A General Introduction to CERN

A presentation for the general public with a focus on high school students

Erwin Bielert

Based on presentations by R. Heuer, H. ten Kate, F. Briard, E. Bracke and J.J. Heinrich as well as outreach material on the CERN website

Content

- About the presenter
- Your visit

- What is CERN?
- Why do we need CERN?
- Some basic principles and ideas
- The accelerator complex
- The (LHC) Experiments
- Scientific Spin-Off

Where the infinitely large meets the infinitely small!

About the presenter

<u>Erwin Bielert</u>

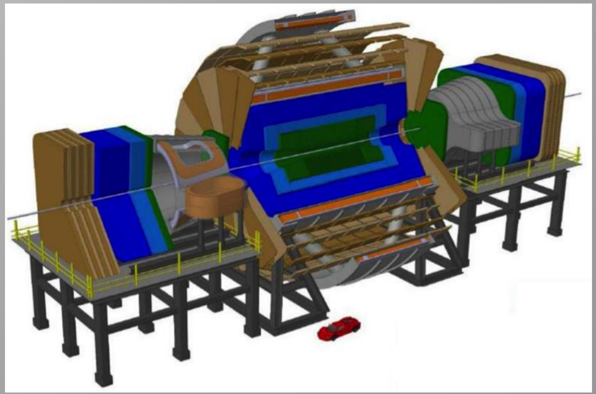
Dutch nationality

MSc at University of Twente: Applied Physics

PhD at CERN/UT: superconducting magnet design

Senior fellow at COMPASS: drift chambers, safety, public outreach, installation, commissioning, technical coordination

Project Associate for FCC: detector magnet design



Your visit

<u>Agenda:</u>

- This presentation (about 45-60 minutes)
- Visiting points (about 2 hours)

<u>Practical points:</u>

- If something is not clear/ if you want to know more: **ask questions!**
- During the visit: you are ~~allowed~~ **obliged** to make pictures everywhere!
- The CERN shop and the permanent expositions (Microcosm and Innovation Globe) are opened daily (Mo-Sa) from about 10.00-17.00

What is CERN?

CERN in extremes…

- The **largest** scientific collaboration *<u>in the world</u>*
- The **largest** particle physics laboratory
- The **BIGGEST** particle accelerator
- The **most** superconducting magnets in a single project
- The ***fa s t e s t*** manmade particles
- The **smallest** structures of matter
- The **warmest** place *<u>in the universe</u>*
- The **coldest** place
- The **largest** cryogenic system
- The **most** generated data
- The **emptiest**
- The **…**

Prejudice…

Where do we come from and where are we going?

What did the universe look like at the beginning?
How did it evolve?
What is the universe made of?
What physical laws govern it?

Answers can be found in the understanding of **matter** and **forces.**

An international effort

1954: Founding of the European Organization for Nuclear Research
(l'Organization Européen pour la Rechere Nucléaire) -> EONR / OERN?

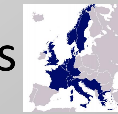
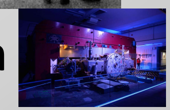
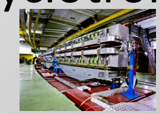
1952: Formation of the European Council for Nuclear Research
(Conseil Européen pour la Recherche Nucléaire)

Interesting choice of name: since CERN is a *world* renowned *High Energy Particle Physics* laboratory, which makes use of top of the bill *technologies.*

A rich history

- 1949, the origins: putting Europe back on the research map -> 12 countries
- 1952, the dest
- 1954, starting

Some major events in CERNs 60+ history

- 1949, the origins: putting Europe back on the research map -> 12 countries 
- 1952, the destination: Geneva 
- 1954, starting the construction: CERN was born 
- 1957, CERN's first accelerator: the synchrocyclotron 
- 1959, the Proton Synchrotron (PS) starts up 
- 1971, first proton collisions: Intersecting Storage Rings

Some major events in CERNs 60+ history

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- 1957, CERN's first accelerator: the synchrocyclotron 
- 1959, the Proton Synchrotron (PS) starts up 
- 1971, first proton collisions: Intersecting Storage Rings 
- 1976, Super Proton Synchrotron (SPS) starts up 
- 1983, W and Z bosons
- 1989, first injection in der (LEP)

Some major events in CERNs 60+ history

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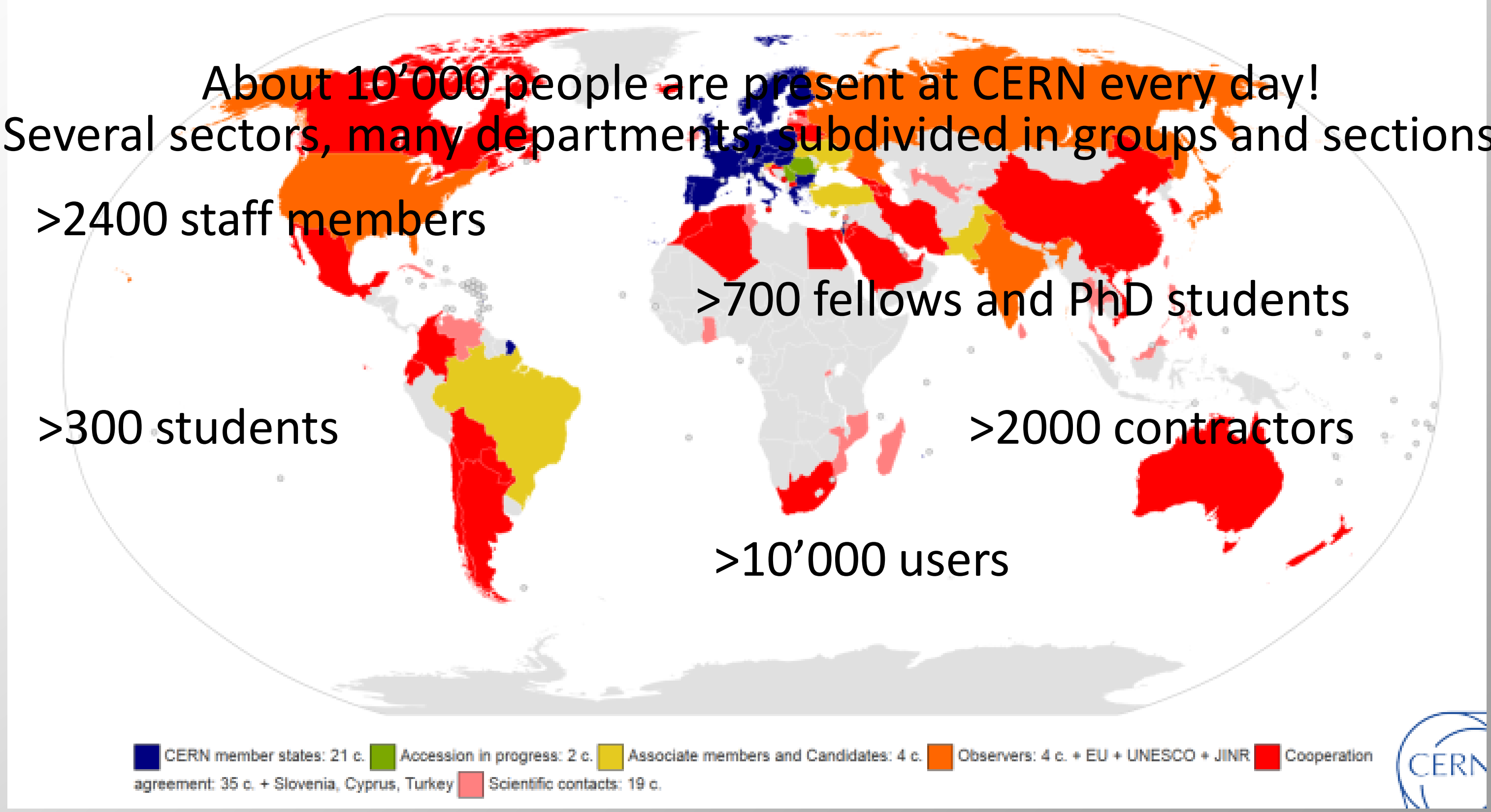
- 1959, the Proton Synchrotron (PS) starts up 
- 1971, first proton collisions: Intersecting Storage Rings 
- 1976, Super Proton Synchrotron (SPS) starts up 
- 1983, W and Z bosons are discovered 
- 1989, first injection in the Large Electron Positron collider (LEP) 
- 1990, first website and server are up
- 2008, Large Hadron Collider (LHC) sta
- 2012, ATLAS&CMS observe the/a Higg

CERN in some impressive numbers

- World's largest particle physics laboratory: 22 member states, 6 (pre) associate states, 5 observers and many partner states



About 10'000 people are present at CERN every day!
Several sectors, many departments, subdivided in groups and sections.

>2400 staff members

>700 fellows and PhD students

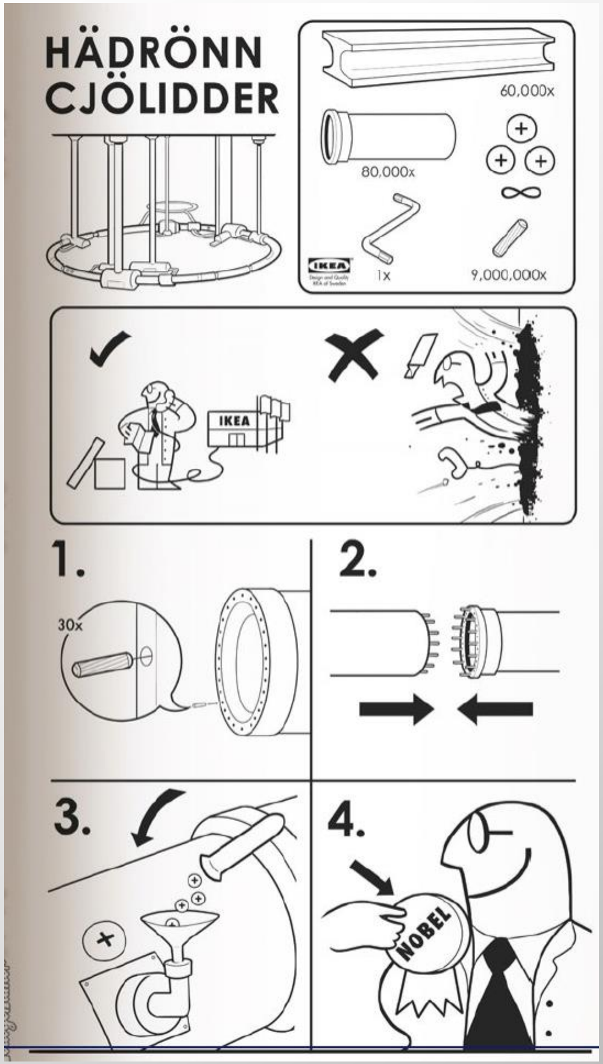
>300 students

>2000 contractors

>10'000 users

- More than 600 related universities and research institutes

Not so easy…


HÄDRÖNN
CJÖLIDDER
60,000x
80,000x
1x
9,000,000x
IKEA
1.
30x
2.
3.
4.
NOBEL

The infrastructure

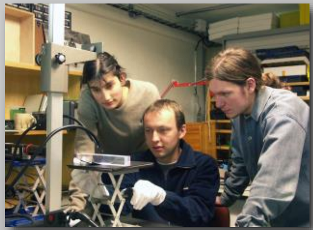
- Restaurants: 2 at Meyrin - and 1 at Prevessin site
- Transport: trams, busses and shuttle service but also car and bike sharing!
- Many sports – and other clubs
- Creche
- Library
- Fire brigade
- Conference rooms
- Etc…

Why do we need CERN?

