



Exploitation of Research results In School practice

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particle physics

2018-04-17

Elementary particles and fundamental forces
- Upper secondary school -

Bogdan Popovici^{1,2}

¹Faculty of Physics, University of Bucharest

²IFIN-HH, Bucharest-Magurele

05.03.2018, Bucharest-Magurele

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The present material is inspired by the International Masterclass program (physicsmasterclasses.org/) developed by the community of physicists working in the field. The author acknowledges the participation together with the IFIN-HH team to LHCb experiment at CERN.

Motivation The importance of the particle physics in the understanding both of the microcosmos and macrocosmos, the growing impact in the practical applications and also the increased popularity in the media of the large experiments justify, I believe, the earlier introduction in schools of concepts from the field.



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- 1 International collaborations, CERN, IFIN-HH, Masterclass
 - Educational resources - Masterclasses
 - Research laboratories
- 2 Introduction to elementary particle physics
 - Why particle physics?
 - The Standard Model of elementary particle physics
- 3 How do we measure?
 - Experimental work
 - Rutherford experiment
- 4 Practical exercise: LHCb masterclass
 - LHCb experiment
 - Measurement of the lifetime of the D^0 meson

2018-04-17

particle physics

Elementary particles and fundamental forces

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The presentation is made of four parts comprising informations on the Standard Model of the particle physics, experimental infrastructures, practical applications, but also exercises and suggestions for hands-on activities. At the end the students are recommended to start analysing real data on computer following the CMS masterclass activities.

The full presentation can cover at least two class hours of exposition and another two hours for solving the exercises from the working sheets. To increase the interactivity in the classroom two Kahoot games were introduced for which students need to use their mobile phones.

1 International collaborations, CERN, IFIN-HH, Masterclass

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- Experimental work
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particle physics

└ International collaborations, CERN, IFIN-HH, Masterclass

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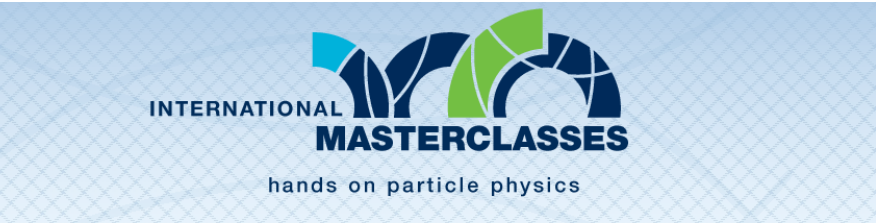


The next section is dedicated to examples of research infrastructures in the field, particularly of the CERN laboratory. Also some applications are introduced.

Introduction Masterclasses



- Home
- Participate!
- Schedule
- My Country
- Physics
- Local Organisation
- In the Media
- Teachers and Educators





International Masterclasses

12th International Masterclasses 2016

Each year about 10.000 high school students in [47 countries](#) come to one of about 200 nearby universities or research centres for one day in order to unravel the mysteries of particle physics. Lectures from active scientists give insight in topics and methods of basic research at the fundaments of matter and forces, enabling the students to perform measurements on real data from particle physics experiments themselves. At the end of each day, like in an international research collaboration, the participants join in a video conference for discussion and combination of their results. See [here](#) for media coverage.

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- particle physics
 - International collaborations, CERN, IFIN-HH, Masterclass
 - Introduction Masterclasses



International Masterclass website



ALICE

Identification of elementary particles such as K_S^0 , Λ^0 and Ξ^- from data and the study of collisions proton - proton and Pb - Pb



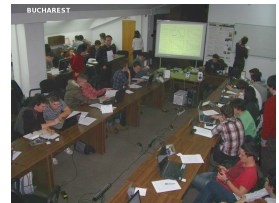
Selection and identification of interaction bosons W^+ , W^- 'si Z^0 . Production of Higgs boson



Study of bosons production ratio W^+/W^-

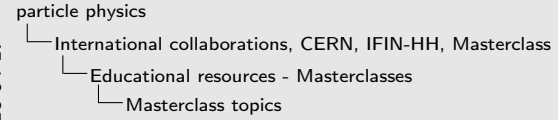


Measurement of the lifetime of the D^0 meson



Bucharest, 2013

2018-04-17



Masterclass topics



Identification of elementary particles such as K_S^0 , Λ^0 and Ξ^- from data and the study of collisions proton - proton and Pb - Pb



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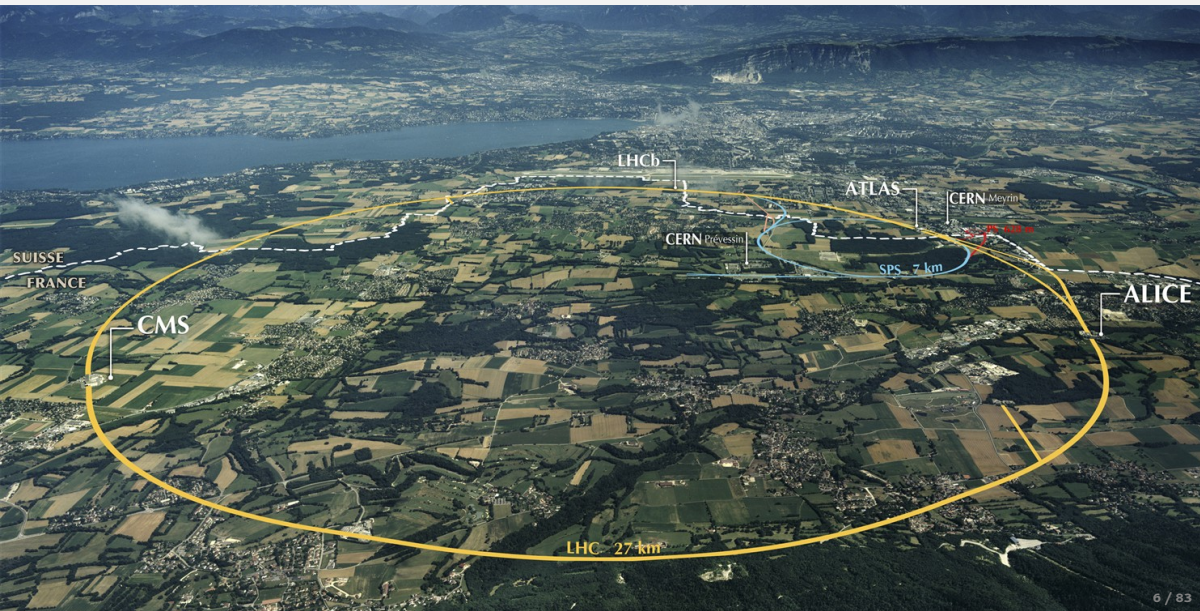


Measurement of the lifetime of the D^0 meson



Bucharest, 2013

What is Cern?



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particle physics

International collaborations, CERN, IFIN-HH, Masterclass

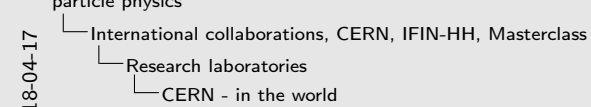
Research laboratories

What is Cern?

To investigate smaller and smaller dimensions requires more and more energy. Even more, to produce particles other than the stable ones require many trials that is large intensities from the particle beams. These conditions makes that the dedicated instalations to grow in size and complexity and become very costly.

The largest laboratory for the study of particle physics, CERN, is placed near Geneva and hosts a complex of particle accelerators the largest one having a circumference of 27 *km*.

Reconstruction of Europe after two world wars, 1954
reconstruction through science



CERN, Organisation européenne pour la recherche nucléaire, was founded in 1954 as a need of cooperation between states in a very demanding field such as the study of nucleus and of the elementary particles.

The scientific successes proven all these years made it a model of international cooperation in science.



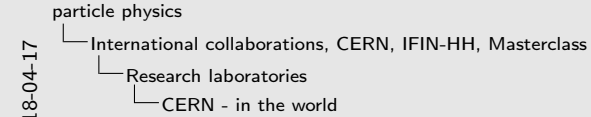
Reconstruction of Europe after two world wars, 1954 reconstruction through science

- The largest scientific laboratory
- 2300 staff, 1050 personal auxiliar, 11000 collaborators
- Budget (2012) 900 MEuro

Member state: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Switzerland, Finland, France, Germany, Greece, Hungary, Israel, Italy, Holland, Norway, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden, UK

Associated members: Cyprus, Serbia, Slovenia, Turkey

Observers: India, Japan, Russia, USA, EC, UNESCO



CERN, Organisation européenne pour la recherche nucléaire, was founded in 1954 as a need of cooperation between states in a very demanding field such as the study of nucleus and of the elementary particles.

The scientific successes proven all these years made it a model of international cooperation in science. In spirit, CERN can be seen as the *European Union of research* an argument that the progress is provided by cooperation, inclusion and opencommunication of science.

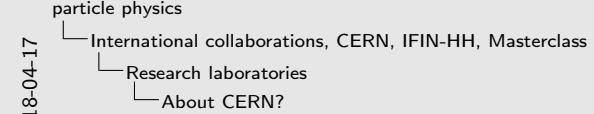
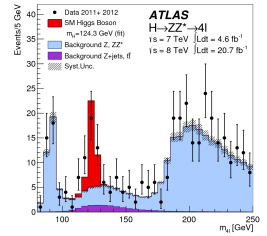
The publications with hundreds of co-authors indicate an evolution of the scientific research paradigm. From the myth of the lonely scientist able to reach the final truth by himself, we see developing networks of researchers which work together to produce complex results, impossible to reach by other means.



About CERN?



