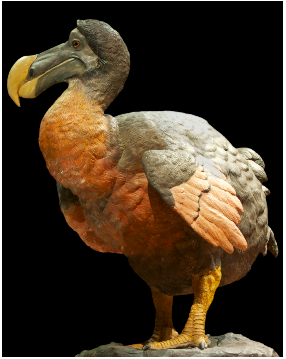
A journey to understand the proton

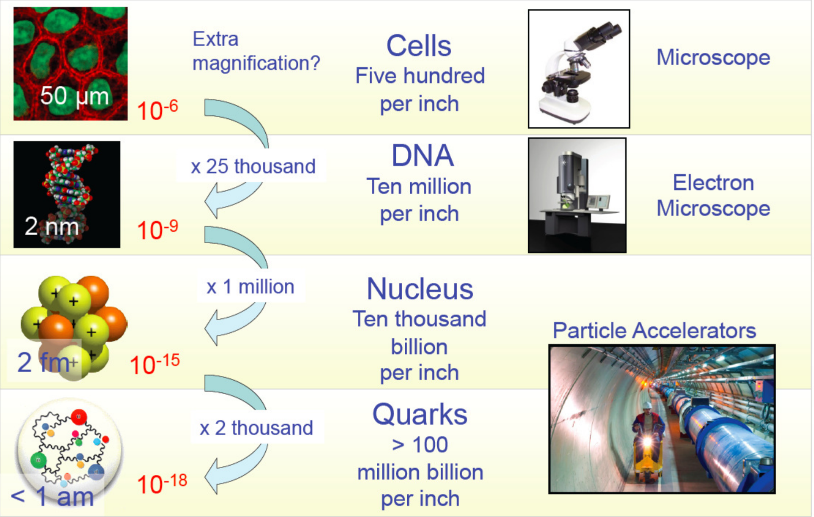
Christophe Royon
University of Kansas, Lawrence, USA
ISMD 2023, Gyöngyös, Hungary

