CERN, Was, Wie, Warum ?

Werner Riegler, CERN

FH Astronomen Wels, 22. November 2021

„CERN – Was, Warum, Wie“

Mit Hilfe riesiger Teilchenbeschleuniger konnten in den vergangenen Jahrzehnten der Natur viele Geheimnisse über den Aufbau der Materie entlockt werden. Mit der Entdeckung des Higgs Teilchens ist das derzeitige Verständnis der subatomaren Welt im Kontext des sogenannten ‘ Standardmodells’ abgeschlossen worden. Viele Fragen über unseren Kosmos sind aber noch unbeantwortet: Woraus besteht die dunkle Materie? Was ist die dunkle Energie? Warum gibt es im sichtbaren Universum nur Materie und keine Antimaterie? Wie lassen sich Gravitation und Quantentheorie vereinigen? Der Vortrag erläutert wie diese Fragen am LHC verfolgt werden, wie die Teilchenkollisionen von 14TeV Energie aufgezeichnet werden, wie die riesigen Datenmengen von 100 PByte/Jahr bewältigt werden und welche ’spin-offs’ sich daraus für Wirtschaft und Gesellschaft ergeben.

CERN: What ? Why ? How ?

- **What**
  - **Institution for research in the field of elementary particle physics**

- **Why**
  - **Structure of Matter**
  - **Fundamental Laws of Science**

- **How**
  - **Accelerators**
  - **Detectors**

CERN

- **CERN-Mission (founded 1954)**
  - **Development, construction of infrastructure (accelerators) for particle physics research**
  - **Participation in particle physics research**
  - **Coordination of European particle physics research**

- **Focus (personnel, budget) on accelerators**
  - **~75 % of staff on accelerator/administration**
  - **~25 % of staff on particle physics research**

- **Experiments and Detectors**
  - **Execution mainly by external research groups (~ 85%)**

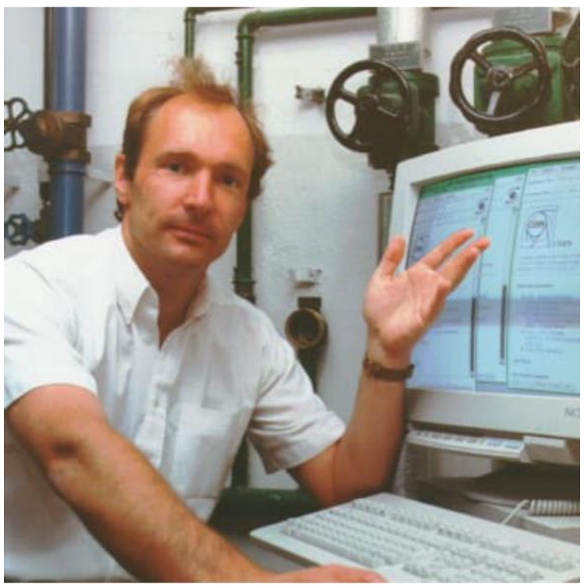
WWW

09:36 4G
edition.cnn.com

CNN style

The World Wide Web's inventor is selling its original code as an NFT

Updated 15th June 2021



Credit: Courtesy Sotheby's

Written by **Oscar Holland, CNN**

09:37 4G
edition.cnn.com

CNN style

Written by **Oscar Holland, CNN**

Tim Berners-Lee, creator of the World Wide Web, is auctioning off his invention's source code as an NFT.

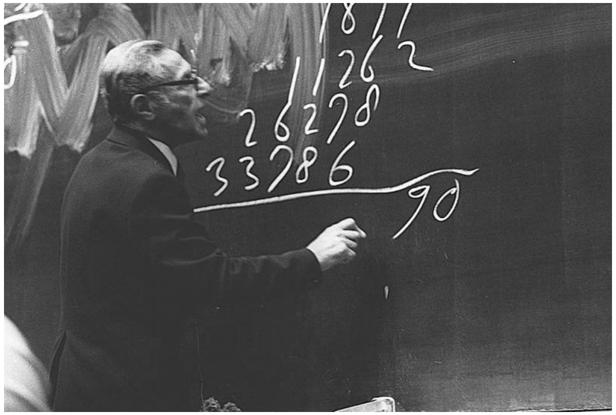
Although the groundbreaking code has long been in the public domain, the British computer scientist has now authorized the sale of a single edition of his original time-stamped files.

Comprising over 9.500 lines of code, the files contain the basis of the languages and protocols underpinning the internet as we know it: Hypertext Transfer Protocol (HTTP), Hypertext Markup Language (HTML) and Universal Document Identified (URI).

They are being sold alongside an animated visualization of the code and a digital "poster" that is "signed" by Berners-Lee via a graphic signature. The winning bidder will also take home a letter, written by the computer scientist, in which he reflects on the code and its creation.

READ NEXT
How NFTs are fueling a digital art boom

CERN: a few numbers



- Budget
  - 1200 M CHF/ Jahr
  - Im Vergleich
    - TU Wien : ~ 400 M Euro/Jahr
    - ETH Zürich : ~1600 CHF/year
  - CERN ≈ a large European University

- Personnel
  - 2600 CERN Staff

- Scientific ‚Users' of CERN
  - ca. 13000
    - ca. 65% from 23 member states
    - ca. 35% from ca. 60 non-member states
      - specifically: USA, Russland, Japan, China,
      - south America, Arab countries

- LHC was built with world-wide participation: Prototype of a 'world lab'

CERN: founded in 1954: 12 European States

"Science for Peace"

Today: 23 Member States

- ~ 2600 staff
- ~ 1800 other paid personnel
- ~ 13600 scientific users

Budget (2019) ~ 1200 MCHF

(8:30)

Member States: Austria, Belgium, Bulgaria, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and the United Kingdom

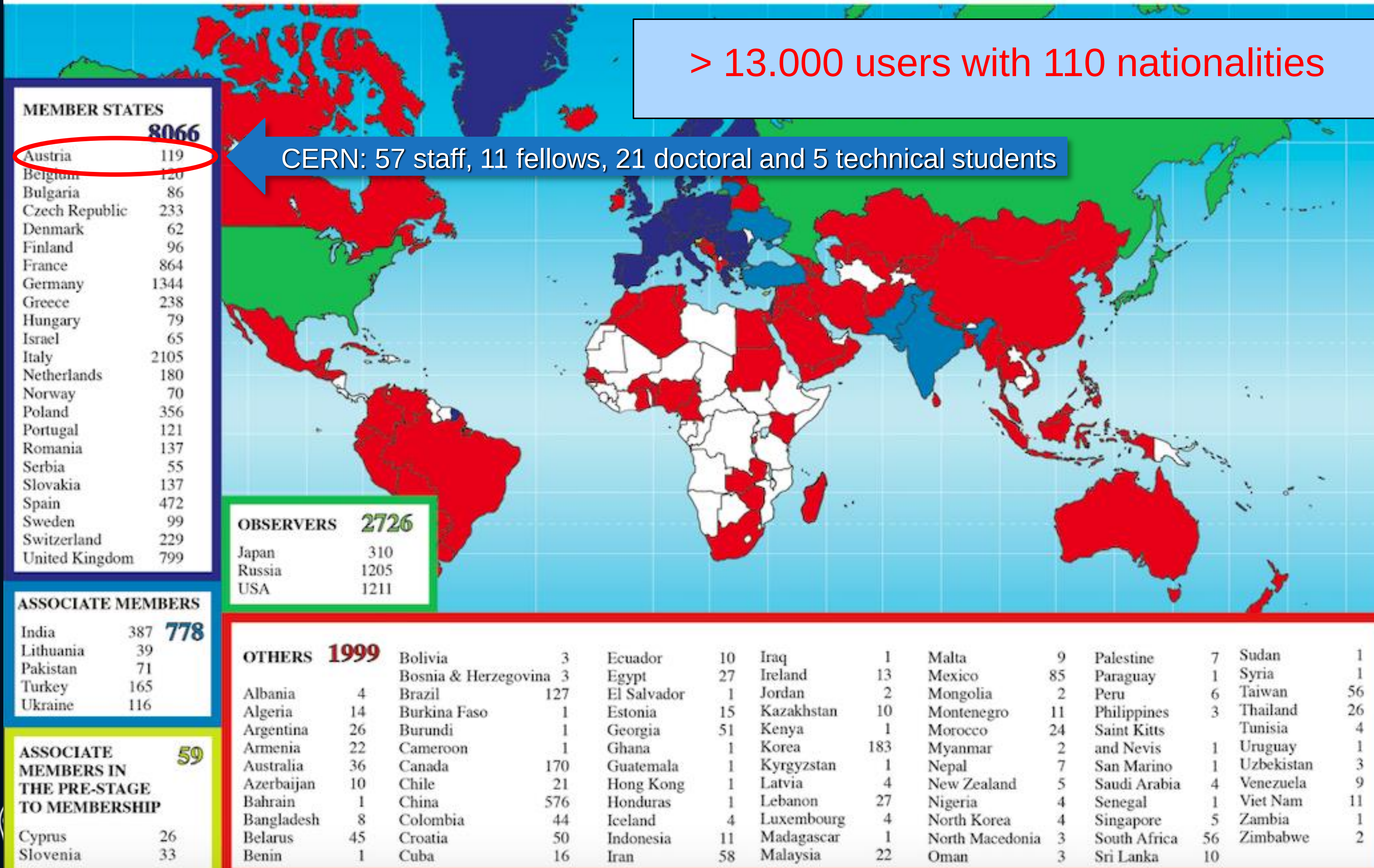
Associate Member: Cyprus, India, Lithuania, Pakistan, Slovenia, Turkey, Ukraine

Applicant States for Membership or Associate Membership: Brazil, Croatia, Estonia

Observers to Council: Japan, Russia, United States of America; JINR, European Union and UNESCO

Science is getting more and more global

Distribution of All CERN Users by Nationality on 10 April 2019



MEMBER STATES 8066

Austria	119
Belgium	120
Bulgaria	86
Czech Republic	233
Denmark	62
Finland	96
France	864
Germany	1344
Greece	238
Hungary	79
Israel	65
Italy	2105
Netherlands	180
Norway	70
Poland	356
Portugal	121
Romania	137
Serbia	55
Slovakia	137
Spain	472
Sweden	99
Switzerland	229
United Kingdom	799

ASSOCIATE MEMBERS 778

India	387
Lithuania	39
Pakistan	71
Turkey	165
Ukraine	116

ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP 59

Cyprus	26
Slovenia	33

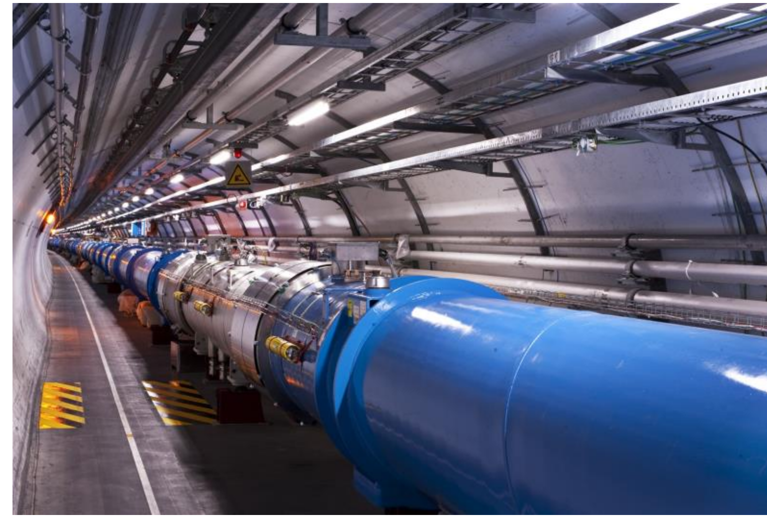
OBSERVERS 2726

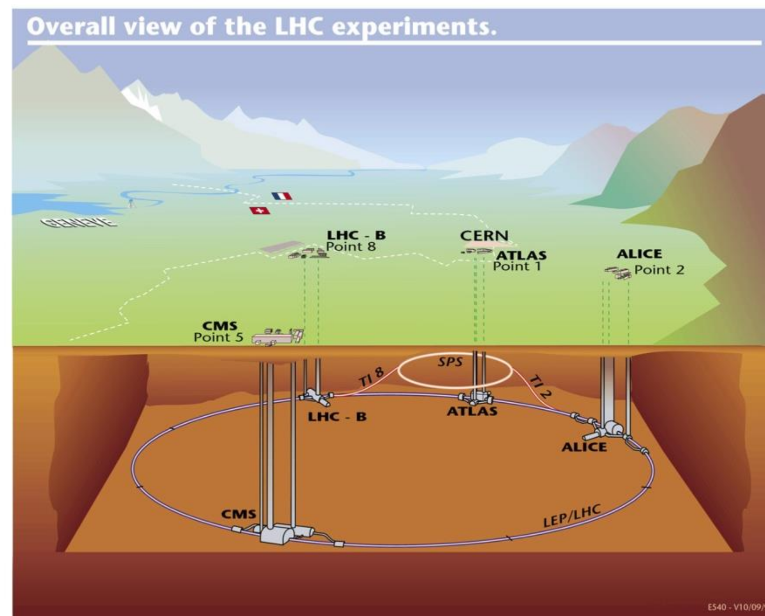
Japan	310
Russia	1205
USA	1211

OTHERS 1999

Albania	4
Algeria	14
Argentina	26
Armenia	22
Australia	36
Azerbaijan	10
Bahrain	1
Bangladesh	8
Belarus	45
Benin	1
Bolivia	3
Bosnia & Herzegovina	3
Brazil	127
Burkina Faso	1
Burundi	1
Cameroon	1
Canada	170
Chile	21
China	576
Colombia	44
Croatia	50
Cuba	16
Ecuador	10
Egypt	27
El Salvador	1
Estonia	15
Georgia	51
Ghana	1
Guatemala	1
Hong Kong	1
Honduras	1
Iceland	4
Indonesia	11
Iran	58
Iraq	1
Ireland	13
Jordan	2
Kazakhstan	10
Kenya	1
Korea	183
Kyrgyzstan	1
Latvia	4
Lebanon	27
Luxembourg	4
Madagascar	1
Malaysia	22
Malta	9
Mexico	85
Mongolia	2
Montenegro	11
Morocco	24
Myanmar	2
Nepal	7
New Zealand	5
Nigeria	4
North Korea	4
North Macedonia	3
Oman	3
Palestine	7
Paraguay	1
Peru	6
Philippines	3
Saint Kitts and Nevis	1
San Marino	1
Saudi Arabia	4
Senegal	1
Singapore	5
South Africa	56
Sri Lanka	10
Sudan	1
Syria	1
Taiwan	56
Thailand	26
Tunisia	4
Uruguay	1
Uzbekistan	3
Venezuela	9
Viet Nam	11
Zambia	1
Zimbabwe	2

Large Hadron Collider (LHC) – most powerful particle accelerator to date In operation since 2009

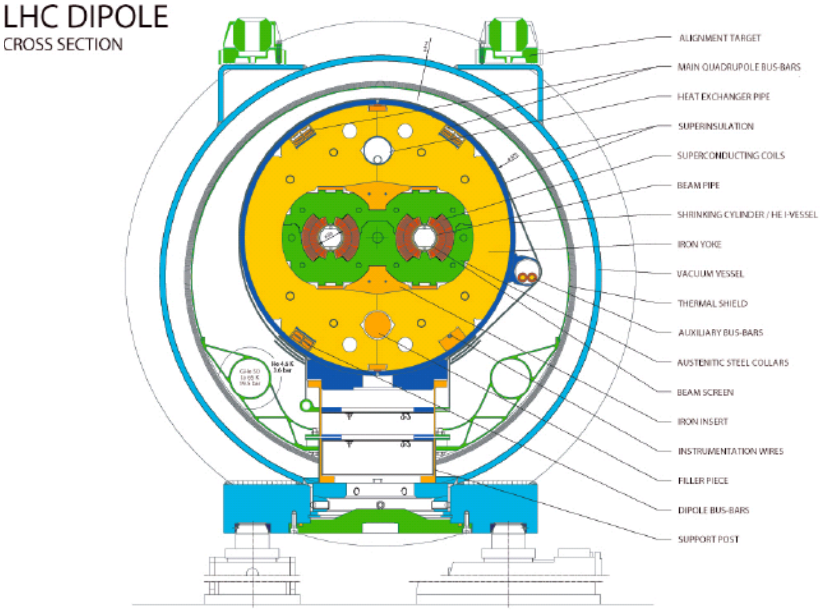




Tunnel:

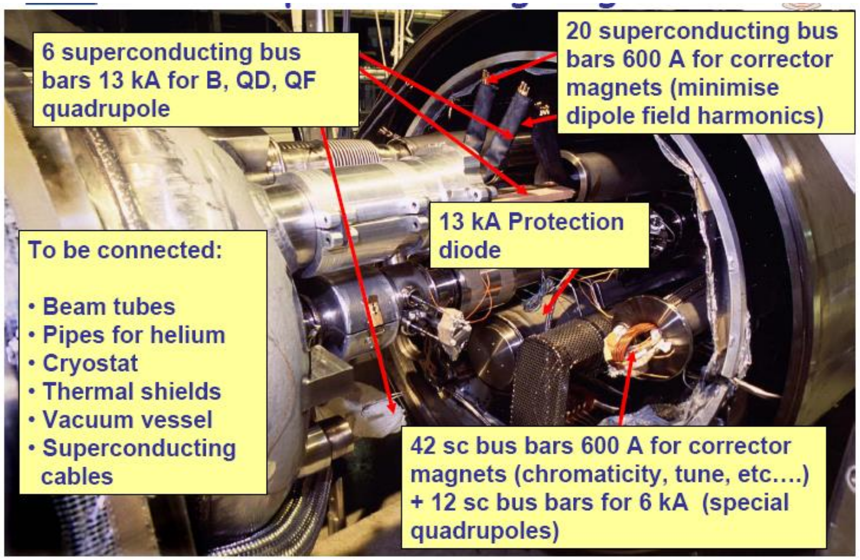
27km Circumference,
100m below sruface
Tunnel diameter ca. 4m

