Elementary particle physics in early physics education

Dr. Jeff Wiener
cern.ch/jeff.wiener


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DISSERTATION / DOCTORAL THESIS

Titel der Dissertation / Title of the Doctoral Thesis

"Elementary particle physics in early physics education"

verfasst von / submitted by

Mag. rer. nat. Gerfried Wiener

angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Doktor der Naturwissenschaften (Dr. rer. nat.)

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Dissertationsgebiet lt. Studienblatt / field of study as it appears on the student record sheet:	Physik / Physics
Betreut von / Supervisor:	Univ.-Prof. Dr. Martin Hopf

“What is a particle?”

Sources for (mis)conceptions

Sources for (mis)conceptions

Everyday experiences

Sources for (mis)conceptions

Everyday experiences

Inadequate learning offers

Sources for (mis)conceptions

Everyday experiences

Inadequate learning offers

Illustrations und animations

Sources for (mis)conceptions

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Illustrations und animations

Documented misconceptions in particle physics

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Overlap of continuum and discontinuum conceptions

CERN

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Transfer of macroscopic properties into the microcosm

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Documented misconceptions in particle physics

Overlap of continuum and discontinuum conceptions

Transfer of macroscopic properties into the microcosm

Negation of constant movement of particles and empty space

Model aspect

Model aspect

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

Model aspect

Linguistic accuracy

"With the model of particle physics, we describe …"

Model aspect

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

Linguistic accuracy

particle

vs.

particle system

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Typographic illustrations

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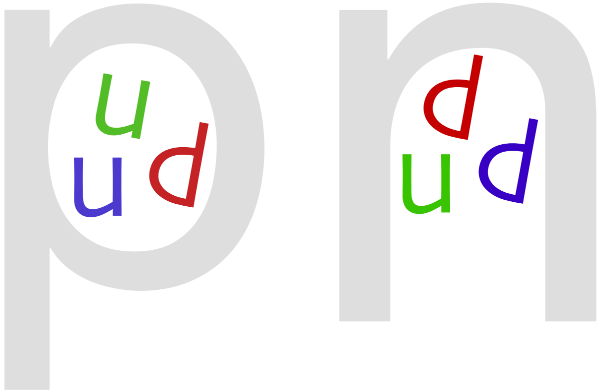

Der subatomare Aufbau der Materie

Kommentierte Originalversion

Key Idea I
Materie ist alles, was man praktisch oder theoretisch berühren kann.

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Alltagsbeispiele zur Materie

Luft als weniger konkretes Beispiel für Materie

Aber was ist dann eigentlich diese Materie?
Was kann man sich unter Materie vorstellen?

Key Idea II
Wir beschreiben die Wirklichkeit durch Modelle.

Key Idea III
Im Modell der Teilchenphysik gibt es Atome (Demokrit). Diese können sich miteinander verbinden.

Key Idea IV
Atome werden in diesem Modell in zwei Bereiche unterteilt: Atomkern-Bereich und Orbital-Bereich.

Diese Frage beschäftigt die Menschheit bereits seit mehr als 2500 Jahren. Damals wie heute konnte man zur Erklärung und Beschreibung der Natur nur Modelle aufstellen. Denn wir beschreiben die Wirklichkeit ja immer durch Modelle. Im alten Griechenland also stellte der Denker Demokrit das bisher beste Modell auf, um zu beschreiben, was Materie ist. Laut diesem Modell besteht Materie aus unteilbaren Einheiten, welche er Atome nannte. Im Griechischen bedeutet "átomos" unteilbar und genau so stellte sich Demokrit diese Atome vor. Alles besteht aus winzig kleinen, unteilbaren Atomen, die sich miteinander verbinden können.
Dieses Modell ist mittlerweile zwar sehr alt, aber da es sich bisher als sehr zutreffend erwiesen hat, wird es im Rahmen der Teilchenphysik nach wie vor verwendet. Allerdings wurde bereits festgestellt, dass Atome doch nicht unteilbar sind. Diese lassen sich nämlich in zwei Bereiche unterteilen. Laut dem Modell kann man einen winzig kleinen Atomkern-Bereich und rundherum einen vergleichsweise riesigen Orbital-Bereich unterscheiden.

Mehrfacher Hinweis auf den permanenten Modellcharakter als integraler Bestandteil des Konzepts

Einbettung in historischen Kontext und etymologische Erklärung

Sprachliche Feinheit
Atomkern-Bereich statt ~~Atomkern~~ und Orbital-Bereich statt ~~Orbital~~

Rein qualitative Unterscheidung der zwei Bereiche mittels typographischer Illustration des Atommodells

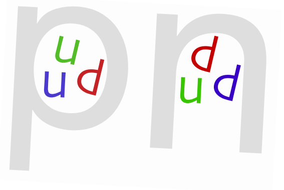
Key Idea V
Im Atomkern-Bereich befinden sich Protonen und Neutronen.

Key Idea VI
Protonen und Neutronen werden durch Quarks gebildet.

Key Idea VII
Quarks sind nicht mehr teilbar. In diesem Modell nennt man sie Elementarteilchen.

In dem winzigen Atomkern-Bereich befinden sich sogenannte Protonen und Neutronen. Das sind Teilchen-Systeme, die man immer nur im Atomkern-Bereich finden kann. Laut dem Modell werden diese Protonen und Neutronen von jeweils drei Teilchen gebildet. Diese Teilchen nennt man Quarks. Und die sind nach aktuellem Forschungsstand wirklich unteilbar. Man nennt sie daher auch Elementarteilchen.

Sprachliche Feinheit
Protonen und Neutronen als Teilchen-Systeme, die von Teilchen gebildet werden, statt ~~Teilchen, die aus Teilchen bestehen~~



Typographische Illustration von Proton und Neutron als Teilchen-Systeme

Quarks als Elementarteilchen in Farbe, Proton und Neutron als Teilchen-Systeme in grau

Key Idea VIII
Im Orbital-Bereich kann man Elektronen finden.

