

The World's Largest Experiment

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IAS

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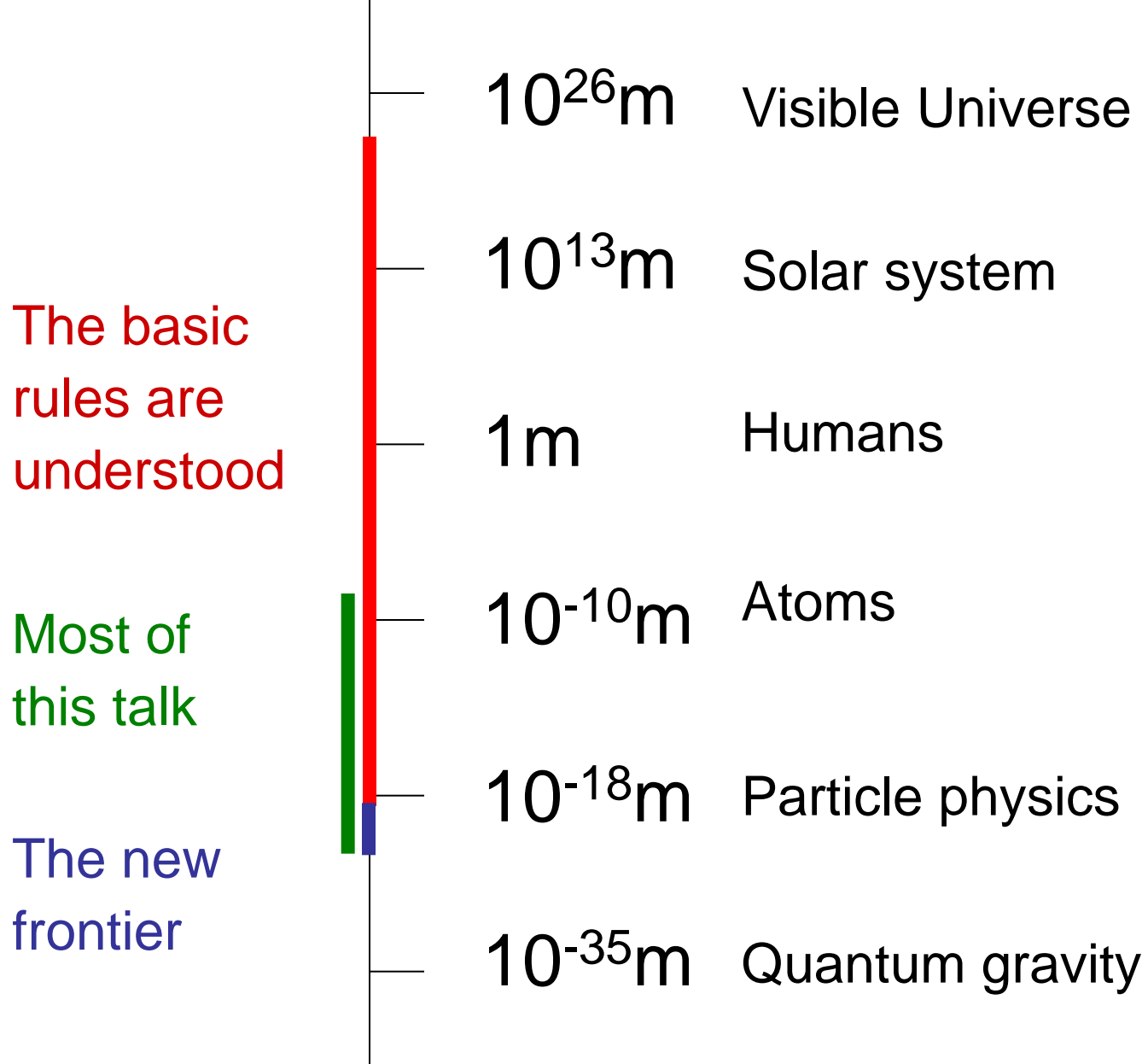
Length scales in natural sciences involve large ratios

Examples of large ratios:

$$\frac{\text{Length of a football field}}{\text{Size of a pin hole}} = 100,000 = 10^5$$

$$\frac{\text{Size of the earth}}{\text{Length of a football field}} = 100,000 = 10^5$$

$$\frac{\text{Size of the earth}}{\text{Size of a pin hole}} = 10,000,000,000 = 10^{10}$$



