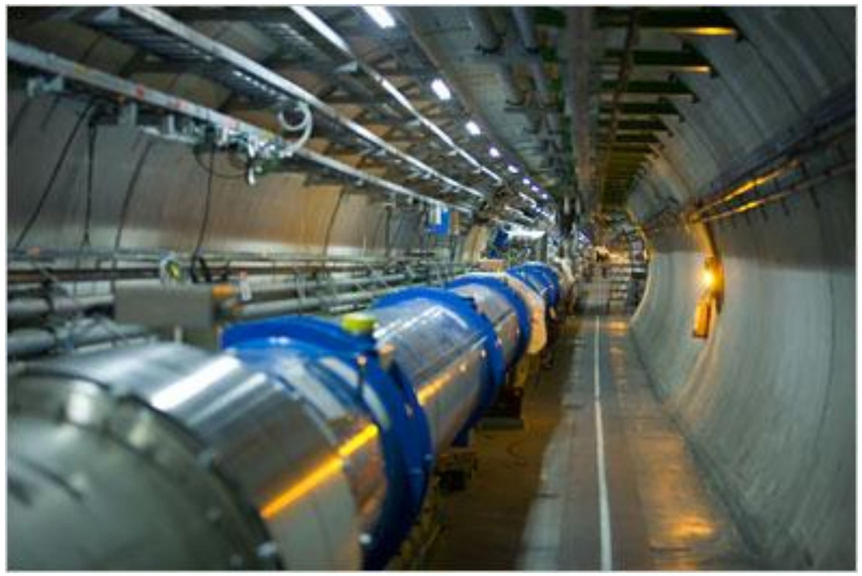
The World's Largest Experiment



Nathan Seiberg, IAS

IIT Delhi & Robosapiens INDIA present

TRYST 2013

1st - 4th March

Commemorating the Weird, Wacky & Wild

The LHC has captured the media and the public attention

The New York Times

Call it the Hubble Telescope of Inner Space

THE TIMES OF INDIA

Higgs boson discovery biggest scientific breakthrough of 2012

REUTERS

Beyond Higgs, CERN searches for unseen particle world

Purpose of this talk

Share the excitement of this ground breaking research.

We will describe

- What we knew before the experiment
- How the experiment works
- What it has already taught us
- What we expect to learn in the future

10^{26}m	Visible Universe
10^{13}m	Solar system
1m	Humans
10^{-10}m	Atoms
10^{-18}m	Particle physics
10^{-35}m	Quantum gravity

The basic rules are understood

Most of this talk

The new frontier

The Standard Model of particle physics

- Principles: quantum mechanics, special relativity
- Matter particles: electrons, quarks…
- Forces: electromagnetic force, strong nuclear force, weak nuclear force

The principles: the three scientific revolutions of the 20^{th} century

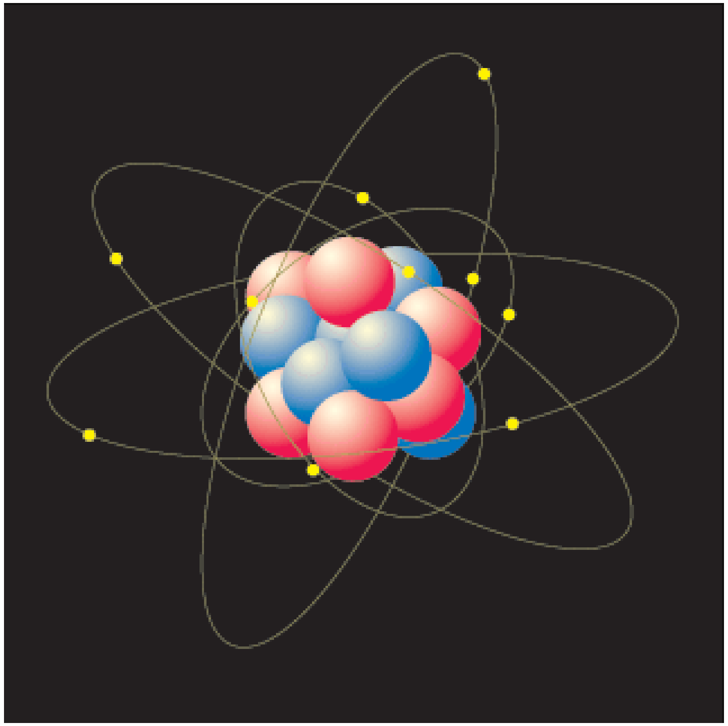
The three revolutionary theories are very counter-intuitive. They apply only in extreme situations, which are far from our everyday experience.