August 26 2023

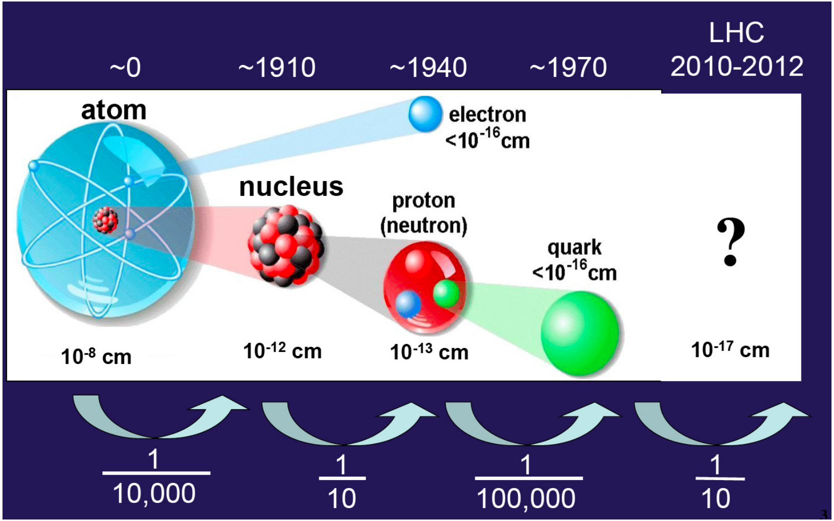


- What is the LHC?
- What is a proton?
- Strange events: diffraction

Scales and tools

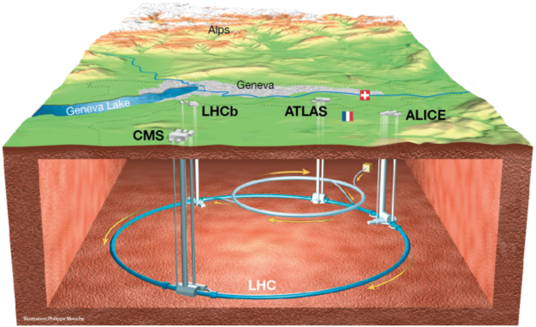


A long history: searching for fundamental particles

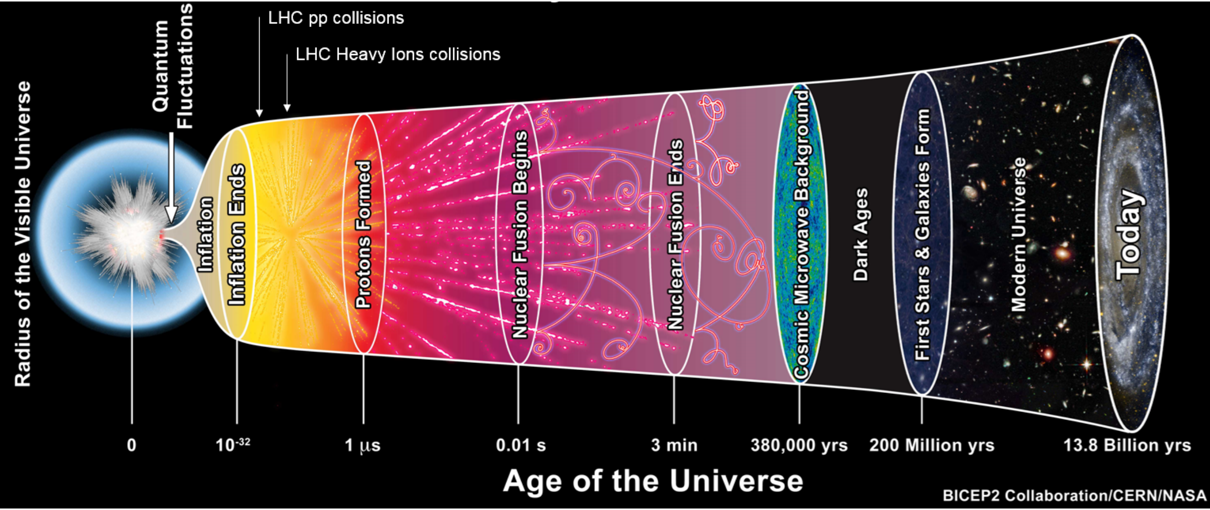


The Large Hadron Collider at CERN

- Large Hadron Collider at CERN: proton proton collider with 13 TeV center-of-mass energy
- Circonference: 27 km; Underground: 50-100 m; Energy per beam $\sim$ 800 MJ (1 MJ melts 2 kg of copper); Power consumption: 120 MW (Ann Arbor: 190 MW in 2008)



Why the LHC? Going back in time....



The LHC: the hottest spot in the universe...?

When two proton beams collide, they reach a temperature of 10^{17} degree, albeit over a miniscule area.
(For comparison, the temperature in the Sun's core is ~10^{7} degree)

It creates a condition similar to that 10^{-13} second after the Big Bang, right after the Universe was born.

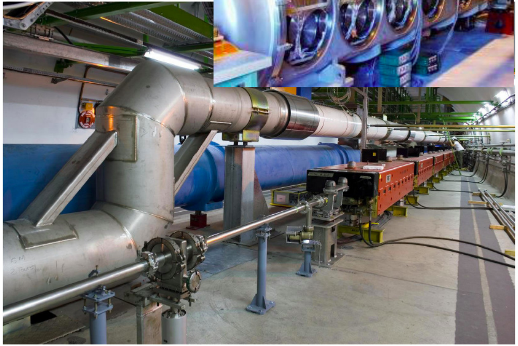
The hottest spots in the Universe today!

The LHC: the coldest spot in the universe...?

LHC beams are kept in orbits by superconducting electromagnets operating at a temperature of -271 °C (-457 °F or 1.9 K).

It takes about a month to cool it down and needs ~10,000 tons of liquid nitrogen and ~100 tons of liquid helium to cool and to keep it cold.

