Durham University

IP3

# MODELLING THE INVISIBLE

SELECTED FOR
**THE ROYAL SOCIETY SUMMER SCIENCE EXHIBITION** 2017

THE INSTITUTE FOR PARTICLE PHYSICS PHENOMENOLOGY (IPPP)
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ALL OF OUR KNOWLEDGE ABOUT THE FUNDAMENTAL BUILDING BLOCKS OF THE UNIVERSE IS ENCODED IN THIS FORMULA....

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi) + \bar{\Psi}_L\hat{Y}\Phi\Psi_R + h.c.$$

WHAT ARE THE FUNDAMENTAL BUILDING BLOCKS OF THE UNIVERSE?

WHAT FORCES ARE ACTING AMONG THEM?

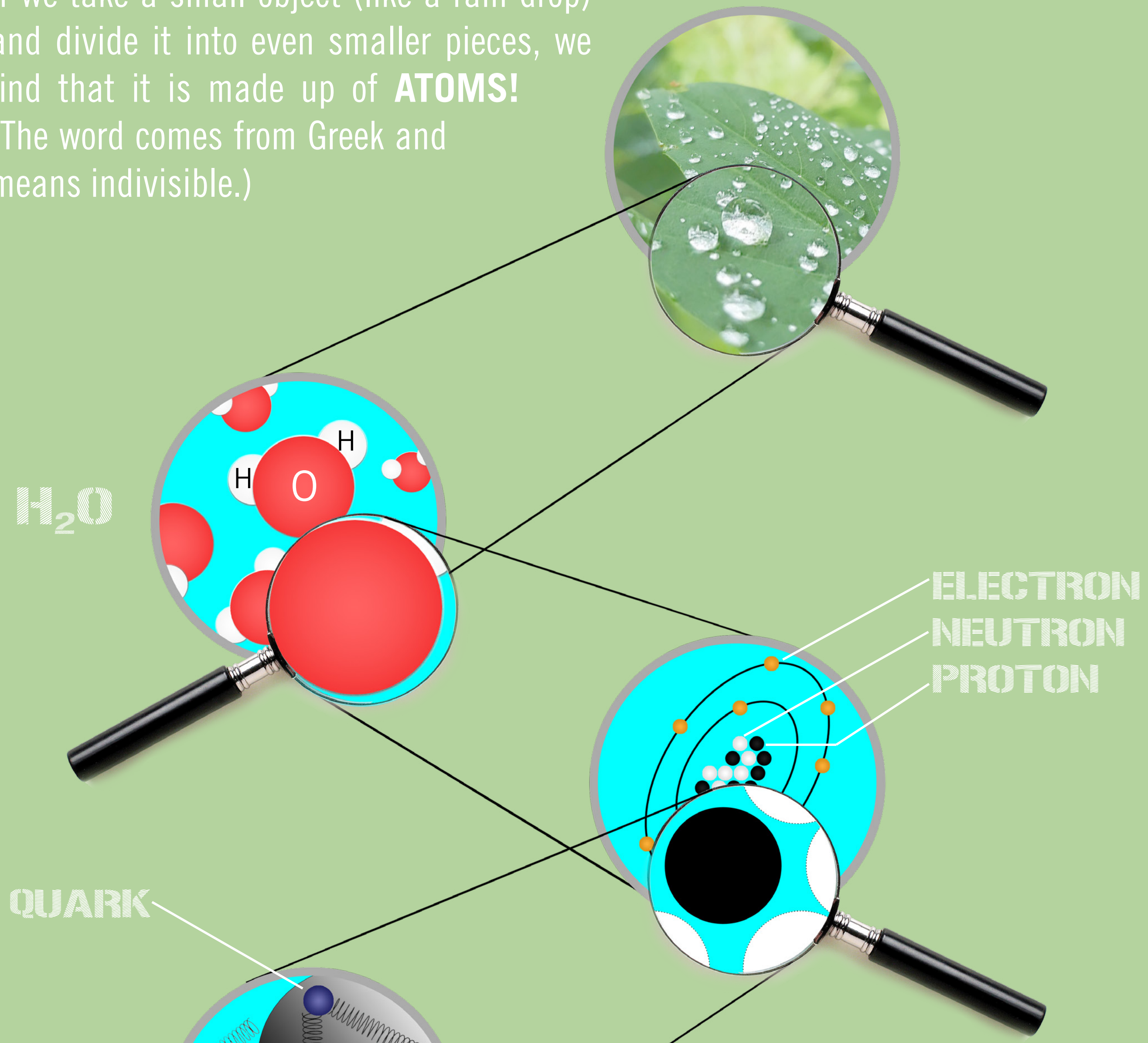
HOW DO WE KNOW ALL THIS?

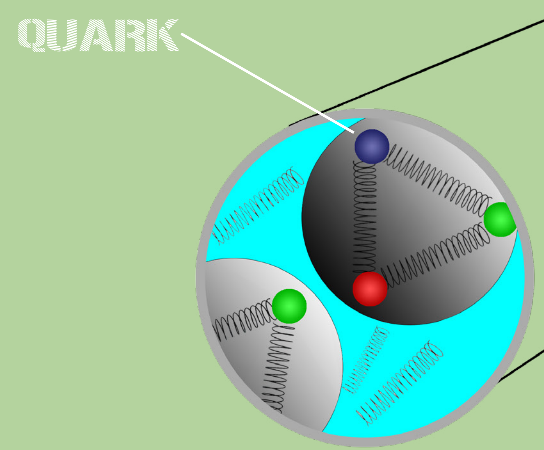
IS THIS ALREADY THE END OF KNOWLEDGE?

IS THERE ANYTHING LEFT TO DISCOVER?

# WHAT IS OUR WORLD MADE OF?

If we take a small object (like a rain drop) and divide it into even smaller pieces, we find that it is made up of **ATOMS!** (The word comes from Greek and means indivisible.)



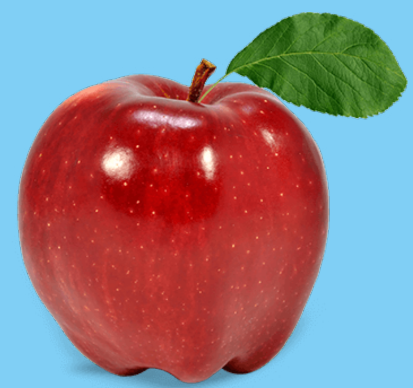




It turns out that even atoms can be further divided into **electrons** and a **nucleus** consisting of **nucleons** (i.e. **protons** and **neutrons**), which are finally built up of **quarks**. According to our current knowledge, quarks and electrons are fundamental particles --- they can be divided no more and have no internal structure or spatial extension.

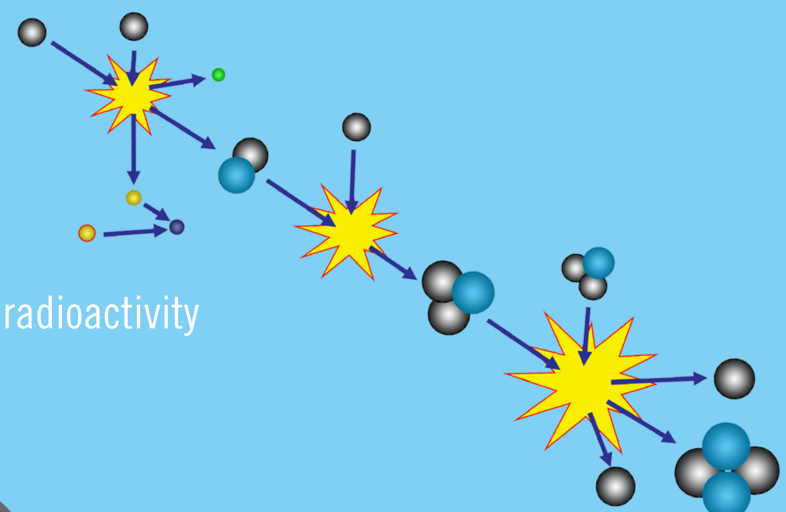
## THE FOLLOWING FUNDAMENTAL FORCES (=INTERACTIONS) ARE FOUND IN NATURE....

