7th EIROforum School on Instrumentation

EIROforum serving european science

CERN - Introduction

Petra Riedler, CERN

Picture: CERN

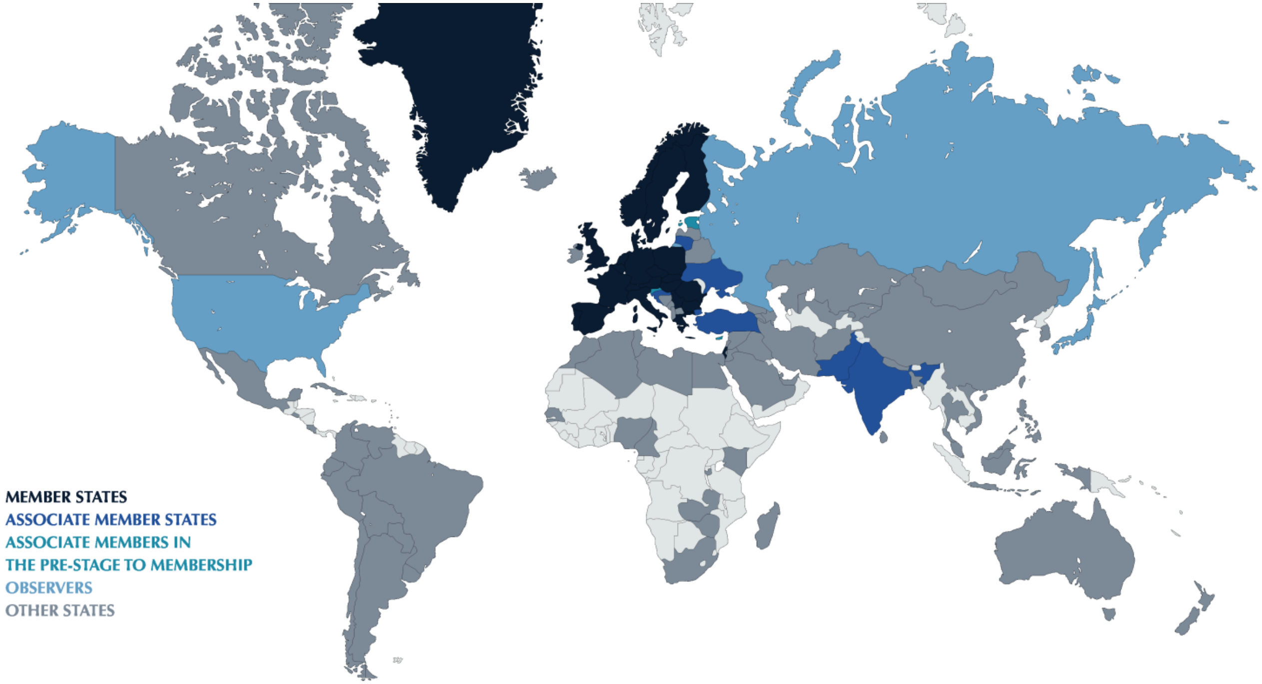
Outlook

- Overview of CERN
- Brief introduction to High Energy Physics (HEP) – the big questions
- Experimental tools to study particles and interactions

ATLAS SCT
http://cdsweb.cern.ch/search?recid=883309

CERN-
European Organization for Nuclear Research

- **Founded in 1954** by 12 countries (Belgium, Denmark, France, Germany, Greece, Italy, Netherlands, Norway, Sweden, Switzerland)
- **Today:** 23 member states, 9 associate member states
- **More than 17 500 scientists and engineers from all over the world** (data from 2017), about 2500 employees
- 110 nationalities from institutes in more than 70 countries

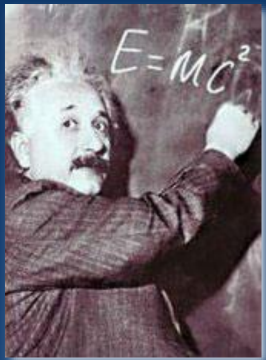



LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
UISSE
FRANCE
ALICE
CMS
LHC 27 km

CERN's Mission

- **Push back** the frontiers of knowledge

  E.g. the secrets of the Big Bang …what was the matter like within the first moments of the Universe's existence?

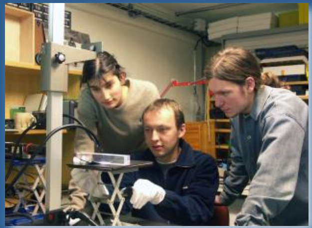


- **Develop** new technologies for accelerators and detectors

  Information technology - the Web and the GRID

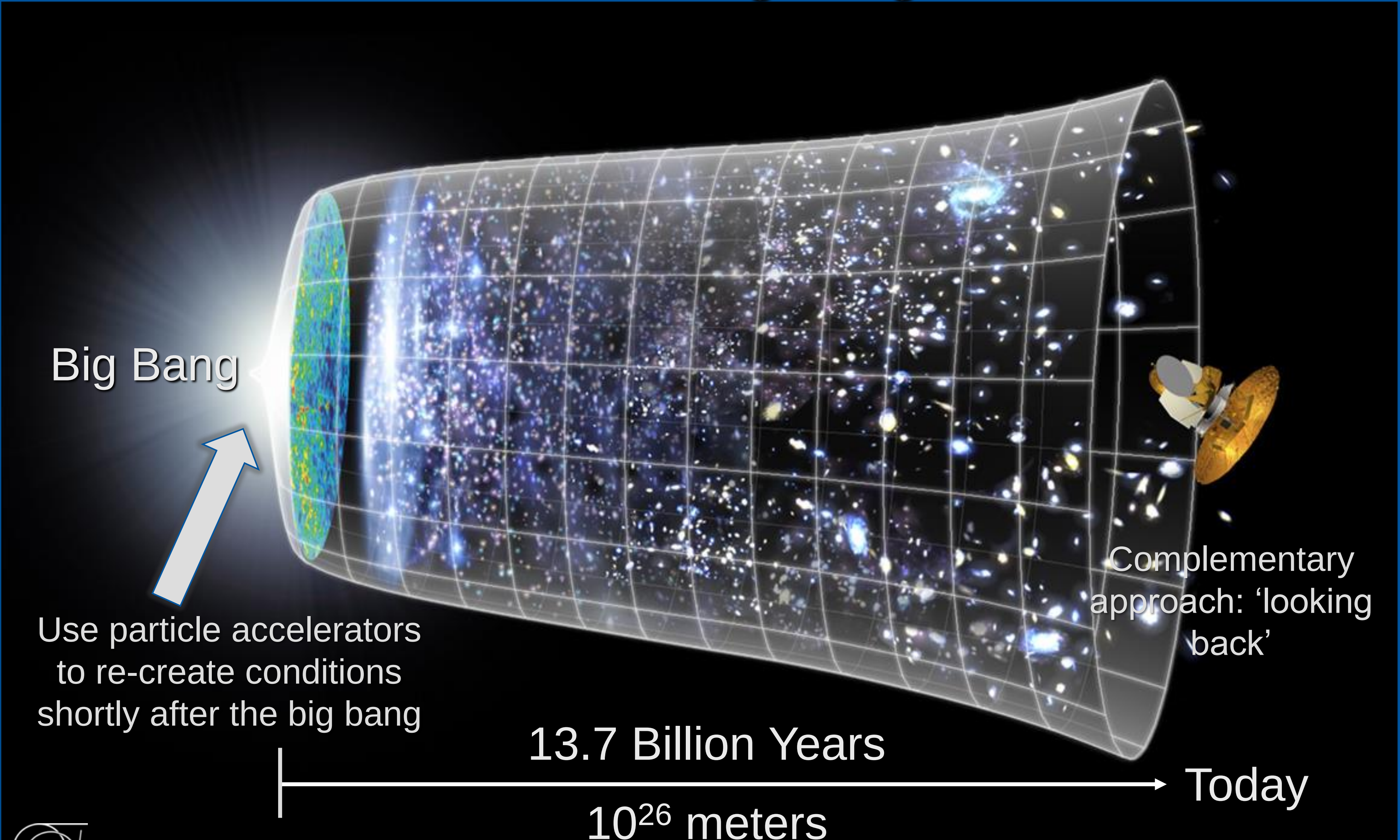
  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow