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 20th century

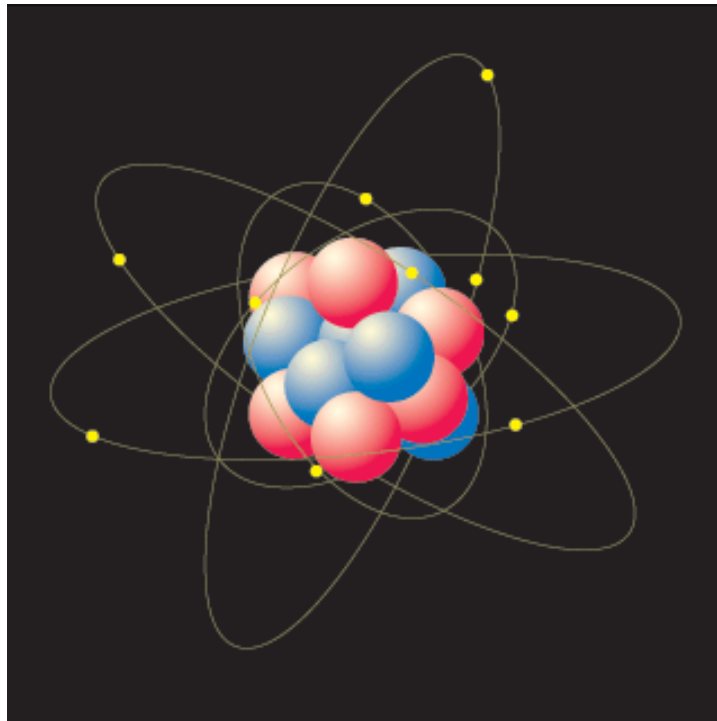
The three revolutions are very counter-intuitive. They apply only in extreme situations which are far from our everyday experience.

- **Quantum mechanics** applies to small objects.
 - Fuzziness, uncertainty at short distances...
- **Special relativity** applies to high velocities.
 - Mixing of space and time, maximal velocity...
- **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.

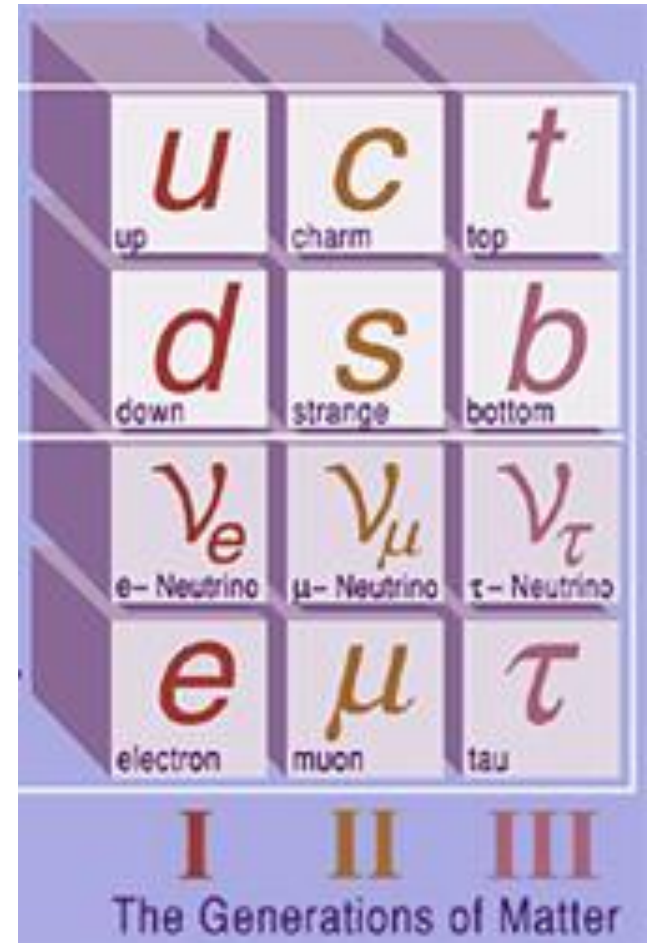
Each atom is made of **electrons**, **protons** and **neutrons**.



