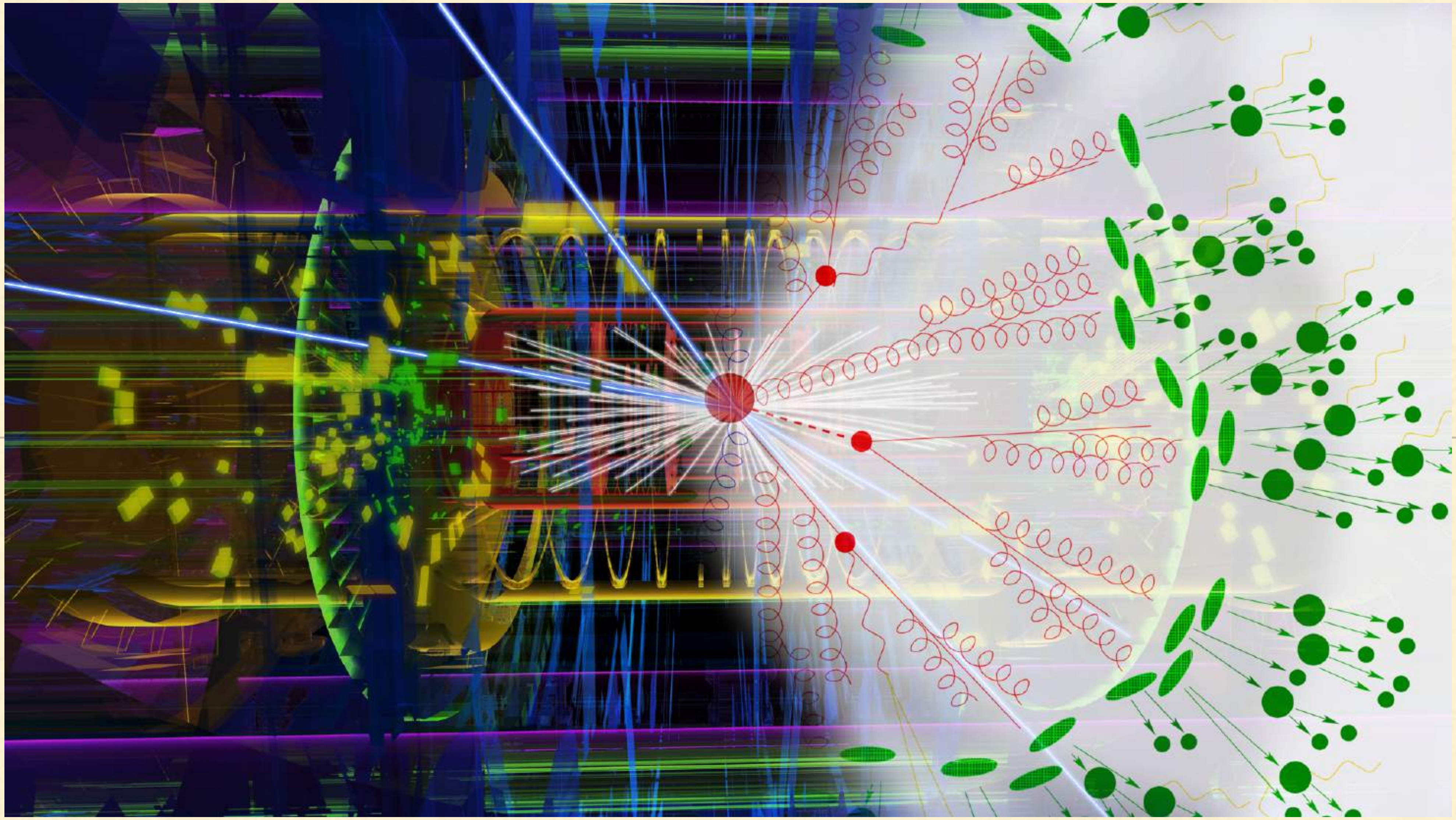
MODELLING THE INVISIBLE



Institute for Particle Physics Phenomenology (IPPP)
Durham University

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?

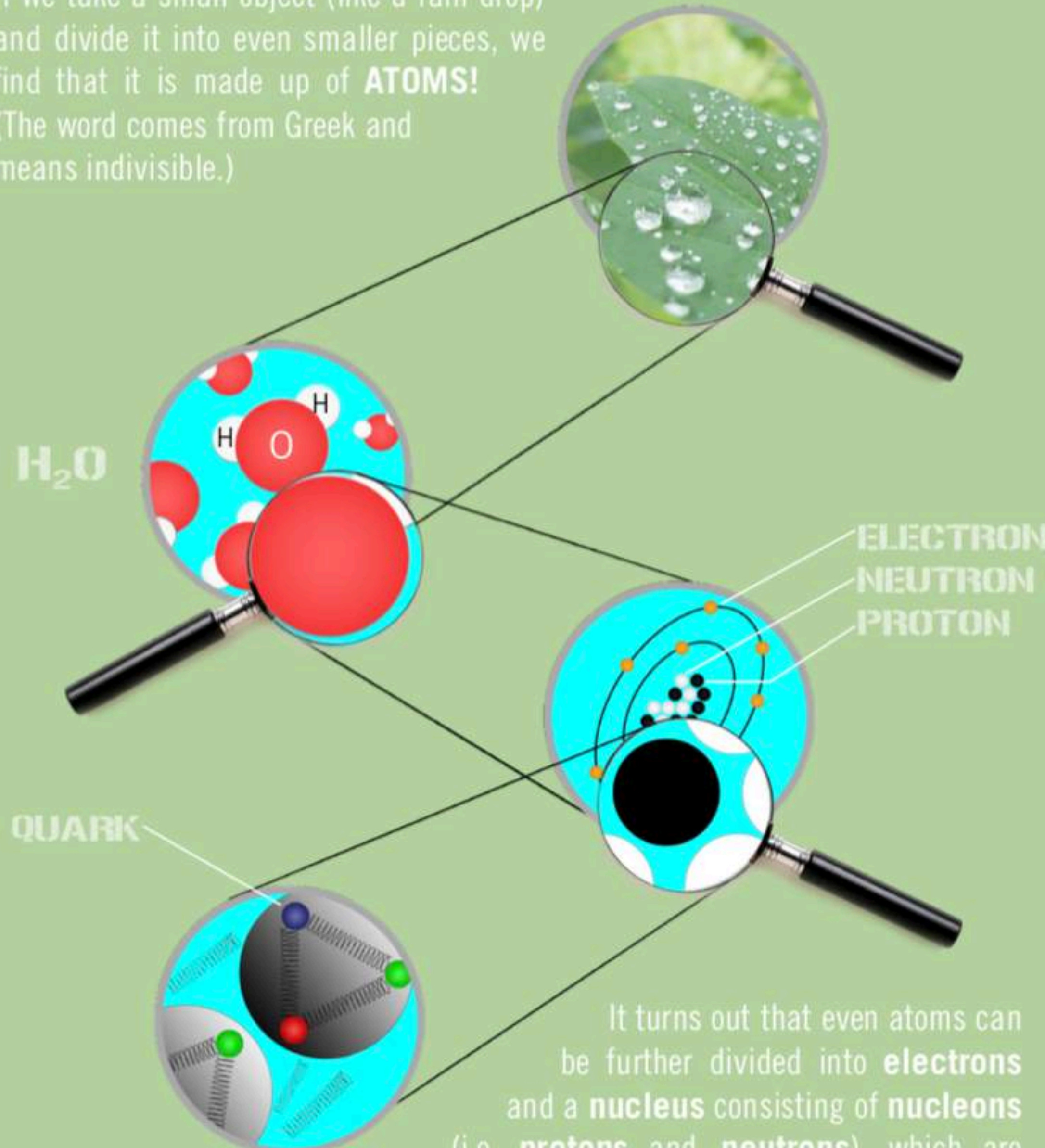
How do we know all this?

