A journey to understand the proton

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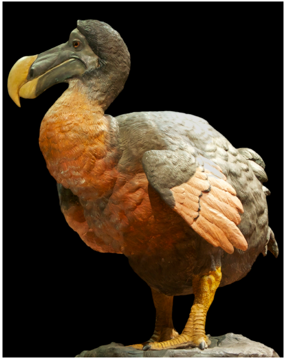
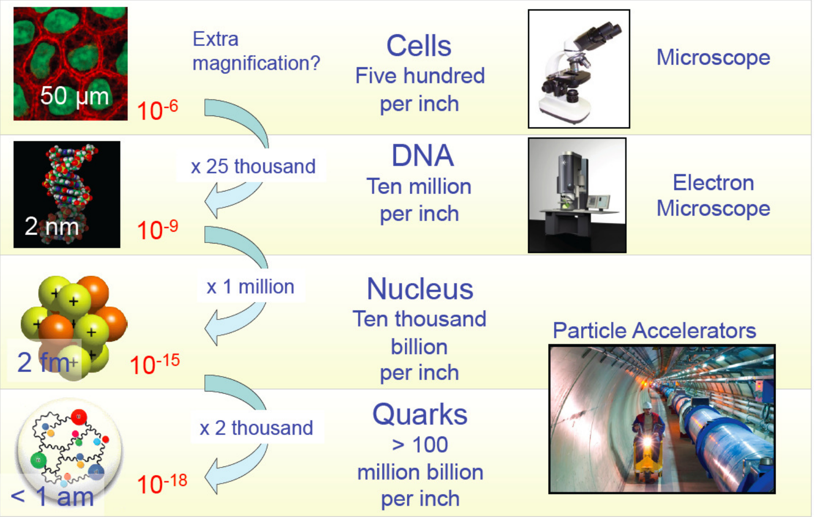
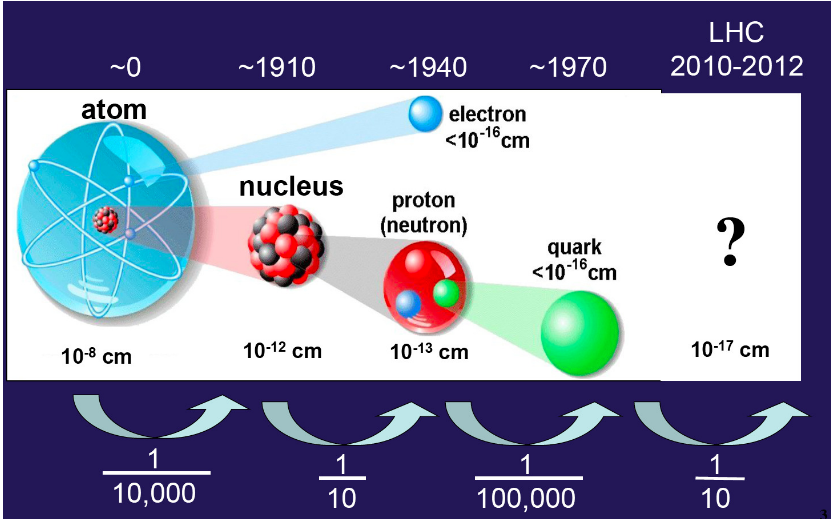


- What is the LHC?
- What is a proton?
- Strange events: diffraction
- The odderon discovery
- Dark matter in the universe and the LHC

Scales and tools



A long history: searching for fundamental particles



Energy units

1 eV (electron volt) is the amount of energy gained by an electron, when accelerated by a 1 volt battery.