By the second half of the 20th 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.



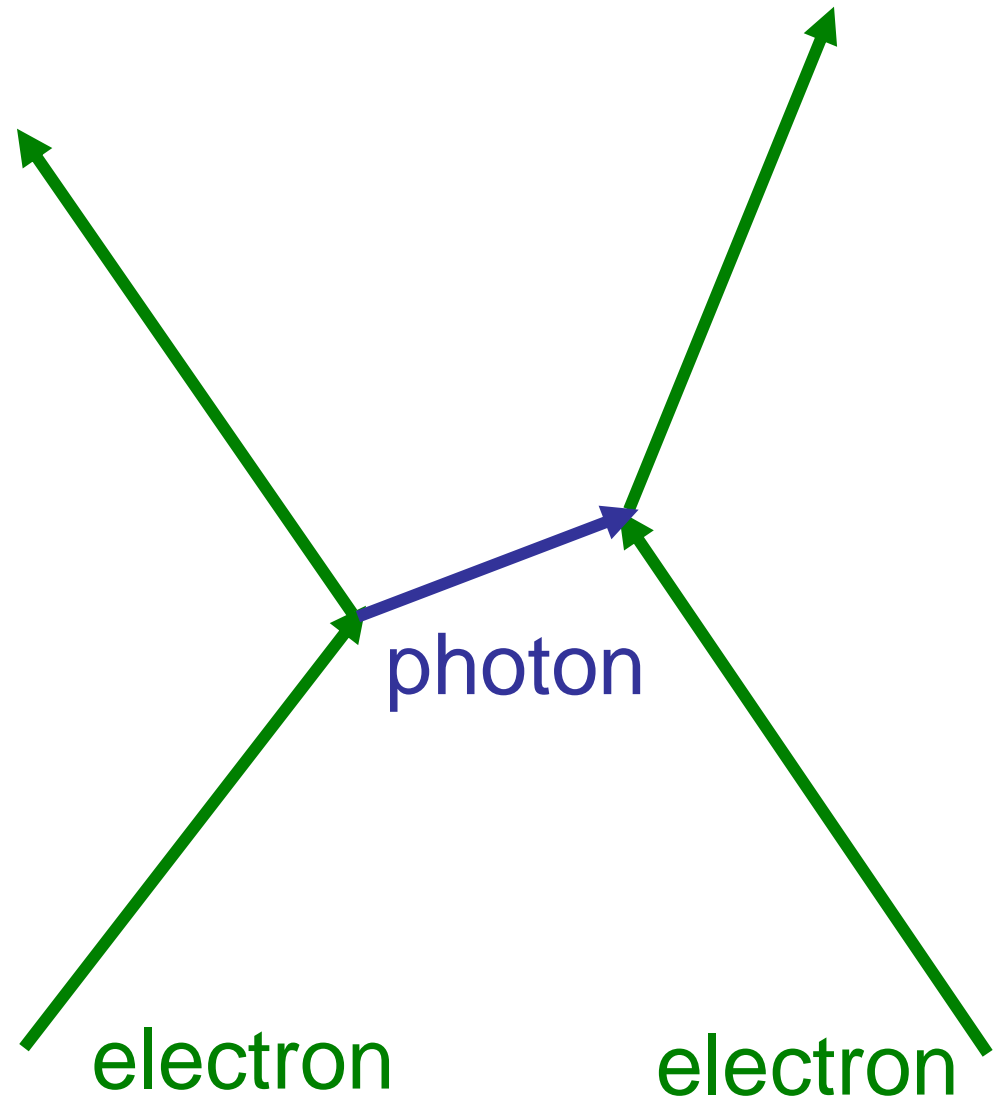
The “periodic table”
of matter particles

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.



Higgs particle

- This is another kind of force particle.
- This particle **gives mass** to matter particles and to the particles of the weak force.
- The Higgs particle has not yet been directly detected. Presumably, it is beyond the reach of our best experiments.



