

# NEXT STEPS IN PARTICLE PHYSICS

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“Particle physics” is a loose way  
of talking ...

It is a modern name for the  
centuries old effort to  
understand the laws of nature

Astronomy, thermodynamics,  
chemistry, atomic physics ...  
many areas of science have  
played a role

We talk about “particle physics” as a short hand for this quest because in the 20<sup>th</sup> century it turned out that the subatomic particles do play an important role ...

Moreover, there are crucial parts of the puzzle that we can only learn by going to the shortest distances, as we do with accelerators





The energy that can be reached depends on the size, and also the strength of the magnetic field that is used to bend the particles in their orbits

Very large accelerators are “colliders” because of the theory of relativity

To give you an idea of the progress that has been made, when I was a graduate student the highest available energy for two colliding protons (in the center of mass) was about 30 times  $Mc^2$

Today we study protons at 2000 times  $Mc^2$

Everything else is much better too ... the beams are more intense ... the detectors much better ... not to mention the computers

Many fundamental questions have been answered ... what holds the nucleus together ... what is the cause of atomic radioactivity ... how does nature distinguish left from right



Other equally big questions still tantalize us ...

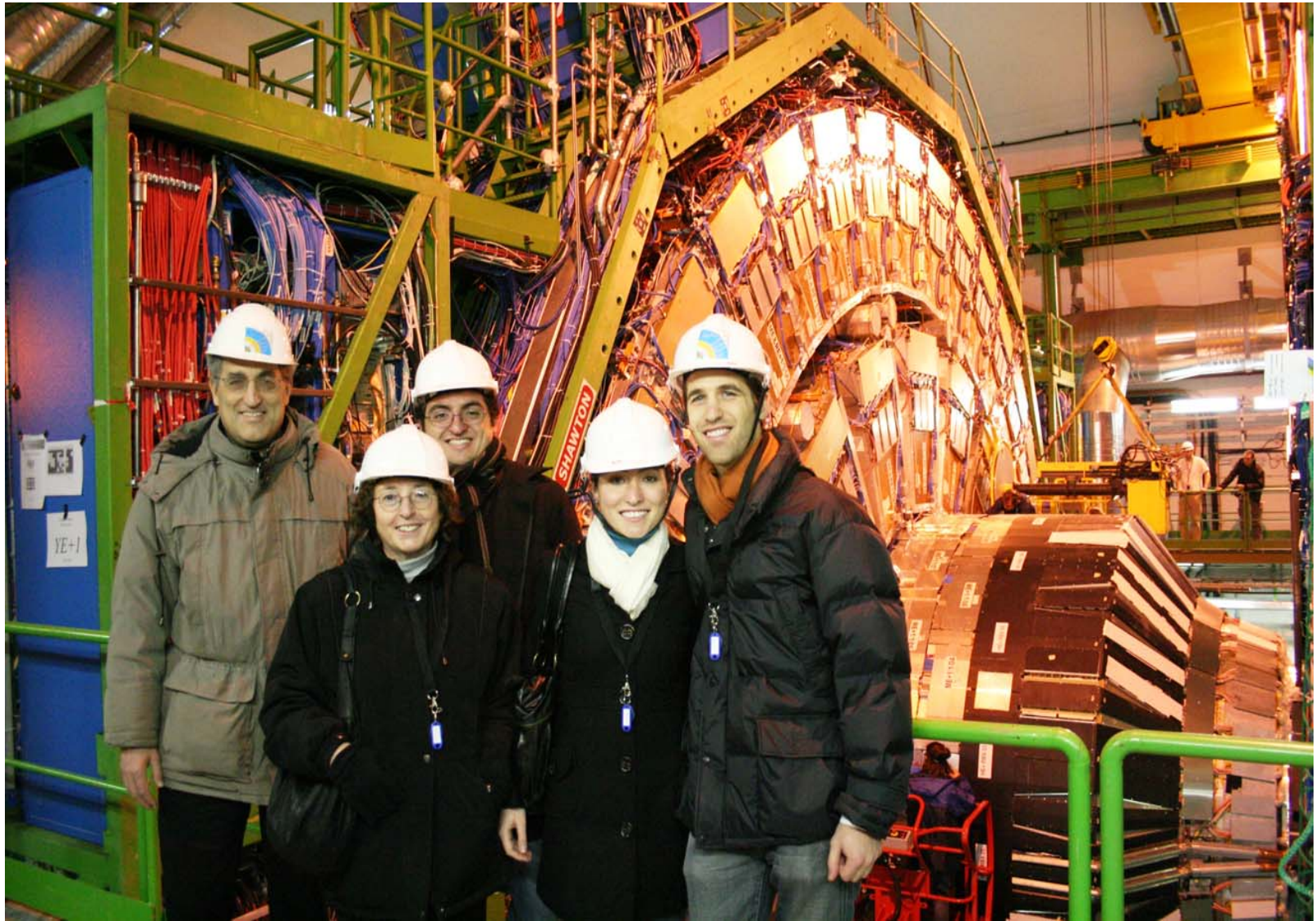
The old riddles ... the particle “flavors,” their masses, the “coupling constants”

