Introducing Particle Physics in the Classroom

Dr. Jeff Wiener

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PARTICLE
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“What is a particle?”

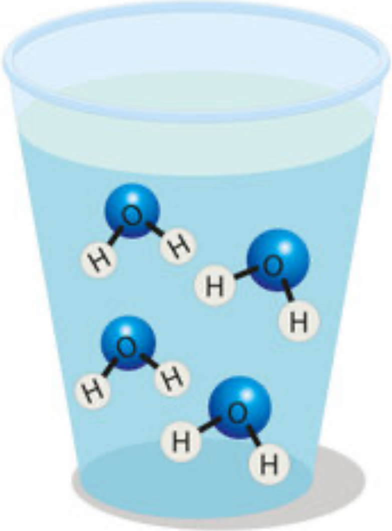
State of research

Sources for (mis)conceptions

Everyday experiences

Inadequate learning offers

Illustrations and animations



Documented misconceptions

Overlap of continuum and discontinuum conceptions

Transfer of macroscopic properties into the microcosm

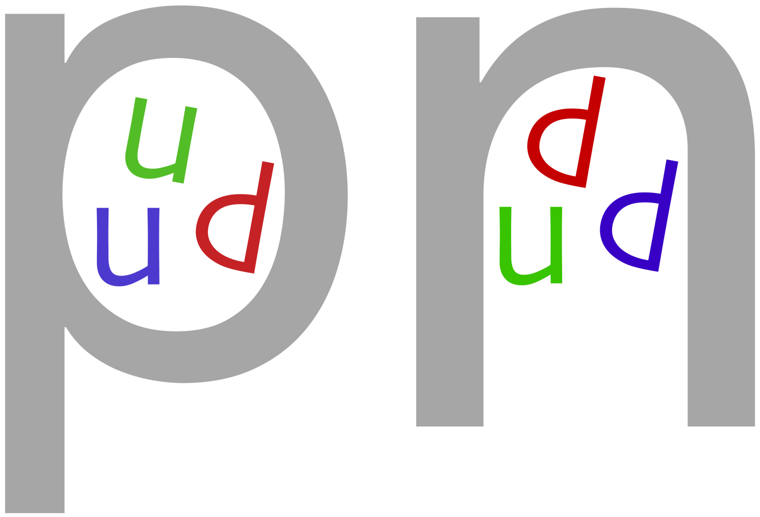
Negation of constant movement of particles and empty space

Research-based suggestions

Nature of science

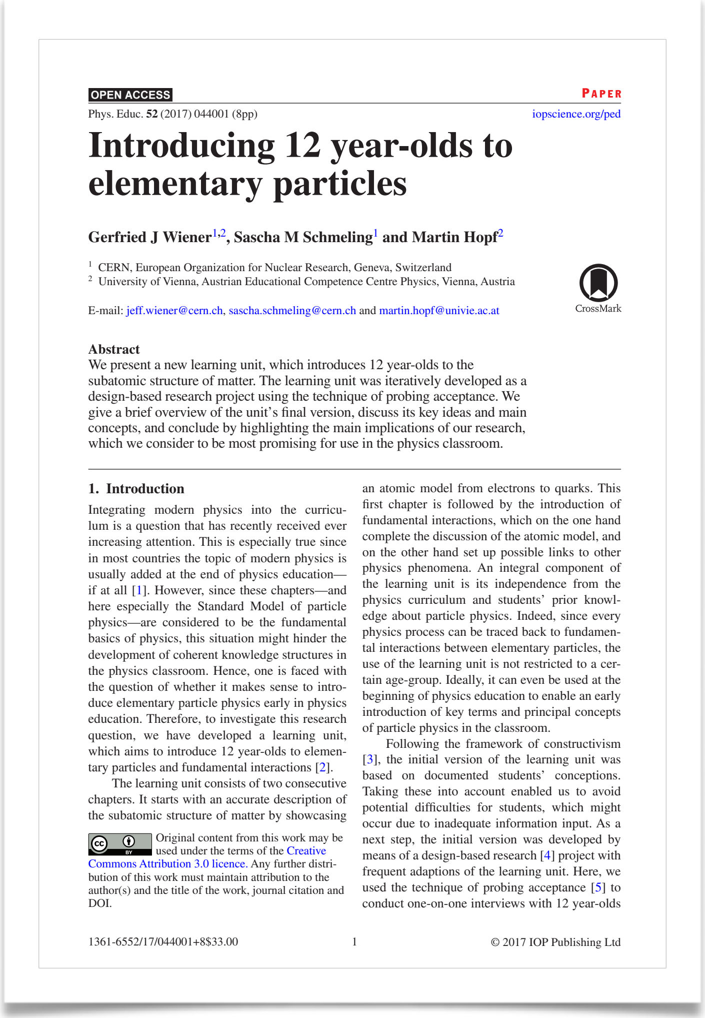
“With the model of particle physics, we describe…”

Typographic illustrations



Linguistic accuracy

particle
vs.
particle system



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Introducing 12 year-olds to elementary particles

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CrossMark

Abstract

We present a new learning unit, which introduces 12 year-olds to the subatomic structure of matter. The learning unit was iteratively developed as a design-based research project using the technique of probing acceptance. We give a brief overview of the unit's final version, discuss its key ideas and main concepts, and conclude by highlighting the main implications of our research, which we consider to be most promising for use in the physics classroom.

1. Introduction

Integrating modern physics into the curriculum is a question that has recently received ever increasing attention. This is especially true since in most countries the topic of modern physics is usually added at the end of physics education—if at all [1]. However, since these chapters—and here especially the Standard Model of particle physics—are considered to be the fundamental basics of physics, this situation might hinder the development of coherent knowledge structures in the physics classroom. Hence, one is faced with the question of whether it makes sense to introduce elementary particle physics early in physics education. Therefore, to investigate this research question, we have developed a learning unit, which aims to introduce 12 year-olds to elementary particles and fundamental interactions [2].

The learning unit consists of two consecutive chapters. It starts with an accurate description of the subatomic structure of matter by showcasing an atomic model from electrons to quarks. This first chapter is followed by the introduction of fundamental interactions, which on the one hand complete the discussion of the atomic model, and on the other hand set up possible links to other physics phenomena. An integral component of the learning unit is its independence from the physics curriculum and students' prior knowledge about particle physics. Indeed, since every physics process can be traced back to fundamental interactions between elementary particles, the use of the learning unit is not restricted to a certain age-group. Ideally, it can even be used at the beginning of physics education to enable an early introduction of key terms and principal concepts of particle physics in the classroom.