According to our theoretical understanding all forces are transmitted by force carriers.

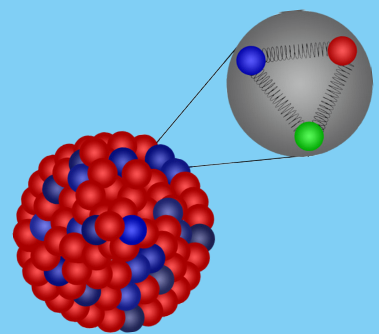
**GRAVITY:** lets apples fall from trees
Force carrier: Graviton (not yet observed)



**ELECTROMAGNETIC INTERACTION:**
makes lightning in a thunderstorm and is the basis of all electricity and magnetism
Force carrier: Photons



**WEAK INTERACTION:**
is responsible for the energy production in the sun and for radioactivity
Force carrier: W, Z Bosons

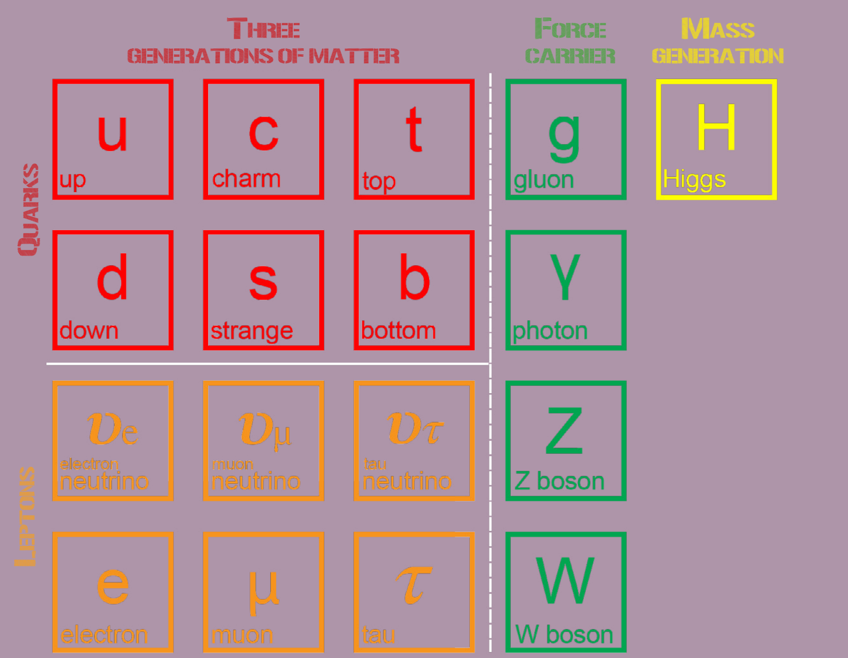


**STRONG INTERACTION:**
binds protons and neutrons into nuclei and quarks into nucleons
Force carrier: Gluons

# THE STANDARD MODEL OF PARTICLE PHYSICS

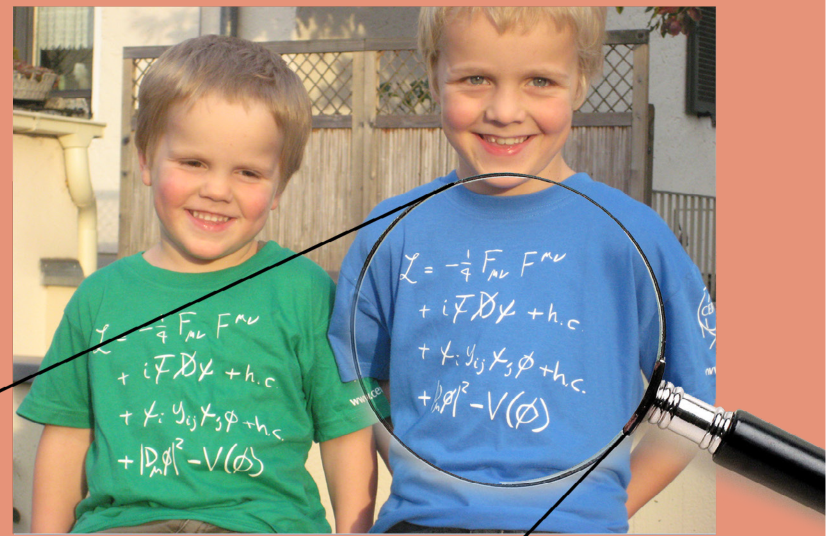
## ALL KNOWN FUNDAMENTAL PARTICLES IN THE UNIVERSE CAN BE CLASSIFIED AS MATTER CONSTITUENTS, FORCE CARRIERS AND PARTICLES RESPONSIBLE FOR THE CREATION OF MASS.

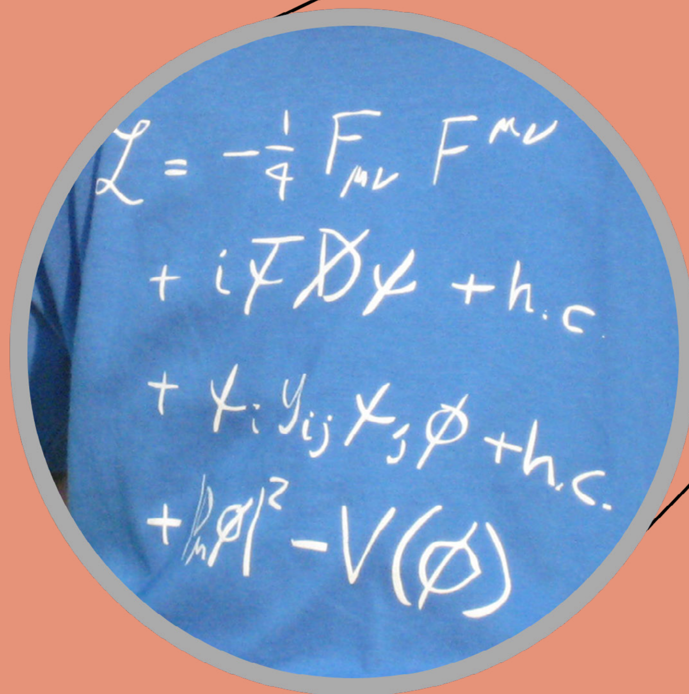
Quarks and leptons are the matter constituents. To a good approximation the proton is made of two **u**p quarks and one **d**own quark. There are also heavier copies of these two quarks: the **c**harm, **s**trange, **b**ottom and **t**op quarks.
The electron is a lepton and it has also heavier copies: the **muon** and the **tau** as well as neutral partners: the neutrinos.
All known fundamental forces are transmitted via force carriers: the electromagnetic interaction by the **photon**, the strong interaction by the **gluon g** and the weak interaction by the **W** and **Z bosons**.




**MASS GENERATION:** Having particles with a mass (as we observe in nature) leads to mathematical problems of our theory. A possible solution was the existence of a new, unknown particle, that was finally observed in 2012: the Higgs boson H.

Mathematically all properties of the fundamental particles and interactions can be encoded in the four line formula from page 3 - known as the Standard Model of Particle Physics.





**THE FIRST LINE** of the formula describes the force carriers.

**THE SECOND LINE** describes quarks and leptons as well as their interactions.

**THE THIRD LINE** makes quarks and leptons massive.

**THE LAST LINE** describes the Higgs particle.

**SO WHERE'S GRAVITY?** Gravity is not included because we do not have a quantum version of it and its effects are also negligible in the microworld.

