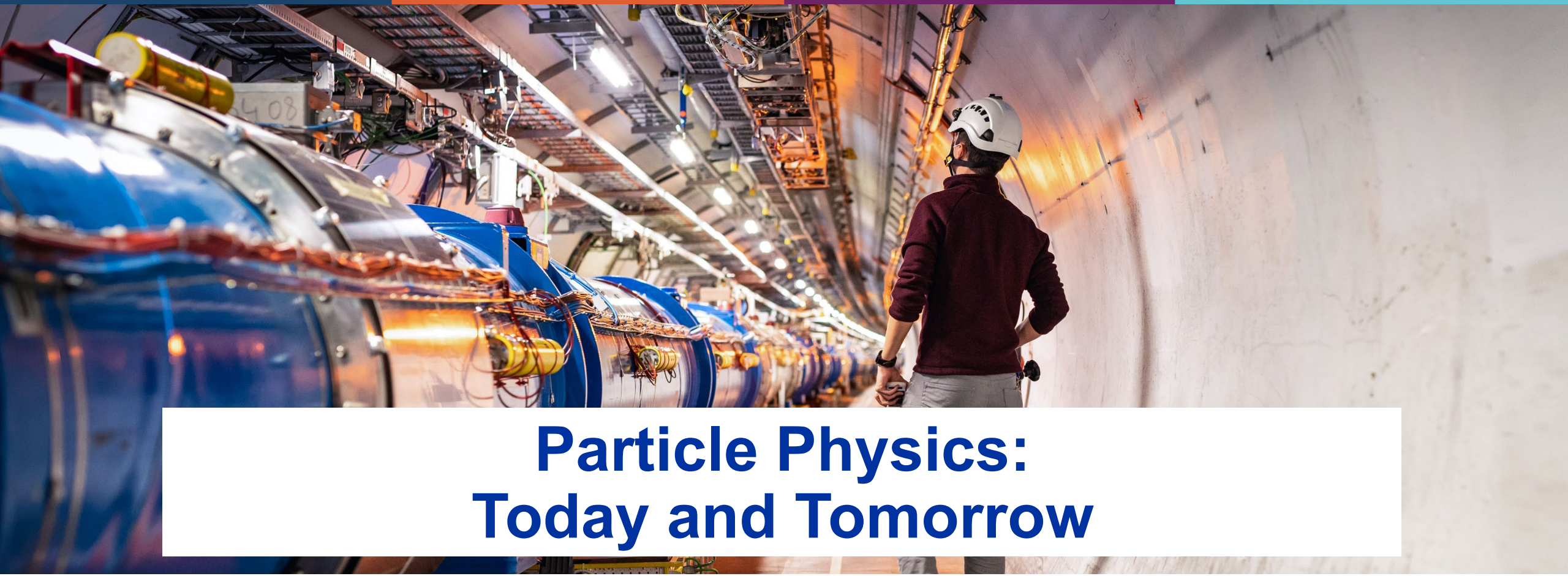


Particle Physics: Today and Tomorrow

Mark Thomson
Director-General
CERN

Today's Presentation

Some **personal** perspectives on

- where we are today with particle physics
- what the next ten years might bring
- and then what?

} Strong CERN focus

Looking back 30 years

- The very massive top quark had just been discovered (1995)

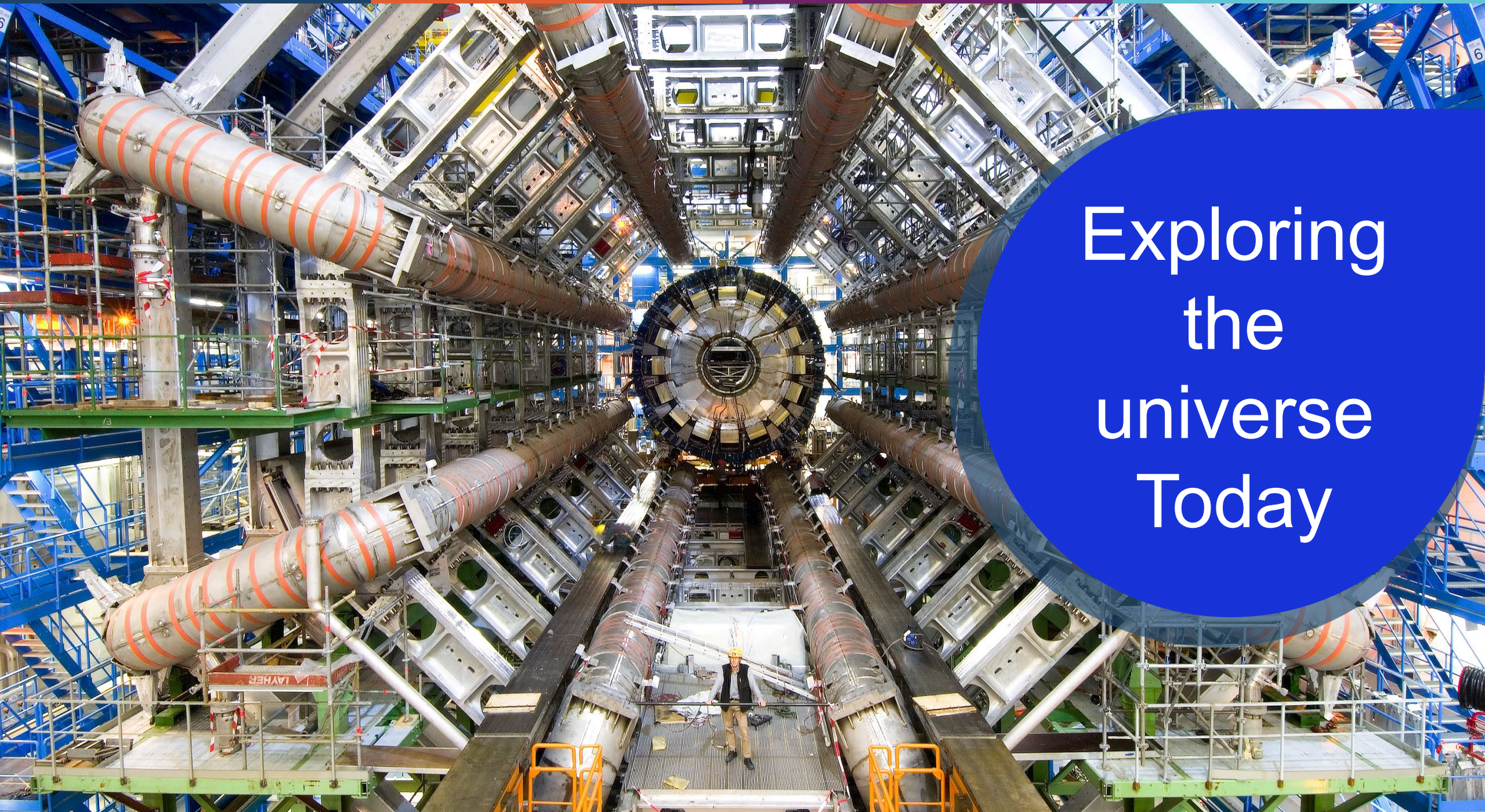
- Neutrinos were usually considered massless (although there was some evidence to the contrary) until 1998

- Dark energy (1998 – 2013 –)

- The Brout–Englert–Higgs mechanism was a beautiful theoretical idea (until the Higgs boson was discovered in 2012)

- Gravitational waves had yet to be observed (until 2016)

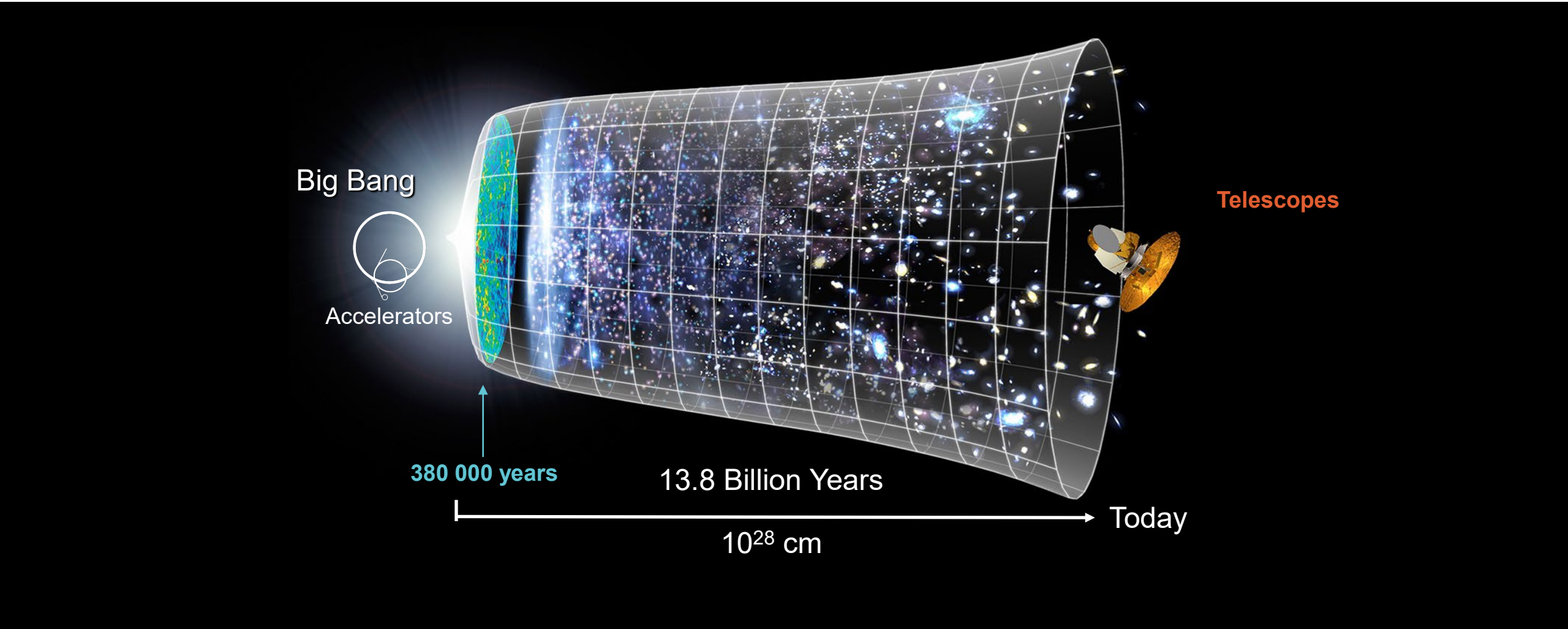
A **profound** discovery every 5–10 years… not bad!



Exploring the universe Today

Uncovering the Secrets of the Universe

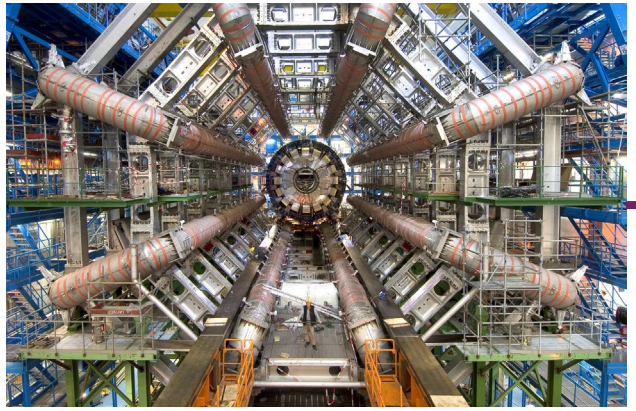
Fundamental physics: aim to understand the Universe from the Big Bang to the stars and galaxies we see today

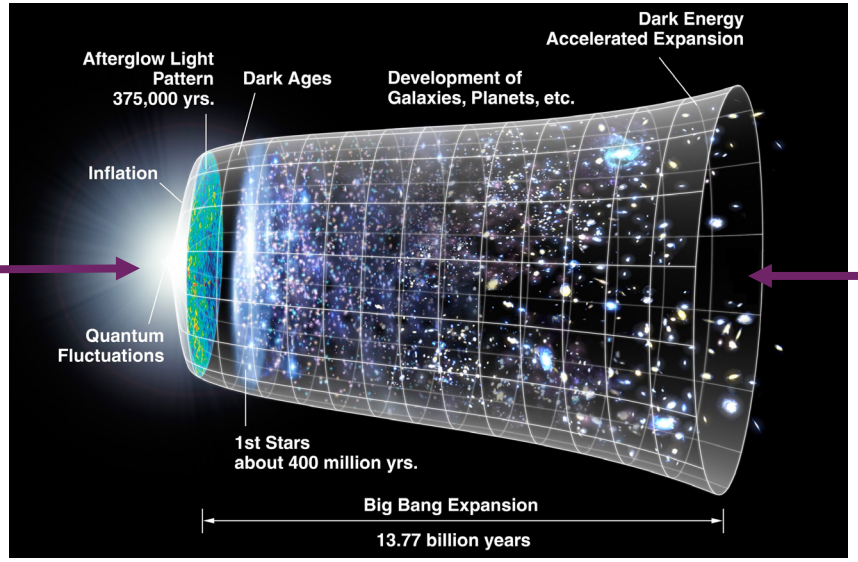


Uncovering the Secrets of the Universe

Fundamental physics: aim to understand the Universe from the Big Bang to the stars and galaxies we see today. We aim to answer questions such as:

- What are the building blocks of the Universe: the particles
- How does the Universe "work": the forces, ultimately including gravity
- How did the Universe evolve: black holes, stars, galaxies, and role of Dark Matter






CERN

CERN

CERN is the world's biggest laboratory for particle physics.

