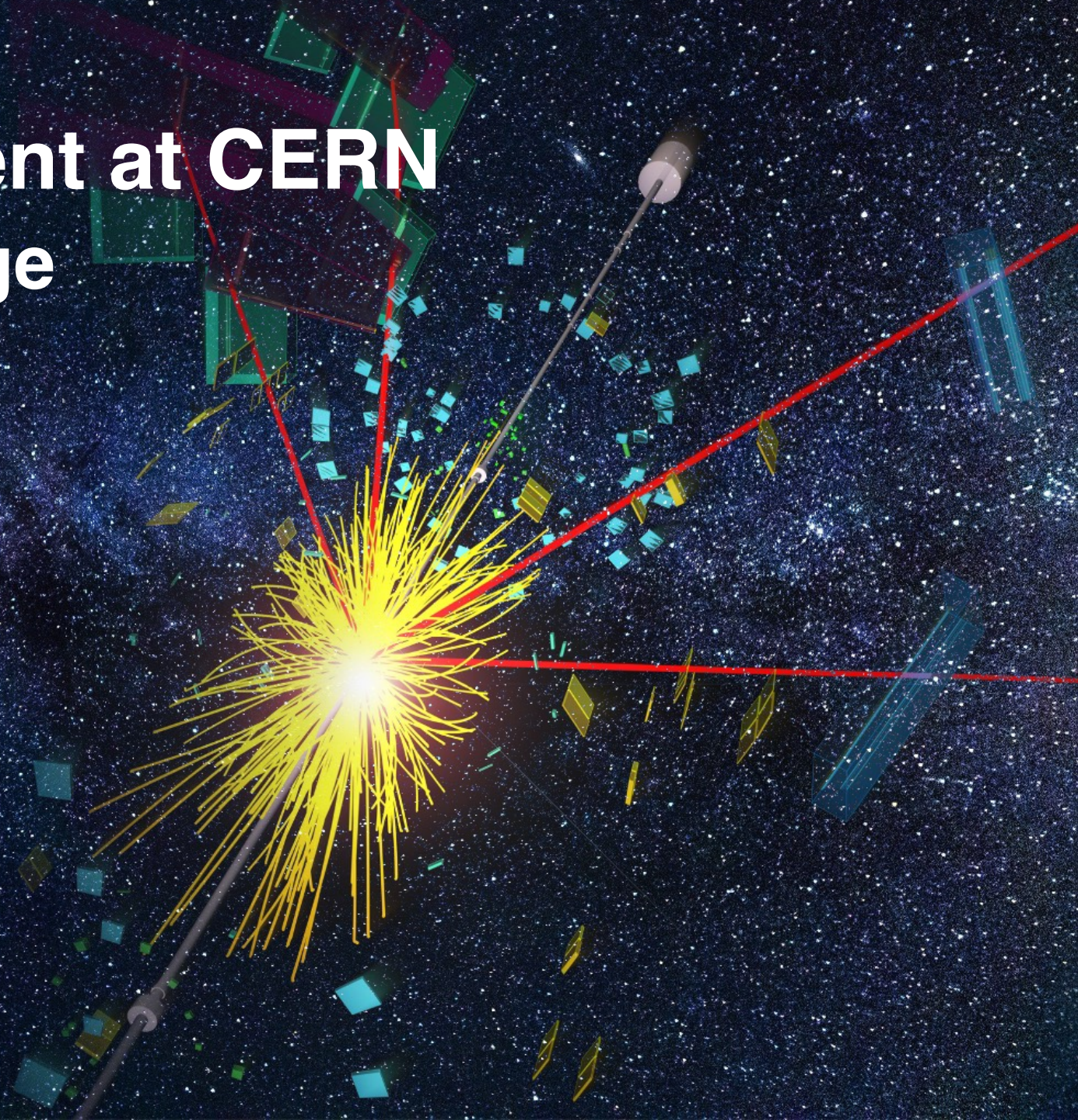


The ATLAS Experiment at CERN

— Lessons from a Large International Research Collaboration

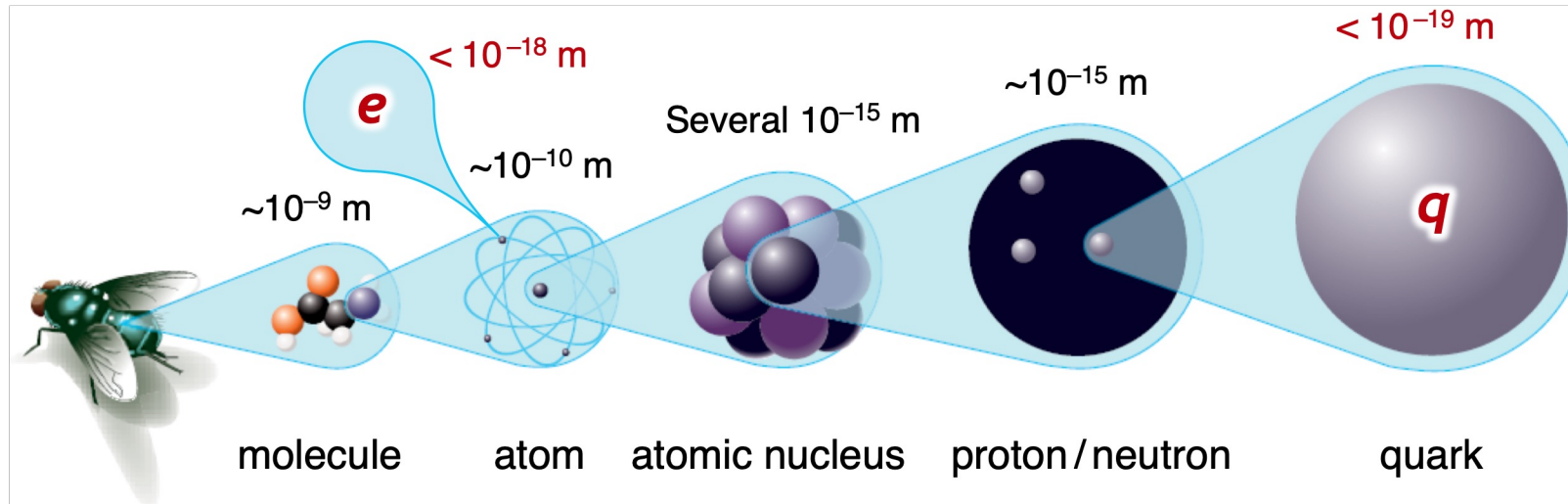
Andreas Hoecker (CERN)
<andreas.hoecker@cern.ch>

*International Open-Source LLM Builders Summit,
EPFL, 9 Feb 2026*



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

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



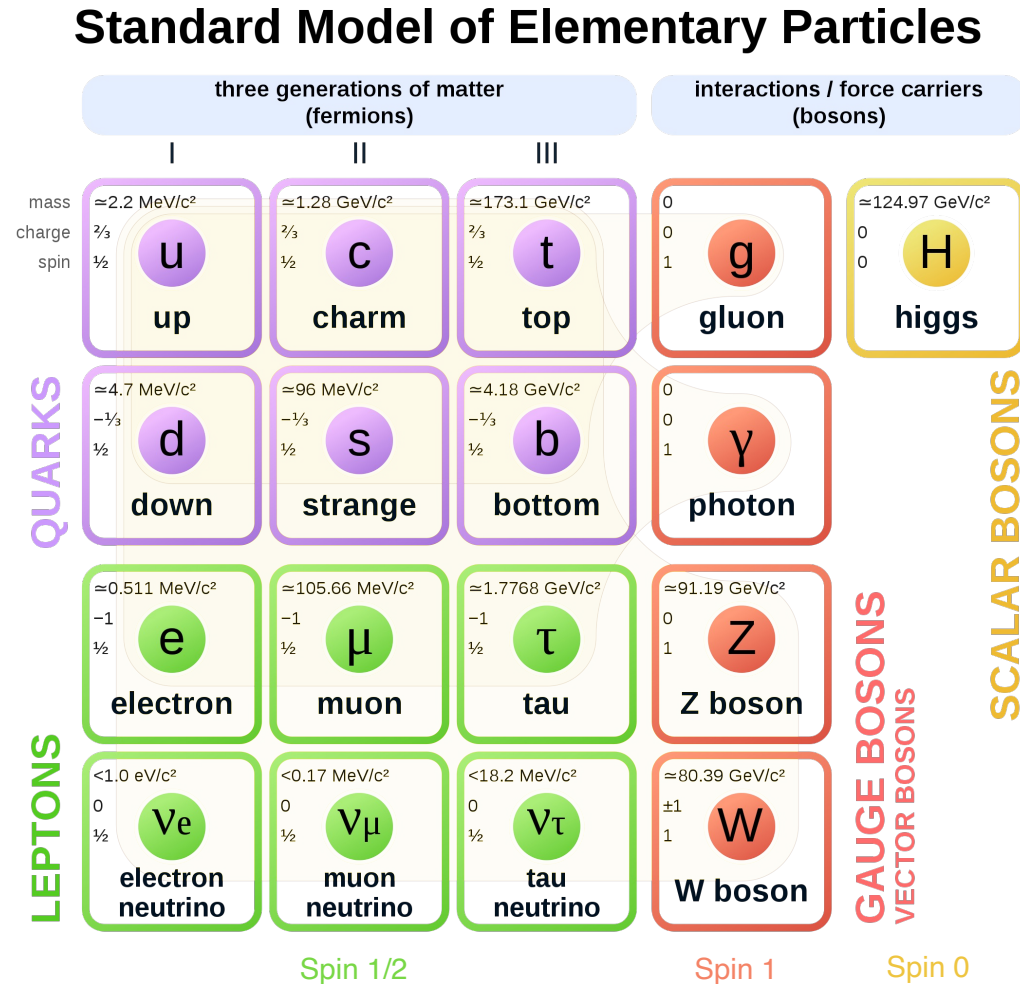
The universe is a strange place

- Elementary particles are point-like — with no spatial extent at all (this is likely not true)
- Without some remarkable mechanism at play, elementary particles would have no mass (except for spin-zero particles)

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**

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

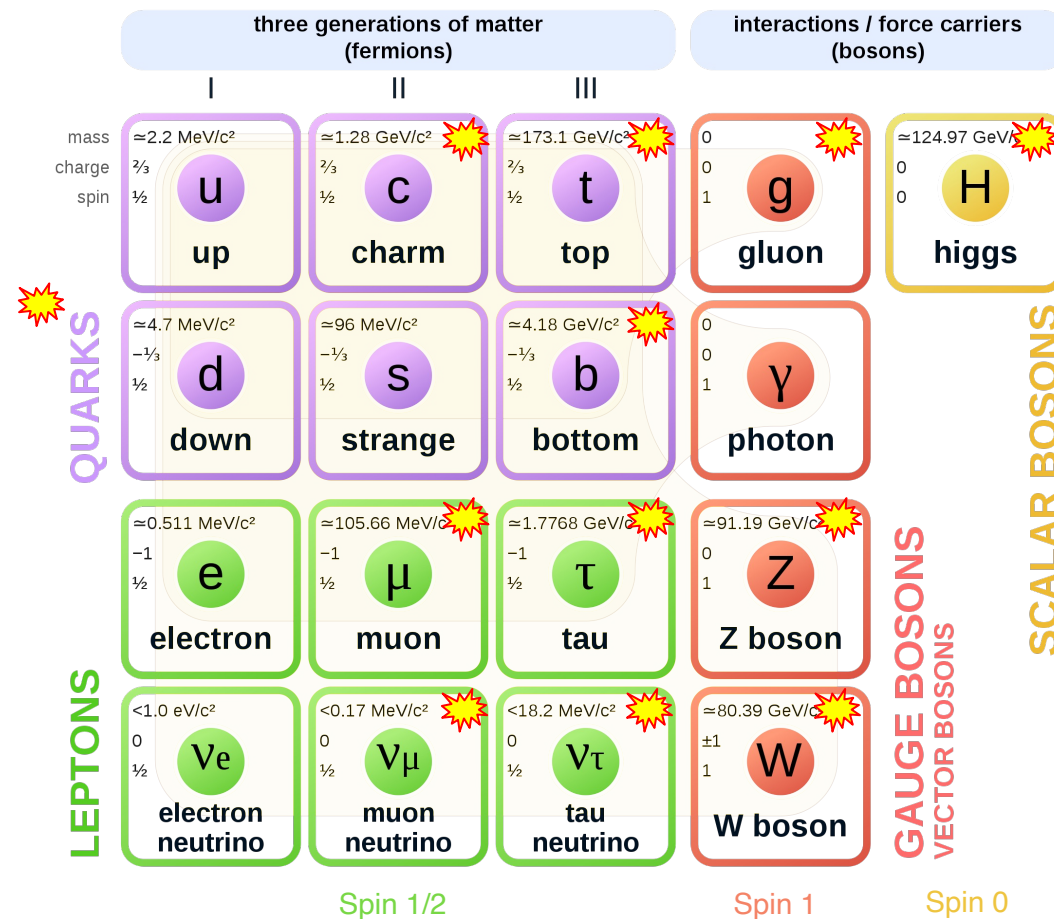


Completely new type of non-universal interactions, nothing to do with known forces

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



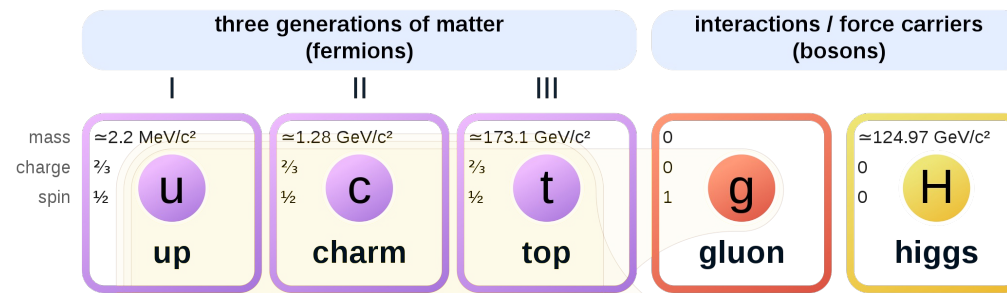
Decades of international high-technology **accelerator-based research** gave us these insights

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

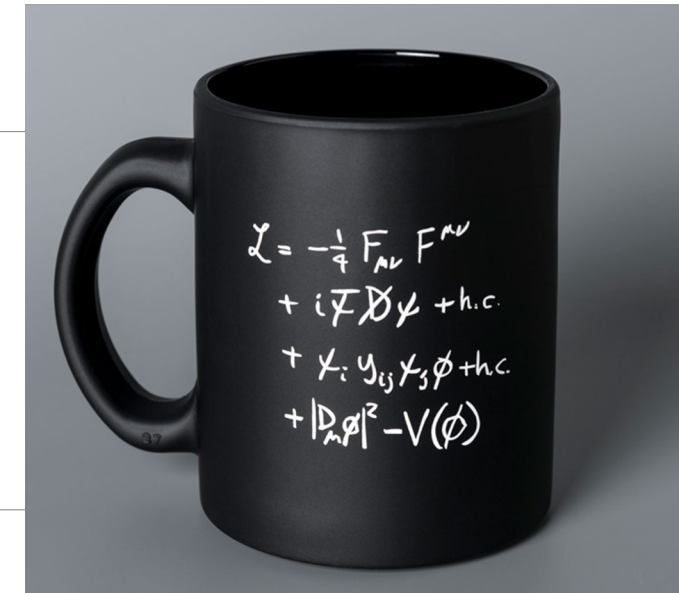
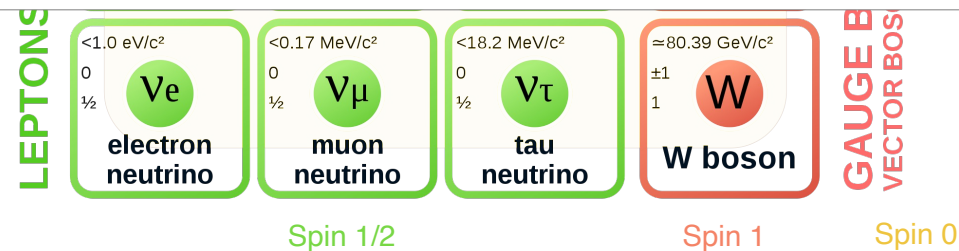


