

CERN: 7 decades of scientific achievements and innovation

FIP Colloquium, 21 November 2024

Luciano Musa
CERN



Peaceful scientific collaboration: a vision takes shape



1945: Europe is in ruins after World War II

1946: French proposal to the United Nations

1949: European Cultural Conference, Lausanne

Common vision of politicians and scientists



Renew peaceful
collaboration following the
destruction of war

Focus on fundamental
scientific research at a scale
beyond the capacity of any
single nation

Restore scientific excellence
and reverse and prevent
brain drain

1940s: first proposals

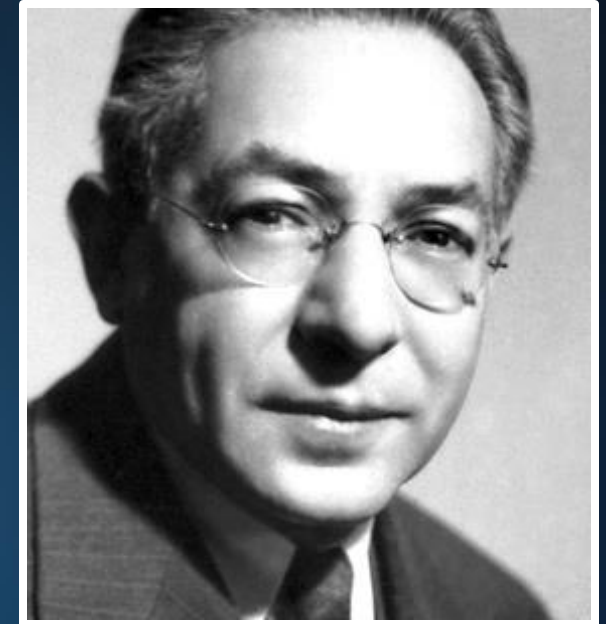
Louis de Broglie proposed: *"the creation of a laboratory or institution where it would be possible to do scientific work, but somehow beyond the framework of the different participating states [Endowed with more resources than national facilities, such a laboratory could] undertake tasks, which, by virtue of their size and cost, were beyond the scope of individual countries"*.



1950: UNESCO Conference

US Nobel laureate Isidor Rabi tables a resolution authorising UNESCO to:

“assist and encourage the formation of regional research laboratories in order to increase international scientific collaboration...”

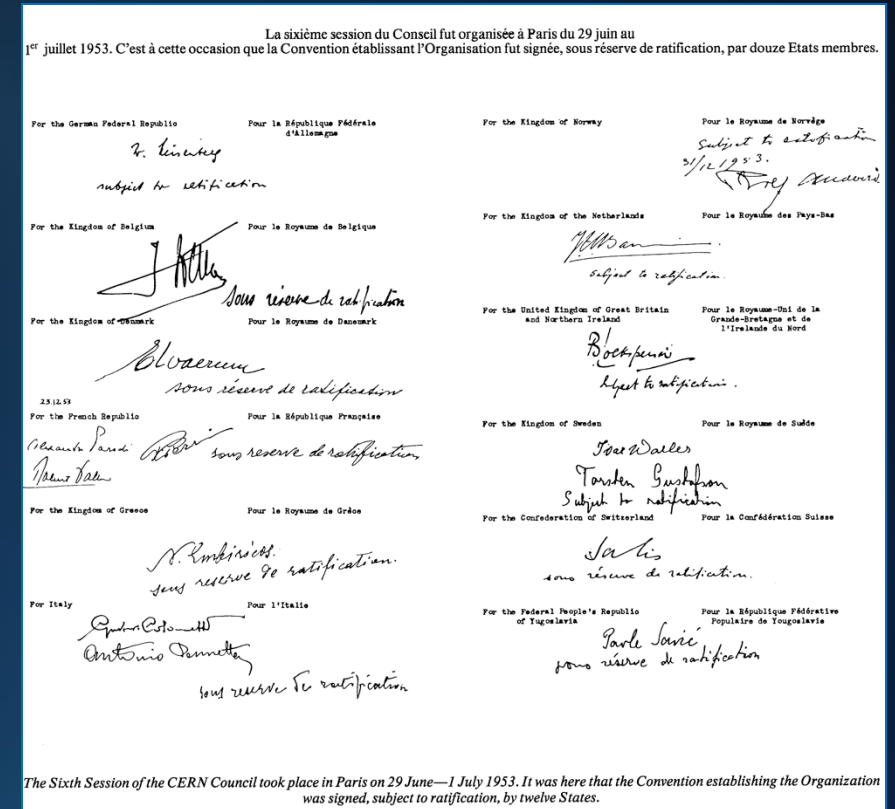


1951: UNESCO Resolution

- At a meeting of UNESCO in Paris in December 1951, the first resolution concerning the establishment of a European Council for Nuclear Research was adopted.
- Two months later, 11 countries signed an agreement establishing the provisional Council – **the acronym CERN was born.** Edoardo Amaldi is made Secretary-General

1954: CERN is born

- The CERN Convention, established in July 1953, was ratified by 12 founding Member States: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the UK, and Yugoslavia.
- On 29 September 1954, the European Organization for Nuclear Research officially came into being.
- CERN was dissolved but the acronym remains.



The convention was signed at the Sixth session of the CERN Council in Paris on 29 June - 1 July.

1957: first accelerator

The Synchrocyclotron



From founders' vision to today's global collaboration

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

2 Associate Member States in the pre-stage to membership

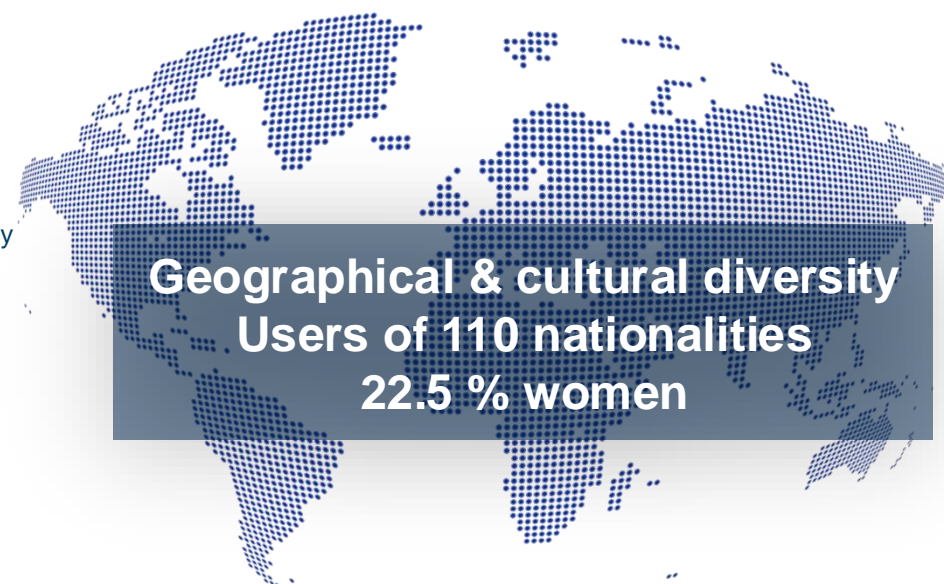
Cyprus – Slovenia

8 Associate Member States

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

6 Observers

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



As of 31 December 2023
Employees:
2666 staff, **1002** graduates
Associates:
12 370 users, **1513** others

Around 50 Cooperation Agreements with non-Member States and Territories

Albania – Algeria – Argentina – Armenia – Australia – Azerbaijan – Bangladesh – Belarus – Bolivia
Bosnia and Herzegovina – Canada – Chile – Colombia – Costa Rica – Ecuador – Egypt – Georgia – Honduras
Iceland – Iran – Jordan – Kazakhstan – 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

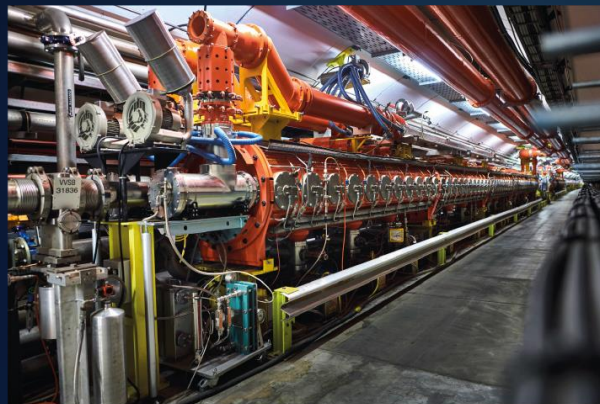
PS – 28 GeV

$$\sqrt{s} \approx 7.3 \text{ GeV}$$



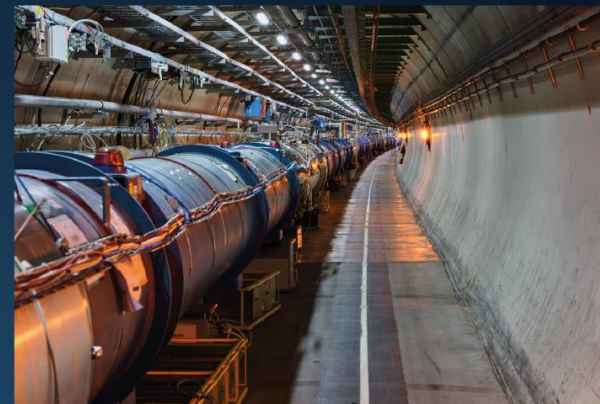
SPS – 630 GeV

$$\sqrt{s} \approx 34.4 \text{ GeV}$$



LHC – 6800 GeV

$$\sqrt{s} \approx 13.6 \text{ GeV}$$



SC 0.6 GeV

$$\sqrt{s} \approx 1.7 \text{ GeV}$$



ISR - 31.5 GeV

$$\sqrt{s} \approx 63 \text{ GeV}$$



LEP – 104.5 GeV

$$\sqrt{s} \approx 209 \text{ GeV}$$



1957

1959

1971

1976

1989

2009

1958: CERN's first discovery

1957: the **Synchrocyclotron** is CERN's first accelerator to begin operation (600 MeV proton beam)

Discovery of “rare pion decays” 1958-1962

$$R = \frac{\Gamma(\pi \rightarrow e\nu_e)}{\Gamma(\pi \rightarrow \mu\nu_\mu)} = (1.22 \pm 0.30) \times 10^{-4}$$

G. Fidecaro et al.

Crucial verification of a universal “weak” force with a Vector - Axial coupling

A turning point for the emerging electroweak theory



1973: the discovery of neutral currents

1959: the **Proton Synchrotron** (PS) begins operation
proton beam of 24 GeV (briefly the highest-energy accelerator)

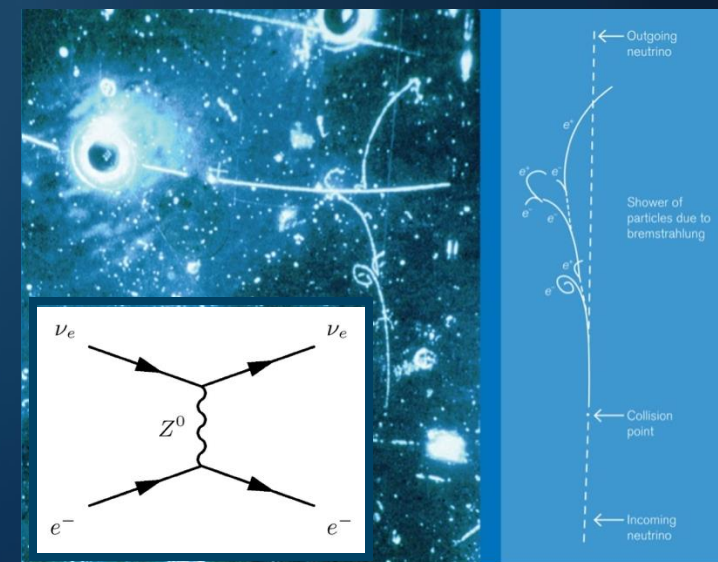
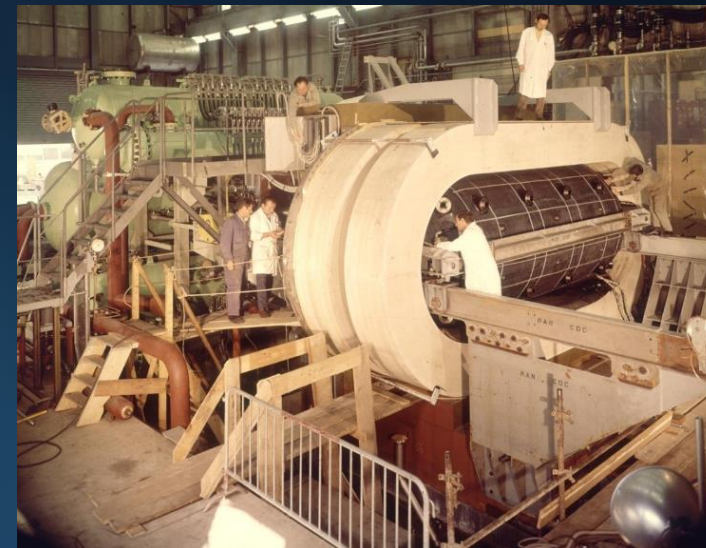
With the PS CERN entered the “high-energy neutrino beam era”

