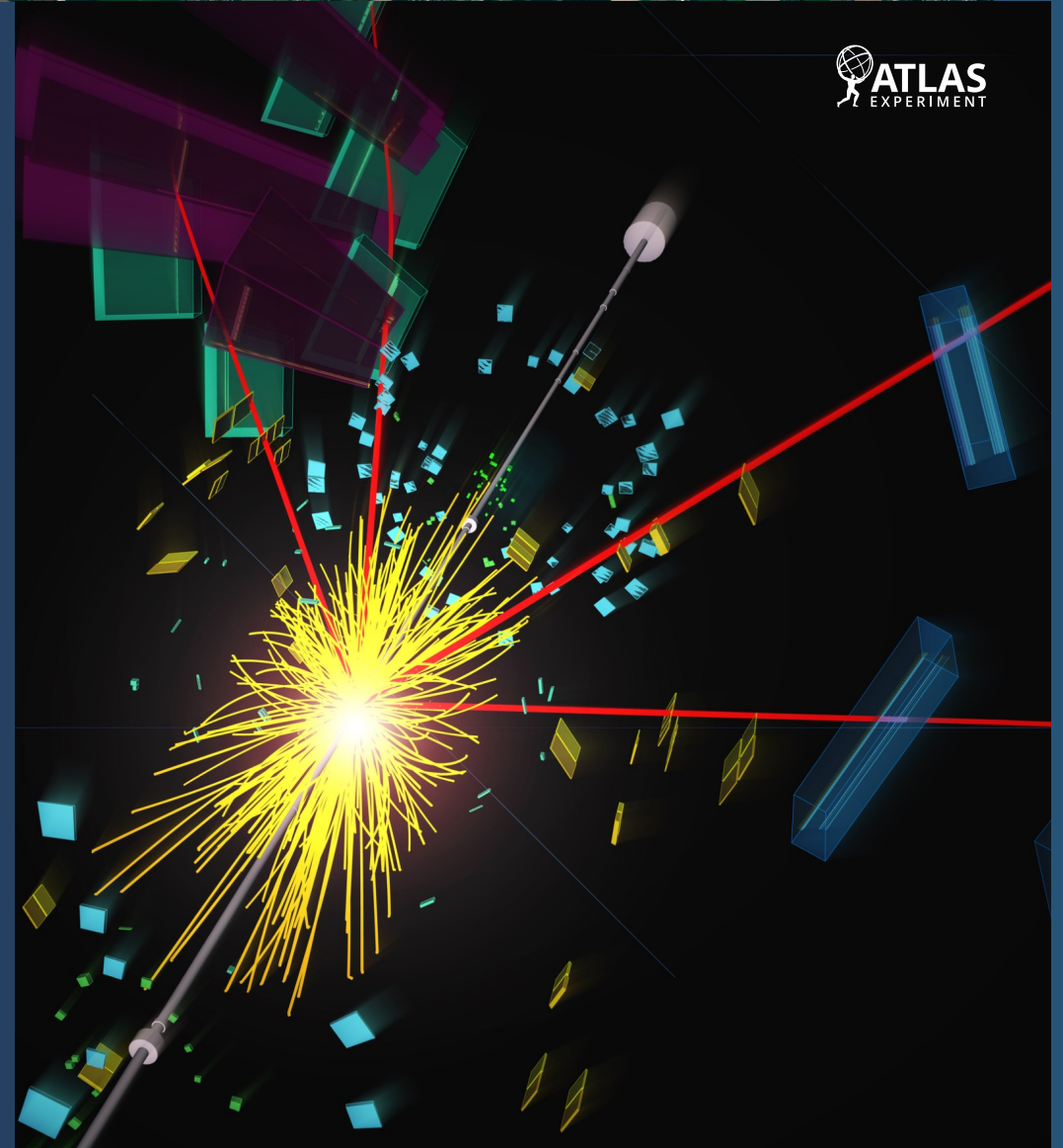
LHC Experiments



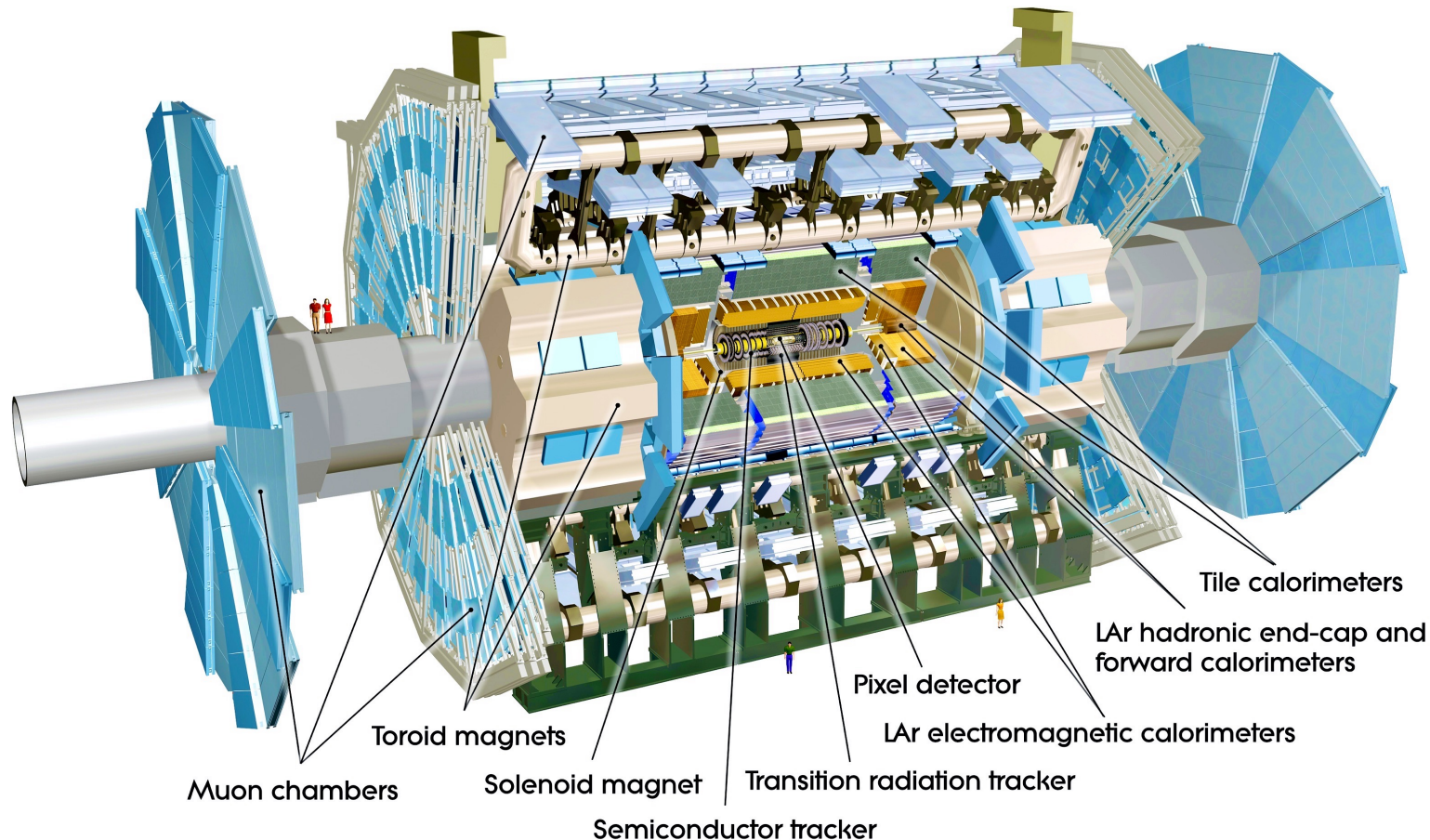
What happens in a high-energy proton–proton collision?

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
- 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

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 azimuth).
Complemented by gaseous transition
radiation tracker at large radius

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

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

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

Trigger based on ultra-fast custom
electronics and high-performance
computers

The ATLAS Collaboration

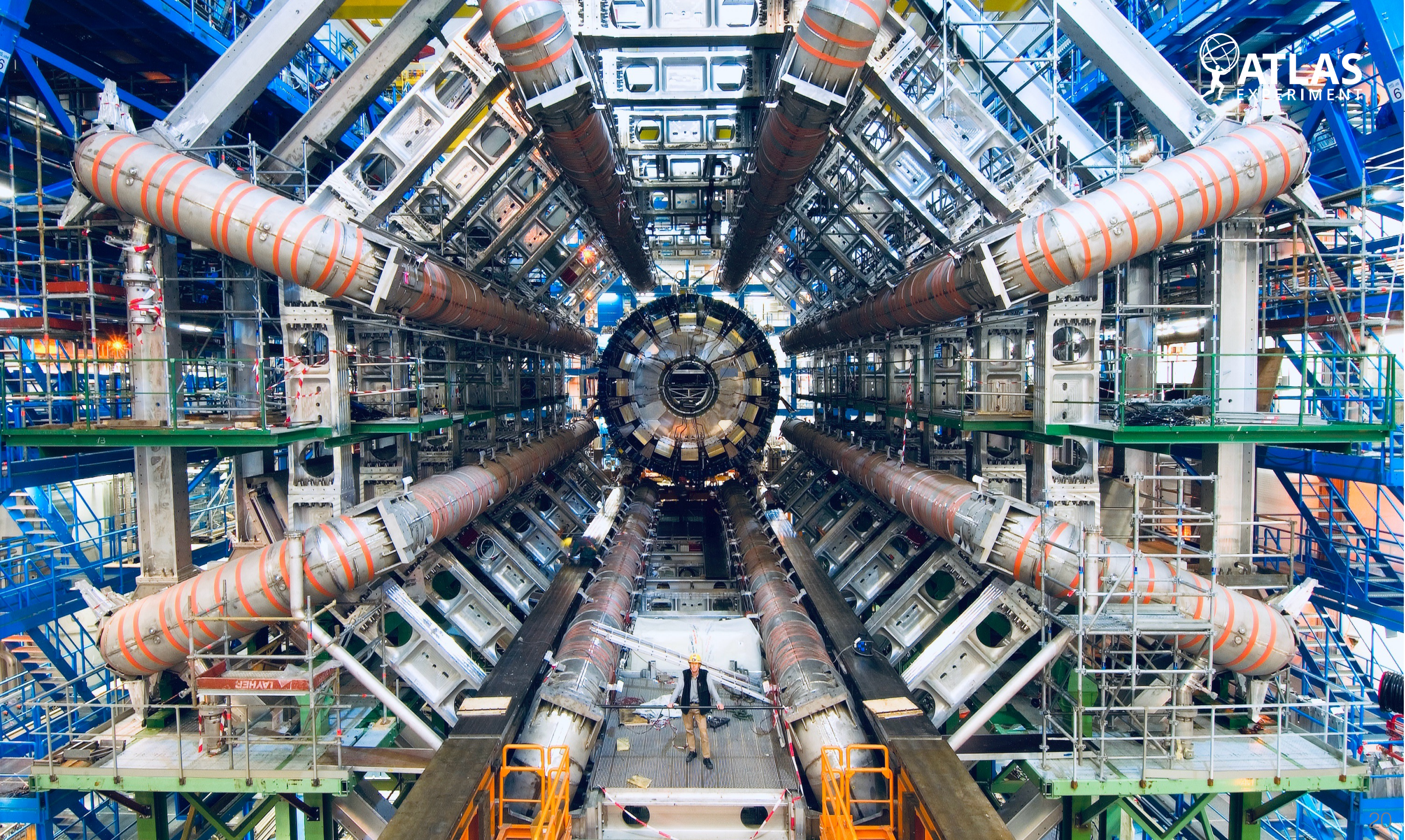
ATLAS is a multi-decade international experimental programme involving:

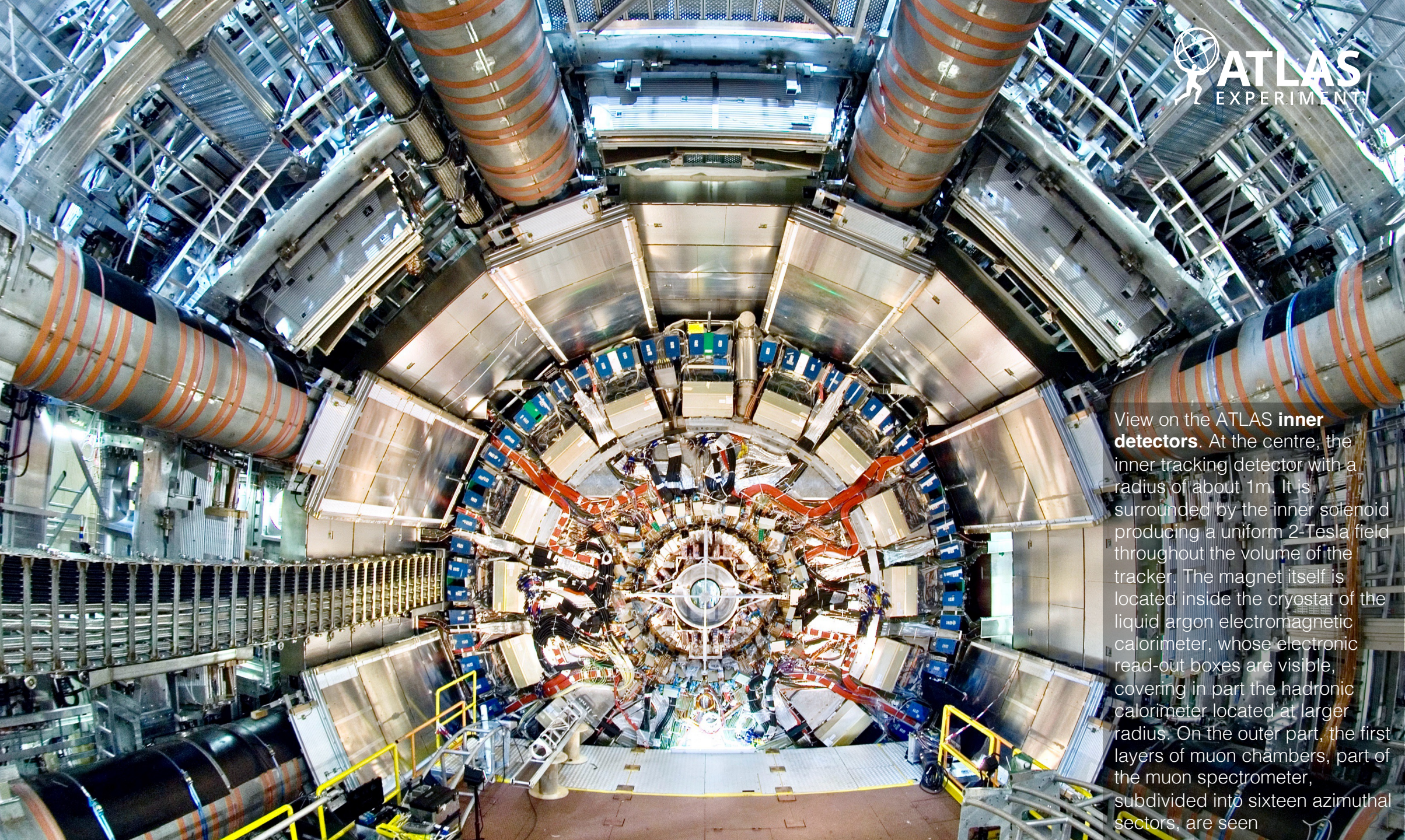
- 242 institutes from 40 countries + 16 Technical Associate Institutes
- 2900 Scientific authors
- 1200 Physics PhD students
- 1300 Engineers or technicians
- 100 Engineering students
- 6000 Active members