The Standard Model is a highly predictive theory

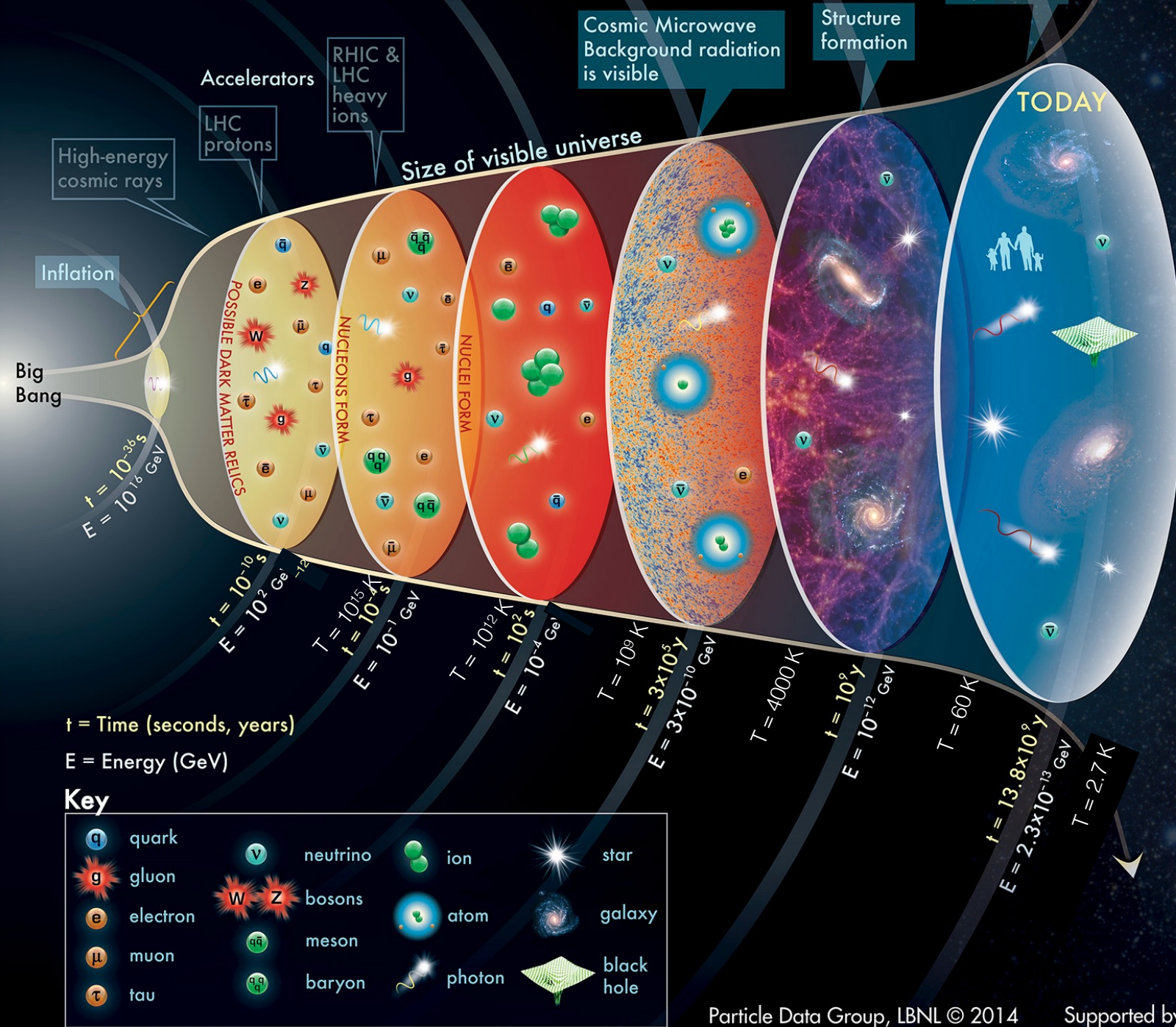
For example, prediction of the magnetic moment of the electron:

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

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

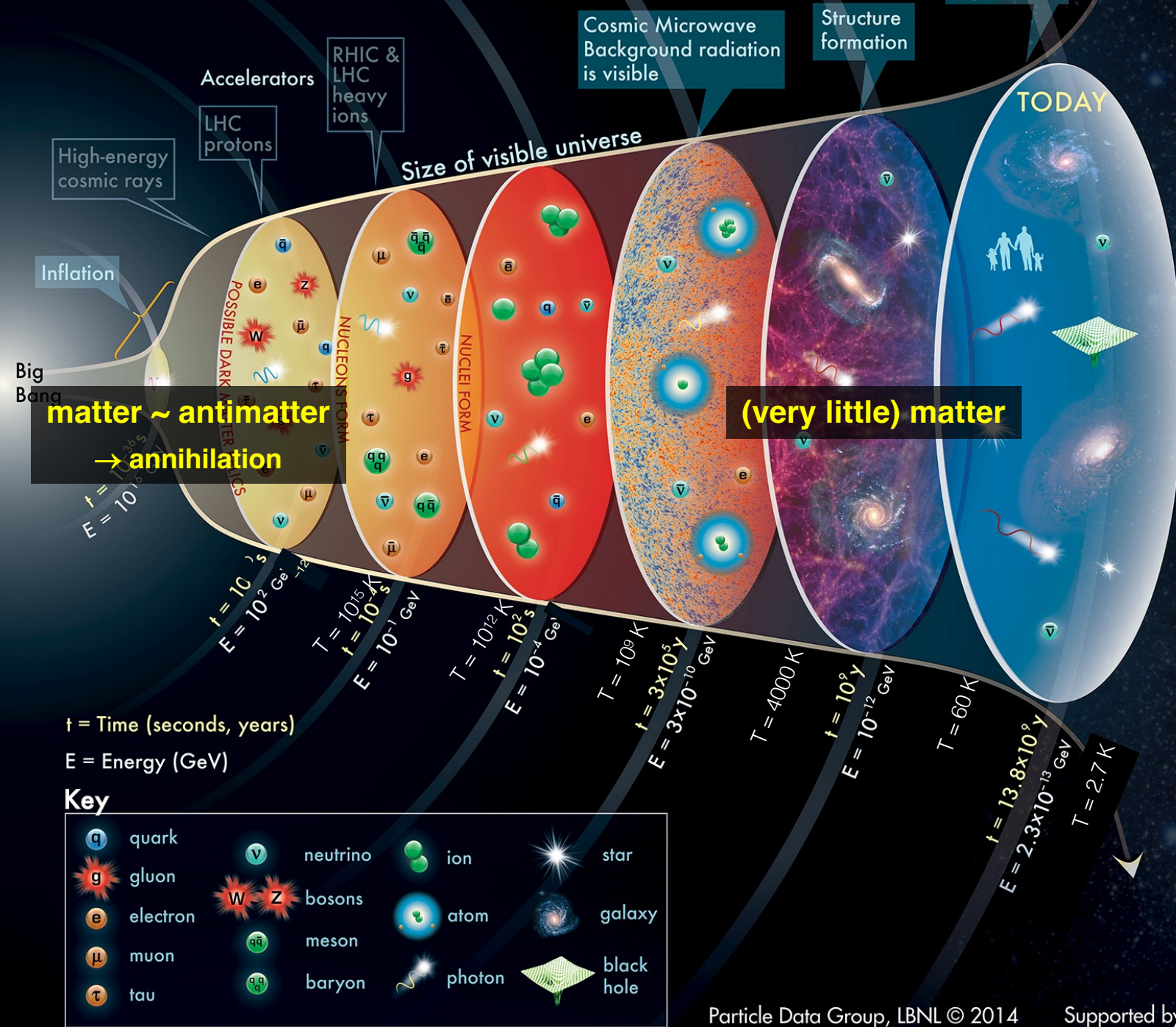


Mathematical structure of the Standard Model



The Standard Model

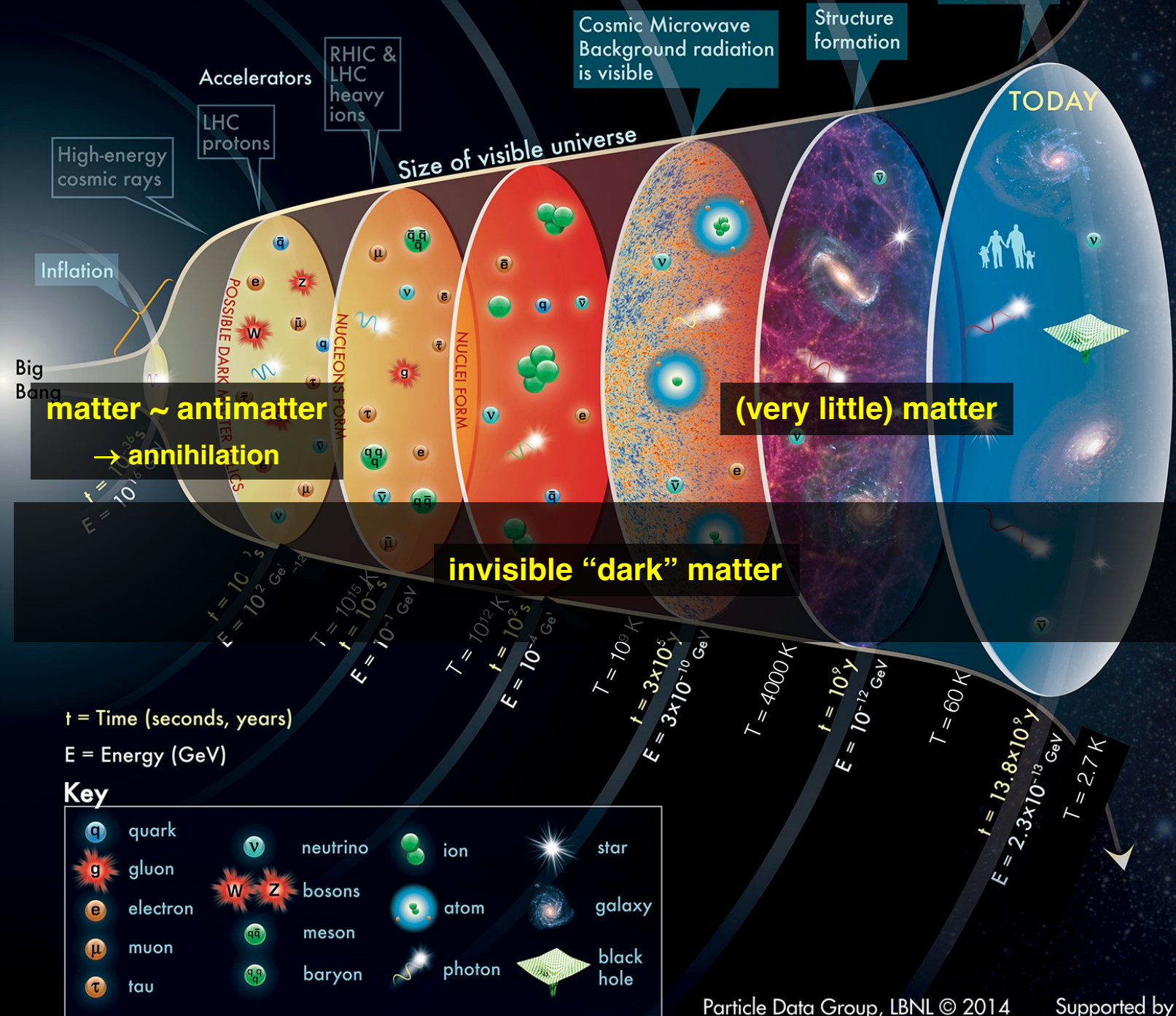
... should not only work today, but also describe the history of the universe since the Big Bang 13.8 billion years ago



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 why is there only matter left in the universe?



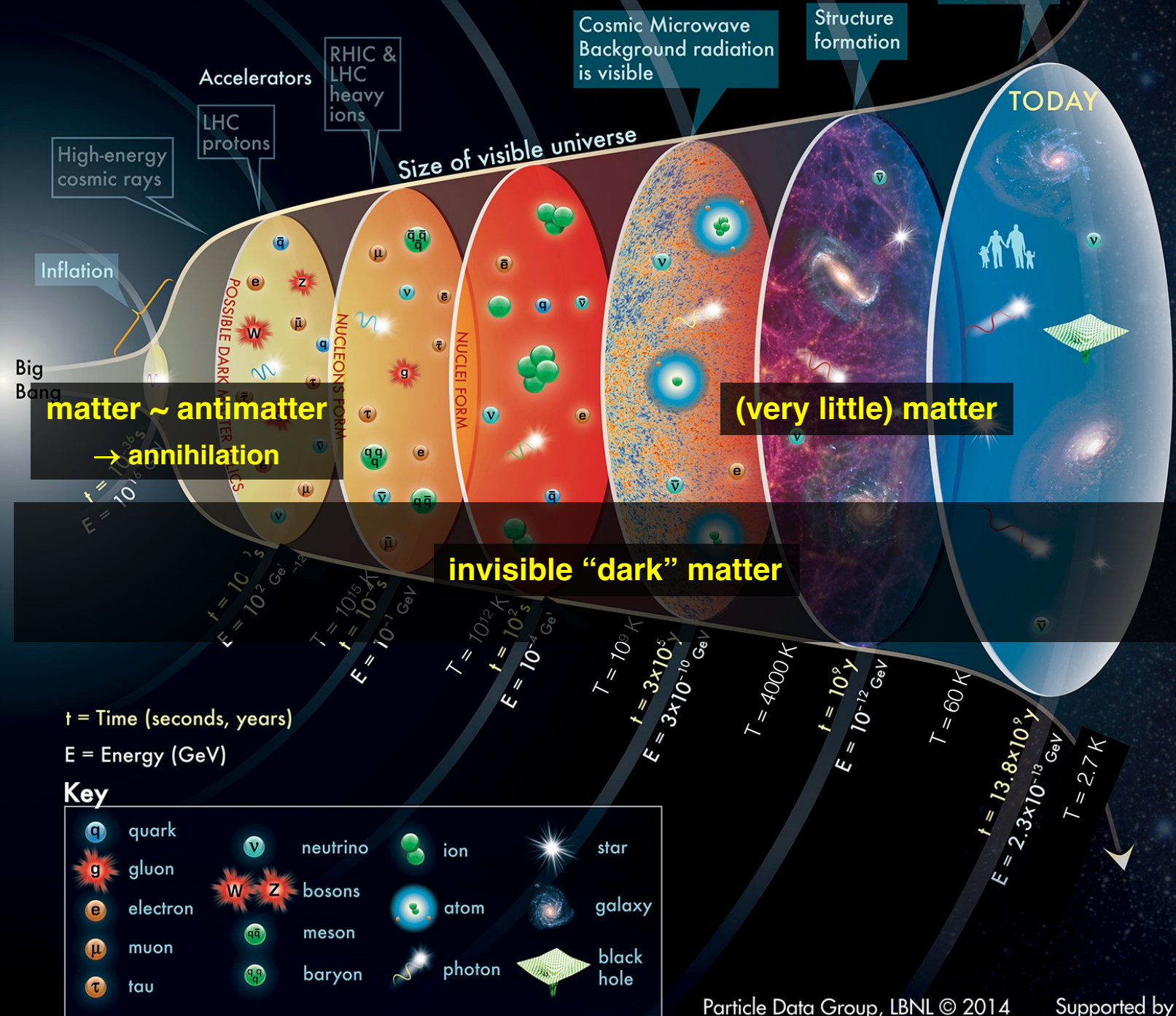
The Standard Model

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

But why is there only matter left in the universe?

And what is the origin of the huge quantity of *dark matter* (5 times more than the baryonic matter)?

And how do elementary particles obtain mass?