Gargamelle (4.8 m x 2 m, 1000 tonnes, 12 m³ heavy-liquid freon)

essential support for the quark model, and essential
contributions to the confirmation of their fractional charge

discovery of neutral currents

⇒ establishes the electroweak theory



Discovery of neutral currents

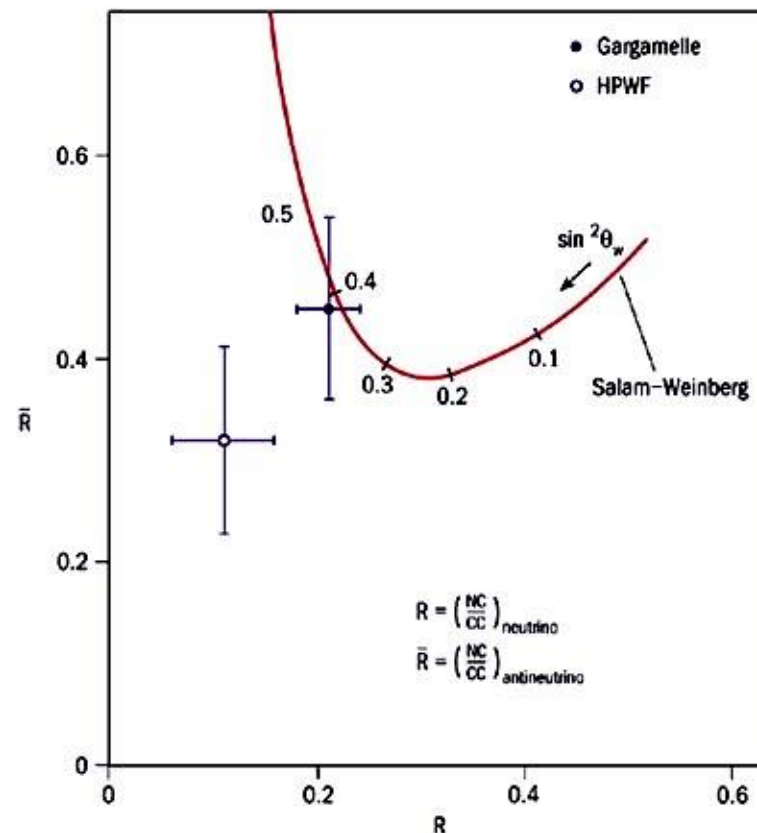
Combined rate measurement of neutral and charged current events using neutrino and anti-neutrino beams:

⇒ first direct evidence for the existence of the W and Z bosons as well as of their mass

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \cdot \frac{1}{\sin\theta_W} = \frac{37 \text{ GeV}}{\sin\theta_W} \approx 70 \text{ GeV}$$

well before the direct observation of W and Z

⇒ guided the CERN future accelerator path

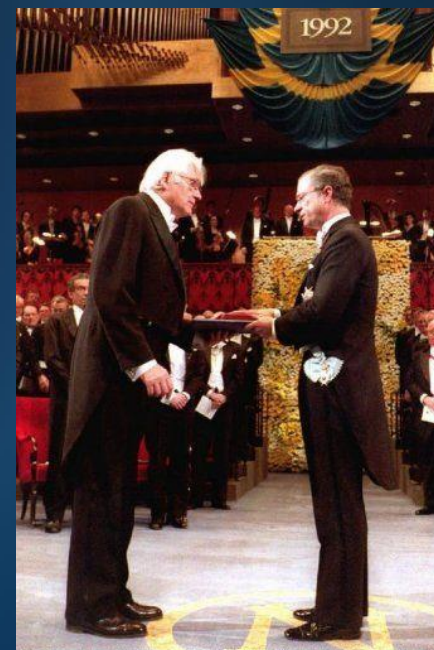


Georges Charpak: Revolutionizing particle detection

from “visual detectors” to “electronic detectors”



1971-1972 – Large-size Multiwire Proportional Chamber



1992 Nobel award ceremony

Multiwire Proportional Chambers: a transformative innovation

Medical imaging and healthcare

Security and inspection

Material science and archaeology

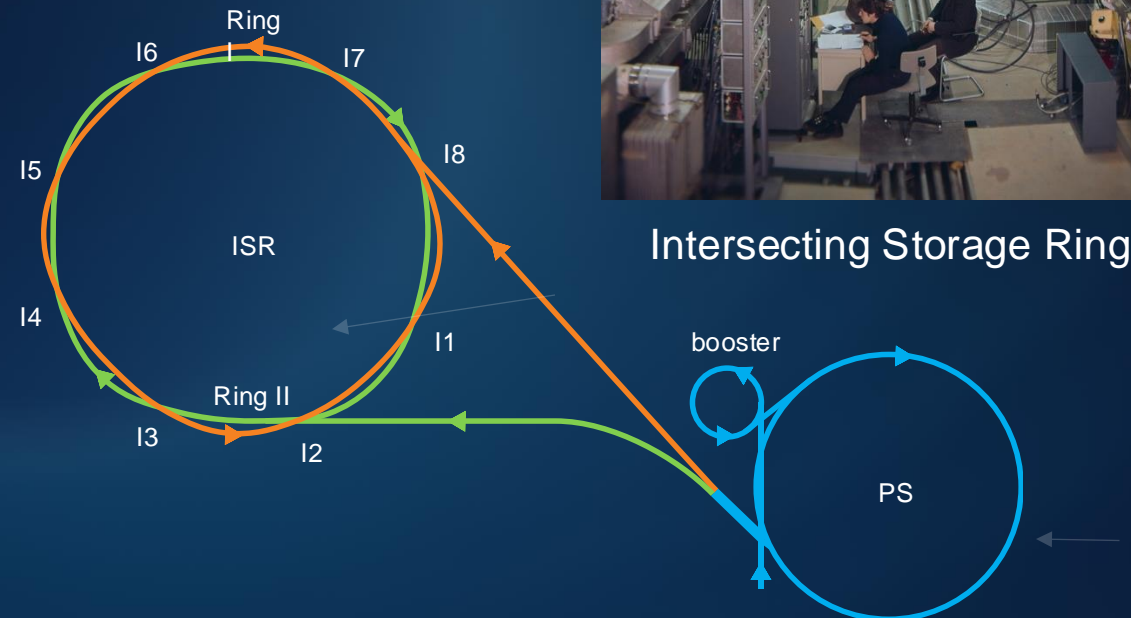
Environmental monitoring

Industrial applications



Intersecting Storage Rings

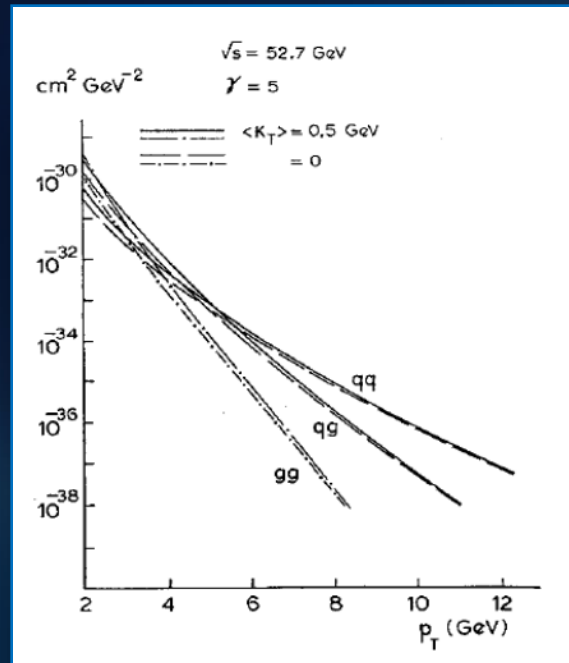
- The **Intersecting Storage Rings** was the **World's first hadron collider** (protons, center of mass energy of up to 62 GeV)
- The rings crossing angle and the detectors were designed to privilege forward going debris of collisions
- Crucial contributions to QCD, the emerging theory of the strong nuclear force and the structure of hadrons, complementing the findings from the deep inelastic scattering experiments at SLAC



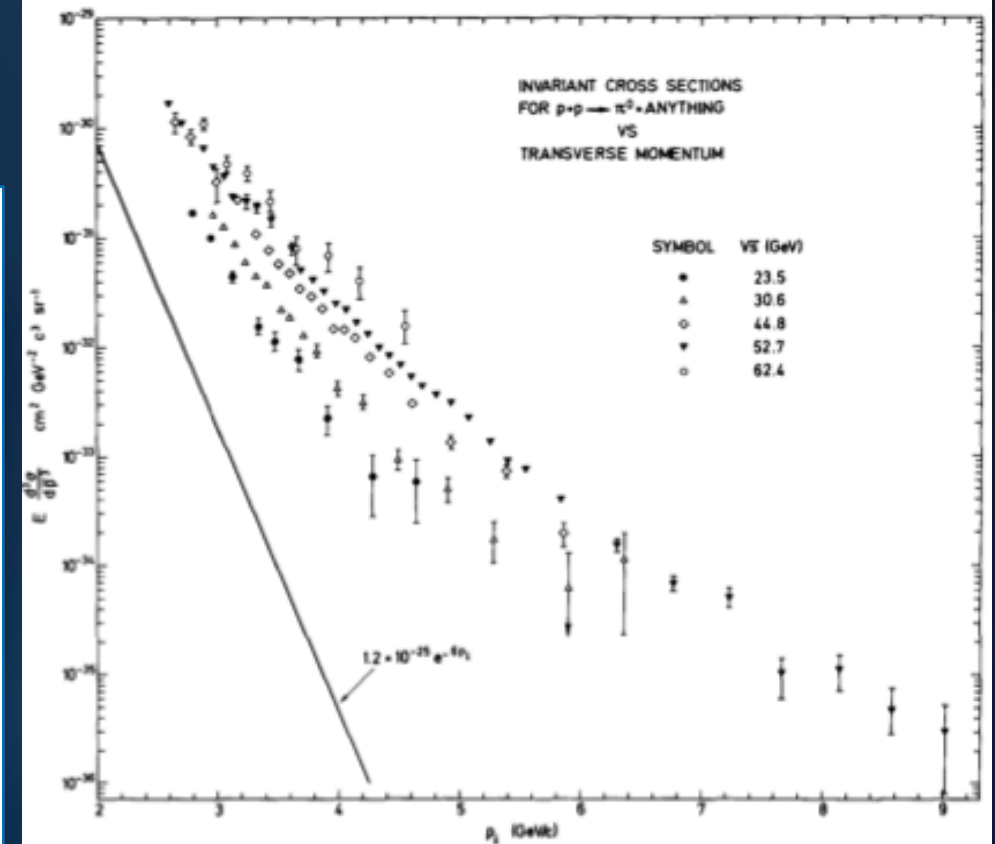
Intersecting Storage Ring

Intersecting Storage Ring

- 1972-1973: ISR announces the observation of totally unexpected production of hadrons at large transverse momentum.
- A shocking surprise, but consistent with the emerging view (QCD) of protons made of quarks and gluons.
- New QCD predictions treating proton collisions as collisions between quarks (qq), gluons (gg) or mixed (qg)

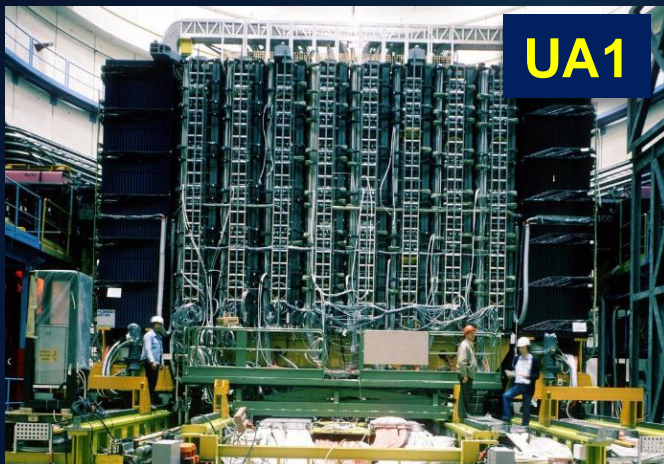
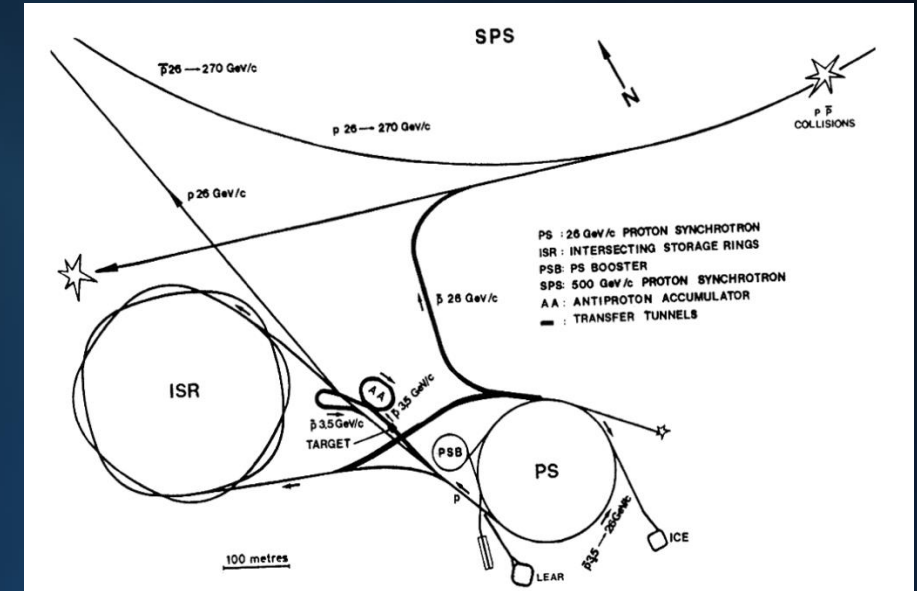


CERN – Columbia – Rockefeller coll., Phys. Lett. B46 (1973) 471
Results presented at the 1972 Int. Conf. on High Energy Physics



1983: discovery of the W and Z

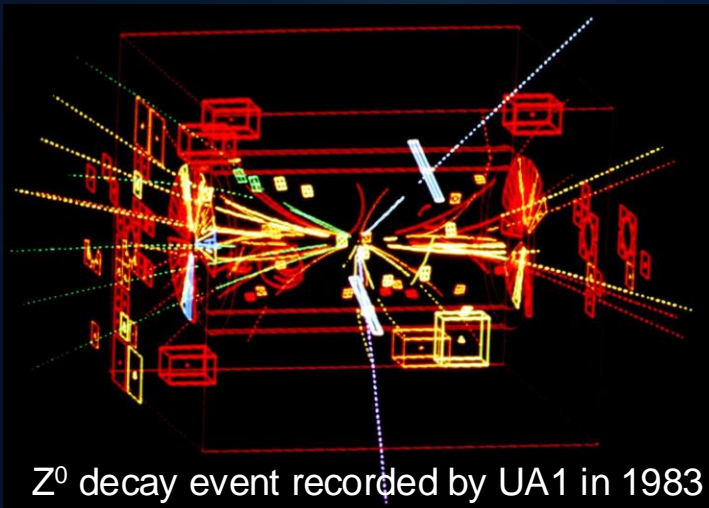
- Gargamelle and the discovery of neutral currents guided the search: look in the region 60-90 GeV
- In 1976 Rubbia proposes to modify the SpS into a collider of protons and antiprotons
- First collisions at $\sqrt{s}=540$ GeV were obtained in 1981



Two multipurpose detectors UA1 and UA2 were built to detect the elusive W and Z in their decays to leptons.