Links: [ATLAS public home page](#), [Physics results](#), [Interactive ATLAS world map](#), [Static world maps](#), [List of ATLAS institutes](#)



Photo taken in Dec 2024 at the ATLAS detector site at CERN





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

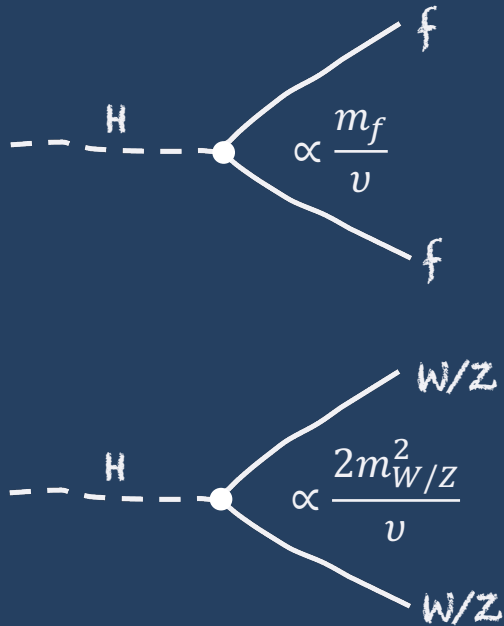


ATLAS endcap in open position during year-end technical stop 2023/2024

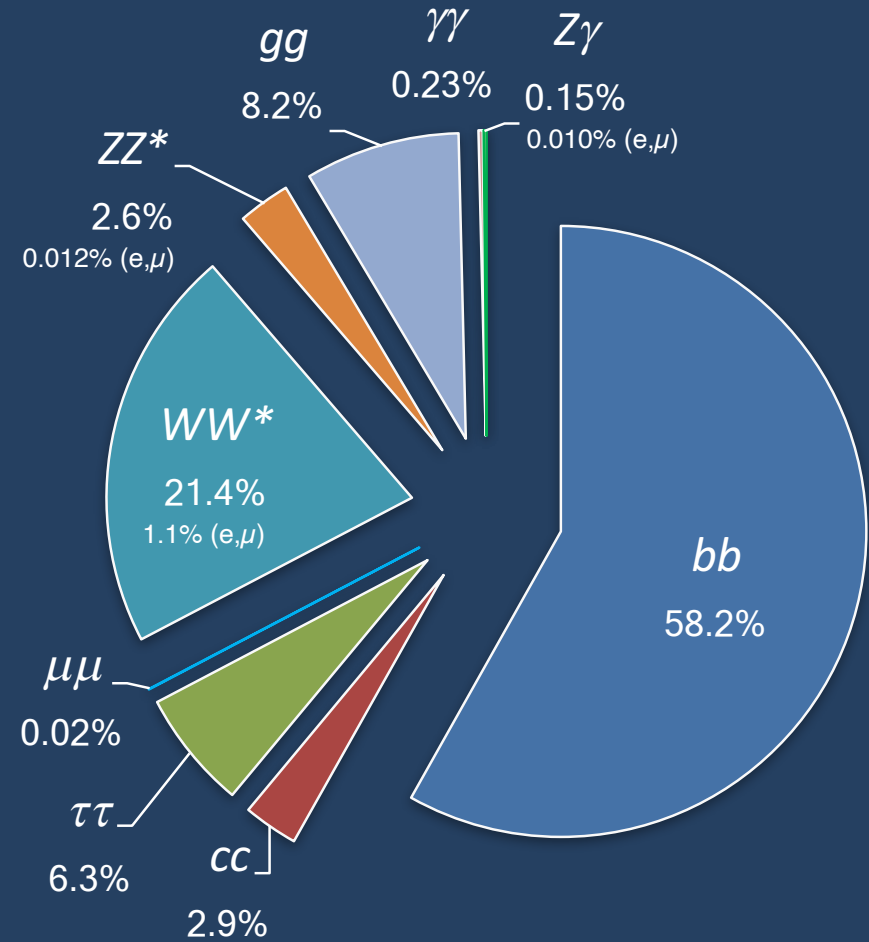
Higgs boson production and decay at the LHC

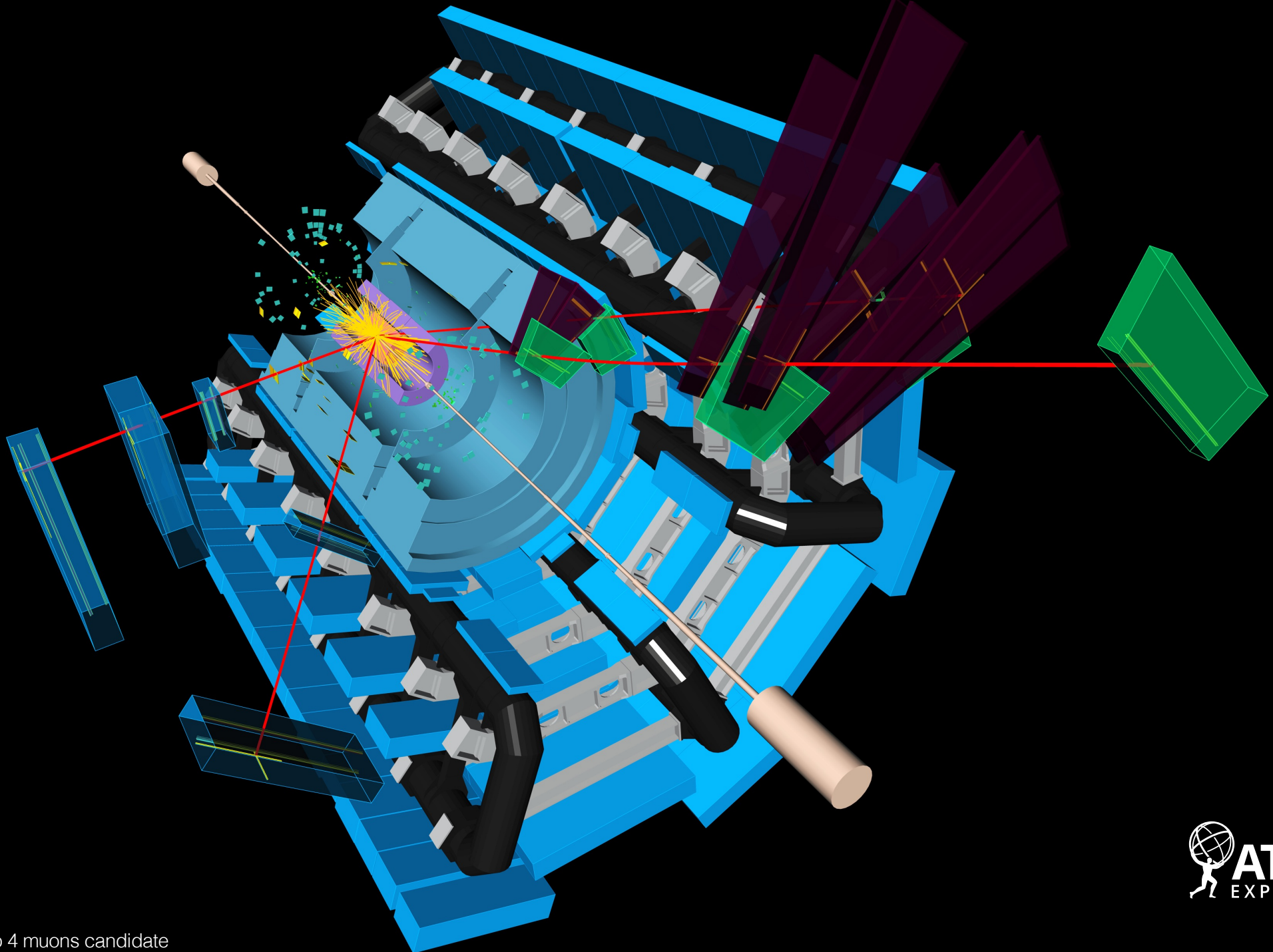
About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)

It decays within 10^{-22} s

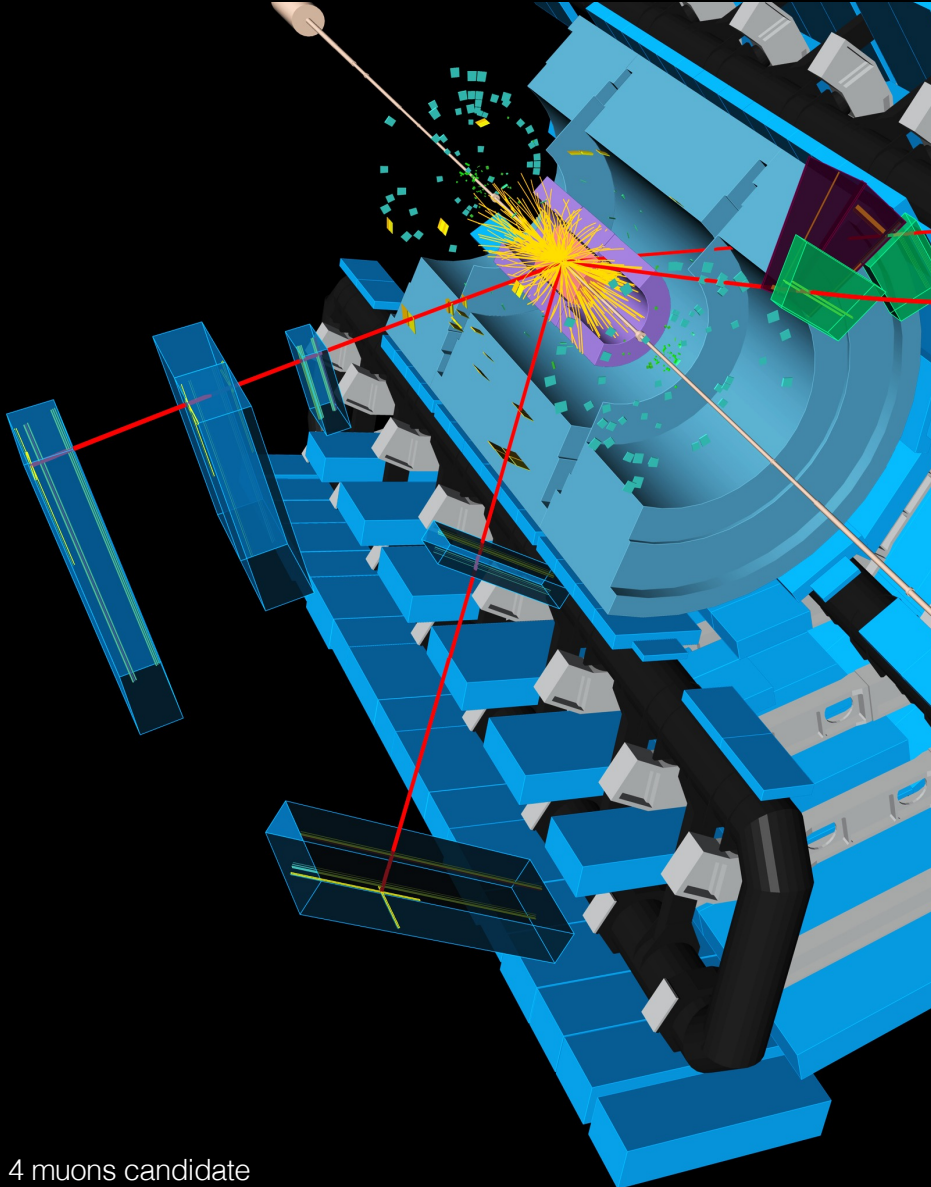


$H \rightarrow \gamma\gamma, Z\gamma$ occur through virtual top or W loops (no direct Higgs coupling to massless particles)