Key Idea IX
Elektronen sind nicht mehr teilbar. In diesem Modell nennt man sie Elementarteilchen

Im riesigen Orbital-Bereich kann man andere Teilchen finden, und zwar sogenannte Elektronen. Diese sind, soweit wir wissen, ebenso wie die Quarks unteilbar. Man nennt sie daher ebenfalls Elementarteilchen. Diese Elektronen befinden sich immer irgendwo im Orbital-Bereich, während die Quarks immer im Atomkern-Bereich zu finden sind.

Sprachliche Feinheit
Im Orbital-Bereich kann man Teilchen finden, statt ~~Elektronen sind im Orbital~~

Atomkern-Bereich	Orbital-Bereich
u d	e

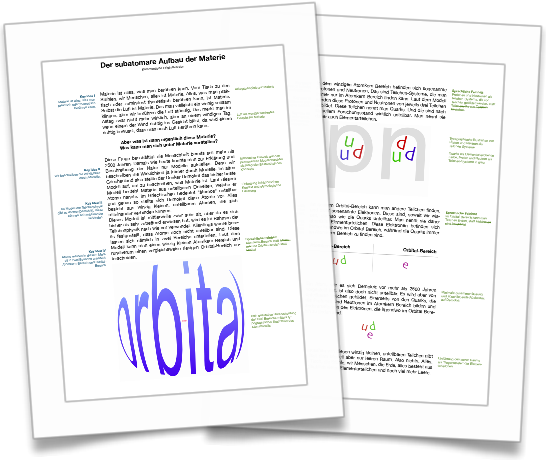
Ein Atom, wie es sich Demokrit vor mehr als 2500 Jahren vorgestellt hat, ist also doch nicht unteilbar. Es wird aber von unteilbaren Teilchen gebildet. Einerseits von den Quarks, die die Protonen und Neutronen im Atomkern-Bereich bilden und andererseits von den Elektronen, die irgendwo im Orbital-Bereich zu finden sind.

Minimale Zusammenfassung und abschließende Rückschau auf Demokrit

Key Idea X
Laut diesem Modell gibt es außer Teilchen nur leeren Raum.

Abgesehen von diesen winzig kleinen, unteilbaren Teilchen gibt es laut dem Modell aber nur leeren Raum. Also nichts. Alles, der Tisch, die Stühle, wir Menschen, die Erde, alles besteht aus unglaublich vielen Elementarteilchen und noch viel mehr Leere.

Einführung des leeren Raums als 'Gegenspieler' der Elementarteilchen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…-Bereich	Orbital-Bereich
u d	e

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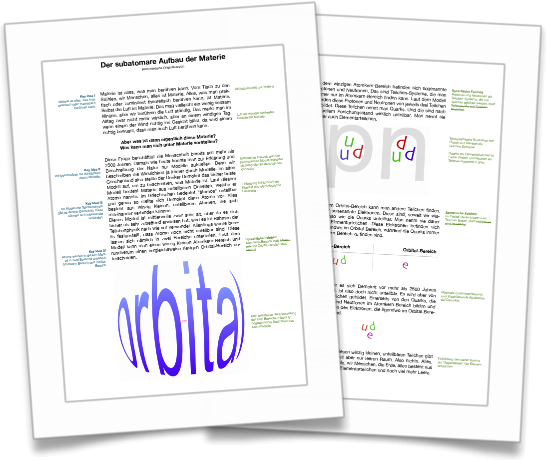
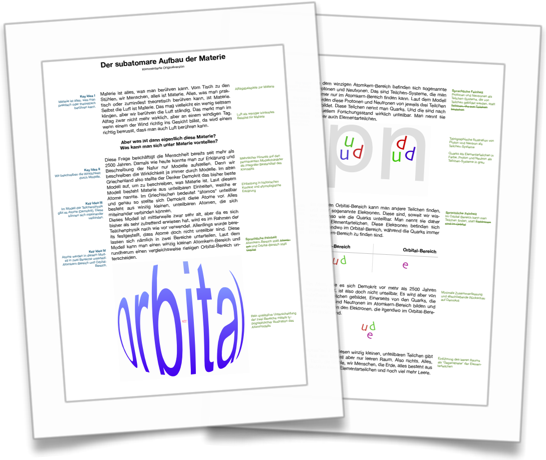
Einführung des leeren Raums als "Gegenspieler" der Elementarteilchen



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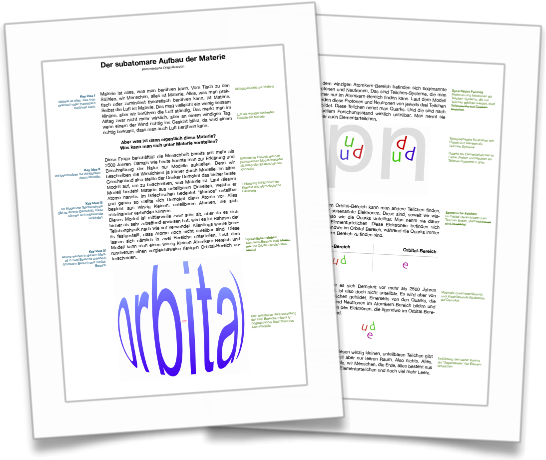
I. Matter is everything that can be touched, practically or theoretically.