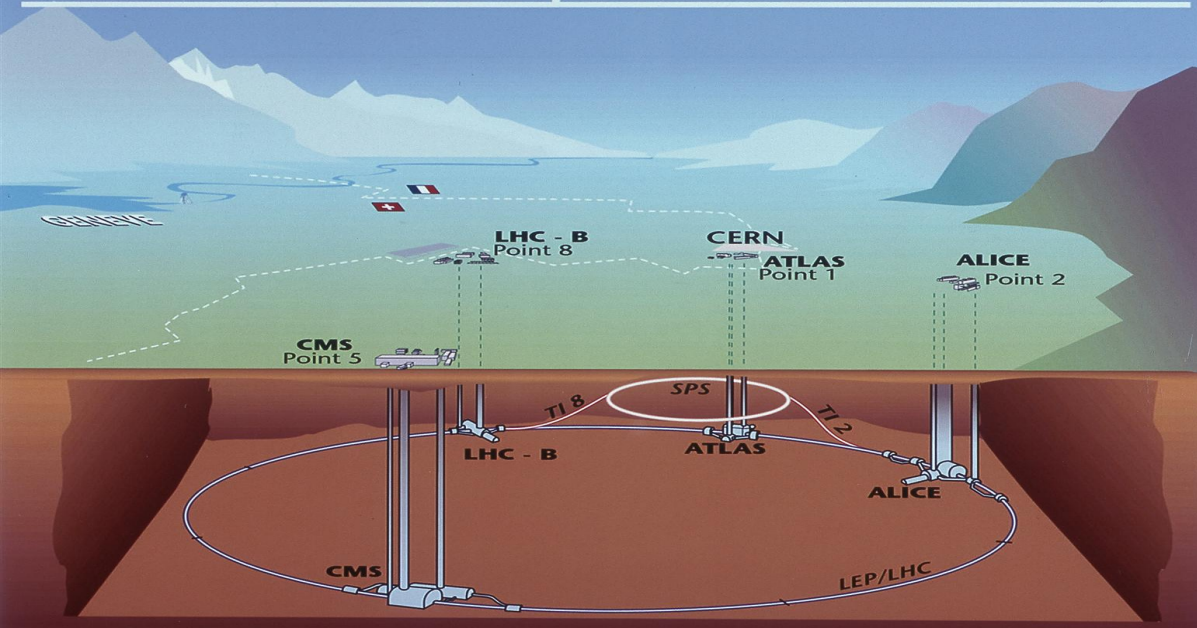
2012 Discovery of the Higgs boson



Two main achievements a usually known about CERN:

1. The invention by Tim Berners-Lee of the `www` protocols in 1990, the basis of the internet website communication.
2. The discovery of the Higgs boson and the confirmation of the mechanism which gives mass to elementary particles. The explanation is based on the existence in the universe of a field of energy, the Higgs field, which interacts with the particles, the strenght of this interaction is a measure of the particle mass.

Overall view of the LHC experiments.

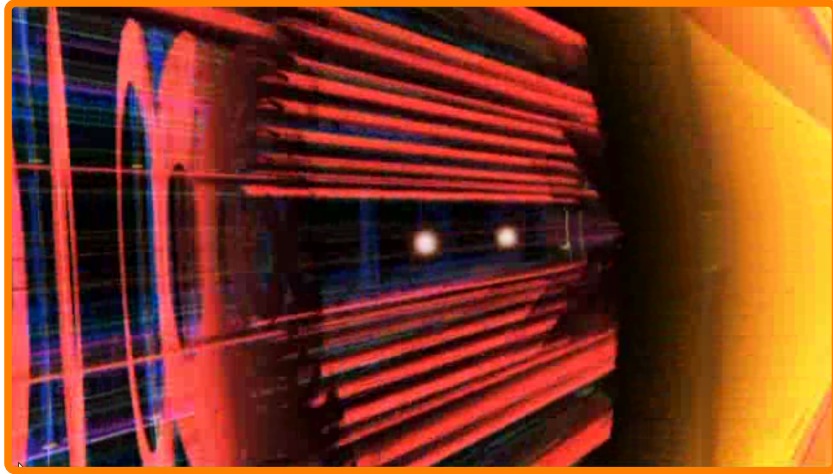


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particle physics
└ International collaborations, CERN, IFIN-HH, Masterclass
└ Research laboratories

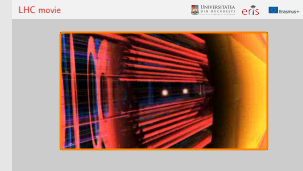
The Large Hadron Collider (LHC) is the largest particle accelerator at present, it uses protons and lead beams which collide in four experimental points on the sites of the four large detectors Atlas, LHCb, CMS and ALICE.

The experiments are mounted 100 meters underground and the complex detector have the dimensions of few stores building.



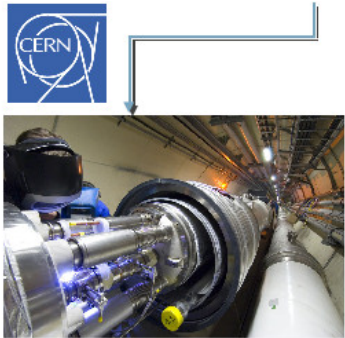
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particle physics
└ International collaborations, CERN, IFIN-HH, Masterclass
 └ Research laboratories
 └ LHC movie



Animation with the proton beams in the LHC accelerator ring.

The protons are extracted from a proton source at lower energy and pass multiple acceleration stages to reach the LHC ring and the maximum energy. Then the two proton beams are put in collision in the center of the detector. Following the collision the energy of reaction is transformed in secondary particles with higher mass. These short lived particle decay in more stable particles which interact with the detector and are recorded.



LHC

Super-Microscope

- the biggest "microscope", 27 km circumference, located 100 m underground
- the protons are accelerated to 6.55 TeV and the collisions have a rate of 40 millions per seconds
- the temperatures produced in the collisions are 100 000 higher than the ones in the centre of Sun
- the coolest place on Earth, 1.9 K (−271.3C) (cooled with liquid nitrogen and helium)
- ultra-high vacuum, the pressure of 10^{-13} atm is 10 times lower than the one on the Moon
- the quantity of data processed is huge breaking record after records (LHCb sends data with a bandwidth equivalent to a phone company for a country of the size of Switzerland)

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particle physics

International collaborations, CERN, IFIN-HH, Masterclass

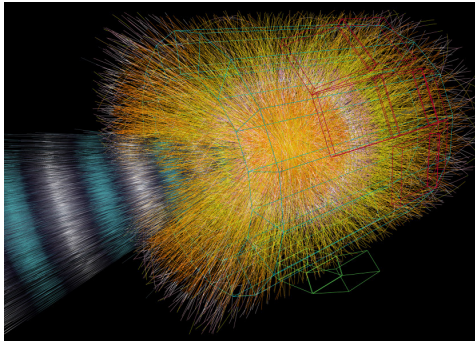
Research laboratories

LHC performances

LHC performances



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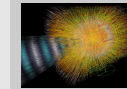
LHC performances

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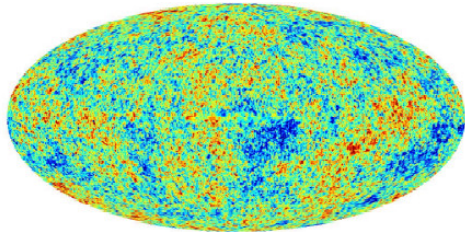
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eris

Erasmus+



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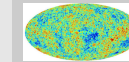
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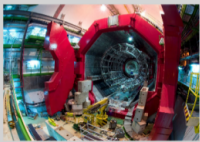
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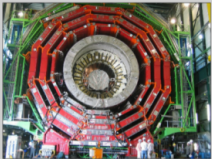
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Atlas



Alice



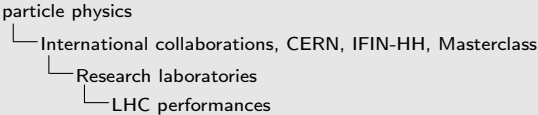
CMS



LHC-b

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LHC performances

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Medical Application as an Example of Particle Physics Spin-off

Combining Physics, ICT, Biology and Medicine to fight cancer



Hadron Therapy

Accelerating particle beams
~30'000 accelerators worldwide
~17'000 used for medicine

Tumour Target
Protons light ions

X-ray
protons

Leadership in Ion Beam Therapy now in Europe and Japan

>70'000 patients treated worldwide (30 facilities)
>21'000 patients treated in Europe (9 facilities)



Imaging

PET Scanner

Brain Metabolism in Alzheimer's Disease: PET Scan

Clinical trial in Portugal for new breast imaging system (ClearPEM)

Detecting particles

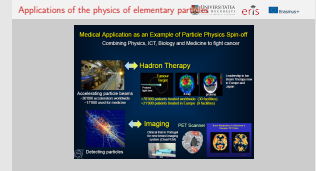
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particle physics

International collaborations, CERN, IFIN-HH, Masterclass

Research laboratories

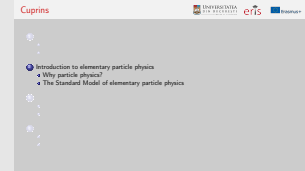
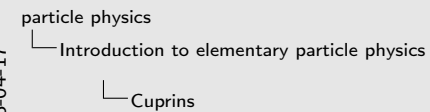
Applications of the physics of elementary particles



- Two of the most known applicative results are:
1. Accelerators for medical use, treating the tumors with the hadronotherapy technique.
 2. The particle detection systems used in imagistic techniques, such as Positron Emission Tomography (PET) which scans the biologic tissues after the infusing of radioactive substances. This technique is an example ao using antimatter in application other than the fundamental science (the positron is the anti-particle of the electron).

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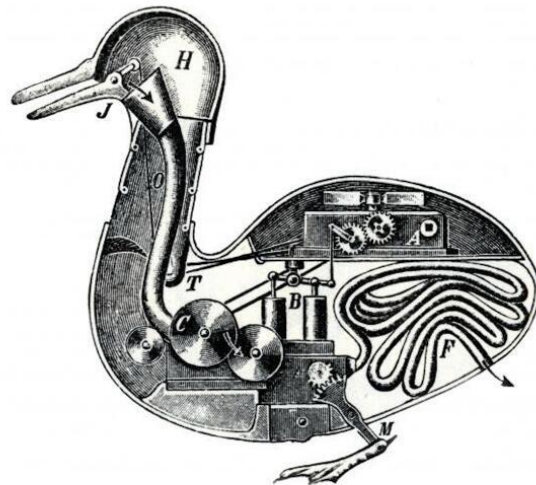
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The section pleads for the study of particle physics and introduces the picture of elementary particles and the fundamental forces as we know it today.

Why do we study particle physics?

A plausible answer would be that we, biologically, are build that way such that the process of learning and explaining facts follows a bottom up path, we decompose phenomena to simpler common causes which once understood can answer the original problem. This process is known as *reductionism* and it denotes both a belief of the hierachical nature and a metodological stand.



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particle physics
 └ Introduction to elementary particle physics
 └ Why particle physics?

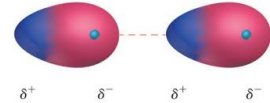
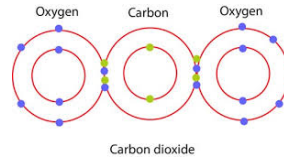
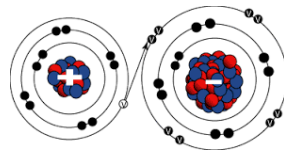
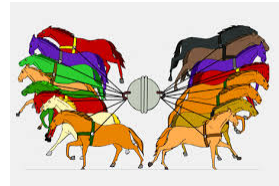
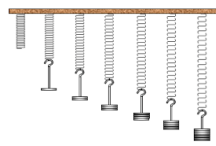
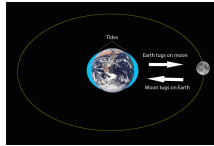


The figure presents an artistic vision of how a duck is "functioning" according to XVIII centuries scientists. Vaucanson's duck poses the triumph of mechanics and of the belief that even the most sensitive phenomena can be explained by the ingenious combinations of the discoveries we already made.