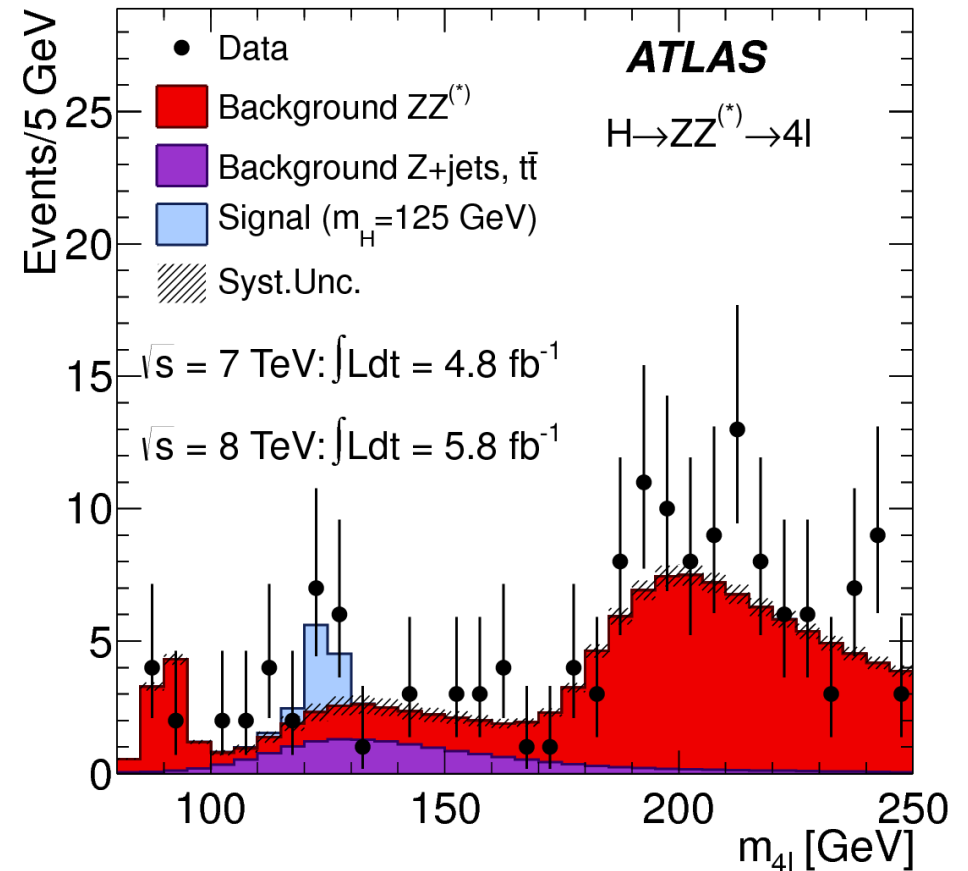


The Higgs boson discovery



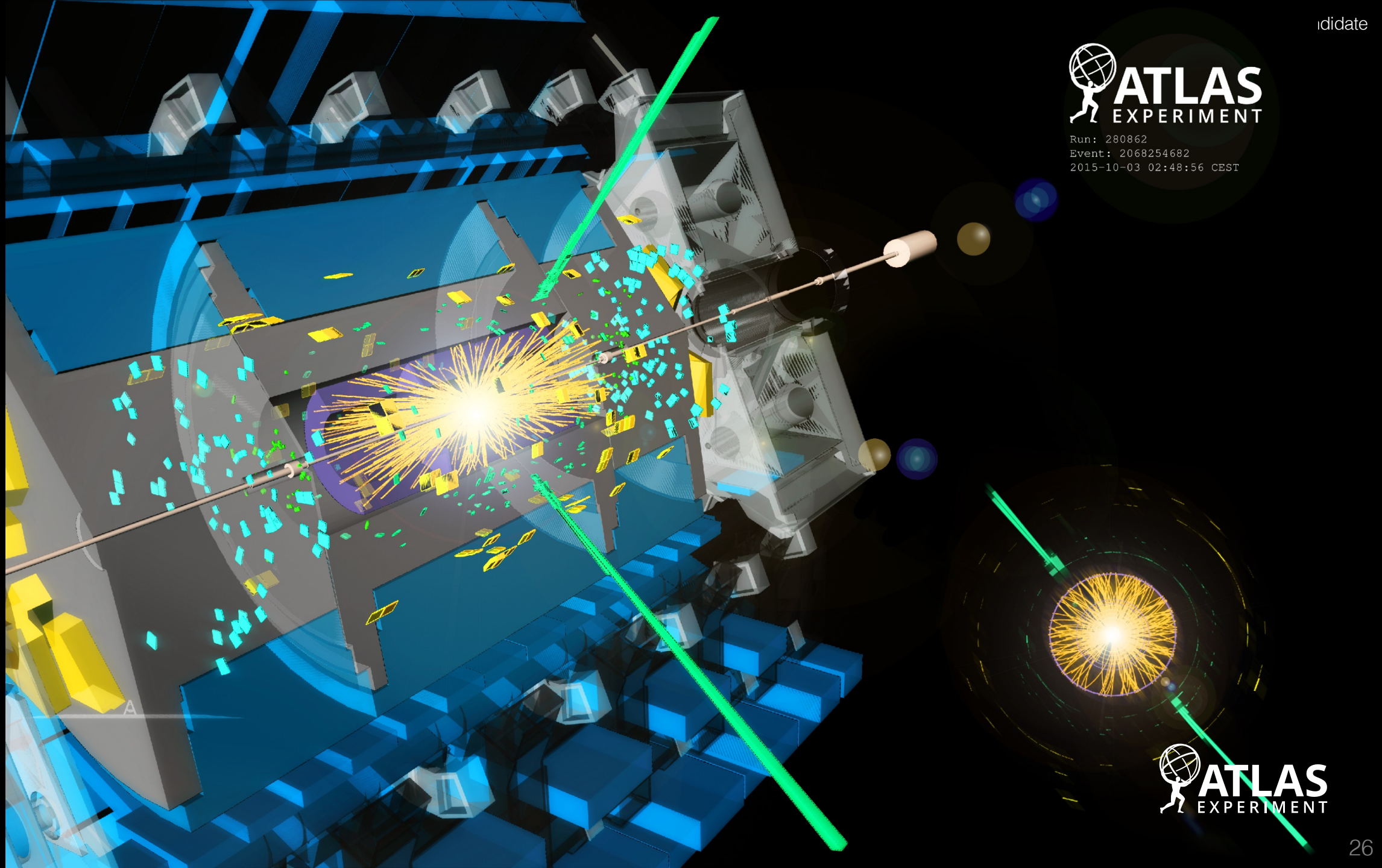
2012

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





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

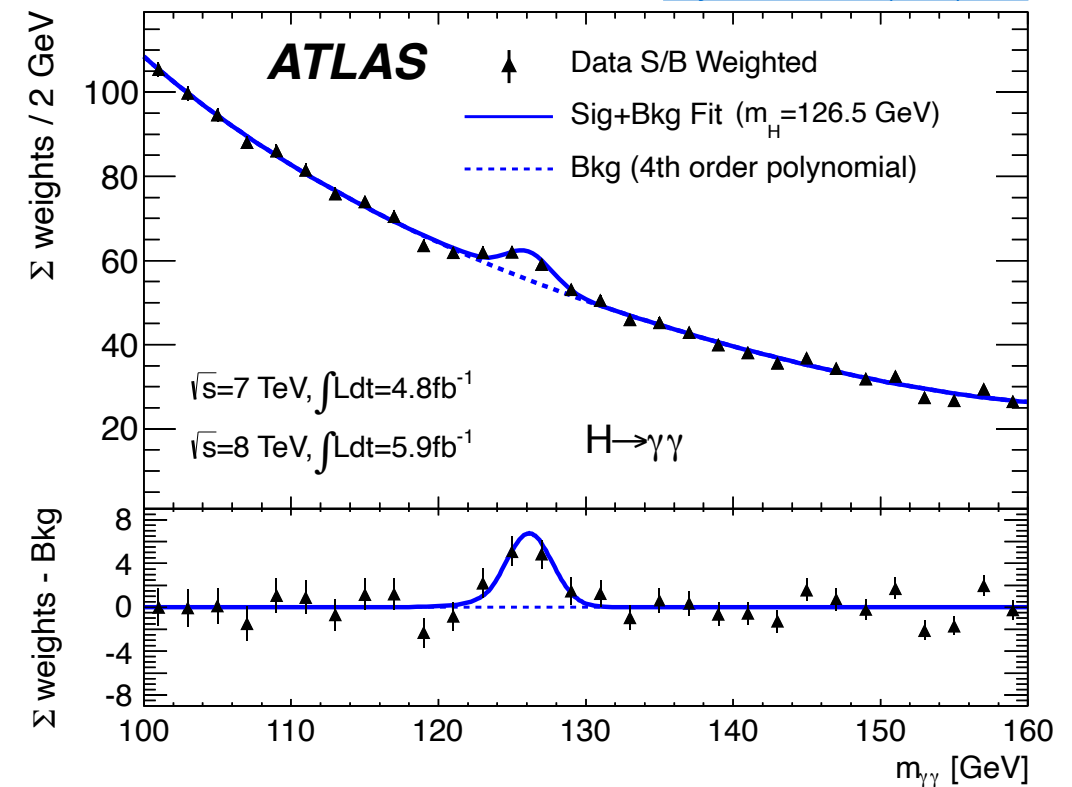




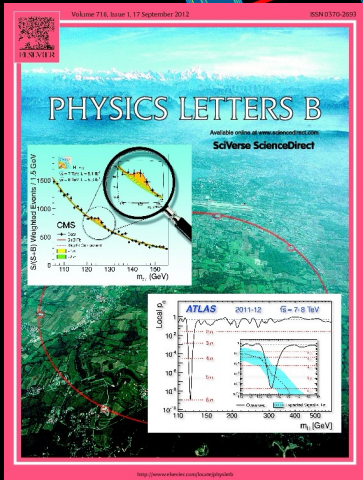
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Event: 2068254682
2015-10-03 02:48:56 CEST

2012

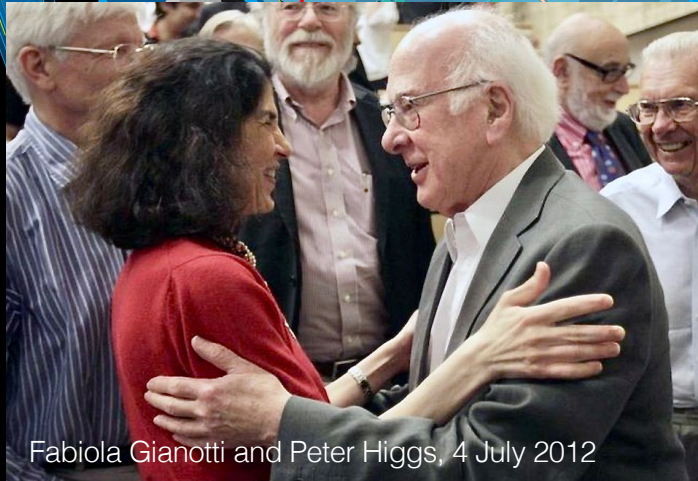
[Phys. Lett. B 716 \(2012\) 1-29](#)



The Higgs boson discovery

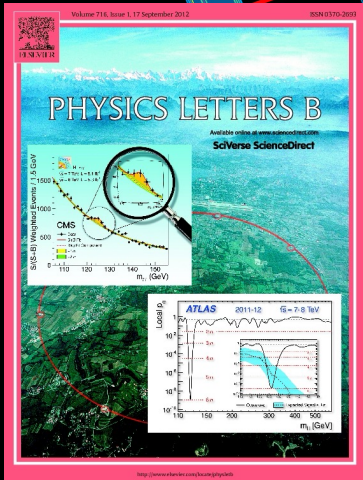


Phys. Lett.B 716 (2012)
Cited almost 15,000 times



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

The Higgs boson discovery



Phys. Lett.B 716 (2012)

Cited almost 15,000 times
(today)



Fabiola Gianotti and Peter Higgs, 4 July 2012

The LHC's magnum opus

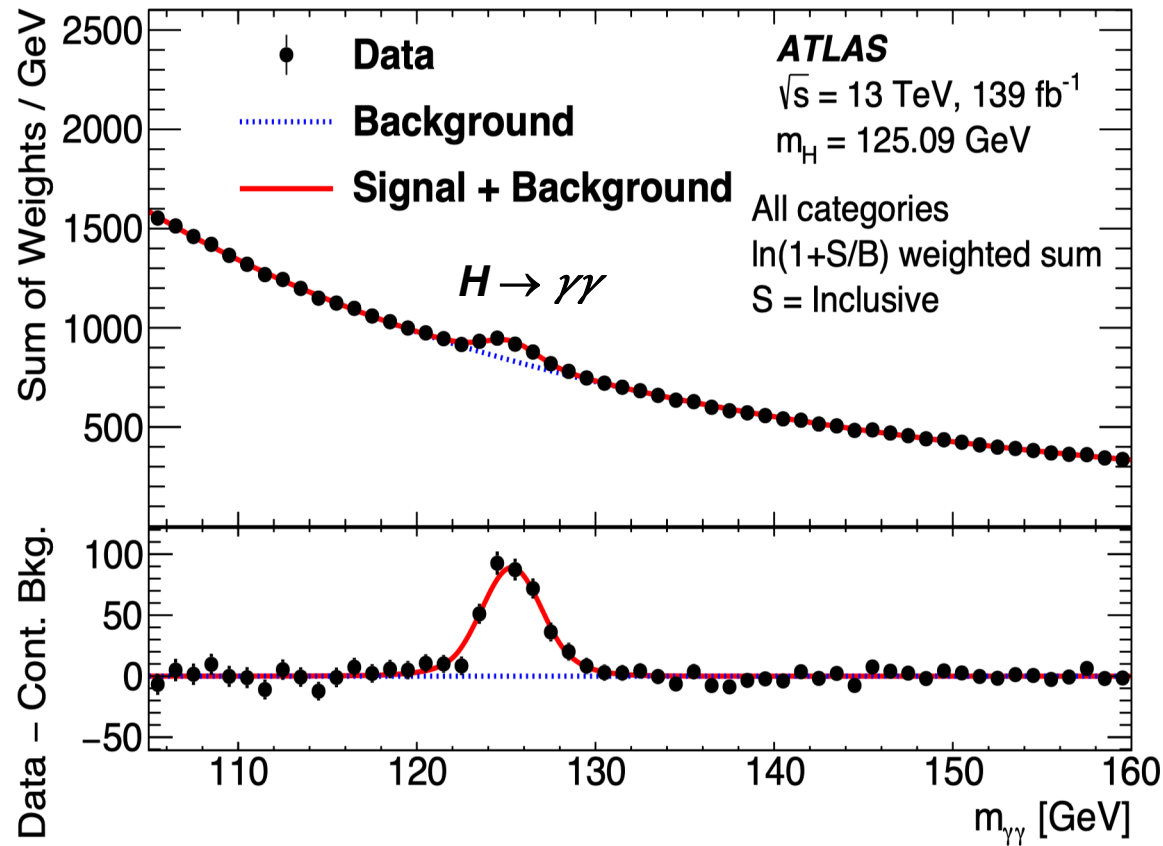
A very special particle... whose discovery allows us to access a **totally new sector** of the Standard Model:

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

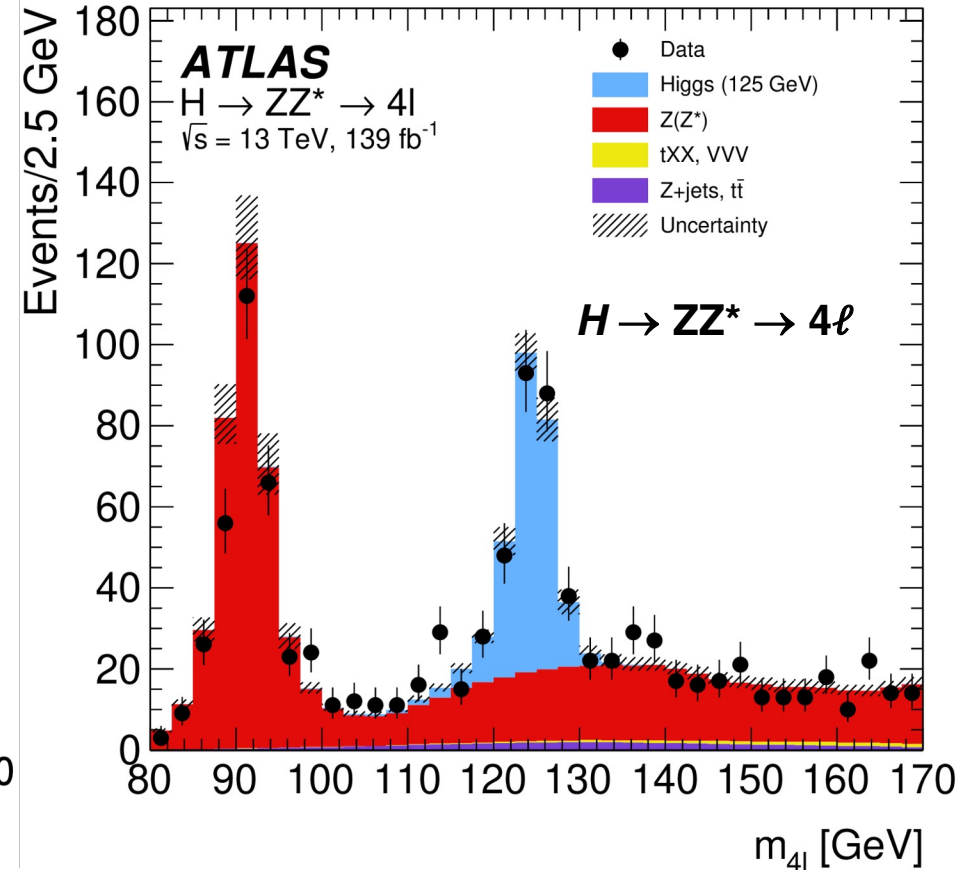
The Higgs boson — At 10

2020

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



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

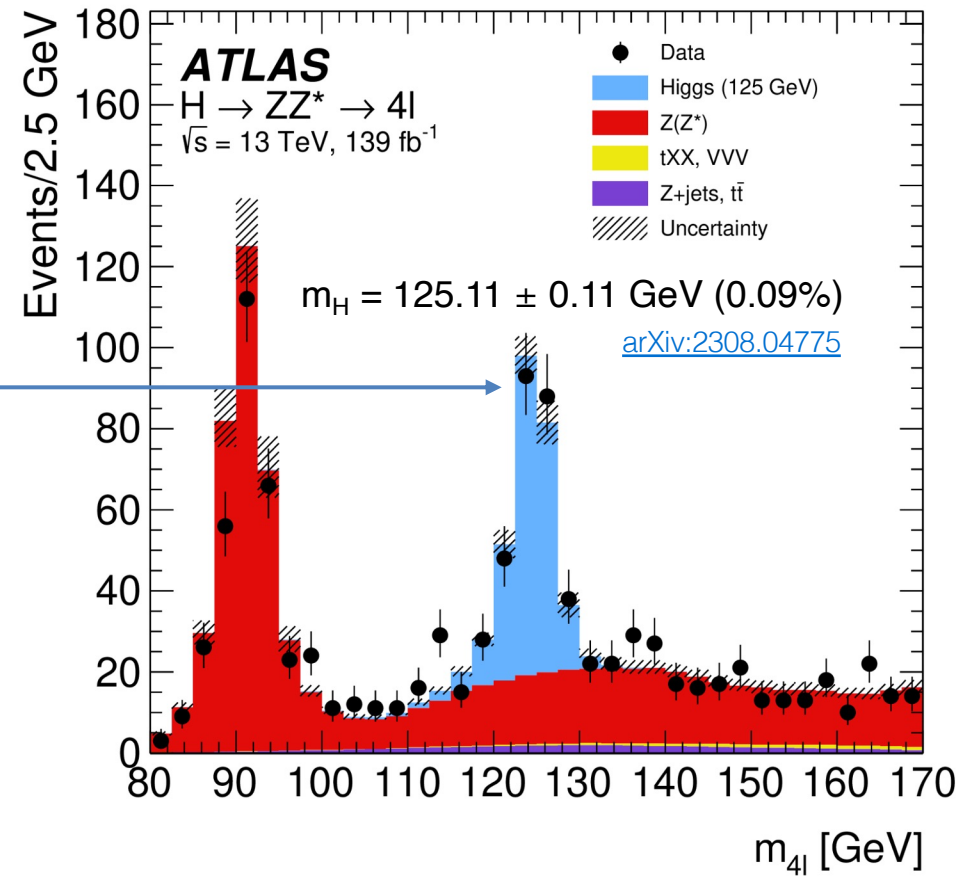


Higgs boson mass

The Higgs mass is peculiar

2020

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



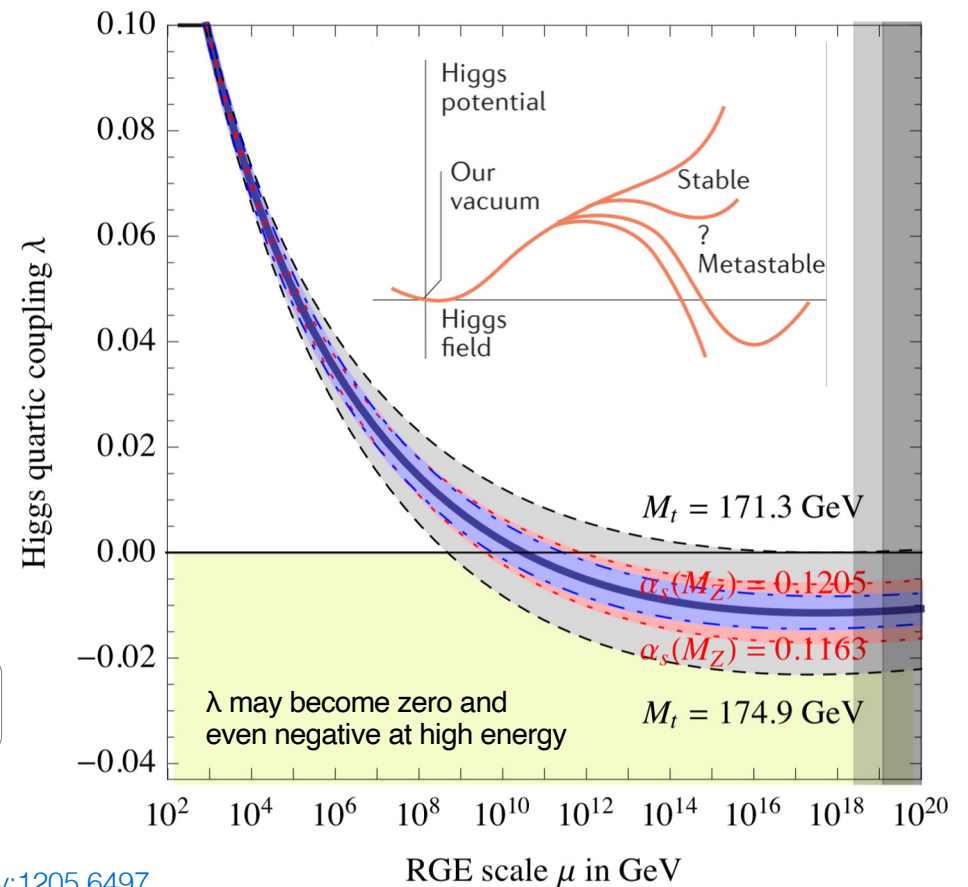
Higgs boson mass

The Higgs mass is peculiar

- It is consistent with the global electroweak fit
- But the electroweak vacuum seems to be metastable

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

Evolution of the Higgs quartic coupling, assuming SM (only)



[arXiv:1205.6497](https://arxiv.org/abs/1205.6497)

Higgs boson couplings

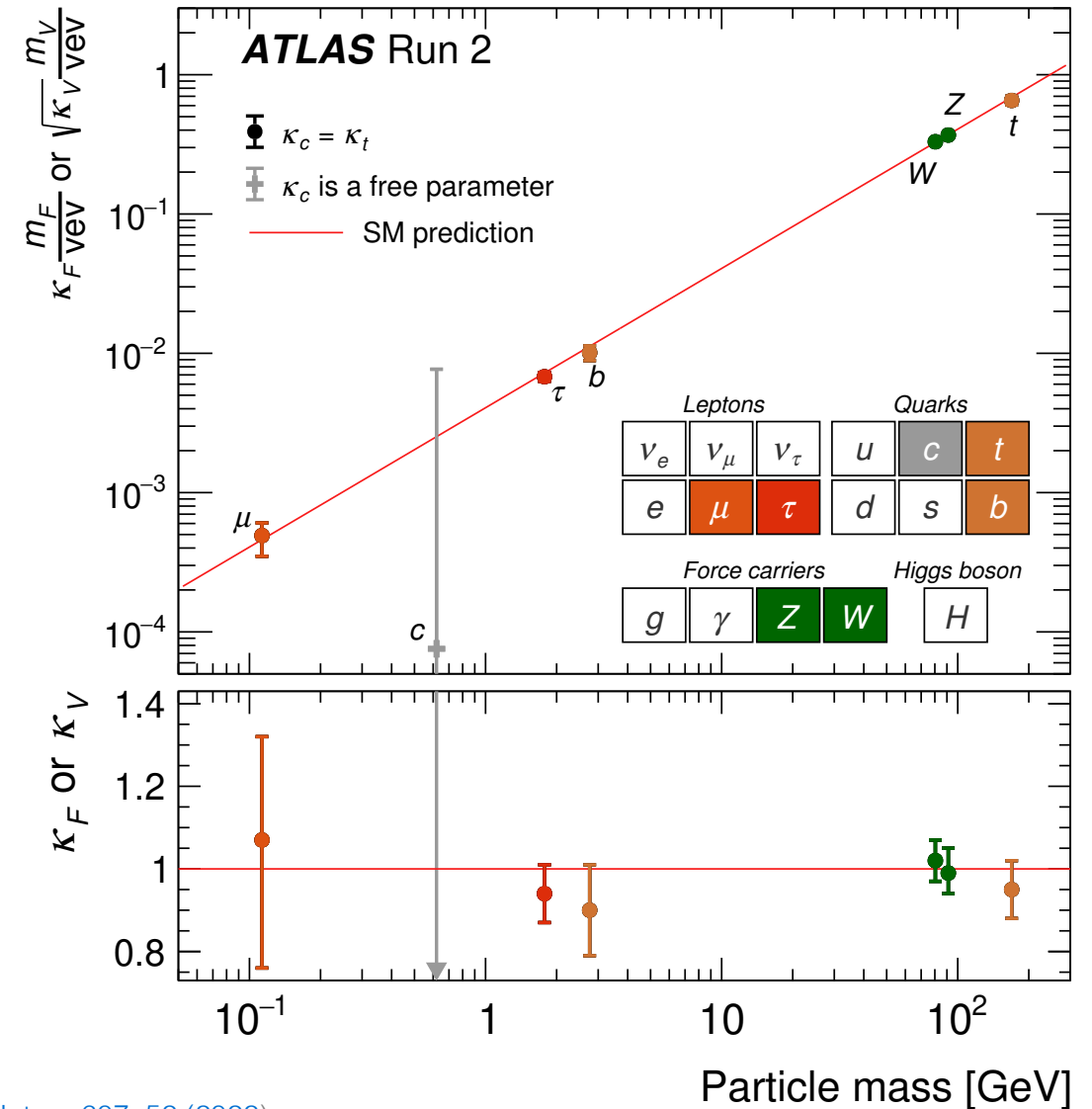
The Higgs boson couplings to the SM particles are experimentally determined by measuring cross-sections of all accessible Higgs boson production and decay modes

Huge experimental programme, some channels suffer from large backgrounds, huge improvements from smart analysis techniques and machine learning

Channel categories		BR	ggF	VBF	VH	ttH
Cross Section (13 TeV)			48.6 pb	3.8 pb	2.3 pb	0.5 pb
$\gamma\gamma$	0.2 %	✓	✓	✓	✓	✓
ZZ	2.6%	✓	✓	✓	✓	✓
WW	21%	✓	✓	✓	✓	✓
$\tau\tau$	6.3 %	✓	✓	✓	✓	✓
bb	58%	✓	✓	✓	✓	✓
$Z\gamma$ (& $\gamma\gamma^*$)	0.2 %	✓	✓	✓	✓	✓
$\mu\mu$	0.02 %	✓	✓	✓	✓	✓

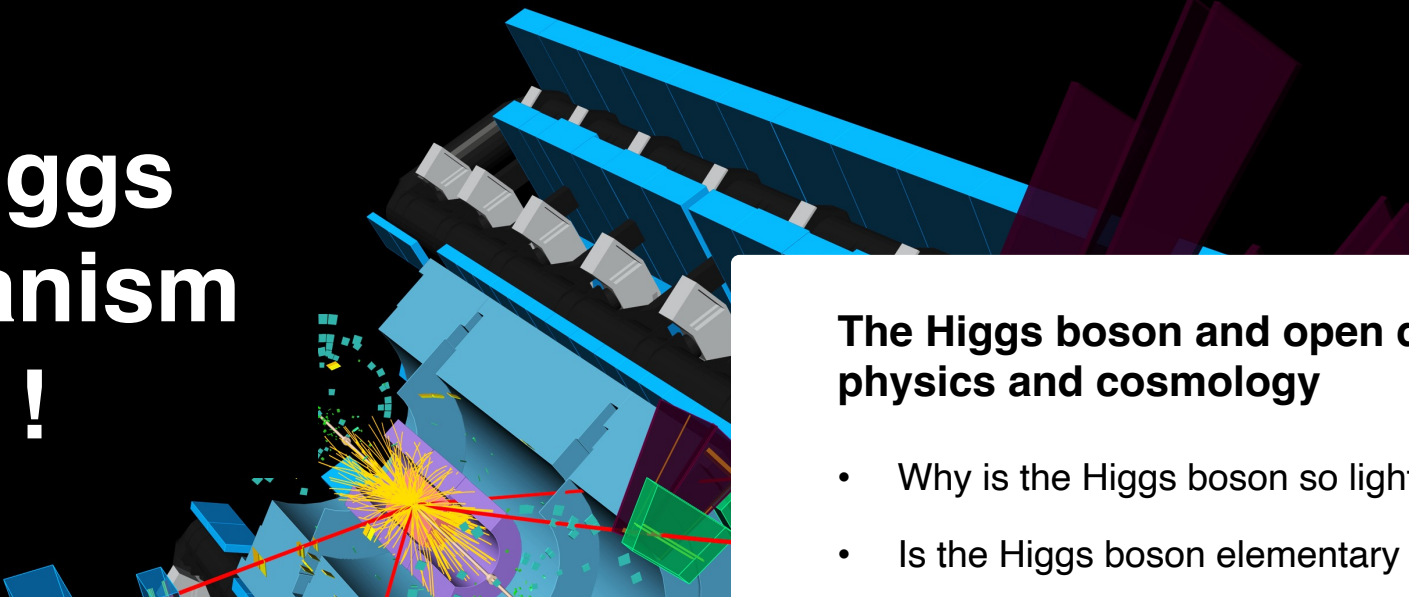
In grey: evidence for decays, but not observed yet

The Higgs mechanism is real !