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



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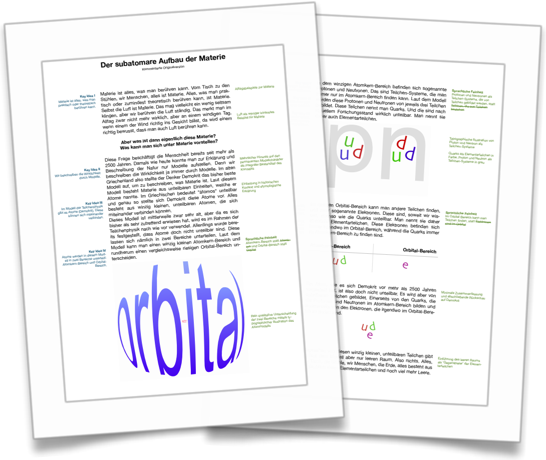

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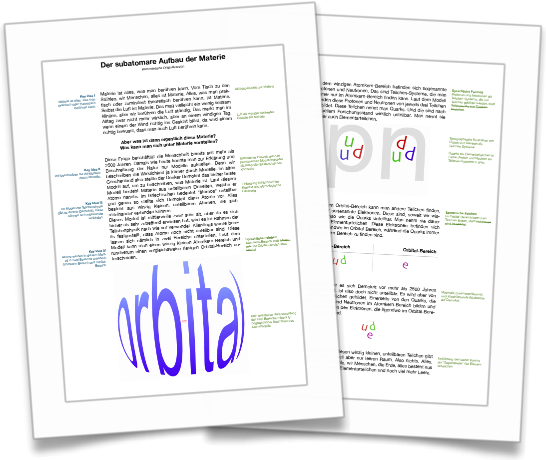
IV. In this model, atoms are divided into two areas: the nucleus-space and the orbital-space.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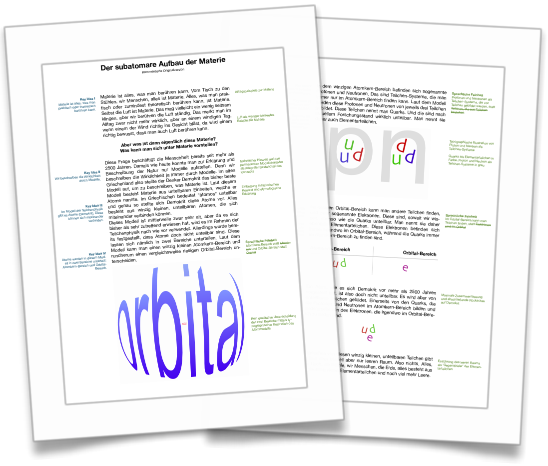

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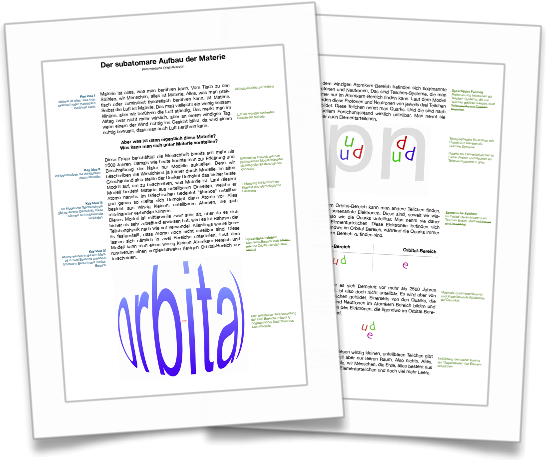
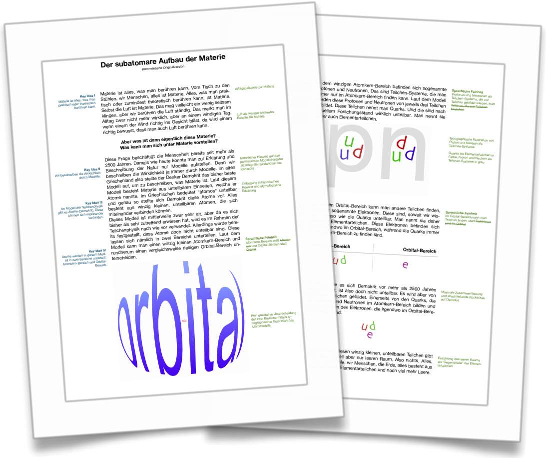


VI. Protons and neutrons are particle systems, which are made of quarks.

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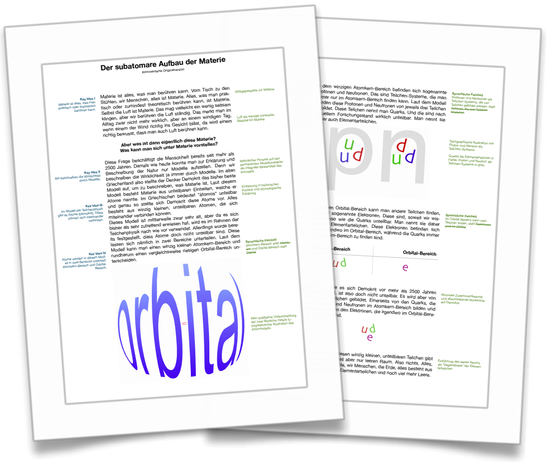

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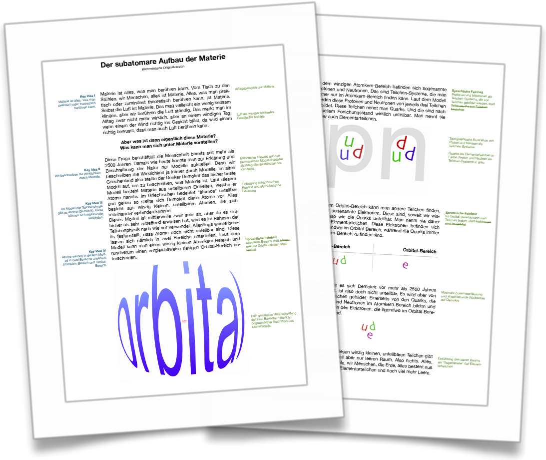
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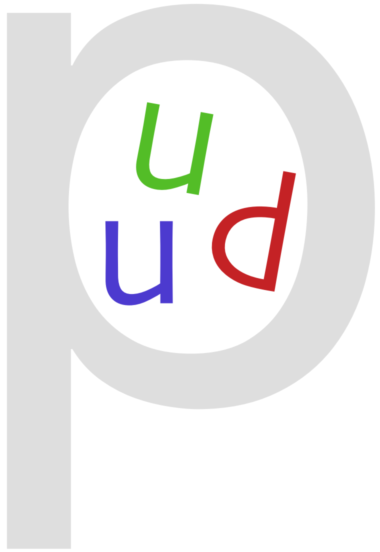
X. In this model, apart from particles, there is only empty space.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Introducing 12 year-olds to elementary particles