Following the framework of constructivism [3], the initial version of the learning unit was based on documented students' conceptions. Taking these into account enabled us to avoid potential difficulties for students, which might occur due to inadequate information input. As a next step, the initial version was developed by means of a design-based research [4] project with frequent adaptions of the learning unit. Here, we used the technique of probing acceptance [5] to conduct one-on-one interviews with 12 year-olds

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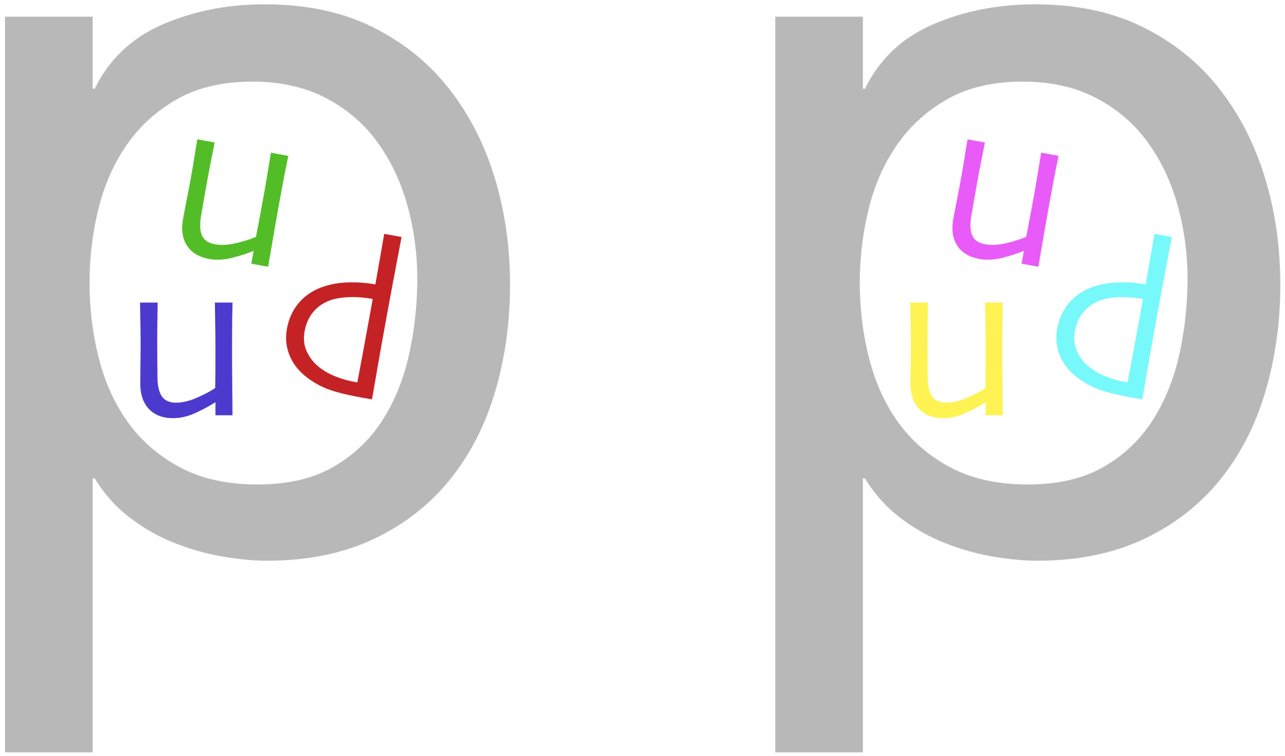
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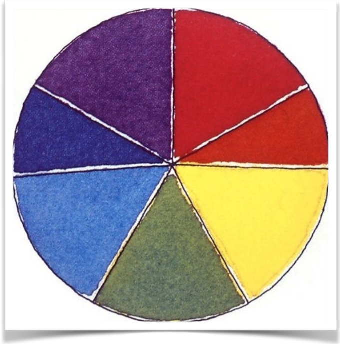
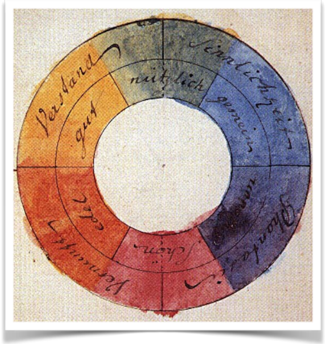


Newton



Goethe

CMYK

“Is not the complementary color of blue, orange, of green, red, and of yellow, pink?” [student, 17]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An Alternative Proposal for the Graphical Representation of Anticolor Charge

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We have developed a learning unit based on the Standard Model of particle physics, featuring novel typographic illustrations of elementary particles and particle systems.[1] Since the unit includes antiparticles and systems of antiparticles, a visualization of anticolor charge was required. We propose an alternative to the commonly used complementary-color method, whereby antiparticles and antiparticle systems are identified through the use of stripes instead of a change in color. We presented our proposal to high school students and physics teachers, who evaluated it to be a more helpful way of distinguishing between color charge and anticolor charge.

Education research shows that carefully designed images can improve students' learning.[2] However, in practice, illustrations commonly contain elements limiting students' learning, as underlined by Cook[3]: "Visual representations are essential for communicating ideas in the science classroom; however, the design of such representations is not always beneficial for learners." To determine what aspects of the typographic representations used in our learning unit (Fig. 1) hinder or promote learning, we tested and adapted them in the context of design-based research[4] using Jung's technique of probing acceptance.[5] In the course of developing our unit, we also formulated this proposal regarding the graphical representation of anticolor charge.

In the Standard Model of particle physics, elementary particles are sorted according to their various charges. A "charge" in this context is the property of a particle whereby it is influenced by a fundamental interaction. In quantum field theory, the electromagnetic, weak, and strong interactions are each associated with a fundamental charge. The abstract naming of the strong interaction's associated charge as "color charge" originated in the work of Greenberg[6] and Han & Nambu[7] in the 1960s. They introduced red, green, and blue as the "color charged" states of quarks and antired, antigreen, and antiblue for antiquarks. According to this model, quarks have a color charge, whereas antiquarks are defined by having an anticolor charge. In addition, particle systems must be color neutral, i.e., "white". This includes mesons, composed of two quarks each, and baryons, made of three. In each case, the distribution of color charge must "balance out" among the quarks. For mesons, this can only be achieved if a color charged quark is bound to an antiquark with the respective anticolor charge. In the case of baryons, all three (anti)color charge states must be

Fig. 1. Typographic illustrations of a proton and a neutron.

Fig. 2. Traditional illustrations of a proton and an antiproton, relying on readers' prior knowledge of the relevant color wheel. Obviously, using colors complementary to the quarks' red, green, and blue presents a challenge for identifying anticolor charges, e.g., cyan as antired.

Fig. 3. Alternative illustrations of a proton and an antiproton, using a stripe pattern to denote anticolor charge. This representation clearly shows corresponding color and anticolor charge states while doing away with any requirement for prior knowledge of complementary colors.