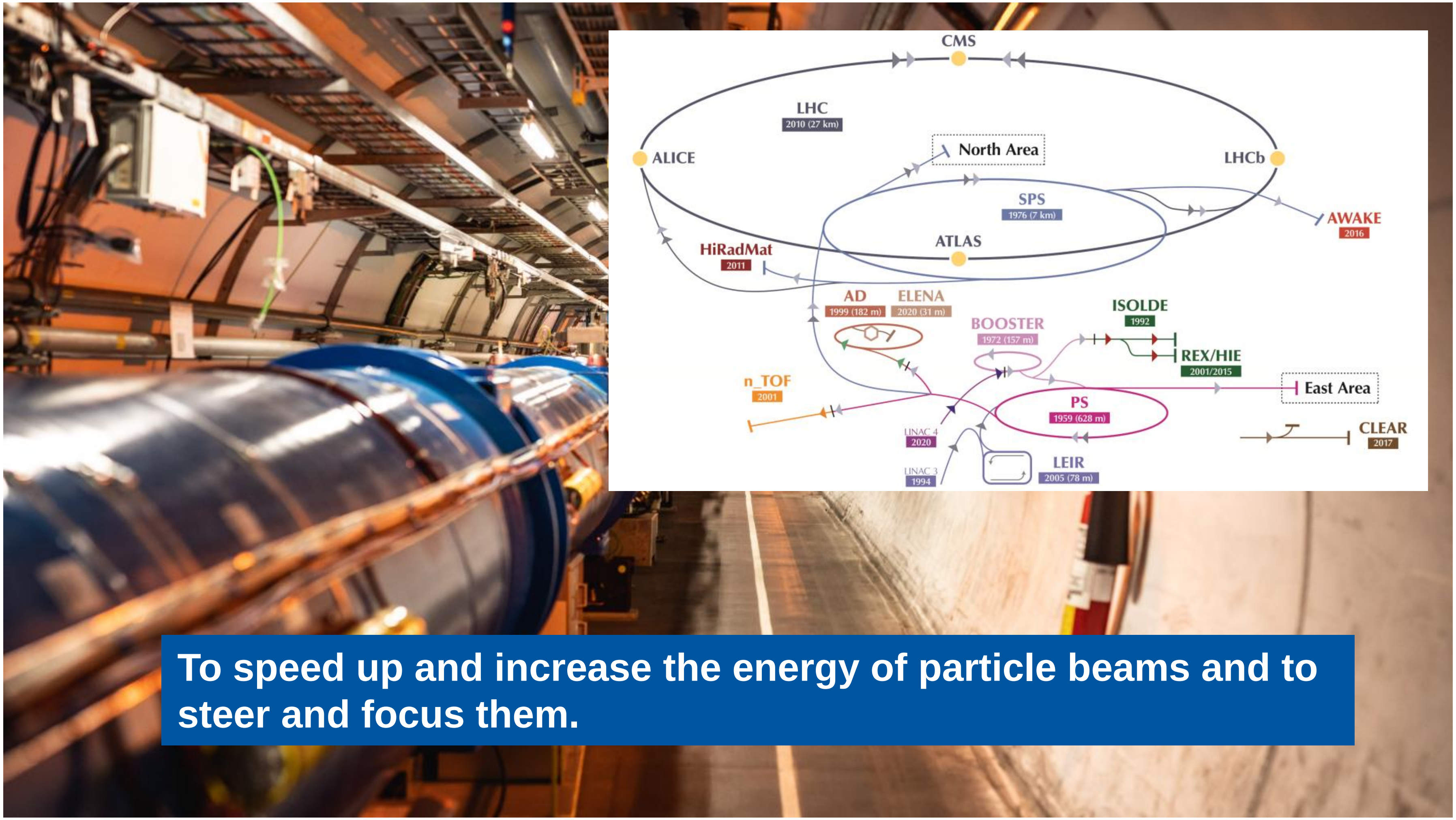


- **Unite** people from different countries and cultures

Try to understand the very first moments of our Universe after the Big Bang

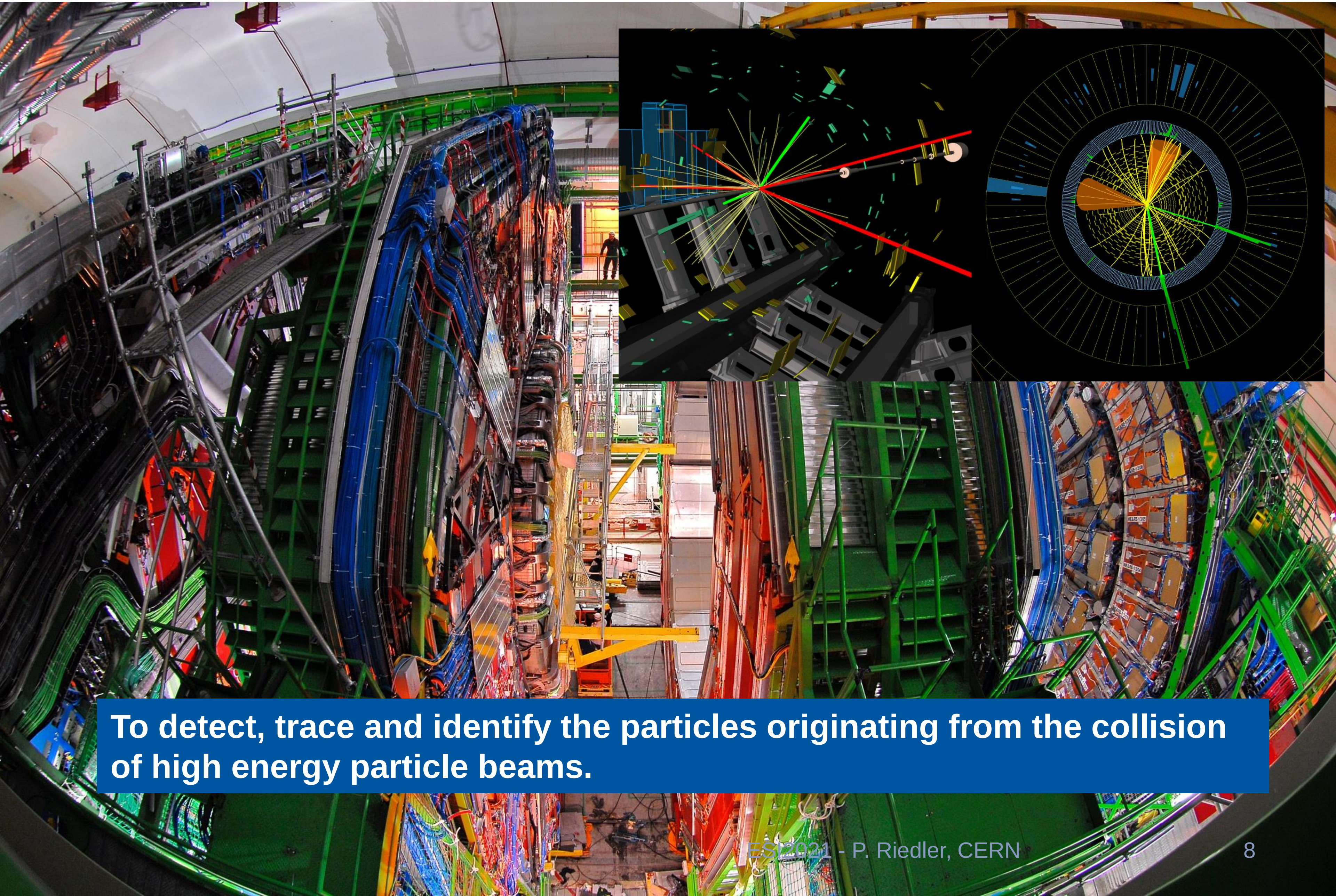


Accelerators ….



To speed up and increase the energy of particle beams and to steer and focus them.

…. and Detectors



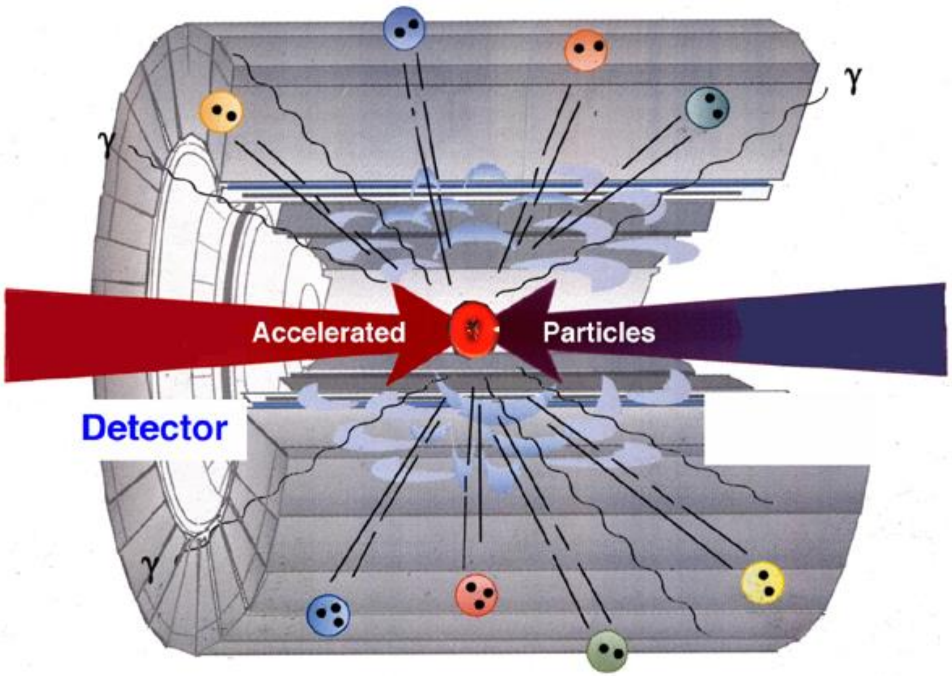
To detect, trace and identify the particles originating from the collision of high energy particle beams.

$E=mc^2$

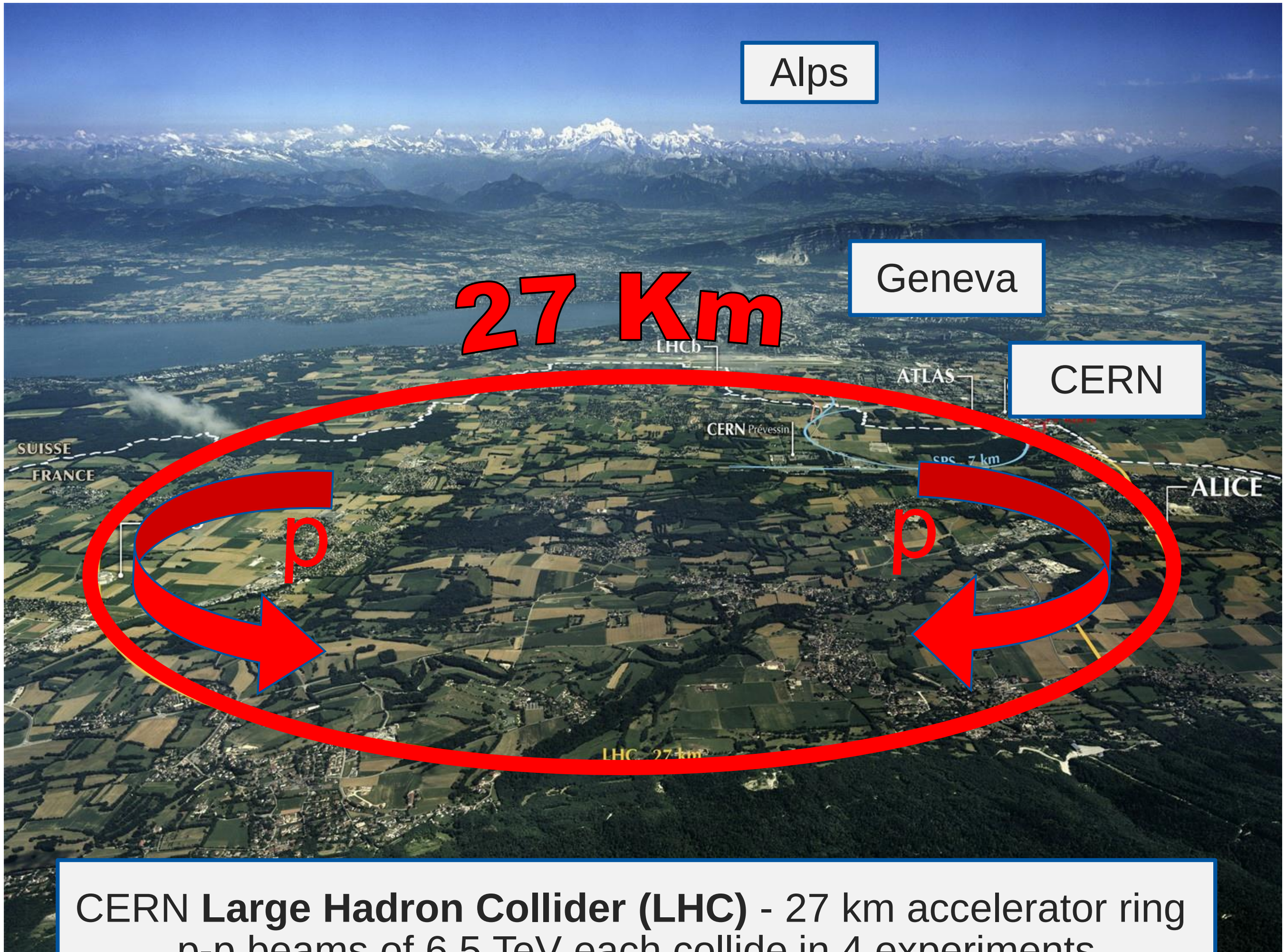
1) Concentrate energy on particles (**accelerator**)

2) **Collide** particles (recreate conditions after Big Bang)

3) Identify created particles in **Detector** (search for new clues)



LHC - Large Hadron Collider



CERN **Large Hadron Collider (LHC)** - 27 km accelerator ring
p-p beams of 6.5 TeV each collide in 4 experiments

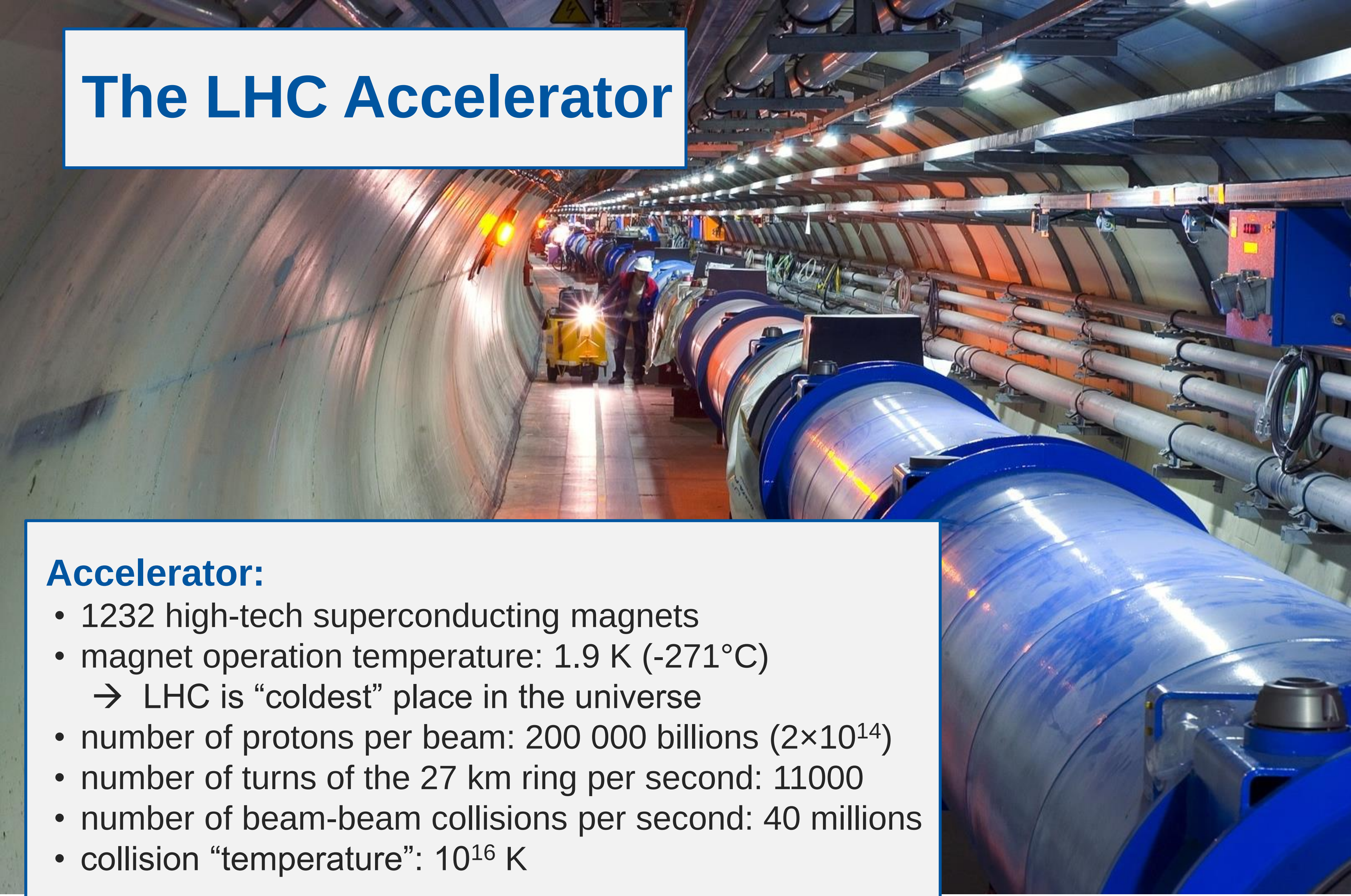
- **LHC: 27 km tunnel**
  - **Largest accelerator**
  - 1232 dipoles B=8.3T
  - Design: pp $\sqrt{s}$ = 14 TeV
    L_{design} = 10^{34} cm^{-2} s^{-1}
    Heavy ions (e.g. Pb-Pb; 5TeV)

- **Circulating beams:**

  2008: first beam
  2012: Run 1 at 2 x 4 TeV
  2015: Run 2 at 2 x 6.5 TeV
  2016: Reaching 10^{34} cm^{-2} s^{-1}
  2018: LS2; 2020: Run 3
  2024: LS3; **2026: HL-LHC**