LHC: 27km of superconducting magnets

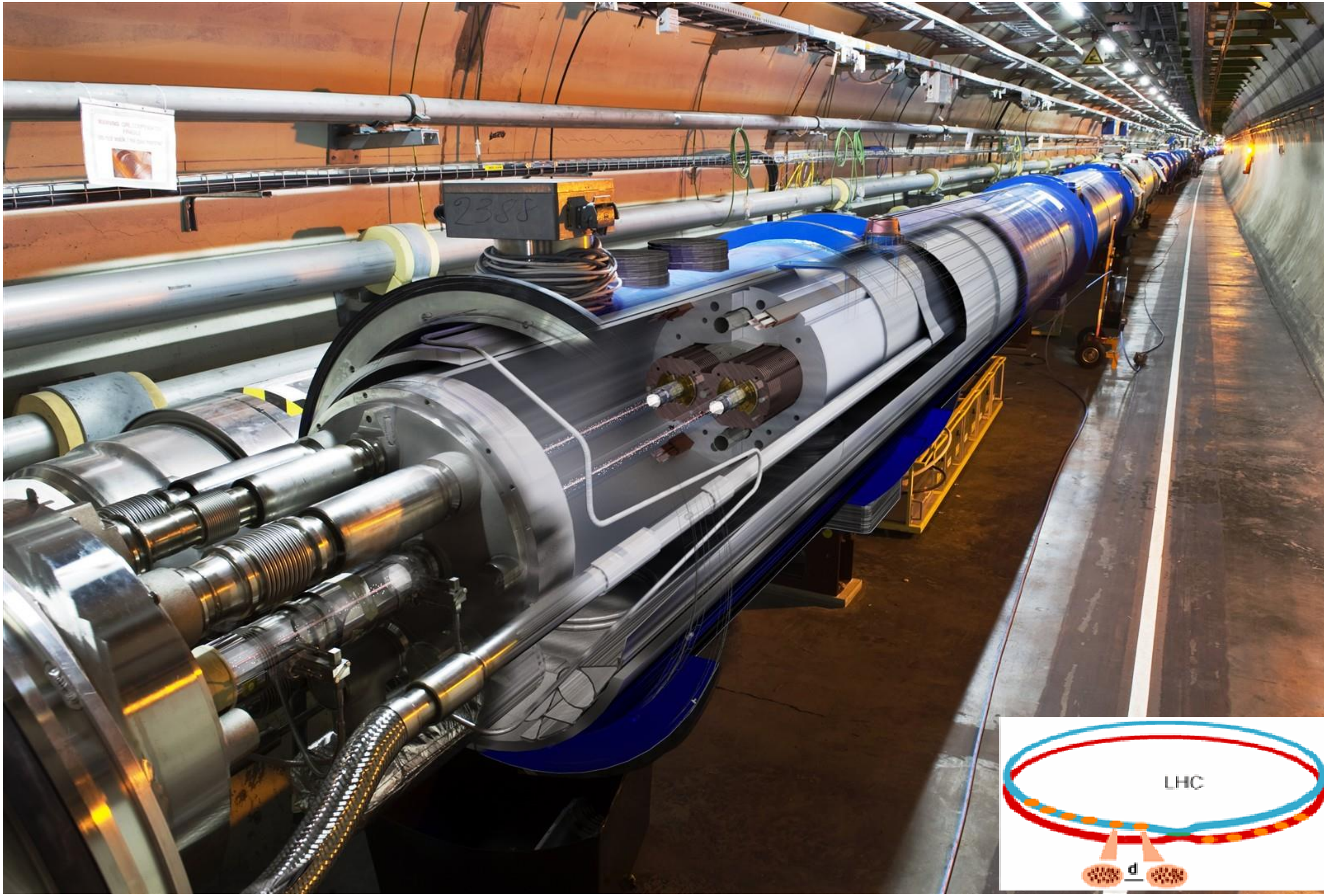


1200 superconducting magnets

11700 Ampere, 8.36 Tesla

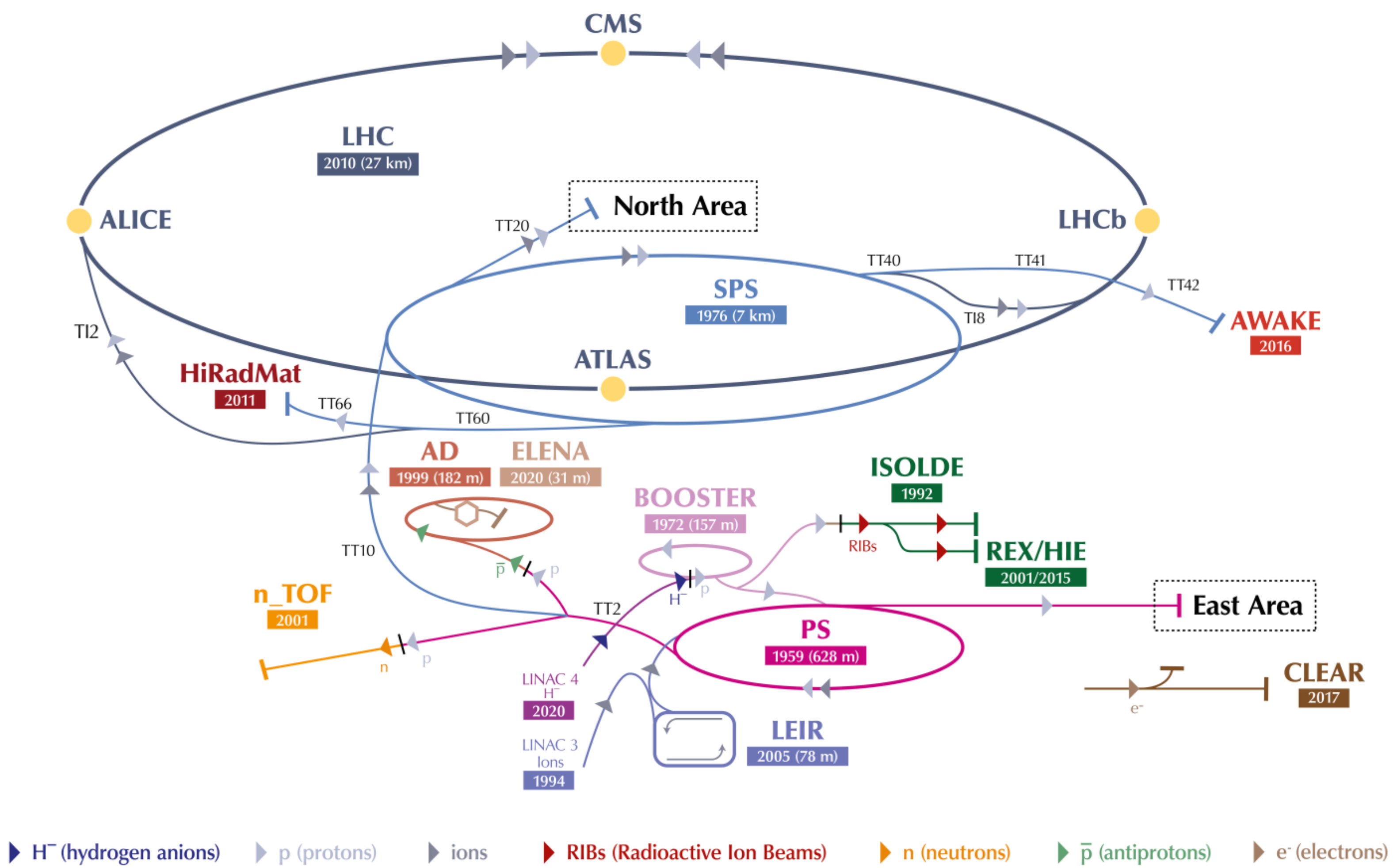


LHC: 27km of superconducting magnets

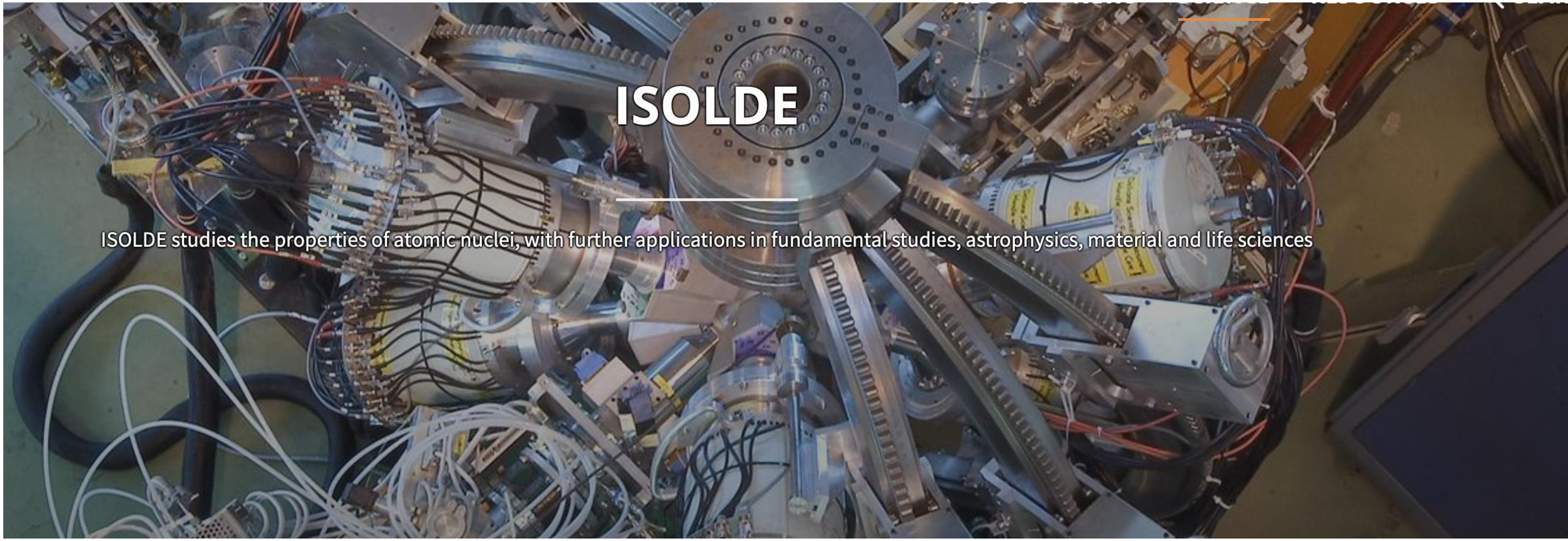


Cooling with suprafluid Helium (-271.5 ^{0}C i.e. 1.7K)

The CERN accelerator complex
Complexe des accélérateurs du CERN



LHC - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n_TOF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials



ISOLDE

ISOLDE studies the properties of atomic nuclei, with further applications in fundamental studies, astrophysics, material and life sciences

The Isotope mass Separator On-Line facility (ISOLDE) is a unique source of low-energy beams of radioactive nuclides, those with too many or too few neutrons to be stable. The facility fulfils in fact the old alchemical dream of changing one element into another. It permits the study of the vast territory of atomic nuclei, including the most exotic species.

The 1.4 GeV proton beam from the Proton Synchrotron Booster (PSB) is directed into specially developed thick targets, yielding a large variety of atomic fragments. Different devices are used to ionize, extract and separate nuclei according to their mass, forming a low-energy beam that is delivered to various experimental stations.

This beam can be further accelerated, allowing various nuclear reaction studies. A newer linear accelerator HIE-ISOLDE began construction in 2015, accelerated beams up to 4.5 MeV/nucleon by 2016 and then close to 10 MeV/nucleon when completed in 2018. HIE-ISOLDE beams are sent to three experimental stations: an array of high purity germanium detectors known as Miniball, the ISOLDE Solenoid Spectrometer, which uses a former MRI magnet and a third beam line where a large vacuum chamber is used for scattering experiments.

The ISOLDE facility has gathered unique expertise in research with radioactive beams. Over 1300 isotopes of more than 70 elements have been used in a wide range of research domains, from cutting edge nuclear structure studies, through atomic physics, nuclear astrophysics, fundamental interactions, to solid state and life sciences. Close to 1000 researchers are active at ISOLDE, working on about 90 experiments. About 50 experiments take data every year.

The Antiproton Decelerator

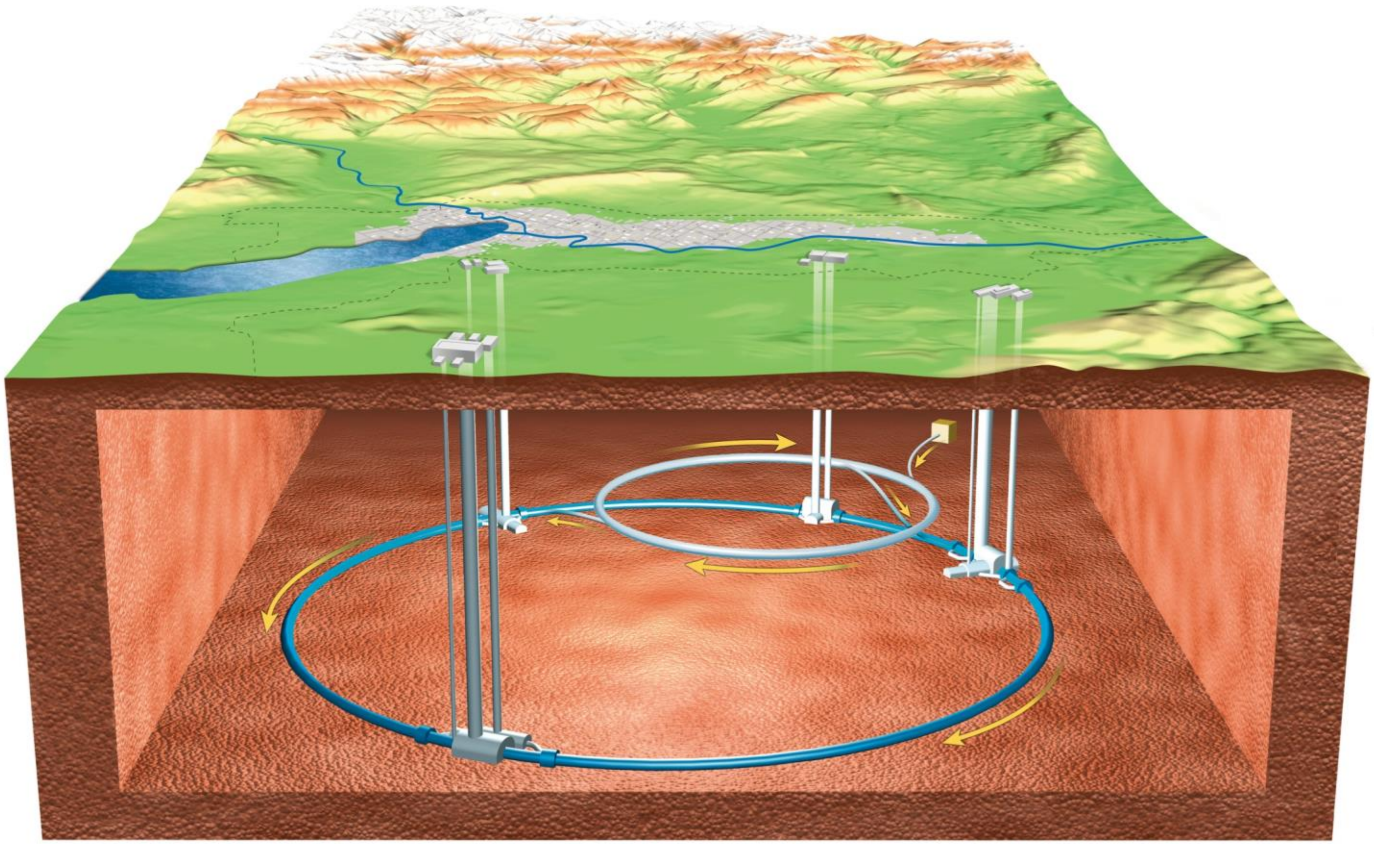
Not all accelerators increase a particle's speed. The AD slows down antiprotons so they can be used to study antimatter

The Antiproton Decelerator (AD) is a unique machine that produces low-energy antiprotons for studies of antimatter, and “creates” antiatoms.
A proton beam coming from the PS (Proton Synchrotron) is fired into a block of metal. These collisions create a multitude of secondary particles, including lots of antiprotons. These antiprotons have too much energy to be useful for making antiatoms. They also have different energies and move randomly in all directions. The job of the AD is to tame these unruly particles and turn them into a useful, low-energy beam that can be used to produce antimatter.
The antiprotons, which emerge from the block at diverging angles, are focused before they reach the AD. Only a fraction of them have the right energy to be injected into and stored in the AD.
The AD is a ring composed of bending and focussing magnets that keep the antiprotons on the same track, while strong electric fields slow them down. The spread in energy of the antiprotons and their deviation from their track is reduced by a technique known as “cooling”. Antiprotons are subjected to several cycles of cooling and deceleration until they are slowed down to around a tenth of the speed of light.
A newer deceleration ring, ELENA (Extra Low ENergy Antiproton), is now coupled with the AD. This synchrotron, with a circumference of 30 metres, slows the antiprotons even more, reducing their energy by a factor of 50, from 5.3 MeV to just 0.1 MeV. An electron cooling system also increases the beam density. With ELENA, the number of antiprotons that can be trapped increases by a factor of 10 to 100, improving the efficiency of the experiments and paving the way for new experiments.
Installed in 2000, the AD made the headlines in 2002 when large numbers of antihydrogen atoms were produced for the first time. Initial attempts were made to store antiatoms for a long enough time to be able to measure their characteristics. In 2011, an experiment announced that it had produced and trapped antihydrogen atoms for sixteen minutes, which was long enough to be able to study their properties in detail. The following year, the first measurement of the antihydrogen spectrum was published. Since 2010, the AD experiments have published numerous measurements of antimatter characteristics, comparing them to those of matter.
Currently the AD and ELENA serve several experiments that are studying antimatter and its properties: AEgIS, ALPHA, ASACUSA, BASE and GBAR.
Whereas ATRAP and ACEhave now completed their experiments.