Now, 300 years later armed with much more sophisticated theories, we can not say we are in a better position. How far away from the truth are our quanta-cellular theories? Perhaps they are the same as this drawing. What we do know is that the reductionism was validated and nowadays we are able to explain things very far from us (down to $10^{-15} m$ the dimension of quarks).

The inverse problem to reductionism is reconstructing lar systems from the smallest compomnents. This problem equally interesting it doesn't have a satisfying solution, yet.

Types of forces in nature



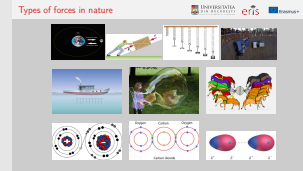
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particle physics

Introduction to elementary particle physics

Why particle physics?

Types of forces in nature



Beginning with the most usual instances of "force", some of them shown here, one can not be unmoved by the thought that all of them share a common explanations. However, what could the following examples of forces could have in common? *Methodological note: Make the explanations starting with the examples most familiar to your group of students.*

1. gravitation
2. the friction force
3. the elastic force
4. the centrifugal force
5. Archimedes' force
6. the superficial tension
7. the static pressure
8. the ionic bond
9. the covalent bond
10. the Van der Waals force



The first hypothesis about the inner structure of the nature are from antiquity times. Then the nature was formed by:

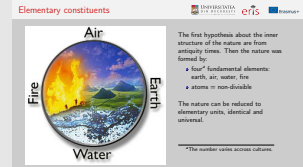
- four^a fundamental elements:
earth, air, water, fire
- atoms = non-divisible

The nature can be reduced to elementary units, identical and universal.

^aThe number varies accross cultures.

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particle physics
└ Introduction to elementary particle physics
└ Why particle physics?
└ Elementary constituents

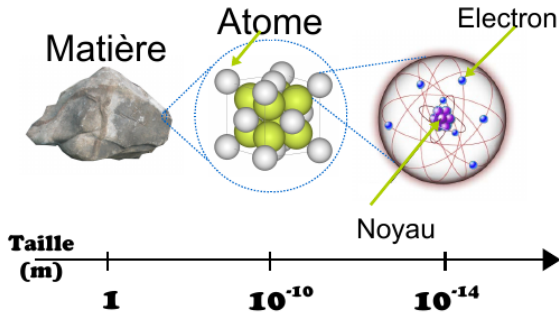
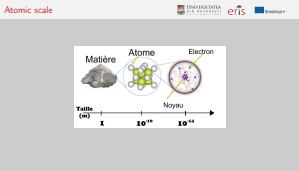


The reuctionist nature of the human thinking can be traced with the first scientific theories from antiquity.

One of the first hypothesis identified the four states of matter as the fundamental elements which could recompose the known univvers. The second hypothesis explicitly assumed that matter has an hierarchical nature and the at the deepest level are the un-divisible atoms.

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- particle physics
 - Introduction to elementary particle physics
 - Why particle physics?
 - Atomic scale



What we know today is that starting from a piece of material, skipping many, many hierarchical levels we reach a level of uniform organization a grid-like structure where the nodes are made of atoms. The atoms are made of the electronic cloud and the nucleus. Different materials vary by the number of electrons and the composition of the nucleus.

- Periodic table

Periodic table

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environment

Periodic Table of the Elements

Atomic Number (Z)

Mass Number (A)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

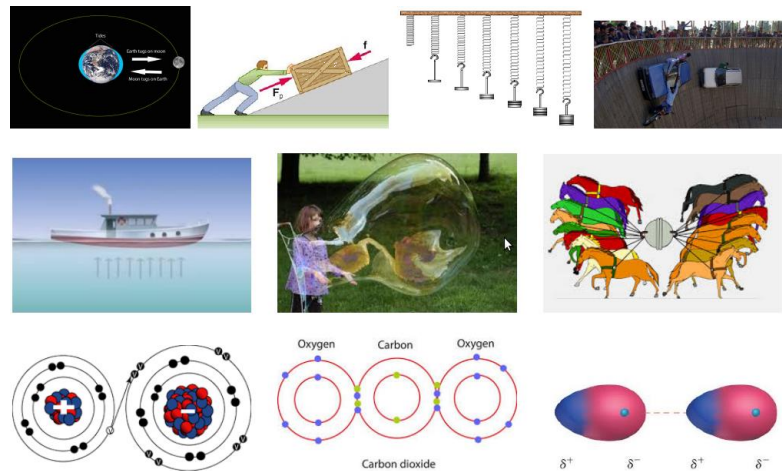
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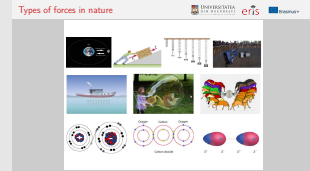
A - mass number

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Types of forces in nature

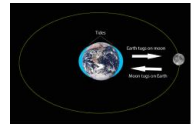


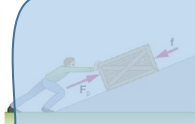
- 2018-04-17
- particle physics
 - Introduction to elementary particle physics
 - Why particle physics?
 - Types of forces in nature

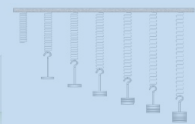


In the same spirit the forces illustrated earlier can be reduced to just two fundamental forces: the electromagnetic force and the gravitational force. Every image contain an instance of one of the two forces.

Types of forces in nature







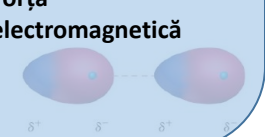
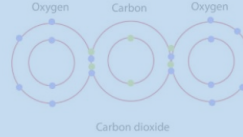
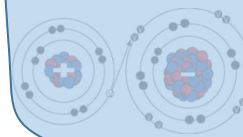




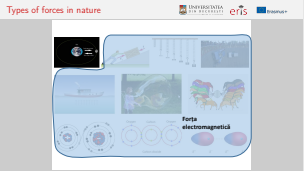




Forța electromagnetică



- 2018-04-17
- particle physics
 - Introduction to elementary particle physics
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At the macroscopic level, they seem very different, but they are only a manifestation of the electromagnetic interaction which ghapens between charget particles.

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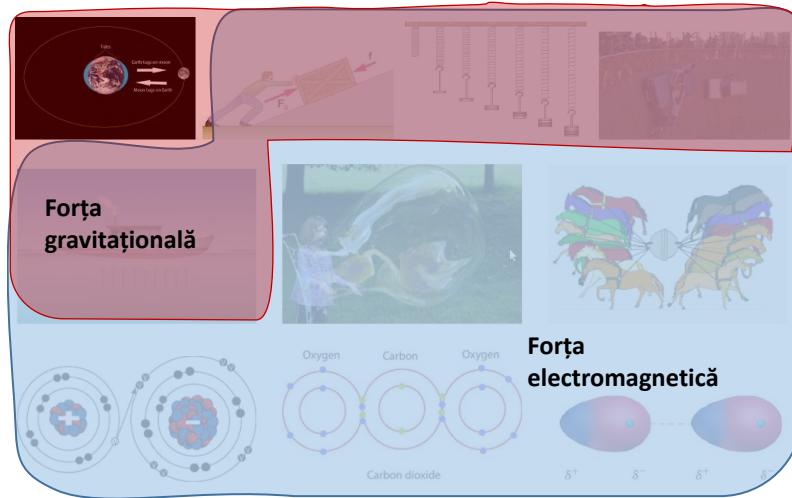
particle physics

└ Introduction to elementary particle physics

└ Why particle physics?

└ Types of forces in nature

Types of forces in nature



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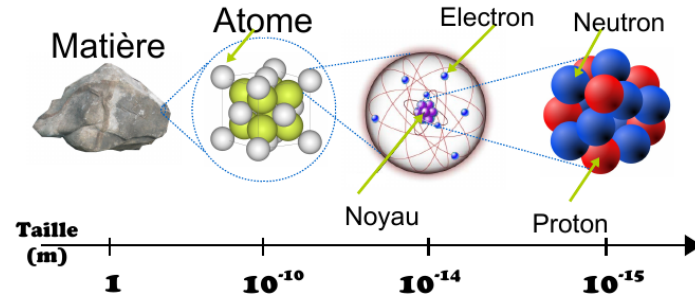
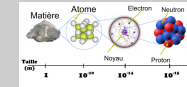
The gravitational is the second instance of force that we meet everywhere.

The study of the particle physics allows us to retrace the path from the macroscopic to the microscopic world.

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particle physics

- Introduction to elementary particle physics
 - Why particle physics?
 - Nuclear scale



The nucleus is 50.000 times smaller than the atom.

The journey is not over, yet, especially when we have hints of unsolved problems. How much can we continue to divide matter?

The nucleus, which is a very dense substance compared with the atom, is made of protons and neutrons. This new level of organization answers questions like the electric neutrality of the atom or its stability, but introduces other new questions.

Kahoot!

Game PIN

Enter

2018-04-17

particle physics

└ Introduction to elementary particle physics

└ Why particle physics?

└ <https://kahoot.it> - Pin: 7595291

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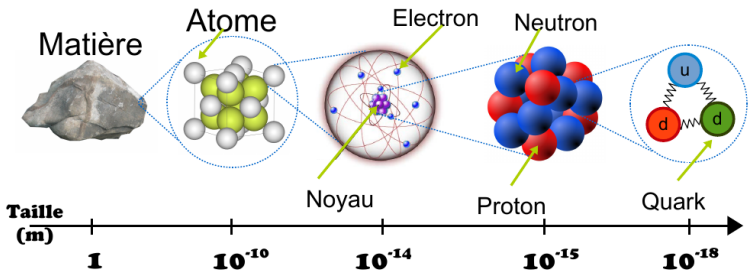
Erasmus+

With this slide we introduce a new moment of the lesson, an online questionnaire with 5 items both for checking for student's attention but also to preview the next section's topics.

The questionnaire is made on kahoo site. The students connect on their phones or laptops to the following address kahoot.it using this pin number 7595291, while the teacher starts the application in browser from this address <https://play.kahoot.it/#/?quizId=89b40b98-e277-498a-9270-82b88c1f83d1>.

The items can also be seen on the slides at the end of the presentation.

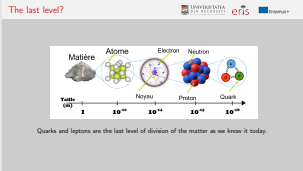
The last level?



Quarks and leptons are the last level of division of the matter as we know it today.

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- particle physics
 - Introduction to elementary particle physics
 - The Standard Model of elementary particle physics
 - The last level?



Continuing the division process we see that there is yet another level available to us. The protons and the neutrons are made by three smaller particles, which we believe are elementary, called quarks. The electrons are the other elementary particles since they can not be divided further.

- Three types of particles: quarks, leptons, interaction bosons

Standard Model table

1. With violet we have the **quarks** and with green we have the **leptons**. Together the two classes form the matter. With red we have the **the interaction bosons**, the carriers of the "forces".