Also a program with Pb beams at 6.5 Z TeV

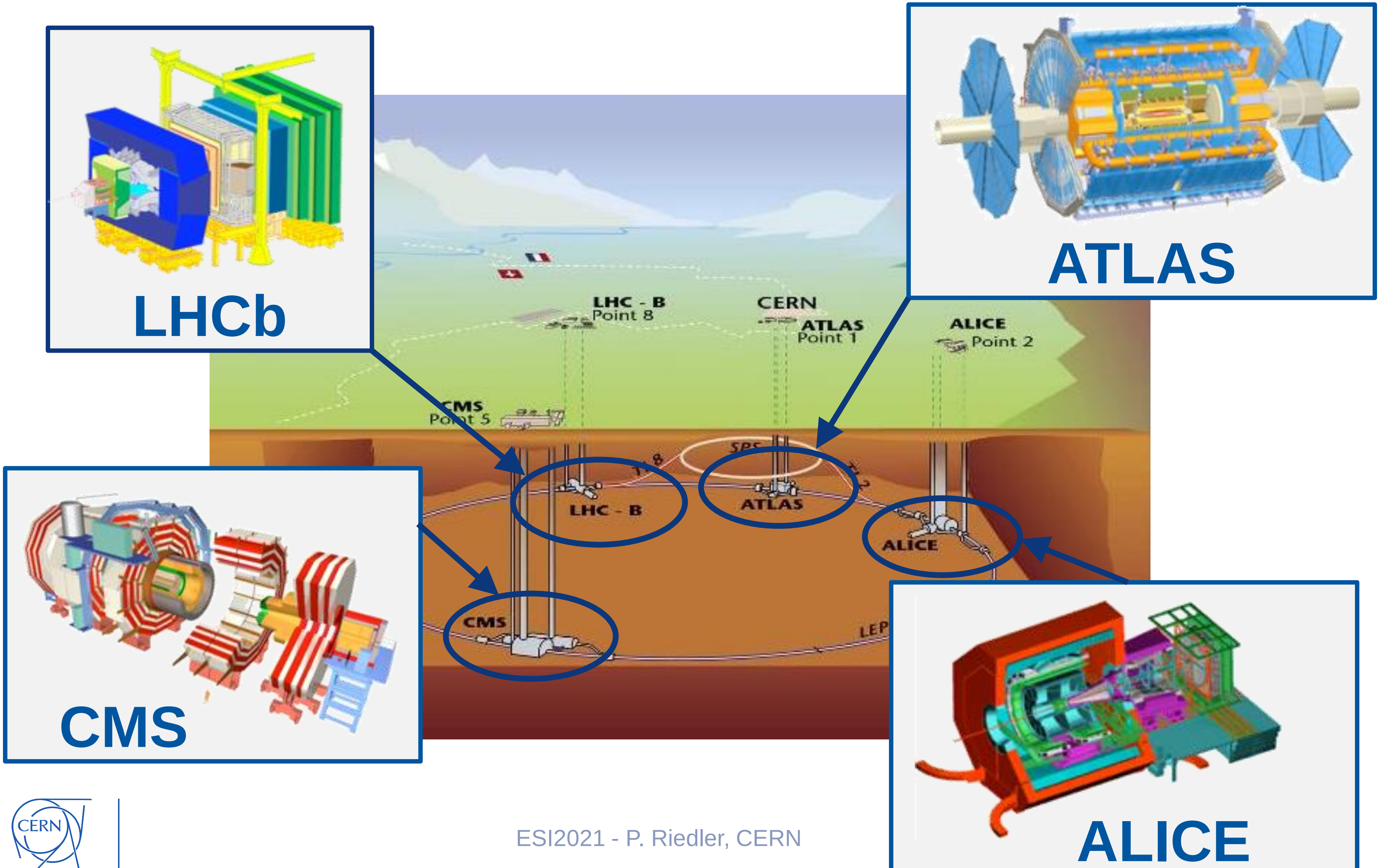
The LHC Accelerator



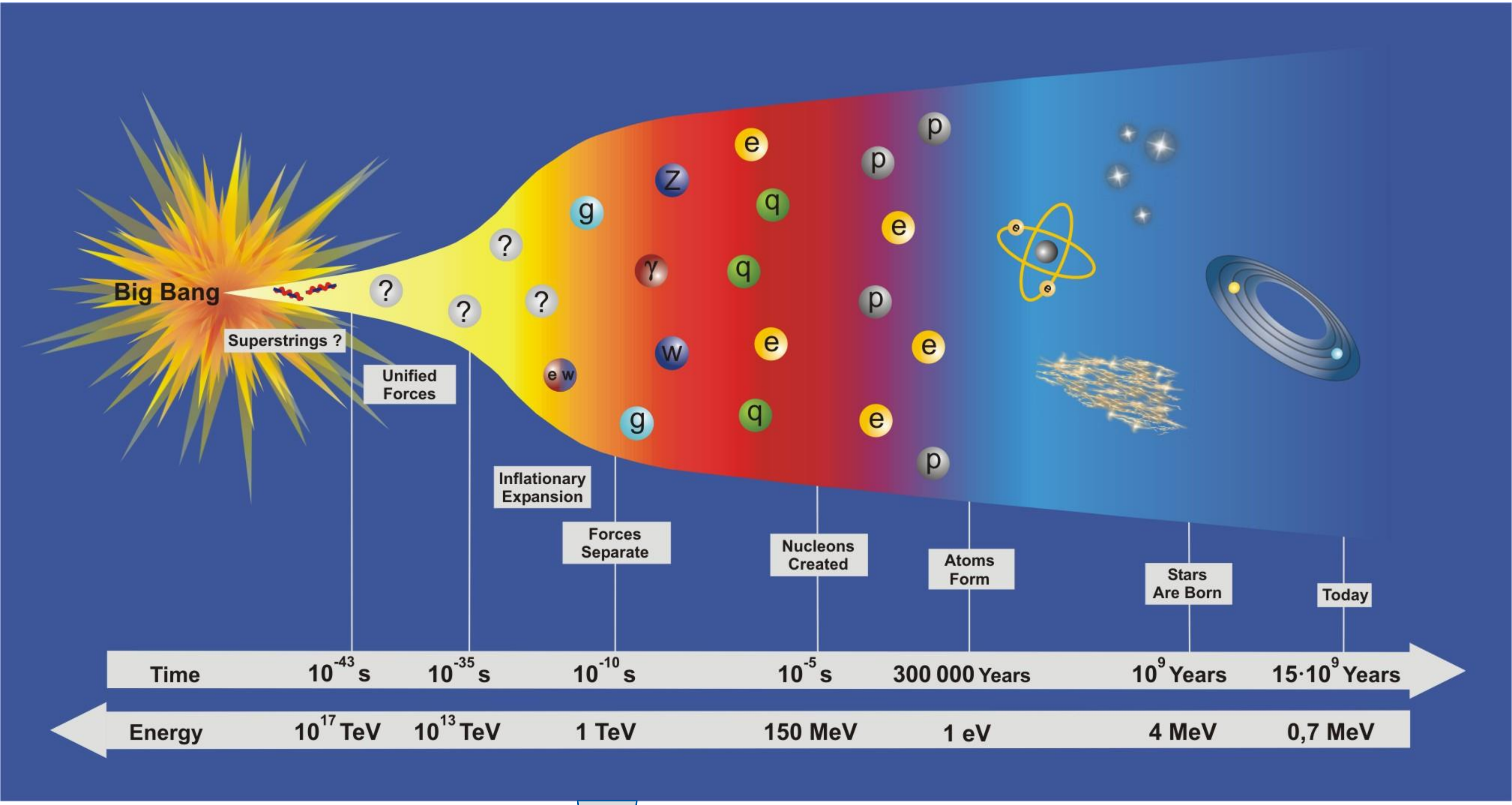
Accelerator:

- 1232 high-tech superconducting magnets
- magnet operation temperature: 1.9 K (-271°C)
  → LHC is “coldest” place in the universe
- number of protons per beam: 200 000 billions (2×10^{14})
- number of turns of the 27 km ring per second: 11000
- number of beam-beam collisions per second: 40 millions
- collision “temperature”: 10^{16} K

The LHC Experiments



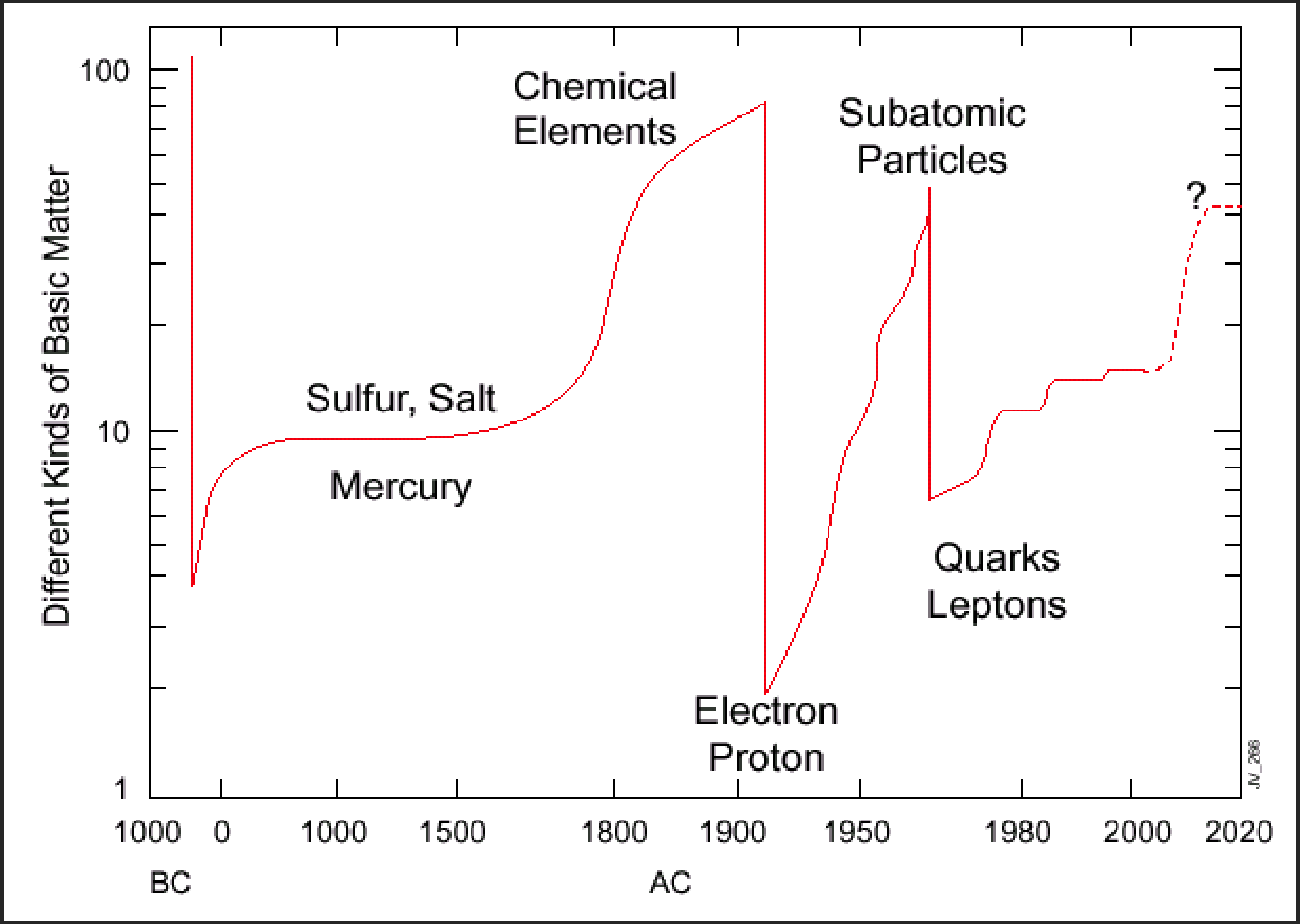
History of the universe



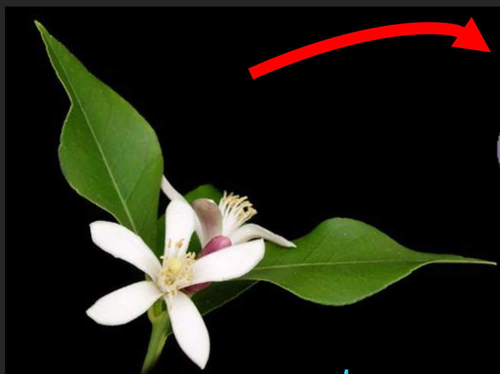
extrapolation via precision

LHC probe

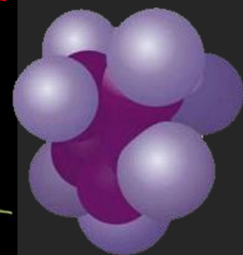
Kinds of matter ➔ Fundamental particles ?



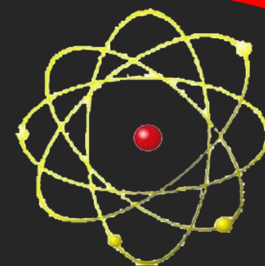
What is ‘normal’ matter made of?



