High Energy Physics Experiments: What? How? Why?

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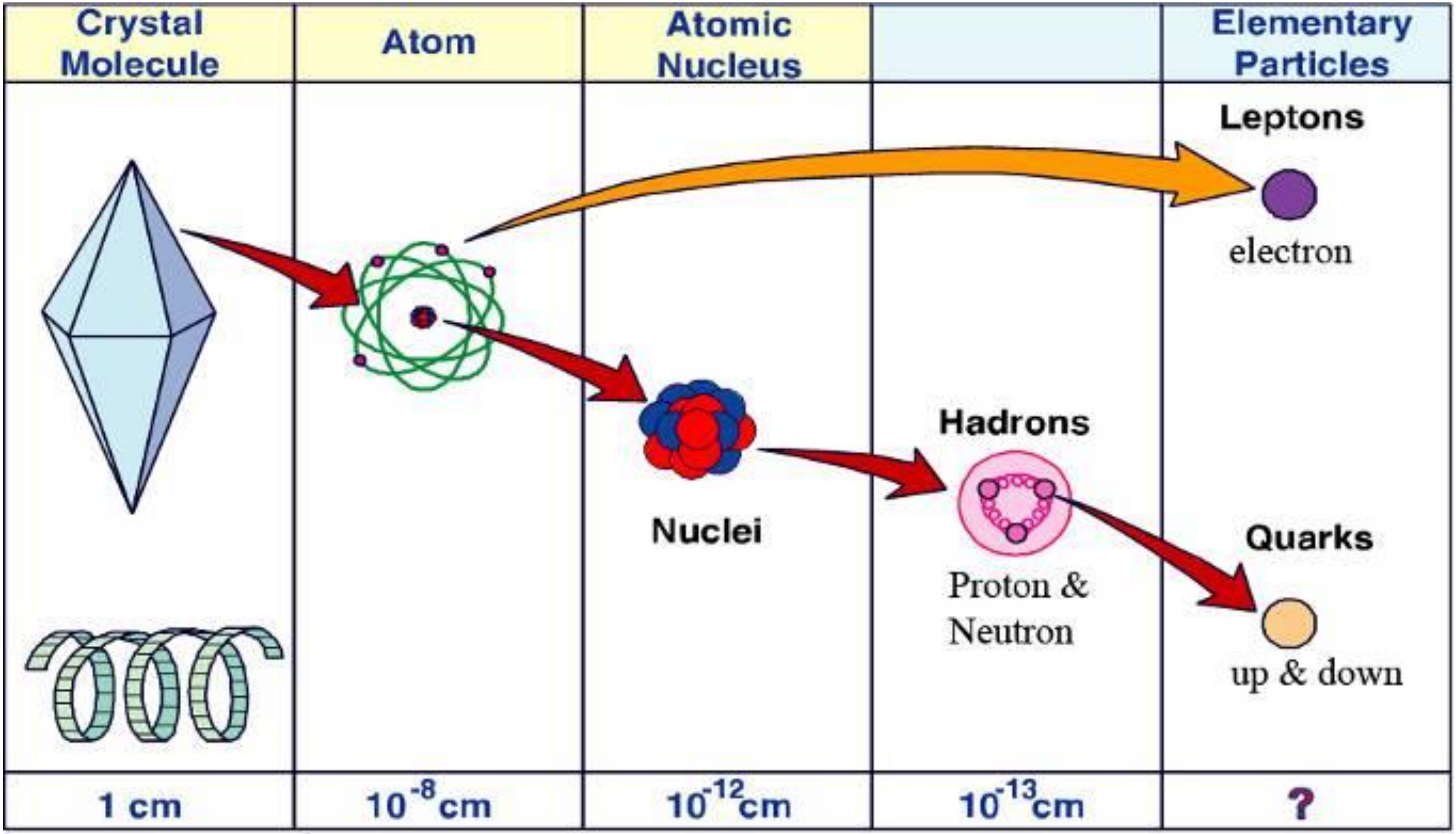
with inputs by K. Shaw, S. Shrestha, J. Stelzer

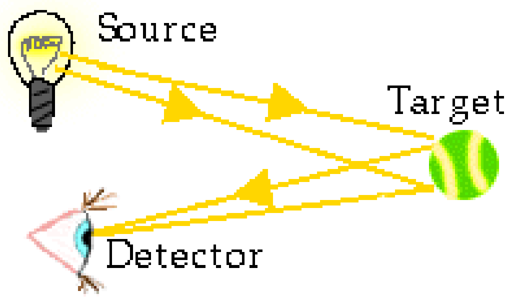
Our Current Understanding



How do we search for new particles?

How do we “see” things

- By observing the things around
- Light waves, reflected from a target are detected by our eyes (colors, distance)



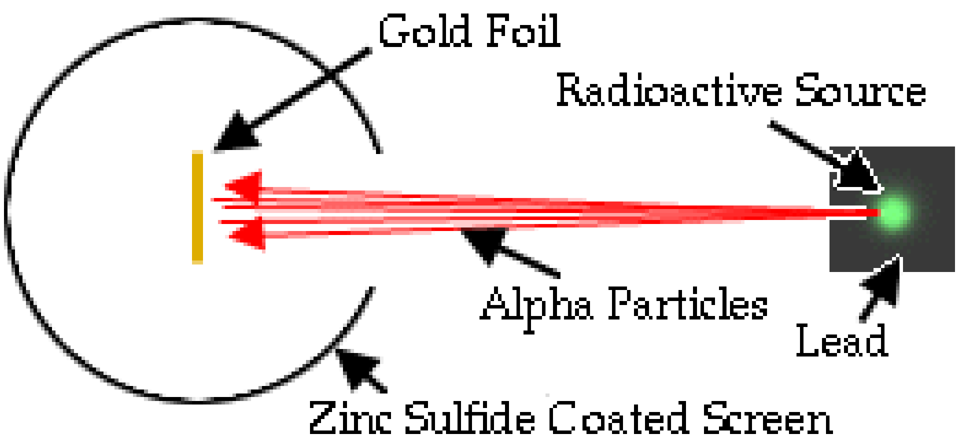
- Our brain analyses the information, and tells us if this is a ball
  - (If we have seen a ball before – so we build up on previous knowledge too)