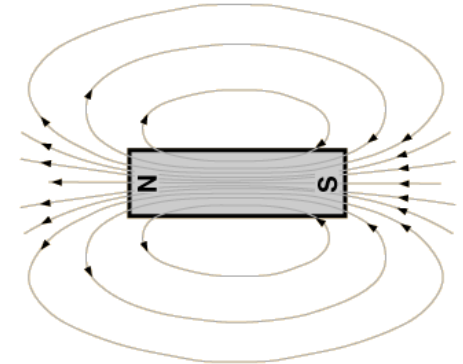
Peter Higgs

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.

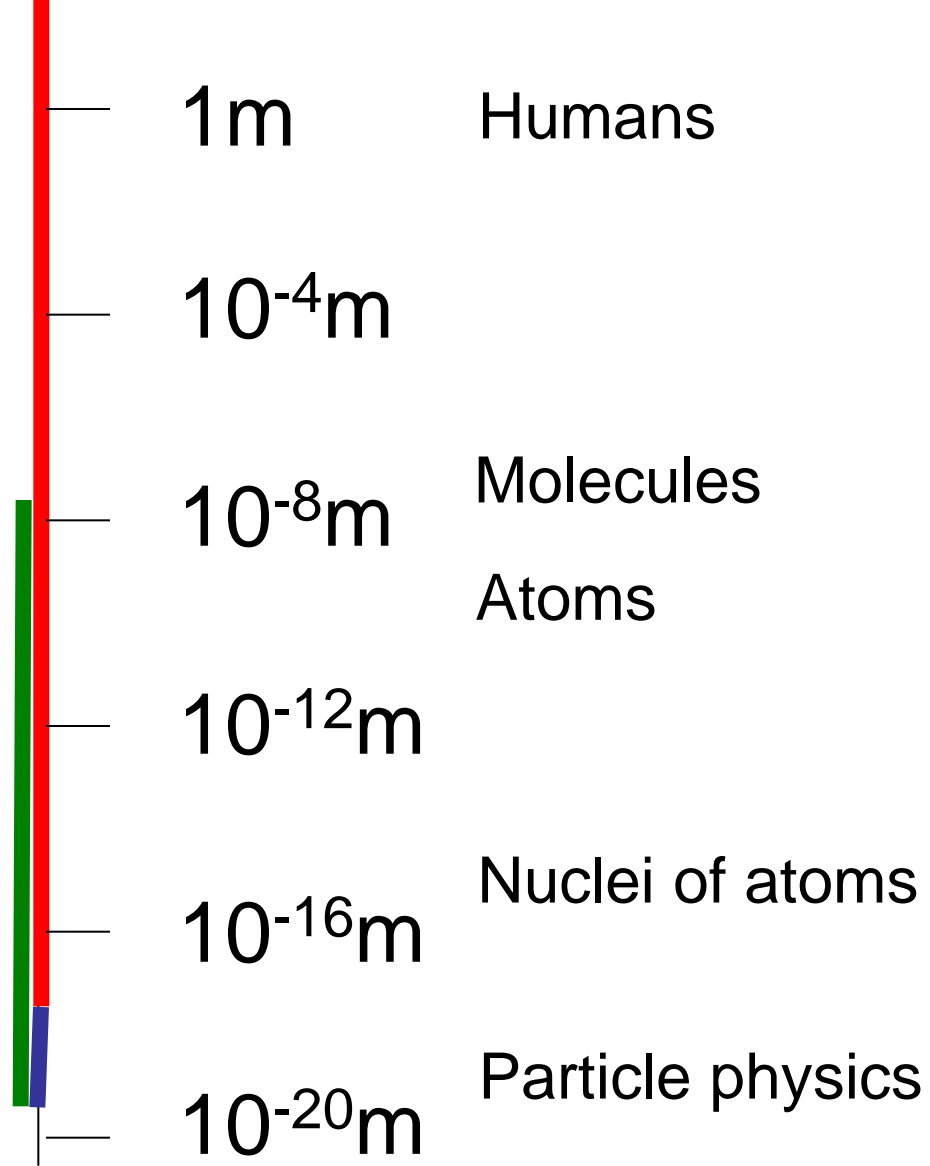
Open problems

- Find 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:
to be explored soon

