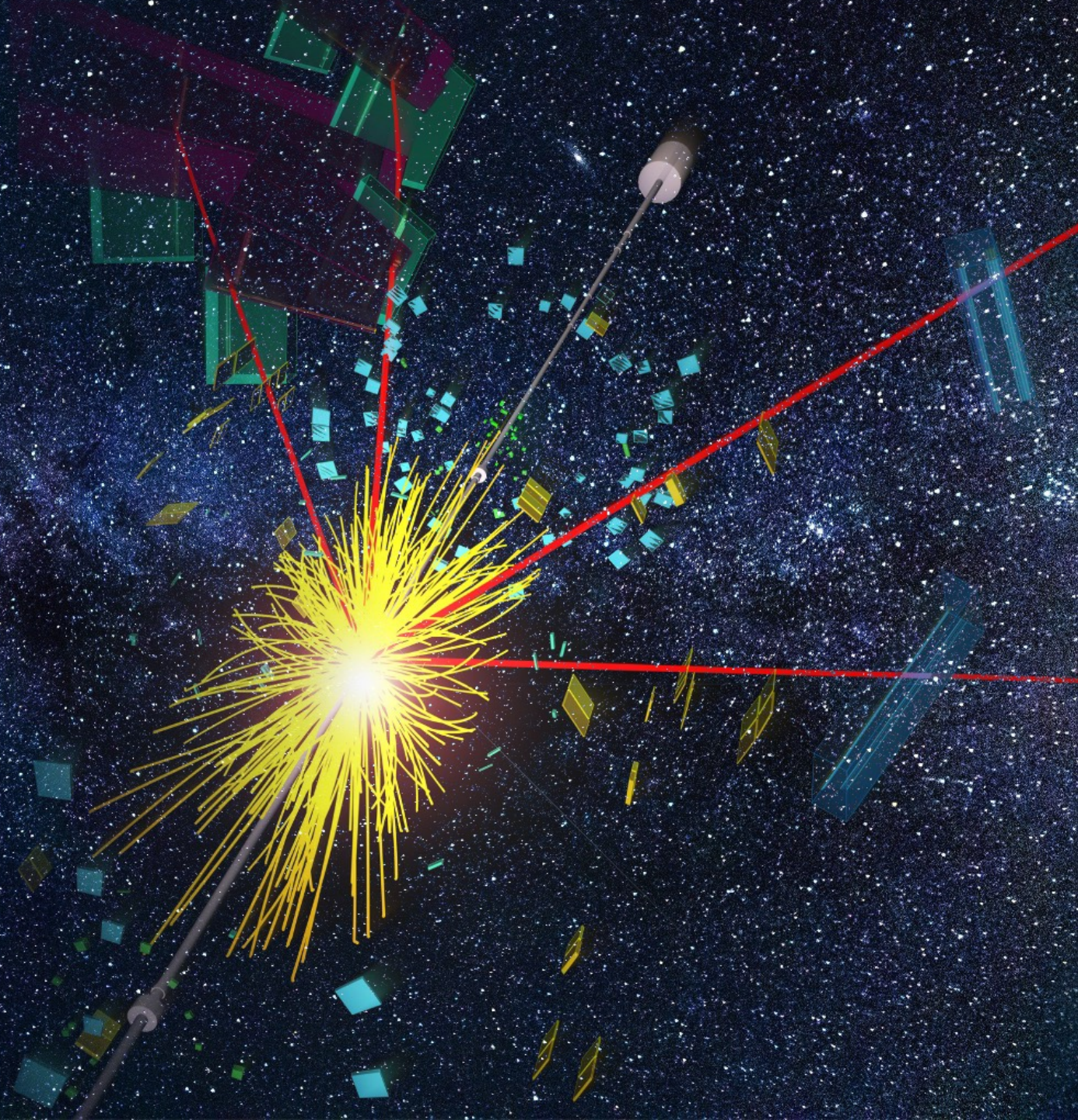


ATLAS and the LHC

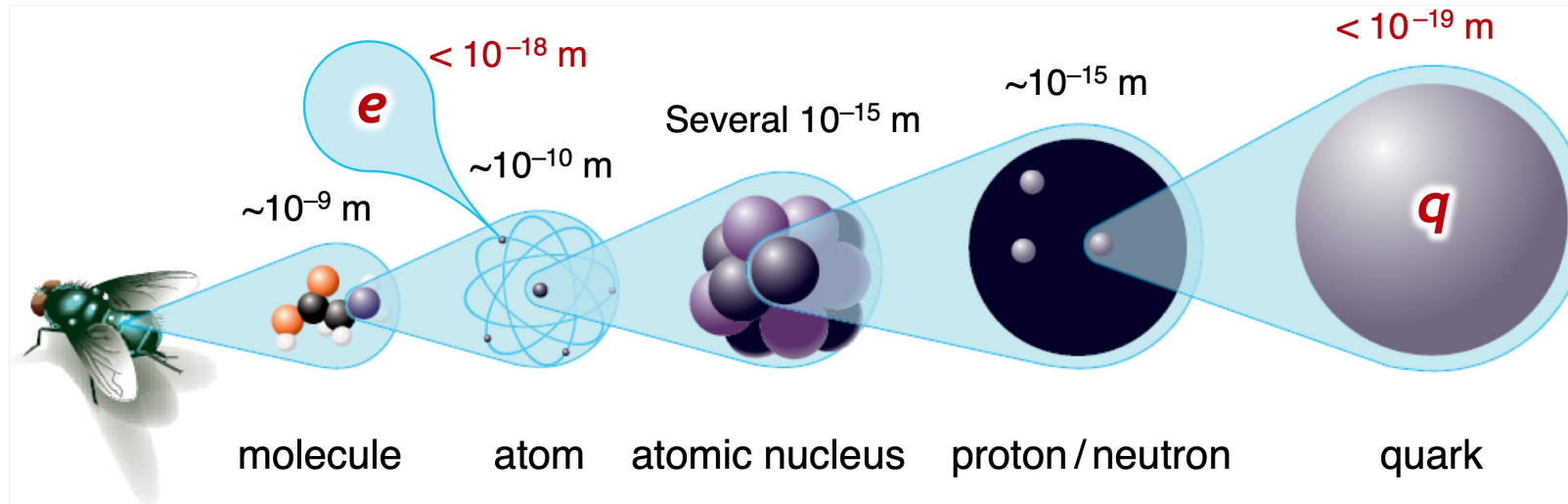
Andreas Hoecker (CERN)

HKUST, 15 January 2026



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

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



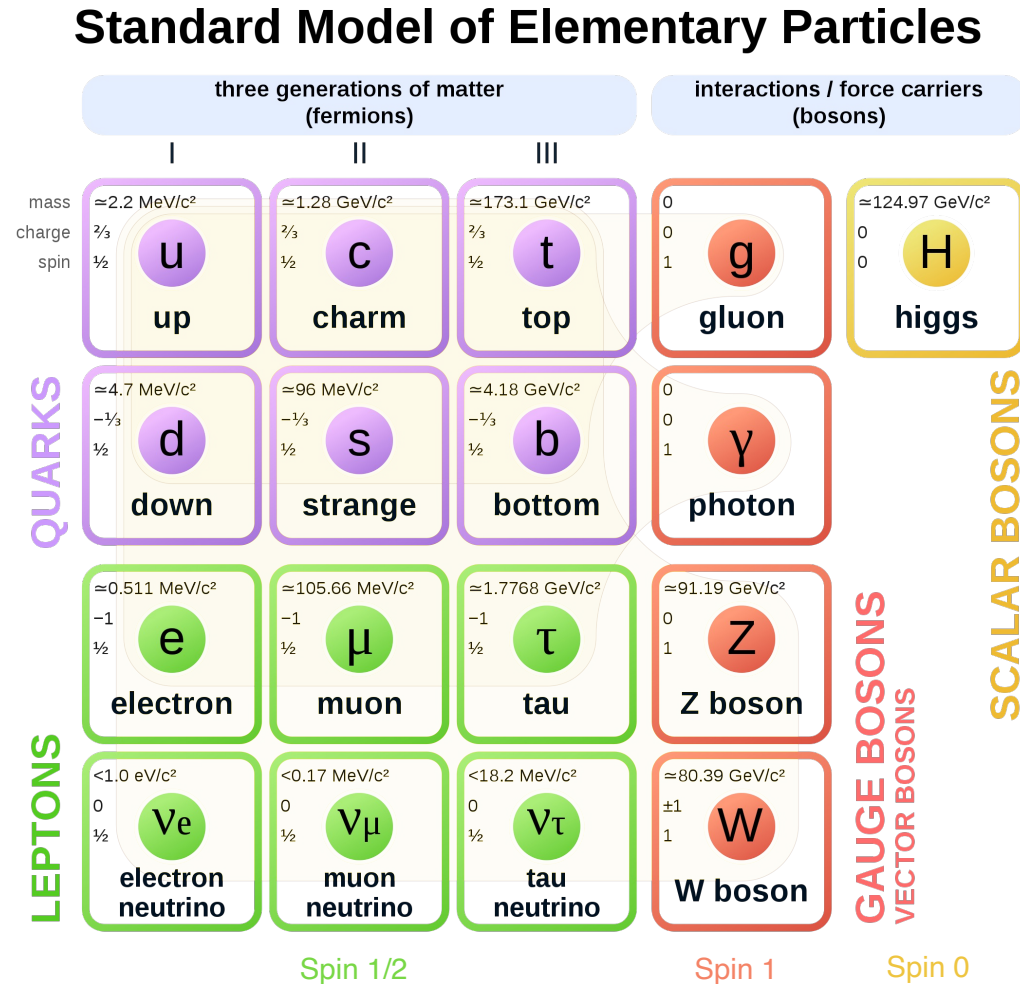
The universe is a strange place

- 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)
- Bare fermion masses are forbidden by chiral structure of weak interaction

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)

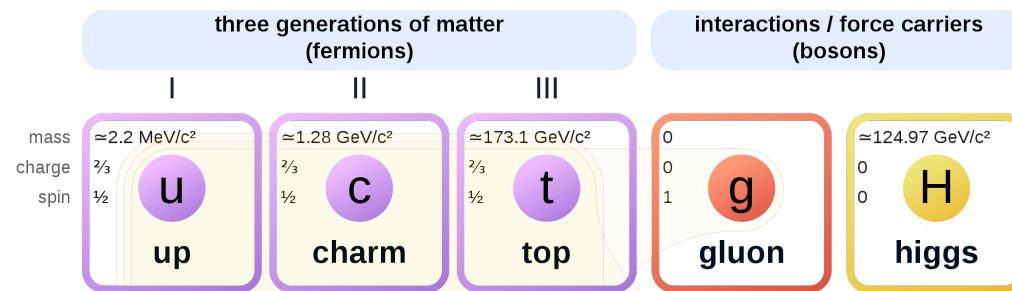


Completely new type of non-universal interactions, nothing to do with known forces

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

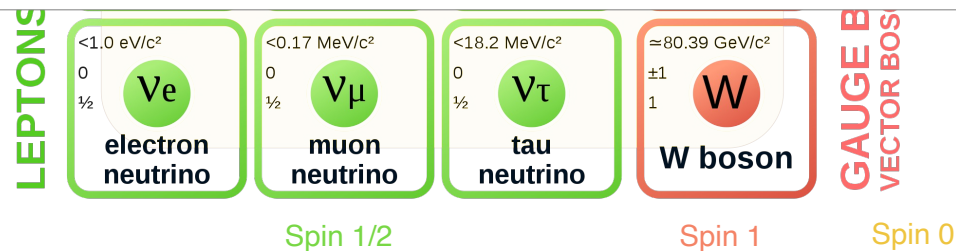


The Standard Model is a highly predictive theory

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} !

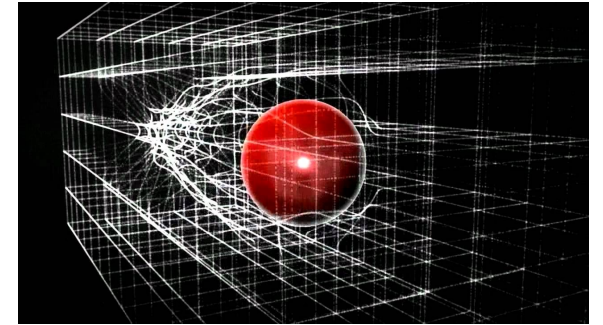


Gauge symmetry and the Brout-Englert-Higgs mechanism

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

The field pervades all space. The interaction of a particle with the Higgs field gives the particle mass. The stronger the interaction the greater the mass ("the Higgs field knows something we do not know").

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



Peter Ware Higgs (1929 – 2024)

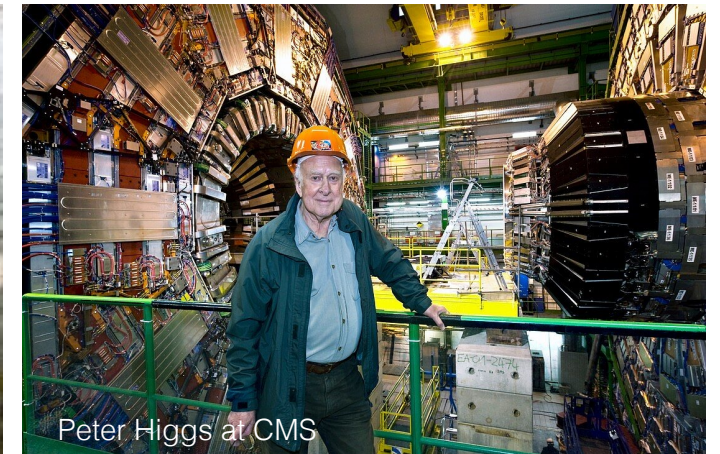


[Broken Symmetries and the Masses of Gauge Bosons](#) — or how to change the course of physics with a good idea on two pages — together with the other famous works from his colleagues in 1964

Superconductivity (BCS theory) was key in the development of the BEH mechanism [[My life as a boson](#), 2010]



Peter Higgs at ATLAS



Peter Higgs at CMS

The Brout-Englert-Higgs mechanism

A few remarks:

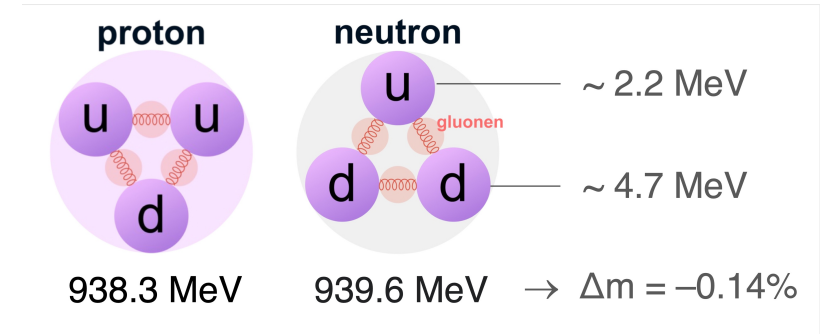
- Chiral (left-right asymmetric, V–A) gauge structure of weak interaction forbids bare fermion masses; both arise only via the BEH mechanism $m_i \propto g_i v$ — making SM fermions naturally light
- The SM structure may propose that there are (many?) super-heavy left-right gauge symmetric fermions (beyond our reach), and the SM fermions only survived down to the EW scale because they cannot have bare masses. This may also explain the very light neutrinos (lepton-number violation has at least D=5, suppressed by super-heavy M)
- The Higgs boson can have bare mass, so why is it (and with it the W and Z bosons) not super heavy?
- **This is the core conceptual challenge of the SM, calling for in-depth study of the scalar sector and potential TeV-scale extensions**

The Brout-Englert-Higgs mechanism

A few further comments:

- BEH mechanism is a new origin of mass via spontaneous symmetry breaking. Other forms: binding energy in composite objects (emergent property of interactions), mass from classical inertia (mass is just a fixed property with no explanation — it's “given”), or the bare Higgs boson mass itself ($m_H = v\sqrt{2\lambda}$), which comes from the curvature of the BEH potential at the minimum, and is a gauge invariant parameter of the Lagrangian
- The BEH 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?
- *Quiz: what would happen, had the electron the mass of a muon (ie, were the electron 200 times heavier)?*

[see [R. Cahn](#), 1996]



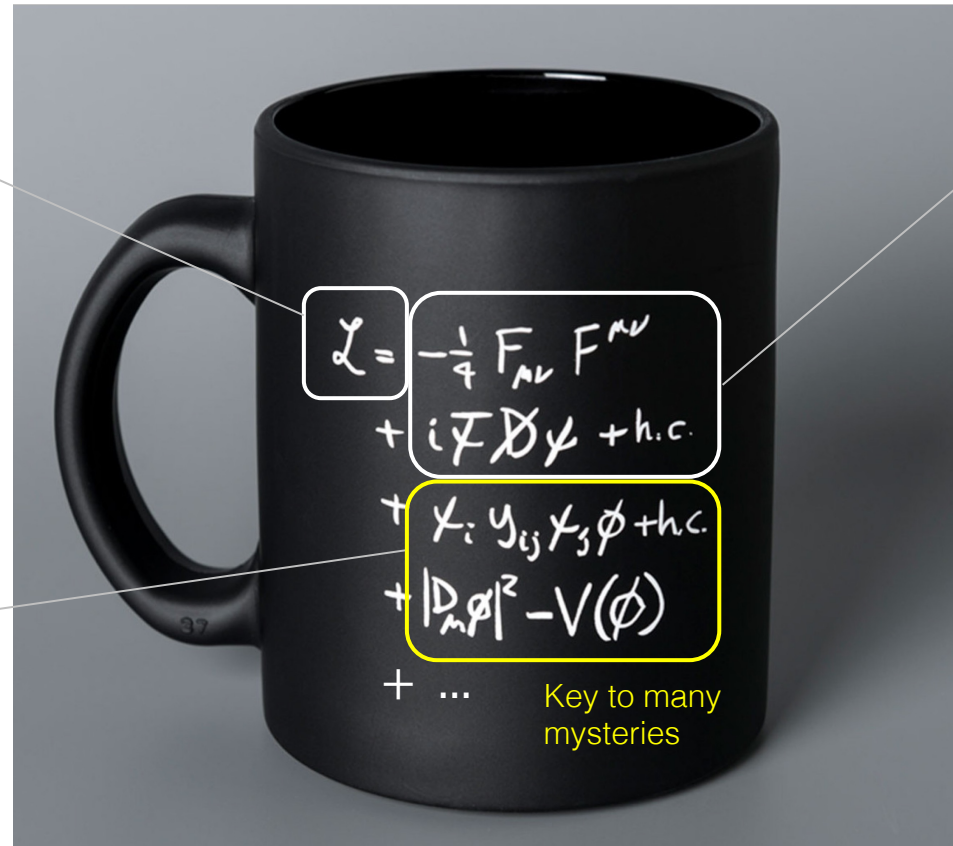
Completing the Standard Model

The scalar Higgs sector completes the Standard Model

The **SM Lagrangian**

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

Unpleasant: not governed by symmetries, 23 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

Key to many mysteries

*Assuming neutrinos are Majorana particles (total of 9 neutrino related parameters)

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 (the strength of the magnets determines the maximum reachable beam energy)
- Proton and ions are accelerated to multi-TeV scale energies before they collide

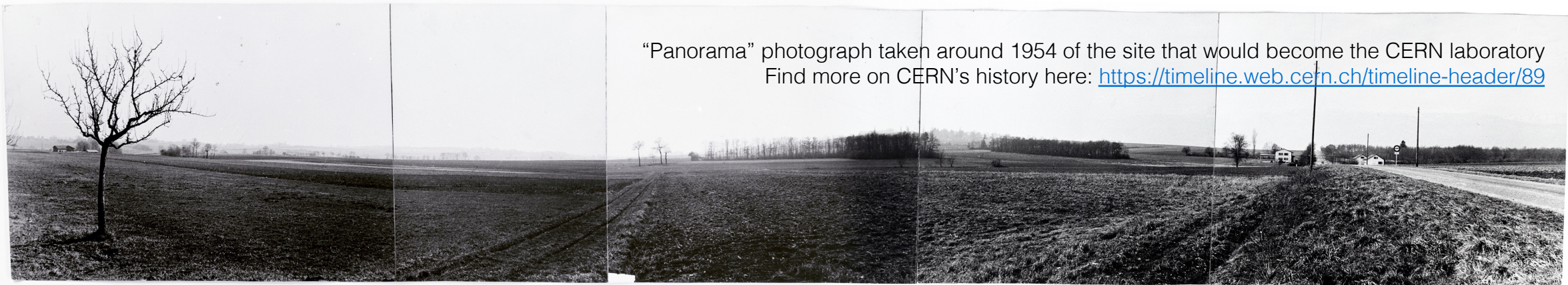
The LHC has a total of 9,300 magnets for beam bending, beam focusing and orbit corrections