- Quantum mechanics applies to small objects.
  - Fuzziness, uncertainty at short distances…
- Special relativity applies to high velocities.
  - Mixing of space and time, maximum speed…
- General relativity applies to strong gravitational forces.
  - Space and time are curved…

Matter particles

Before the 20th century physicists knew that matter was made of atoms.

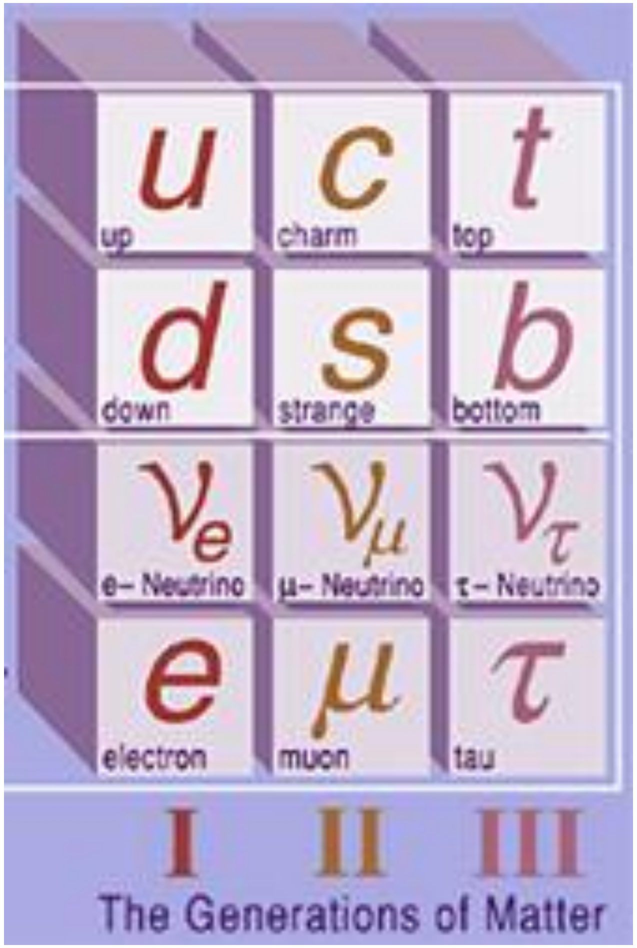
Each atom is made of electrons, protons and neutrons.



By the second half of the 20^{th} century, physicists realized that protons and neutrons are made of quarks.

There are several different species of quarks.

The electron is part of a larger family of particles.