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.)



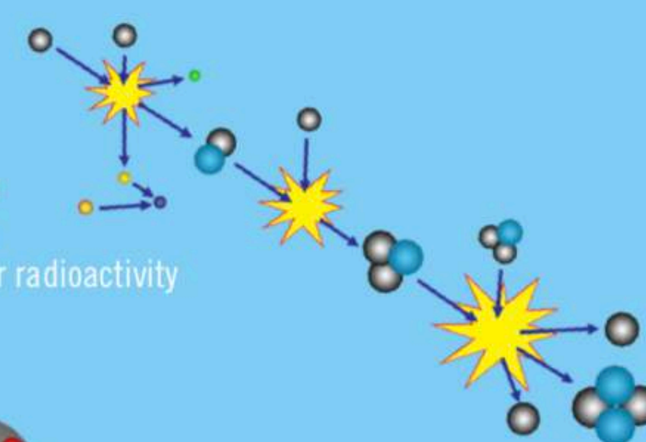
It turns out that even atoms can be further divided into **electrons** and a **nucleus** consisting of **nucleons** (i.e. **protons** and **neutrons**), which are finally built up of **quarks**. According to our current knowledge, quarks and electrons are fundamental particles --- they can be divided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

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

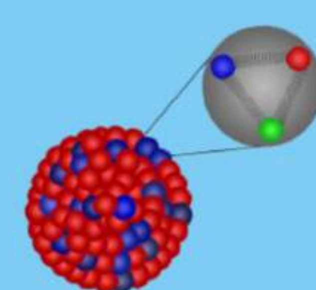
According to our theoretical understanding all forces are transmitted by force carriers.

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

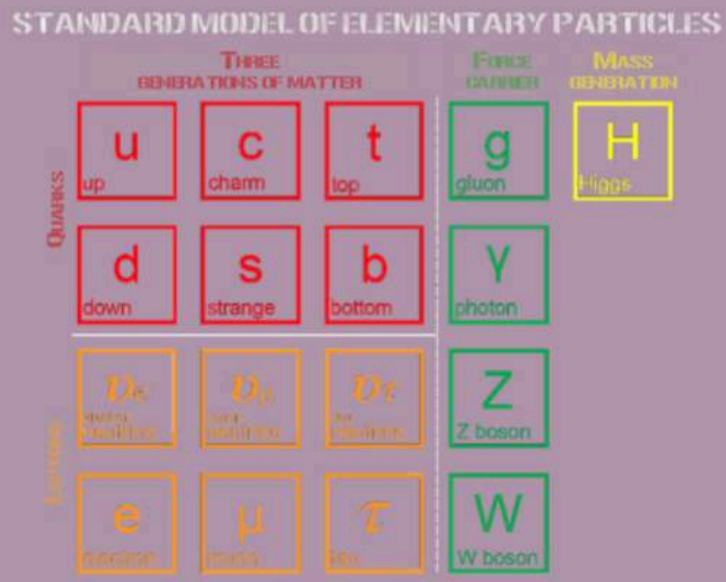


STRONG INTERACTION:
binds protons and neutrons into nuclei and quarks into nucleons
Force carrier: Gluons

THE STANDARD MODEL OF PARTICLE PHYSICS

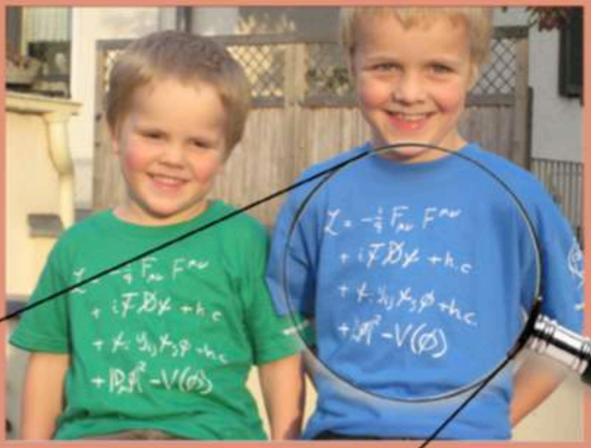
ALL KNOWN FUNDAMENTAL PARTICLES IN THE UNIVERSE CAN BE CLASSIFIED AS MATTER CONSTITUENTS. FORCE CARRIERS AND PARTICLES RESPONSIBLE FOR THE CREATION OF MASS.

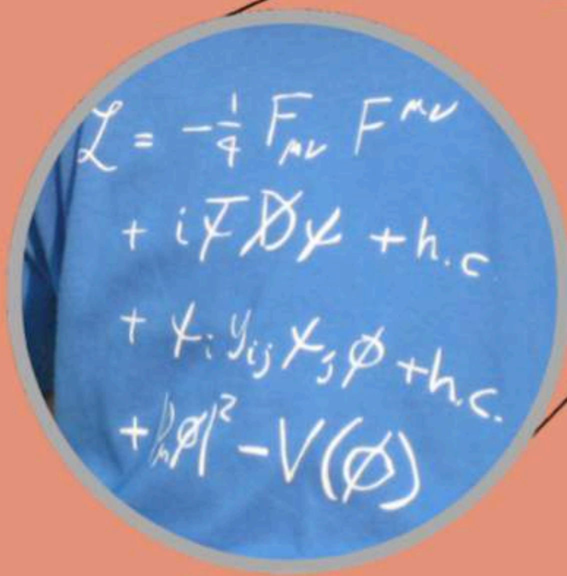
Quarks and leptons are the matter constituents. To a good approximation the proton is made of two **u**p quarks and one **d**own quark. There are also heavier copies of these two quarks: the **c**harm, **s**trange, **b**ottom and **t**op quarks.
The electron is a lepton and it has also heavier copies: 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)