Gerfried J Wiener[1,2], Sascha M Schmeling[1] and Martin Hopf[2]

[1] CERN, European Organization for Nuclear Research, Geneva, Switzerland
[2] University of Vienna, Austrian Educational Competence Centre Physics, Vienna, Austria

E-mail: jeff.wiener@cern.ch, sascha.schmeling@cern.ch and martin.hopf@univie.ac.at

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 basis 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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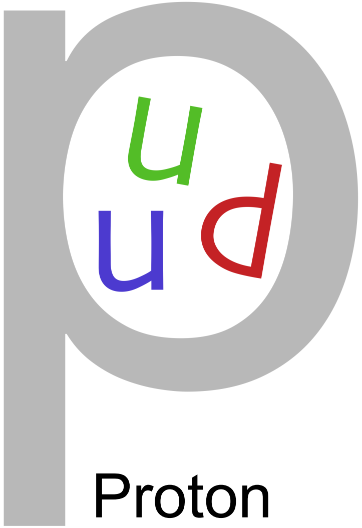

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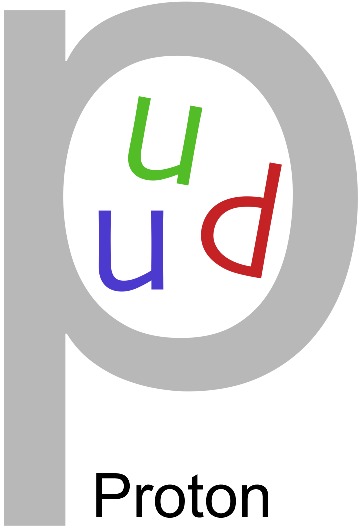
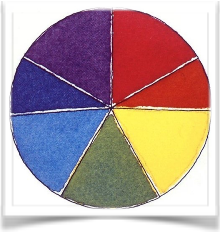


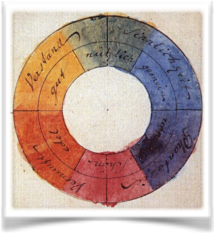
Proton

Antiproton

“Is not the complementary color of blue, orange, of green, red, and of yellow, pink?” [student, 17]



Newton



Goethe

CMYK

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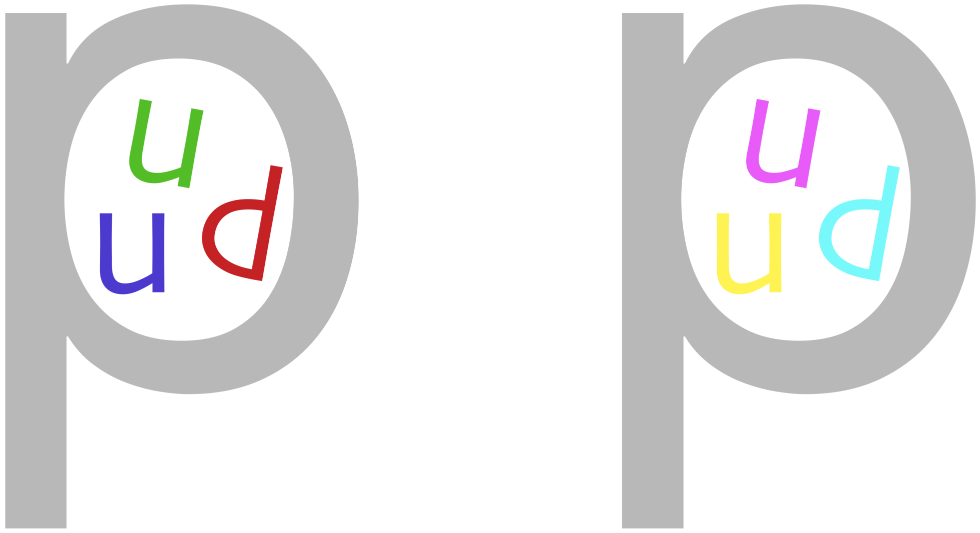
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An Alternative Proposal for the Graphical Representation of Anticolor Charge

Gerfried J. Wiener, CERN, European Organization for Nuclear Research, Geneva, Switzerland, and Austrian Educational Competence Centre Physics, University of Vienna, Austria
Sascha M. Schmeling, CERN, European Organization for Nuclear Research, Geneva, Switzerland
Martin Hopf, Austrian Educational Competence Centre Physics, University of Vienna, Austria

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

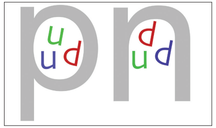

Fig. 1. Typographic illustrations of a proton and a neutron.

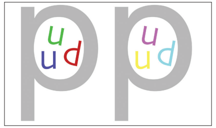

Fig. 2. Traditional illustrations of a proton and an antiproton, relying on readers' prior knowledge of the relevant color wheel. Obviously, using colors complementary to the quarks' red, green, and blue presents a challenge for identifying anticolor charges, e.g., cyan as antired.

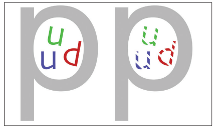

Fig. 3. Alternative illustrations of a proton and an antiproton, using a stripe pattern to denote anticolor charge. This representation clearly shows corresponding color and anticolor charge states while doing away with any requirement for prior knowledge of complementary colors.