New riddles have come from astronomy ... the dark matter ... the dark energy ... the neutrino masses

Right now particle physics is on the brink of a very big jump into the unknown ... that is because of the Large Hadron Collider (LHC), the new accelerator that will very soon be operating at the European Laboratory for Particle Physics (CERN) near Geneva

The LHC is eagerly anticipated because it will involve a huge jump in energy ... from 2000 times  $Mc^2$  to 14,000 times  $Mc^2$

One of the largest jumps ever, and in a range of energies – sometimes called the Terascale – that we suspect is particularly significant



Our visit to CMS ... one of the particle detectors at the LHC ... last December

What do we expect to learn from the LHC?

Part of the answer, of course, is that we can't give a complete answer. That is why we do the experiments.

But there is one really big question that we reasonably do expect to answer at the LHC ...

This is the question of why “electromagnetism” is so different from the “weak interactions.”

We literally detect electromagnetic effects – light waves – with our eyes. Other such effects – magnets, static electricity, lightning bolts – are also obvious in everyday life.

Instead, it takes modern equipment to detect and study the weak interactions – whose most well-known manifestation is in certain forms of atomic radioactivity.

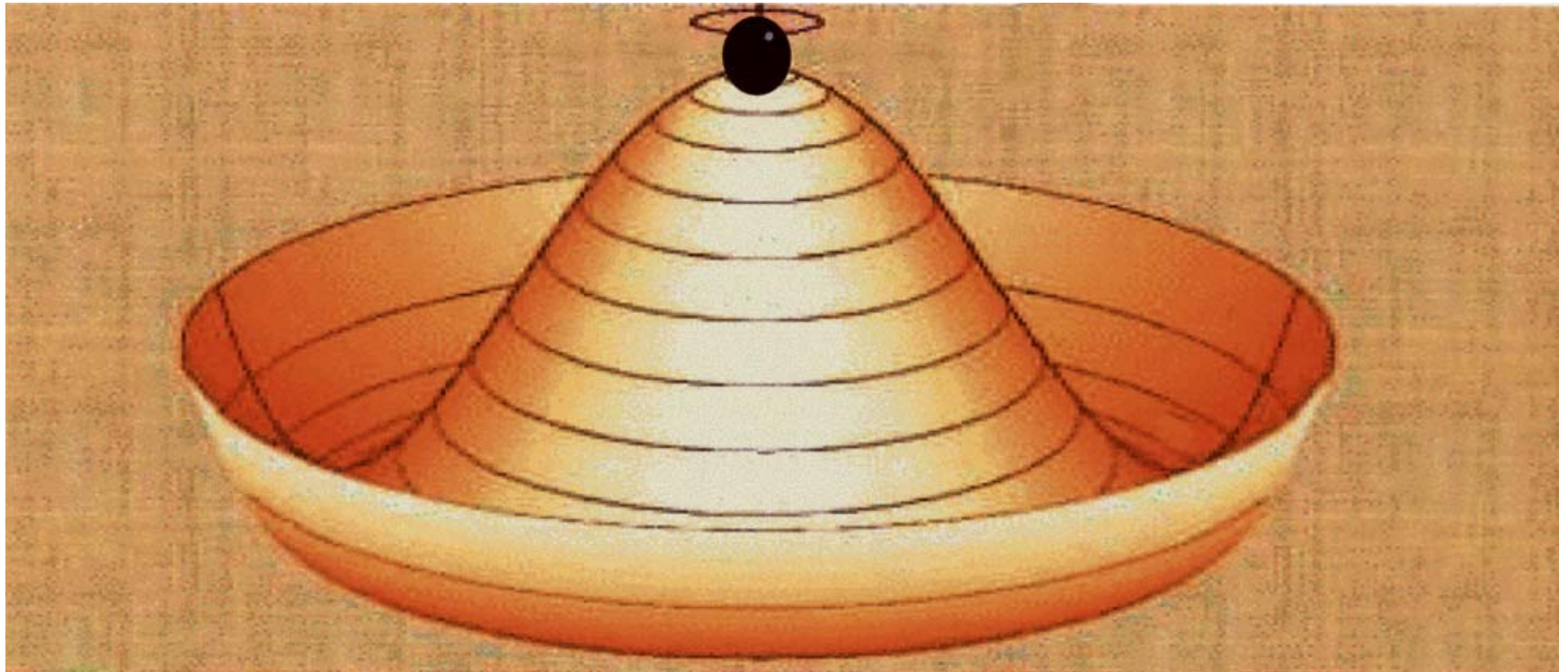
Yet according to our best understanding, the same type of equations describe electromagnetism and the weak interactions at a fundamental level.

Indeed, this is one of our most incisive insights about the unity of the most fundamental laws of nature.



If electromagnetism and the weak interactions are fundamentally the same, why do they look so different?

Our best understanding is that a process of “spontaneous symmetry breaking” that occurred in the very early Universe is responsible for the difference.



We don't have any direct experimental information about the nature of this "symmetry breaking" but, based on what we've already measured, there are solid reasons to believe that the answer can be found at the "Terascale," the energy range of the LHC.

The simplest explanation – given what we already know – involves the existence of a new particle, the "Higgs particle."

The Higgs particle is the simplest explanation, and so far very successful.

Personally I'd guess it is at least partly right. But there are also competing theories – dreamed up by theoretical physicists, who by now have pondered the problem of electroweak symmetry breaking for over 30 years.

For a long time, we've known that the Terascale is the place to look for the answer, and finally the LHC will let us look and find out.

This search is linked to many other questions.

It is believed that the symmetry breaking process is also the origin of the masses of familiar particles such as the electron. So we have a good chance of understanding the electron mass better.