The "periodic table" of matter particles

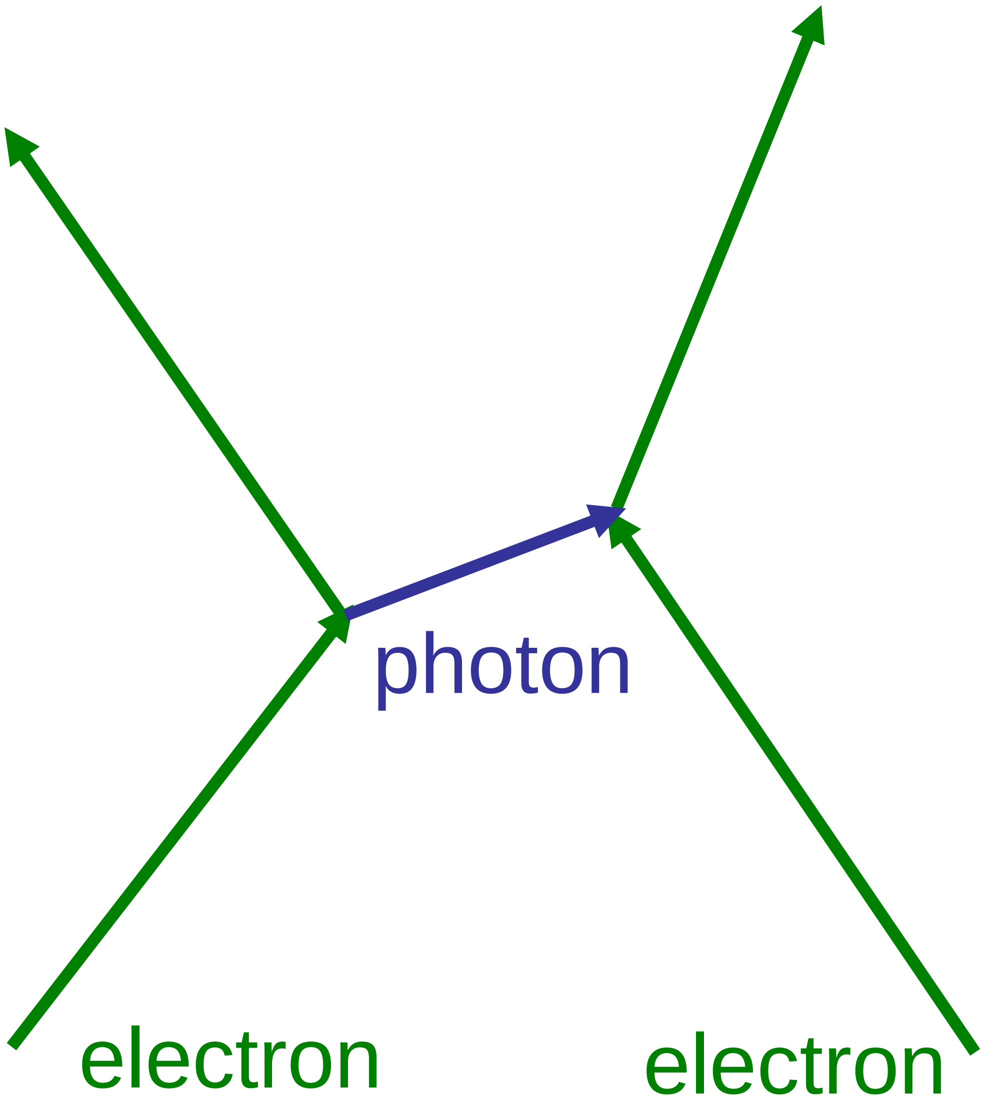
Forces

- Known forces before the 20th century:
  - The electromagnetic force is associated with light.
  - The gravitational force attracts us to the earth, and is responsible for the motion of the stars.

- Forces discovered during the 20th century:
  - The strong nuclear force holds protons and neutrons together in the nucleus and is associated with nuclear energy.
  - The weak nuclear force is associated with radioactive decays.

Forces are mediated by the exchange of "force particles."

For example, the electromagnetic force is mediated by exchanging photons.



The Higgs particle

- This is another kind of force particle.
- This particle gives mass to matter particles and to the particles of the weak force. (Quite technical, no simple intuitive explanation)
- The Higgs particle had not been discovered before the LHC. It was expected to be found there. And indeed it was.

Peter Higgs

The Standard Model is extremely successful

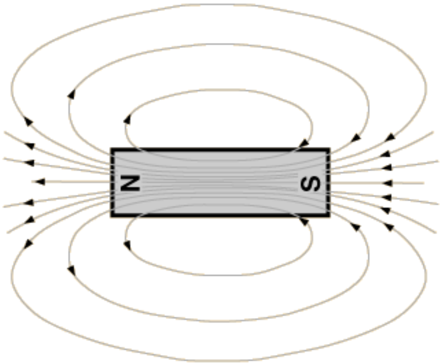
- Small number of parameters (like particle masses) explain many experimental results.

- It is not contradicted by any known experiment!

- Unprecedented success…

Example of the success of the Standard Model

An electron is like a little magnet.



Theoretically, its strength (in natural units) is

1.001 159 652 …

Experimentally it is *1.001 159 652 18...*

Spectacular success!

This example is not typical!

Most quantities are not calculable.