# HOW DO WE KNOW ALL THIS?

## OUR MICROSCOPES FOR LOOKING INTO THE SUB-ATOMIC WORLD ARE PARTICLE ACCELERATORS- THE BIGGEST ONE IS THE LARGE HADRON COLLIDER (LHC)

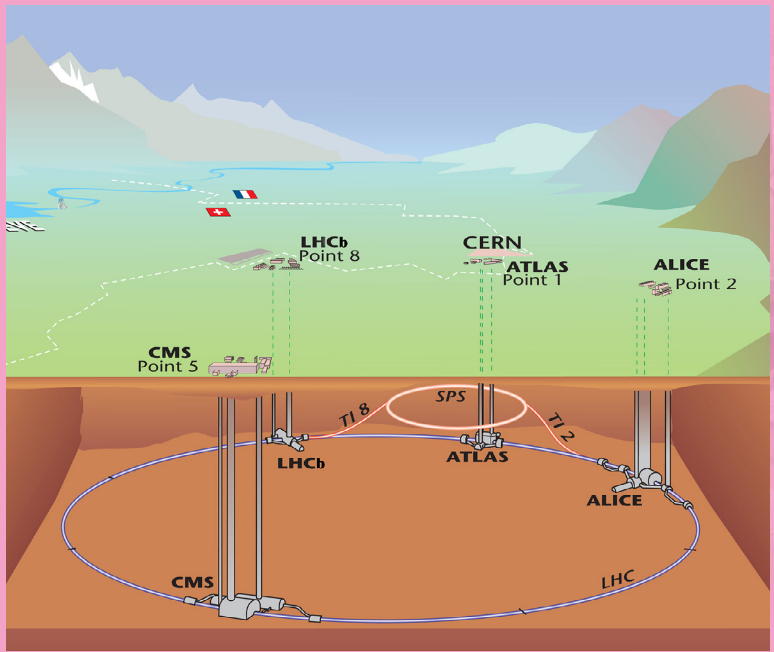
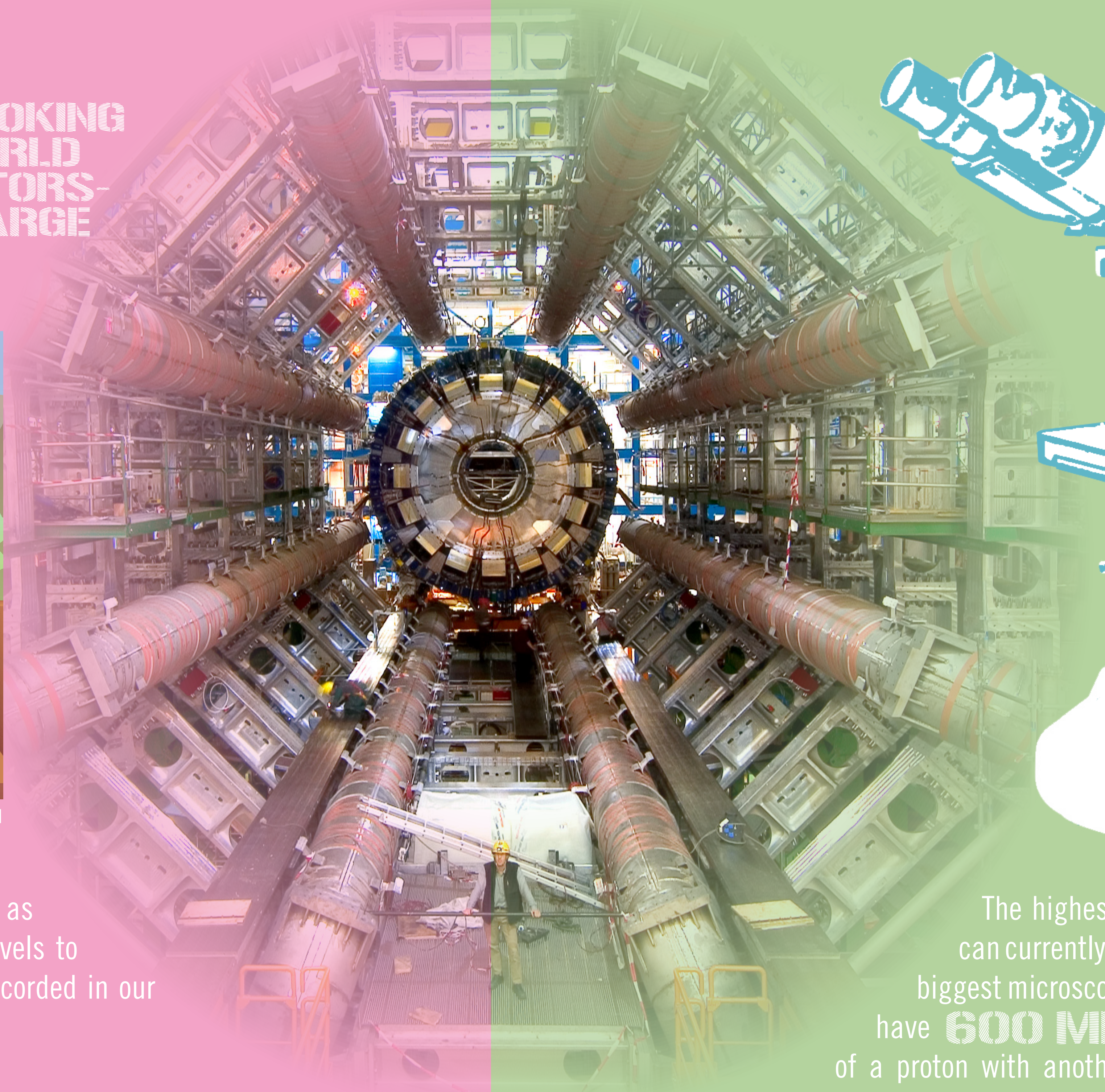
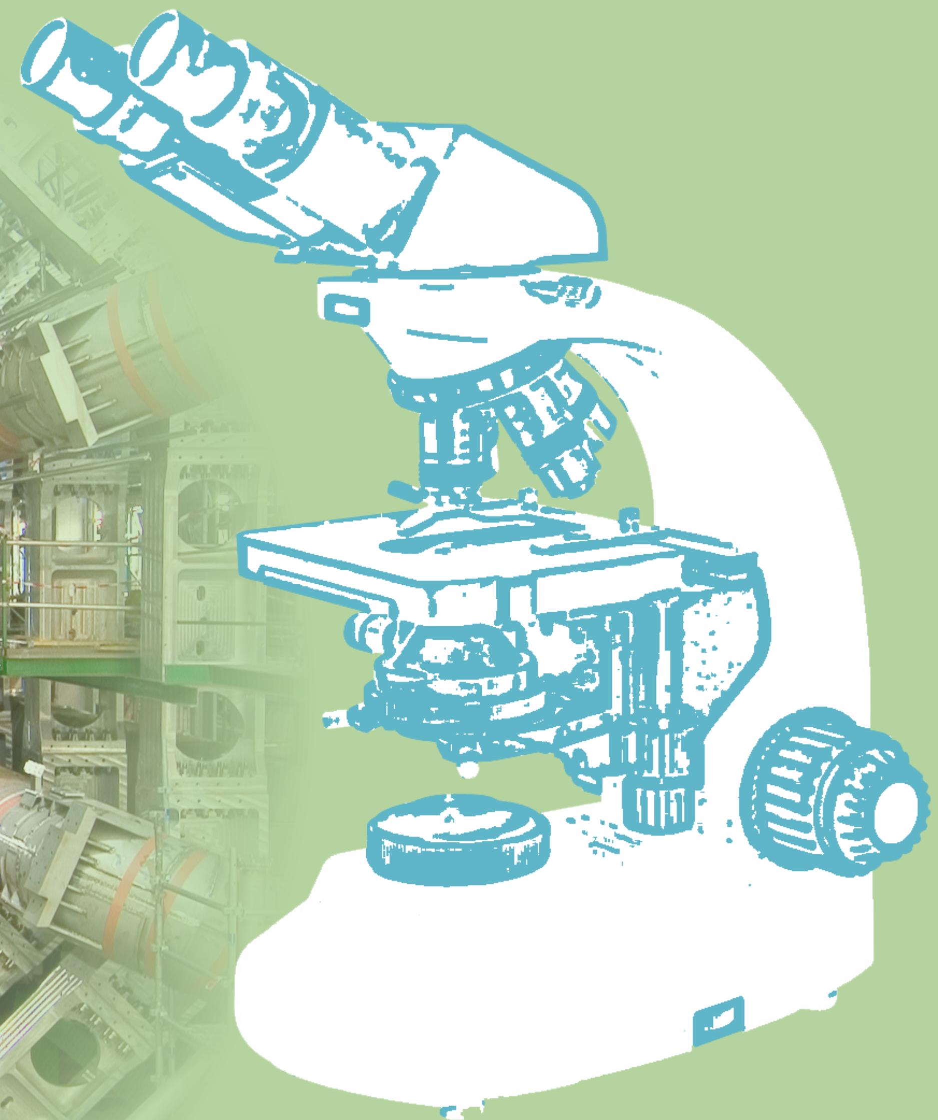