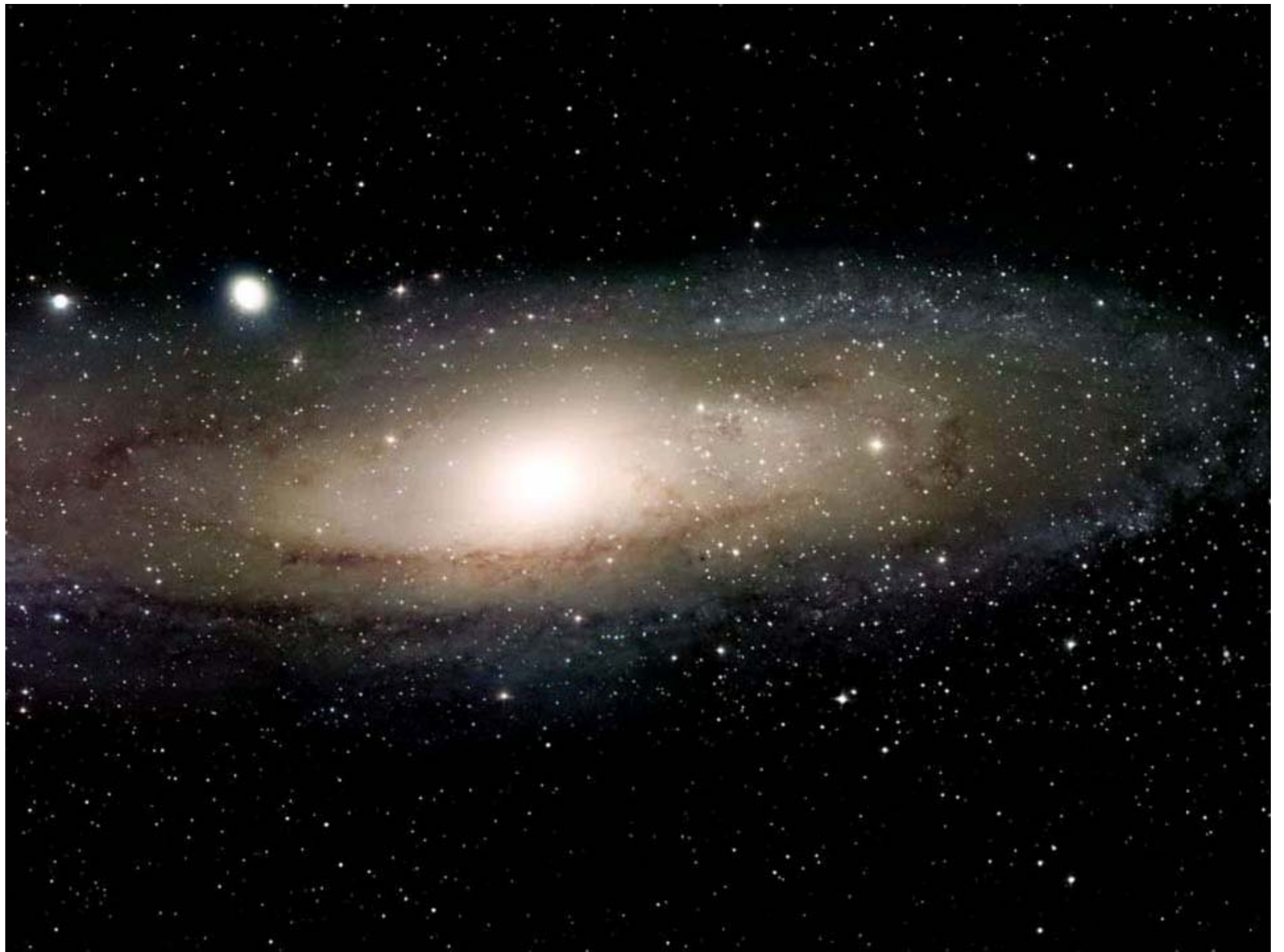
The Higgs particle is actually most often described as the key to particle masses -- though I chose to emphasize symmetry breaking.

One reason I did so is that symmetry breaking is believed to be a key ingredient in understanding the unity of elementary particle forces.