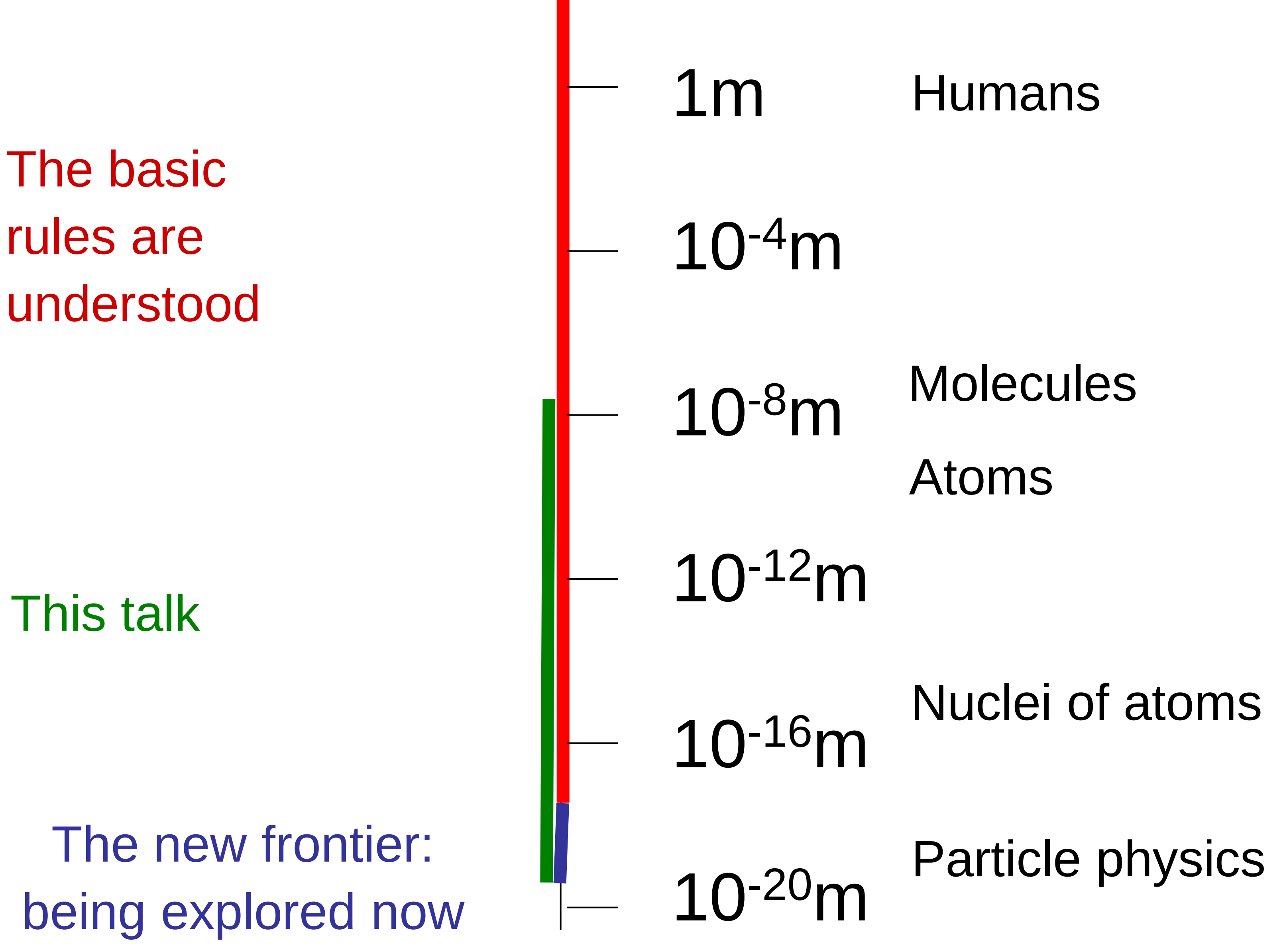
Open problems

- The LHC has already discovered the Higgs particle.

- Explain the Standard Model:
  - Origin of particles, the "periodic table", etc.
  - Origin of forces, their number, their strengths, etc.
  - Origin of the parameters like masses of particles (most of the parameters in the Standard Model are associated with the Higgs particle).

- What are the dark matter (explained later) and dark energy of the Universe?

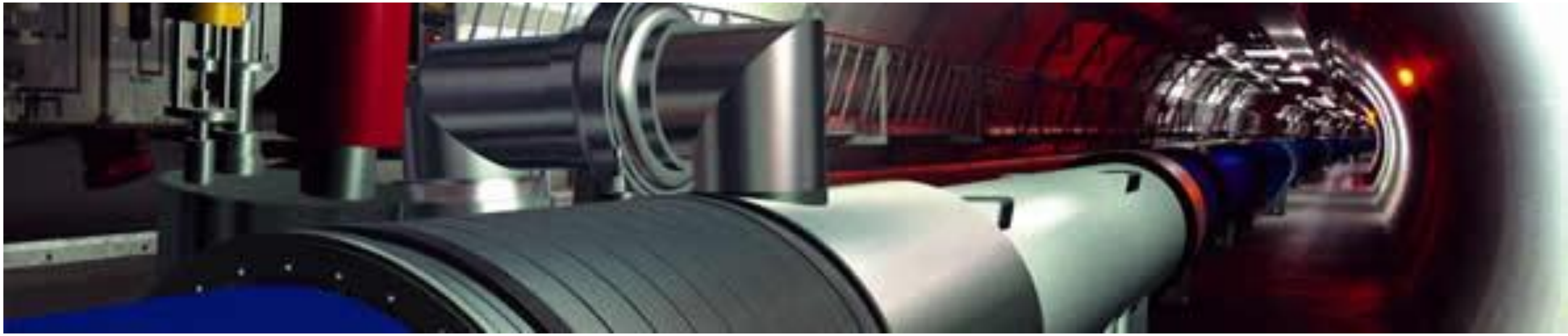
- Include the gravitational force (string theory?).