Straddles the French – Swiss border near Geneva

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

Built on over 70 years of deep international collaboration

Science for peace

CERN was founded in 1954 with 12 European Member States

- Success built on long-term international collaboration in science

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

11 Associate Member States

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

4 Observers

Japan – USA – European Union – UNESCO

CERN's annual budget is 1200 MCHF (1.2 BCHF) – equivalent to a medium-sized European university

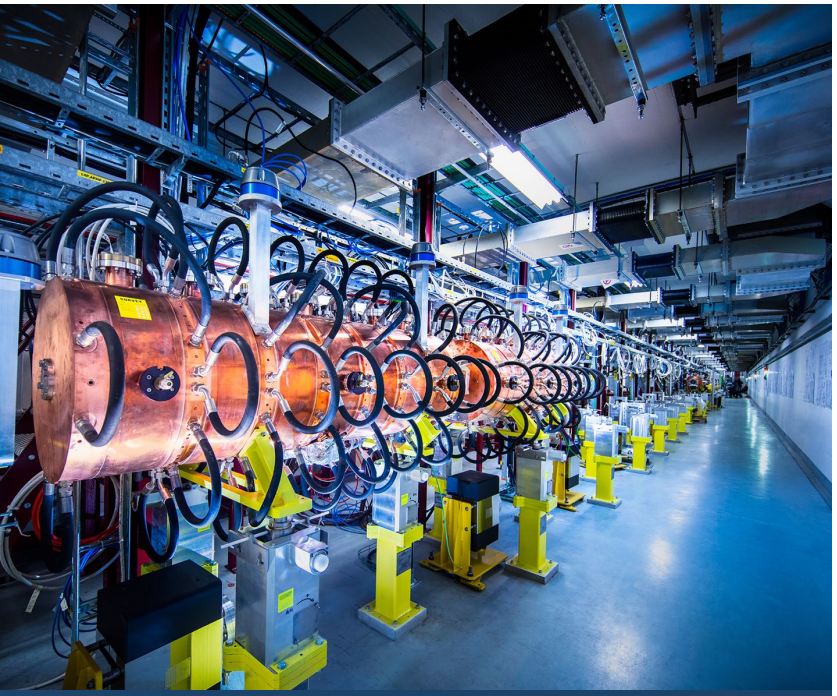
Employees:
~2700 staff, **~1200** graduates
Associates:
12 000+ users

At CERN we use very advanced technology

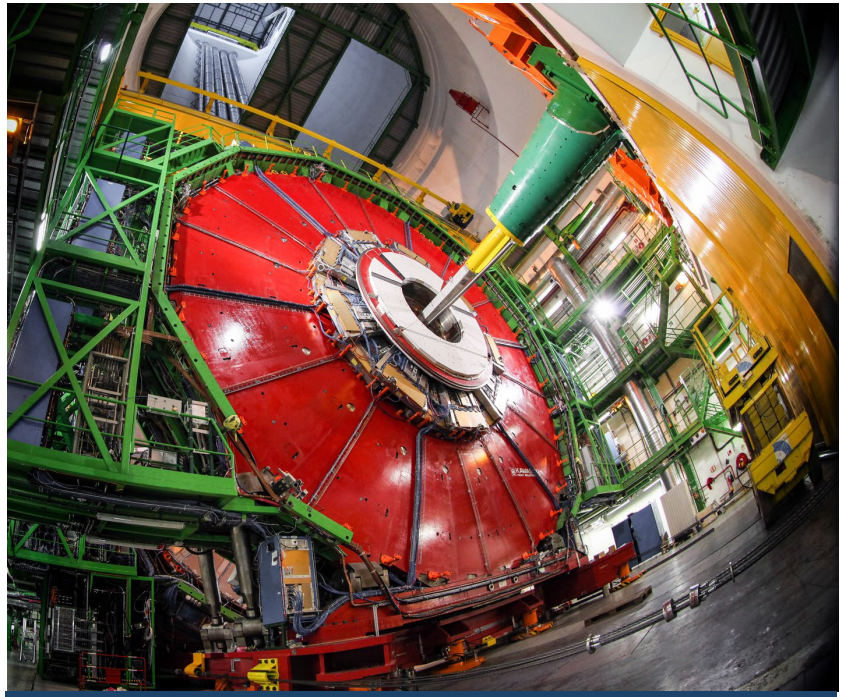
Technology and **engineering** is the driver for discovery in fundamental science

- we are constantly pushing the boundaries beyond what exists today…

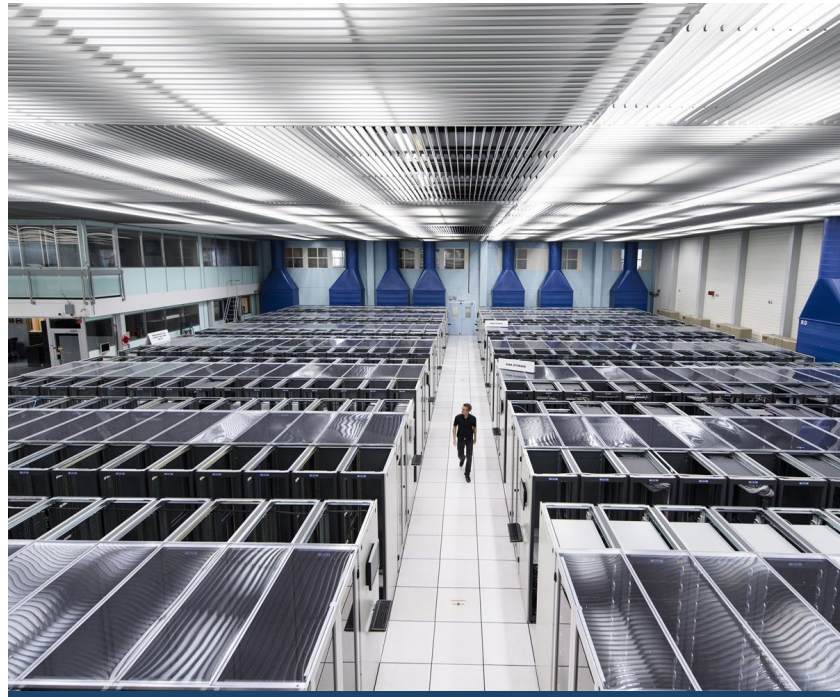
At CERN there are three central technology areas



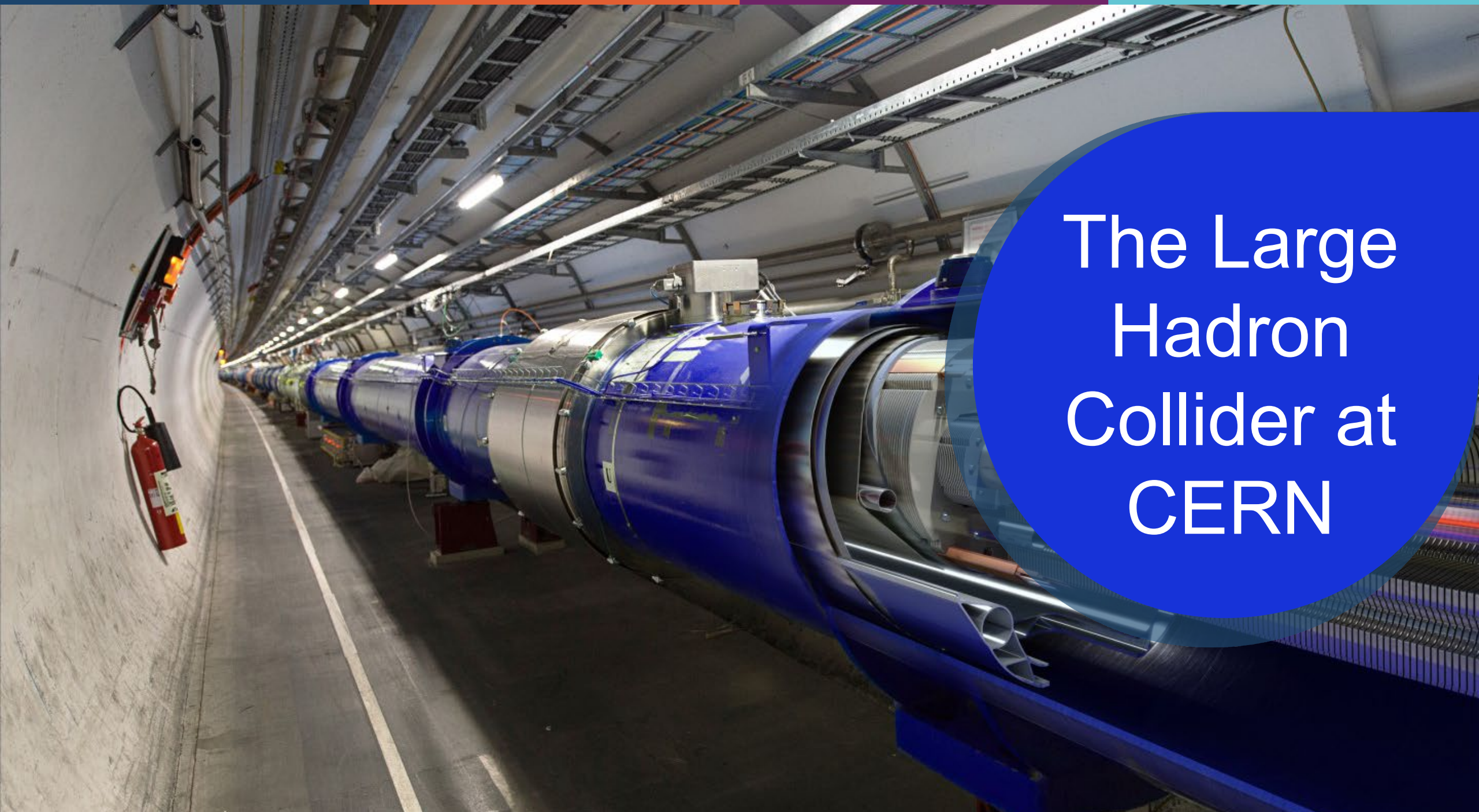
ACCELERATORS



DETECTORS



COMPUTING



The Large Hadron Collider at CERN

The Large Hadron Collider

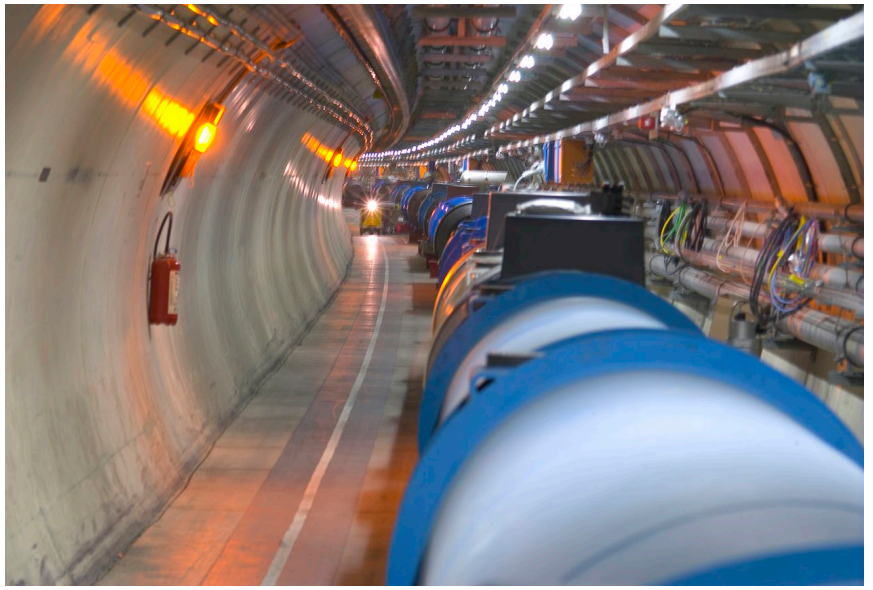
Our most powerful “tool” to understand the “particle-verse”

- **Large: 27 km** circumference ring of superconducting magnets
- **Hadron**: accelerates protons (hadrons) to almost the speed of light… 99.9999991%
- **Collider:** two proton beams collide 40 million times a second at four points around the ring where the fragments are “photographed” with **massive imaging detectors**

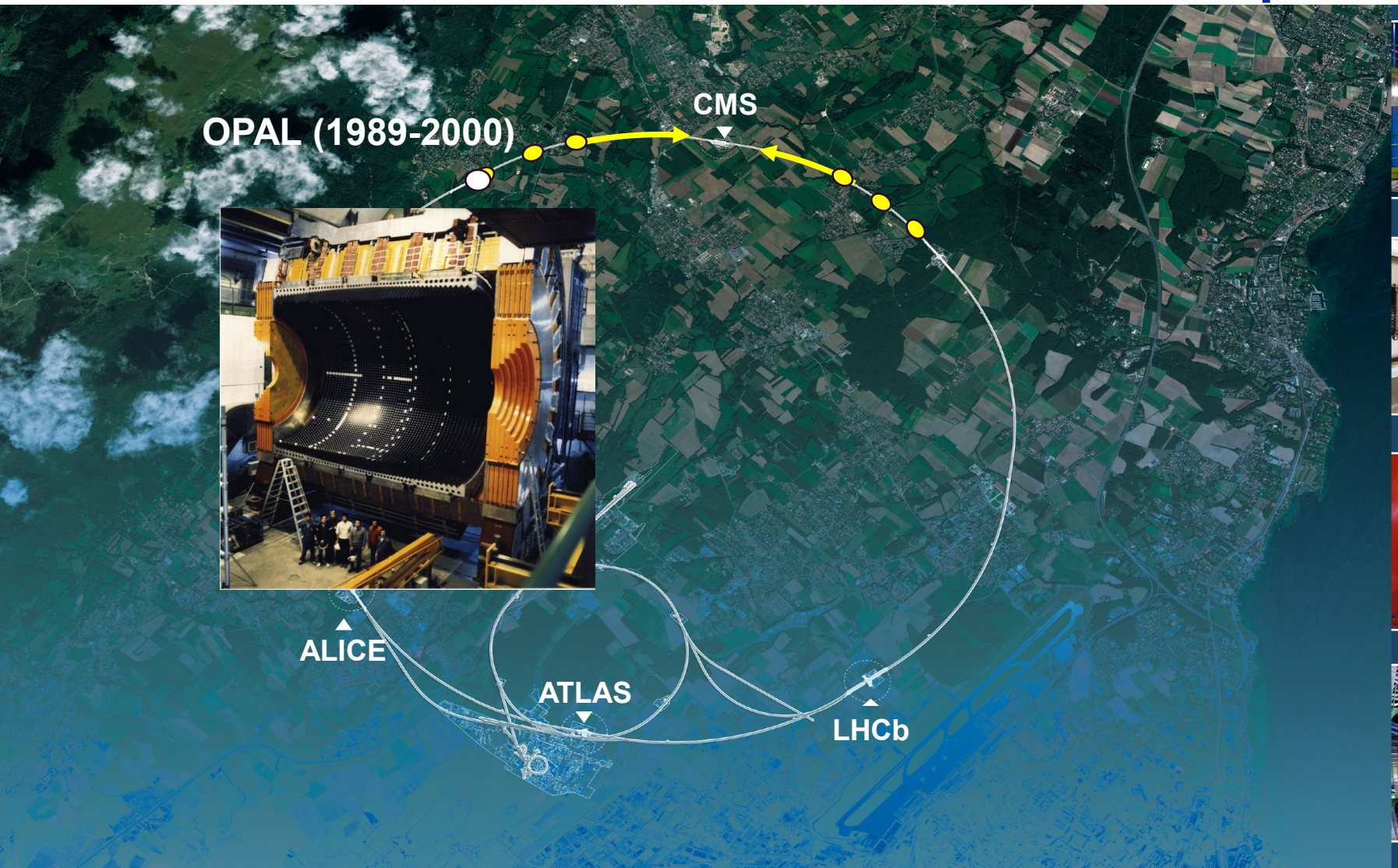
The LHC is Incredible

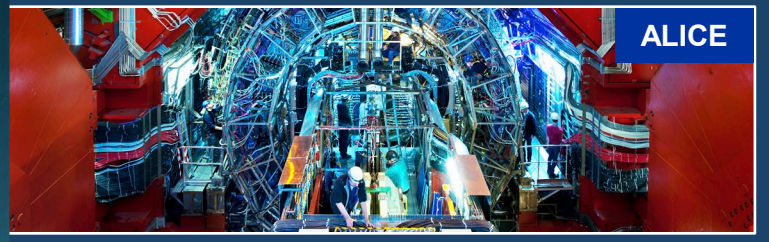
The LHC is the most powerful collider ever built