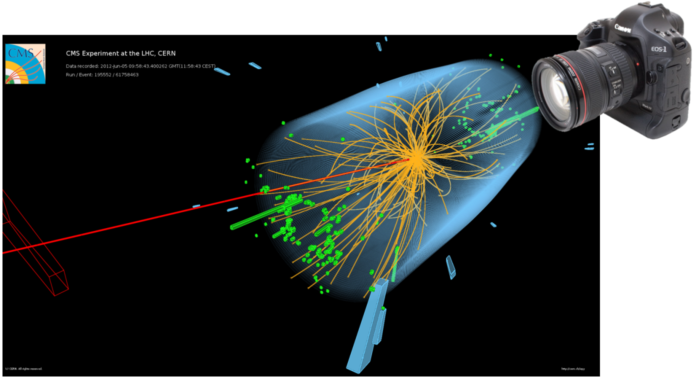
The world's largest refrigerator !



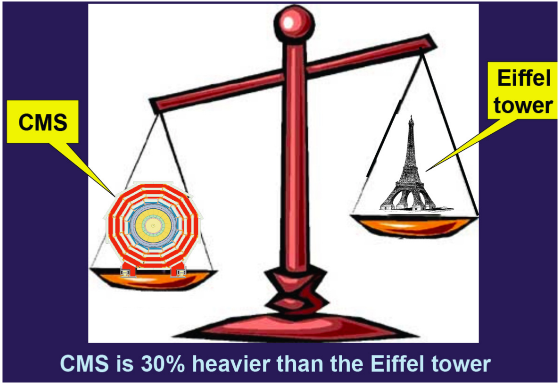
One of the largest instrument on earth: cathedral of physics...

Largest scientific instruments ever built to track particles with micron precision over more than 50 m with over 100 million electronic read-out channels

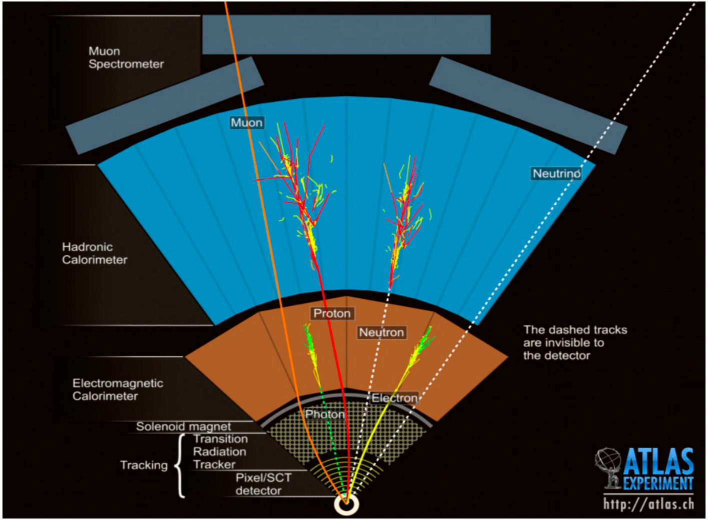
These detectors are similar to a digital camera with 100 megapixel that takes 40 millions pictures per second.
They are sensitive to light and all other types of radiations.



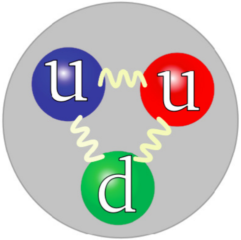
Two general purpose experiments: ATLAS and CMS



Particle signatures

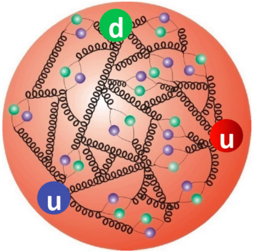


What is a proton?



LHC is a proton-proton collider,
so what are protons?