1.5 V

$E_e = 1.5$ eV

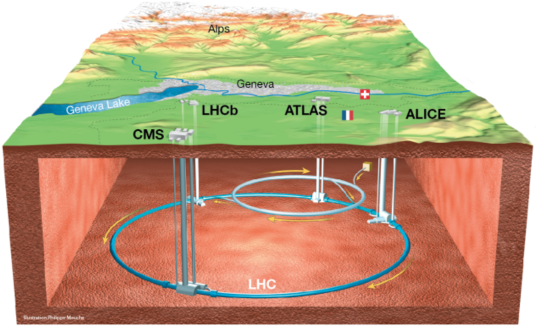
1 eV = 3.8×10^{-23} Calorie

υ = 1,340,000 mph

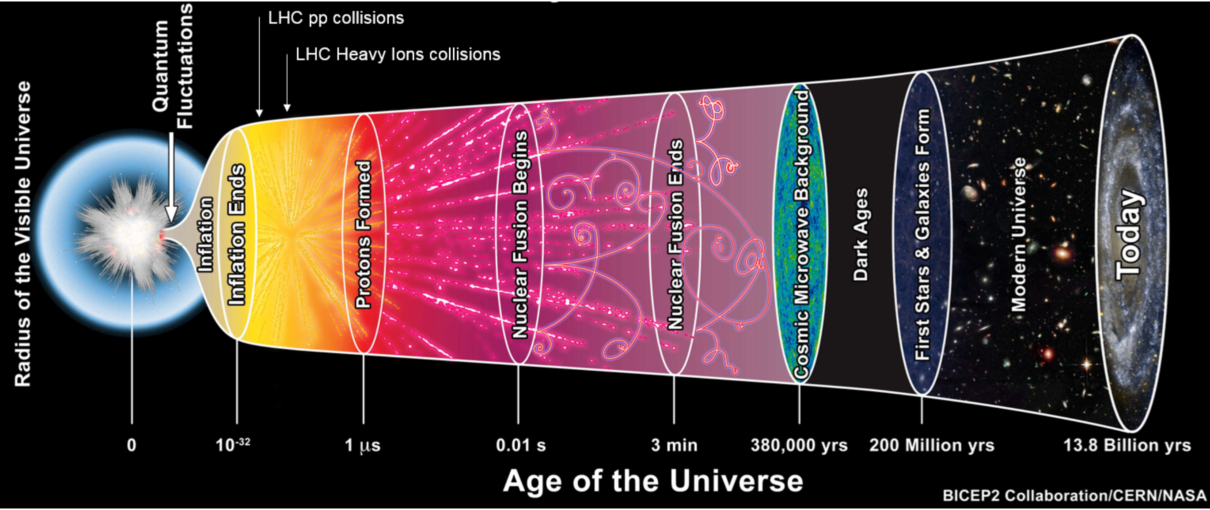
1 keV (kilo electron volt)	10^3 (1,000) eV x-rays, TV
1 MeV (mega electron volt)	10^6 (1,000,000) Radioactivity
1 GeV (giga electron volt)	10^9 Cosmic rays &
1 TeV (tera electron volt)	10^{12} Accelerators

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...?

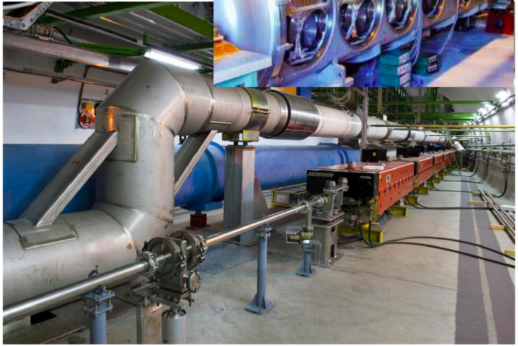
When two proton beams collide, they reach a temperature of 10^{17} degree, albeit over a miniscule area.
(For comparison, the temperature in the Sun’s core is $\sim 10^{7}$ degree)

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!

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.

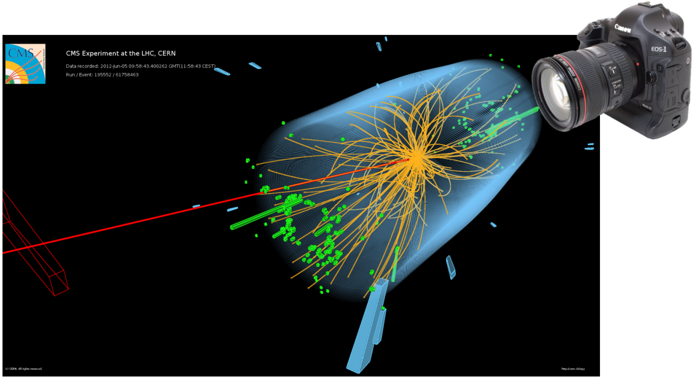


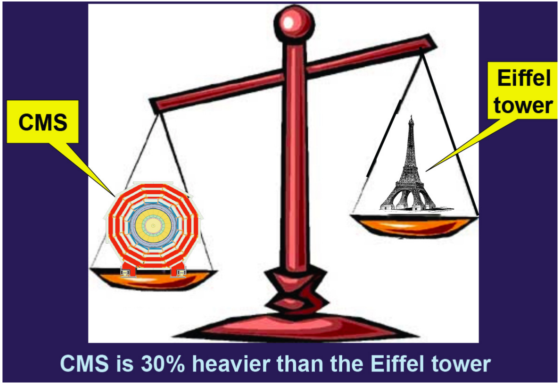
The world's largest refrigerator !