In High Energy Physics

- We need

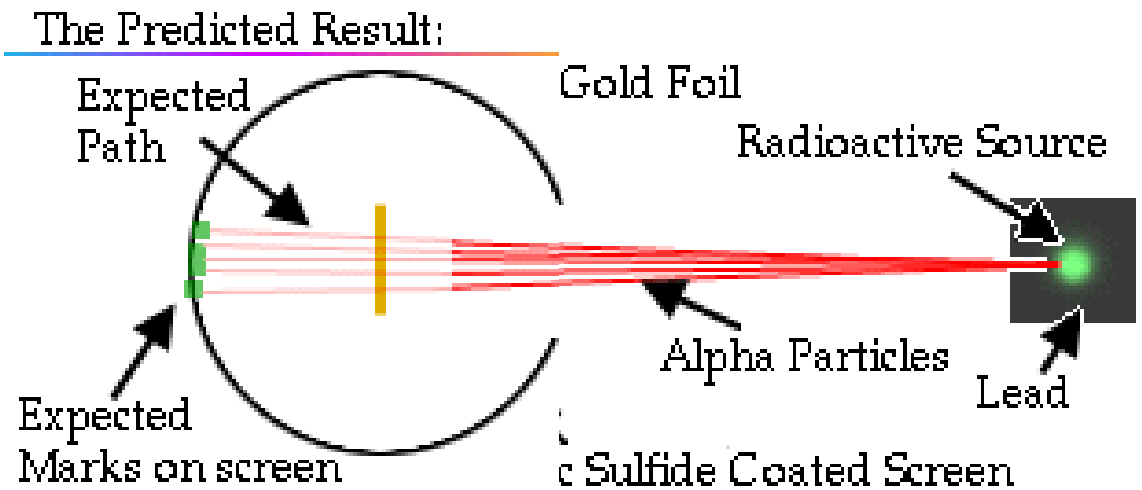
1) A beam of electrons, (anti-)protons, ions
2) A target – what we want to see and understand
3) A detector

- and often a theory !



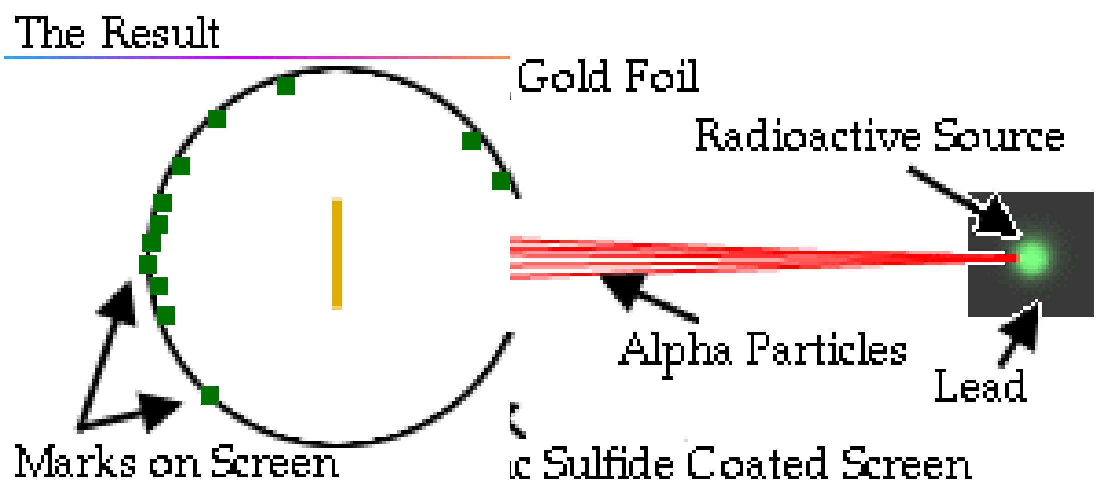
E. Rutherford (1909) shot a stream of alpha-particles on a gold foil.

In High Energy Physics



He expected the particles to go right through

In High Energy Physics



Found points everywhere around on the screen.

Discovery of the atomic substructure!

The first particle physics experiment ! Principles are still valid.

High Energy Physics

Small

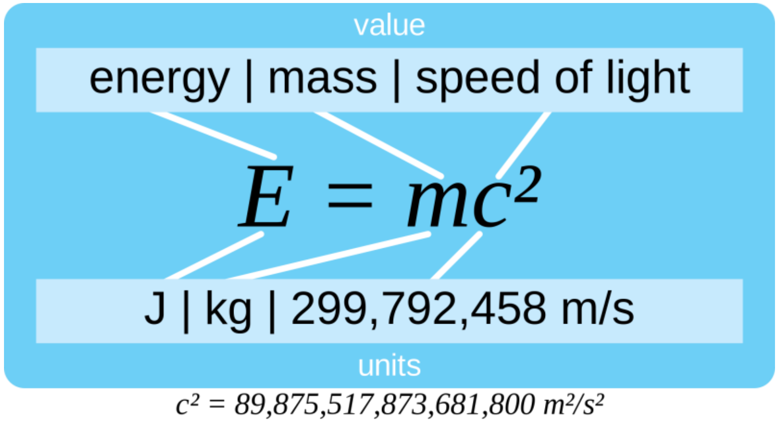
Fast		
	Classical Mechanics	Quantum Mechanics
	Relativistic Mechanics	Quantum Field Theory

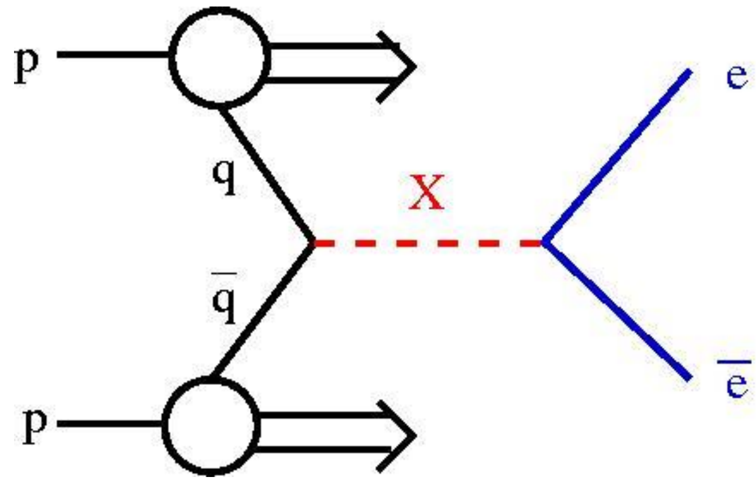
Units and Numbers in HEP

- Mass is measured in eV/c^2 where c = speed of light
  - $1\ eV/c^2 = 1.8 \times 10^{-36}\ kg$
  - $m_{proton} = 1\ GeV/c^2 = 2 \times 10^{-27}\ kg$
  - $m_{electron} = 0.5\ MeV/c^2 = 1 \times 10^{-30}\ kg$
  - $m_{sun} \sim 2 \times 10^{30}\ kg$
  - $m_{Higgs} = 125\ GeV/c^2 \sim 10^{-25}\ kg$

We will mostly use the unit "GeV"= Giga electronvolt

A bit of Special Relativity





- Collide 2 protons with E=3,500 GeV
  - Total energy: E=7,000 GeV
  - Can create particle X with mass $m_X < 7{,}000\ \mathrm{GeV}/c^2$
    - Actual interactions occur between quarks and gluons that carry part of proton energy
    - Most particles we create live only for a very short fraction of a second and then decay

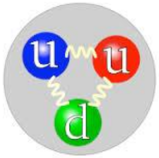
A bit of Quantum Mechanics

- de Broglie: the wavelength λ associated with a massive particle is related to its momentum p through the Planck const h:

$$\lambda = h/p$$

($h = 6.62607004 \times 10^{-34}\ \mathrm{m^2\ kg / s}$
or $h = 4.135\,667\,662 \times 10^{-15}$ eV s)

- Fundamental relation to “seeing” smaller
- Resolution increases as energy (momentum) goes up
- For examples:
  - $p = 1$ GeV/c $\Rightarrow 10^{-15}$ m ≈ size of proton
  - $p = 1000$ GeV/c $\Rightarrow 10^{-18}$ m ≈ size of proton sub-structure



Derive it!