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"

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

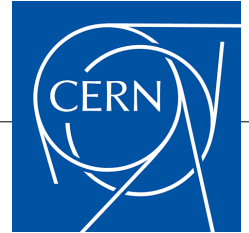


CERN today

ATLAS Experiment



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



24 Member States

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

3 Associates Member States in the pre-stage to membership

Cyprus – Slovenia

8 Associate Member States

Brazil – Croatia – India – Latvia – Lithuania – Pakistan
Turkey – Ukraine

6 Observers

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

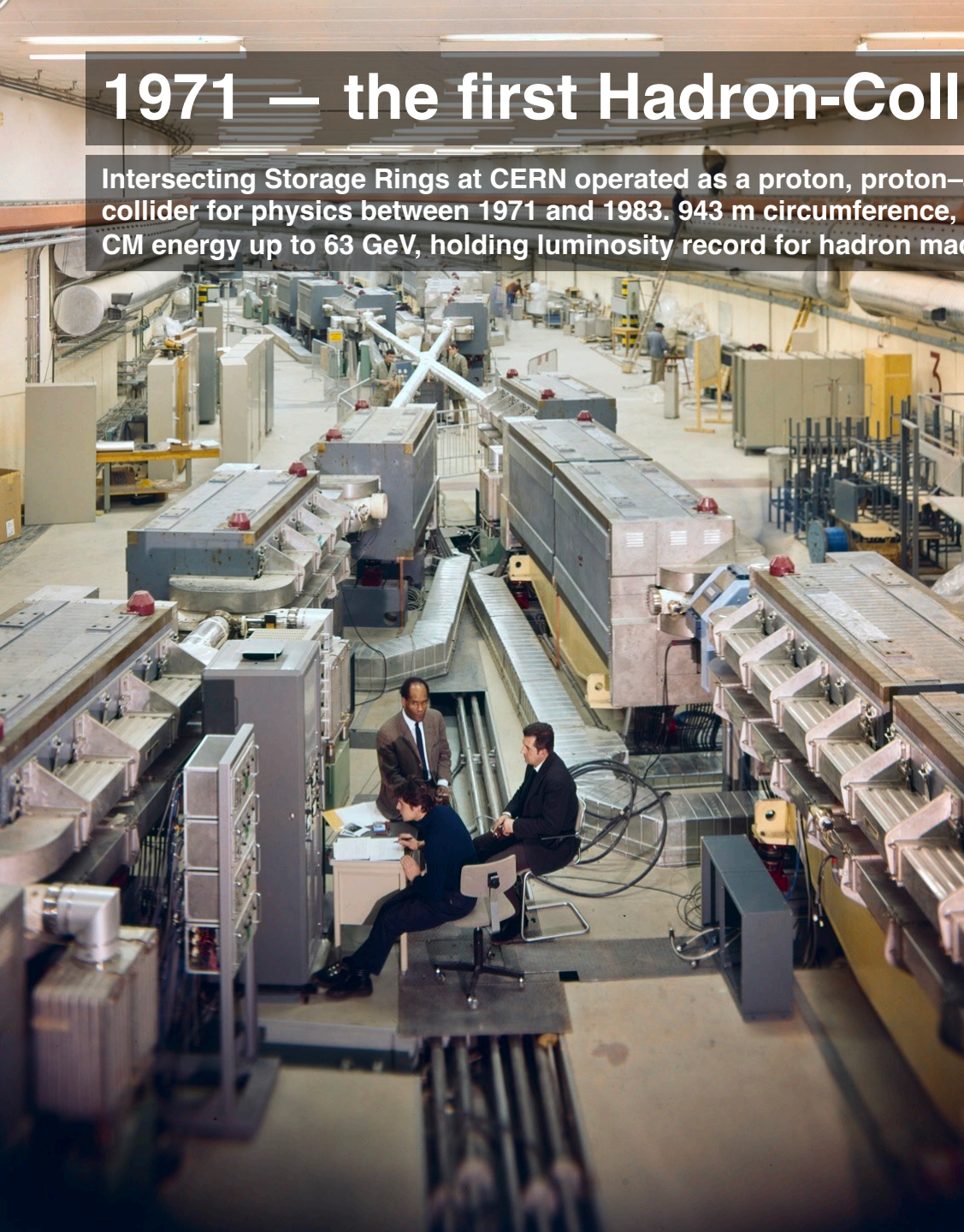


As of 31 December 2023
Employees:
2,666 staff, 1,002 graduates
Associates:
12,370 users, 1,513 others

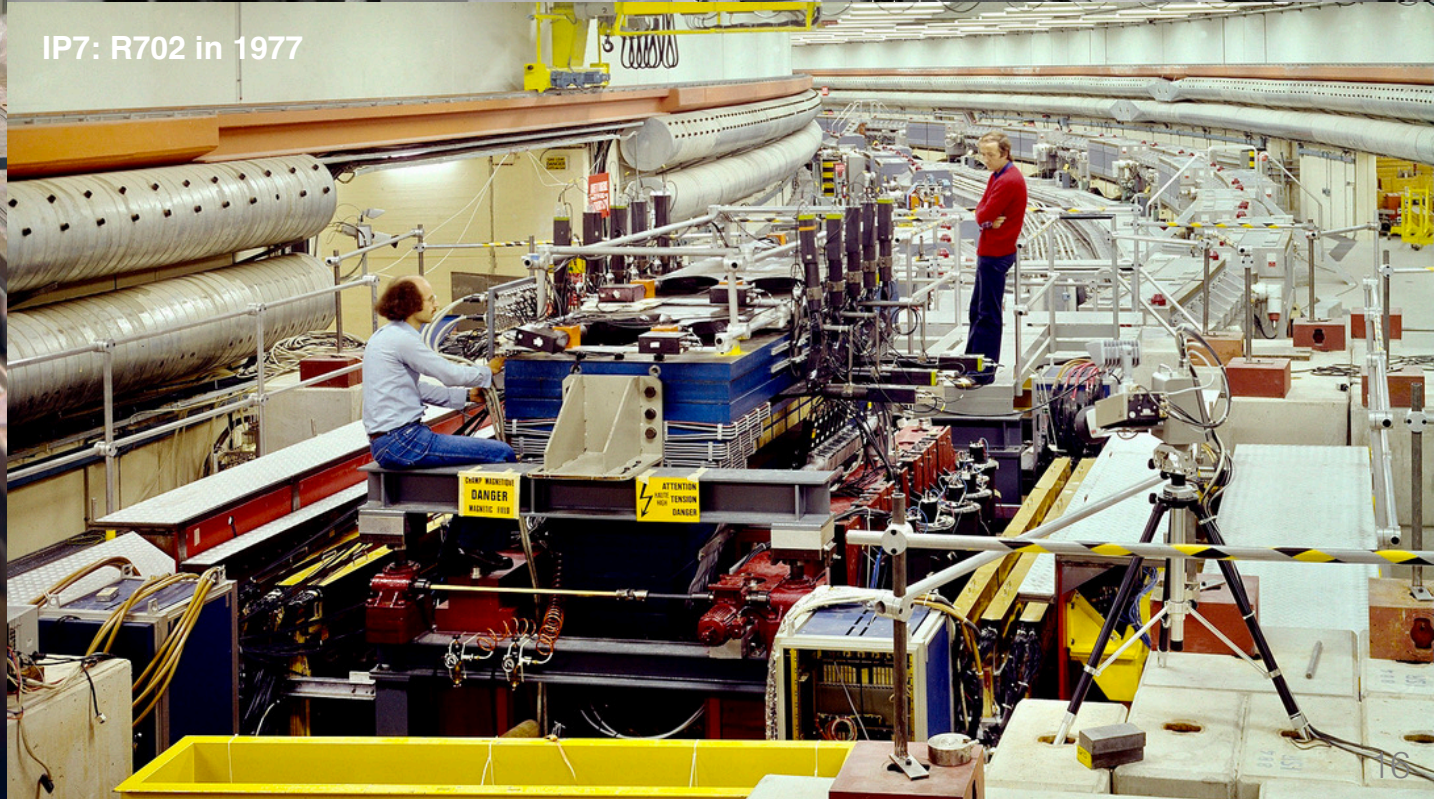
Very successful: **CERN
Summer Student
Programme**, open to Non-
Member States

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



ISR Control Room (early 70s)



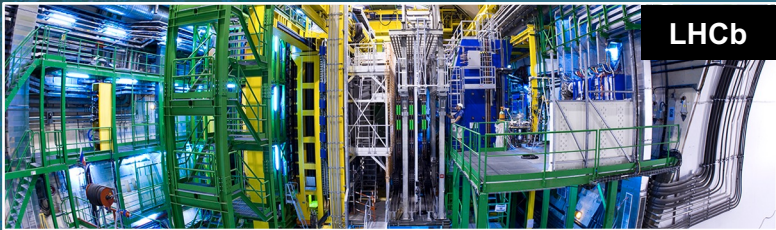
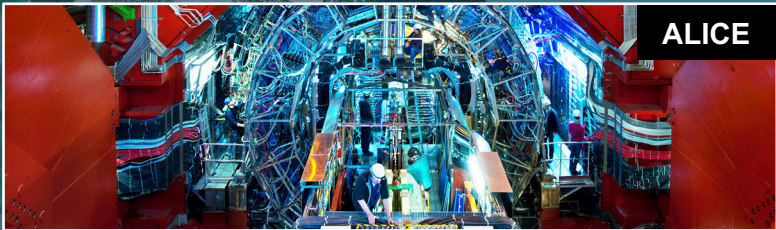
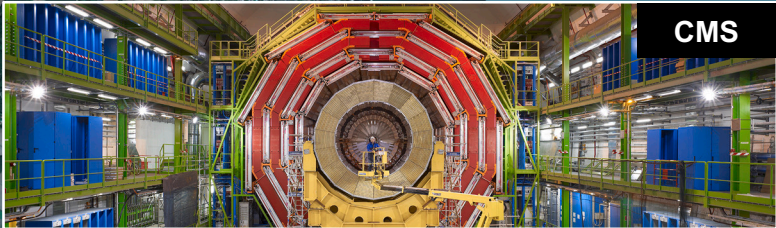
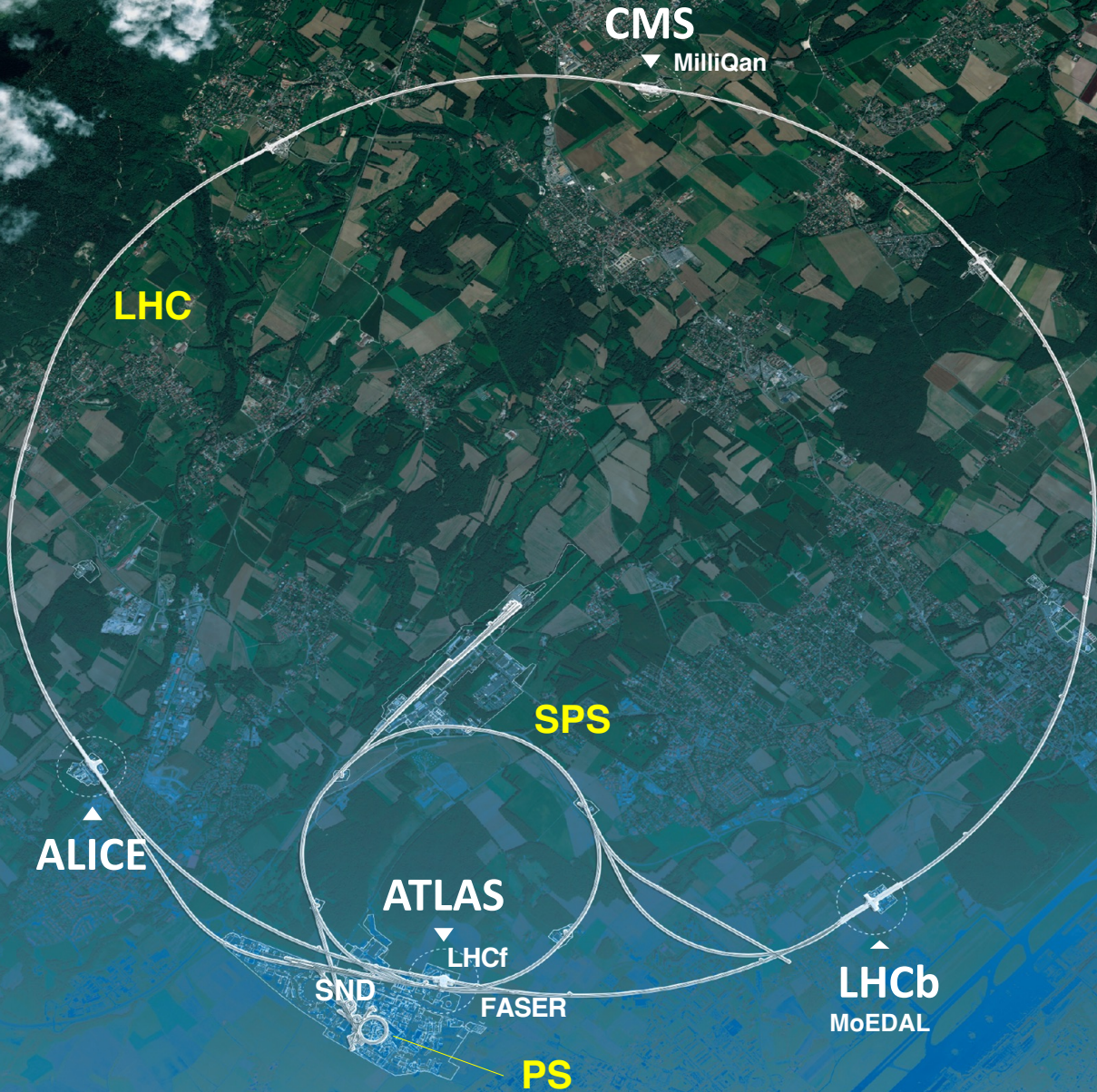
LHC Control Room (July 2022)



LHC Experiments



joined ATLAS in 2014



Aerial view

Important design considerations for the LHC (around 1990)

The new machine must be capable of exploring the full mass range up to the TeV mass scale. The question of the existence of the Higgs boson must be clarified, i.e. the detectors must have a discovery potential over the full mass range up to 1 TeV

To reach this goal with the given ring of 27 km and the centre-of-mass energy in the range of 14–16 TeV, required very high luminosities of the order of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

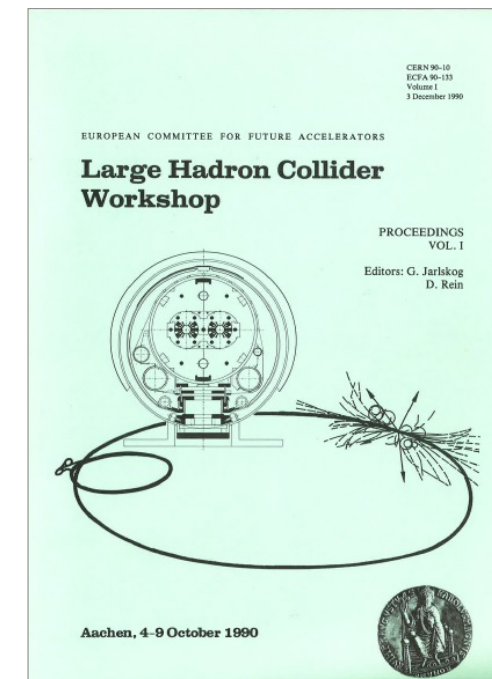
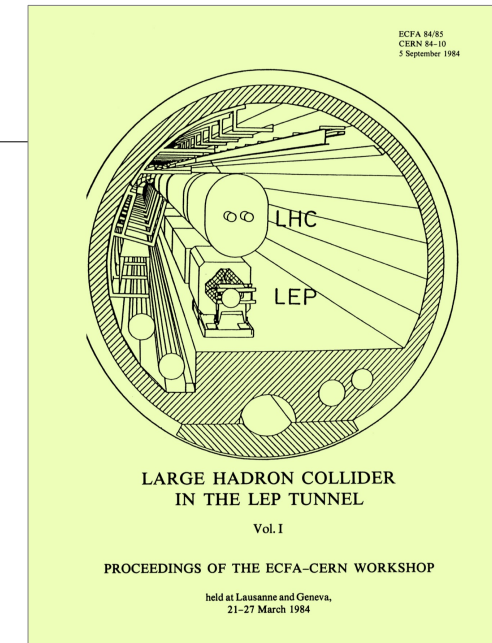
This required a huge programme on detector and accelerator research and development

Theoretical view at the time: **No-Loose theorem:**

→ *The LHC will either discover the Higgs boson, or new physics, or both*

History of 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
- 1986:** **LAA** (Italian project) R&D on new detector technologies started, later followed by the **DRDC** (Detector Research & Development Committee)
- 1987:** **La Thuile Workshop:** many LHC colleagues were already involved in this workshop set up by Carlo Rubbia as part of **CERN's Long Range Planning Committee**
- 1989:** **ECFA Study Week in Barcelona** for LHC instrumentation
- 1990:** **Large Hadron Collider Workshop Aachen (CERN-ECFA)**
- 1992:** **CERN – ECFA meeting “Towards the LHC Experimental Programme” in Evian**



History of the LHC experiments

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

For proton–proton:

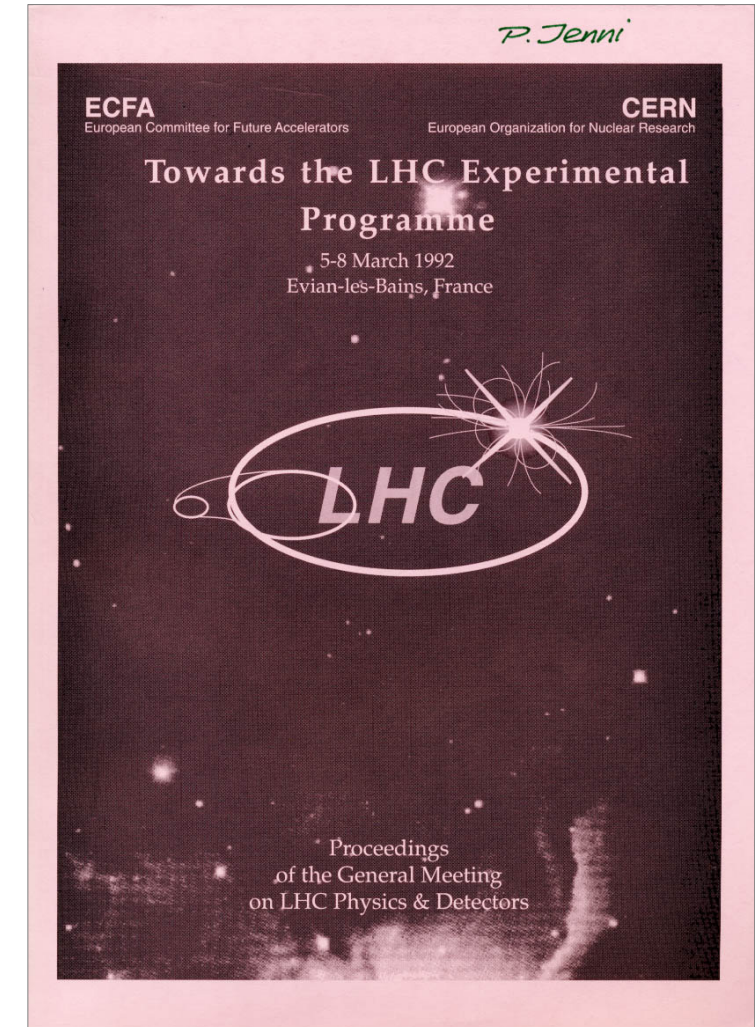
•	ASCOT	P. Norton
•	CMS	M. Della Negra / H. Desportes
•	EAGLE	P. Jenni
•	L3P	S. Ting, F. Pauss



Peter Jenni (CERN)

In addition:

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



History of ATLAS

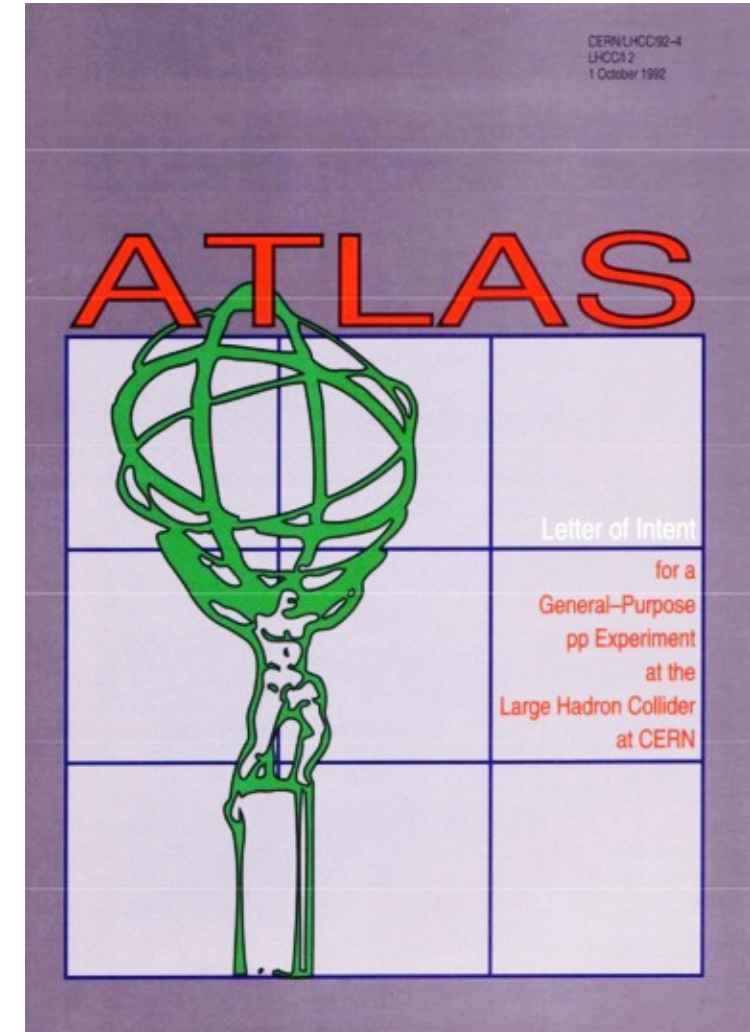
March 1992 – Summer 1992: merging of EAGLE and ASCOT

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

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

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

Official birth of the **ATLAS* Collaboration**



Status: November 2024



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

177 institutions (248 institutes) from 41 countries



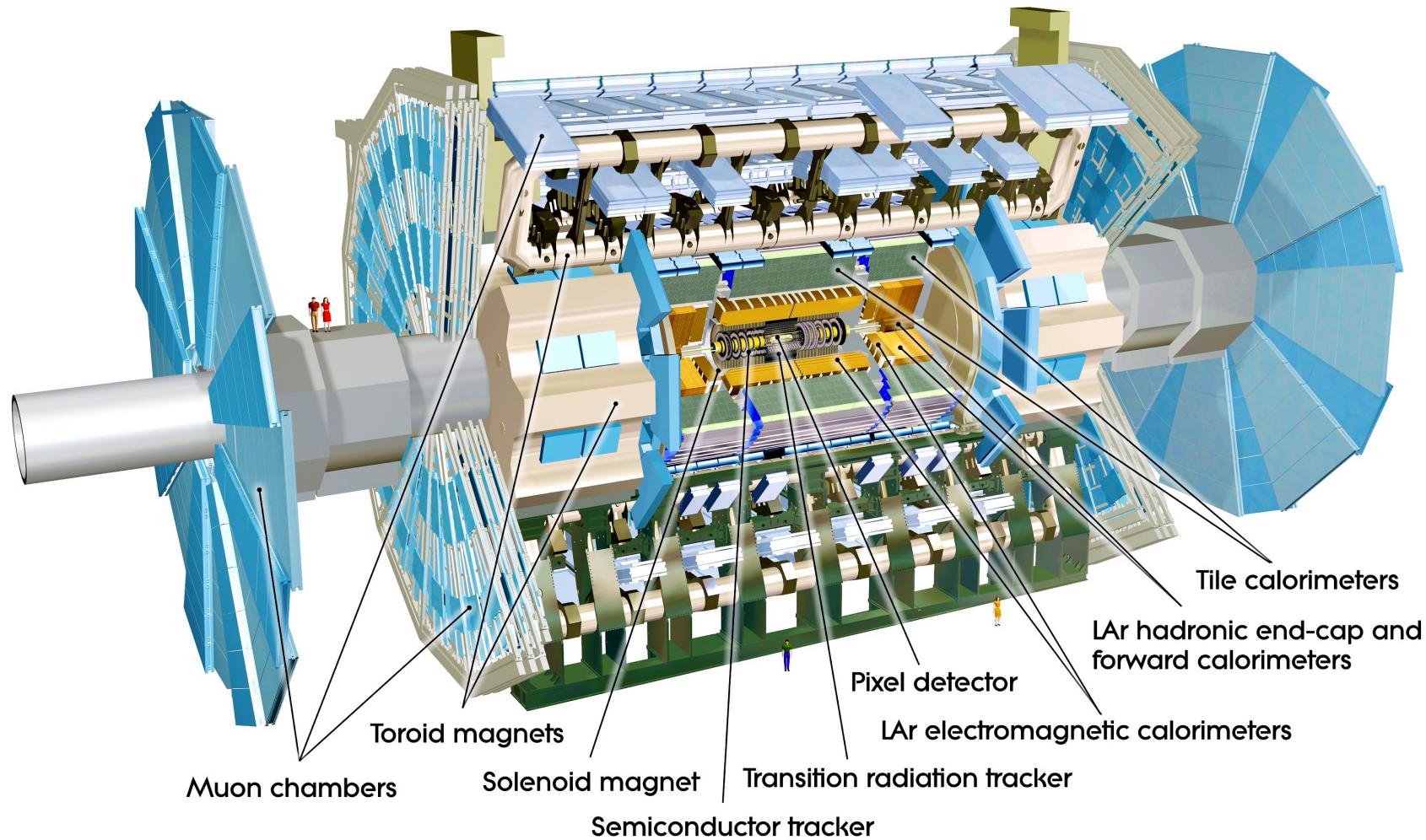
177 Institutions (248 Institutes) from 41 countries
(>100 nationalities) + 13 Technical Associate Institutes

- 2900 scientific authors
- 1950 with PhD contributing to M&O share
- **1200 physics PhD students**
- 1300 engineers and technicians
- 6000 members

Try the interactive ATLAS map: <http://atlas.web.cern.ch/Atlas/Management/Map.html>

Status: January 2026

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

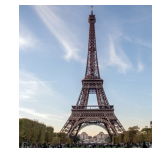
spatial resolution $\sim 15\ \mu\text{m}$ (in azimuthal direction)

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 ~



ATLAS Detector construction and installation



ATLAS cavern after excavation in July 2002

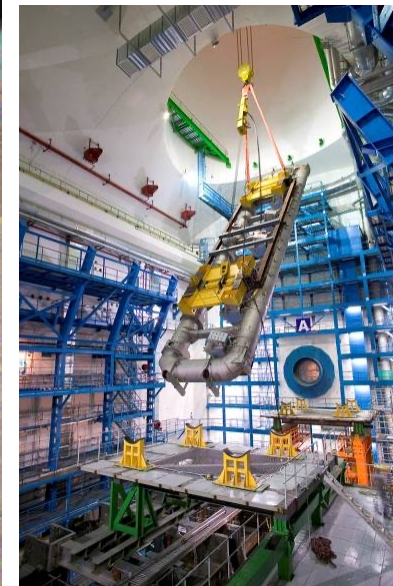
- 53 m long
- 35 m high (10-storey building)
- 30 m wide

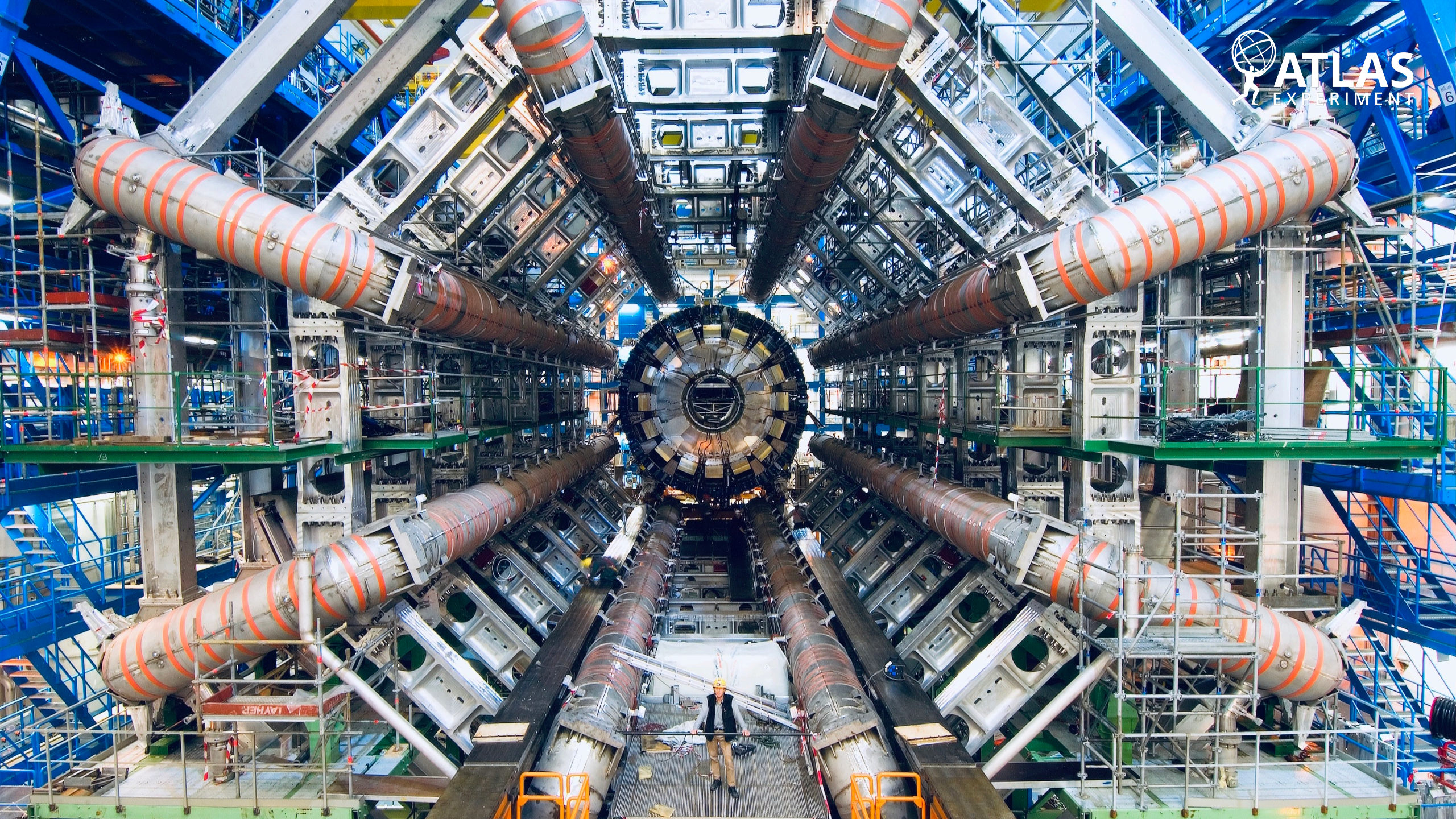
ATLAS Detector construction and installation

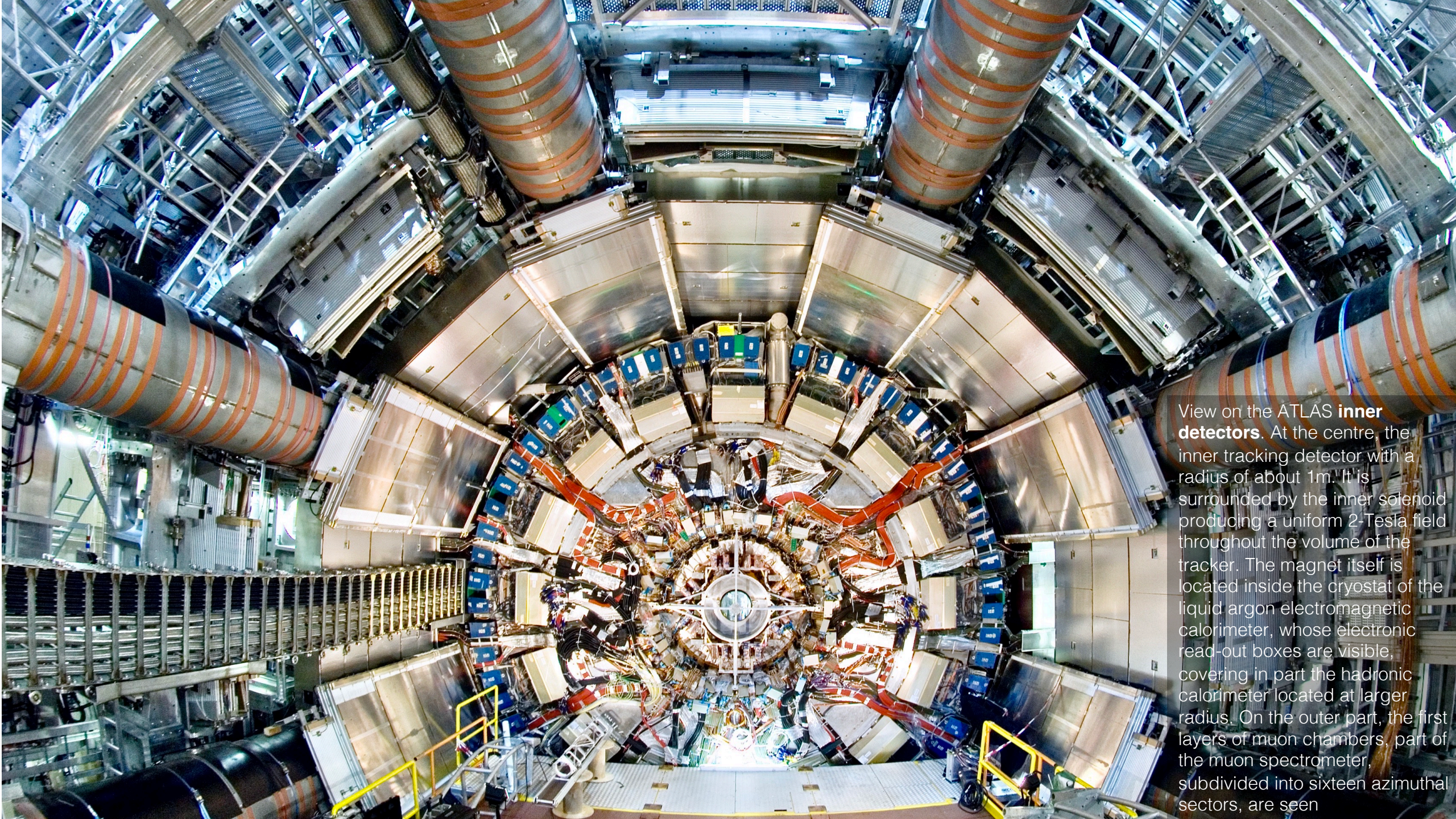


Barrel Toroid coil integration and testing in Hall 180 (CERN)

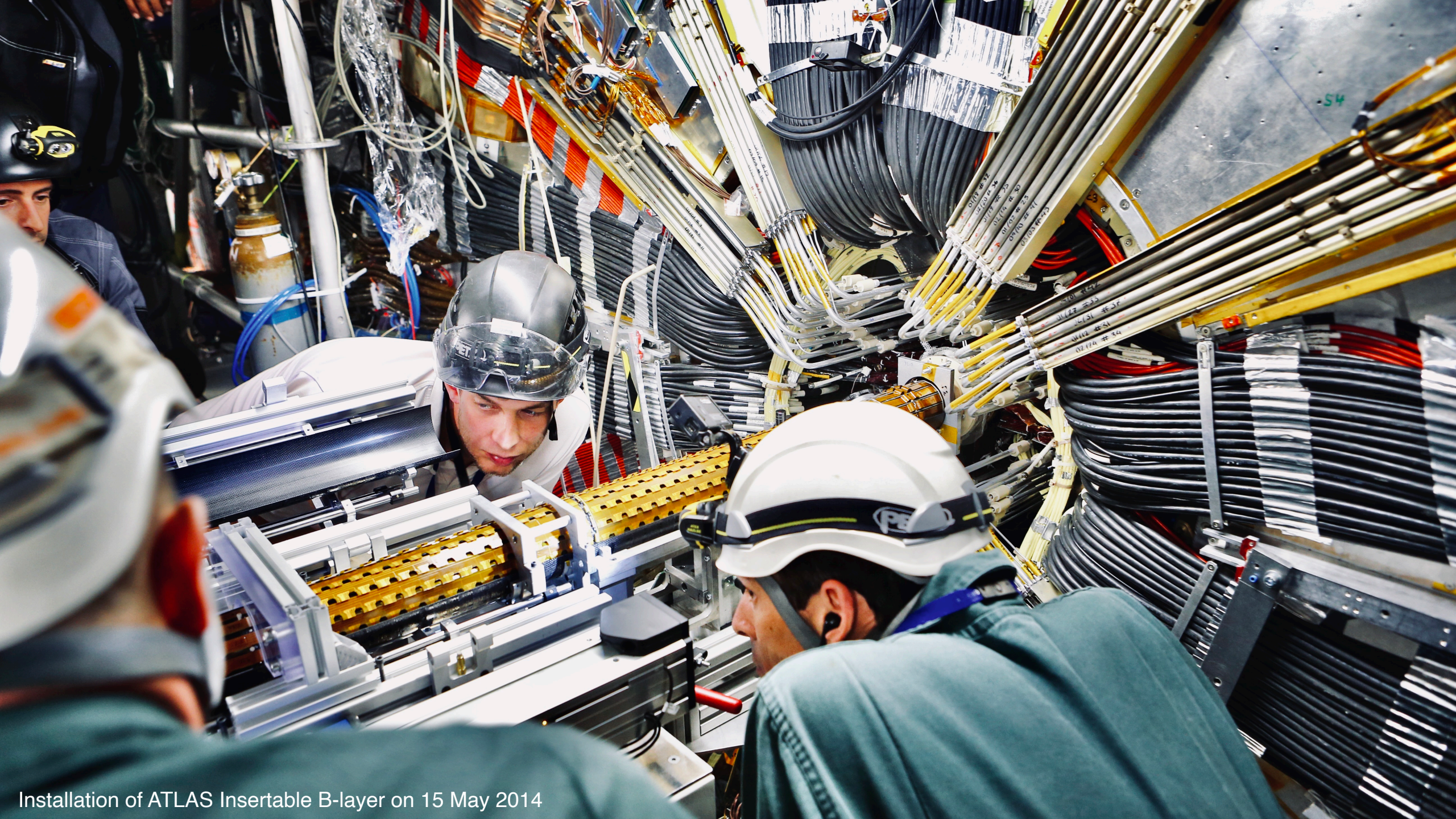
ATLAS Detector construction and installation