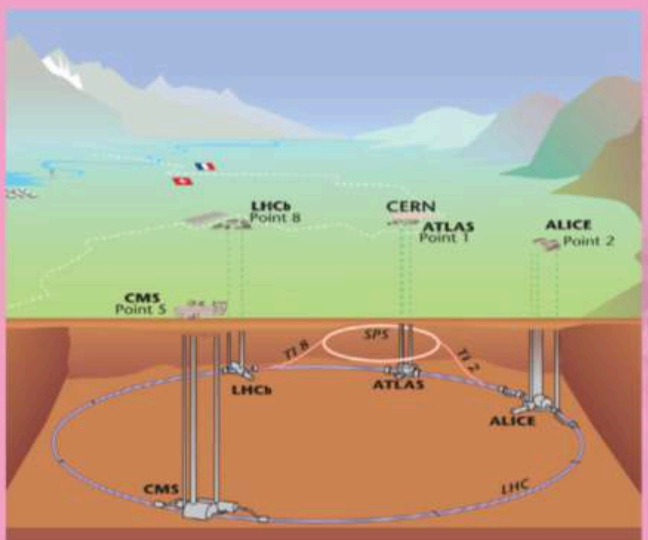
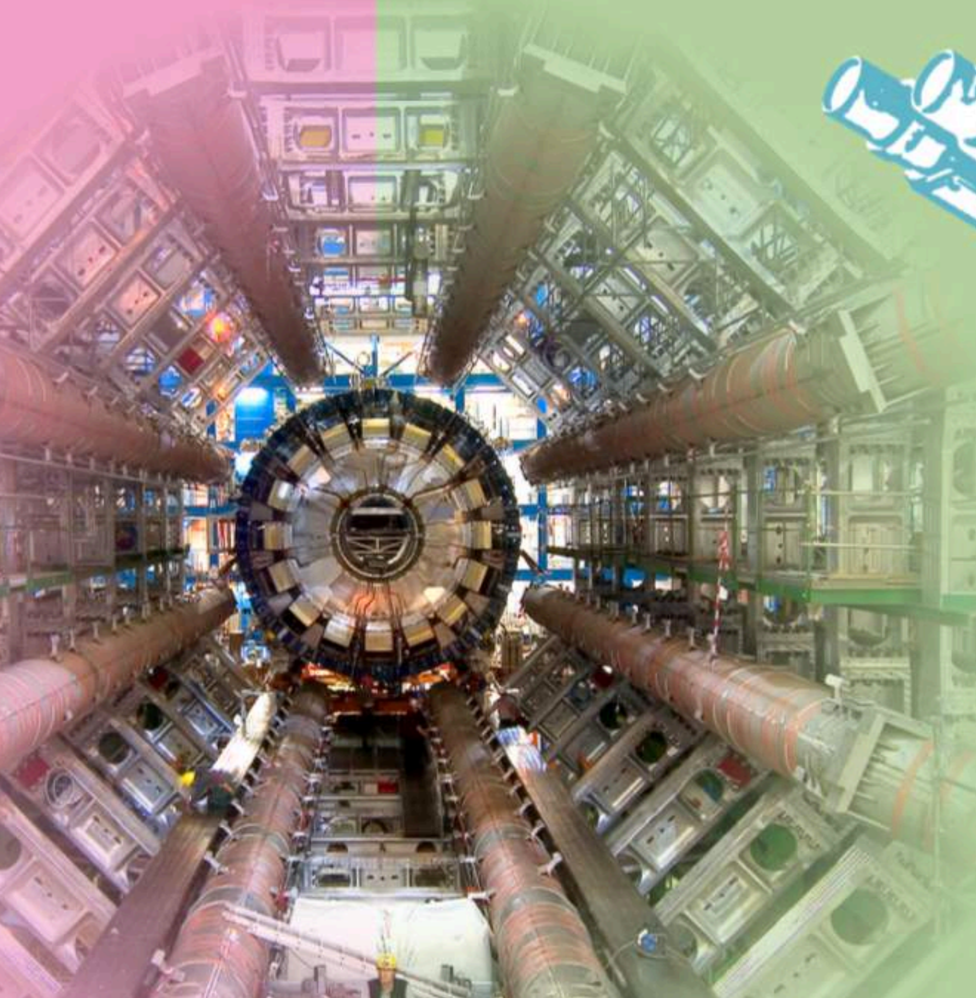
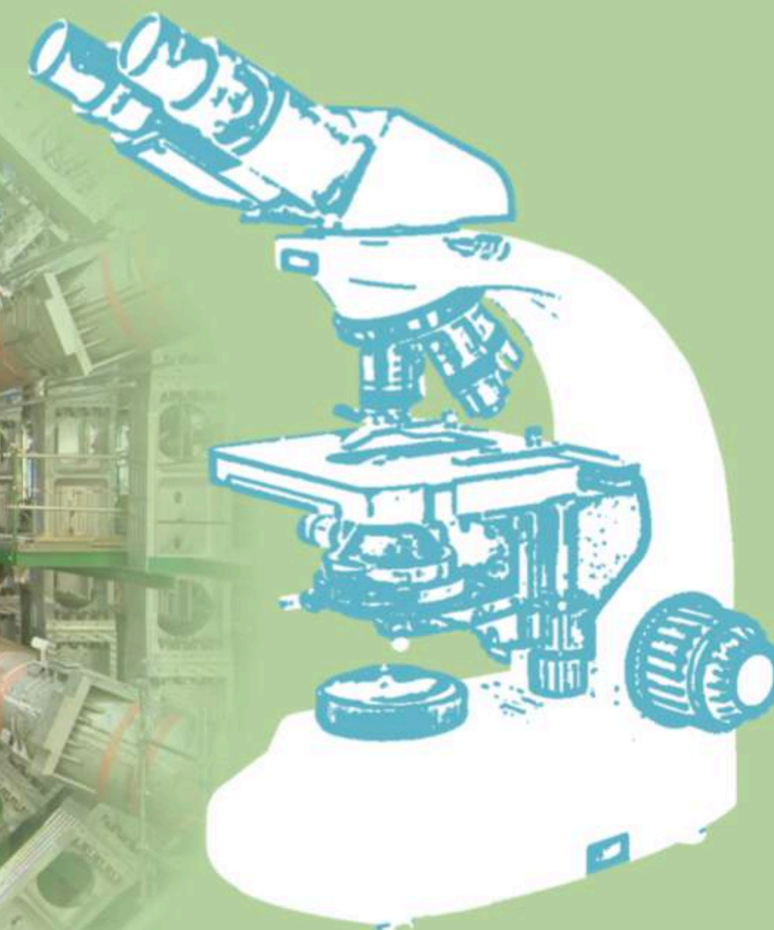


Image credit:CERN





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.