Einstein's equation : $E = mc^2$

Planck's equation : $E = h\nu$

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$$mc^2 = h\nu$$

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$$mc^2 = h\frac{c}{\lambda}$$

$$mc = \frac{h}{\lambda}$$

or,

$$h = \frac{\lambda}{mc}$$

For macroscopic objects, velocity 'v' can replace speed of light 'c'.

Thus, our equation becomes :

$$h = \frac{\lambda}{mv}$$

Now, $mv = p$ (momentum of particle) and therefore,

$$\boxed{h = \frac{\lambda}{p}}$$

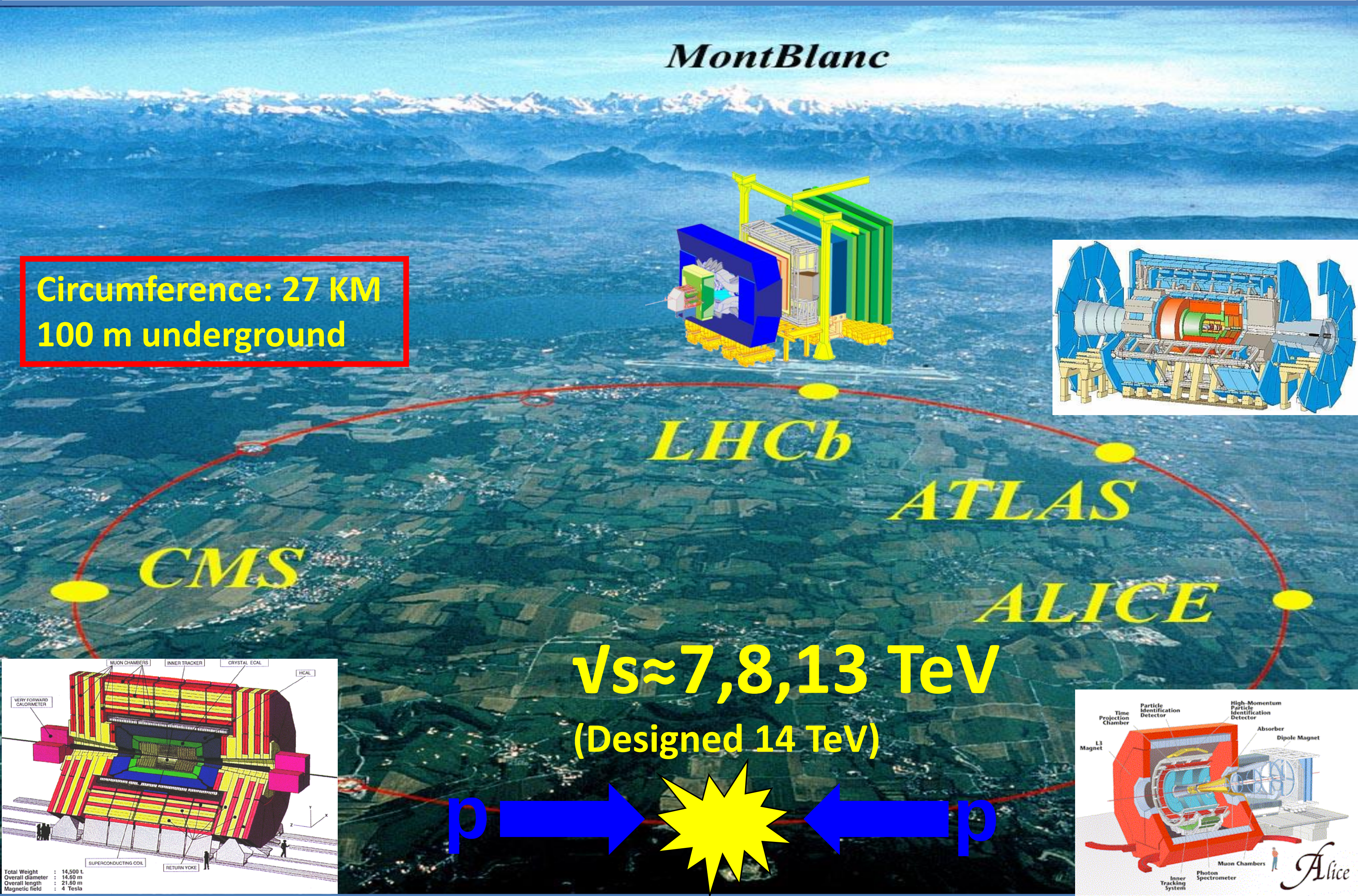
Why Colliders?

- Rutherford's experiment is a "fixed target" experiment
  - Center of Mass Energy ∝ √(Incoming Energy)
- Not as much energy as when colliding beams of particles: Center of Mass Energy ∝ Incoming Energy
- But you can also miss "target" more easily
- So put them in a ring – if you miss it once, you can re-use the same particles again ⇒ Birth of colliders!

Fermilab outside Chicago, p(antip) collision
Discovery of Top Quark

CERN, Previously e+e- collision (LEP)
Now p-p (LHC), Higgs Boson

The Large Hadron Collider (LHC)



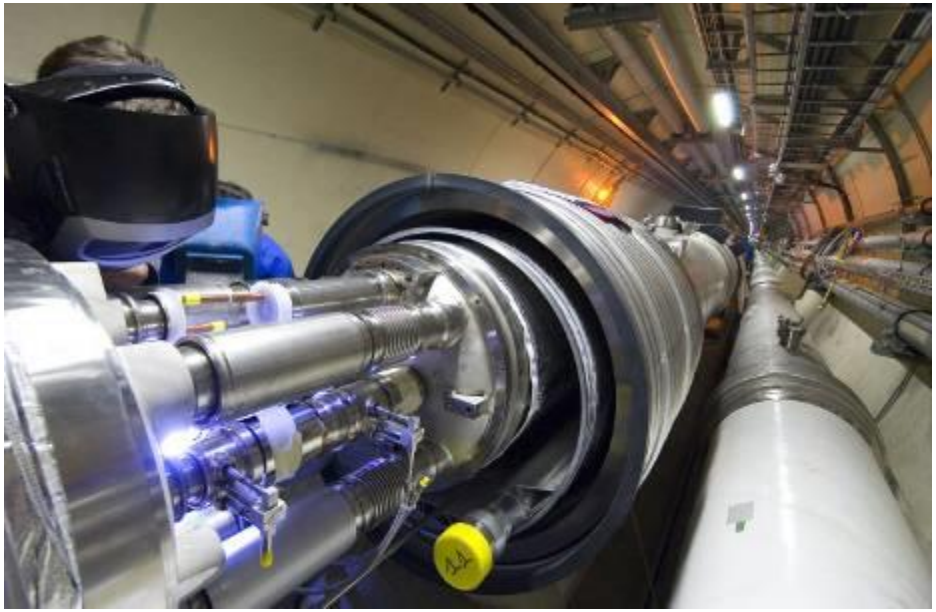
Circumference: 27 KM
100 m underground

√s≈7,8,13 TeV
(Designed 14 TeV)

One of the **fastest** racetracks on the planet – the **L**arge **H**adron **C**ollider (LHC)

Several thousand billion protons travelling at 99.9999991% of the speed of light will travel round the 27km ring over 11000 times a second!