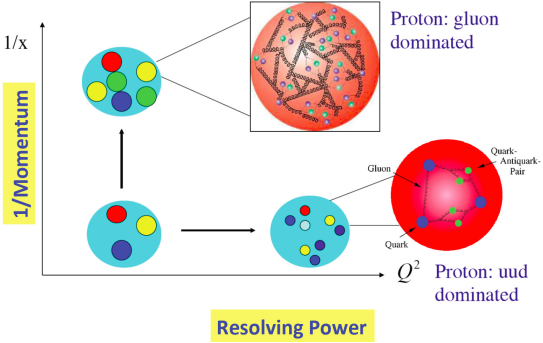
Protons are constituents of nuclei. They are small and have a size of ~10^{-15} m (1 fermi) or about 1/1000 of the size of a hydrogen atom.



It “consists” three valence quarks and many gluons and sea quarks, bound together by nuclear (strong) interaction.

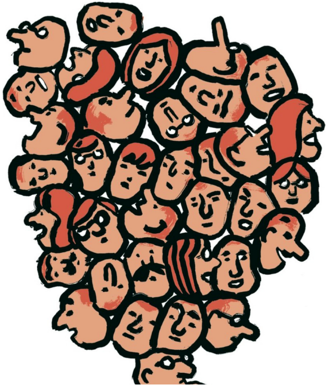
About half of the proton energy is carried by quarks while the other half by gluons.

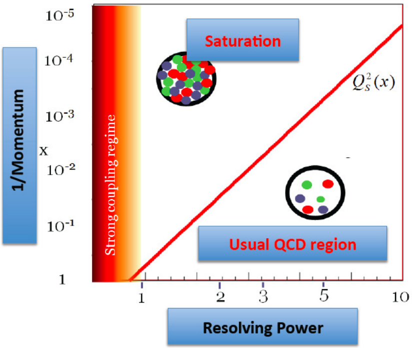
The proton structure



- The proton is a complicated object: it appears differently according to its energy (quantum object)
- Q^2: Resolution power (like a microscope): *the higher the energy of an accelerator is (bigger machines), the higher values of Q^2 (the resolution) and the smaller distances that we can reach*
- x: momentum fraction of the proton possessed by the quark/gluon (proton constituent)

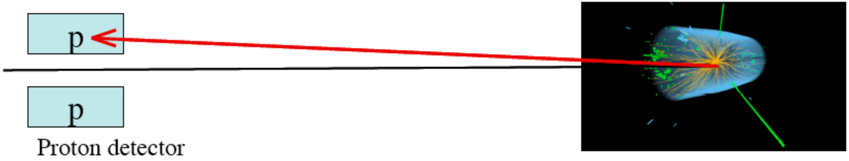
New kinematical domain: saturation





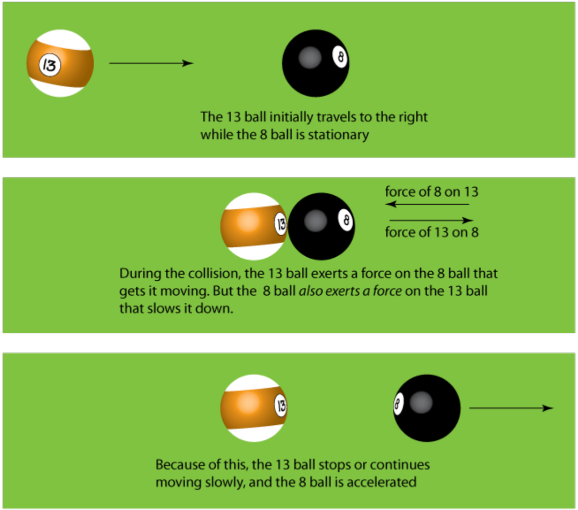
- The proton is even more complicated: Regions where the density of gluons is very large, “saturation”
- The usual equations are no longer valid!
- Can be studied at the LHC and at the future Electron-Ion Collider in the US