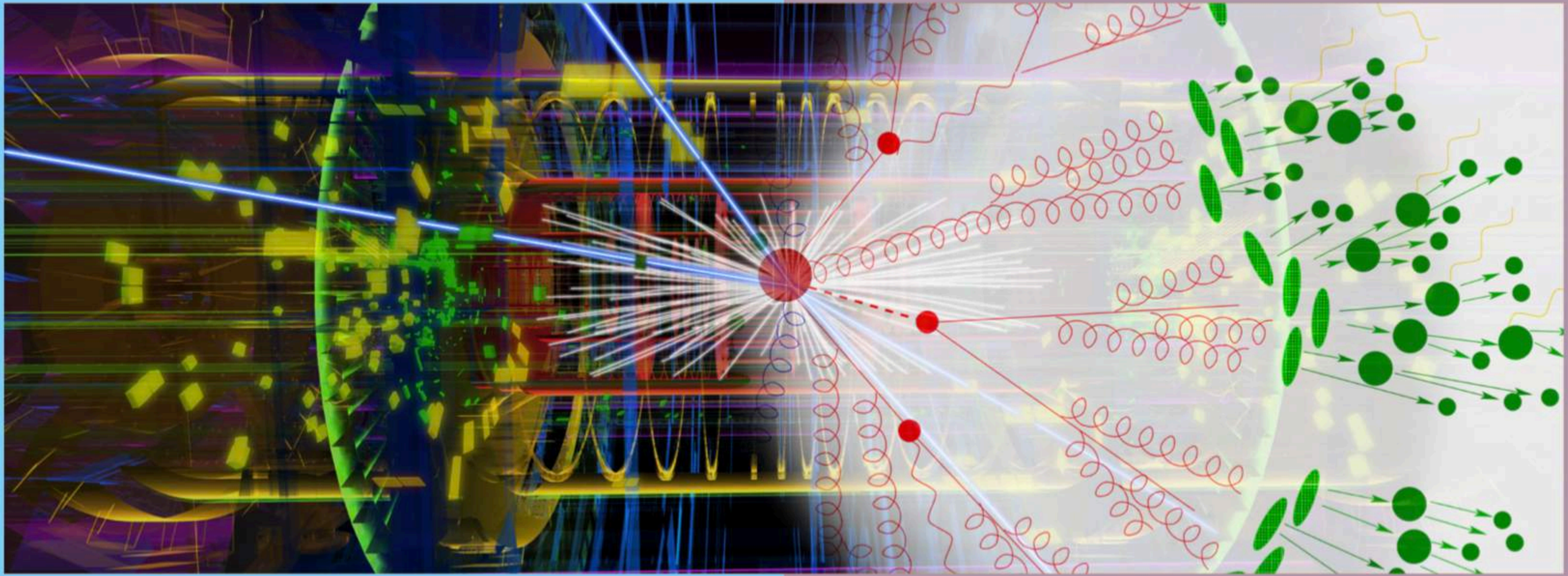
For smaller objects we need shorter wavelengths - which is equivalent to higher energies.

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....



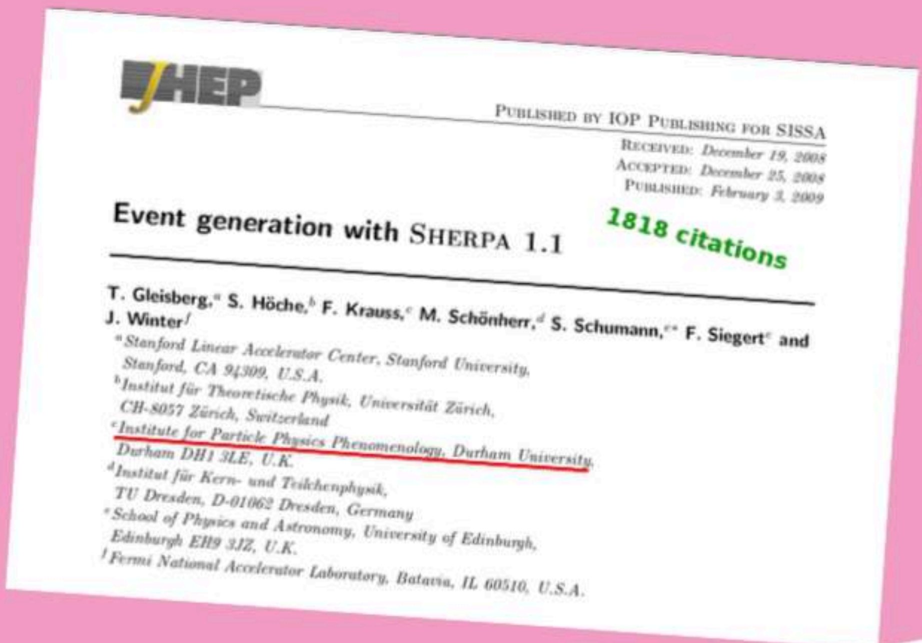
…. but we can infer their existence and their properties by looking at the recorded decay products, and their distribution in the detector over many thousands of collisions.

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.

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....



JHEP

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Event generation with SHERPA 1.1

1818 citations

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THE EUROPEAN PHYSICAL JOURNAL C

Eur. Phys. J. C (2008) 58: 639–707
DOI 10.1140/epjc/s10052-008-0798-9

Special Article - Tools for Experiment and Theory

1464 citations

Herwig++ physics and manual

Manuel Bähr[1], Stefan Gieseke[1], Martyn A. Gigg[2], David Grellscheid[2], Keith Hamilton[3], Oluseyi Latunde-Dada[4], Simon Plätzer[1], Peter Richardson[2,5,a], Michael H. Seymour[5,6], Alexander Sherstnev[4], Bryan R. Webber[4]

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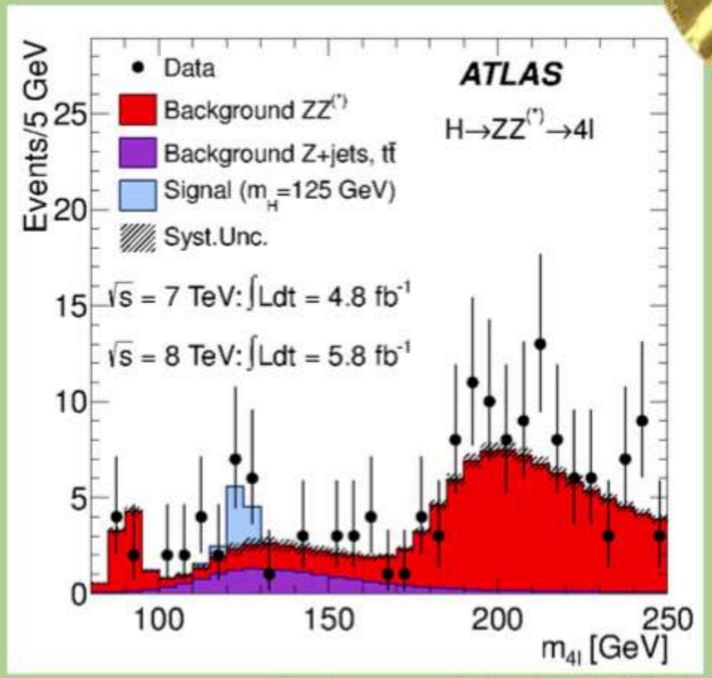
HERWIG AND SHERPA HAVE BEEN INSTRUMENTAL IN THE DISCOVERY OF THE HIGGS BOSON AT THE LHC IN 2012