The **emptiest** space in the solar system

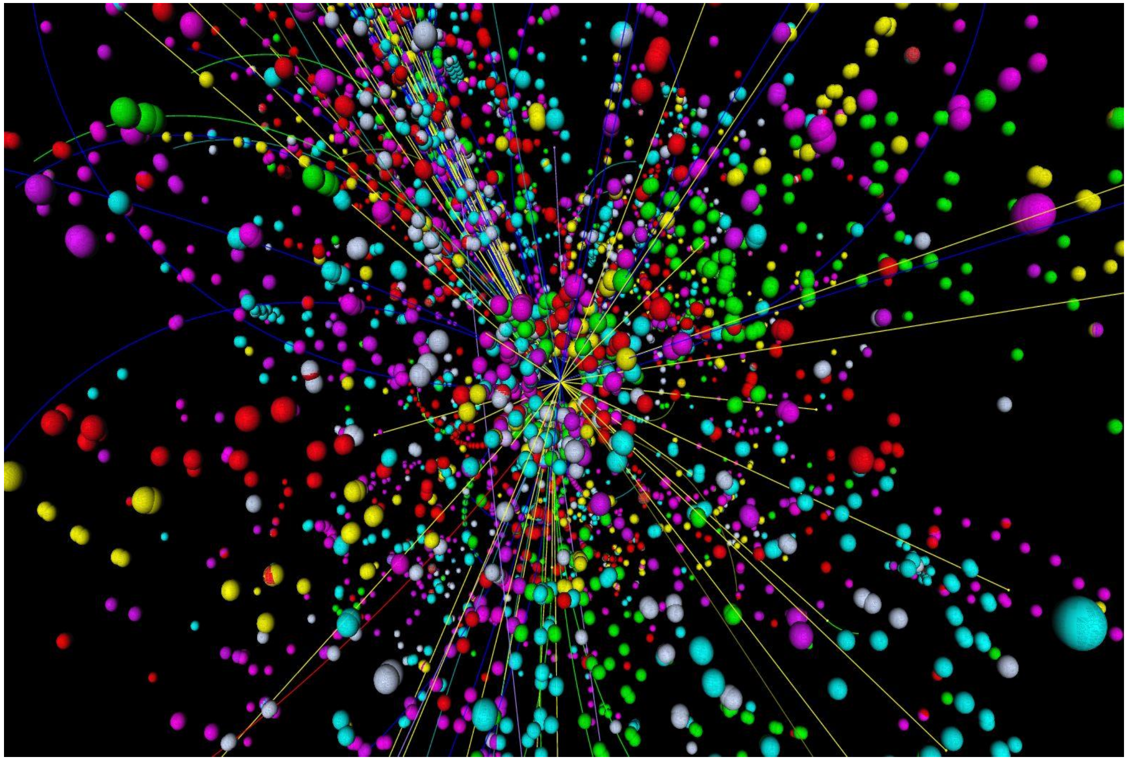


To accelerate protons to almost the speed of light, we need a vacuum similar to outer space. The pressure in the beam-pipes of the LHC will be about ten times lower than on the moon.

One of the **coolest** places in the Universe

With a temperature of around -271 degrees Celsius, or 1.9 degrees above absolute zero, the LHC is colder than outer space.

One of the **hottest** places in the Galaxy



When two beams of protons collide they generate, within a tiny volume and for a tiny fraction of a second, temperatures more than a billion times those in the very heart of the Sun.

LHC the Accelerator

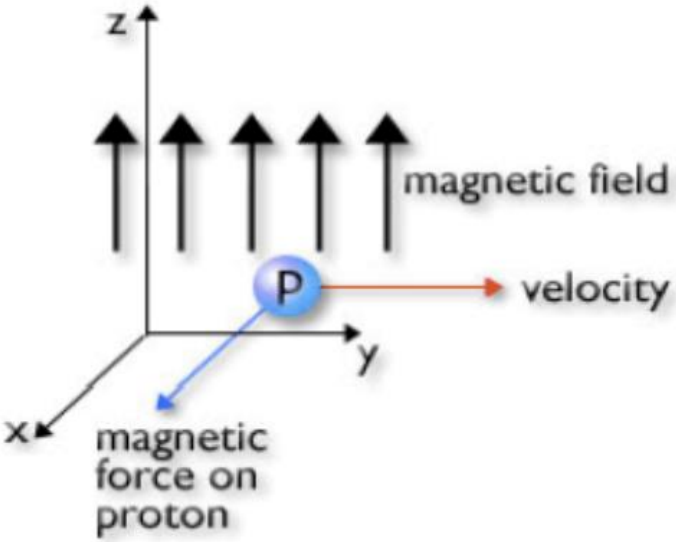
- 30,000 tons of 8.4T dipole magnets (1232 magnets)
- Cooled to 1.9K with 96 tons of liquid helium
- Energy of beam = 362 MJ
  - 15 kg of Swiss chocolate