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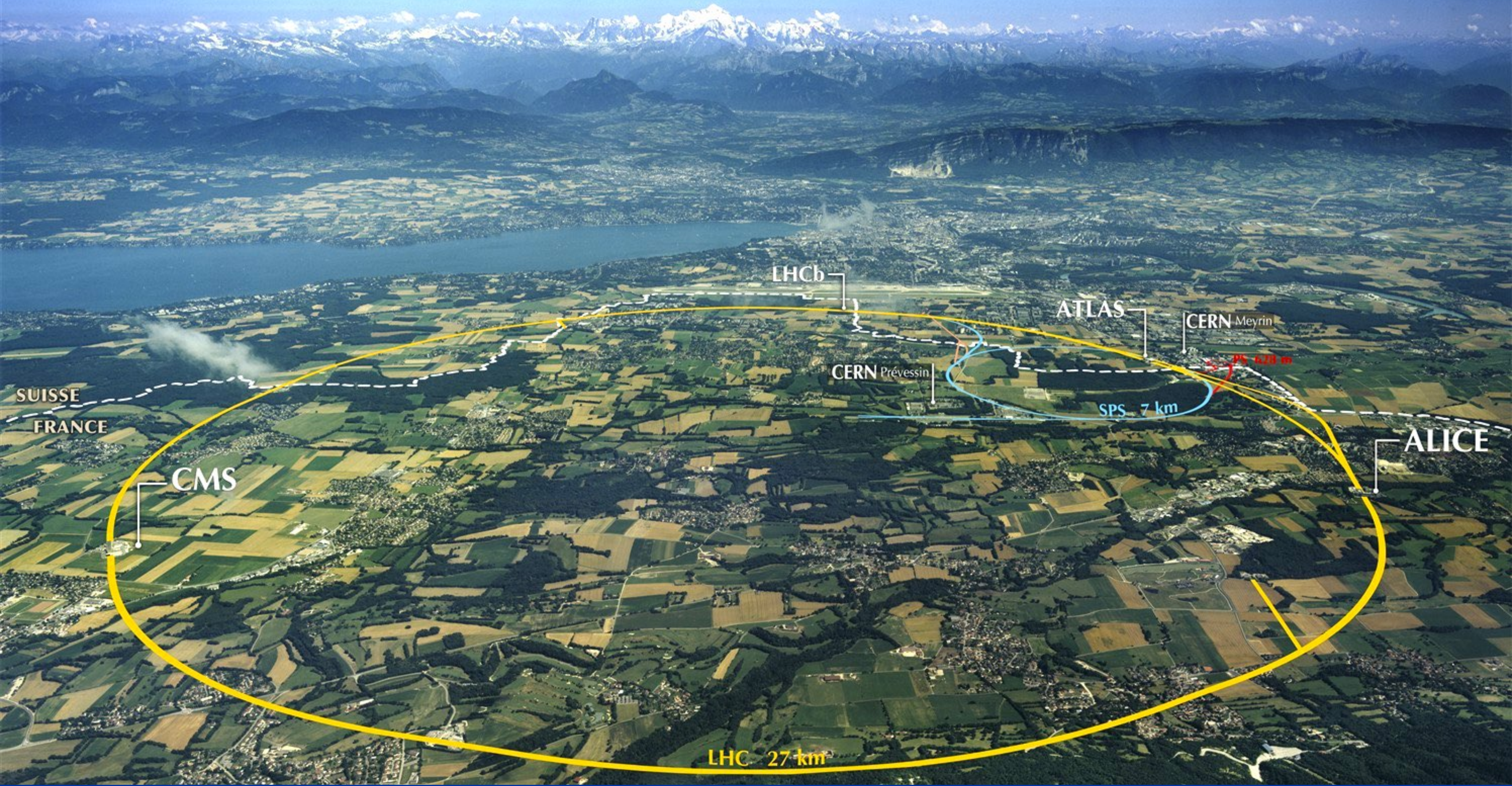
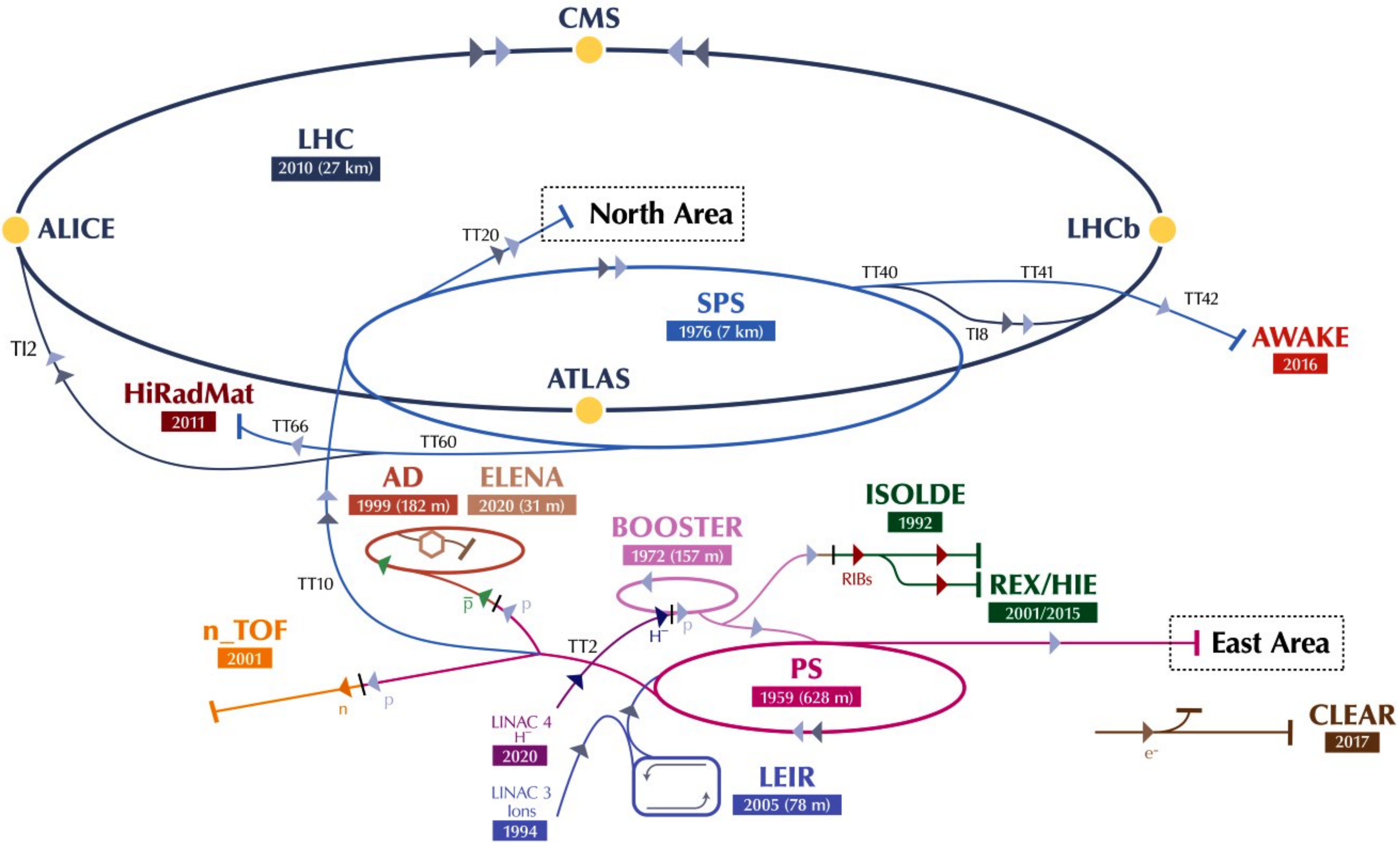

LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km


CMS
LHC
2010 (27 km)
ALICE
TT20
North Area
LHCb
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
HiRadMat
2011
ATLAS
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
TT10
p̄
p
H⁻
p
n_TOF
2001
TT2
East Area
PS
1959 (628 m)
n
p
LINAC 4
H⁻
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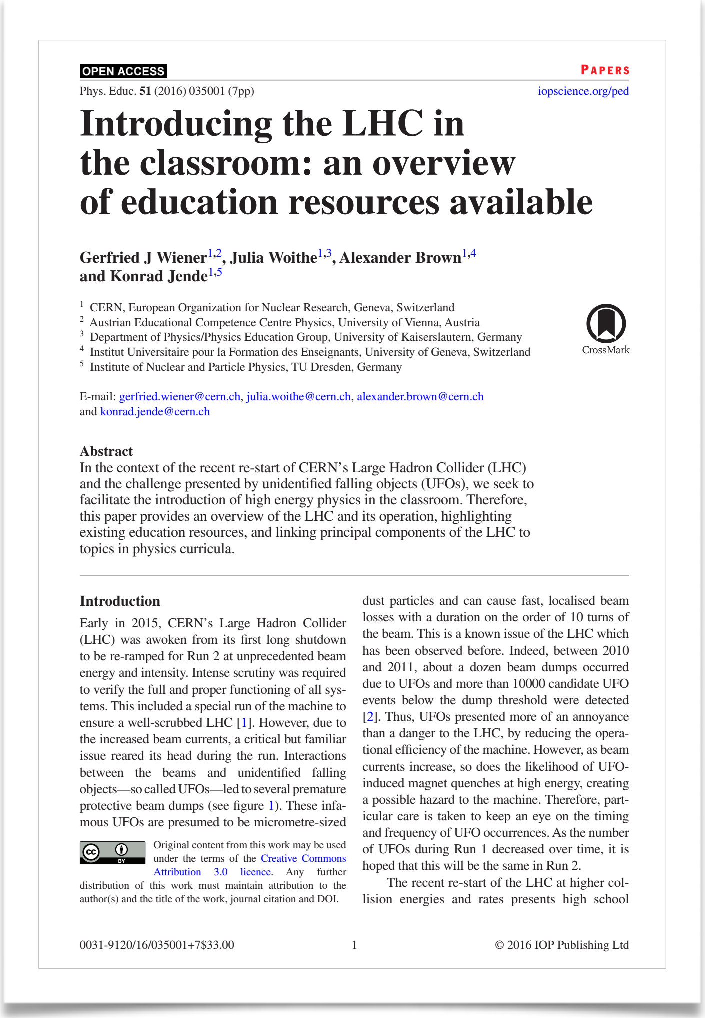
CLEAR
2017
e⁻
LINAC 3
Ions
1994
LEIR
2005 (78 m)