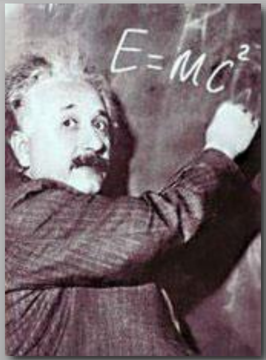
CERN mission statements

Global **C**ollaboration: Unite people from different countries and cultures

Education: Train scientists and engineers



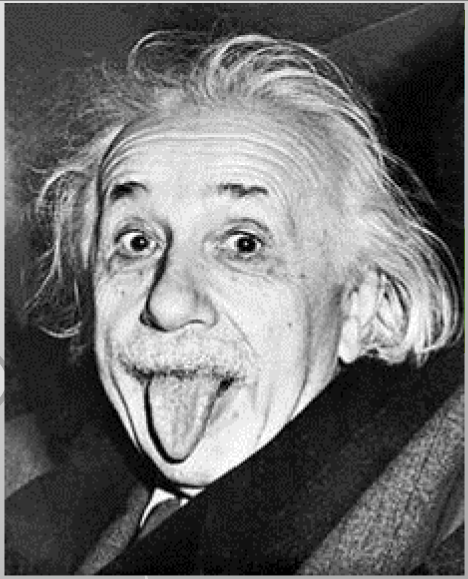
Fundamental **R**esearch: pushing forward the frontiers of knowledge



New Technologies: (development for accelerators and detectors)

Fundamental research

How does Nature (everything we see around us) work?



Observations

Interpretation

Experimentation
(observation under controlled conditions)

- approves the theory
- gives limits and raises new questions
- disapproves the theory

Explanation
(Theory)

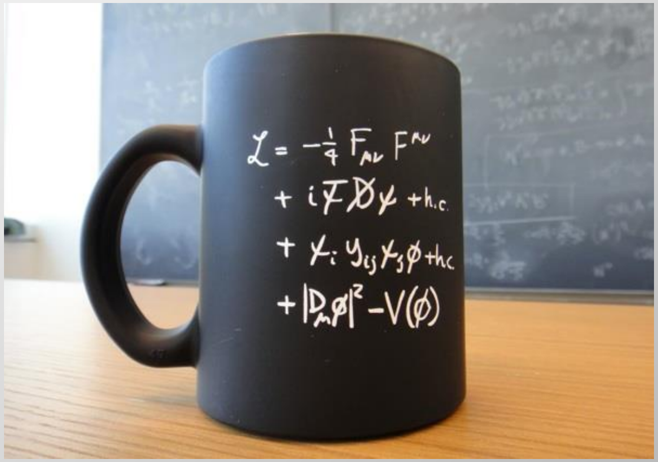
Predictions

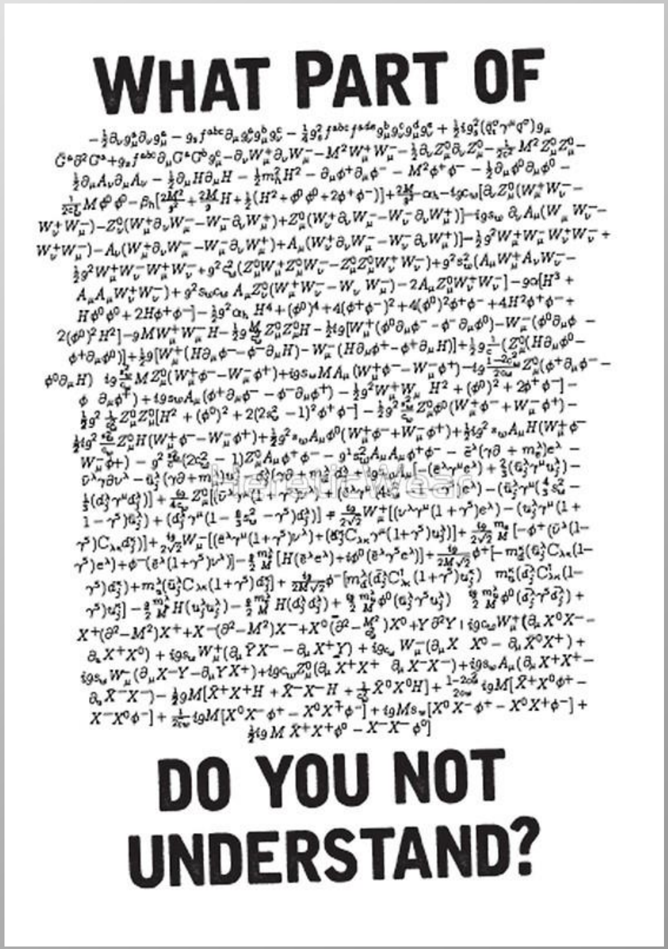
A theory is useless if:

- it cannot be validated
- it makes no predictions

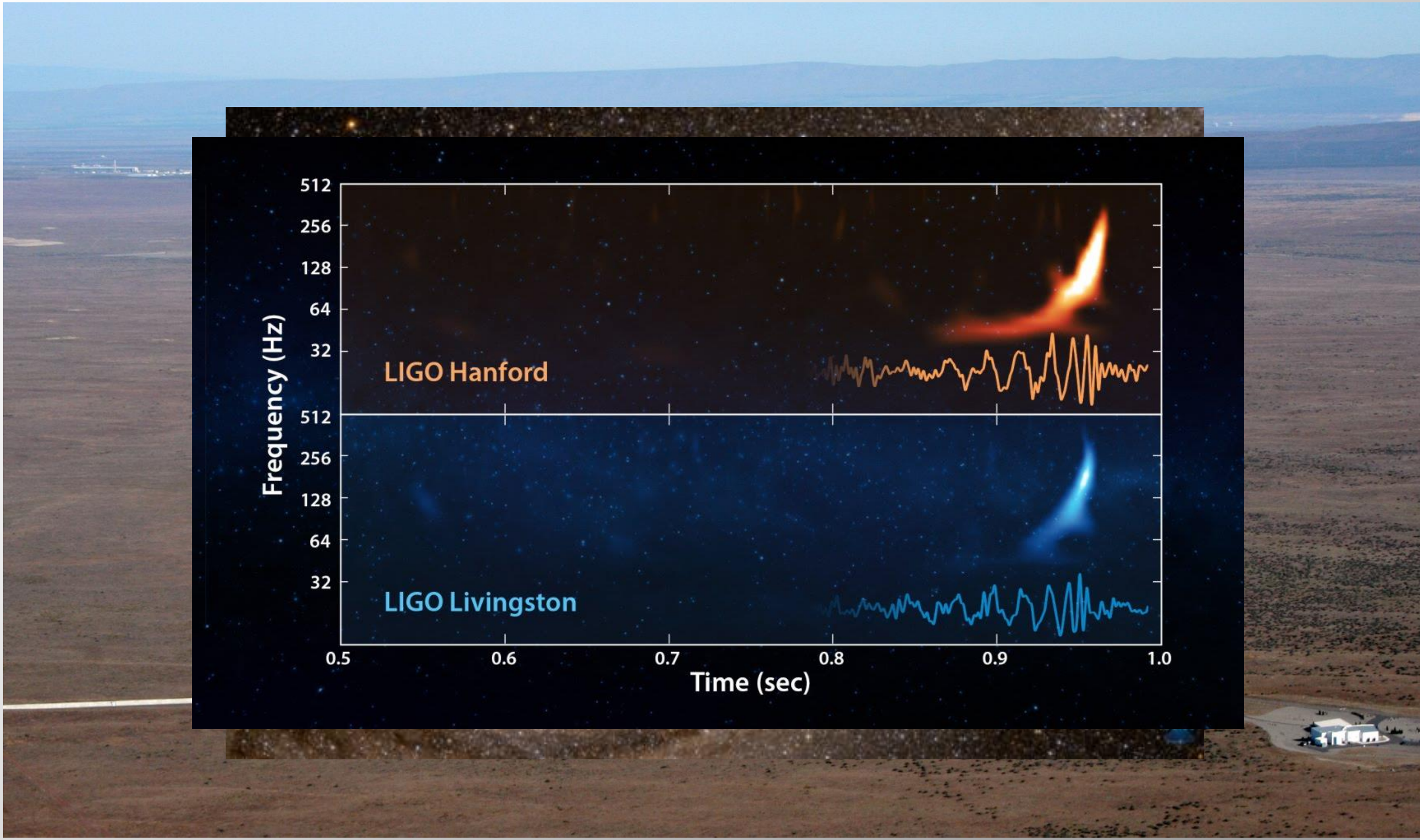
Standard model Lagrangian

- Physical laws should be summarized in easy, workable mathematical models.
- Some of the basic principles indeed are based on very simple formulae.
- The standard model is the simplest mathematical model that describes and predicted/predicts almost all physical phenomena concerning matter and forces:

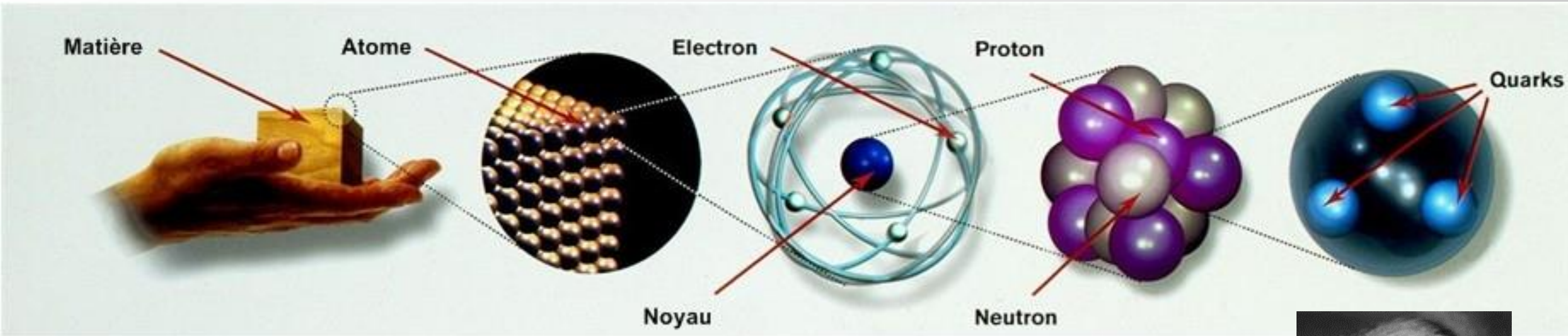




Gravitational waves -> graviton?!



Small scales

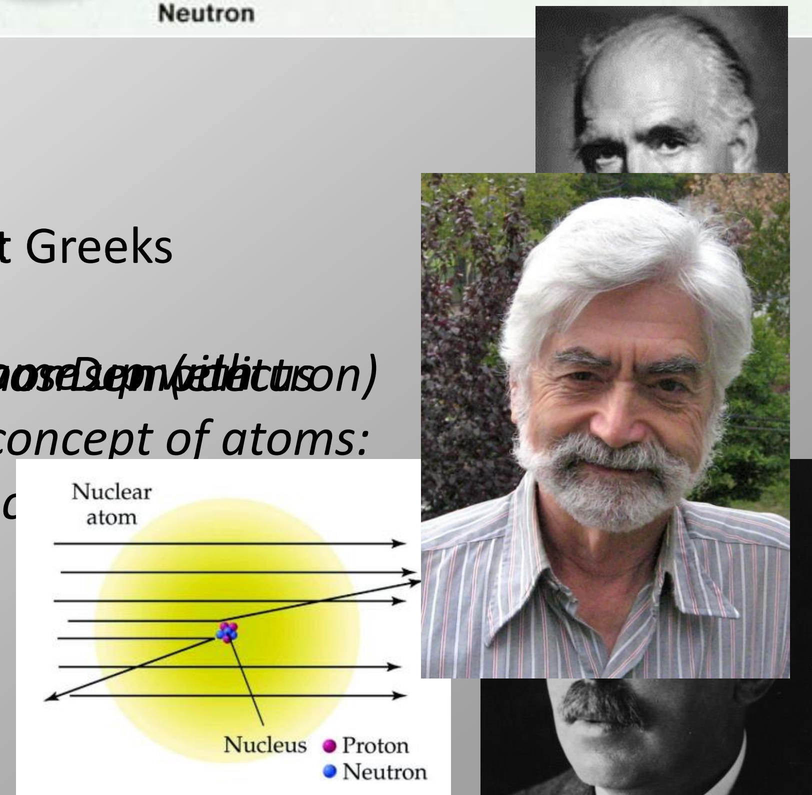


... Greeks

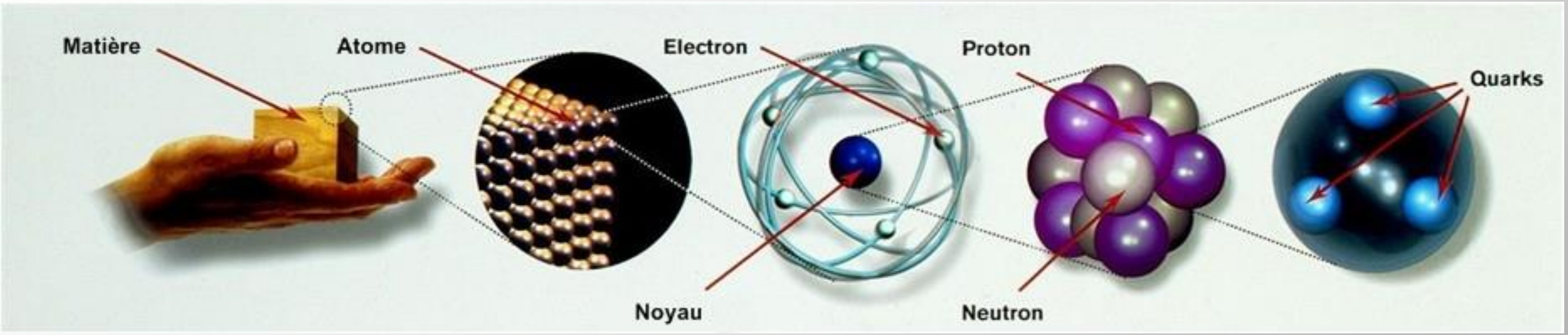
... on)

quarks and aces ... who came up with the concept of atoms:

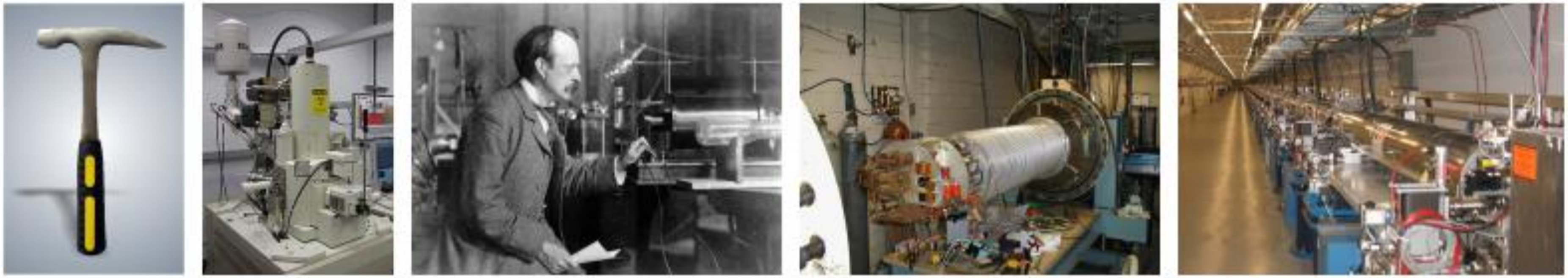
undivisable building bloc



Small scales

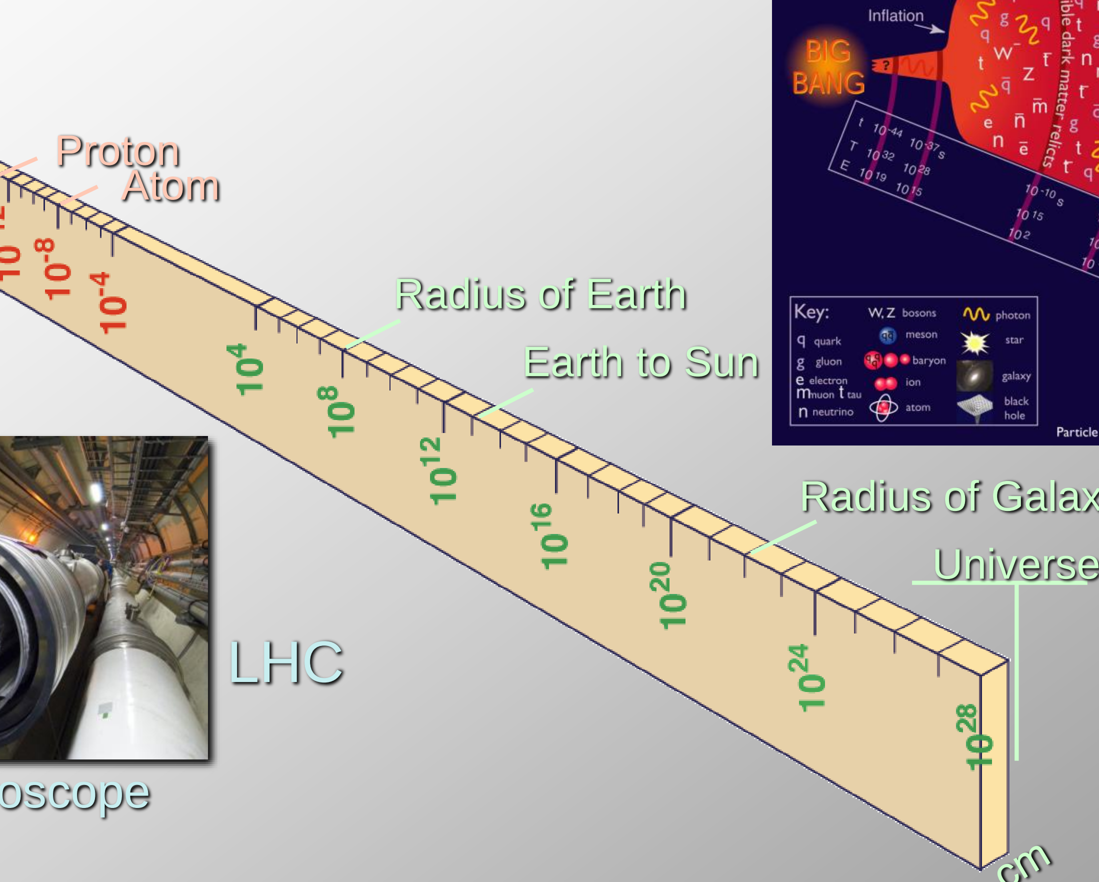


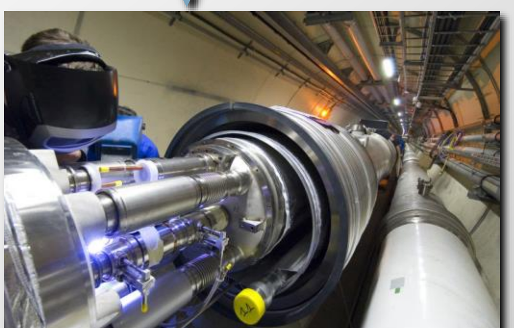
To reach and understand smaller length scales…



The experimental setups need to be larger and larger!

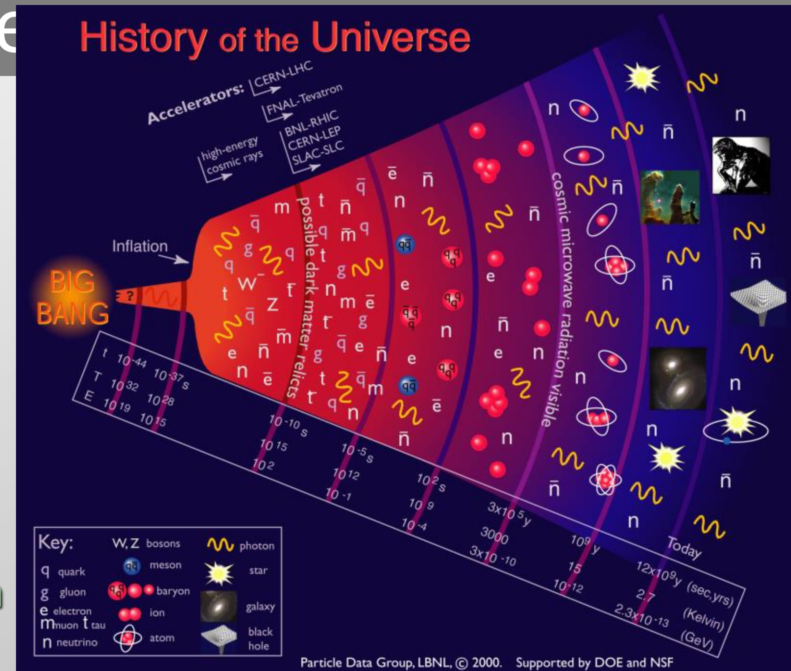
Size, time, temperature and ene

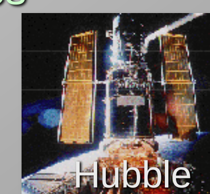




LHC

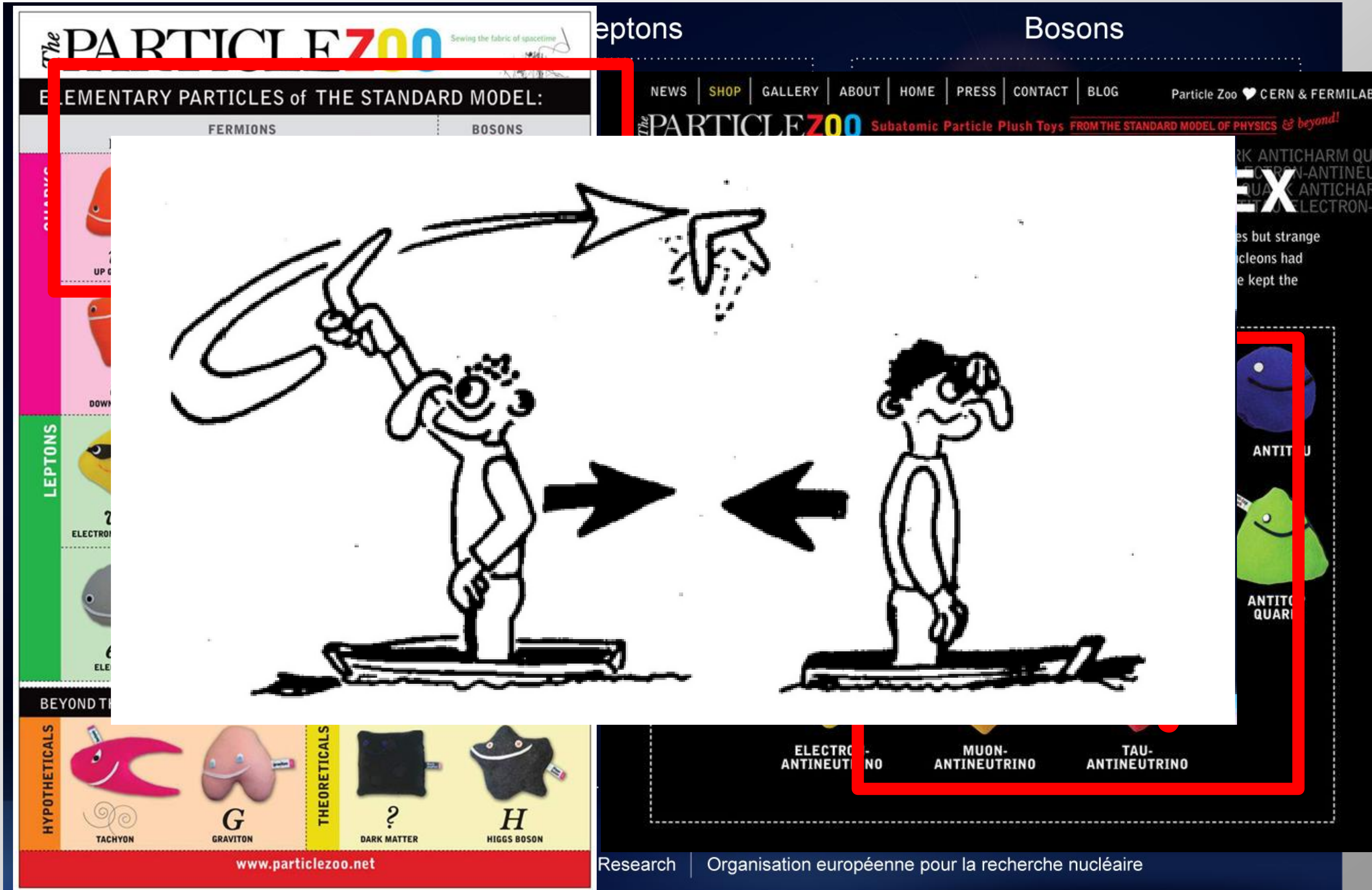
Super-Microscope





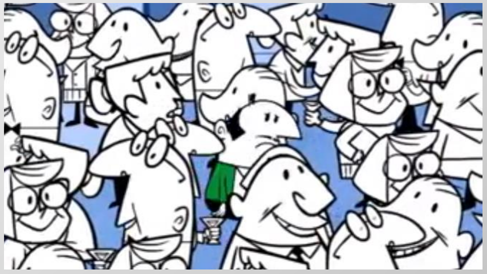
Increase the symbiosis between Particle Physics, Astrophysics and Cosmology

The Standard Model

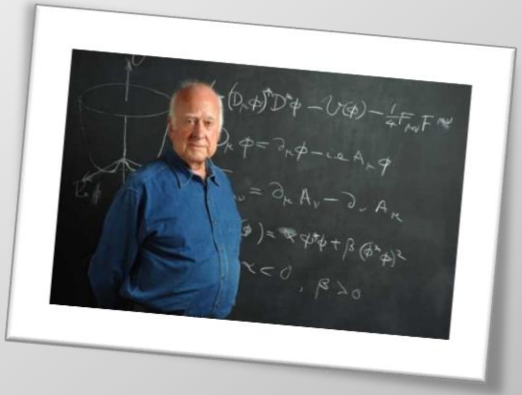


The Higgs boson

- Why do particles have mass?
- A theory from back in the 60s developed by several people under whom Peter Higgs, Francois Englert and Robert Brout



- Two experiments at CERN, ATLAS and CMS confirmed a newly observed particle in 2012, consistent with the Higgs boson
- The Nobel Prize for Physics 2013 was awarded to Higgs and Englert



What else?