Standard Model table

mass →	≈2.3 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
QUARKS	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
				GAUGE BOSONS	

- Three types pf particles: **quarks**, **leptons**, **interaction bosons**
- Each particle has an anti-particle

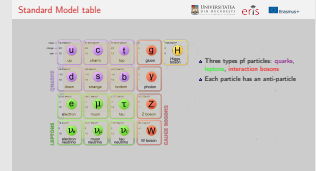
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particle physics

└ Introduction to elementary particle physics

└ The Standard Model of elementary particle physics

└ Standard Model table



The theory that explains today the structure of the matter at its lowest level is called the *Standard Model of elementary particles*. In a similar manner to the periodic table of the chemical elements the Standard Model can be presented synoptic in table. Here each class of particles is represented with a different color.

1. With violet we have the **quarks** and with green we have the **leptons**.. Together the two classes form the matter. With red we have the **the interaction bosons**, the carriers of the "forces".
2. Each particle has a partner called **anti-particle**, a particle with the same properties, but with opposite electric charge. The antiparticles has started to be discovered since 1930s and their existence is irrefutable.

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	u up	c charm	t top	g gluon	H Higgs boson
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

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particle physics

Introduction to elementary particle physics

The Standard Model of elementary particle physics

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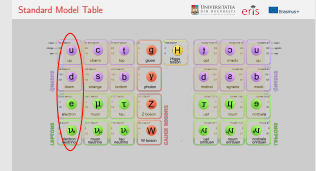
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3. Beyond the antiparticles we still need some new hypothesis to explain the formation and the evolution of the universe. Some researchers speak about the **dark matter** or **dark energy**, but this is not confirmed, yet.

Standard Model Table

mass →	≈2.2 MeV/c ²	≈1.275 GeV/c ²	≈173.07 GeV/c ²	0	≈126 GeV/c ²				
charge →	2/3	2/3	2/3	0	0				
spin →	1/2	1/2	1/2	1	0				
QUARKS	u up	c charm	t top	g gluon	H Higgs boson	ū anti-up	c̄ anti-charm	t̄ anti-top	
	d down	s strange	b bottom	γ photon		d̄ anti-down	s̄ anti-strange	b̄ anti-bottom	LEPTONS
	e electron	μ muon	τ tau	Z Z boson		ē positron	μ̄ anti-muon	τ̄ anti-tau	
LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		ν̄_e anti-electron neutrino	ν̄_μ anti-muon neutrino	ν̄_τ anti-tau neutrino	GAUGE BOSONS

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- particle physics
 - Introduction to elementary particle physics
 - The Standard Model of elementary particle physics
 - Standard Model Table



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3. The usual matter around us is formed by particles from the first column the quarks **u**, **d** and the electron. The other elementary particles have a very short lifetime and don't have time to form stable structures.

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- Three types of particles: quarks, leptons, interaction bosons
- Each particle has an anti-particle
- Ordinary matter: u , d quarks and electrons

- particle physics
 - Introduction to elementary particle physics
 - The Standard Model of elementary particle physics
 - Standard Model table

The Standard Model table is organized into two main sections: **LEPTONS** (left) and **QUARKS** (right). Each section has a vertical axis for **Generation** (1st, 2nd, 3rd) and a horizontal axis for **Charge** (0, $-\frac{1}{3}$, $+\frac{2}{3}$, 0 , $-\frac{1}{2}$, $+\frac{1}{2}$). The table contains 24 colored boxes representing different particles, each with a letter and a name. The **LEPTONS** section includes $\nu_e, e, \nu_\mu, \mu, \nu_\tau, \tau$. The **QUARKS** section includes u, d, s, c, b, t . The **GAUGE BOSONS** section includes $\gamma, W^\pm, Z, g, H$.

	CHARGE					
	0	$-\frac{1}{3}$	$+\frac{2}{3}$	0	$-\frac{1}{2}$	$+\frac{1}{2}$
1st Generation	ν_e (electron neutrino)	e^- (electron)	u^+ (up quark)	d^+ (down quark)	γ (photon)	H^0 (Higgs boson)
2nd Generation	ν_μ (muon neutrino)	μ^- (muon)	c^+ (charm quark)	s^+ (strange quark)	W^+ (W boson)	Z^0 (Z boson)
3rd Generation	ν_τ (tau neutrino)	τ^- (tau lepton)	t^+ (top quark)	b^+ (bottom quark)	g (gluon)	

LEPTONS
 1st Generation: ν_e (electron neutrino), e^- (electron)
 2nd Generation: ν_μ (muon neutrino), μ^- (muon)
 3rd Generation: ν_τ (tau neutrino), τ^- (tau lepton)

QUARKS
 1st Generation: u^+ (up quark), d^+ (down quark)
 2nd Generation: c^+ (charm quark), s^+ (strange quark)
 3rd Generation: t^+ (top quark), b^+ (bottom quark)

GAUGE BOSONS
 γ (photon), $W^\pm$ (W boson), Z^0 (Z boson), g (gluon), H^0 (Higgs boson)

Three types of particles: quarks, leptons, interaction bosons
 Each particle has an anti-particle
 Ordinary matter: u, d quarks and electrons

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- Three types of particles: quarks, leptons, interaction bosons
- Each particle has an anti-particle
- Ordinary matter: *u*, *d* quarks and electrons
- Interaction bosons are "carriers" of forces: electromagnetic, strong, weak

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particle physics

Introduction to elementary particle physics

The Standard Model of elementary particle physics

Standard Model table

Standard Model table



Legend:

- Three types of particles: quarks, leptons, interaction bosons
- Each particle has an anti-particle
- Ordinary matter: *u*, *d* quarks and electrons
- Interaction bosons are "carriers" of forces: electromagnetic, strong, weak

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 3. The usual matter around us is formed by particles from the first column: the quarks **u**, **d** and the electron. The other elementary particles have a very short lifetime and don't have time to form stable structures.
 4. **The bosons** are particles which "carry" the interaction. There are four fundamental forces and for every one the corresponding bosons have been found, the gravitation being an exception.



Forces act by exchange of interaction particles. The interaction particles are the photon, $W^{\pm}$ bosons, Z^0 boson, gluon, graviton. They all have different mass and behaviour.

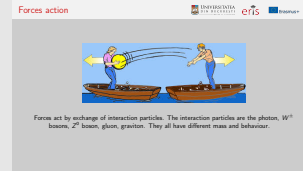
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└ Introduction to elementary particle physics

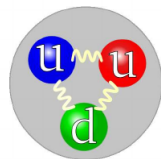
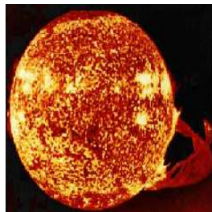
└ The Standard Model of elementary particle physics

└ Forces action



The modern vision on the notion of force (interaction) can be understood from this picture. The particle which forms matter, quarks and leptons, interact with each other by exchanging bosons specific to each type of force. The bosons carry the energy and the momentum obeying the conservation laws. The names of the bosons are: This slide can be used to review the notion of conservation laws (electric charge, energy and momentum).

1. electromagnetic force - photon
2. weak force - bosons W^+ , W^- , Z^0 ,
3. strong force - gluon,
4. gravitational force - by analogy we assume the existence of the graviton.



Types of forces

- gravitational force
 - graviton
- electromagnetic force
 - photon
- strong force
 - gluon
- weak force
 - W^+ , W^- , Z^0 bosons

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Fundamental interactions

Fundamental interactions

Types of forces

- gravitational force
 - graviton
- electromagnetic force
 - photon
- strong force
 - gluon
- weak force
 - W^+ , W^- , Z^0 bosons

The Standard Model is made of particles and forces that explain the dynamic at the fundamental level. Two of these interactions are more familiar to us since they have what is called infinite range, that is the effect of forces is felt at long distance and manifest to macroscopic distances too.

1. The gravitational force act between all kinds of particles which have mass. It is considered a weak force, but when there are large accumulations of mass, like in astronomical bodies, it becomes the dominant force.
2. The electromagnetic force subsumes both the electric and magnetic forces. It is the force that produces the most evident effects at the scale we live, it is stronger than the gravitational force. It does not produce important effects at large distances since we have both positive and negative charges which screens each other.
3. The strong force explains why the atomic nuclei with positive electric charge are stable. It manifests at the levels of quarks and the protons and neutrons feel it as an attractive force compensating the electric force. It doesn't act on leptons.
4. The weak force was introduced to explain phenomena which can not be explained by the other force like the transitions from one element to another (radioactivity) etc. The strength and the range of the force is limited

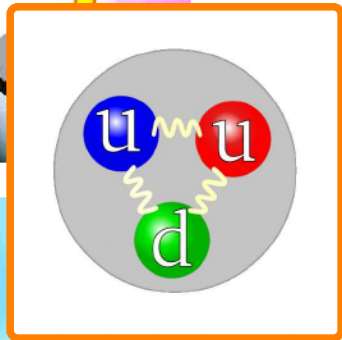
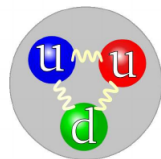
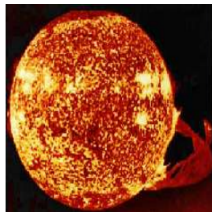
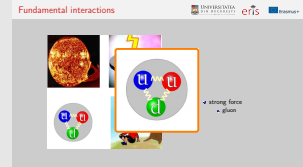
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particle physics

Introduction to elementary particle physics

The Standard Model of elementary particle physics

Fundamental interactions



- strong force
- gluon



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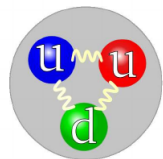
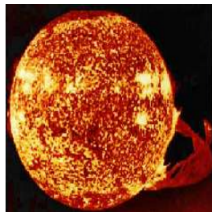
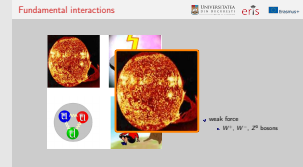
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particle physics

└ Introduction to elementary particle physics

└ The Standard Model of elementary particle physics

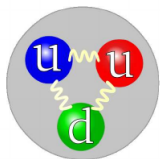
└ Fundamental interactions



- weak force
 - W^+ , W^- , Z^0 bosons

The Standard Model is made of particles and forces that explain the dynamic at the fundamental level. Two of these interactions are more familiar to us since they have what is called infinite range, that is the effect of forces is felt at long distance and manifest to macroscopic distances too.