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

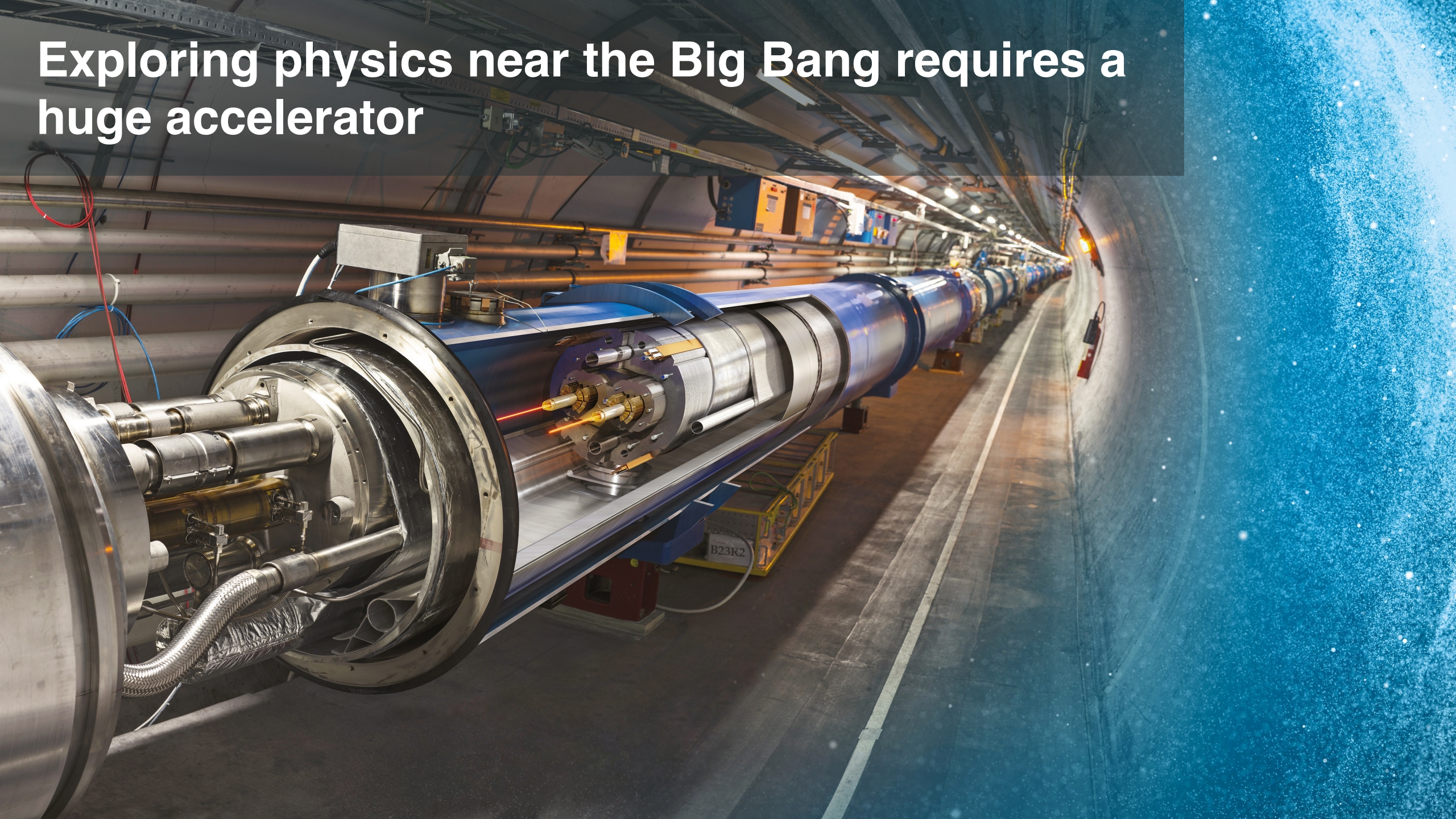
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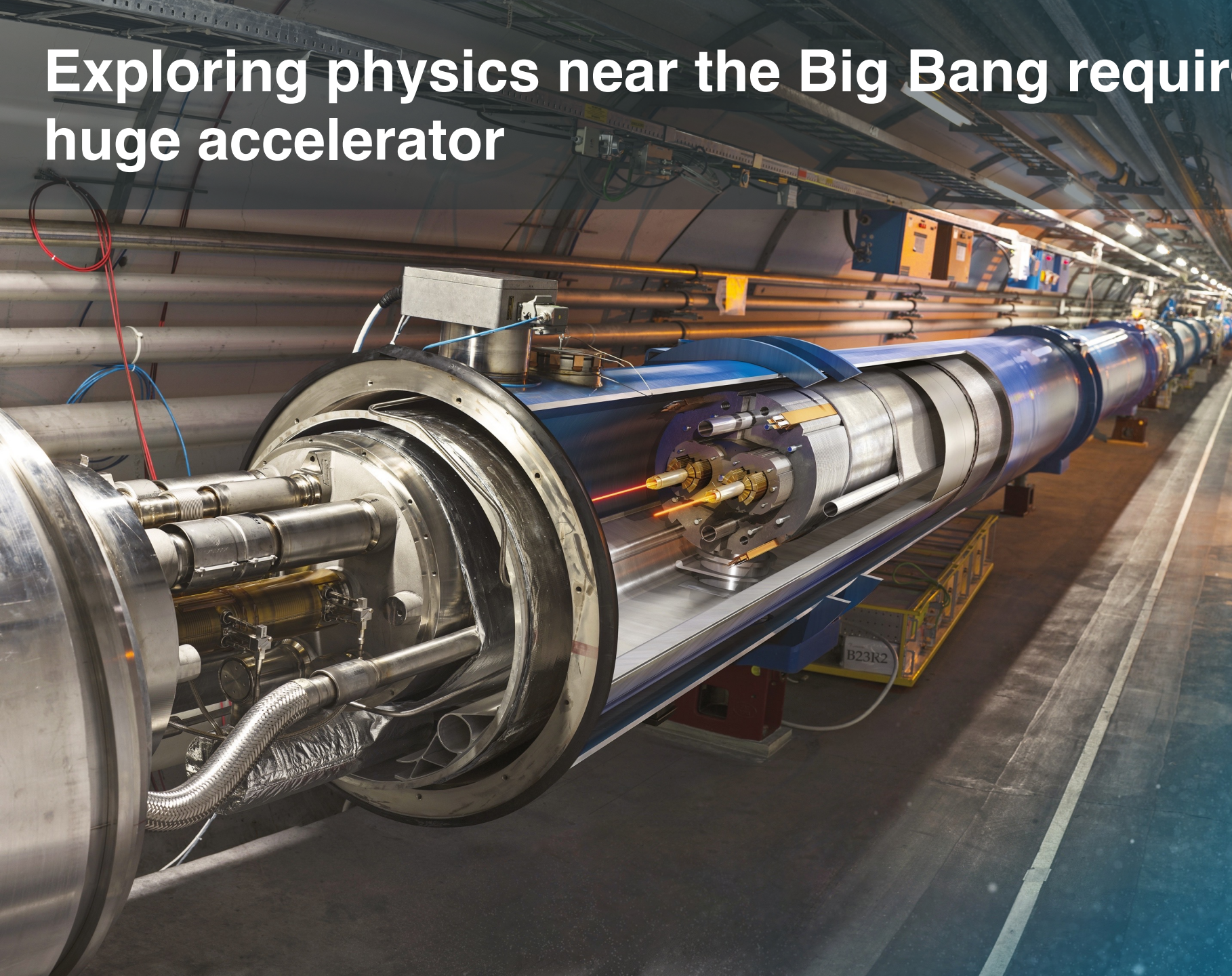
And how do elementary particles obtain mass?

We do not know why the laws and parameters of physics are set in a way to permit complex chemistry and life

Exploring physics near the Big Bang requires a huge accelerator



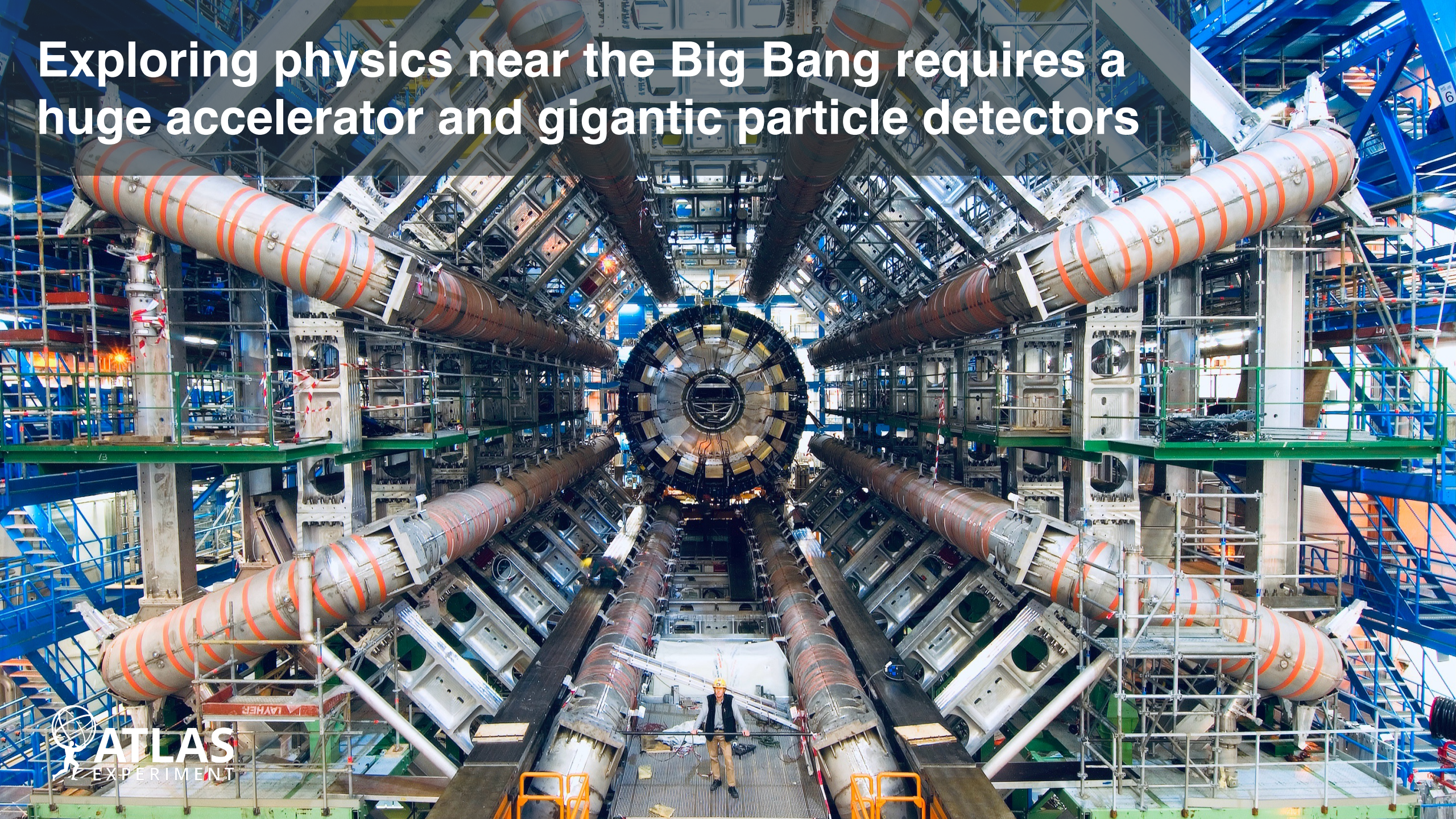
Exploring physics near the Big Bang requires a huge accelerator

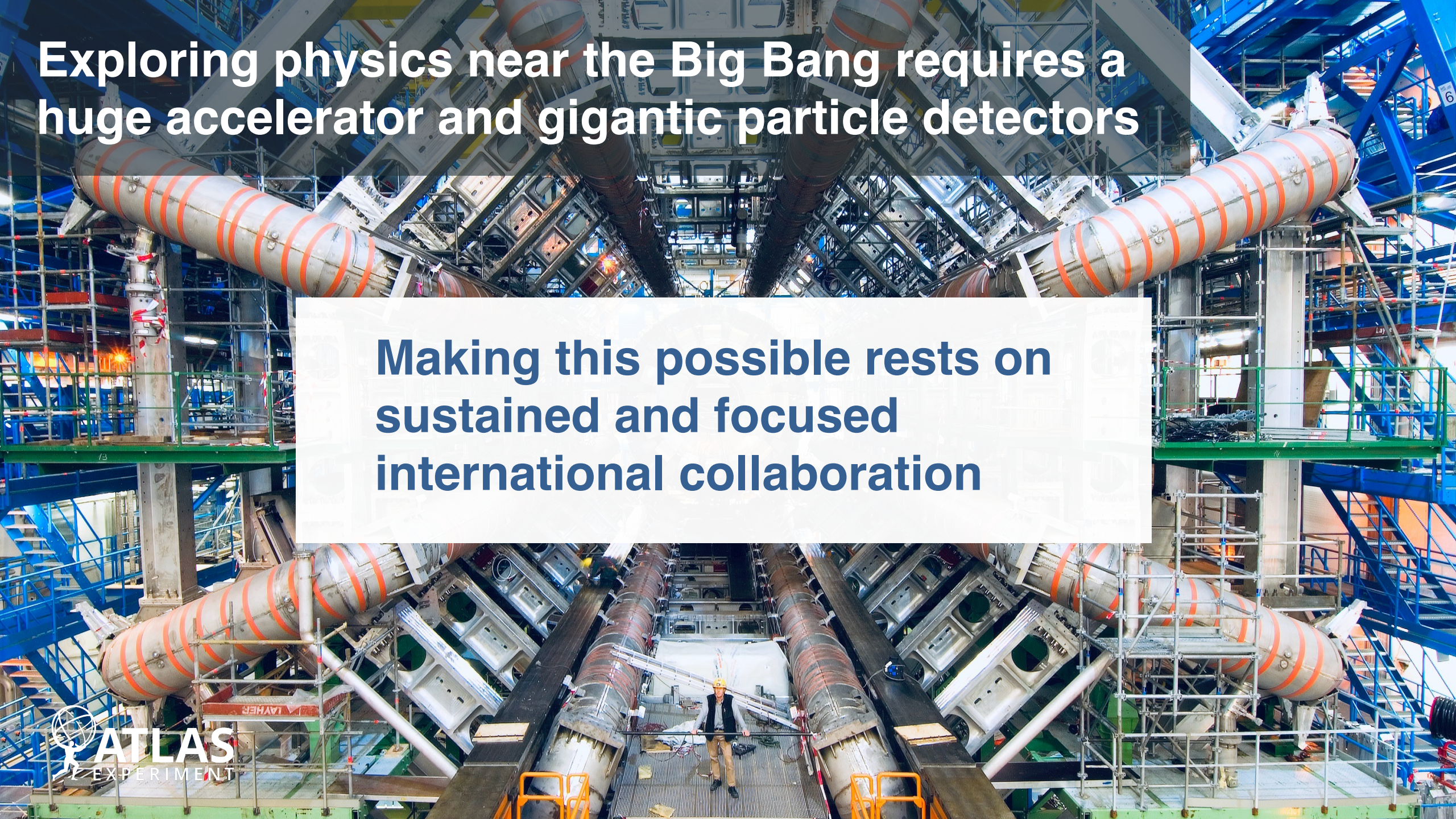


Large Hadron Collider (LHC)

- 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

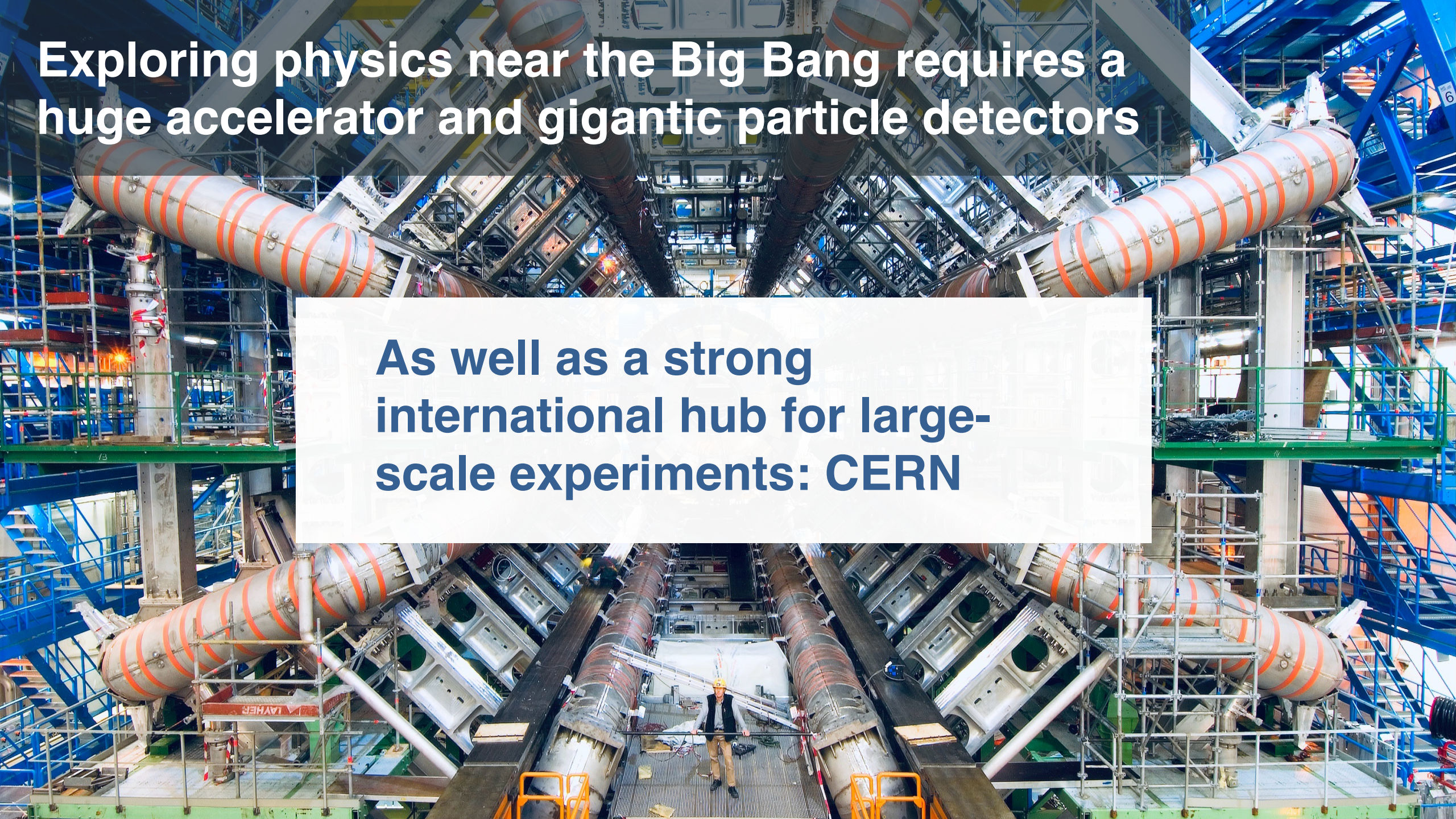
Exploring physics near the Big Bang requires a huge accelerator and gigantic particle detectors





Exploring physics near the Big Bang requires a huge accelerator and gigantic particle detectors

Making this possible rests on sustained and focused international collaboration

A wide-angle, low-perspective shot of a massive particle accelerator tunnel. The tunnel is filled with complex machinery, including large cylindrical components with orange and silver bands. A person stands in the center of the tunnel, providing a sense of scale. The tunnel is supported by a dense network of blue metal scaffolding and structural beams. The lighting is bright, highlighting the industrial environment.