- Anti-matter (LHCB, AD/ELENA: AEGIS, ASACUSA, ATRAP, ALPHA, BASE, GBAR)
- Quark-gluon plasma (ALICE)
- Dark matter (ATLAS, CMS, AMS…)
- Quantum Chromo Dynamics, QCD (COMPASS)
- Isotopes (ISOLDE)
- Other interesting things: AWAKE, CAST, CLOUD, DIRAC, LHCf, MOEDAL, NA61/SHINE, NA62, NA63, nTOF, OSQAR, TOTEM, UA9, irradiation facilities, R&D programs, neutrino platform, future accelerators

Some basic principles and ideas

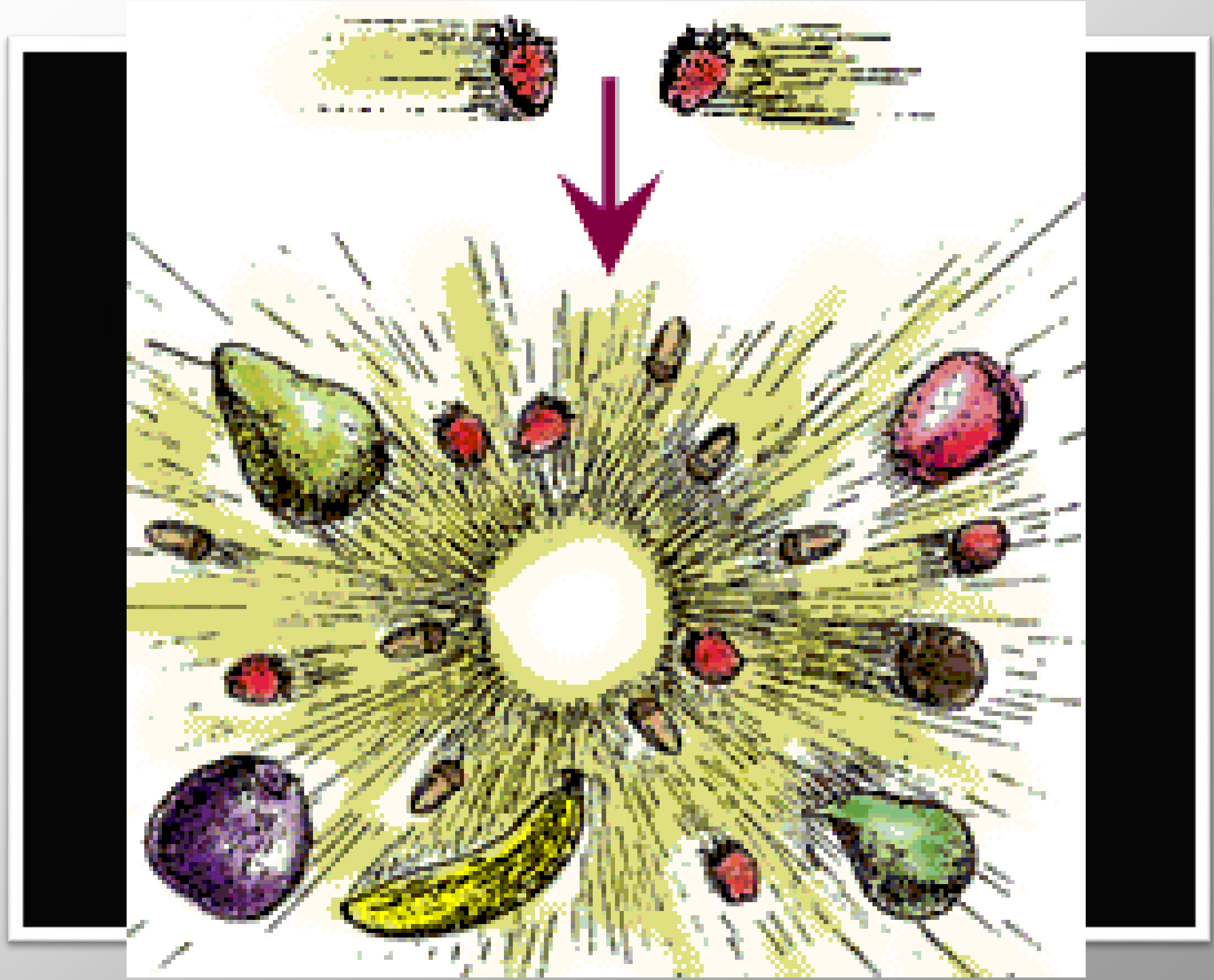
Einstein

$$E=mc^2$$

- It works in both directions, just like currencies: exchange rate $E/m = c^2$
- c=speed of light=300,000 km/s = 7.5 times around our planet in 1 second
- $c^2 = 90,000,000,000,000,000\ m^2/s^2$
- Therefore, if mass (m) is changed into energy (E), we get a lot of it

- But, if energy is changed into mass, the mass is very small: particles!

Collisions



New particles and seeing small structures

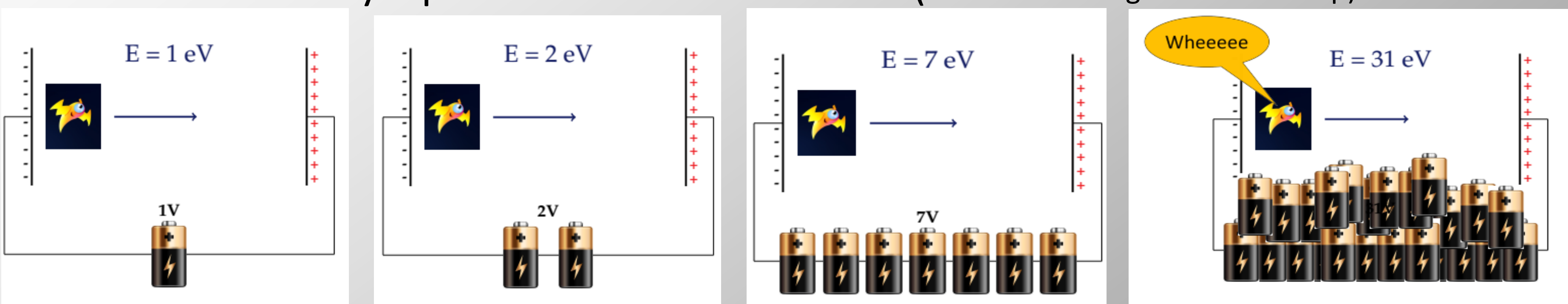
- At the beginning of the 20th century, Einstein explained the photoelectric effect and De Broglie described matter waves, both reflecting the wave-particle duality
- $E=hf$ (Einstein): photon energy is dependent on frequency
- $\lambda=h/p$ (De Broglie): ALL matter has a wave-like nature
- Combining this with $\lambda=c/f$ gives:

$$E=cp=hc/\lambda$$

- Planck's constant and the speed of light are known constants: roughly speaking, 1eV of energy corresponds to 10^{-6} m of length
- Therefore, having the desire to look at the nuclei of the atom, several GeV or even TeV are needed!

The recipe: acceleration

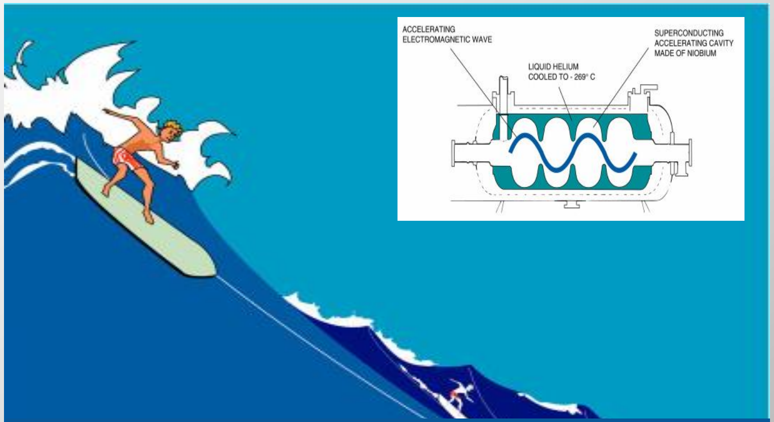
- We need fast particles: **accelerators**
- Charged particles are accelerated in an **electric field** (**F**=ma and $\mathbf{F_e}$=q**E**)
- The nominal energy of the protons in the LHC is **7 TeV**
- 1 eV is only $1.6 \cdot 10^{-19}$ J and equals the amount of energy when an electron is accelerated by a potential difference of 1 V (4.2 J = 1 cal = 1 g of water 1°C up)



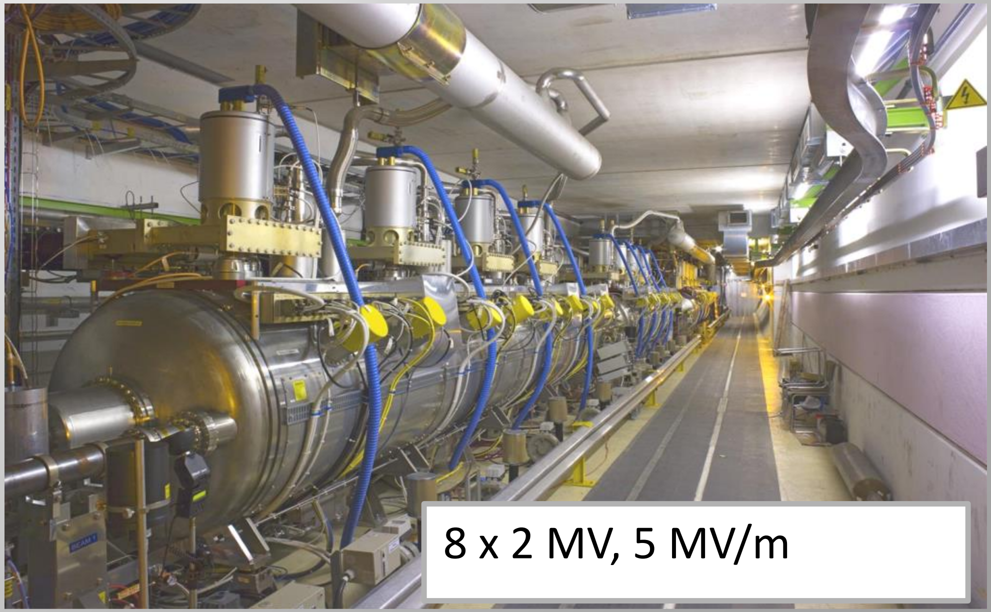
- 7 TeV = 7,000,000,000,000 eV (lots of batteries!)
- But, 7 TeV ≈ 1 µJ = 0.000001 J (total kinetic energy of a flying mosquito…)
- But… it consists of approximately 10^{24} atoms
- In the LHC, every proton has an energy of 7 TeV

Cavities and beam energy

- 2808 bunches * 1.15 10^{11} protons @ 7 TeV each = $2808*1.15*10^{11}*7*10^{12}*1.602*10^{-19}$ Joules = 362 MJ per beam
- The Thalys, intercity train weighs about 400 tonnes
- 0.5 * 400000 * $\mathbf{v}^2 = 3.62*10^8$
- So **v** is about 150 km/hour



Like a water wave propels a surfer,
an electromagnetic wave accelerates particles



8 x 2 MV, 5 MV/m

MV -> TeV -> Mm (little bit too long)

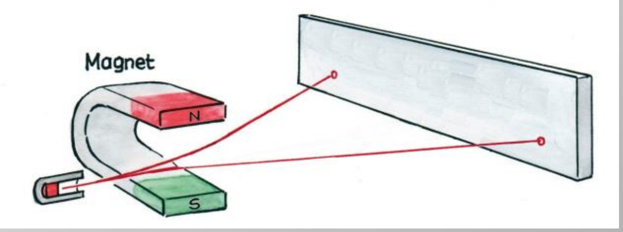
What about re-using the same cavities by letting the particles go around in circles?!