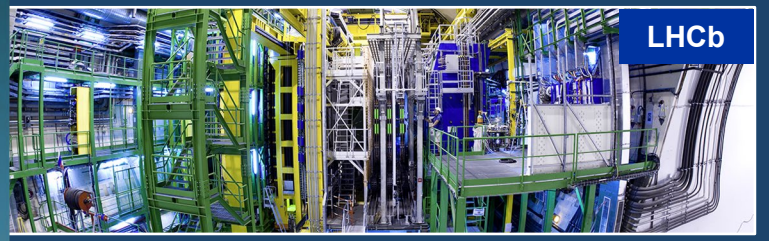
- **A truly remarkable feat of engineering**
- Accelerating **protons** to close to the speed of light and steer them around the 27 km ring
- The proton beams brought into collision in four detectors areas 40 million times a second
- The energy stored is huge: ~350 MJ
  - Equivalent to the kinetic energy of 1000 stampeding African elephants
  - Or equivalently, the kinetic energy of a Boeing 777 aircraft as it lands
  - Or equivalently, more than enough energy to melt tonnes of Copper…



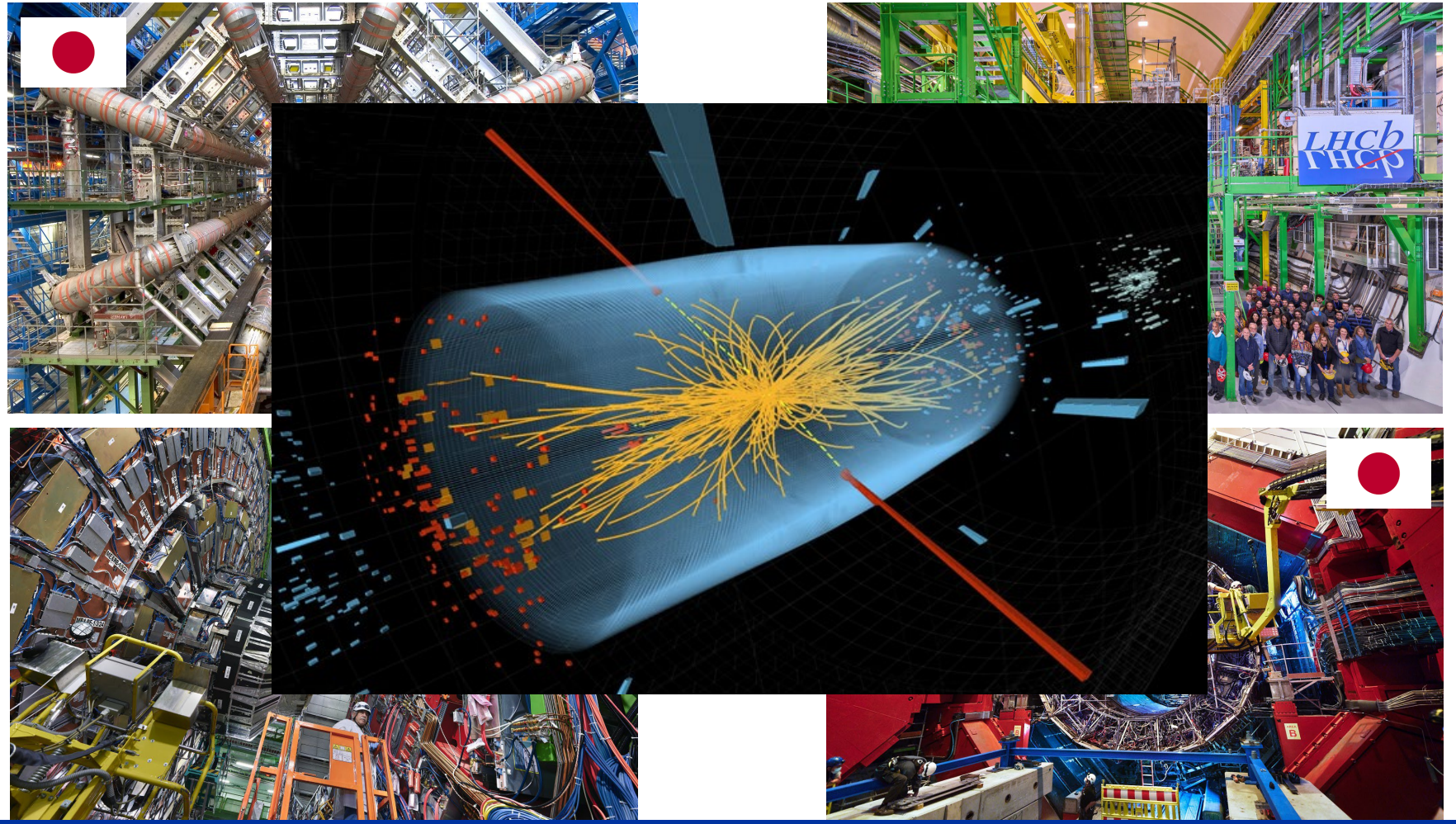
Giant detectors record the particles formed at the four collision points







The LHC Detectors

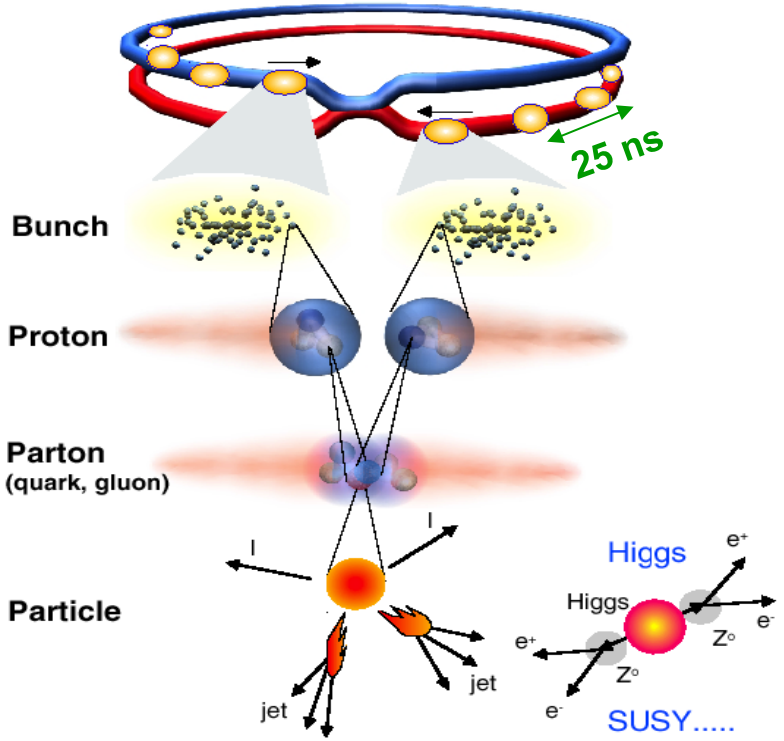


Giant cameras operating at 40,000,000 frames per second

The LHC Detectors are also incredible

The most complex detector systems ever built - a remarkable achievement

The challenges (are many)…



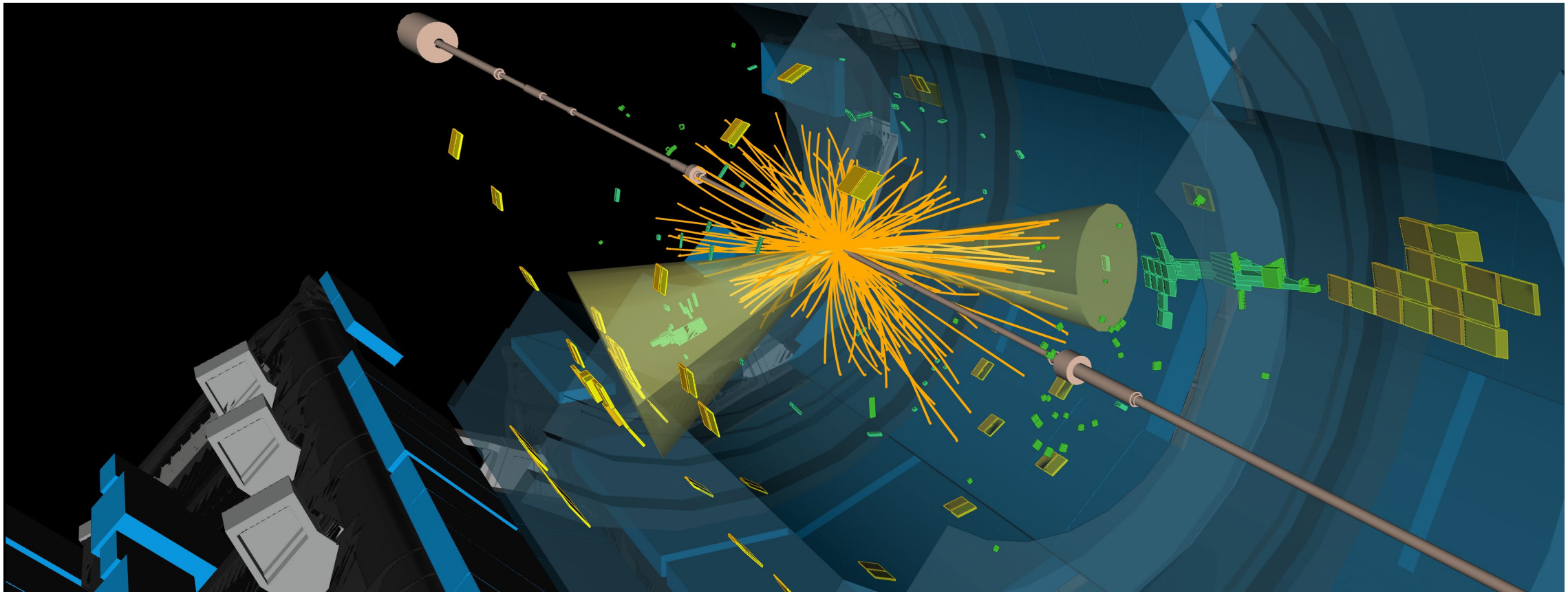
Proton/Proton collisions, with 10^{11} protons per bunch every, 25 ns

Very high event rate 1,000,000,000+ pp interactions per second

“the most interesting events” are very rare: 1 in 10,000,000,000,000 interactions

Detectors designed to image these “events” in great detail and identify the “rare ones”

The LHC Detectors are also incredible



The energy of the particles in collision is converted into new particles.

The detectors measure the energy, direction and charge of new particles formed.

They are analogous to 3D cameras taking 40 million pictures a second, of which 1000 are selected and recorded.

The Higgs Boson is Special

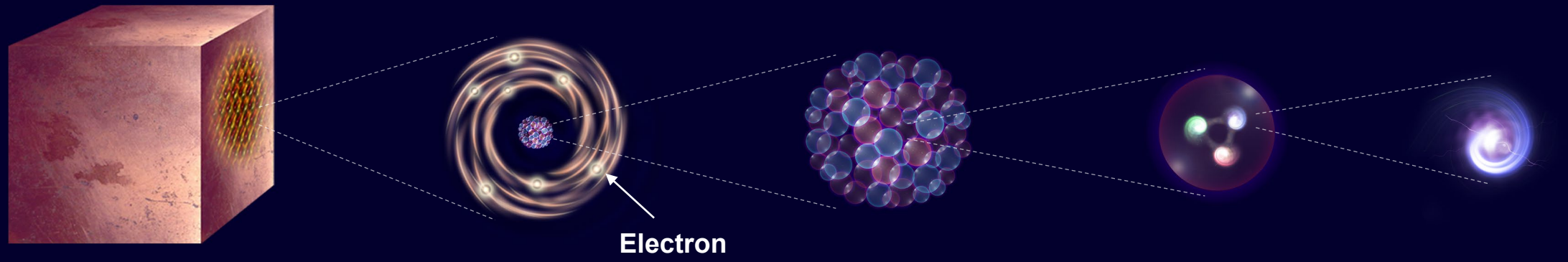
What is the universe made of?