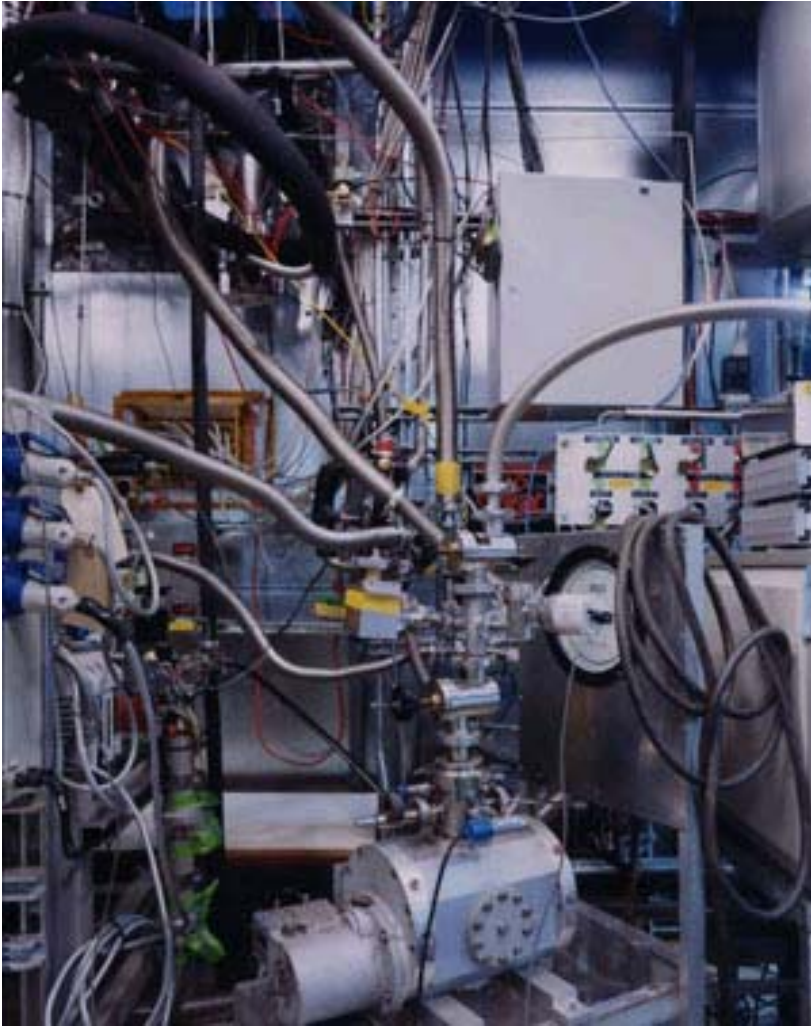
This is our chance to study it experimentally.

On a slightly more speculative note, there is a reasonable chance that the LHC will enable us to understand the “dark matter” of the Universe.

Wherever astronomers look, they see signs of dark matter.... for instance in our neighbor, the Andromeda galaxy







It may be possible to directly detect cosmic dark matter particles using detectors placed deep underground to avoid cosmic rays

... Here is one dark matter detector In Minnesota

Even if we can observe the dark matter, to really understand what we have, we need to produce and detect the dark matter particles in the laboratory.