Exploring physics near the Big Bang requires a huge accelerator and gigantic particle detectors

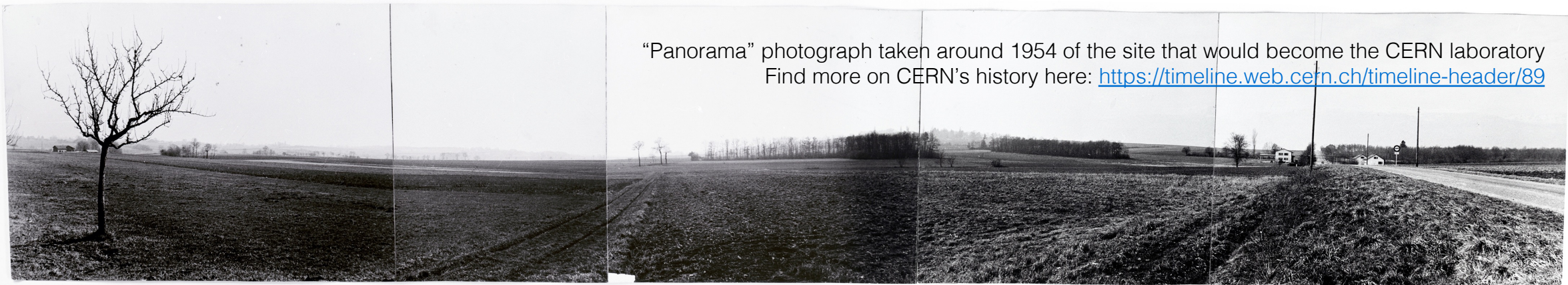
As well as a strong international hub for large-scale experiments: CERN

Objective: Creation of a powerful and competitive infrastructure for fundamental research in nuclear / particle physics in Europe

1952: Creation of a Council: "Conseil Européen pour la Recherche Nucléaire" (CERN)

Belgium, Denmark, France, West Germany, Greece, Italy, The Netherlands, Norway, Sweden, Switzerland, United Kingdom, Yugoslavia

Coming into force of the convention on 29 September 1954: Foundation as "Organisation Européenne pour la Recherche Nucléaire"





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



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

CERN today



CERN today

ATLAS Experiment



CERN today — the world's largest centre for particle physics

25 Member States

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

10 Associate Member States

Brazil – Croatia – Cyprus – India – Ireland – Latvia
Lithuania – Pakistan – Türkiye – Ukraine

6 Observers

Japan – JINR (suspended) – USA
European Union – UNESCO

Around 50 Cooperation Agreements with non-Member States and Territories

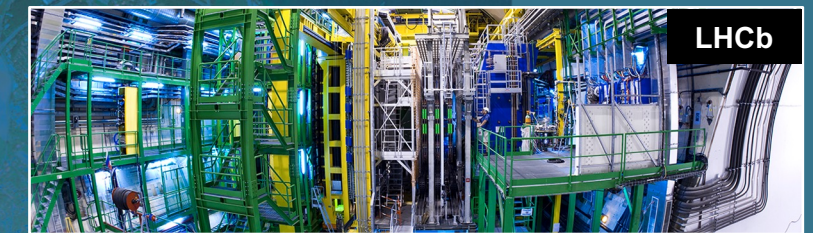
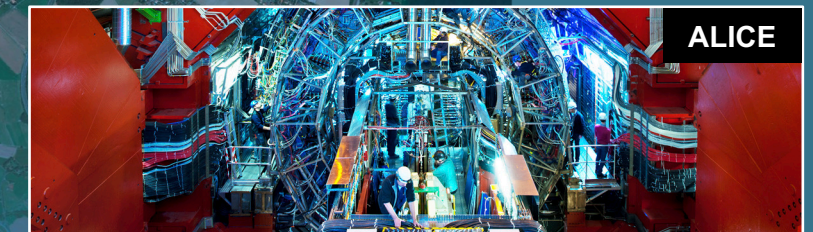
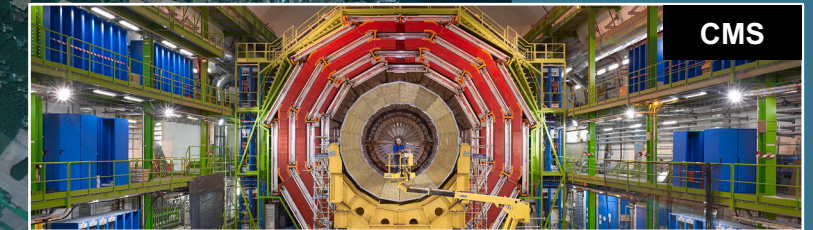
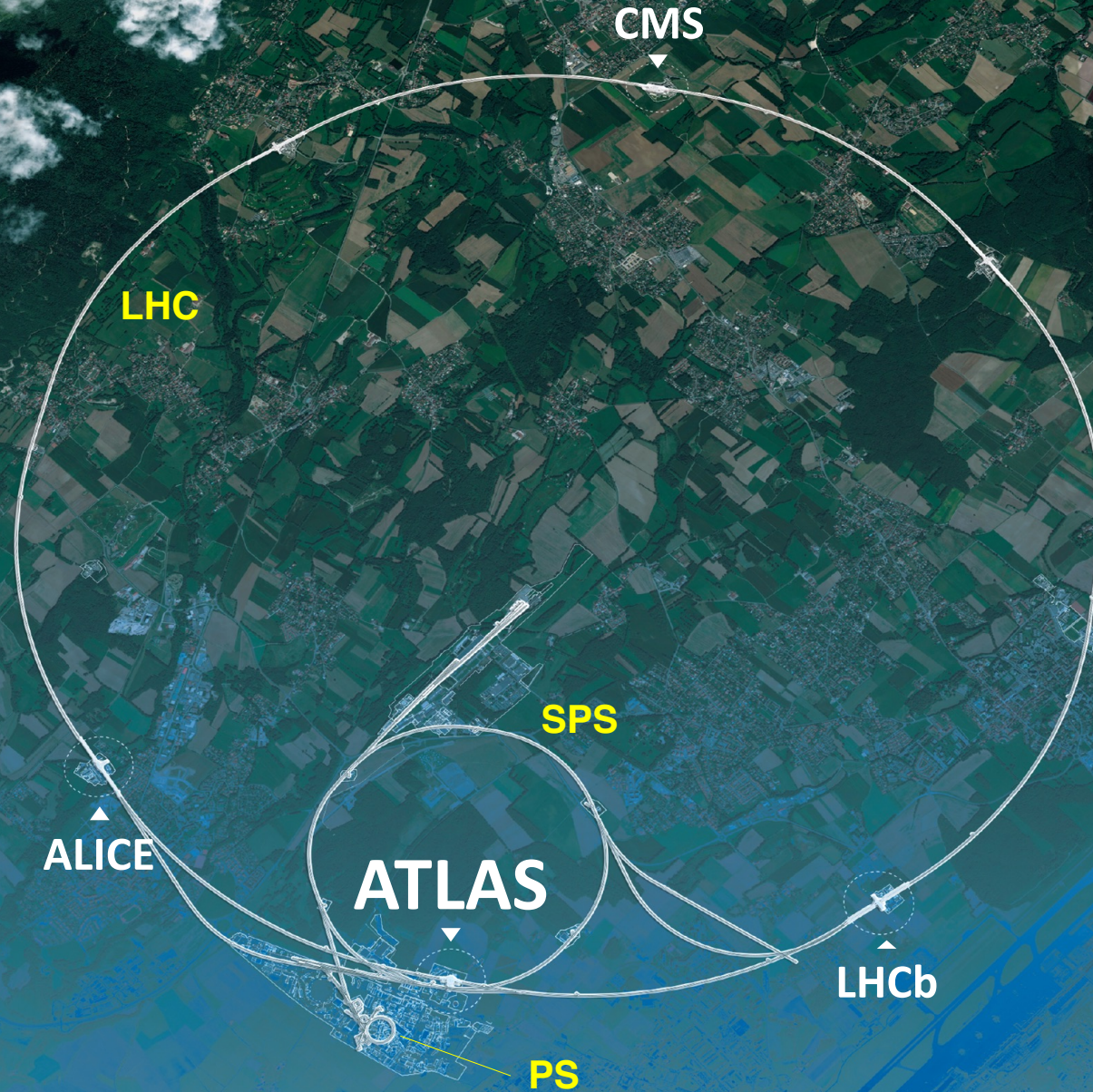
Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Brazil – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Iceland
Iran – Jordan – Kazakhstan – Latvia – Lebanon – Malta – Mexico – Mongolia – Montenegro – Morocco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



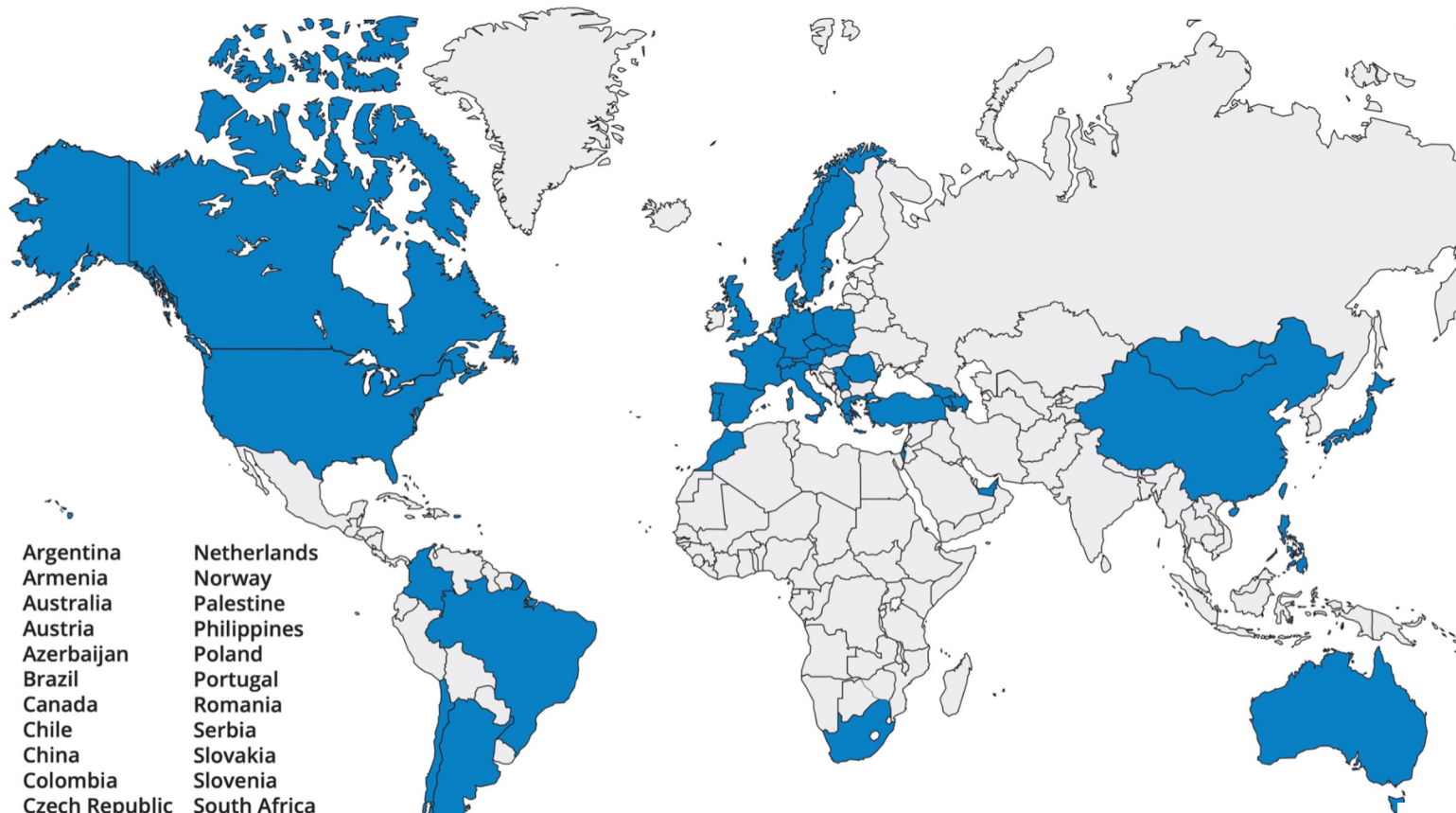
As of 31 December 2023
Employees:
2,666 staff, 1,002 graduates
Associates:
12,370 users, 1,513 others

Very successful: **CERN
Summer Student
Programme**, open to Non-
Member States

LHC and Detectors



Aerial view



Argentina	Netherlands
Armenia	Norway
Australia	Palestine
Austria	Philippines
Azerbaijan	Poland
Brazil	Portugal
Canada	Romania
Chile	Serbia
China	Slovakia
Colombia	Slovenia
Czech Republic	South Africa
Denmark	Spain
France	Sweden
Georgia	Switzerland
Germany	Taiwan
Greece	Türkiye
Israel	UAE
Italy	UK
Japan	USA
Mongolia	CERN
Morocco	JINR

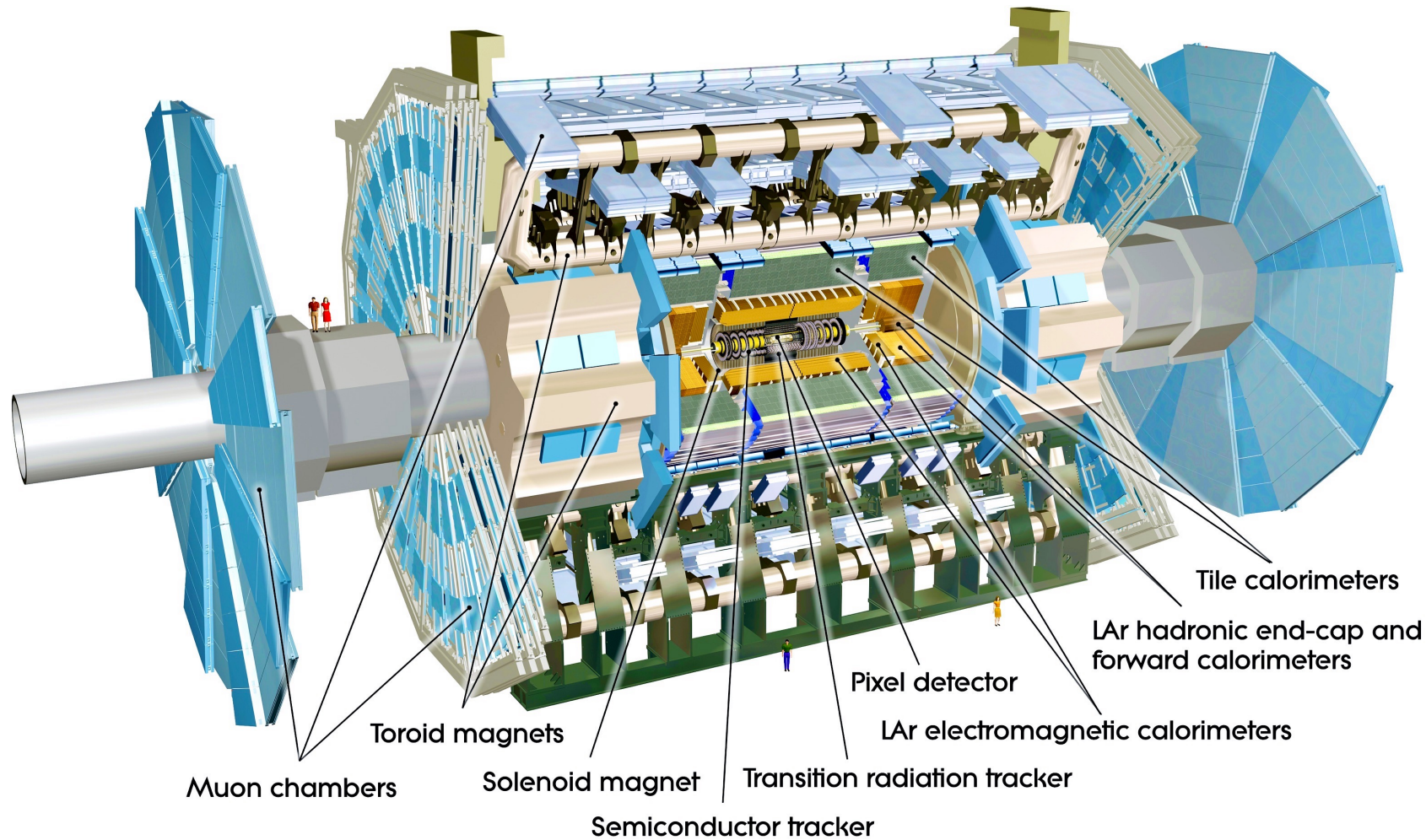
ATLAS Collaboration



248 Institutes from 41 countries (>100 nationalities)

- 2900 scientific authors
- **1200 physics PhD students**
- **1300 engineers and technicians**
- 6000 members