The basic building blocks of most of the “low-energy” universe

- The electrons: that orbit the nucleus in atoms : determines chemical properties
- The “up-quarks” and “down-quarks”: the building blocks of protons and neutrons
- The neutrino: very weakly interacting almost massless particles

The reality is somewhat (but not very much) more complex, e.g. 3 generations

- we also want to know **“why the universe is as it is?”** – here there are many questions



Cooking the Standard Model

Deep Theoretical Concepts

- **Einstein**: Special Relativity
- **Schrödinger** +… : Quantum Mechanics
- **Dirac**: a relativistic theory of QM
  - Spin and anti-matter
- **Feynman** + … : Quantum Field Theory
  - Particles are excitations of fields
- Local Gauge symmetry principle
  - the forces: QED, …
- Brout–Englert–Higgs mechanism

Experimental Observations

- Observed particles and types of force
- Observed parameters, e.g. masses

The Standard Model

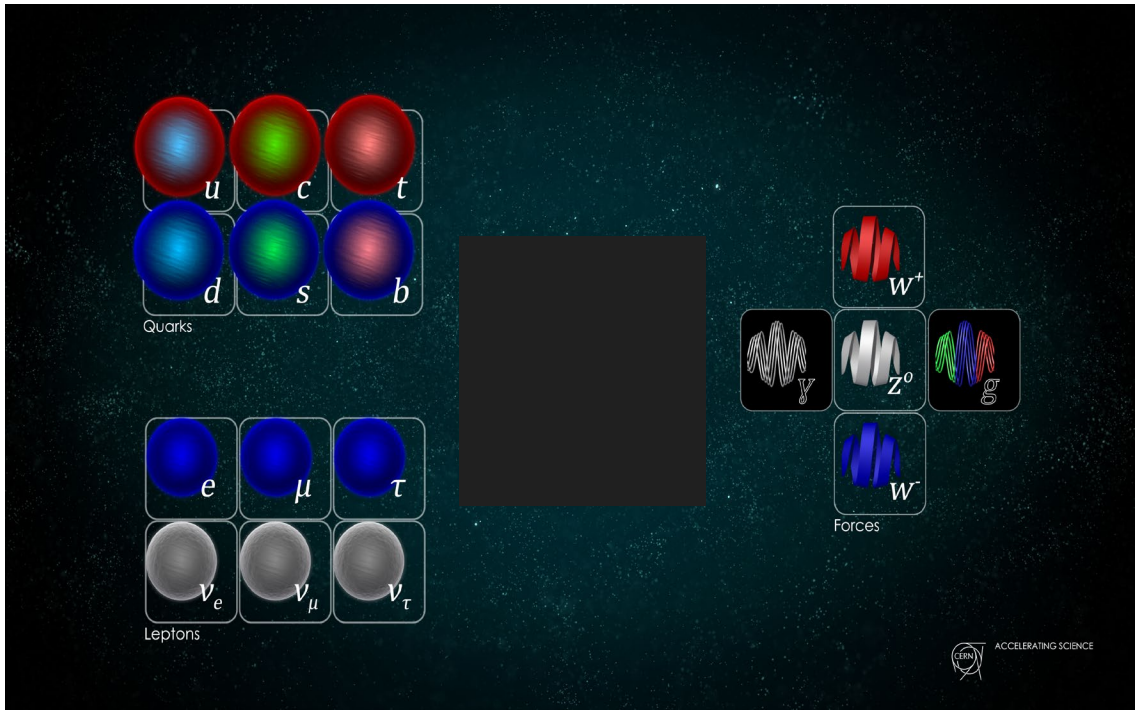
The Higgs Boson is Special

The Higgs Boson was and is a key component of the LHC science case

- Not just “another” particle

Standard Model (SM) building blocks

- 12 matter particles (fermions)
- 5 force particles (bosons)



The Universe is a strange place…

- As far as we know, fundamental particles have no size – pin pricks in space-time
- **Without some “magic”, the SM would only work for massless particles – but we know they are not massless…**

The Higgs Boson is Special

The Higgs Boson was and is a key component of the LHC science case

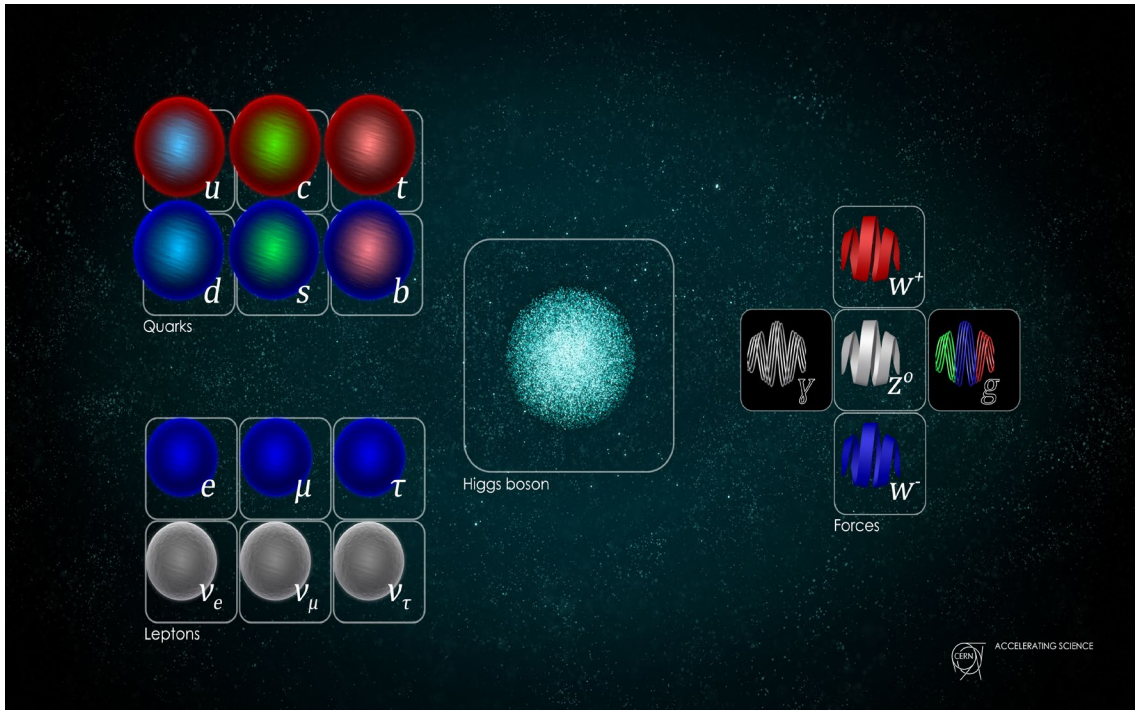
- Not just “another” particle

Standard Model (SM) building blocks

- 12 matter particles (fermions)
- 5 force particles (bosons)
- **1 Higgs boson (a scalar field!)**

The Universe is a strange place!

- As far as we know, fundamental particles have no size – pin pricks in space-time
- **Particles, in some sense, are massless, but the Higgs field gives all particles their (apparent) masses**



The Higgs Boson – a dubious analogy

Can think of the Higgs "field" as a property of the vacuum

- All *other* particles have a zero "vacuum expectation value"
  - makes sense – it is the vacuum, there is nothing there
- But this is not the case for the Higgs "field"…
  - in some sense it is always there – a non-zero vacuum expectation value

The Higgs *field* makes the vacuum "sticky"

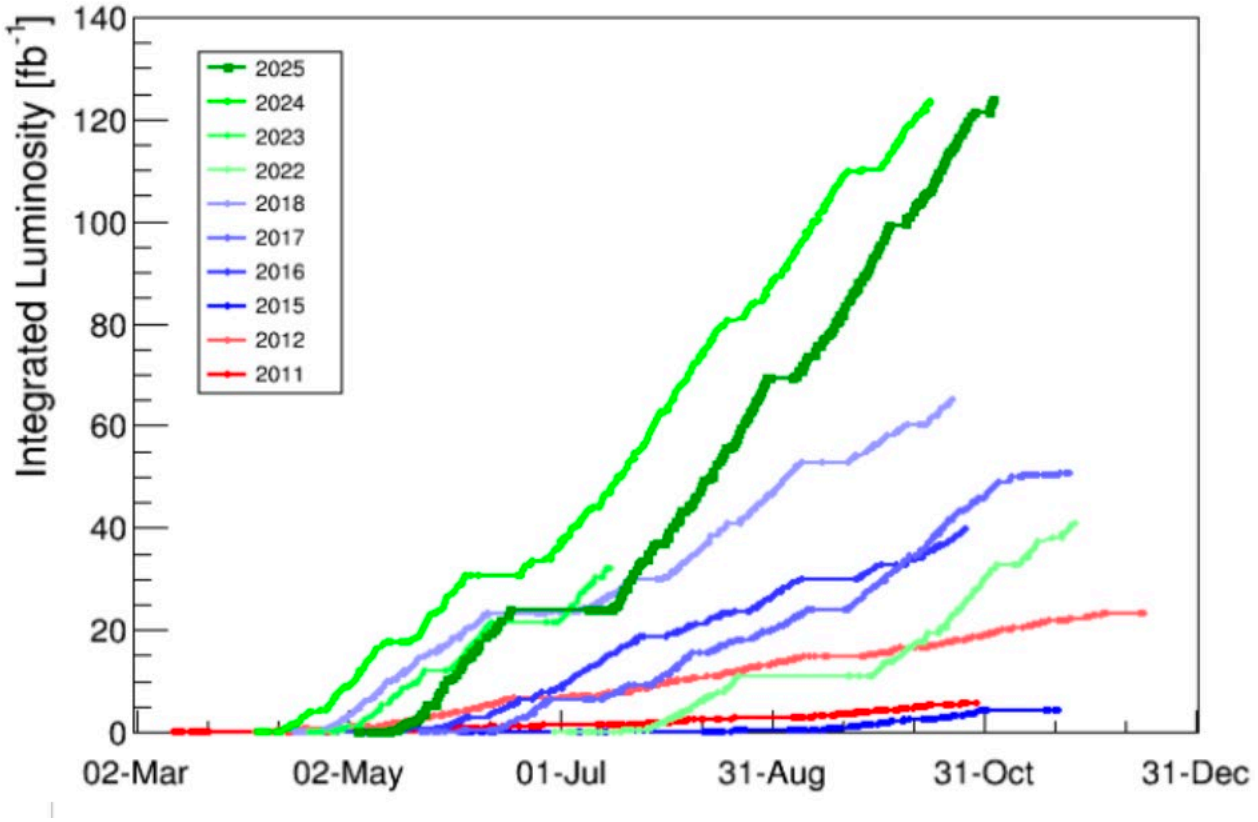
- Other particles feel the presence of Higgs field as they wander through space: this gives them inertia, a.k.a. **mass**
  - generates a "Lagrangian" term that looks like mass
- If you collide particles hard enough, they can cause ripples in the Higgs Field
  - the Higgs Bosons that we can detect at the LHC

LHC Physics Today

The LHC is a beautiful machine

2025 was a record-breaking year: delivered over **125 fb^{-1}**

- 2026: preparing for a shorter run before start of Long-shutdown 3 at the end of June

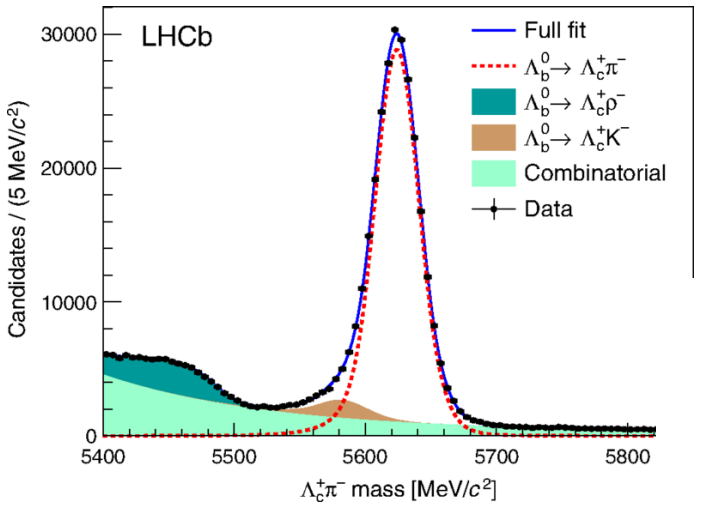


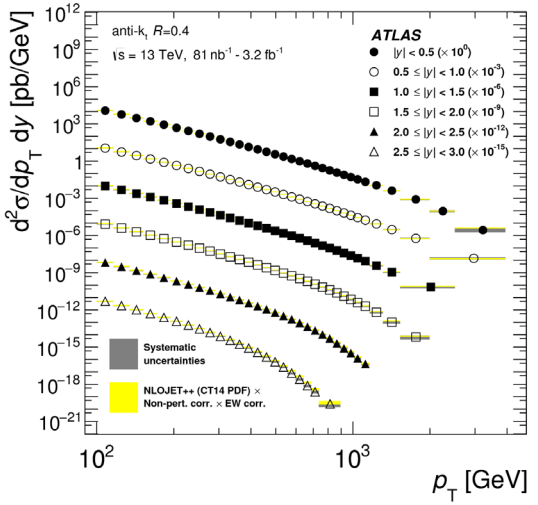
Total ATLAS/CMS data now each **~520 fb^{-1}**

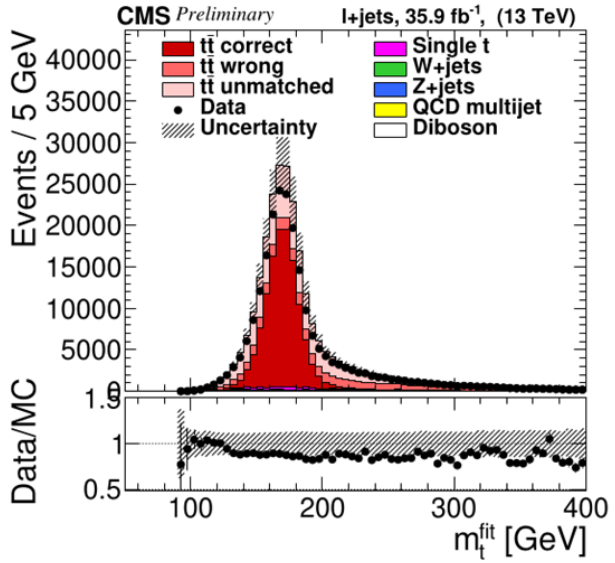
Many discoveries and new measurements

Covering a vast range of topics

- **Higgs boson discovery in 2012**
- Higgs boson properties
- Over fifty new hadronic states
- Rare decays like Z→eeμμ and $B_s \rightarrow \mu\mu$
- CP violation in the charm sector
- Jet quenching in heavy ions
- VVHH Higgs four-boson coupling
- **Publications galore:**
  - **LHC experiments ~4000 publications !**