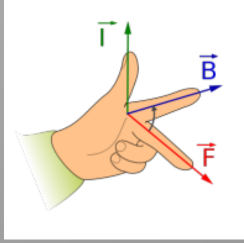
Circular accelerators, the need for magnets

- A force is required to keep the particles on track
- We already saw the electric force: $\mathbf{F}_e = q\mathbf{E}$
- But more generally, the Lorentz force can be written as:

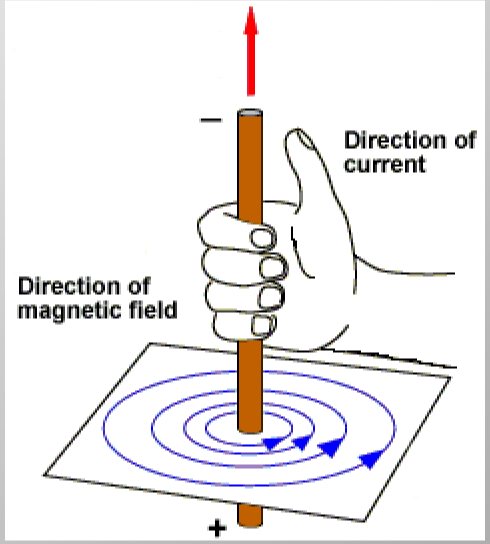
$$\mathbf{F}_e = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

- In other words: **v** x **B** plays a similar role as **E**
- Since relativistic velocities are considered the impact of **B** is huge
- A 1 T **magnetic** field is equivalent to a 0.3 GV/m **electric** field
- Force is a **vector**: due to the cross product relation, the force cannot be used to accelerate, but merely to change the direction of the particles!

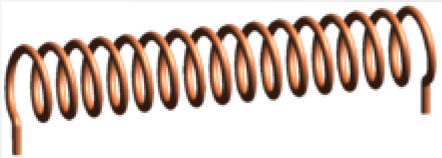


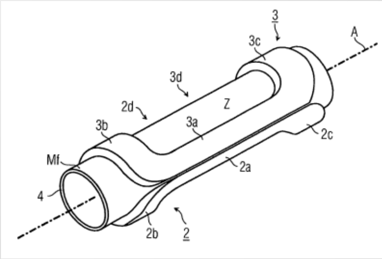


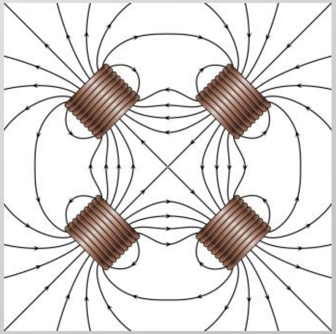
Magnets continued…



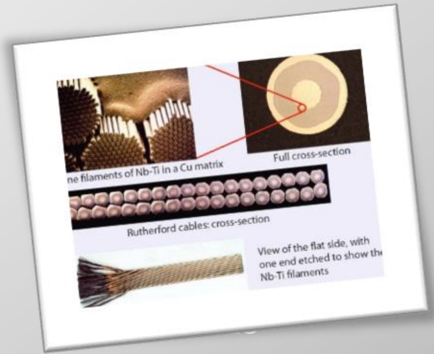
- Oersted and later on Biot and Savart
- **B** is linearly depending on current
- Different shape: different magnetic field -> coils!
- Solenoids, dipoles, quadrupoles, …

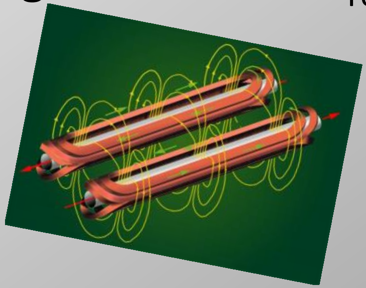






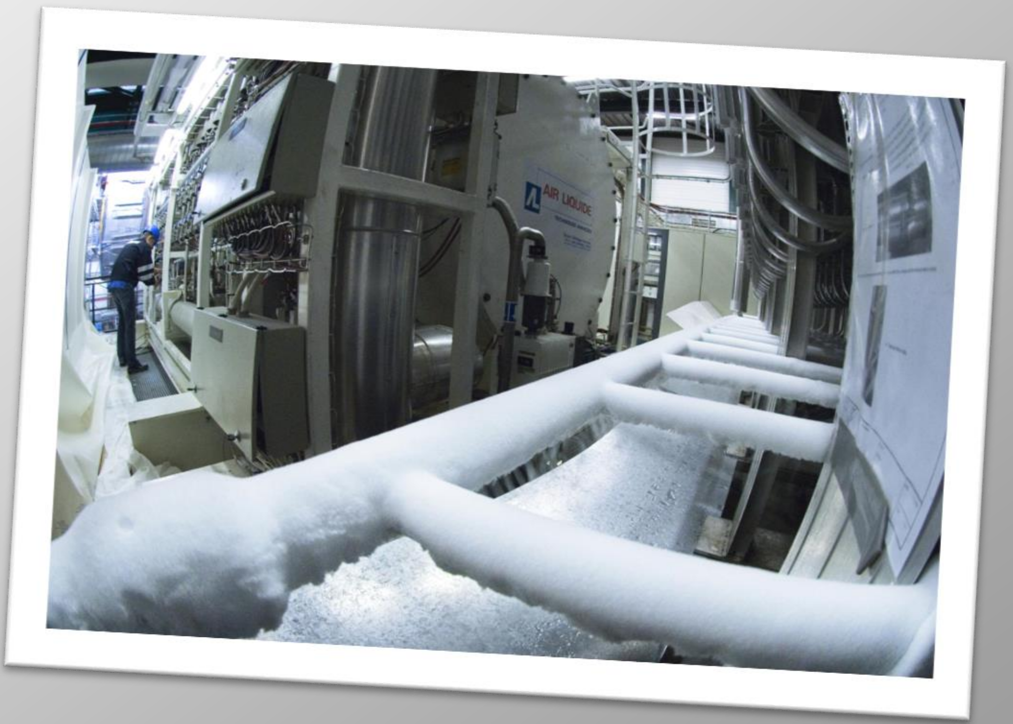
- But Ohm's law (V=IR) tells us that current cannot flow freely, with P=VI we see that a coil heats up when a current is flowing
- We need very large **B** because $E_{TeV} \cong 0.3\ \mathbf{B}_T\ \mathbf{R}_{km}$: superconducting magnets!





Cryogenics

- Since superconductors, especially Nb-Ti (the workhorse in this field) only perform at extremely low temperatures, cryogenic technology is required

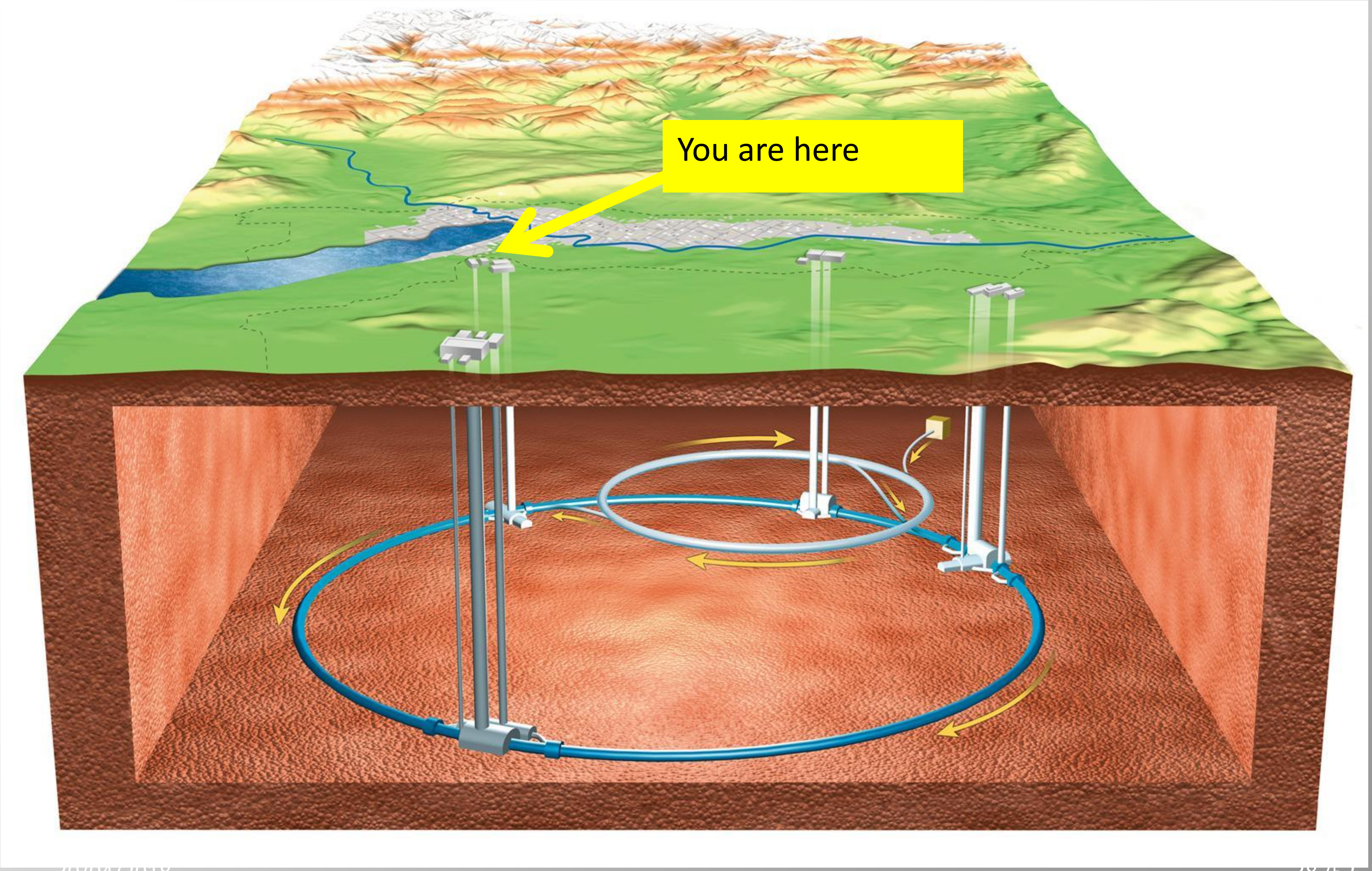


- With superfluid helium, low temperatures are maintained: lower than in outer space!