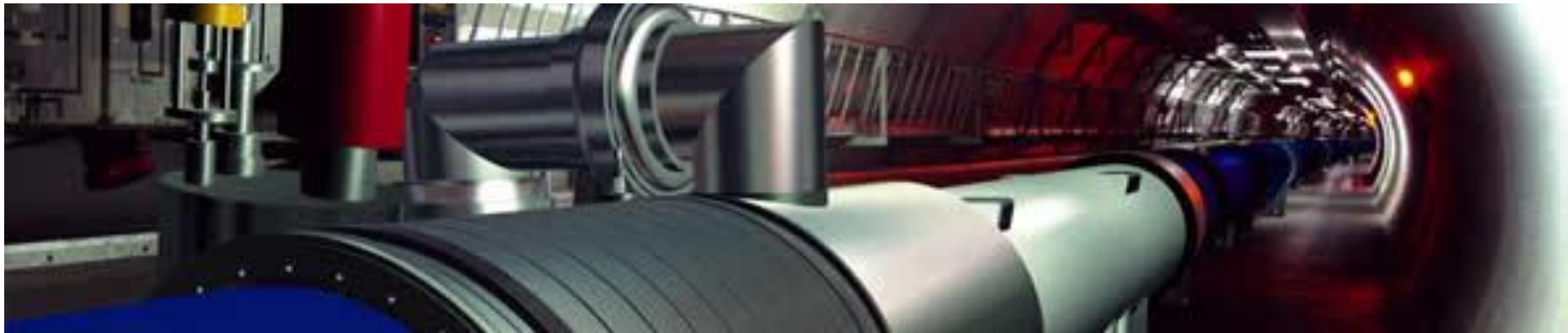


Exploring the shorter distance frontier

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

The physics at distances around 10^{-19}m is being explored at **Fermilab** near Chicago, and will be explored at **CERN** in Geneva, Switzerland.

The results are expected in a few years.



LHC

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

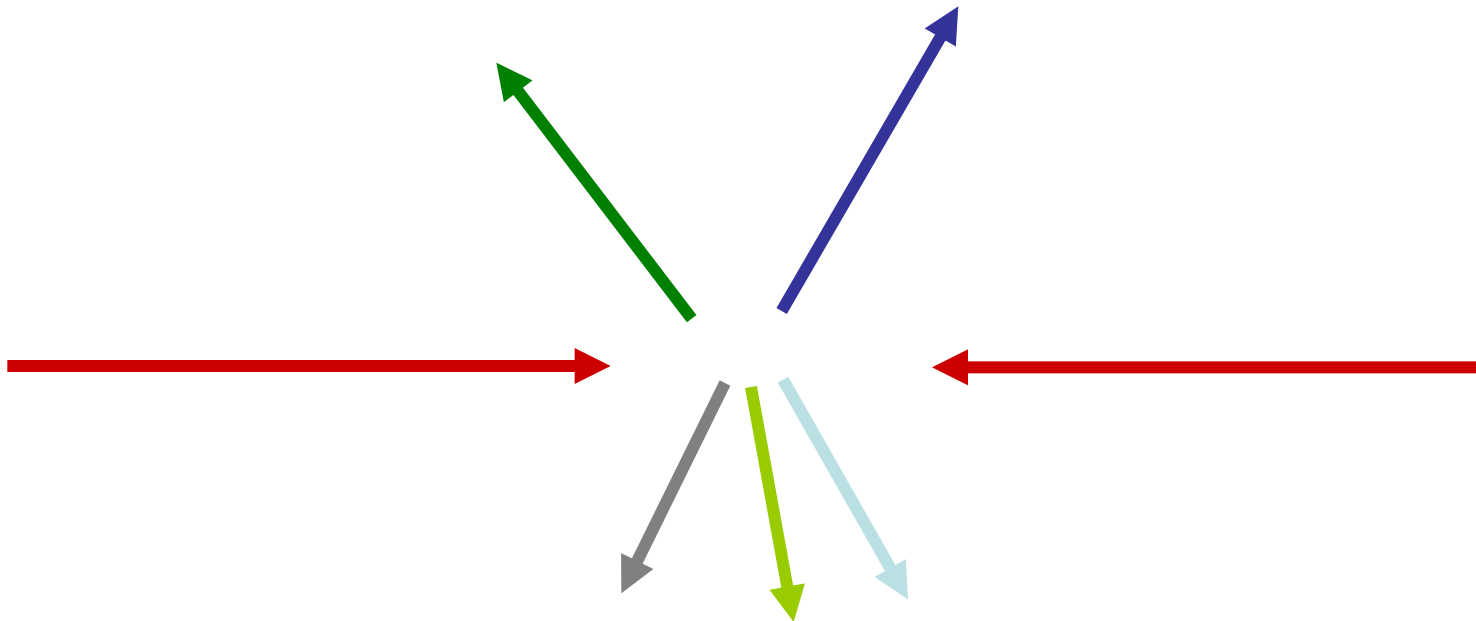
Its approximately \$2.5 billion cost is paid by contributions from various countries, mostly in Europe.