The ATLAS Detector



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 ($80\ \mu\text{m} \times 12\ \text{cm}$)

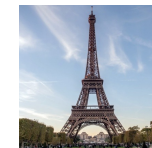
spatial resolution $\sim 15\ \mu\text{m}$ (in azimuthal direction)

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

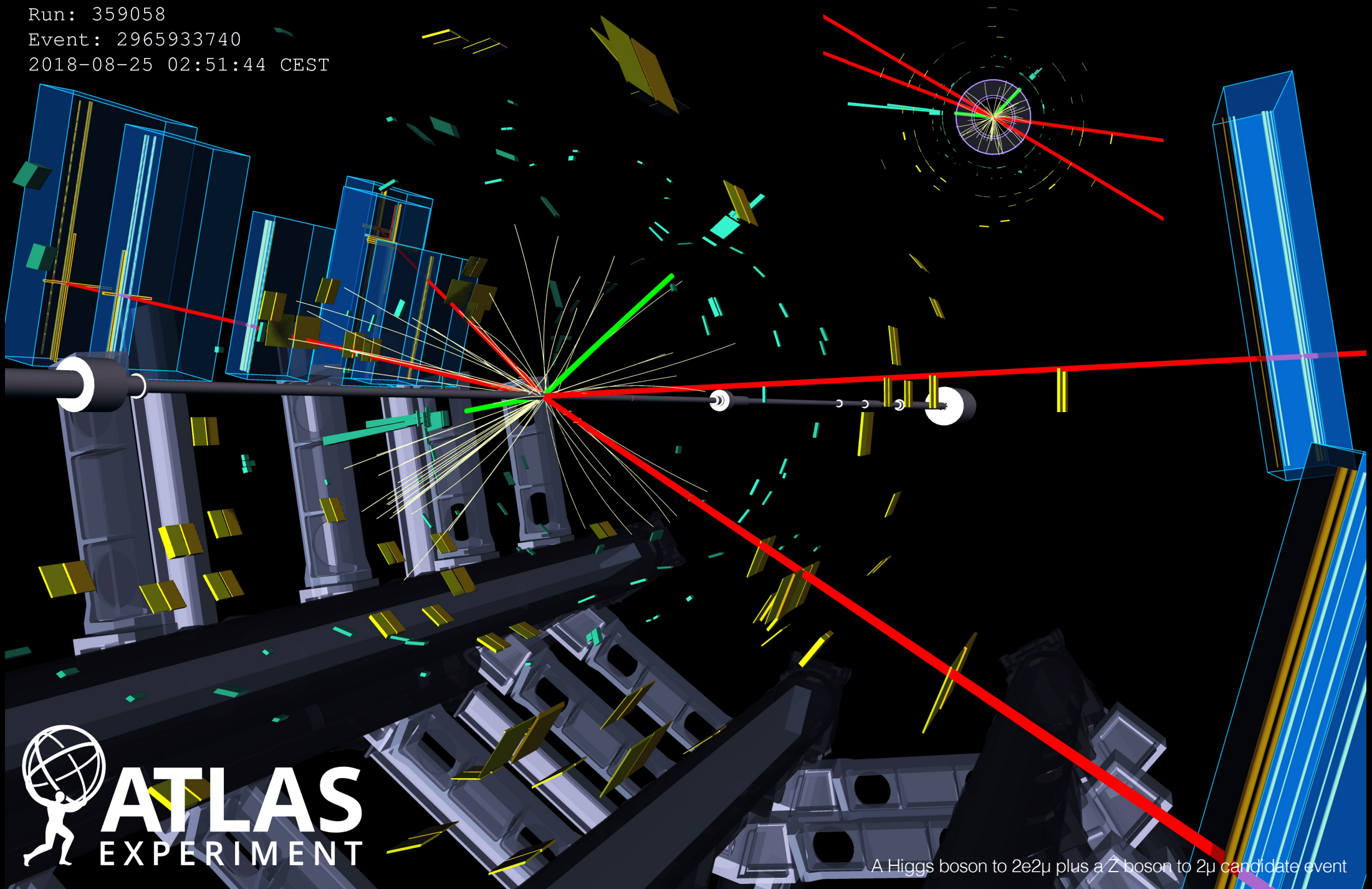
Independent **muon spectrometer** (superconducting toroidal magnet system)

Ultra-fast custom electronics and high-performance computers filter the collisions: only 1 out of 20,000 collisions is kept

25 m diameter, 44 m long, 7000 tons weight ~



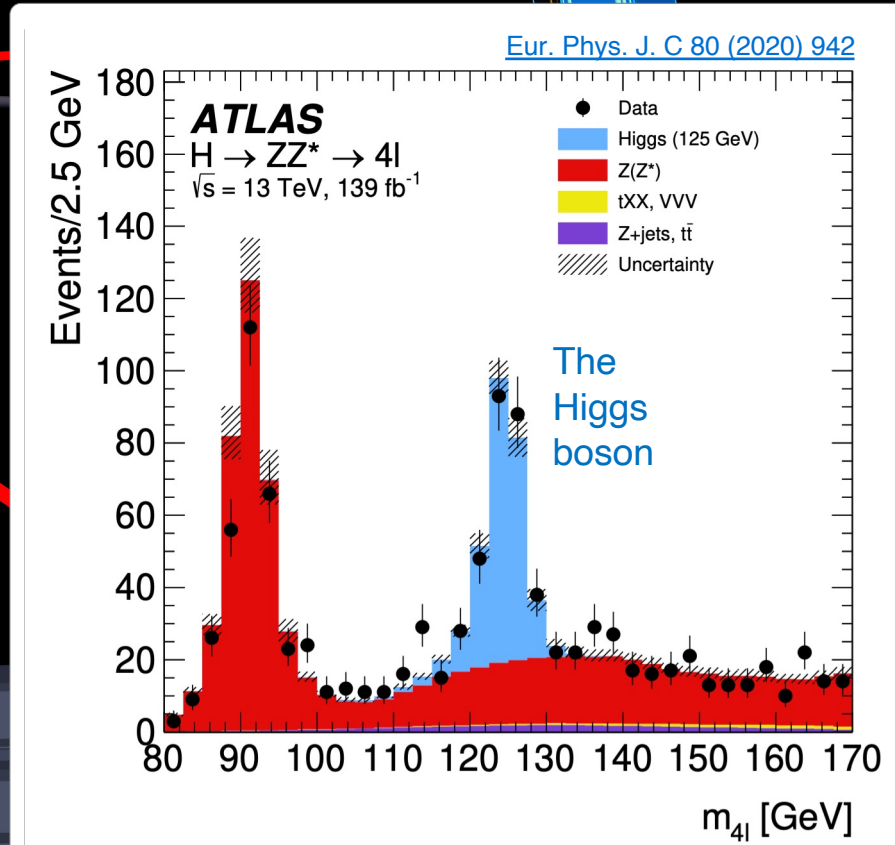
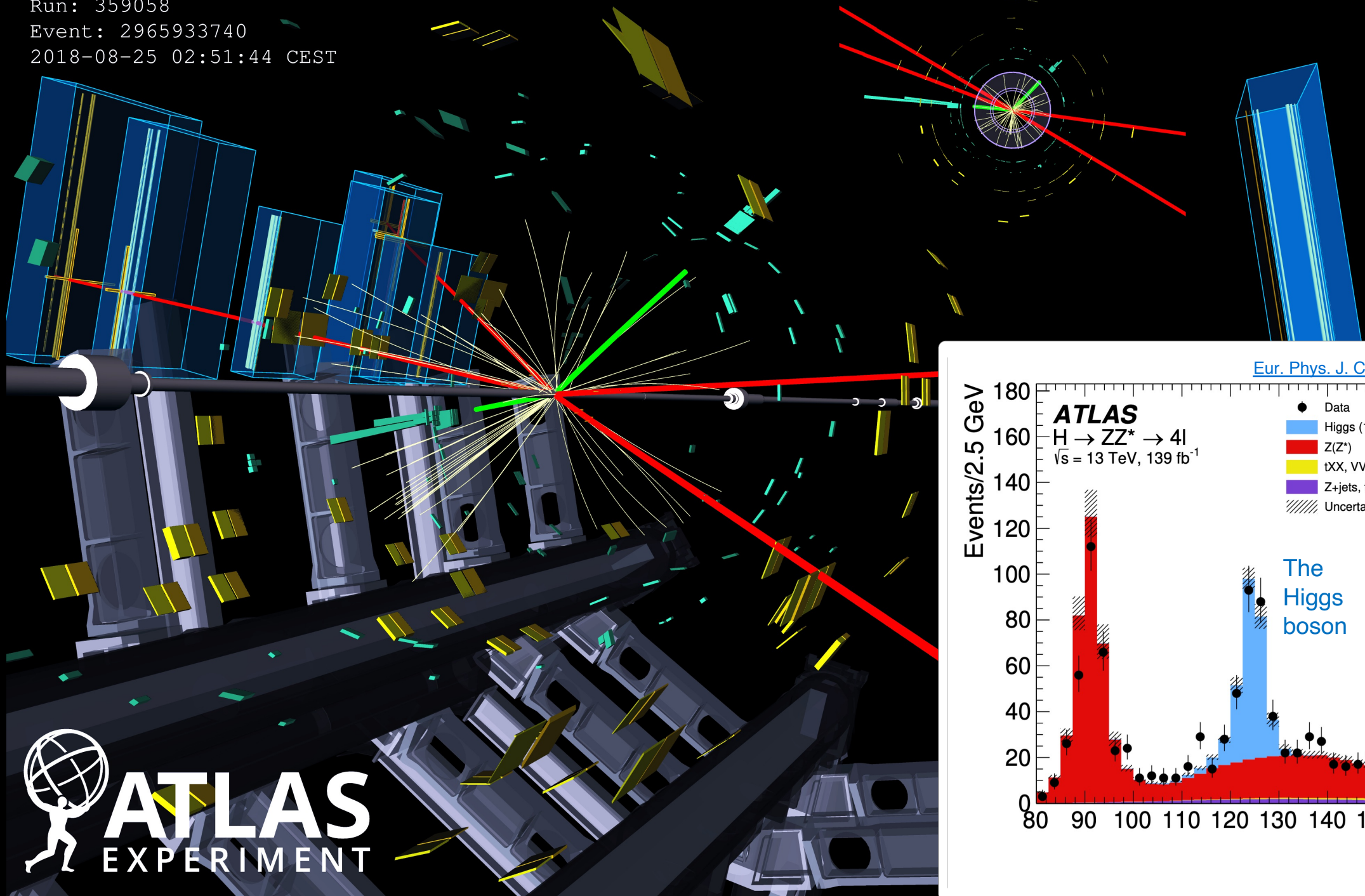
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Event: 2965933740
2018-08-25 02:51:44 CEST



ATLAS
EXPERIMENT

A Higgs boson to $2e2\mu$ plus a Z boson to 2μ candidate event

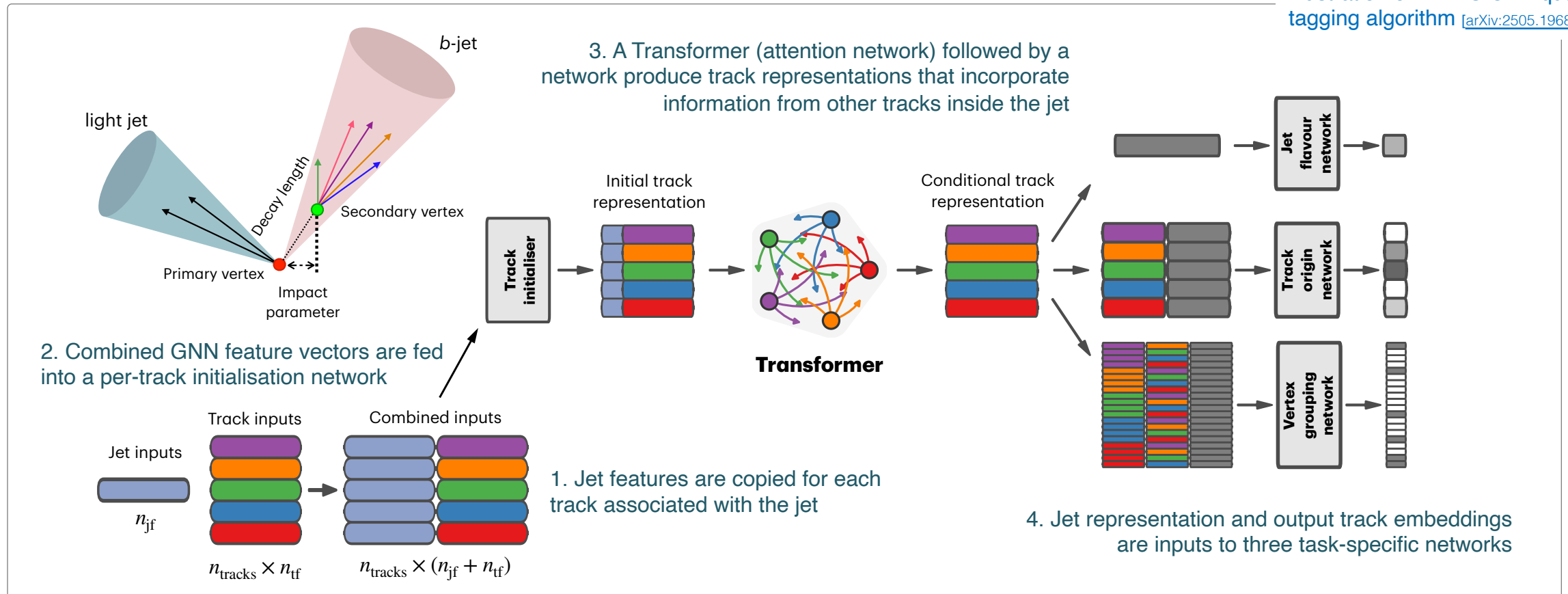
Run: 359058
Event: 2965933740
2018-08-25 02:51:44 CEST