 DOI: 10.1119/1.5008340

An Alternative Proposal for the Graphical Representation of Anticolor Charge

Gerfried J. Wiener, CERN, European Organization for Nuclear Research, Geneva, Switzerland, and Austrian Educational Competence Centre Physics, University of Vienna, Austria
Sascha M. Schmeling, CERN, European Organization for Nuclear Research, Geneva, Switzerland
Martin Hopf, Austrian Educational Competence Centre Physics, University of Vienna, Austria

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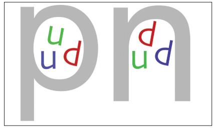

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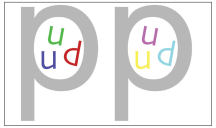

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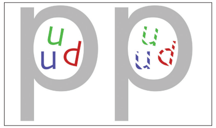

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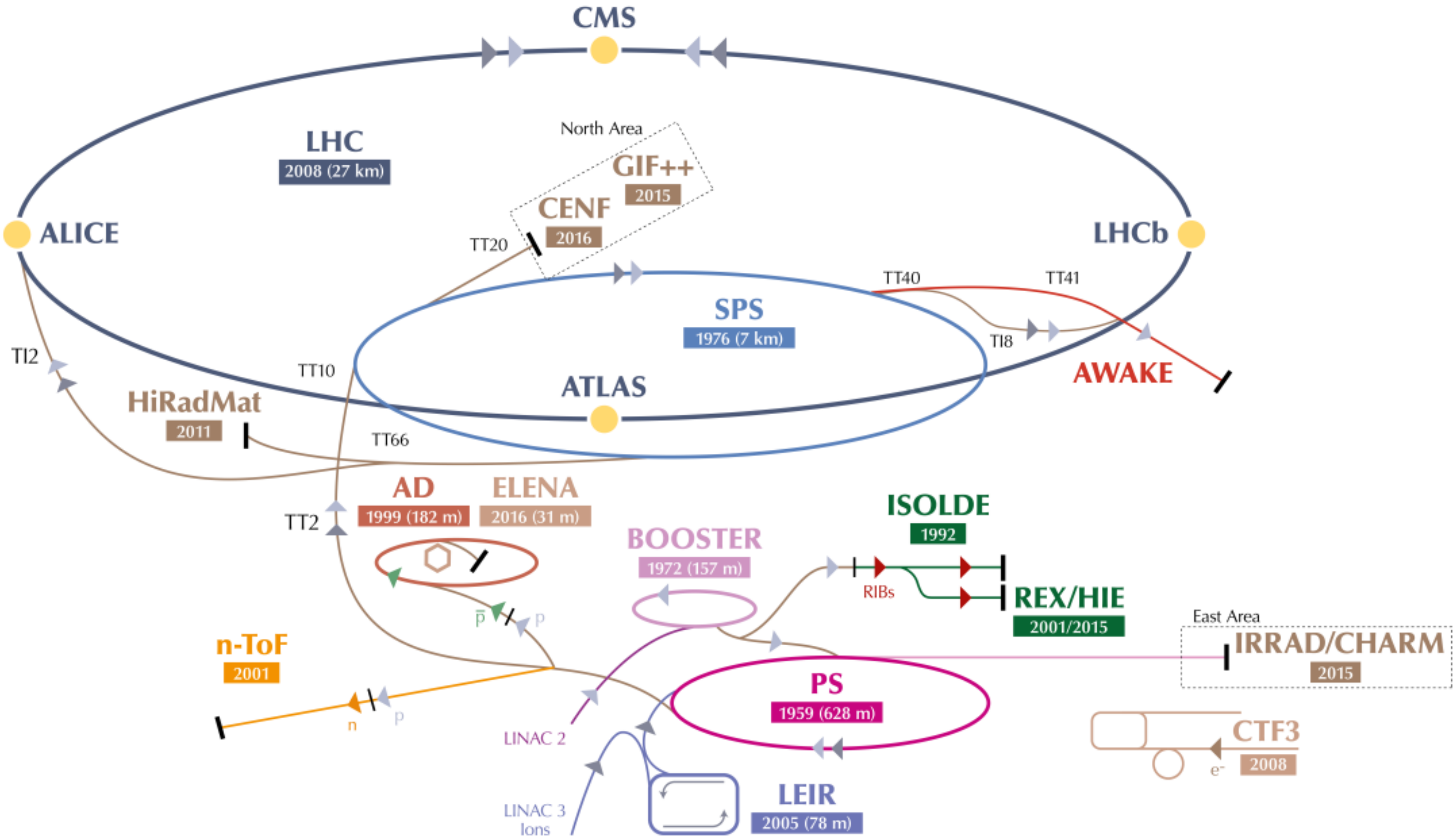
LHCb
ATLAS
CERN Meyrin
PS 628 m
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km


CMS
LHC
2008 (27 km)
North Area
GIF++
2015
CENF
2016
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
HiRadMat
2011
TT66
AD
1999 (182 m)
ELENA
2016 (31 m)
ISOLDE
1992
TT2
BOOSTER
1972 (157 m)
RIBs
REX/HIE
2001/2015
p̄
p
East Area
IRRAD/CHARM
2015
n-ToF
2001
PS
1959 (628 m)
n
p
LINAC 2
CTF3
e⁻
2008
LINAC 3
Ions
LEIR
2005 (78 m)

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

Gerfried J Wiener[1,2], Julia Woithe[1,3], Alexander Brown[1,4] and Konrad Jende[1,5]