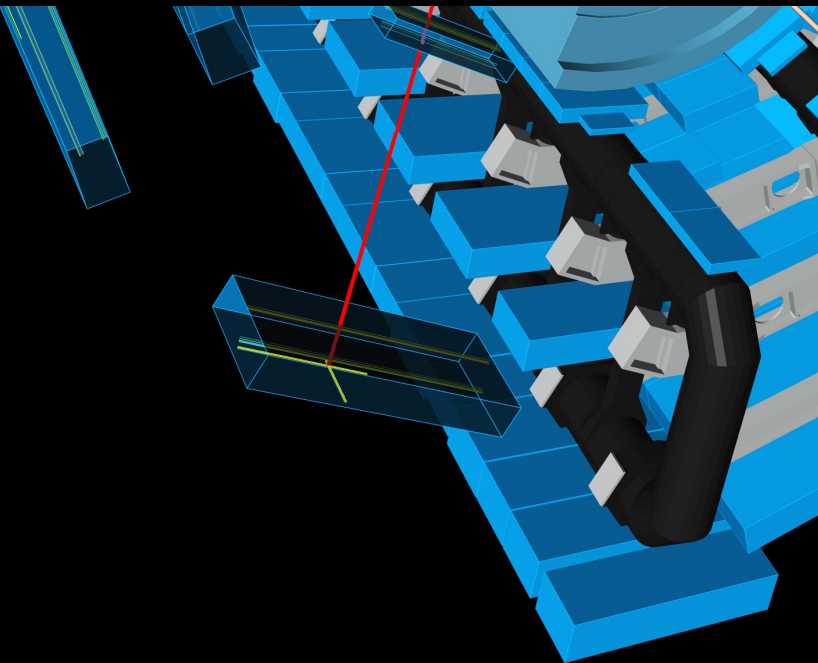


[Nature 607, 52 \(2022\)](#)

The Higgs mechanism is real !



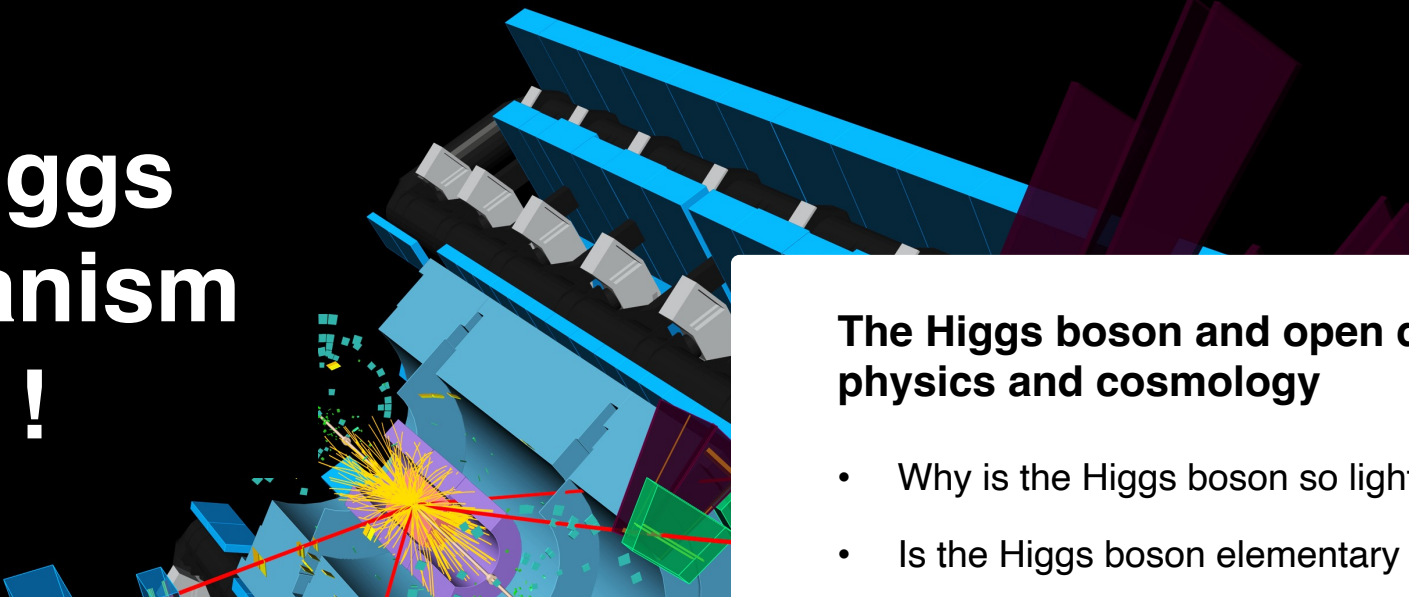
The Higgs sector is directly connected with very profound and crucial questions



The Higgs boson and open questions in particle physics and cosmology

- Why is the Higgs boson so light?
- Is the Higgs boson elementary or composite ?
- Do Higgs interactions violate matter-antimatter symmetry?
- 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?

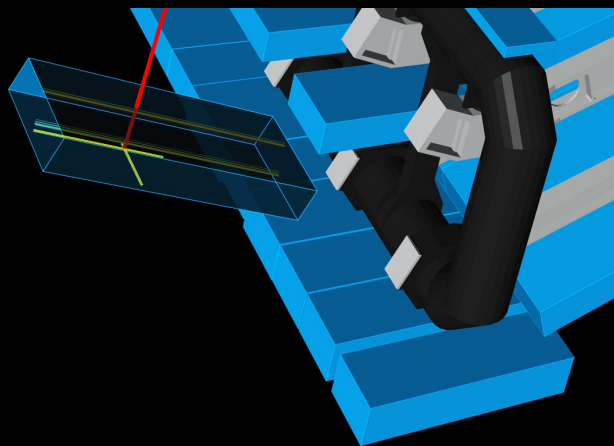
The Higgs mechanism is real !



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**

The Higgs boson and open questions in particle physics and cosmology

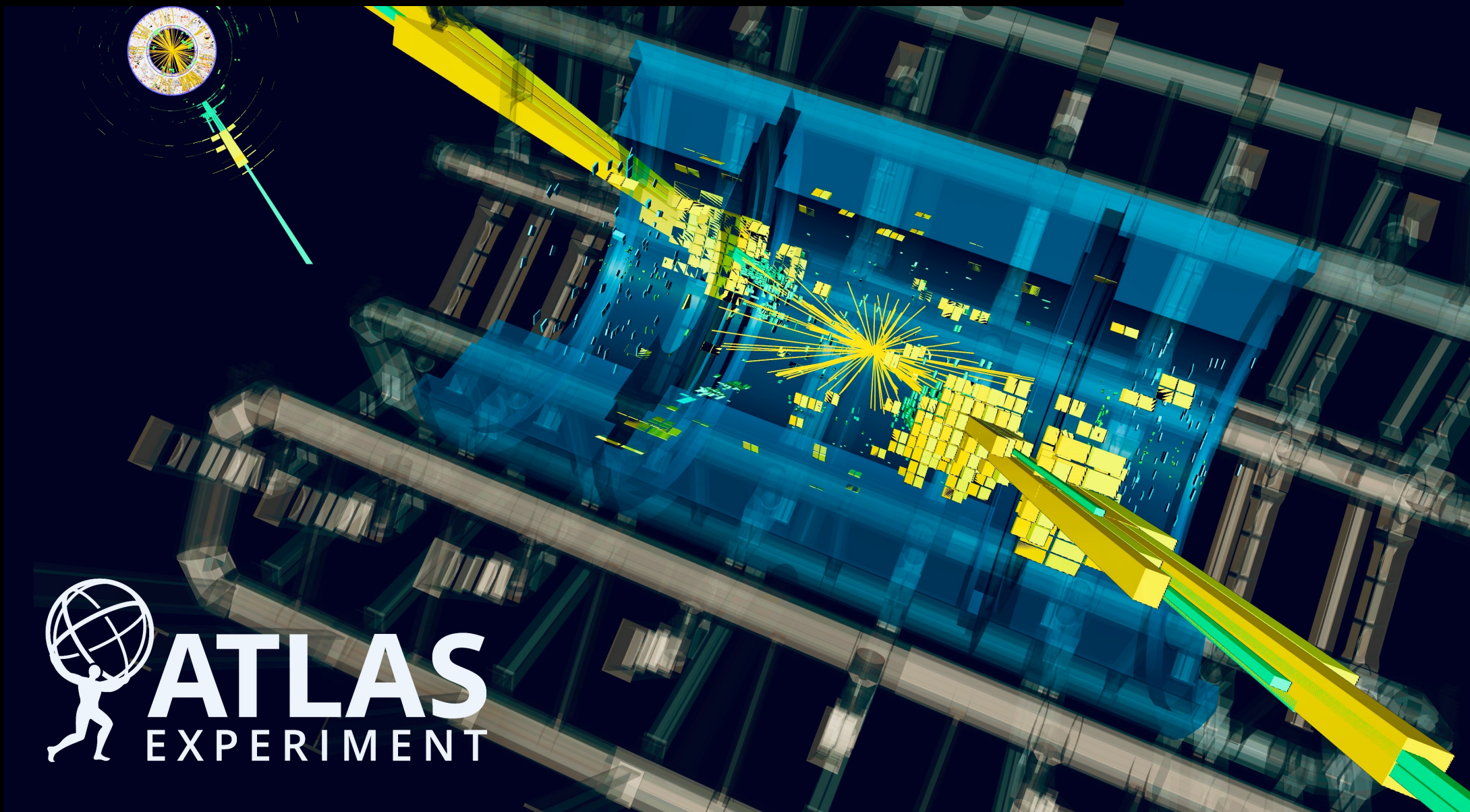
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- 

Run: 329716

Event: 857582452

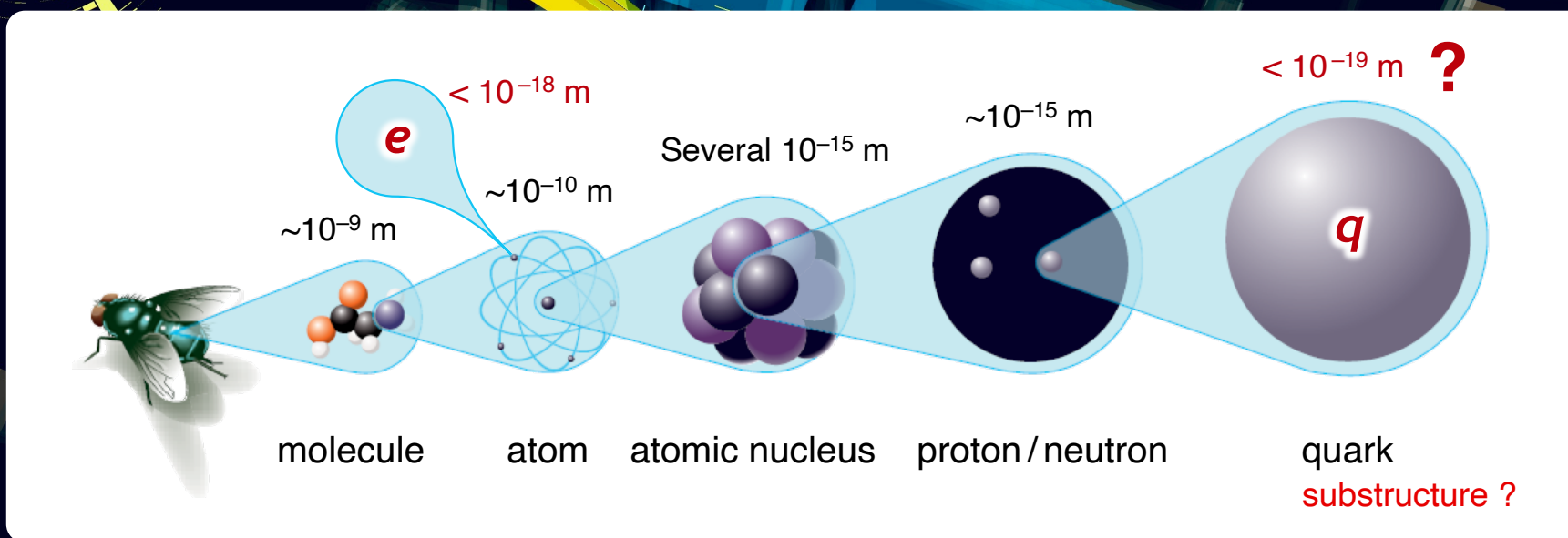
2017-07-14 10:48:51 CEST

Deep searches for new phenomena



ATLAS
EXPERIMENT

Are quarks elementary particles?