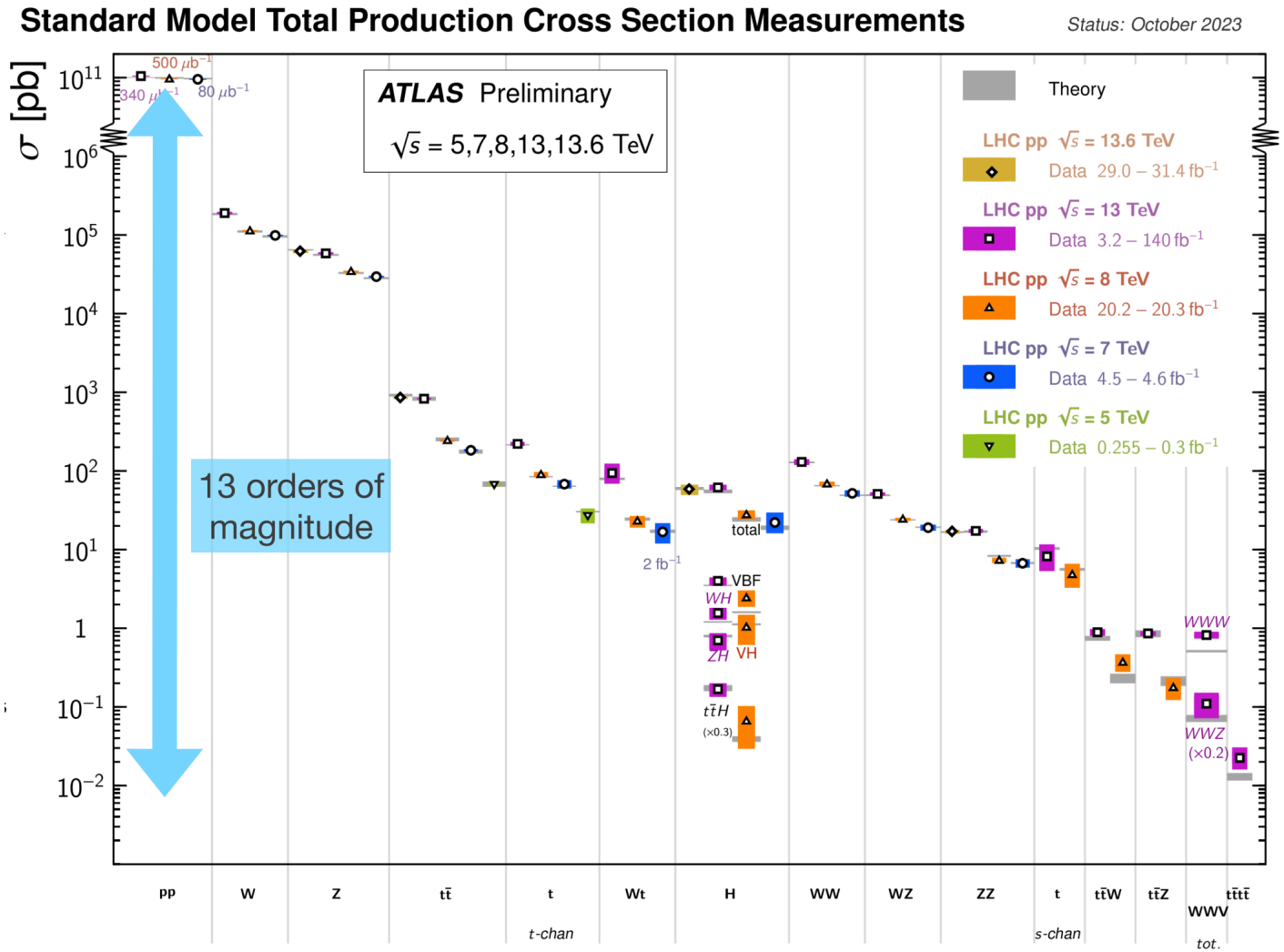




The Standard Model remains in good shape

The precision achieved is an incredible achievement many scientists

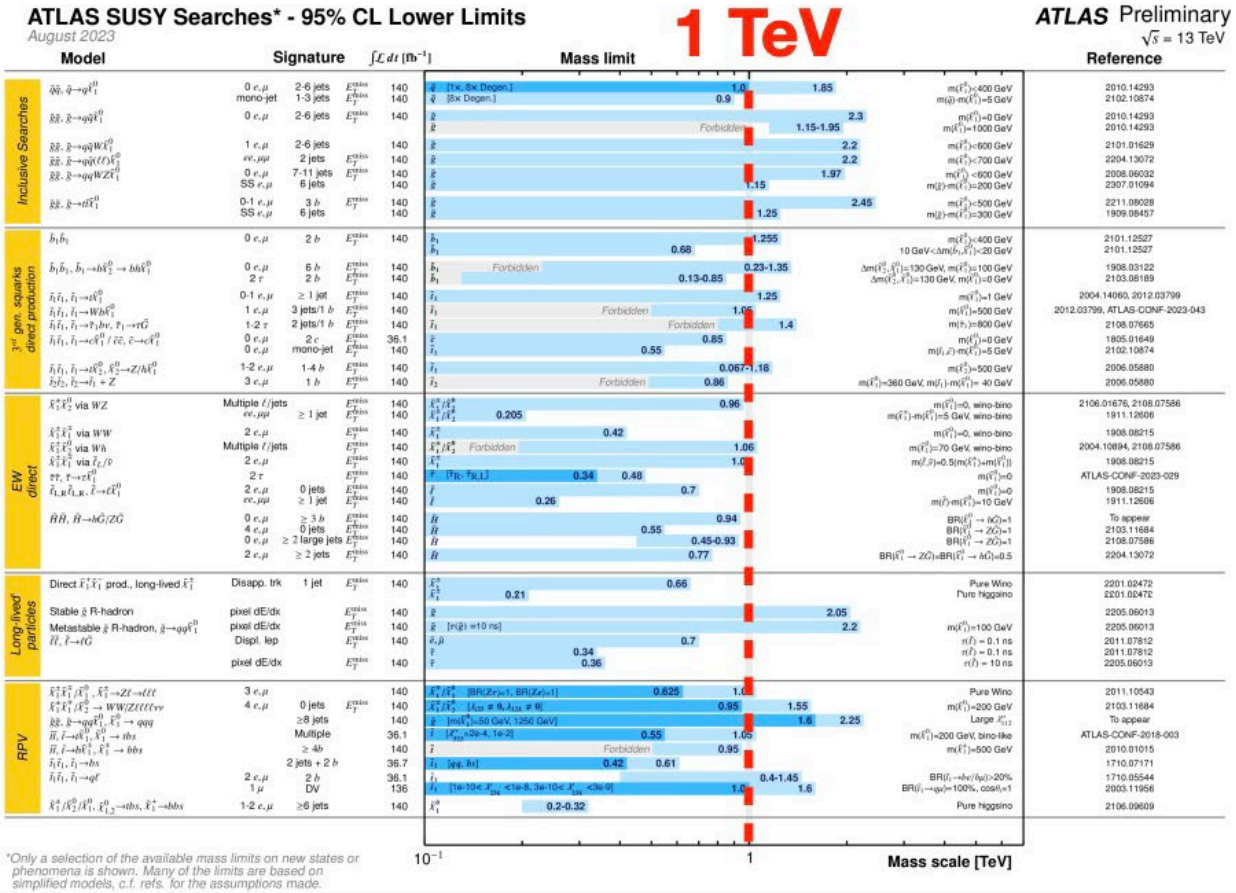
- Often (usually) surpassing the original design goals
- Despite occasional anomalies, the Standard Model of particle physics remains in very good health



We continue to search far and wide

Precision measurements complemented by searches for a wide range of BSM phenomena

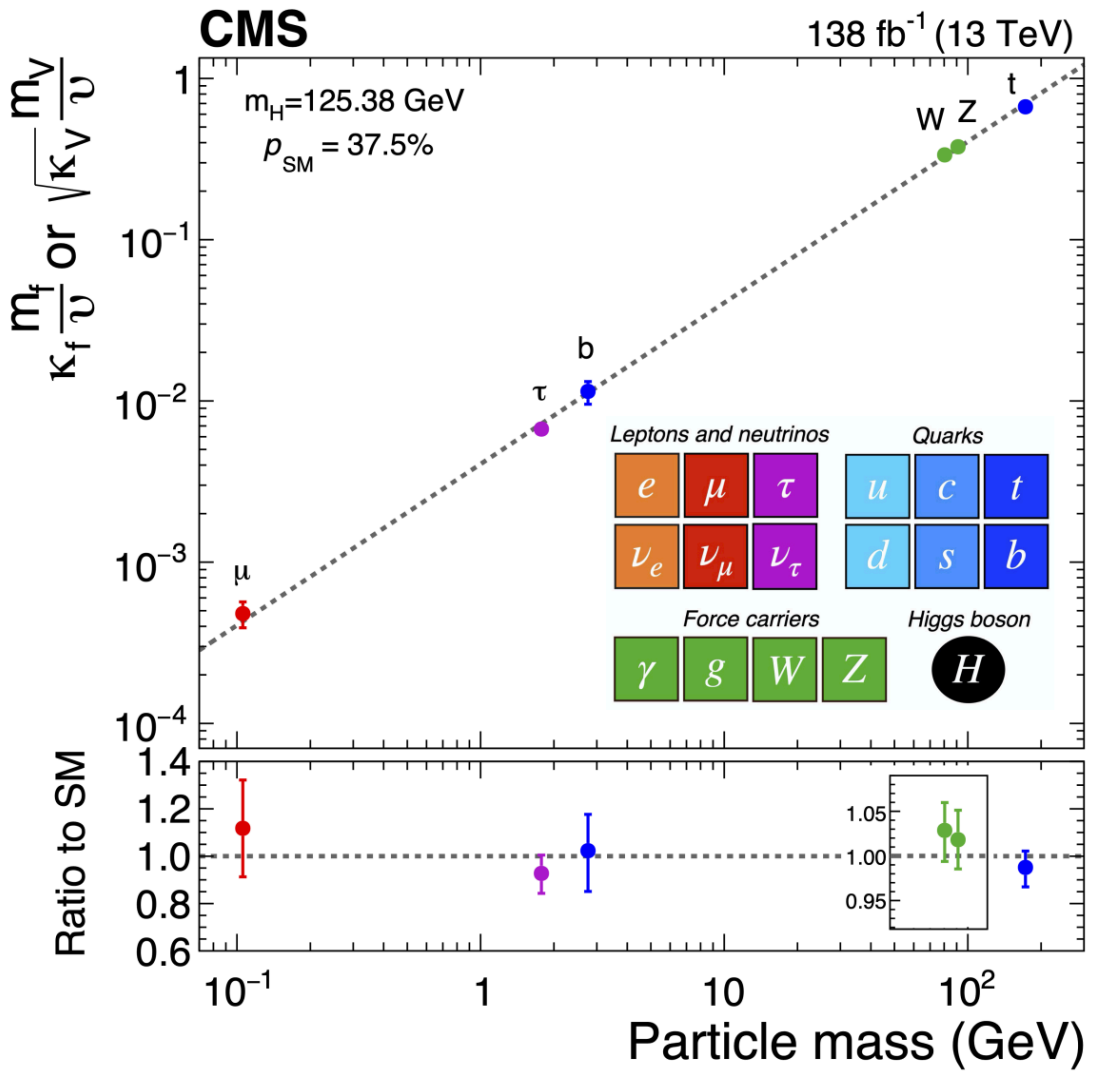
- Despite occasional hints, no strong signals for the manifestation of BSM physics (yet)
- Probing scales in the range of 1 – 10 TeV
  - e.g. SUSY to ~1 TeV
  - with a few blind spots



The Higgs Boson as a probe of BSM

Probing couplings over a mass-range of ~3 orders of magnitude

- So far, couplings look as expected, but we have just started to scratch the surface
  - typically, measurements at the 5% – 10% level
- Far from the end of the story…
  - for the Higgs mechanism to "do its job" there are strong constraints on the size and nature of possible BSM deviations
  - **need to be aiming for 1% level precision or better**