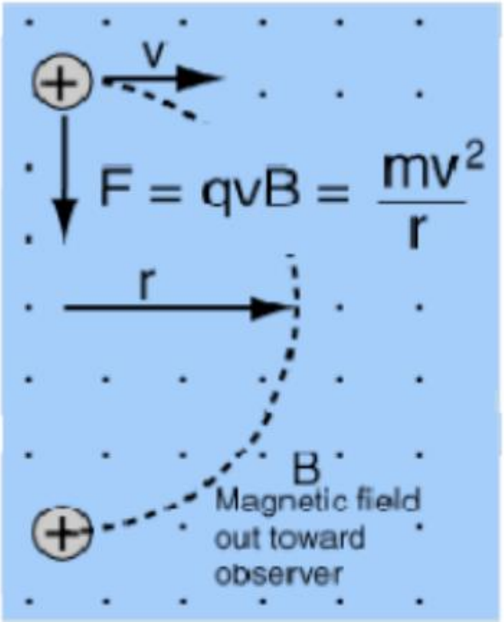
April 26th 2007

Protons in the Accelerator

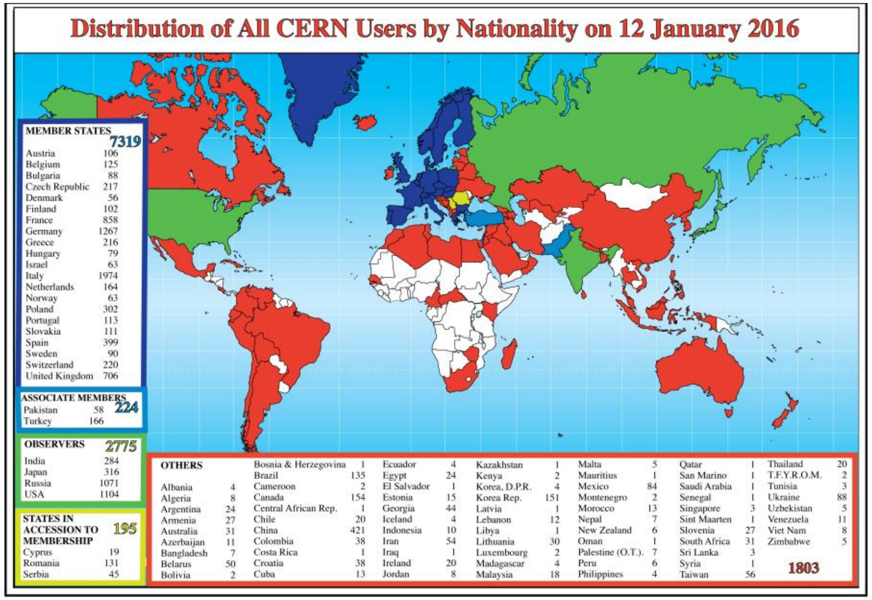
With F=qE (Maxwell) and F=ma (Newton)
Acceleration: a = qE/m

Magnets are used to steer proton beams in circle using
Lorentz Force ($F=qvB=mv^2/r$)



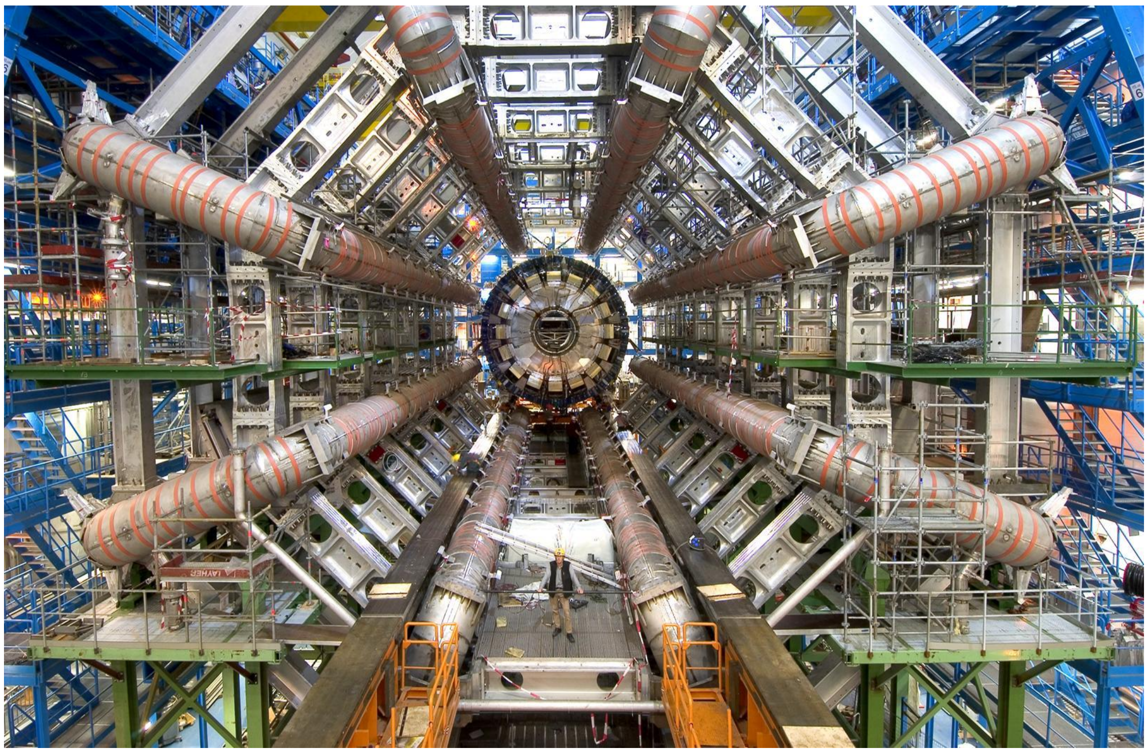


Every day more than **10000 scientists** do their work at CERN



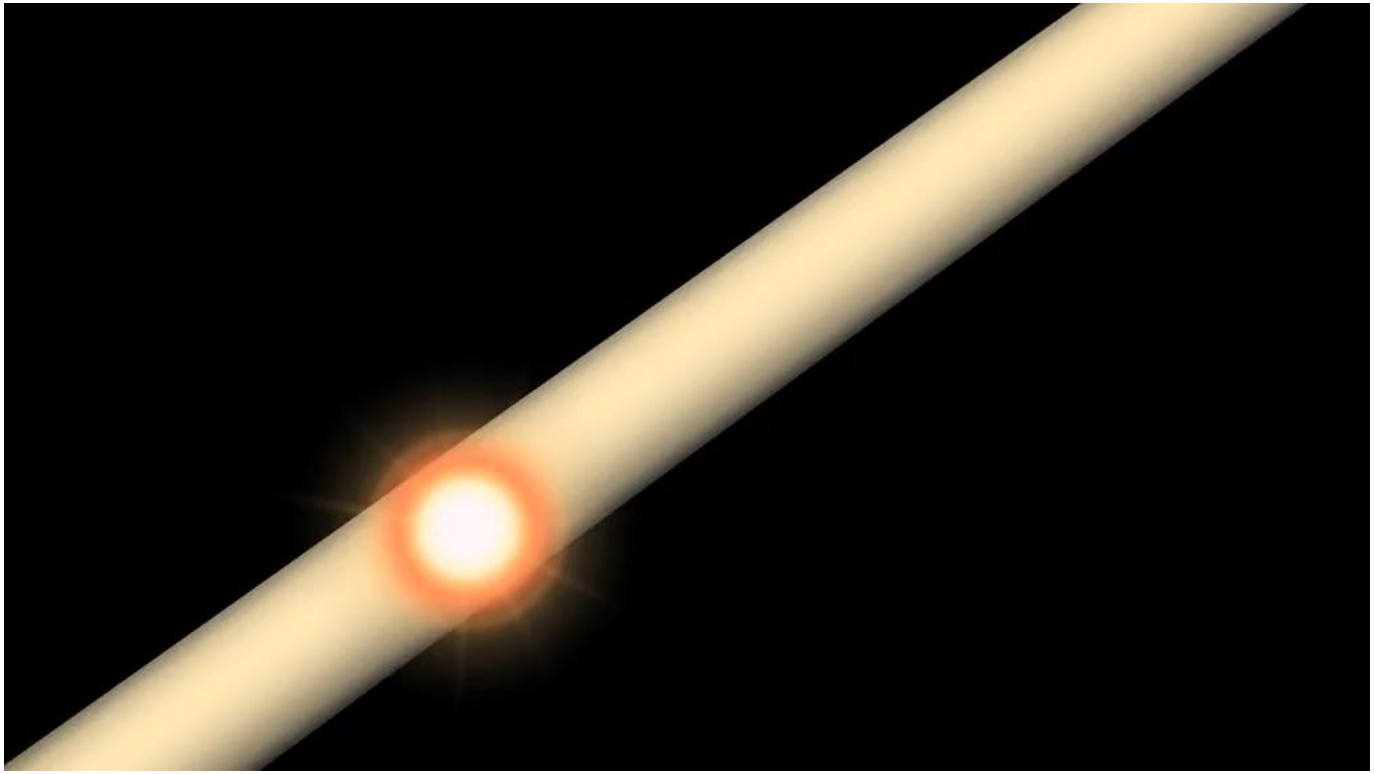
22 Member States and around 600 institutions and universities around the world use CERN's facilities

Using the **largest and most complex detectors** ever built



ATLAS detector during construction (see the person there?)