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Introducing the LHC in the classroom: an overview of education resources available

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CrossMark

Abstract
In the context of the recent re-start of CERN's Large Hadron Collider (LHC) and the challenge presented by unidentified falling objects (UFOs), we seek to facilitate the introduction of high energy physics in the classroom. Therefore, this paper provides an overview of the LHC and its operation, highlighting existing education resources, and linking principal components of the LHC to topics in physics curricula.

Introduction

Early in 2015, CERN's Large Hadron Collider (LHC) was awoken from its first long shutdown to be re-ramped for Run 2 at unprecedented beam energy and intensity. Intense scrutiny was required to verify the full and proper functioning of all systems. This included a special run of the machine to ensure a well-scrubbed LHC [1]. However, due to the increased beam currents, a critical but familiar issue reared its head during the run. Interactions between the beams and unidentified falling objects—so called UFOs—led to several premature protective beam dumps (see figure 1). These infamous UFOs are presumed to be micrometre-sized dust particles and can cause fast, localised beam losses with a duration on the order of 10 turns of the beam. This is a known issue of the LHC which has been observed before. Indeed, between 2010 and 2011, about a dozen beam dumps occurred due to UFOs and more than 10000 candidate UFO events below the dump threshold were detected [2]. Thus, UFOs presented more of an annoyance than a danger to the LHC, by reducing the operational efficiency of the machine. However, as beam currents increase, so does the likelihood of UFO-induced magnet quenches at high energy, creating a possible hazard to the machine. Therefore, particular care is taken to keep an eye on the timing and frequency of UFO occurrences. As the number of UFOs during Run 1 decreased over time, it is hoped that this will be the same in Run 2.

The recent re-start of the LHC at higher collision energies and rates presents high school

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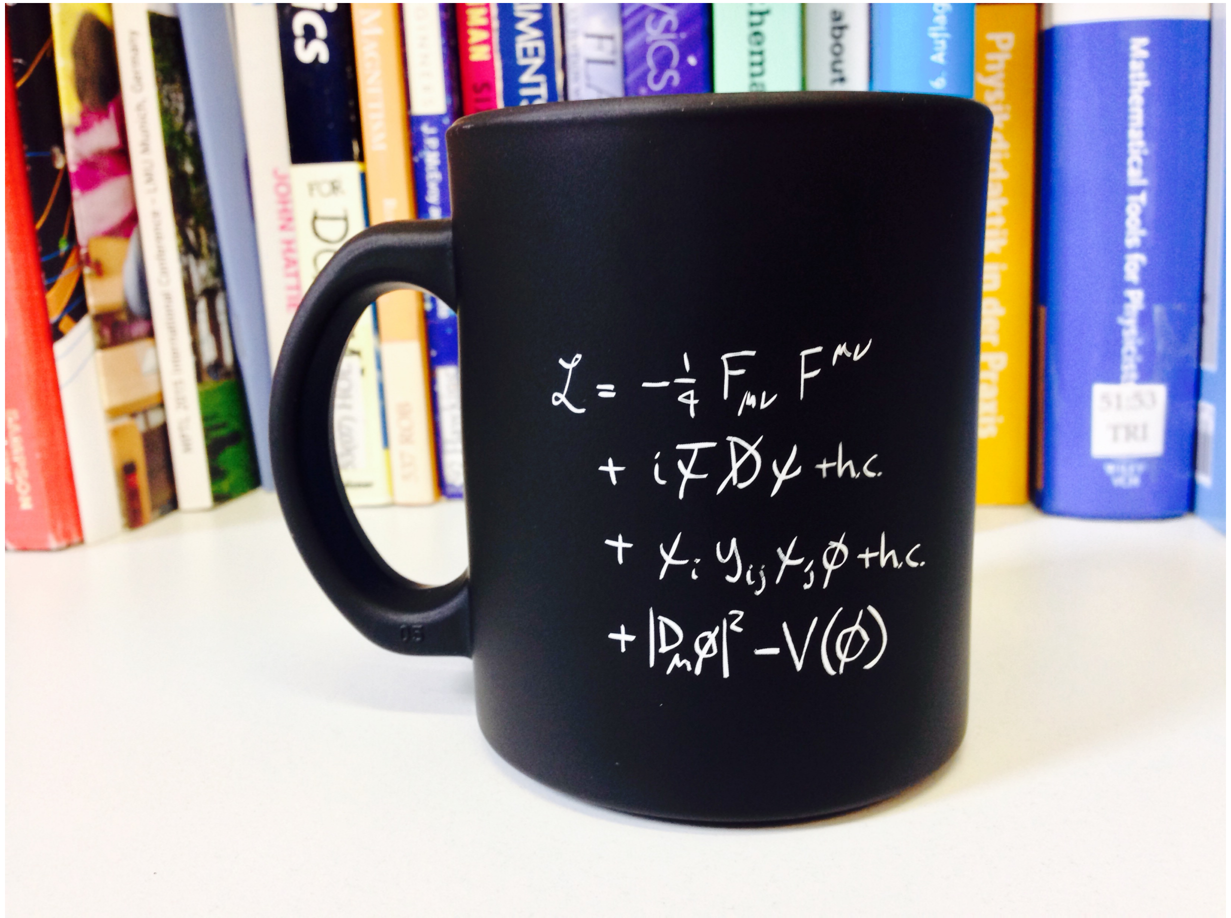
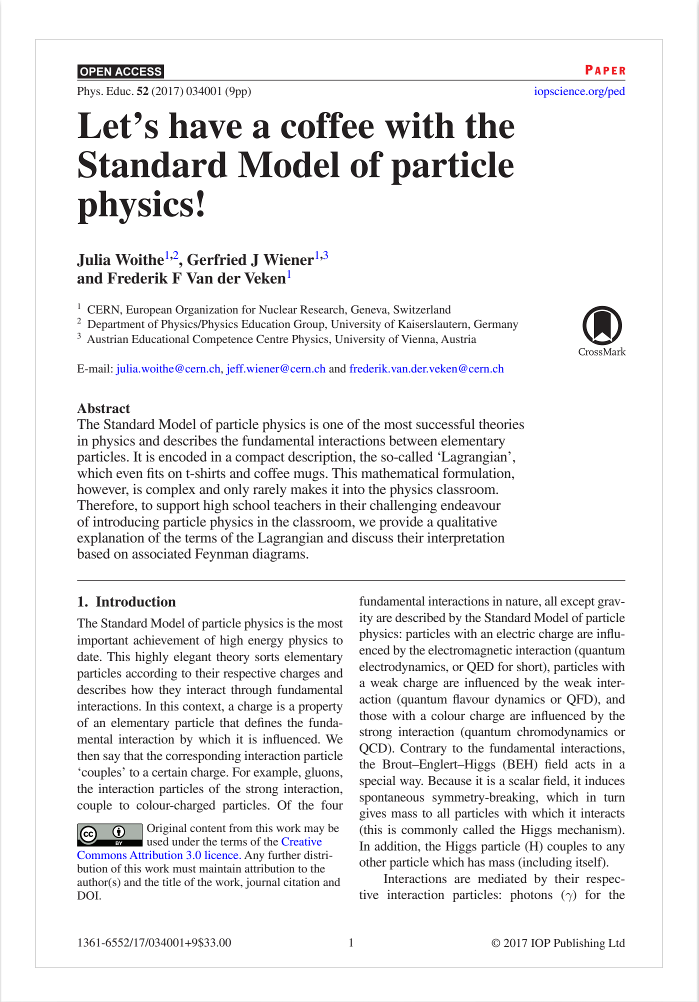