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

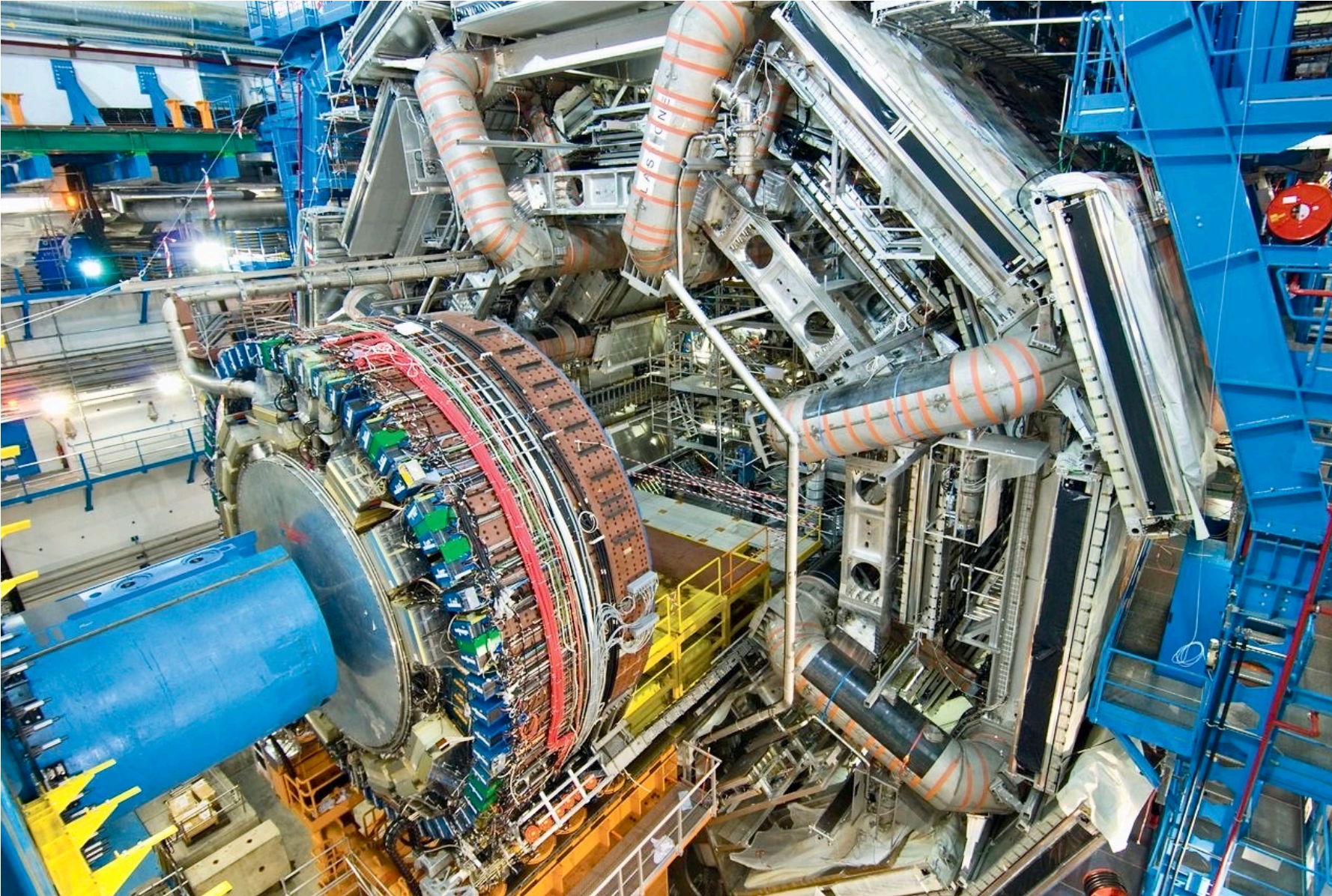


Installation of ATLAS Insertable B-layer on 15 May 2014

A complete ATLAS tile calorimeter module covering 1/64 of the full azimuth

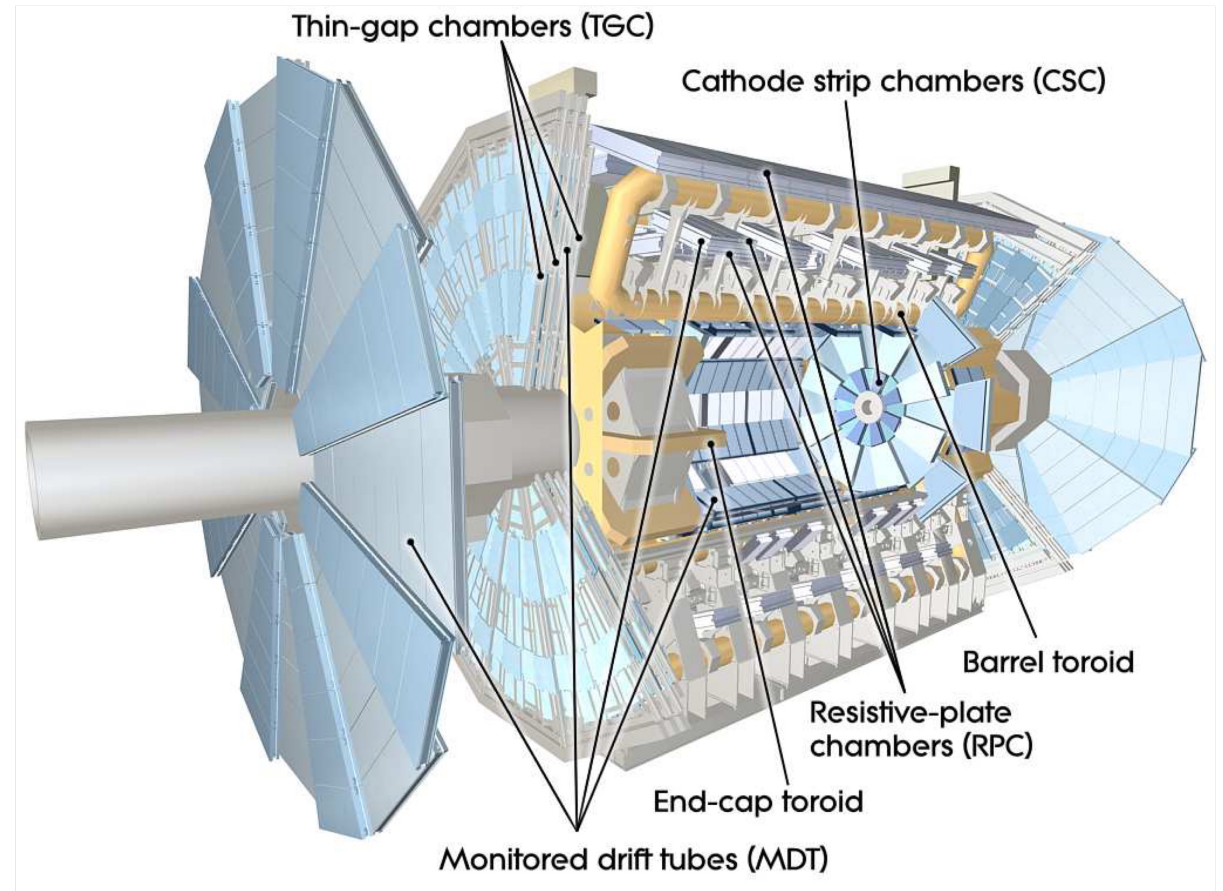
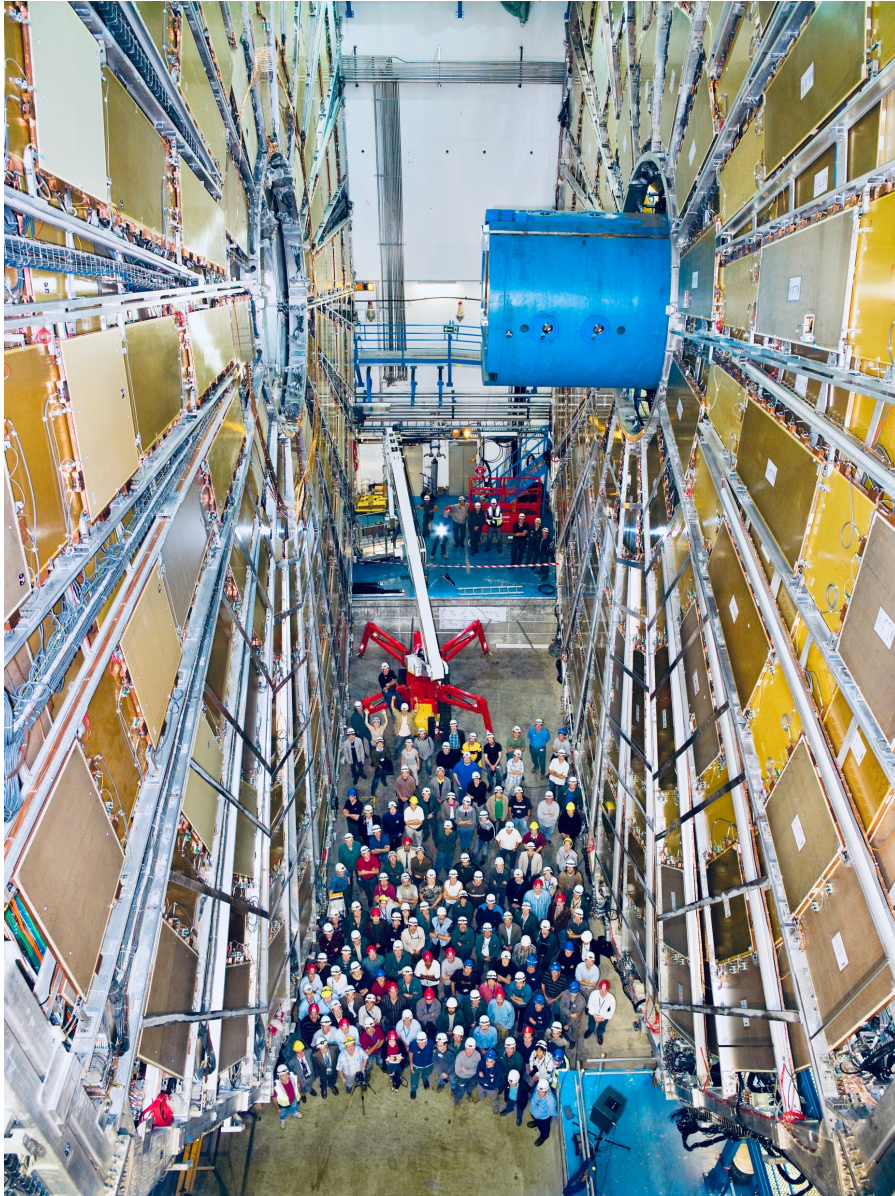


ATLAS Detector construction and installation – Calorimeters



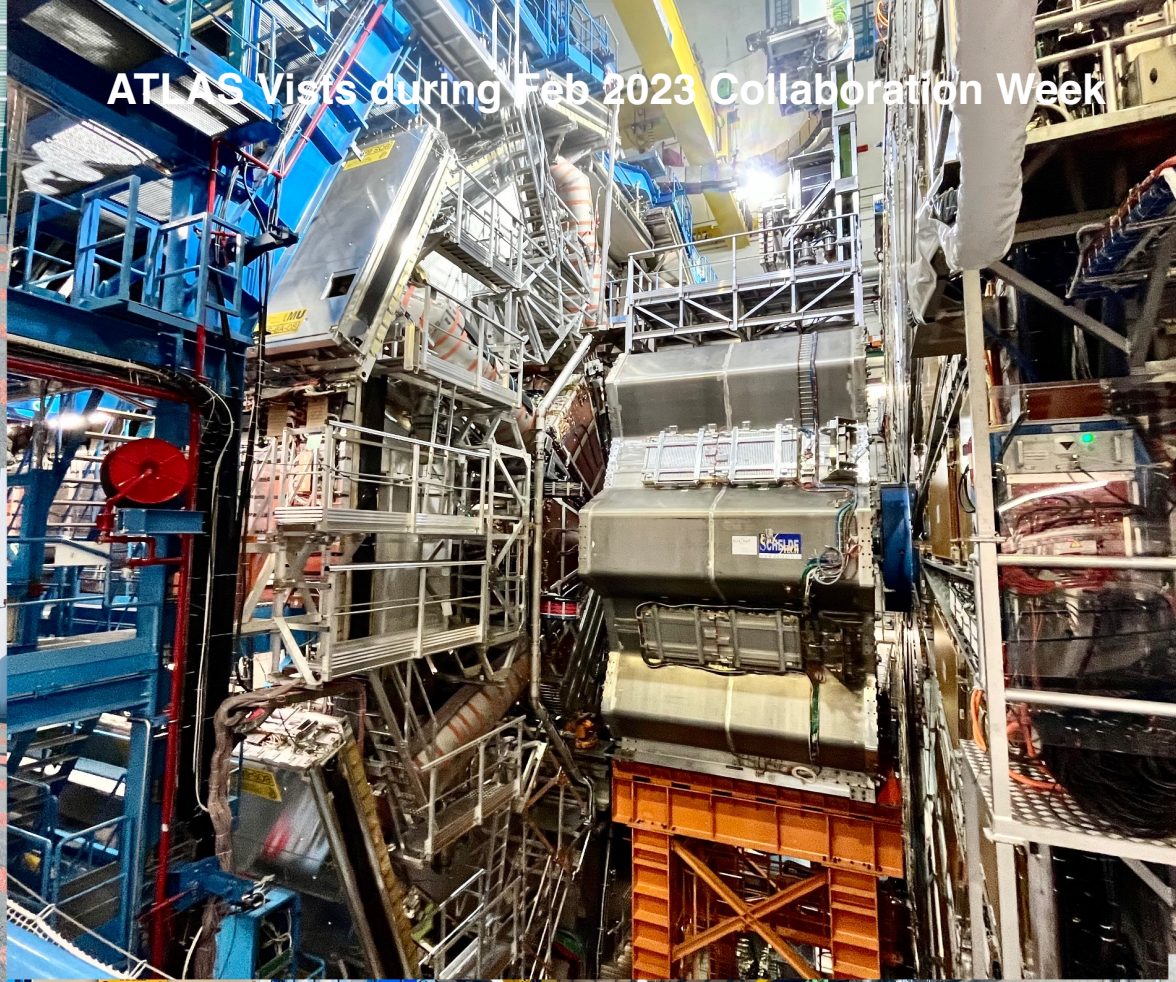
View of the central part of ATLAS during final assembly stages. The wire chambers mounted inside and around the toroid magnet cryostats are well visible, as is part of the end-cap hadronic calorimeter before its insertion inside the magnet

ATLAS Detector construction and installation – Muon Spectrometer

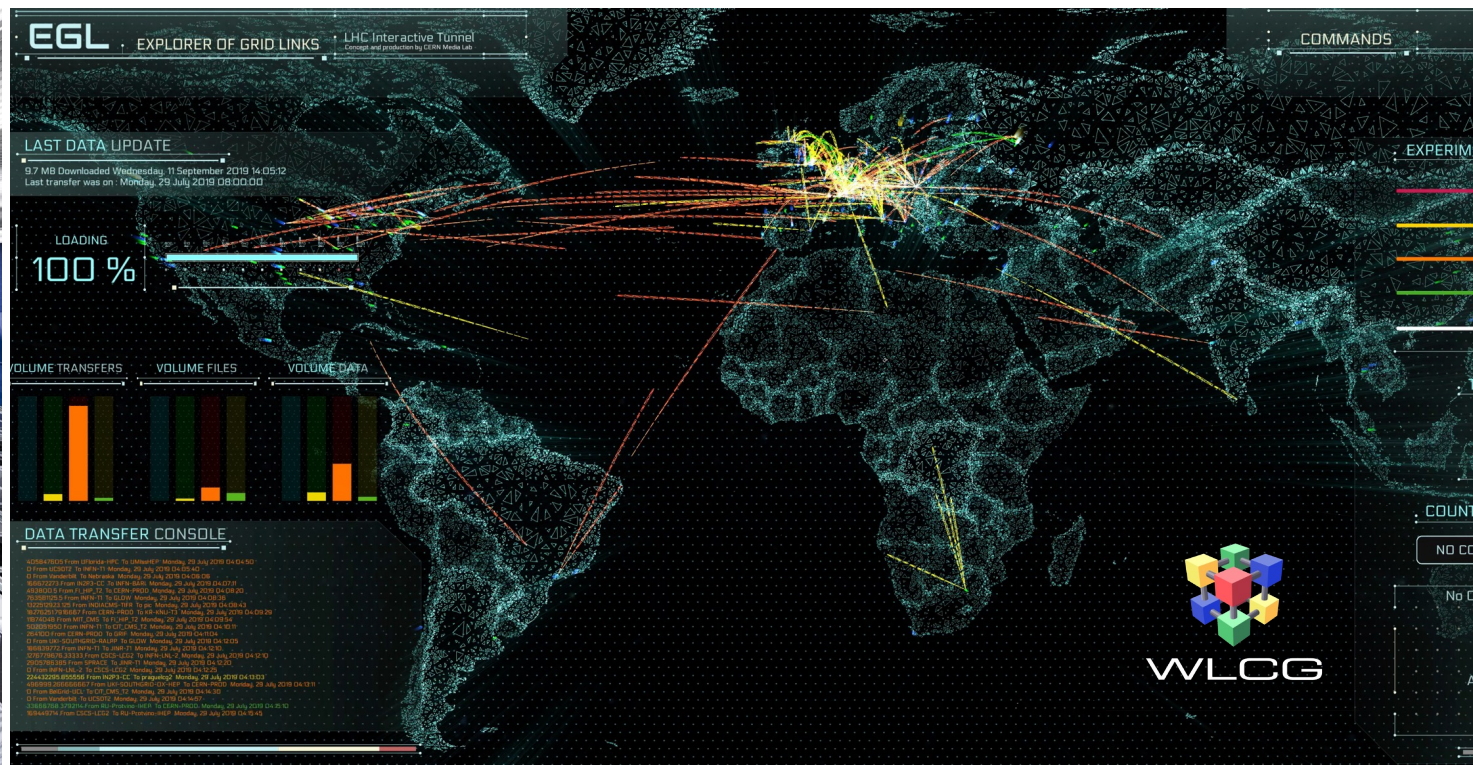


View on the Big Wheels, intermediate muon stations with four 25 m diameter wheels on each forward side

ATLAS Visits during Feb 2023 Collaboration Week



The Worldwide LHC Computing Grid (WLCG)



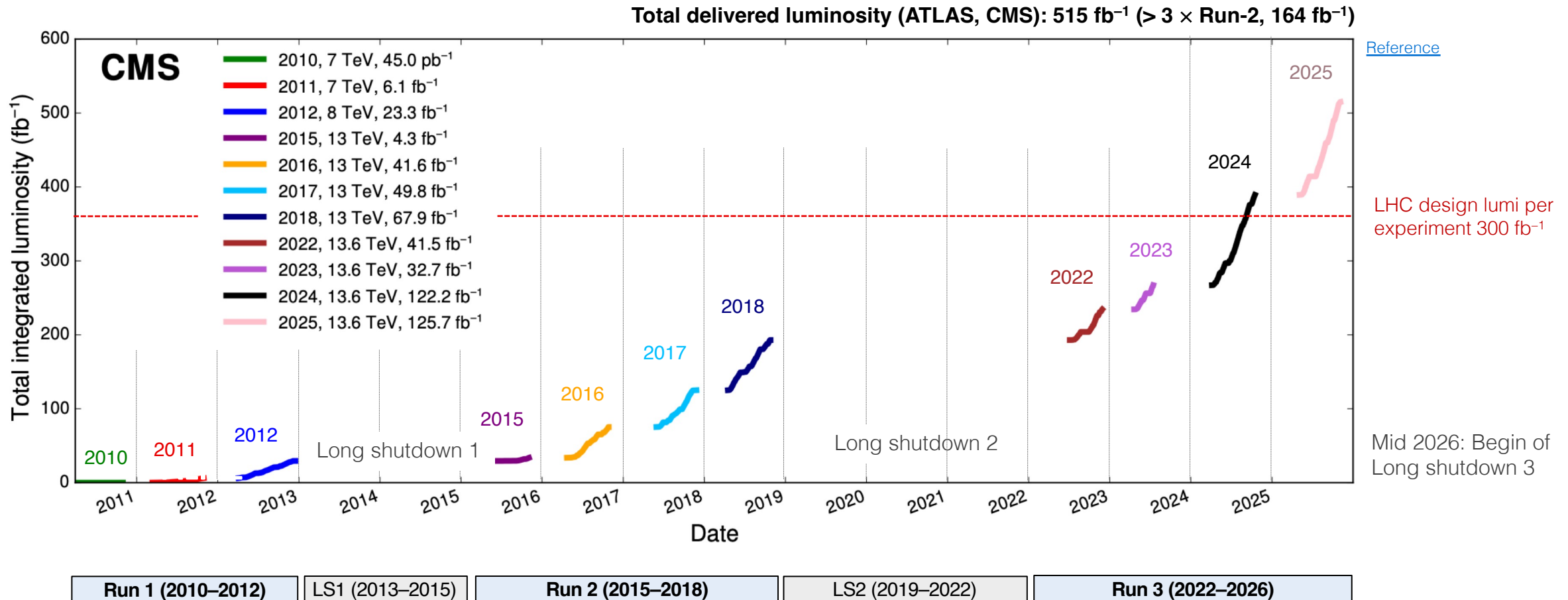
WLCG stores, distributes,
processes and analyses
LHC experiments' data