~meters
matter



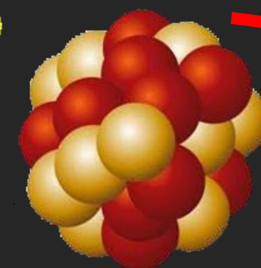
10^{-9} m
molecules



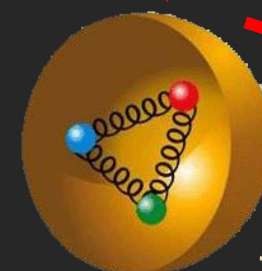
10^{-10} m
one atom

is made from electrons around a nucleus

the nucleus is made from
protons and neutrons



10^{-14} m



10^{-15} m

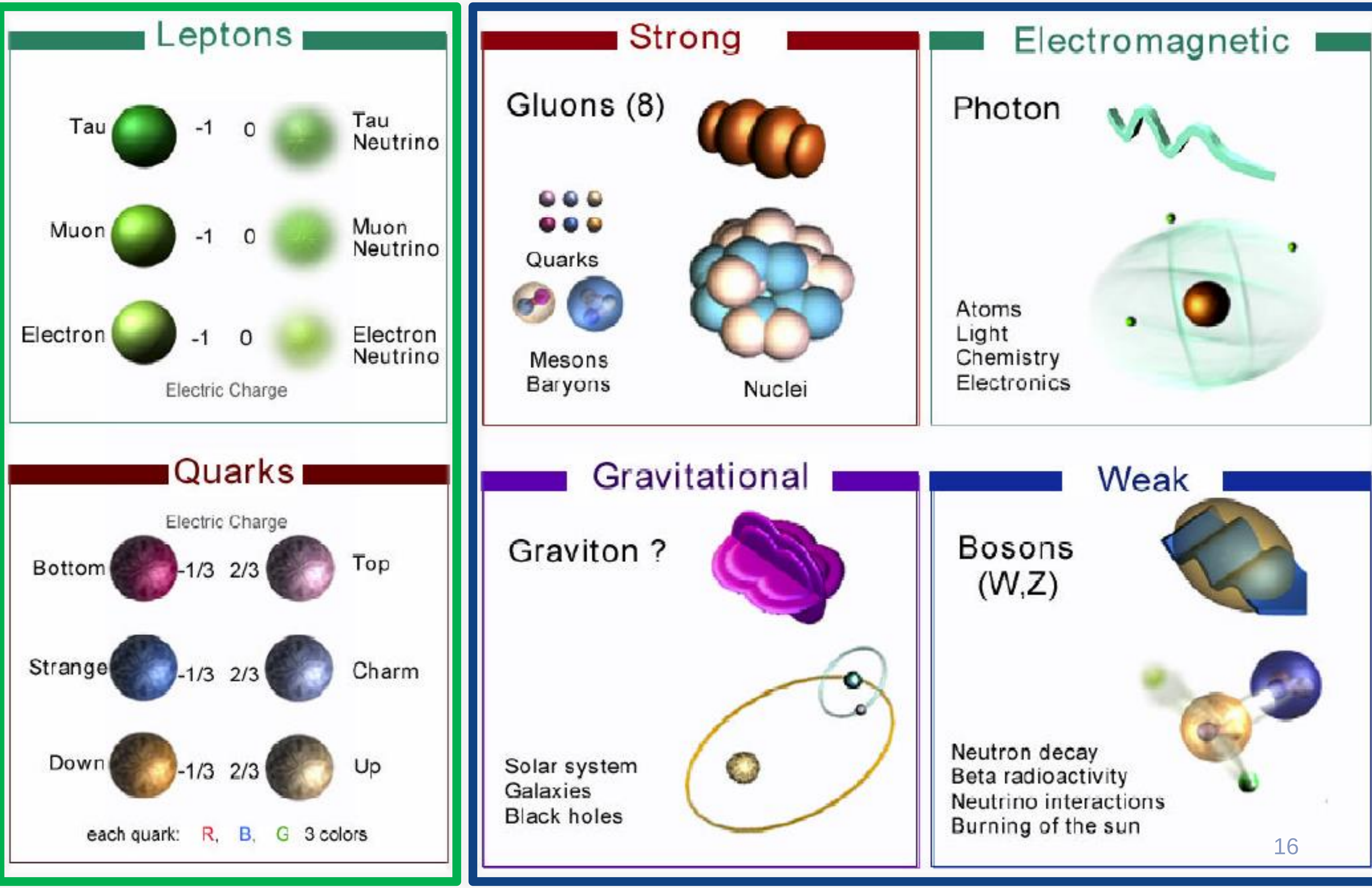
protons and neutrons
contain quarks

$<10^{-18}$ m

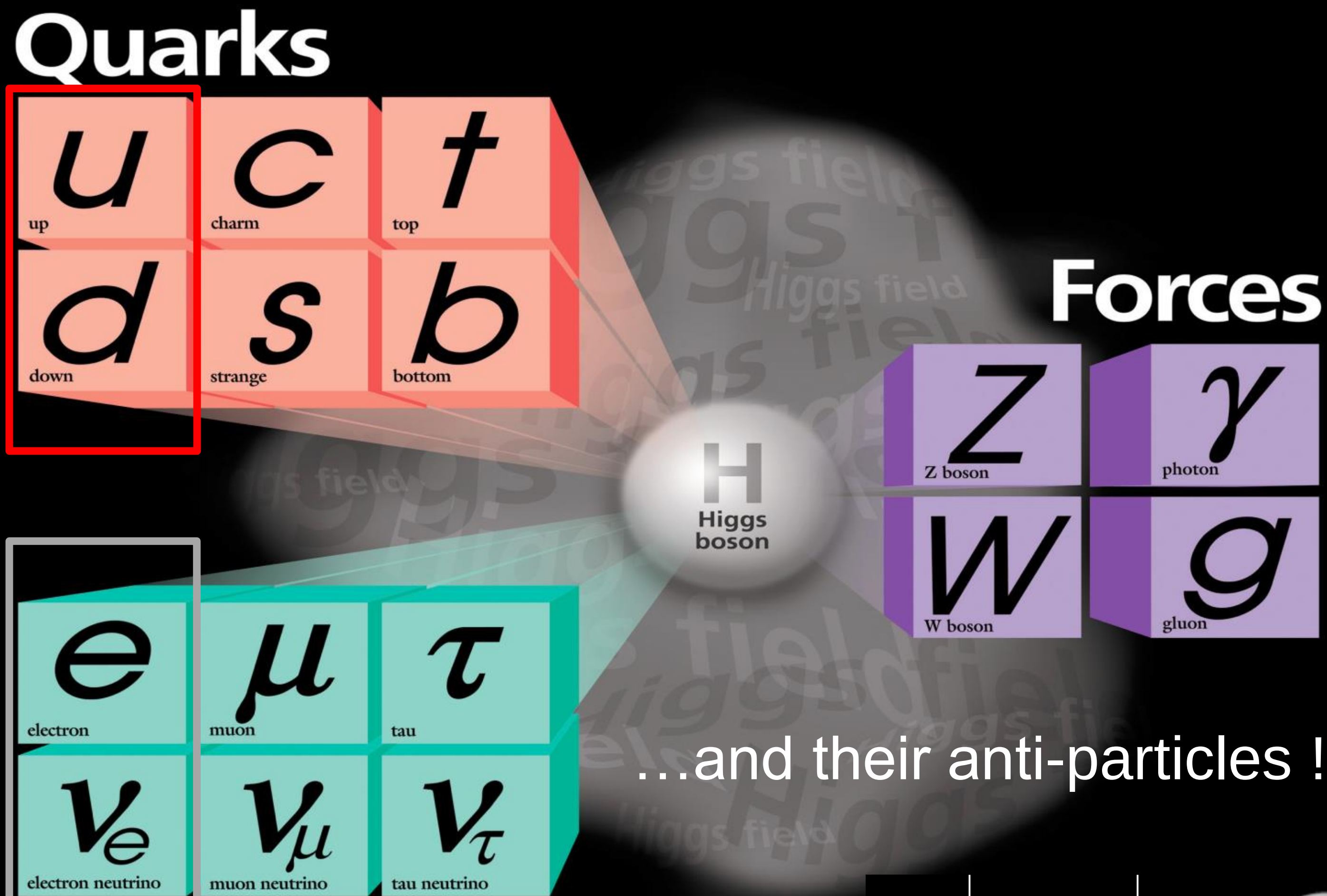
quarks, electrons
(= fermions)

electron, quark $< 10^{-18}$ m = 0.000,000,000,000,000,001 m
→ fundamental constituents

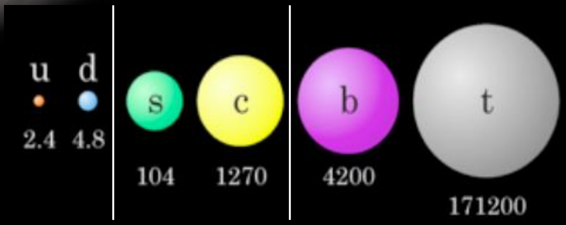
Matter and Forces and associated particles



The Standard Model of Particle Physics
(without gravity)

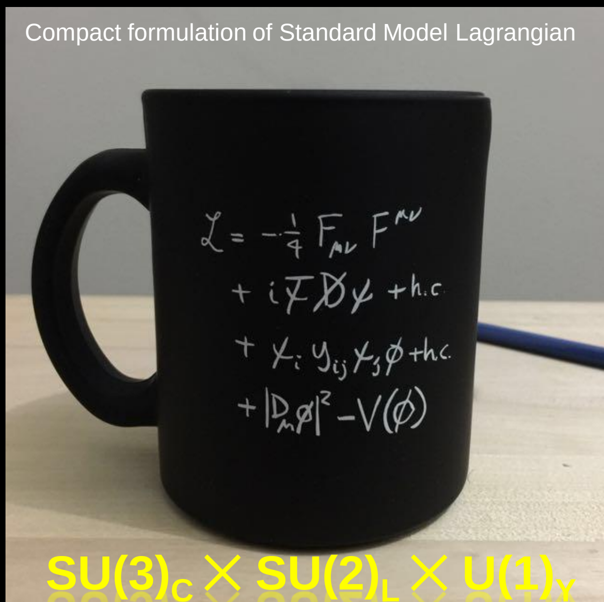


…and their anti-particles !



The Standard Model is much more than an order scheme for elementary particles. It's the theory of almost everything.

Compact formulation of Standard Model Lagrangian



$SU(3)_C \times SU(2)_L \times U(1)_Y$

Unfortunately it has ~20 free parameters which need to be measured.

Neutrinos remain massless!

Parameters of the Standard Model [hide]

Symbol	Description	Renormalization scheme (point)	Value
m_e	Electron mass		511 keV
m_μ	Muon mass		105.7 MeV
m_τ	Tau mass		1.78 GeV
m_u	Up quark mass	$\mu_{\overline{MS}}$ = 2 GeV	1.9 MeV
m_d	Down quark mass	$\mu_{\overline{MS}}$ = 2 GeV	4.4 MeV
m_s	Strange quark mass	$\mu_{\overline{MS}}$ = 2 GeV	87 MeV
m_c	Charm quark mass	$\mu_{\overline{MS}} = m_c$	1.32 GeV
m_b	Bottom quark mass	$\mu_{\overline{MS}} = m_b$	4.24 GeV
m_t	Top quark mass	On-shell scheme	172.7 GeV
θ_{12}	CKM 12-mixing angle		13.1°
θ_{23}	CKM 23-mixing angle		2.4°
θ_{13}	CKM 13-mixing angle		0.2°
δ	CKM CP-violating Phase		0.995
g_1 or g'	U(1) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.357
g_2 or g	SU(2) gauge coupling	$\mu_{\overline{MS}} = m_Z$	0.652
g_3 or g_s	SU(3) gauge coupling	$\mu_{\overline{MS}} = m_Z$	1.221
θ_{QCD}	QCD vacuum angle		~0
v	Higgs vacuum expectation value		246 GeV
m_H	Higgs mass		~ 125 GeV ~~(tentative)~~

CERN

The origin of particle masses

log-scale !

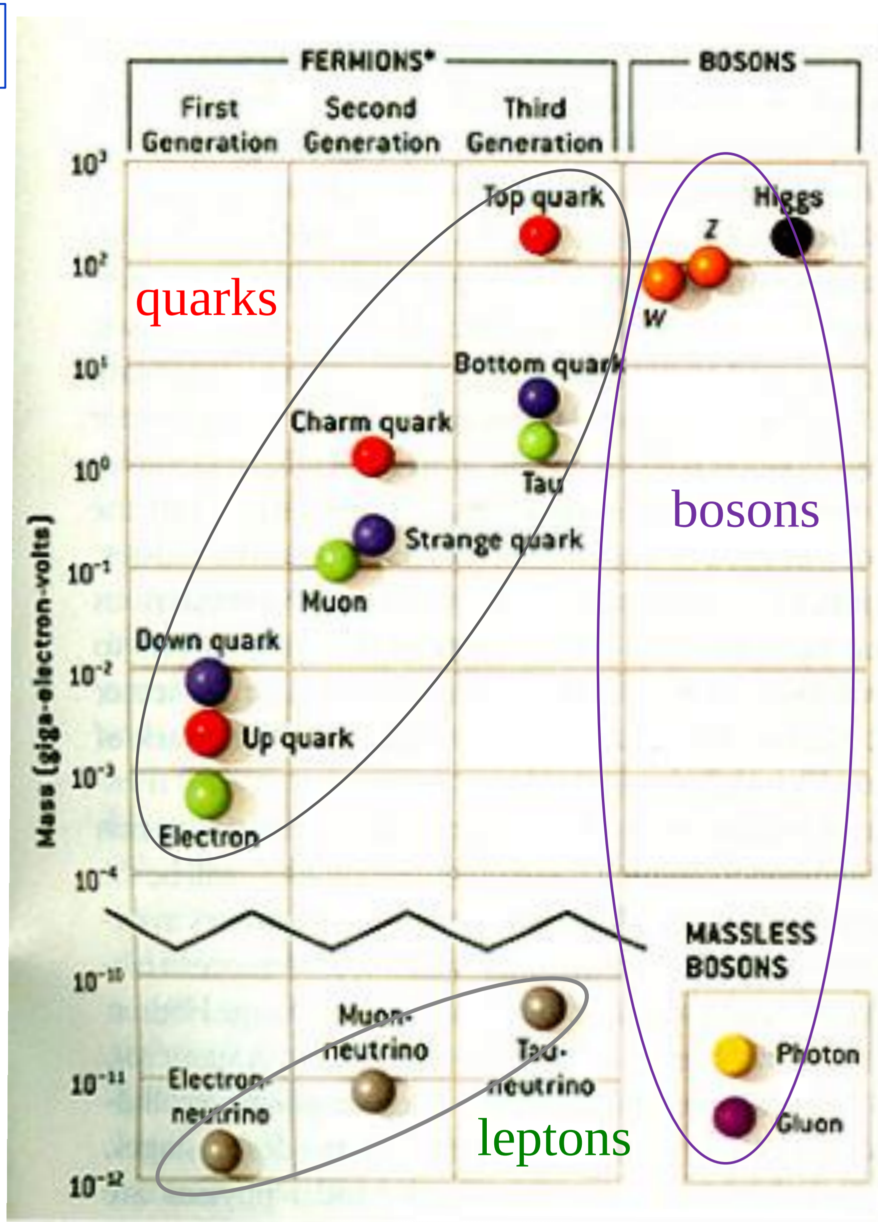
1 TeV

100 GeV

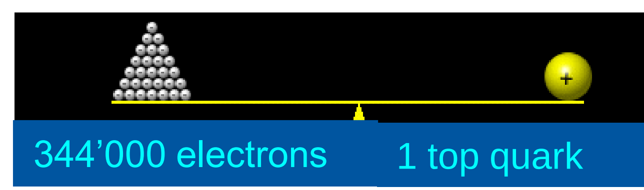
1 GeV

1 MeV

0.01 eV



- ✓ photon is massless (pure energy)
- ✓ W and Z bosons have 100 times the proton mass
- ✓ top quark is the heaviest elementary particle observed
- ✓ mass of top quark ≈ mass of gold atom and ~350'000 times larger than electron mass



➢ WHY ???