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$



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Let's have a coffee with the Standard Model of particle physics!

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Abstract
The Standard Model of particle physics is one of the most successful theories in physics and describes the fundamental interactions between elementary particles. It is encoded in a compact description, the so-called 'Lagrangian', which even fits on t-shirts and coffee mugs. This mathematical formulation, however, is complex and only rarely makes it into the physics classroom. Therefore, to support high school teachers in their challenging endeavour of introducing particle physics in the classroom, we provide a qualitative explanation of the terms of the Lagrangian and discuss their interpretation based on associated Feynman diagrams.

1. Introduction

The Standard Model of particle physics is the most important achievement of high energy physics to date. This highly elegant theory sorts elementary particles according to their respective charges and describes how they interact through fundamental interactions. In this context, a charge is a property of an elementary particle that defines the fundamental interaction by which it is influenced. We then say that the corresponding interaction particle 'couples' to a certain charge. For example, gluons, the interaction particles of the strong interaction, couple to colour-charged particles. Of the four fundamental interactions in nature, all except gravity are described by the Standard Model of particle physics: particles with an electric charge are influenced by the electromagnetic interaction (quantum electrodynamics, or QED for short), particles with a weak charge are influenced by the weak interaction (quantum flavour dynamics or QFD), and those with a colour charge are influenced by the strong interaction (quantum chromodynamics or QCD). Contrary to the fundamental interactions, the Brout–Englert–Higgs (BEH) field acts in a special way. Because it is a scalar field, it induces spontaneous symmetry-breaking, which in turn gives mass to all particles with which it interacts (this is commonly called the Higgs mechanism). In addition, the Higgs particle (H) couples to any other particle which has mass (including itself).

Interactions are mediated by their respective interaction particles: photons (γ) for the

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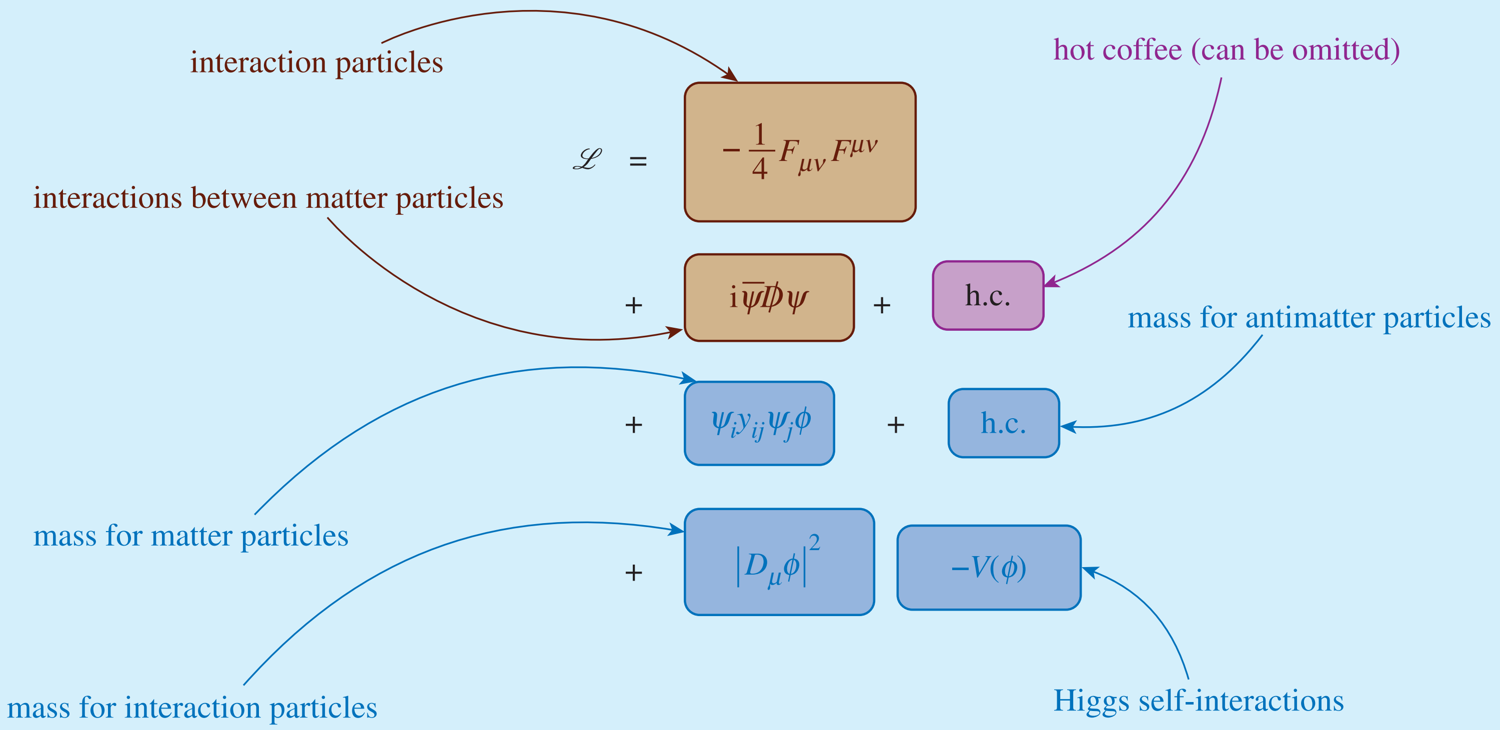


interaction particles

hot coffee (can be omitted)