The basic rules are understood
This talk
The new frontier: being explored now
1m
10^{-4}m
10^{-8}m
10^{-12}m
10^{-16}m
10^{-20}m
Humans
Molecules
Atoms
Nuclei of atoms
Particle physics

Exploring the shorter distance frontier

Short distances are studied with a powerful “microscope” – an accelerator.

The physics at distances around 10^{-19}m was explored at the Tevatron in Fermilab near Chicago. Now it is being studied at the LHC in CERN in Geneva, Switzerland.



LHC

The Large Hadron* Collider (LHC) is located at the European Centre for Nuclear Research (CERN).

Its approximately €7.5 bn cost is paid by contributions from various countries, mostly in Europe.

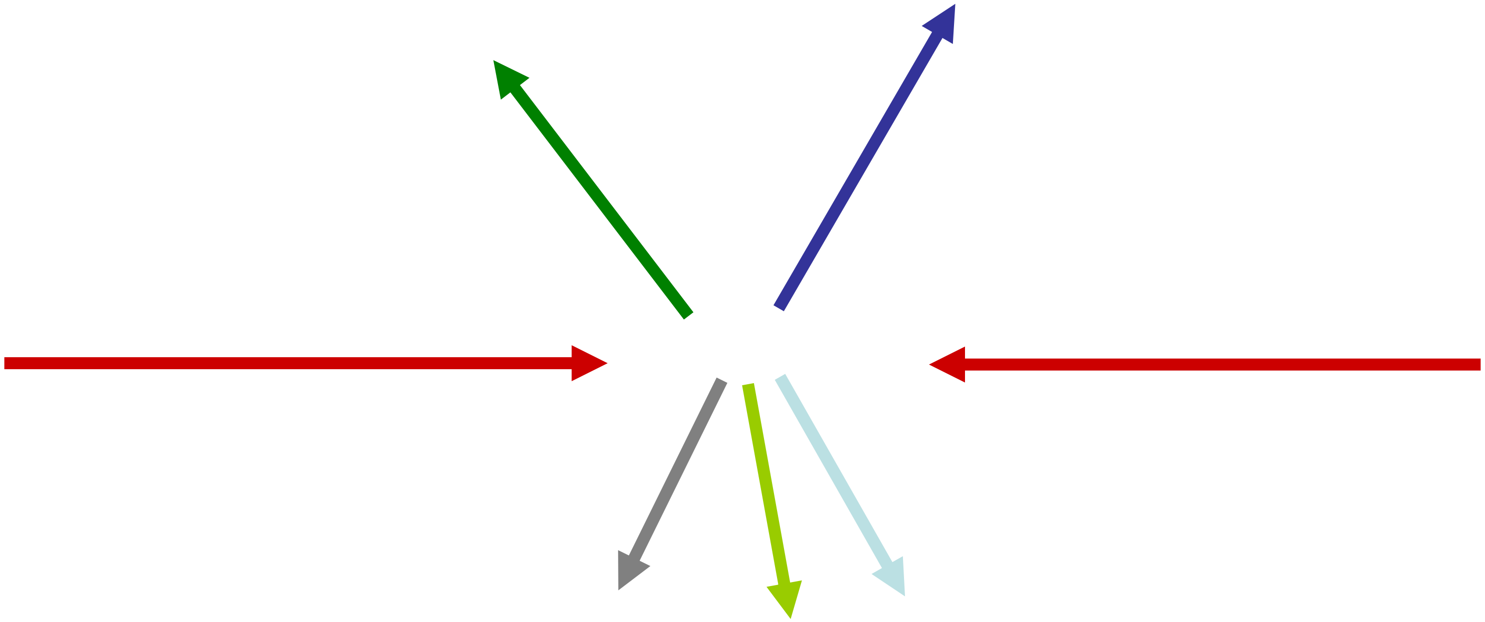
More than 10,000 scientists and engineers from over 100 countries are involved.

* A Hadron is a particle made of quarks. In this case it refers to a proton.

The protons move in a tunnel. It is about 100m below ground and its circumference is 27Km (17miles).

The LHC accelerates protons and collides them.

Detectors explore the debris of these collisions.



Time Line

- September 2008 – The LHC starts working, but an explosion forces a shutdown
- November 2009 – The LHC starts operating again far below the design energy
- March 2010 – The LHC runs at half the design energy
- July 2012 – Discovery of a Higgs particle
- February 2013 – Shutdown for upgrade
- 2015 – Run at close to the design energy

LHC – the accelerator

- Need very high energy for short distance resolution (less than one thousandth the size of a proton).