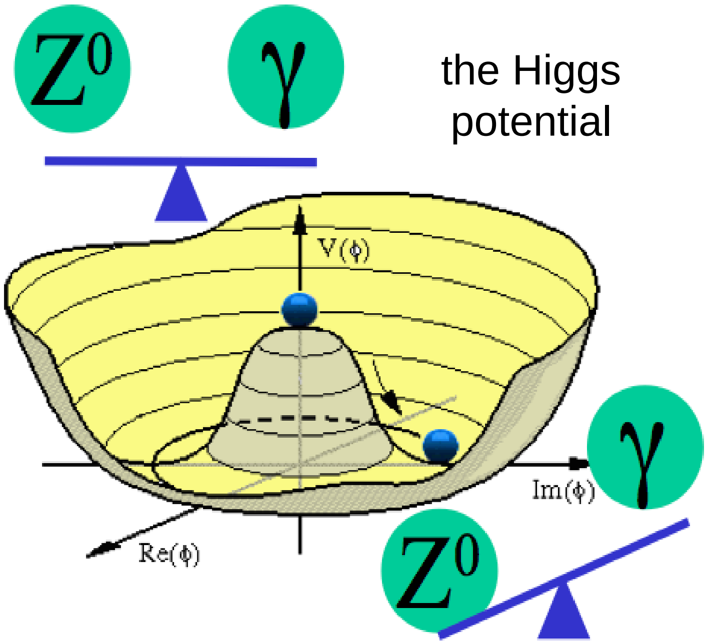
The origin of particle masses

Proposed explanation (by Brout, Englert, Higgs et al., 1964)

- ✓ "Brout-Englert-Higgs mechanism (BEH)" → origin of masses
- ➢ ~ 10^{-11} s after the Big Bang, when **Higgs field** became active, particles acquired masses proportional to the strength of their interactions with this Higgs field

Consequence: existence of a **Higgs boson**

- ✓ the Higgs boson is the quantum of the new postulated field
- ➢ this particle has been searched for > 30 years at accelerators all over the world
- ➢ finally discovered at the LHC

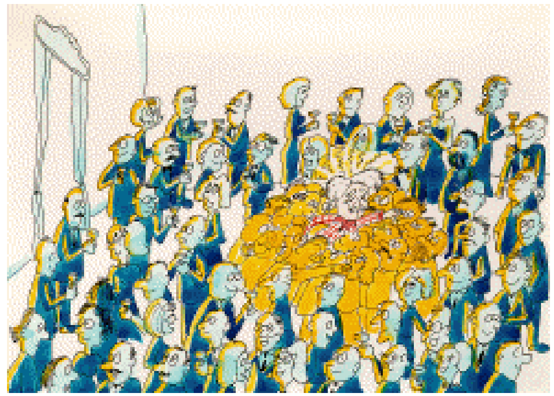


the Higgs potential

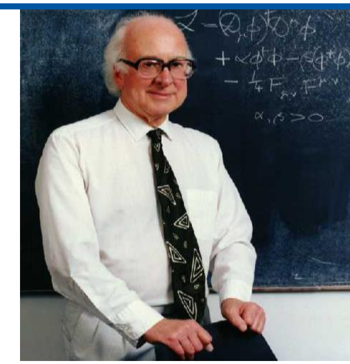
- ➢ spontaneous symmetry breaking

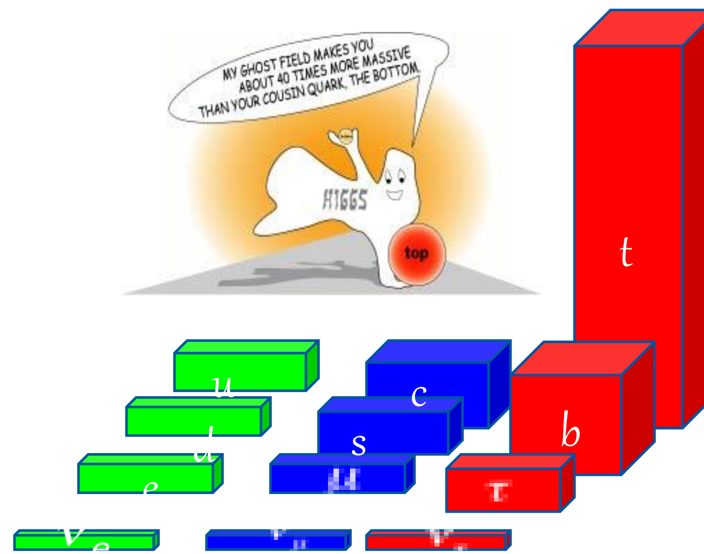
The origin of particle masses

What is so special about the Higgs field ?



P.W. Higgs, Phys. Lett. 12 (1964) 132





- The missing “key-stone” in the SM
- Explains the origin of mass
  - Massless fermions acquire mass through interaction with Higgs field

But there are many open questions that are not answered …..

Why is there a matter & anti-matter asymmetry?

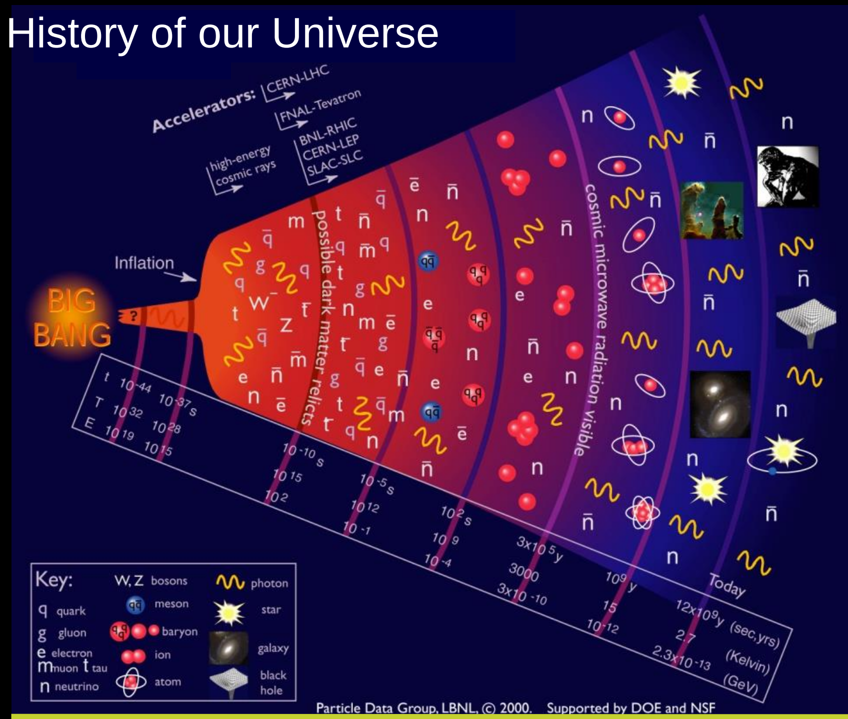
Why are there three generations?

Dark matter, dark energy?

..to name just a few!

Why is there a matter & anti-matter asymmetry?

BIG BANG



NOW

The same amount of matter & antimatter was created

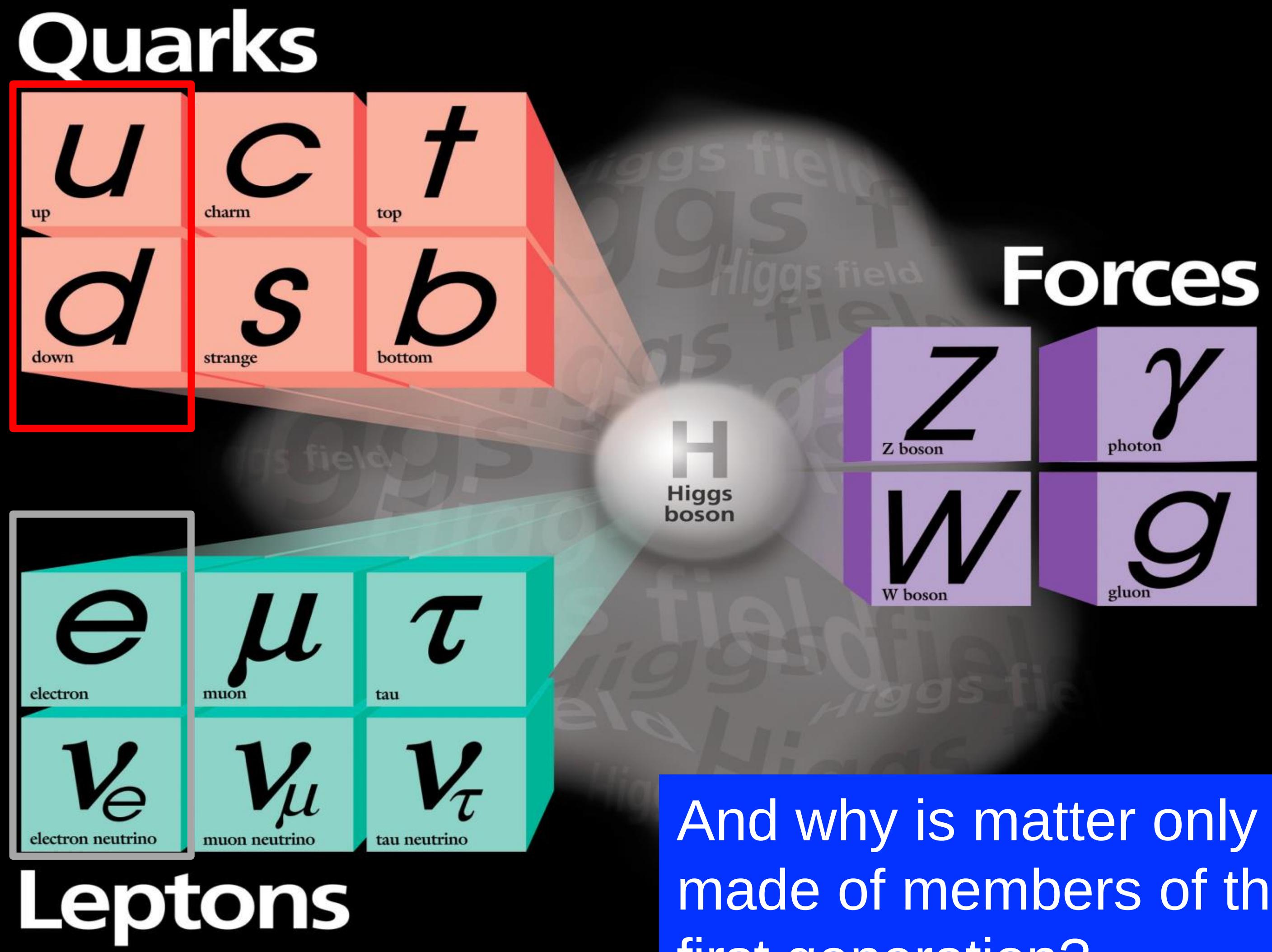
\> > >

Why?

Only matter (us) survived

$$\frac{N_{baryons}}{N_{photons}} \sim 10^{-9}$$

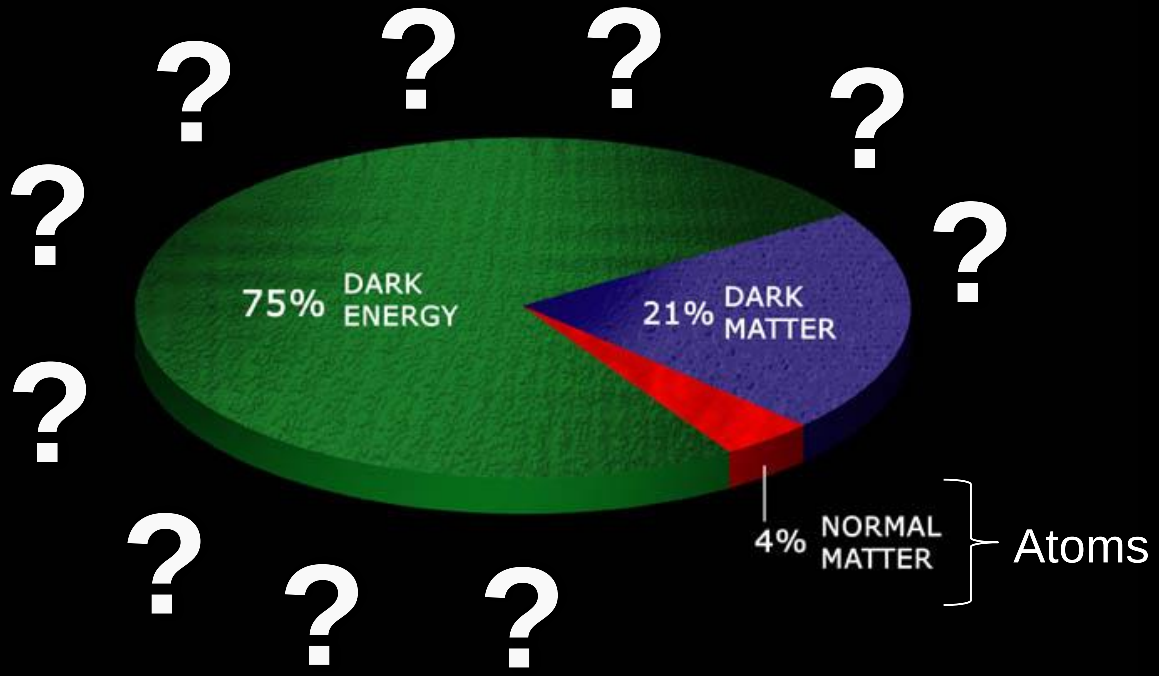
Why are there three generations?