1983: discovery of the W and Z

- UA1 and UA2 presented the first results (in two separate seminars) at CERN on 20 and 21 **January 1983**
- 6 candidates for both experiments with high energy electrons and high missing energy (i.e. neutrinos).
- **The quest for the W boson was over!**



Z^0 decay event recorded by UA1 in 1983

In **July 1983**, **clear evidence of the Z boson** was also presented.

Carlo Rubbia and Simon van der Meer were awarded the 1984 Nobel prize

Nailing down the Standard Model

In the mid-1970s the Standard Model was an attractive theory, but many aspects were still unknown:

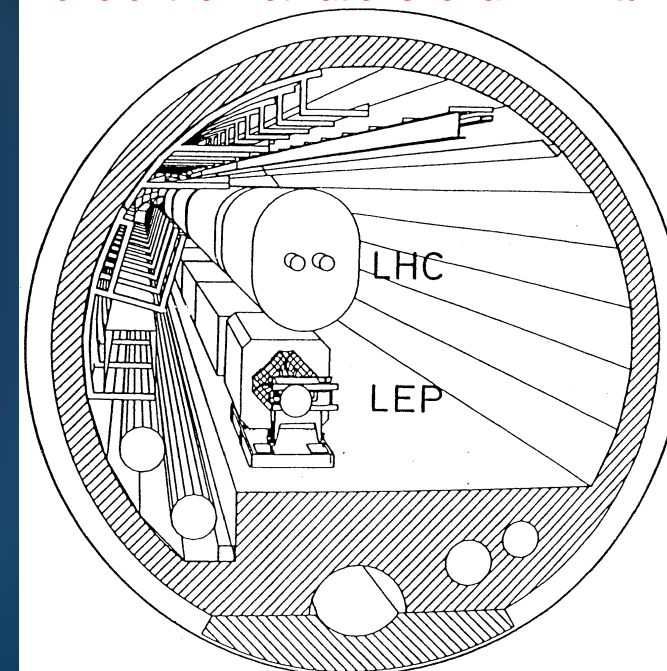
- QCD was increasingly confirmed, but the number of families (both for leptons and for quarks) was unclear. CP violation provided some clue for the quark sector, but not much for leptons.
- The vector bosons, which mediate the electroweak force, were believed to be around the corner, in the 60 - 100 GeV range.

In 1976, CERN established a study group for a Large Electron–Positron Collider (LEP) to produce and study the W and Z bosons.

LEP was approved in 1982, around the time as the discovery of the W and Z bosons.

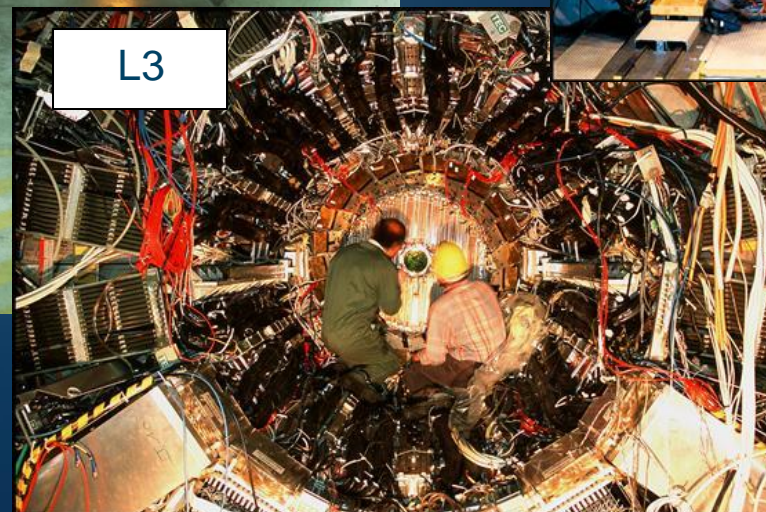
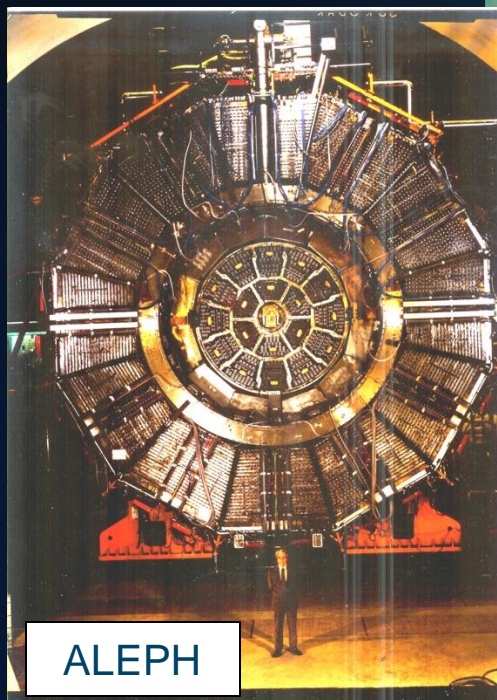
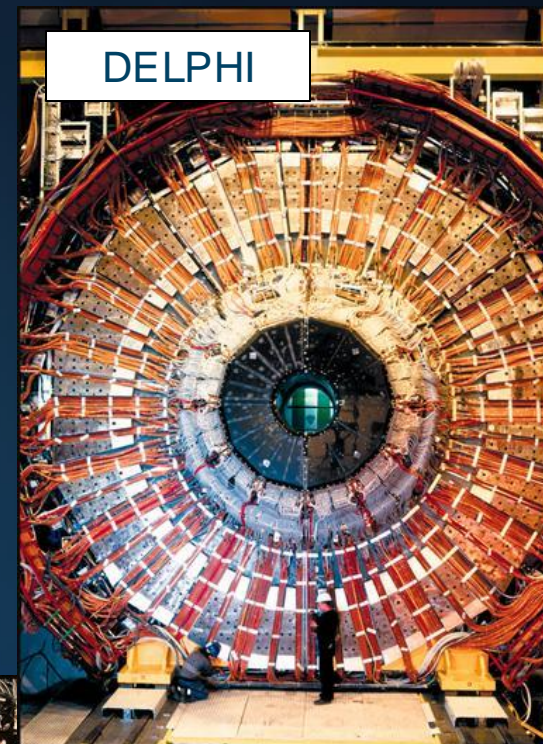
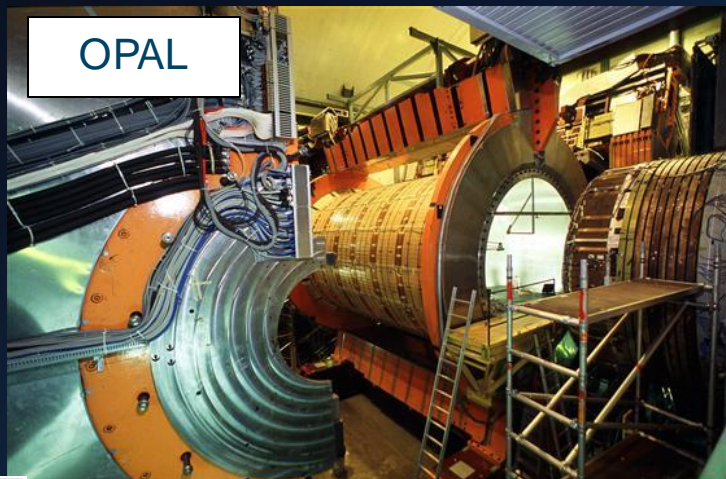
ECFA – CERN Workshop Lausanne, 5 Sep 1984

This possibility of hosting the LHC was one of the motivations for a 27km tunnel.



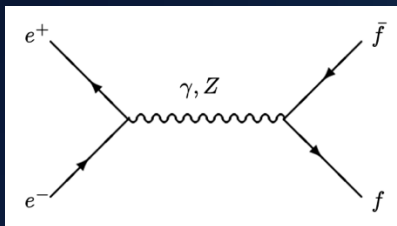
LARGE HADRON COLLIDER
IN THE LEP TUNNEL

LEP era

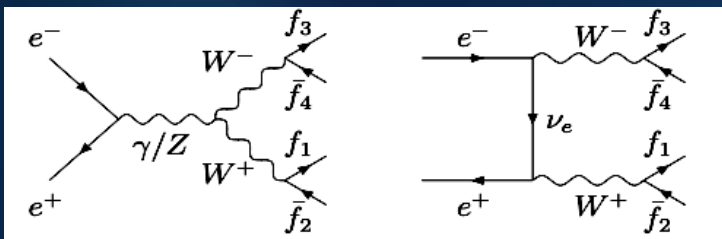


LEP era

- First beams in LEP: 15 July 1989
- LEP 1: center of mass energy around the mass of the Z boson (91 GeV) for 7 years. LEP was a Z-factory with millions of produced Z bosons.



- LEP 2: starting in 1996, energy reached and surpassed the threshold for production of 2 W boson (160 GeV). Max energy reached 209 GeV.



The World Wide Web

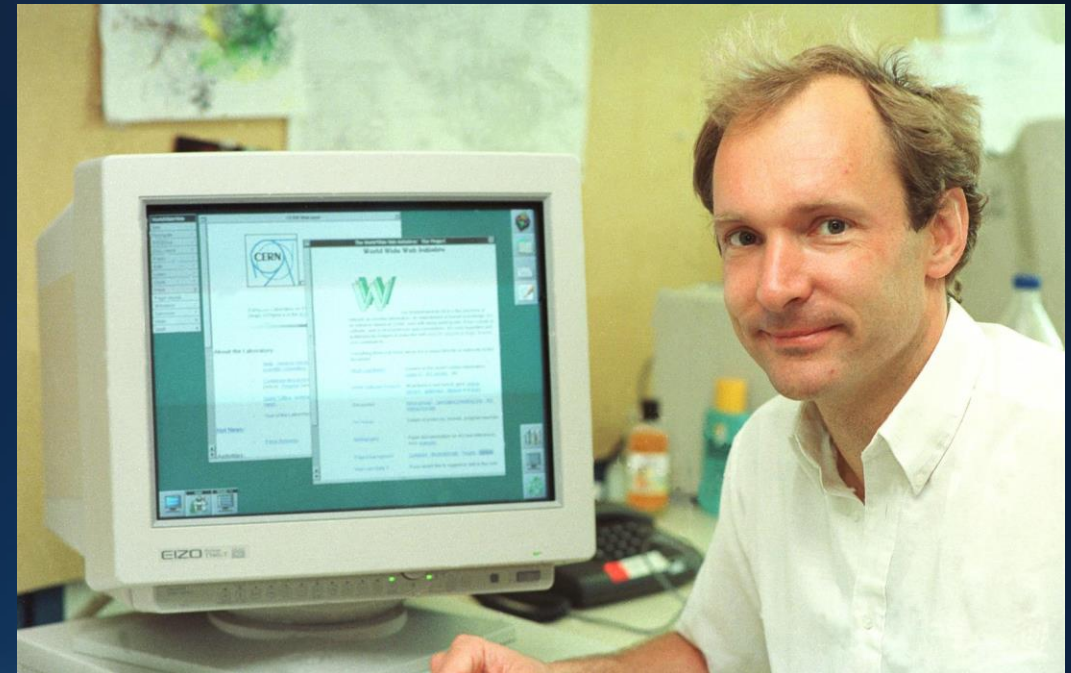
March 1989: Tim Berners Lee submits the first proposal for the World Wide Web

merge data networks and hypertext in an easy-to-use global information system

By the **end of 1990**, the first Web server and browser is up and running

In **1993**, CERN makes the source code of the World Wide Web available on a royalty-free basis

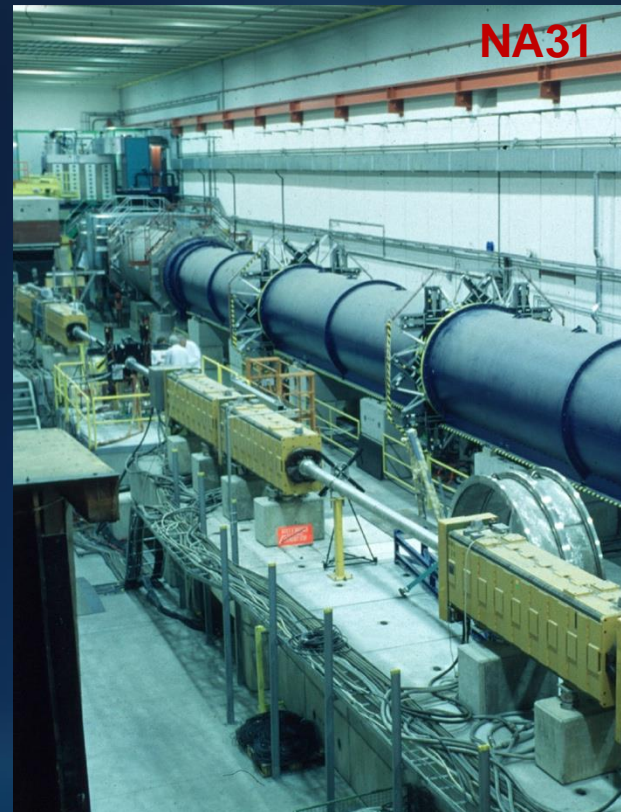
By the **end of 1994**, the Web already has **10,000 servers** and **10 million users**