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \text{h.c.} + \psi_i y_{ij}\psi_j\phi + \text{h.c.} + \left|D_\mu\phi\right|^2 - V(\phi)$$

interactions between matter particles

mass for antimatter particles

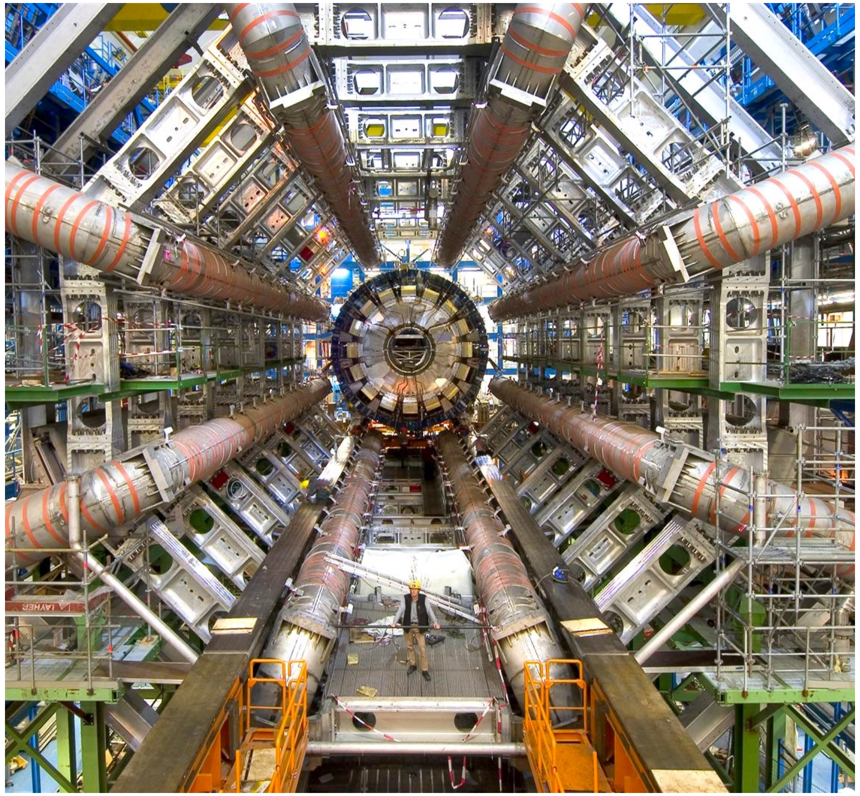
mass for matter particles

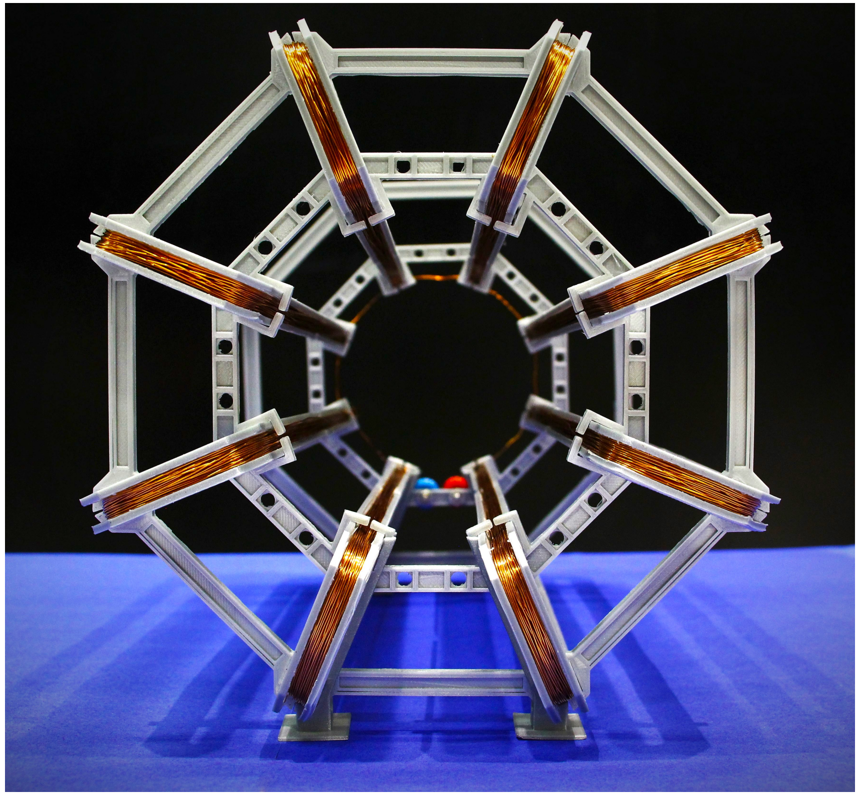
mass for interaction particles

Higgs self-interactions

S'Cool LAB


There is always a way to do it better... find it!
If you can't explain it simply, you don't understand it well enough.
Albert EINSTEIN





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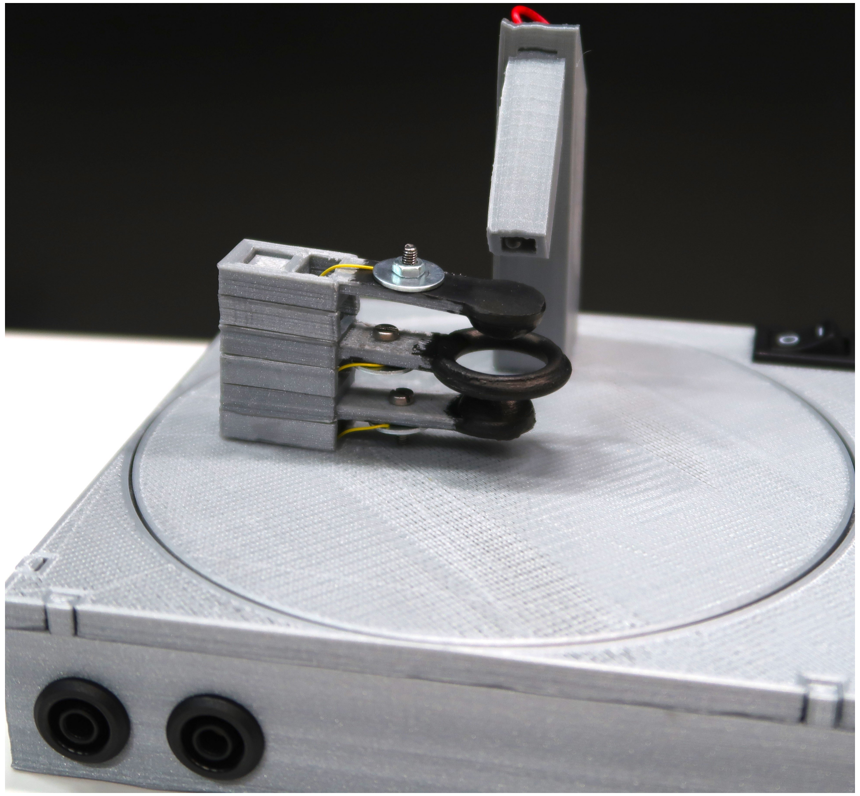