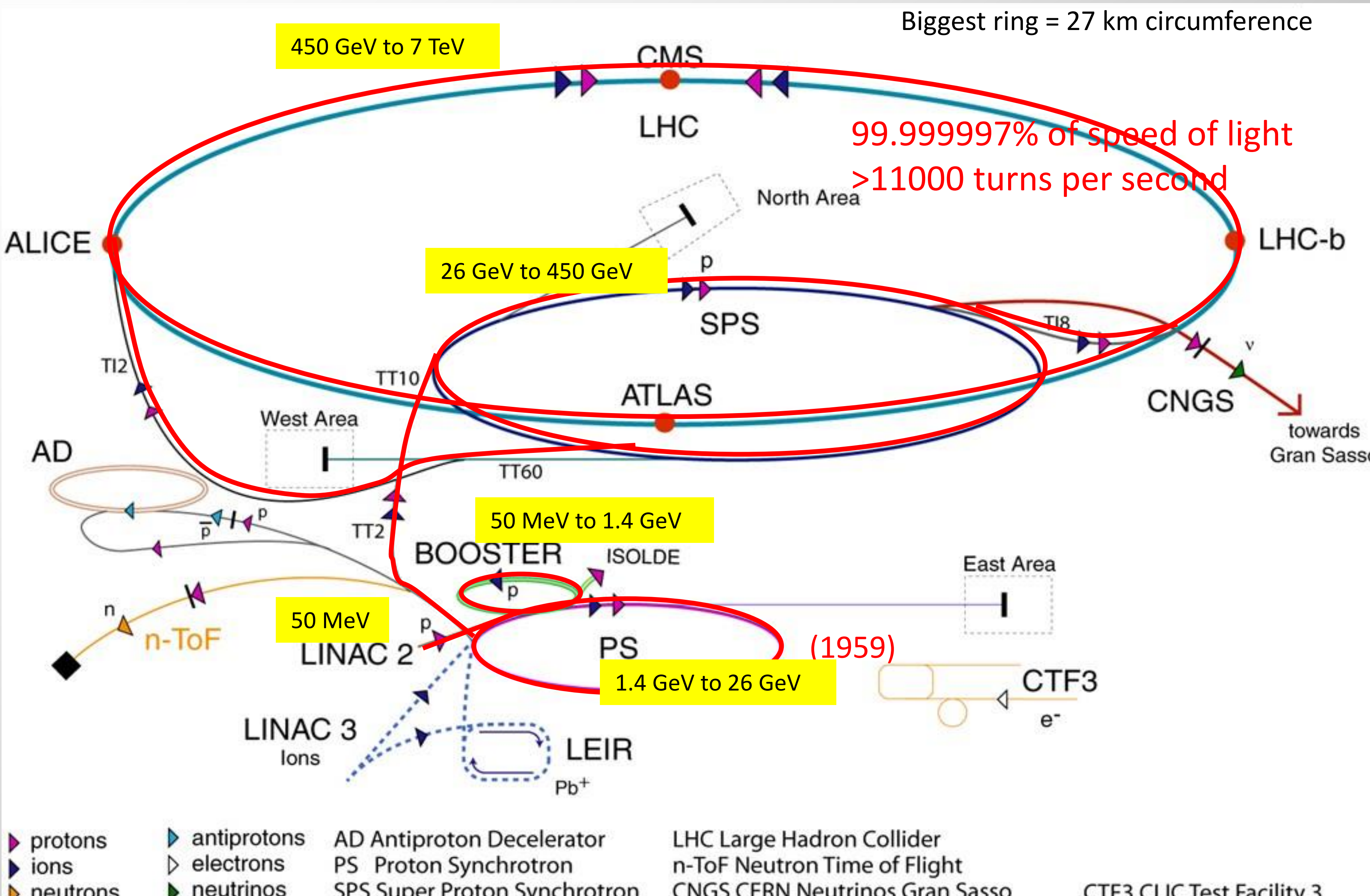
The accelerator complex


LHCb
ATLAS
CMS
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
ALICE
CMS
ALICE
LHC ring:
27 km circumference

90-140 m underground



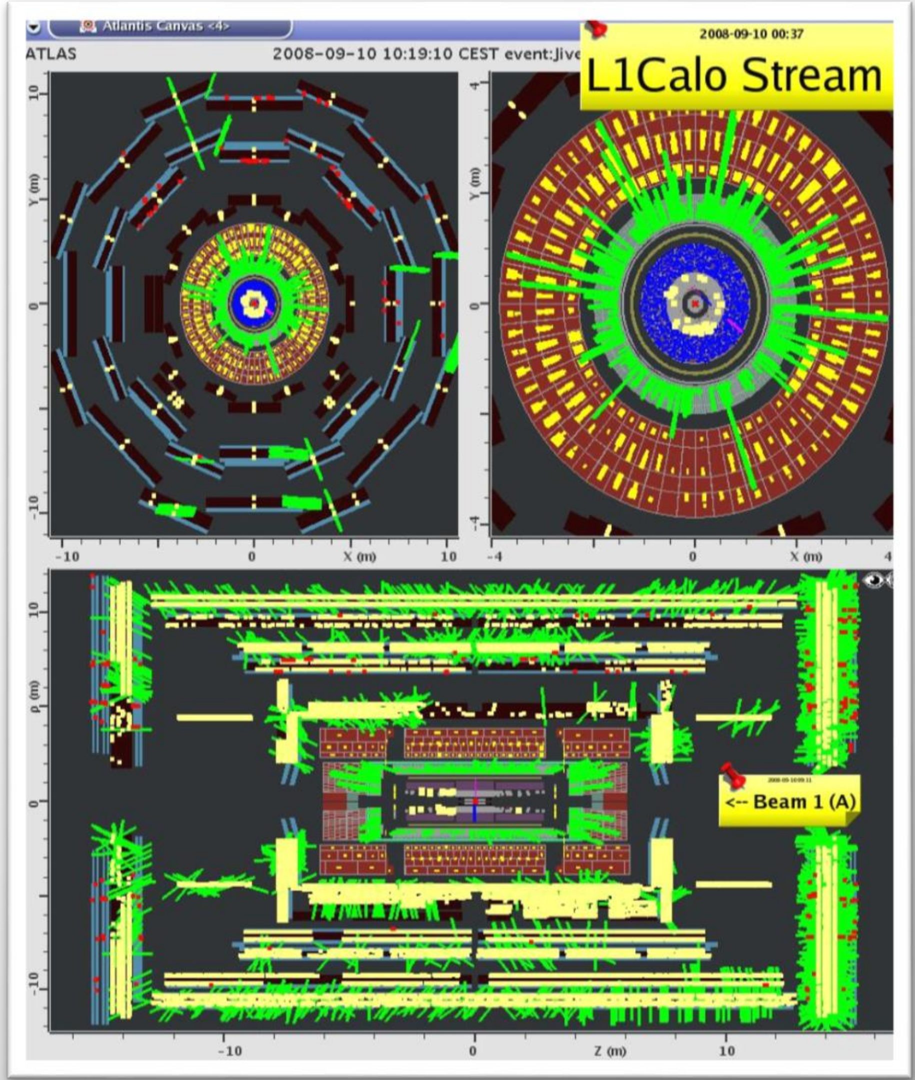
The accelerator complex



From the bottle to the bang!

- It takes a couple of **micro**seconds to cross the linac2 to reach the booster.
- In the PSB it is accelerated from 50 MeV to 1.4 GeV in **530 ms** and then after less than a microsecond it is injected in the PS.
- There it can either:
  - be accelerated/manipulated/extracted in **1025 ms**
  - or wait for **1.2 more seconds** before being accelerated, if it's part of the first PSB batch to the PS. Then it is sent to the SPS.
- Then it is sent to the SPS where it waits for **10.8, 7.2, 3.6, or zero seconds** whether it's part of the first, second, third, or fourth PS batch to the SPS.
- The SPS accelerates it to 450 GeV in 4.3 seconds, and sends it to the LHC.
- So the time it takes from the source to the exit of the SPS is between 0.53 + 1.025 + 4.3 = **5.86 s** and 0.53 + 1.2 + 1.025 + 10.8 + 4.3 = **17.86 s**
- Then our proton has to wait up to 20 minutes on the LHC 450 GeV injection plateau before the 25 minutes ramp to high energy, and these **45 minutes** dominates the transit time.

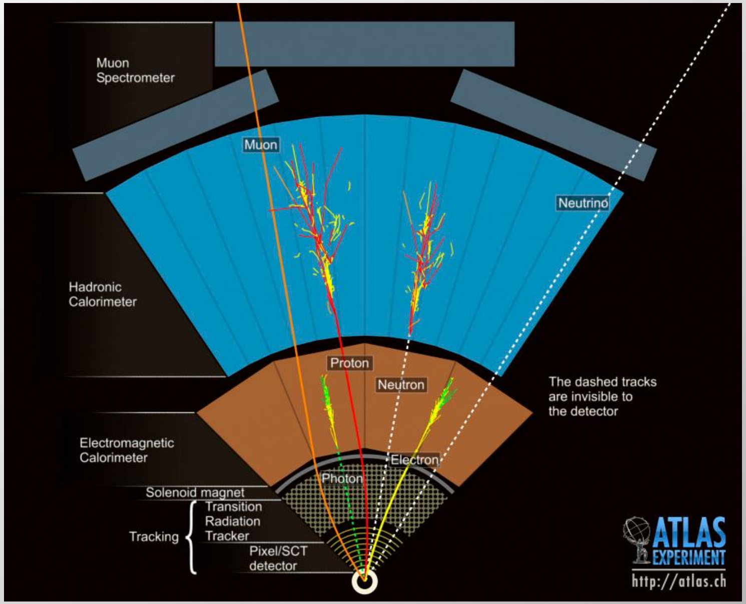
First beam events on 10 Sep 2008 10:19



The (LHC) Experiments

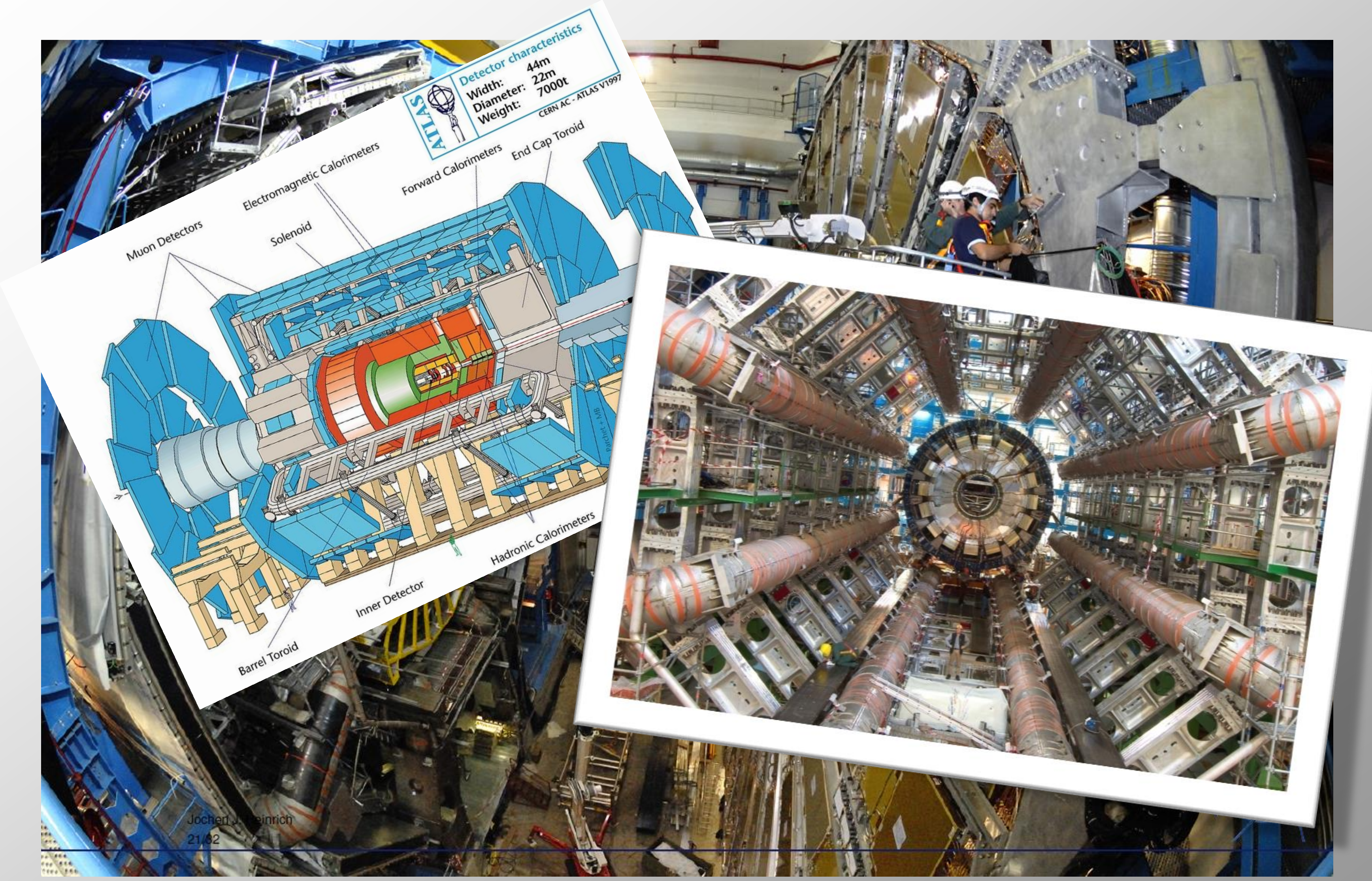
The recipe continued: detection

- We need to measure the new “stuff”: detectors
- We want to know several properties of the new particles, i.e. **charge**, **mass**, etc.
- **Charge** can be measured by deflecting particles in a magnetic field: **magnet coils**
- **Mass** can be calculated from the deposited energy and the curve of the particle track: **calorimeters** and **trackers**
- Particles are not measured or seen directly: but they leave tracks in the detectors, just like footprints in the snow