Tim Berners Lee displaying some of the first web pages in 1994

Discovery of direct CP Violation

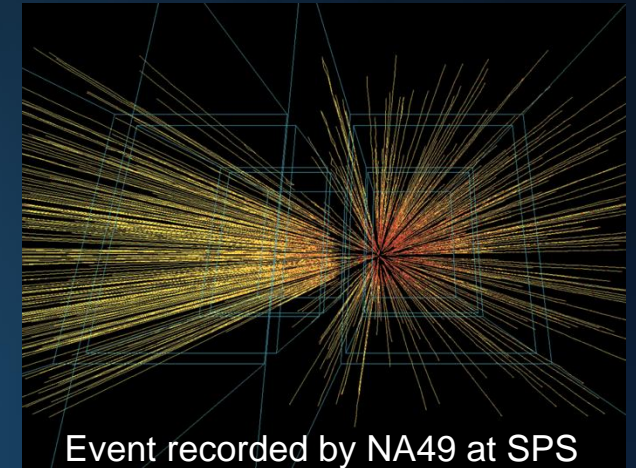
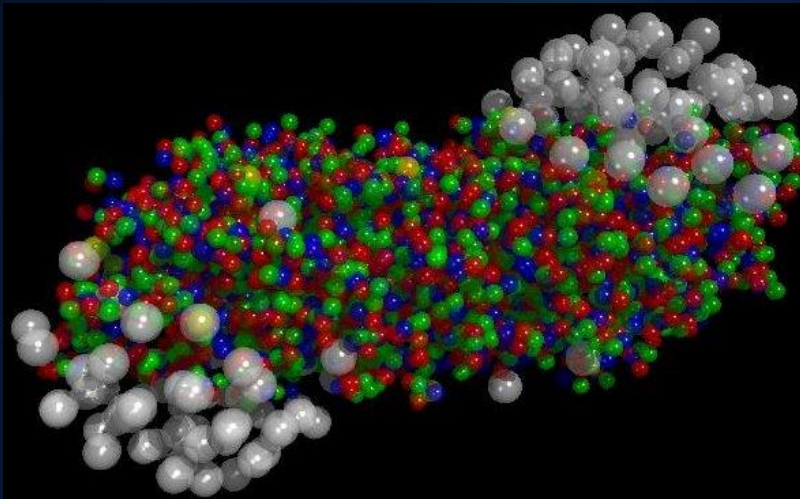
- CERN uses the powerful SPS beam to produce conspicuous yields of Kaons
- Two generations of experiments, NA31 and NA48, were setup between 1982 and 1993 to study direct CP violation through kaon decays
- NA31: first evidence of direct CP violation (a 3 standard deviation effect) in 1988.
- NA48 (final publication in 2002): observation well above 5 standard deviation.



$$\epsilon \sim 2.2 \times 10^{-3} \text{ indirect} \quad \epsilon'/\epsilon \sim 1.7 \times 10^{-3} \text{ direct}$$

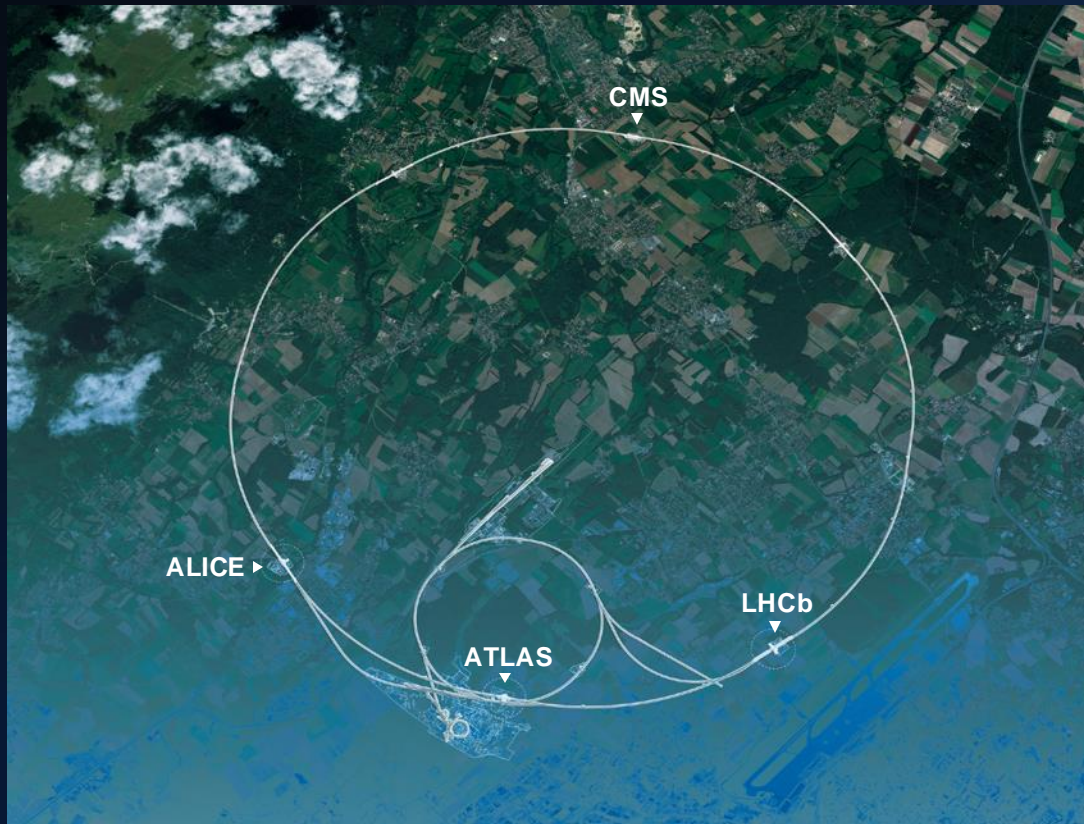
CERN, February 2000: first evidence of a new state of matter, the quark-gluon plasma

- Combined data from the 7 experiments on CERN's HI programme
- Proves an important prediction of the QCD theory. An important step forward in the understanding of the early evolution of the Universe.

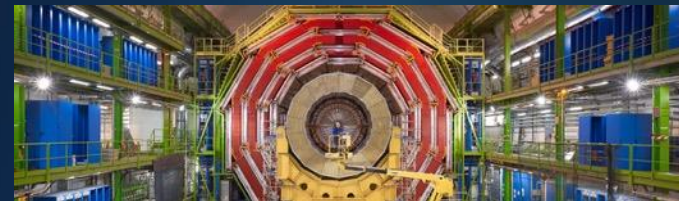


Luciano Maiani (CERN DG): "... We now have evidence of a new state of matter where quarks and gluons are not confined. ... There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to RHIC at BNL and later to the LHC."

The Large Hadron Collider era



ATLAS



CMS



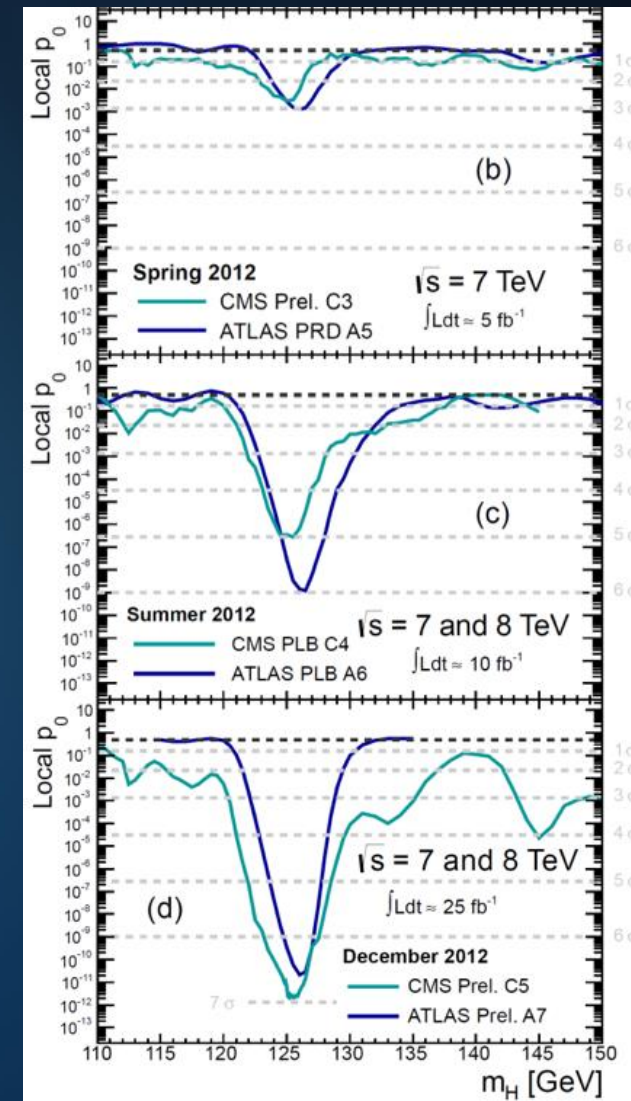
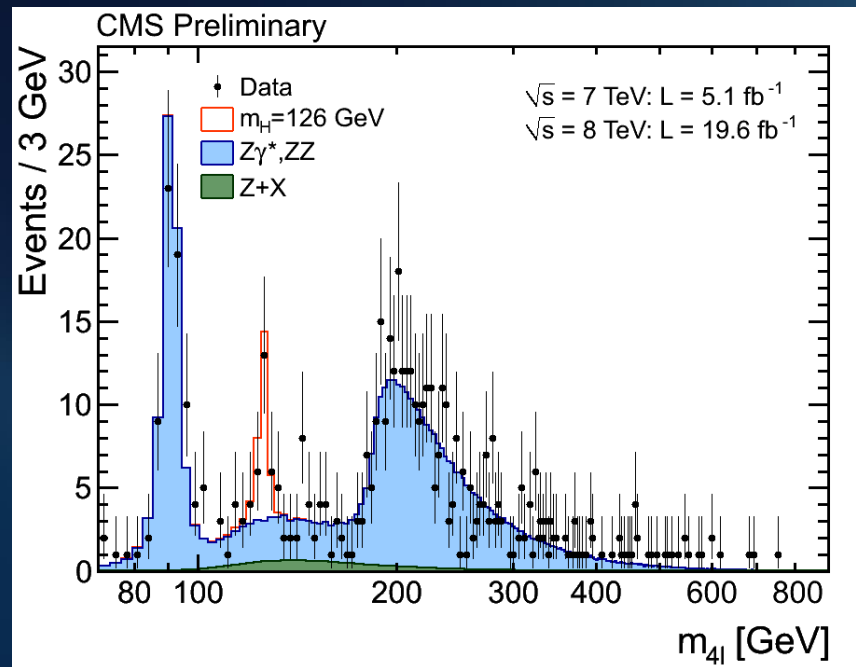
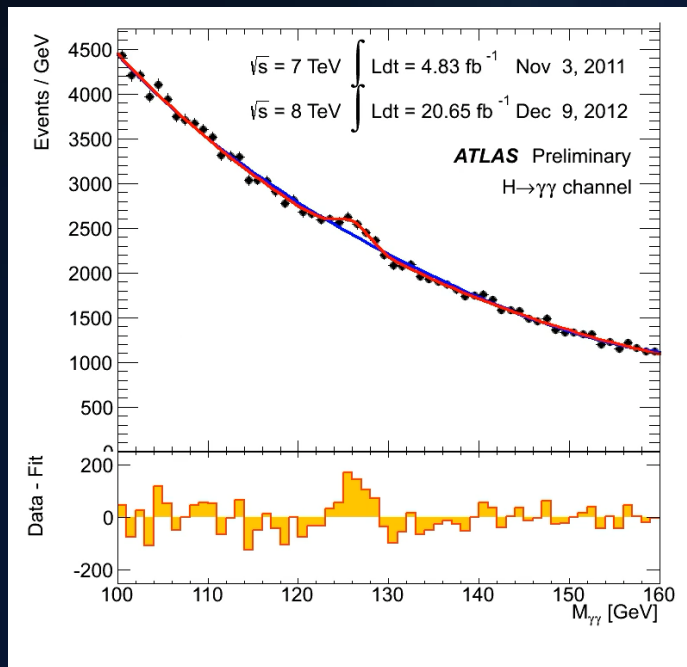
ALICE



LHCb

Higgs discovery

- End of 2011: tantalizing hint, the trail begins
- Summer 2012: discovery! 5σ from both experiments
- End of 2012: confirmation! Measurement era begins