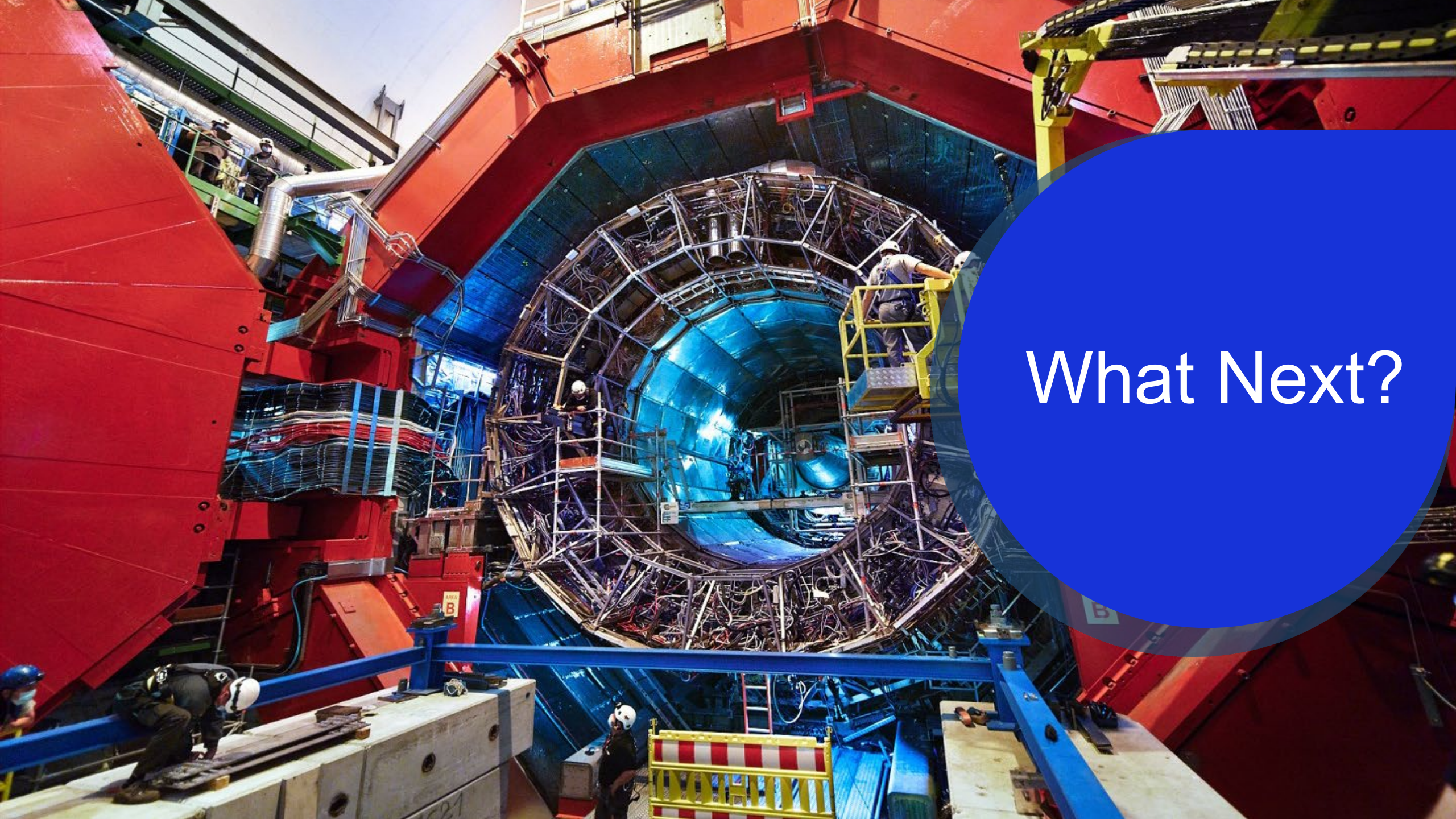


What next?

We know a vast amount about the nature of the universe, but…

…there are many deep mysteries, including

Why is the universe made only of matter, with hardly any antimatter?	What is the unknown 95% of the mass and energy of the universe?	Does the Higgs boson interact with dark matter? H	Is the Higgs Boson a fundamental particle? H
Unification and why is gravity so weak compared to the other forces?	Why three generations and are there more?	What determines the hierarchy of masses of the particles? H	What is the nature and stability of the Higgs potential H



What Next?

The next major discoveries?

Where will the next breakthroughs/discoveries come from?

- Obviously, we don't know – and that's OK, if we knew they wouldn't be discoveries

But in the next ~10 years we are looking in the right places

- **HL-LHC: Higgs and more**
- **Next generation neutrino experiments**
- **Cosmology/astrophysics**
- Searches for Dark Matter – we know it is out there…
- Exploring the Flavour Sector (LHCb, Belle-II, mu2e, …)
- + ….

And we are necessarily planning for the very long term

- **Higgs factory – e.g. FCC-ee**
- Pushing the energy frontier for discovery – e.g. FCC-hh and/or a muon collider
- ….

What Next for CERN? HL-LHC

The High-Luminosity LHC

- major “upgrade” of the LHC, starting operations ~2030 and running until 2041
- based on new cutting-edge technology that didn’t exist when the LHC was built

With 10 times increased “brightness” compared to the LHC

- so we are just at the start of the LHC/HL-LHC journey

Meanwhile the detectors and triggers become ever more capable

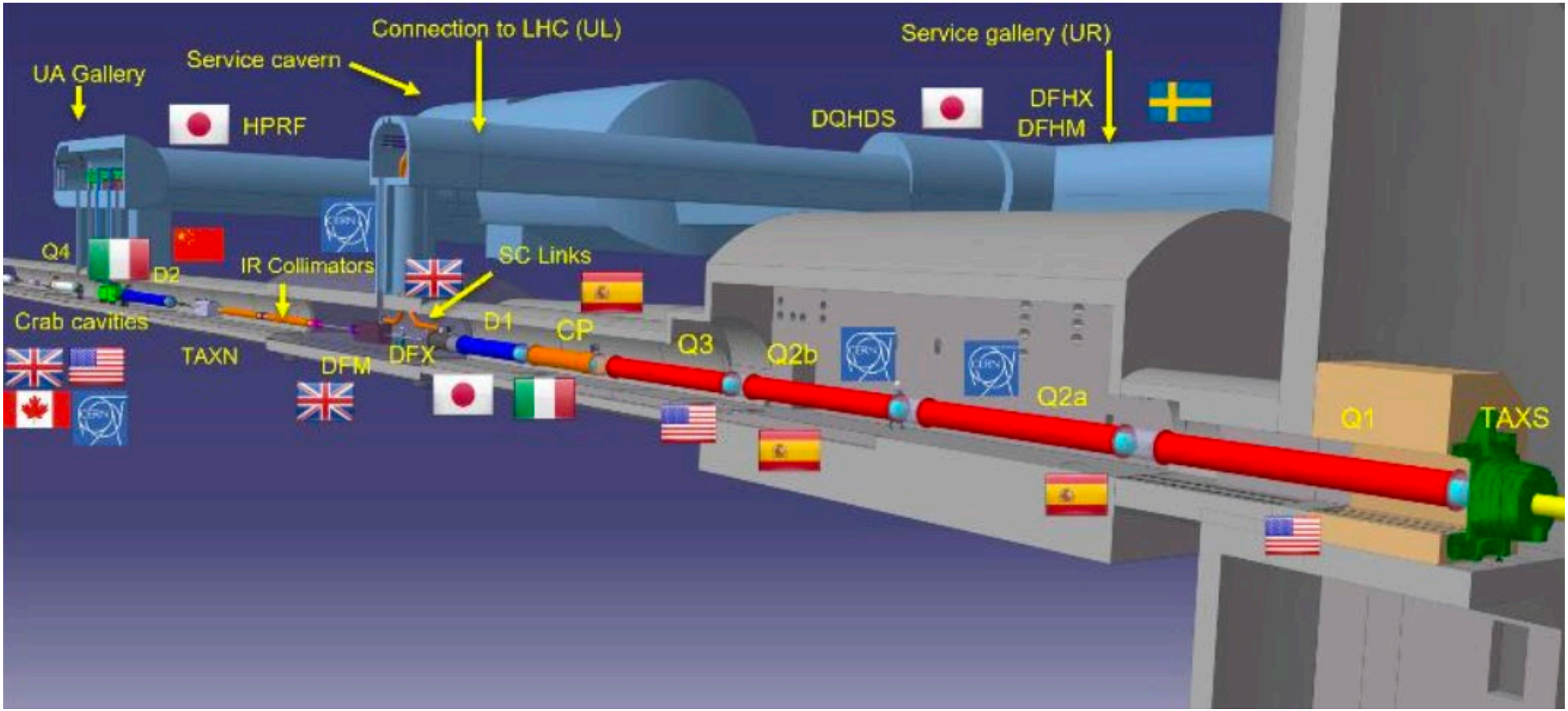
- wider range of processes targeted more precisely

And never forget the people

- Brilliant young researchers, aided by AI tools, will give ever greater power

The HL-LHC is an incredible scientific opportunity
- a lot more data, even better detectors, new techniques
- **real discovery potential!**

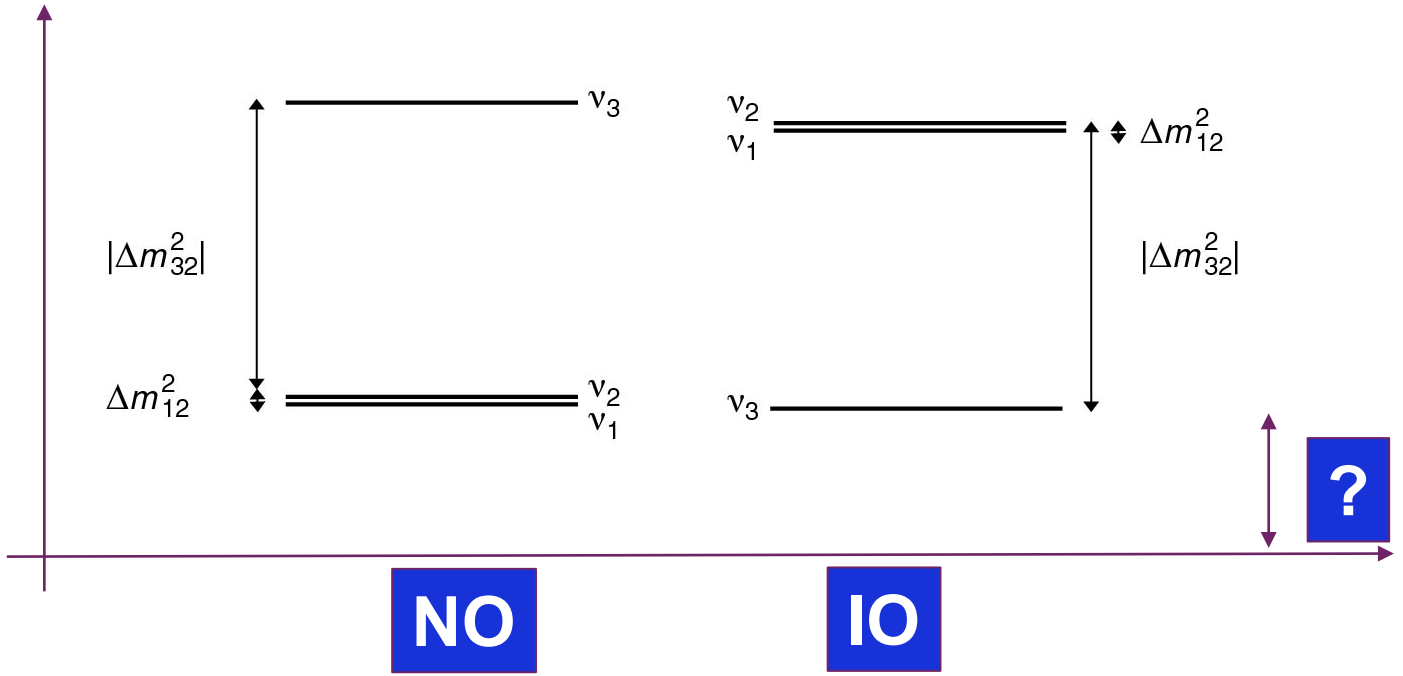
HL-LHC: a major international collaboration



A few words about neutrinos

Three big questions

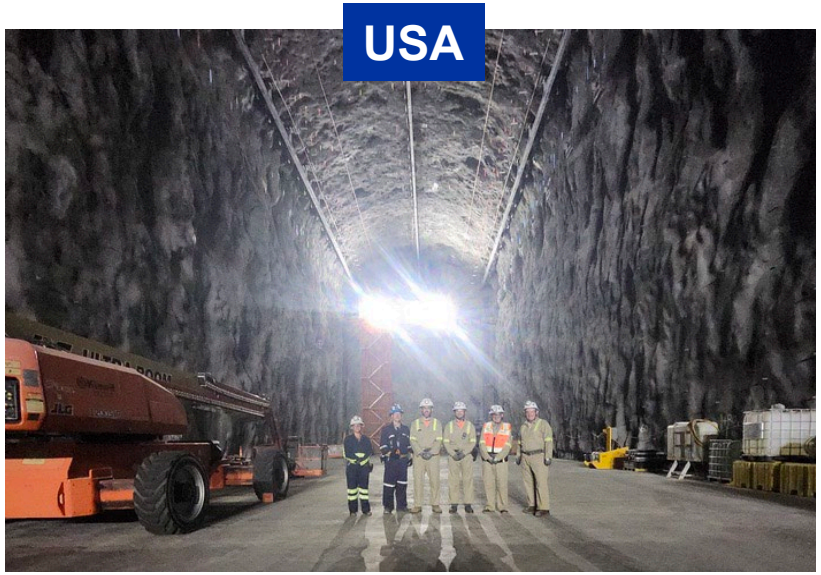
- Neutrino masses (mass ordering and absolute scale)
- CP violation in the neutrino sector?
- Are neutrinos Majorana particles?