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[2] Austrian Educational Competence Centre Physics, University of Vienna, Austria
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[4] Institut Universitaire pour la Formation des Enseignants, University of Geneva, Switzerland
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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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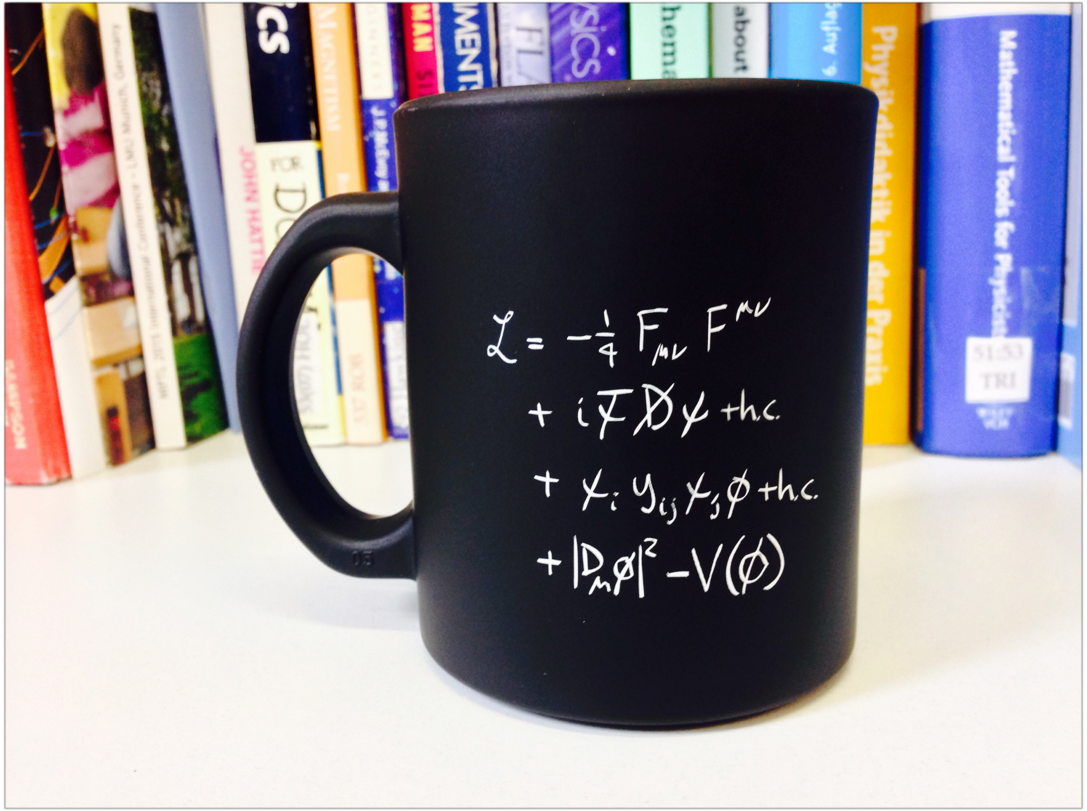
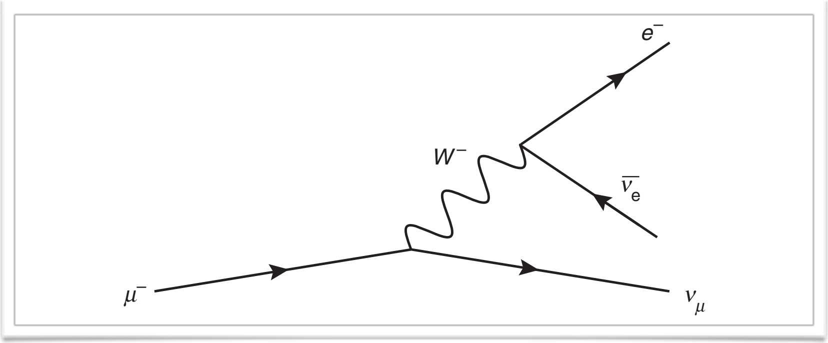

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
Mathematical Tools for Physicists
Physikdidaktik in der Praxis
JOHN HATTIE

“Actually, ‘decay’ is not the correct word. They transform into each other.” *[student, 15]*



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

Julia Woithe[1,2], Gerfried J Wiener[1,3] and Frederik F Van der Veken[1]