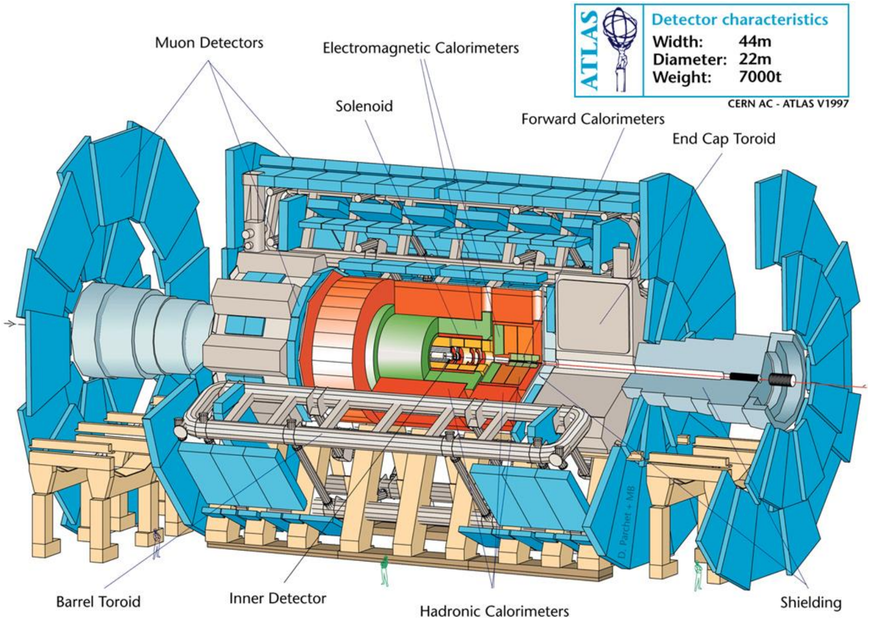
LHC Experiments/Detectors

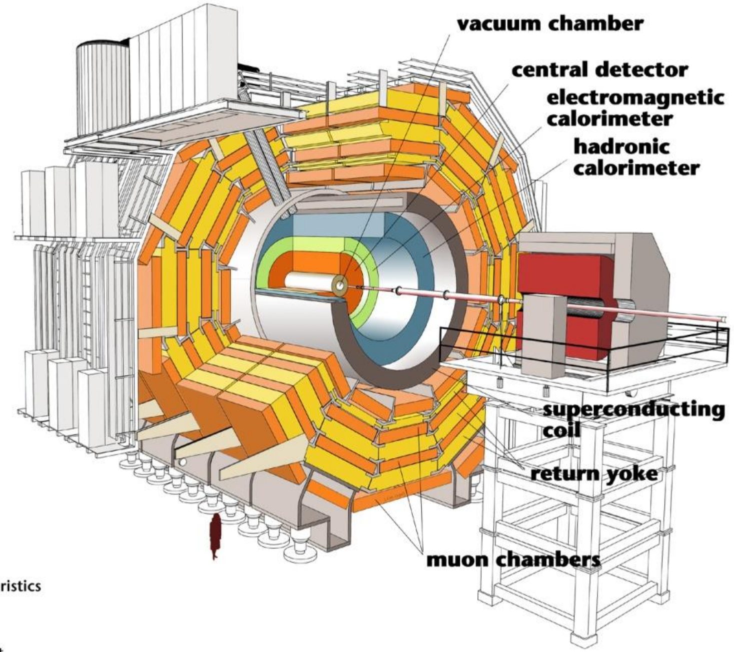
At the 4 collision points around the ring there are particle detectors that are measuring the recording the collisions.

The ‘experiment’ consists in colliding many protons (10^9/s) over a very long time to find very rare events – e.g. the Higgs particle.



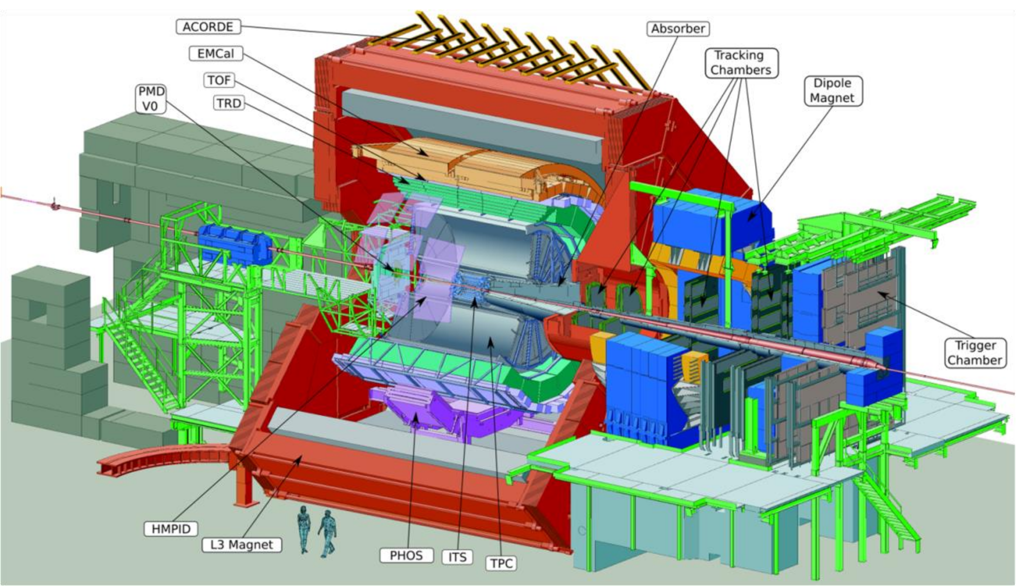
ATLAS, CMS, ALICE, LHCb

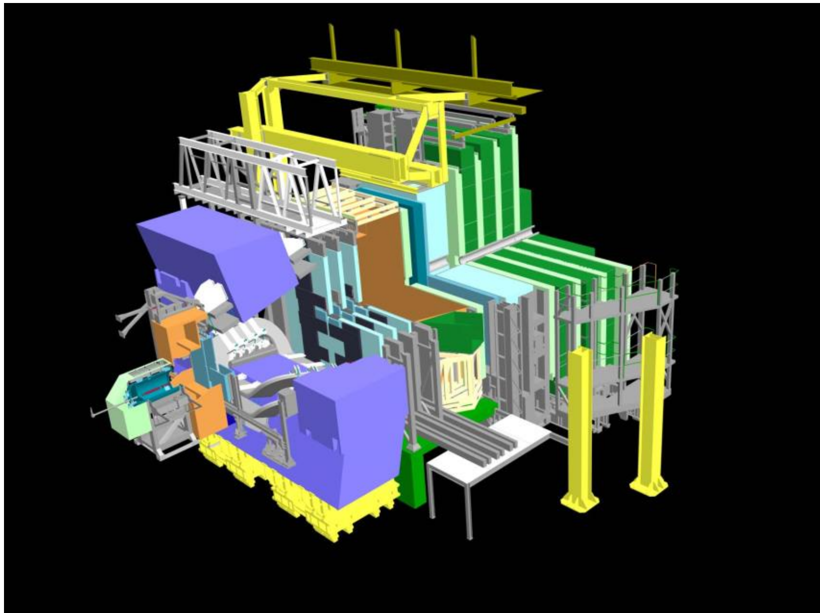




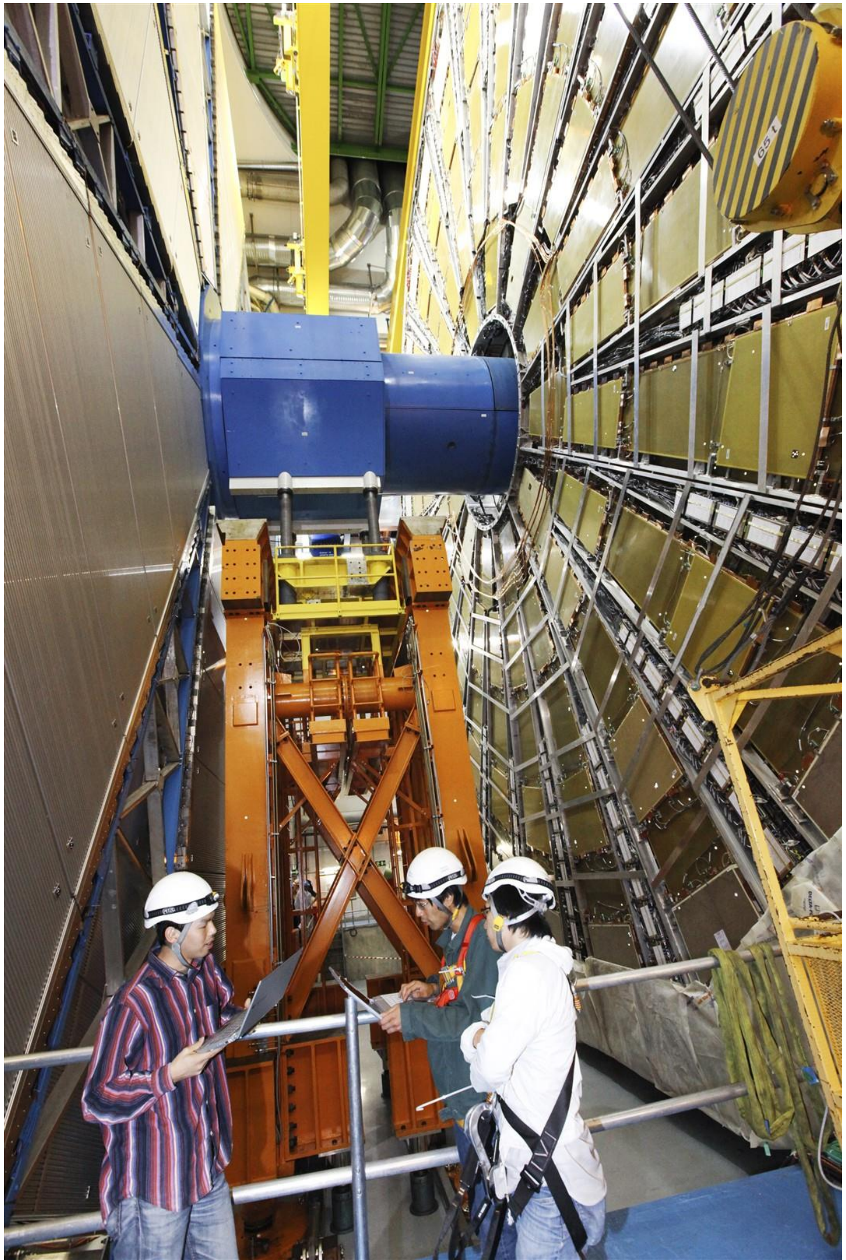
Detector characteristics

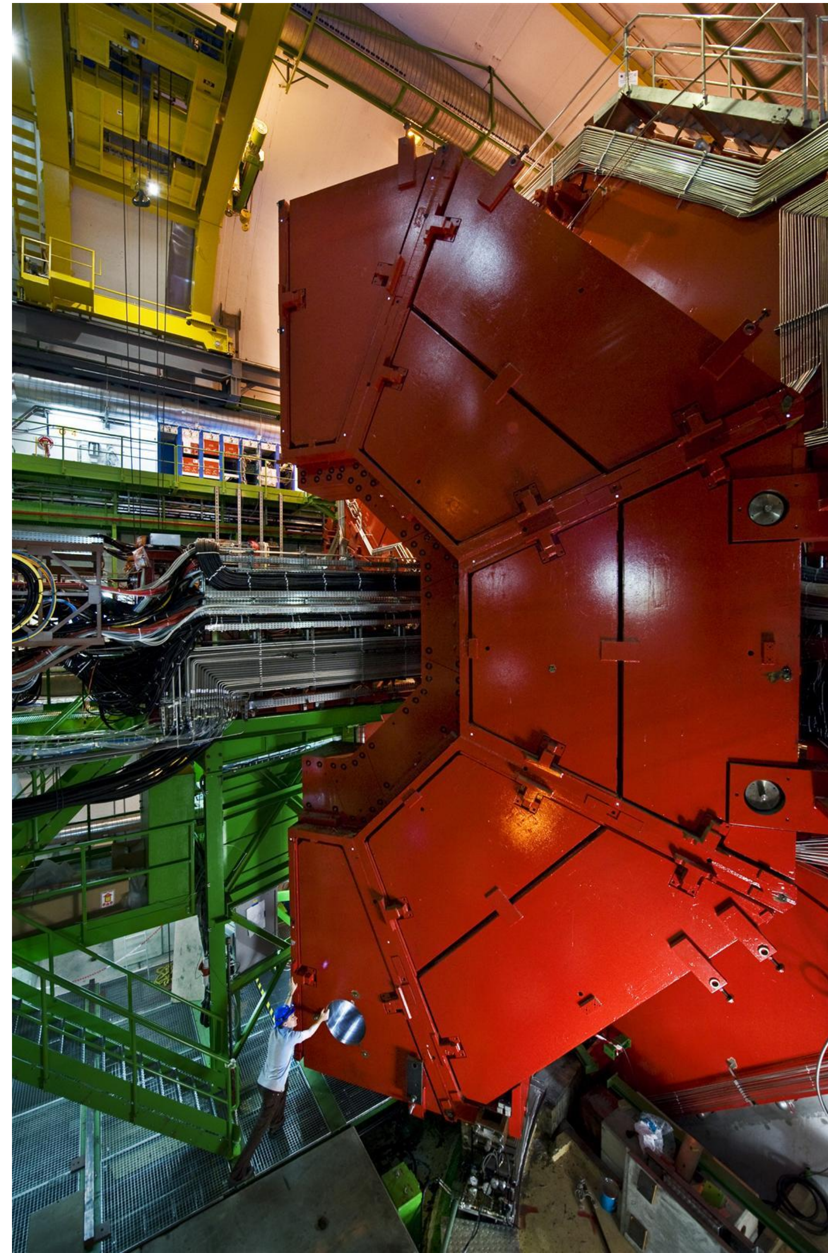
Width: 22m
Diameter: 15m
Weight: 14'500t