The US contribution is \$0.5 billion.

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

The LHC will accelerate protons and will collide them.

Detectors will explore the debris of these collisions.



LHC – the accelerator

- Need **very high energy** for short distances resolution (less than one thousandth the size of a proton).
- Need **very high luminosity** – many collisions per second for sensitivity to tiny effects.



Collide **two protons** each with energy **7TeV**.

(1TeV is roughly the kinetic energy of a flying mosquito. This energy is squeezed into a region 10^{-12} of a mosquito.)

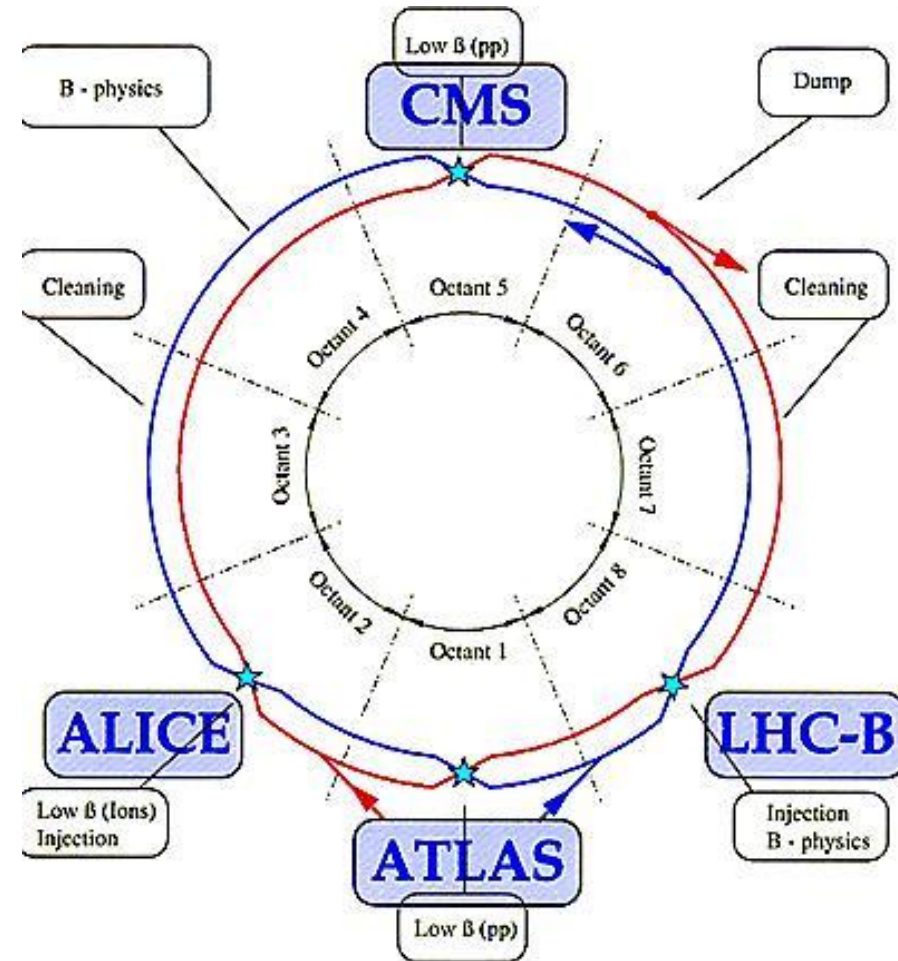
The total energy in the beam is comparable to an aircraft carrier moving at about 10 knots.