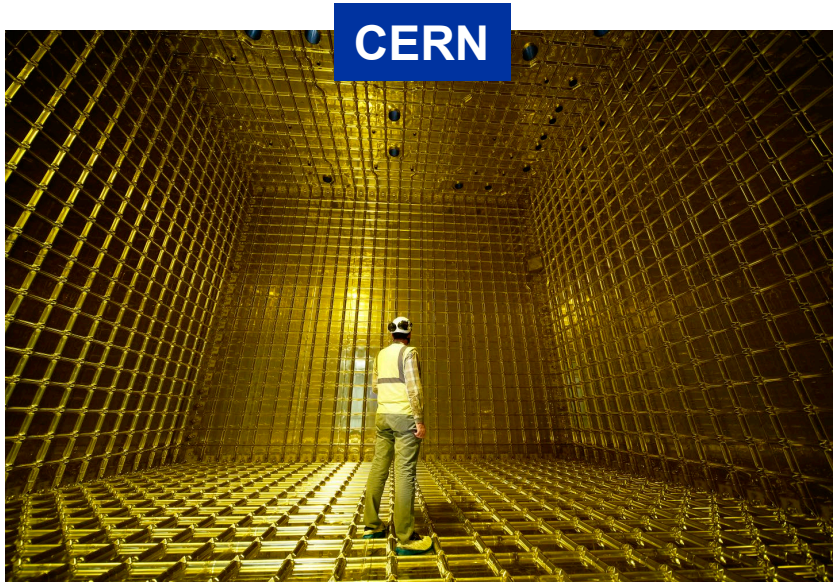


A few words about neutrinos

Can be confident that we will have *some* (but not all) answers in next 10 years

- We are building the right experiments
  - e.g. **Hyper-Kamiokande** in Japan and DUNE in the US
- By 2035, **we will know** the mass ordering and a lot more about CP violation
  - … and there could be surprises





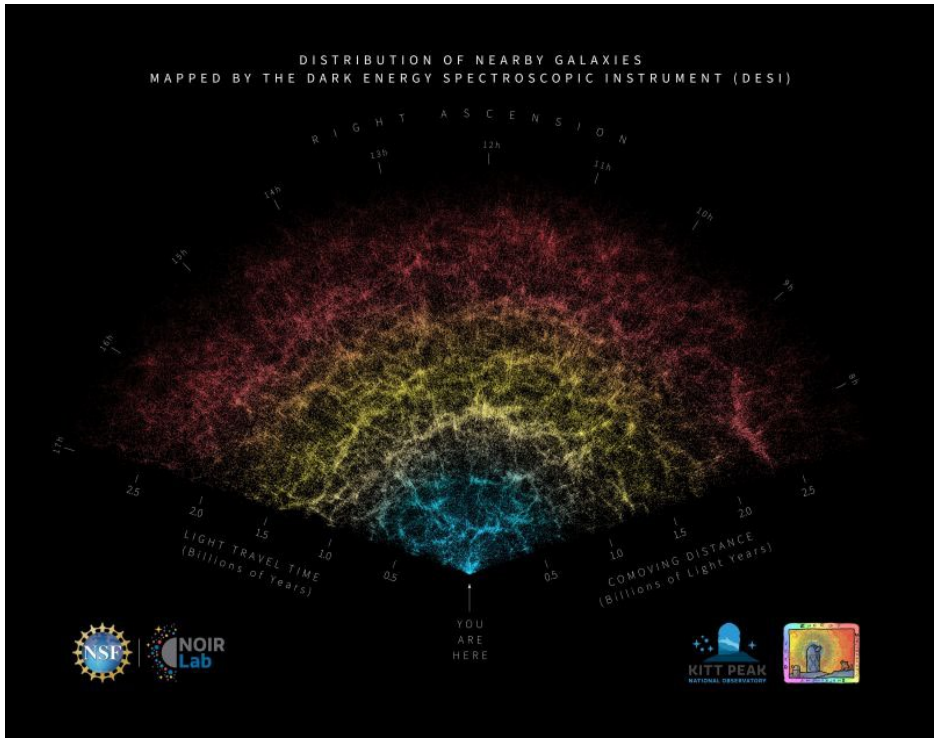
Neutrinos and Cosmology: DESI, EUCLID, …

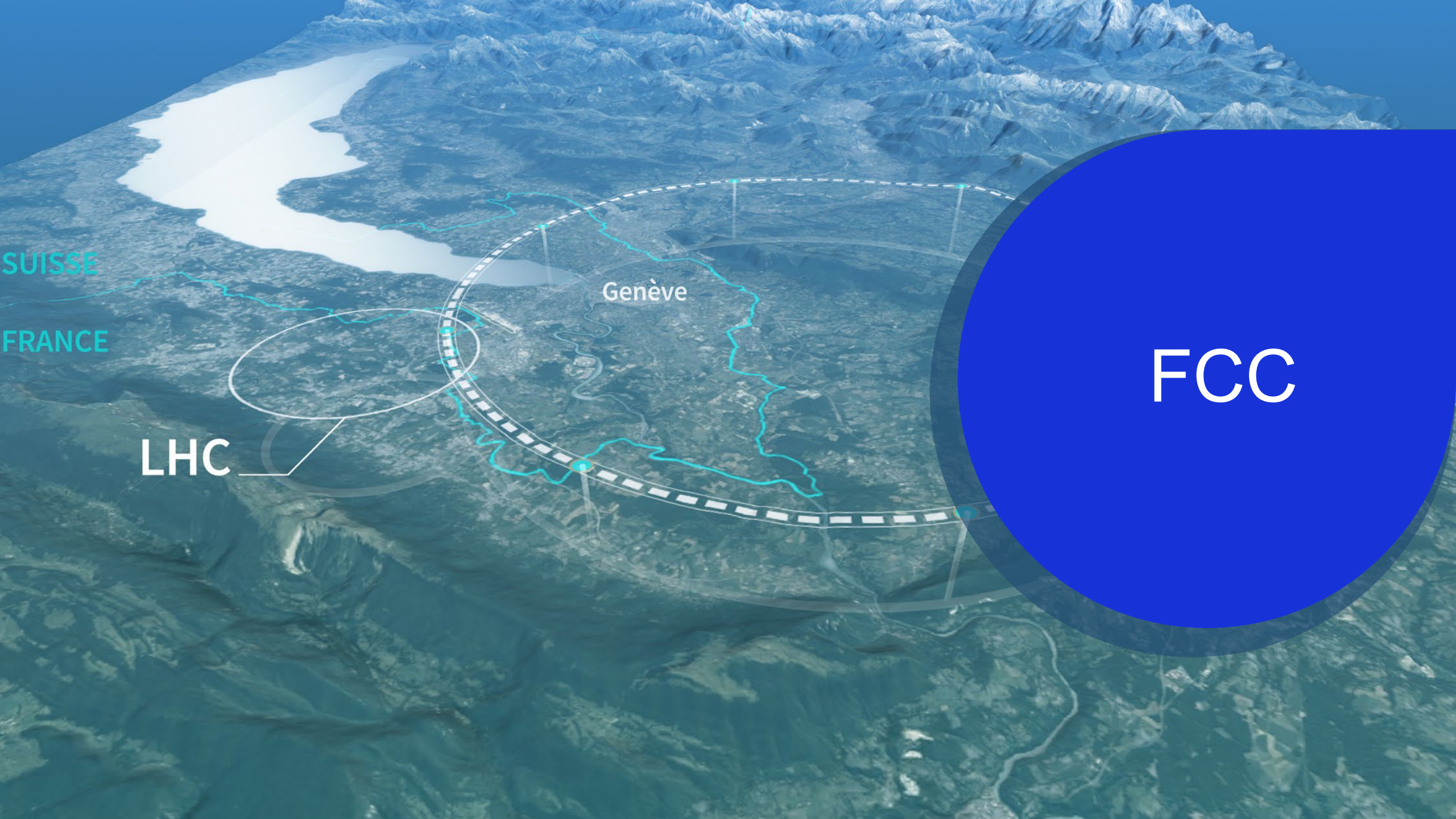
Current and next generation ground-based and space-based galaxy surveys looking at large-scale structure will increase knowledge of (for example)

- Dark energy
- …and particle physics

For example: Dark Energy Spectroscopic Instrument (DESI) Year 1 results

- 600,000 “local” galaxies
- Indirect measurement of neutrino masses
  -
- Compared to what we know from oscillations
  -
- Taken at face value…
  - But in the future, could see tensions…




SUISSE
FRANCE
Genève
LHC
FCC

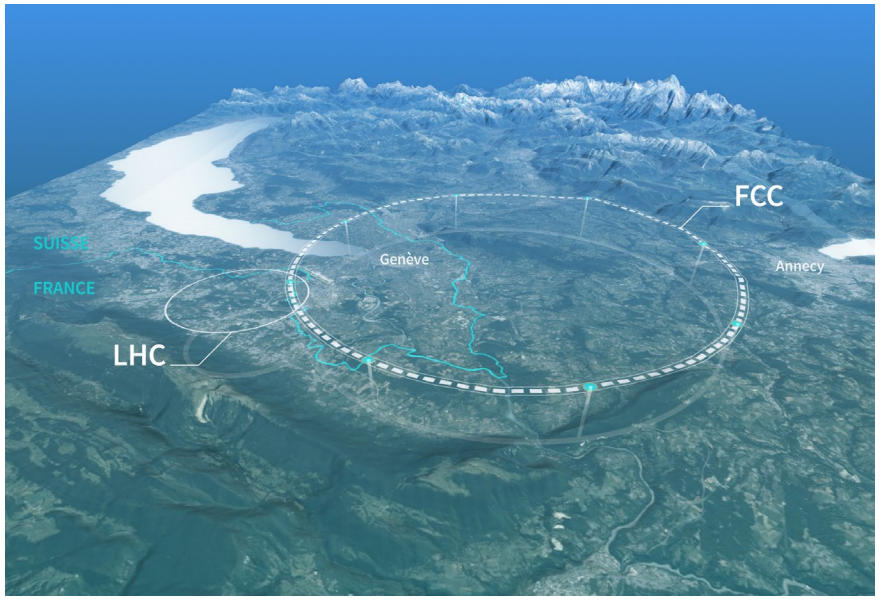
CERN's long-term vision

The Higgs Boson is a genuinely new and unique type of matter

- It is also very strange – and may well provide a new window for discovery
- A strong scientific case for a new "Higgs Factory" machine to study it in fine detail

The "Future Circular Collider" (FCC)

- A new 91km ring
- First stage collides electrons & positrons: **FCC-ee**
- An ambitious and exciting scientific programme
  - Higgs and **much more (Z, flavour, …)**
- Targeting start of operations in ~2045-2048
- Total cost over ~15 years of about 15 BCHF…



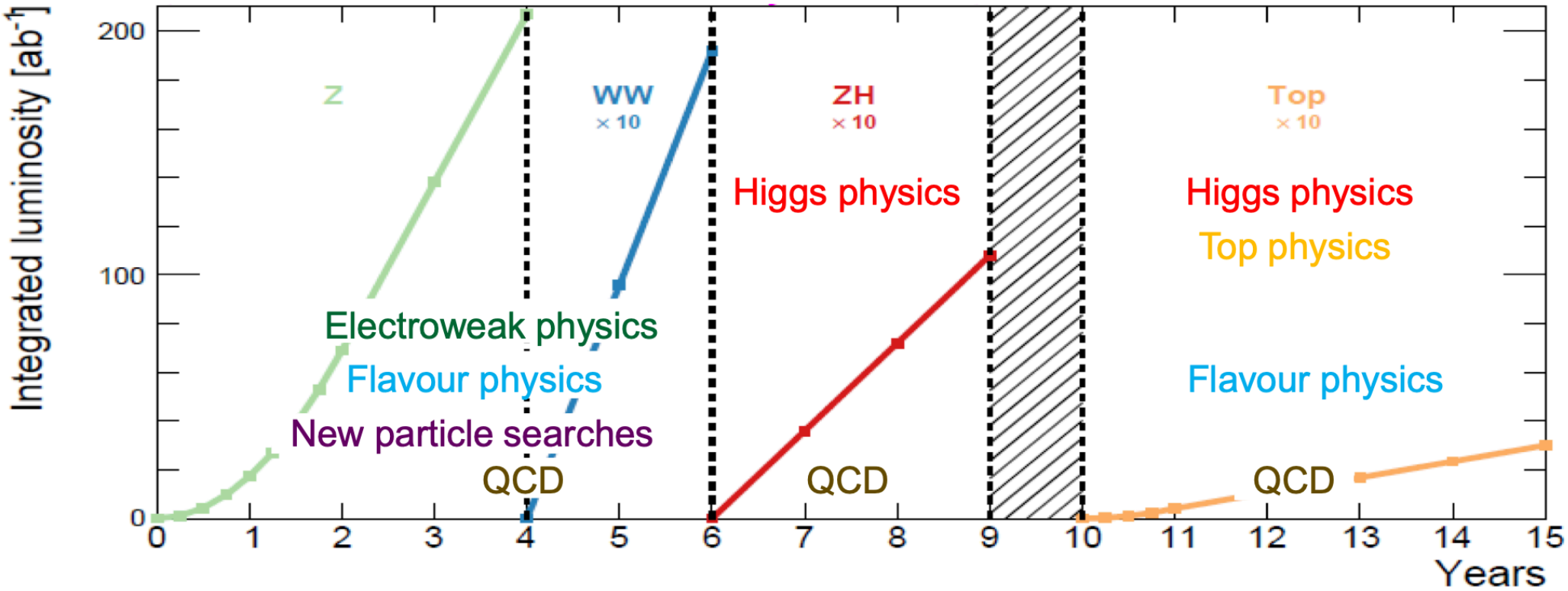
It is incredibly exciting and is a suitably ambitious next project for CERN

- Not yet approved, but we are hoping for a positive decision in ~2028

FCC-ee Physics

Flexible exploration of the Higgs and the wider electro-weak sector

- Flexibility to run at Z, WW and ZH and subsequently top-pair production
- Huge event samples for incredible precision – e.g. 10^{12} Z bosons = 1,000,000 x LEP



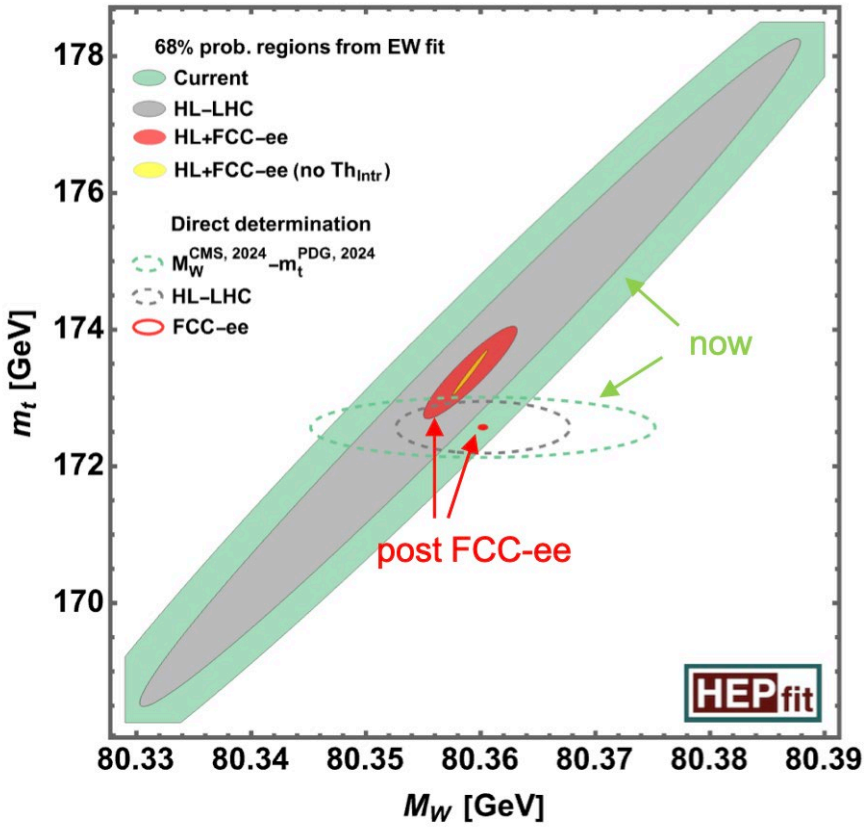
FCC-ee Physics

A large step-change in precision!