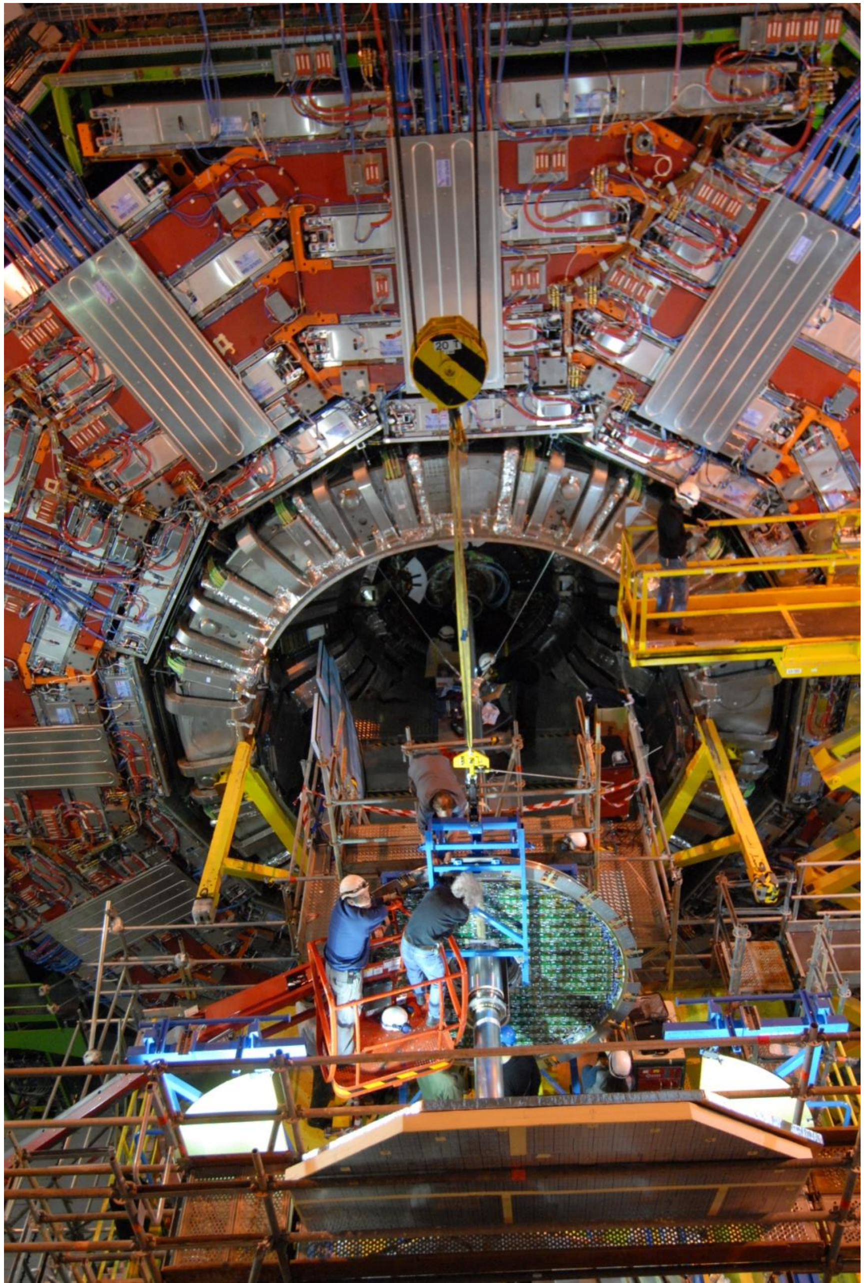


ATLAS, ALICE

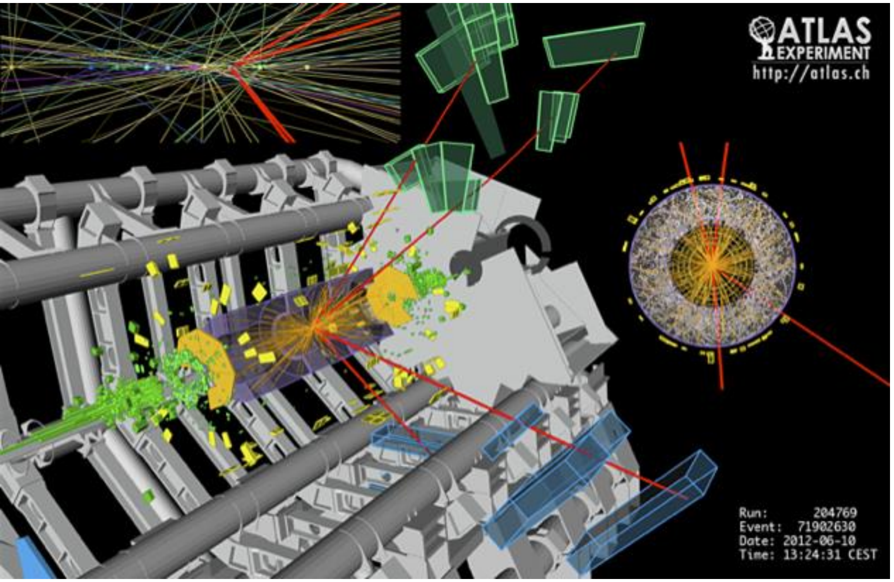


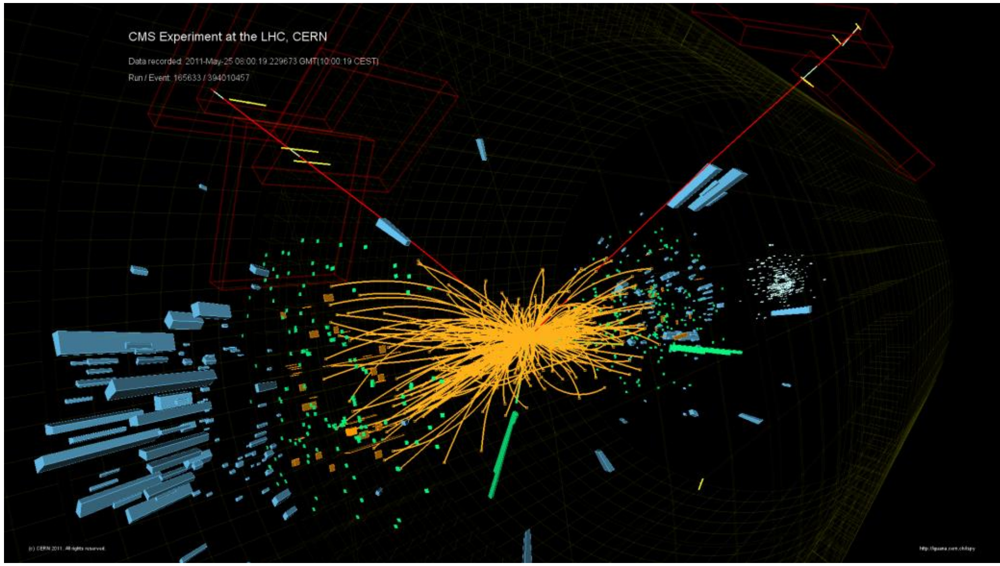


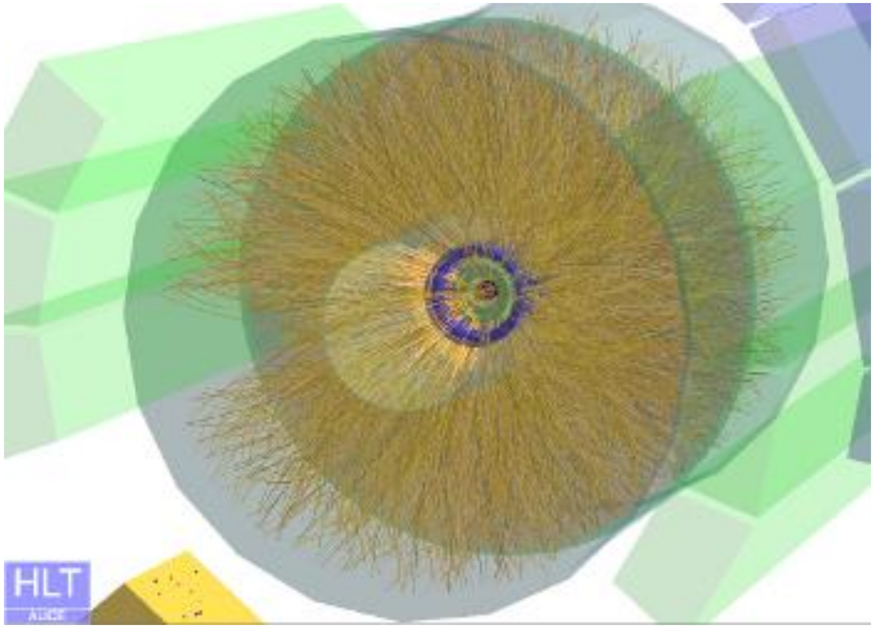
CMS, LHCb



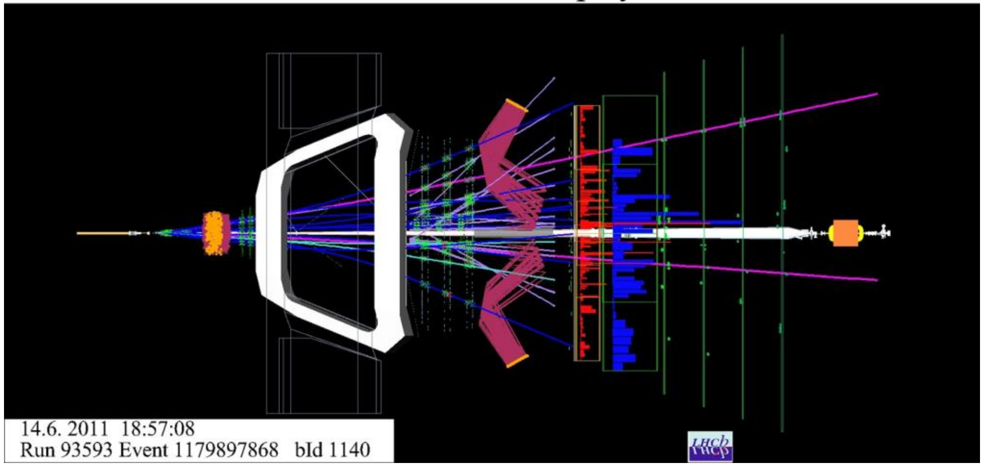
ATLAS, CMS, ALICE, LHCb







LHCb Event Display



Data of the LHC experiments

1 billion collisions per second

10 000 000 billion collisions/year.

Among these ca. 10 000 particles Higgs particles

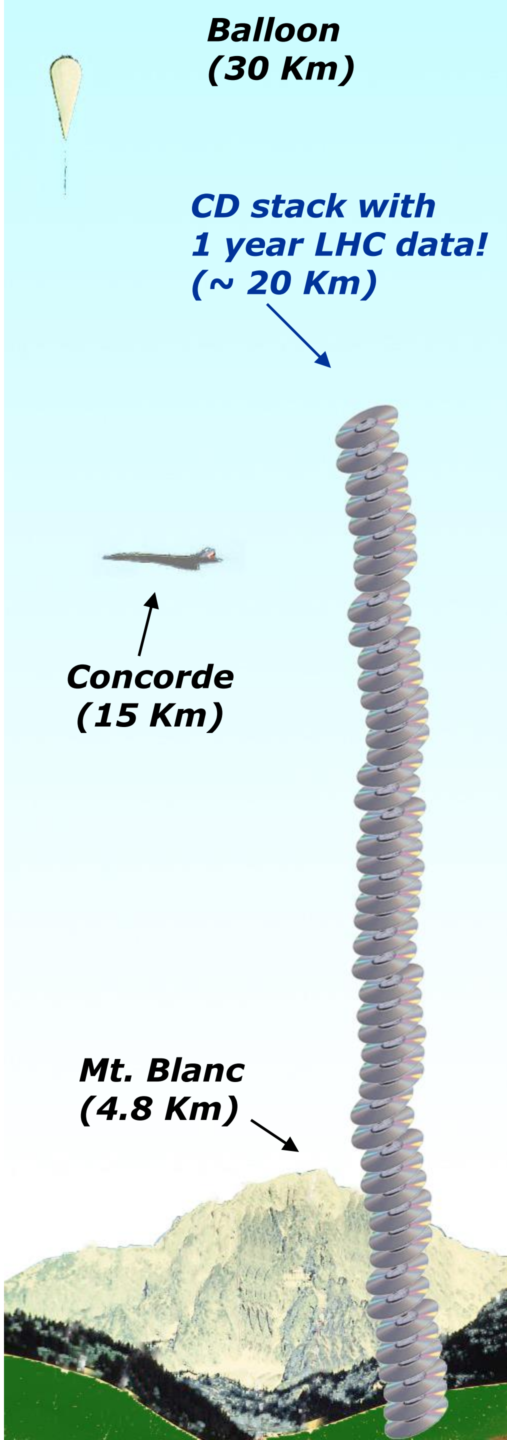
After on-line filtering around 100-1000 interesting collisions/s recorded.

10 MegaByte of digitised data/s:1-10 Gigabyte/sec recording rate

1-10 billion collisions/year recorded.

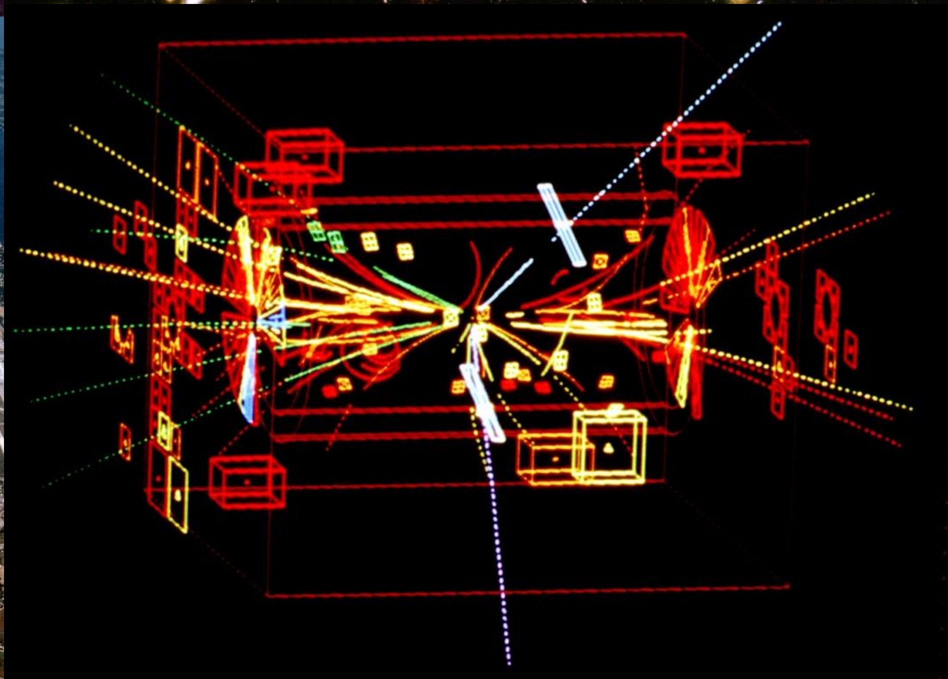
10-100 Petabyte/year

LHC computing GRID: Further development of the WWW



Particle Physics, the Structure of Matter



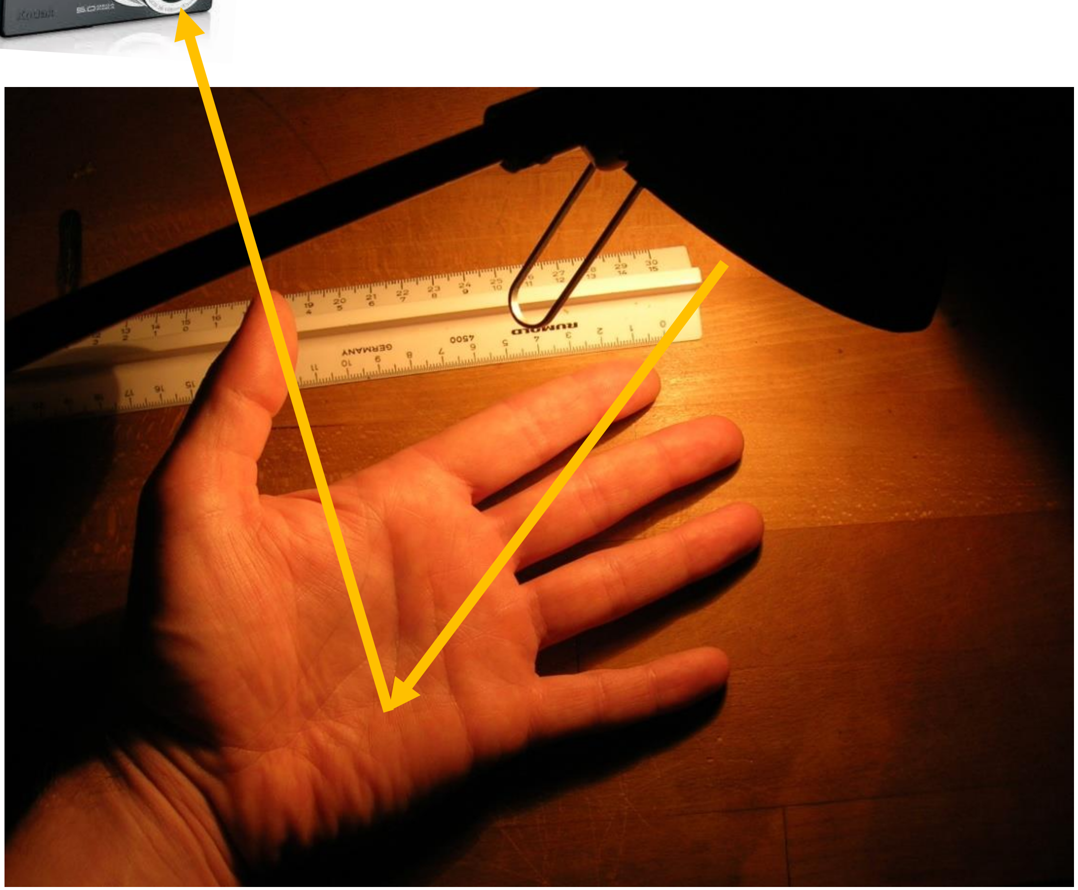
What are the fundamental building blocks of Nature ?

What are the laws of Physics that govern the interaction of these elementary building blocks ?

Why do we need these giant accelerators …

… to find the smallest constituents of matter ?

A Photon Scattering Experiment



A digital image of my hand.

Light is reflected by the hand in different ways which reveals the structure of the hand to the camera – or the eye.

With a microscope one can resolve smaller details, but there is a fundamental limit !

One cannot resolve structures smaller than the wavelength of the light !

Visible light ~ 1 micrometer = 0.001mm ~ the size of a bacterium

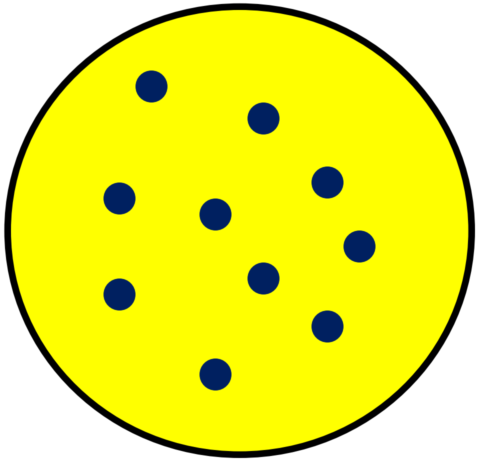
The Birth of Particle Physics

In 1899 J.J. Thomson discovered the electron and formulated the following model of atoms:

An atom is a sphere of positive charge in which the electrons are embedded.

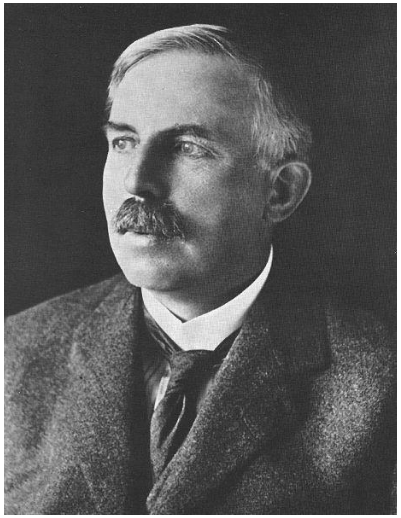
The size of the atoms is around 10^{-10} meters.

J.J. Thomson



How to look at it ?