To select and record the signals from the 600 million proton collisions every second, CERN scientists are building huge detectors to measure the tiny particles to an extraordinary precision.

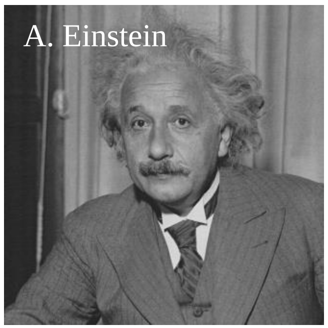


QUESTIONS

But what does CERN and its accelerators and detectors have to do with everyday life?

Innovation

Fundamental research has always been a driving force for **innovation**



Relativity

100% SCIENCE

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!

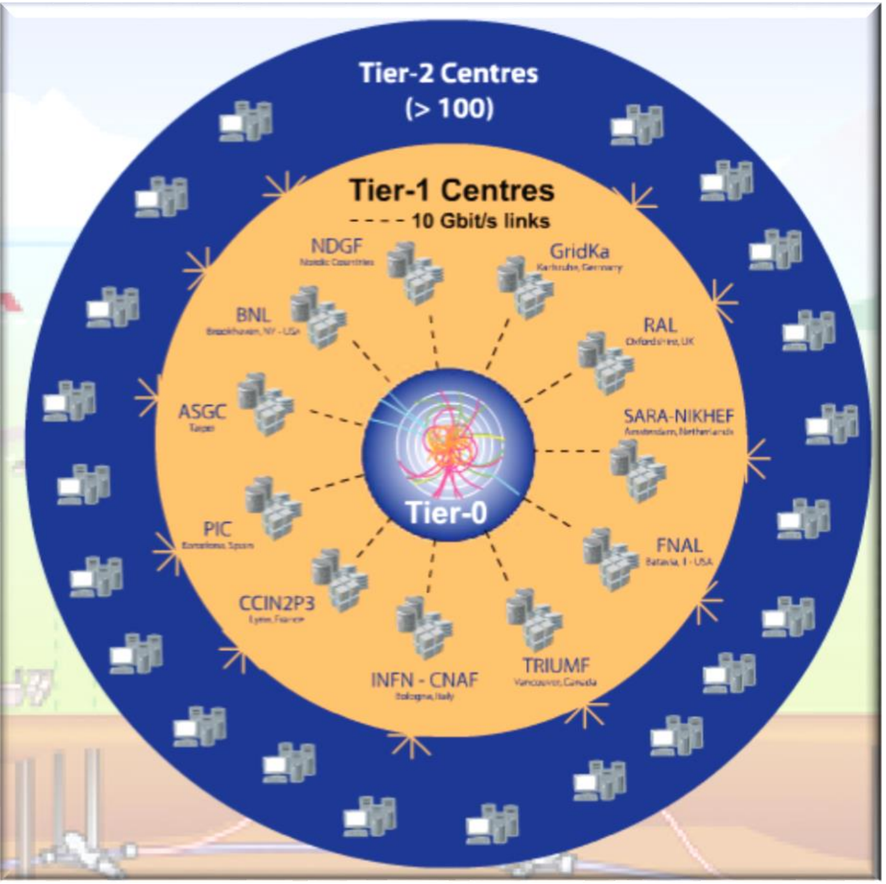

J.C. Maxwell

Electromagnetism

100% SCIENCE

Telephones use electromagnetic waves to communicate

Worldwide LHC Computing Grid



- Huge data volumes
  - 600 MB/s
  - 5,000 TB/year
- Huge CPU requirements:
  - 15 s/event

Application in Medicine

Courtesy of IBA

Accelerators:

developed in physics labs & used in hospitals

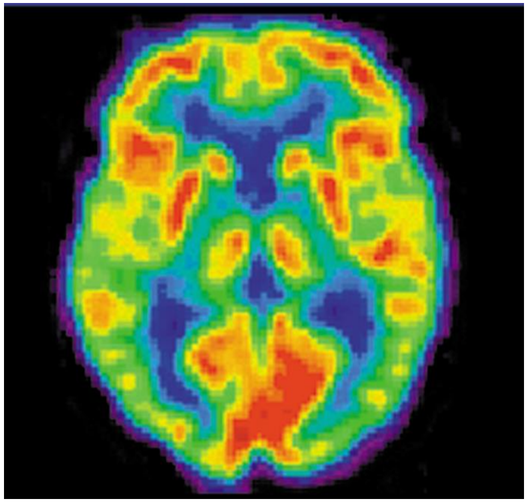
Around 9000 of the 17000 accelerators operating in the World today are used for medicine.

Hadron therapy is a growing method of treating tumours

Medical Imaging

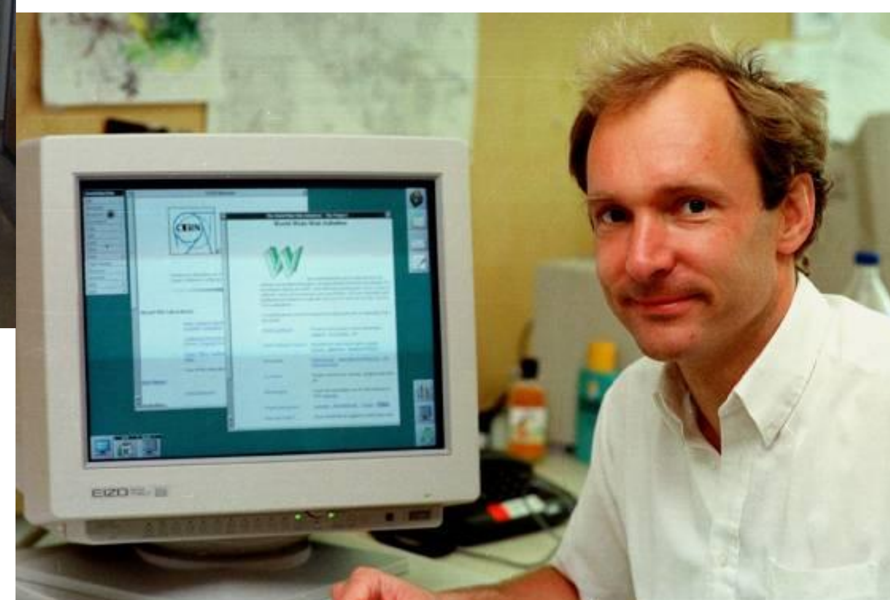
Detectors: developed in physics labs & used for medical imaging

PET (Positron Emission Tomography) uses antimatter (positrons).