Image credit:CERN





When we see an object, our eyes are working as detectors! Light is emitted by the sun and travels to Earth before bouncing off objects and being recorded in our eyes.

With a normal microscope we can only see objects that are as large as the wavelength of light, which is about the size of small bacteria.

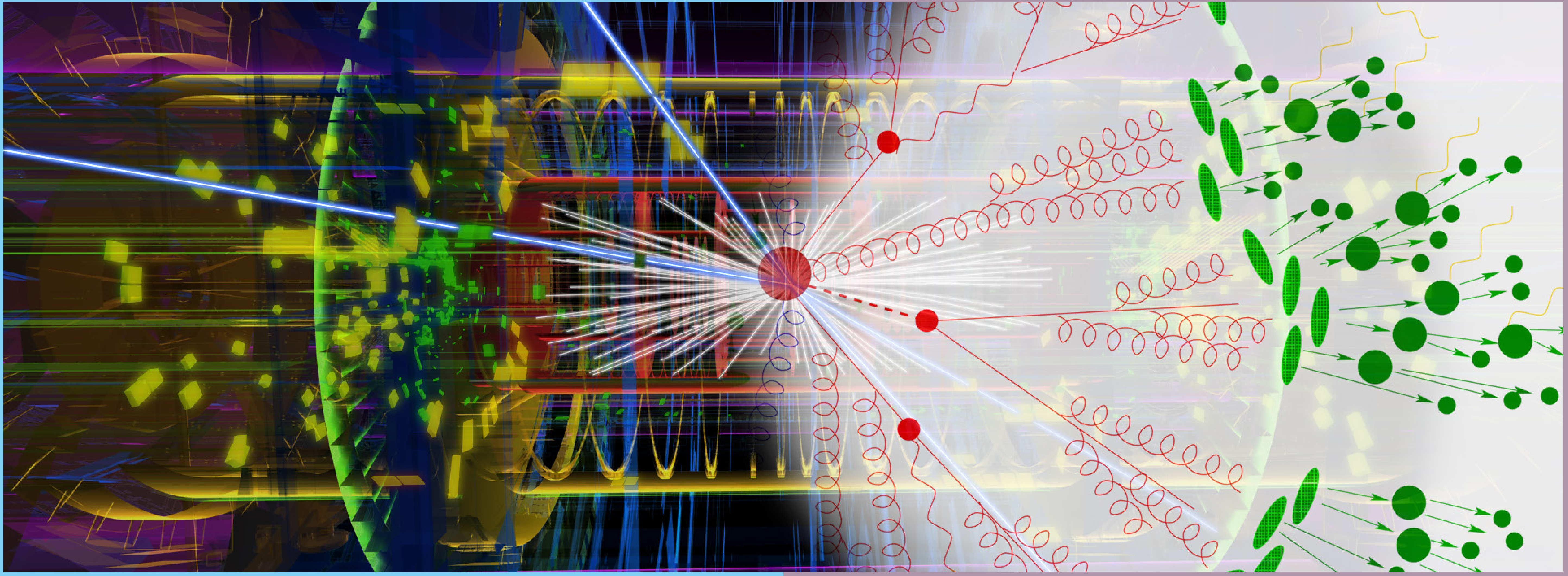
For smaller objects we need shorter wavelengths - which is equivalent to higher energies.

The highest possible energies in the laboratory can currently be created with the LHC, making it our biggest microscope. In every second at the LHC, we can have **600 MILLION COLLISIONS** of a proton with another proton. The energy of the proton beam in the LHC corresponds to the energy of a 200 ton train with a velocity of **MORE THAN 100 MPH!**

With the LHC we can see structures that are more than 100 billion times smaller than bacteria!

# NUMERICAL SIMULATIONS ARE NECESSARY

## EACH COLLISION CAN CREATE THOUSANDS OF PARTICLES, MANY OF WHICH WE CANNOT OBSERVE SINCE THEY DECAY LONG BEFORE THEY REACH THE DETECTOR....

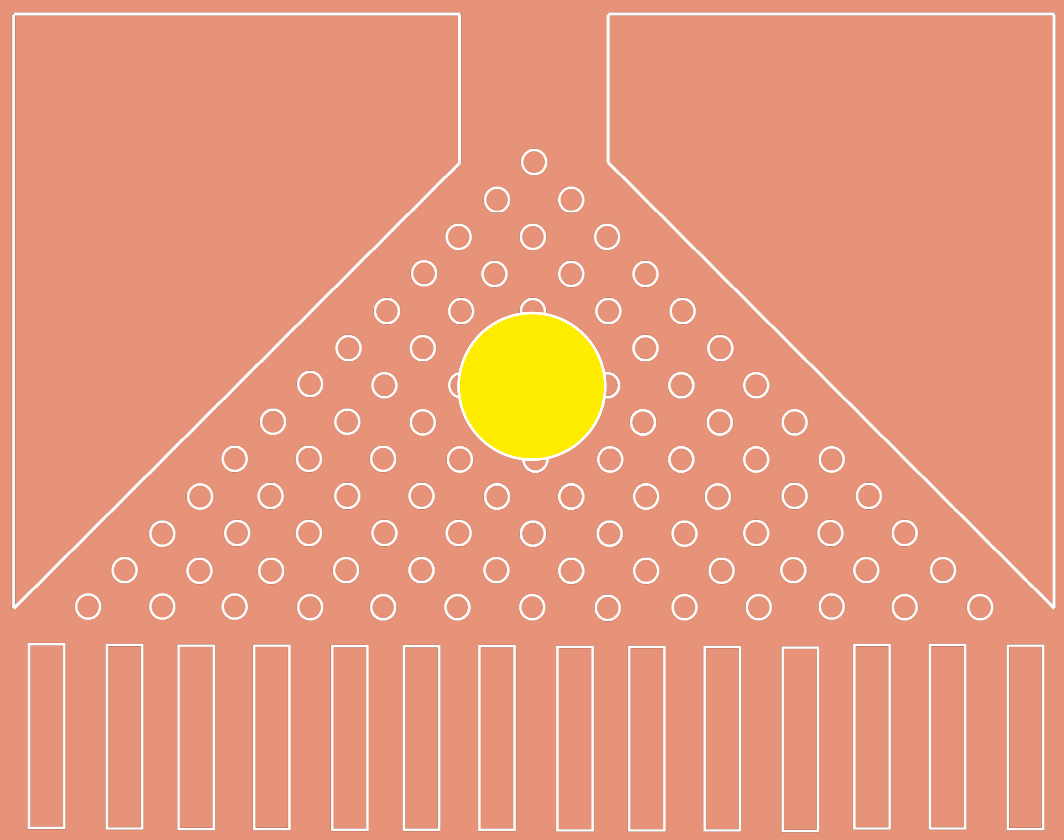


…. but we can infer their existence and their properties by looking at the recorded decay products, and their distribution in the detector over many thousands of collisions.