The Structure of the Atom

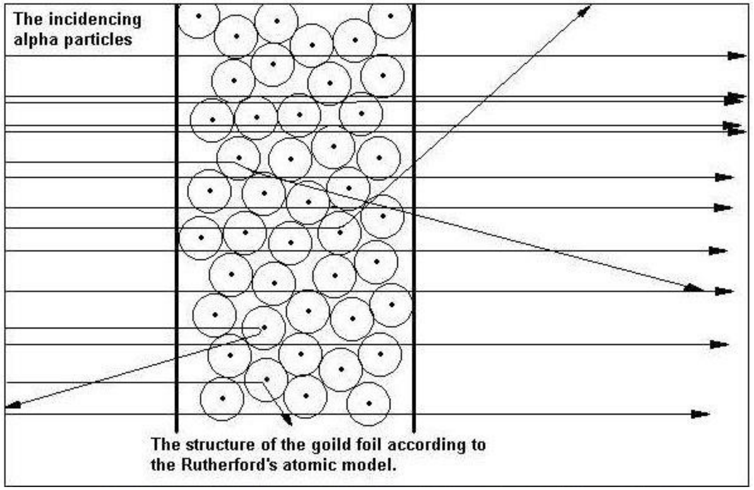


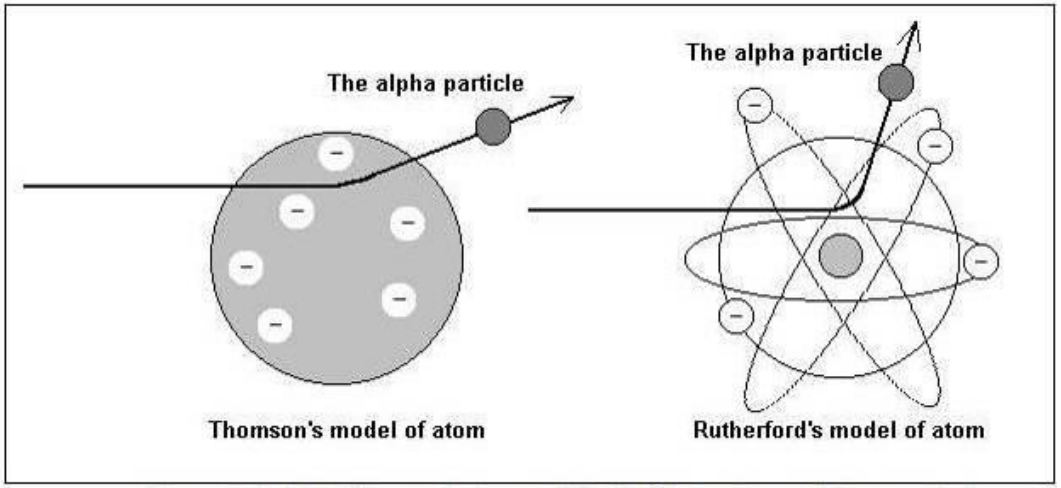
Ernest Rutherford

Rutherford (1911):

Bombarded material with high energy α-particles.

From the scattering pattern of the α-particles he was able to tell the structure of the atom !

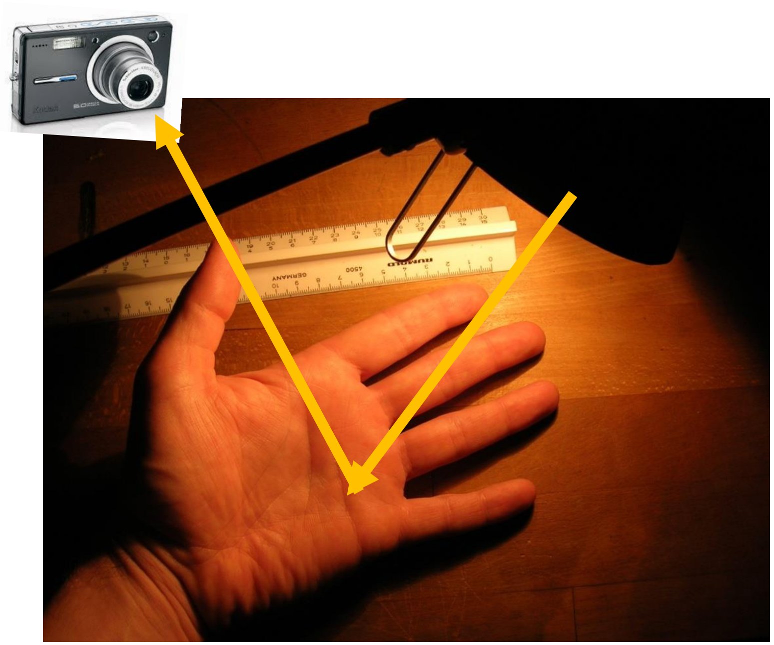




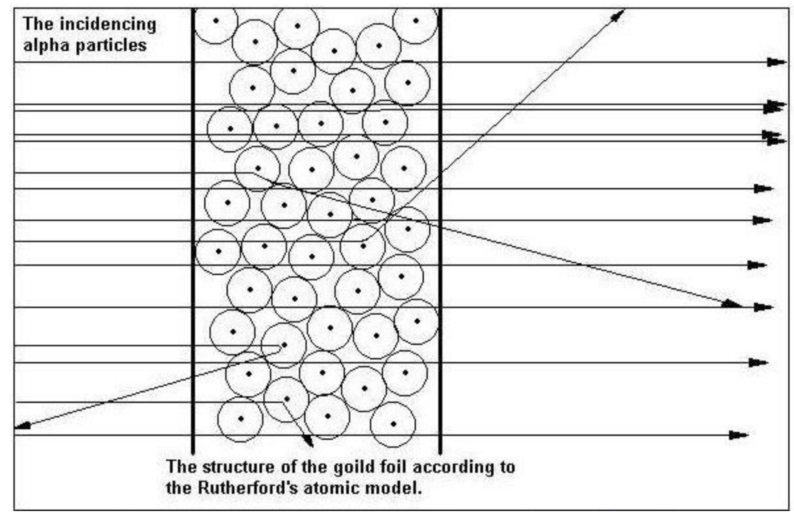
Atoms (10^{-10} m) consist of an extremely small Nucleus (10^{-15} m), around which the electrons are moving.

How can we see the Structure of Atoms ?

Pattern of the scattered light → structure of the hand.



Pattern of scattered high energy particles → structure of the atom.



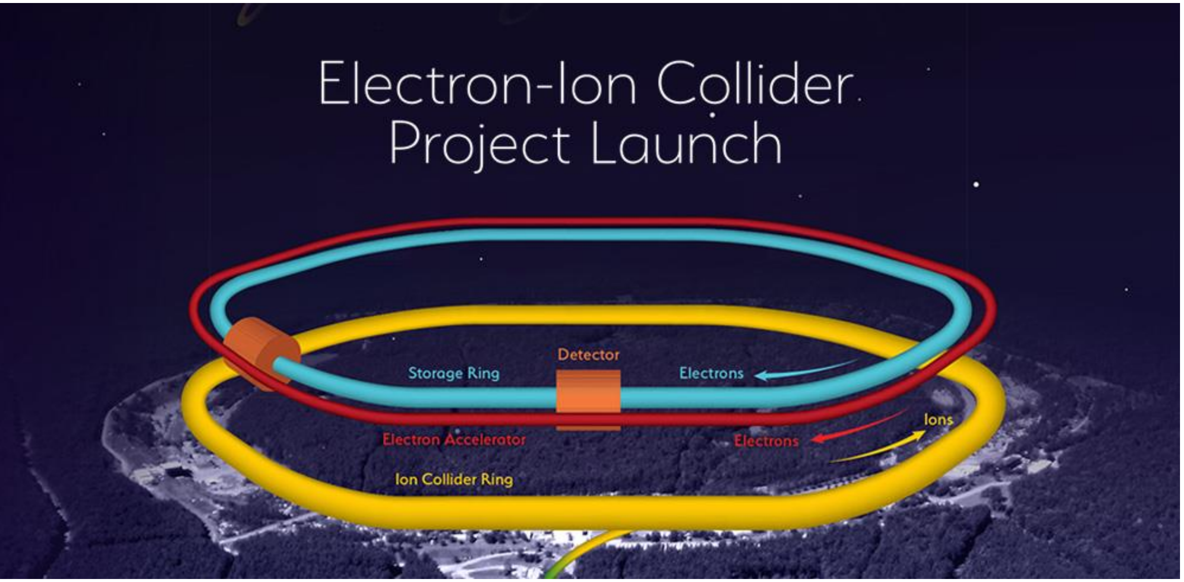
With the particle wave dualism of quantum mechanics the energy (momentum) of a particle is related to it's wavelength ($\lambda=h/p$).

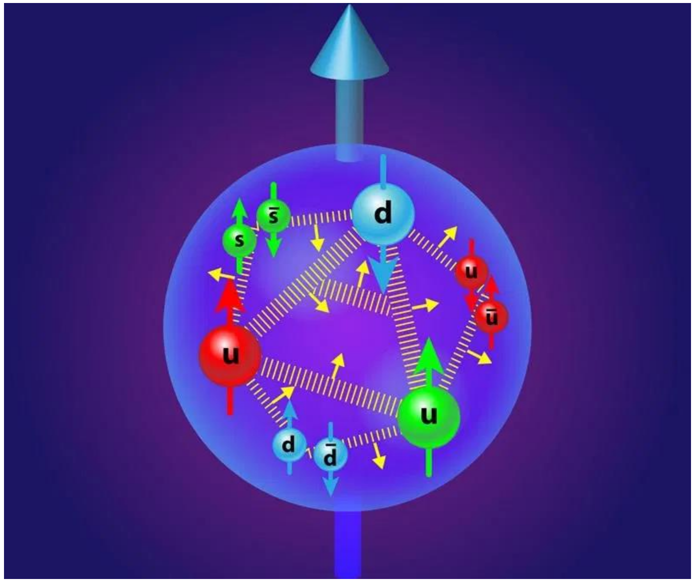
Higher particle energy → smaller wavelength → smaller structures

→ Accelerators are Super-Microscopes !

Today – dedicated research facilities for 'deep inelastic scattering' of electrons on protons (collider) to understand proton parton structure etc.

BNL (Brookhaven, US)

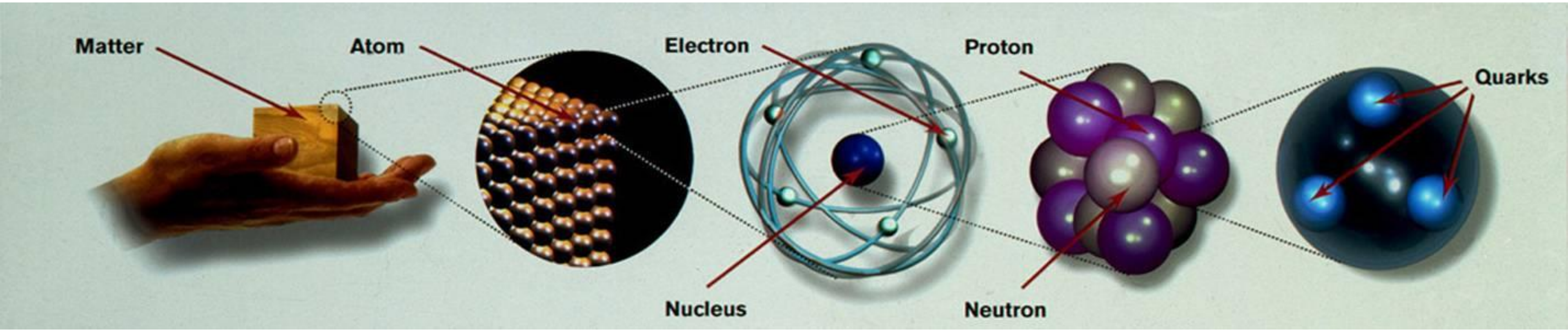




The fundamental Building Blocks of Matter ?

Optical Microscope: 10^{-6} m
Radioactive Source: 10^{-14} m
LHC: $<10^{-21}$ m

1900 **1911** **1932** **1967**



Quantenmechanik + Relativitätstheorie

$$i\hbar\frac{\partial}{\partial t}\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi$$

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$E = mc^2$$

Quantenmechanik + Relativitaetstheorie = Quantenfeldtheorie → Elementarteilchen

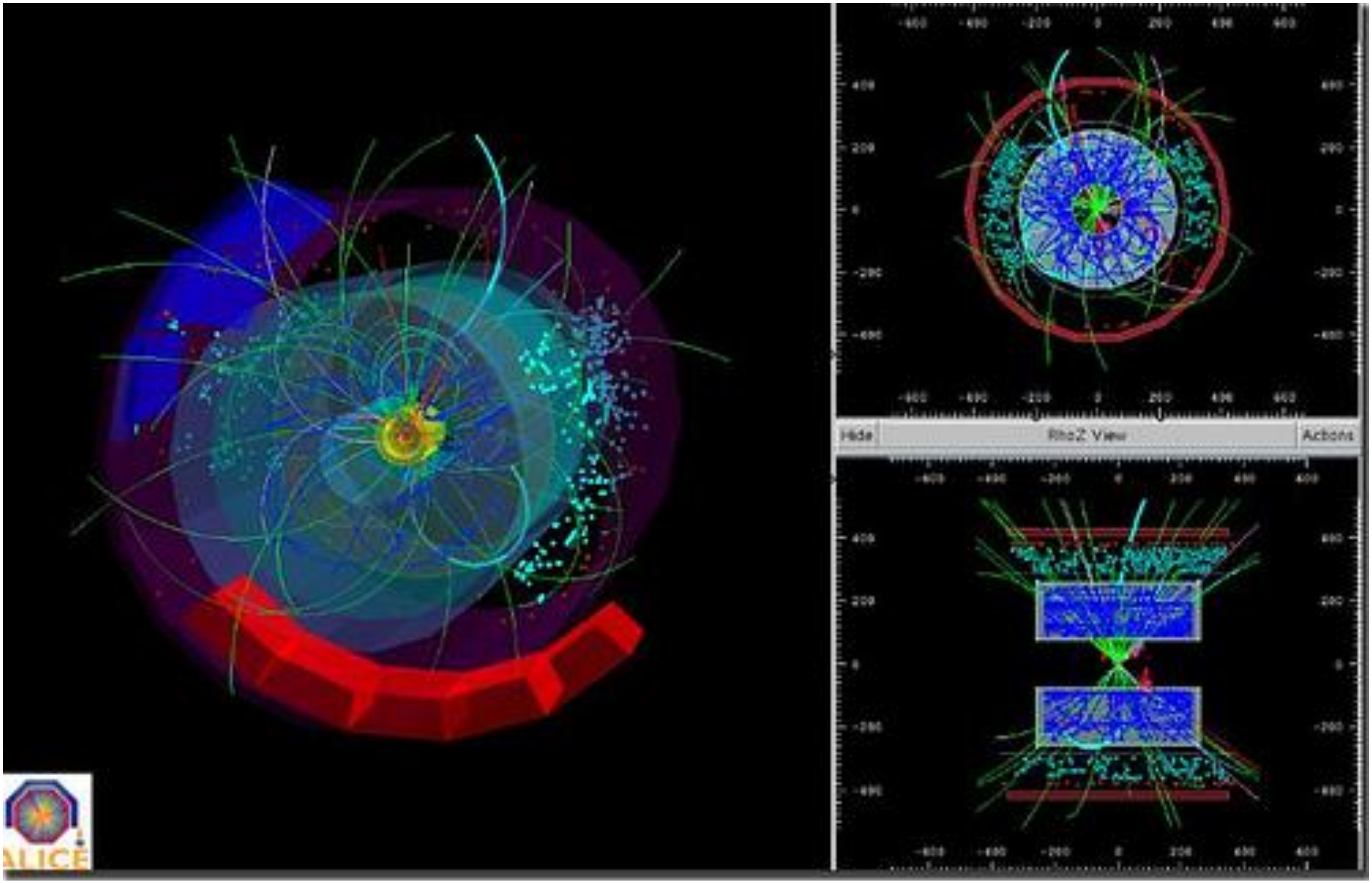
The creation of new particles is a consequence of the combination of quantum mechanics and relativity.

The investigation of the structure of matter i.e. the attempt to measure small distances and scales, is inevitably connected with the creation of new particles.

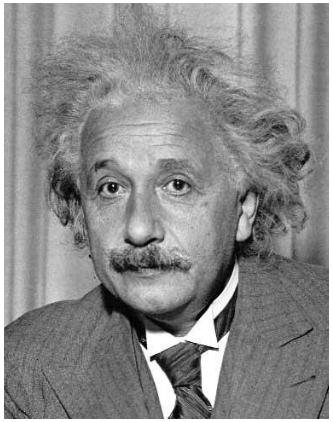
The higher the energy, the smaller the structures that can be resolved, the larger the masses of particles that can be produced.