Higgs discovery ... and the SM triumph

July 4th 2012 announcement



F. Gianotti (ATLAS) and J. Incandela (CMS)



F. Englert and P. Higgs

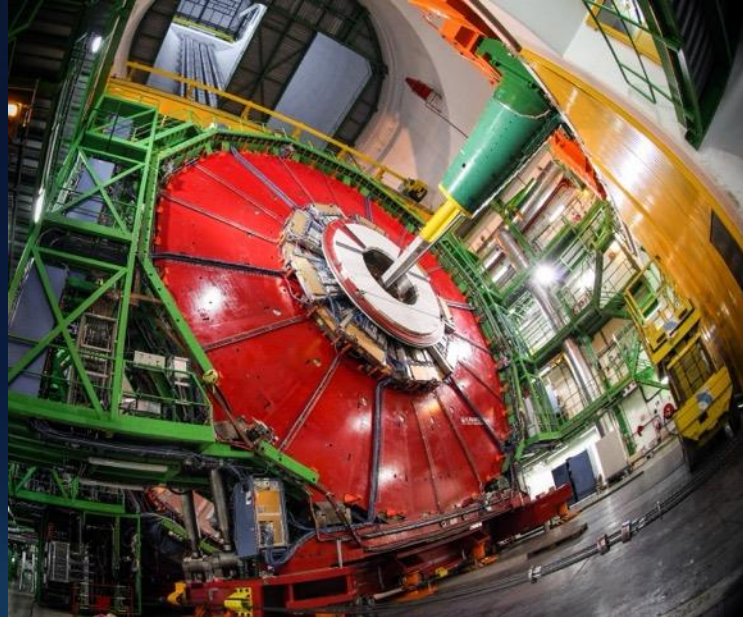
2013 Nobel Prize



CERN develops technologies in three key areas



ACCELERATORS



DETECTORS



COMPUTING

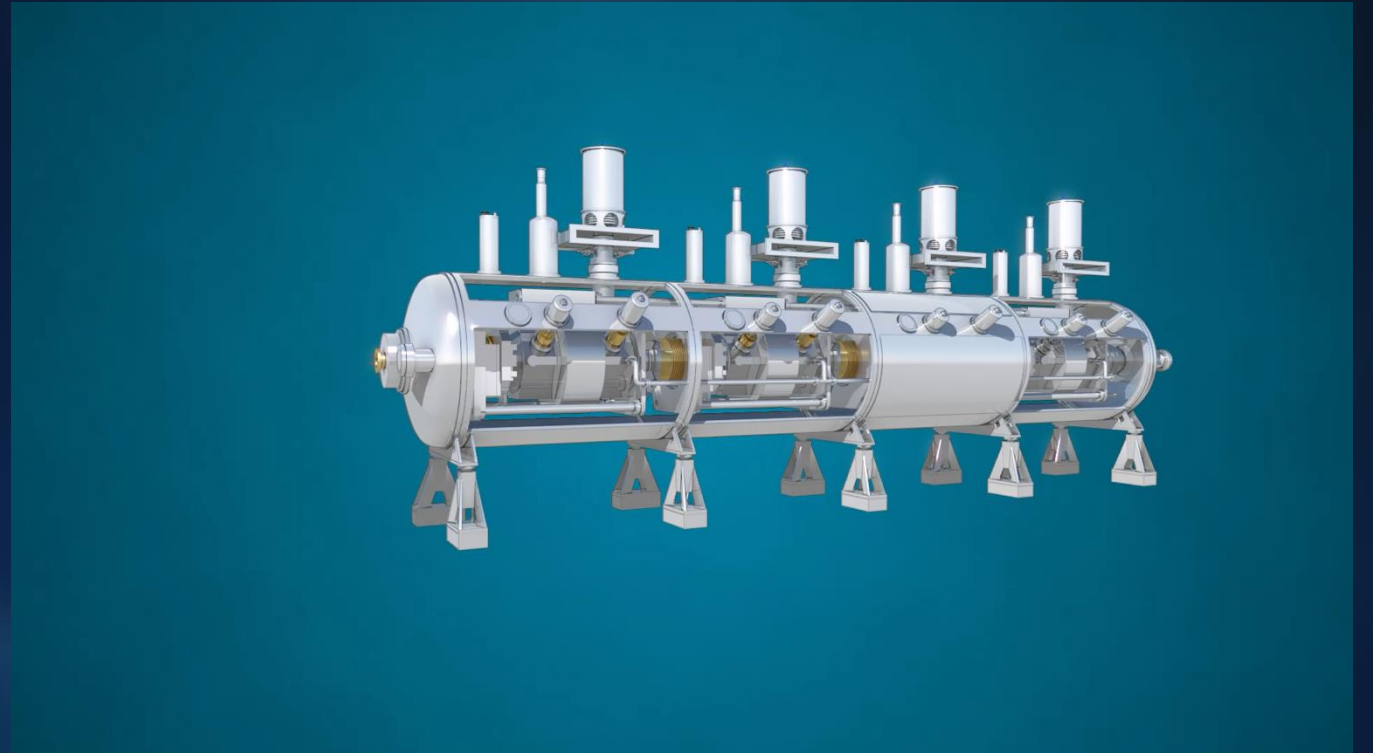
CERN will continue to play a crucial role in the journey of exploration

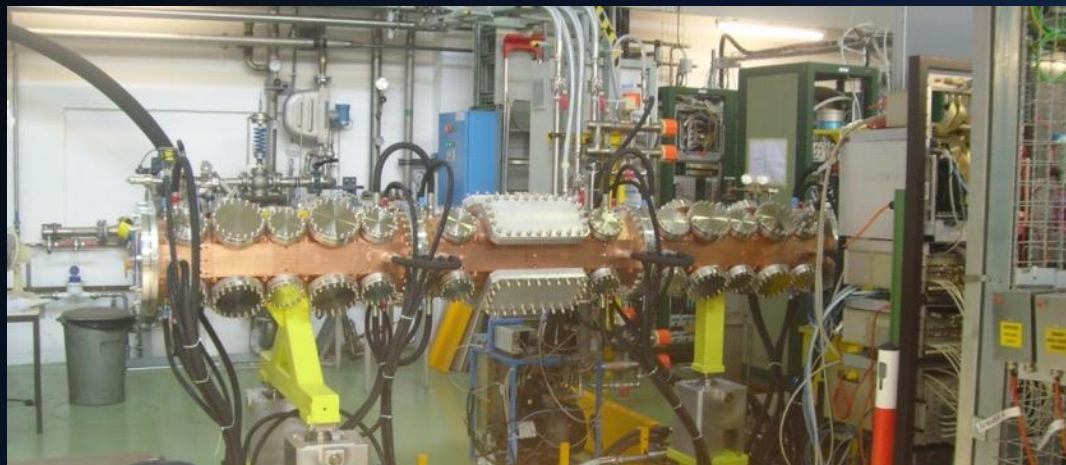


Fundamental research is a cornerstone of our future, driving the continuous cycle of discovery and application that propels human progress