1. The gravitational force act between all kinds of particles which have mass. It is considered a weak force, but when there are large accumulations of mass, like in astronomical bodies, it becomes the dominant force.
2. The electromagnetic force subsumes both the electric and magnetic forces. It is the force that produces the most evident effects at the scale we live, it is stronger than the gravitational force. It does not produce important effects at large distances since we have both positive and negative charges which screens each other.
3. The strong force explains why the atomic nuclei with positive electric charge are stable. It manifests at the levels of quarks and the protons and neutrons feel it as an attractive force compensating the electric force. It doesn't act on leptons.
4. The weak force was introduced to explain phenomena which can not be explained by the other force like the transitions from one element to another (radioactivity) etc. The strength and the range of the force is limited



Types of forces

- gravitational force
 - graviton
- electromagnetic force
 - photon
- strong force
 - gluon
- weak force
 - W^+ , W^- , Z^0 bosons

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particle physics

Introduction to elementary particle physics

The Standard Model of elementary particle physics

Fundamental interactions

Fundamental interactions

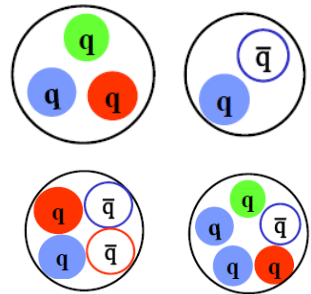
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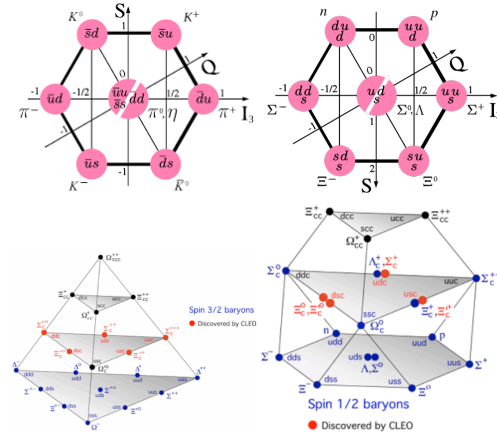
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Composed particles



Combinations of quarks have entire (0, ±1, ±2 ...) electric charge and they classify by the number of quarks in: mesons, barions, tetraquarks, pentaquarks.

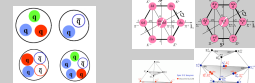


Quarks combinations obey certain well defined geometric laws.

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Composed particles



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Quarks combinations obey certain well defined geometric laws.

Due to the strong force, the quarks can form combinations which survive long enough to be detected and studied. The combinations of three quarks qqq or three anti-quarks $\bar{q}\bar{q}\bar{q}$ are called barions, the proton and the neutron belong to this class. Heavily studied combinations are also the mesons formed of a q_1 and of antiquark $\bar{q}_2$.

More recently, after 2015, there have been found evidences also for combinations of four and five quarks. The rules of quark compositions are very well understood and depend also on the other properties of the quarks isospin, strangeness etc. Mathematically this combinations can be expressed with geometric figures, see on the left, where each node is a particle that can be formed.

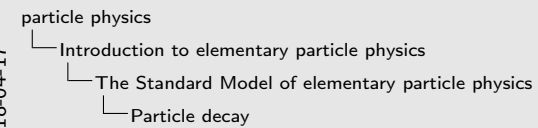
Beside protons and neutrons there are particles like pions (π), kaons (K), eta particles(η), sigma (Σ), xi (Ξ), lambda (Λ), omega (Ω) etc., most of them discovered after 1950 with the advent of the large particle accelerators. To produce new particles one needs more energy and bigger intensities. The study of the composed particles brings us information about the strong and weak



Trivia (about particles):

- Particles live a finite time
- The life time varies with the type of force and the particle weight
- Protons and electrons are stable particles
- The neutron life time is about 10 min.

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Particle decay

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The existence of the limited lifetime of the particles can be understood by the analogy with the unstable equilibrium from static mechanics. Quarks combinations are usually unstable states of quarks and they try to reach out a lower energy state. The average time after which they make the transition is called lifetime and it can be different for each combination.

The lifetime for neutron is about 10 minutes in open space.

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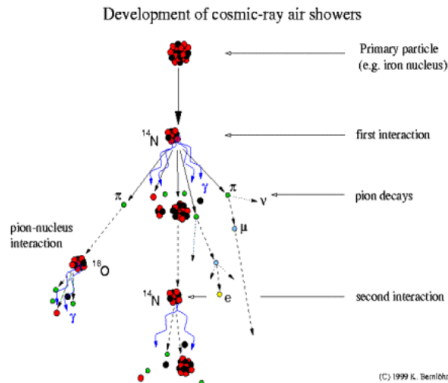
Particle decay



Development of cosmic-ray air showers

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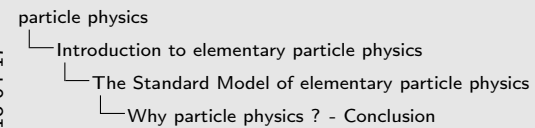
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The lifetime for neutron is about 10 minutes in open space. The cosmic radiation is another important source of particles. In the left image we a *Fe* nucleus entering the Earth atmosphere and decaying after multiple collisions, first into a nitrogen atom and then in smaller nuclei and lighter particles such as pions, muons, electrons, neutrino, gamma rays etc.

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Why particle physics ? - Conclusion

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- It offers answers about the structure of the matter
- It gives explanations to fundamental questions (symetries, conservations laws, time - space, extra-dimensions, quantum interferences, dualities etc.)
- The theory ha a beautiful structure: a small number of fundamental constituents, rigourous mathematical framework
- It connects microscopic world to the macroscopic world
- It is a truly global effort with thousands of researchers working together

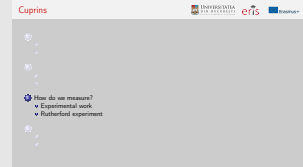
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 - Educational resources - Masterclasses
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- 2 Introduction to elementary particle physics
 - Why particle physics?
 - The Standard Model of elementary particle physics
- 3 How do we measure?
 - Experimental work
 - Rutherford experiment
- 4 Practical exercise: LHCb masterclass
 - LHCb experiment
 - Measurement of the lifetime of the D^0 meson

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particle physics

- └ How do we measure?
 - └ Cuprins



This second part explains the basic of experiments in particle physics. These can be understood using knowledge on collisions and probabilities.

We introduce the notions of graphical representation, histograms and propose exercises and a practical activity for class.

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particle physics

- How do we measure?
 - Experimental work
 - How do we investigate the microscopic world?



Direct measurements



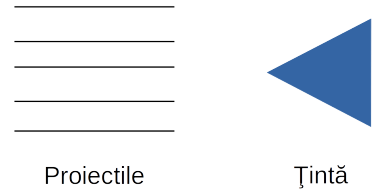
Indirect measurements



The experiments in physics we can think of belonging to one of the following types, direct measurements when the subject is accessible to our inspection or as indirect measurements when the tools used to inspect the subject exceed the complexity of the phenomenon under study.

In the case of elementary particles, we are always in the case of indirect experiments and their properties are inferred in particle - particle collision experiments which usually destroy the initial states. The effort of the physicist is to "rebuild" the initial states based on information from the collision remnants.

Next we will illustrate this type of experiments with the case of macroscopic elastic collisions.



Through away balls to a solid brick.

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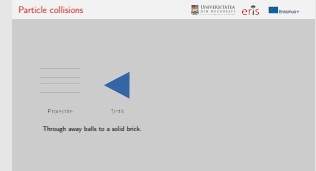
particle physics

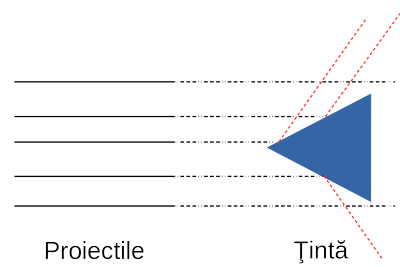
How do we measure?

Experimental work

Particle collisions

Let's have a target object in the shape of a triangle set in the plane as on the left figure, we throw with balls at it in th horizontal direction. Assuming that we have a fix target and the balls have negligible dimensions, the balls are reflected by the sides of the triangles.





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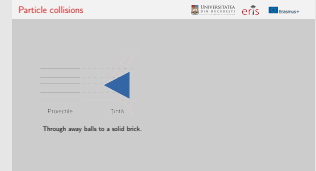
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particle physics

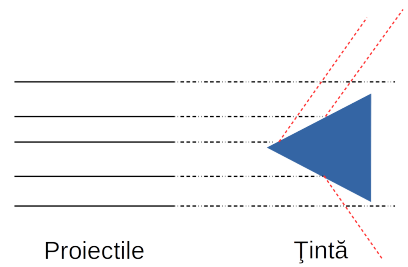
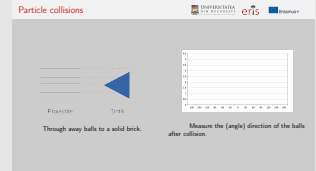
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Experimental work

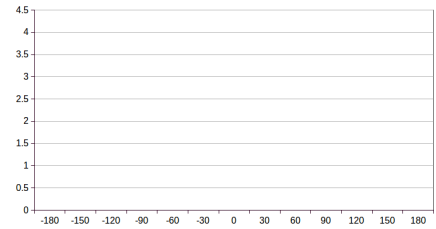
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Through away balls to a solid brick.



Measure the (angle) direction of the balls after collision.

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1. Note on a plot like the one in the left the results from the collisions, on the OX we have the angles with the horizontal of the emergent balls and on OY axis there are the number of balls deflected in a given direction.

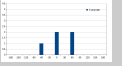
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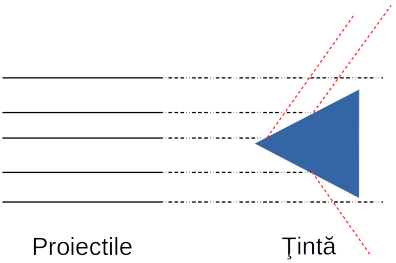
- particle physics
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Particle collisions

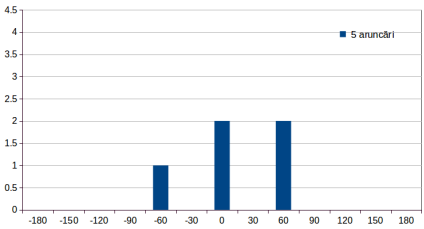








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 - For the first series we have one ball at -60° deflected on the lower side of the triangle, two balls at 0° which pass undeflected and two balls deflected at 60° by the upper side of th triangle.

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- particle physics
 - How do we measure?
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 - Particle collisions

Particle collisions

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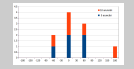
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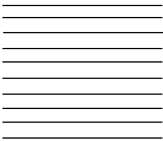
Proiectile

Țintă

Through away balls to a solid brick.