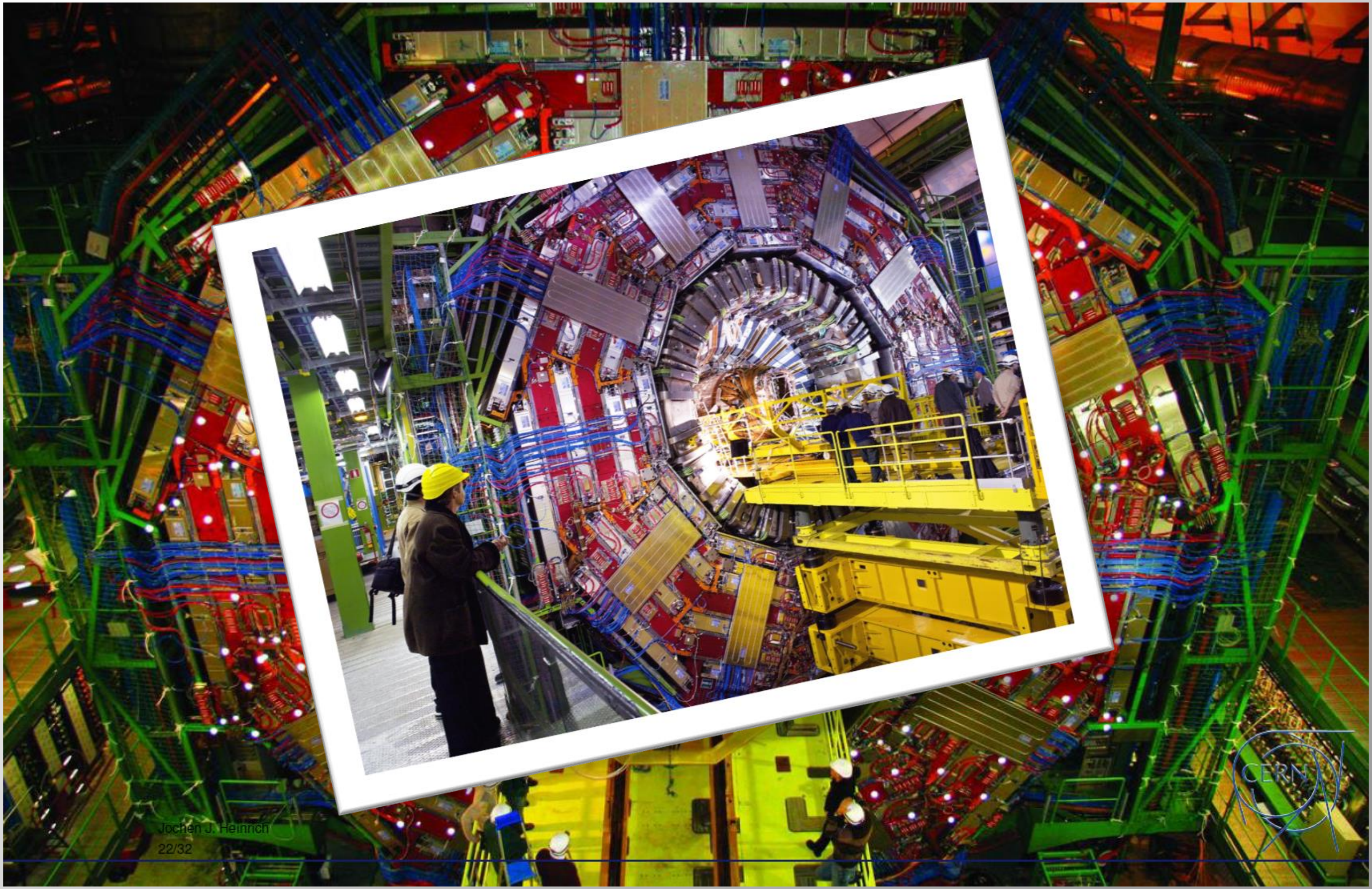


- Three basic techniques are applied in different shapes and forms, but all have to do directly with the interaction of matter and forces
- Scintillating material (plastics and crystals)
- Semi-conductors (silicon etc.)
- Gas ionization

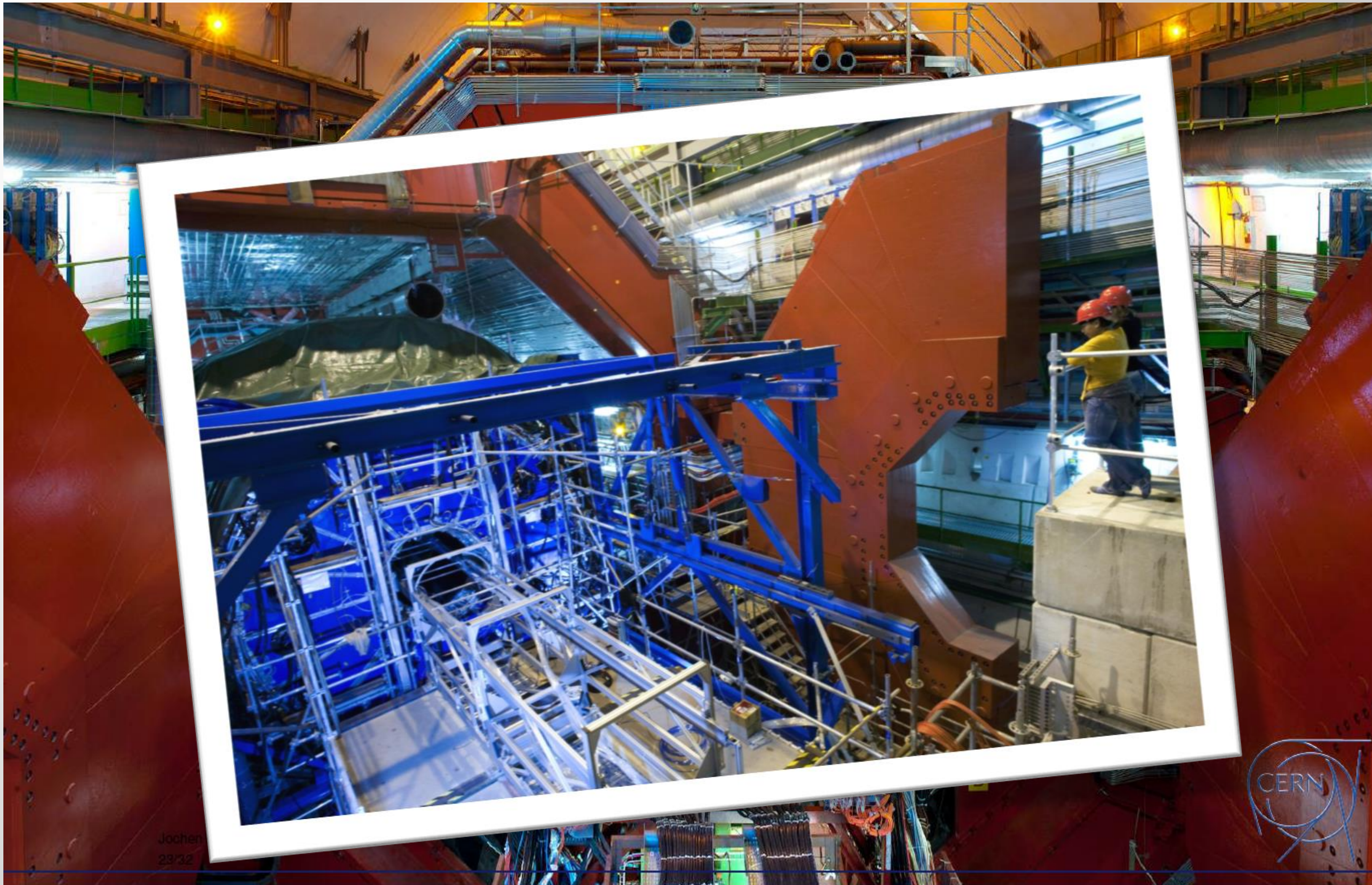
ATLAS: A Toroidal LHC ApparatuS



CMS: Compact Muon Solenoid



ALICE: An LHC Ion Collider Experiment



LHCb: LHC beauty

Detection

- Most interesting particles decay before they reach the first detector…
- How do we measure them?
- We don’t
- We measure the decay products, which we can: theory helps us on the way
- Now we simply count (a lot!), it is all about statistics