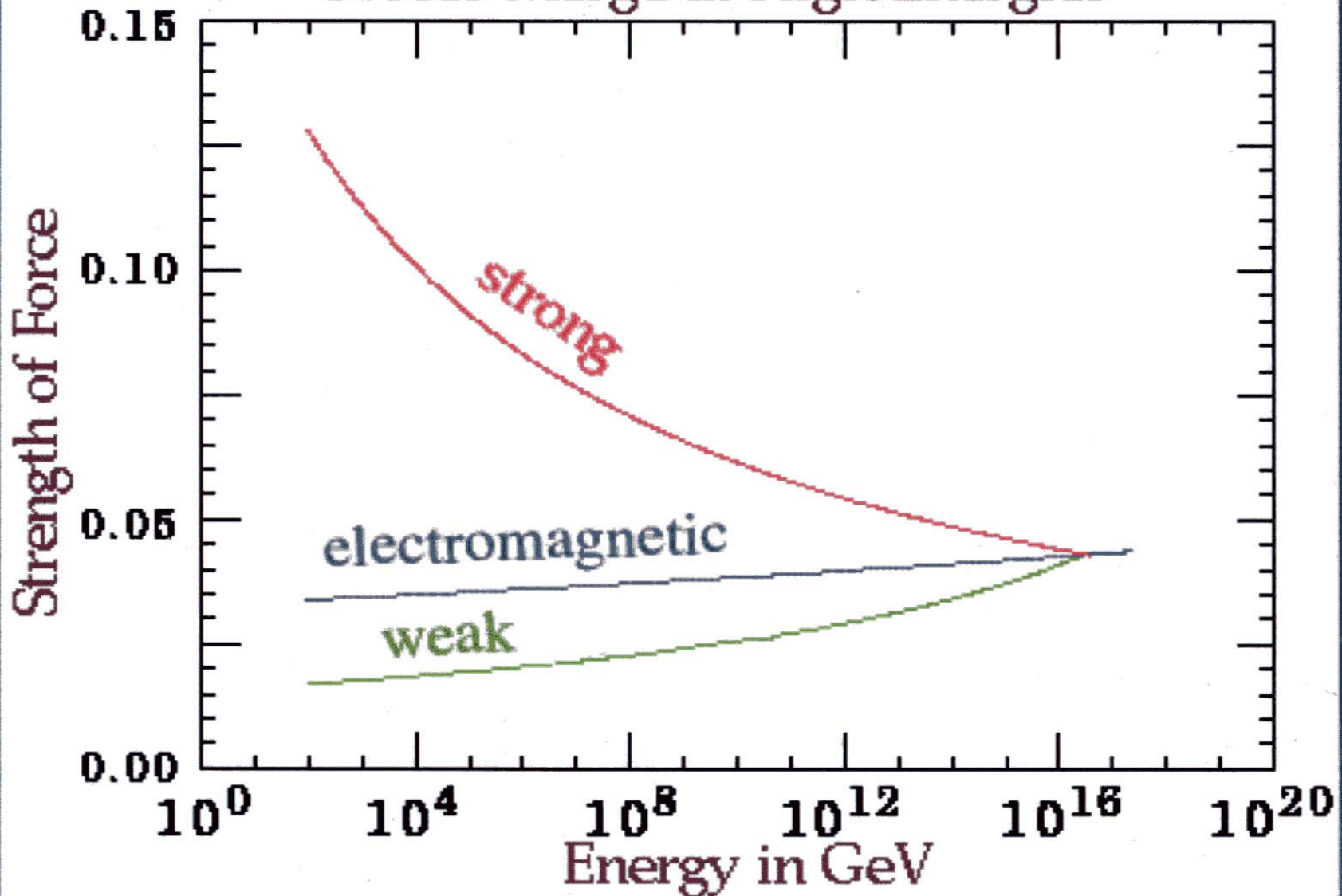
That is where the LHC comes in ... according to some of the most interesting theories of dark matter, the dark matter particles are also lurking at the Terascale.

Finally, the LHC actually has a chance to probe the unity of the laws of Nature at a much deeper level than we know them so far.

The next graph summarizes a huge amount of experimental data.

# Running Couplings

Forces Merge at High Energies



Any two curves are likely to meet somewhere, but for three curves to meet at the same point is exceptional.

While it might be a coincidence, it may also be a clue about the *Unity Of All Elementary Particle Forces*, to quote the title of a celebrated 1974 paper (by Georgi and Glashow) that initiated this line of thought.

The very precise experimental measurements of the 1980's and 90's led, however, to a key insight:

To explain the meeting of the three curves in terms of unity of elementary particles, one needs another ingredient called Supersymmetry.

Supersymmetry is roughly speaking an updating of Einstein's Special Relativity in the light of quantum theory.

According to supersymmetry, in addition to the obvious dimensions of space and time, there is an additional "quantum dimension."

An ordinary particle, like the electron, vibrating in the quantum dimension, would be observed as a new particle (electrically charged like the electron, but spinless and non-magnetic) that could be produced and detected at the LHC.

Supersymmetry is actually part of an even bigger picture in String Theory. But I'll have to leave that for another day... and conclude with one more picture.





This is a prototype component for the International Linear Collider – which in fifteen years or so may be helping us to unravel the secrets of Supersymmetry ... or whatever there is at the Terascale

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