- e.g. Model-independent Higgs couplings at the sub-1% level
- e.g. Three-orders of magnitude improvement w.r.t. LEP – this is a paradigm change

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.49
κ_g (%)	2*	0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

* next to HL-LHC numbers → not model independent



CERN's long-term vision

FCC and the "FCC Feasibility Study":

- Provides an exciting scientific vision for CERN's future…
- A luminosity-frontier electron-positron collider (FCC-ee)

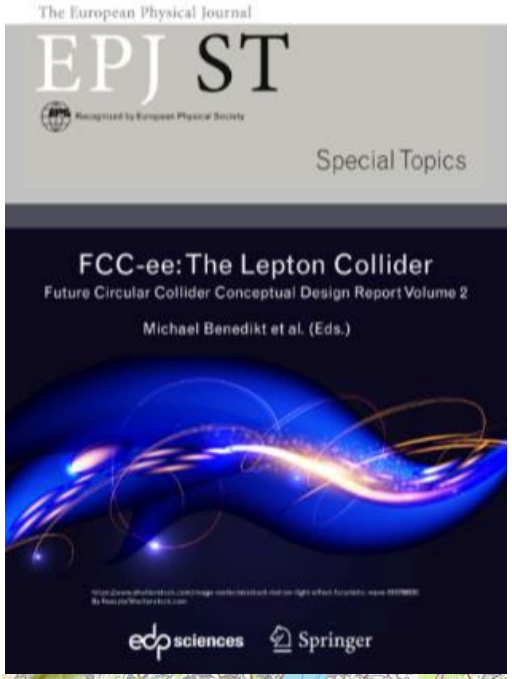
FCC as a route to a *possible* future hadron collider

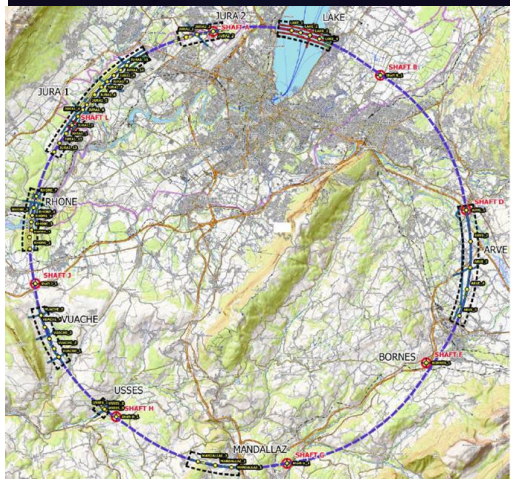
- At some stage (I believe) we are going to want/need a very high energy hadron collider to explore new mass scales…
  - Much of the FCC-ee infrastructure *could* be reused (2060+) to provide p-p collisions at a centre-of-mass energy of ~100 TeV

FCC in CERN's strategy

- **Focus today is firmly on FCC-ee**
- Is FCC-ee the right option for the next collider at CERN?

– in my view YES





CERN's Scientific Strategy 2026-2030

1: HL-LHC: let us not forget

The construction of the HL-LHC and the ATLAS/CMS upgrades will dominate the next five years at CERN

- Long Shutdown 3 (LS3) for the LHC commences on 30 June 2026
- The plan and clear intent is to be commissioning the machine and detectors in 2030

This is a major task

- The HL-LHC installation will be the largest project undertaken by CERN in around 20 years
- The Phase 2 detector upgrades, are the largest projects undertaken by ATLAS and CMS since the construction of the original detectors

The HL-LHC *and* the detector upgrades represent *by far* the highest priority for CERN in the coming years

- Meeting the current schedule, which is our intention, will require **laser focus**

HL-LHC and the Phase 2 upgrades are CERN's highest priority

2: FCC-ee

The key points from the European Strategy for Particle Physics:

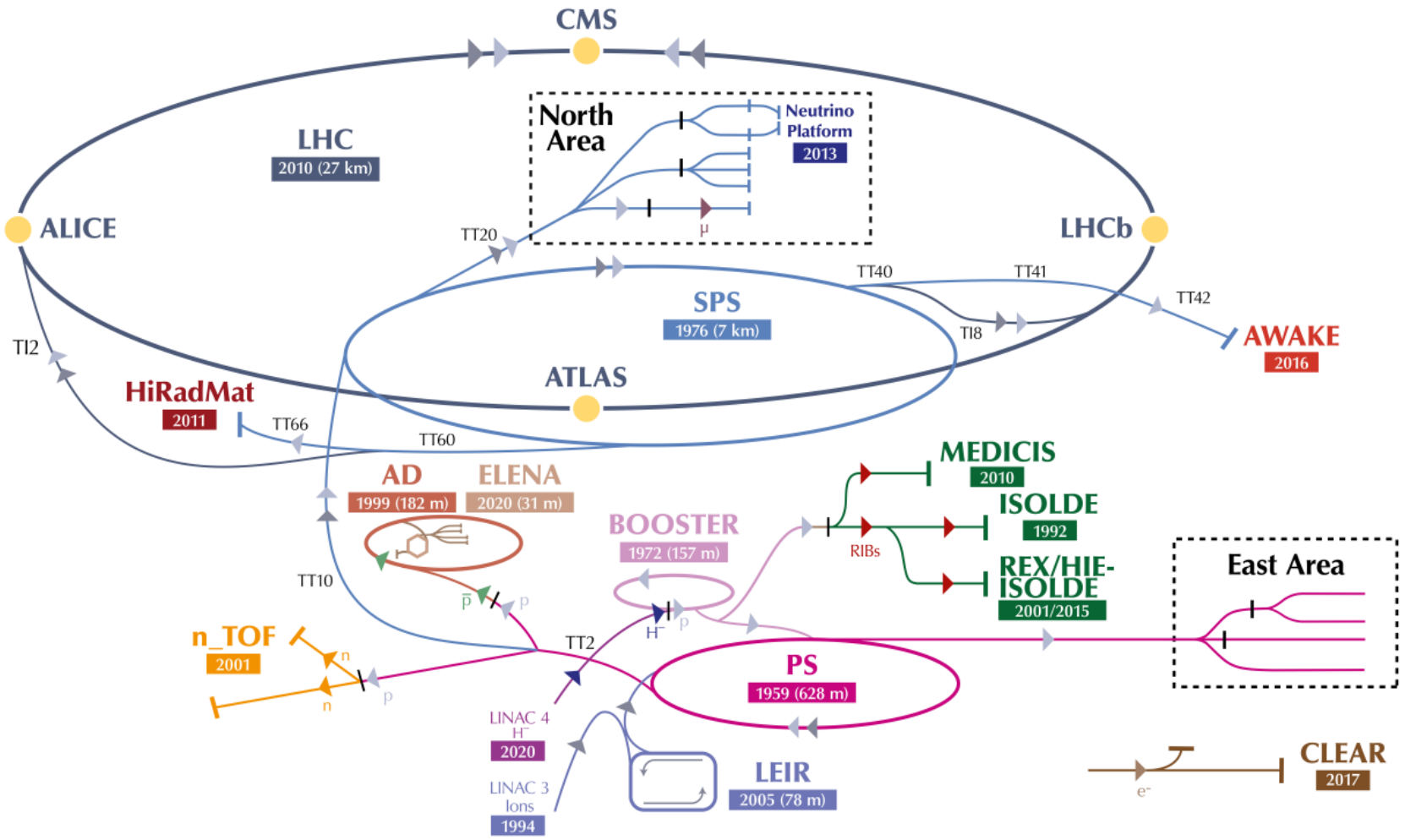
- Strong endorsement of the physics and strategic case for FCC-ee as the next flagship collider for CERN
  - Near consensus on this point within the particle physics communities in CERN's Member States
- A descoped/staged FCC is preferred to other options as an alternative

The further development of FCC-ee will be CERN's *clear second highest scientific priority* for 2026-2030 after HL-LHC

- The goal remains to take FCC-ee to CERN Council in 2028, hopefully for a positive decision

3: Non-Collider Physics at CERN

There's more to CERN than the LHC…



3: Non-Collider Physics at CERN

The non-collider physics programme must remain a priority for CERN

- The diversity of science at CERN as an essential part of the attractiveness of the laboratory and its scientific output (and excitement)
- It also supports a large scientific user community of ~3,000 users
- **Many ideas** for options for new projects, for example (no priorty implied)
  - Forward Physics Facility – high-energy neutrinos from the LHC
  - ISOLDE upgrades – nuclear physics
  - AD/ELENA – the anti-matter factory
  - AICE – quantum atom interferometry
  - …

This year CERN will work with the scientific community to develop a long-term roadmap for Non-Collider Physics at CERN


Final
Words

Final Words

The future of particle physics is incredibly exciting – we should not forget this

- We are going to address some profound fundamental questions
  - the next breakthrough could come from many places, so it is essential that we keep asking the right questions and pursuing multiple approaches

HL-LHC will be amazing

- HL-LHC will be a giant leap forward in capability
  - ~10x the current LHC integrated luminosity, upgraded detectors, AI, …
  - Precision measurements (Higgs and more)
  - Higgs self-coupling + genuine opportunity for BSM discovery

Planning for next major collider facility is moving at pace

- I believe the FCC is a truly outstanding scientific opportunity
  - we need make the strongest possible case (science + …) – **it will be well worth it!**

Thank You!

The Wider Case for HEP and the FCC

(if time allows)

The wider case for the FCC

I believe this needs to be based on three pillars

- **The scientific case – which comes first**
  - ESPPU is an opportunity for the particle physics community to make a clear statement of scientific priorities
  - I believe the science case for the FCC is very strong - we as a community need to articulate it for the wider scientific audience
- **The diplomatic benefits of international scientific collaboration**
  - Should not be underestimated
- **The wider technological and economic benefits of particle physics, CERN and ultimately the FCC**
  - The long-term economic return in investing in “Big Science”
  - In Europe, particle physics the domain where we have the global scientific and technological leadership…

What are the wider benefits of CERN?

Science and more…

- Particle physics and Astronomy have made incredible scientific contributions
- Beyond the science, I believe there is a deep cultural value in humanity's quest to understand the universe we live in

International Collaboration and "Science Diplomacy", e.g.

- CERN built on 70 years of deep international collaboration across Europe & beyond
- Science is a domain where nations can come together behind a common positive goal, this was true 70 years ago and is true today

+ direct economic benefits

- Innovation and technology
- High-end training
- Inspiring the next generation

} explored in the next few slides

The Economics of “Big Science”

Caveat Emptor: this is not easily quantified

- very difficult to quote a reliable measure of “Return on Investment”
- also defining the “counterfactual” for technology development is often hard
- and sometimes the timescales for return on fundamental science / advanced technology are long…

Example: GPS

- accurate GPS relies on being able to correct for General Relativistic corrections
- a downstream “by-product” of Einstein’s General Theory of Relativity published 110 years ago
- for a long-time there was no obvious practical benefit…

Driving Technology Forward

I believe that one of the largest impacts of “big fundamental science projects” is pushing technology beyond the current state-of-the art

- Major fundamental discoveries in basic science almost always happen because of a new technology or new technological capability

In particle physics we are often trying to do the “near impossible” to get a better or new understanding of the nature of the universe

- This often requires a new capability – that doesn’t yet exist
- We then try to develop the technology required to the answer the scientific question
- The new technology then may have wider applications
- **Being driven by the scientific need is the key difference**

Disruptive Technologies

The big disruptive technologies have the largest long-term impact

- The World Wide Web – sharing information and data within CERN
  - Probably would have been developed in some form – but possibly not “open”
- Accelerators – technology developed as our main tools for particle physics
  - Cancer treatment: Hadron therapy, Ion therapy, Medical isotopes, …
  - Synchrotron Light Sources: underpin our understanding of **structural biology**, **advanced materials**, **drug discovery** and much more

I would argue

- The reason that we now have the underpinning accelerator technology is that it was needed for fundamental discovery science
- Without this mission, I doubt that we would have these large-scale “light-sources” today

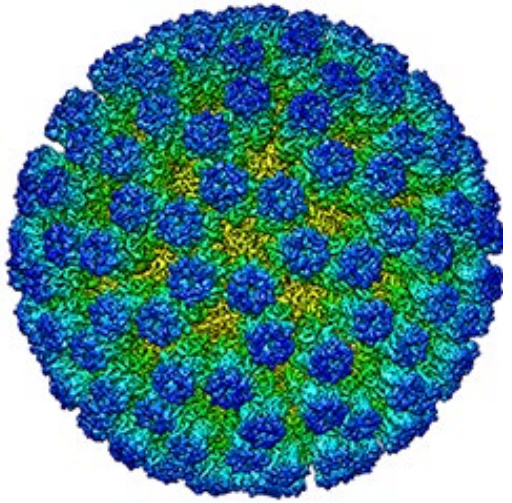
Final Example

Silicon sensor development for the ATLAS experiment at the LHC

- Traditional silicon sensors, e.g. those in phone cameras, would not survive the high radiation environment at the LHC
- Required designing special radiation-hard technology - a niche application?

Technology drives discovery: Richard Henderson won the 2017 Nobel Prize for Chemistry for developing **cryo-electron microscopy** to allow researchers to freeze and "see" biomolecules "mid-movement"

- Cryo-EM microscopy was revolutionized by the radiation hard-sensors first developed for **particle physics** and which can be used to directly image energetic electrons



Cryo-EM is revolutionising structural biology… made possible by new technology