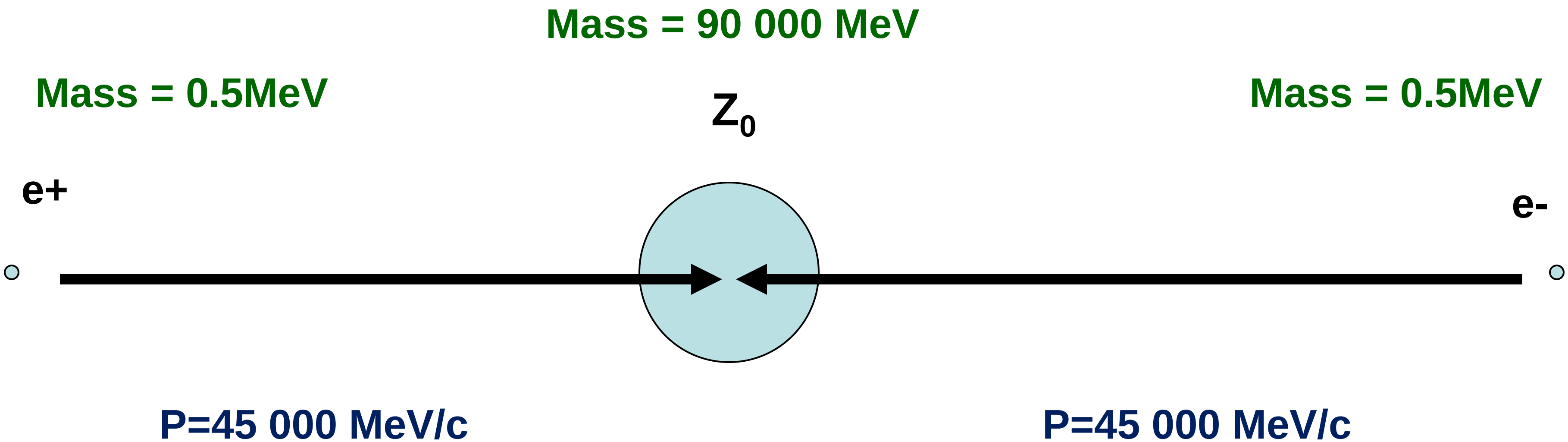
$$\Delta x \Delta p \geq \frac{\hbar}{2} \qquad E = mc^2$$

Proton-Proton Kollision in ALICE



$E=mc^2$



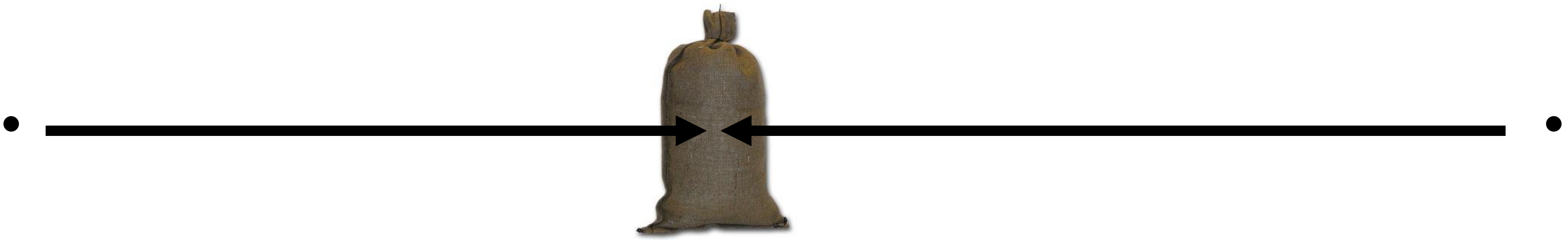

Mass = 90 000 MeV
Mass = 0.5MeV
Z0
Mass = 0.5MeV
e+
e-
P=45 000 MeV/c
P=45 000 MeV/c

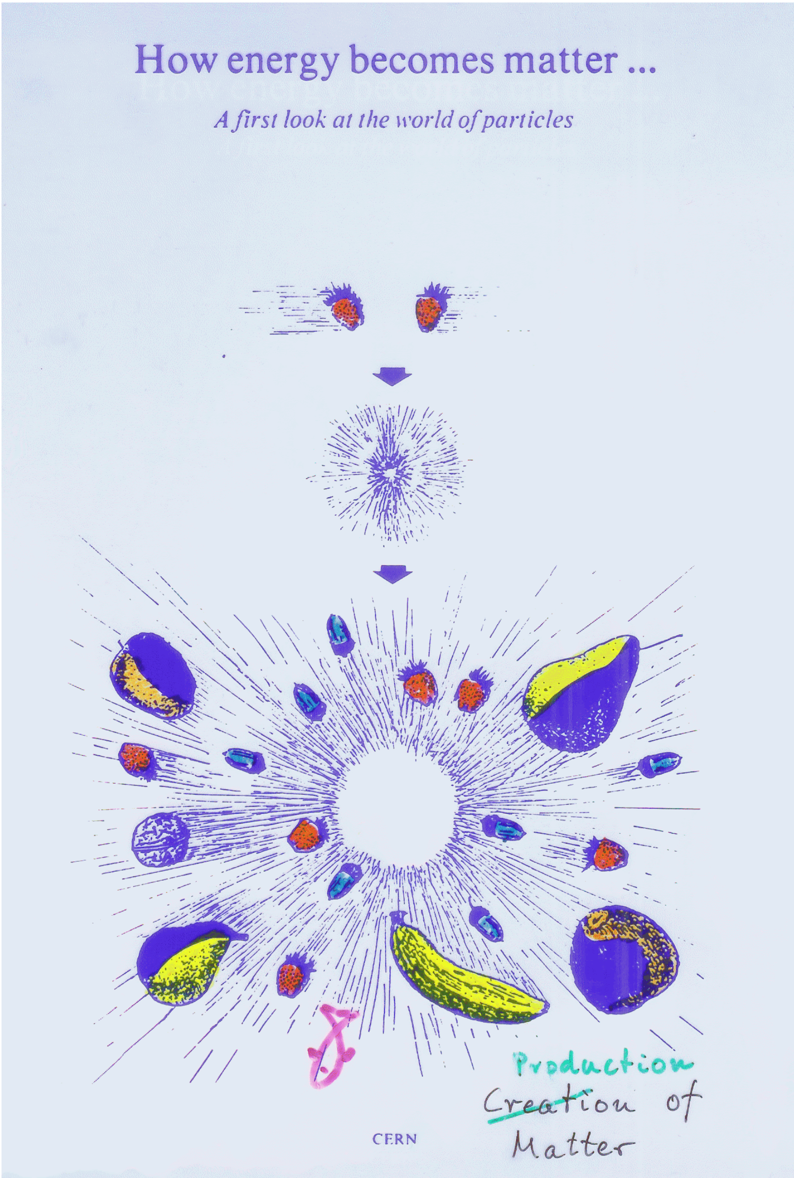
$E=mc^2$

Mass = 90 kg

Mass = 0.5g

Mass = 0.5g



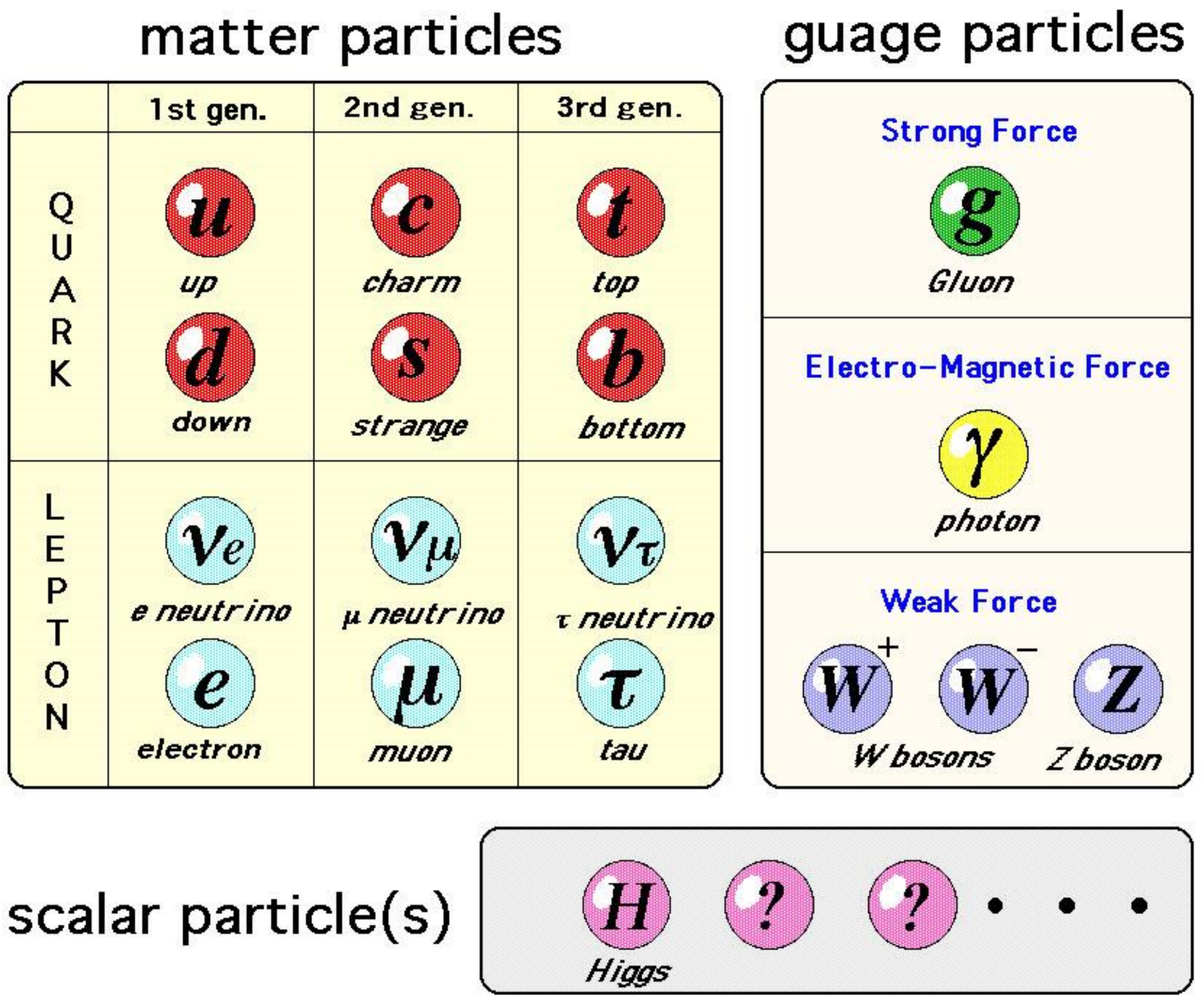

How energy becomes matter ...
A first look at the world of particles
Production
Creation of
Matter
CERN

http://pdg.lbl.gov ~ **180 Selected Particles**

γ, $W^{\pm}$, Z^0, g, e, μ, τ, ν_e, ν_μ, ν_τ, $\pi^{\pm}$, π^0, η, $f_0(600)$, $\rho(770)$,
$\omega(782)$, $\eta'(958)$, $f_0(980)$, $a_0(980)$, $\phi(1020)$, $h_1(1170)$, $b_1(1235)$,
$a_1(1260)$, $f_2(1270)$, $f_1(1285)$, $\eta(1295)$, $\pi(1300)$, $a_2(1320)$,
$f_0(1370)$, $f_1(1420)$, $\omega(1420)$, $\eta(1440)$, $a_0(1450)$, $\rho(1450)$,
$f_0(1500)$, $f_2'(1525)$, $\omega(1650)$, $\omega_3(1670)$, $\pi_2(1670)$, $\phi(1680)$,
$\rho_3(1690)$, $\rho(1700)$, $f_0(1710)$, $\pi(1800)$, $\phi_3(1850)$, $f_2(2010)$,
$a_4(2040)$, $f_4(2050)$, $f_2(2300)$, $f_2(2340)$, $K^{\pm}$, K^0, K^0_S, K^0_L, $K^*(892)$,
$K_1(1270)$, $K_1(1400)$, $K^*(1410)$, $K_0^*(1430)$, $K_2^*(1430)$, $K^*(1680)$,
$K_2(1770)$, $K_3^*(1780)$, $K_2(1820)$, $K_4^*(2045)$, $D^{\pm}$, D^0, $D^*(2007)^0$,
$D^*(2010)^{\pm}$, $D_1(2420)^0$, $D_2^*(2460)^0$, $D_2^*(2460)^{\pm}$, $D_s^{\pm}$, $D_s^{*\pm}$,
$D_{s1}(2536)^{\pm}$, $D_{sJ}(2573)^{\pm}$, $B^{\pm}$, B^0, B^*, B_s^0, $B_c^{\pm}$, $\eta_c(1S)$, $J/\psi(1S)$,
$\chi_{c0}(1P)$, $\chi_{c1}(1P)$, $\chi_{c2}(1P)$, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$,
$\psi(4415)$, $\Upsilon(1S)$, $\chi_{b0}(1P)$, $\chi_{b1}(1P)$, $\chi_{b2}(1P)$, $\Upsilon(2S)$, $\chi_{b0}(2P)$,
$\chi_{b2}(2P)$, $\Upsilon(3S)$, $\Upsilon(4S)$, $\Upsilon(10860)$, $\Upsilon(11020)$, p, n, $N(1440)$,
$N(1520)$, $N(1535)$, $N(1650)$, $N(1675)$, $N(1680)$, $N(1700)$, $N(1710)$,
$N(1720)$, $N(2190)$, $N(2220)$, $N(2250)$, $N(2600)$, $\Delta(1232)$, $\Delta(1600)$,
$\Delta(1620)$, $\Delta(1700)$, $\Delta(1905)$, $\Delta(1910)$, $\Delta(1920)$, $\Delta(1930)$, $\Delta(1950)$,
$\Delta(2420)$, Λ, $\Lambda(1405)$, $\Lambda(1520)$, $\Lambda(1600)$, $\Lambda(1670)$, $\Lambda(1690)$,
$\Lambda(1800)$, $\Lambda(1810)$, $\Lambda(1820)$, $\Lambda(1830)$, $\Lambda(1890)$, $\Lambda(2100)$,
$\Lambda(2110)$, $\Lambda(2350)$, Σ^+, Σ^0, Σ^-, $\Sigma(1385)$, $\Sigma(1660)$, $\Sigma(1670)$,
$\Sigma(1750)$, $\Sigma(1775)$, $\Sigma(1915)$, $\Sigma(1940)$, $\Sigma(2030)$, $\Sigma(2250)$, Ξ^0, Ξ^-,
$\Xi(1530)$, $\Xi(1690)$, $\Xi(1820)$, $\Xi(1950)$, $\Xi(2030)$, Ω^-, $\Omega(2250)^-$,
Λ_c^+, Λ_c^+, $\Sigma_c(2455)$, $\Sigma_c(2520)$, Ξ_c^+, Ξ_c^0, $\Xi_c'^+$, $\Xi_c'^0$, $\Xi(2645)$
$\Xi_c(2790)$, $\Xi_c(2815)$, Ω_c^0, Λ_b^0, Ξ_b^0, Ξ_b^-, $t\bar{t}$

There are many more

The ‘Standard Model’



The Standard Model of Particle Physics

$$\mathcal{L}_{SM} = \underbrace{\frac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a}_{\text{kinetic energies and self-interactions of the gauge bosons}}$$

$$+ \underbrace{\bar{L}\gamma^\mu\left(i\partial_\mu - \frac{1}{2}g\tau\cdot\mathbf{W}_\mu - \frac{1}{2}g'YB_\mu\right)L + \bar{R}\gamma^\mu\left(i\partial_\mu - \frac{1}{2}g'YB_\mu\right)R}_{\text{kinetic energies and electroweak interactions of fermions}}$$

$$+ \underbrace{\frac{1}{2}\left|\left(i\partial_\mu - \frac{1}{2}g\tau\cdot\mathbf{W}_\mu - \frac{1}{2}g'YB_\mu\right)\phi\right|^2 - V(\phi)}_{W^\pm, Z, \gamma \text{ and Higgs masses and couplings}}$$

$$+ \underbrace{g''(\bar{q}\gamma^\mu T_a q)G^a_\mu}_{\text{interactions between quarks and gluons}} + \underbrace{(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)}_{\text{fermion masses and couplings to Higgs}}$$

$$U(1) \times SU(2) \times SU(3)$$

1 hypercharge

2 left-handed isospin charges

3 colour charges

Higgs Particle

Within the standard model, the properties of the Higgs particle are specified in detail for a given (previously unknown) mass

1983: First LHC concepts

1990: First detector concepts

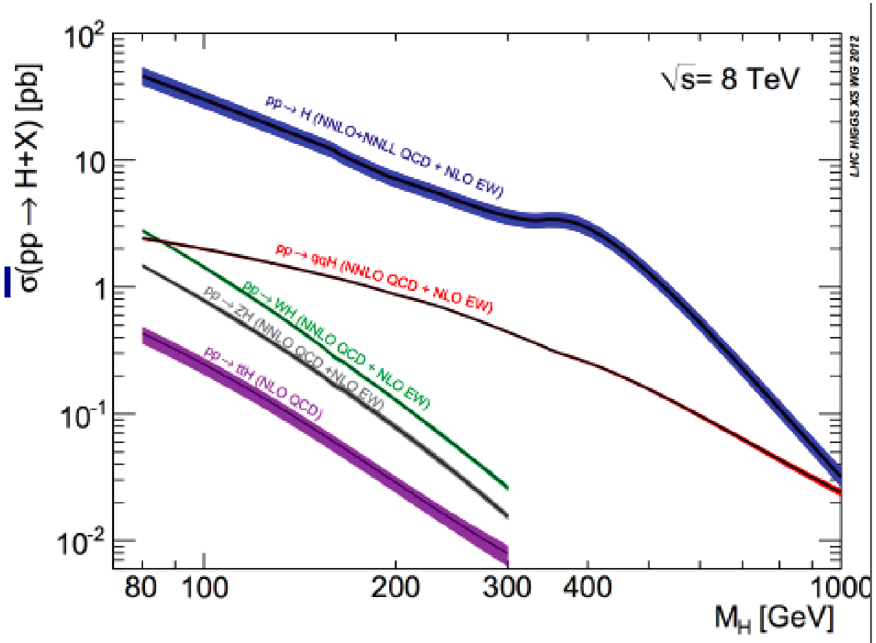
2009 Start of LHC experiments

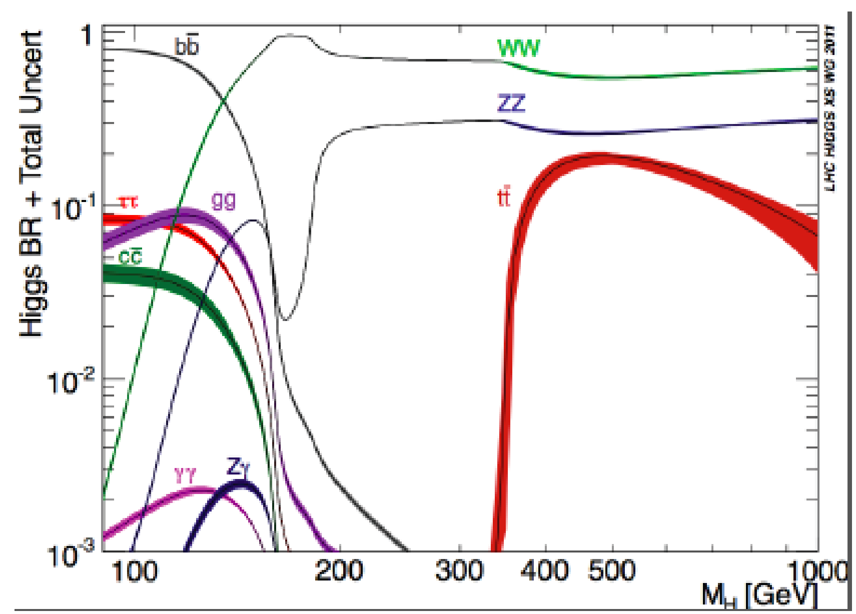
Dec. 2011: First hints that Higgs exists

July 4 2012: official announcement of Higss discovery

February 2013: Higgs Boson significant in several decay channels.