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

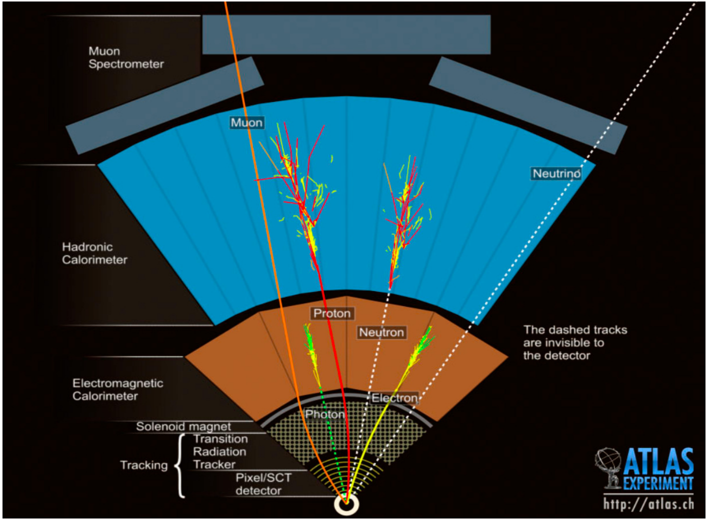
Largest scientific instruments ever built to track particles with micron precision over more than 50 m with over 100 million electronic read-out channels

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.




CMS
Eiffel tower
CMS is 30% heavier than the Eiffel tower

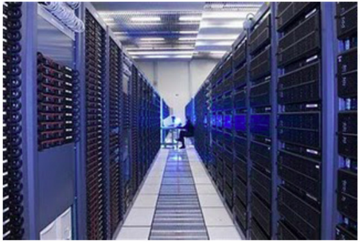
Particle signatures

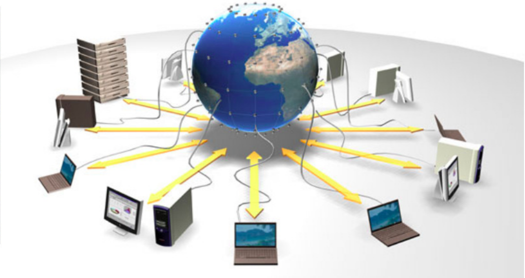


ATLAS and CMS computing

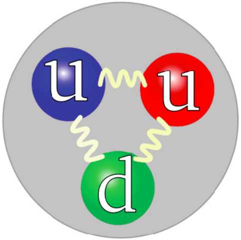
The data recorded by each LHC experiment will fill 2,000,000 DVDs (or 15,000,000 CDs) every year.

Hundreds of thousands of computers around the world are integrated together as a world-wide computing grid like the power grid



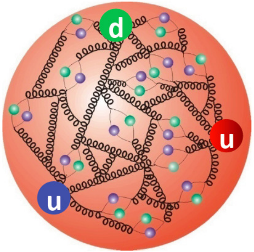


What is a proton?



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

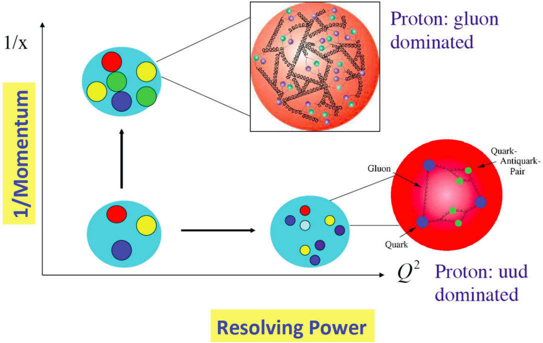
Protons are constituents of nuclei. They are small and have a size of ~10^{-15} m (1 fermi) or about 1/1000 of the size of a hydrogen atom.



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.

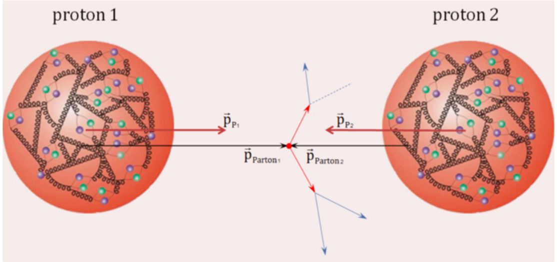
The proton structure

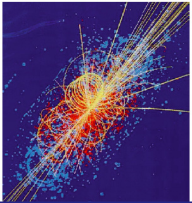


- The proton is a complicated object: it appears differently according to its energy (quantum object)
- Q^2: Resolution power (like a microscope): *the higher the energy of an accelerator is (bigger machines), the higher values of Q^2 (the resolution) and the smaller distances that we can reach*
- x: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