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

1500 Petabytes (1.5 Exabytes)
of CERN data stored worldwide

Most successful LHC Runs 1, 2, 3

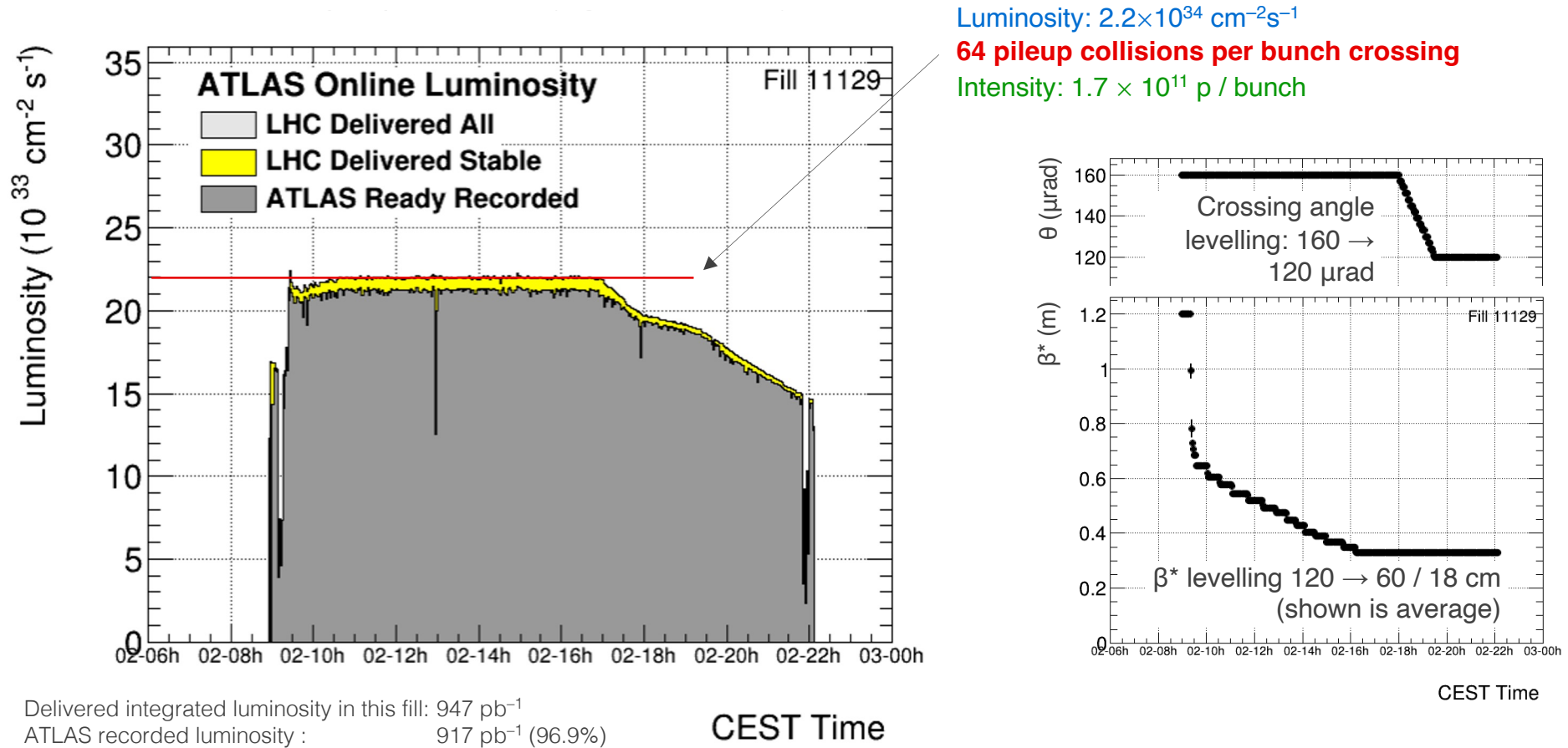
Superb LHC performance in 2024 and 2025 — on track for a strong Run-3 finish



Treasure trove: ATLAS & CMS can each expect $> 450 \text{ fb}^{-1}$ of good-for-physics data from LHC Runs 2 + 3

Most successful LHC Runs 1, 2, 3

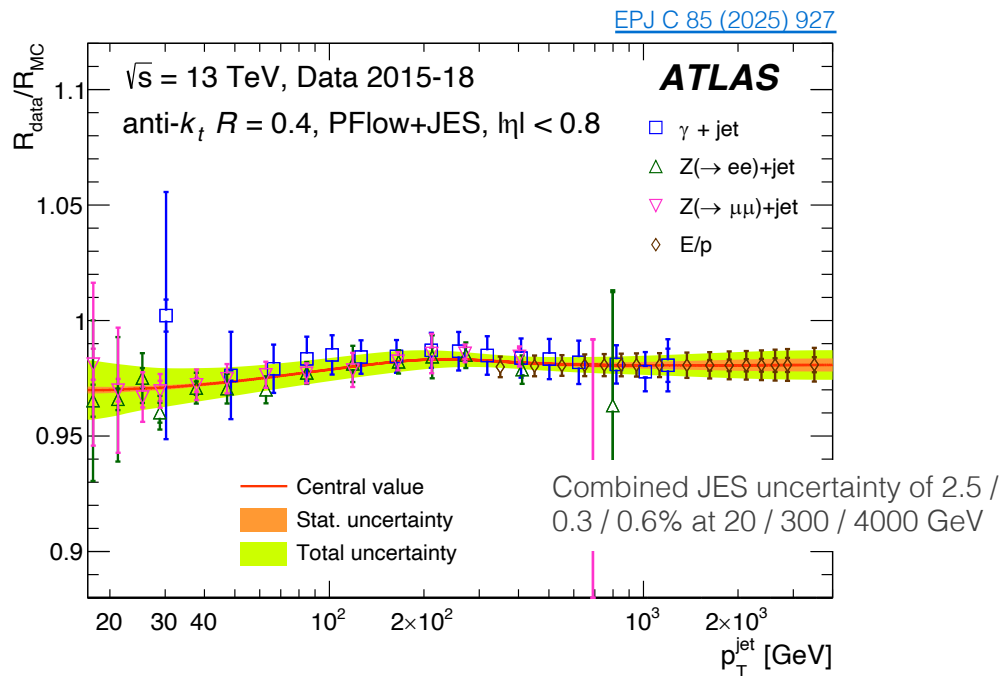
Luminosity profile in ATLAS & CMS during a 15h28 fill (13h07 in stable beams), 2 Oct 2025



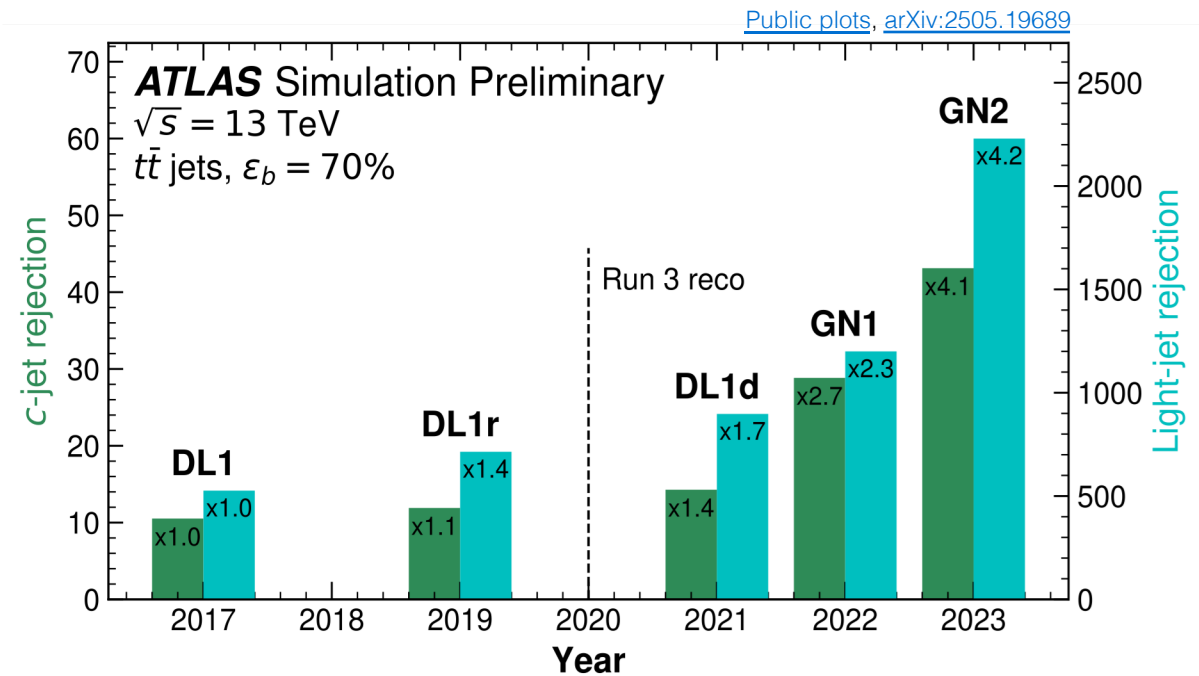
What have we learned from the LHC so far — a bold summary

Performance of accelerator and ATLAS experiment

- LHC, ATLAS detector, software & computing, object reconstruction and physics analysis all perform(ed) beyond design



Detailed jet energy calibration using in-situ processes enables, among others, high-precision top mass measurements (0.2%)



Efficient and pure jet-flavour tagging and further ML based performance and analysis improvements enhance physics reach

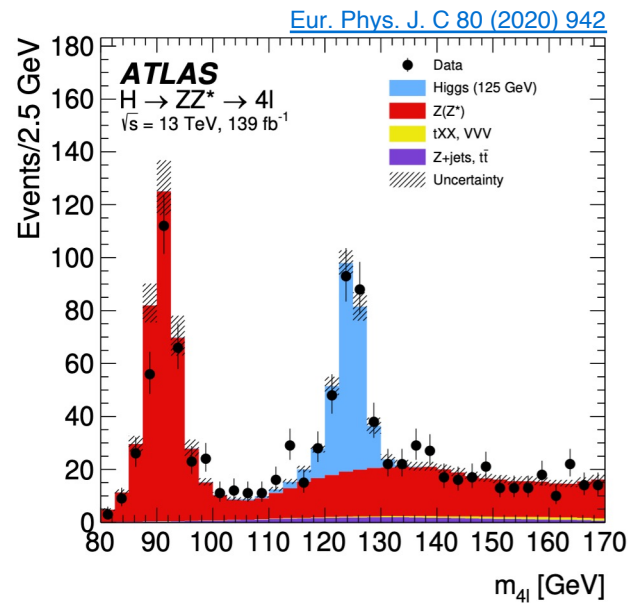
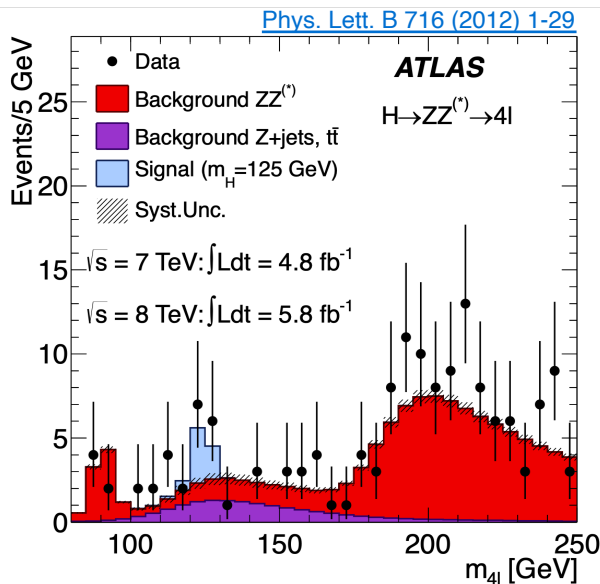
What have we learned from the LHC so far — a bold summary

Discovery and characterization of the Higgs boson

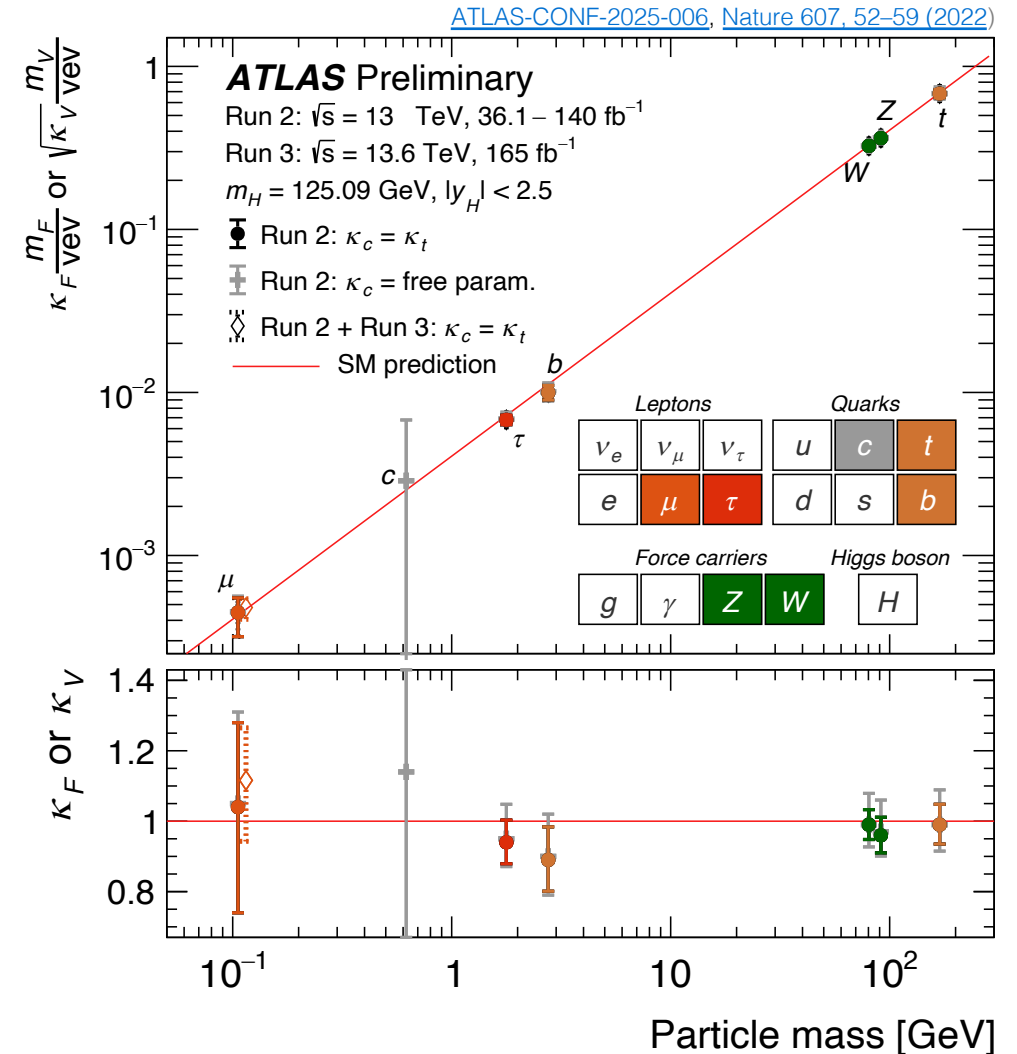
- Discovery of scalar Higgs boson enables for the first time direct study of electroweak symmetry breaking and the process of mass generation
- Higgs couplings to bosons and fermions match SM expectations within 5–20%. Γ_H is as SM within ~50% uncertainty. $B(H \rightarrow \text{inv}) < 11\%$



Fabiola Gianotti and Peter Higgs, 4 July 2012



Left: at moment of discovery. Right: after Run 2



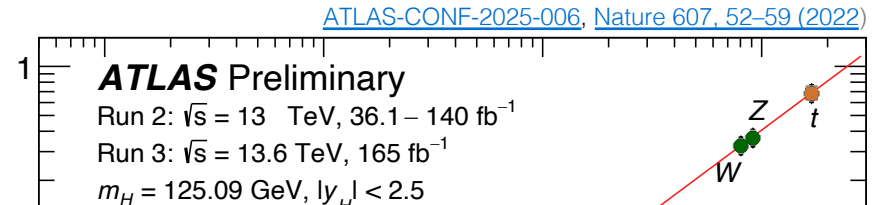
What have we learned from the LHC so far — a bold summary

Discovery and characterization of the Higgs boson

- Discovery of scalar Higgs boson enables for the first time direct study of electroweak symmetry breaking and the process of mass generation

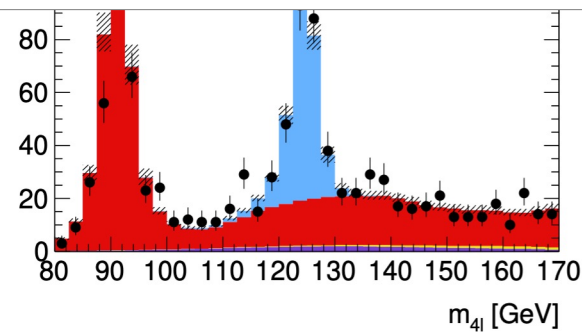
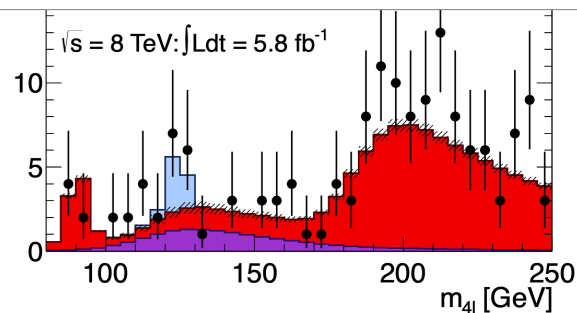


$$m_\nu$$
 or $\sqrt{\kappa_\nu} \text{ vev}$

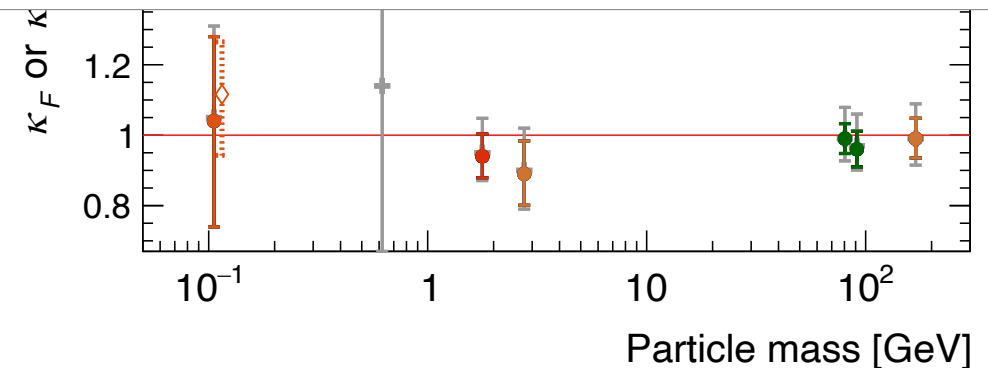


The scalar sector is directly connected with very profound questions: naturalness, vacuum stability & energy, flavour. Also: is the Higgs boson actually elementary?

The Higgs boson is a completely new type of particle whose detailed study requires a broad experimental programme that will extend over decades



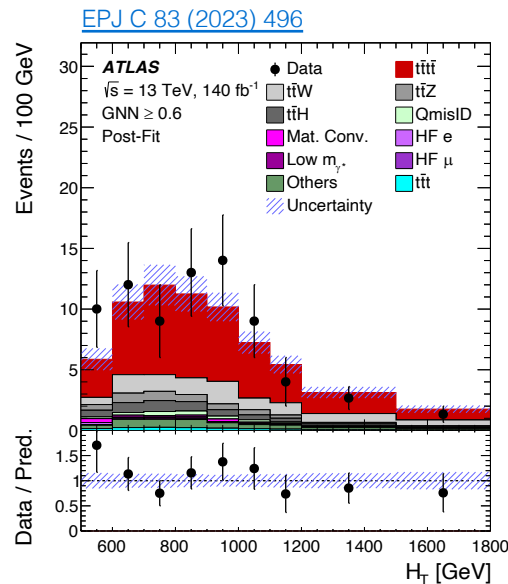
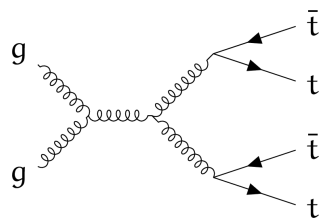
Left: at moment of discovery. Right: after Run 2