Nobel prize for physics 2013 - Peter Higgs - François Englert

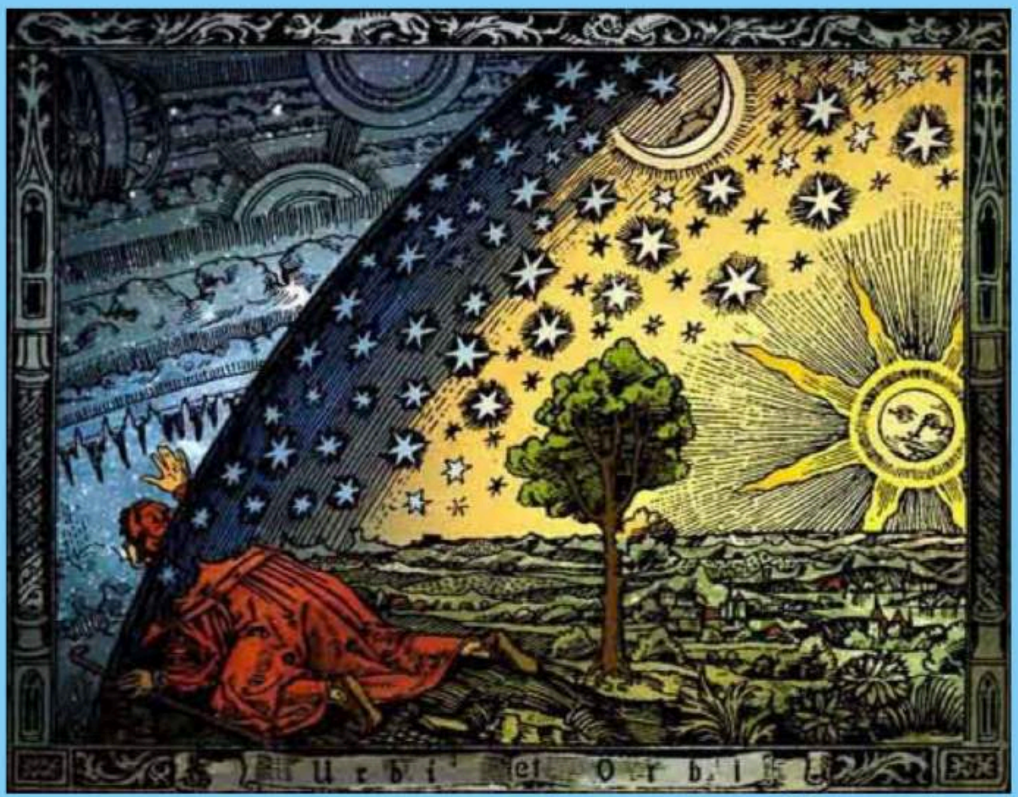


Higgs discovery paper of ATLAS, Phys. Lett. B 716 (2012)

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).

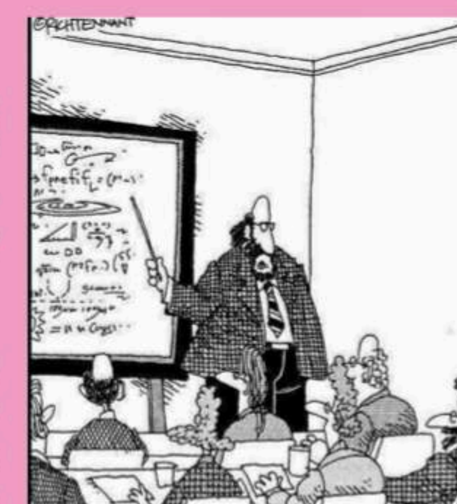
Our observations indicate that dark matter is five times more abundant than the ordinary visible matter that we are made of.

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."

HOW TO SEARCH FOR NEW PHYSICS I

There are (at least) six kinds (=**flavours**) of quarks → BESSIII, LHCb,..

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \begin{pmatrix} q = +2/3 \\ q = -1/3 \end{pmatrix}$$

NA62, KOTO…

BELLE II, LHCb,..

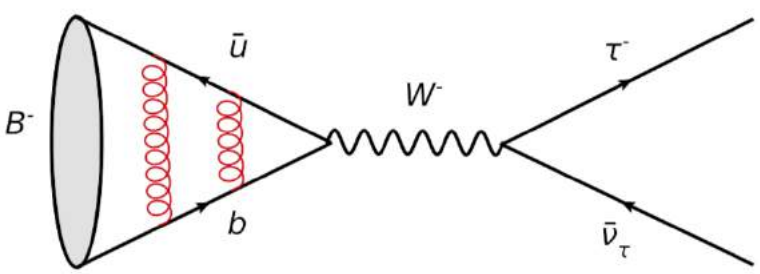
- Proton p = $|uud\rangle$
- **(Heavy) Flavour Physics** describes hadrons with a charm- or a bottom-quark

	$D^0 = (\bar{u}c)$	$D^+ = (\bar{d}c)$	$D_s^+ = (\bar{s}c)$	$\Lambda_c = (udc)$
Mass (GeV)	1.86486	1.86962	1.96850	2.28646
Lifetime (ps)	0.4101	1.040	0.500	0.200