Particle reconstruction / tagging — eldorado for modern ML

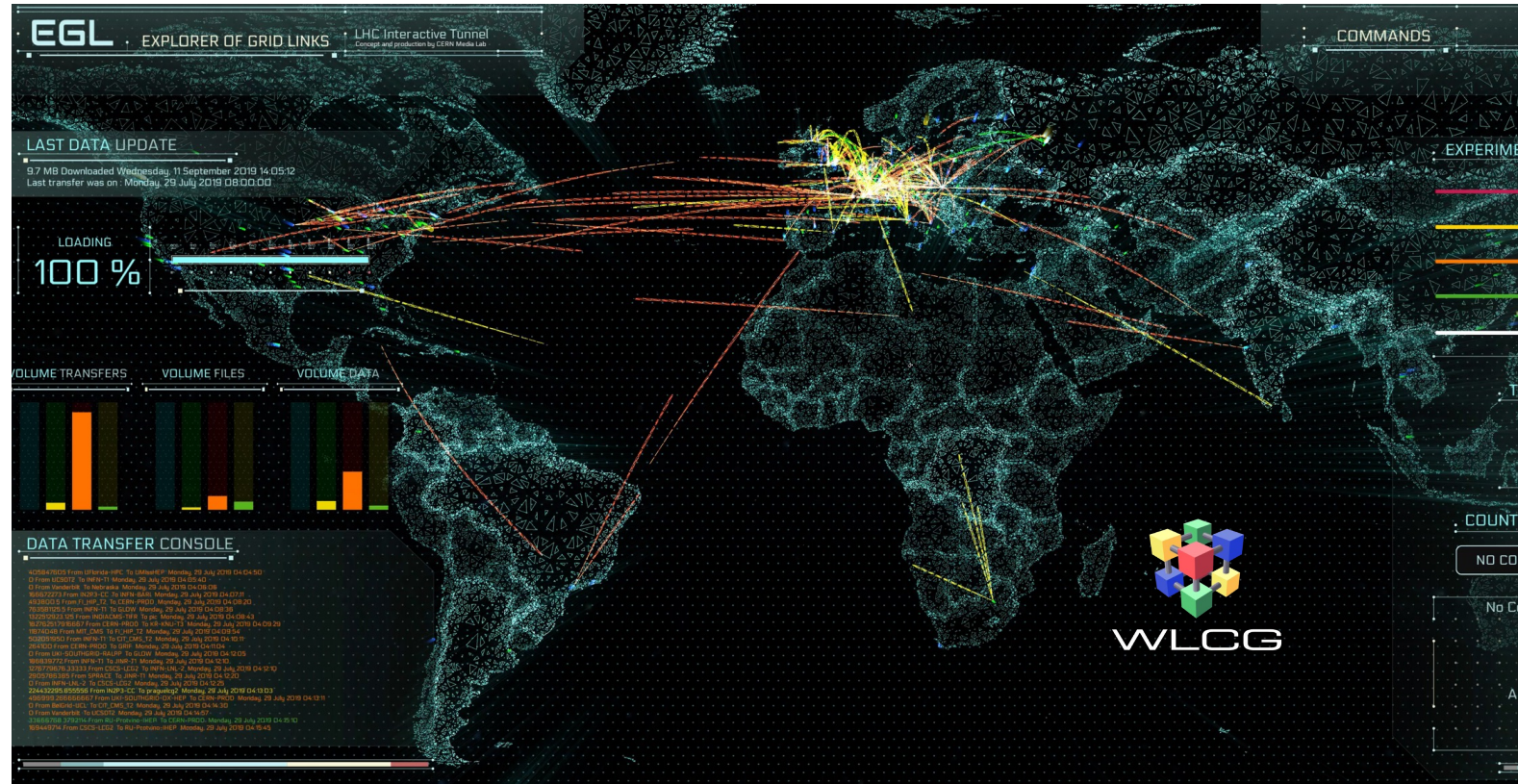
Neural networks have been used in particle physics since the 1990s; boosted decision trees since the 2000s
GNNs with Transformers are currently among the most performing ML algorithms (but much smaller than LLMs)

Illustration of ALTAS GN2 quark tagging algorithm [\[arXiv:2505.19689\]](https://arxiv.org/abs/2505.19689)



Jet/track features → Per-track embeddings → Transformer builds context across tracks → 3 heads deliver (i) jet flavour, (ii) track origins, and (iii) explicit displaced-vertex structure

The Worldwide LHC Computing Grid (WLCG)



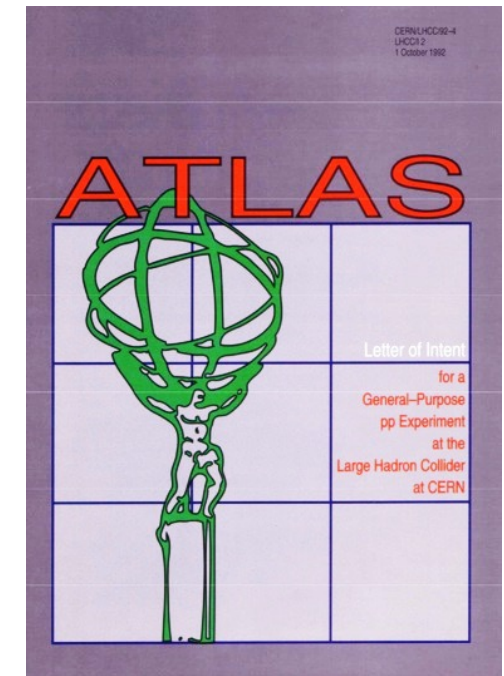
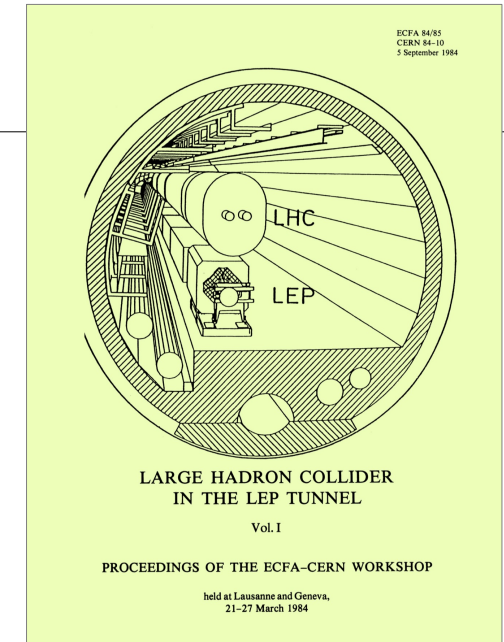
WLCG stores, distributes, processes and analyses LHC experiments' data

1.4 million processing cores in 170 data centres and more than 40 countries

> 2000 Petabytes (2 Exabytes) of LHC data stored worldwide

Brief history of ATLAS and the LHC

- 1984:** For the community it all started with the **CERN-ECFA Workshop in Lausanne** on the feasibility of a hadron collider in the future LEP tunnel
- 1990:** **Large Hadron Collider Workshop Aachen (CERN-ECFA)**
- 1992:** **ATLAS Letter of Intent** (official birth of ATLAS)



Brief history of ATLAS and the LHC

- 1984:** For the community it all started with the **CERN-ECFA Workshop in Lausanne** on the feasibility of a hadron collider in the future LEP tunnel
- 1990:** **Large Hadron Collider Workshop Aachen (CERN-ECFA)**
- 1992:** **ATLAS Letter of Intent** (official birth of ATLAS)
- 1994:** **ATLAS Technical Proposal**, followed by series of **Technical Design Reports**
- 1997:** **Formal approval of ATLAS Construction**
- 2008:** **Start of LHC Operation**



Google doodle on 10 September 2008 to celebrate LHC startup



Following slides discuss:

- Pathway of large particle physics experiments
- Governance and oversight
- Collaboration organisation
- Keys to success
- Challenges and pitfalls
- General lessons

Pathway of large particle physics experiments

Large particle-physics collaborations form bottom-up, evolving from informal discussions through workshops, simulations, and R&D into a formal collaboration defined by an Lol and TDR and approved by governing bodies and funding agencies. Following approval, MoUs establish responsibilities and deliverables, leading to construction, commissioning, and the transition to long-term experimental operation and exploitation

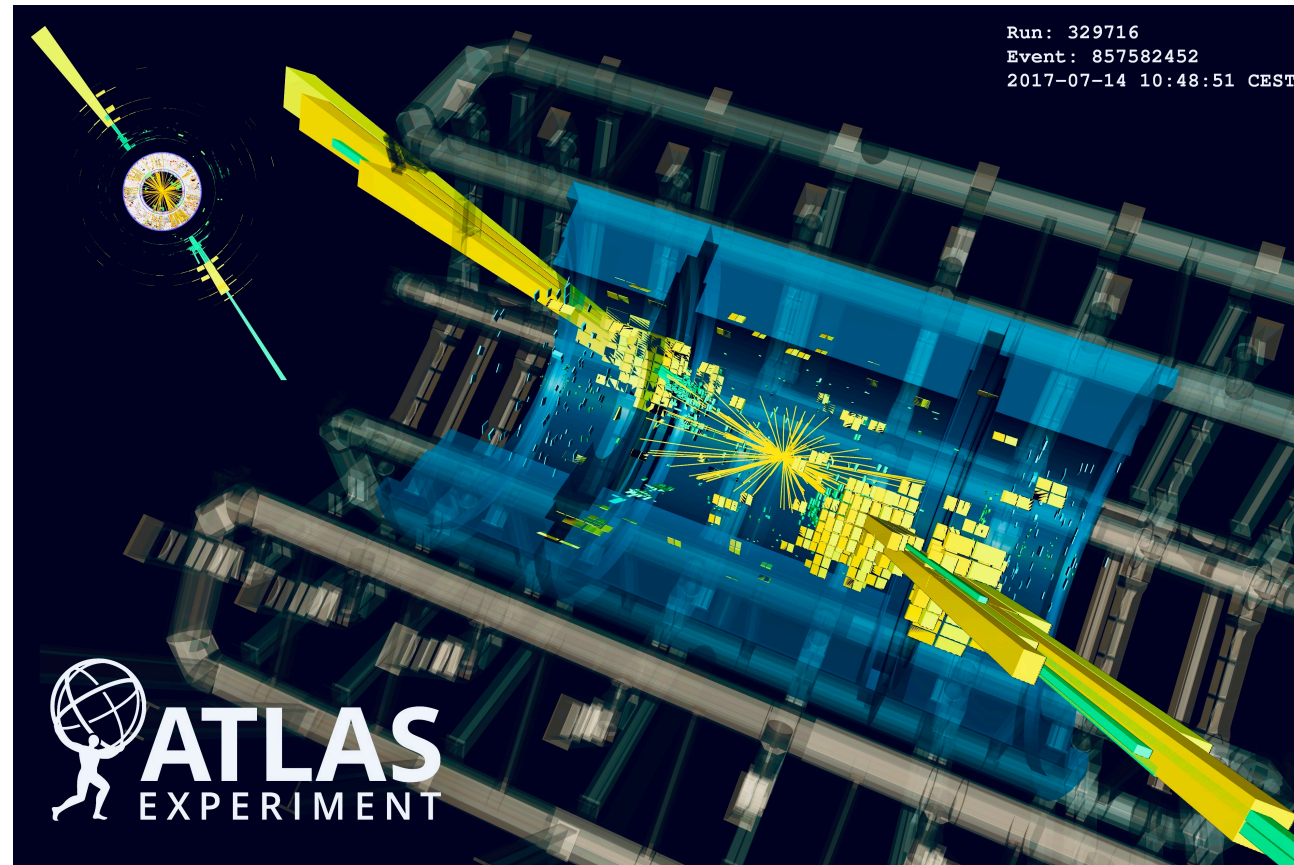
Pathway of large particle physics experiments

Historically, **particle physics collaborations form “bottom-up” ...**

- **Initial scientific and technical convergence** At the outset of a major project (e.g. the LHC), small groups of colleagues from different institutes — motivated by physics goals and/or detector technologies — begin informal discussions and concept development
- **Community building and concept maturation** Workshops are organised to present ideas, compare approaches, and explore detector and physics concepts. Informal proto-collaborations emerge and grow organically
- **Early studies with limited resources** At this stage, there is usually no dedicated project funding. Researchers rely on existing grants, institutional support, or small R&D funds to pursue feasibility studies
- **Physics and detector simulations** Simulation studies are carried out to establish the scientific case, evaluate performance, and optimise detector layouts and subsystem designs
- **Targeted R&D and prototyping** R&D proposals are submitted, leading to the construction of small-scale prototypes that are tested in laboratories and test beams to validate technologies
- **Letter of Intent (LoI)** The collaboration formally crystallises with the submission of an LoI, marking its official beginning. While not all technologies are finalised, major design directions are established. A governance structure is defined (see later)
- **Technical Design Report (TDR)** A TDR is produced, detailing the final detector design, technology choices (this may be painful), performance, cost estimates, schedules, organisational structure, and risk mitigation
- **Review and approval** The TDR is submitted to the project’s governing bodies and funding agencies for technical and scientific review and approval

Pathway of large particle physics experiments

- **Formal commitments and construction phase** Following approval, Memoranda of Understanding (MoUs) are signed, defining institutional responsibilities, funding commitments, and deliverables. Large-scale construction, integration, and installation begin
- **Commissioning and transition to operation** The collaboration evolves from a construction project into an operational experiment, with increasing emphasis on detector commissioning, data taking, physics analysis, and long-term governance





ATLAS Resources Review Board meeting at CERN in the 1990s



Governance and oversight

Large particle-physics experiments combine exceptional technological complexity with international collaboration, requiring robust management, review, and approval structures. At CERN, projects are supported by a stable host-laboratory framework, governed through coordinated national and international oversight, internal project management, independent technical reviews, and a deliverables-based funding model supervised by the Resources Review Board

Governance and oversight of large particle physics experiments

The scale of particle physics experiments requires robust management, review, and approval procedures

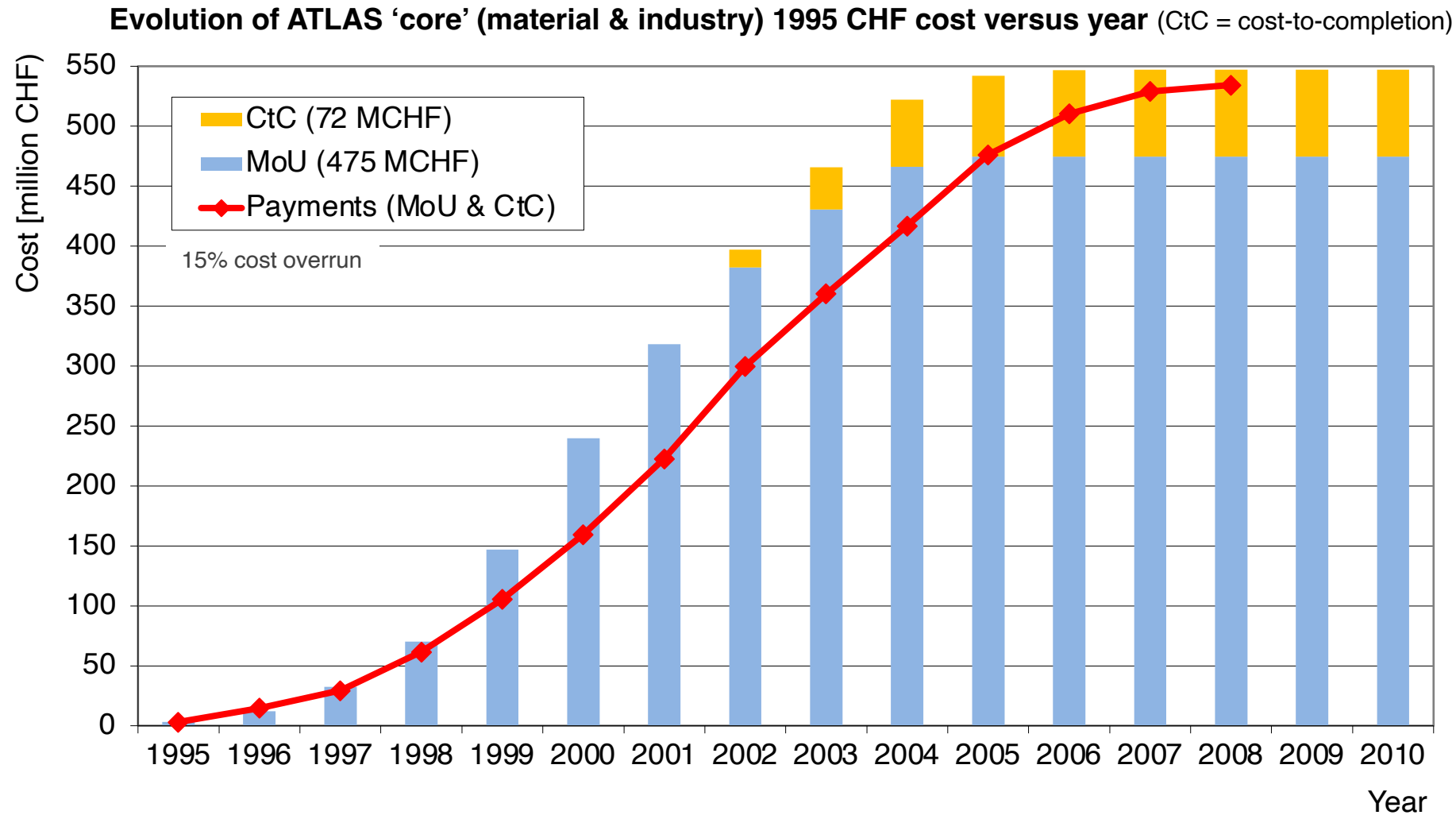
- **Technological scale and complexity** Particle-physics experiments are exceptionally complex and expensive, requiring the development of custom detector, electronics, and computing technologies
- **Role of CERN as host laboratory** CERN-based experiments benefit from a stable institutional framework, well-defined procedures, and decades of experience in R&D, construction, and operation of large-scale projects — an essential ingredient for their success
- **International collaboration and national funding** Experiments are conducted by international collaborations supported by national funding agencies with their own review processes, requiring coordinated national and international approvals
- **Project approval and oversight** Large experiments are approved by CERN management (strategic projects like the LHC also by the CERN Council), often following extensive technical, scientific, and financial reviews involving the funding agencies
- **Internal project management** The collaboration's project office is responsible for coordinating technical progress, schedules, costs, and risk mitigation across detector systems and institutes
- **External technical reviews** Independent expert review committees regularly assess progress of project milestones. Their findings are reported to CERN management and to the Resources Review Board (RRB)
- **Resources Review Board (RRB)** CERN-led board of funding agencies with financial-legal responsibility. The RRB reviews project status and approves, usually by consensus, evolving budgets for construction, operation, and upgrades
- **Deliverables-based funding model** Funding agencies commit to providing specific detector components, systems, or services rather than fixed monetary amounts, except for agreed cash contributions to common items and operations according to fair share

Governance and oversight of large particle physics experiments

Financing is obviously the basis of everything

The RRB provides a framework for resolving funding issues despite differing agency practices — such as US contingency requirements, their absence in much of Europe, or Japan's tendency not to quote full costs. Conservative cost estimates are essential for building trust, while cost overruns are usually managed through the deliverables model, though this is not always sufficient...