The main way we understand and interpret these observations is to simulate on a computer what we expect to see for different theoretical models, and then compare the simulated result with real data.

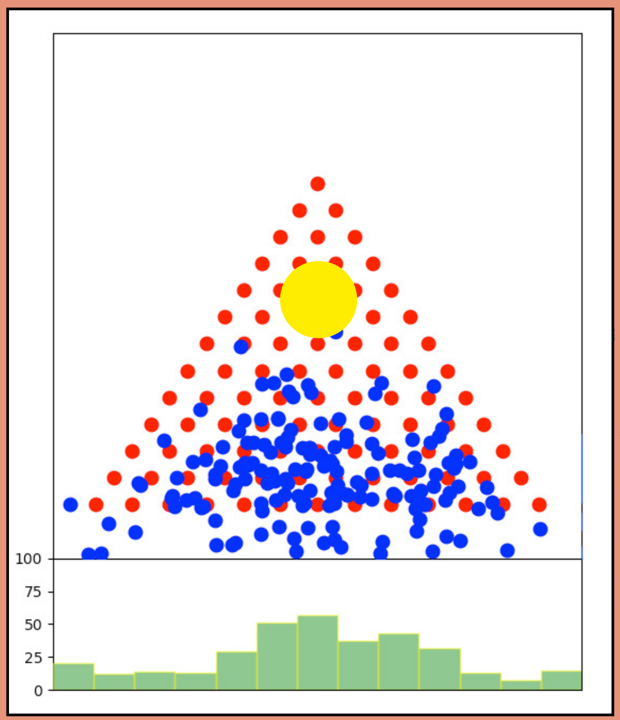
## SIMULATIONS PROVIDE A BRIDGE BETWEEN OUR BEST THEORIES AND OUR MOST POWERFUL EXPERIMENTS.

# EXHIBIT 1: THE GALTON BOARD



The Galton board exhibit shows a similar problem: As the steel balls roll down, they scatter off the needles and a hidden shape (yellow circle), but just from looking at the collection bins, it is hard to work out the shape directly.

What can be done, however, is to simulate the board with different hidden shapes and compare the outcome…



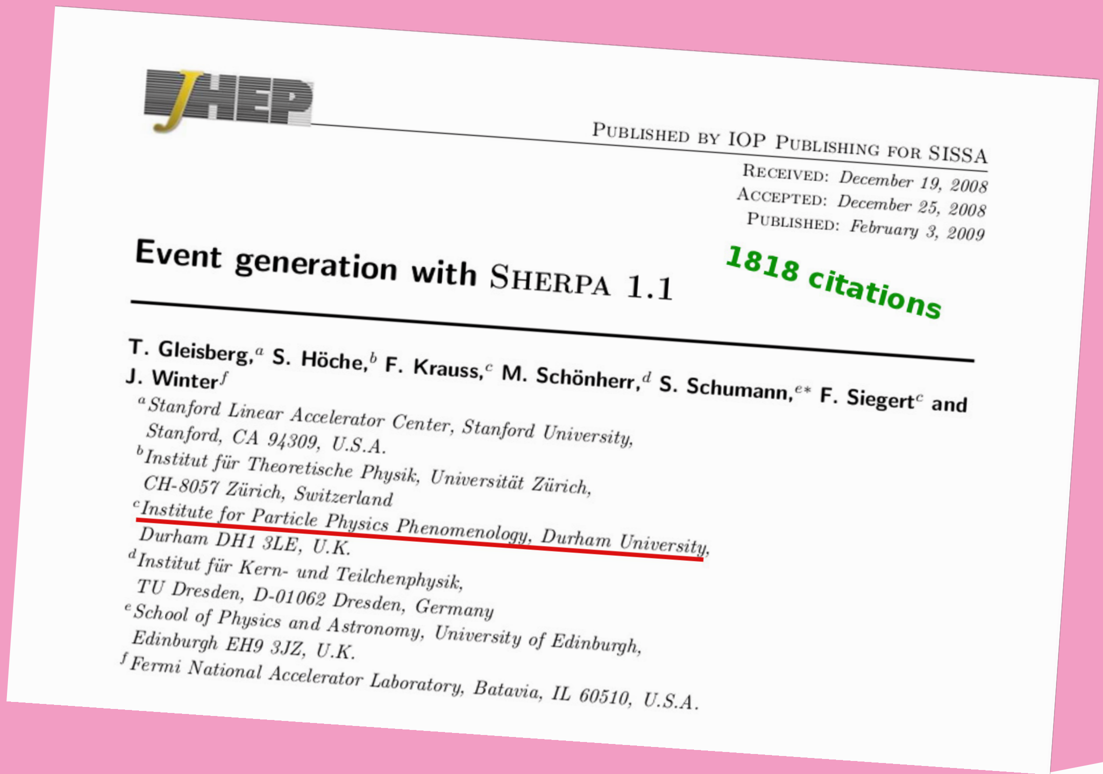


The procedure at the LHC is very similar; simulated data of various possible models is compared with the measured data points.

**The more data we collect, the better the comparison becomes** at distinguishing between different options.

# SIMULATIONS AT THE EDGE OF KNOWLEDGE

The IPPP in Durham is world leading in developing computer programs, such as Sherpa and Herwig, which are used to simulate the high-energy collisions occuring at the LHC....



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Event generation with Sherpa 1.1

1818 citations

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The European Physical Journal C

1464 citations

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Special Article - Tools for Experiment and Theory

Herwig++ physics and manual

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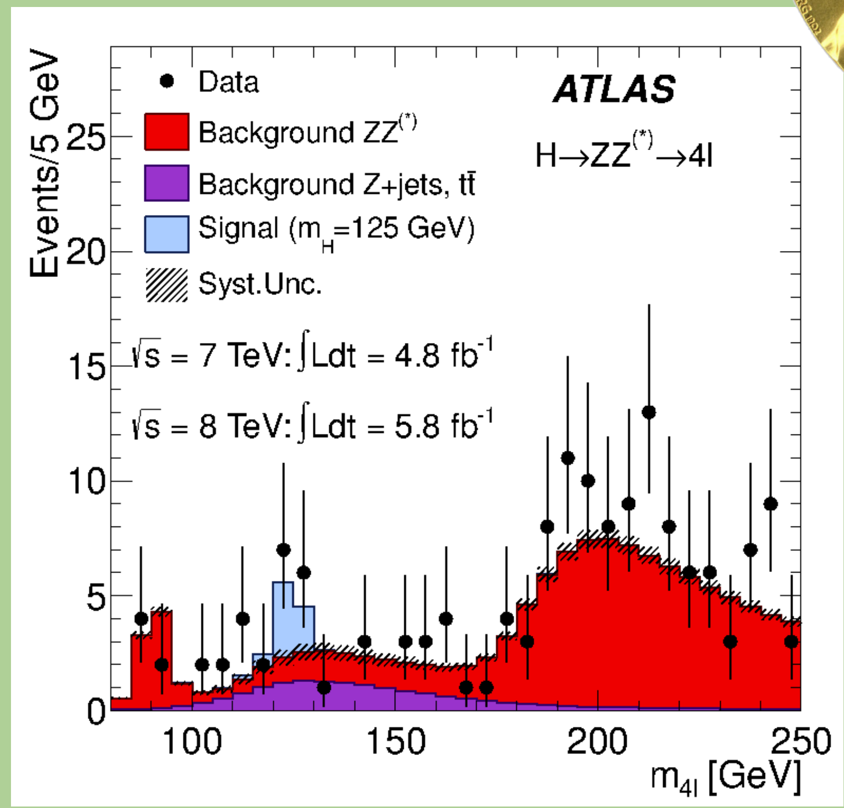
## HERWIG AND SHERPA HAVE BEEN INSTRUMENTAL IN THE DISCOVERY OF THE HIGGS BOSON AT THE LHC IN 2012