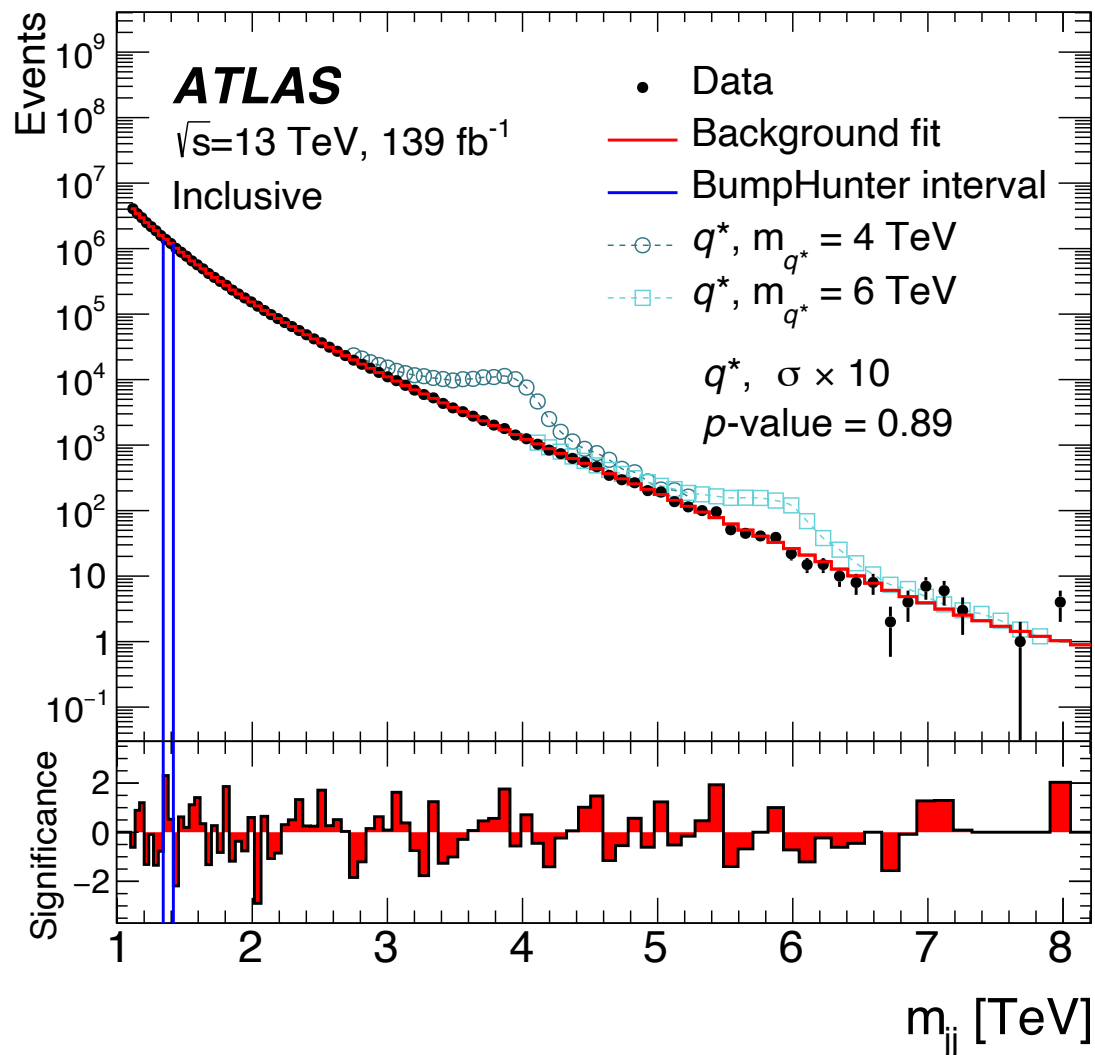


Run: 329716

Event: 857582452

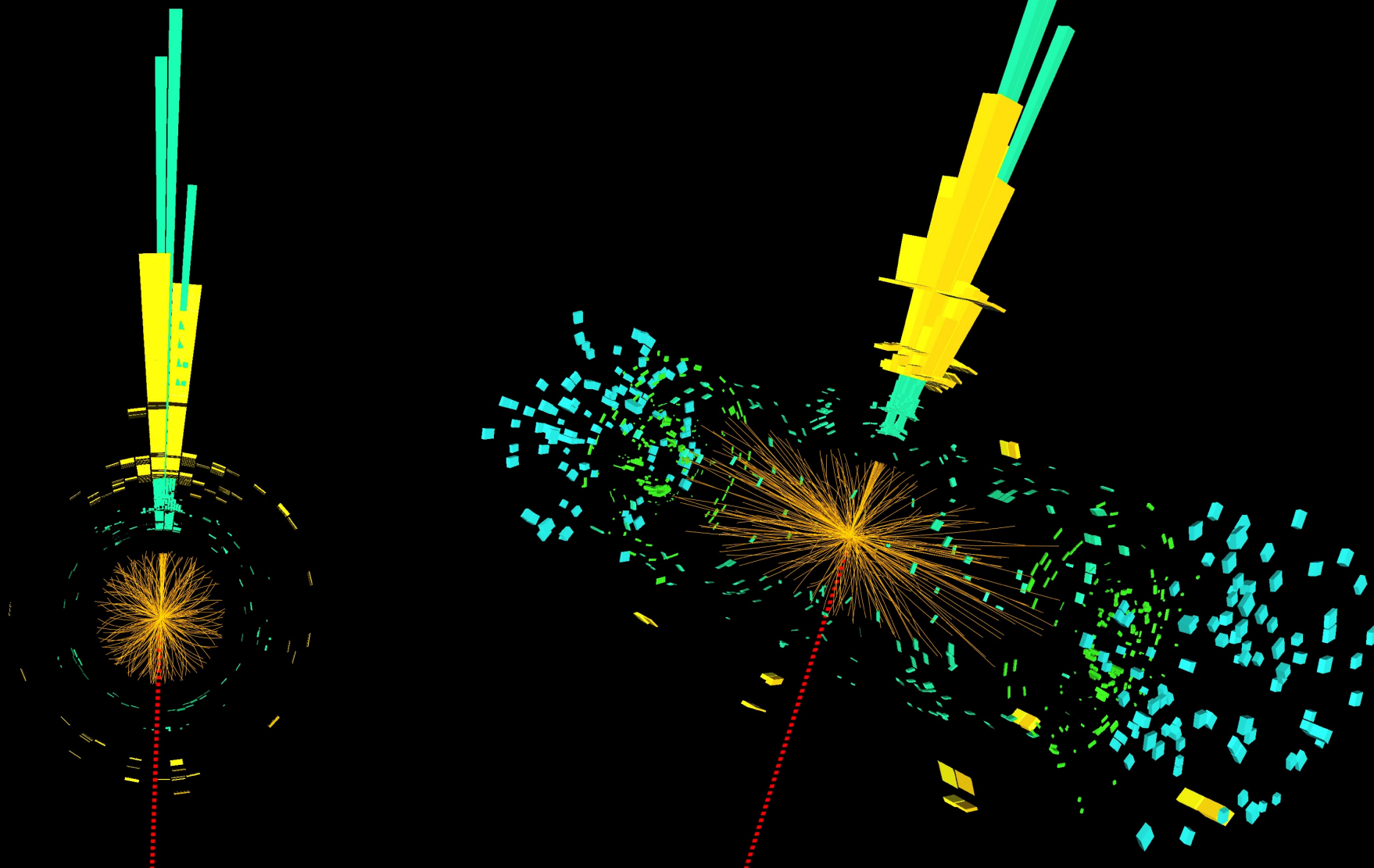
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Are quarks elementary particles?

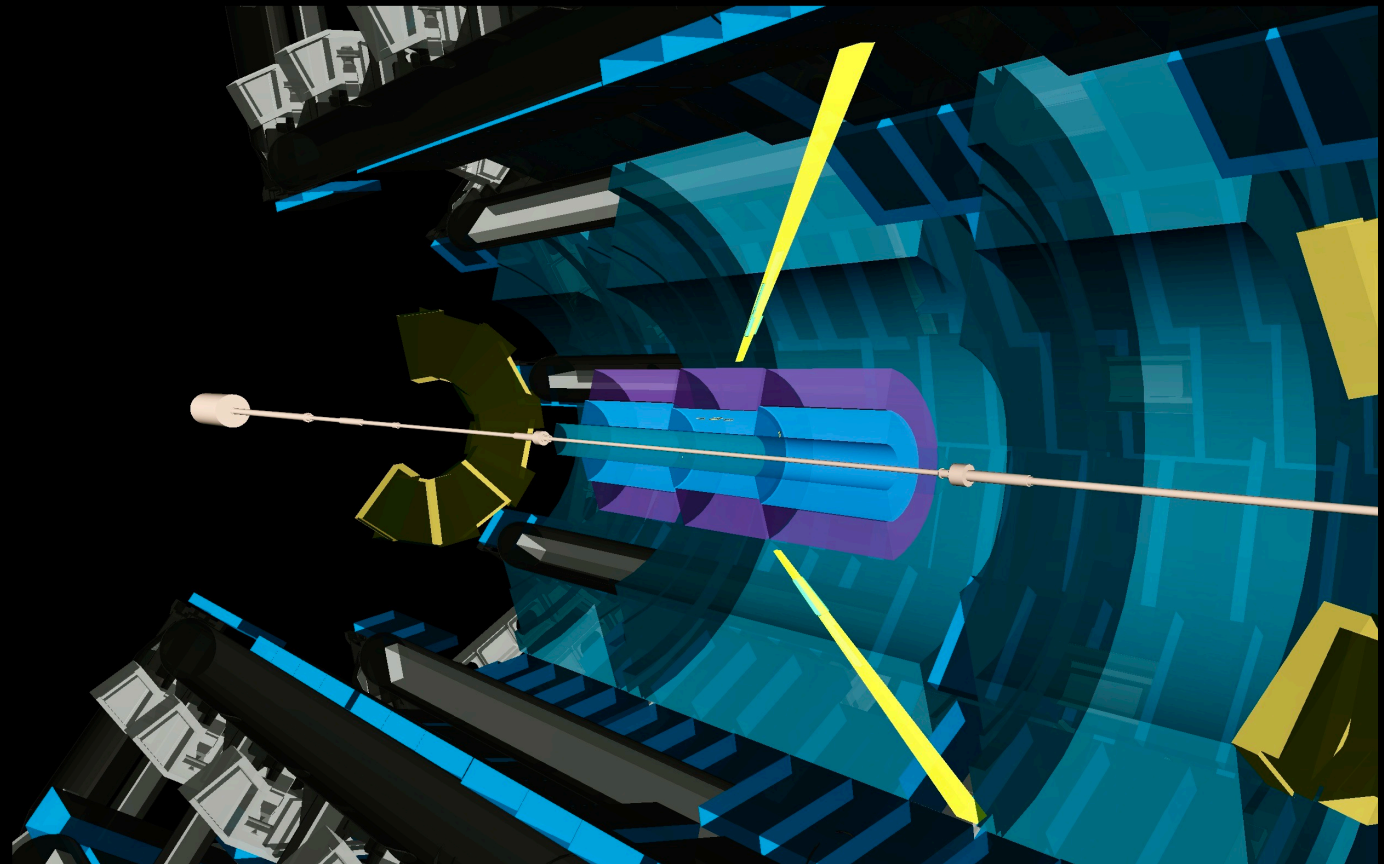
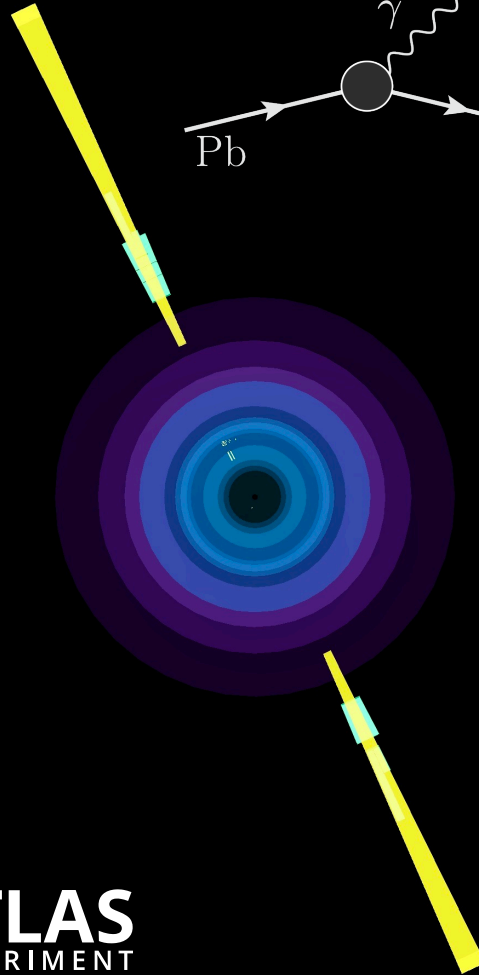
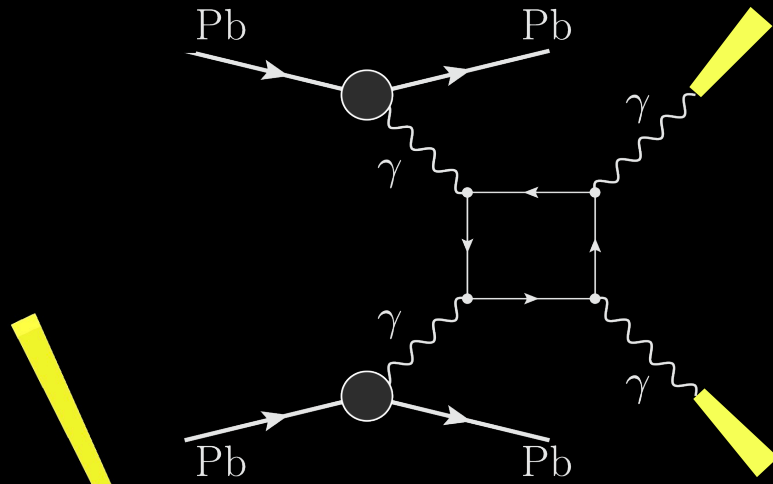


Searches for Dark Matter

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

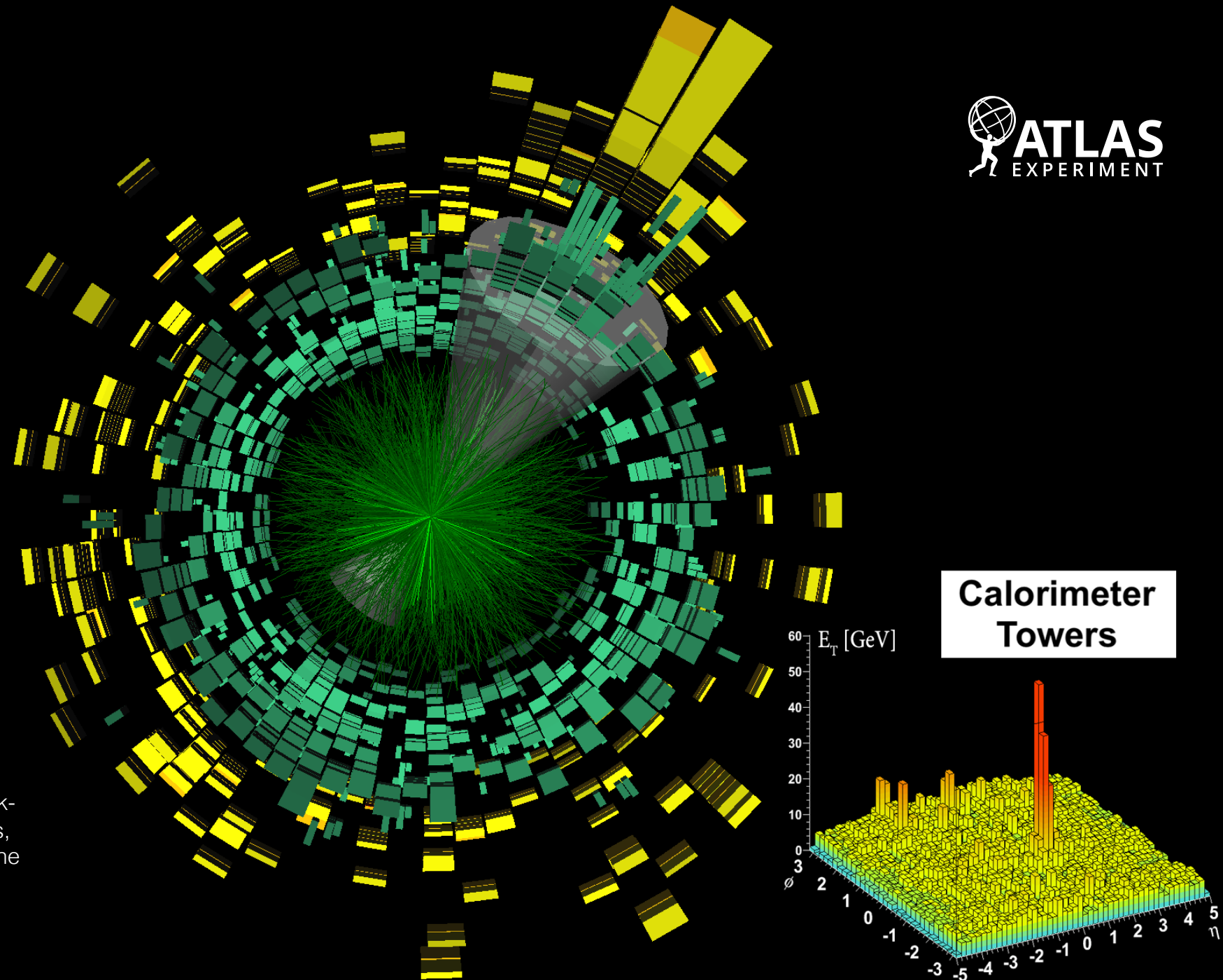


Studies of physics in extreme electromagnetic fields



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

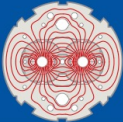


An aerial photograph of a landscape featuring a patchwork of green and brown agricultural fields, some urban areas, and a body of water in the bottom right. A white line is overlaid on the map, forming a large circle with a smaller loop inside. Four small satellite icons are placed along this path: one 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 in the middle of the image.