What have we learned from the LHC so far — a bold summary

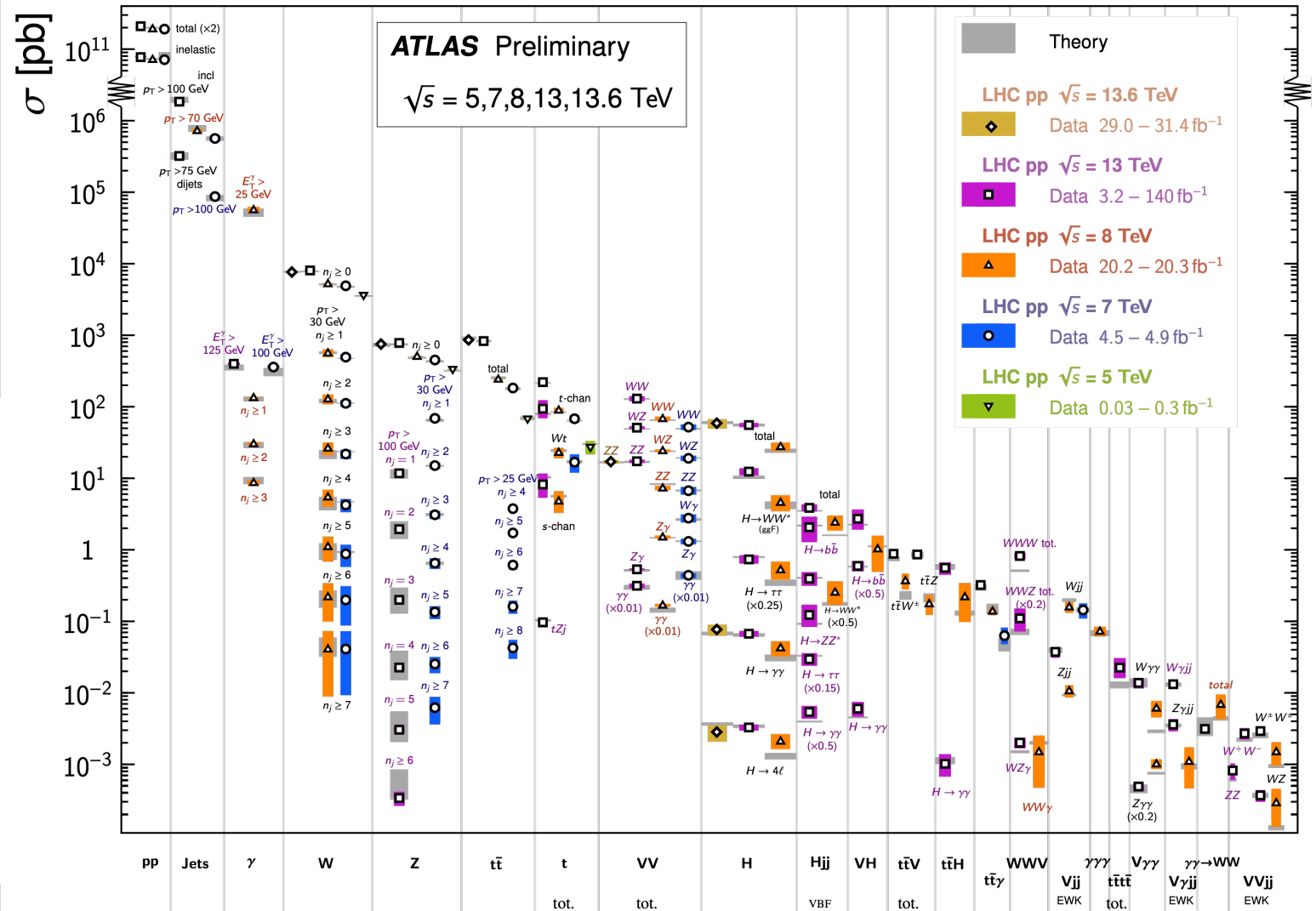
Scrutinising the Standard Model

- A plethora of unique measurements probing new forms of particle interactions and very rare processes, and (so far) confirming the predictive power of the Standard Model
- Theory developments and computations are key to this progress



Standard Model Production Cross Section Measurements

Status: June 2024



Deep searches for new phenomena

Run: 329716

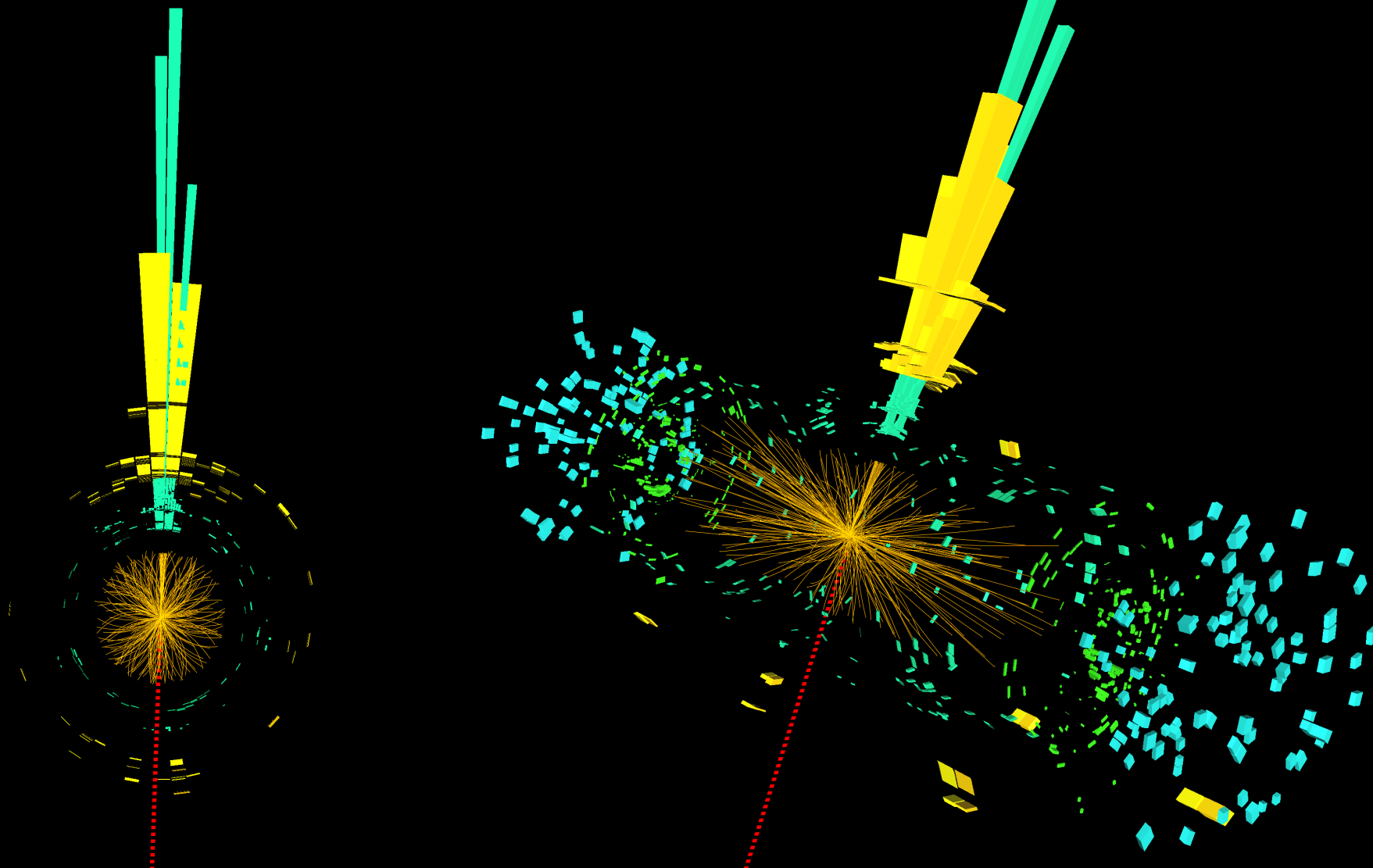
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2017-07-14 10:48:51 CEST

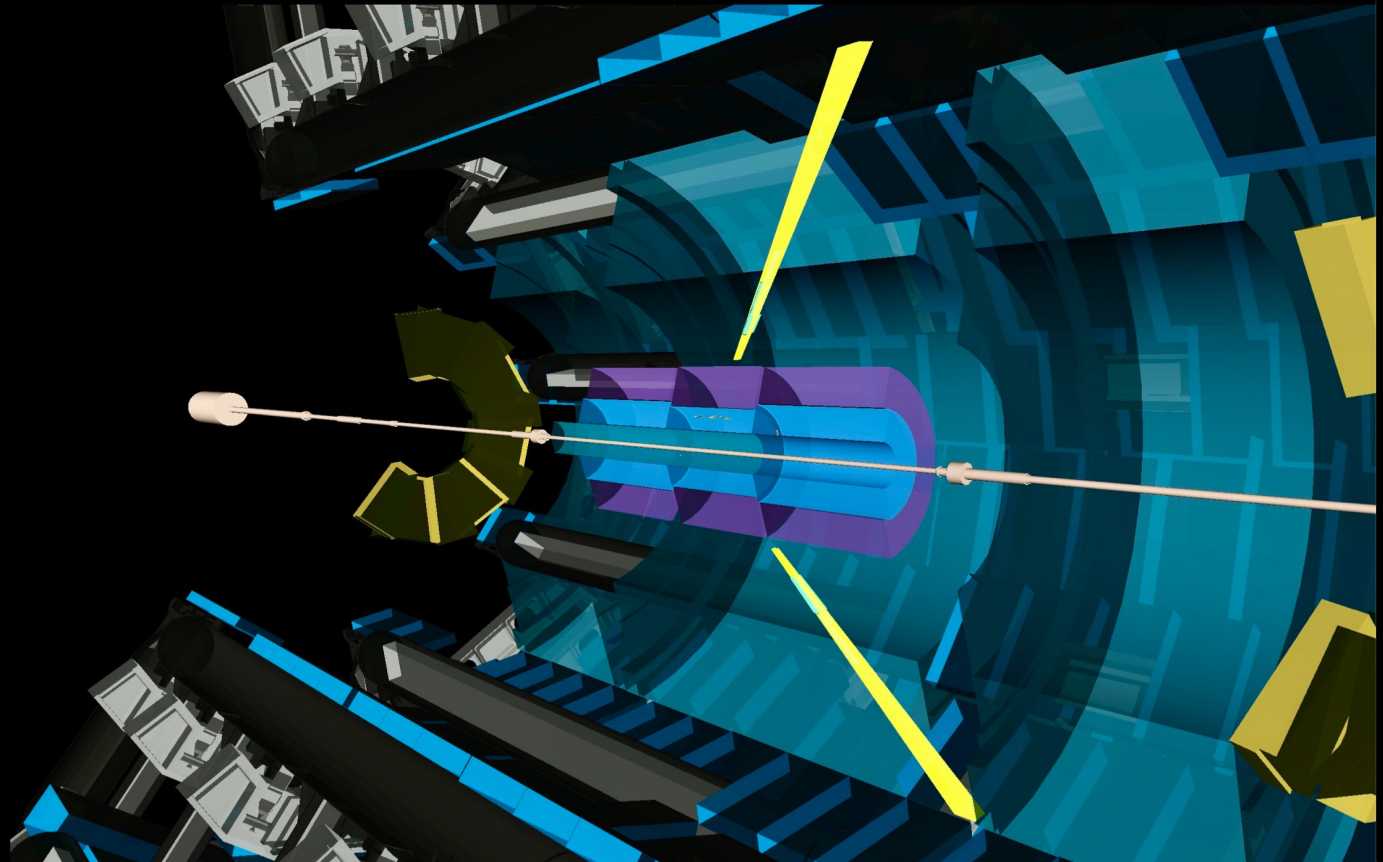
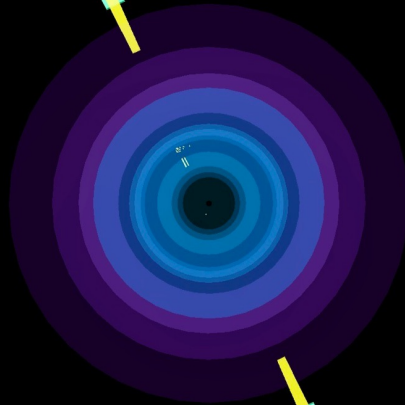
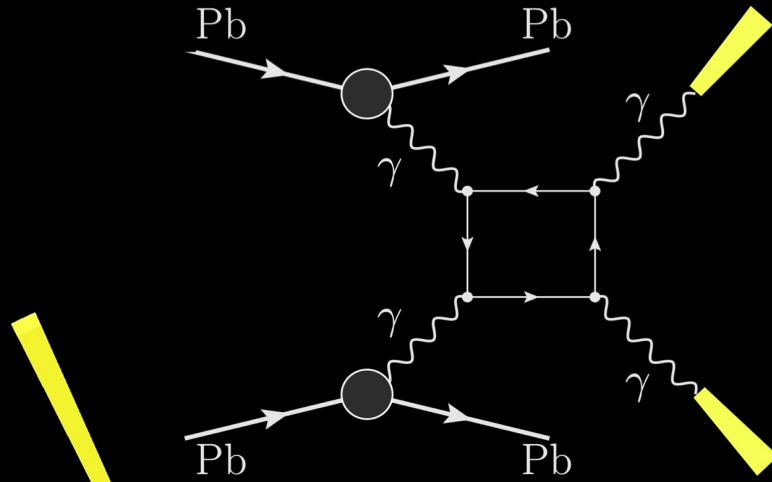


ATLAS
EXPERIMENT

Searches for Dark Matter

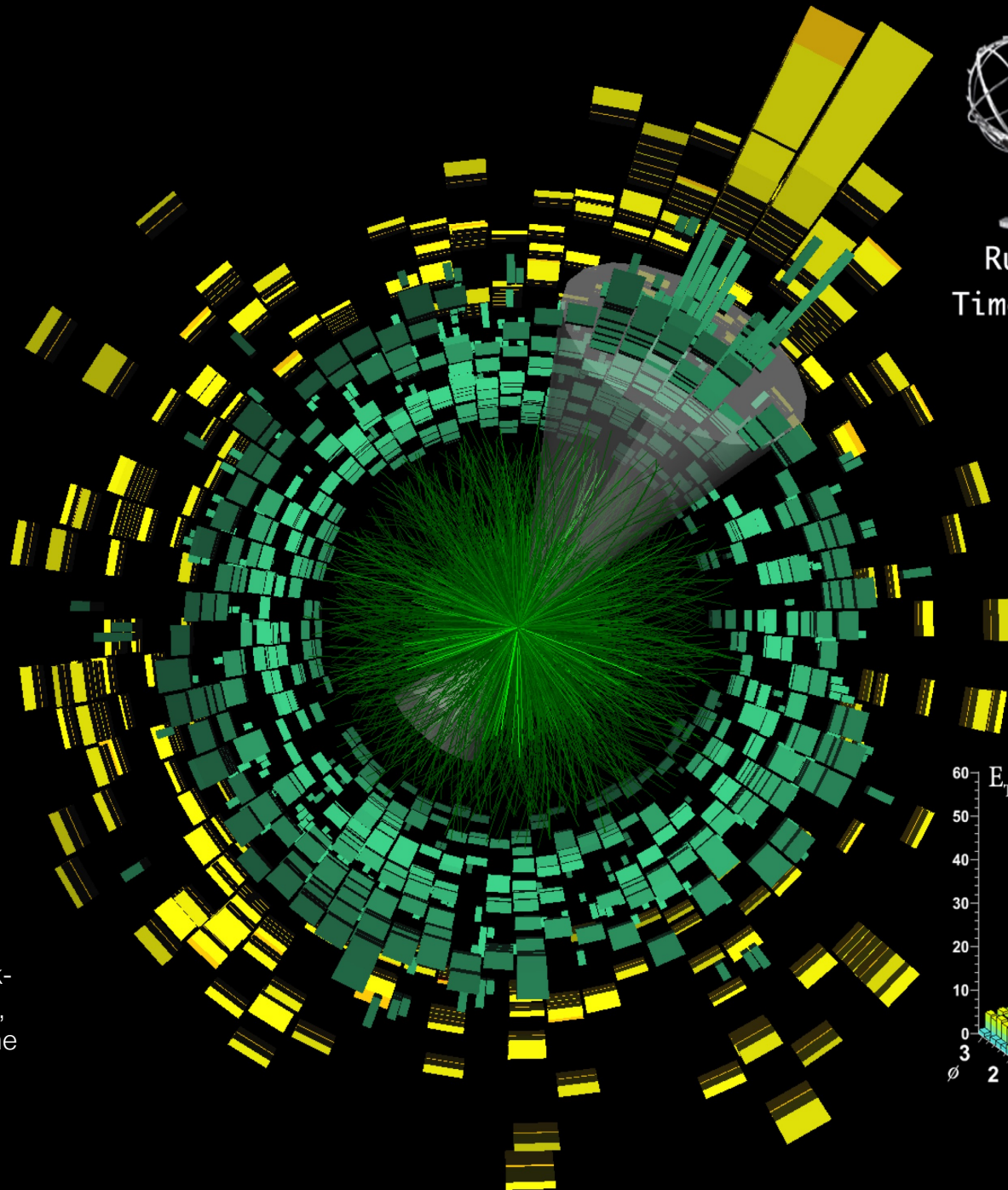


Studies of physics in extreme electromagnetic fields



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

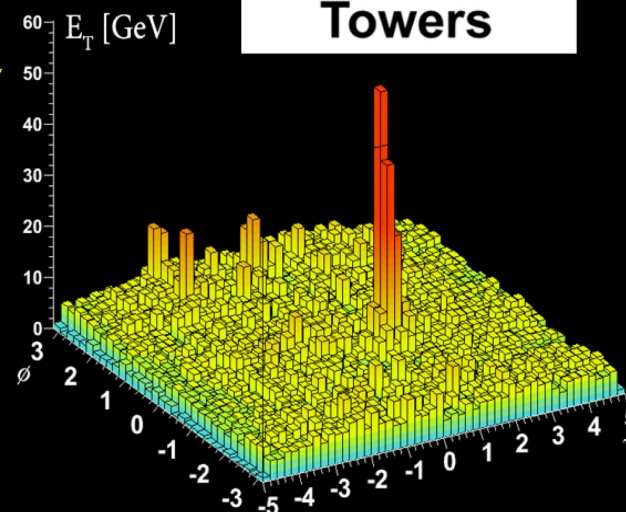
In collisions of heavy ions, the LHC creates for a very brief moment a quark-gluon plasma of up to 6 trillion degrees, almost half a million times hotter than the core of the sun



ATLAS EXPERIMENT

Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET

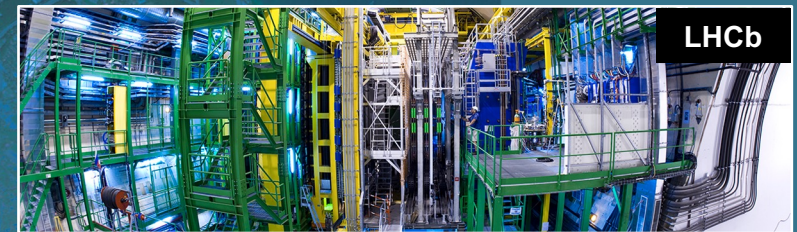
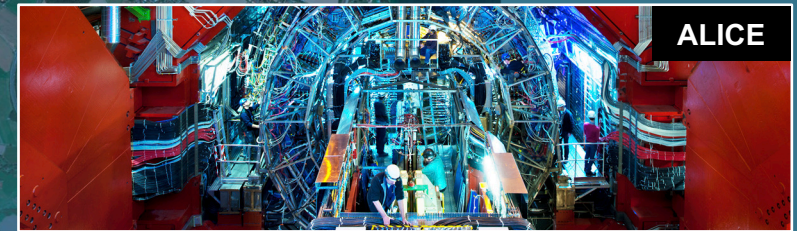
**Calorimeter
Towers**



LHC: the next phase



Areal view



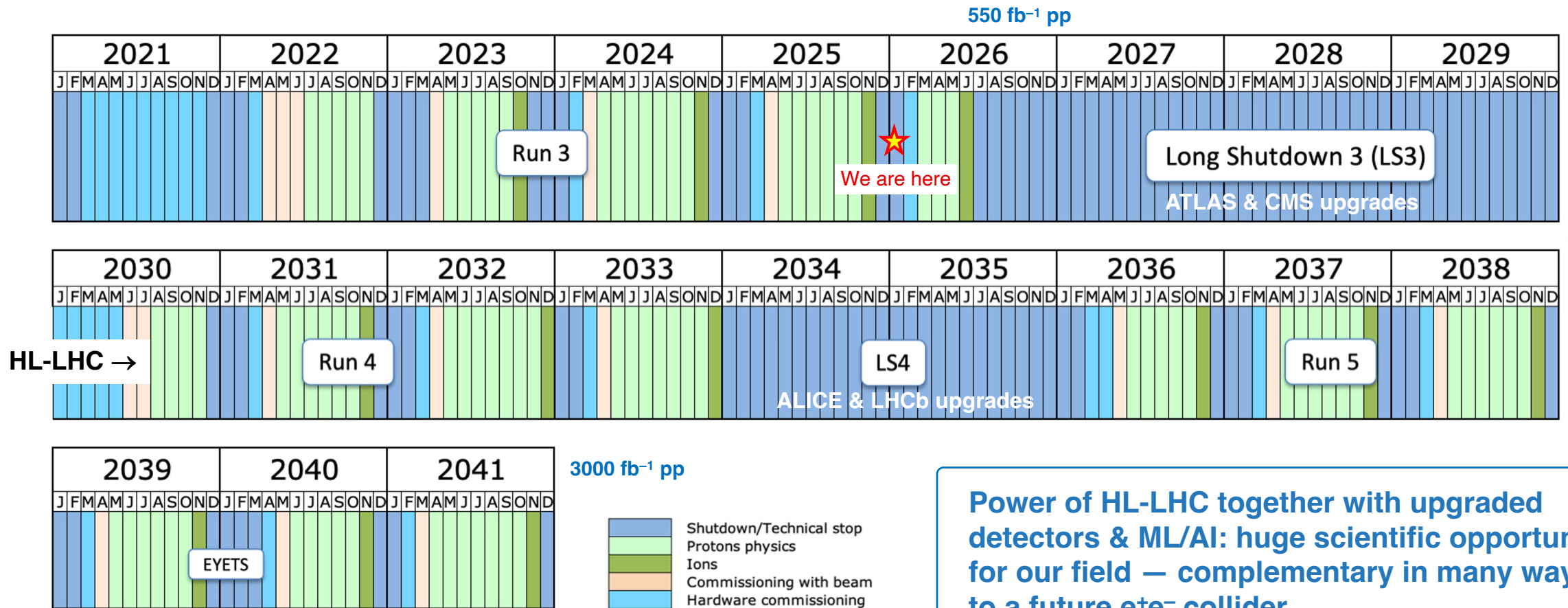
Not shown: additional smaller experiments