Nobel prize for physics 2013 - Peter Higgs - François Englert

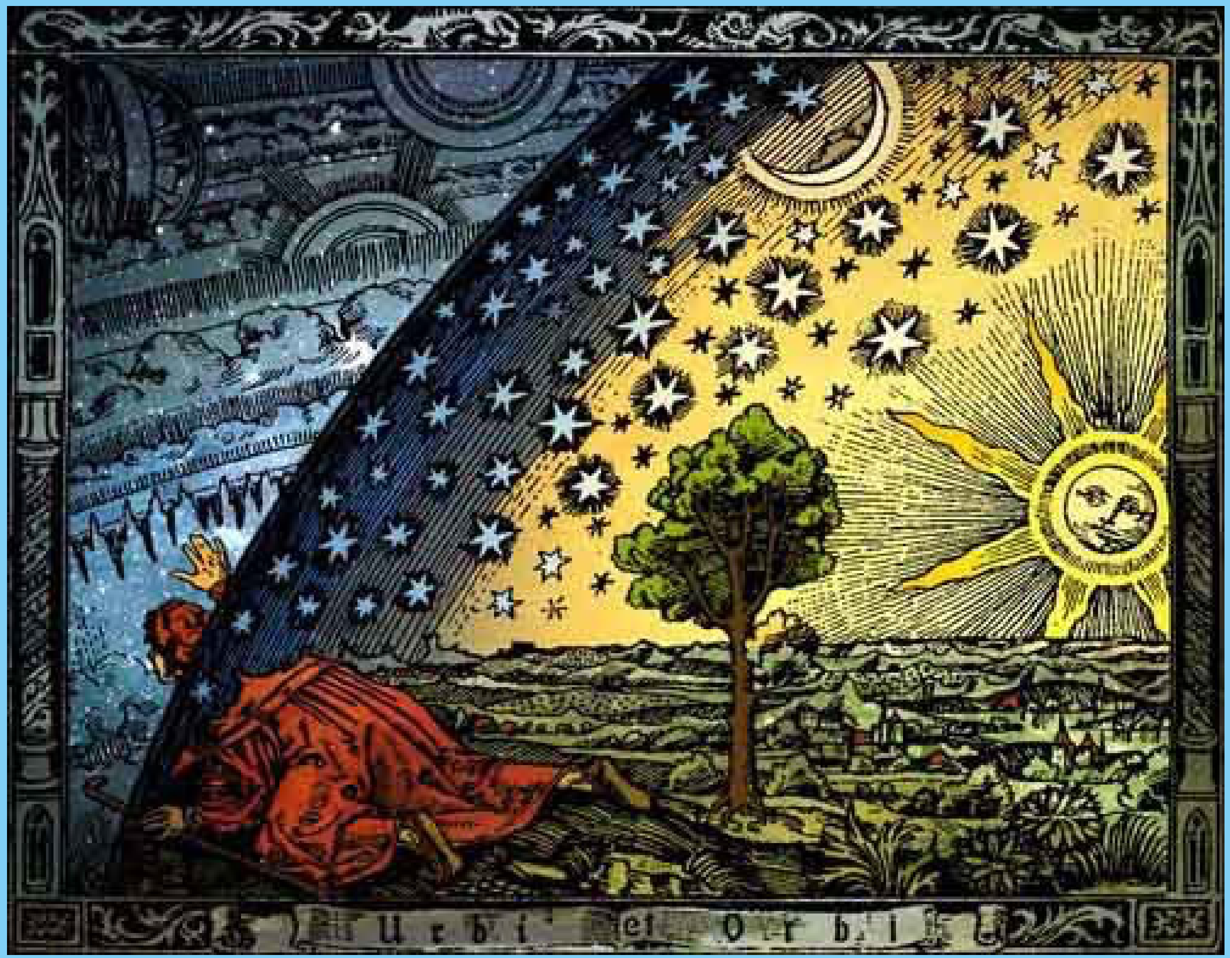



Higgs discovery paper of ATLAS, Phys. Lett. B 716 (2012)

The plot above shows the comparison between experimental data (black dots) and the results of simulations (coloured areas).

To match the experimental data, a signal contribution (pale-blue area) needed to be added to the background. This provided the evidence of the existence of a particle of mass 125 GeV, identified with the Higgs Boson.

# IS THERE ANYTHING BEYOND THE STANDARD MODEL?



Flammarion engraving 1888 (colourised version)

The enquiring mind of humankind is determined to look behind the curtain, representing the limit of current knowledge.
Centuries ago this curtain was given by the borders of the known world - looking beyond these boundaries new countries were discovered, later we even reached out for the whole Universe. Besides making discoveries at larger and larger distance scales, we also started to investigate the smallest building blocks. Now the Standard Model is the limit of knowledge in the micro-world....

....WHAT LIES BEYOND?

## THE STANDARD MODEL IS EXTREMELY SUCCESSFUL

it accurately predicts
hundreds of observables at the quantum level

$$a_e = \frac{g-2}{2}$$

Predicted value $= 0.0011596521816(\pm 8)$

Measured value $= 0.0011596521807(\pm 3)$

- $g$ is the strength of the coupling of a photon to an electron
- $a_e$ is the deviation of this coupling from 2
- Experiment and Standard model agree to an extremely high precision

## BUT

it leaves many questions open, like

What is the origin of DARK MATTER?
How was MATTER CREATED in the Universe?
Why are NEUTRINOS almost MASSLESS?
Why do we have three copies of Quarks and LEPTONS?
Is there a QUANTUM THEORY OF GRAVITY?
Why is the top QUARKS SO MUCH HEAVIER than the ELECTRON?

# DARK MATTER

Image credit: Hubble space telescope

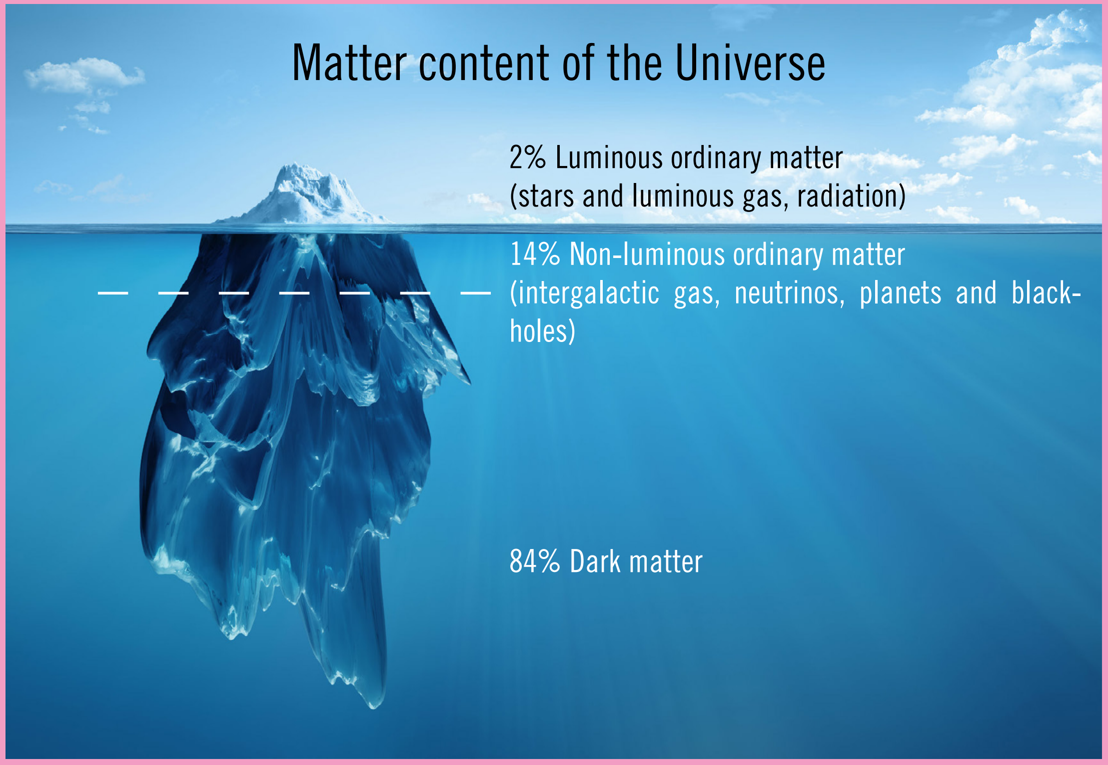
During the past century, numerous astrophysical and cosmological observations have revealed gravitational effects that cannot be explained by the luminous matter that we can see.