Governance and oversight of large particle physics experiments



Full US-type costing (incl. all salaries) would increase numbers by factor of 2~3

Operation costs of ~21 MCHF / year, shared among funding agencies according to author count

Collaboration organisation

Particle physics experiments have a democratic structure with a policy making and executive branch

Collaboration board

Composed of institute PIs, each one vote
Elects leadership and sets policy

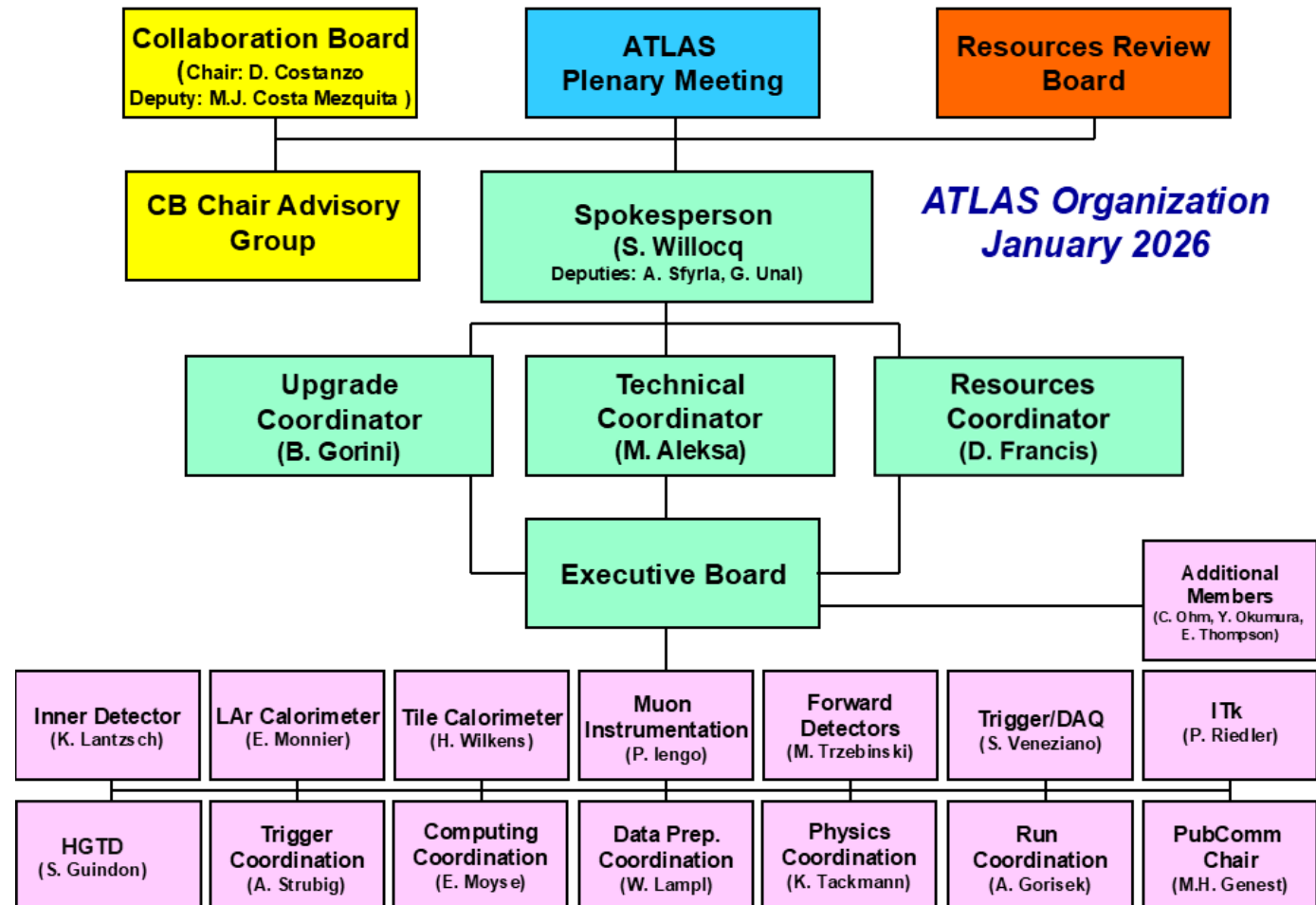
Collaboration management

Elected or endorsed by Collaboration Board



Executive board

System and activity leaders — all elected or endorsed by Collaboration Board



Keys to success



Keys to success



Successful large collaborations are built on mutual trust, respect, and transparent, fair procedures, with leadership grounded in excellence and expertise. Open and inclusive governance — through clear structures, representative decision bodies, merit-based evaluation of ideas, consensus building, and collective ownership of major decisions — ensures that all members, including early-career researchers, have a voice and that innovation is encouraged and rewarded

Mutual trust and respect, as well as transparent and fair procedures are key

- **Trust-based governance** Large collaborations rely on mutual trust and respect. Leadership hierarchies are collectively defined, and there is typically no formal line management
- **Excellence-driven leadership** Scientific and technical excellence, as well as demonstrated expertise, should be the primary criteria for leadership at all levels
- **Clear organisational structure** A well-defined and transparent organisational structure is essential and has served ATLAS well
- **Open and inclusive discussion** The collaboration should provide open forums in which all members can express their views and contribute to discussions
- **Transparent decision processes** For major technical choices, the decision path, criteria, and timeline must be clearly defined and communicated before engaging in discussions of competing options
- **Collective ownership of major decisions** Decisions that affect the experiment as a whole must be understood and supported by the entire collaboration, not only by the subgroups directly involved
- **Representative decision-making bodies** A Collaboration Board with equal institutional representation (one vote per institute) encourages consensus-building and has proven effective. At the same time, project leaders must maintain close dialogue with the contributing institutes

Keys to success

Input by Peter Jenni

Give the individual a voice in large collaborations

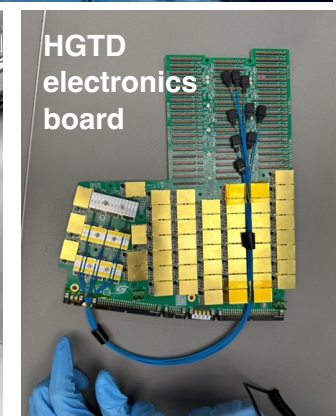
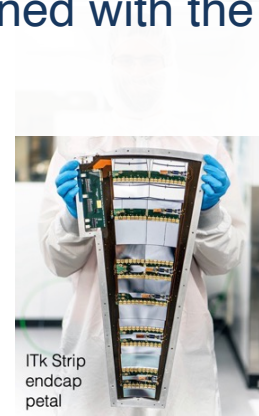
- **Value and reward innovation** Large collaborations need to actively encourage, recognise, and reward new ideas, whether they concern scientific strategy, technical solutions, or organisational practices, independent of their origin within the collaboration
- **Merit-based evaluation of ideas** Proposals should be assessed on their scientific and technical merit, feasibility, and impact, rather than on seniority, institutional weight, or established conventions
- **Ensure a fair representation at all levels** Inclusiveness, representation of early career researchers, fair assignment of talks





Challenges and pitfalls in delivering large collaborative research projects

Large-scale particle-physics projects must deliver mission-critical systems on time and on budget while managing a difficult transition from R&D to production, rising technological complexity, and the need for transparent technology selection and robust project management. Success depends on pragmatic choices, strong technical reviews, realistic ambition, and sustained long-term funding commitments aligned with the project's full lifecycle



Challenges and pitfalls in delivering large research projects

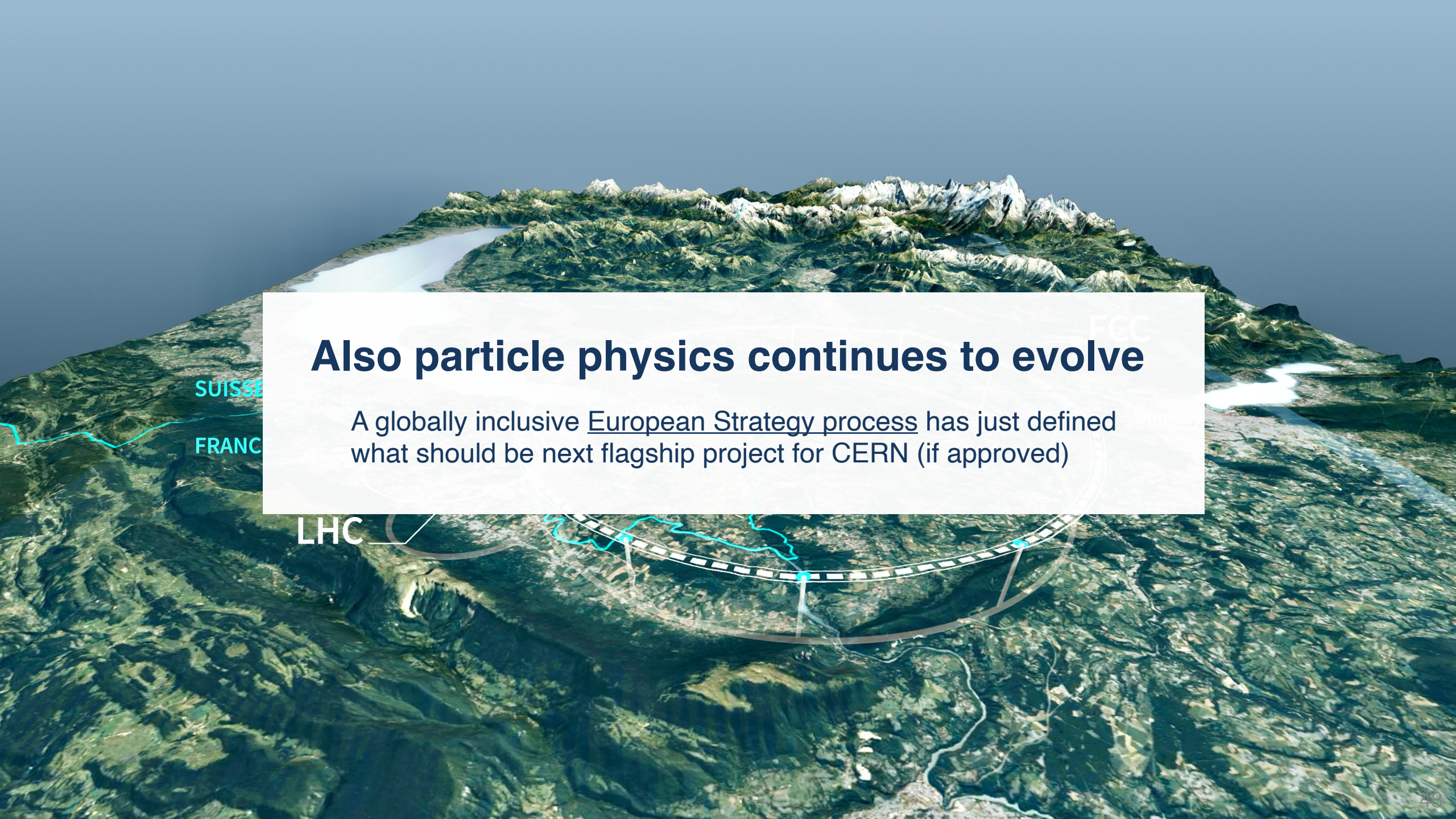
Staying on budget and schedule while focusing on mission-critical developments is essential yet challenging

- **From R&D to production** Researchers in curiosity-driven fields are R&D-oriented; the transition to large-scale production is critical and often starts too late
- **Rising technological complexity** Modern detector technologies are increasingly complex and require strong engineering support, which is costly and scarce in research environments (e.g. radiation-hard, low-power, high-throughput ASICs)
- **Technology down-selection** Choosing among competing options with many person-years R&D invested is difficult in consensus-driven collaborations, making transparent criteria and decision processes essential
- **Project management culture** Industrial-style project management may clash with academic culture, yet is essential and often mandated by funding agencies
- **Strength of technical reviews** Expert reviews must be enabled to recommend stopping or restructuring projects when justification or feasibility is insufficient — a threshold too rarely enforced
- **Pragmatism over perfection** The pursuit of technically “perfect” solutions can delay or jeopardise delivery. Pragmatic and robust technological choices often lead more reliably to the desired scientific outcome
- **Long-term funding commitments** Large projects require funding agencies to commit over their full duration. This can be challenging, particularly for agencies in smaller countries or with limited experience in long-term big-science investments
- **Managing ambition** Over-ambitious project scopes increase risk and can lead to failure. Striking the right balance between innovation and feasibility is crucial

A few general lessons from particle physics for you

- **Collaborate out of necessity** Very large projects exceed the capacity of any single group
- **Earn trust through delivery and openness** Deliver on commitments; work transparently and open-source by default
- **Enable, don't control** Use clear governance and transparent decisions, not rigid hierarchies
- **Reward excellence wherever it appears** Leadership follows expertise and contribution, not seniority or resources
- **Plan the R&D to production transition early** Innovation needs freedom; large-scale delivery needs discipline
- **Be pragmatic** Robust, timely solutions beat “perfect” ones that arrive too late
- **Make hard choices transparently** Down-selection preserves trust when criteria are clear
- **Invest in people** Empower early-career contributors and sustain the community
- **Anchor in stable institutions** Long-term success needs neutral, reliable hubs
- **Remember the human side** Large-scale collaboration is demanding — and deeply rewarding

By joining forces with trust, openness, and pragmatism, communities can achieve game-changing science and technology beyond the reach of any single group — and enjoy doing it

An aerial photograph of a mountainous region, likely the Alps, with green valleys and snow-capped peaks. Overlaid on the landscape are several circular and semi-circular lines representing particle accelerator paths. A cyan line traces a path through the valleys, while a dashed white line and a solid brown line form larger loops. Labels 'SUISSE', 'FRANCE', 'LHC', and 'FCC' are visible in cyan text. A white rectangular box with a drop shadow is centered in the image, containing text.