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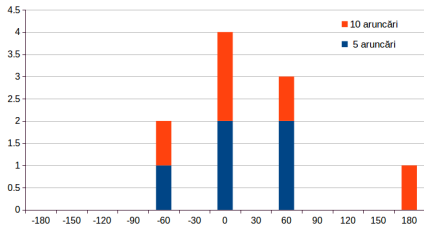


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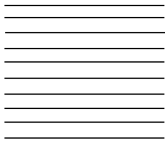
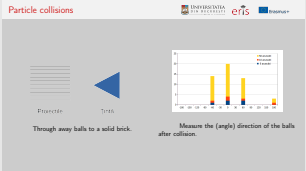


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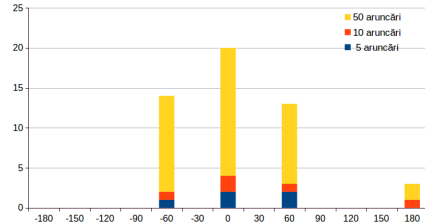


Proiectile



Țintă

Through away balls to a solid brick.



Measure the (angle) direction of the balls after collision.

After mor throws the shape of the plot stabilizes.

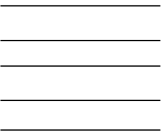
This type of plot is called **histogram** and in a typical experiment with particles is all that we have, the target is hidden we just see the deflected particles. The shape of the target can be infered from the plot.

In this case we can deduce that we have three sides, plus the bin for the undeflected particles. Two of the sides are bigger than the last one and are tilted 30° and -30° to the horizontal. The smaller side, the vertex of the triangle, has an angle of 90° (we considered it a blunt tip).

Conclusion: starting with the information from the plot we could deduce the shape of the target, otherwise unaccessible.

The exercise can be repeated with other tyoes of target in both ways, starting with the plot to predict the target or starting with the target and predicting the plot.

Exercise

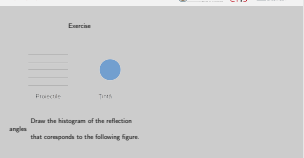
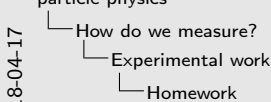


Proiectile



Țintă

Draw the histogram of the reflection
angles
that coresponds to the following figure.



The following two exercises are presented on large in the worksheet:

1. Given the target in a shape of a circle draw the histogram of the deflection angles.

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particle physics
└─ How do we measure?
 └─ Experimental work
 └─ Homework

Exercise

Proiectile

●

Țintă

Draw the histogram of the reflection angles that corresponds to the following figure.

Practical exercise

Proiectile

●

●

●

●

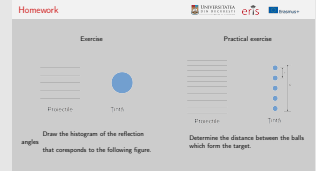
●

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D

Țintă

Determine the distance between the balls which form the target.



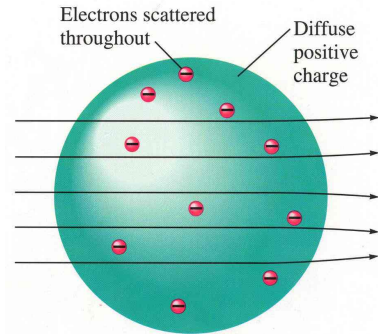
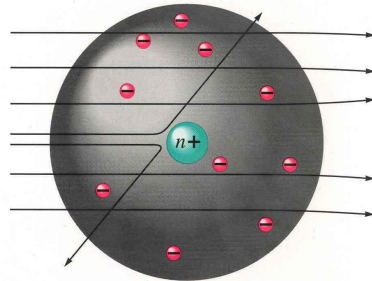


Figure : a) Pudding model



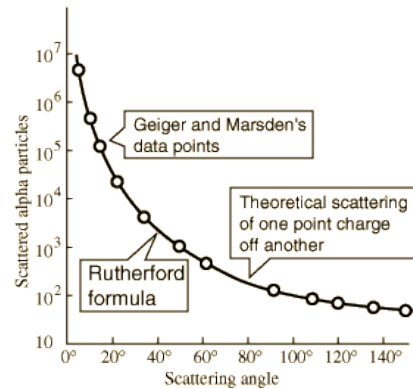
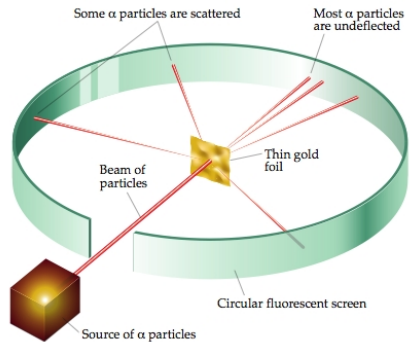
b) Orbital model

The experiments shown earlier are inspired by the famous Rutherford experiment from the beginning of the XX century. At the time he knew that the atom is electrical neutral and that it contains electrons, particles which were already discovered.

There were two hypotheses, the pudding model which assumed that the atom was a ball uniformly charged with positive charge and where electrons were floating in random positions. The second model suggested that the atom looks more like the solar system with the positive nucleus at the center and a negative cloud of electrons orbiting.

The answer came out from the Rutherford experiment in which he observed the deflections of the alpha particles which were fired at a nucleus. The large angle observed supported the orbital model of the atom.

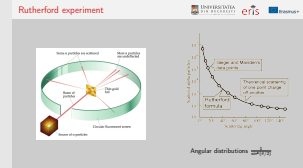
Rutherford experiment



Angular distributions $\frac{1}{\sin^4(\theta/2)}$

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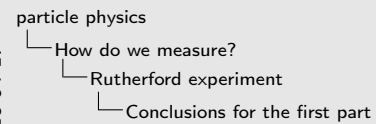
particle physics
└─ How do we measure?
 └─ Rutherford experiment
 └─ Rutherford experiment



The Rutherford experiment is a paradigm of the experiments in particles physics which use this idea to this days. The positive charged alpha particles were sent on a thin foil of gold. The foil was surrounded by a fluorescent screen which measure the angles of the deflected particles.

According to the plot, most of the particle pass undeflected, but there were a significant number of particles deflected at large angles indicating the existence of a strong defelction angle. The histogram is similar in principle with ones made by us earlier and allowed to decide on the target shape.

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Conclusions for the first part

- There are four fundamental forces known in nature:
 - gravitational, electromagnetic, strong force and weak force
 - The force that we encounter daily are only two
- The smallest particle we know are quarks and leptons
 - quarks: up, down, charm, strange, top, bottom + anti-particles
 - leptons: electrons, muons and tausons + neutrinos + anti-particles
 - interaction bosons: photon, gluon, $W^\pm$, Z^0 , graviton, Higgs
- Elementary particles have many characteristics different from the macroscopic bodies
 - Electrical charge, color, spin, partners/anti-matter ...
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- Experiments in particle physics are collision type experiments

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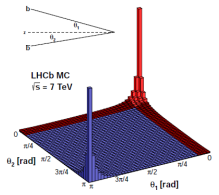
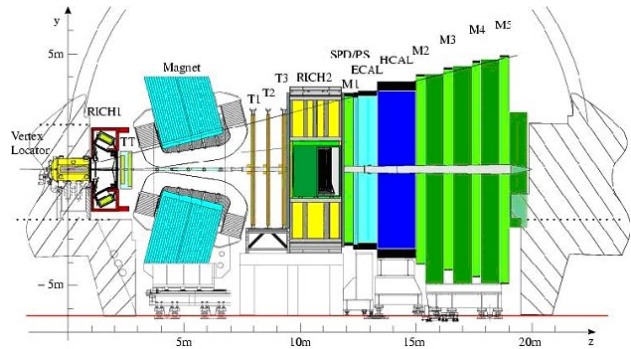
particle physics

- └ Practical exercise: LHCb masterclass
 - └ Cuprins



For the full explanation of the next exercises follow LHCb International Masterclass link
lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach/masterclasses/en/

Experimental LHCb - "flavour factory"



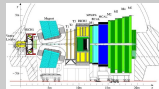
The LHCb experiment search for New Physics, phenomena that are not predicted by the current Standard Model studying properties of *b* and *c* quarks.

Precision measurements and the study of rare decays will give new explanations on the asymmetry between matter and anti-matter from Universe.

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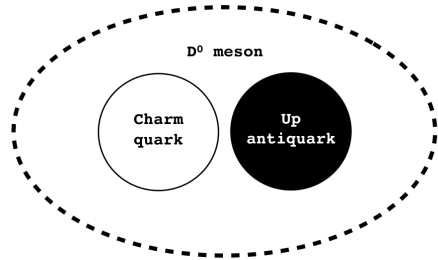
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Experimental LHCb - "flavour factory"



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- Mass : 1864 MeV
- Lifetime: $0.4101 \pm 0.0015 * 10^{-12}$ s
- What distance travels the D^0 particle in detector?
 $d = t * v = 3 * 10^{-4}$ meters or 0,3 mm ???
 But the particle obeys relativistic laws, i.e.
 the particle lives longer in laboratory system,
 time is dilated:

$$t_L = t / \sqrt{1 - v^2/c^2}$$

Recalculating, the particle travels ≈ 1 cm

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particle physics

└ Practical exercise: LHCb masterclass

└ Measurement of the lifetime of the D^0 meson

└ Study of D^0 meson

Study of D^0 meson

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 the particle lives longer in laboratory system,
 time is dilated:
 $t_L = t / \sqrt{1 - v^2/c^2}$

Recalculating, the particle travels ≈ 1 cm

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particle physics

— Practical exercise: LHCb masterclass

— Measurement of the lifetime of the D^0 meson

— Objectives

Objectives

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The purpose of the exercises is:

- To illustrate how the decay events look like in the detector
- To perform the selection of D^0 candidates using the particle properties
- Extract the lifetime values by modelling (fitting) the signal
- To introduce the concept of systematic errors vs. statistical errors

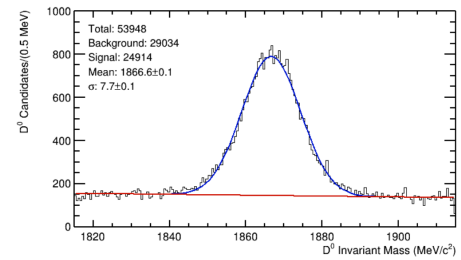
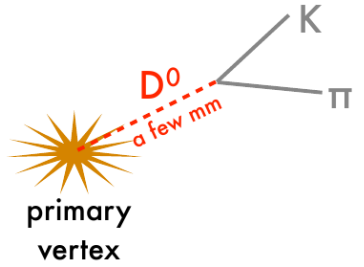
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D⁰ candidates

D⁰ meson decays according to the formula:

$$D^0 \rightarrow K^+ \pi^- \quad (\bar{D}^0 \rightarrow K^- \pi^+)$$



- The kaon and the pion are the "final state" particles that are measured (the energy and the momentum) in the detector
- The D⁰ properties are inferred from the conservation laws:

$$M = \sqrt{E^2 - P^2 c^2}, \text{ unde } E = E_1 + E_2 \text{ 'si' } \vec{P} = \vec{P}_1 + \vec{P}_2$$