Proton-proton collisions

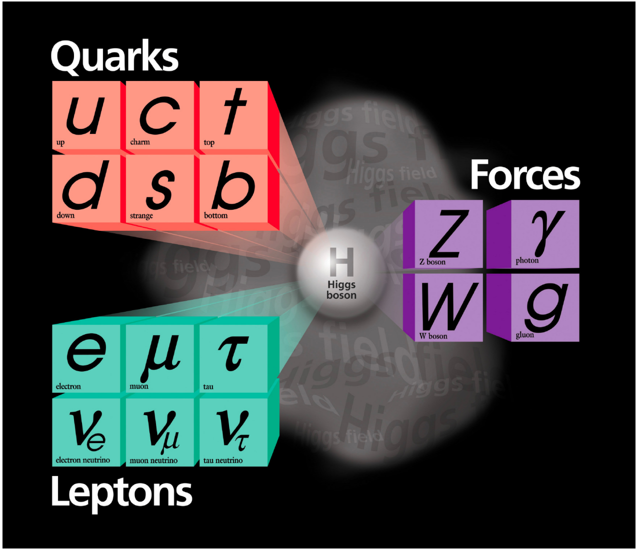
When a proton collides with another proton, the actual collision occurs between quarks and gluons



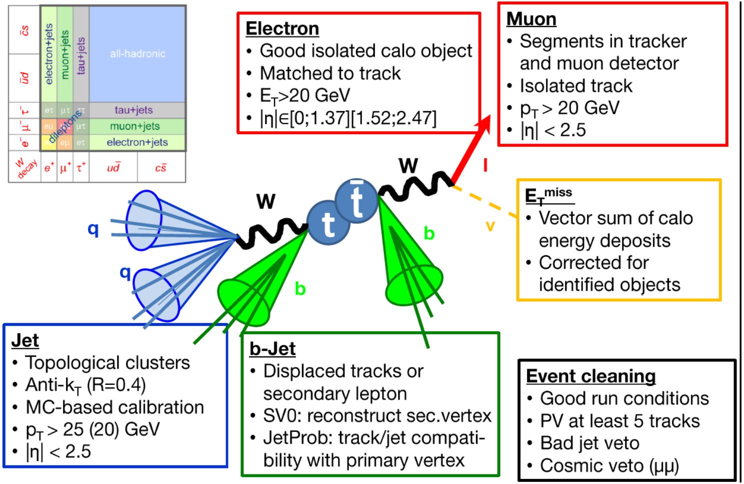


We have no control what process actually takes place! Our job is to figure out what actually happened.

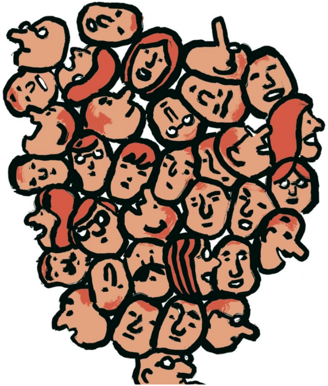
The "Standard Model" of Particle Physics

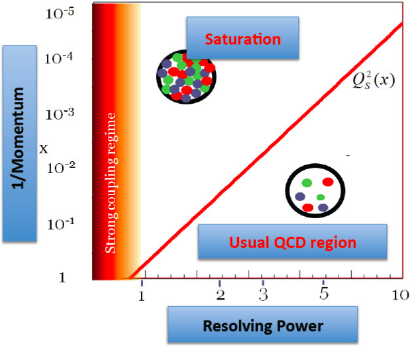


One aside: one example of measurements at the LHC : identifying top quark events



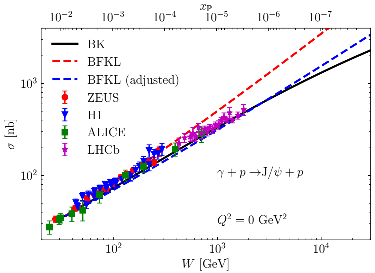
New kinematical domain: saturation

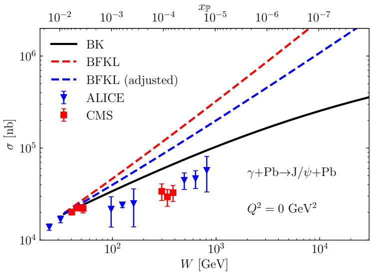


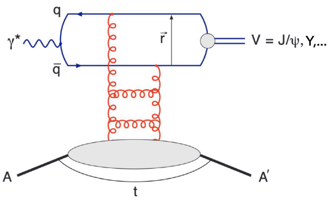


- The proton is even more complicated: Regions where the density of gluons is very large, "saturation"
- The usual equations are no longer valid!
- Can be studied at the LHC and at the future Electron-Ion Collider in the US