Accelerator key technologies





Radio Frequency Quadrupole



Drift Tube Linac

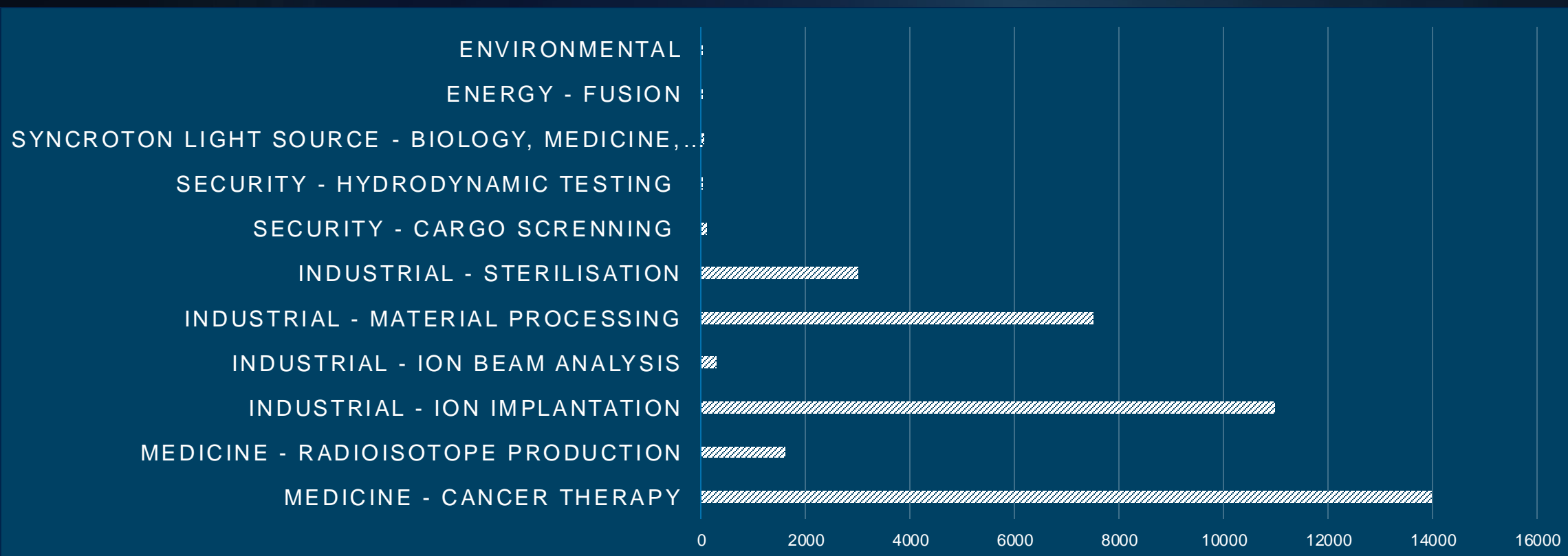


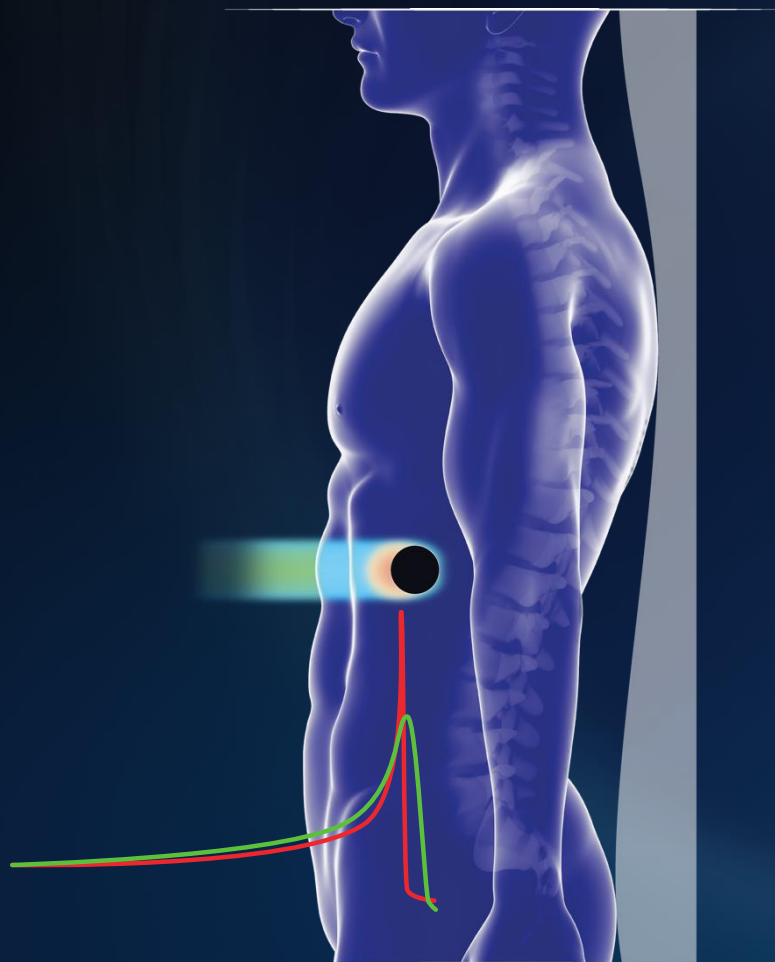
Cell-coupled DTL



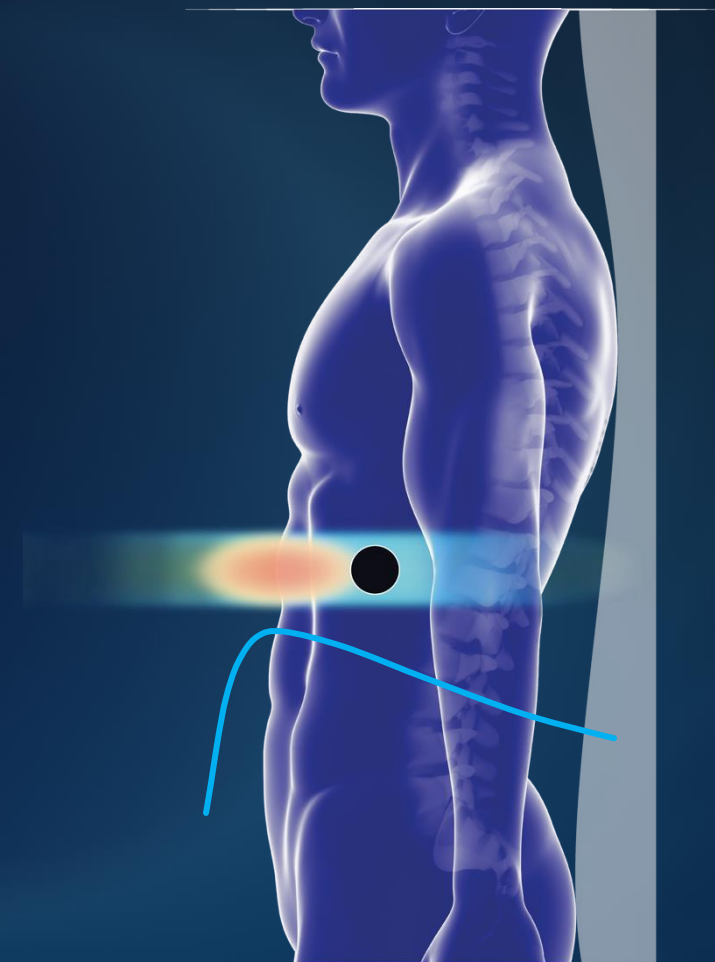
PI-mode Structure

Application of low-energy accelerators



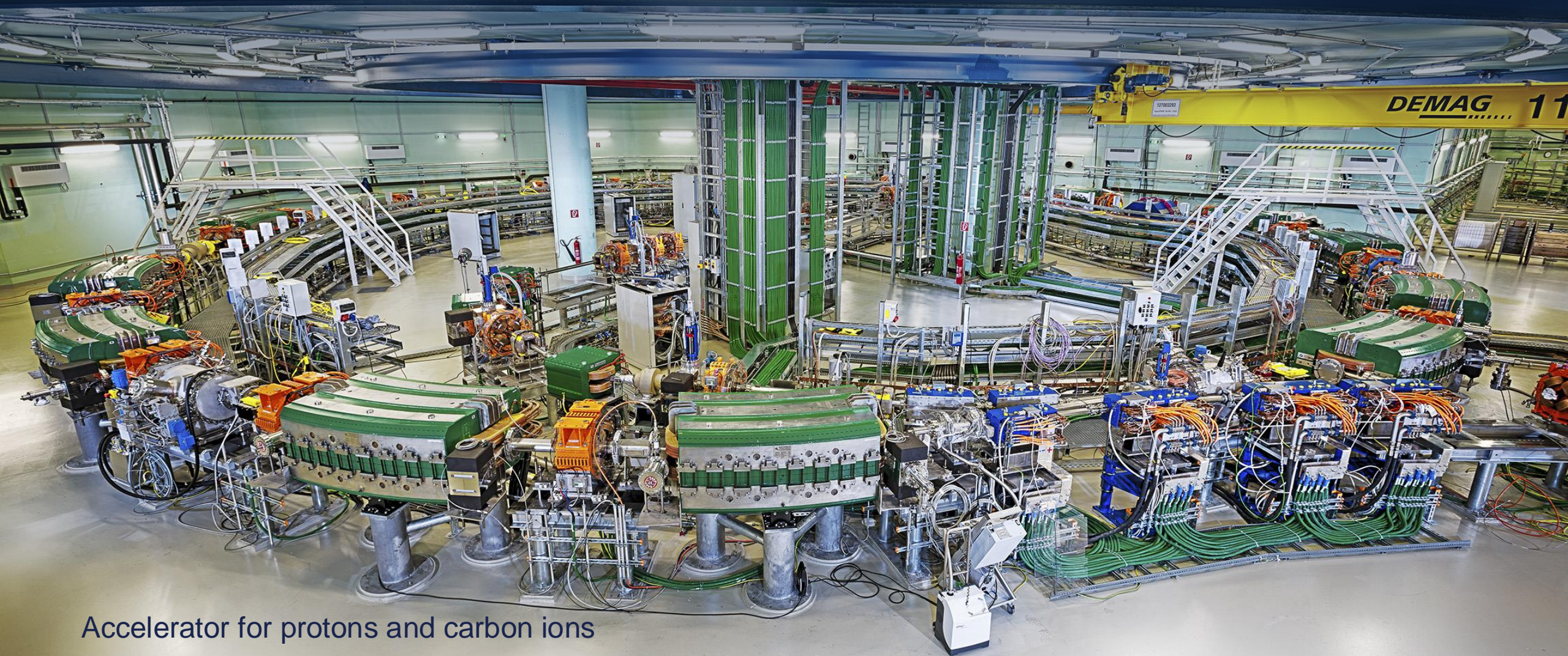


PROTON THERAPY



CONVENTIONAL RADIATION THERAPY

- Photons
- Carbon ions
- Protons



Accelerator for protons and carbon ions



Carbon ion therapy treatment room

Credit: CNAO

Superconductivity in the LHC

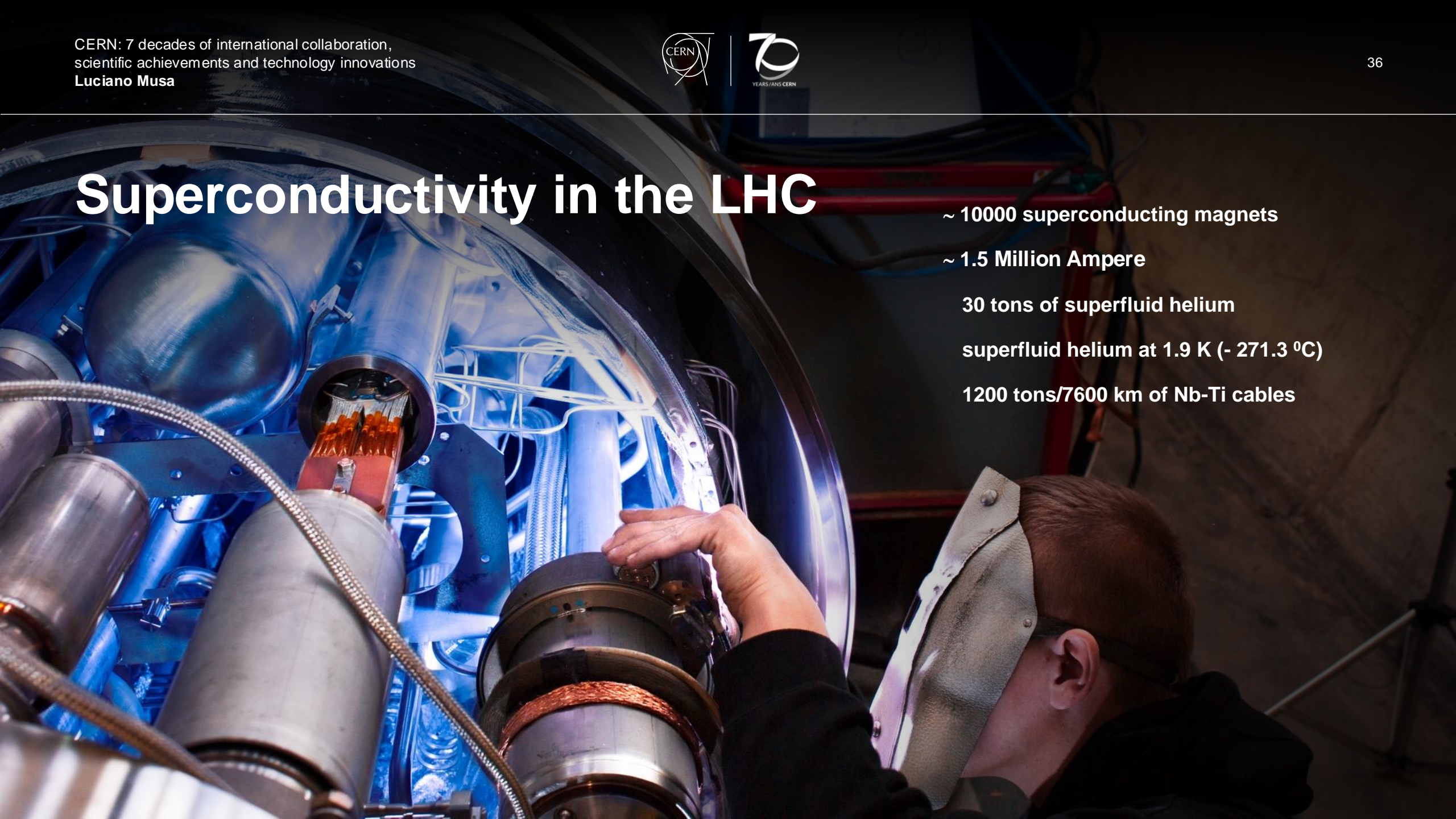
~ 10000 superconducting magnets

~ 1.5 Million Ampere

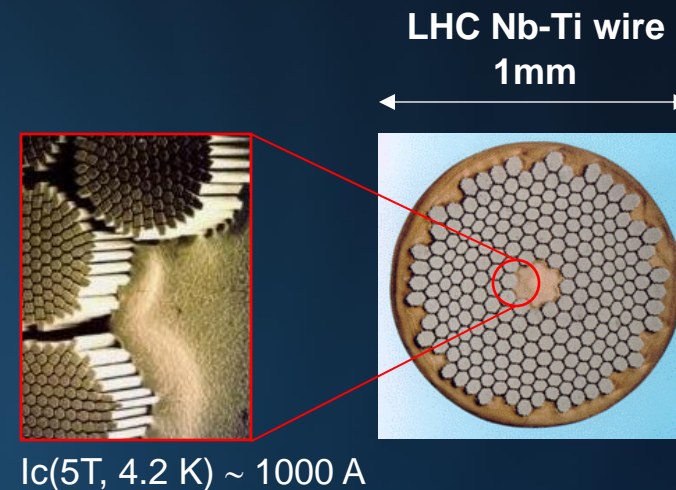
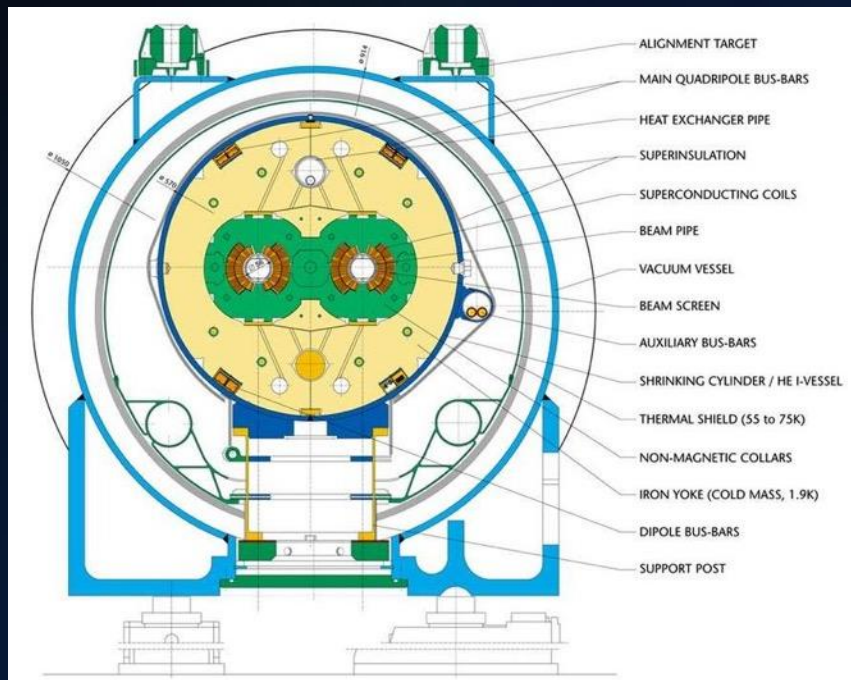
30 tons of superfluid helium

superfluid helium at 1.9 K (- 271.3 °C)

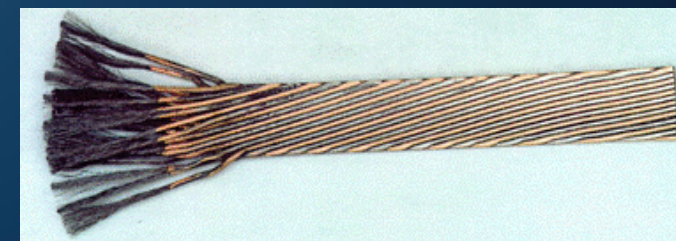
1200 tons/7600 km of Nb-Ti cables



The Large Hadron Collider Magnets



LHC Nb-Ti Cable



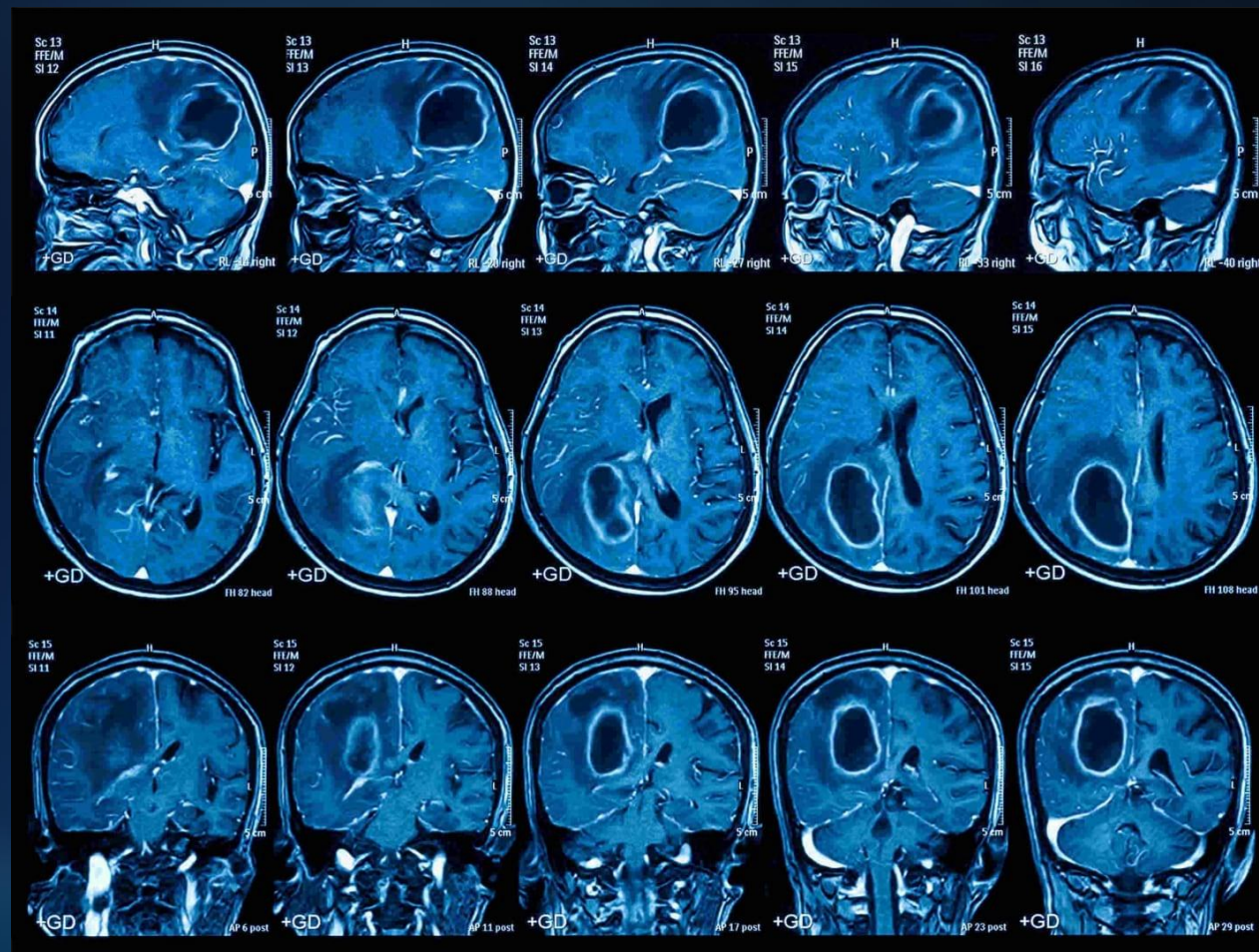
$I_c(10T, 1.9 K) \sim 13000 A$

MRI Magnets

Superconducting magnets in MRI:
Non-invasive 3D anatomical imaging

MRI industry consumes ~4000 tons of Nb-Ti annually

Over 50,000 MRI scanners worldwide



Transmission of Electric Power

High-Temperature Superconductors:

Used for High Luminosity upgrade of the LHC

T_c above liquid nitrogen temperature
(77 K or $-195.15\text{ }^{\circ}\text{C}$)

Handles 120 kA in DC mode at up to 50 K
($-223.1\text{ }^{\circ}\text{C}$)



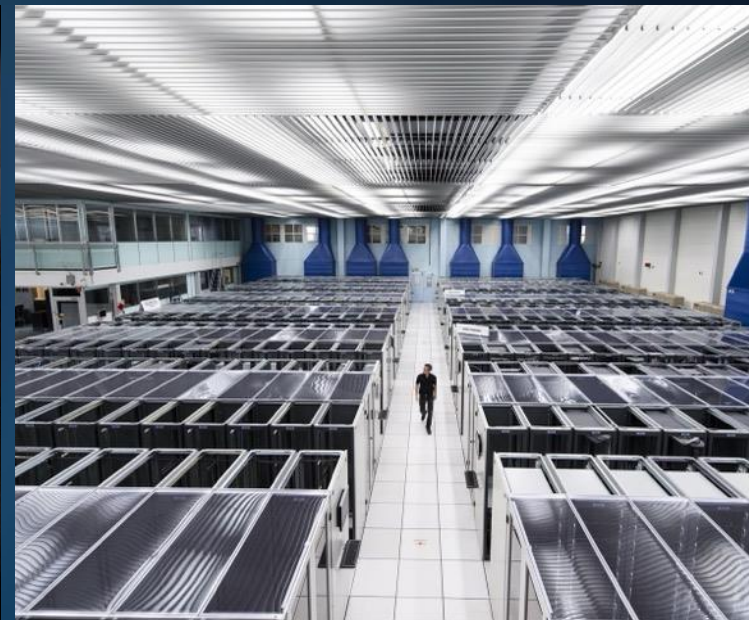
We develop technologies in three key areas



ACCELERATORS

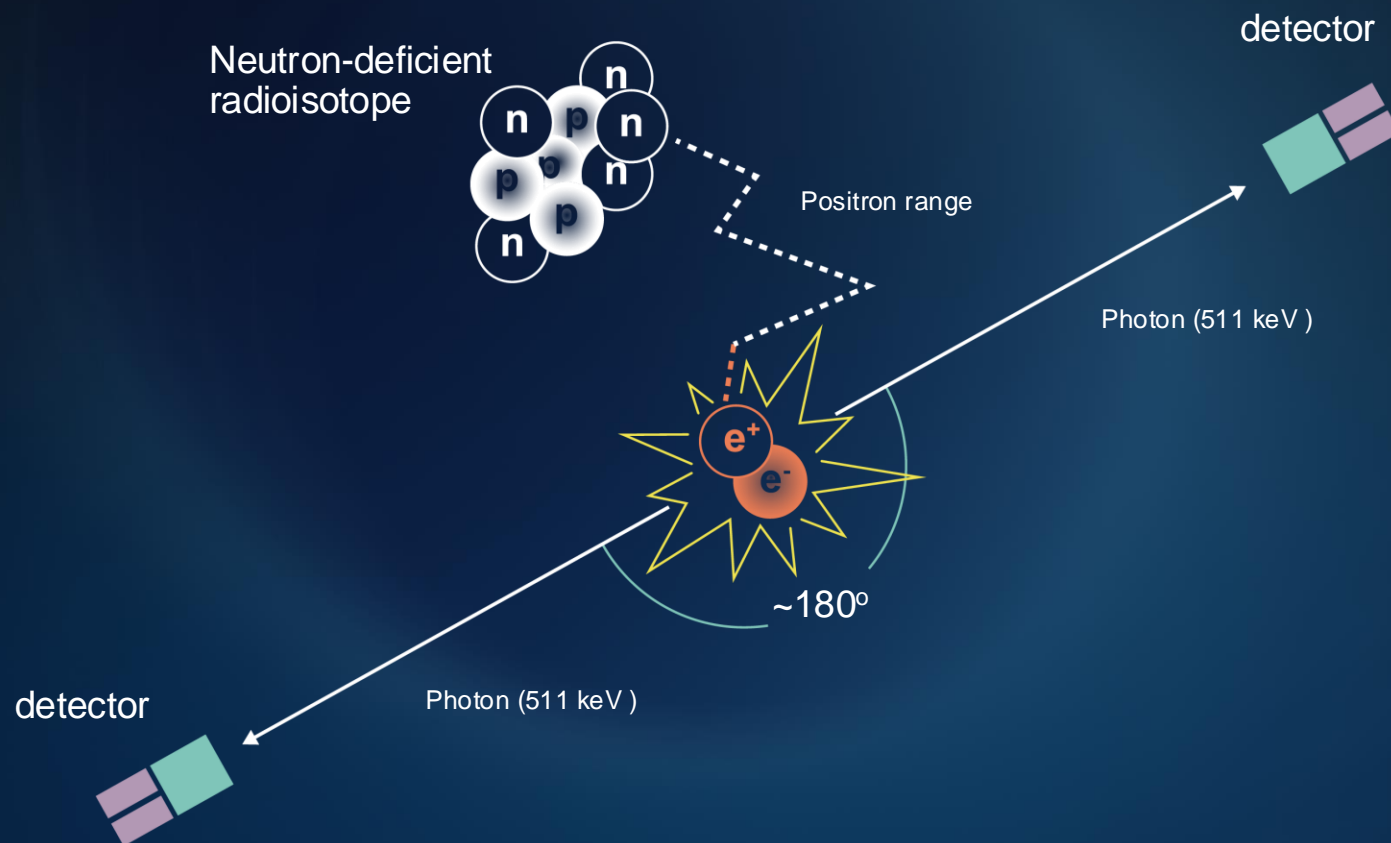
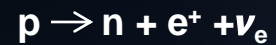


DETECTORS



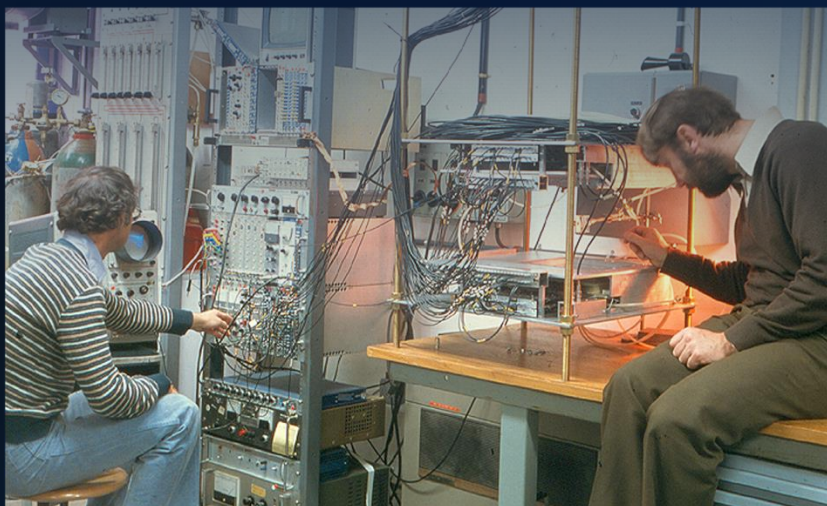
COMPUTING

Positron Emission Tomography

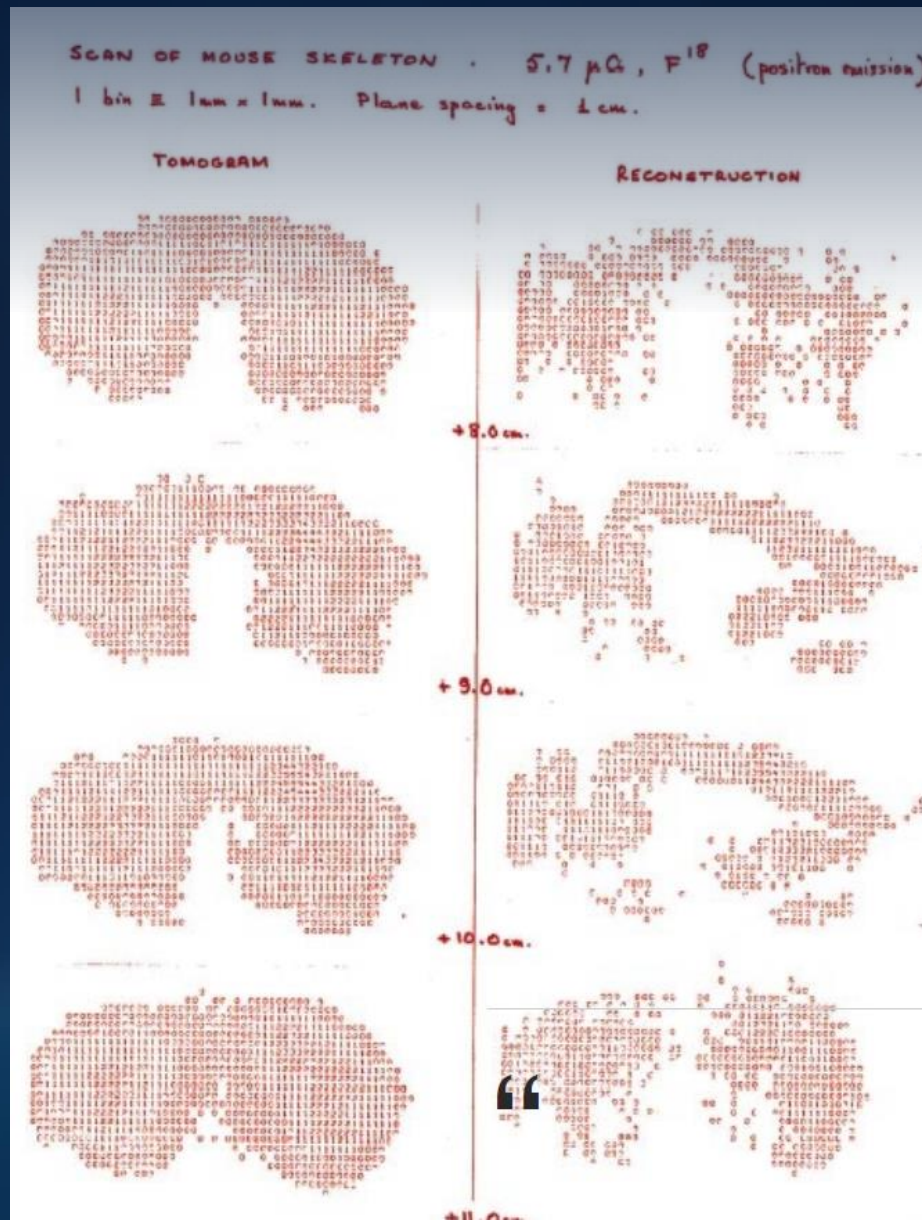


■ PHOTONS FROM POSITRON ANNIHILATION

1977



Credit: CERN



The silicon revolution and discoveries

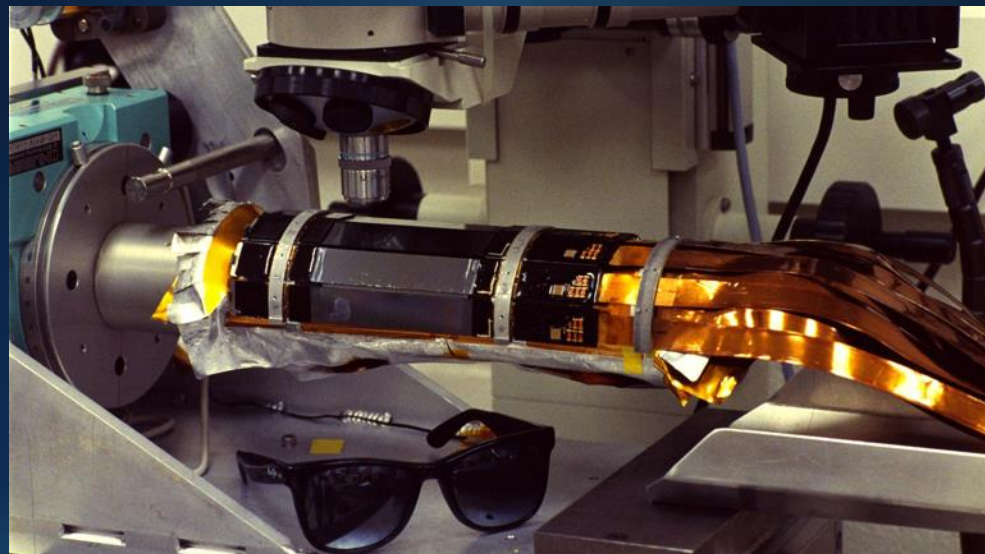
1980 - search for particles with charm and beauty quarks (decay length $\sim 100 \mu\text{m}$)