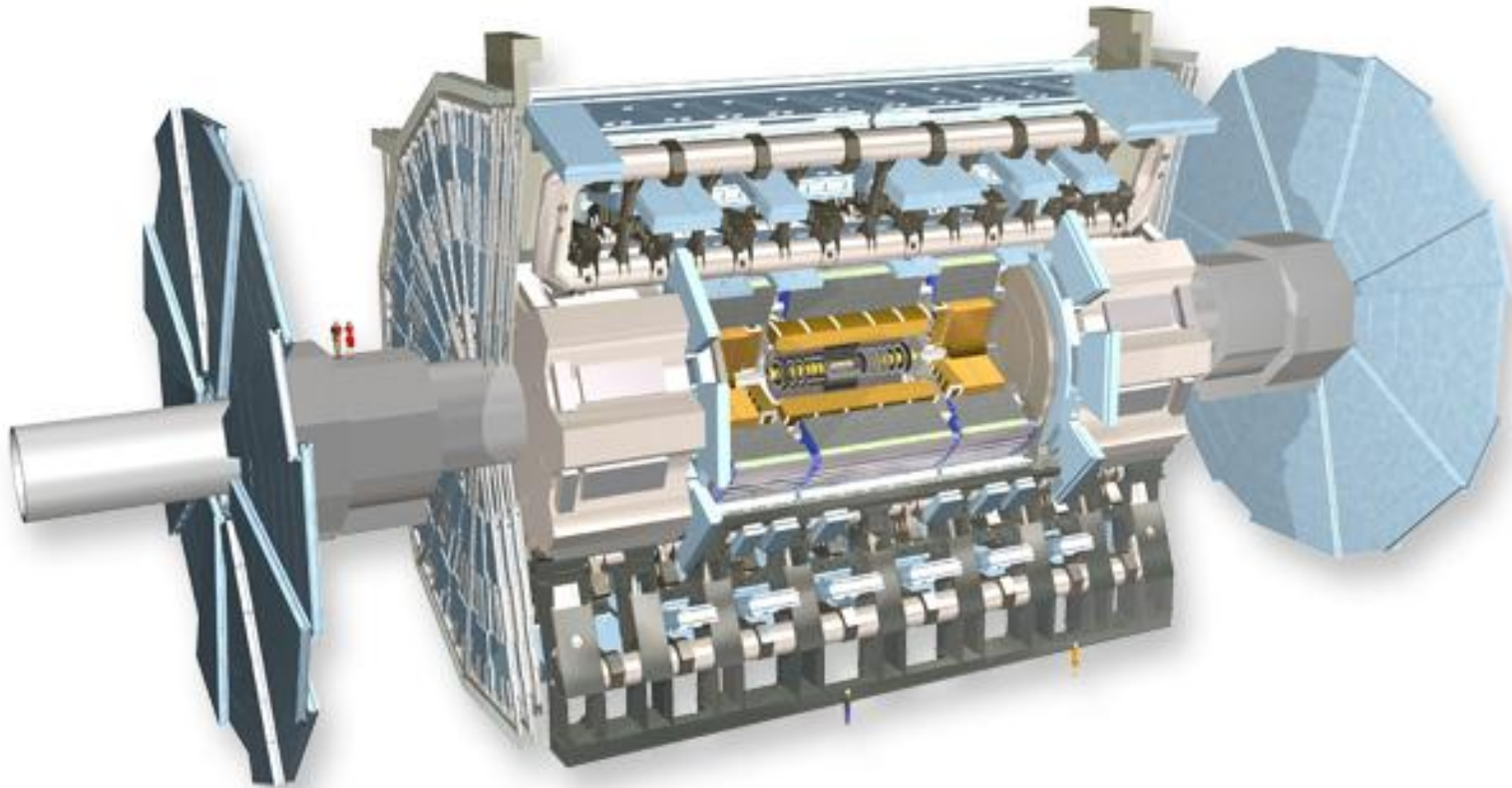
The protons will move in a tunnel. It is about 100m below ground and its circumference is 27Km (17miles).

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



LHC – Detectors

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



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

- The detectors will record and stores “only” around **100 collisions per second**. An online computer will decide in real time which collisions to record.
- The total amount of data to be stored will be 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 could reflect **new physics** at a shorter distance.
- The leading candidate for such new physics is supersymmetry.