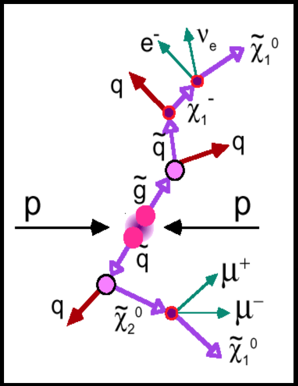


And why is matter only made of members of the first generation?

Dark matter, dark energy?

What are the remaining 96%?



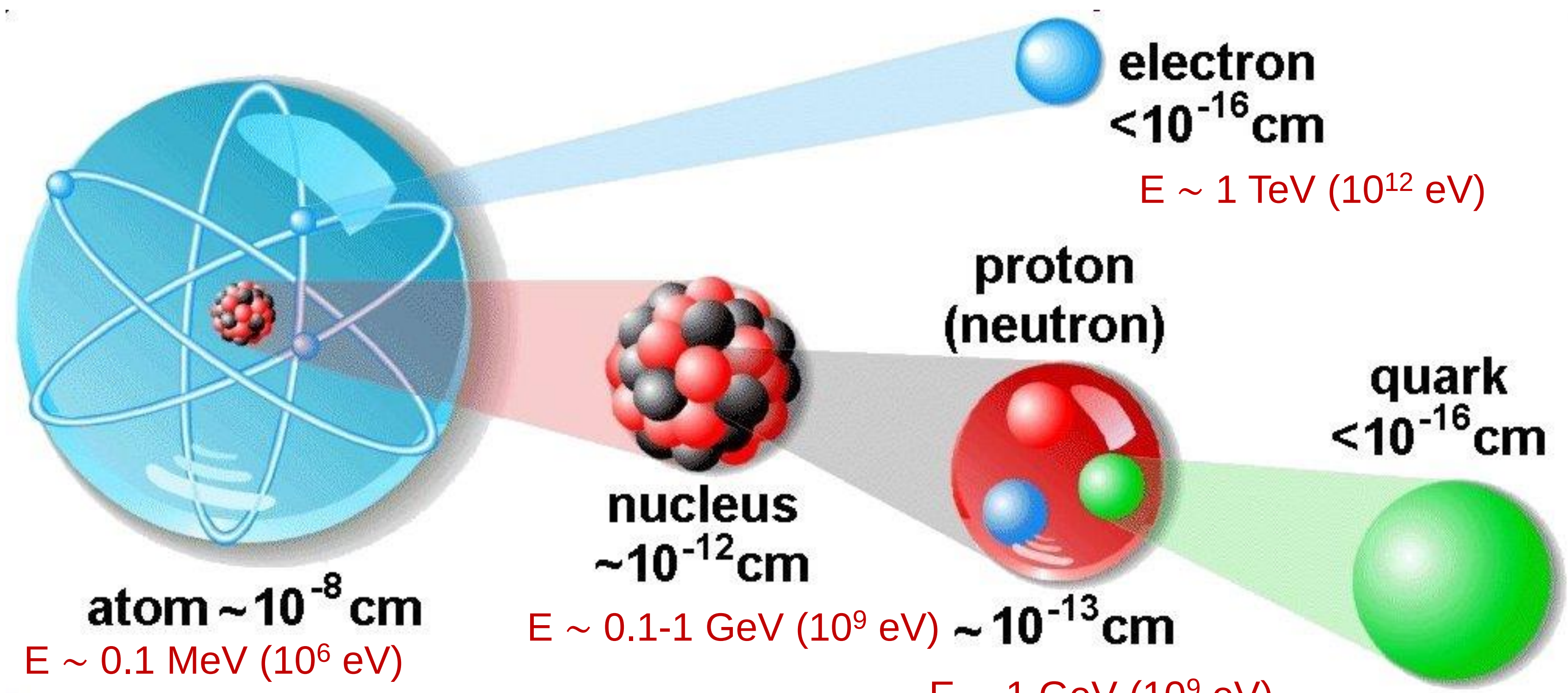


Is supersymmetry a candidate to explain dark matter?

How do we explore small scales or new particles?

Resolving structures: Use particle beam like light in a microscope. Need very short wavelength, i.e. particles at very high energies **$E = hc/\lambda$**

Creating new particles: collide particles with ‘available’ collision energy corresponding to <u>at least</u> the rest mass of the new particle **$E = mc^2$**

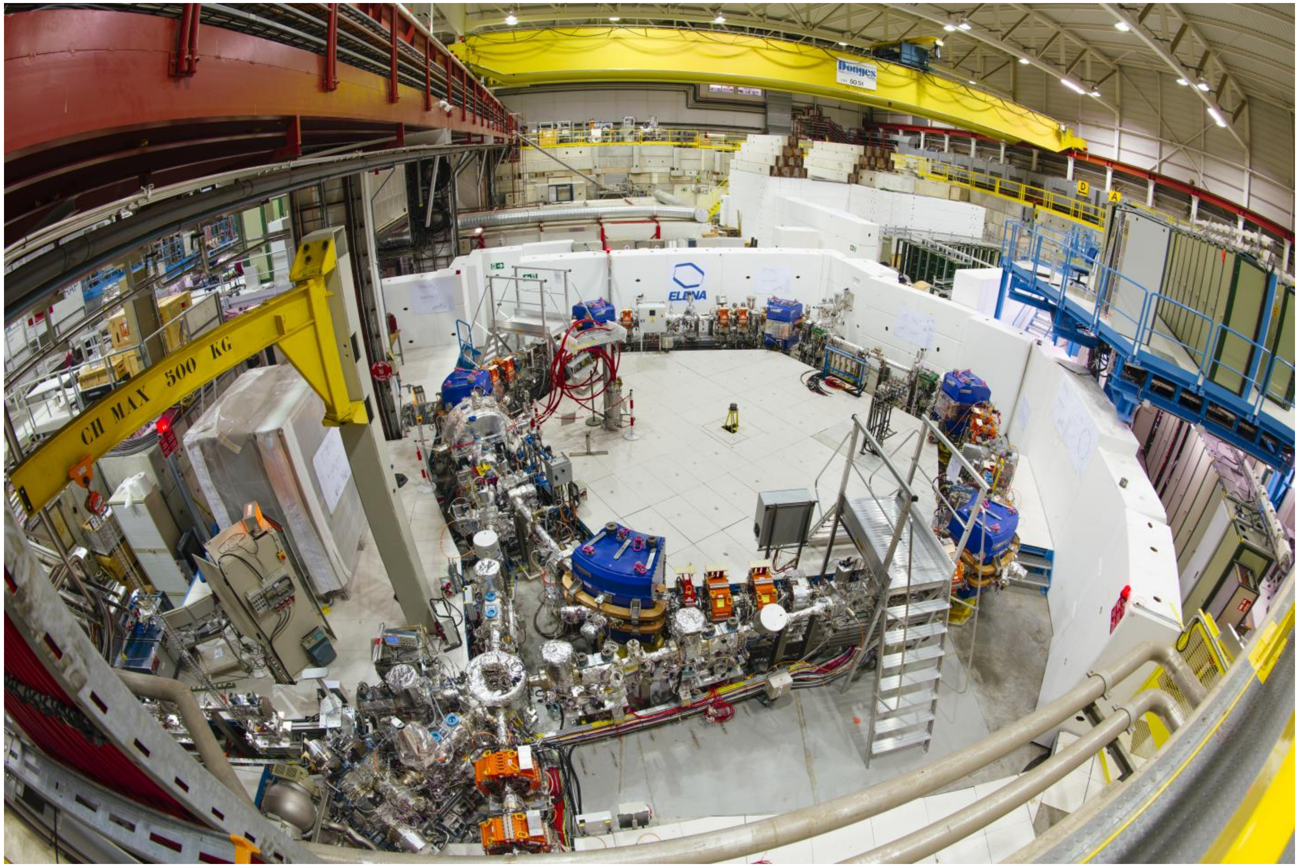


Particle Physics Tools

- Accelerators
  - Luminosity, energy, particle type, .….
- Particle Detectors
  - Efficiency, speed, resolution, …
- Trigger / DAQ (Online)
  - Efficiency, large compression factors and through-put, optimized for physics channels, …
- Data Analysis (Offline)
  - Large scale computing, physics results,…

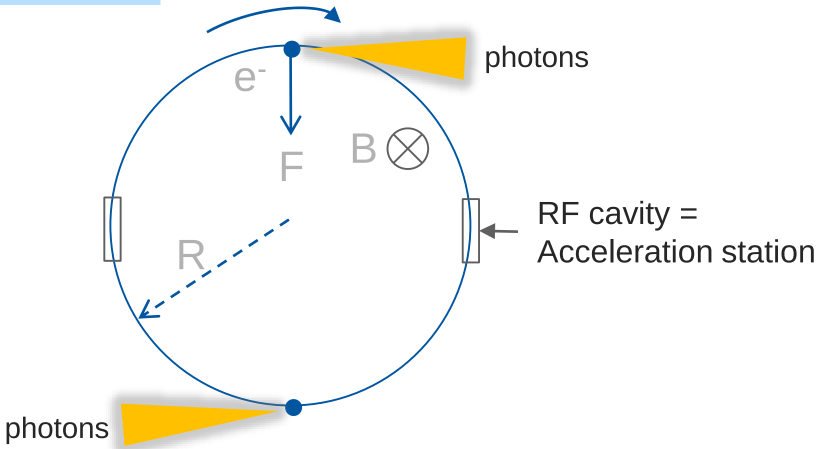
Accelerators

- **Electric fields** are used to accelerate charged particles (RF cavities with alternating potentials)
- **Magnetic fields** are used to steer the particle beams and to focus the beams.



Circular vs Linear Colliders

Circular



- **Particles are accelerated in every turn → achieve highest energy**
- Need magnetic field to force particles on a circle → <u>permanent</u> acceleration towards the centre.

Linear

- **Need to arrange many acceleration stations with very high gradient** (many MV/m).
- (Almost) no synchrotron radiation.
- Particles have a single chance to collide → need very precise beam focusing and steering

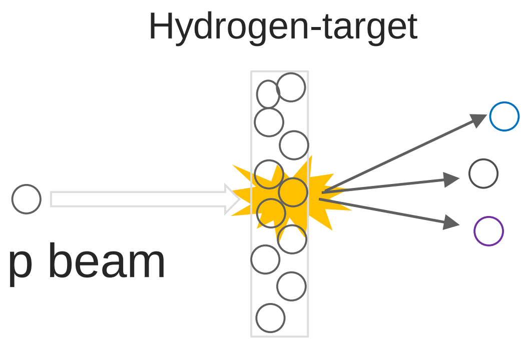
Emission of synchrotron radiation:

Irradiated power $$P_r = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{m^4} \frac{E^4}{R^2}$$

- Serious problems to accelerate e^+ and e^- in a circular machine to >100 GeV.
- See ESRF, XFEL and EMBL presentations!