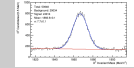
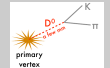
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- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D⁰ meson
 - D⁰ candidates

D⁰ candidates

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Exercise I - Identification of D^0 and $\bar{D}^0$ candidates

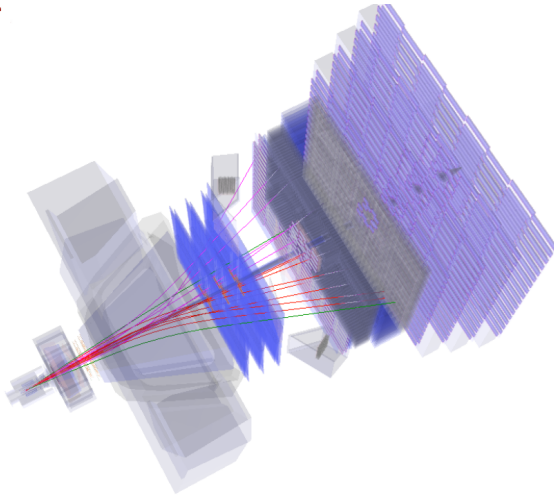
- Open LHCb Masterclass application
- Visualise the tracks which belongs to the kaons and pions originating found in the events
- Look at 30 events and identify the tracks from D^0 candidates

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particle physics
└─ Practical exercise: LHCb masterclass
 └─ Measurement of the lifetime of the D^0 meson

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particle physics

└ Practical exercise: LHCb masterclass

└└ Measurement of the lifetime of the D^0 meson

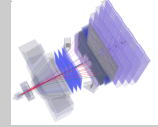
└└└ Event reconstruction in detector

Event reconstruction in detector

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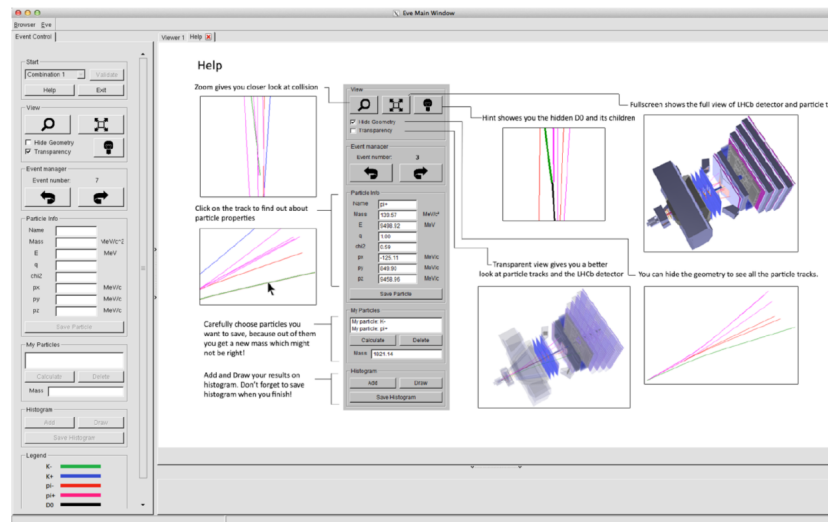
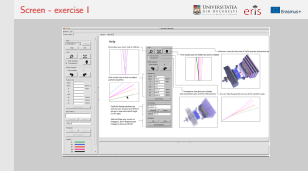
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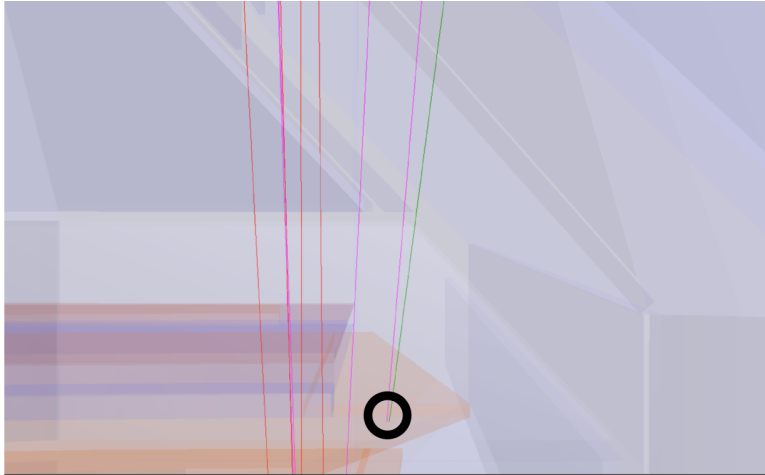


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- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Screen - exercise I



D^0 vertex - simple event



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particle physics

└ Practical exercise: LHCb masterclass

└ Measurement of the lifetime of the D^0 meson

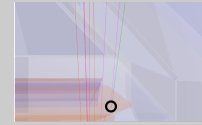
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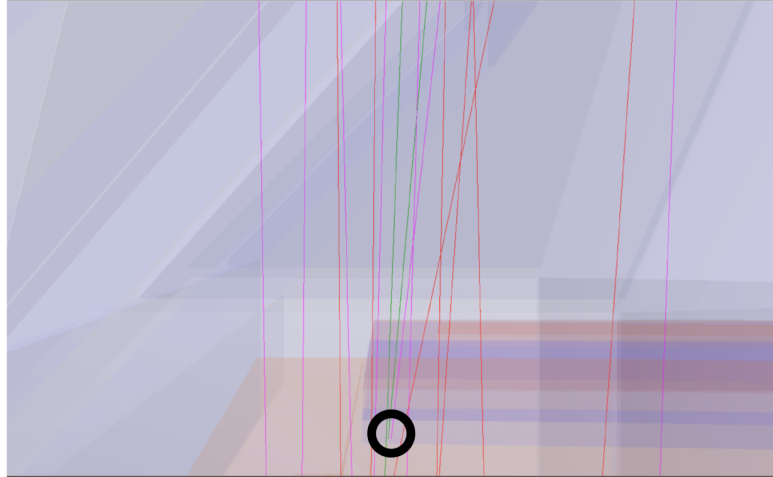
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D^0 vertex- rich event



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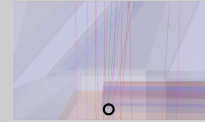
particle physics

└ Practical exercise: LHCb masterclass

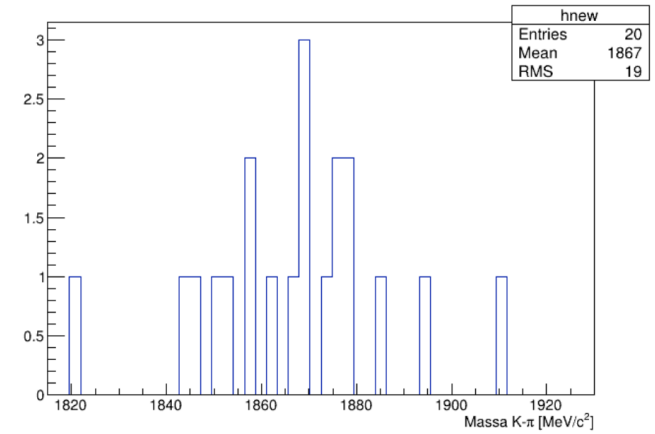
└ Measurement of the lifetime of the D^0 meson

└ D^0 vertex- rich event

D^0 vertex- rich event

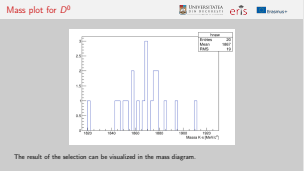


Mass plot for D^0



The result of the selection can be visualized in the mass diagram.

- 2018-04-17
- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Mass plot for D^0



Exercise II

The measurement of the lifetime of D^0 particle with LHCb data from 2012 run

The next steps will be followed:

- monitor signal and background in different histograms types
- fit the mass distribution and the lifetime distribution
- study the lifetime as a function of impact parameter(IP)

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particle physics
└─ Practical exercise: LHCb masterclass
 └─ Measurement of the lifetime of the D^0 meson

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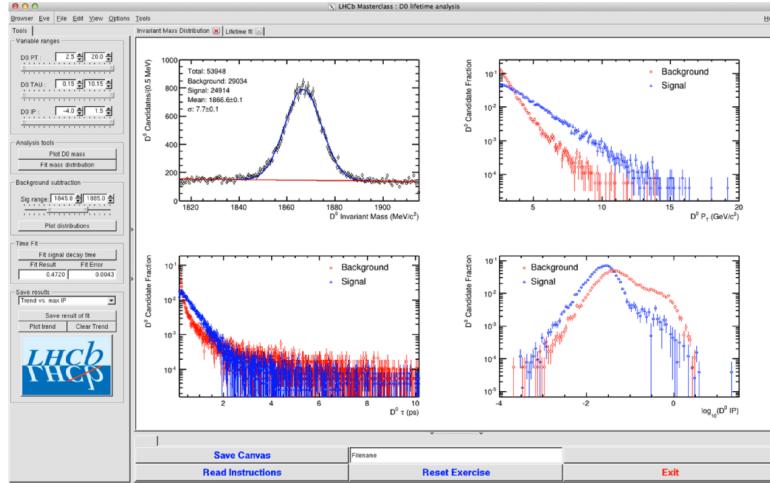
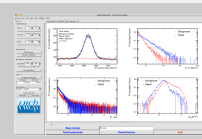
particle physics

Practical exercise: LHCb masterclass

Measurement of the lifetime of the D^0 meson

Signal vs. background distributions

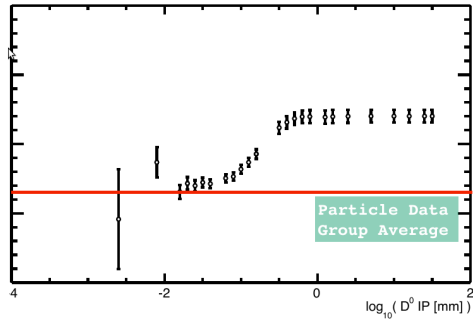
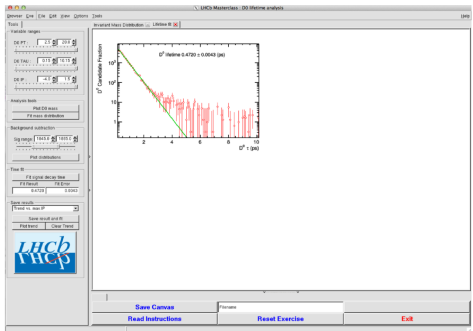
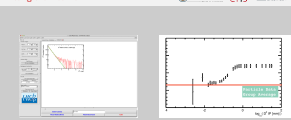
Signal vs. background distributions



- Looking at different quantities, usually, the signal and the background have different behaviours.
- Mass is one of the variables that allows the discrimination between the signal and the background.
- Other available plots are:
 - transversal momentum p_T of D^0 ,
 - impact parameter - $\log_{10}$ (IP for D^0) - it is a length measure of the path travel by the particle before decaying,
 - The lifetime of the D^0 particles.