LHC and High-Luminosity-LHC (HL-LHC) project timeline

Huge effort ongoing to construct HL-LHC and experiment upgrades – a bright future

World's flagship collider project during next decade — 10 times currently analysed dataset (350M H, 240k HH, 13B top, ..., BSM reach +2 TeV)

Large-scale ATLAS & CMS upgrades under construction, ALICE & LHCb plan significant upgrades for Run 5



Last update: November 24

Power of HL-LHC together with upgraded detectors & ML/AI: huge scientific opportunity for our field — complementary in many ways to a future e⁺e⁻ collider

LHC machine upgrade to HL-LHC

Ambitious goal: $L_{\text{int}} > 2500 \text{ fb}^{-1}$ in 9 years of operation (for a total delivered luminosity of 3 ab^{-1})

	Bunch intensity [protons / bunch]	β^* [cm]	Peak lumi [$\text{cm}^{-2}\text{s}^{-1}$]	Pileup $\langle \mu \rangle$	Int. lumi / year [fb^{-1}]
LHC design	$1.15 \cdot 10^{11}$	55	$1 \cdot 10^{34}$	23	30
LHC today	$1.6 \cdot 10^{11}$	60/18	$2.2 \cdot 10^{34}$	64	120
HL-LHC	$2.2 \cdot 10^{11}$	15	$5\text{--}7 \cdot 10^{34}$	140–200	up to 300

Improved cryogenic cooling and collimators,
make all systems more radiation hard

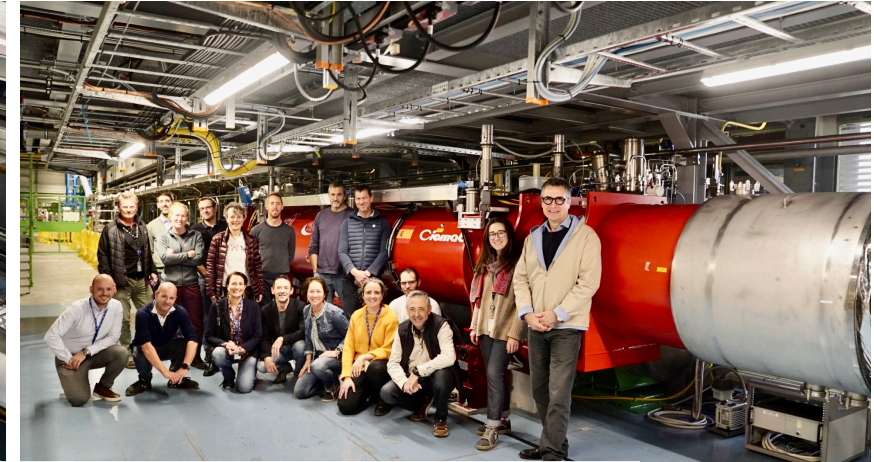
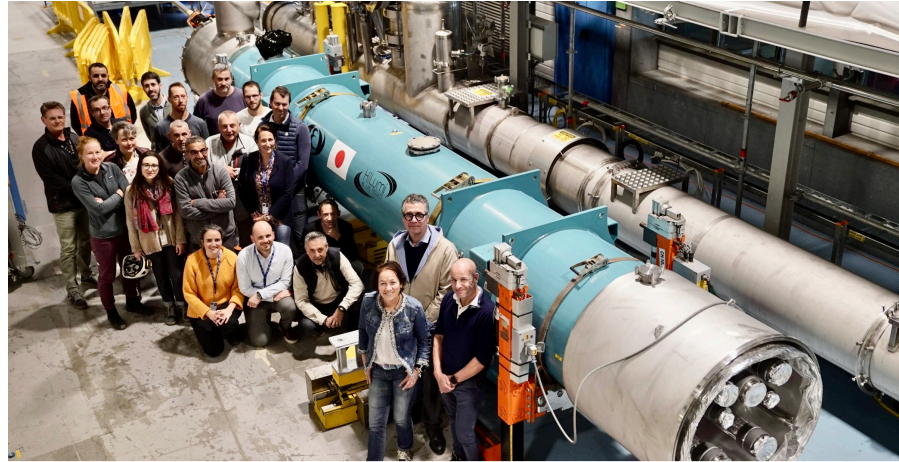
RF crab cavities to restore effective head-on collisions,
LIU high-brightness upgrade during LS2

Stronger focussing: 12 new Nb₃Sn “inner triplet”
quadrupoles at ATLAS & CMS (aperture: 70 →
150 mm, B-field: 8 → 11.5 T)

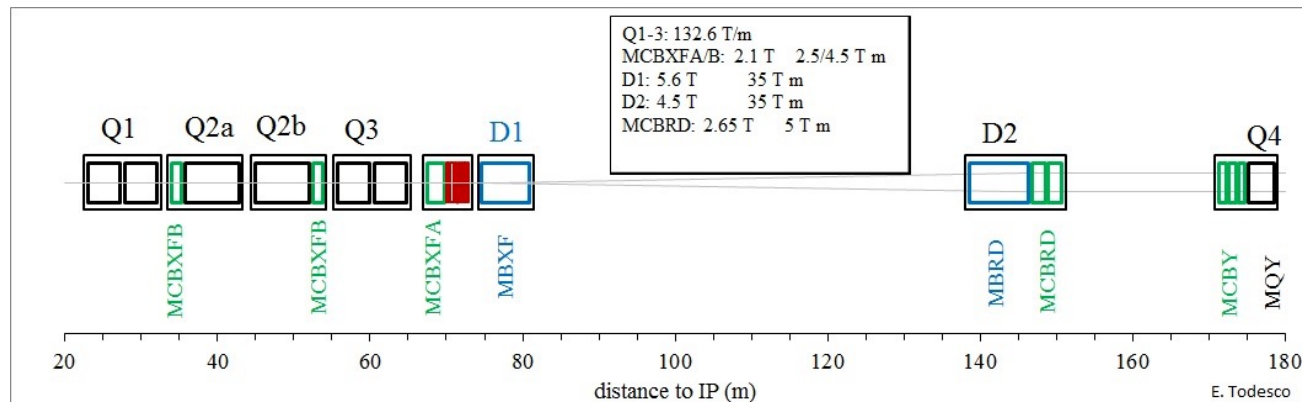
Civil engineering for two 300-metre new service tunnels next to ATLAS & CMS

LHC machine upgrade to HL-LHC

New Nb₃Sn “inner triplet” quadrupoles



Fully realistic inner triplet string test facility at CERN, from left to right: installation of superconducting link, installation of D1 and Q2a cryo-assemblies, tests to start in Oct 2025

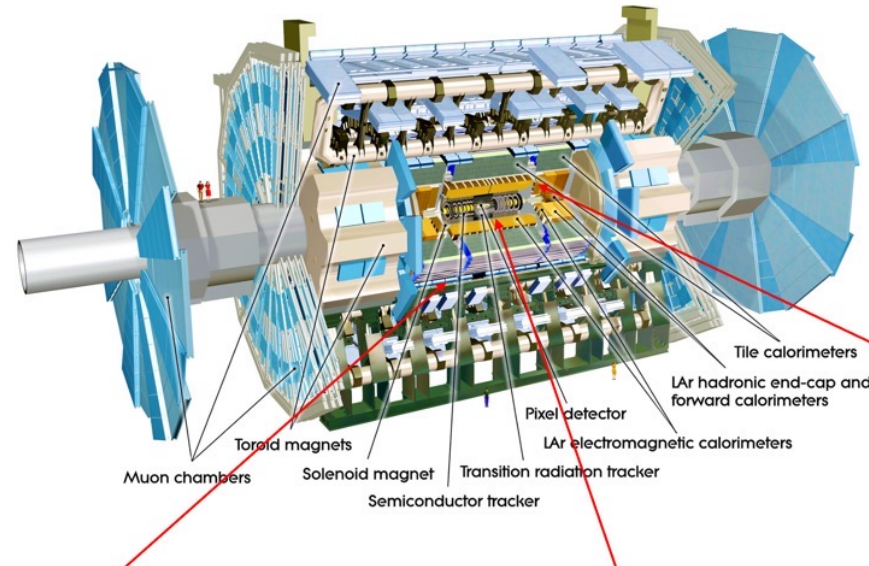


Nb₃Sn technology for new high-field superconducting quadrupole magnets successfully demonstrated for HL-LHC!

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



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

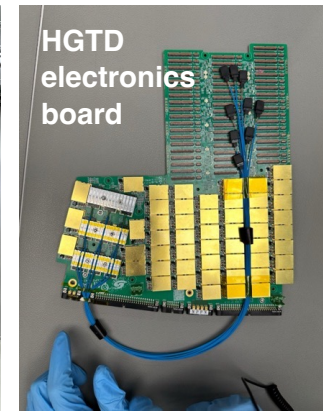
High Granularity Timing Detector (HGTD)

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

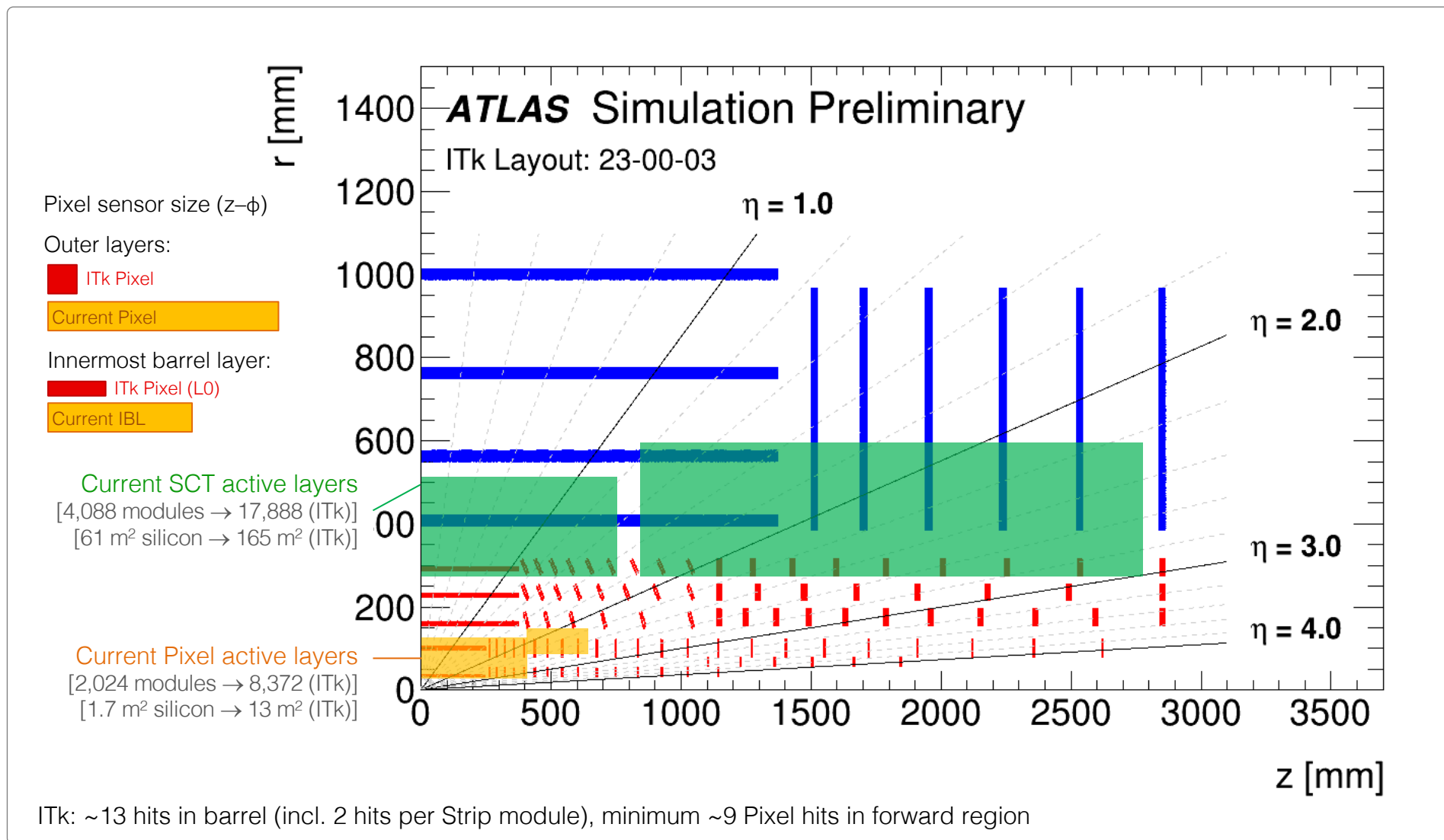
Additional small upgrades

Luminosity detectors (1% precision goal)
HL-ZDC

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



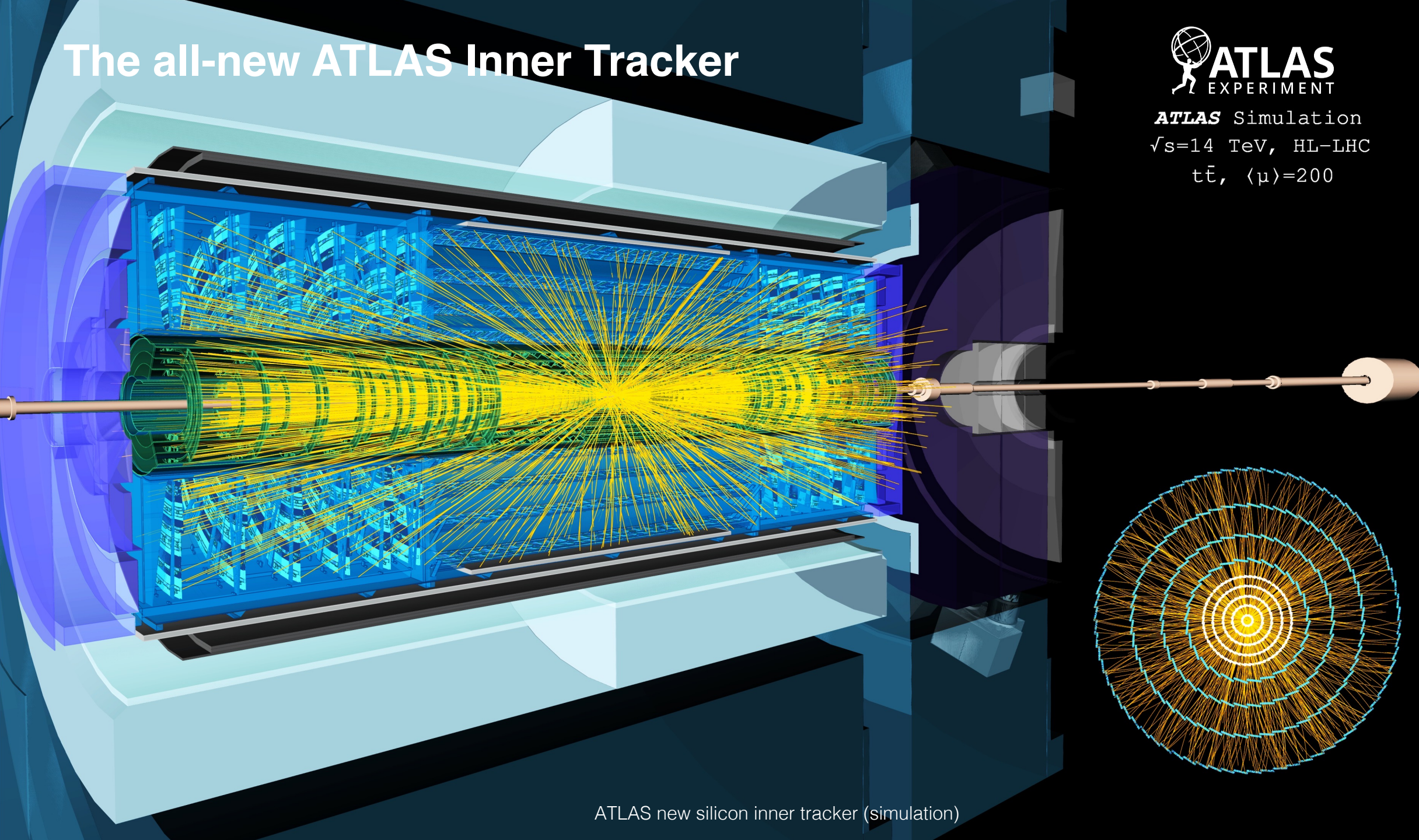
The all-new ATLAS Inner Tracker (ITk)



The all-new ATLAS Inner Tracker

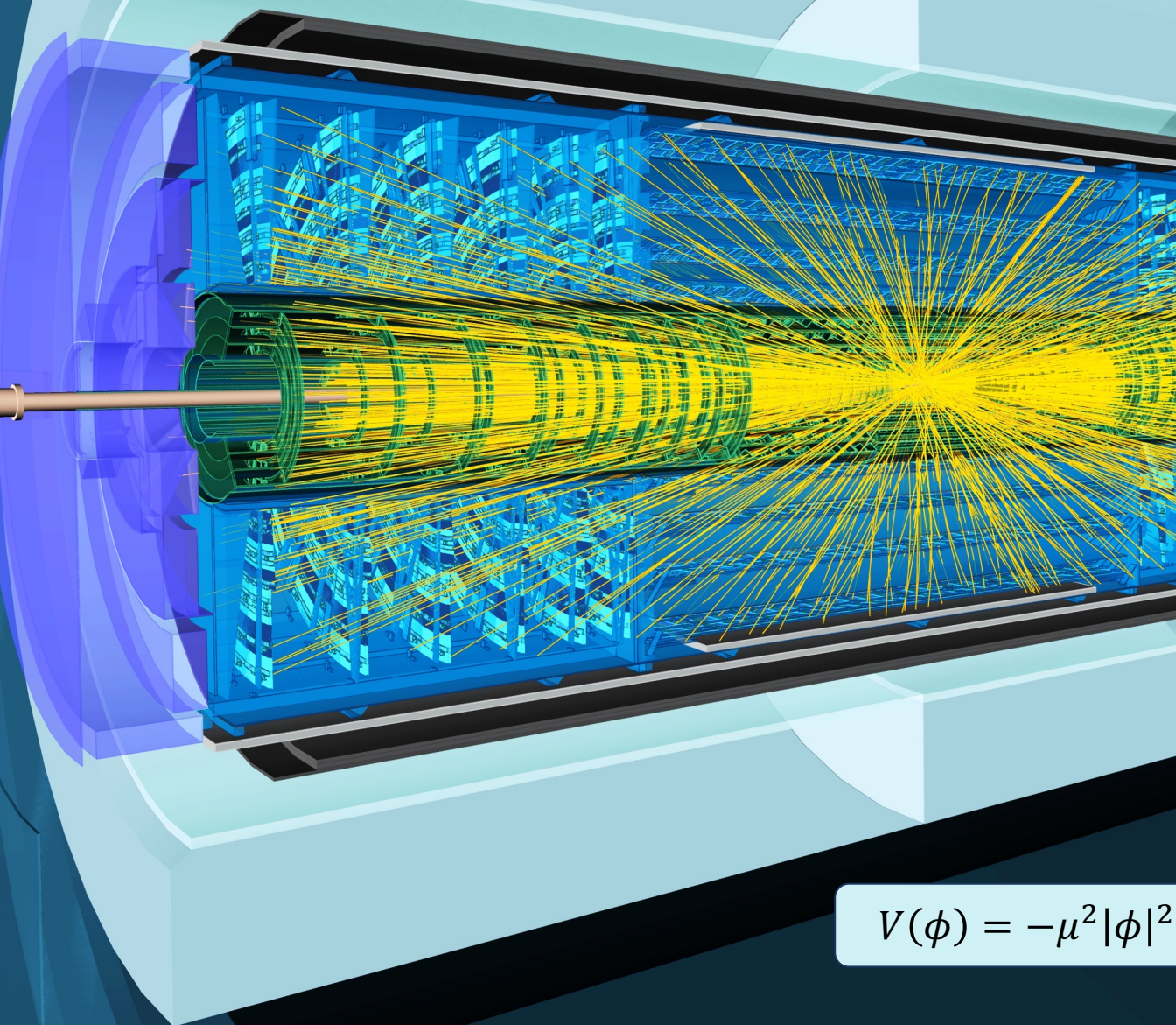


ATLAS Simulation
 $\sqrt{s}=14$ TeV, HL-LHC
 $t\bar{t}$, $\langle\mu\rangle=200$

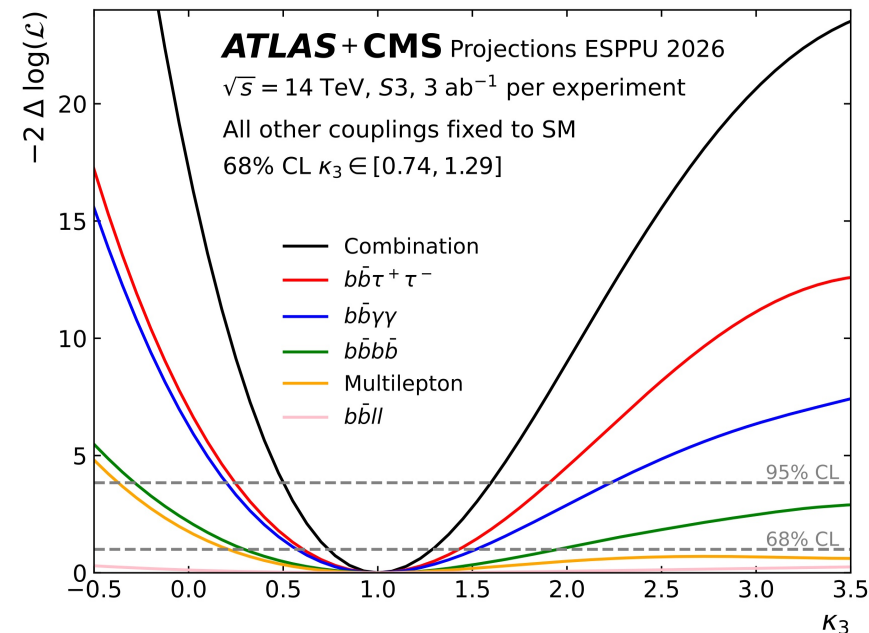


ATLAS new silicon inner tracker (simulation)