Today: Higgs precision measurements





July 4th 2012

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

ARTICLE INFO

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ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

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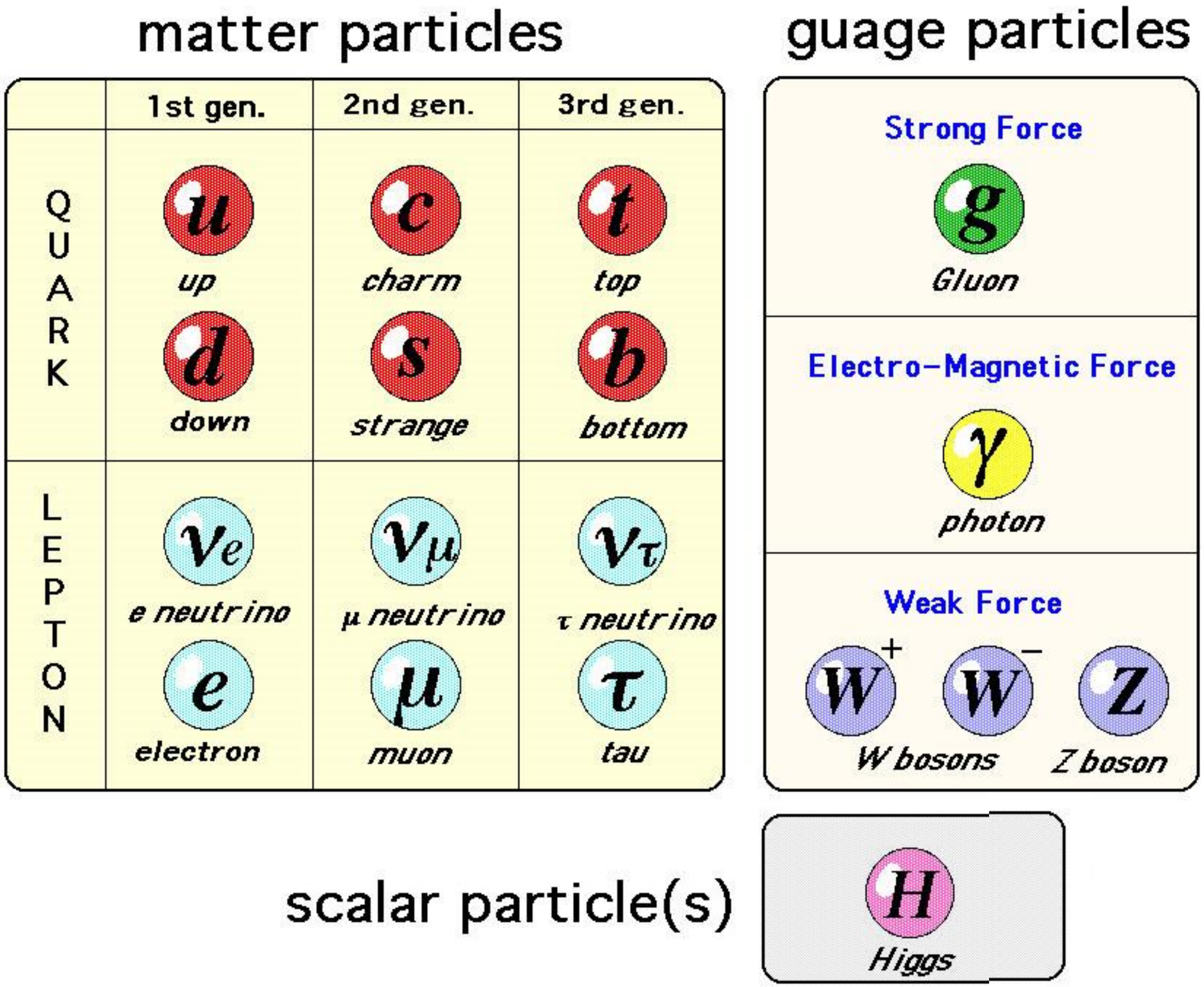
ABSTRACT

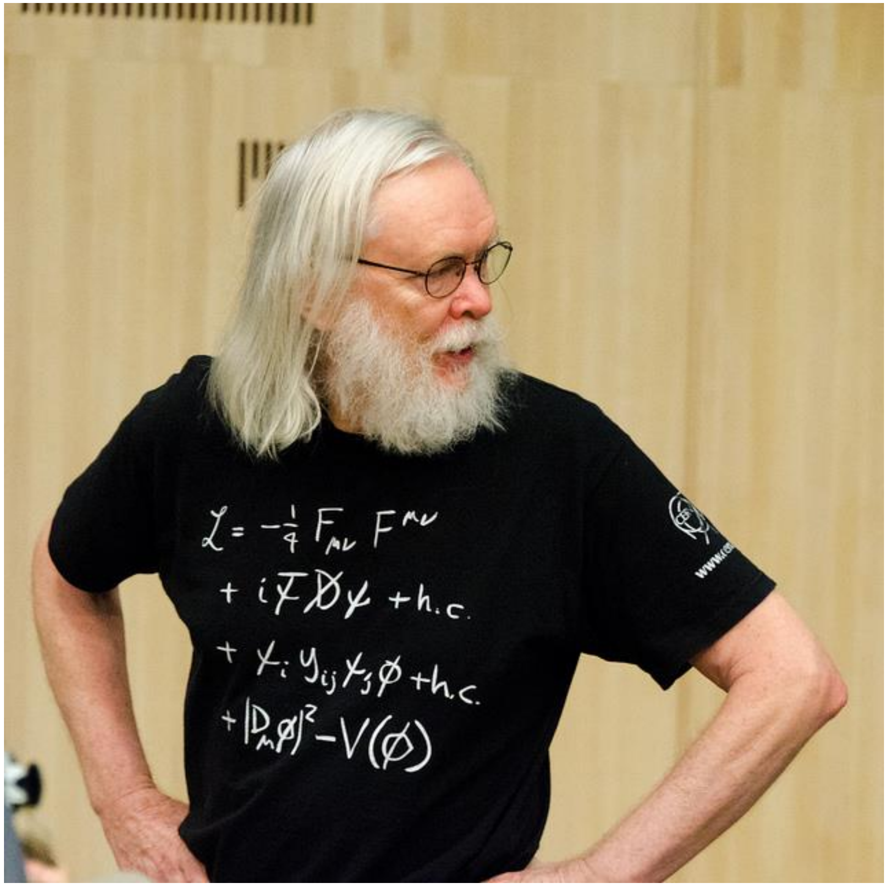
Results are presented from searches for the standard model Higgs boson in proton–proton collisions at $\sqrt{s} = 7$ and 8 TeV in the Compact Muon Solenoid experiment at the LHC, using data samples corresponding to integrated luminosities of up to 5.1 fb^{-1} at 7 TeV and 5.3 fb^{-1} at 8 TeV. The search is performed in five decay modes: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, and $b\bar{b}$. An excess of events is observed above the expected background, with a local significance of 5.0 standard deviations, at a mass near 125 GeV, signalling the production of a new particle. The expected significance for a standard model Higgs boson of that mass is 5.8 standard deviations. The excess is most significant in the two decay modes with the best mass resolution, $\gamma\gamma$ and ZZ; a fit to these signals gives a mass of 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV. The decay to two photons indicates that the new particle is a boson with spin different from one.

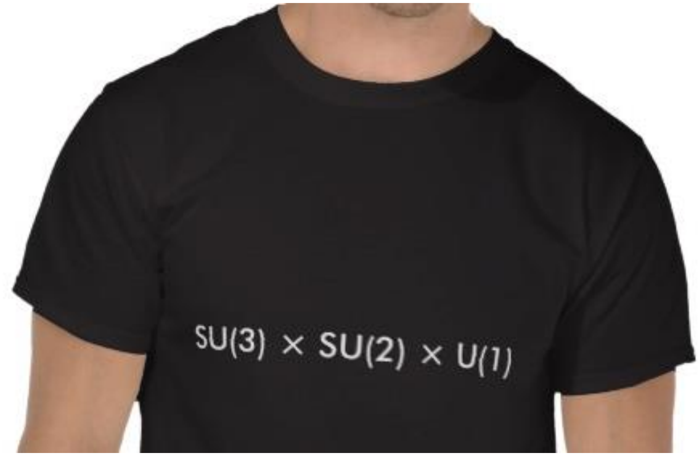
Standard Model

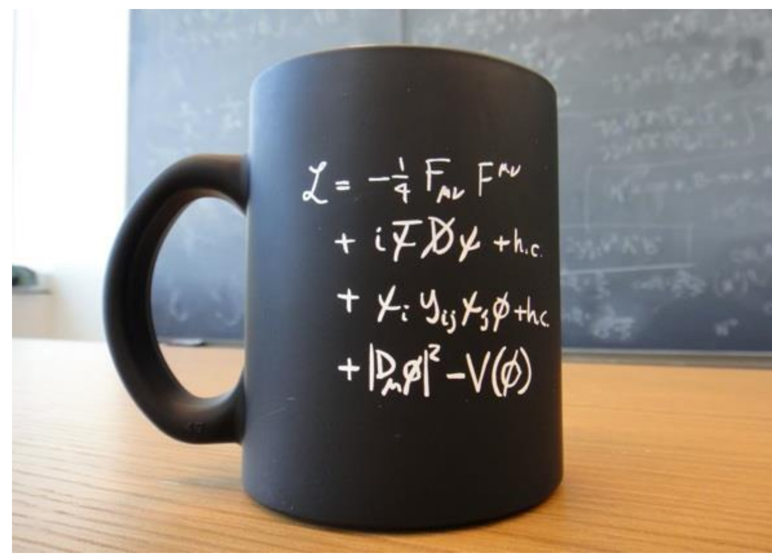
The Higgs particle exists and confirms the Standard Model of Particle Physics in impressive fashion.



The Standard Model of Particle Physics







Particle Physics and Cosmology

The Universe was created in the Big Bang 13.8 Billion years ago.

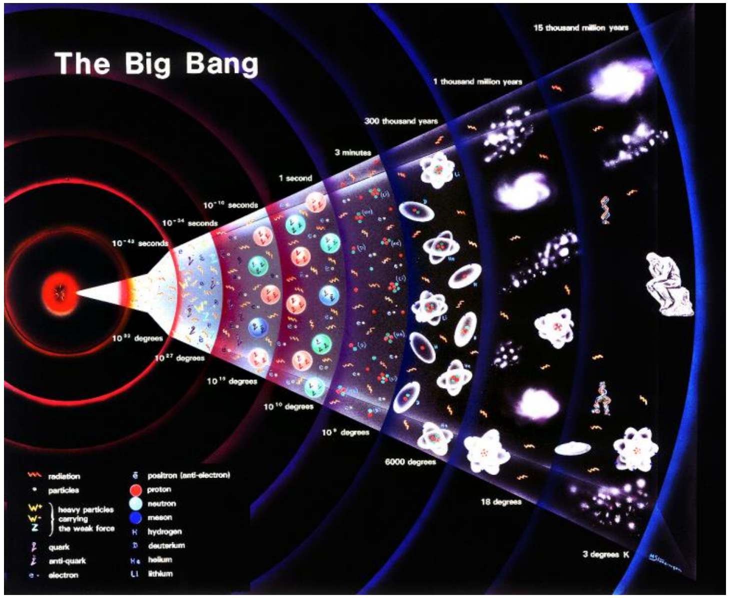
Today the universe is very cold (2.73K) and particle physics process play ‘on average’ no role.

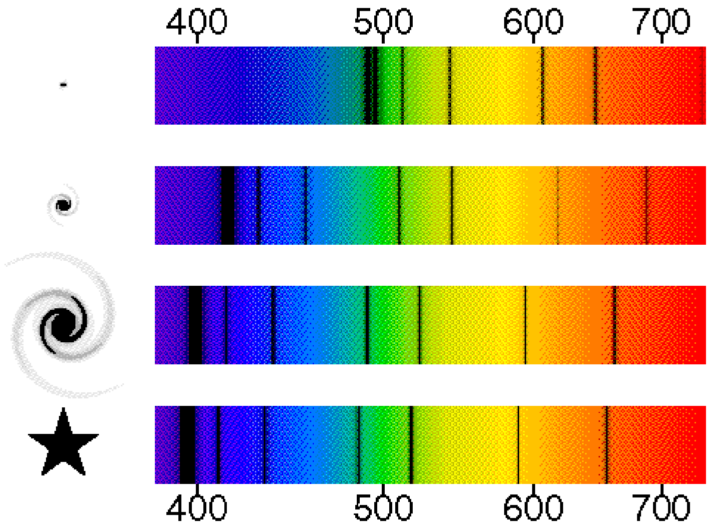
‘Nuclear processes’ play the dominant role in stars.

Particle physics processes play a role in in violent astrophysics events like supernovae etc., or in extremely dense environments like neutron stars.

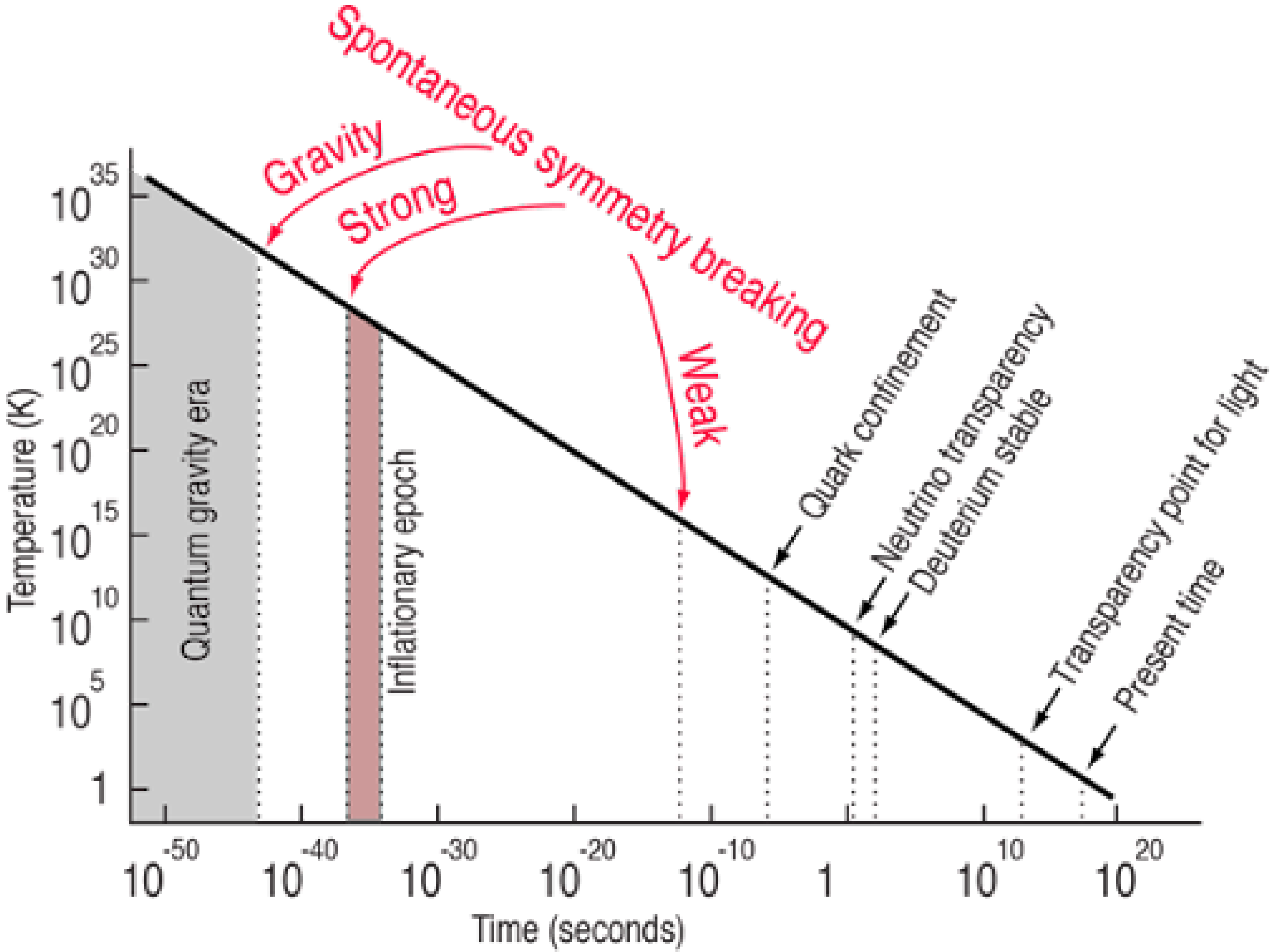
Shortly after the big bang, the temperatures were so high that particle physics played the dominant role in the development of the universe.