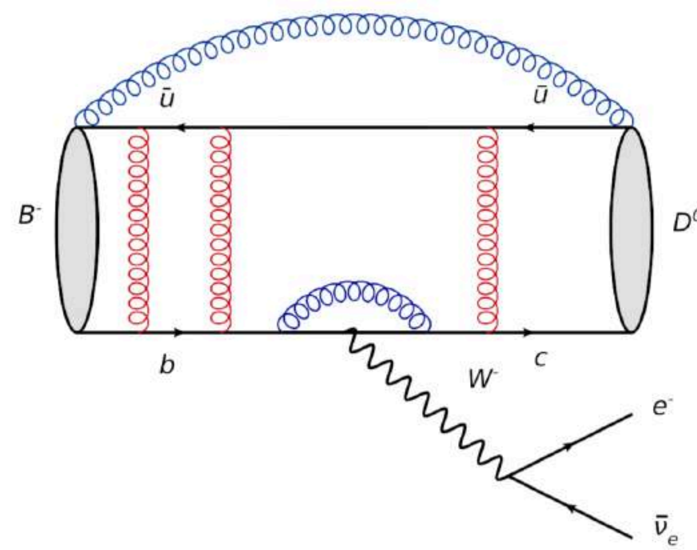
	$B_d = (\bar{b}d)$	$B^+ = (\bar{b}u)$	$B_s = (\bar{b}s)$	$B_c^+ = (\bar{b}c)$	$\Lambda_b = (udb)$
Mass (GeV)	5.27958	5.27926	5.3667	6.2745	5.6194
Lifetime(ps)	1.519	1.638	1.512	0.500	1.451