The next steps

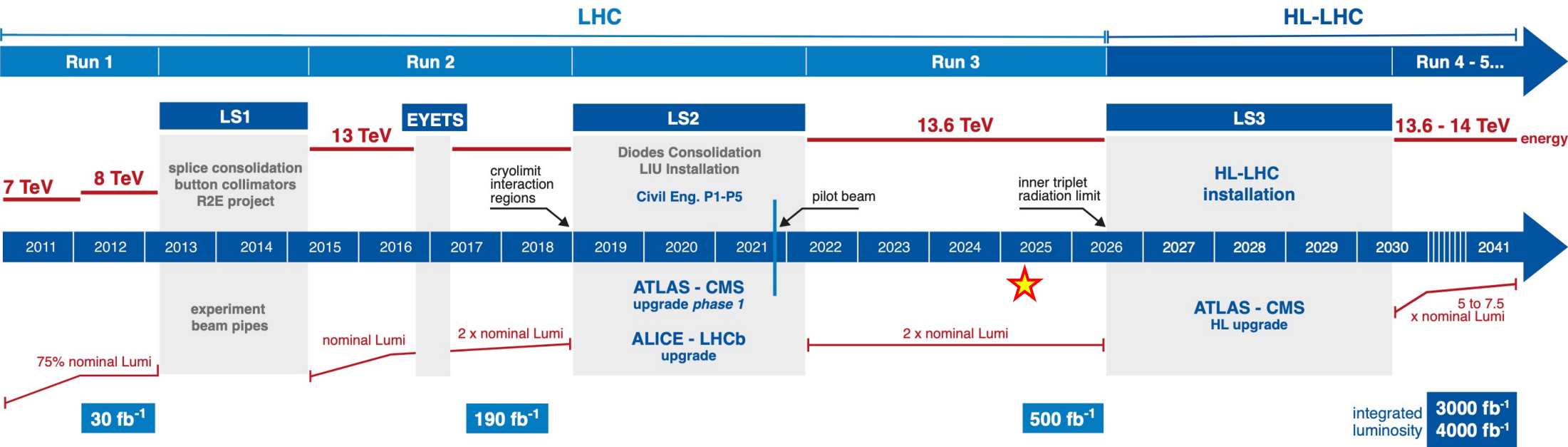
LHC and High-Luminosity-LHC project timeline





LHC / HL-LHC Plan

HL-LHC is the world's flagship collider project during the next decade



HL-LHC TECHNICAL EQUIPMENT:

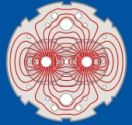


HL-LHC CIVIL ENGINEERING:



CORES

LHC and High-Luminosity-LHC project timeline

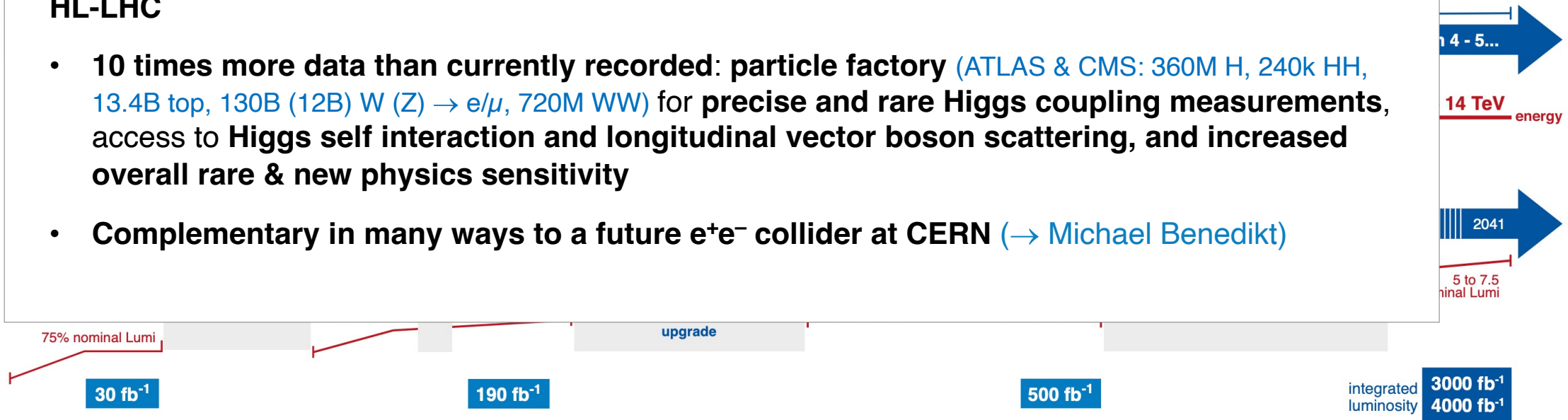


LHC / HL-LHC Plan

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HL-LHC

- **10 times more data than currently recorded: particle factory** (ATLAS & CMS: 360M H, 240k HH, 13.4B top, 130B (12B) W (Z) $\rightarrow e/\mu$, 720M WW) for **precise and rare Higgs coupling measurements**, access to **Higgs self interaction and longitudinal vector boson scattering**, and **increased overall rare & new physics sensitivity**
- **Complementary in many ways to a future e^+e^- collider at CERN** ($\rightarrow$ Michael Benedikt)



HL-LHC TECHNICAL EQUIPMENT:



HL-LHC CIVIL ENGINEERING:

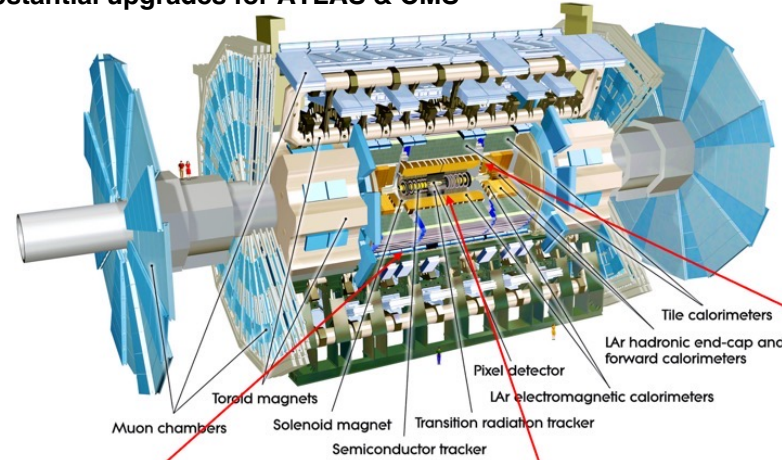


Upgrade to the High-Luminosity LHC (HL-LHC)

The HL-LHC's intensity requires unprecedented detector and computing technologies:

- Radiation hardness
- High detection granularity and resolution
- Precise timing detectors
- More powerful triggers
- Deeply embedded ML & AI
- High-performance software & computing

Substantial upgrades for ATLAS & CMS



New Muon Chambers

Inner barrel region with new RPC and sMDT detectors

New Inner Tracking Detector (ITk)

All silicon, up to $|\eta| = 4$

Upgraded Trigger and Data Acquisition system

Level-0 Trigger at 1 MHz
Improved High-Level Trigger (150 kHz full-scan tracking)

Electronics Upgrades

LAr Calorimeter
Tile Calorimeter
Muon system

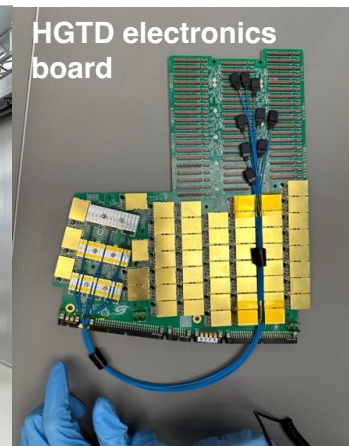
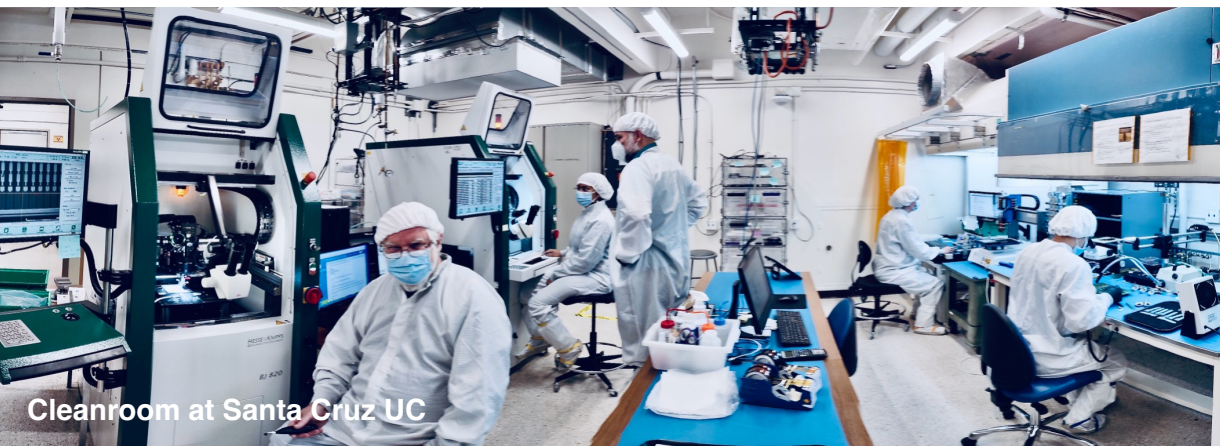
High Granularity Timing Detector (HGTD)

Forward region ($2.4 < |\eta| < 4.0$)
Low-Gain Avalanche Detectors (LGAD) with 30 ps track resolution

Additional small upgrades

Luminosity detectors (1% precision goal)
HL-ZDC

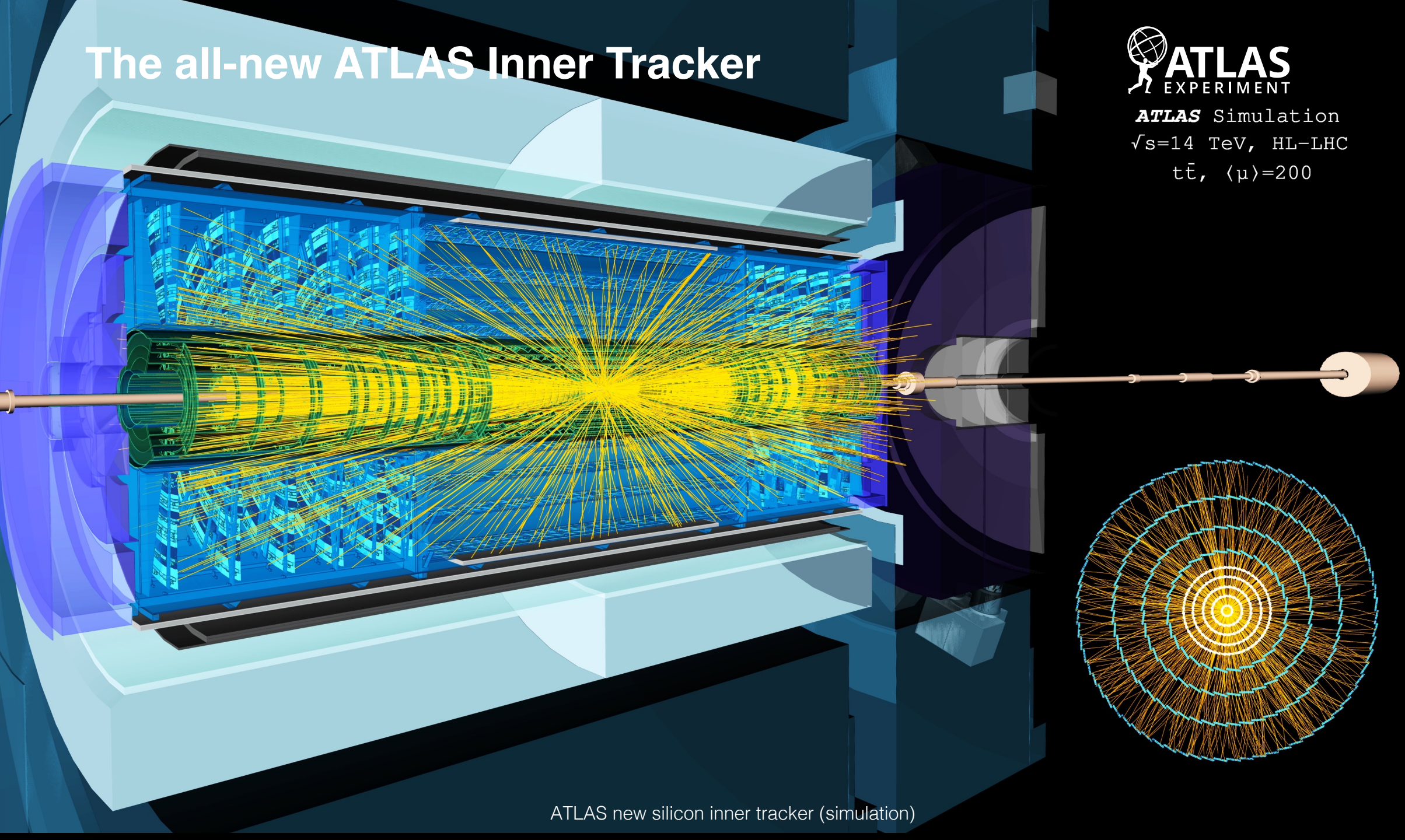
Detailed scope described in 7 TDRs approved by the CERN Research Board in 2017, 2018, 2020