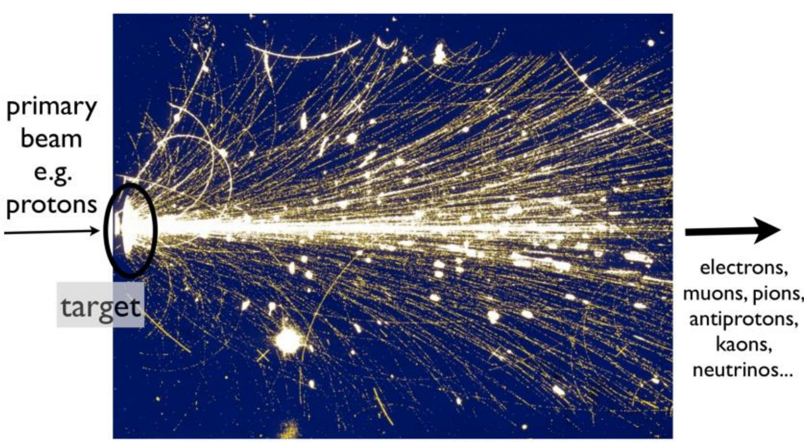
Fixed Target vs Collider

Beam onto fixed target:



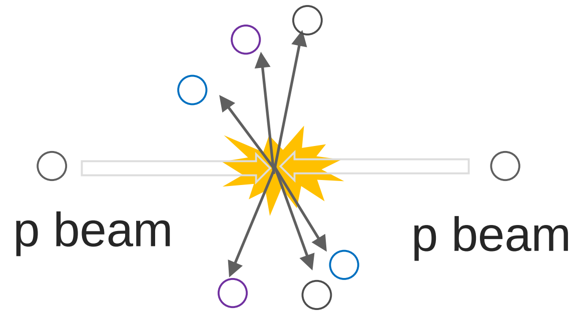
Available energy in the collision:

$$E^* = \sqrt{2\cdot(E_{kin}+m_p)\cdot m_p}$$

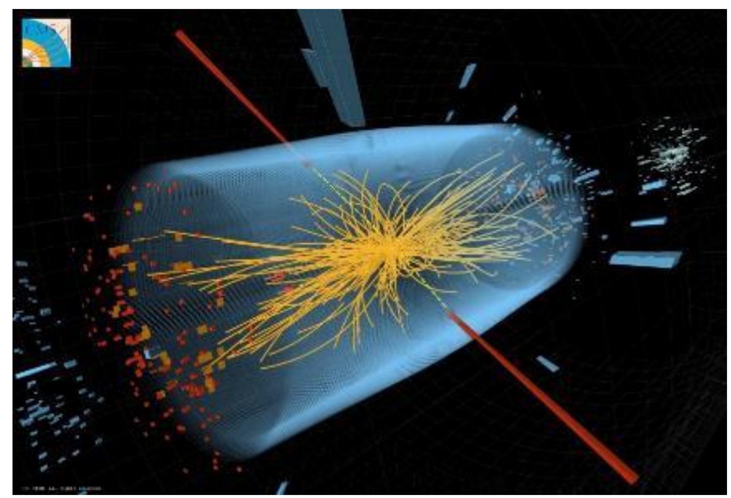


Picture: a collision of a sulphur ion onto a gold target, recorded by the NA35 experiment at the SPS in 1991

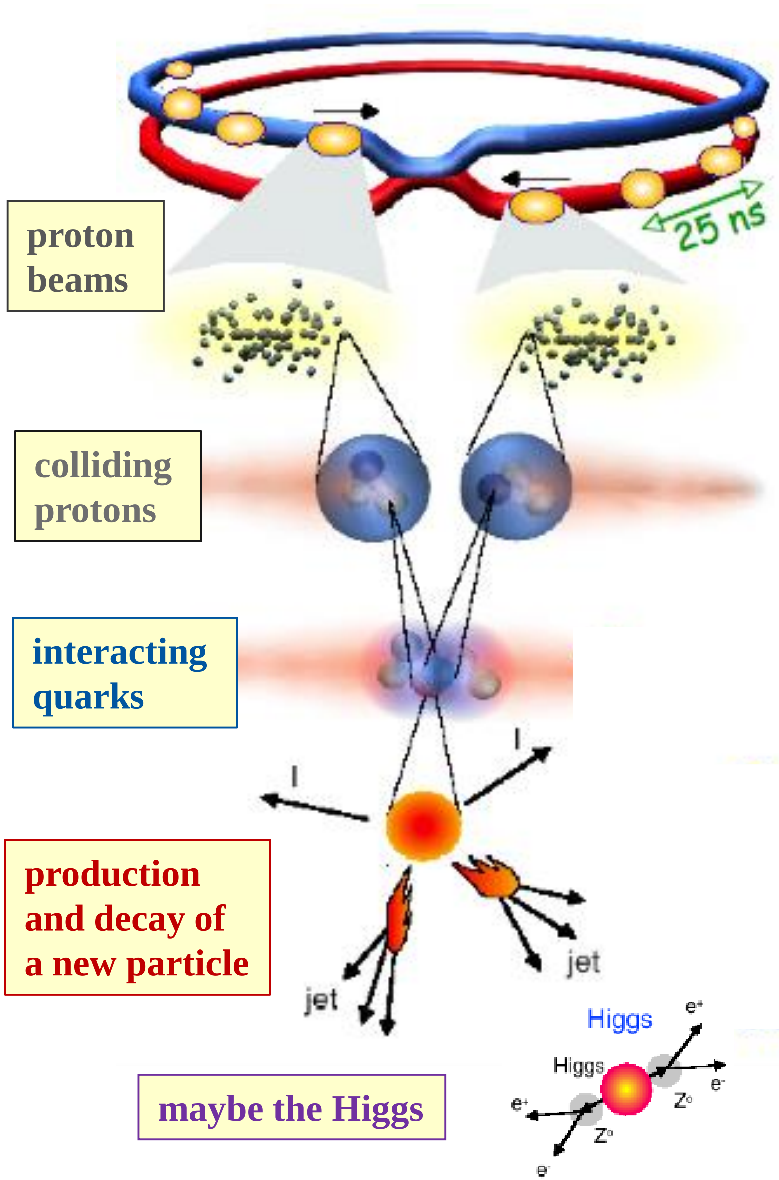
Colliding two beams



Available energy in the collision: $E^* = 2E_{inc}$



Collisions at LHC



- Two independent proton beams are brought to collision (at specific interaction points)
- Protons are arranged in bunches (~10^{11}). Several pp-collisions per bunch crossing.
- the colliding protons “break” into their fundamental constituents (i.e. quarks) → only a fraction of the proton energy is available for the creation of new particles.
- → lots of non-interesting background
- The new particles are generally unstable and decay promptly into lighter (known) particles: electrons, photons, etc.

Detectors must be ultra-selective

Distinguish (new) rare particle decays from (known) abundant particle decays
→ very performant detectors with excellent particle identification

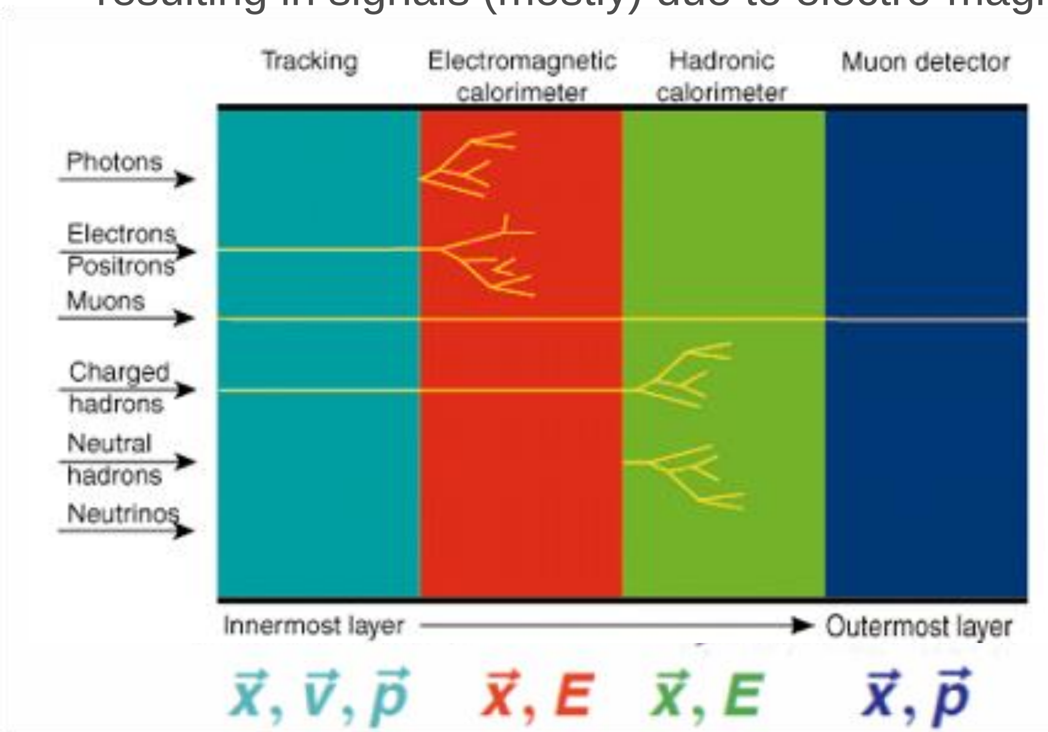
You are looking for this particular particle physicist!

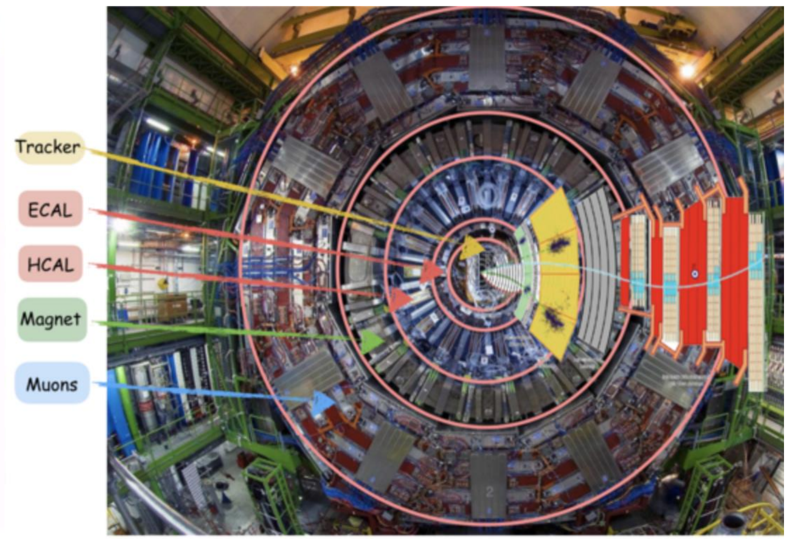
Needs VERY high
- ✓ precision
- ✓ statistics
- ✓ selectivity
- ✓ background suppression

Note:
- ➢ the world population is ~$7.5 \cdot 10^9$
- ➢ typical very rare decay $B(B_s \rightarrow \mu\mu) = (3.65 \pm 0.23) \times 10^{-9}$

Particle Detectors

- **There is no type of detector which provides all measurements we need**
  → "Onion" concept → different systems taking care of certain measurement
- **Detection of particles (collision products) within the detector volume**
  - resulting in signals (mostly) due to electro-magnetic interactions

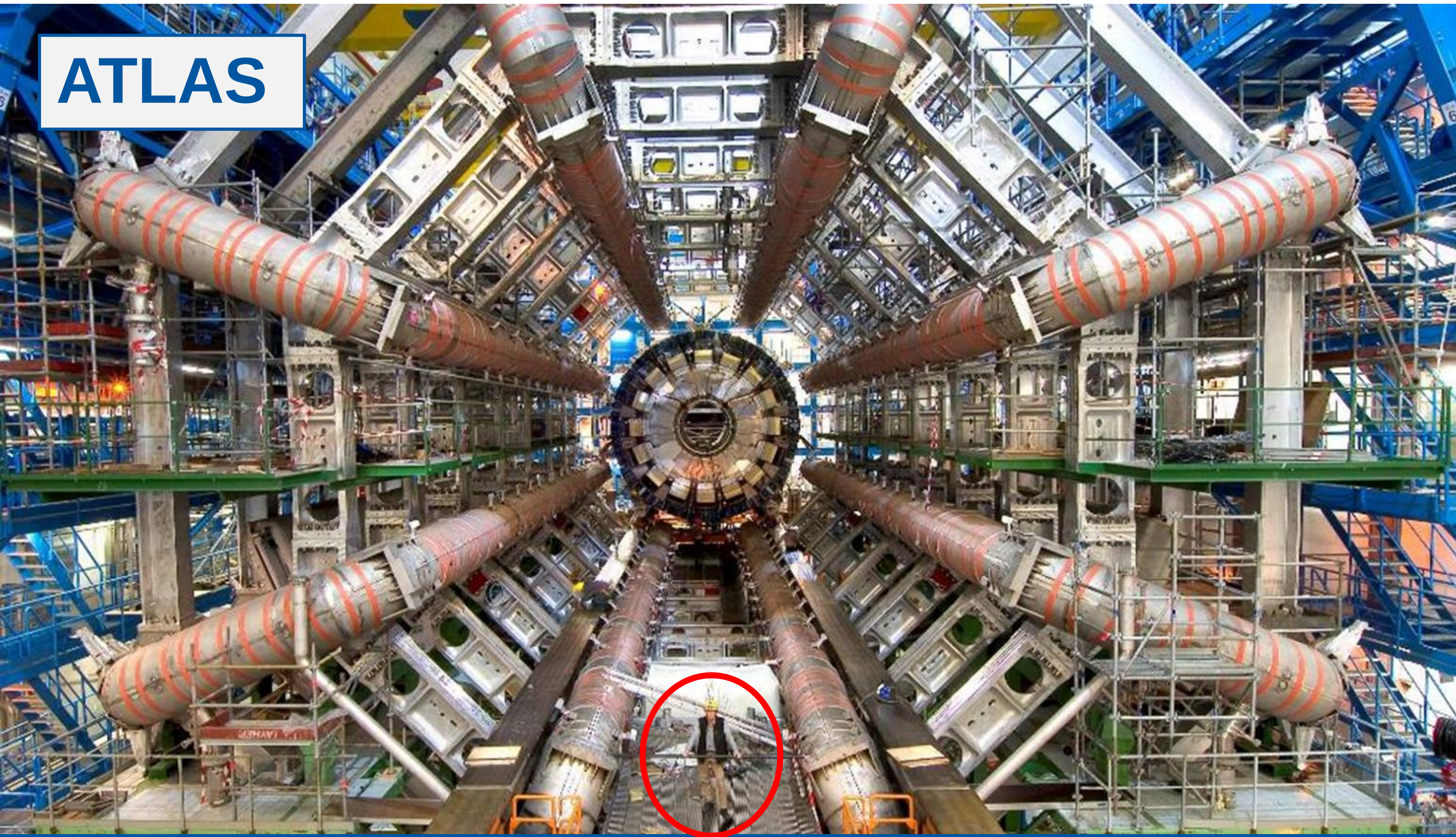




Low density → High density
High precision → Low precision
High granularity → Low granularity