HOW TO SEARCH FOR NEW PHYSICS II

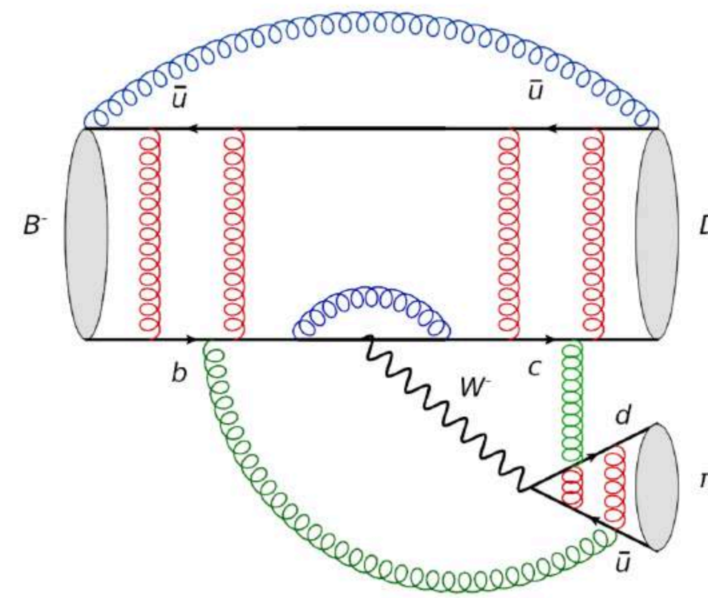
- **Leptonic decays**



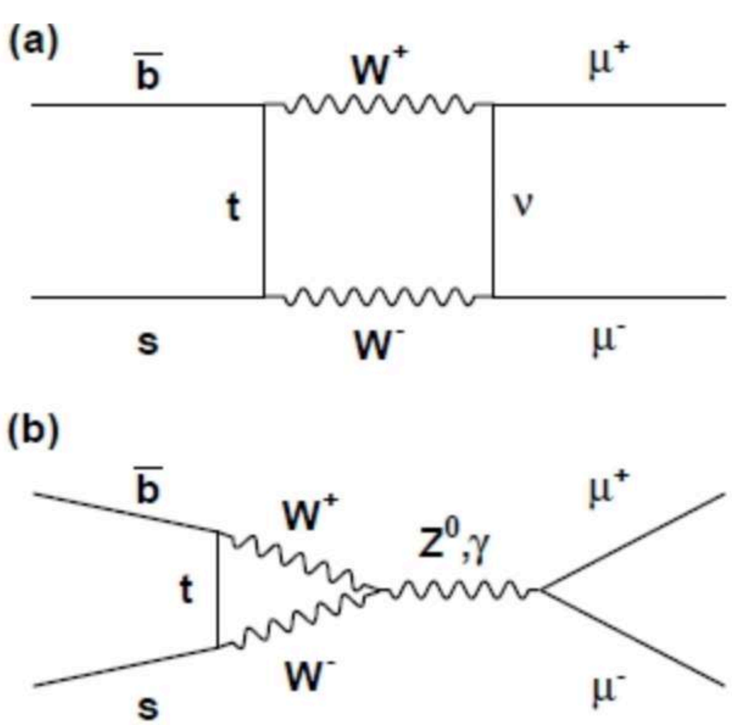
- **Semi-Leptonic decays**



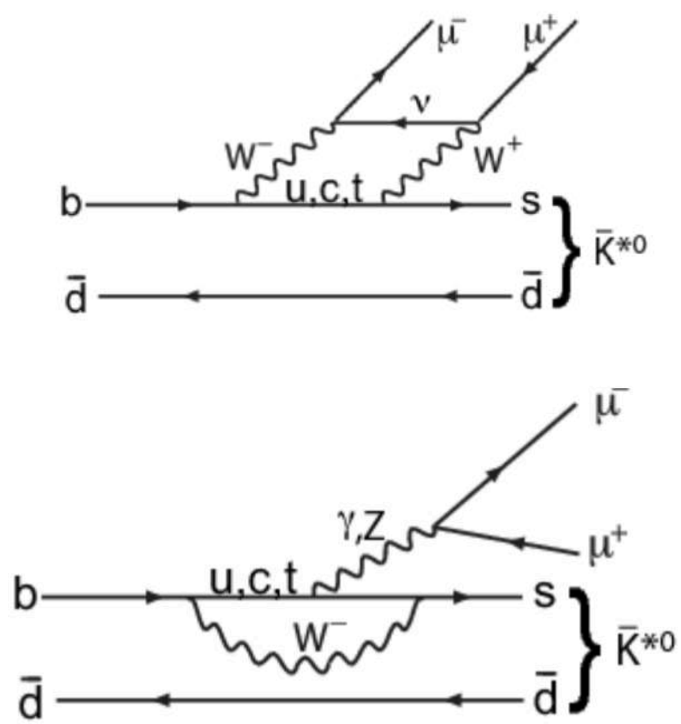
- **Non-Leptonic decays**



- **Leptonic decays**

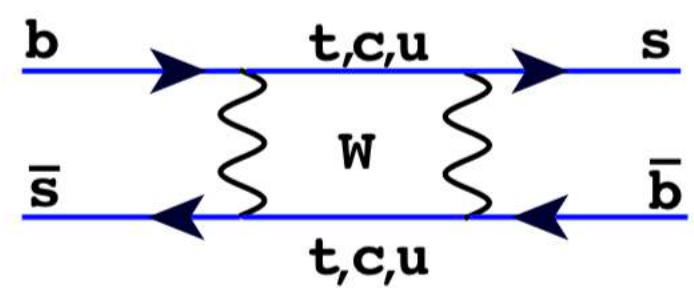


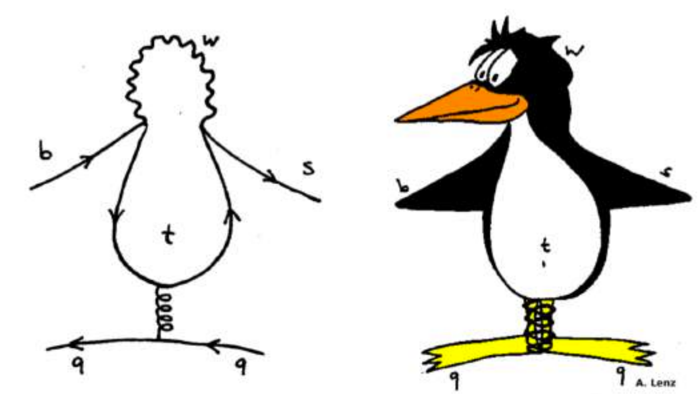
- **Semi-Leptonic decays**



like $K \to \pi\nu\nu$

- **Mixing**





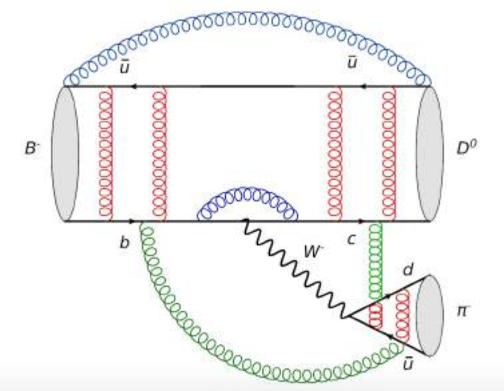
HOW TO SEARCH FOR NEW PHYSICS III

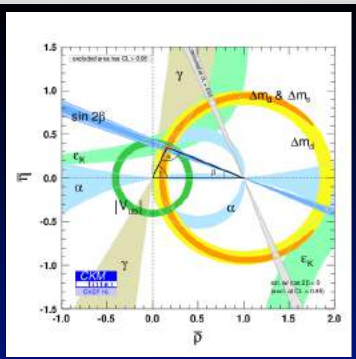
Baryon Asymmetry in the Universe:
A violation of the CP symmetry - which causes matter and anti-matter to evolve differently with time - seems to be necessary to explain the existence of matter in the Universe.
CP violation has so far only been found in hadron decays, which are experimentally investigated at LHCb and NA62 (CERN), SuperBelle (Japan),…

Indirect Search for BSM Physics:
To find hints for Physics beyond the Standard Model we can either use brute force (= higher energies) or more subtle strategies like high precision measurements.
New contributions to an observable f are identified via:

$$f^{\rm SM} + f^{\rm NP} = f^{\rm Exp}$$

Understanding QCD:
Hadron decays are strongly affected by QCD (strong interactions) effects, which tend to overshadow the interesting fundamental decay dynamics. Theory tools like effective theories, Heavy Quark Expansion, HQET, SCET ,…enable a control over QCD-effects and they are used in other fields like Collider Physics, Higgs Physics, DM searches…





Standard Model parameters:
Hadron decays depend strongly on Standard Model parameters like quark masses and CKM couplings (which are the only known source of CP violation in the SM). A precise knowledge of these parameters is needed for all branches of particle physics.

ABOUT

News › Press release › Topic: Physics

Voir en français

LHCb sees a new flavour of matter–antimatter asymmetry

The LHCb collaboration has observed a phenomenon known as CP violation in the decays of a particle known as a D0 meson for the first time

physicsworld

Magazine | Latest

particle and nuclear

PARTICLE AND NUCLEAR | RESEARCH UPDATE

CERN physicists spot symmetry violation in charm mesons

21 Mar 2019 Michael Banks

CERN: Study sheds light on one of physics' biggest mysteries – why there's more matter than antimatter

March 21, 2019 9.48am GMT

The Milky Way as seen from Yellowstone National Park. Neal Herbert/Flickr

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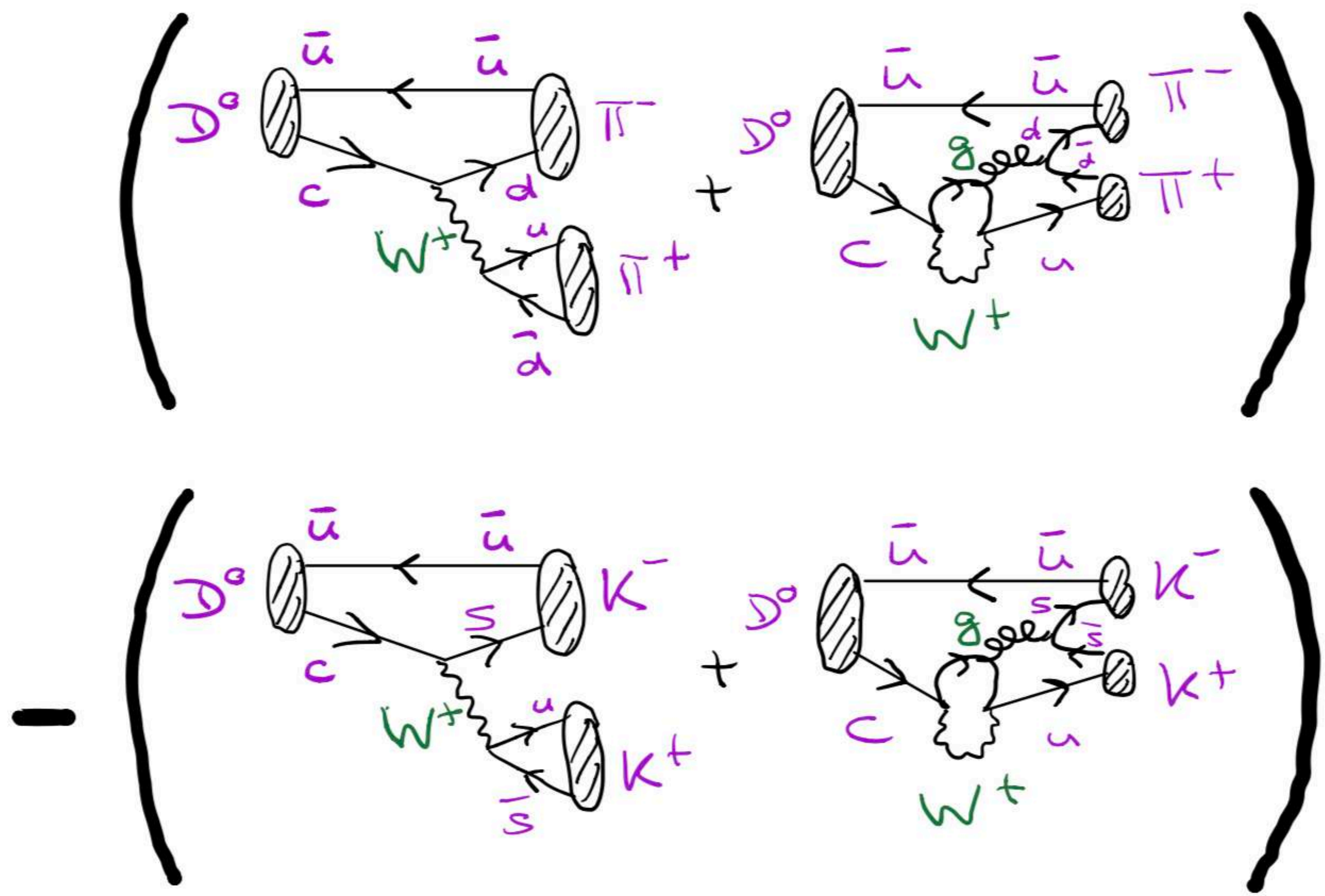
Why do we exist? This is arguably the most profound question there is and one that may seem completely outside the scope of particle physics. But our new experiment at CERN's Large Hadron Collider has taken us a step closer to figuring it out.