Silicon technology for microelectronics



Kemmer 1979, KETEK
from electronics to detector fabrication

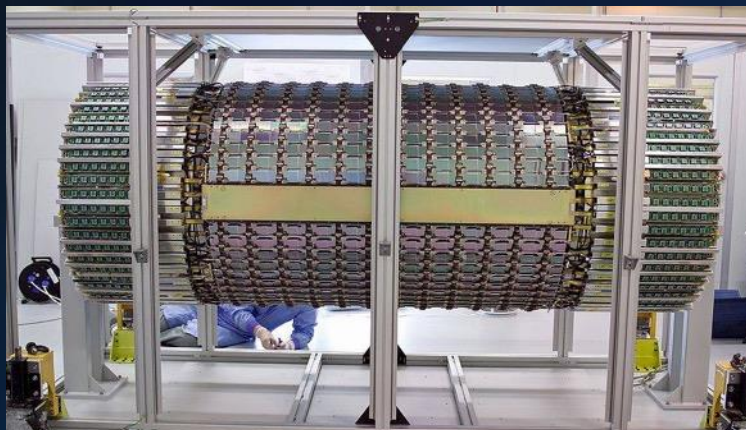
NA11- NA32: measurements of Lifetimes of particles containing c-quarks
MARK II: measurement of charm, tau, and b-lifetime



Silicon trackers at the heart of all LHC experiments

Giant, ultra-fast and very complex 3D camera

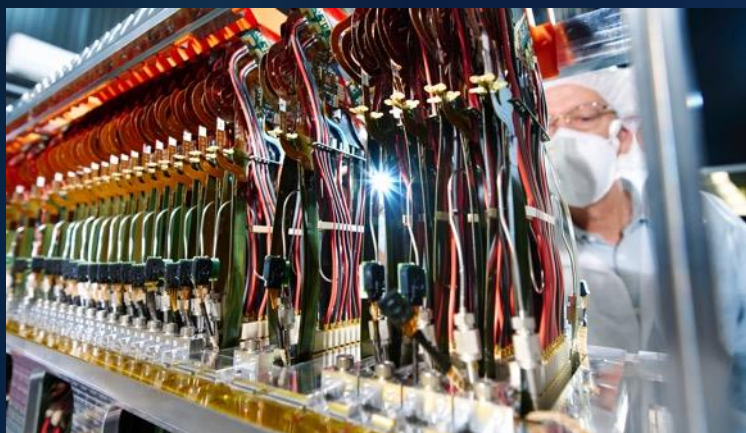
ATLAS



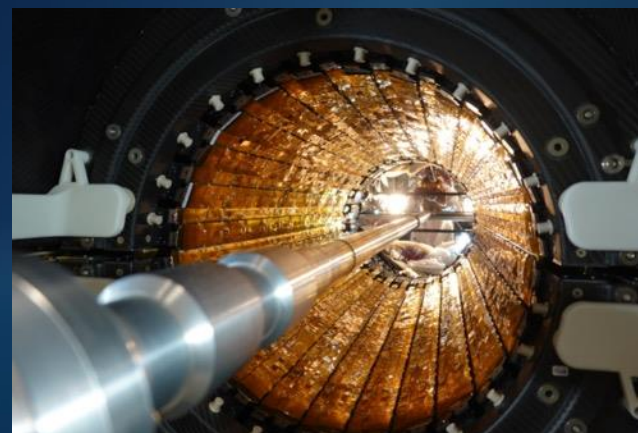
CMS



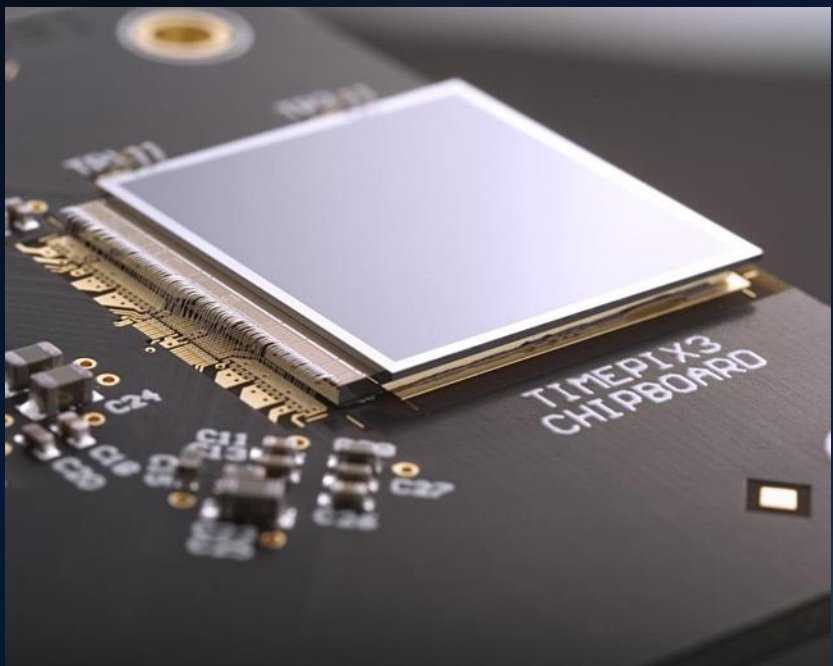
LHCb



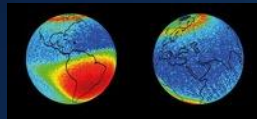
ALICE



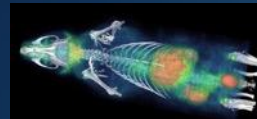
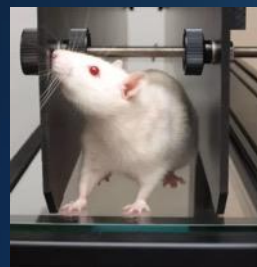
From particle physics to technology and back



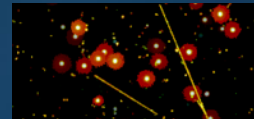
Space



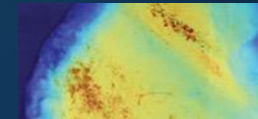
Biology



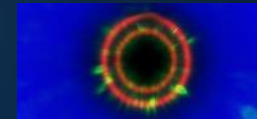
Research



Mining



Non-destructive testing



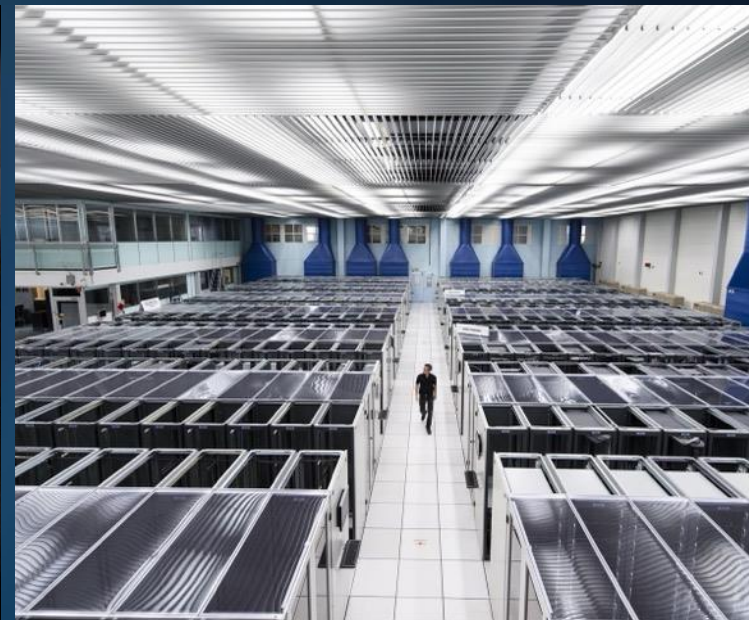
We develop technologies in three key areas



ACCELERATORS

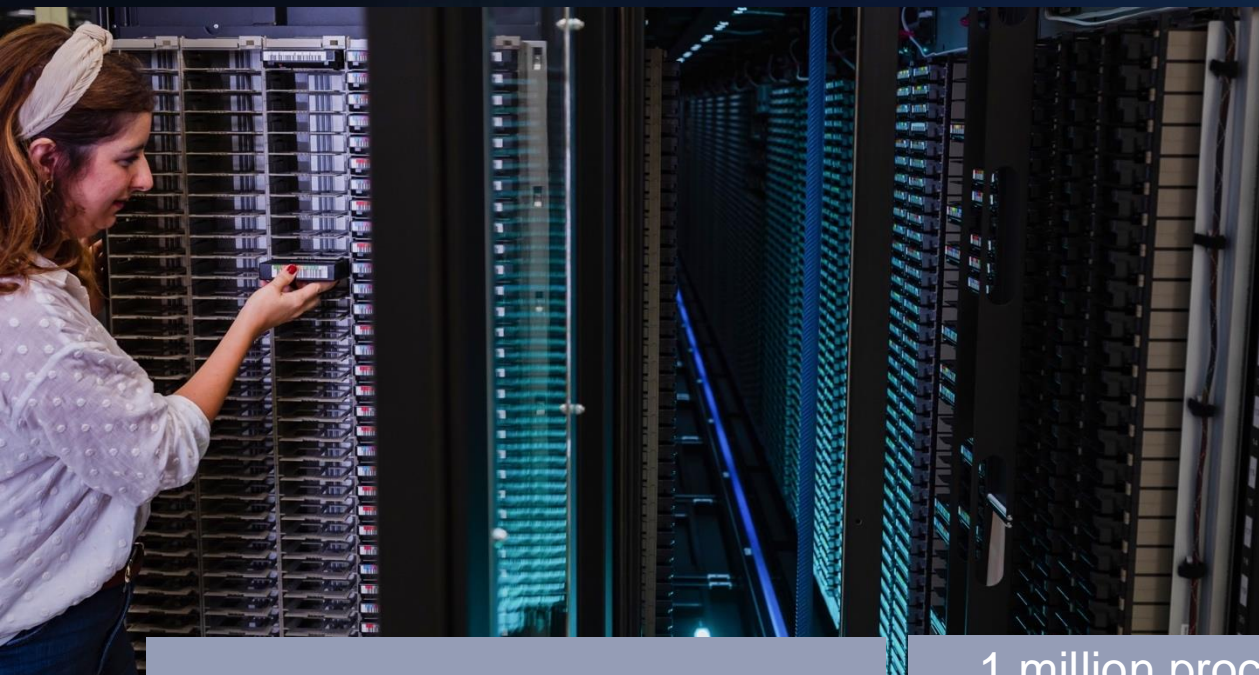


DETECTORS



COMPUTING

The Worldwide LHC Computing Grid (WLCG)



Used to store, distribute, process
and analyse data.

1 million processing cores in
about 160 data centres
and 42 countries.



More than 1000 Petabytes of
CERN data stored world-wide.

Core value underlying the collaboration: Open Science

CERN Convention Art. II.1.: *The Organization shall have no concern with work for military requirements, and **the results of its experimental and theoretical work shall be published or otherwise made generally available***

- **Open Access Policy (2014)**

>90% of research produced at CERN published OA (CC-BY licenses)

Sponsoring Consortium for Open Access Publishing in Particle Physics -
SCOAP³ (44 countries)

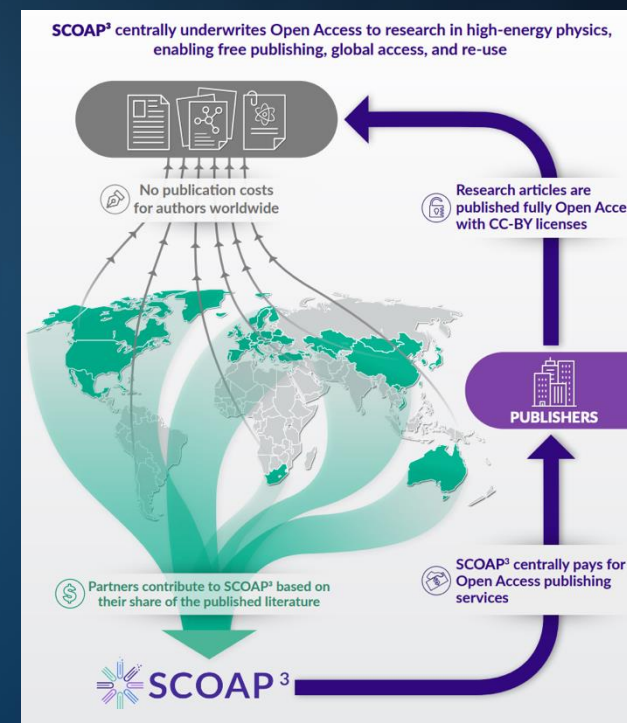
Inspired major global OA initiatives: PlanS, OA2020, etc.

- **LHC Open Data Policy (2020)**

LHC experiments release experimental data and associated analysis tools
for diverse scientific and educational uses

- **CERN Open Science Policy (2022)**

Policy broadened to explicitly include open software, hardware, research
integrity and assessment, education, training and outreach, citizen science



CERN will continue to play a crucial role in the journey of exploration



Fundamental research is a cornerstone of our future, driving the continuous cycle of discovery and application that propels human progress