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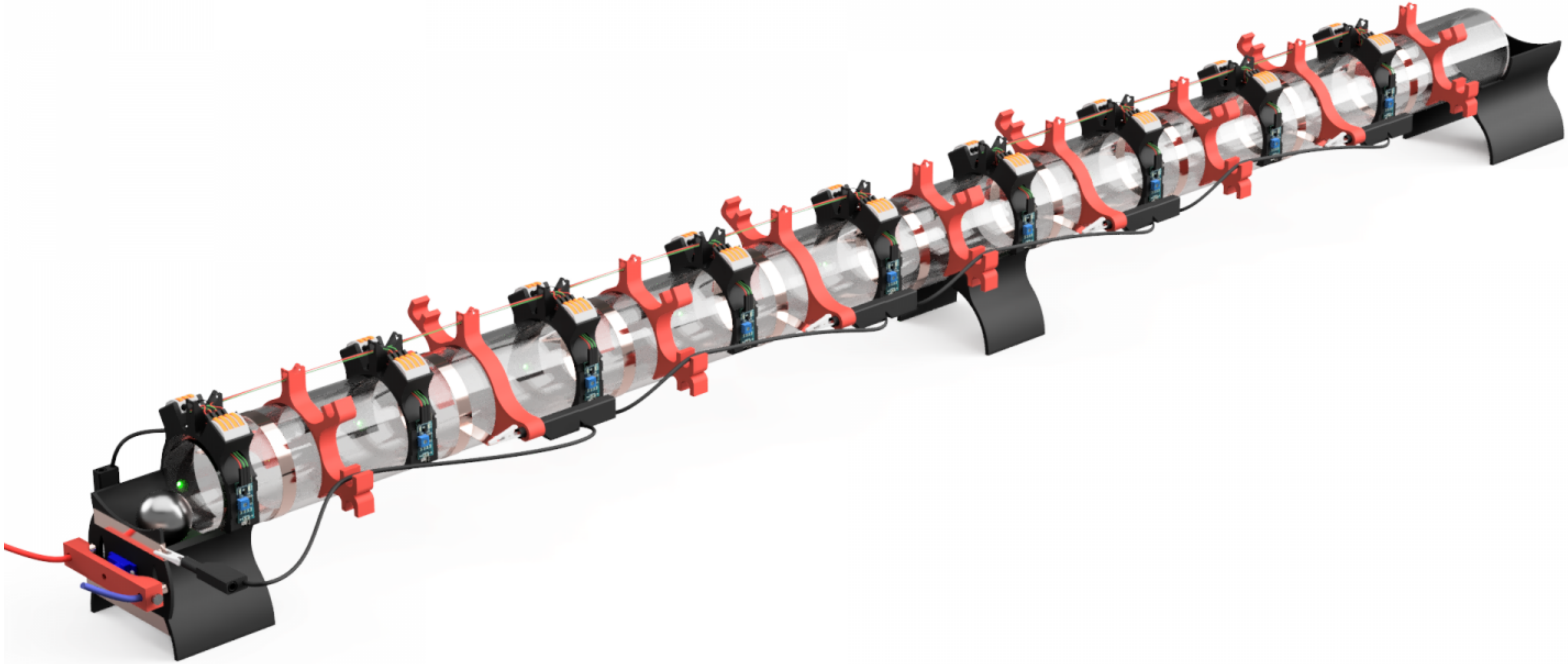

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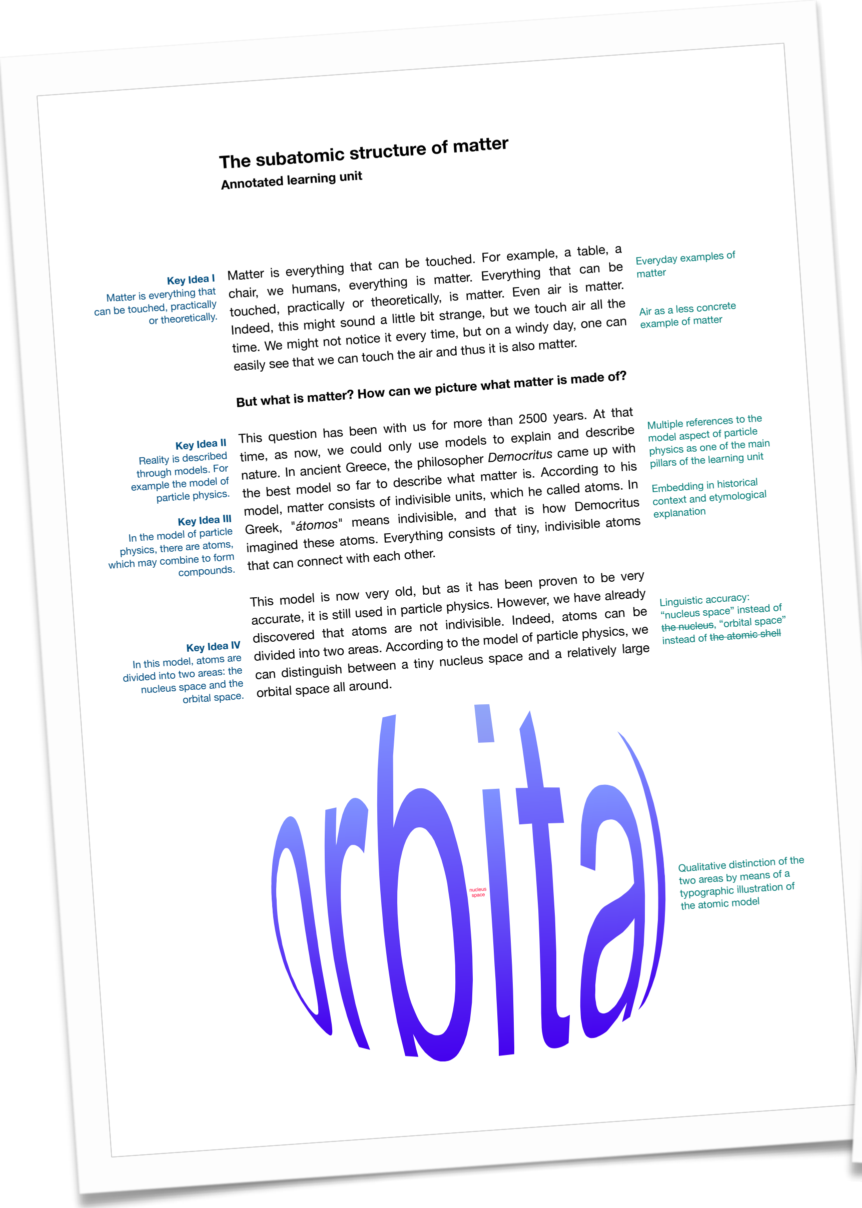
Merci bien!

Questions?

Backup Slides



The subatomic structure of matter

Annotated learning unit

Key Idea I
Matter is everything that can be touched, practically or theoretically.

Matter is everything that can be touched. For example, a table, a chair, we humans, everything is matter. Everything that can be touched, practically or theoretically, is matter. Even air is matter. Indeed, this might sound a little bit strange, but we touch air all the time. We might not notice it every time, but on a windy day, one can easily see that we can touch the air and thus it is also matter.

Everyday examples of matter

Air as a less concrete example of matter

But what is matter? How can we picture what matter is made of?

Key Idea II
Reality is described through models. For example the model of particle physics.

Key Idea III
In the model of particle physics, there are atoms, which may combine to form compounds.

This question has been with us for more than 2500 years. At that time, as now, we could only use models to explain and describe nature. In ancient Greece, the philosopher *Democritus* came up with the best model so far to describe what matter is. According to his model, matter consists of indivisible units, which he called atoms. In Greek, "*átomos*" means indivisible, and that is how Democritus imagined these atoms. Everything consists of tiny, indivisible atoms that can connect with each other.