Strange events: intact protons after interaction

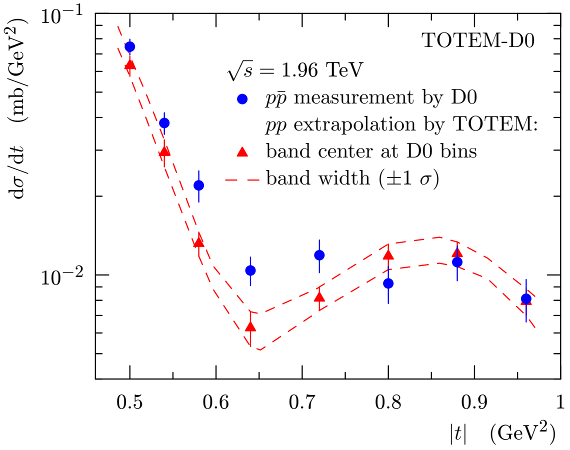


- Some unique events can be produced where the proton is not destroyed! The proton loses part of its energy
- These events are vital to probing extra-dimensions
- An everyday analogy would be an accident between two large trucks (the protons) that lead to the two trucks remaining intact in addition to small cars!

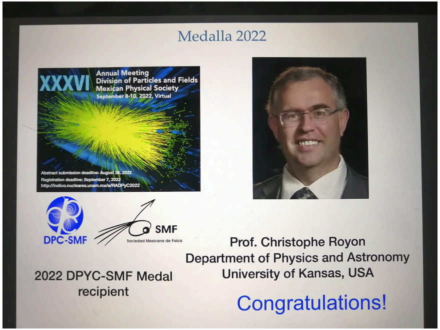
What is elastic scattering? The pool game...



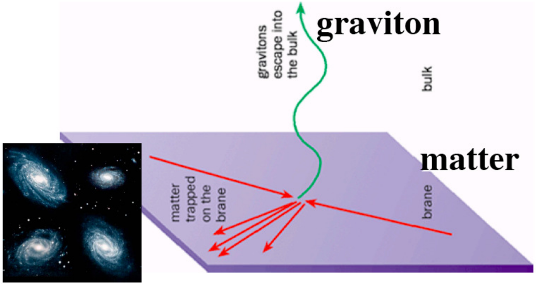
- We want to study "elastic" collisions between protons and proton-antiprotons
- In high energy physics: $pp \to pp$ and $p\bar{p} \to p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum as in the pool game



- Comparison between pp and $p\bar{p}$ data
- **Clear difference observed: discovery of the odderon!**



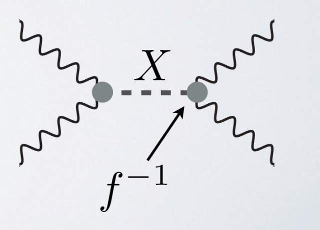
Looking for extra-dimensions in the universe

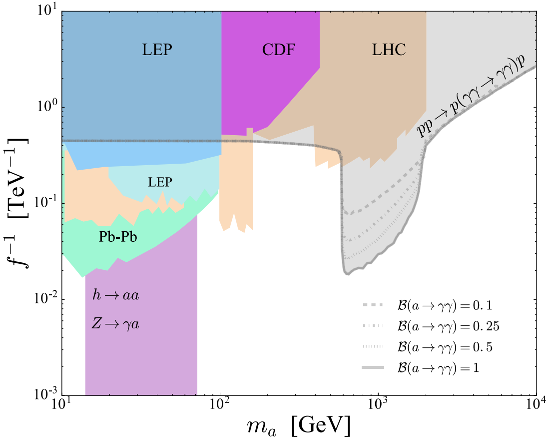


- We live in a 4-dimensional space: space-time continuum
- Gravity might live in extra-dimensions: this idea is being explored at the LHC by looking for new couplings between particles and production of new particles
- If discovered at the LHC, this might lead to major changes in the way we see the world

Searching for dark matter, axion-like particles

Looking for example for axion-like particles candidates decaying into two photons





Conclusion

- The Large Hadron Collider: Highest energy collider in the world
- Led to the Higgs boson/odderon discovery, and could bring many more unexpected results: for instance, extra-dimensions, axion-like particles..., would change the way we see the world; bridge between infinitely small (particles) and large (cosmology) domains
- The LHC is now taking data: stay tuned

One needs to look everywhere