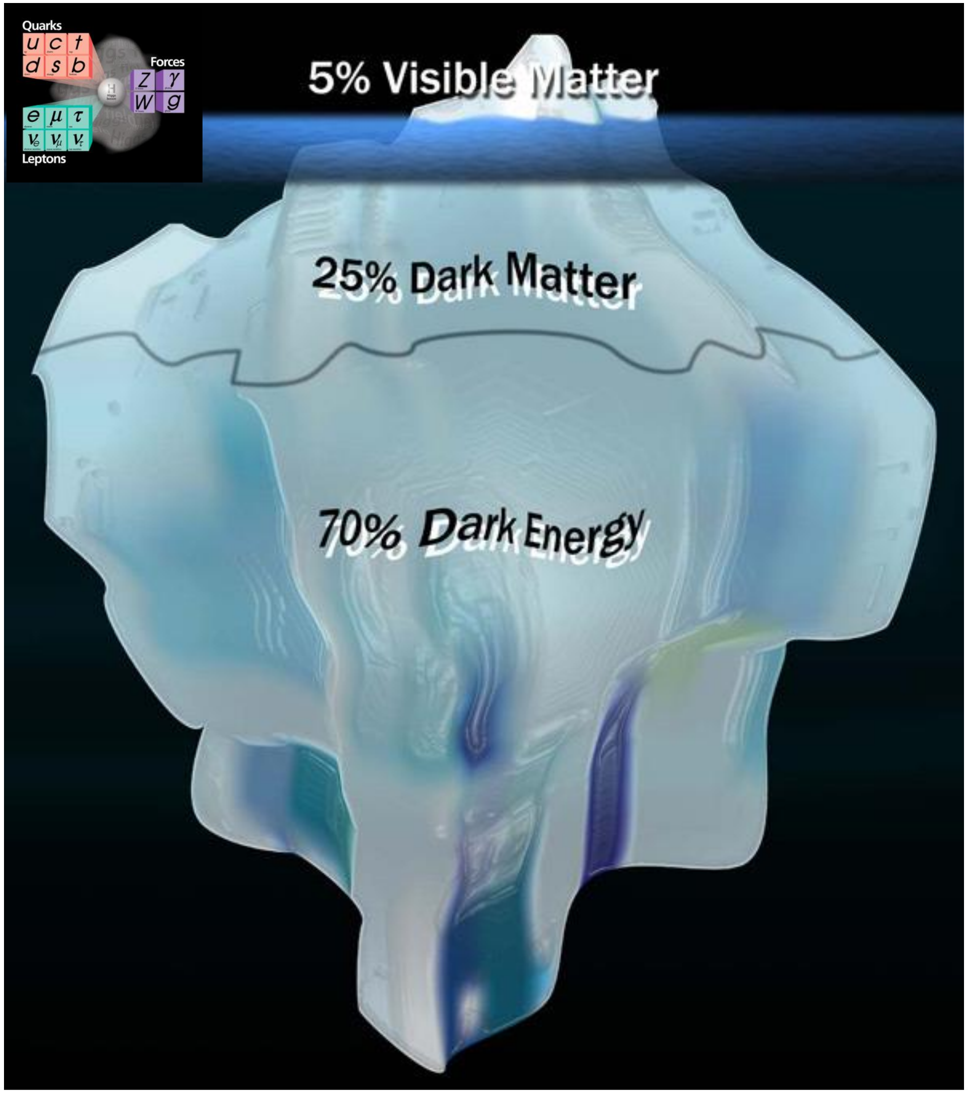


World Wide Web

Other spinoffs include… WWW >20 years old!



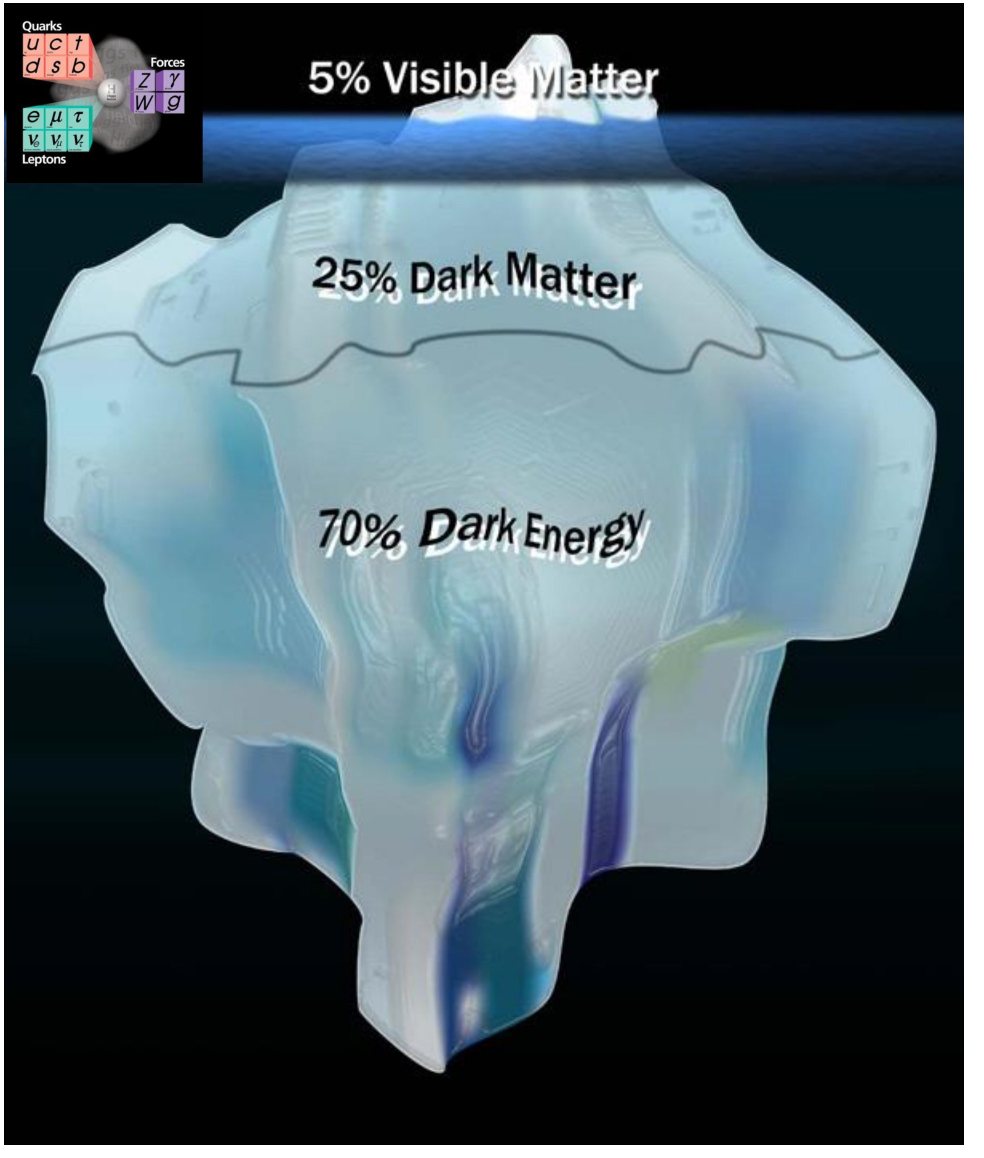
Why continue to run the LHC?