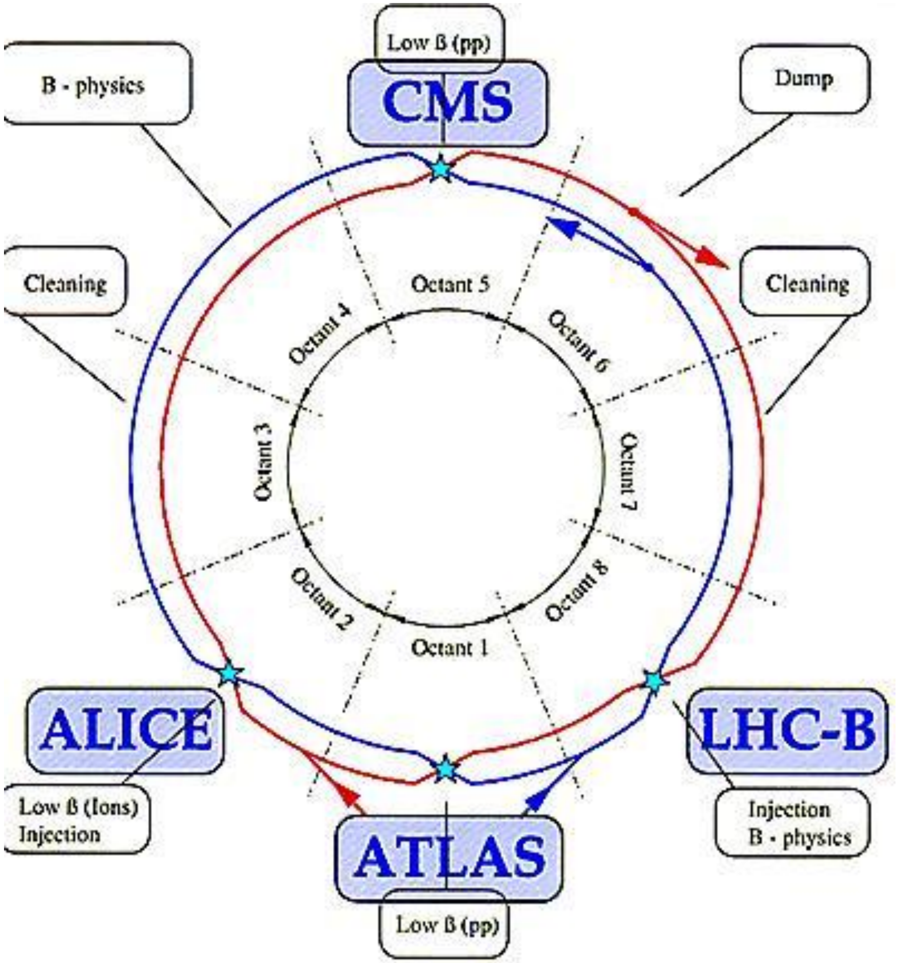
- Need very high luminosity – many collisions per second for sensitivity to tiny effects.

Original design: Collide two protons each with energy 7TeV (currently "only" 4TeV; after the shutdown and the upgrade 6.5TeV).

This is roughly the kinetic energy of a flying mosquito. (But each mosquito has 10^{23} protons.)