Looking for saturation: LHC data

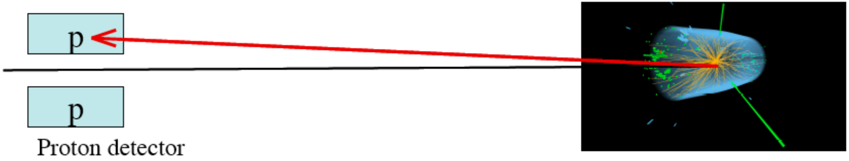






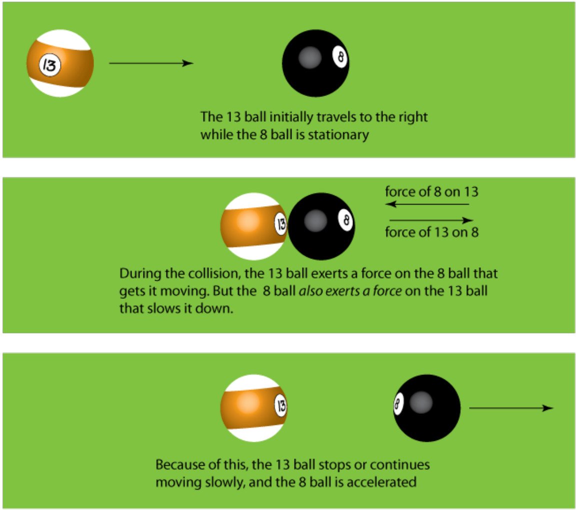
- Use dense objects to look for saturation: Pb instead of protons
- BFKL: no saturation, BK: saturation
- Study effects of saturation for vector meson, *c*, *b* quark

Strange events: intact protons after interaction



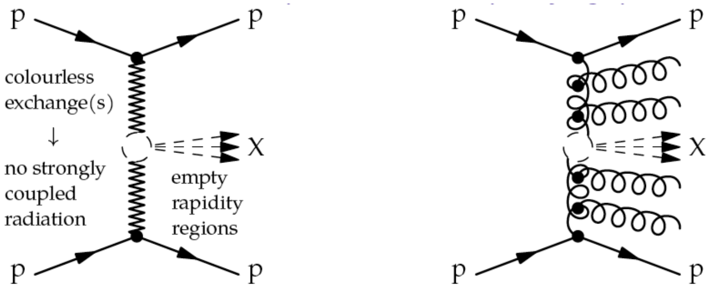
- Some unique events can be produced where the proton is not destroyed! The proton loses part of its energy
- These events are vital to probing extra-dimensions
- An everyday analogy would be an accident between two large trucks (the protons) that lead to the two trucks remaining intact in addition to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

What is elastic scattering? The pool game...



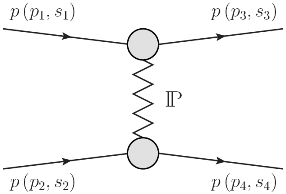
- We want to study "elastic" collisions between protons and proton-antiprotons
- In high energy physics: $pp \to pp$ and $p\bar{p} \to p\bar{p}$
- In these interactions, each proton/antiproton remains intact after interaction but are scattered at some angles and can lose/gain some momentum as in the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

How to explain the fact that protons can be intact?



- Quarks/gluons radiate lots of gluons when one tries to separate them (confinement)
- Gluons exchange color, interact with other gluons in the proton and in that case protons are destroyed in the final state
- In order to explain how protons can remain intact: we need colorless exchanges, or at least 2 gluons to be exchanged

The odderon in a nutshell



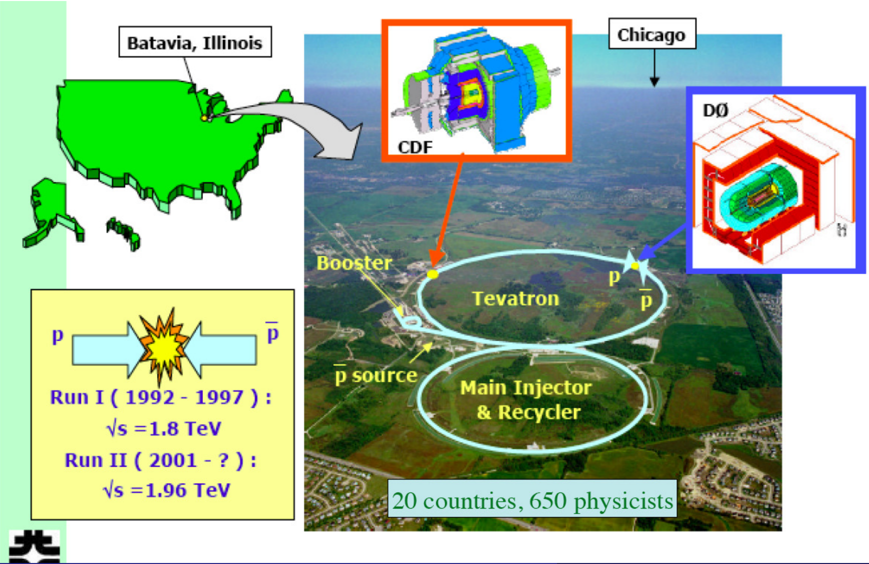
- Let us assume that elastic scattering can be due to exchange of colorless objects: Pomeron and Odderon