The all-new ATLAS Inner Tracker



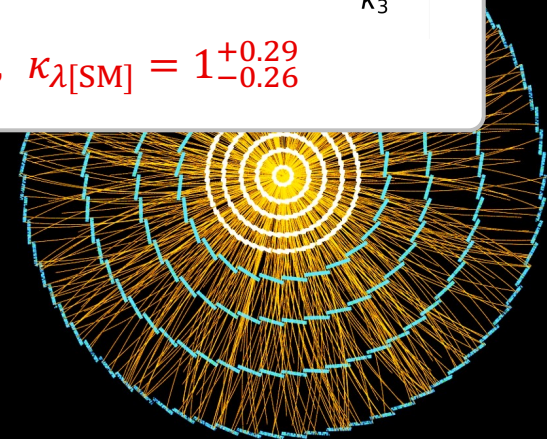
ATL-PHYS-PUB-2025-018



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

$$H \text{ --- } \bullet \text{ --- } H \propto 6\lambda v$$

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



Conclusions

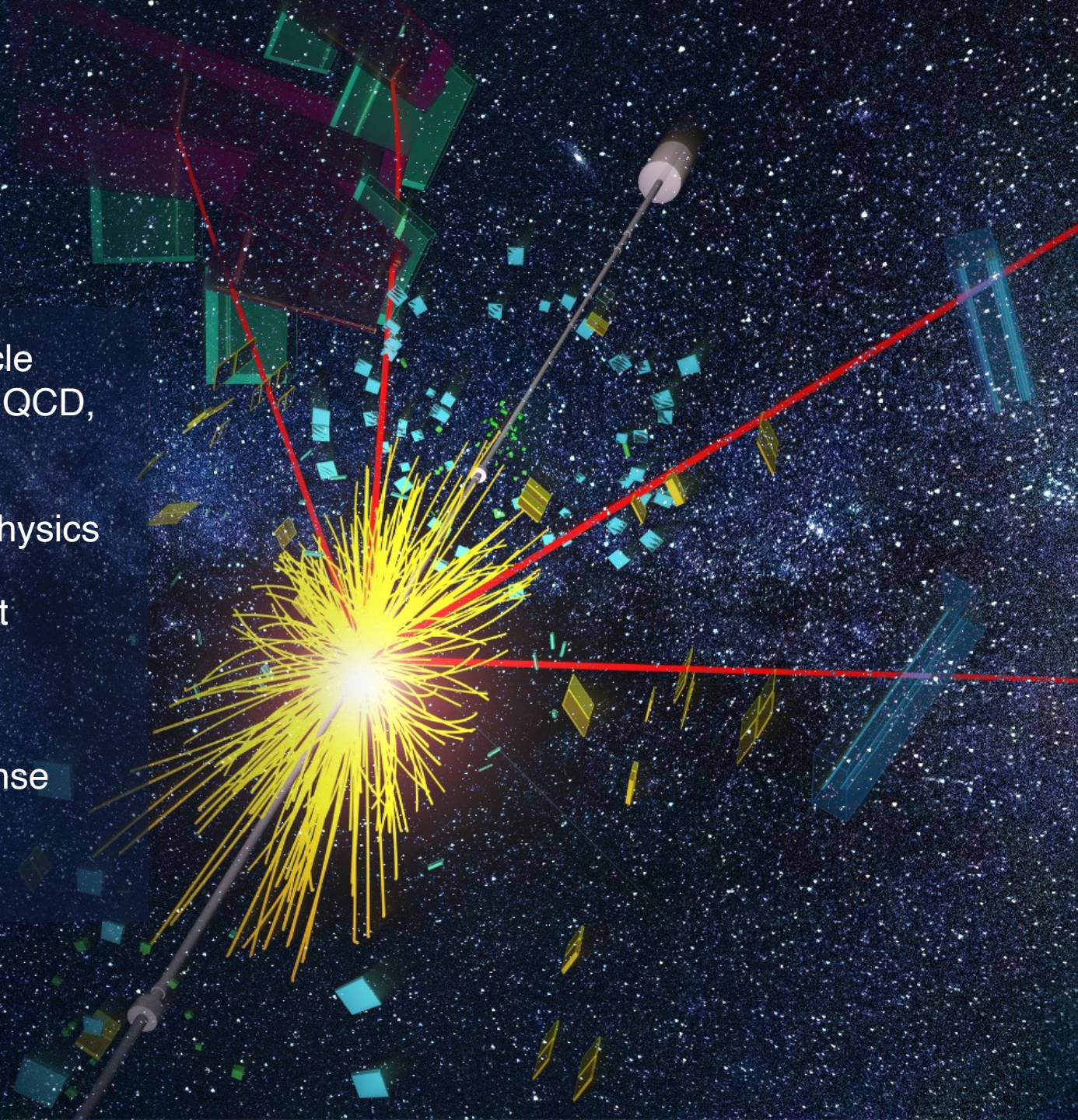
The LHC is the most powerful and versatile particle collider ever built, enabling deep Higgs, EW, top, QCD, flavour, BSM, and quark-gluon plasma studies

Its results have been transformative for particle physics

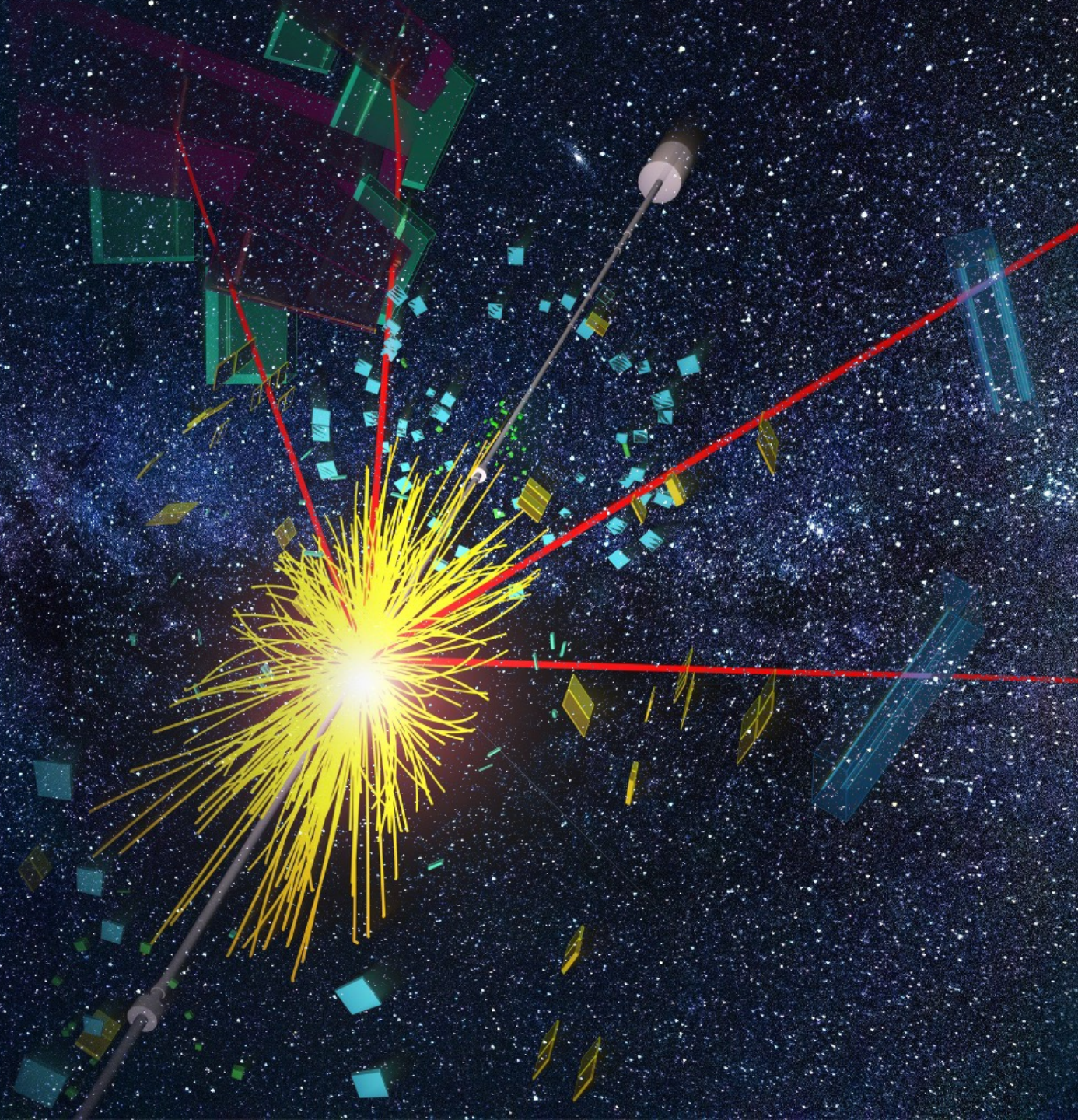
Runs 3–5 will provide 95% of the full LHC dataset

We will do better than any of our extrapolations

The HL-LHC and upgraded detectors offer immense opportunities, we are in the midst of a storm of innovation



Extra slides



The Brout-Englert-Higgs (BEH) mechanism

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

The BEH 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 $|\phi_{min}| = v_{T_{EW}} > 0$

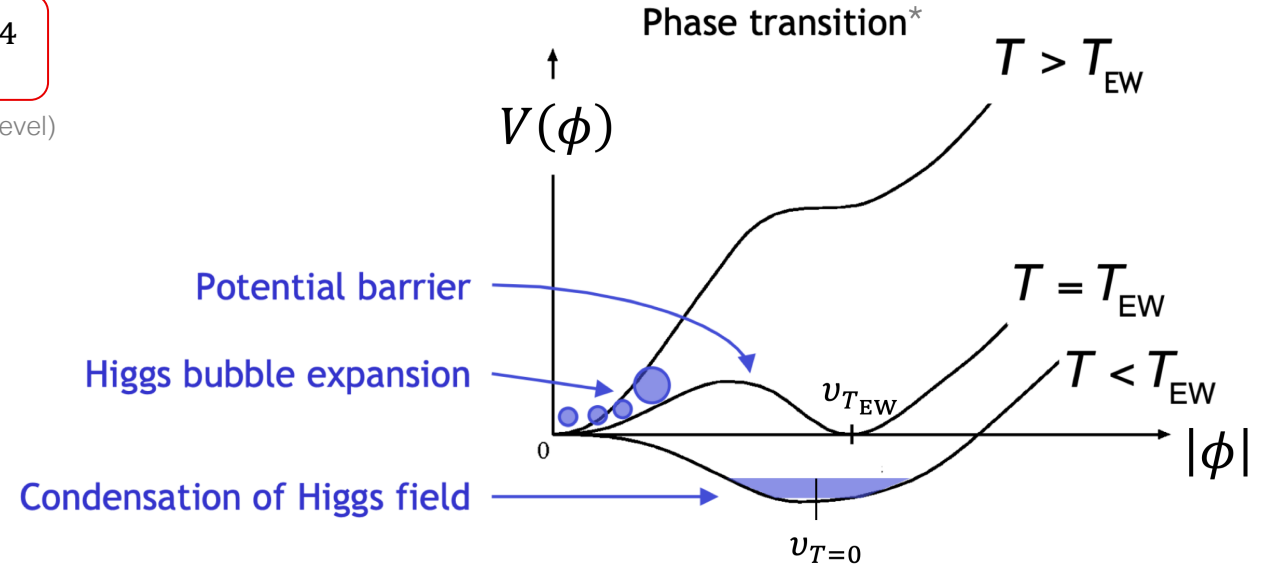
At $T = 0$, $V(\phi)$ has a minimum at:

$$v = v_{T=0} = \sqrt{\frac{\mu^2}{2\lambda}} \quad (v = \frac{1}{\sqrt{\sqrt{2}G_F}} \approx 246 \text{ GeV})$$

where was used: $g/m_W \propto \sqrt{G_F}$

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

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

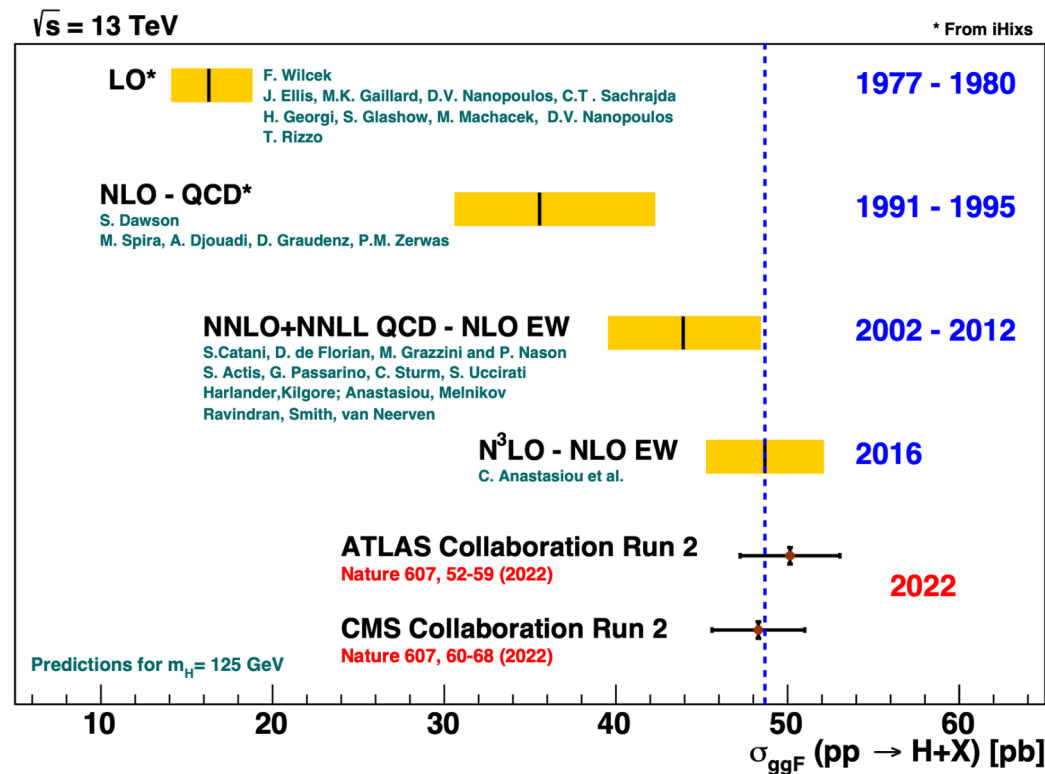
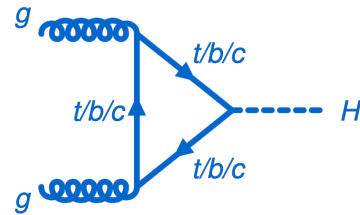


Huge progress also in theoretical calculations and modelling

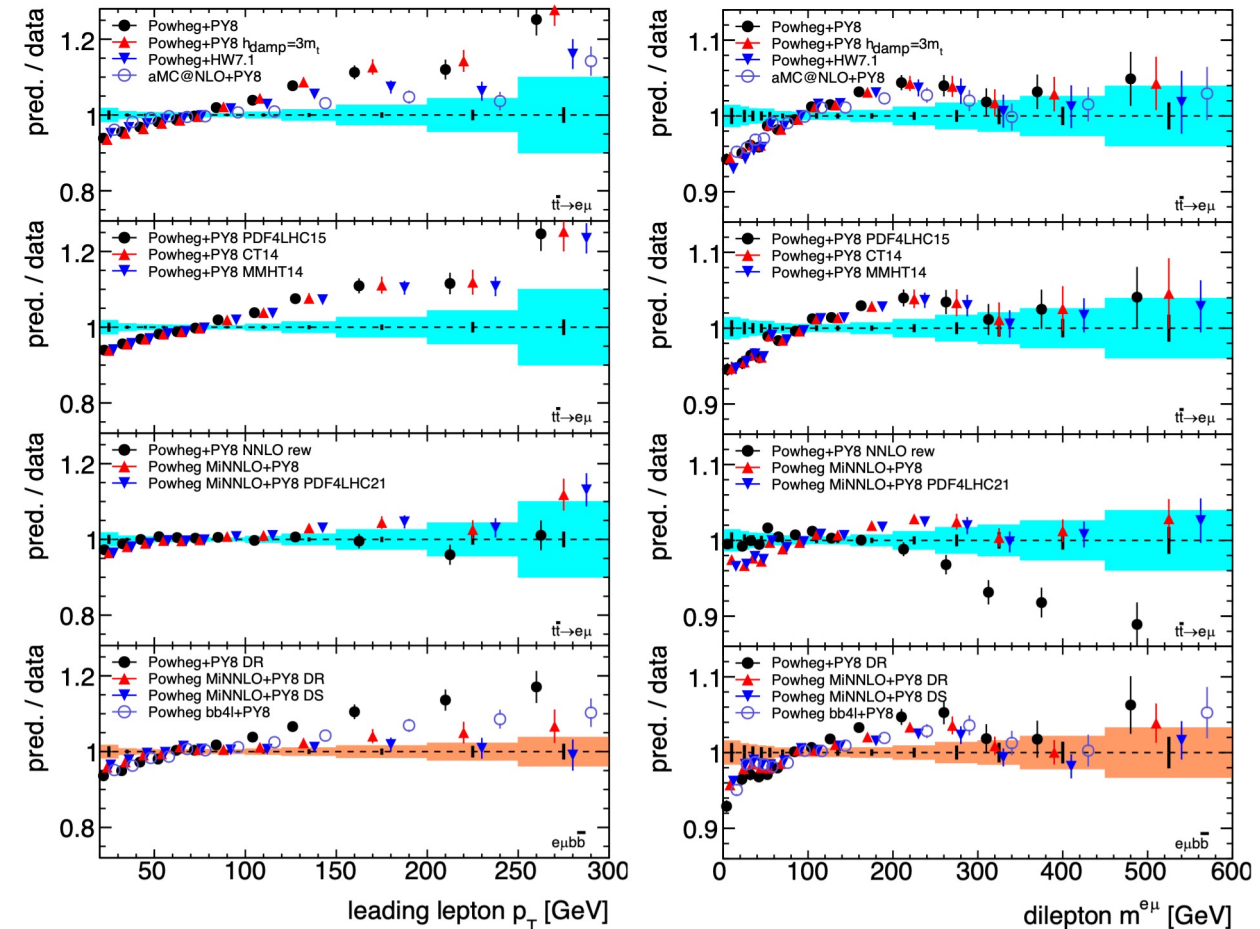
And more needed: theory uncertainties will dominate many HL-LHC measurements and their interpretation

Interpretation relies on theory:

calculations of Higgs boson production via gluon fusion versus time



High-precision top-antitop diff. cross section measurement in the $e\mu$ channel
Powheg+MiNNLO: differential NNLO+PS ($t\bar{t} + 1 \text{ jet}$ NLO) accuracy + small- q_T resummation



[arXiv:2509.15066](https://arxiv.org/abs/2509.15066)