LHC → Universe ca. 10^{-12} s after the big bang.



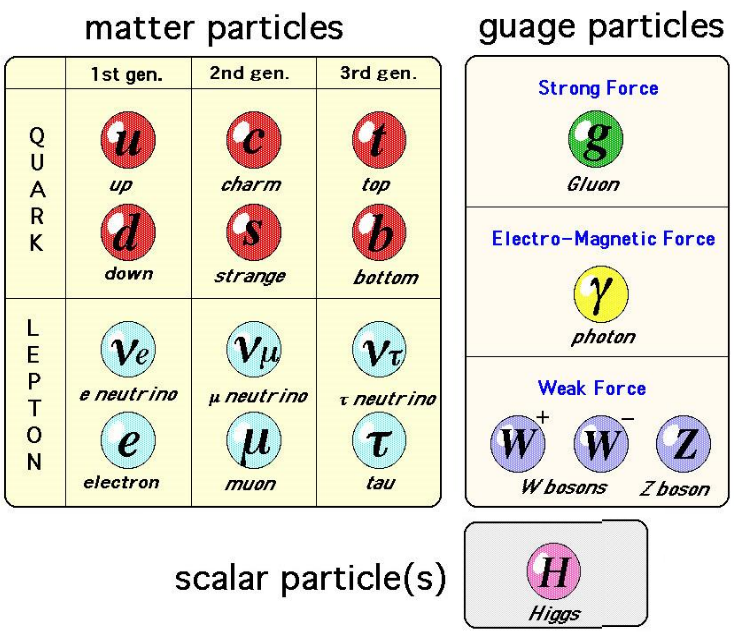


Particle Physics and Cosmology



Big Questions

Standardmodel →



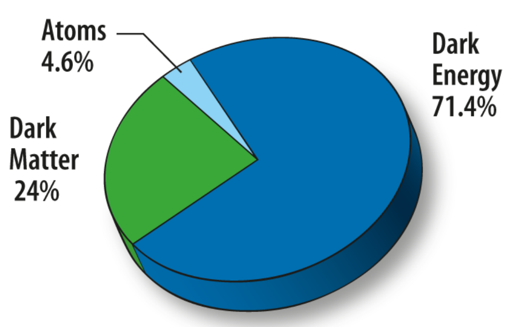
What is dark matter made of ?

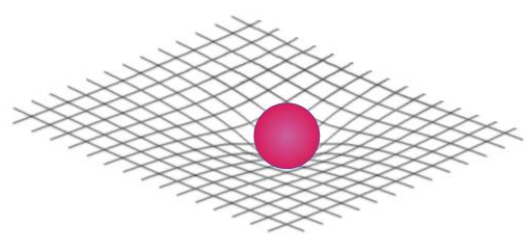
Why is there matter and no antimatter in the universe ?

How do we describe gravitation at energies where quantum effects play a role ?

Why is the universe isotropic and homogeneous ? Inflation ?

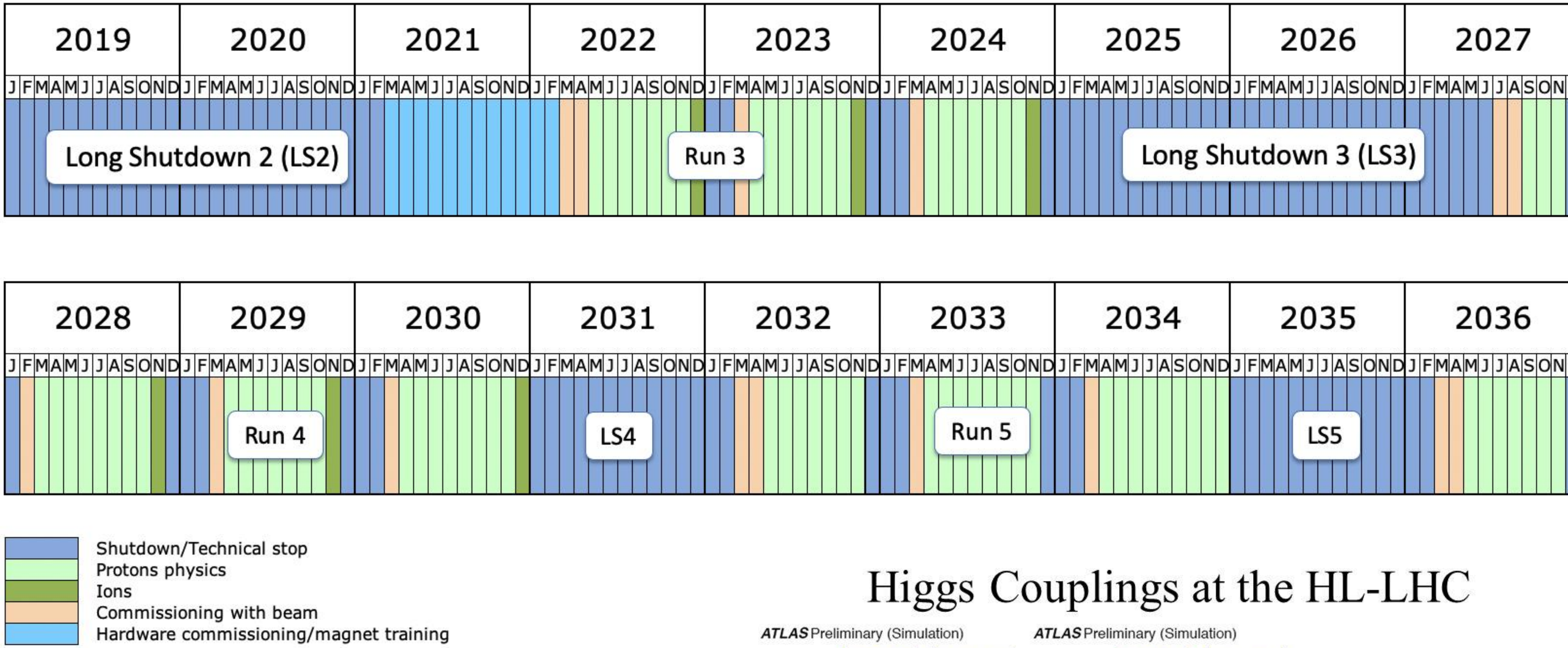
What is the nature of the cosmological constant ?





$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

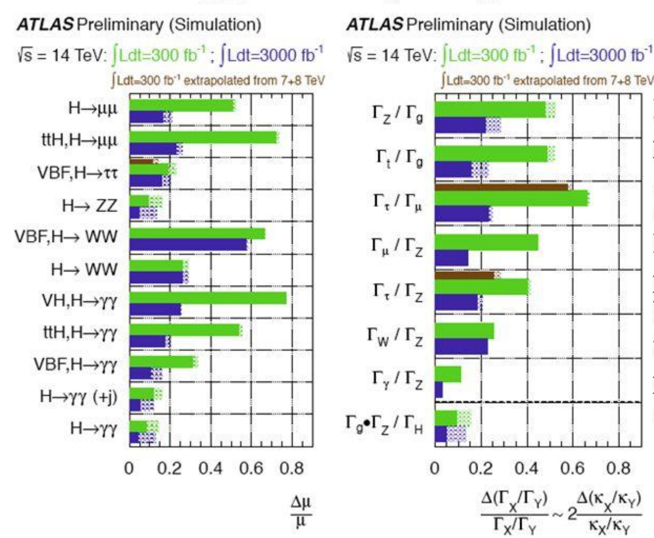
LHC exploitation



Large upgrade of LHC (HL-LHC) and detectors in 2025/2026 to accumulate 10 times more data until ca. 2040.

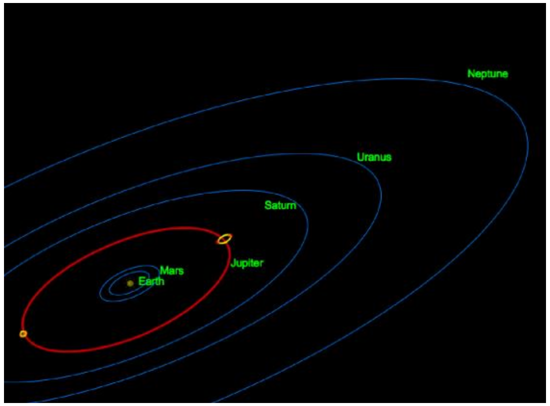
- Precision measurements
- Sensitivity to ‘new physics’
- Test of predictions of theories beyond Standard Model (there are many)

Higgs Couplings at the HL-LHC



Left: Expected measurement precision on the signal strength $\mu = (\sigma\times BR)/(\sigma\times BR)_{SM}$ in all considered channels.
Right: Expected measurement precisions on ratios of Higgs boson partial widths without theory assumptions on the particle content in Higgs loops or the total width.

The Discovery of Neptun

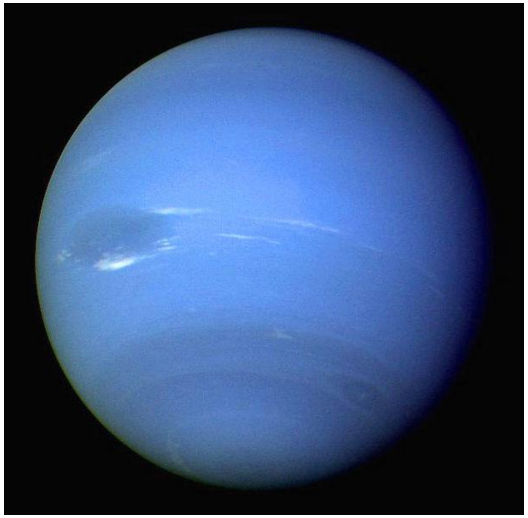


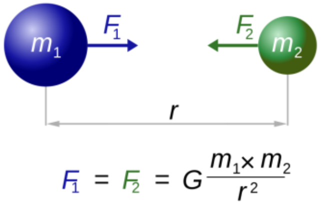
The precise measurement of the orbit of Uranus showed differences to the calculated orbits based on the gravitational force of the sun and the other planets.

The hypothesis was made that another planet could exist that is disturbing the orbit of Uranus.

From 1843 to 1846 detailed calculations of the possible position of such a planet were made.

The planet was indeed discovered in 1846 at the predicted position !
→ Neptun





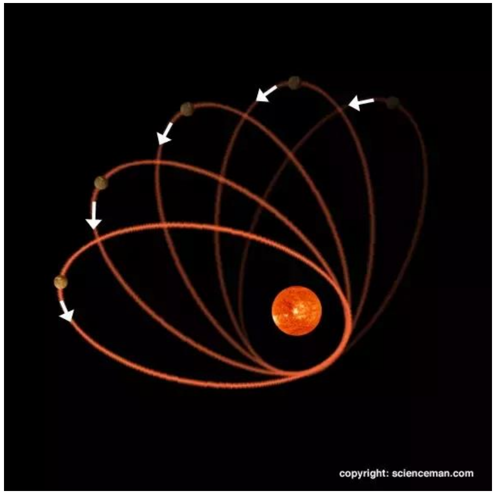
Newton rules !

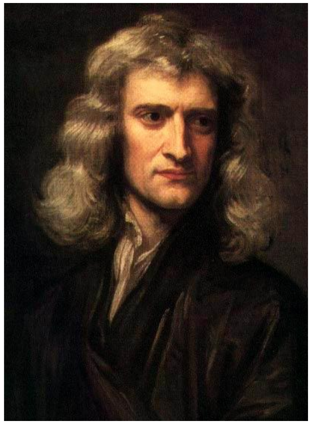
A more fundamental law of Gravitation

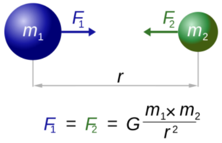
Further precision measurements and calculations showed that the Perihelion motion of Mercury differs from the precision:

- Measured 574''/cent,
- calculated from gravitational disturbance form other planets 532''/cent
- Difference 42''/cent.

This motion was the first hint at a more fundamental theory of Gravitation.







$$R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

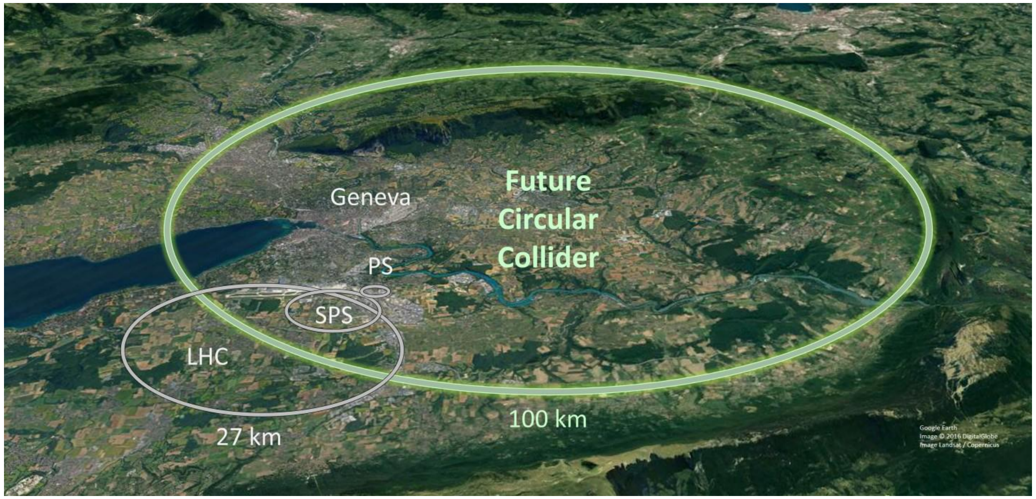
Einstein rules !

Future Collider Projects beyond LHC 2040+

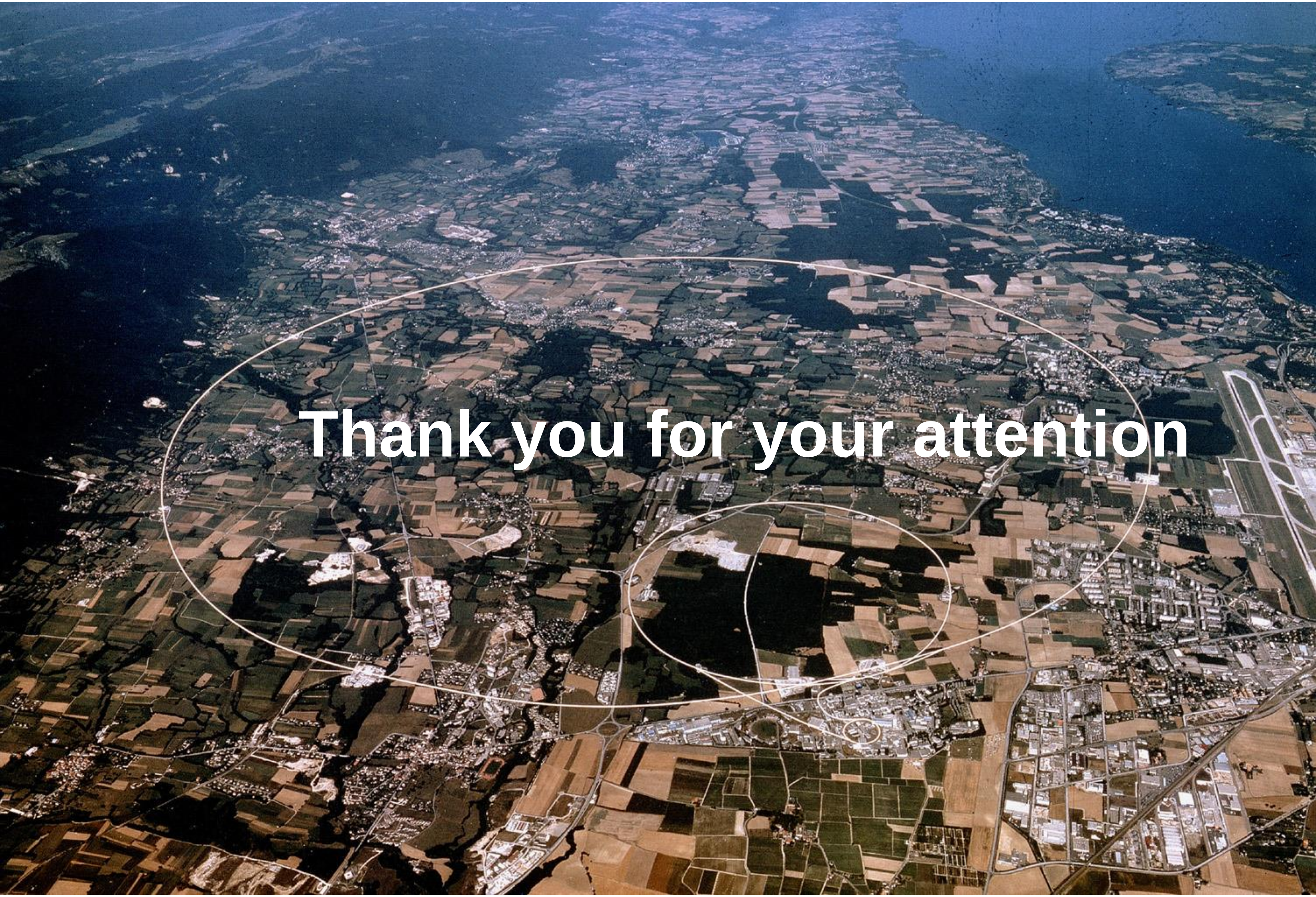
These will be large projects with a global community

Design studies are being conducted at this moment
→ Very long lead time.

Future Circular Collider (FCC)



Future Linear Collider (CLIC)


Thank you for your attention