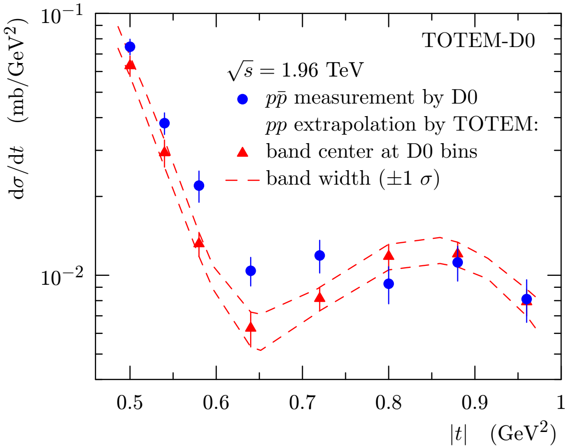
- Pomeron is made of two gluons (or an even number) whereas the odderon is made of 3 gluons (or an odd number)
- Scattering amplitudes can be written as:

$$A_{pp} = Even + Odd$$
$$A_{p\bar{p}} = Even - Odd$$

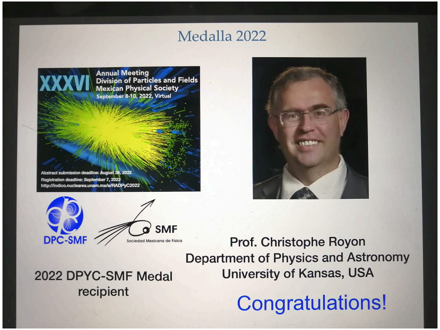
- From the equations above, it is clear that observing a difference between pp and $p\bar{p}$ interactions would be a clear way to observe the odderon

$p\bar{p}$ interactions: the Tevatron

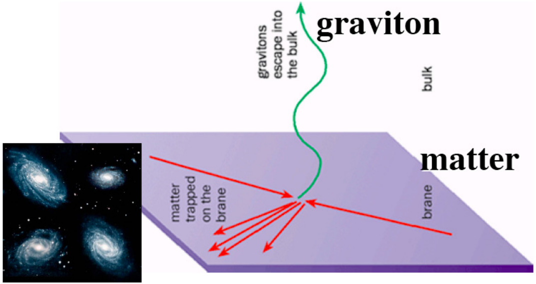




- Comparison between *pp* and *p$\bar{p}$* data
- **Clear difference observed: discovery of the odderon!**

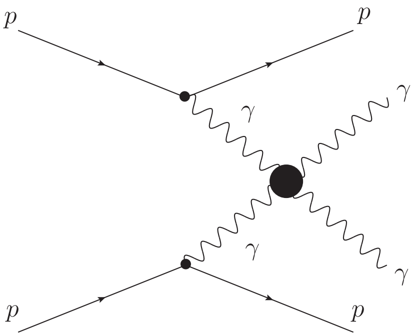


Looking for extra-dimensions in the universe



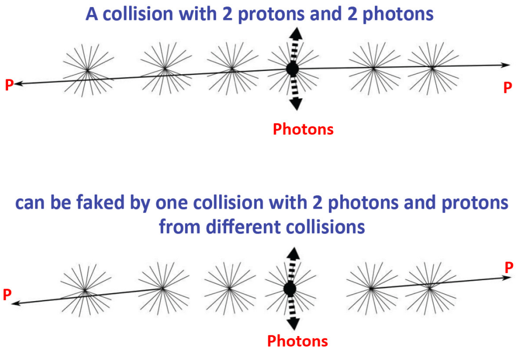
- We live in a 4-dimensional space: space-time continuum
- Gravity might live in extra-dimensions: this idea is being explored at the LHC by looking for new couplings between particles and production of new particles
- If discovered at the LHC, this might lead to major changes in the way we see the world

Search for extra dimensions in the universe using $\gamma\gamma$ and two intact protons



- Search for production of two photons and two intact protons in the final state: $pp \to p\gamma\gamma p$
- Number of events predicted to be increased by extra-dimensions, dark matter particles...
- Discovering those extra-dimensions would be a very fundamental discovery in physics
- Look in other channels: WW, ZZ, $Z\gamma$..

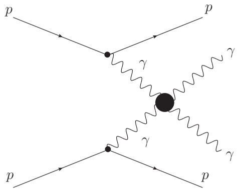
So what is pile up at LHC?