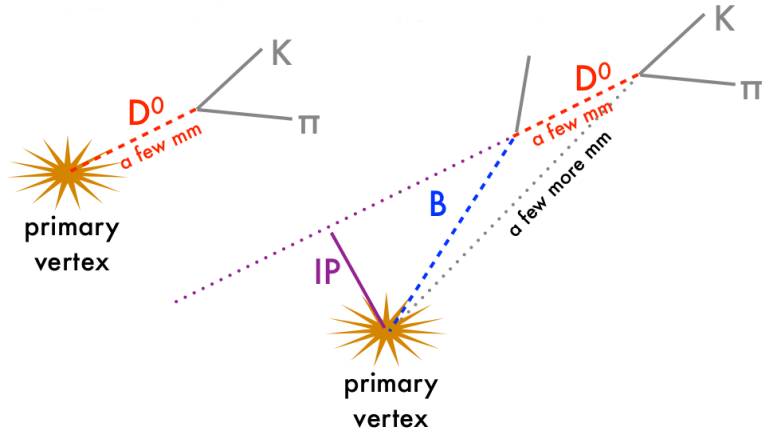
Fitting the lifetime

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- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Fitting the lifetime



The dataset with the highest purity produces the closest results to the official measurements.
Possible systematic errors are investigated.

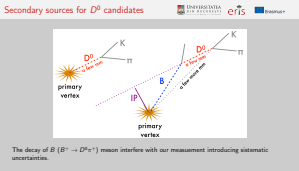
Secondary sources for D^0 candidates



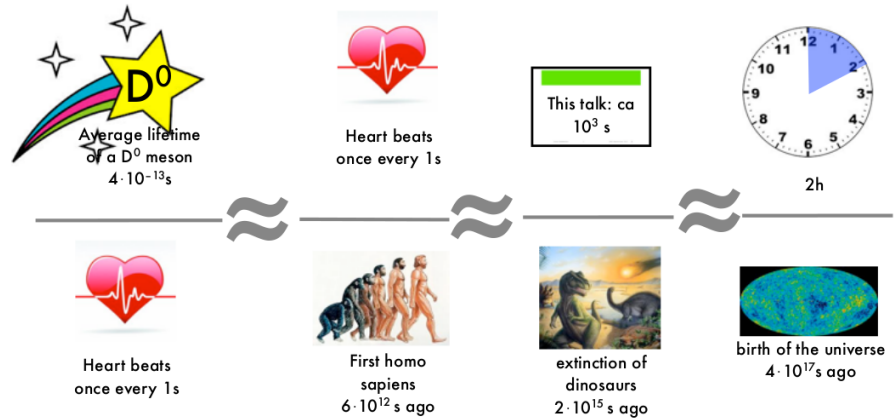
The decay of B ($B^+ \rightarrow D^0 \pi^+$) meson interfere with our measuement introducing sistematic uncertainties.

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- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Secondary sources for D^0 candidates

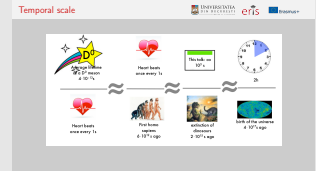


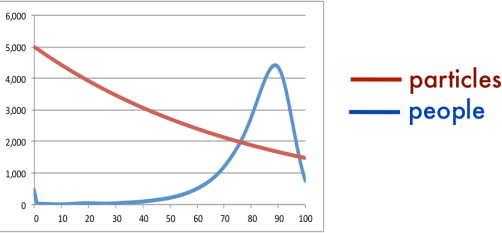
Temporal scale



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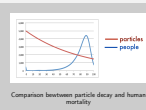
- particle physics
 - Practical exercise: LHCb masterclass
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 - Temporal scale

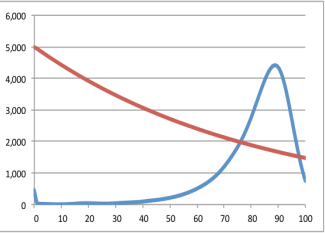




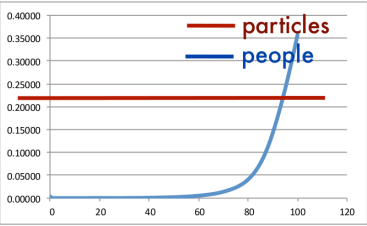
Comparison bewtween particle decay and human mortality

- 2018-04-17
- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Lifetime





— particles
— people



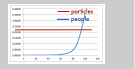
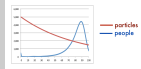
Comparison bewtween particle decay and human mortality

Probability of decaying in time for particles and people

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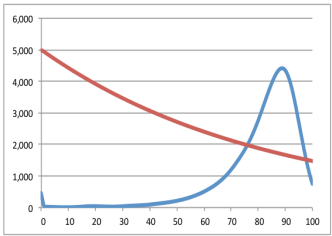
- particle physics
 - Practical exercise: LHCb masterclass
 - Measurement of the lifetime of the D^0 meson
 - Lifetime

Lifetime

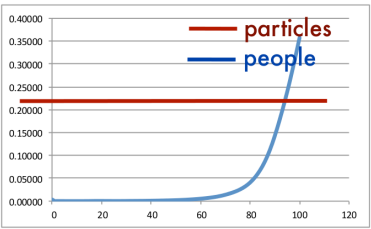


Comparison between particle decay and human mortality

Probability of decaying in time for particles and people



— particles
— people

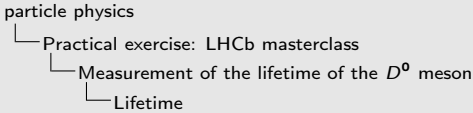


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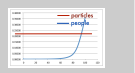
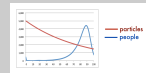
Probability of decaying in time for particles and people

- Particles decay, but don't age.
- The decay law of particles (exponential decay) is a direct consequence of this.

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Lifetime

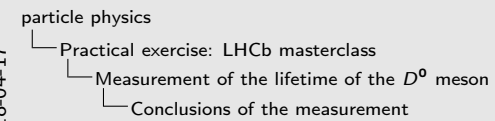


Comparison between particle decay and human mortality

Probability of decaying in time for particles and people

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- Conclusions of the measurement
- A very small time have been measured
 - This was possible due to the performances of LHCb detector, the high energies and the special relativity
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 - The result is important for present research topics

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Kahoot!

Game PIN

Enter

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particle physics

└ Practical exercise: LHCb masterclass

└ Measurement of the lifetime of the D^0 meson

└ <https://kahoot.it> - Pin: 4277826

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Another Kahoot moment with questions from the Standard Model

This questionnaire might require computation and complex reasoning, ensure that your students have all the concepts made known to them.

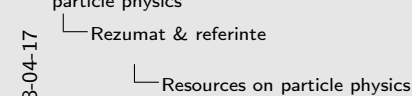
The game is initiated by the teacher at the address play.kahoot.it/#/?quizId=b8fb8212-b6ce-4c28-83cb-92432f4c1881 while students connect to kahoot.it introucing the pinul code 4277826.

Conclusions

- There four fundamental forces known in nature: gravitational, electromagnetic, strong and weak force
- The elementary particles are the quarks and the leptons (electrons, muons, tauon)
- Elementary particles have more properties than the electrical charge which influence the interaction they take part in (color, anti-partners, spin ...). These properties don't have a macroscopic manifestation
- The LHCb masterclass exercise give access to real data
- Modern physics is the result of cooperation on large scale and a succesfull scientist learns to communicate his research.

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-  "Particle adventure" website (eng, fr, it) <http://particleadventure.org/>
-  Mobile phone application, Android and iPhone: LHSee
-  Video animation with LHC accelerator
<https://www.youtube.com/watch?v=pQhbhpU9Wrg>
www.youtube.com/watch?v=08x49b9tTNQ
-  Advanced data analysis for programming enthusiasts
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-  Resources proposed by the Quarknet
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Resources on particle physics

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The activities can be continued with the ones suggested here.

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particle physics
└ Rezumat & referinte
└ References for LHCb & Masterclass

References for LHCb & Masterclass

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- 1 LHCb International Masterclass internet webpage
<http://lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach/masterclasses/en/>.
- 2 Masterclass exercises - video www.youtube.com/watch?v=x2qJUbf2qUQ
- 3 Overview of LHCb experiment: www.youtube.com/watch?v=rsmBMuTFdA,
lhcb-public.web.cern.ch/lhcb-public/.
- 4 International Masterclass program physicsmasterclasses.org/.

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Items from Kahoot questionnaire - I

- 1 Which particle are considered elementary today?

a) Protons, neutrons and electronsb) Quarks and electrons
c) Atoms! Particles which can not be divided (gr. a thomos).
- 2 Does antimatter have been discovered yet?

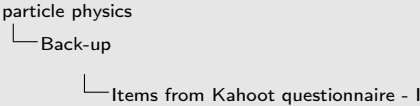
a) Yes, it exists in certain parts of the Universe.
b) Not yet, we just assume it exists.
c) Yes, it is used in current daily applications.
- 3 Which of the following forces have an electrostatic origin?

a) Friction force, elastic force.
b) Archimedes' force.
c) Van der Waals forces, ionic and covalent bonds.
d) Forzza Milan!
- 4 The www internet pages have been invented by scientist studying particle phycs?

a) Americans have invented them
b) Yes, they invented them to deliver faster the research data.
c) It doesn't matter, is more important who invented Facebook
- 5 The transmutation of the elements, is it physically possible(Ex. Pb -> Au)?

a) Yes, it is possible.
b) No, the alchemists have given up when Chemistry was born!

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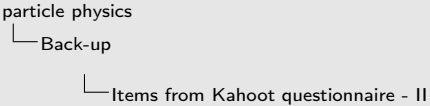
Kahoot 7595291



Items from Kahoot questionnaire - II

- 1 Which particle intermediates the strong force?
 - a) neutralino
 - b) lion
 - c) gluon
 - d) fortino
- 2 What percent of the Universe is formed by dark matter and dark energy?
 - a) 13%
 - b) 100%
 - c) 96%
 - d) 32.8%
- 3 If the nucleus would be 1 cm, how much would measure the whole atom?
 - a) As a paper sheet
 - b) As a basket court
 - c) As 5 football fields
 - d) As Bucharest city
- 4 What is the total distance travelled by the protons within LHC ring in 10 hours?
 - a) The distance between Earth and Sun forth and back
 - b) The distance between Earth and Neptun forth and back
 - c) The distance between London and Paris
 - d) The distance around the Earth
- 5 What is the most abundant elementary particle in the human body?
 - a) up quark
 - b) down quark
 - c) electron
 - d) bottom quark

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Kahoot 4277826