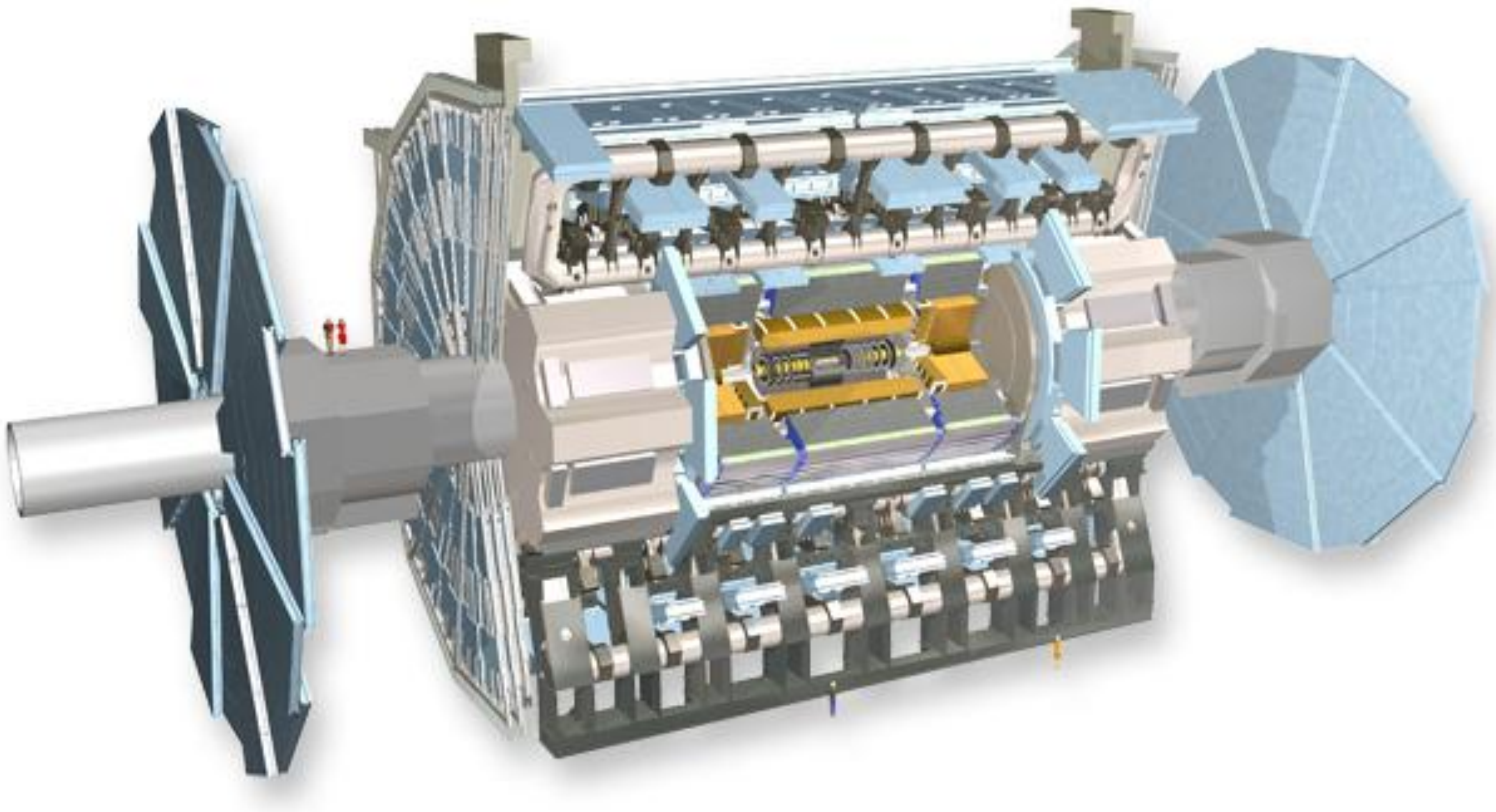
The total energy in the beam is comparable to an aircraft carrier moving at about 10 knots.

- There are two tubes in the tunnel in which protons move in opposite directions.
- These protons collide at four points, where the two tubes cross each other.
- These protons are in around 1000 bunches (eventually 3000) of 10^{11} protons in each. These bunches pass every 25-75 ns (nanosecond, one billionth of a second).



LHC – Detectors

The ATLAS detector is about the size of a five story building.



- There are about a billion collisions per second in each detector.
- Only 10 – 100 of the billion collisions per second are interesting.
- Very interesting collisions, signaling new physics, happen only every few hours or days.

- The detectors record and store “only” around 100 collisions per second. An online computer decides in real time which collisions to record.

- The total amount of data to be stored is 15 petabytes (15 million gigabytes) a year.

  It would take a stack of CDs 20Km tall per year.

What will the LHC find?