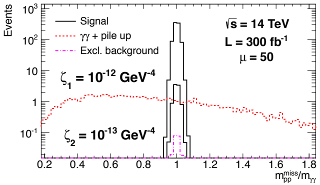


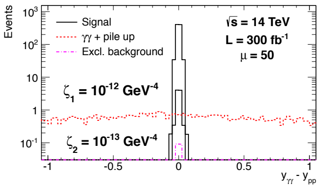
- The LHC collides packets of protons
- Due to high number of protons in one packet, there can be more than one interaction between two protons when the two packets collide
- Typically up to 50 pile up events

Example of an analysis

- We detect all produced particles after interaction: two intact protons and two photons
- Any observation would be a discovery!: no background by requesting same energy balance between the two photons and the two protons

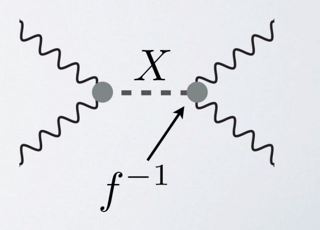


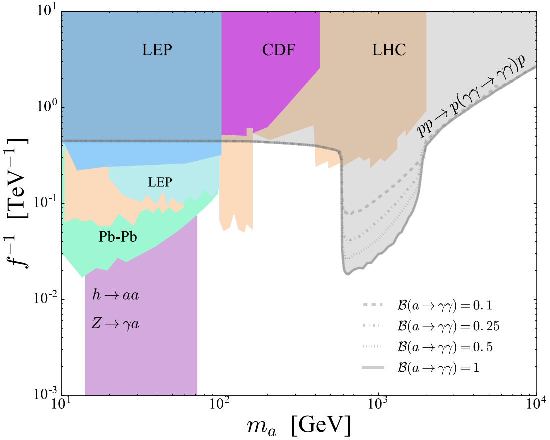




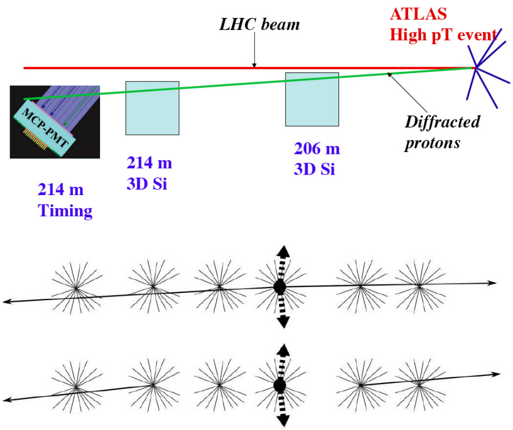
Searching for dark matter, axion-like particles

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





Removing pile up: Measuring proton time-of-flight

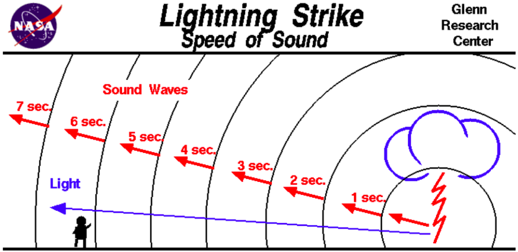


- Measure the proton time-of-flight in order to determine if they originate from the same interaction as the selected photon
- Typical precision: 10 ps means 2.1 mm

Timing measurements: order of magnitude

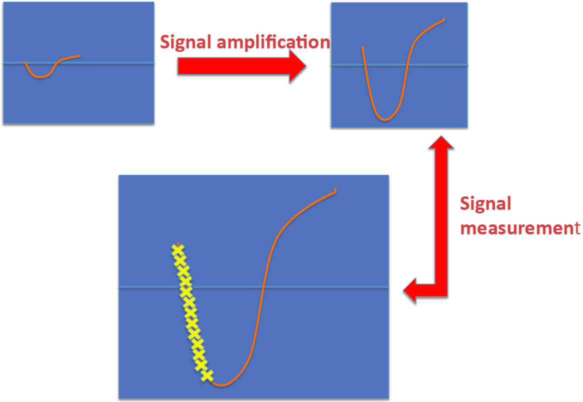
- Everyday life: hour, minute, seconds are typical timescales, we use watches, clocks

Timing measurements: order of magnitude



- Everyday life: hour, minute, seconds are typical timescales
- Speed of sound (thunderstorms) - 343 meters per second: sound travels 343 meters in one second, we always see lightning before hearing it!
- Particles traveling at the speed of light - 300,000 kilometers per second: 0.000000000001 s $= 10^{-12}$s=1 ps; in 10 ps, particles travel 3 mm!