Author

Marco Gersabeck
Lecturer in Physics, University of Manchester

HOW TO SEARCH FOR NEW PHYSICS V



$\neq$ Experiment !

HOW TO SEARCH FOR NEW PHYSICS VI

ΔA_{CP} within the Standard Model and beyond

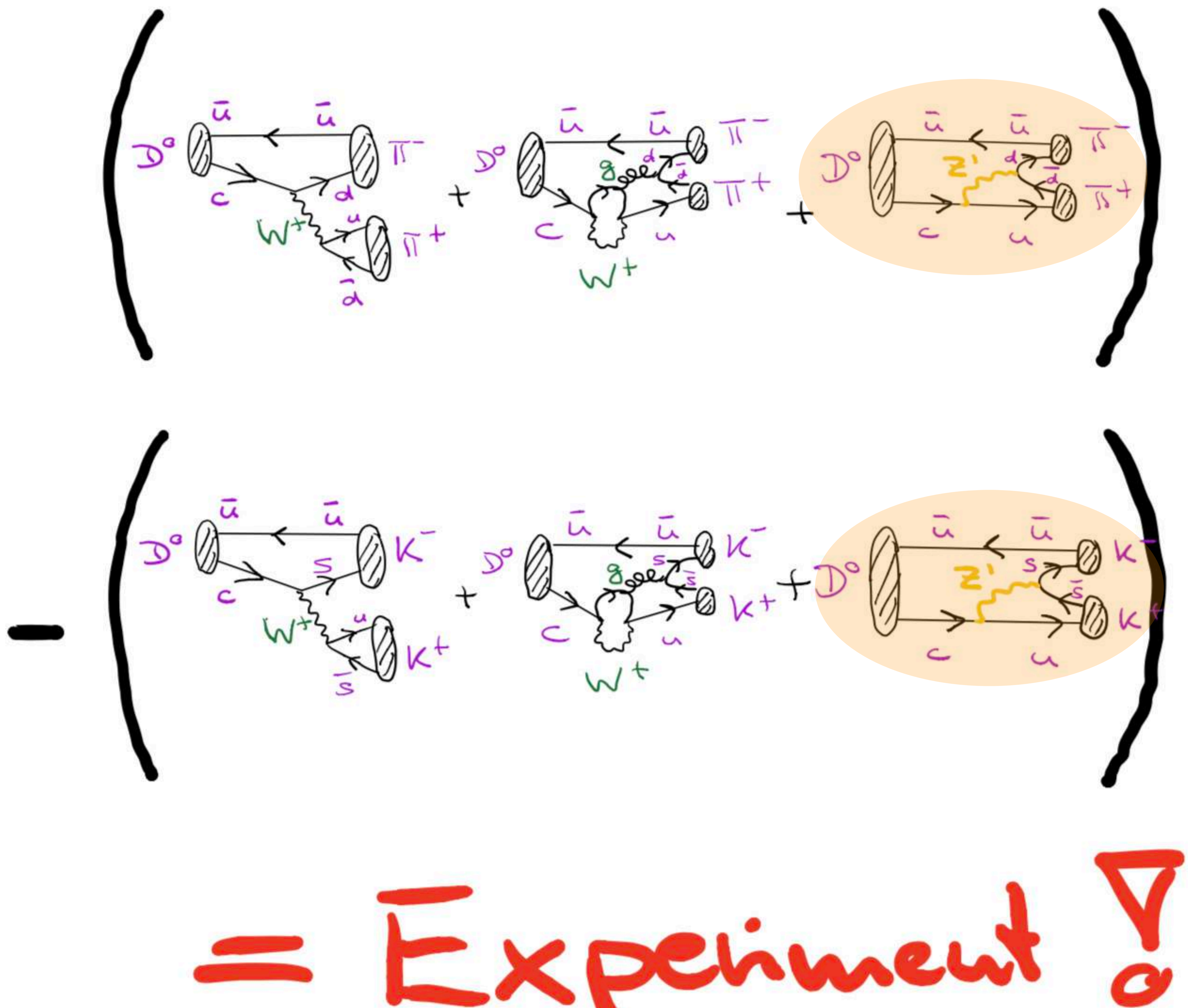
Mikael Chala, Alexander Lenz, Aleksey V. Rusov and Jakub Scholtz

Institute for Particle Physics Phenomenology, Durham University, DH1 3LE Durham, United Kingdom

Abstract

In light of the recent LHCb observation of CP violation in the charm sector, we review standard model (SM) predictions in the charm sector and in particular for ΔA_{CP}. We get as an upper bound in the SM $|\Delta A_{CP}^{\rm SM}| \leq 3 \times 10^{-4}$, which can be compared to the measurement of $\Delta A_{CP}^{\rm LHCb2019} = (-15.4 \pm 2.9) \times 10^{-4}$. We discuss resolving this tension within an extension of the SM that includes a flavour violating Z' that couples only to $\bar{s}s$ and $\bar{c}u$. We show that for masses below 80 GeV and flavour violating coupling of the order of 10^{-4}, this model can successfully resolve the tension and avoid constraints from dijet searches, $D^0 - \overline{D}^0$ mixing and measurements of the Z width.

HOW TO SEARCH FOR NEW PHYSICS VII



HOW TO SEARCH FOR NEW PHYSICS VIII

Good luck in your search for new gauge bosons!!!!

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.

MODELLING THE INVISIBLE

More info about the exhibits:
https://www.modellinginvisible.org

Some articles about our exhibition:
https://www.dur.ac.uk/news/newsitem/?itemno=31877
http://community.dur.ac.uk/blogs/modelling-invisible-royal-society/
https://www.raspberrypi.org/blog/royal-society-galton-board/
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