The all-new ATLAS Inner Tracker



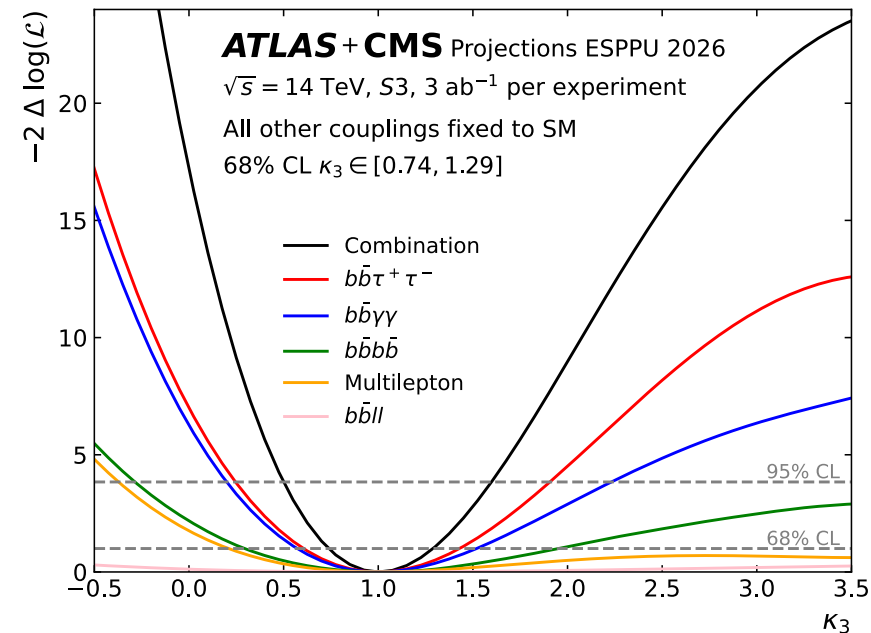
ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$



ATLAS new silicon inner tracker (simulation)

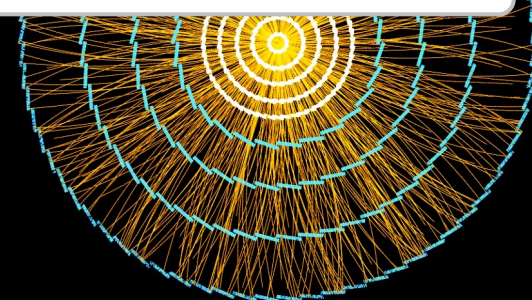
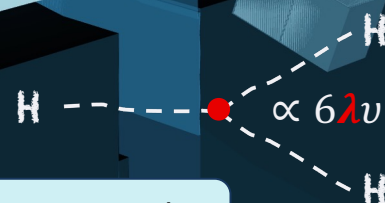
Measuring Higgs self-coupling

ATL-PHYS-PUB-2025-018



$$Z_{HH}[\text{SM}] = 7.6\sigma, \quad \kappa_\lambda[\text{SM}] = 1^{+0.29}_{-0.26}$$

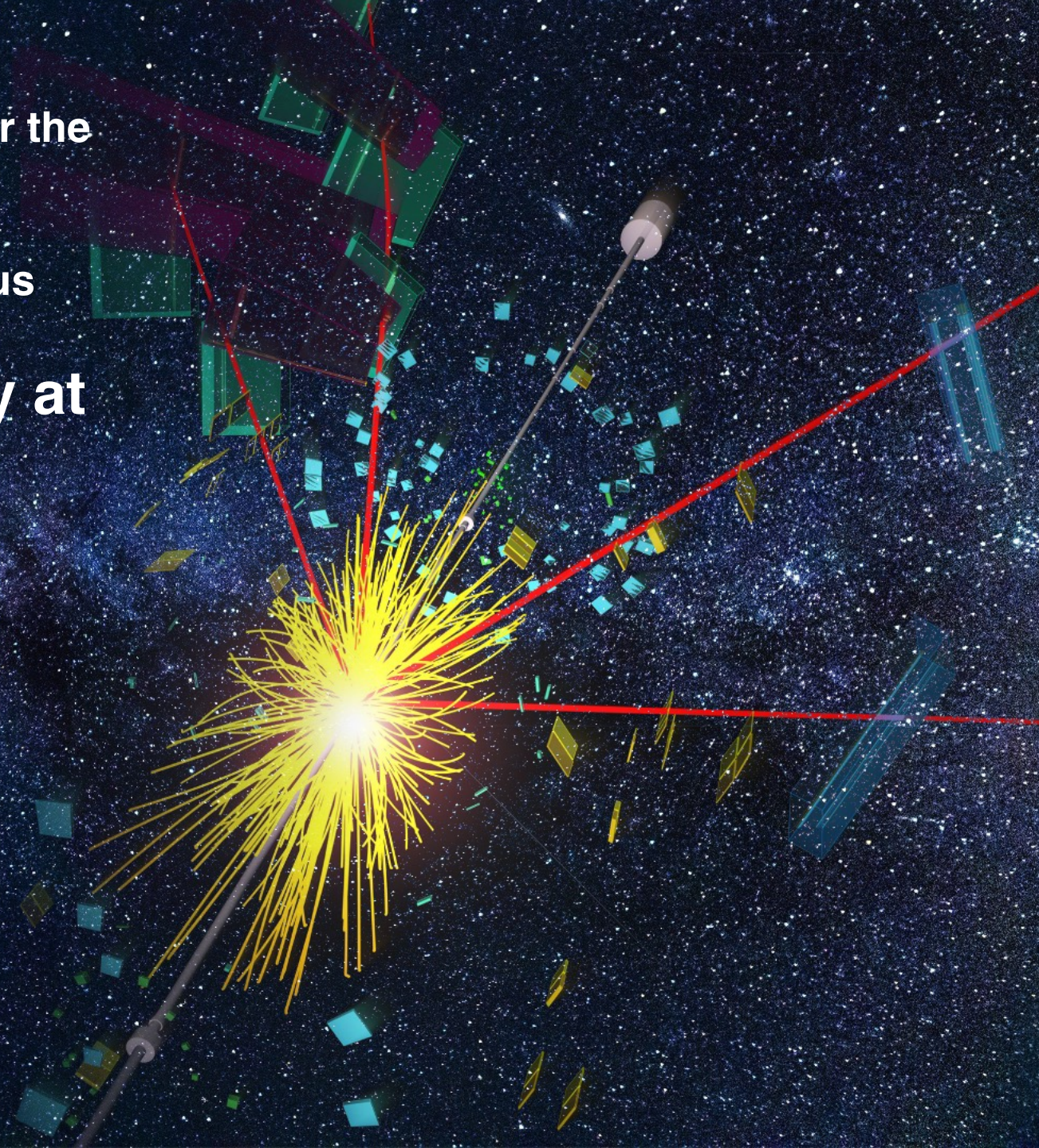
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$



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

Yet many secrets remain hidden from us

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





Extra 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

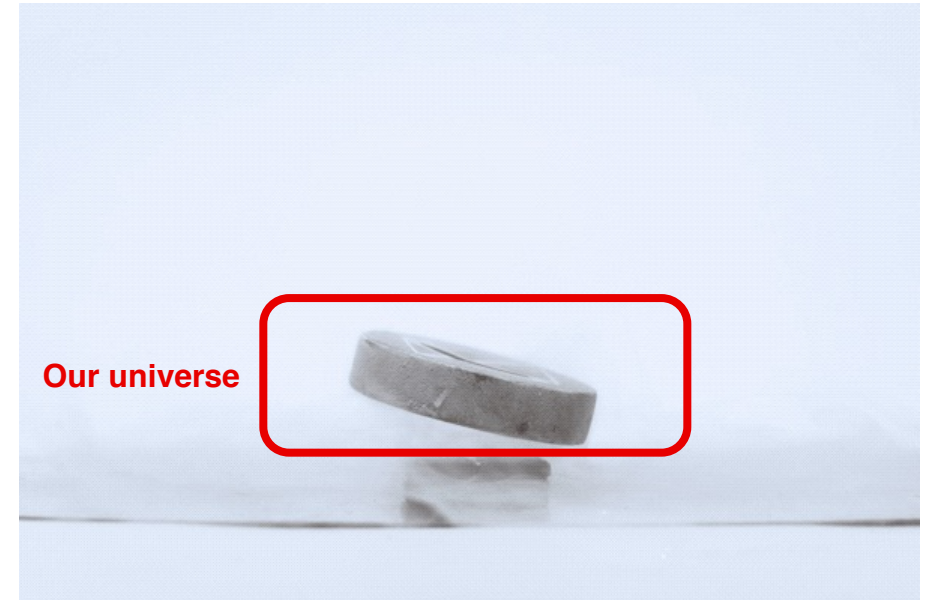
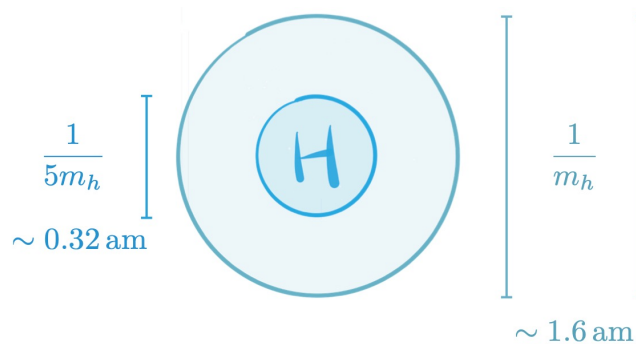
Condensed Higgs field

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?



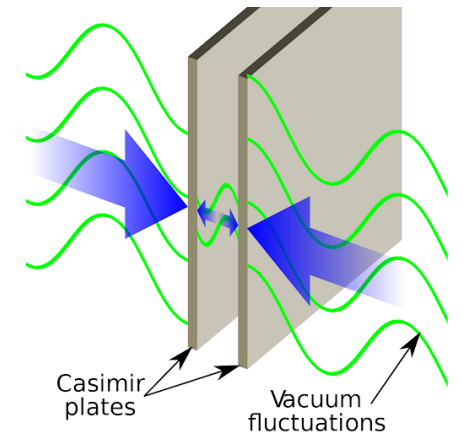
A superconductor is locked mid-air in different orientations above a permanent magnet — superconductive levitation due to the expulsion of the static magnetic field (Meissner effect) [\[Source\]](#)

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

Vacuum energy

Quantum field theory describes the fabric of empty space

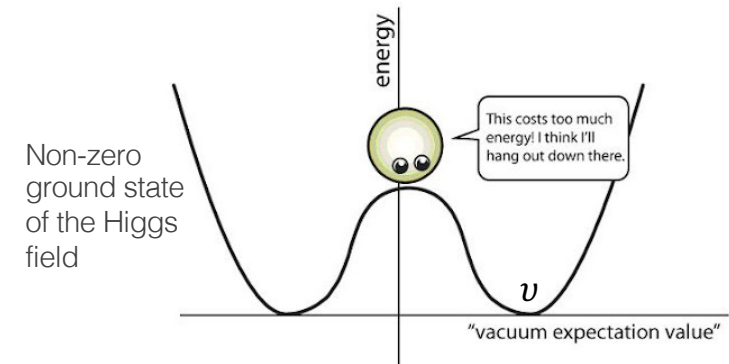
- In QFT, the vacuum is not an empty void but a dynamic and structured entity with **vacuum fluctuations, virtual particles, zero-point energy** (*Nullpunktsenergie*)
- Zero-point energy: quantum fields have vacuum energy even in absence of real particles
(cosmological constant problem: $\rho_{\text{QFT}} \propto m_{\text{Pl}}^4 \sim (10^{19} \text{ GeV})^4 \rightarrow 10^{110} \text{ eV}^4 \gg \rho_{\Lambda} \sim (2 \times 10^{-3} \text{ eV})^4 \sim 10^{-11} \text{ eV}^4$)



Harnessing the zero-point energy

Electroweak theory and Brout-Englert-Higgs mechanism

- Higgs field has vacuum expectation value $\langle 0|\phi|0\rangle = v \approx 246 \text{ GeV}$
($|\rho_{\text{Higgs}}| \sim m_{\text{H}}^2 v^4 / 2 \sim 10^{45} \text{ eV}^4$)

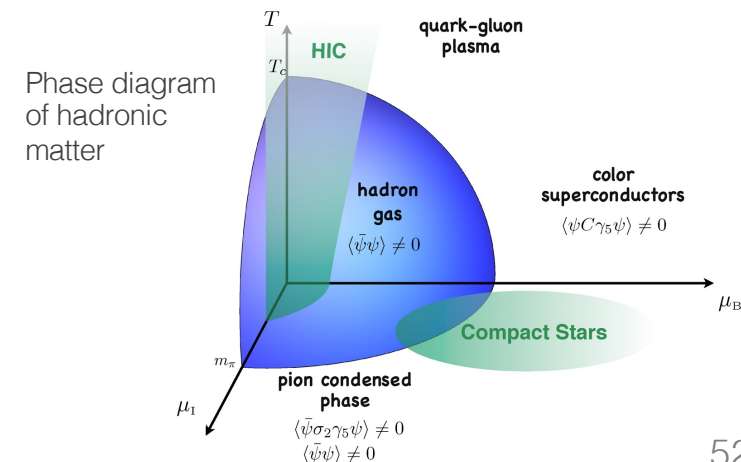


QCD vacuum

- The non-perturbative QCD vacuum involves the quark condensate (breaking chiral symmetry) and gluon condensate characterising the confined phase of quark matter
($|\rho_{\text{QCD}}| \sim (0.1 \text{ GeV})^4 \sim 10^{32} \text{ eV}^4$)

General relativity

- In General Relativity, the cosmological constant (Λ) which can be interpreted as a form of (dark) vacuum energy, drives the accelerated expansion of the universe



Higgs boson production at the LHC

About 1 Higgs boson per second is produced in ATLAS at the LHC (about 20M total by today)