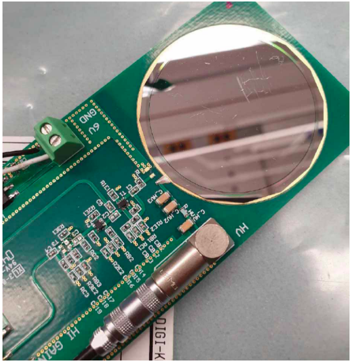
Signal analysis



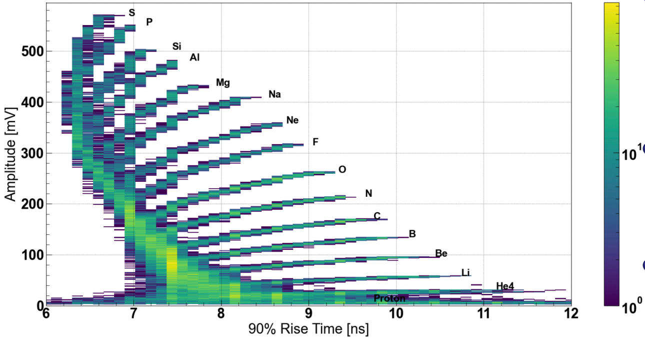
- Amplify the signal
- Measure many points on the fast signal
- Leads to full knowledge of signal: precise timing measurements, and energy/type of particle measurements

Measuring cosmic ray in space: the AGILE project

- We want to measure the type of particles (*p*, *He*, *Fe*, *Pb*, ...) and at the same time their energies
- Analysis of cosmic ray particles: using a cube sat, cheap to be sent into space
- Measure radiation before sending astronauts to Mars
- Another application: measure radiation when people are treated for cancer



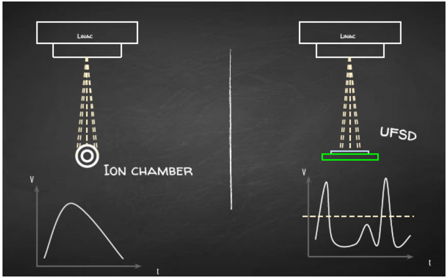
Particle identification with AGILE



- Maximum amplitude vs time needed to reach 90% of maximum of amplitude (rise time) for p-Fe ions stopping in the detector
- Allows to obtain Particle Id since curves do not overlap for many values of rise time
- Inefficiencies for small rise time values where curves overlap

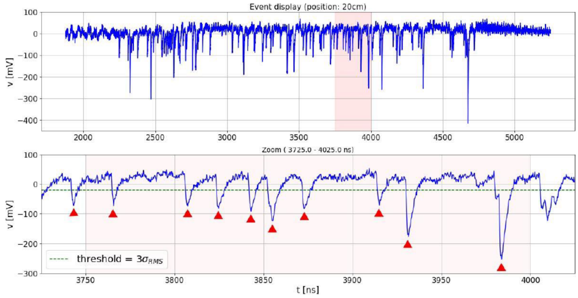
Measuring radiation in cancer treatment

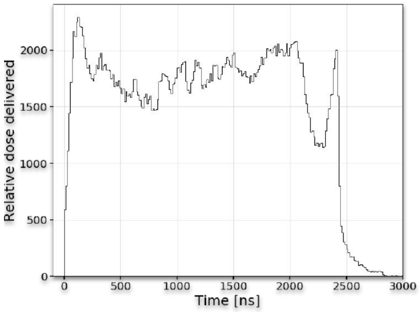
- Ultra fast silicon detectors and readout system were put in an electron beam used in the past for photon therapy at St Luke Hospital, Dublin, Ireland
- Precise and instantaneous measurements of dose during cancer treatment (especially for flash proton beam treatment)
- Develop a fast and efficient detector to count the particles up to a high rate: very precise instantaneous dose measurement, no need of calibration, high granularity (mm^2)



What Si detector can do better: Single particle Id in Dublin hospital

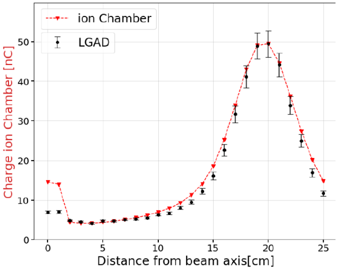
- Use UFSD and their fast signal in order to identify and measure spikes in signal due to particles passing by
- Allows measuring doses almost instantaneously

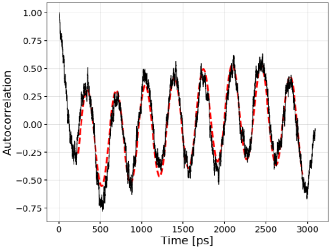




- Very precise dose measurement allowing to adapt better treatment to patients especially for flash dose treatments (brain cancer for instance)

Tests performed at St Luke hospital, University of Dublin, Ireland





- Measurement of charge deposited in Si detector compared to standard measurement using an ion chamber: good correlation
- Our detectors see in addition the beam structure (periodicity of the beam of ∼330 ps, contrary to a few seconds for the ion chamber): measure single particles from the beam
- Fundamental to measure instantaneous doses for high intensity proton therapy as example
- For more details: Arxiv 2101.07134, Phys. Med. Biol. 66 (2021) 135002

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
- Fast timing detectors originally developed for particle physics
- Many applications of timing detectors: medicine, cosmic ray measurements (NASA), measuring doses received during cancer treatment...

One needs to look everywhere