Also particle physics continues to evolve

A globally inclusive European Strategy process has just defined what should be next flagship project for CERN (if approved)

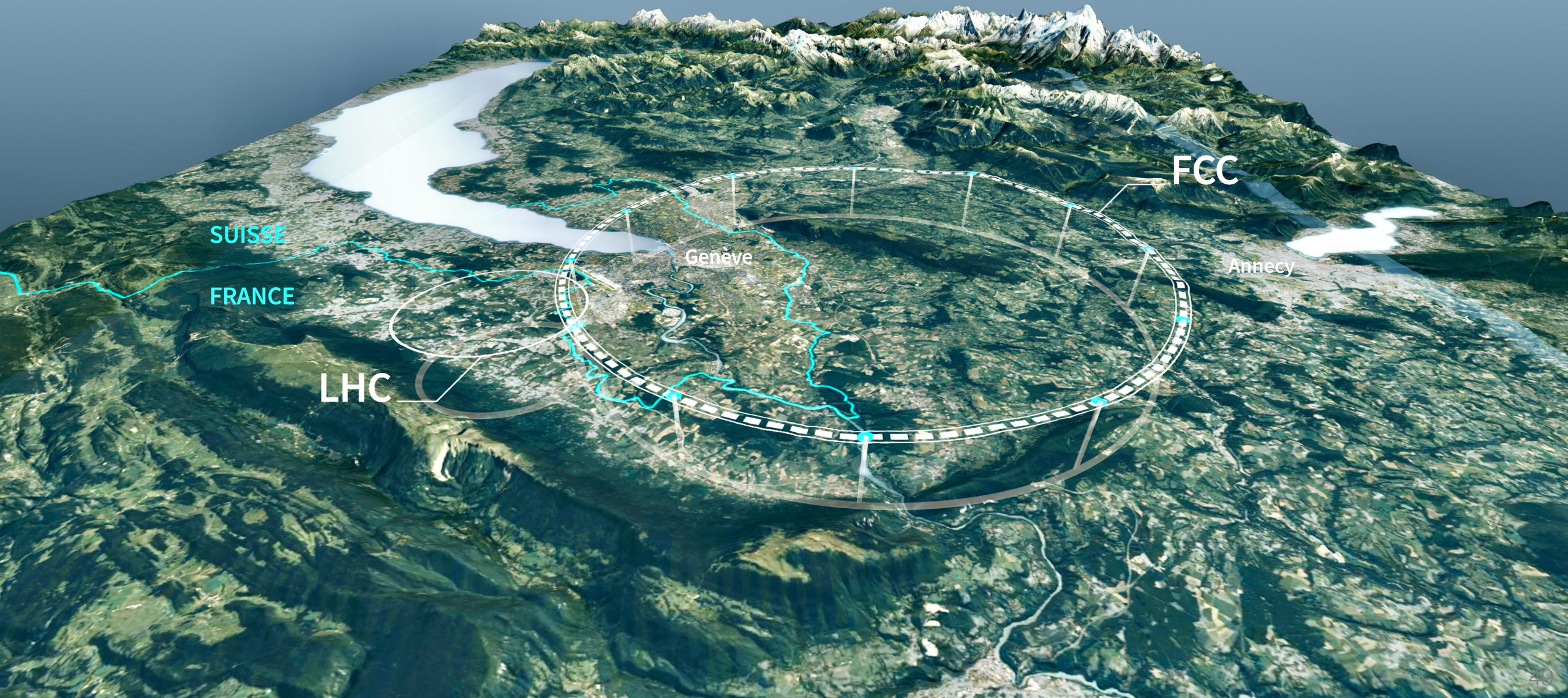
LHC

Future Circular Collider at CERN

90.7 km circumference tunnel facility to host an e^+e^- and, later, a hadron collider

Feasibility study [Vol 1](#), [Vol 2](#) (March 2025)

Preferred option by
national inputs to
European Strategy for
Particle Physics Update

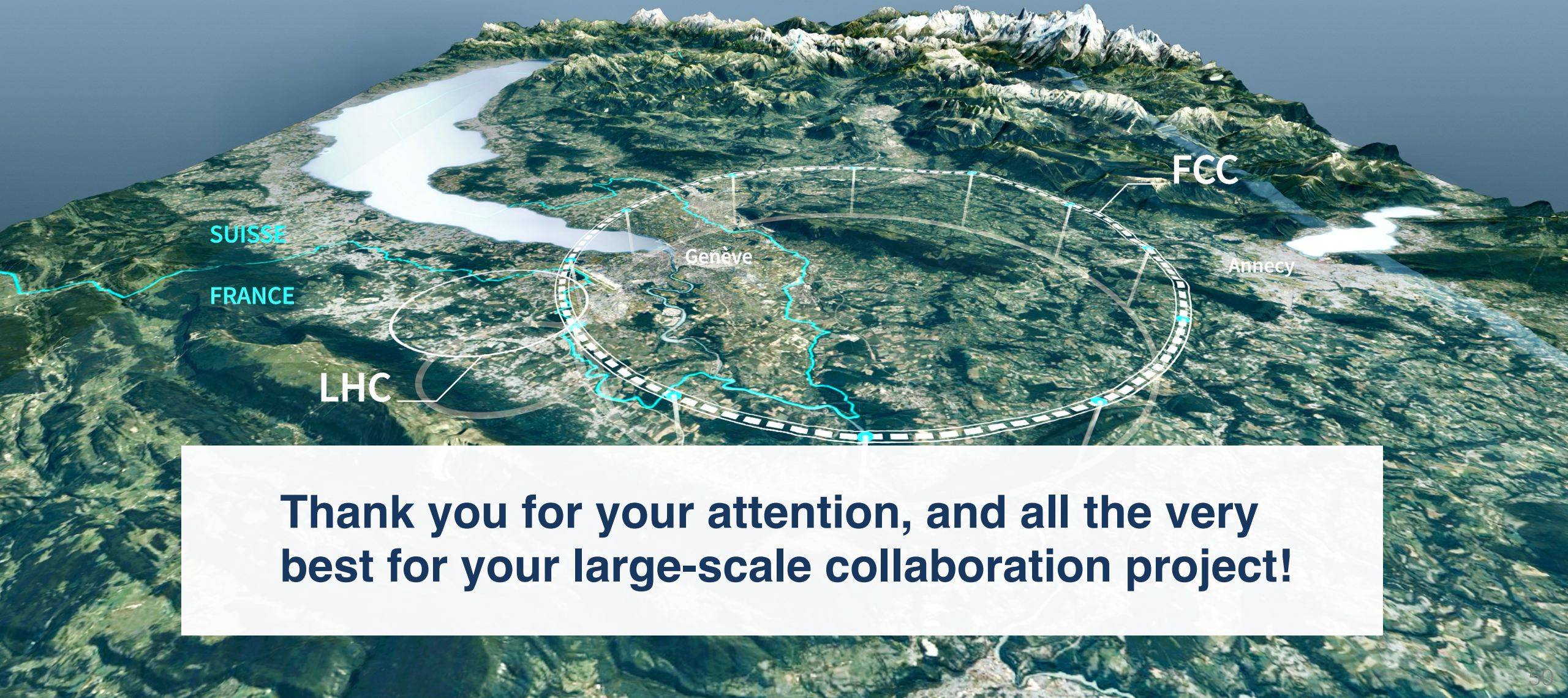


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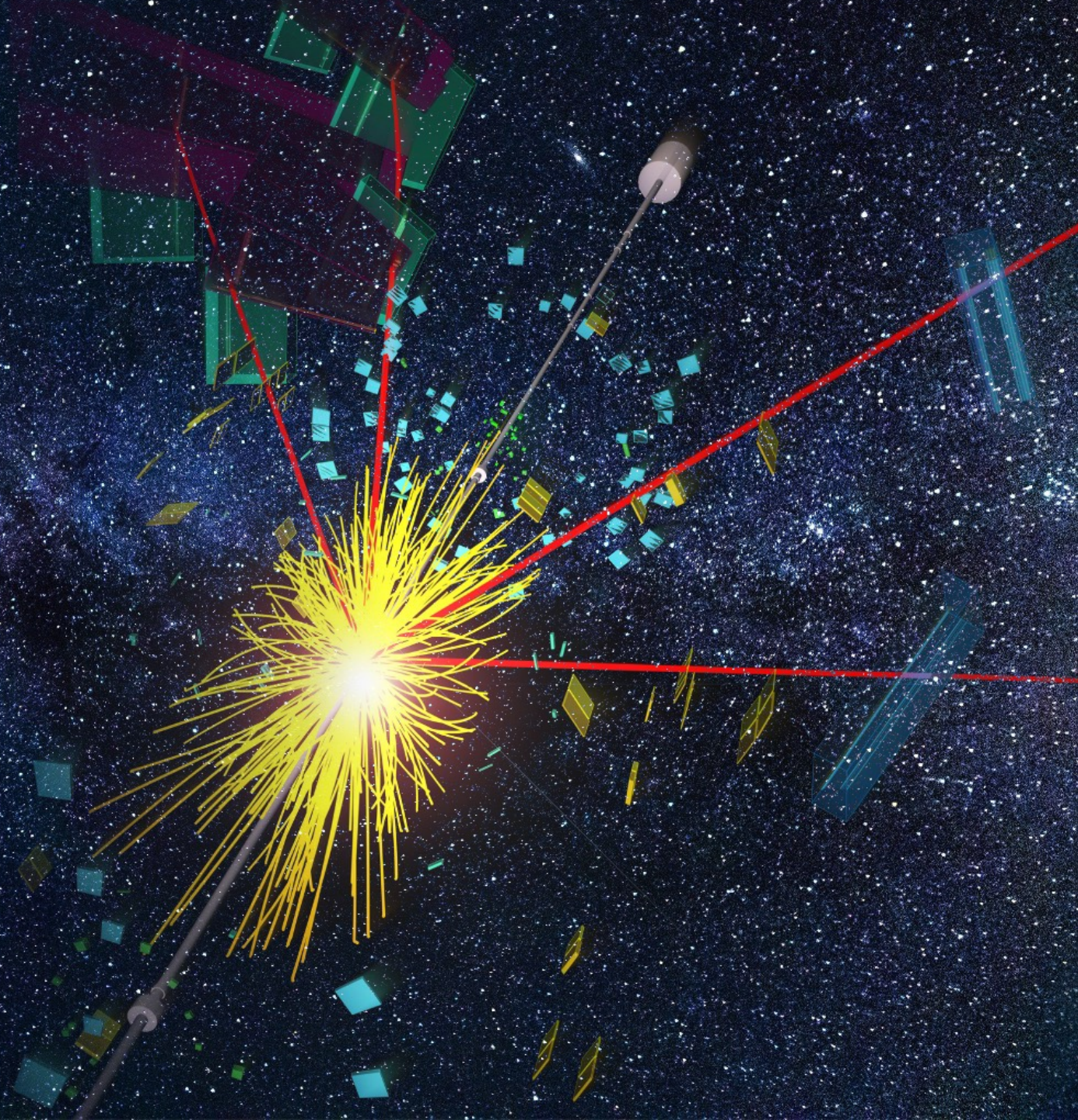
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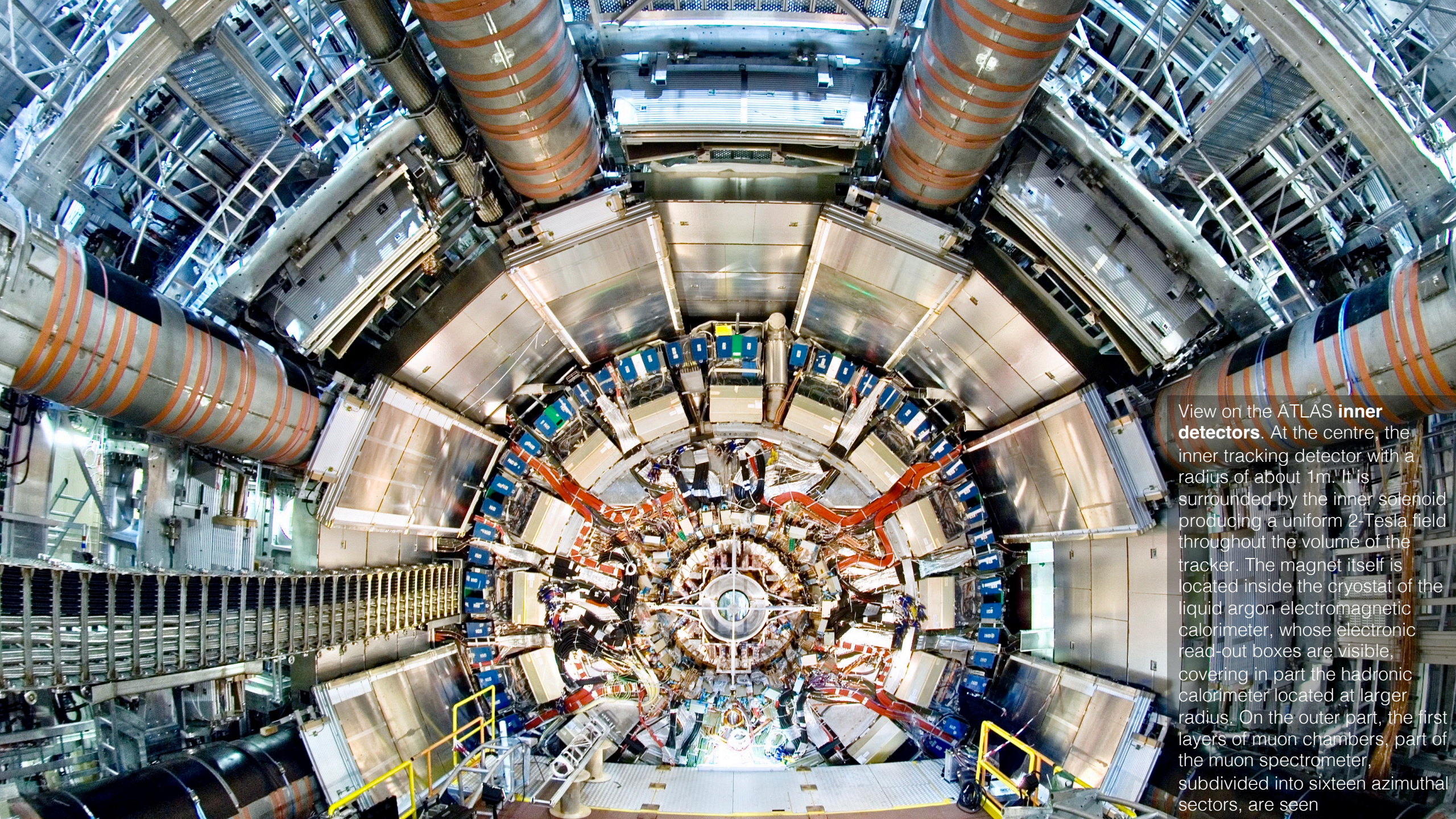
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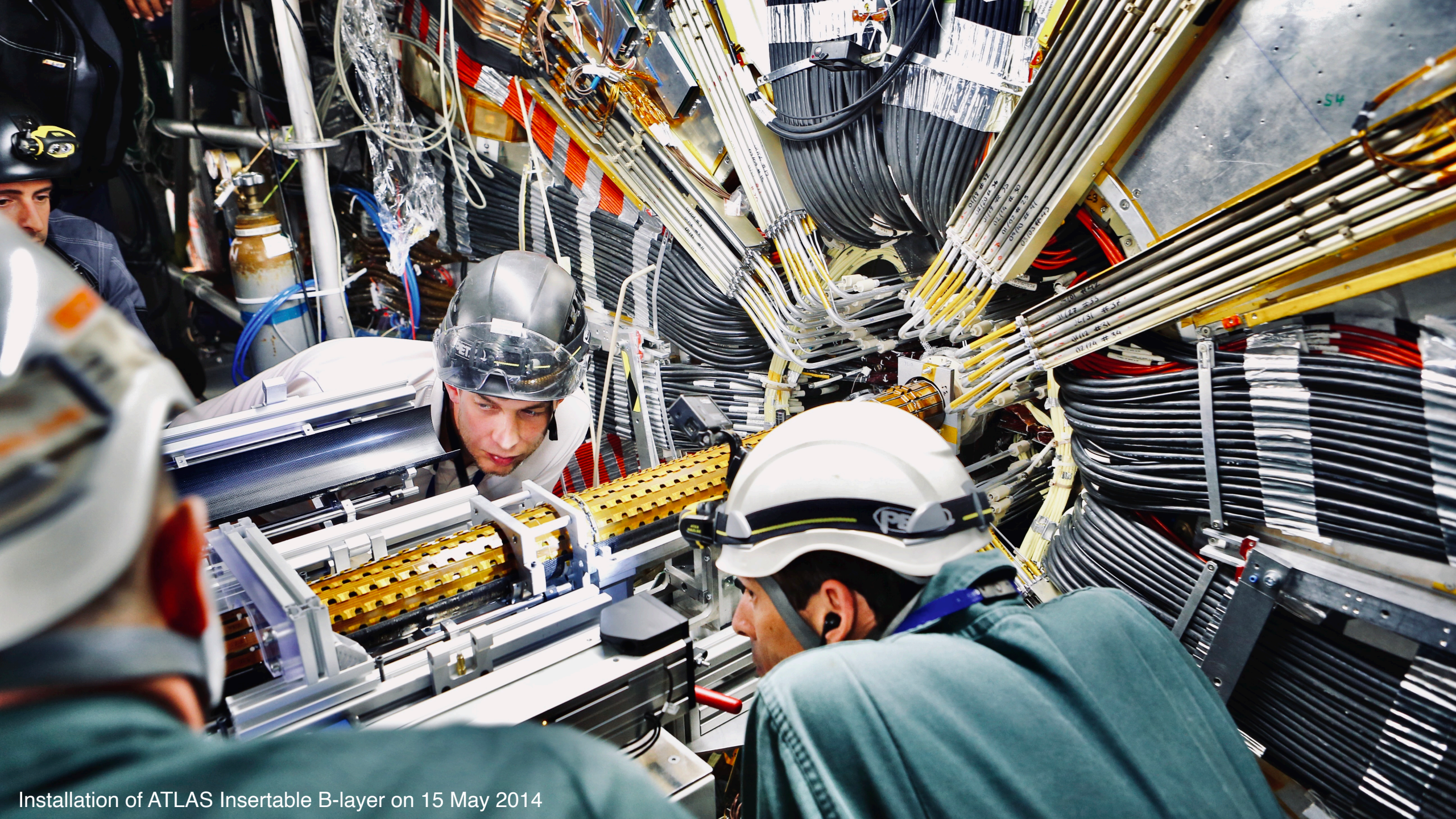
Thank you for your attention, and all the very best for your large-scale collaboration project!

Extra slides





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



Installation of ATLAS Insertable B-layer on 15 May 2014

Organisation is key in any project, and especially in large-scale international ones: it must empower efficient, creative, and trust-based collaboration — not hinder it