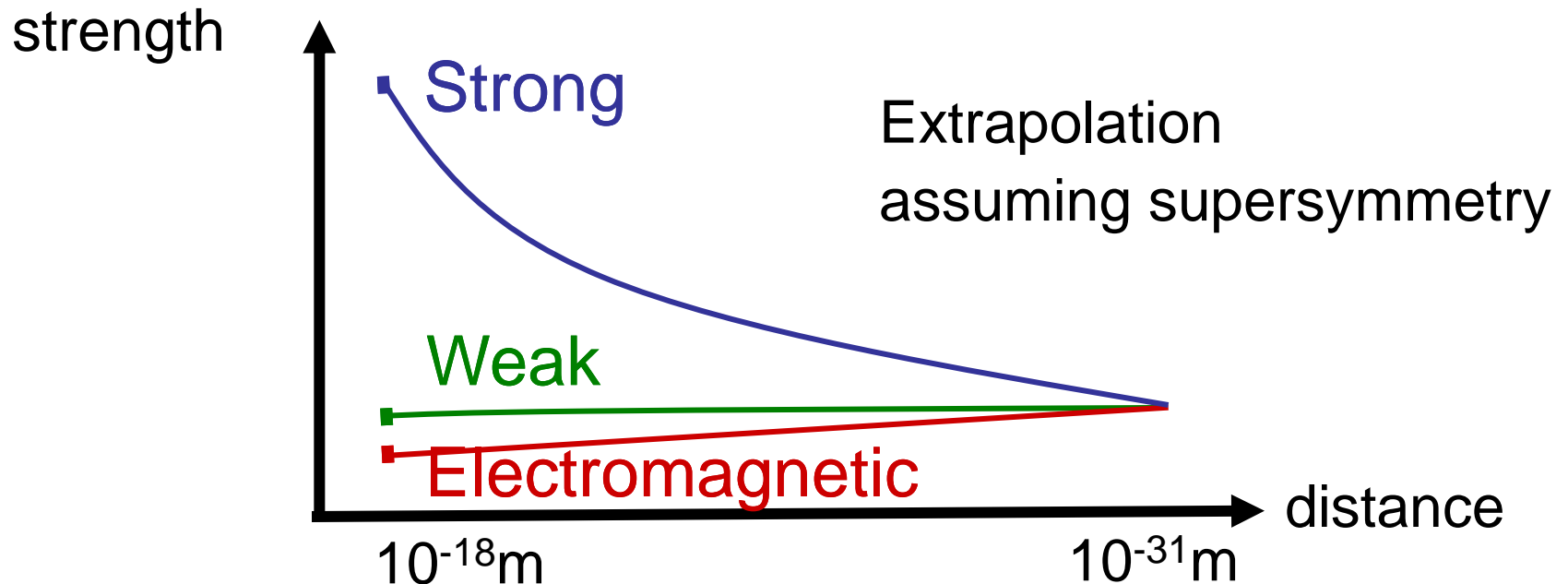
Supersymmetry

- **Unification of matter and forces** – matter particles are paired with force particles.
- According to supersymmetry every force particle has a “sister” matter particle. For example, the **electron**’s sister is called a “**selectron**.”
- Known matter particles (electrons, quarks...) are related to heavier force particles.
- 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 indirectly detected.
 - 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 which we have not yet thought of.

After the LHC

A possible **upgrade** of the **LHC** has been discussed.

An **International Linear Collider** (ILC) could give more details about supersymmetry or any other discoveries at LHC. (This year a committee of the National Academies strongly endorsed the ILC.)

The ultimate goal is to **include gravity**. The leading (known) theory which includes gravity is **string theory**.

Conclusions

- The **Standard Model of particle physics** is extremely successful. It explains all phenomena at distances larger than 10^{-18}m .
- The **LHC** will explore the physics at shorter distances.
- We do not know what 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.
- **Supersymmetry** is the most likely candidate to be experimentally discovered at the LHC.

Many physicists are eagerly waiting for the LHC and anticipate that its discoveries will be very exciting. They will stimulate scientific research for decades to come.

To be continued...