We don’t understand 95% of our Universe!!
Physics needs young scientists like YOU to help unravel many mysteries

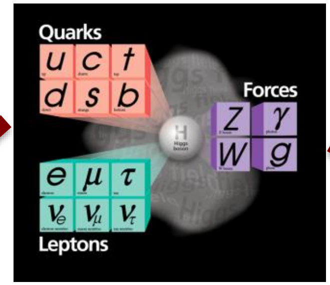
Glimpse of Our Ignorance

- SM has passed all experimental tests, but still not complete
- Several problems with the SM
  - Dark Matter
  - Dark Energy
  - Neutrino Oscillation
  - Matter-Antimatter Asymmetry
  - Fermion Mass hierarchy
  - Higgs Mass Stability
  - Gravity
- More than sufficient reasons to look for Physics beyond the SM



Propositions for beyond the SM

Standard Model



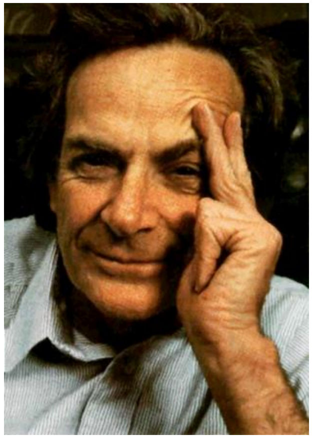
Super-Symmetry

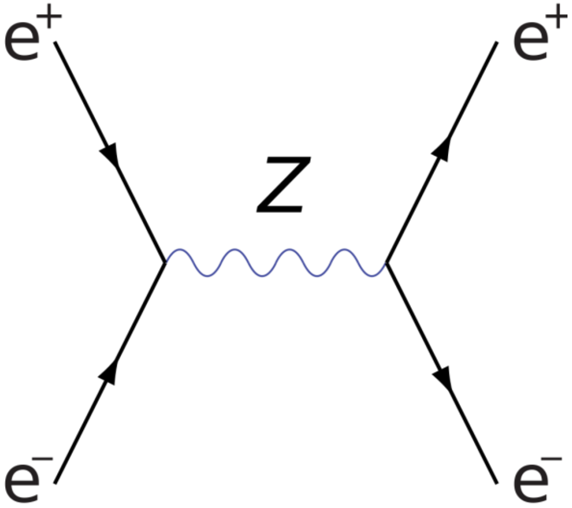
- Several variants of SUSY
- Can resolve
  - Hierarchy problem
  - Higgs mass stability
  - Dark Matter problem
- Predicts new particles such as heavy super-partners, scalar particles, neutral light Higgs

Exotics

- Several independent models
- Aims to resolve
  - Matter Anti-Matter Asymmetry
  - Higgs mass stability
  - Dark Matter problem
- Predicts new particles such as new heavy quarks, new heavy bosons, composite Higgs, extra dimensions

Feynman Diagrams

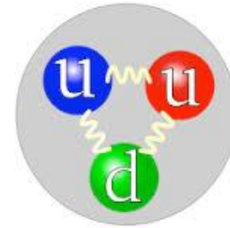


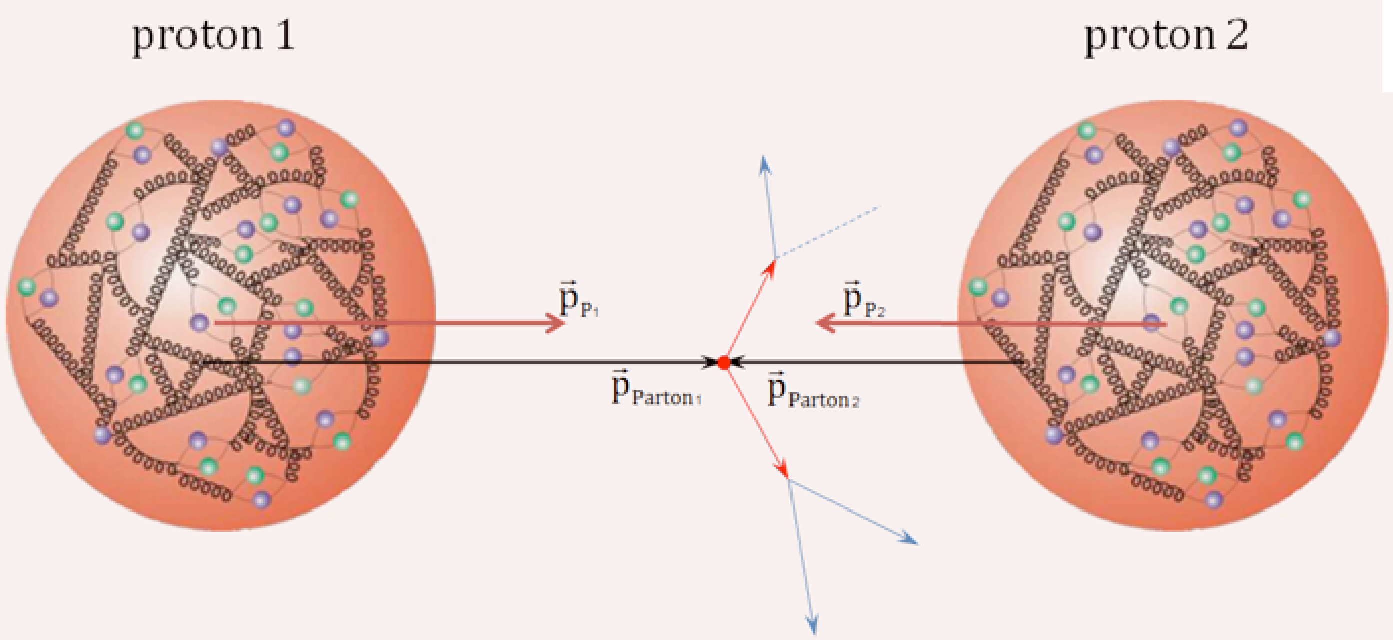


- Pictorial representation of the mathematical expressions describing the behavior of elementary particles
- In the example, an electron and a positron annihilate each other to form a Z boson, which then decays into an electron and a positron

Colliding protons …

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)





$\vec{p}_{P_1}$ … momentum proton 1

$\vec{p}_{P_1}$ … momentum proton 2

• interaction vertex

$\vec{p}_{Parton_1}$ … momentum parton 1

$\vec{p}_{Parton_2}$ … momentum parton 2

… is a mess