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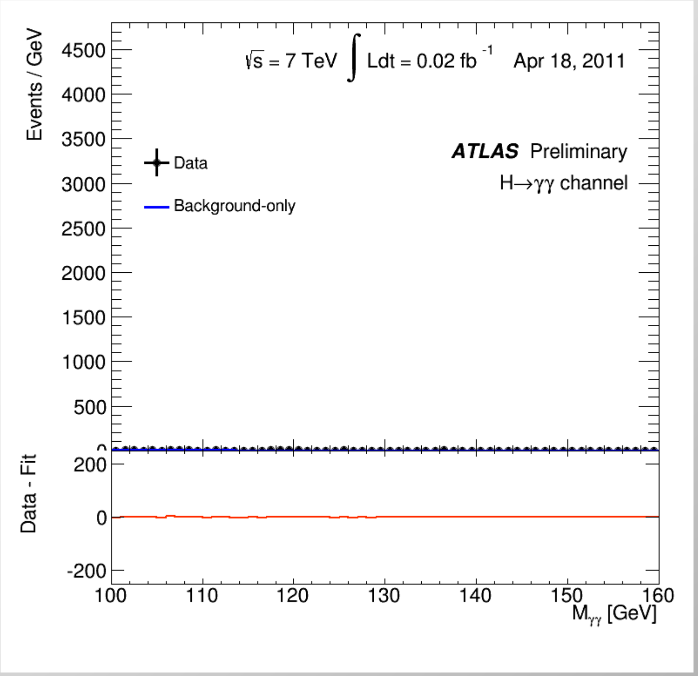
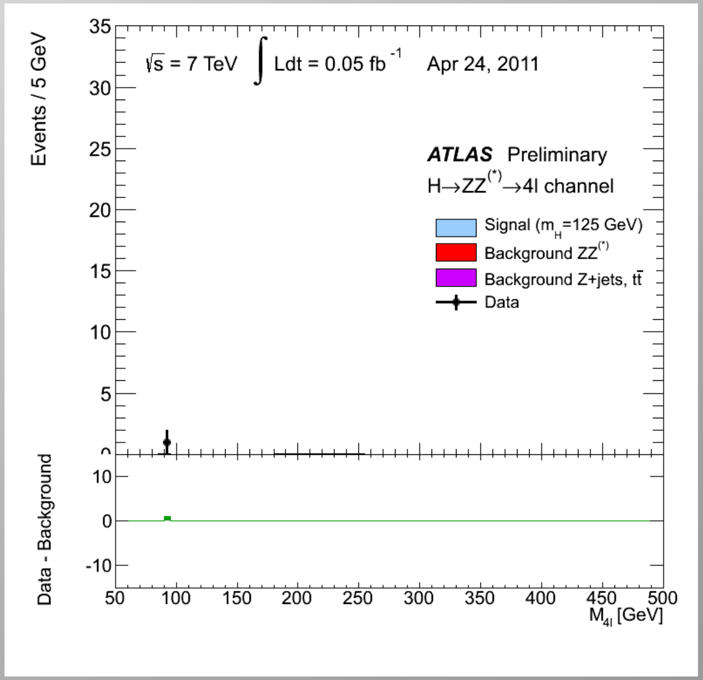
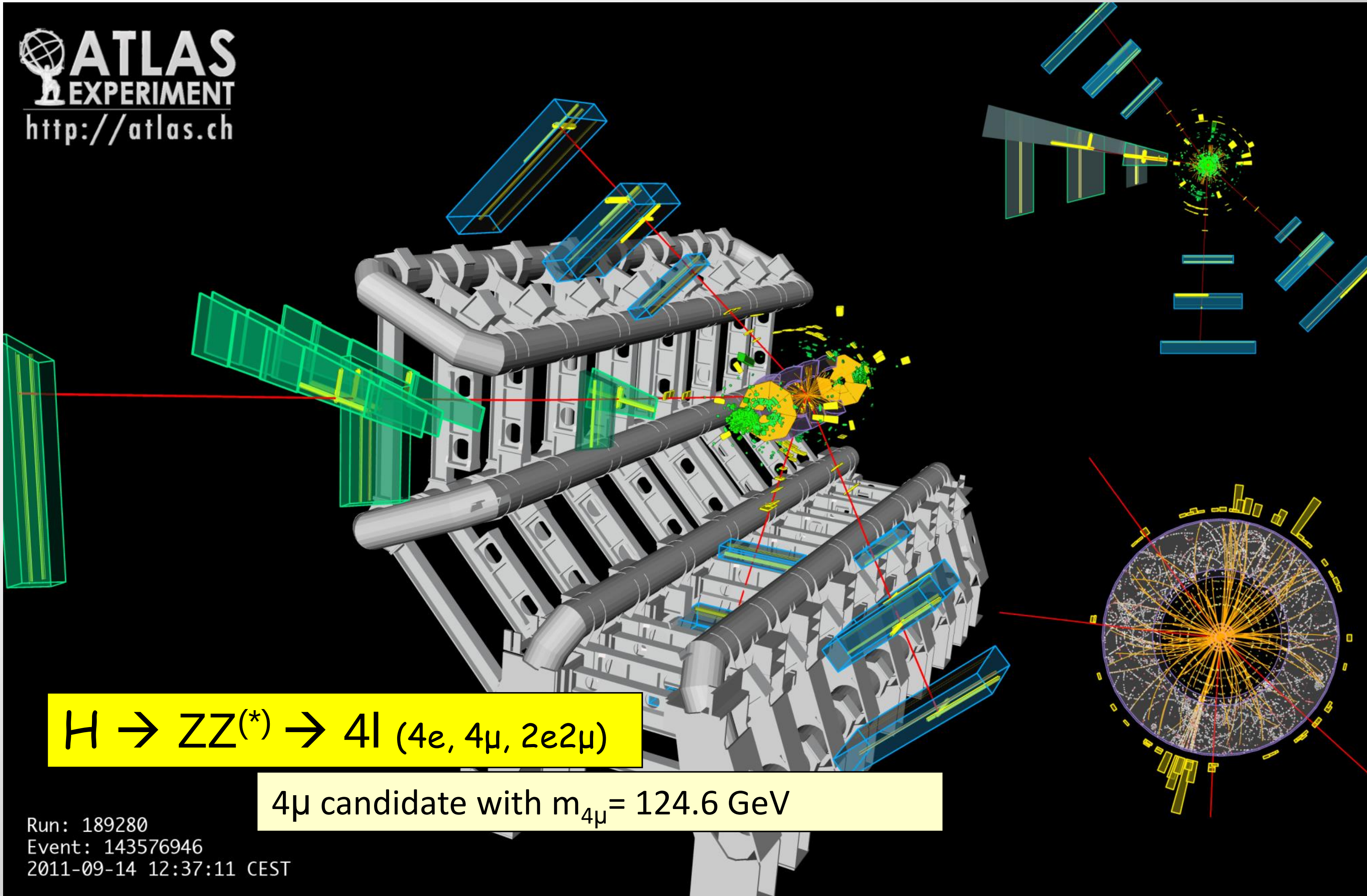




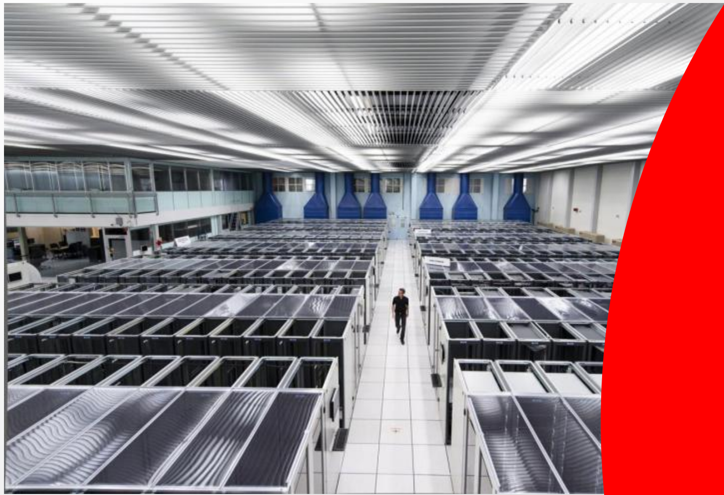
Higgs events in ATLAS



by Erwin Bielert

Collected data

https://www.wired.com/2013/04/bigdata



Business email sent per year	2,986,100
Content uploaded to Facebook each year	182,500
Google's search index	97,656
Kaiser Permanente's digital health records	30,720
Large Hadron Collider's annual data output	15,360
Videos uploaded to YouTube per year	15,000
National Climactic Data Center database	6,144
Library of Congress' digital collection	5,120
US Census Bureau data	3,789
Nasdaq stock market database	3,072
Tweets sent in 2012	19
Contents of every print issue of WIRED	1.26

ATLAS/CMS **RAW** data:
3456 PB/Day

40 MHz x 1 MB/event

Scientific spin-off

Technological spin-off

- Electricity in 1850
  When asked about the **practical value of electricity** by the British minister of finance in 1850, Faraday replied “One day sir, you may tax it”.
- Radio isotopes
- X-rays (between first observing them and using them only a couple of days!)
- Superconductivity (HTS)
- Nuclear Magnetic Resonance (NMR, MRI)
- Quantum mechanics (Quantum encryption)


Bent Stumpe, with a 1973 capacitive touch screen

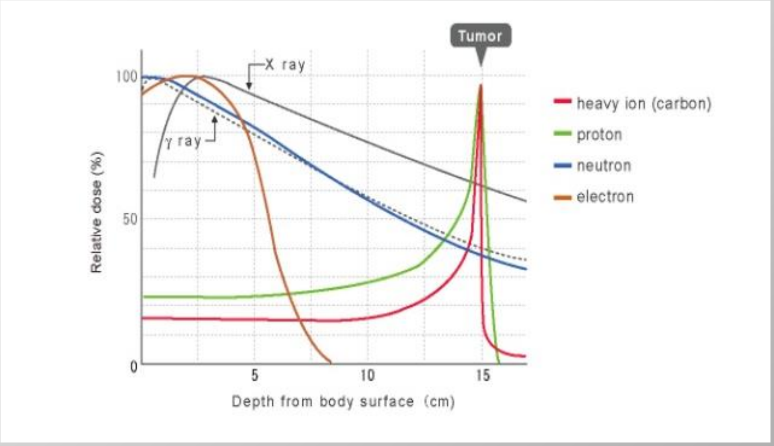

Tracker ball (computer mouse)

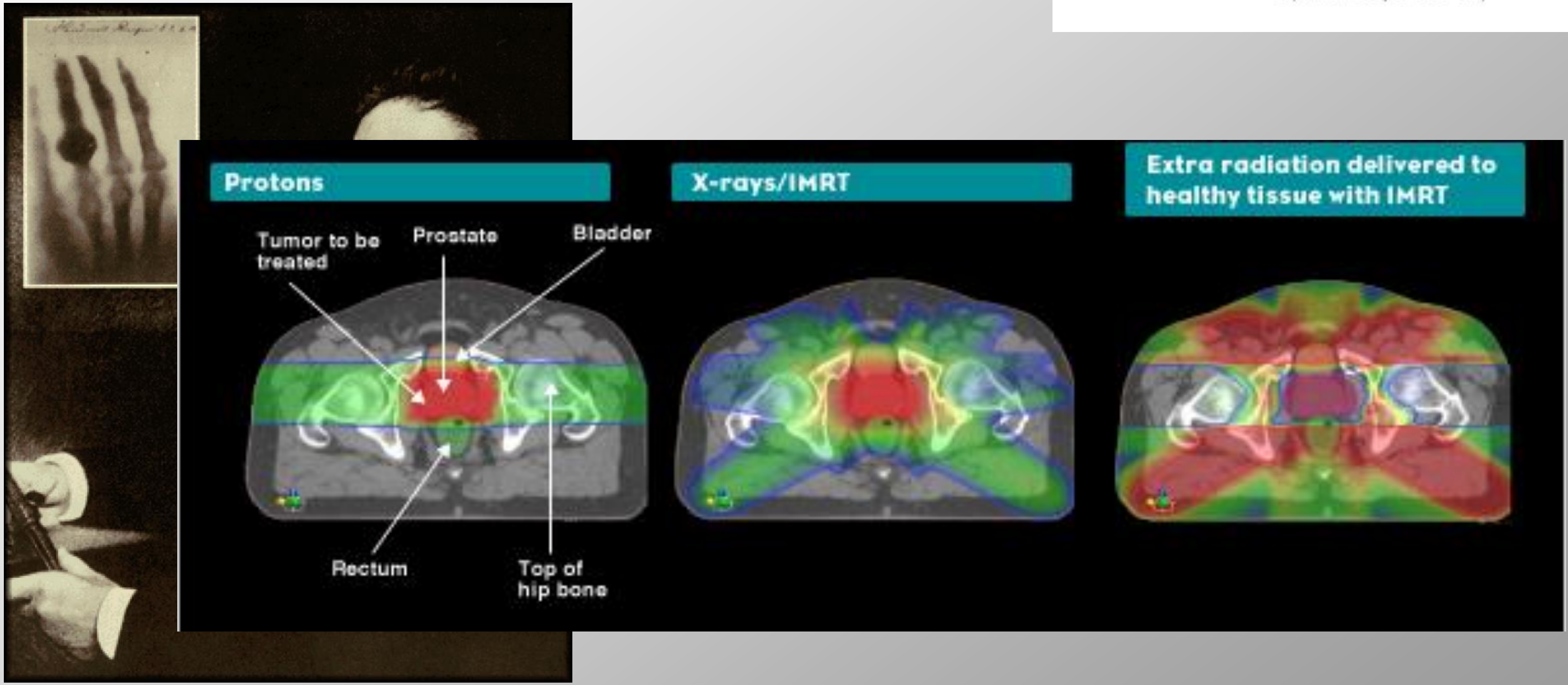

Sir Tim Berners-Lee, inventer of the WWW (http protocol)

Medical world: hospital equipment

Detection and treatment of cancer:

- MRI scan (superconducting magnets)
- PET scan (scintillators, antimatter annihilation)
- CT scan (x-ray imaging)
- Proton therapy (particle interaction)

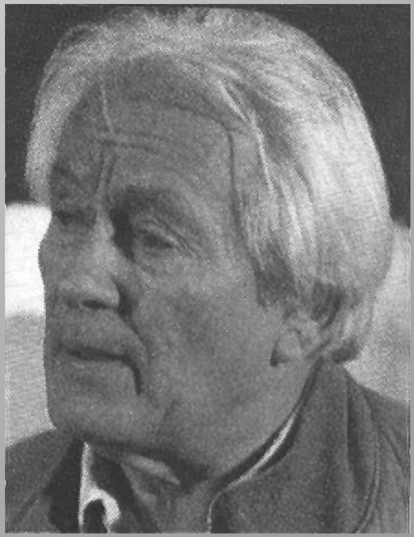




Nobel prize in physics

The Nobel prize in physics was awarded to:

- Carlo Rubbia and Simon van der Meer in 1984 for inventions which made it possible to discover the W and Z bosons
- Georges Charpak in 1992 for the development of particle detectors and multiwire proportional chambers in particular



The end

« ***Magic*** does not happen here, ***magic*** is being explained »

Tom Hanks

- *(2009, during his visit for the movie*
- *« Angels and Demons »)*

Information: www.cern.ch

CERN TV: www.youtube.com/cern

Recruitment: www.cern.ch/jobs

Thank you and enjoy your visit!

Are there any questions?