For example, galaxies seem to be rotating too fast, which suggests that they contain a substantial amount of extra matter that does not emit or absorb light.

The effect of this new type of "dark matter" can also be observed in larger systems (such as galaxy clusters).

Our observations indicate that dark matter is five times more abundant than the ordinary visible matter that we are made of.

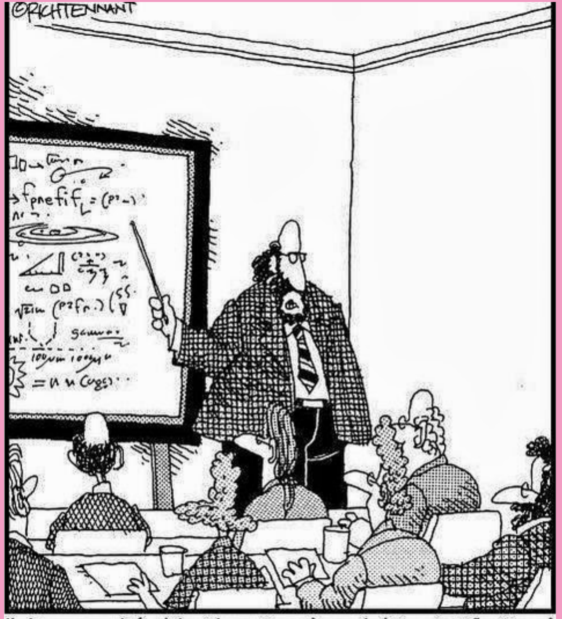
## HOW DOES DARK MATTER FIT IN THE STANDARD MODEL?




None of the particles predicted by the Standard Model can explain dark matter, as they do not have the right properties. Neutrinos would be the only possibility, but they are simply not massive enough. Dark Matter must therefore be something that experiments have never seen before!

What we know is that dark matter must be massive, electrically neutral, stable, and interact very weakly with ordinary particles, since otherwise we would have already observed it.

Physicists have proposed extensions to the Standard Model, trying to include these elusive new particles. These new theories are currently being tested by very sensitive experiments.



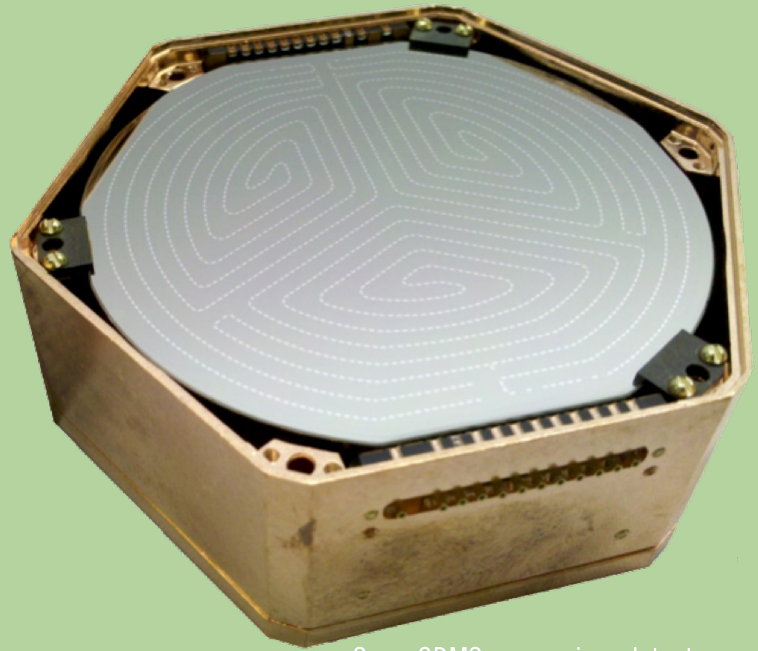

"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

# EXHIBIT 2: THE DARK MATTER DETECTOR

We can build a detector specifically designed to observe Dark Matter particle as they travel through it.

However, since Dark Matter interacts very weakly, the chances to detect a Dark Matter particle are very small. Furthermore, the radiation emitted by materials around us and the muons created by cosmic rays in the atmosphere produce a very similar signal in the detector.

For example, a muon passes through your hand every two seconds and therefore, the high frequency of these fake signals makes detecting a Dark Matter particle even more challenging.



SuperCDMS germanium detector

Image credit: Hubble space telescope

In order to increase the odds of discovering a Dark Matter particle, we have to, for example:

**1)** Place the detector in a laboratory deep underground so that the cosmic muons get stopped by the rocks within the Earth.

**2)** Shield the detector to stop the photons and electrons emitted by the rocks around the detector.

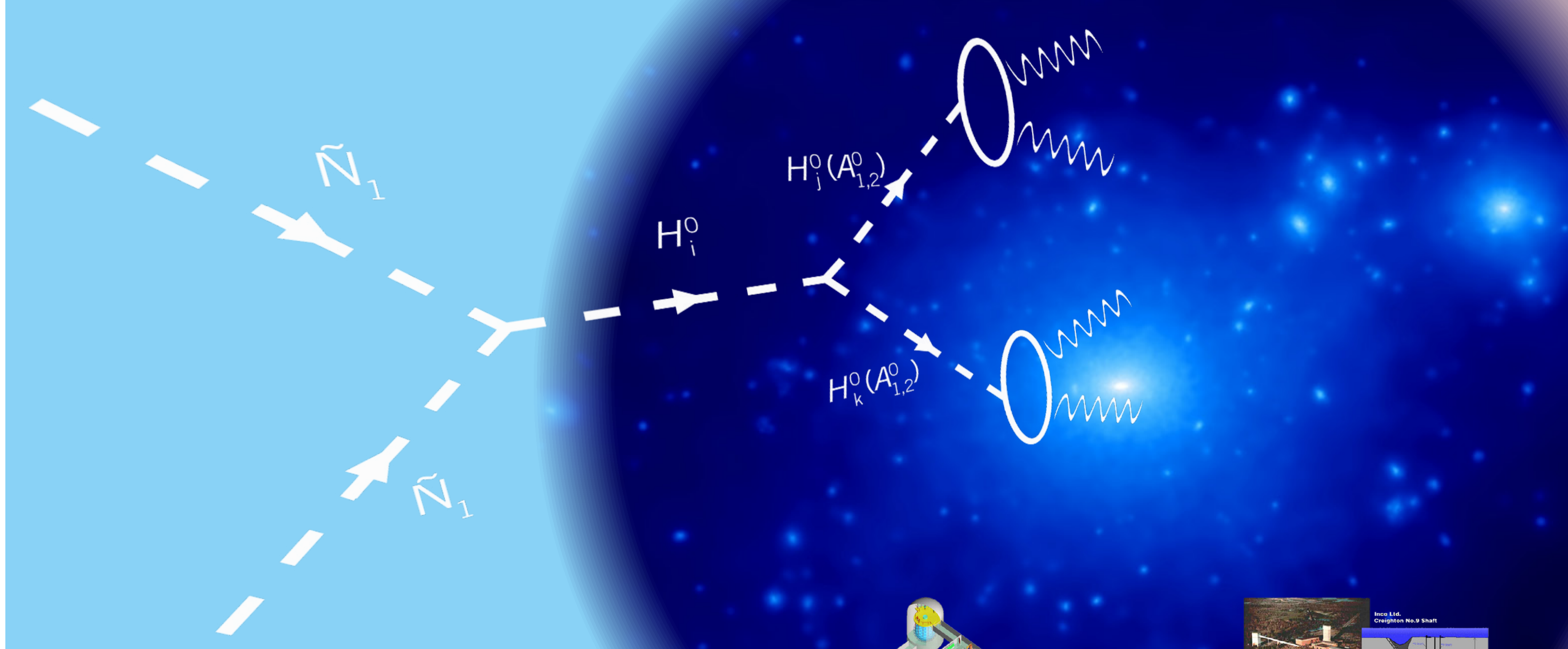
**3)** Improve the purity of the detector materials so that it does not emit any radioactivity that could be confused with a signal.