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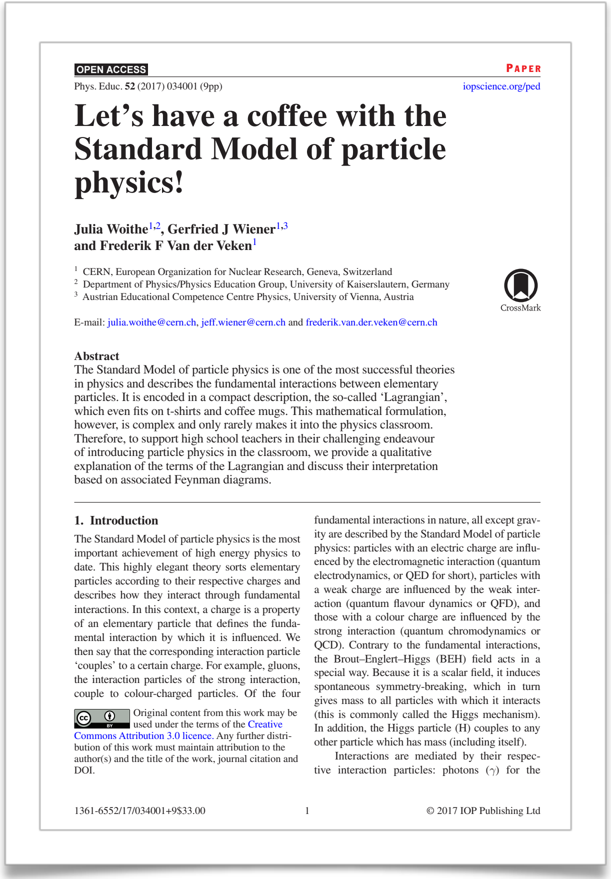
The Standard Model of particle physics is one of the most successful theories in physics and describes the fundamental interactions between elementary particles. It is encoded in a compact description, the so-called 'Lagrangian', which even fits on t-shirts and coffee mugs. This mathematical formulation, 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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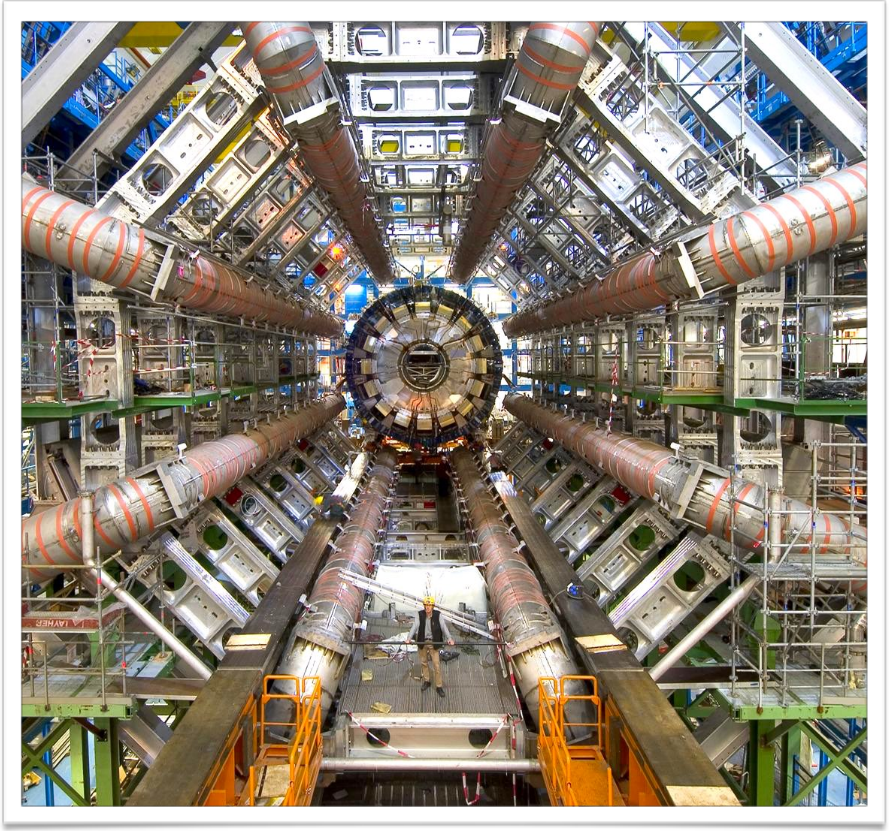

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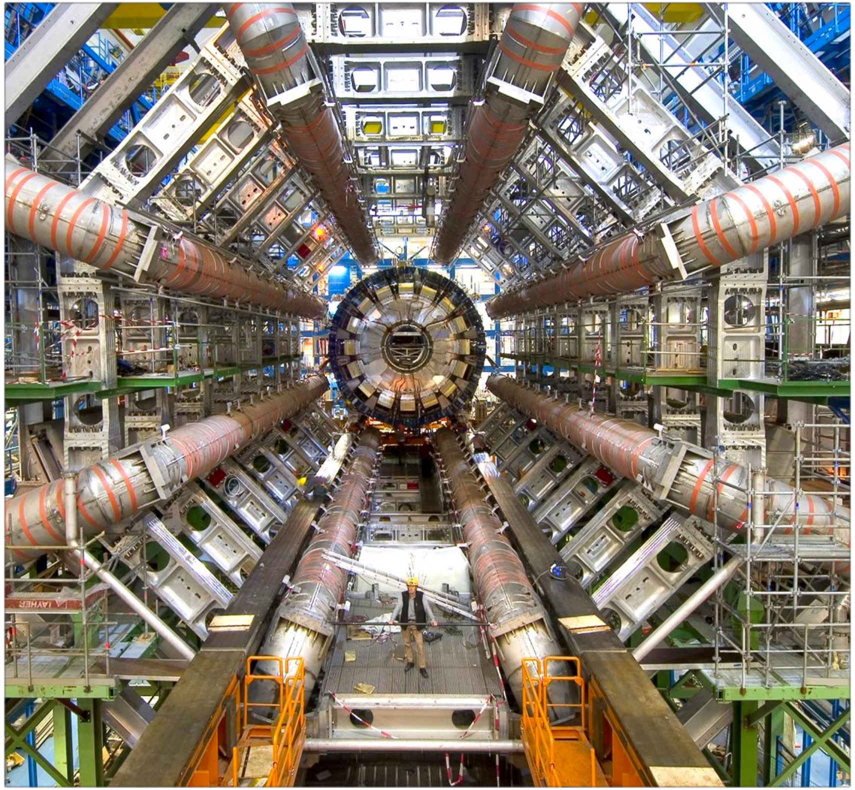