→see presentations by
E. Oliveri & D. Abbaneo

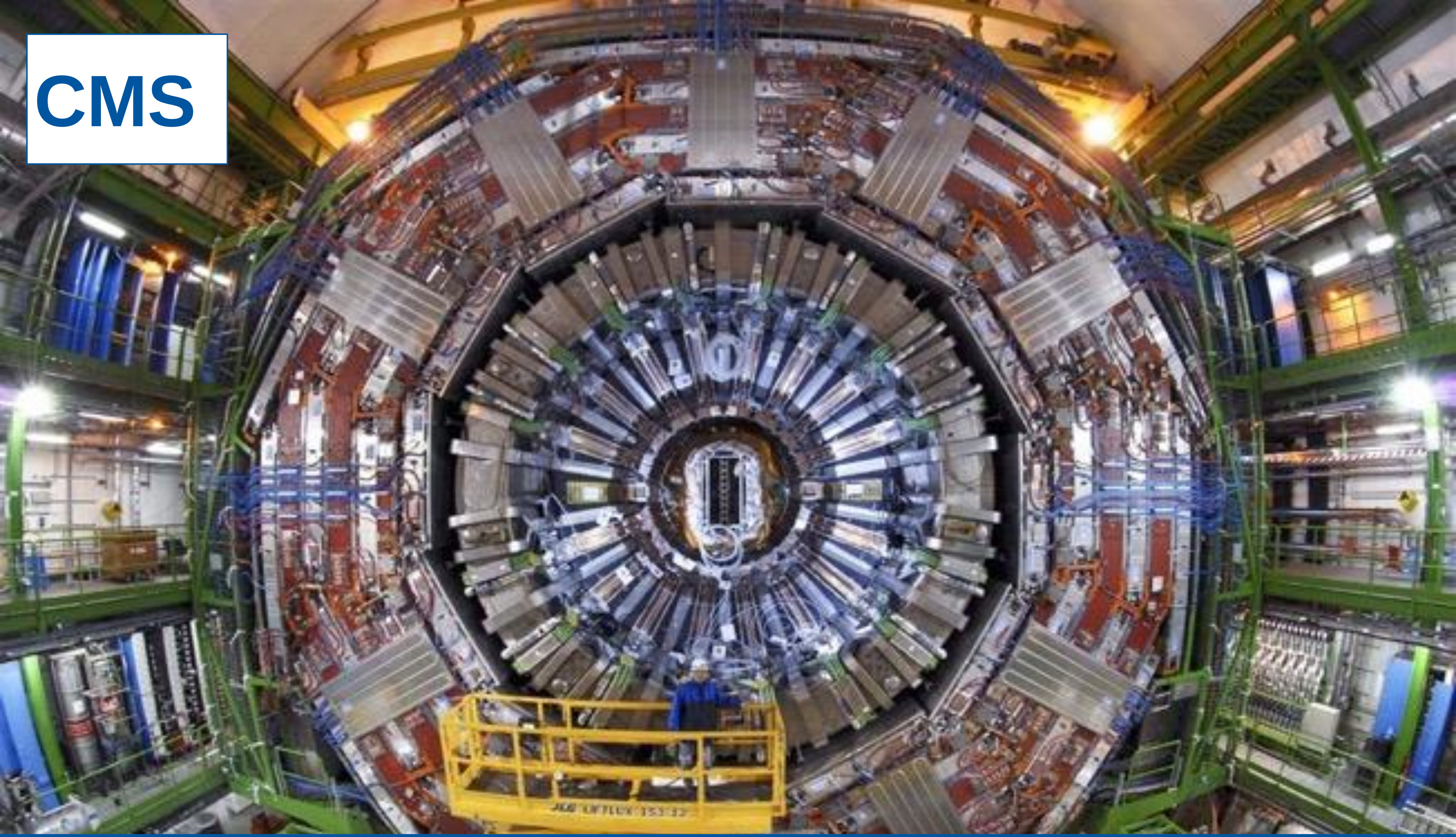
ATLAS



The ATLAS detector:

- Largest general purpose detector: ~ half Notre Dame cathedral
- number of detector sensitive elements: 160 millions
- cables needed to bring signals from detector to control room: 3000 km
- data in 1 year per experiment: ~10 PB (2 million DVD)

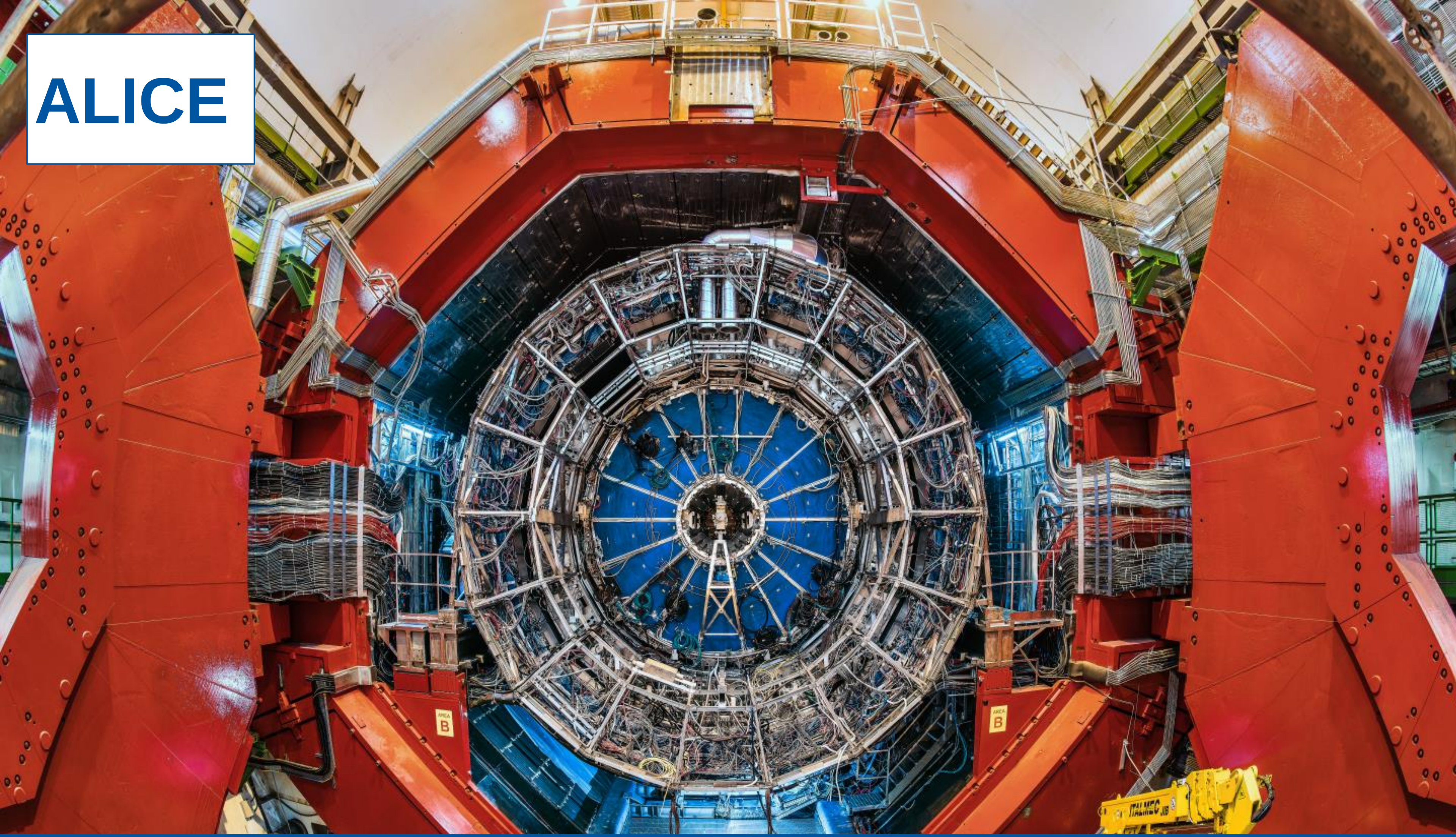
CMS



The CMS detector:

- Very compact general purpose detector
- Heavier than the Eiffel tower: 14 000 tons
- 4T superconducting magnet, about 100 000 times the magnetic field of the Earth
- It was built in 15 sections on the ground before lowering it into the cavern

ALICE



The ALICE detector:

- Built for collisions of nuclei at ultra-relativistic energies
- To study quark-gluon plasma as a few millionth seconds after the Big Bang.
- 90 m^3 large gas detector as central tracking device
- Installation of the largest monolithic silicon pixel detector in HEP just completed

LHCb

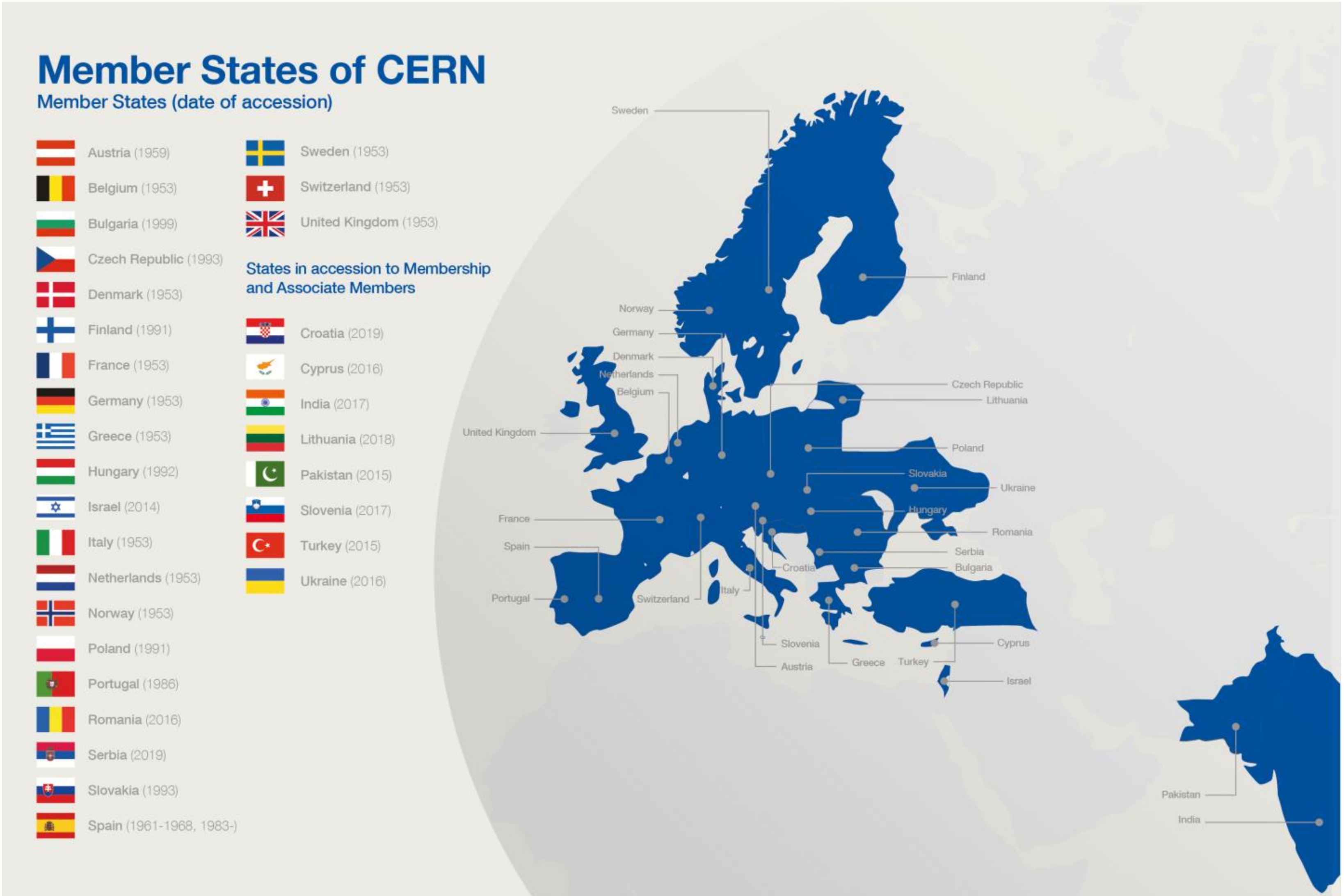
The LHCb detector:

- Specializes in investigating the differences between matter and antimatter
- Sub-detectors are arranged in a row, different from the other experiments
- Allows to study particles that emerge mainly in the forward direction from the collision
- The “b” in LHCb stands for “beauty” as it is the key particle of study

Conclusion

- The discovery of the Higgs boson completes the standard model.
- However, it does not provide all answers – today we only know about 5% of the universe!
- Particle physics tools, the powerful accelerators and complex detectors, allow to address fundamental questions.
- The LHC and its experiments are currently undergoing major upgrades to increase its discovery potential– it will restart data taking in 2022.

Thank you!


Member States of CERN
Member States (date of accession)
Austria (1959)
Belgium (1953)
Bulgaria (1999)
Czech Republic (1993)
Denmark (1953)
Finland (1991)
France (1953)
Germany (1953)
Greece (1953)
Hungary (1992)
Israel (2014)
Italy (1953)
Netherlands (1953)
Norway (1953)
Poland (1991)
Portugal (1986)
Romania (2016)
Serbia (2019)
Slovakia (1993)
Spain (1961-1968, 1983-)
Sweden (1953)
Switzerland (1953)
United Kingdom (1953)
States in accession to Membership and Associate Members
Croatia (2019)
Cyprus (2016)
India (2017)
Lithuania (2018)
Pakistan (2015)
Slovenia (2017)
Turkey (2015)
Ukraine (2016)