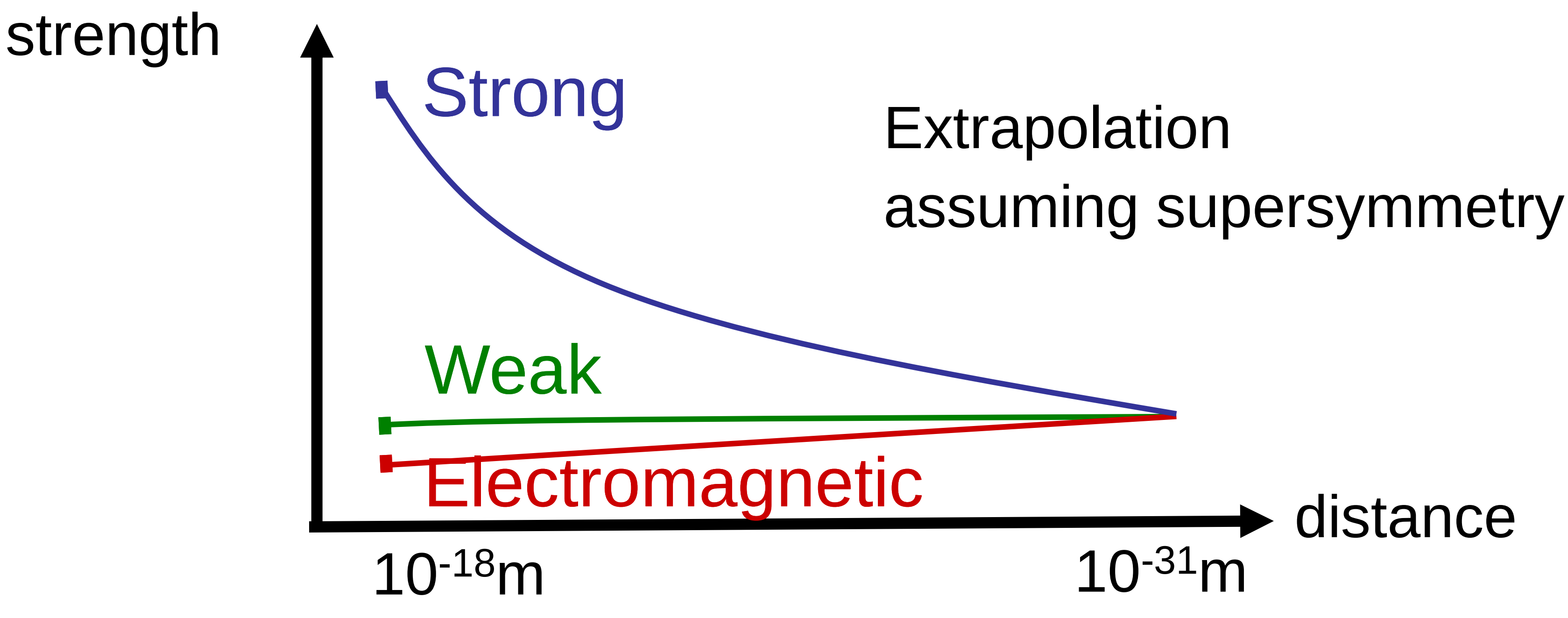
- We do not know.
- Search for the Higgs particle ✓ and explore its properties. This will complete the picture of the Standard Model and will clarify the origin of mass.
- Find more particles. This will reflect new physics at a shorter distance.
- The leading candidate for such new physics is supersymmetry.

Supersymmetry

- Unification of matter and forces – matter particles are paired with force particles.
- According to supersymmetry every force particle has a “sister’’ matter particle.
- Known matter particles (electrons, quarks…) are related to heavier force particles. For example, the electron’s sister is called a “selectron.”
- Known force particles (photons…) are related to heavier matter particles.

Why supersymmetry?
Unification of forces

- The strength of each force depends on the distance.
- Use the known measured values of the strengths and extrapolate them to shorter distances.



- With supersymmetry the strengths of the distinct forces become equal at a certain distance.
- This suggests that they can be unified there to a single force.
- Such unification of forces can explain other facts, *e.g.* some aspects of the “periodic table” of matter particles.

Why supersymmetry?
Dark matter

- Recent astronomical results show that only 1/6 of the matter in the Universe is made out of particles we know of – the particles in the Standard Model.

- Supersymmetry naturally leads to a new, stable particle, which might be the dark matter:
  - It does not interact with electromagnetism, and therefore appears dark.
  - It has mass, it interacts with gravity, and can be detected indirectly.
  - It is stable, and therefore cannot decay and disappear.

Why supersymmetry? Other motivations

- It explains why the scale of quantum gravity, 10^{-35}m, is so much shorter than the scale of particle physics, 10^{-18}m (more technical).

- Supersymmetry arises naturally in string theory. (It was originally motivated by string theory.)

- Beautiful theoretical idea
  - unifying matter particles and force particles
  - many applications in other branches of physics and mathematics

- None of the previous motivations prove it, but they suggest that supersymmetry might be discovered at the LHC.

- Supersymmetry could be wrong. There might be another theory addressing the same issues. The LHC could find the experimental signatures of this other theory.
  - One possibility is the existence of new strong forces whose range is extremely short.
  - Another possibility is the existence of more space dimensions of extremely small size.
  - There might be something else that we have not yet thought of.

Conclusions

- The Standard Model of particle physics is extremely successful. It explains all phenomena at distances larger than 10^{-18}m.
- The LHC explores the physics at shorter distances.
- The LHC has already discovered the Higgs particle.
- We do not know what else the LHC will find.
- It could lead to new insights about the structure of matter, forces, mass, origin of the Universe and the nature of space and time.

Many physicists are eagerly waiting for the results of the measurements and anticipate that the discoveries at the LHC will be very exciting.

They will stimulate scientific research for decades to come.

To be continued…