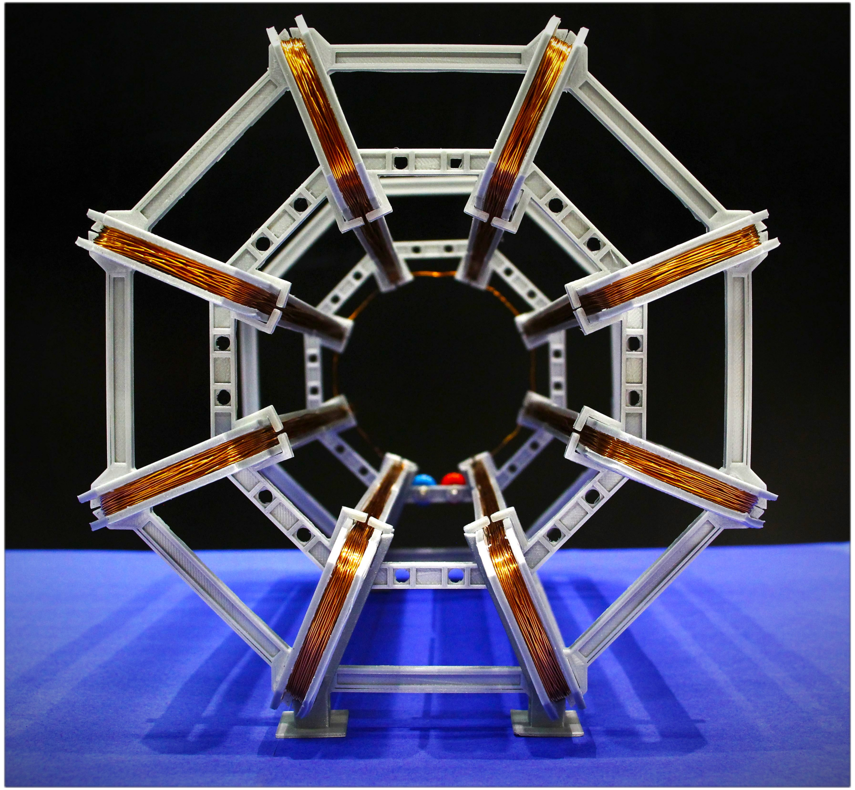

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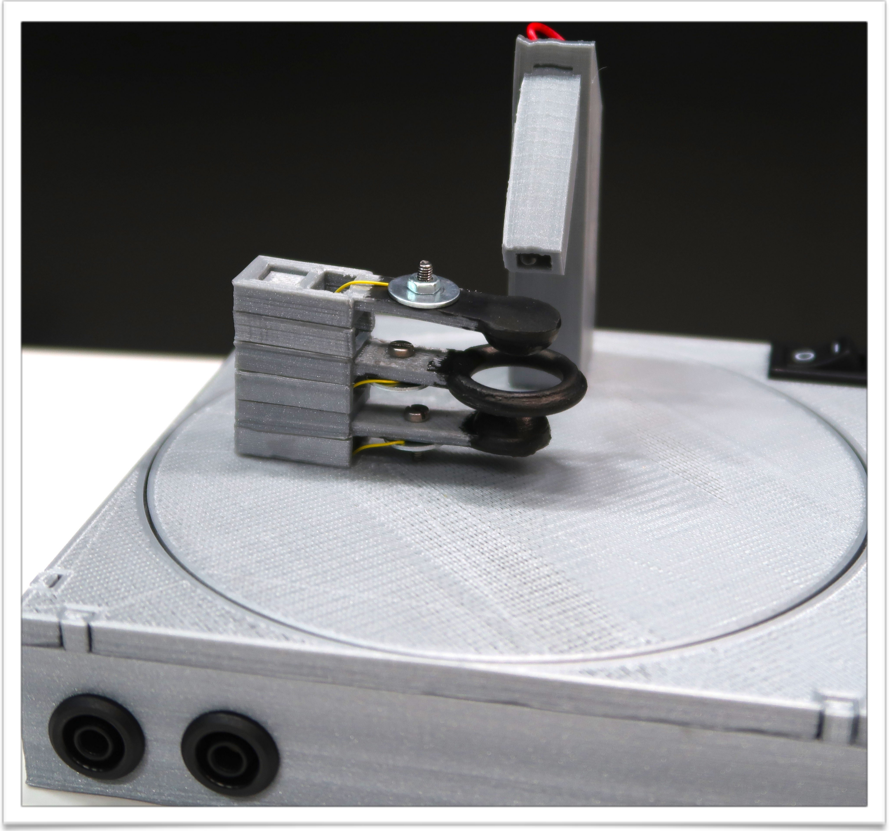

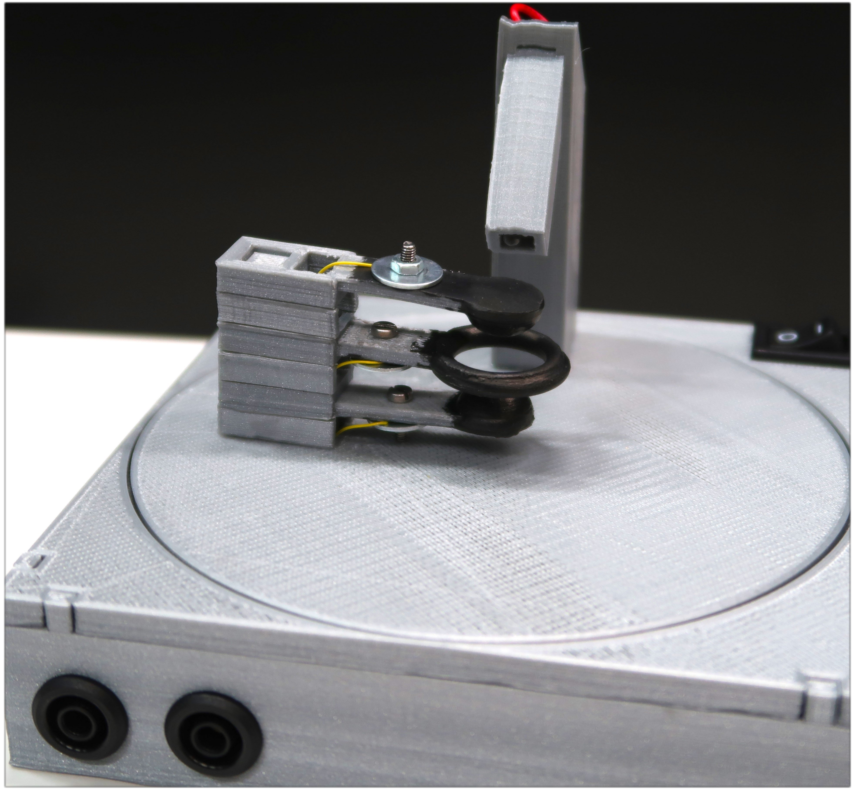

"There is nothing more enriching and gratifying than learning." [Fabiola Gianotti, CERN Director-General]

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Merci bien!

Dr. Jeff Wiener
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