Multiple references to the model aspect of particle physics as one of the main pillars of the learning unit

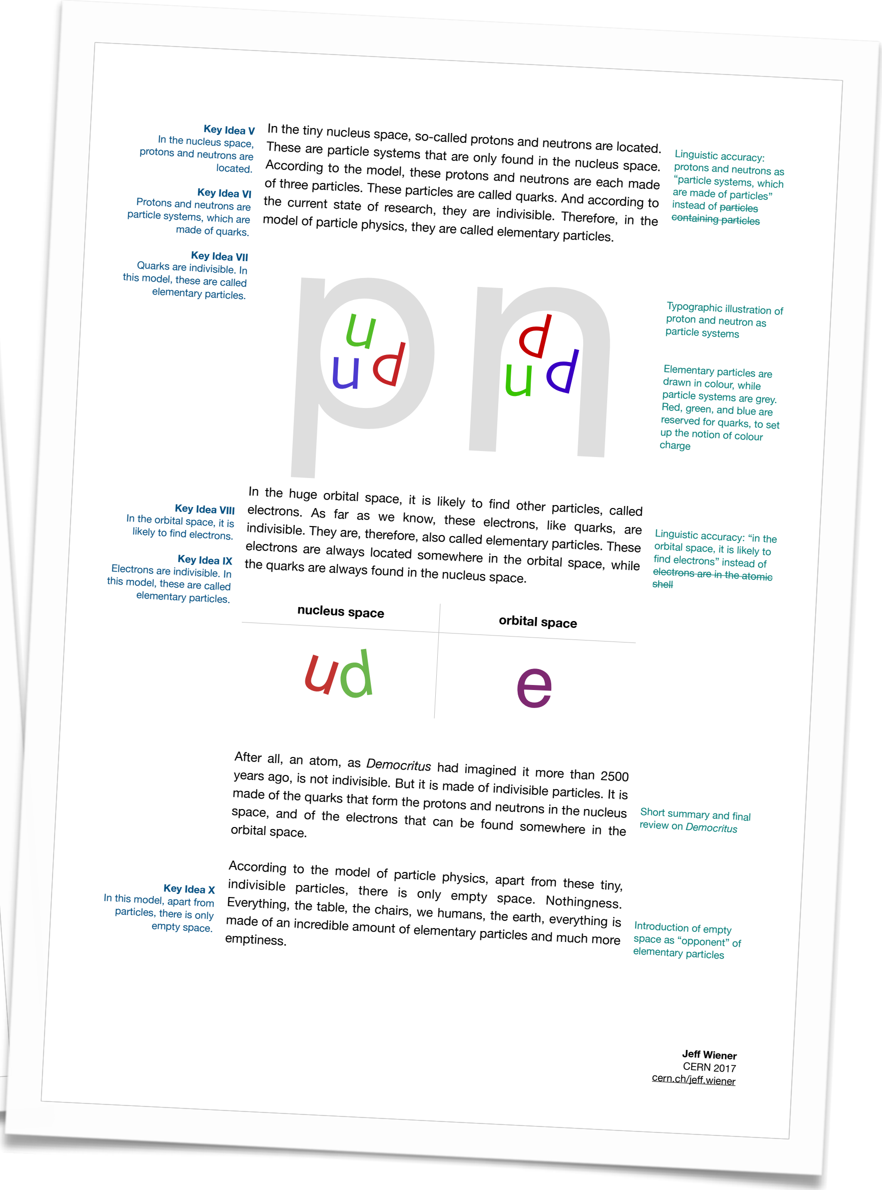
Embedding in historical context and etymological explanation

Key Idea IV
In this model, atoms are divided into two areas: the nucleus space and the orbital space.

This model is now very old, but as it has been proven to be very accurate, it is still used in particle physics. However, we have already discovered that atoms are not indivisible. Indeed, atoms can be divided into two areas. According to the model of particle physics, we can distinguish between a tiny nucleus space and a relatively large orbital space all around.

Linguistic accuracy: "nucleus space" instead of ~~the nucleus~~, "orbital space" instead of ~~the atomic shell~~

Qualitative distinction of the two areas by means of a typographic illustration of the atomic model



Key Idea V
In the nucleus space, protons and neutrons are located.

Key Idea VI
Protons and neutrons are particle systems, which are made of quarks.

Key Idea VII
Quarks are indivisible. In this model, these are called elementary particles.

In the tiny nucleus space, so-called protons and neutrons are located. These are particle systems that are only found in the nucleus space. According to the model, these protons and neutrons are each made of three particles. These particles are called quarks. And according to the current state of research, they are indivisible. Therefore, in the model of particle physics, they are called elementary particles.

Linguistic accuracy: protons and neutrons as "particle systems, which are made of particles" instead of ~~particles containing particles~~

Typographic illustration of proton and neutron as particle systems

Elementary particles are drawn in colour, while particle systems are grey. Red, green, and blue are reserved for quarks, to set up the notion of colour charge

Key Idea VIII
In the orbital space, it is likely to find electrons.

Key Idea IX
Electrons are indivisible. In this model, these are called elementary particles.

In the huge orbital space, it is likely to find other particles, called electrons. As far as we know, these electrons, like quarks, are indivisible. They are, therefore, also called elementary particles. These electrons are always located somewhere in the orbital space, while the quarks are always found in the nucleus space.

Linguistic accuracy: "in the orbital space, it is likely to find electrons" instead of ~~electrons are in the atomic shell~~

nucleus space	orbital space
ud	e

After all, an atom, as *Democritus* had imagined it more than 2500 years ago, is not indivisible. But it is made of indivisible particles. It is made of the quarks that form the protons and neutrons in the nucleus space, and of the electrons that can be found somewhere in the orbital space.

Short summary and final review on *Democritus*

Key Idea X
In this model, apart from particles, there is only empty space.

According to the model of particle physics, apart from these tiny, indivisible particles, there is only empty space. Nothingness. Everything, the table, the chairs, we humans, the earth, everything is made of an incredible amount of elementary particles and much more emptiness.

Introduction of empty space as "opponent" of elementary particles

Jeff Wiener
CERN 2017
cern.ch/jeff.wiener

I. Matter is everything that can be touched, practically or theoretically.

II. Reality is described through models. For example the model of particle physics.

III. In the model of particle physics, there are atoms, which may combine to form compounds.

IV. In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.

V. In the nucleus-space, protons and neutrons are located.

VI. Protons and neutrons are particle systems, which are made of quarks.

VII. Quarks are indivisible. In this model, these are called elementary particles.

VIII. In the orbital-space, it is possible to find electrons.

IX. Electrons are indivisible. In this model, these are called elementary particles.

X. In this model, apart from particles, there is only empty space.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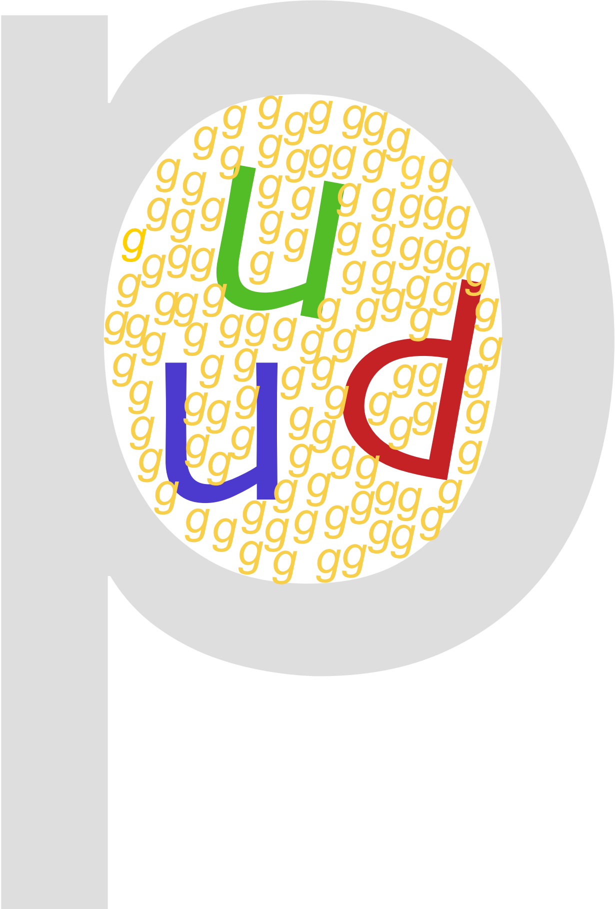
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