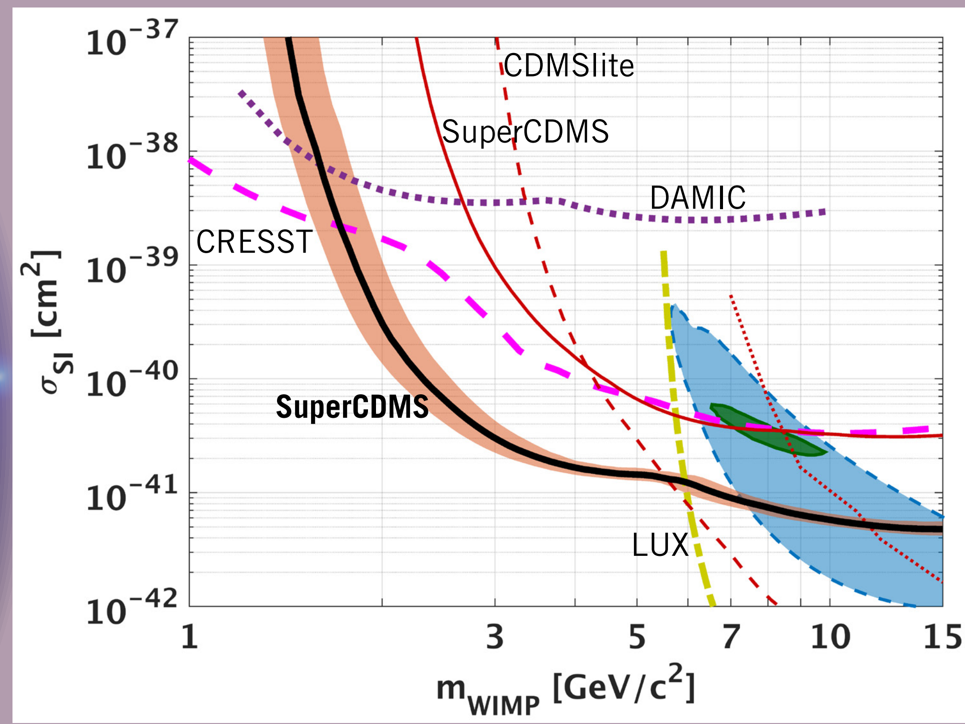
This sounds simple, but one needs to make sure that the cost of the experiment stays within budget. Maximizing the chances of discovery while keeping the expenses in mind then becomes a difficult task!

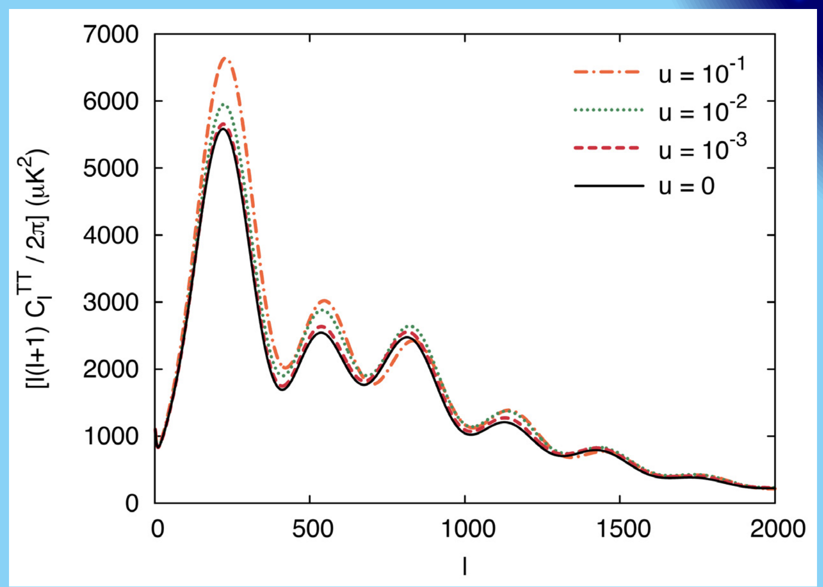
# DARK MATTER RESEARCH AT THE IPPP

The IPPP is at the forefront of theoretical research on dark matter with members studying existing models and their predicted signals in current and future experiments. We also propose new models of particle physics that can explain experimental observations. Our goal is to contribute to the identification of this elusive component of the Universe.

## THE IPPP IS A MEMBER OF THE SUPERCDMS COLLABORATION WHICH IS LOOKING FOR DARK MATTER USING CRYOGENIC GERMANIUM AND SILICON CRYSTALS.




SuperCDMS is currently leading the search for low-mass dark matter particles, while other experiments, such as LUX (which employs liquid xenon), excel at searching for heavier particles.

The future phase of SuperCDMS (featured in this exhibition) will operate at the SNOLAB underground laboratory in Canada, using 50 kilograms of germanium and silicon crystals.

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

# IPPP AT DURHAM UNIVERSITY

## LOCATED IN THE NORTH-EAST OF ENGLAND


The IPPP is the national institute for particle physics phenomenology - the bridge between theory and experiment in the study of the tiny building blocks of all matter in the Universe and of the fundamental forces that operate between them. With an international team of about 80 scientists, PhD students and support staff, the IPPP is one of the largest phenomenology centres in the world.
In 2016 our team published more than 200 articles and was involved in the organisation of more than 30 scientific meetings.

Our research shed light on the composition of the Universe. Huge particle accelerators like the Large Hadron Collider (LHC) act as microscopes that give us insights into the microscopic world. We use the concepts of quantum theory to describe the properties and interactions of the elementary particles. All our current knowledge of the field is summarised in the Standard Model of Particle Physics (SM).

Despite being extremely successful, the SM leaves several crucial questions open, like the mysteries surrounding antimatter and dark matter. Searches for beyond SM effects - so-called new physics - form another pilar of our activities.

The IPPP was founded in Durham in 2000 as a joint venture of Durham University and the UK Science and Technology Facilities Council (STFC). Our activities are overseen by an international Steering Committee consisting of renowned experts in particle physics.

# IPPP AT DURHAM UNIVERSITY

Currently, 18 permanent members of staff - leading experts in their field from 9 different nations - are working at IPPP.

We have about 20 post-doctoral researchers, i.e. scientists having a PhD degree.

The institute hosts a big cohort of more than 30 PhD students. In their first year our PhD students attend an intensive lecture series, taught in cooperation with the Mathematics department.

Our staff members are supervising final year project students. This is the first chance for undergraduate students to get in contact with real research.

Every year the IPPP offers about 10 summer studentships to exceptionally talented undergraduate students.

Our staff are involved in undergraduate teaching at the Physics Department of Durham University, in particular, lecture course related to Quantum Theory and Mathematical tools needed for theoretical physics.

For more information visit www.modellinginvisible.org

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Durham University
Department of Physics

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SUMMER SCIENCE
EXHIBITION 2017

PRODUCED BY THE DEPARTMENT OF PHYSICS, DURHAM UNIVERSITY FOR THE INSTITUTE FOR PARTICLE PHYSICS PHENOMENOLOGY